Studying the Nucleon Sea at the EIC

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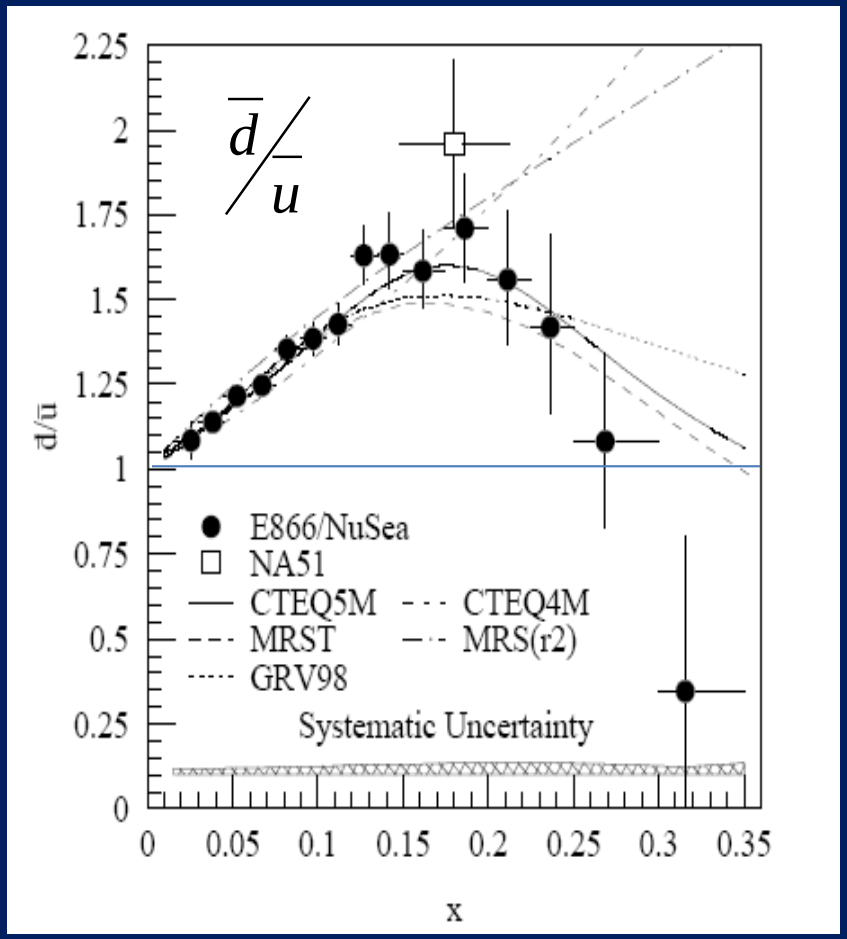
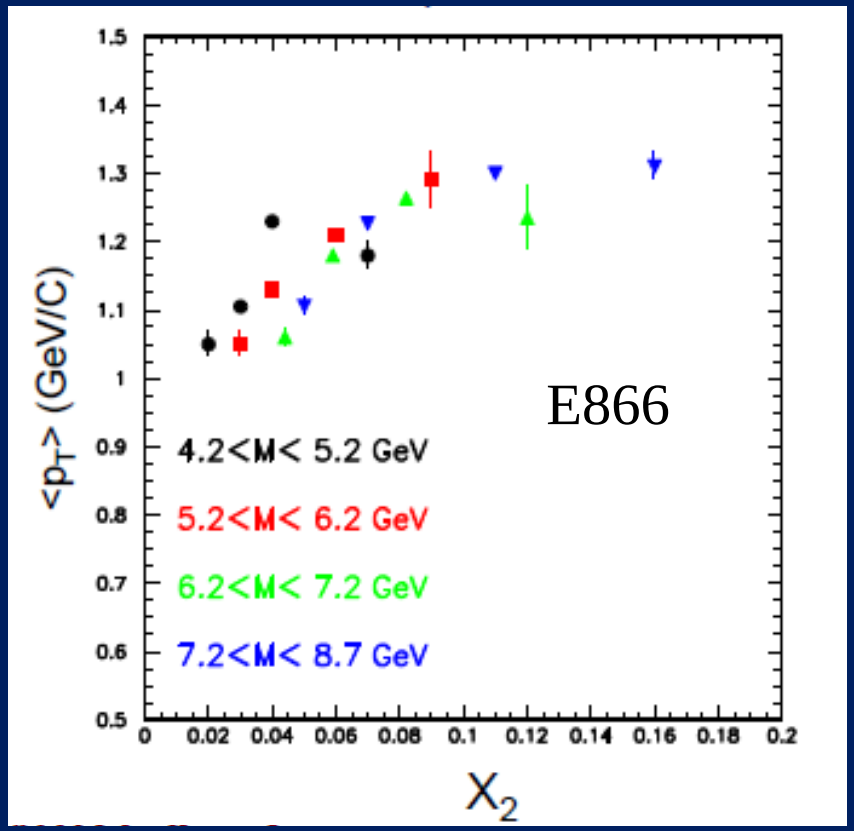
Sea quarks—many hints of interesting behavior already!

Light quark sea: Not simply gluon splitting

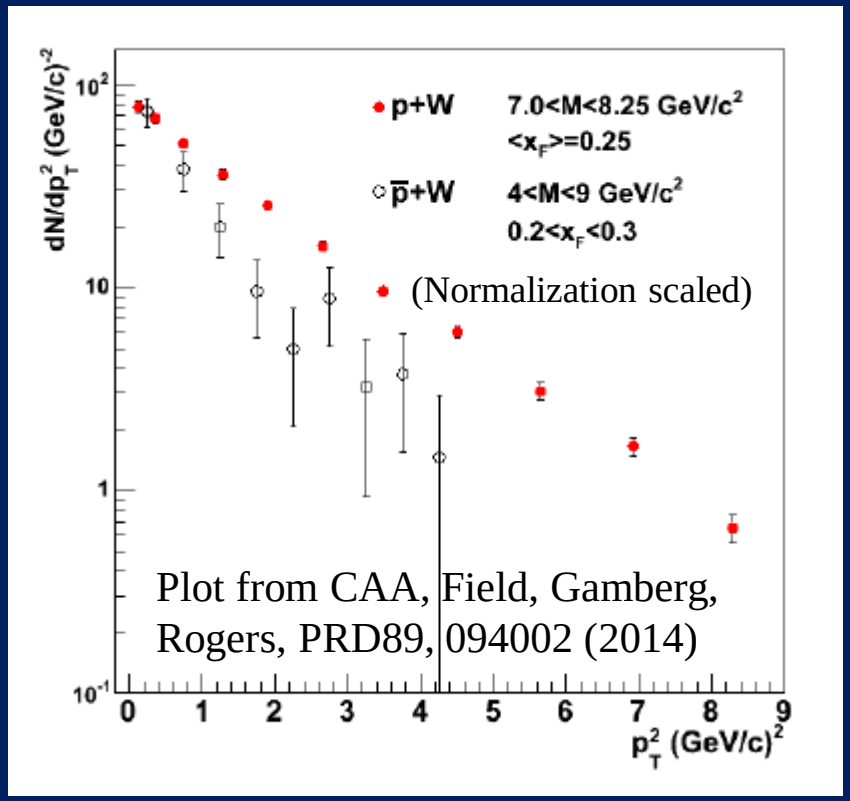


E866 proton-induced Drell-Yan: PRD64, 052002 (2001)



Mean p_T of Drell-Yan pair rises with x of sea quark?

