QCD and Baryon Polarization
Lecture 4:
Hadronization and hadron structure: Sea quarks

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Outline of lectures

1. Introduction; collinear and TMD nucleon structure
2. Spin-momentum correlations in the nucleon in terms of TMD PDFs and collinear twist-3 multiparton correlations
3. Hadronization: collinear and TMD fragmentation functions, collinear twist-3 correlations; dihadron FFs; different hadronization mechanisms/pictures
4. *Hadron structure and hadronization: Sea quarks/non-valence quarks*
5. Hyperon and heavy flavor baryon polarization I
6. Hyperon and heavy flavor baryon polarization II

Diving into the sea

- Sometimes we focus our attention on the sea, sometimes we make a lot of simplifying assumptions about the sea, sometimes we neglect it entirely
- There's a lot going on in there . . . Dynamics essential!
- Understanding the sea will be crucial to understanding QCD bound states

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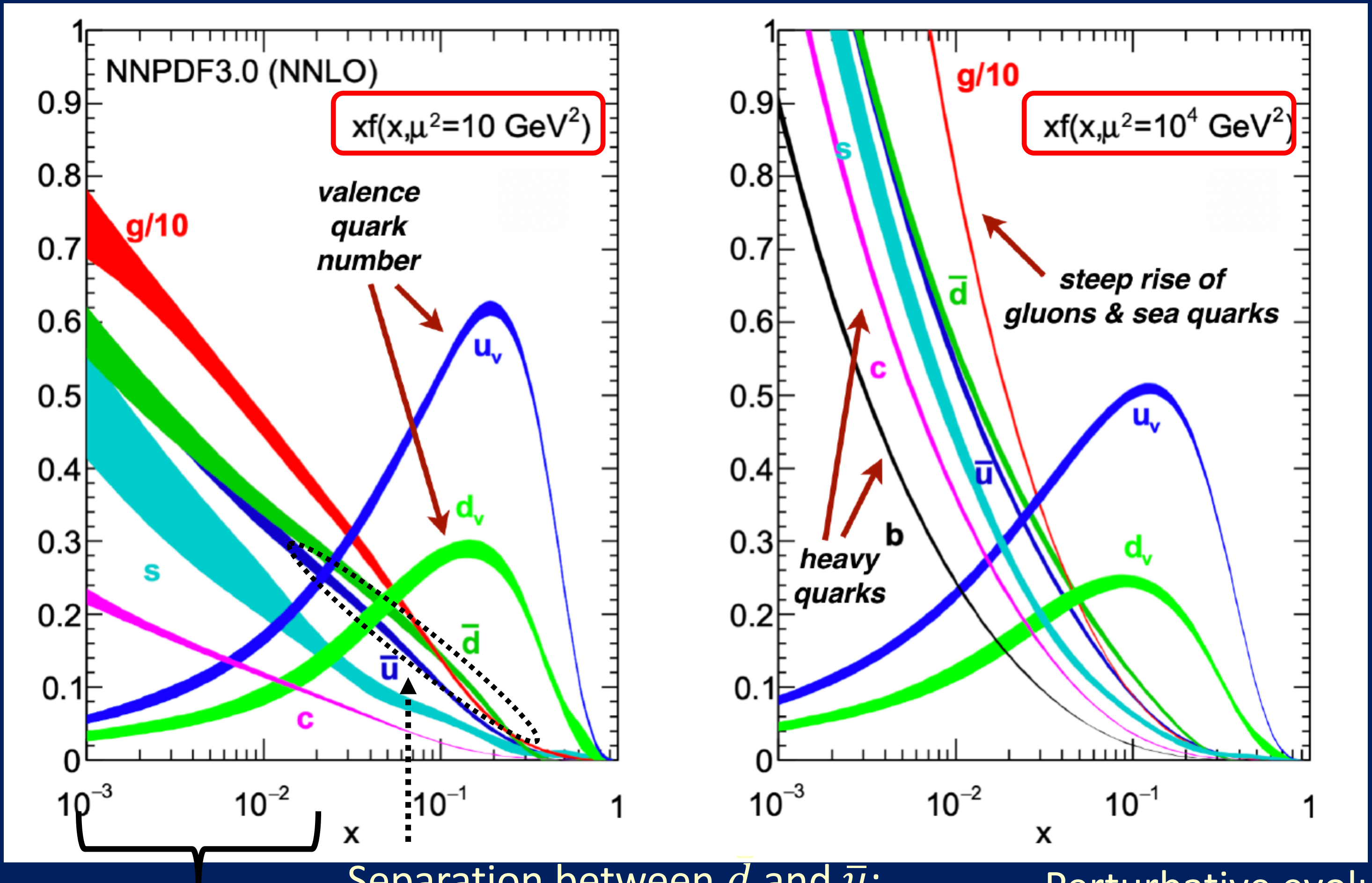
- Understanding the sea will be crucial to understanding QCD bound states!

Sea quarks—many hints of interesting behavior already!

Recall (Lecture 1): PDF fits

J. Rojo, arXiv:1910.03408



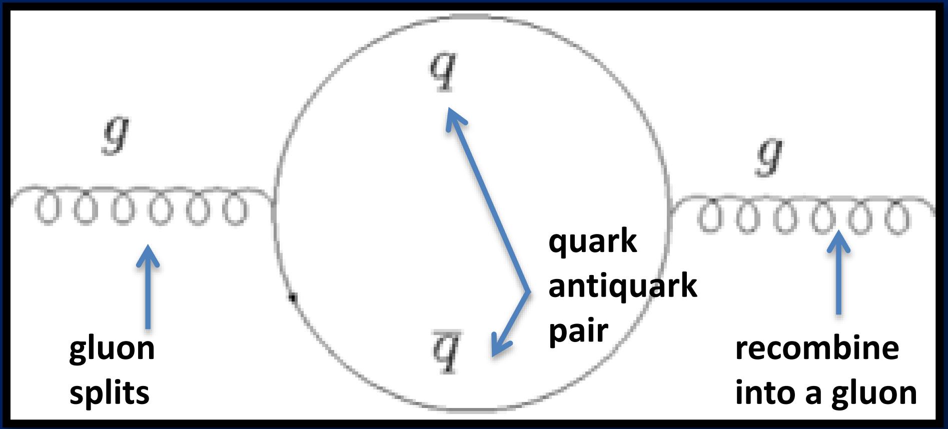
Perturbative sea

Separation between $\bar{d}$ and $\bar{u}$: nonperturbative sea

Perturbative evolution to other energy scales

Generating the sea by gluon splitting

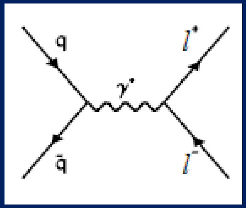
- Nucleon sea (was) naively assumed to be symmetric in the light flavors (u,d)
  - Gluons don't couple to flavor
  - Masses of u and d quarks are small and similar, compared to proton mass and probing energies



- Perturbative calculation differences between u and d are very small!
  - D. A. Ross and C. T. Sachrajda, Nucl. Phys. B149, 497 (1979)

