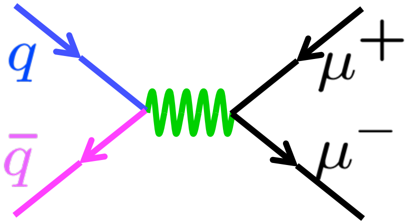
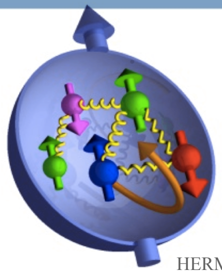
What can more Drell-Yan data tell us about QCD (or Drell-Yan Overview)?

Paul E. Reimer
Physics Division
Argonne National Laboratory

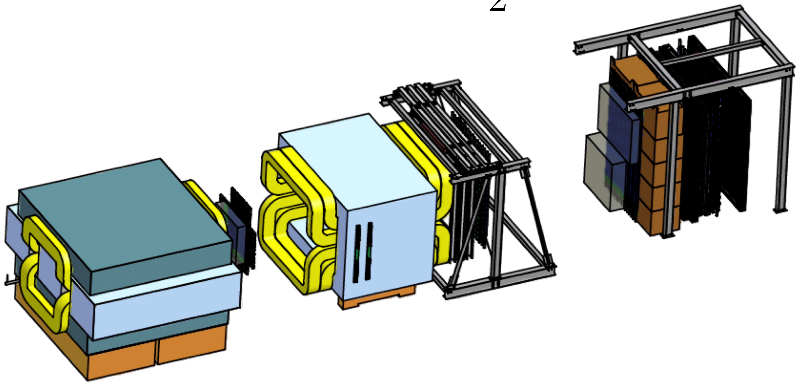




HERMES
U. Elschenbroich

1. The Drell-Yan Process: The Big Picture
2. Unpolarized Measurements
    1. Longitudinal parton distributions $\frac{d\sigma^{\mathrm{pd}}}{d\sigma^{\mathrm{pp}}} = \frac{1}{2}\left(1 + \frac{\bar{d}}{\bar{u}}\right)$
    2. Angular distributions $\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$
3. Polarized Measurements

$$f_{1T}^{\perp}\big|_{\mathrm{DIS}} = -\, f_{1T}^{\perp}\big|_{\mathrm{DY}}$$



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

The Big Picture

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

VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

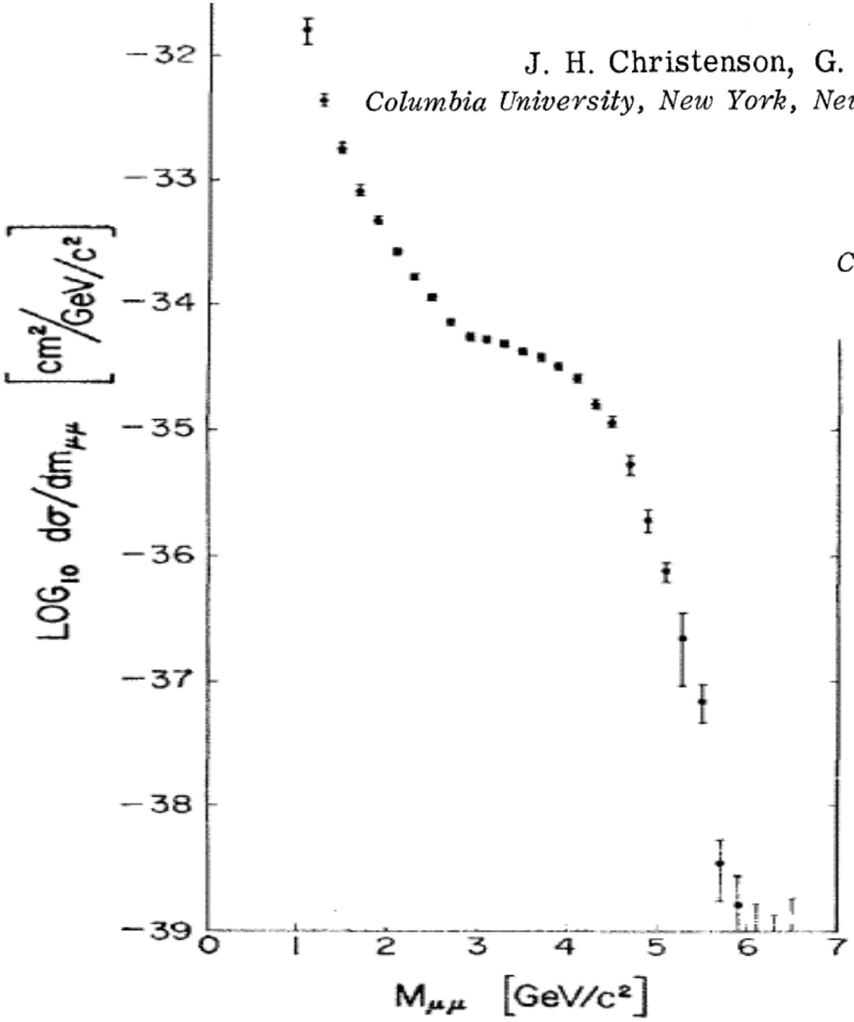
Observation of Massive Muon Pairs in Hadron Collisions*

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 $d\sigma/dm_{\mu\mu} \approx 10^{-32} / m_{\mu\mu}^5\ \mathrm{cm}^2\ (\mathrm{GeV}/c)^{-2}$ 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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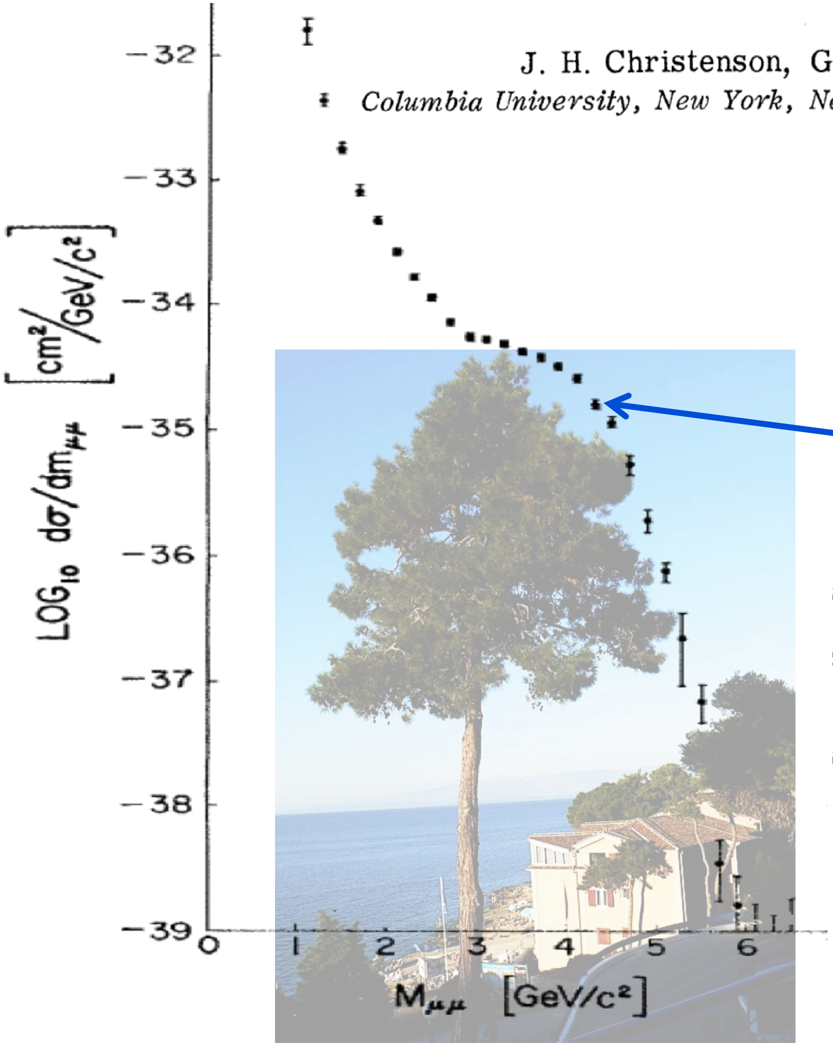
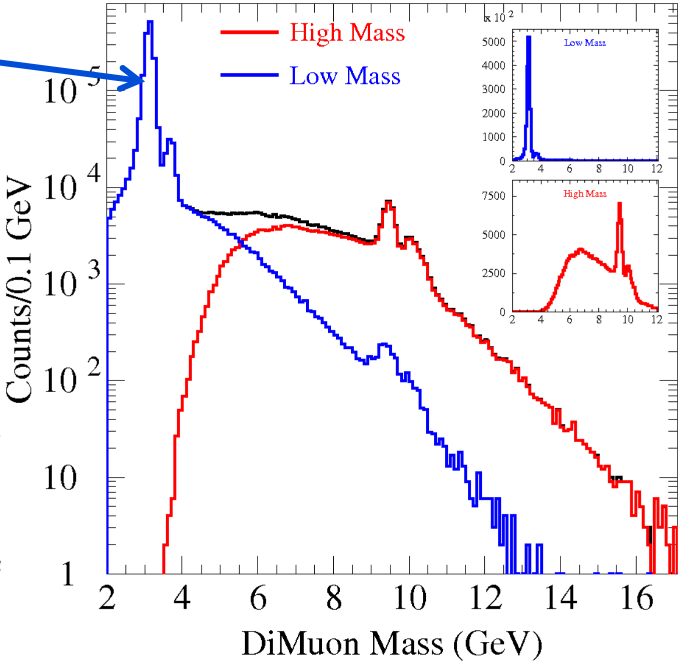
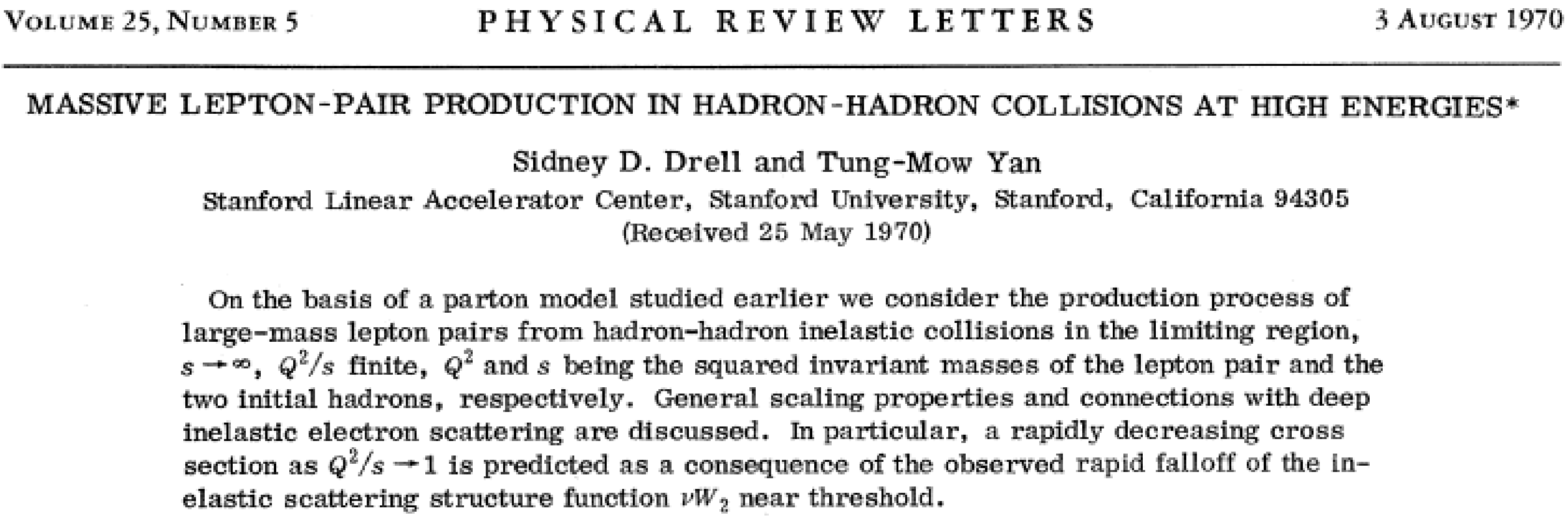




Don't miss the tree when looking at the beautiful scenery

Drell and Yan’s explanation



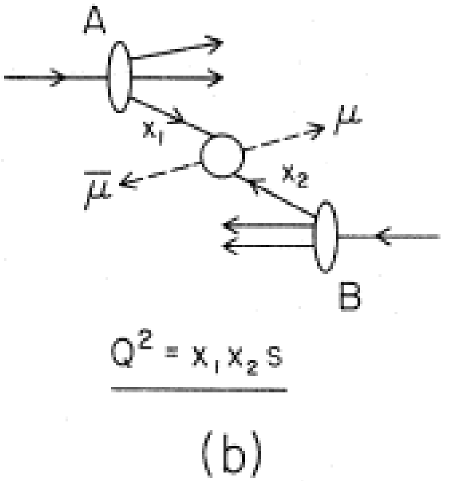
VOLUME 25, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1970

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 νW_2 near threshold.



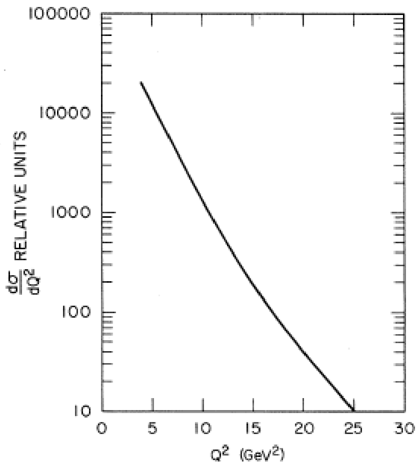
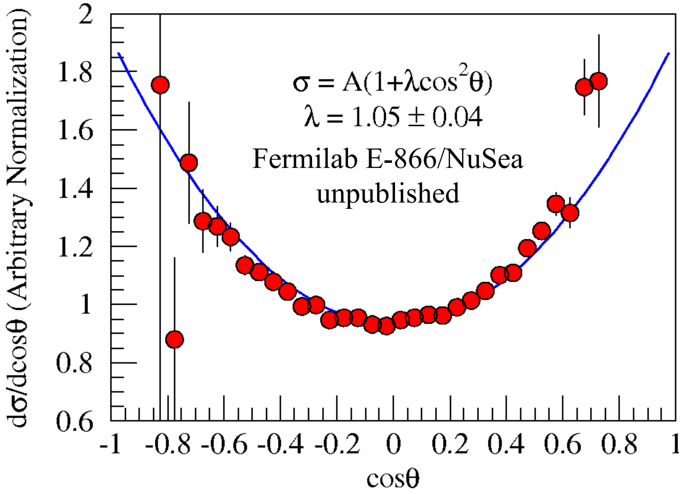


FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributions and with relative normalization.

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



Drell-Yan Cross Section

- These
  of the
- **Parton**
- Intrins
  (althou
- **Soft glu**
- $\frac{d\sigma}{d\Omega}$

Drell-Yan Cross Section

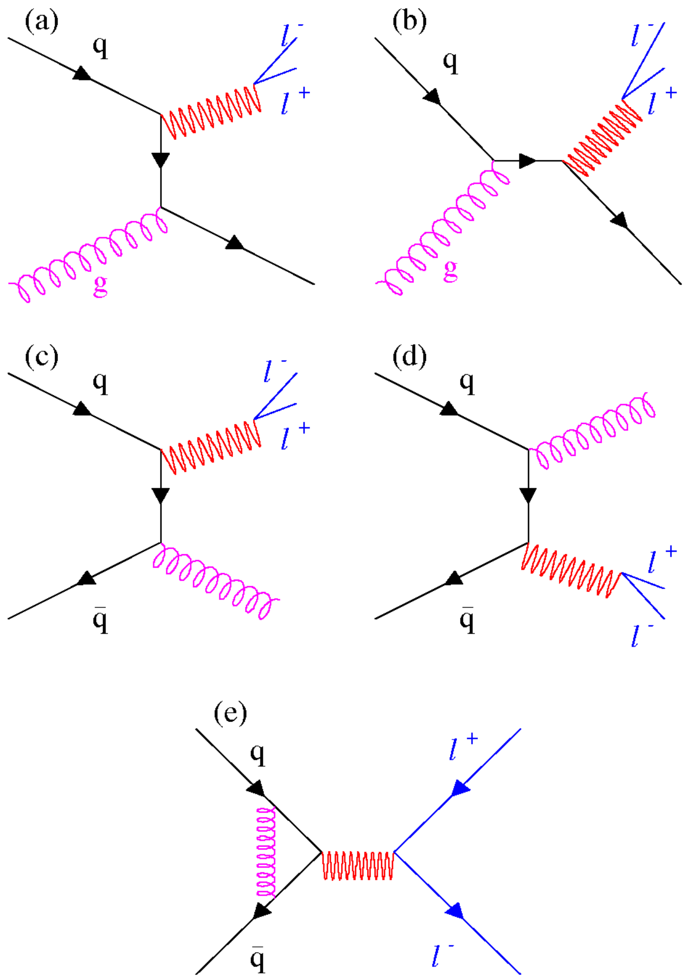
Next-to-Leading Order

- These diagrams are responsible for up to **50% of the measured cross section**
- **Parton distributions are Universal!**
- Intrinsic transverse momentum of quarks (although a small effect, λ > 0.8)
- **Soft gluon resummation at all orders**

Angular Distributions

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

Higher Twist??