Drell-Yan: Transverse momentum of valence vs. sea quarks

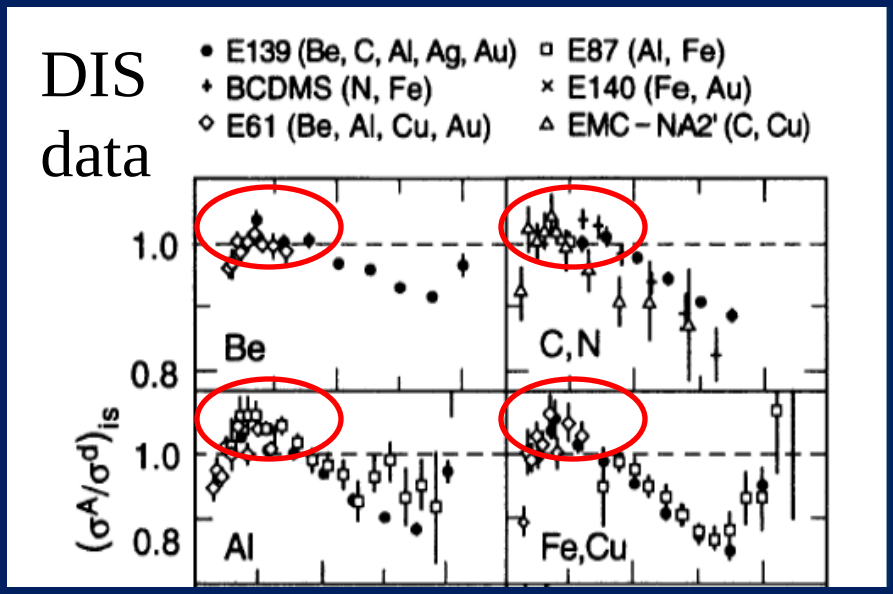


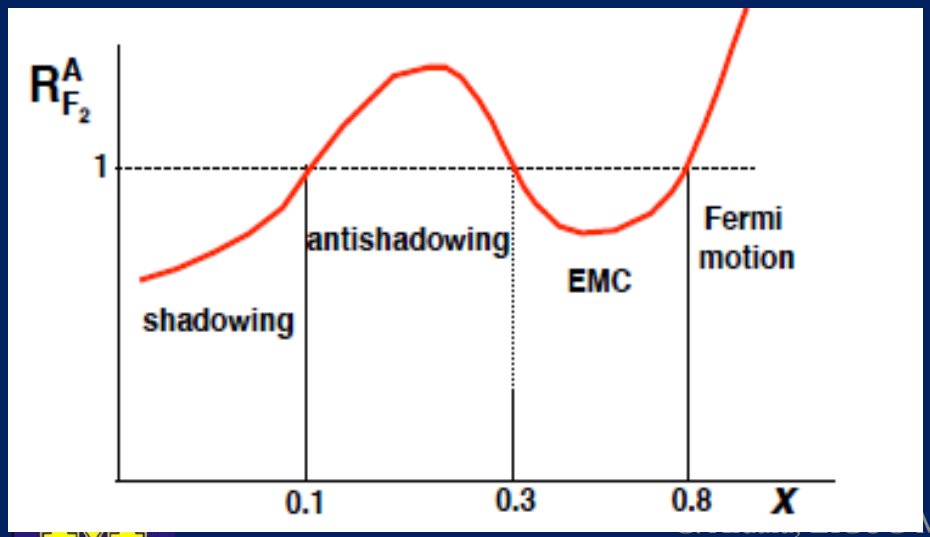
- p+W: (Valence) quark from p, (sea) antiquark from W
- pbar+W: (Valence) quark from W, (valence) antiquark from pbar
- (Valence x sea) spectrum harder → Larger mean k_T for sea than valence quarks?
  - Agrees with chiral soliton model predictions (e.g. Schweitzer, Strikman, Weiss 2013)
  - Consistent with work by Bacchetta et al.

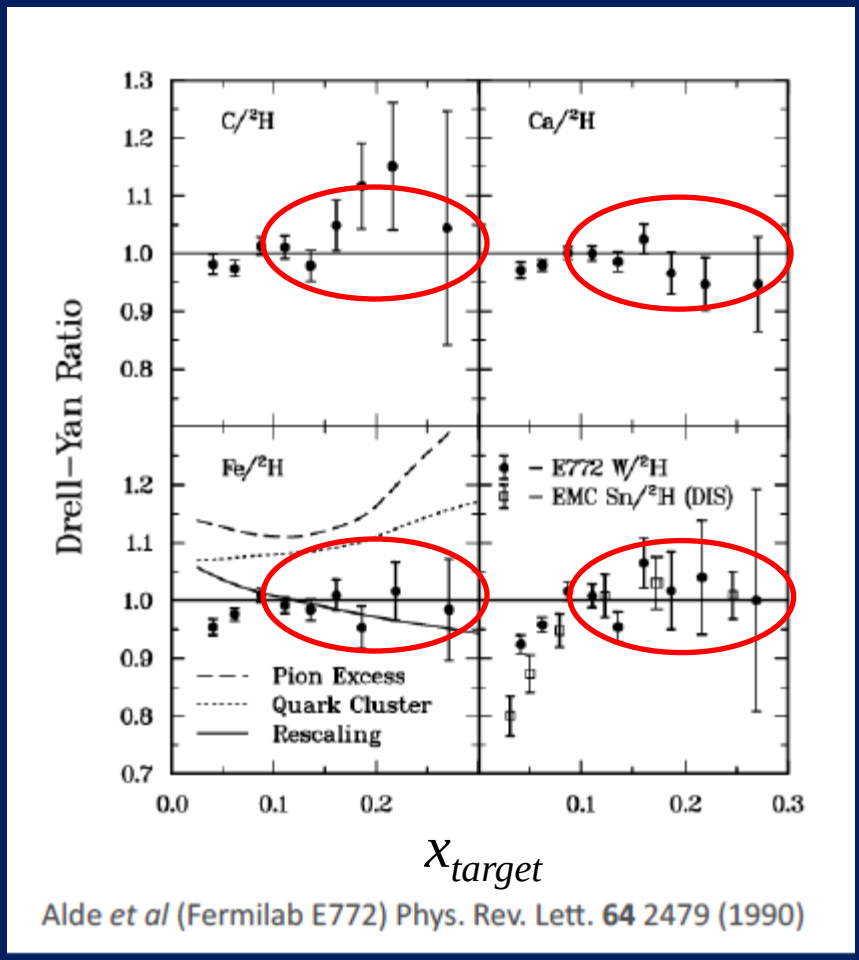
Data from E537 (pbar+W): PRD38, 1377 (1988)
E439: (p+W): AIP Conf. Proc. 45, 93 (1978)