Light flavor sea: Experimental surprises

- Drell-Yan process of q$\bar{q}$ annihilation to dimuons



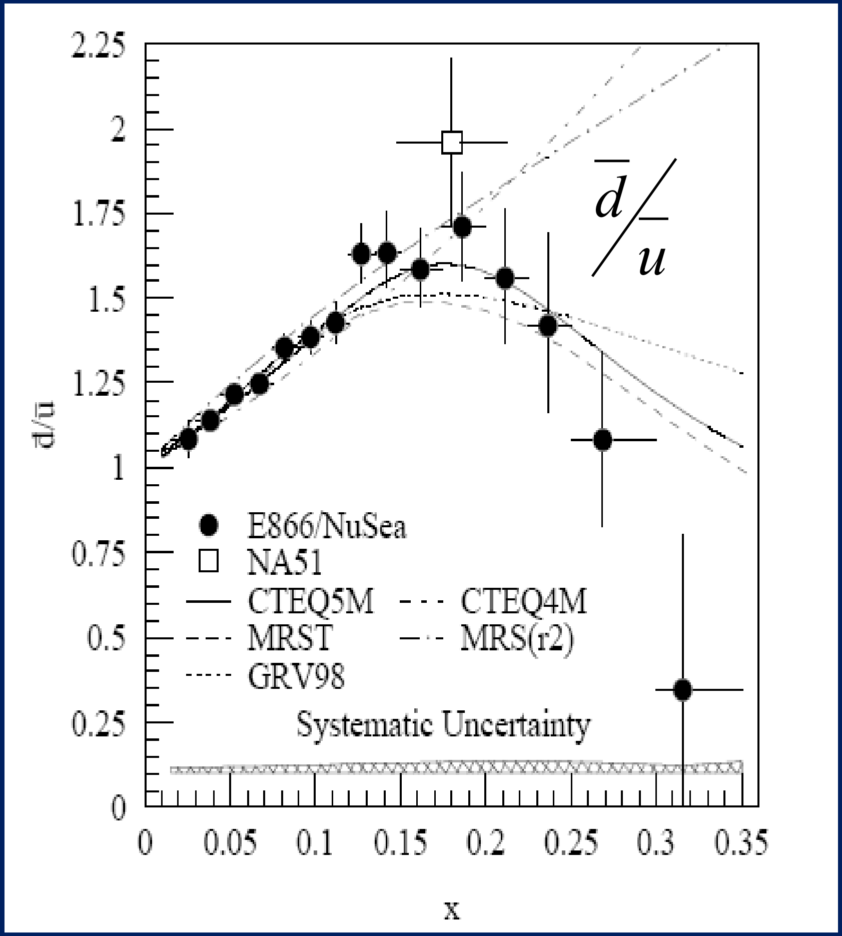
- Proton-hydrogen and proton-deuterium collisions

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

*simplest leading-order expression

- Indicates additional mechanism to generate sea quarks—still not well understood

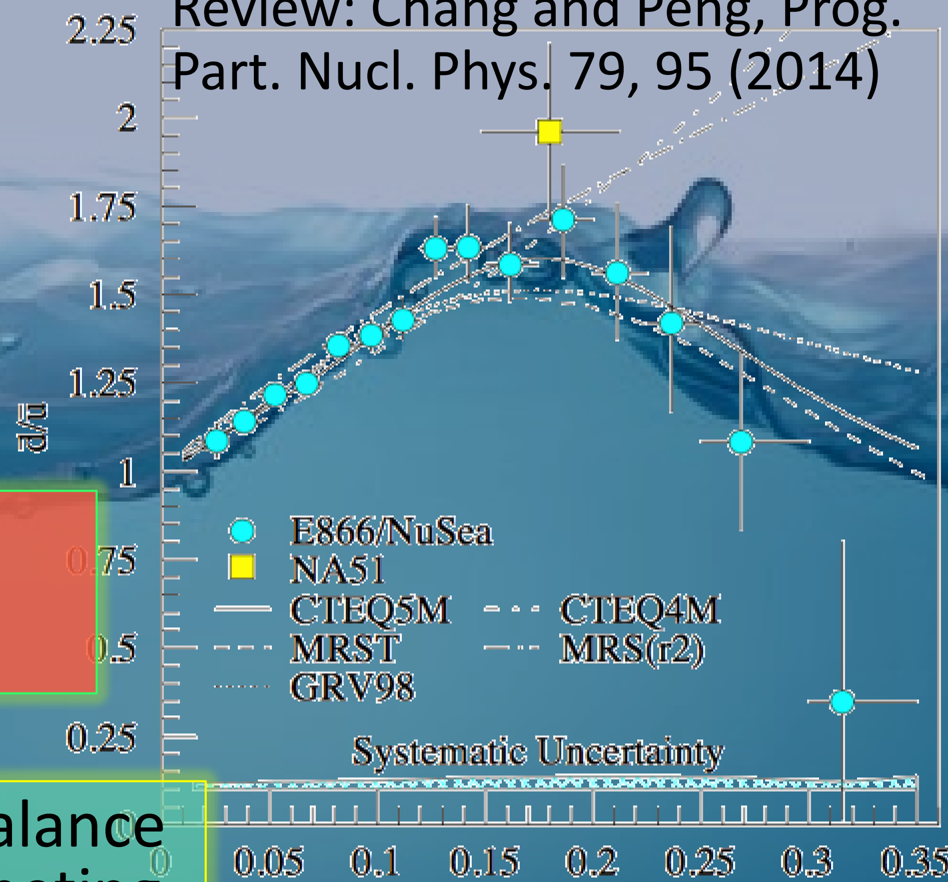
$$\int \left(\bar{d}(x, Q^2) - \bar{u}(x, Q^2)\right) dx = 0.118 \pm 0.012$$



Fermilab E866 data: PRD64, 052002 (2001)
CERN NA51 data: PLB332, 244 (1994)

How is the nucleon sea generated?

Review: Chang and Peng, Prog. Part. Nucl. Phys. 79, 95 (2014)



Connected and disconnected sea partons?

Chiral Quark Soliton model?

Hybrid model?

Meson Cloud model?

Delicate balance of all competing mechanisms?

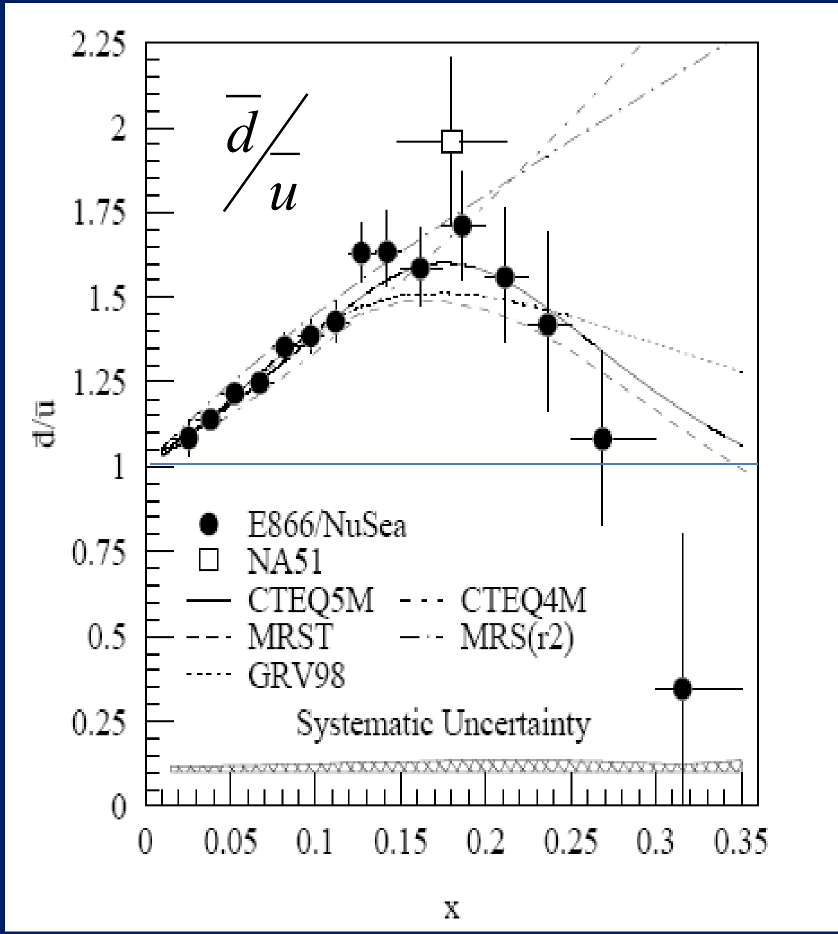
Statistical parton distribution functions?

Instanton model?

Your model??