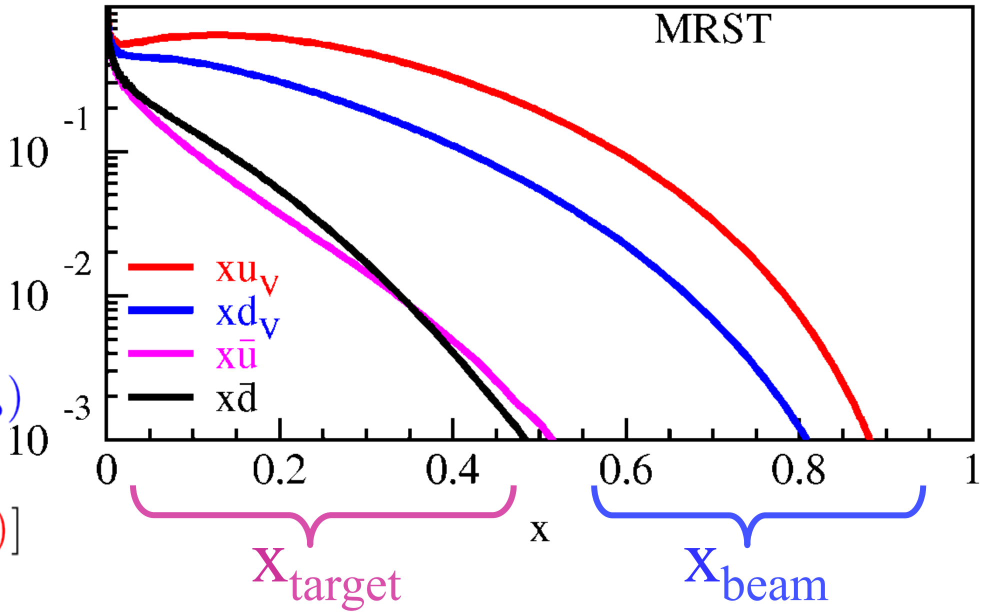
Drell-Yan Cross Section

- Measured cross section is a convolution of beam and target parton distributions
- **Proton Beam**
  - Target antiquarks and beam

$$\frac{d^2\sigma}{dx_{\mathrm{b}}\,dx_{\mathrm{t}}} = \frac{4\pi\alpha^2}{x_{\mathrm{b}}x_{\mathrm{t}}s}\sum_{q\in\{u,d,s,\dots\}} e_q^2\left[\bar{q}_{\mathrm{t}}(x_{\mathrm{t}})q_{\mathrm{b}}(x_{\mathrm{b}}) + \bar{q}_{\mathrm{b}}(x_{\mathrm{b}})q_{\mathrm{t}}(x_{\mathrm{t}})\right]$$

- u-quark dominance

  $(2/3)^2$ vs. $(1/3)^2$



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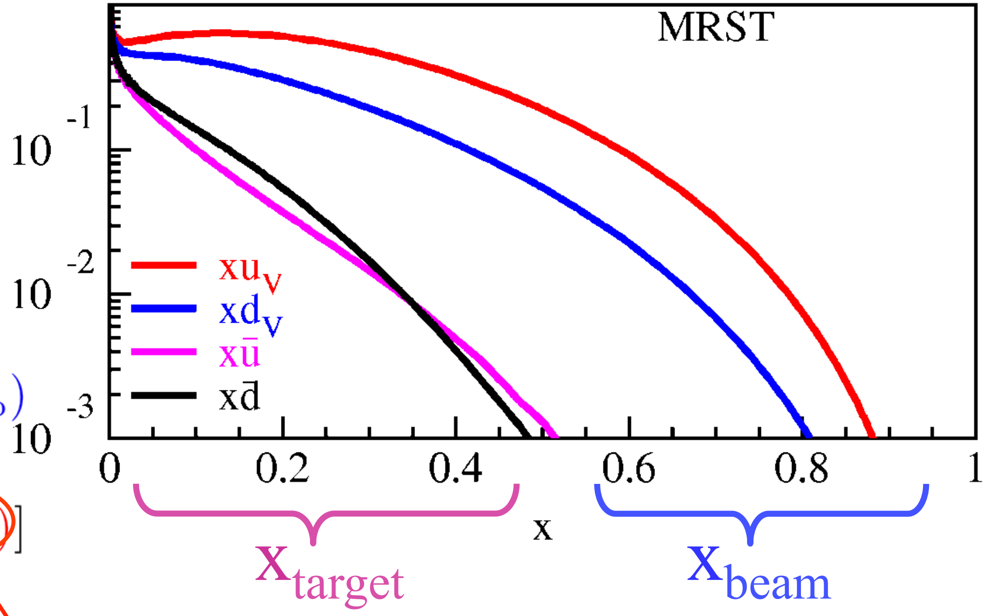
Acceptance limited



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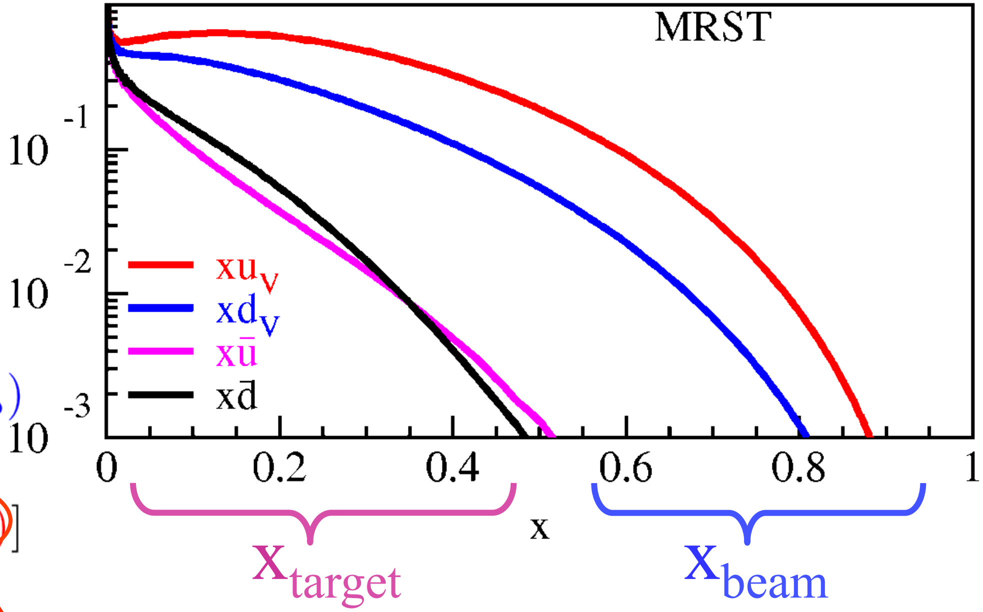
Acceptance limited



- u-quark dominance

  $(2/3)^2$ vs. $(1/3)^2$

- **π^- beam**
  - Valence beam anti-u quark and u target quark

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

Drell-Yan Cross Section

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Acceptance limited

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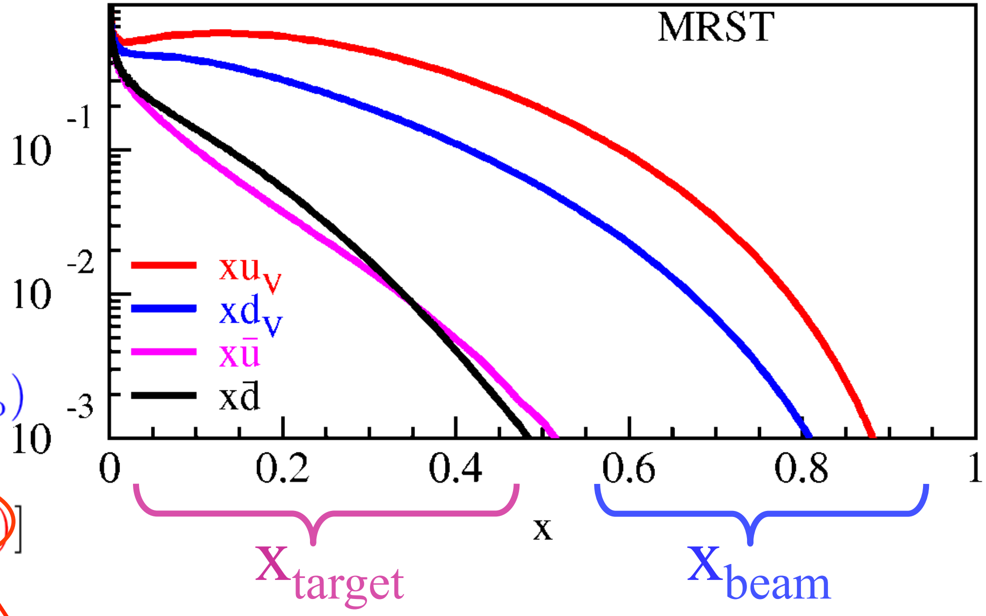
Valence × Valence

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

Unpolarized Drell-Yan—Boring?

Unpolarized Drell-Yan—No Exciting!!!!

- **Measurements of longitudinal structure of target and beam**
- **Measurements of Boer-Mulders through angular distributions**

Drell-Yan Cross Section

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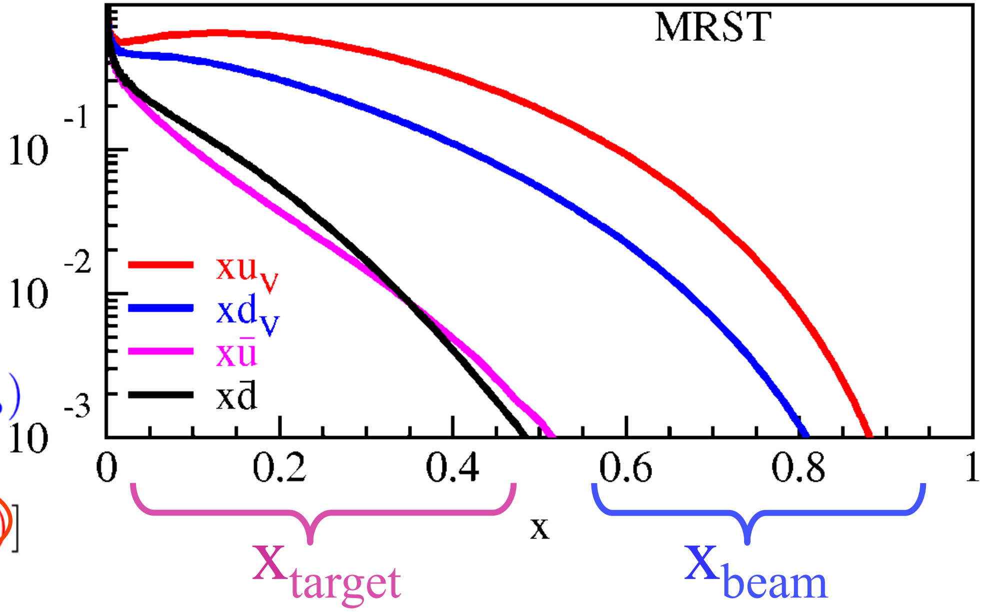


- In leading order w/above assumptions

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

Next-to-leading order terms have minimal effect on the ratio

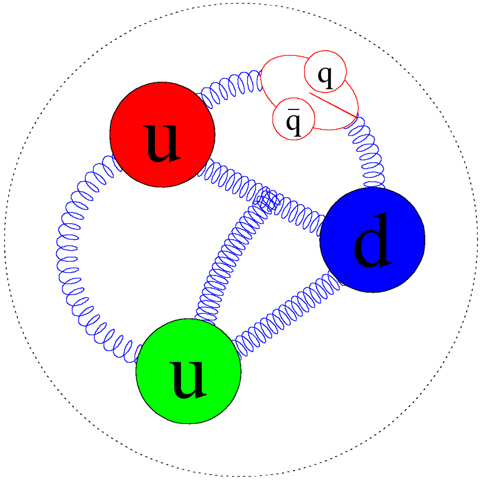
- Suggested by Martin, Stirling and Roberts Phys.Lett. B308 (1993) 377

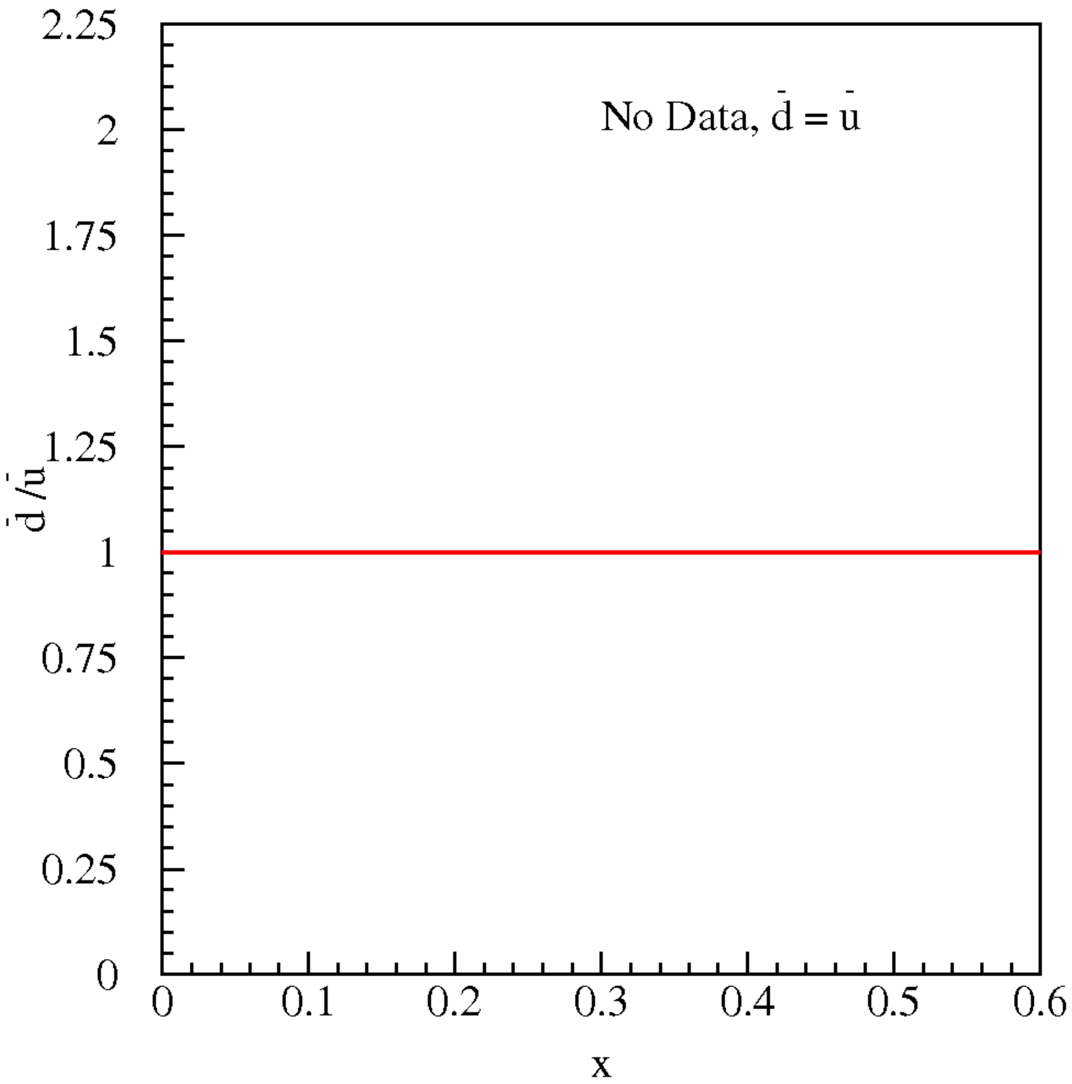
Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

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

- Why shouldn't it be
  - the sea is generated by gluon splitting.
  - Gluons couple to color, not flavor!





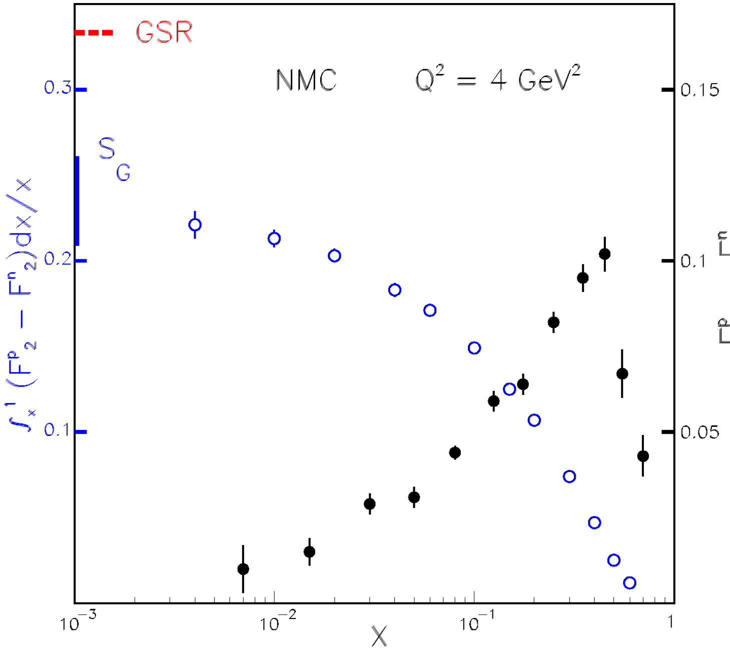
Light Antiquark Flavor Asymmetry: Brief History

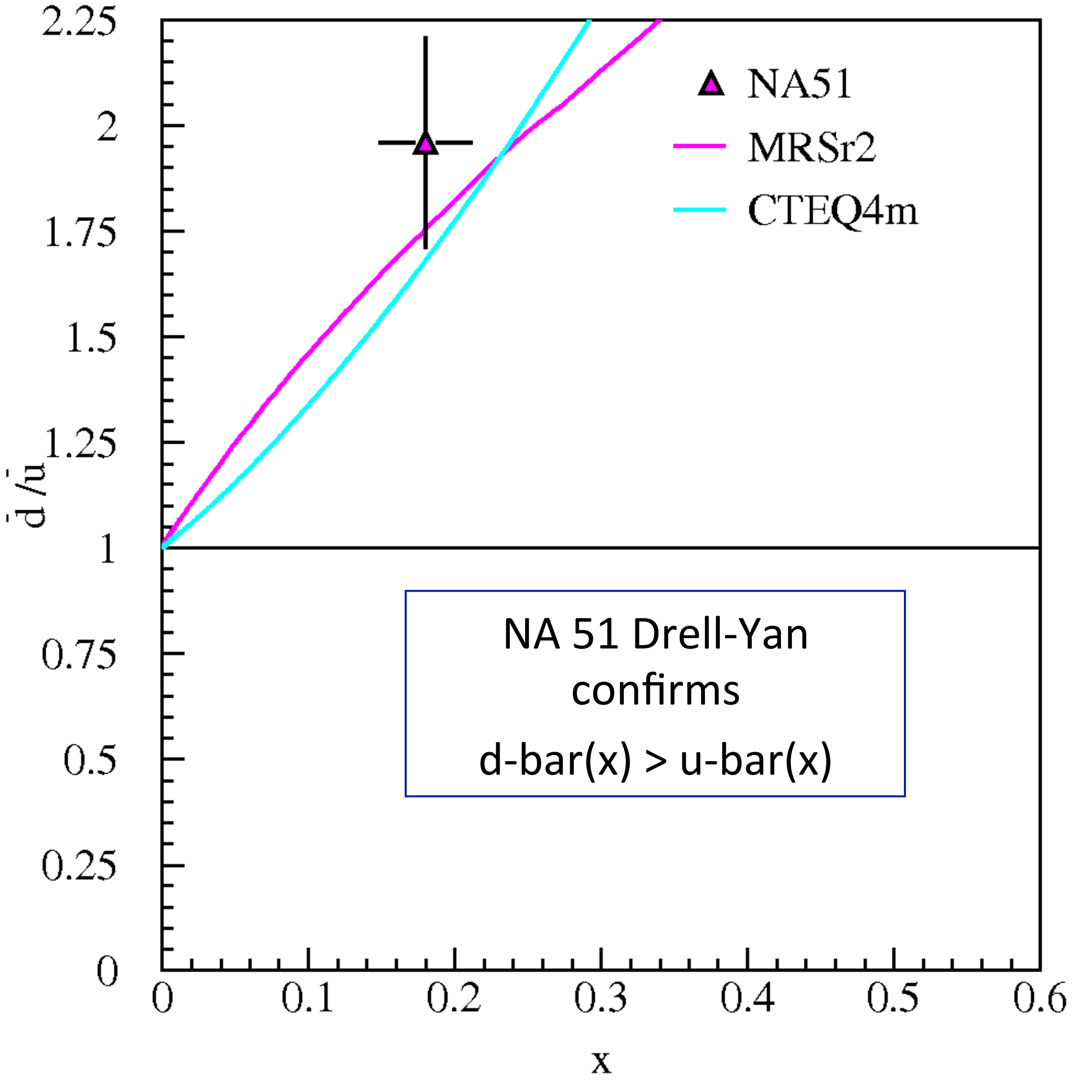
- Naïve Assumption:

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

- CERN NMC (Gottfried Sum Rule)

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$





NA 51 Drell-Yan confirms

d-bar(x) > u-bar(x)

Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

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

- NMC (Gottfried Sum Rule)

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$

- NA51 (Drell-Yan)