…And nuclear effects seen in Drell-Yan that differ from DIS

DIS data



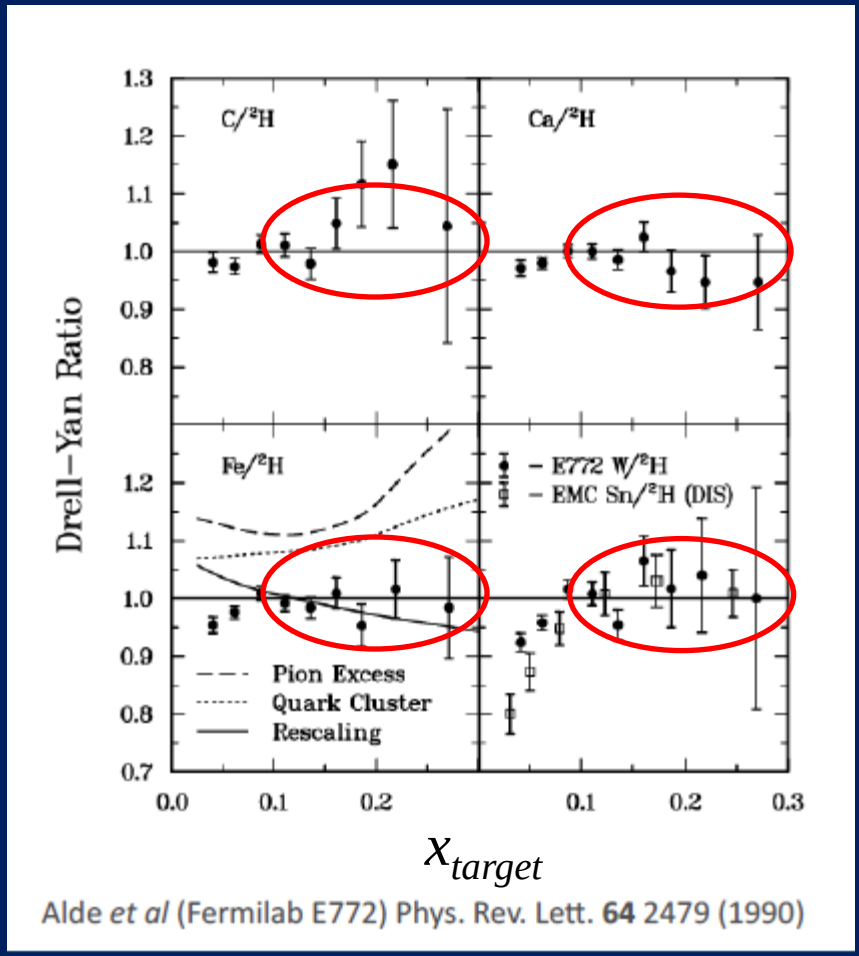




No clear "antishadowing" in Drell-Yan

…And nuclear effects seen in Drell-Yan that differ from DIS

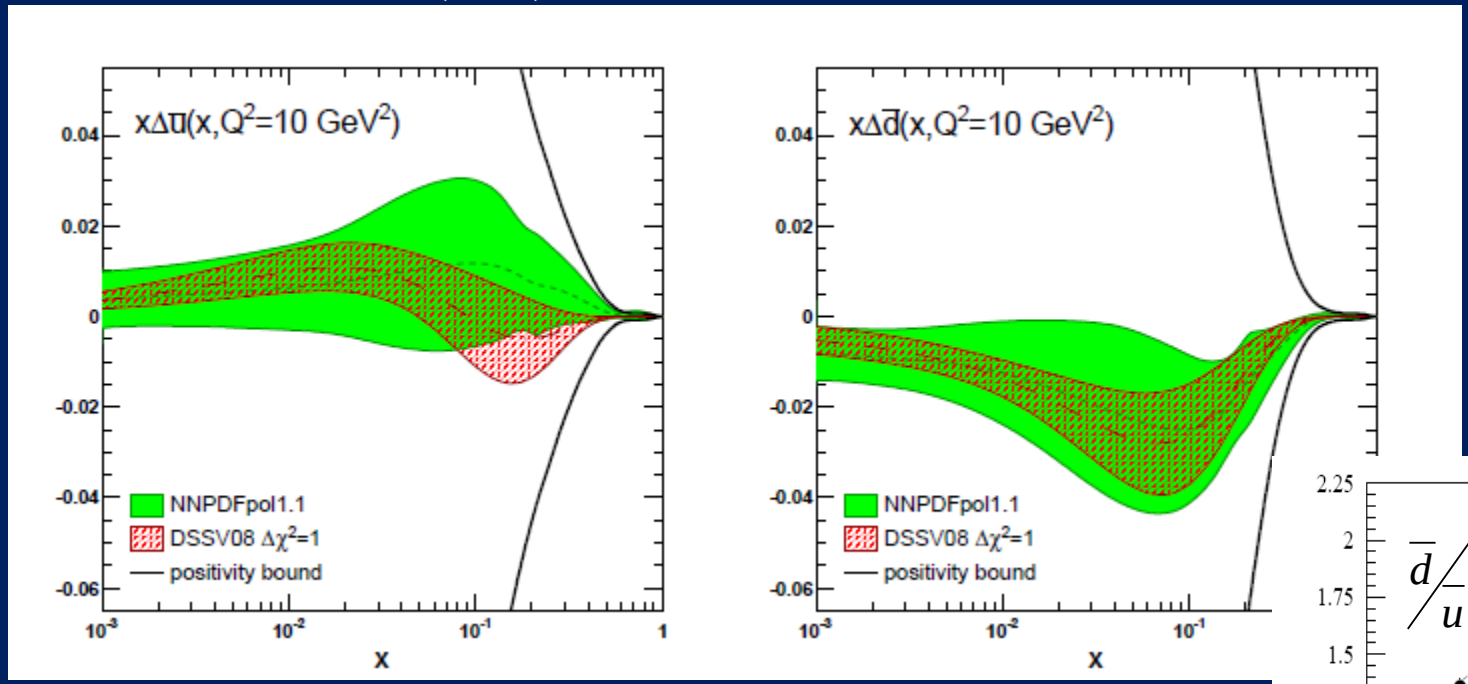
- Proton-beam Drell-Yan results shown vs. x_{target}, which is x of sea quark in nucleus
- If it's a relevant picture to think of nuclear binding mediated by pions, why no clear excess of antiquarks in nuclei??



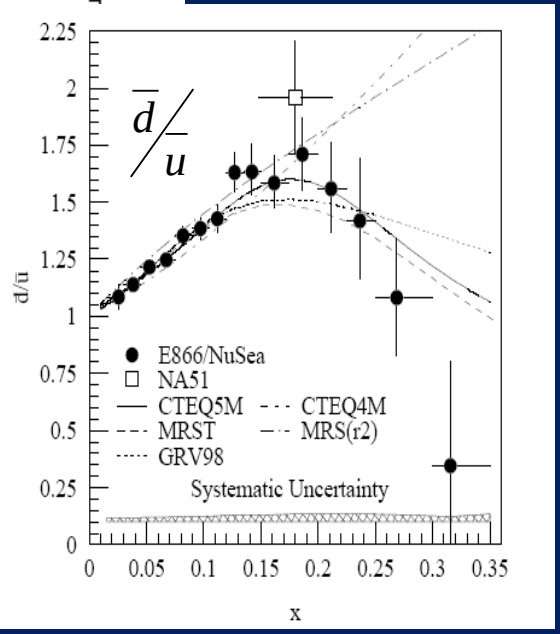
No clear "antishadowing" in Drell-Yan

Flavor asymmetry in the sea helicity distributions

NNPDF, NPB 887.276 (2014)