Slide from Arun Tadepalli

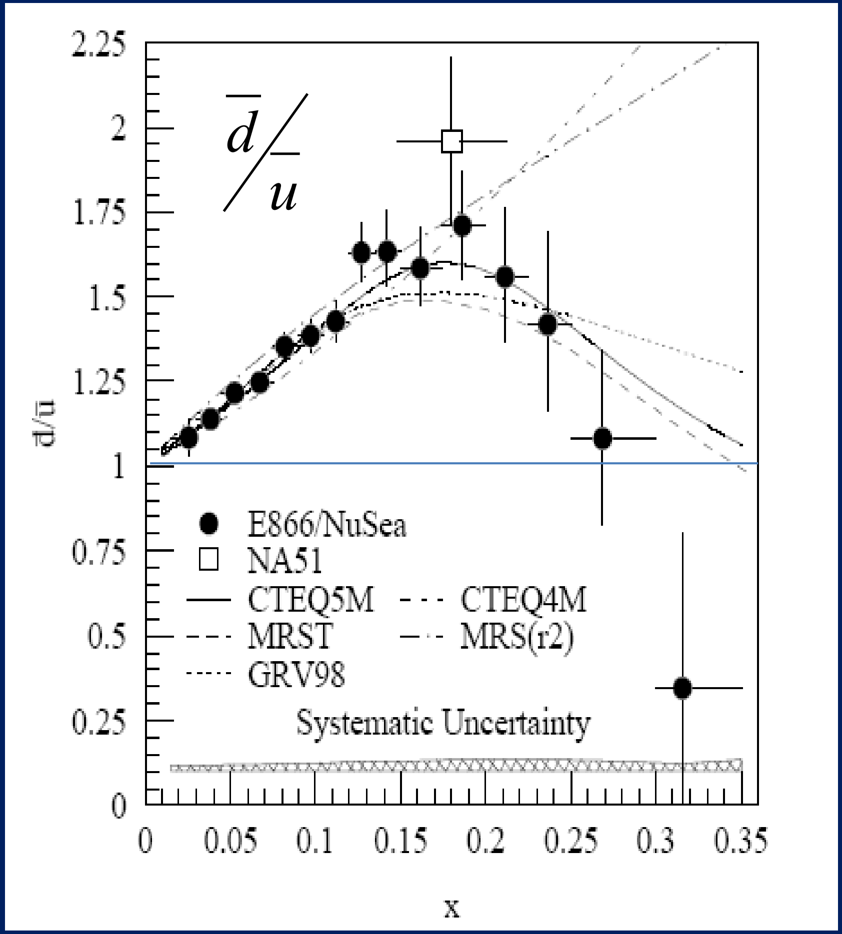
Light quark (unpolarized, collinear) sea: Not simply gluon splitting



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

- Ratio appears to deviate from 1 for (at least) momentum fractions x ~0.02-0.2
- One idea: meson cloud models suggest fluctuation of p into $n + \pi^+$, with $\bar{d}$ in π^+ at relatively large momentum
  - But meson cloud model calculations don't reproduce shape so well…
- Still no clear mechanism(s) identified!

Light quark (unpolarized, collinear) sea: Not simply gluon splitting



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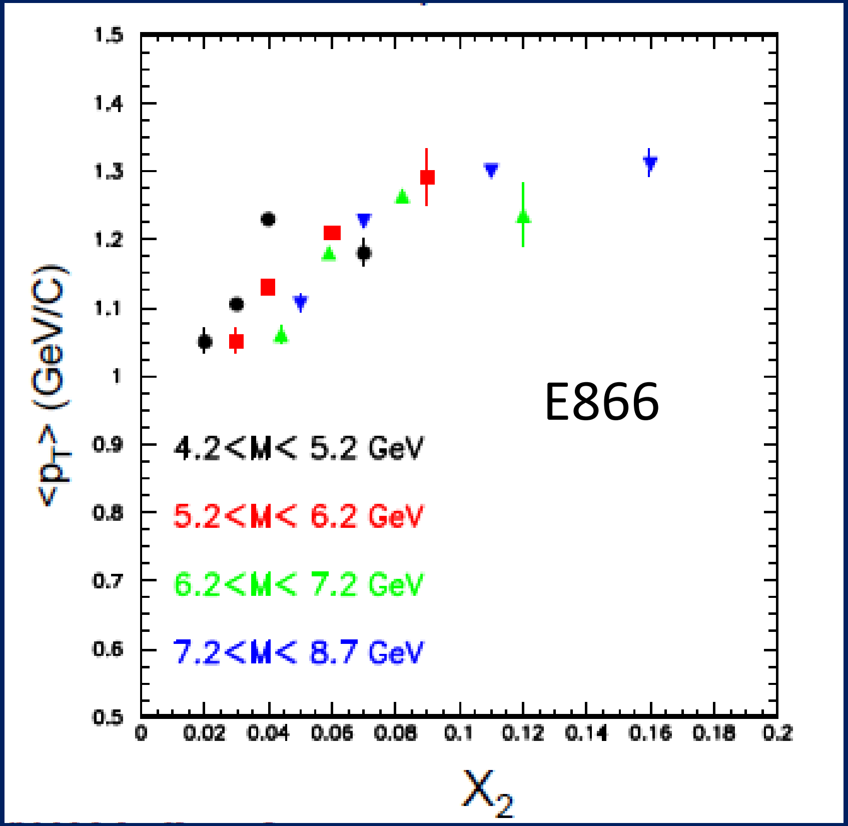
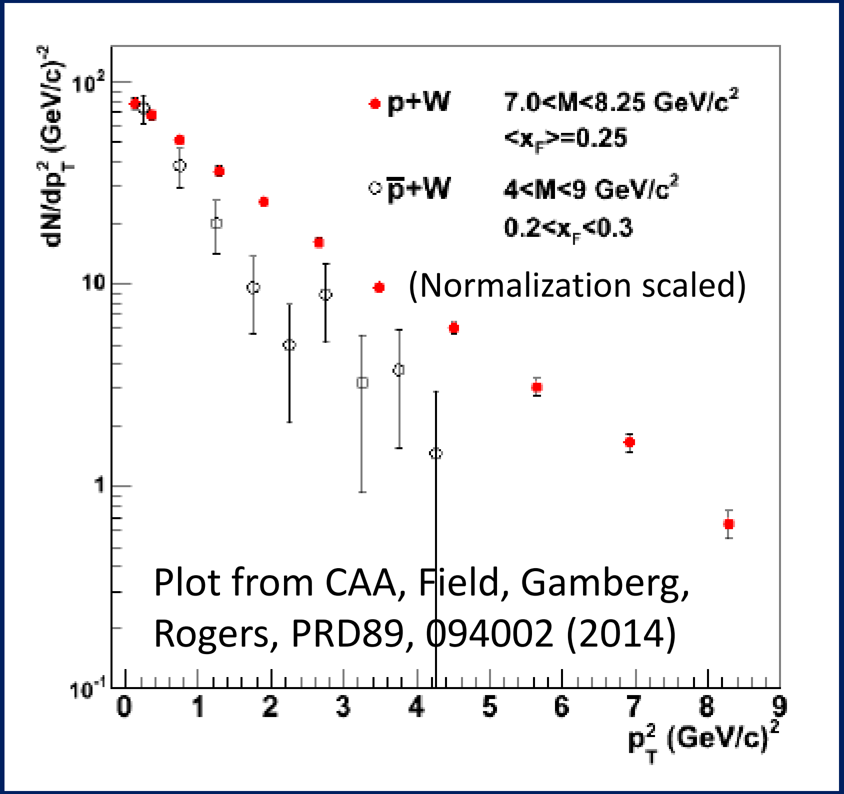


Hints from dynamics?
Mean p_T of Drell-Yan pair rises with momentum fraction of sea quark

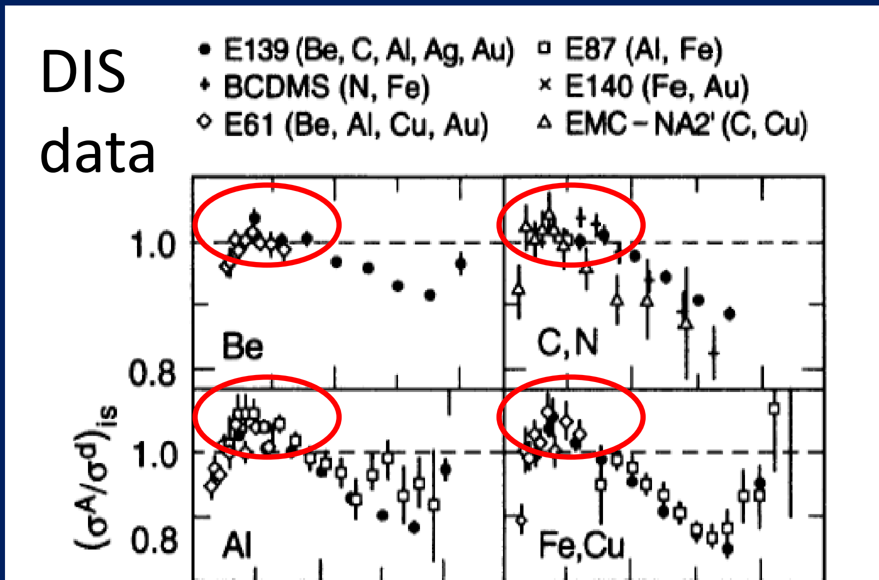
Dynamics: Transverse momentum of valence vs. sea quarks