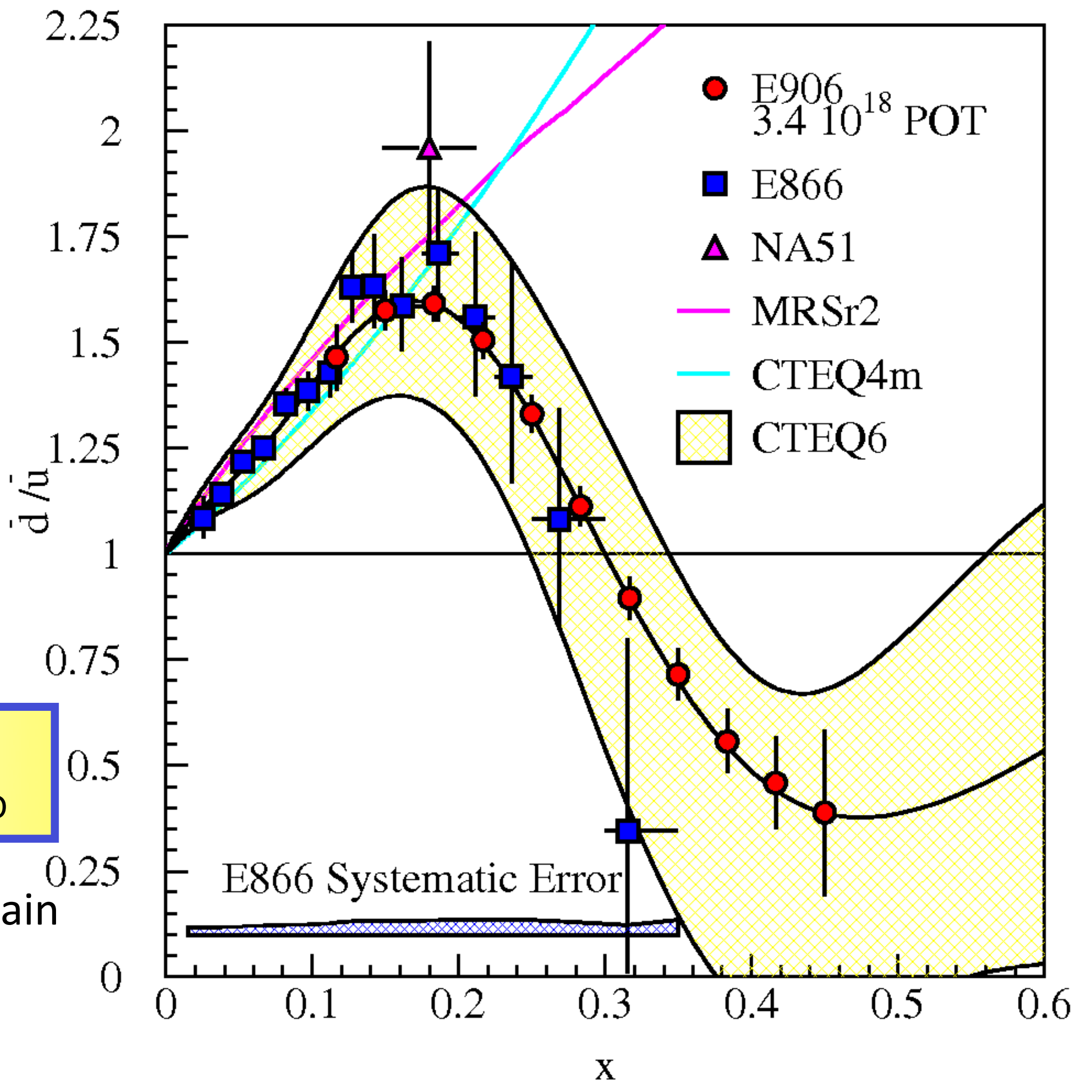
$$\bar{d} > \bar{u} \text{ at } x = 0.18$$

- E866/NuSea (Drell-Yan)

$$\bar{d}(x)/\bar{u}(x) \text{ for } 0.015 \leq x \leq 0.35$$

- Knowledge of sea dist. are data driven
  - Sea quark distributions are difficult for Lattice QCD

- Non perturbative QCD models can explain excess d-bar quarks, but not return to symmetry or deficit of d-bar quarks



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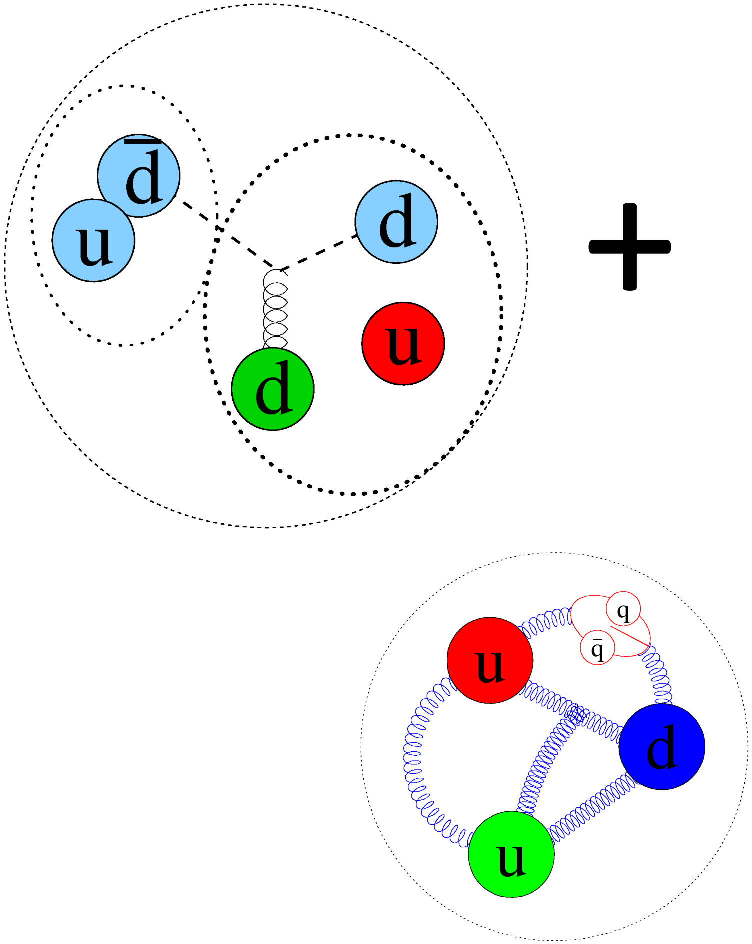
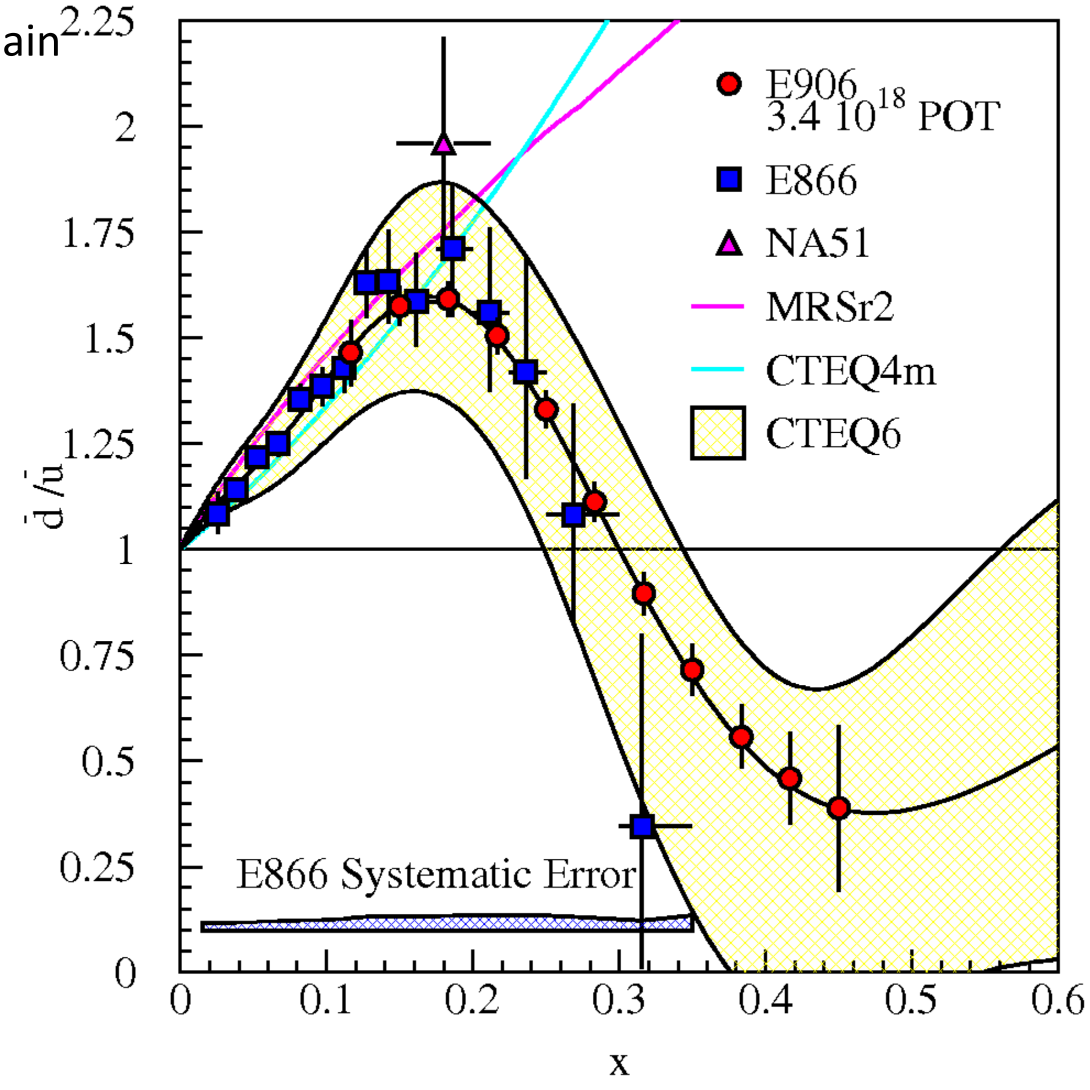
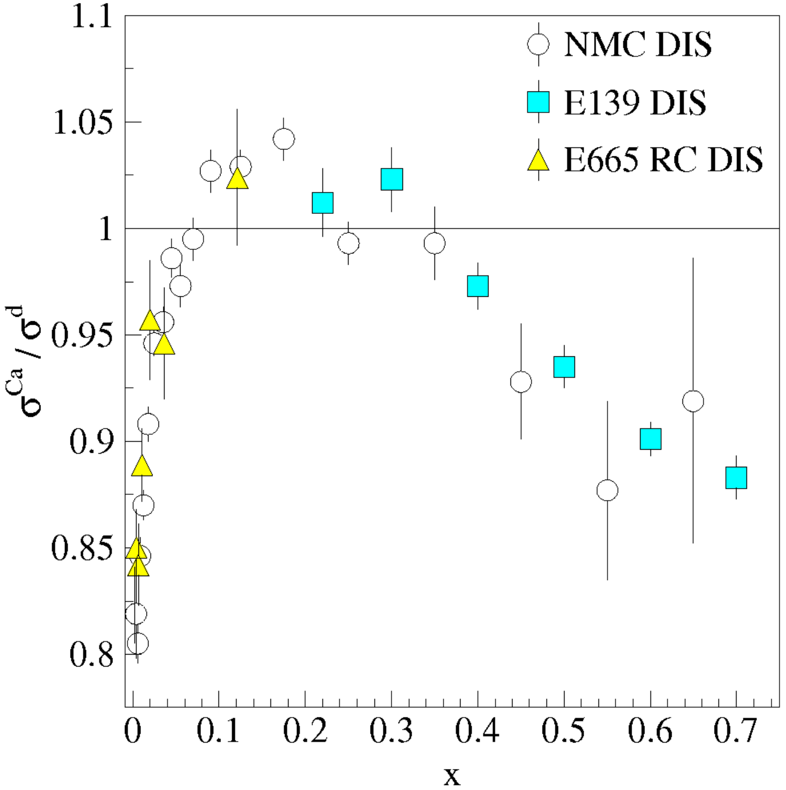


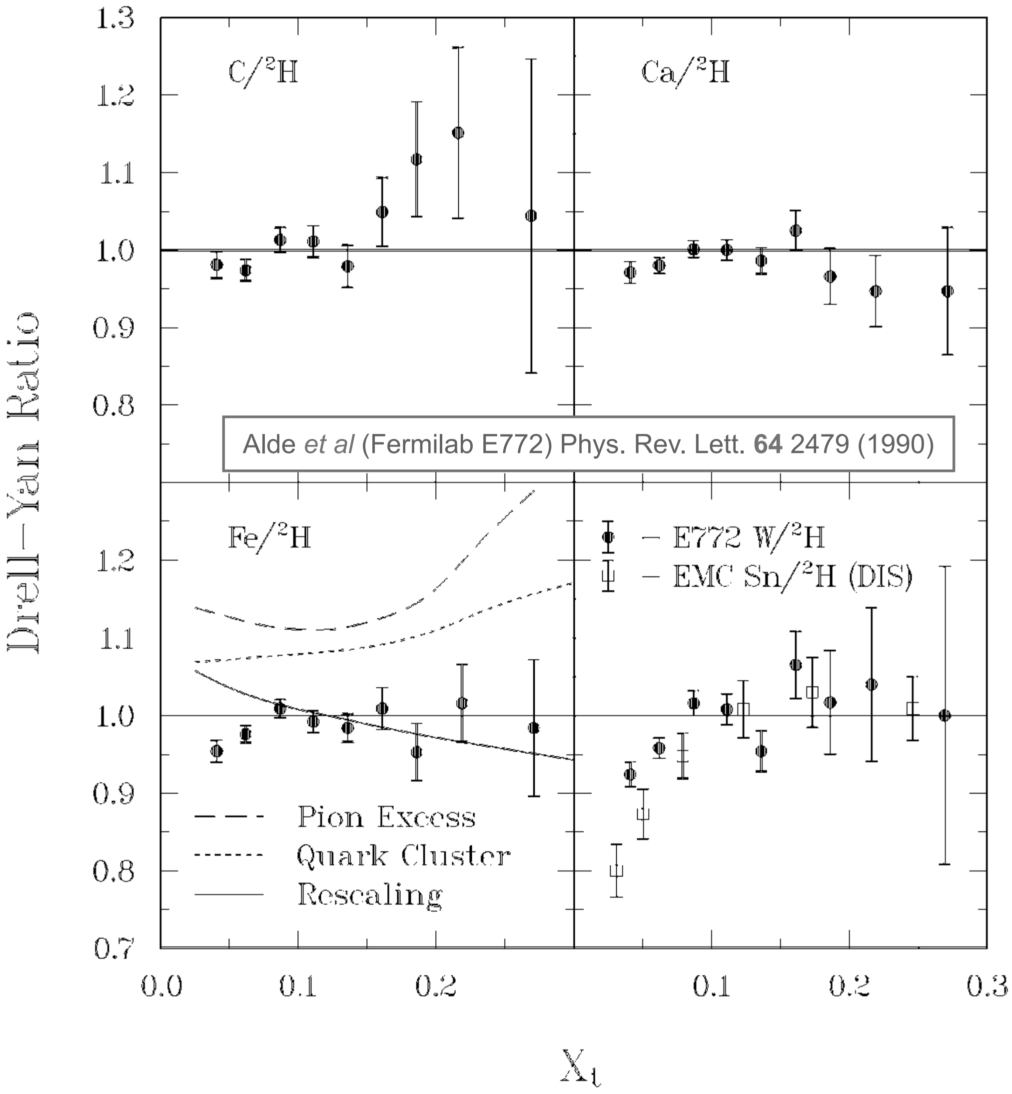


Structure of nucleonic matter: How do sea quark distributions differ in a nucleus?

Comparison with Deep Inelastic Scattering (DIS)