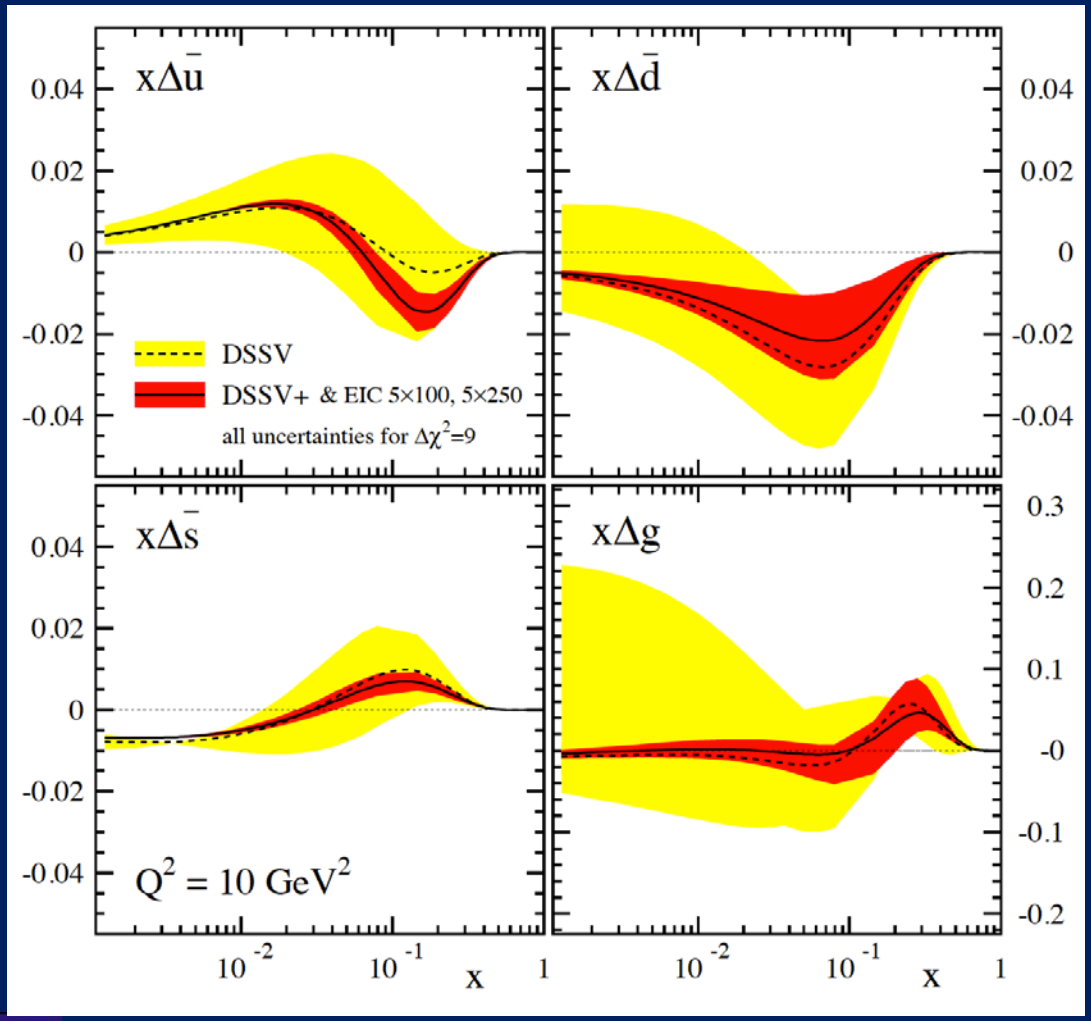


(DSSV08: Before RHIC W data)



Shouldn't be surprising given flavor asymmetry in unpolarized sea? Or unrelated??

Flavor asymmetry in the sea helicity distributions

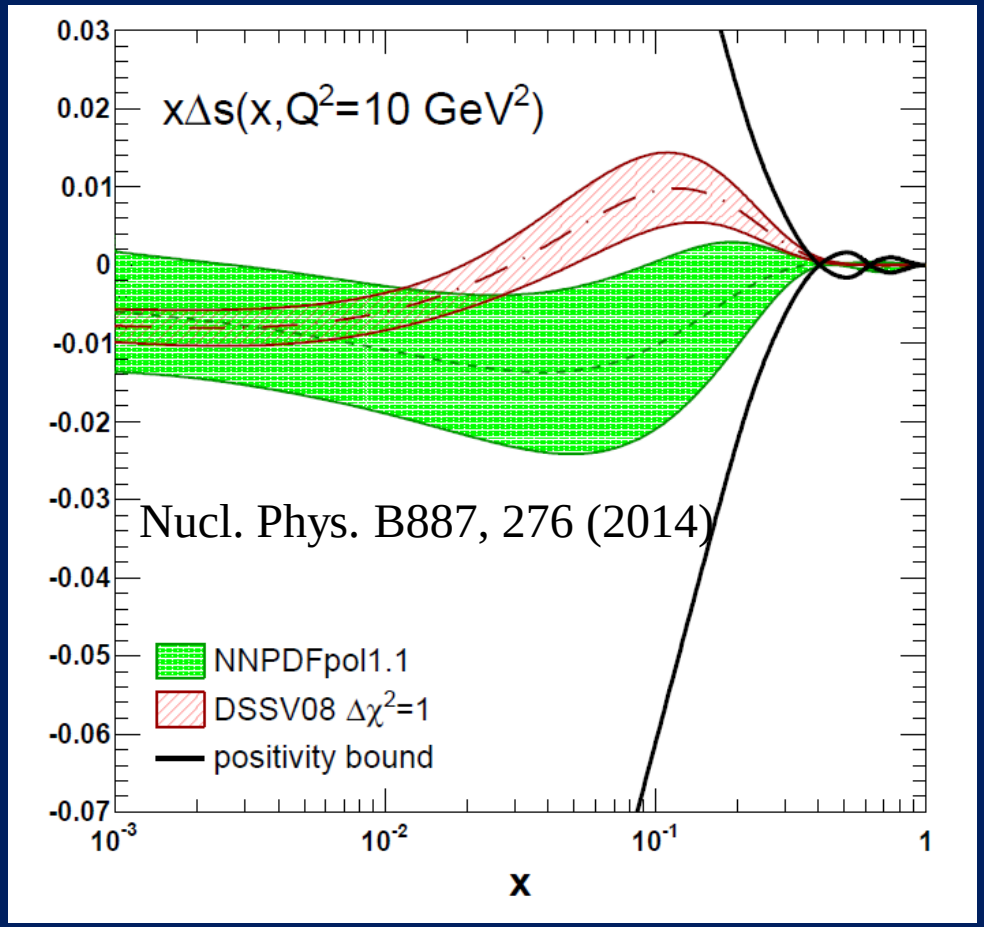


From Elke Aschenauer's talk

SIDIS at EIC including $\sqrt{s} = 45$ and 70 GeV pseudodata

Strangeness helicity distribution from inclusive vs. semi-inclusive DIS

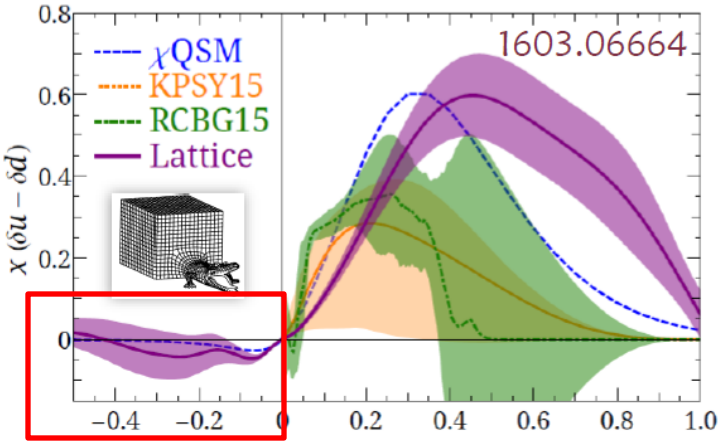
- NNPDF fit an indirect extraction of strangeness using only inclusive DIS
- DSSV includes SIDIS kaon data
- Extensive data from EIC will be important to resolve!