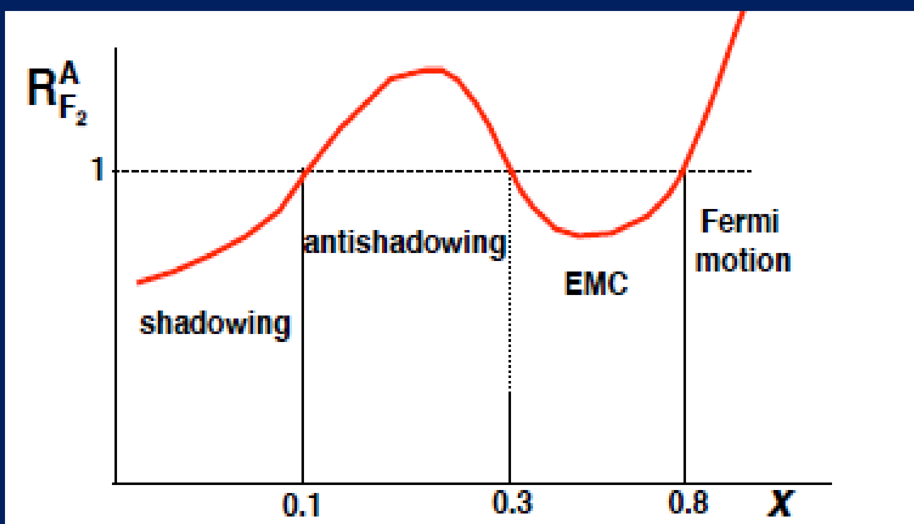


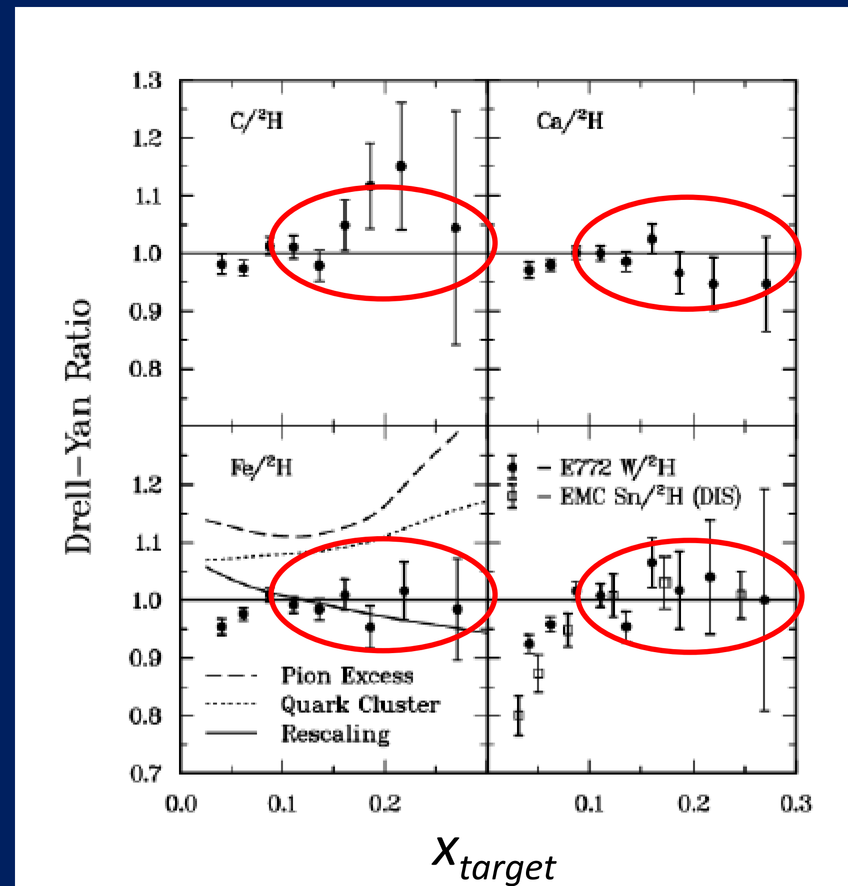
Data from E537 (pbar+W): PRD38, 1377 (1988)
E439: (p+W): AIP Conf. Proc. 45, 93 (1978)

- 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.

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





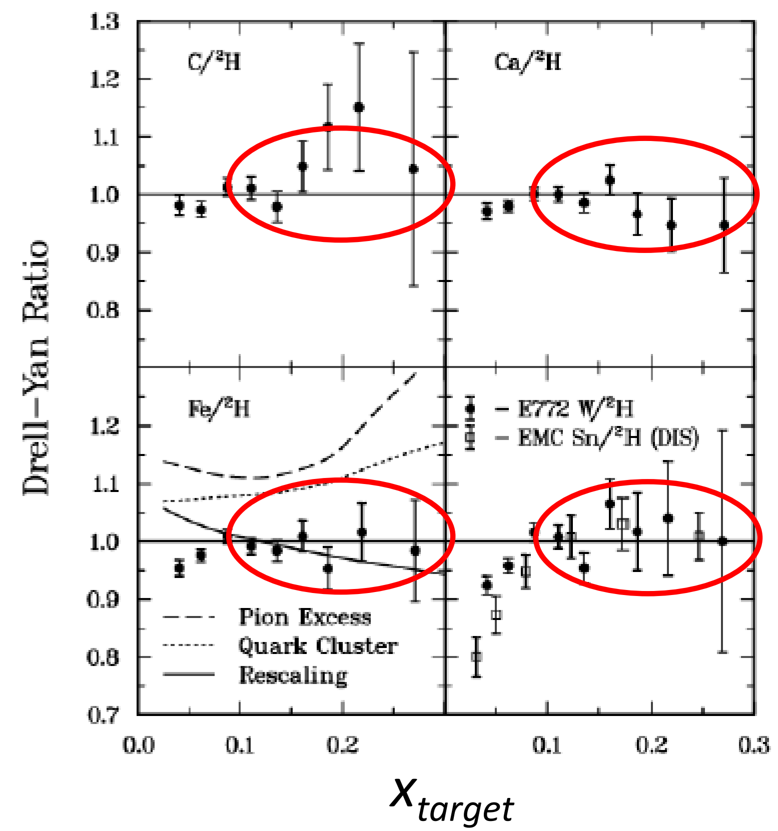


Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

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??



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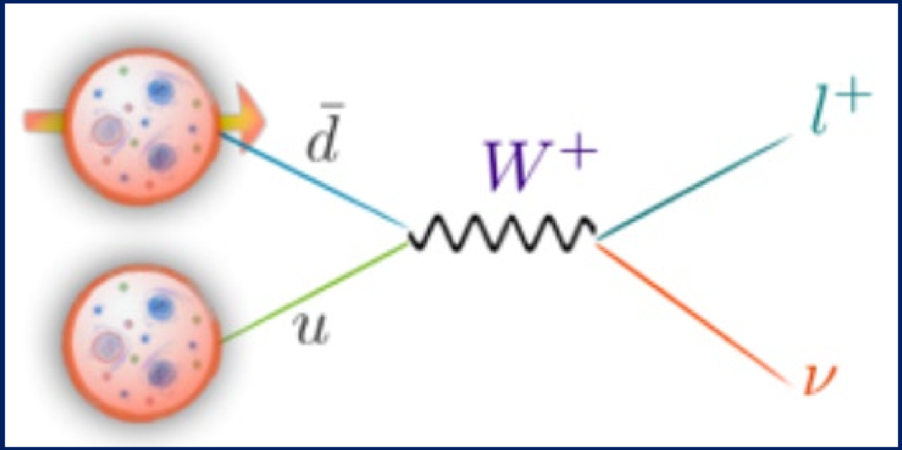
No clear "antishadowing" in Drell-Yan