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

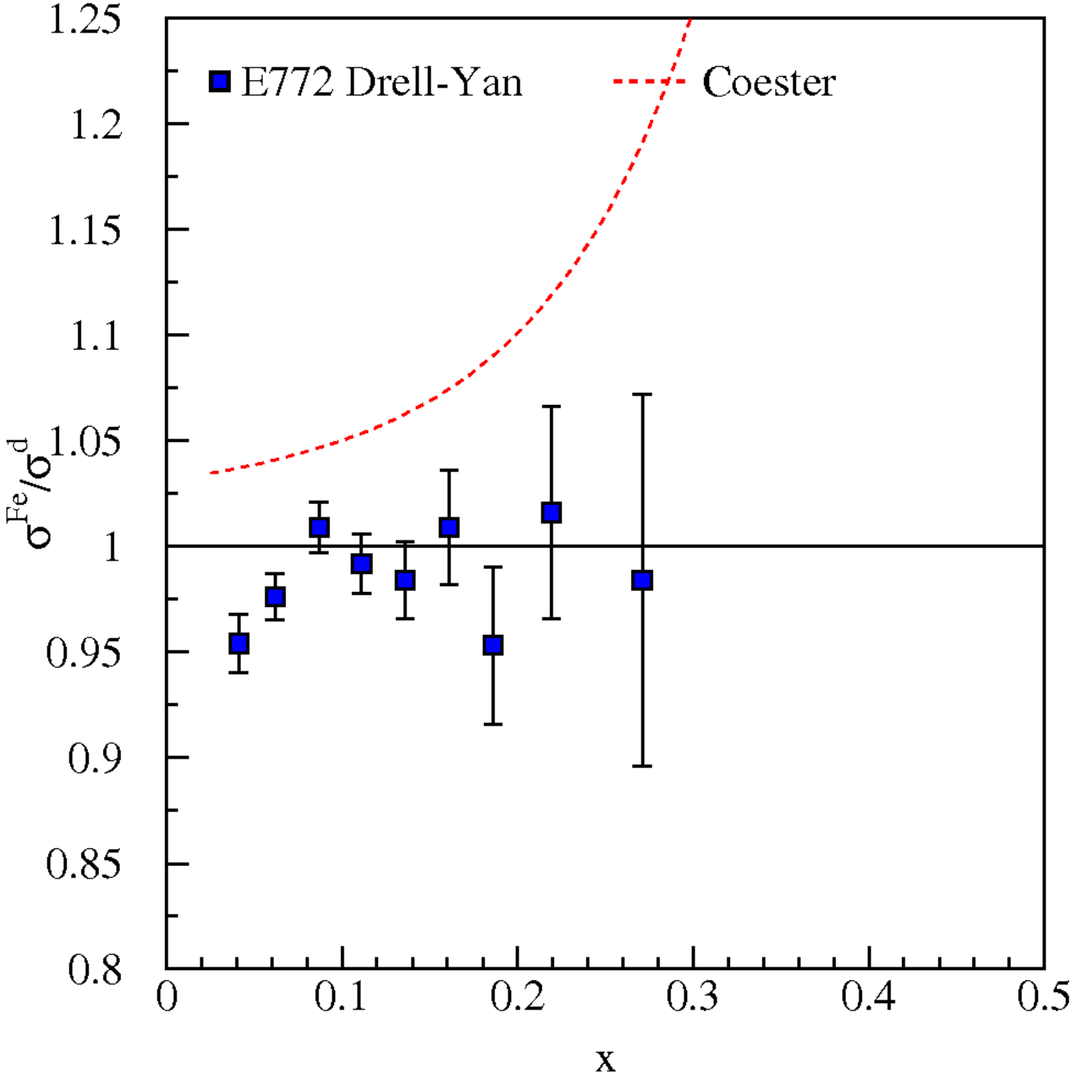




Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

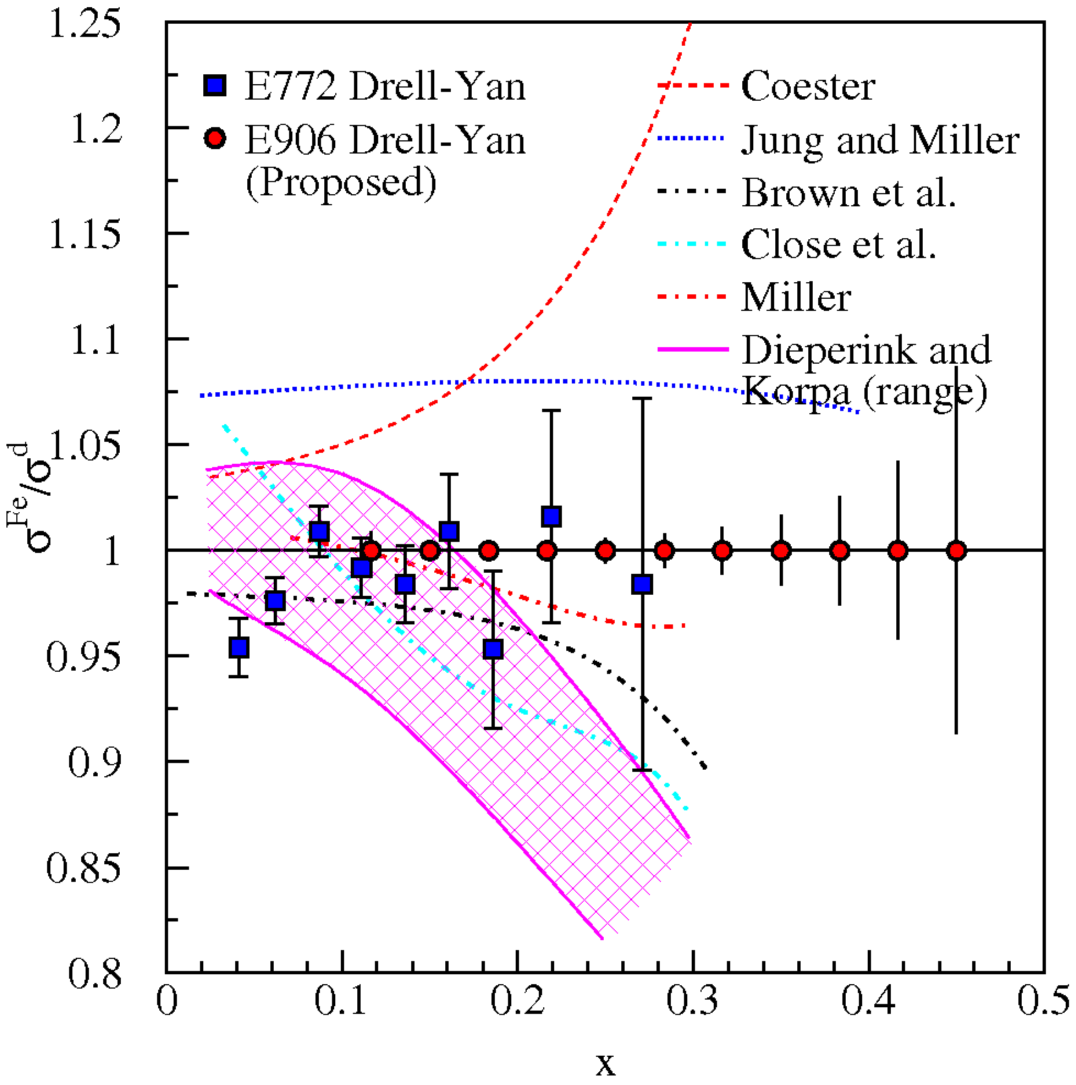
Structure of nucleonic matter: Where are the nuclear pions?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual “Nuclear” mesons (pions).
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.

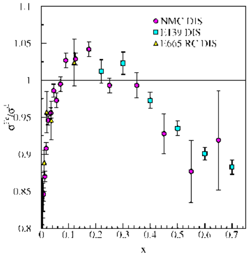


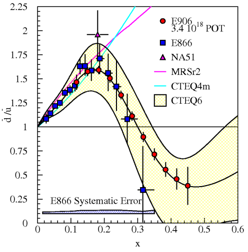
Structure of nucleonic matter: Where are the nuclear pions?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual “Nuclear” mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.
- Contemporary models predict large effects to antiquark distributions as x increases.
- Models must explain both DIS-EMC effect and Drell-Yan



Pionic Parton Distributions: Why are should you be interested in the pion?





1. Explains quark asymmetry in nucleon sea.
2. Key role in nuclear binding and structure

3. Simple quark-antiquark system (valence).
   - *Should* have an easy theoretical interpretation.
   - What about mass—constituent quark mass ≈300 MeV each?

3. QCD's Goldstone Boson

How do we treat 3 and 4 in a unified way?

Models predict different behavior as x→1

At some base Q_0

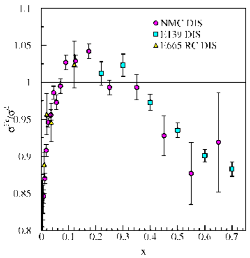
pQCD: $xq(x)/(1-x)^{\beta}$ $\beta = 2$

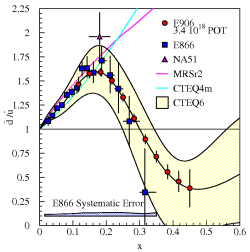
NJL: $xq(x)/(1-x)^{\beta}$ $\beta = 1$

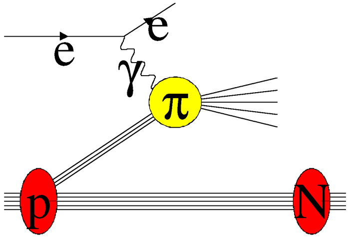
DSE: $xq(x)/(1-x)^{\beta}$ $\beta \sim 1.9$

Evolution to experimental Q increases β.

Pionic Parton Distributions: Why are should you be interested in the pion?







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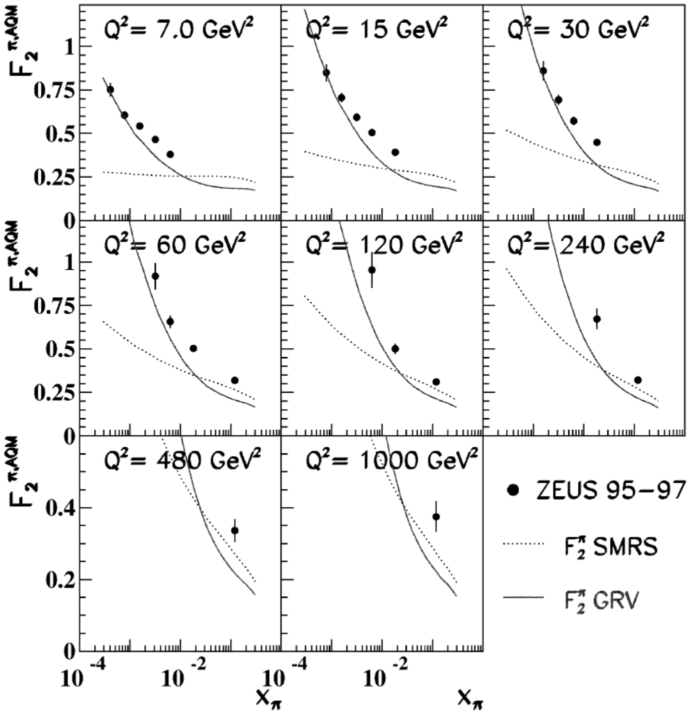
"Pion targets are not abundant" Hecht

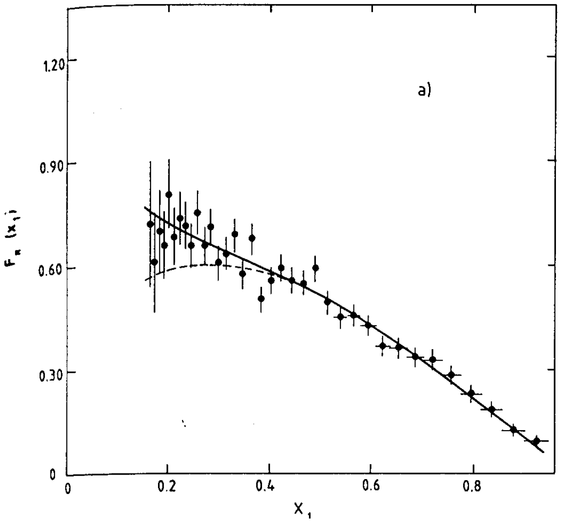
DIS on virtual pions:

ep→eNx HERA data [ZEUS, NPB637 3 (2002)]

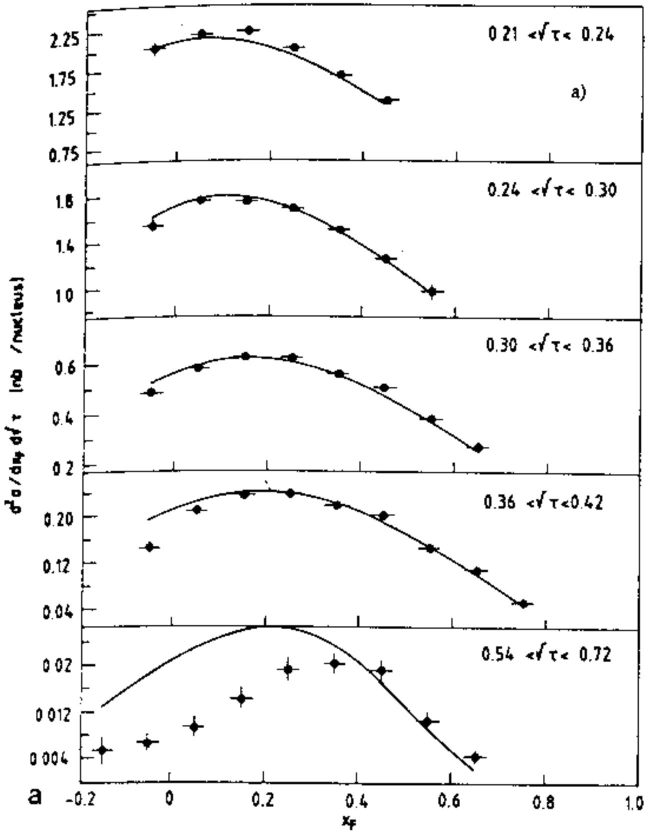
Possible JLab and EIC.



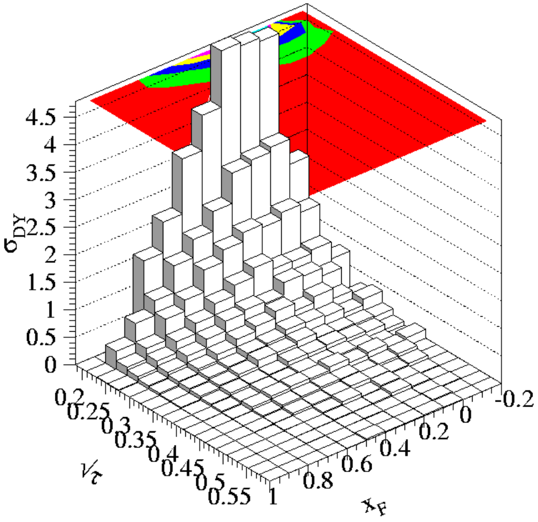
Pion Drell-Yan Data: CERN NA3 (π^+) NA10 (π^-)



CERN NA3 200 GeV π^- data (also have 150 and 180 GeV π^- and 200 GeV π^+ data).

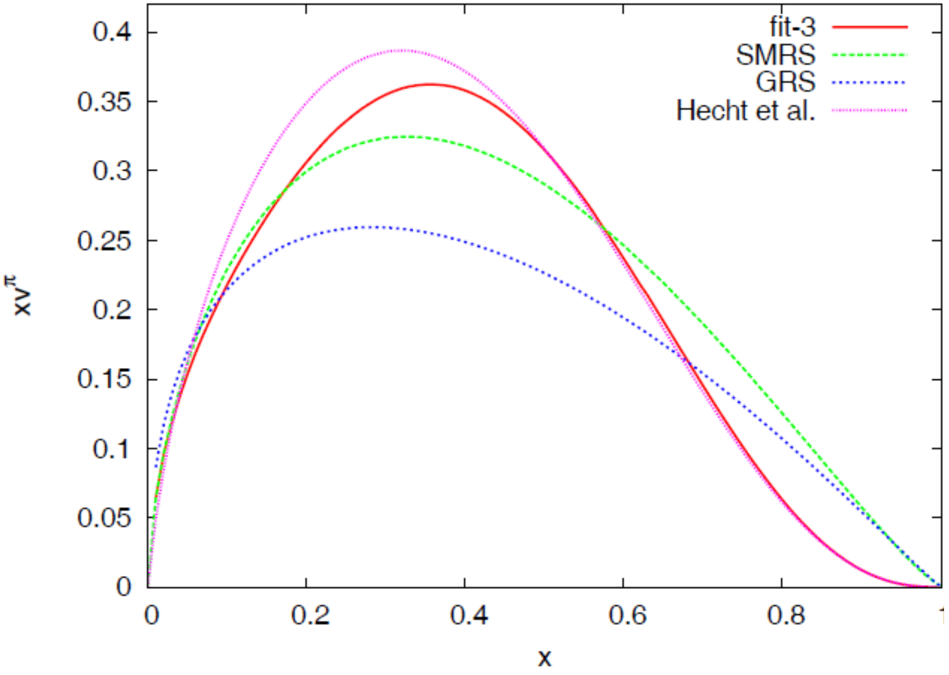


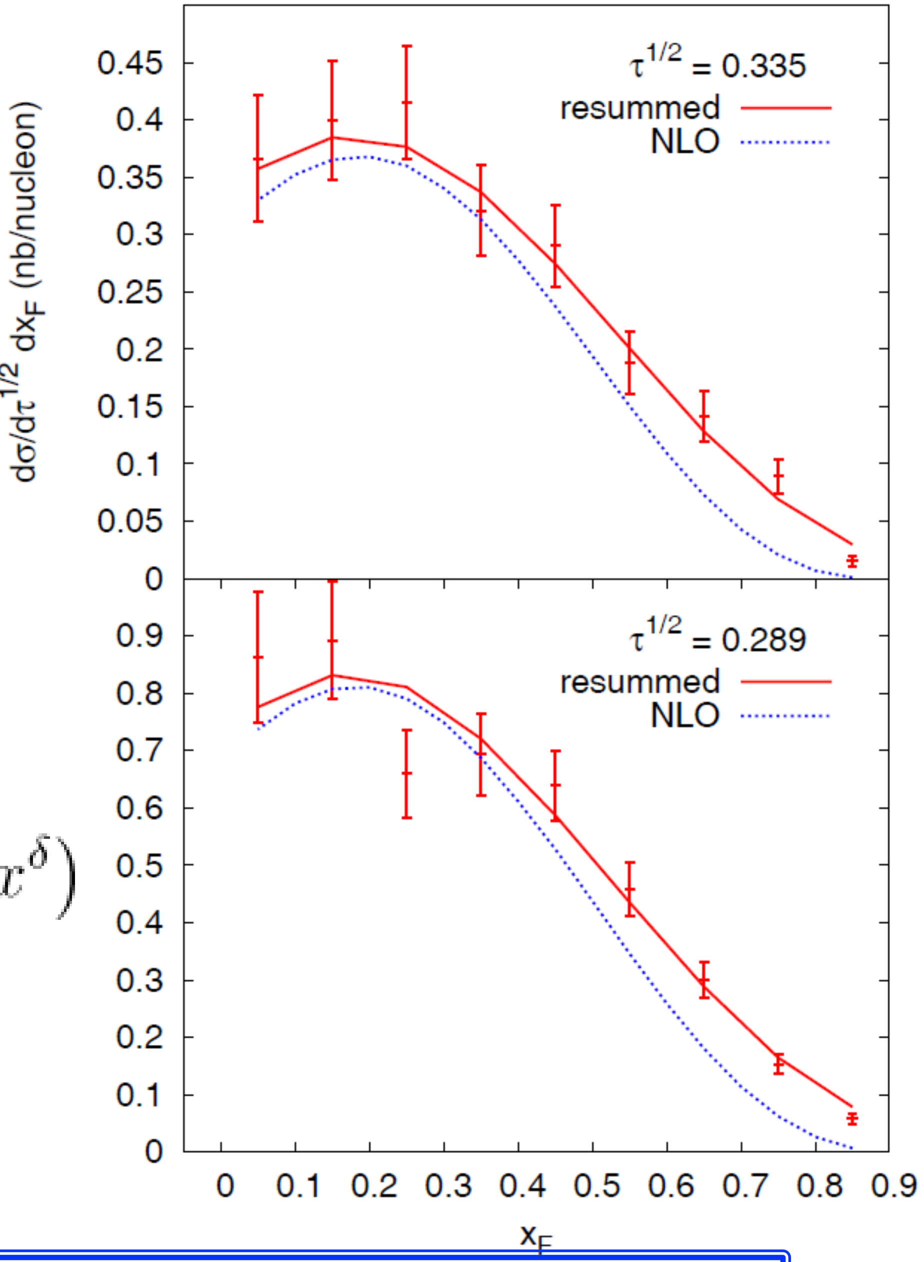
CERN NA10 194 GeV π^- data



Fermilab E-615 π^- data

Soft Gluon Resummation





$$xq_V^\pi(x) = A_V^\pi x^\alpha (1-x)^\beta \left(1+\gamma x^\delta\right)$$

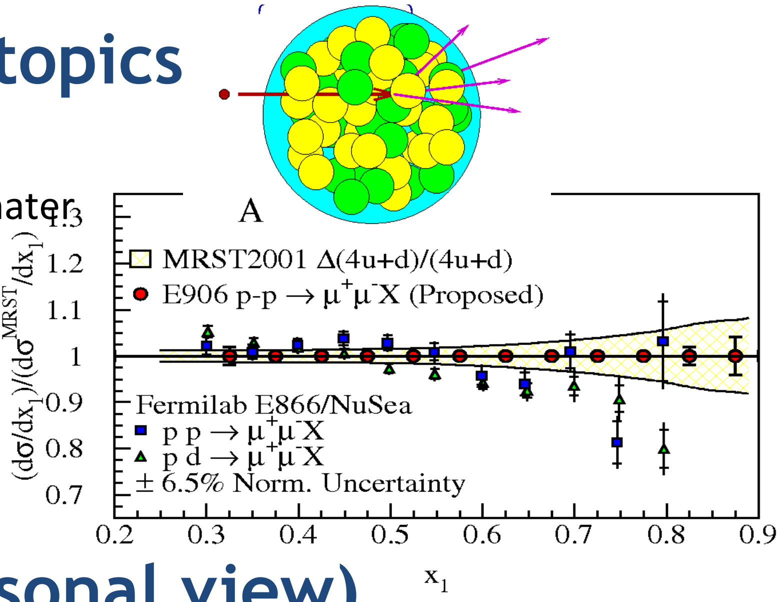
$\beta = 2.03 \pm 0.06$

QCD and Dyson-Schwinger survive!
pQCD: $xq(x)/(1-x)^\beta$ $\beta = 2$
DSE: $xq(x)/(1-x)^\beta$ $\beta \sim 1.9$

Caveat: Better data would really help establish this.