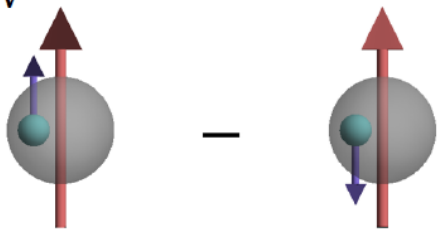


Transversity for sea quarks significant and flavor-asymmetric?

Transversity Distribution

§ Exploratory study $M_\pi \approx 310$ MeV





Removing $O(M_N^n/P_z^n) + O(\Lambda_{QCD}^2/P_z^2)$ errors

$\delta\bar{q}(x) = -\delta q(-x)^{\,x}$ 1505.05589; 1503.03495

- We found sea asymmetry of $\int dx\,(\delta\bar{u}(x) - \delta\bar{d}(x)) \approx -0.10(8)$
- Chiral quark-soliton model $\int dx\,(\delta\bar{u}(x) - \delta\bar{d}(x)) \approx -0.082$

P. Schweitzer et al., PRD 64, 034013 (2001)

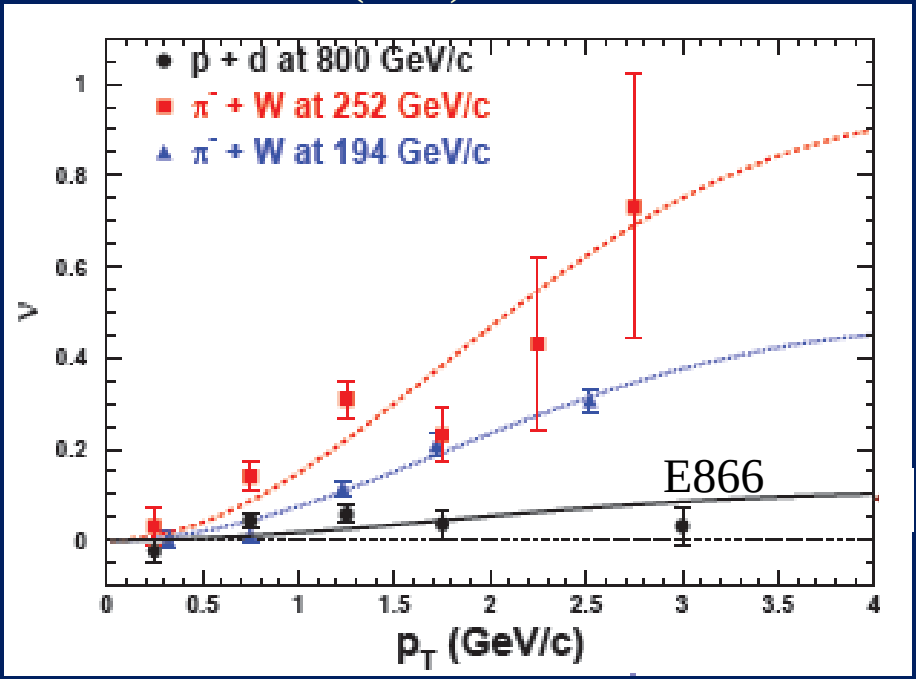
- SoLID at JLab, Drell-Yan exp't at FNAL (E1027+E1039), EIC, ...

Slide from Huey-Wen Lin, INT Workshop Oct 2017

Lattice calculation agrees with chiral quark-soliton model calculation

Boer-Mulders TMD PDF for sea quarks small?

E866, PRL 99, 082301 (2007);
PRL 102, 182001 (2009)



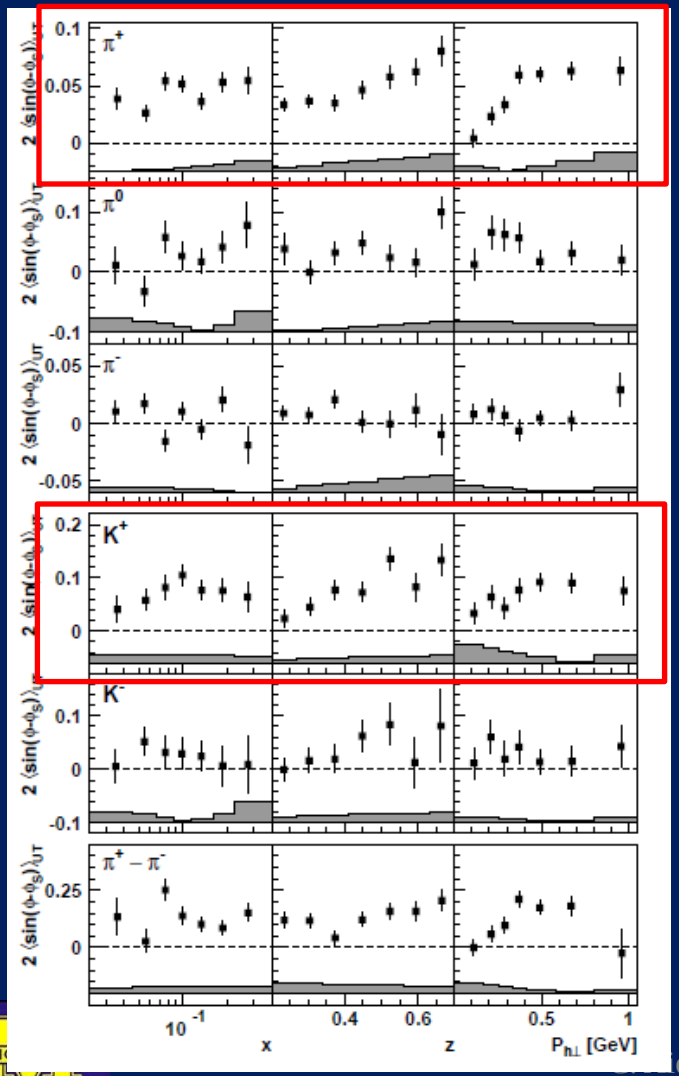
- Significantly reduced cos2ϕ dependence in proton-induced Drell-Yan compared to pion-induced Drell-Yan
- Suggests this transverse spin-momentum correlation for sea quarks is small?