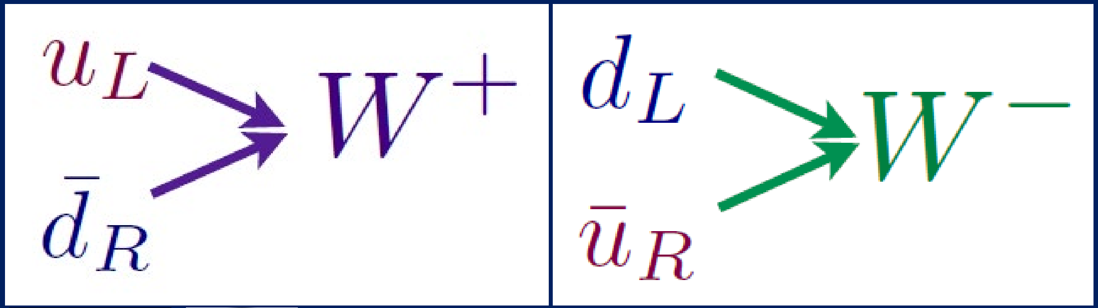
Sea quark spin-spin correlations (helicity distributions)

$$\Delta q(x), \Delta\overline{q}(x)$$



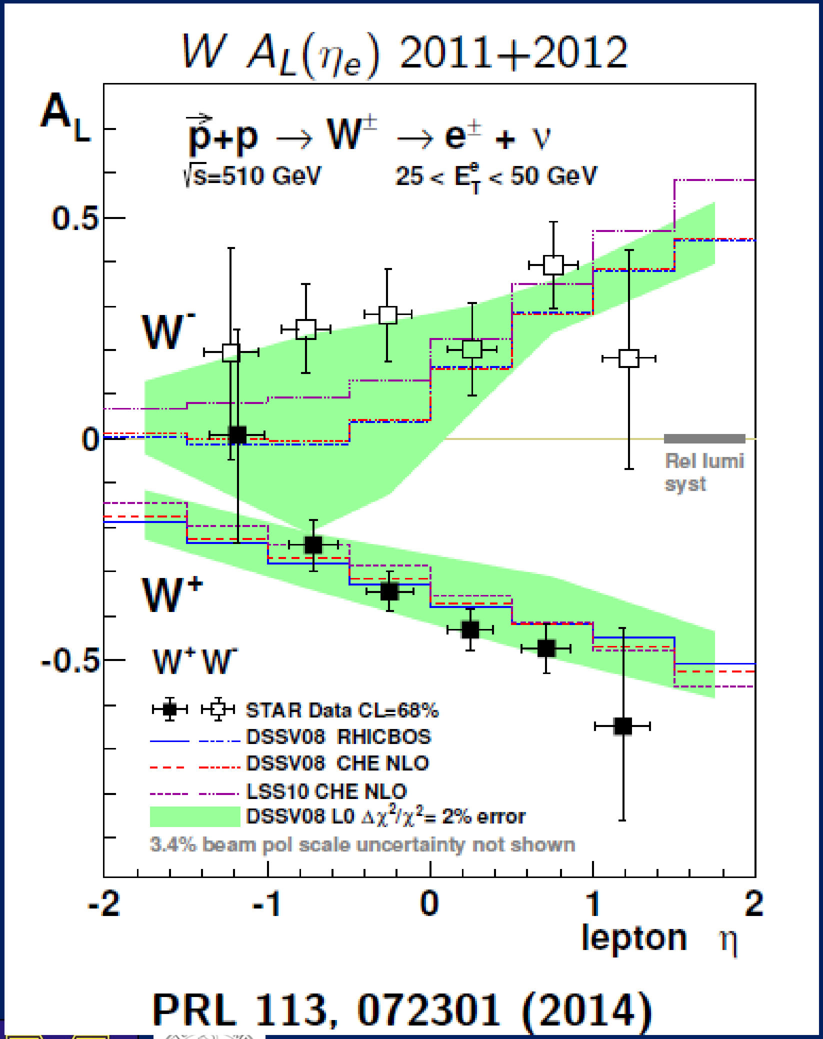
$$A_L^{W^+} \approx -\frac{\Delta u(x_1)\overline{d}(x_2) - \Delta\overline{d}(x_1)u(x_2)}{u(x_1)\overline{d}(x_2) - \overline{d}(x_1)u(x_2)}$$

$$A_L^{W^-} \approx -\frac{\Delta d(x_1)\overline{u}(x_2) - \Delta\overline{u}(x_1)d(x_2)}{d(x_1)\overline{u}(x_2) - \overline{u}(x_1)d(x_2)}$$



Parity violation of weak interaction + control over proton spin orientation at the Relativistic Heavy Ion Collider gives access to *flavor*-spin structure of proton

Large parity-violating single-helicity asymmetries

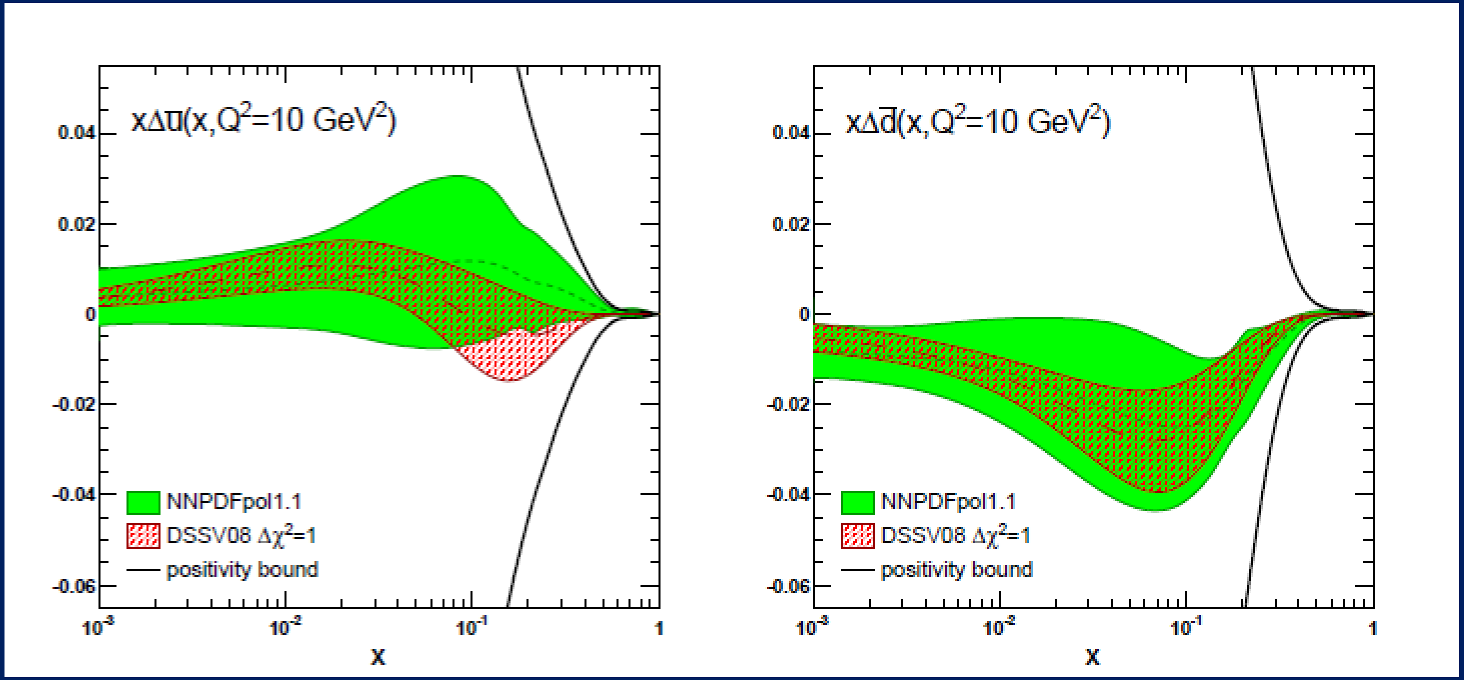


- Improve constraints on light antiquark helicity distributions

$$A_L = \frac{1}{P}\frac{N^+/L^+ - N^-/L^-}{N^+/L^+ + N^-/L^-}$$

Flavor asymmetry in the sea helicity distributions

NNPDF, NPB 887.276 (2014)