Longitudinal Structure: Other topics

- Partonic energy loss
  - quarks traveling through cold, strongly interacting mater
  - Are antiquarks the same?
- Large-x proton parton distributions



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
  - K-p Drell-Yan (another test of low energy QCD)
- Double Polarized Drell-Yan—Δq(x) nice complement for SIDIS and $W^{\pm}$
  - CERN Compass, J-PARC, RHIC

Transverse Momentum Distributions: Introduction

Survive k_T integration

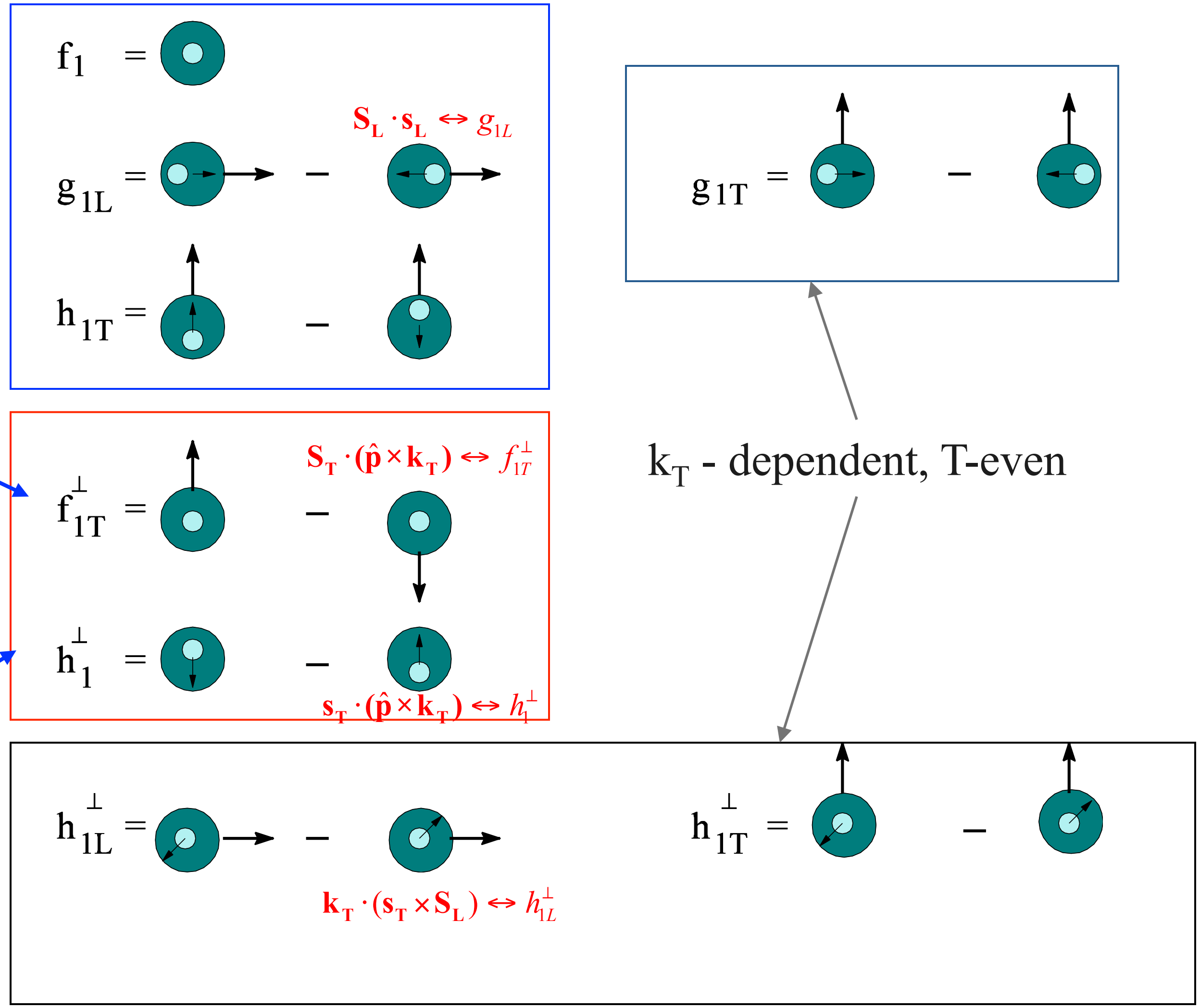
Sivers' Function

k_T - dependent,

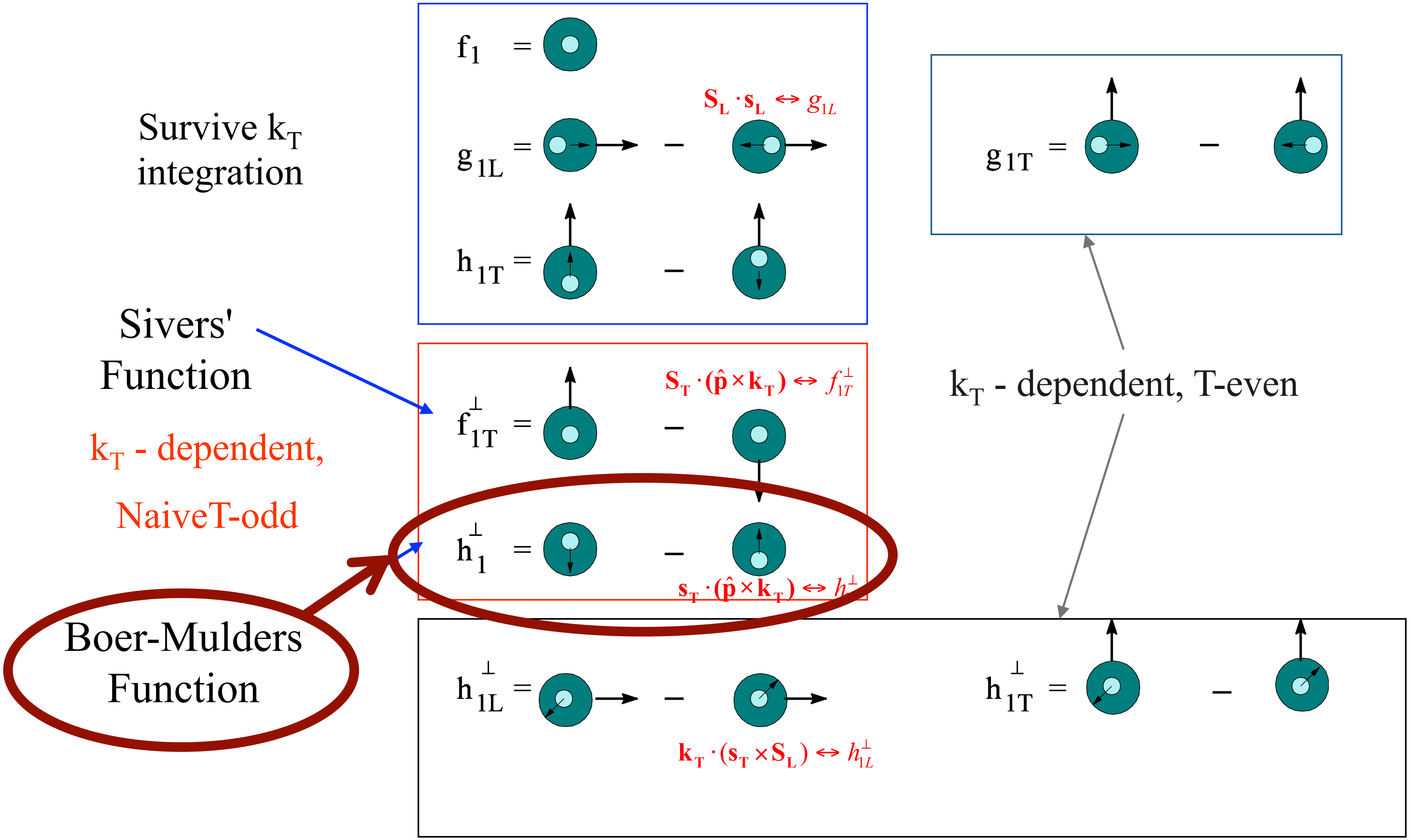
NaiveT-odd

Boer-Mulders Function

k_T - dependent, T-even



Transverse Momentum Distributions: Introduction



Survive k_T integration

$f_1 =$

$g_{1L} = \quad - $

$\mathbf{S}_L \cdot \mathbf{s}_L \leftrightarrow g_{1L}$

$h_{1T} = \quad - $

$g_{1T} = \quad - $

Sivers' Function

k_T - dependent,

NaiveT-odd

$f_{1T}^{\perp} = \quad - $

$\mathbf{S}_T \cdot (\hat{\mathbf{p}} \times \mathbf{k}_T) \leftrightarrow f_{1T}^{\perp}$

$h_1^{\perp} = \quad - $

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

Boer-Mulders Function

k_T - dependent, T-even

$h_{1L}^{\perp} = \quad - $

$\mathbf{k}_T \cdot (\mathbf{s}_T \times \mathbf{S}_L) \leftrightarrow h_{1L}^{\perp}$

$h_{1T}^{\perp} = \quad - $

Generalized Angular Distributions & Lam Tung relation

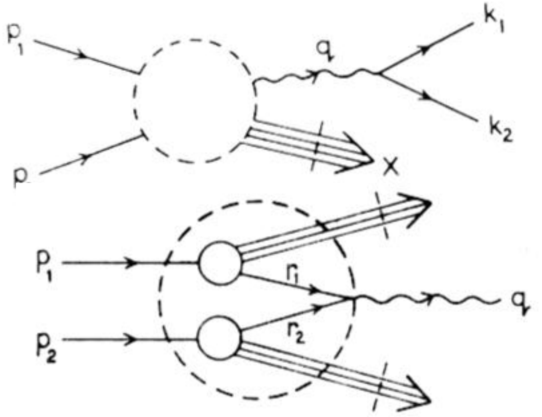
Chi-Sing Lam and Wu-Ki Tung—basic formula for lepton pair production angular distributions PRD **18** 2447 (1978)

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

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

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

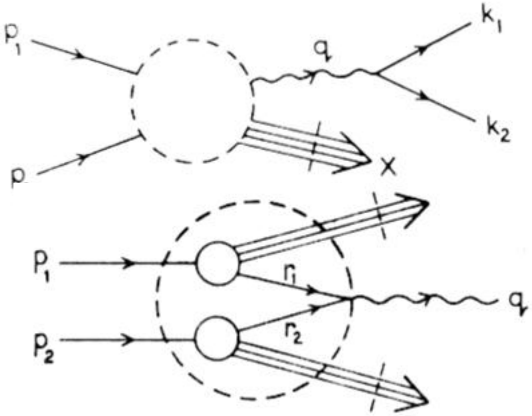
Generalized Angular Distributions & Lam Tung relation

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

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

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

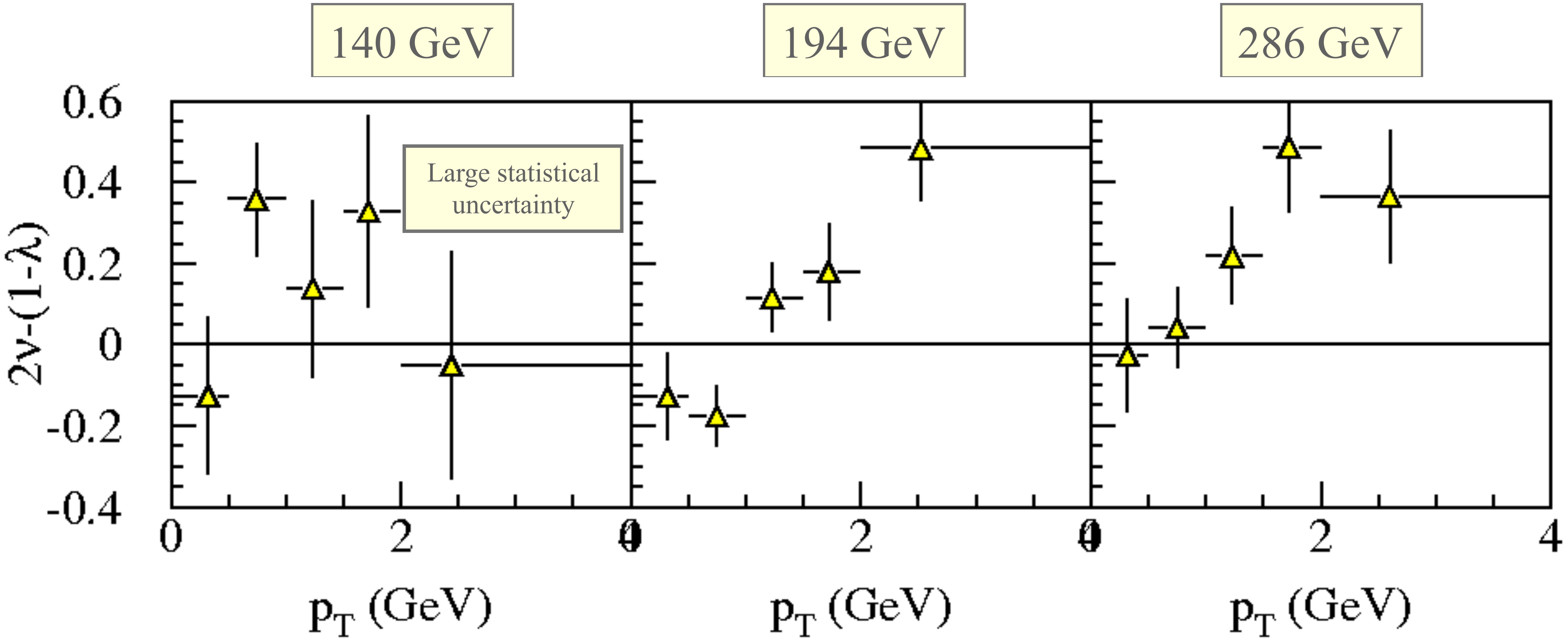


Lam-Tung relation

- Derived in analogy to Colin-Gross relation of DIS

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

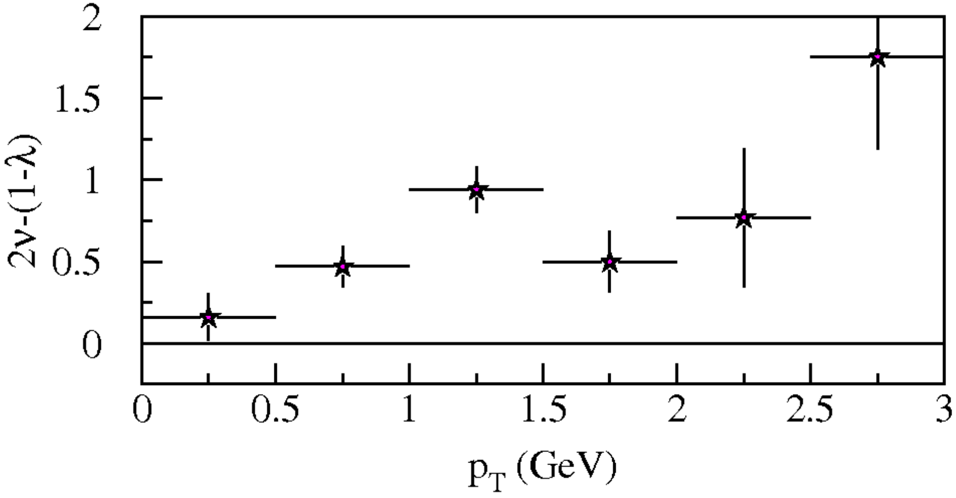
NA10 Lam-Tung Relation vs. p_T



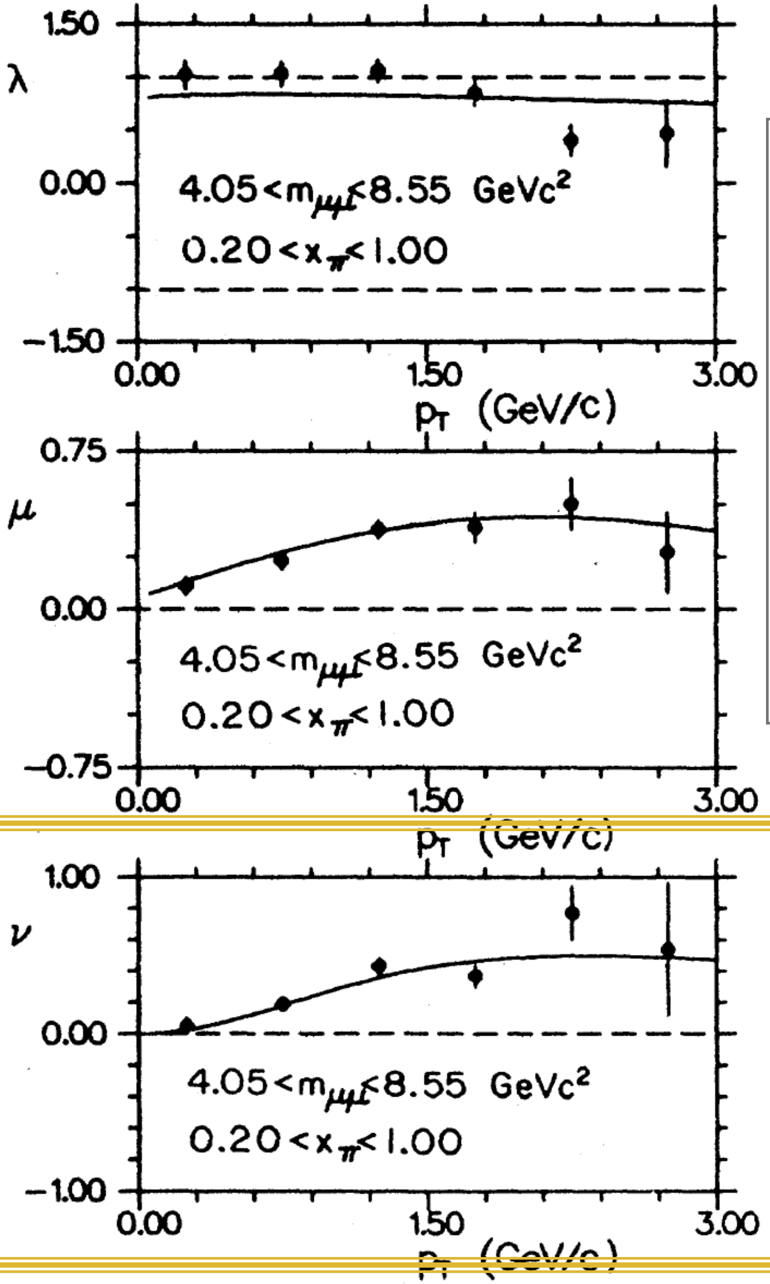
- Violation of Lam-Tung relation as p_T increases in higher momentum data. Statistics poor in 140 GeV data.
- Note: Correlation between λ and ν uncertainties not considered.
- Since most data is at low p_T, *on average* the Lam-Tung relationship holds
- For all three energies **$\lambda \sim 1$** and **$\nu > 0$**

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)

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)

- **k_T dependent transverse momentum distribution (Boer Mulders $h_1^{\perp}$)**
- **Factorization breaking QCD Vacuum**

- Alternatives:
  - → Nuclear effects
  - → Higher-Twist effects from quark-antiquark binding in pion

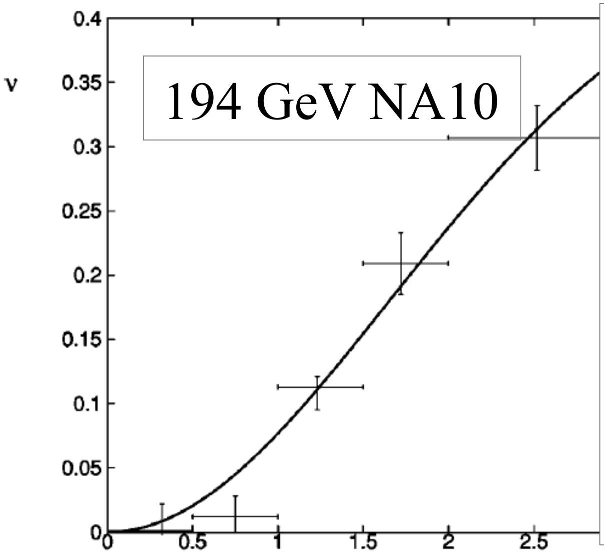
  - → Neither seen in data

Boer-Mulders Structure Function

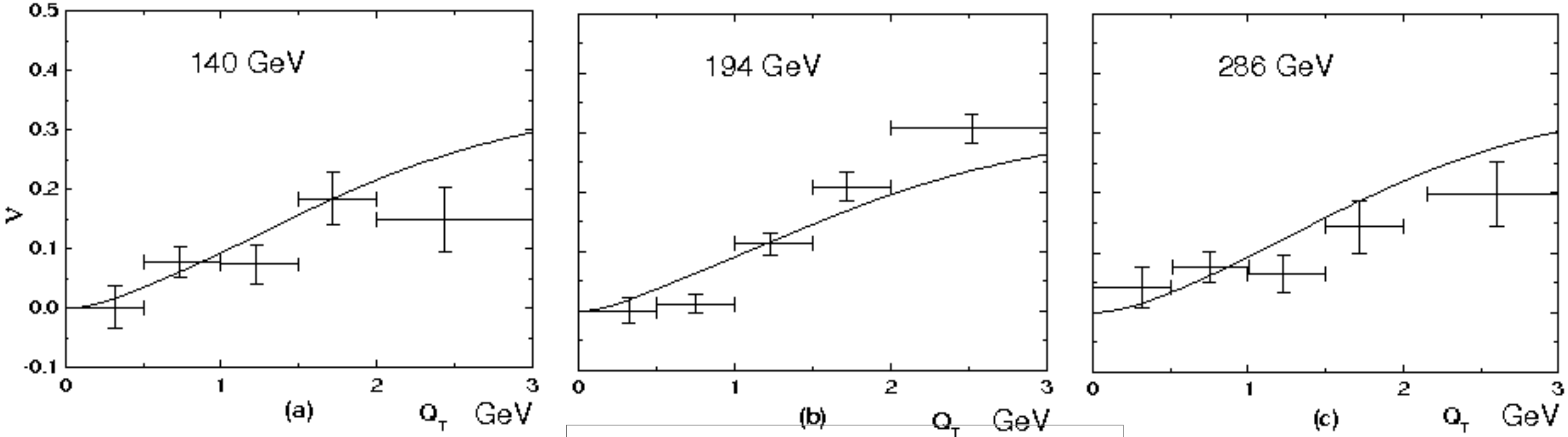
- Relates transverse spin and transverse momentum (k_T) in an unpolarized nucleon.
- Presence in both quark and antiquark in annihilation could form correlation contributing to cos(2ϕ) distribution

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

- 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).