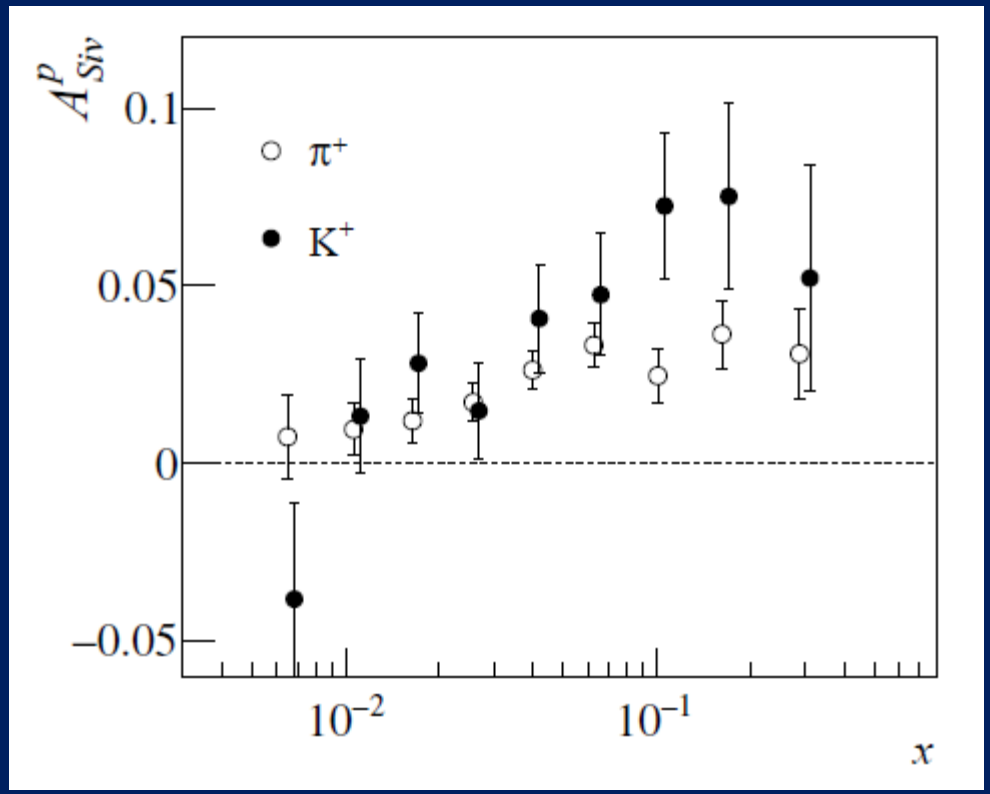
Boer - Mulders function $h_1^{\perp}$

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

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

*Sivers TMD PDF for sea quarks **not** small? SIDIS asymmetries larger for K^+ than π^+*



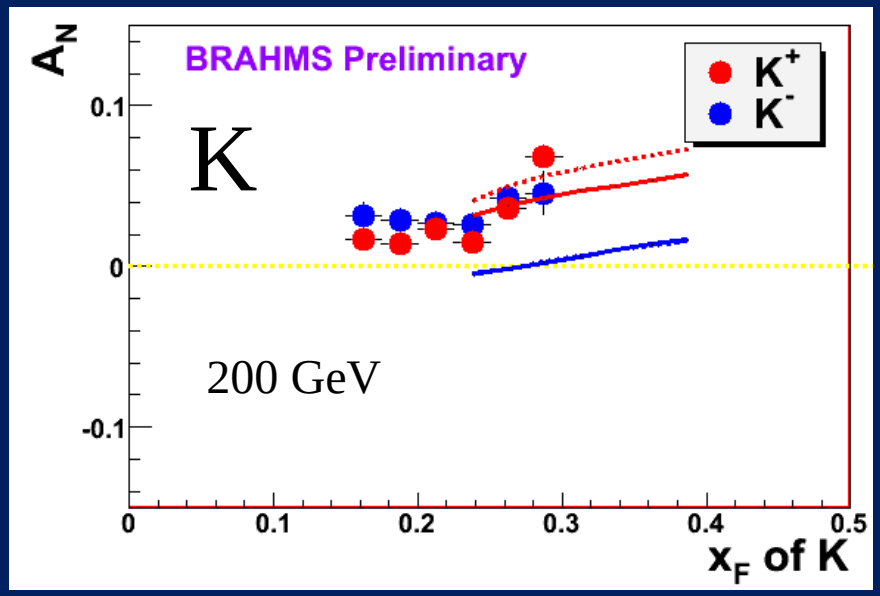


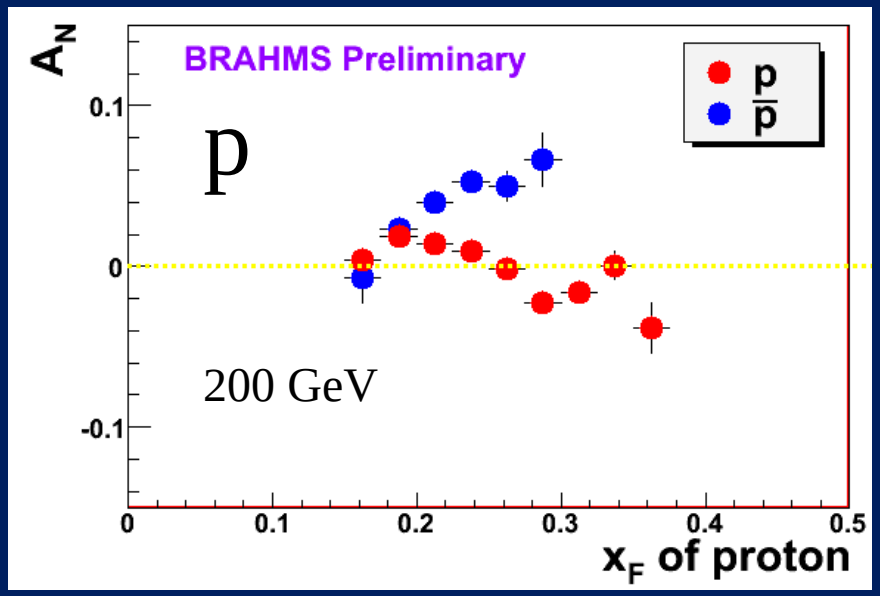
COMPASS, PLB744, 250 (2015)

HERMES, PRL103, 152002 (2009)

Note scale difference for π^+ vs. K^+!

Large K^- and antiproton(!) transverse single-spin asymmetries in p+p

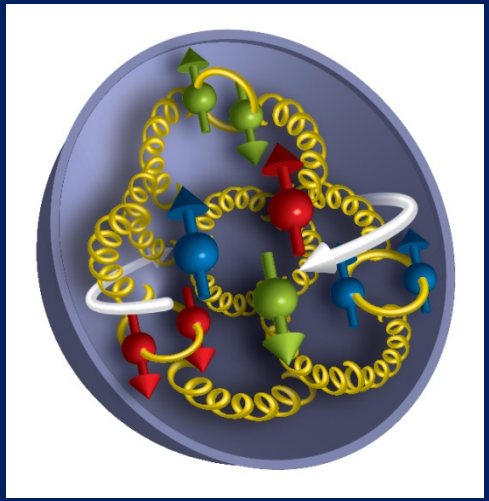




BRAHMS

Need more experimental data!

- And with more measurements to provide meaningful constraints, will need consistent treatment of sea quarks in theory/phenomenology



- Understanding the *dynamics* of sea quarks, which probe beyond static pictures of antiquarks in the nucleon and nucleus, will be crucial to understanding the way(s) in which the sea is generated

Importance of PID to study sea quarks at the EIC

Reiterating from Elke Aschenauer's talk:

- Quark flavor tagging via semi-inclusive DIS
  - Hadron PID super-important!

- ID of *many* or *all* particles in reconstructed jets would be an even more powerful tool to study the sea, as well as hadronization!

Oct 2017: INT Workshop on The Flavor Structure of the Nucleon Sea

www.int.washington.edu/PROGRAMS/17-68W/

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Seminar schedules

Application form
For full consideration, please apply by May 15, 2017

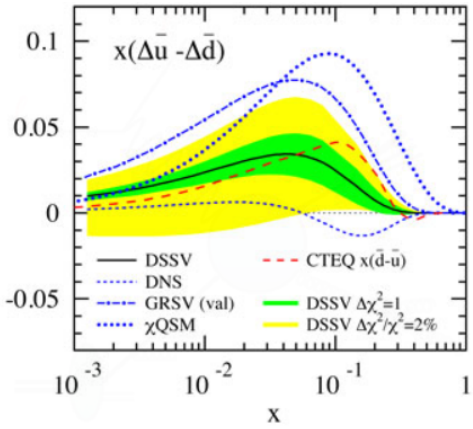
Talks Online

Exit Survey

INT Workshop INT-17-68W

The Flavor Structure of Nucleon Sea

October 2-13, 2017



The main goal of this workshop is to address theoretical calculation and interpretation issues associated with the flavor structure of the nucleon's light sea, including its number or momentum distributions (PDFs), helicity distributions, transverse-momentum-dependent parton distributions (TMDs) such as the Sivers distribution, and the flavor asymmetry of these distributions. New data from ongoing experiments will become available from jet, hadron, direct photon, and W+/-boson measurements at the RHIC STAR and PHENIX experiments, from Fermilab E906 Drell-Yan measurements, and from semi-inclusive deep-inelastic scattering (SIDIS) measurements at COMPASS. In addition, several new experiments are in the preparation stage and aim to collect data over the next few years, including the polarized target Drell-Yan experiment at Fermilab (E1039), RHIC's run with transversely polarized protons at 510 GeV in Run-2017, and a new generation of SIDIS experiments with the JLab-12GeV upgrade.