(DSSV08: Before RHIC W^- data pulled up the $\bar{u}$ helicity distribution)

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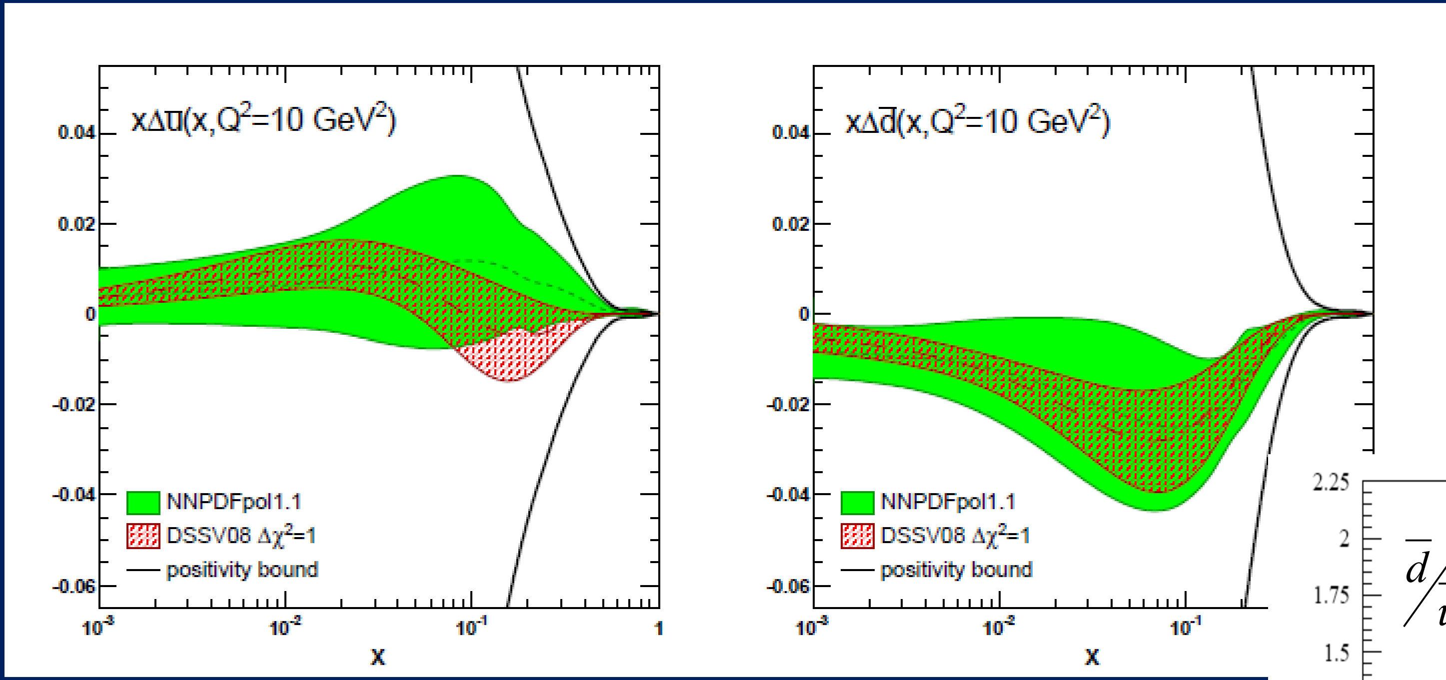

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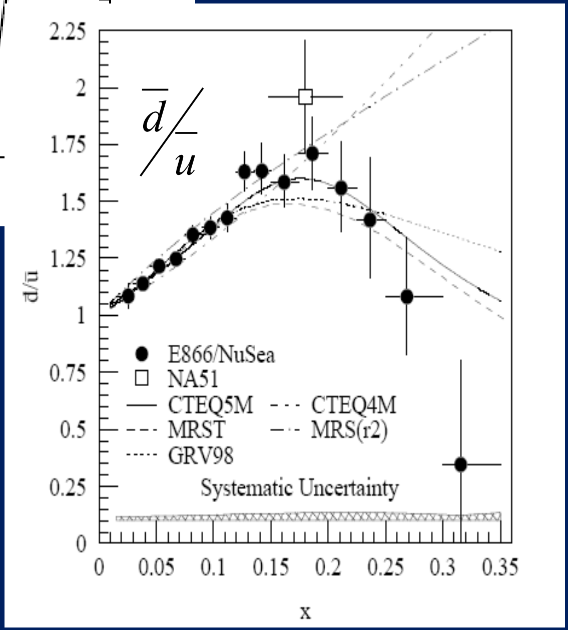
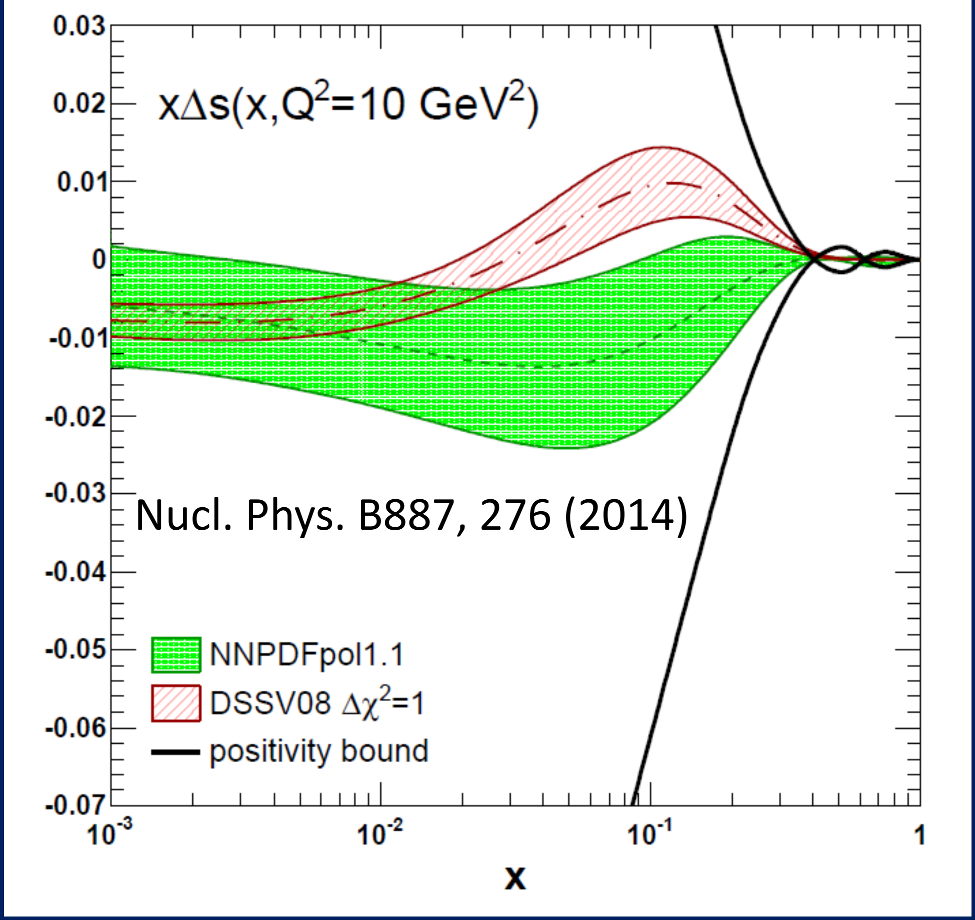


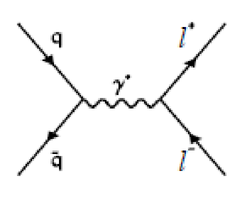
Shouldn't be surprising given flavor asymmetry in unpolarized sea? Or unrelated??