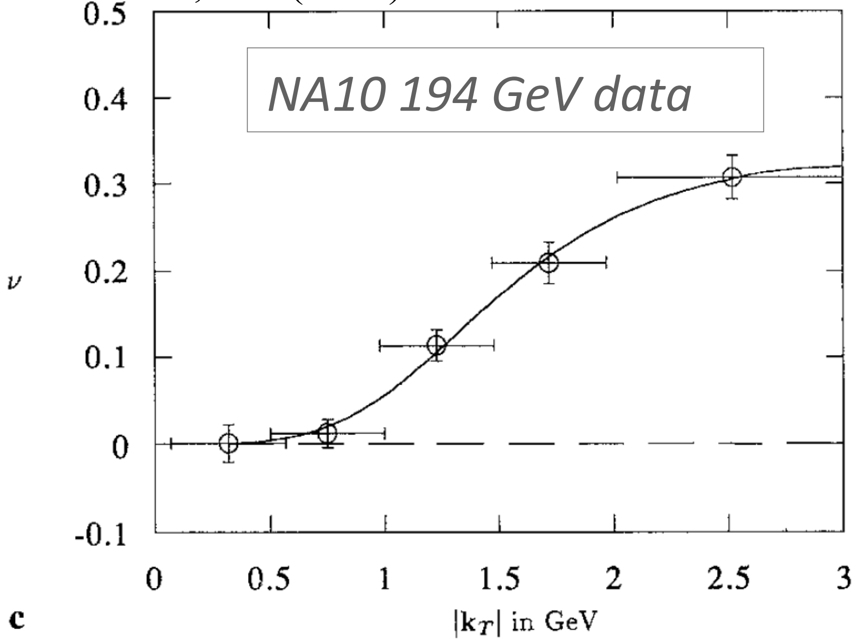
$$\nu \approx 2\mathcal{K} = 2\mathcal{K}_0 \frac{p_T^4}{p_T^4 + m_T^4}$$

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

  - Fit NA10:

    $\kappa = 0.17$

    $m_T = 1.5$

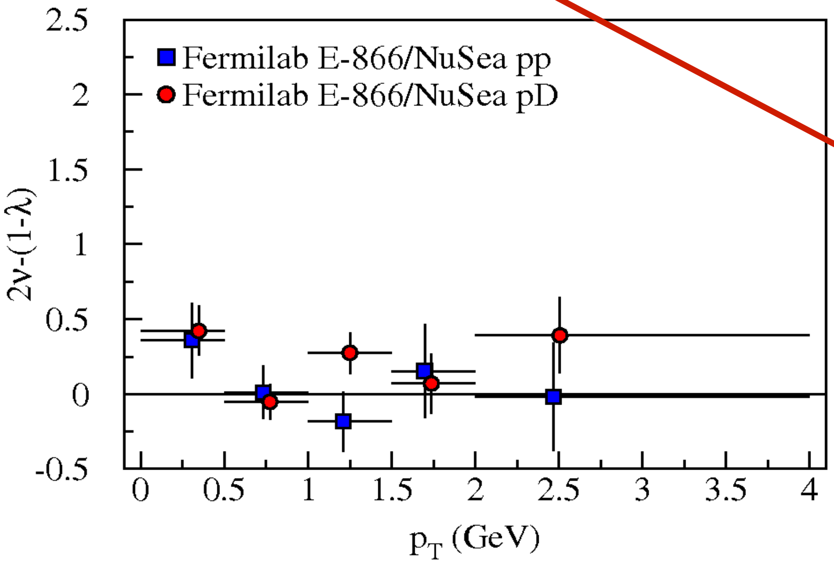


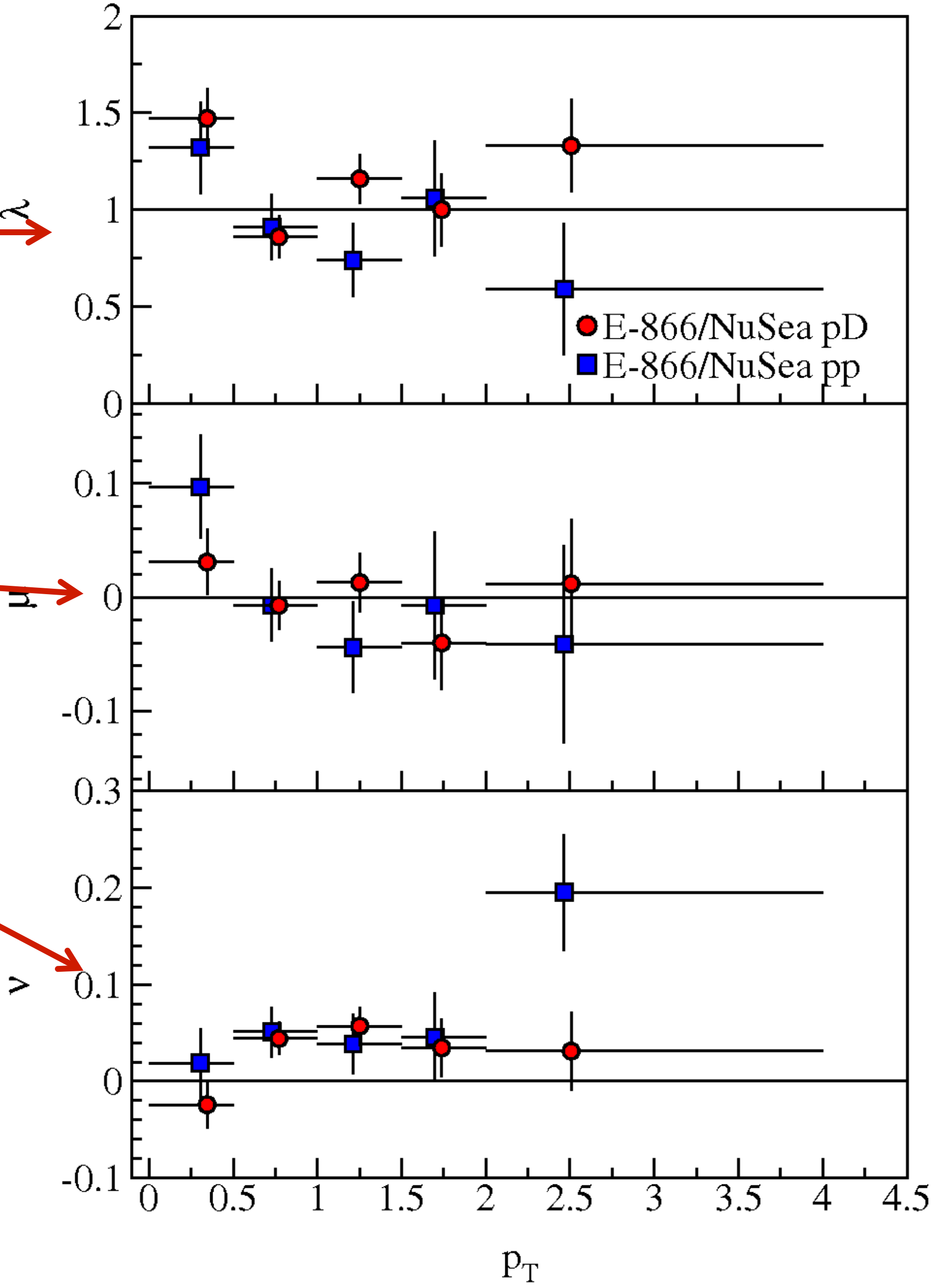
Should be flavor blind and seen in both sea and valence distributions

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

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

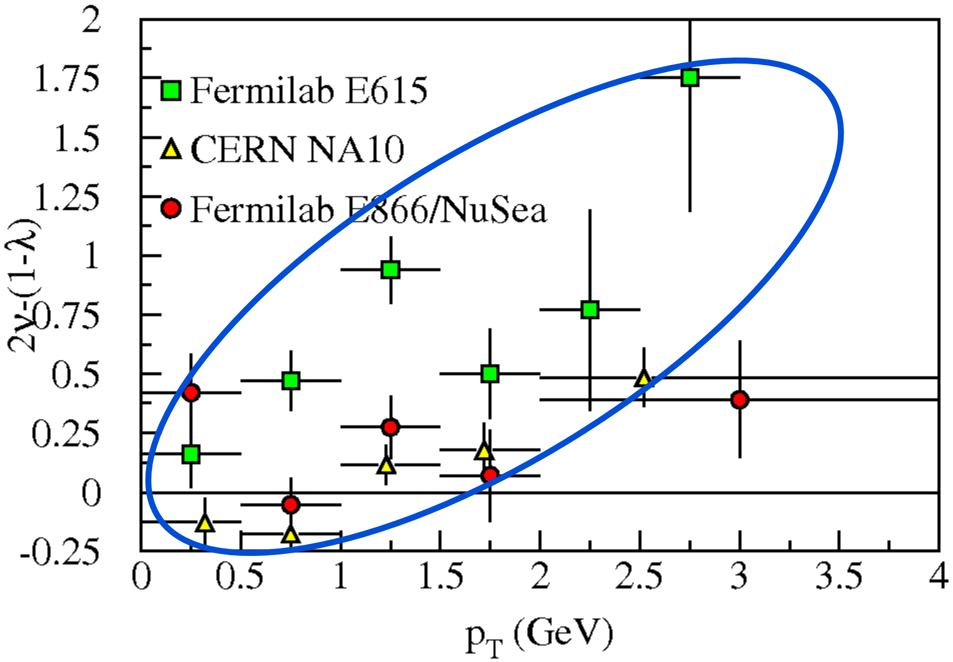
- λ consistent with 1
- μ consistent with 0
- ν consistent with 0 (or slightly positive)

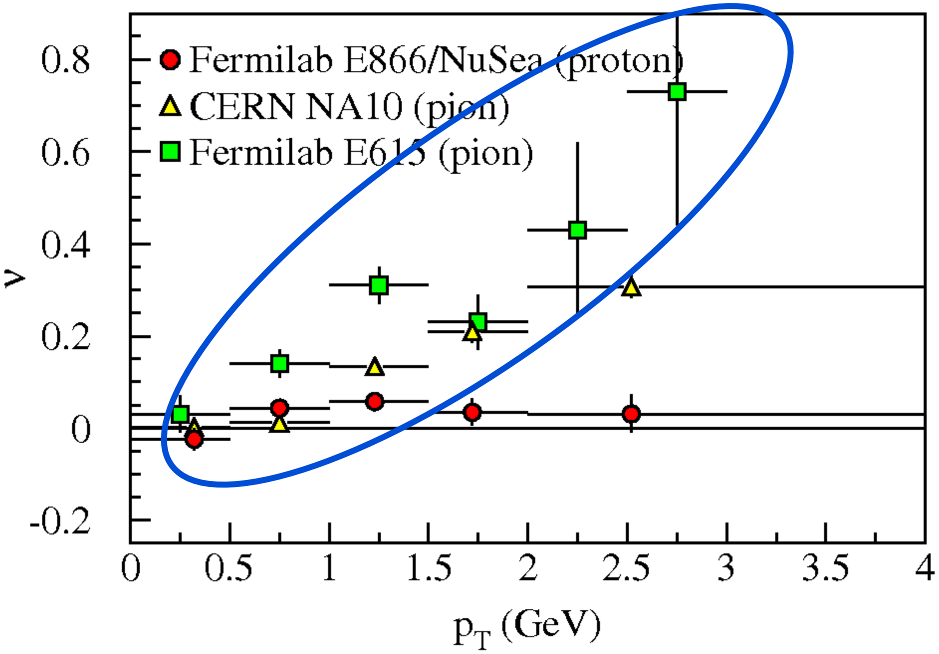




Lam-Tung Relation

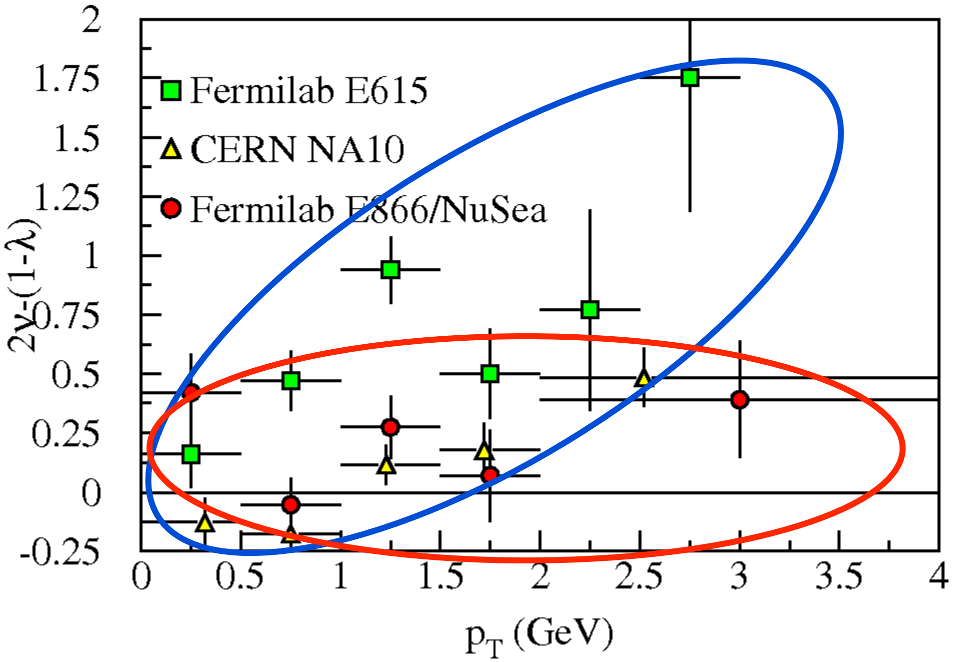
- π^- Drell-Yan
  - Violates L-T relation
  - Large ν ($\cos 2\phi$) dependence
  - Strong with p_T

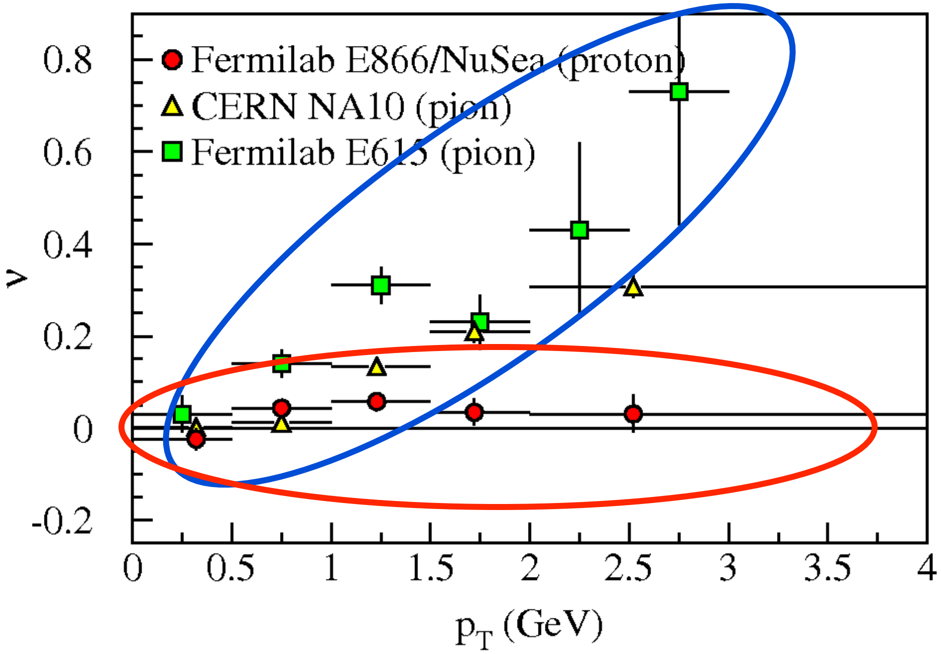




Lam-Tung Relation

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





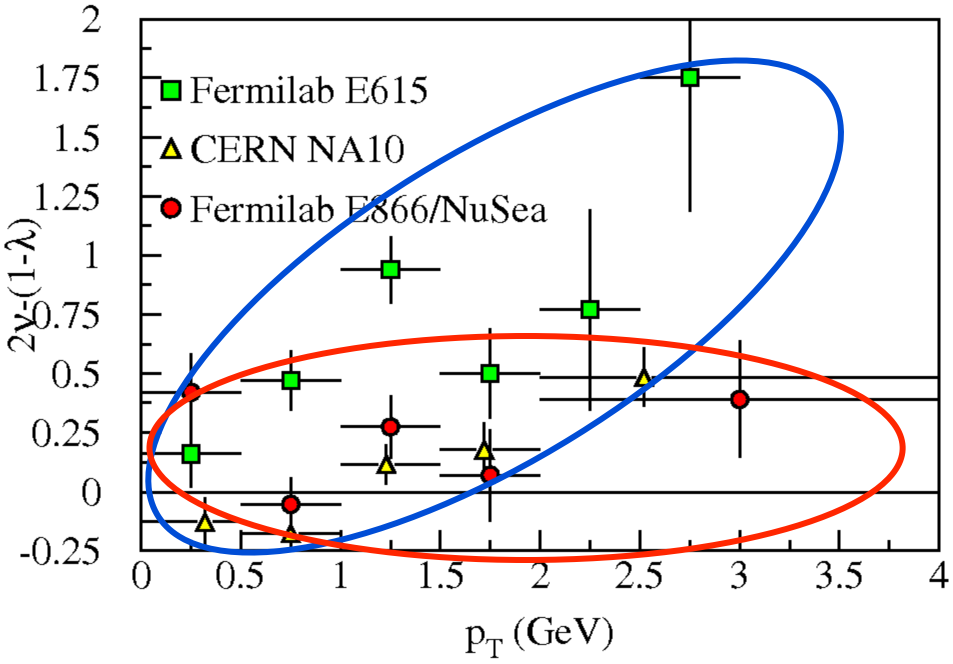
Lam-Tung Relation

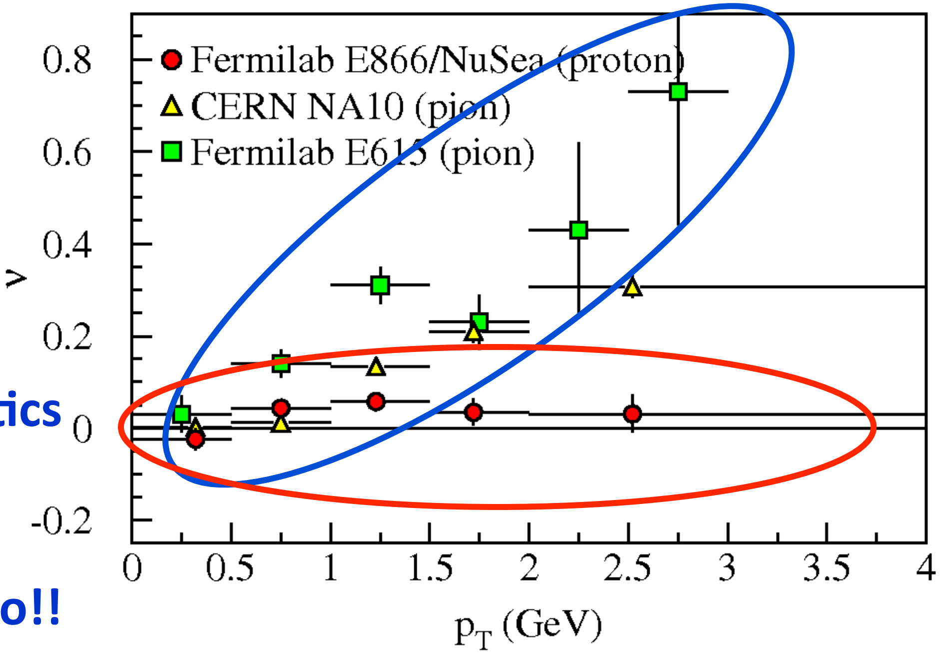
- π^- Drell-Yan
  - Violates L-T relation
  - Large ν ($\cos 2\phi$) dependence
  - Strong with p_T
- Proton Drell-Yan
  - **Consistent** with L-T relation
  - **No** ν ($\cos 2\phi$) dependence
  - **No** p_T dependence
- With Boer-Mulders function $h_1^\perp$:
  - ν π-W → $\mu^+\mu^-X$