Oct 2017: INT Workshop on The Flavor Structure of the Nucleon Sea

- http://www.int.washington.edu/PROGRAMS/17-68W/
- 35 participants + 4 organizers; 39 talks

- Experimental presentations of Drell-Yan and W production

- Lots of lattice talks! (12, i.e. nearly 1/3)
  - Lattice will clearly play an increasing and important role in understanding the nucleon sea as we move toward the EIC era

- Phenomenology, including fragmentation functions
  - Fragmentation functions needed for SIDIS

- Models of nucleon structure
  - Ultimately want not just well-constrained fits and more precise calculations, but also insight

Relationship between gluons and sea quarks

- What can be learned about gluons from sea quark distributions, and vice-versa, for
  - unpolarized, collinear PDFs?
  - helicity PDFs?
  - transversity PDFs and linearly polarized gluons?
  - TMD PDFs?

- Perturbative vs. nonperturbative interplay between sea quarks and gluons?
  - Do the nonperturbative mechanisms that must be generating the flavor asymmetry observed in the unpolarized, collinear sea affect gluon distributions at all?
  - In the low-x regime, is the relationship between gluons and sea quarks straightforward?

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  - In the low-x regime, is the relationship between gluons and sea quarks straightforward?

- What role does Q^2 evolution play in the relationship?
  - Is this role exactly the same for DGLAP vs. CSS evolution, i.e. are collinear and TMD PDFs affected differently?
  - What about evolution of the transversity distributions?

- Recent work on gluons in nuclei that aren't associated with a single nucleon. Does this have implications for sea quarks not associated with a single nucleon?
  - Any relationship to pion exchange models?

Proton vs. neutron sea

- Isospin symmetry between proton and neutron ultimately an approximation
- Different masses
  - Well, okay, only a 0.1% difference here.
- What about different electromagnetic charges of valence quarks?
  - Thinking in particular of a “dilute” picture of a nucleon, could this affect parton spin-momentum correlations or other dynamics?

Baryon vs. meson sea

- Would naively expect dynamics of valence quarks in baryons vs. mesons to be different. Also dynamics of sea quarks?
  - Three-(anti)quark system vs. quark-antiquark pair
  - Baryons as fermions vs. mesons as bosons—different spins

- Is strangeness suppressed in the sea of the phi meson through Pauli blocking? Charm suppressed in the sea of the J/Psi? Does it even make sense to think of these resonances as having a "sea"?

- Do different binding energies e.g of different heavy quarkonium states lead to different dynamics in the sea, or of the valence quarks?

Can we learn anything about the sea of hadrons by thinking about hadronization?

- How should we think about colored partons binding, color neutralizing, and “getting dressed” with their dynamical sea as they snap into a particular quantum state, i.e. hadron?

- Is thinking about hadronization via “string breaking” vs. “parton recombination” vs. threshold production helpful? Every possible mechanism has to lead to same final state.

What do we really mean by "valence" and "sea" anyway??

- At any given instant, the proton has a net up content of 2 and net down content of 1, which determines the +1 charge.
- It also determines the total spin somehow . . .

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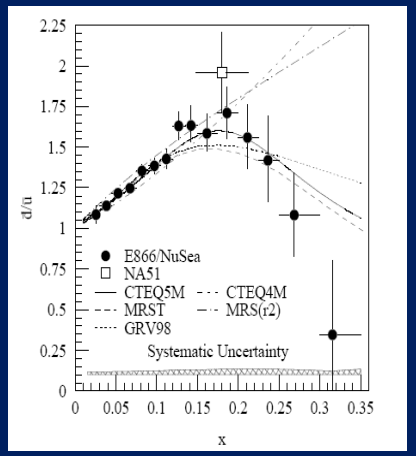
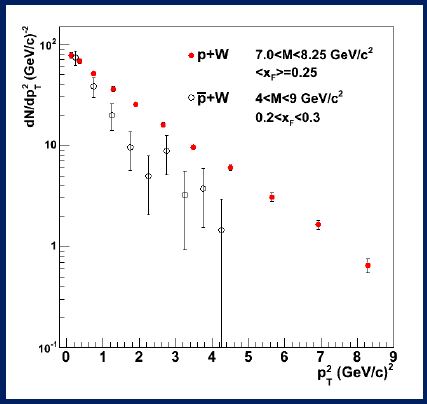
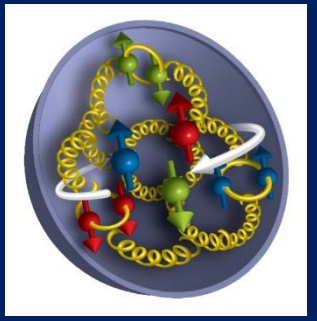


- We talk about "the valence quarks" being at large x, but e.g. Drell-Yan experiments have already measured (sea) antiquarks up to 0.35. Is it meaningful to think also of sea *quarks* at these high x values, i.e. up or down sea quarks rather than antiup or antidown?
  - If we measure an up or down quark at x~0.35, we call it "valence."
  - So what do hints of different dynamics for sea quarks than "valence" quarks mean? Should what we call "valence" vs. "sea" be associated with different processes/behavior within the proton?

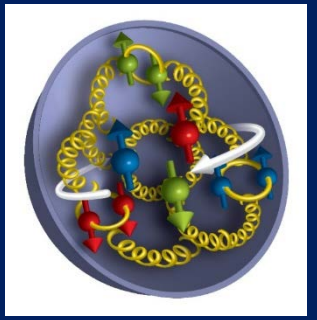


Conclusions and outlook



- While some of the questions posed here may already have known answers—and others may not even be sensible to ask—it's important to push ourselves to think about the sea of QCD bound states more deeply and in new ways.
  - Understanding the sea will be critical to understanding hadron structure!

Conclusions and outlook



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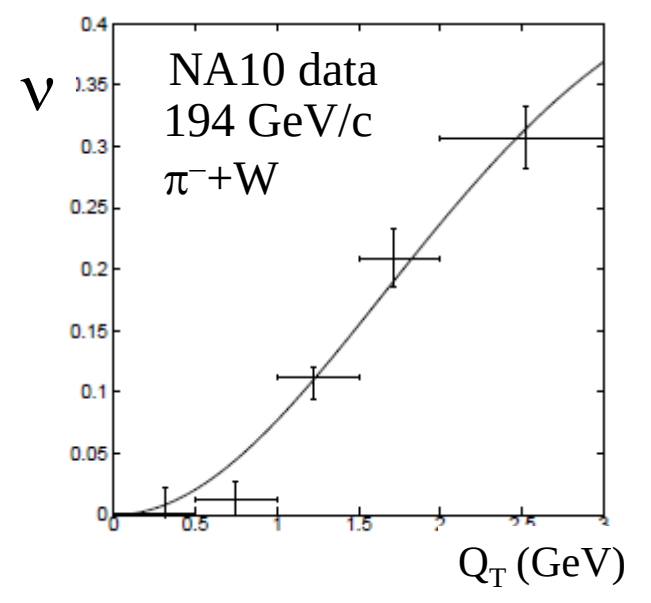
  - Understanding the sea will be critical to understanding hadron structure!