Strangeness helicity distribution from inclusive vs. semi-inclusive DIS

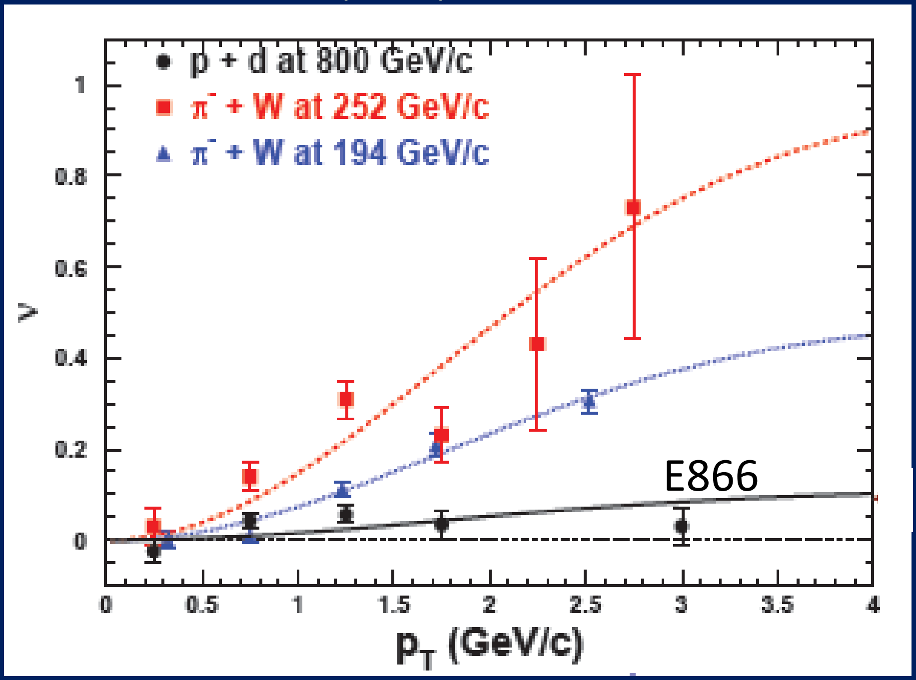
- NNPDF fit an indirect extraction of strangeness using only inclusive DIS
- DSSV includes semi-inclusive DIS kaon data
- Is the strange sea polarized, and if so, with or against the proton??
  - Need more data!



Spin-orbit coupling for sea quarks in unpolarized protons small?



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



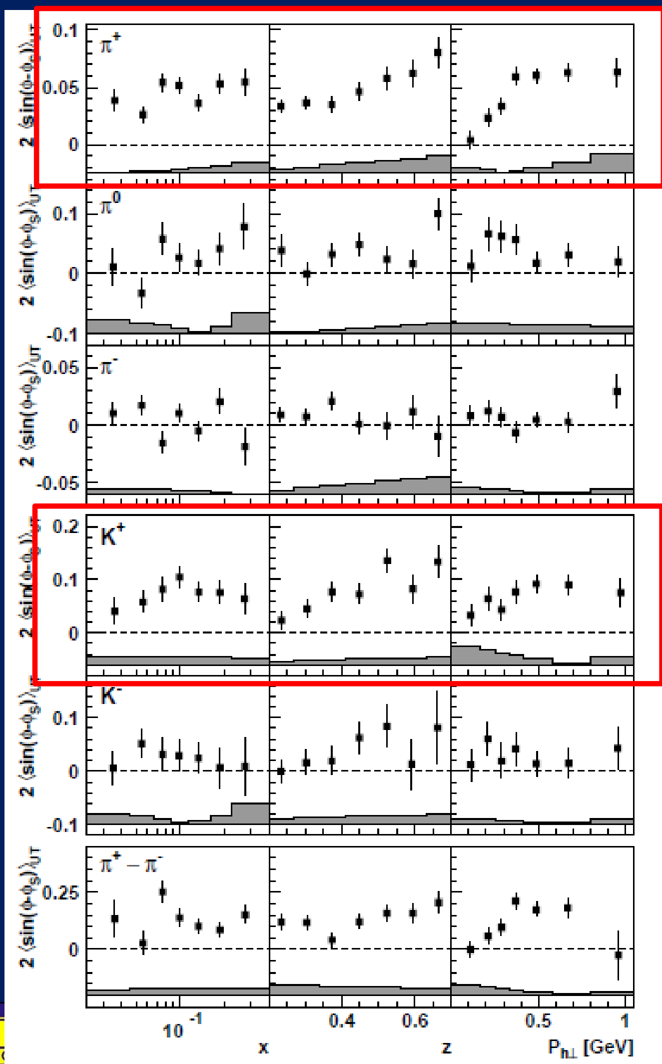
- Significantly reduced $\cos 2\phi$ dependence in *proton*-induced Drell-Yan compared to *pion*-induced Drell-Yan
- Suggests this spin-orbit correlation for sea quarks is small?
  - Boer-Mulders TMD PDF: describes correlation between orbital motion of quark and the quark's own transverse spin, in an unpolarized hadron

Boer - Mulders function $h_1^\perp$

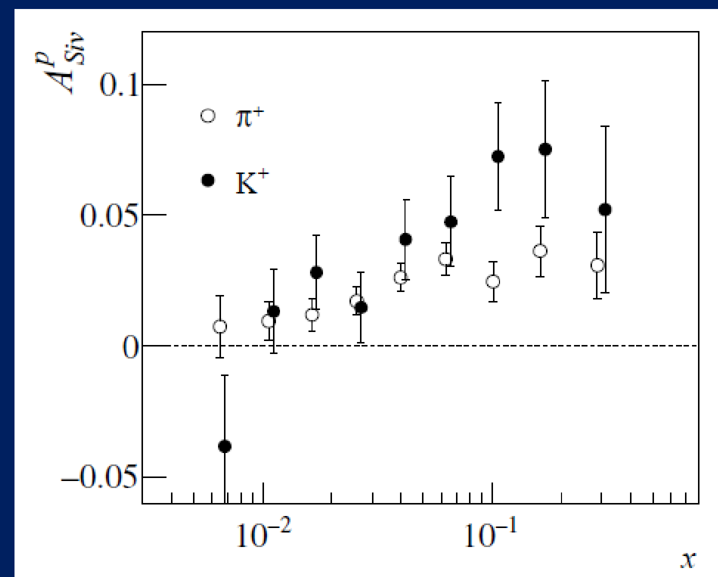
$\nu(\pi^- W \rightarrow \mu^+ \mu^- X) \sim$ [valence $h_1^\perp(\pi)$] * [valence $h_1^\perp(p)$]

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

Spin-orbit coupling for sea quarks in ***polarized*** *protons* ***not*** *small?*



Spin-momentum correlation measurements from two semi-inclusive DIS experiments seem larger for K^+ $(u\bar{s})$ than π^+ $(u\bar{d})$. $\bar{s}$ effect??

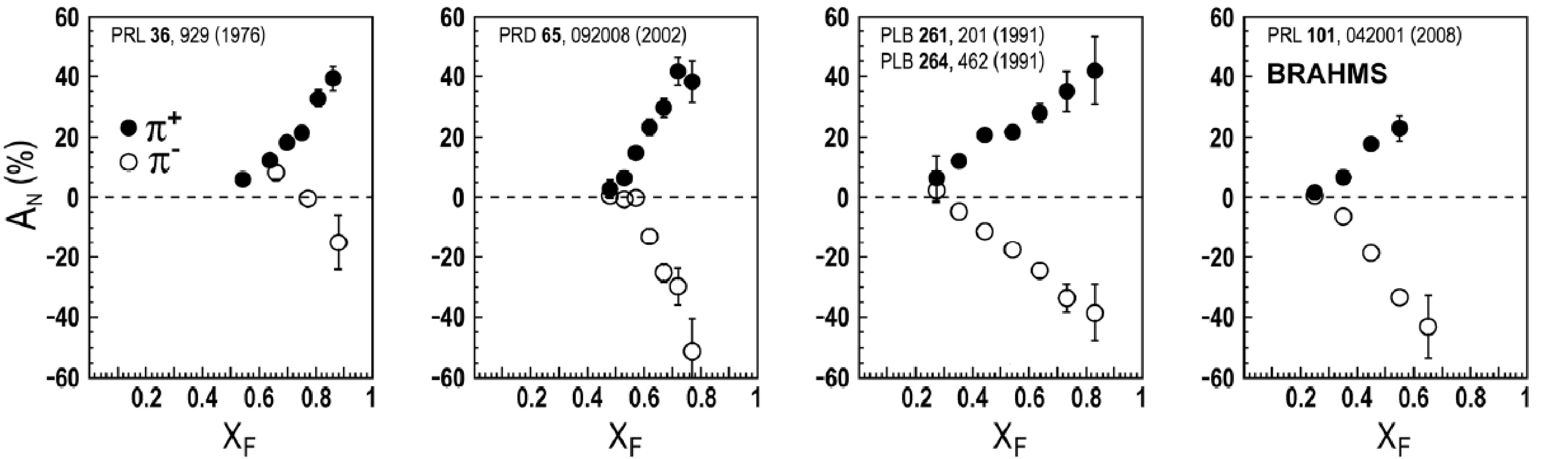


COMPASS, PLB744, 250 (2015)