    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!!**





Spin Asymmetries in Drell-Yan reactions

Single Spin Leading Order Drell-Yan Cross Section

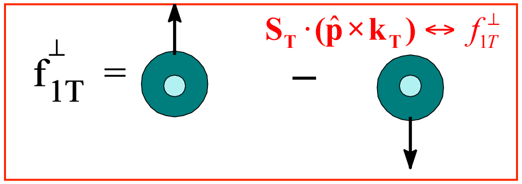
$$
\begin{aligned}
\frac{d\sigma^{\mathrm{LO}}}{d^4q\,d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_{\mathrm{U}}^{\mathrm{LO}} \Big[1 &+ D_{\sin^2\theta}^{\mathrm{LO}} A_{\mathrm{U}}^{\cos 2\phi} \cos 2\phi \\
&+ S_{\mathrm{L}} D_{\sin^2\theta}^{\mathrm{LO}} A_{\mathrm{L}}^{\sin 2\phi} \sin 2\phi \\
&+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

Formula: from Aram Kotzinian
Slide: content Oleg Denisov's Transversity 2011 talk

$A_{\mathrm{U}}^{\cos 2\phi}$	Boer-Mulders of beam hadron
$A_{\mathrm{T}}^{\sin \phi_{\mathrm{S}}}$	Sivers' for target nucleon
$A_{\mathrm{T}}^{\sin(2\phi+\phi_{\mathrm{S}})}$	Boer-Mulders of beam hadron and $h_1^{\perp}$ and pretzelosity of target nucleon
$A_{\mathrm{T}}^{\sin(2\phi-\phi_{\mathrm{S}})}$	Boer-Mulders of beam hadron and h_1 and transversity of target nucleon

Transverse Momentum Distributions: The Sivers' function

1. What is the Sivers' function?



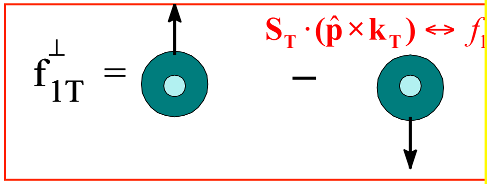
$\mathbf{S}_T \cdot (\hat{\mathbf{p}} \times \mathbf{k}_T) \leftrightarrow f_{1T}^{\perp}$

k_T - dependent,
Naïve T-odd

2. When will we have Drell-Yan data?

Transverse Momentum Distributions: The Sivers' functi

1. What is the Sivers' function?



$f_{1T}^{\perp} =$ −

$\mathbf{S_T} \cdot (\hat{\mathbf{p}} \times \mathbf{k_T}) \leftrightarrow f_1$

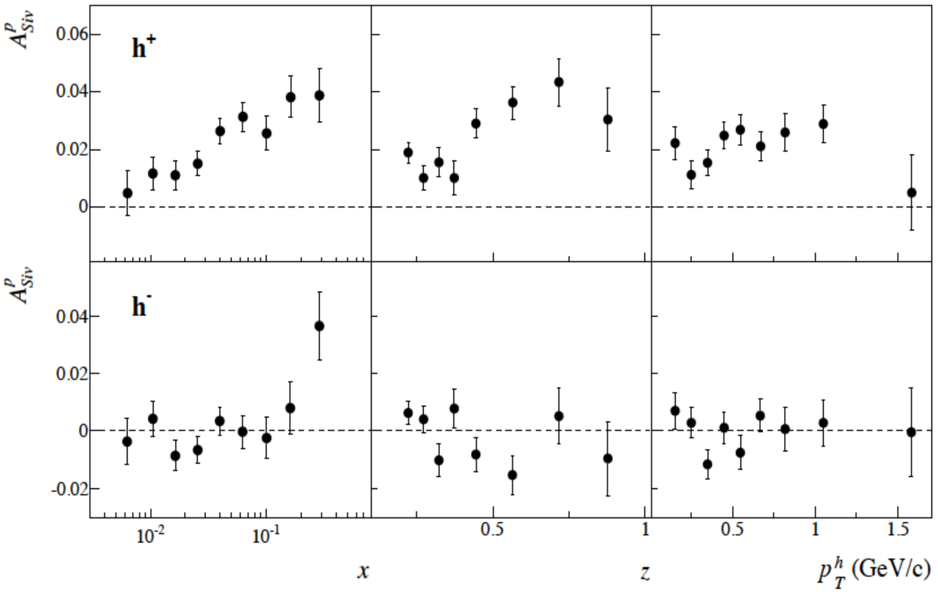
k_T - dependent,
Naïve T-odd

2. When will we have Drell-Ya

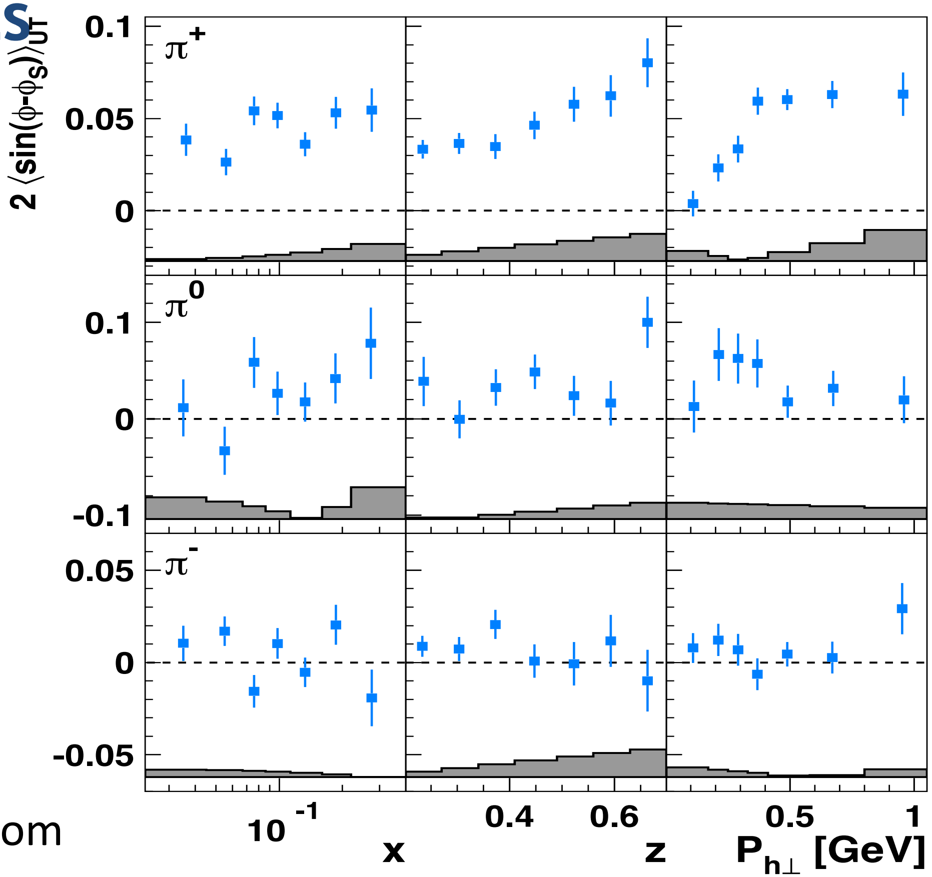
$$f_1^{\perp}(x,k_T)\big|_{\mathrm{DIS}} \overset{?}{=} -f_1^{\perp}(x,k_T)\big|_{\mathrm{D\text{-}Y}}$$

SIDIS Sivers' measurements

COMPASS



HERMES



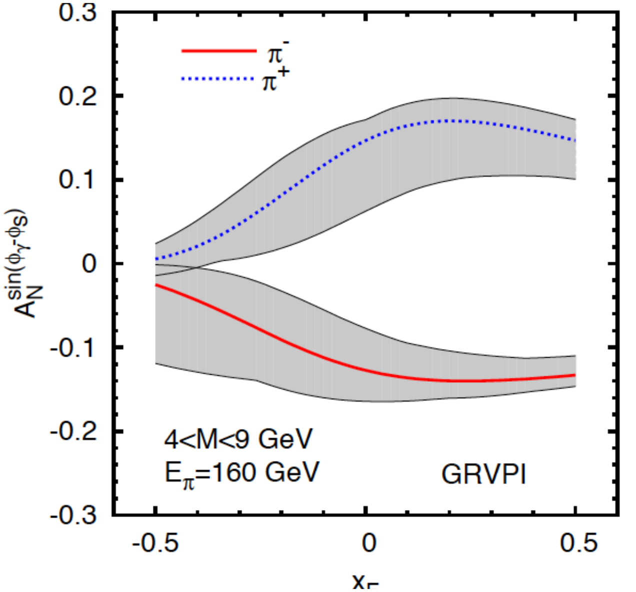
- Global fit to $\sin(\phi_h - \phi_S)$ asymmetry in SIDIS from HERMES, and COMPASS
- Comparable measurements needed for single spin asymmetries in Drell-Yan process
- Caution:
  - Must cover same kinematics with Drell-Yan and SIDIS (or have robust QCD evolution)
  - Right now, nothing excludes a node

Future Polarized Drell-Yan Measurements

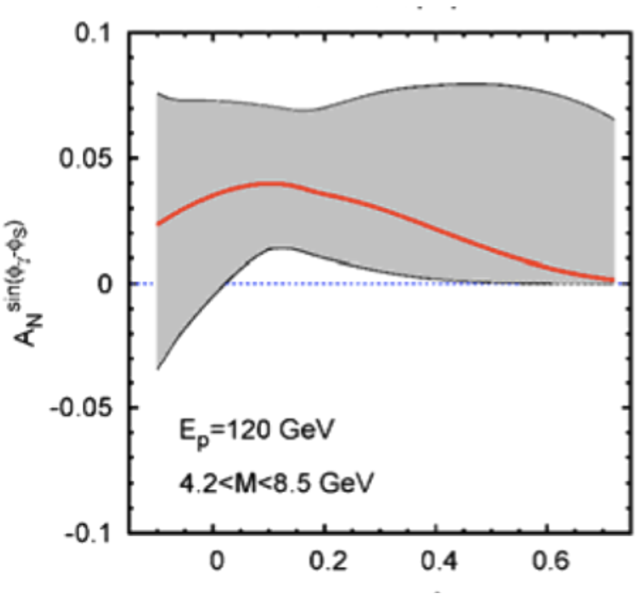
experiment	particles	energy	x_b or x_t	Luminosity	timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s} = 17.4$ GeV	$x_t = 0.2 - 0.3$	2×10^{33} cm^{-2} s^{-1}	2014
PAX (GSI)	$p^{\uparrow} + p_{bar}$	collider $\sqrt{s} = 14$ GeV	$x_b = 0.1 - 0.9$	2×10^{30} cm^{-2} s^{-1}	>2017
PANDA (GSI)	$p_{bar} + p^{\uparrow}$	15 GeV $\sqrt{s} = 5.5$ GeV	$x_t = 0.2 - 0.4$	2×10^{32} cm^{-2} s^{-1}	>2016
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s} = 20$ GeV	$x_b = 0.1 - 0.8$	1×10^{30} cm^{-2} s^{-1}	>2014
PHENIX (RHIC)	$p^{\uparrow} + p$	collider $\sqrt{s} = 500$ GeV	$x_b = 0.05 - 0.1$	2×10^{32} cm^{-2} s^{-1}	>2018
SeaQuest (unpol.) (FNAL)	$p + p$	120 GeV $\sqrt{s} = 15$ GeV	$x_b = 0.35 - 0.85$ $x_t = 0.1 - 0.45$	3.4×10^{35} cm^{-2} s^{-1}	2012
pol. SeaQuest[§] (FNAL)	$p^{\uparrow} + p$	120 GeV $\sqrt{s} = 15$ GeV	$x_b = 0.35 - 0.85$	1×10^{36} cm^{-2} s^{-1}	>2015

Actual luminosity at Fermilab limited to 2 10^{35} cm^{-2}s^{-1} by proton needs of other experiments

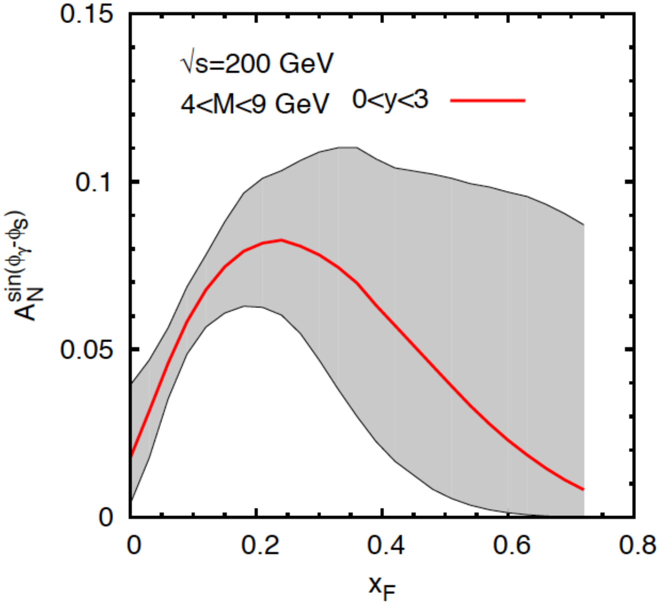
$A_N^{\sin(\varphi\gamma-\varphi s)}$ prediction Anselmino *et al*



COMPASS



Fermilab



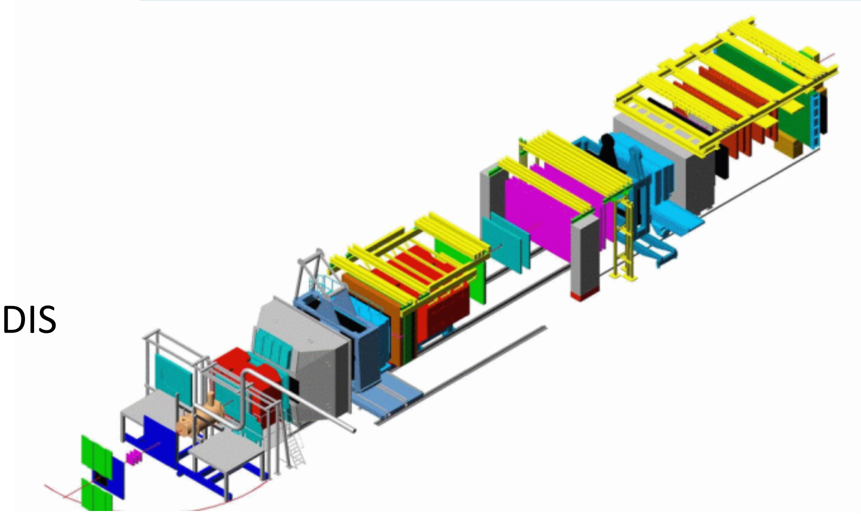
RHIC

Anselmino, *et al* Phys. Rev. D79 (2009) 054010 and private communication (for Fermilab)

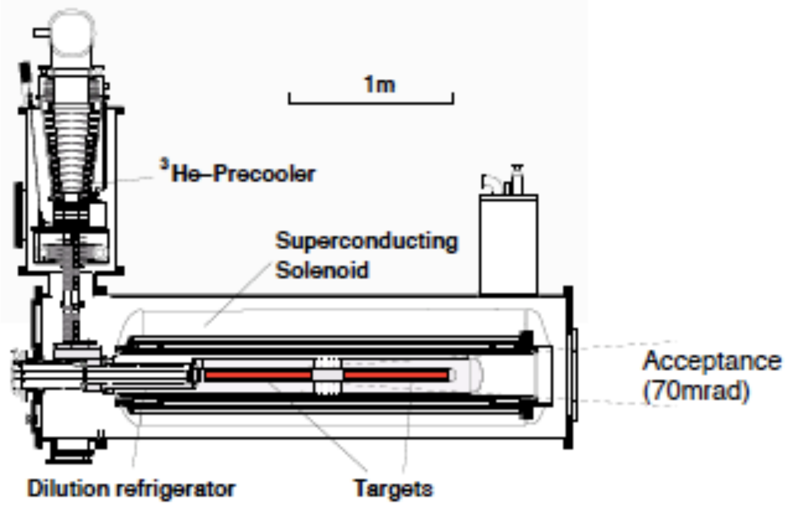
- Uncertainties in predictions dominated by uncertainties in SIDIS data
- Also predictions for GSI PAX, GSI PANDA, J-PARC, JINR NCIA, IHEP SPASCHARM