- The EIC will be a powerful facility to explore the sea well beyond known horizons.

Extra material

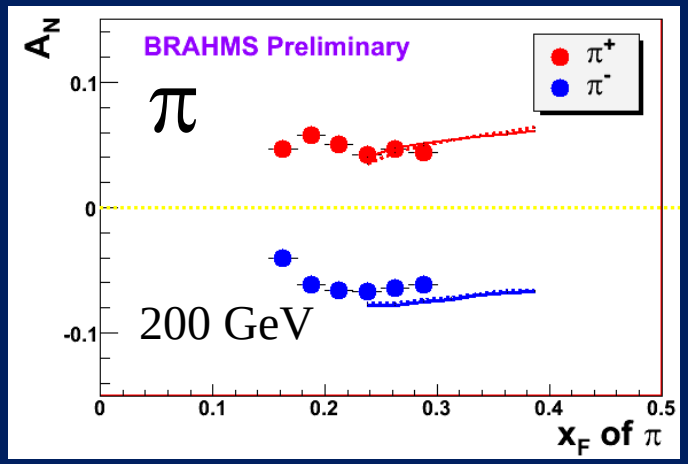
Probing quark spin in unpolarized Drell-Yan

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

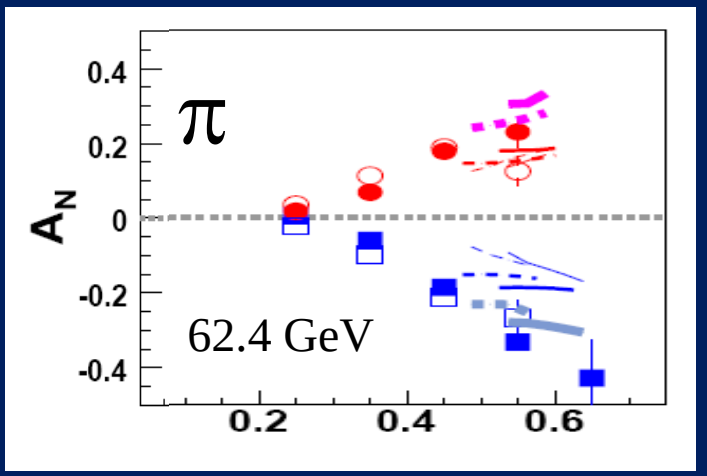


D. Boer, PRD60, 014012 (1999)

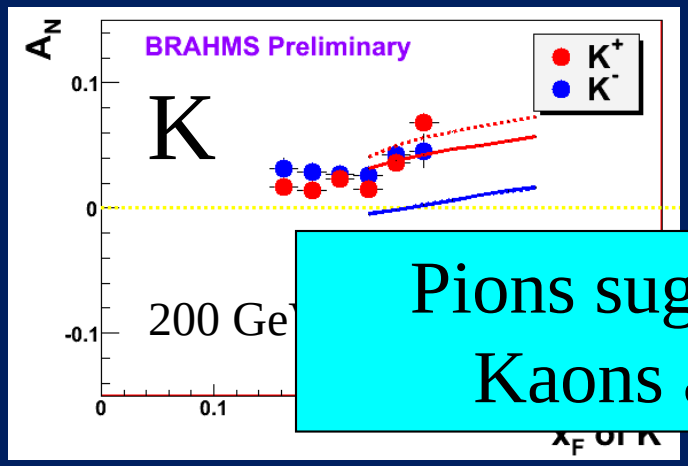
- cos2ϕ term sensitive to *correlations between quark transverse spin and quark transverse momentum* → Boer-Mulders transverse-momentum-dependent parton distribution function
- Evidence for such correlations also in semi-inclusive DIS data
- Large cos2ϕ dependence seen in pion-induced Drell-Yan from multiple experiments



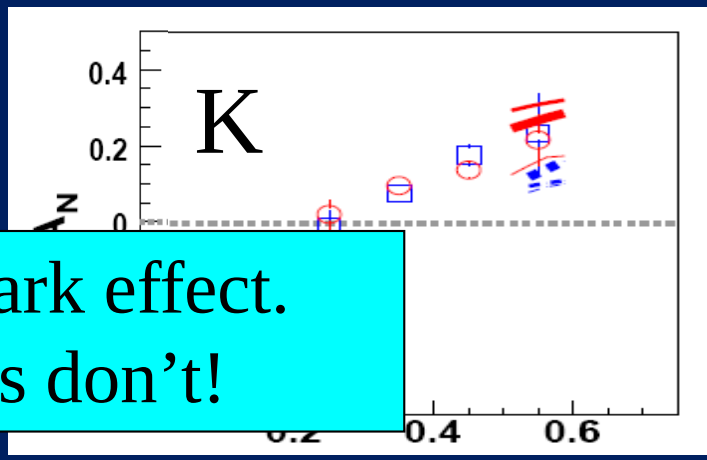
π, K, p at 200 and 62.4 GeV



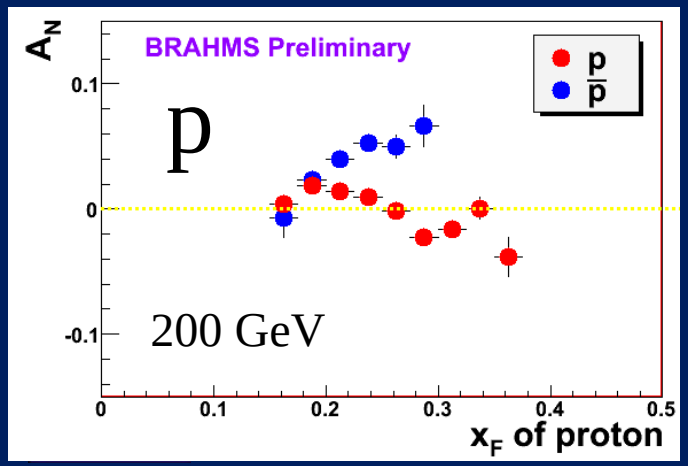
Note different scales



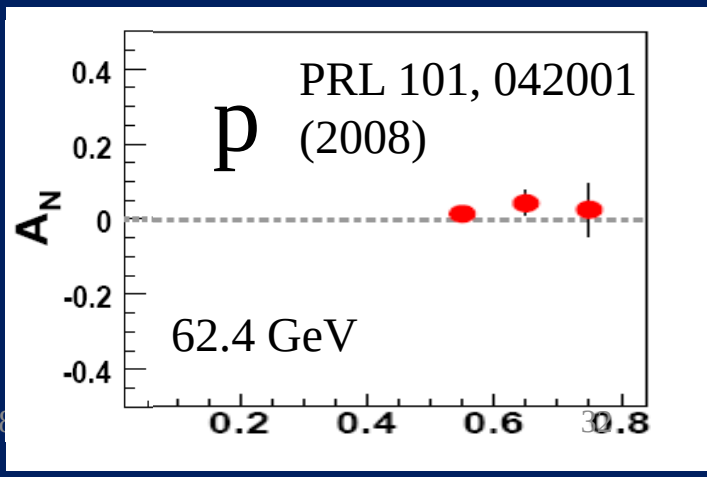
K- asymmetries underpredicted



Pions suggest valence quark effect.
Kaons and (anti)protons don't!



Large antiproton asymmetry??
Unfortunately no 62.4 GeV measurement



$p+p$ η A_N larger than π^0?? Same?