COMPASS@CERN

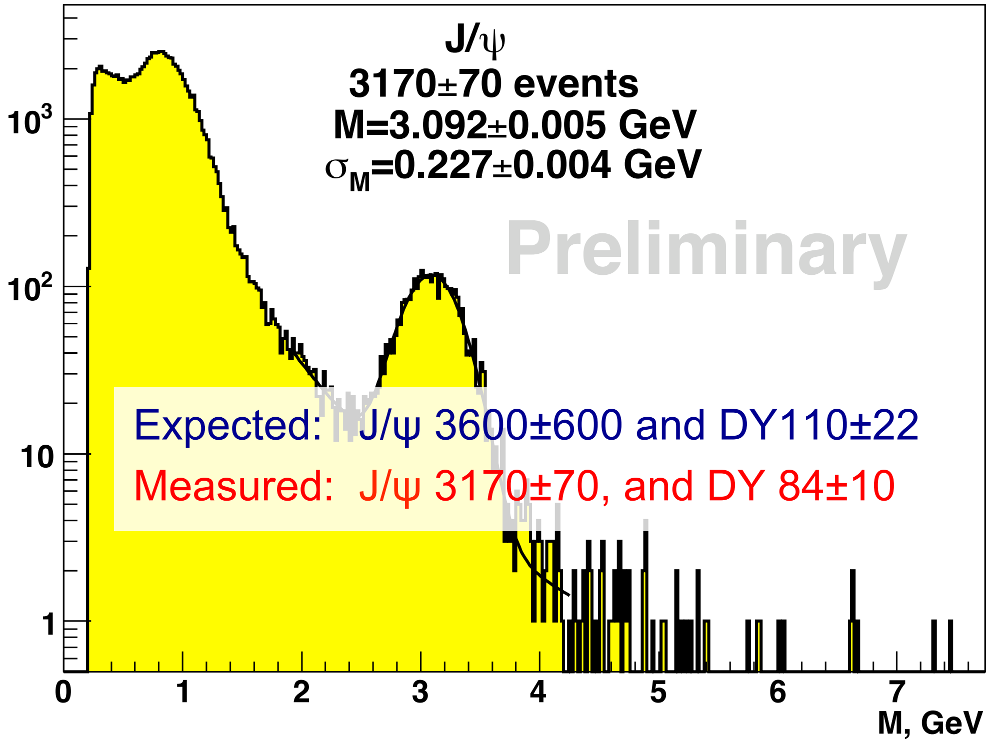
- See talk by S. Takekawa (next)
- Very well understood apparatus
  - A_N angular measurements already completed for SIDIS
  - MC and test data match
- Polarized target
- Data in 2014



Polarized target: ^{6}LiD or NH_3



COMPASS DY beam test 2009



Expected: J/ψ 3600±600 and DY110±22

Measured: J/ψ 3170±70, and DY 84±10

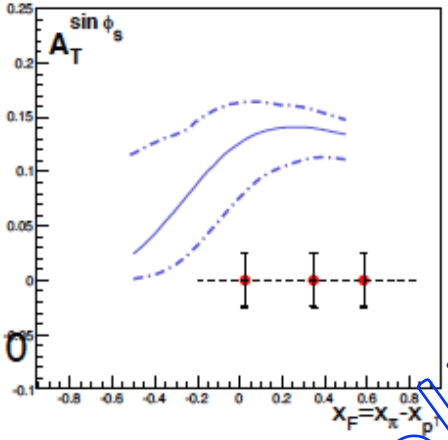
Comparing with theory predictions

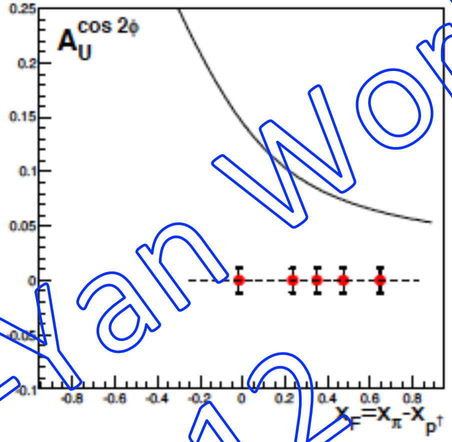
...but: Q^2 evolution not properly accounted for in the predictions...

DY: $4 < M_{\mu\mu} < 9$ GeV/c^2

$f_1^\pi \otimes$ Sivers^p

Anselmino et al,
PRD79(2009)054010



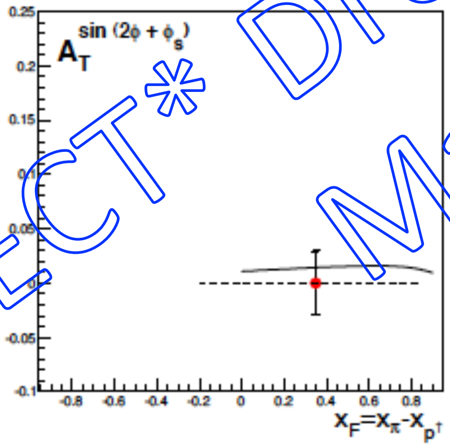


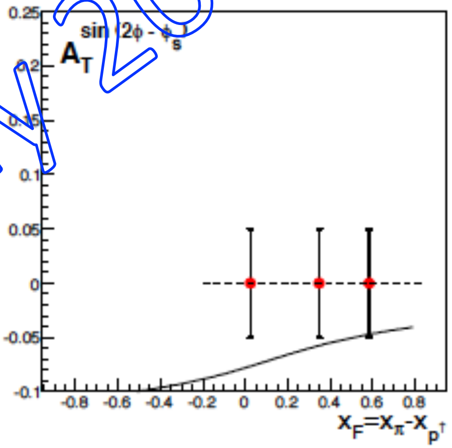
BM$^\pi \otimes$ BM^p

B. Zhang et al,
PRD77(2008)054011

BM$^\pi \otimes$ pretzel.^{p}

Zhun Lu et al,
arXiv:1101.2702v2



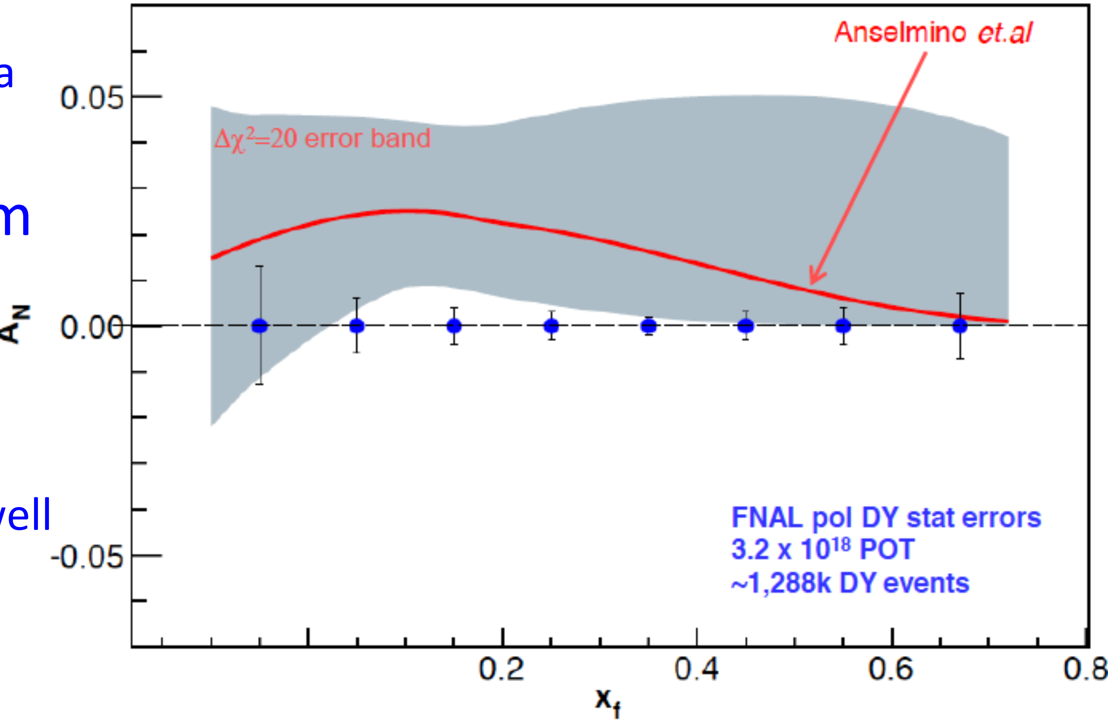


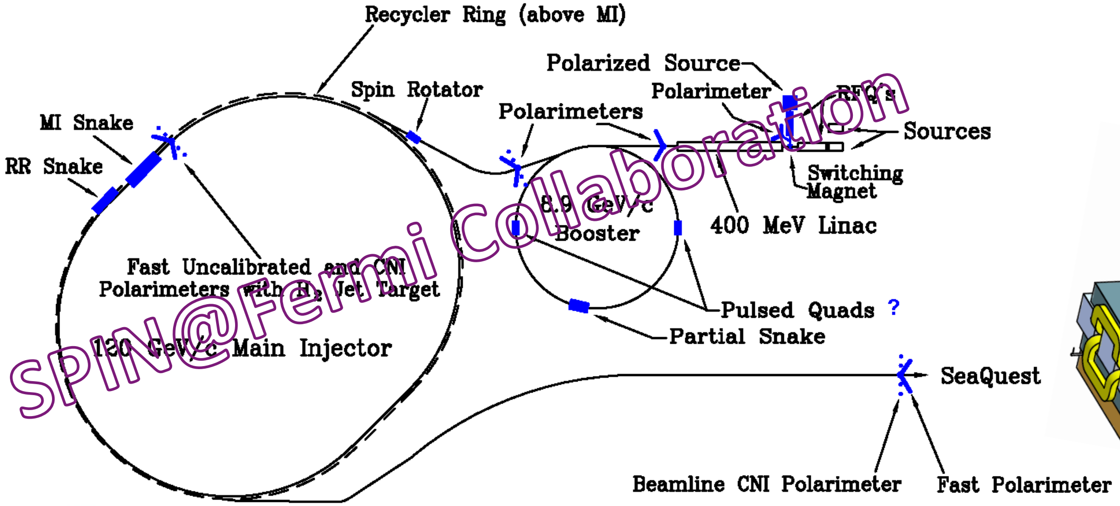
BM$^\pi \otimes$ transv.^{p}

A.N. Sissakian et al,
Phys.Part.Nucl.41:
64-100,2010

Polarized Drell-Yan@Fermilab Main Injector

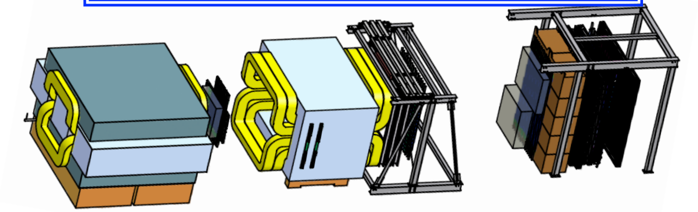
- Polarized beam
  - Major advantage—the beam is a blow torch—Luminosity
  - Major disadvantage—the beam polarization is presently ***virtual***—only a proposal
- Spectrometer:
  - By 2014, spectrometer will be well understood, including angular acceptance





Exploring polarized target

- sea quark Sivers'



Drell-Yan Data: What data would I like to see? (My personal view)

- Siver's function relation to DIS tested

$$f_{1T}^{\perp}\big|_{\mathrm{DIS}} = - f_{1T}^{\perp}\big|_{\mathrm{DY}}$$

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

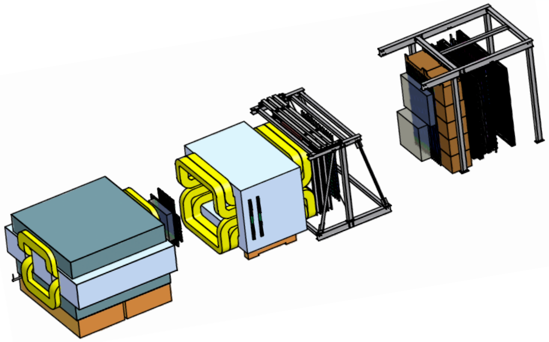
- Unpolarized Angular Distributions—Boer-Mulders Structure Function, QCD
  - Fermilab E-906/SeaQuest, J-PARC, RHIC (pp, pA)
  - CERN COMPASS (πp)

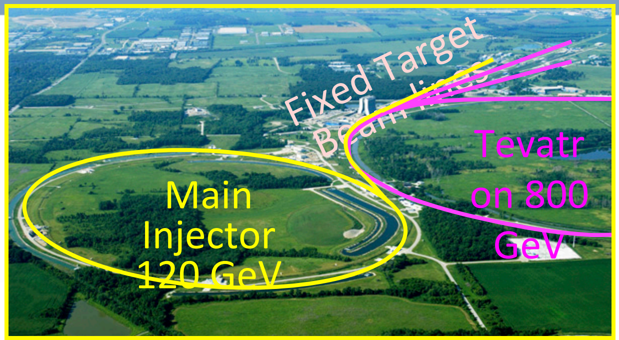
- Double polarized Drell-Yan—$h_1(x)$

$$\begin{aligned} A_{TT}^{\mathrm{DY}} &= \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} \\ &= \alpha_{TT} \frac{\sum_i e_i^2 \left[h_{1i}(x_1)\bar{h}_{1i}(x_2) + \bar{h}_{1i}(x_1)h_{1i}(x_2)\right]}{\sum_i e_i^2 \left[f_i(x_1)\bar{f}_i(x_2) + \bar{f}_i(x_1)f_i(x_2)\right]} \\ &\approx \alpha_{TT} \frac{h_{1u}(x_1)h_{1u}(x_2)}{u(x_1) + u(x_2)} \end{aligned}$$

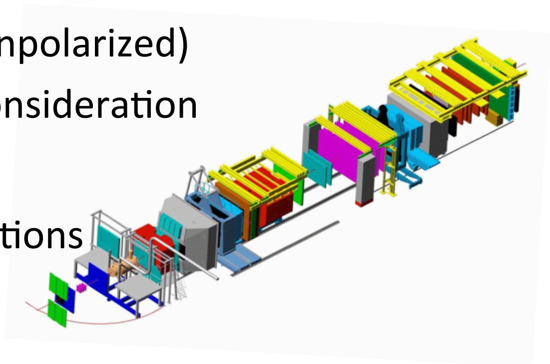
- GSI-FAIR PAX antiproton-proton
- Fermilab polarized beam and target

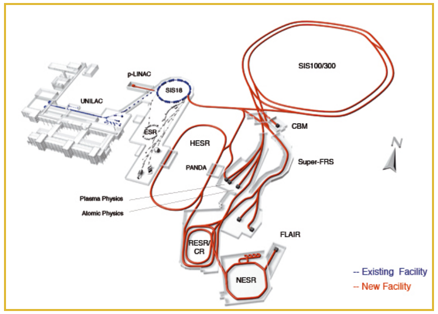
Future Drell-Yan Experiments



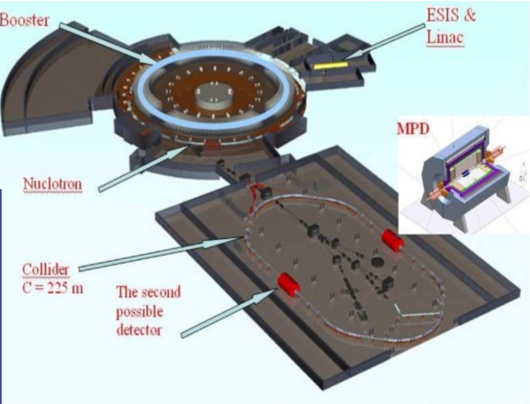


- Fermilab E-906/Drell-Yan
  - Better statistical precision (unpolarized)
  - Polarized extension under consideration
- COMPASS
  - Pion beam—valence distributions





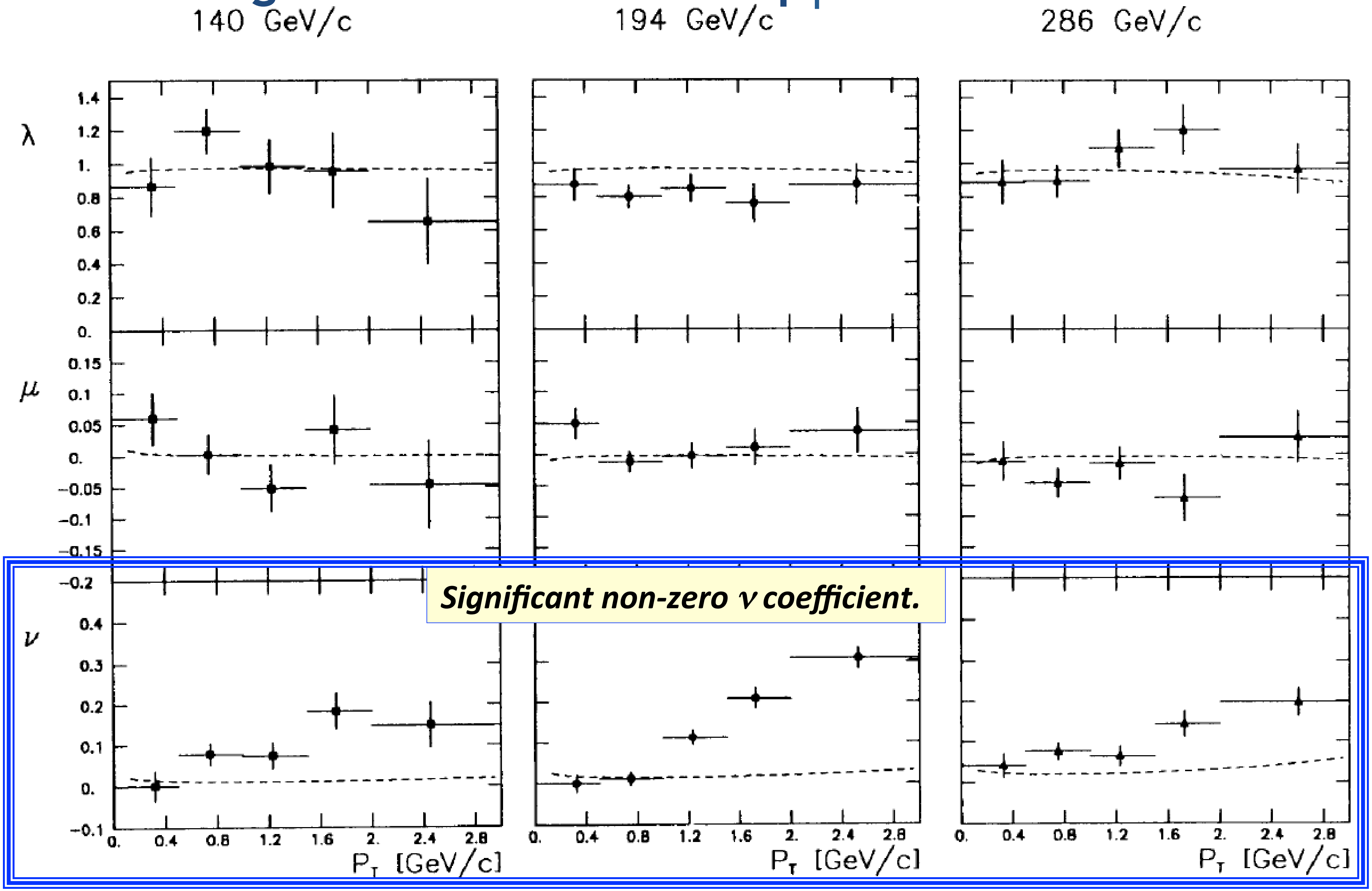
- GSI FAIR—PAX experiment
  - Antiproton beam will sample valence distributions of targets
- JINR Dubna-NICA
- J-PARC
- RHIC



Epilogue:

This is a “simulated” (that is, equivalent to Monte Carlo?) picture of what the effect might look like done with GIMP software.

NA10 angular distributions vs. p_T



Significant non-zero ν coefficient.