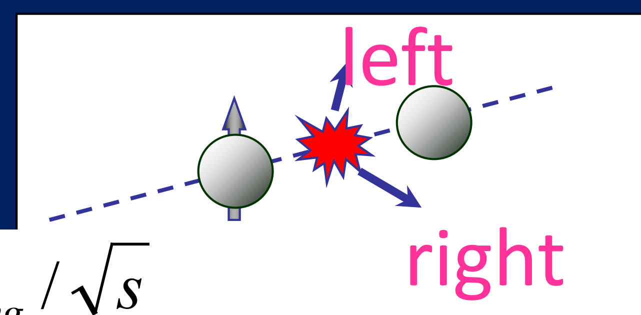
HERMES, PRL103, 152002 (2009)
Note scale difference for π^+ vs. K^+!

Recall: Huge spin-momentum correlations observed in hadronic collisions involving transversely polarized protons

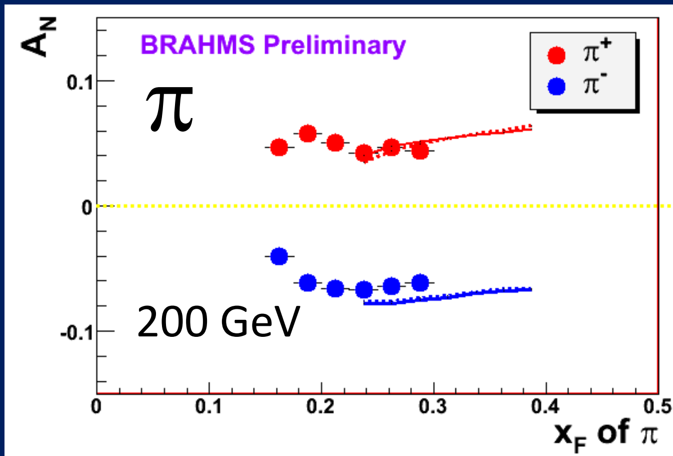
ANL	BNL	FNAL	RHIC
√s=4.9 GeV	√s=6.6 GeV	√s=19.4 GeV	√s=62.4 GeV



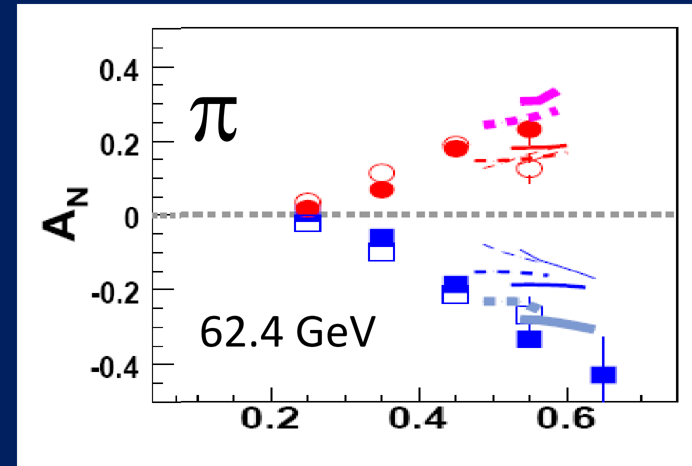
Large asymmetries for more forward pion production with respect to polarized beam and opposite sign for π^+ and π^- suggest valence quark effect with opposite sign spin-momentum correlation for u vs. d



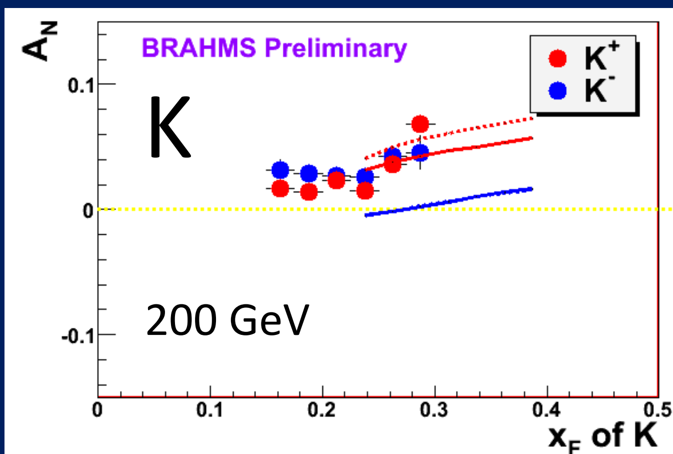
$$x_F = 2p_{long}/\sqrt{s}$$



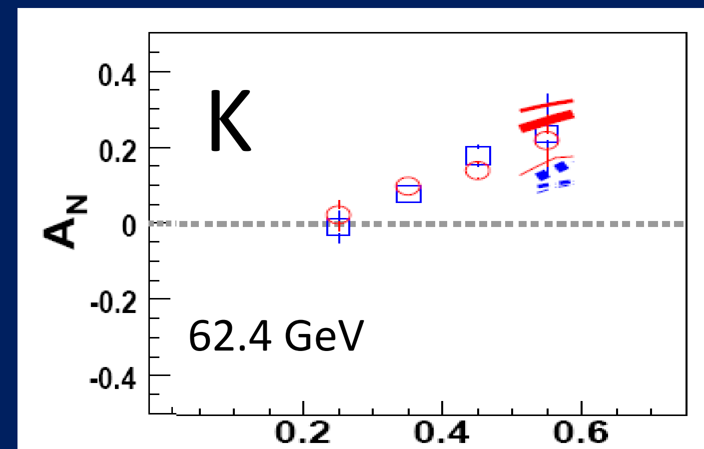
π, K, p
at 200 and
62.4 GeV

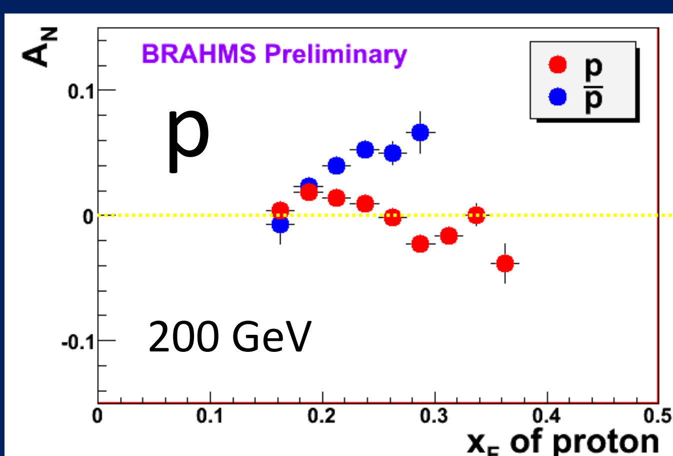


Note different scales

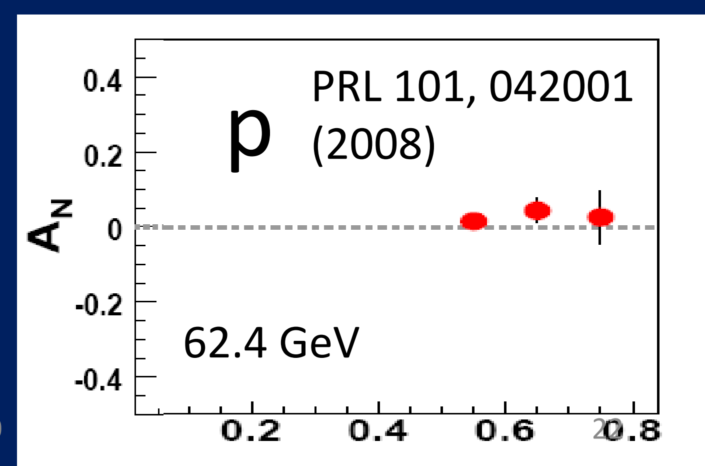


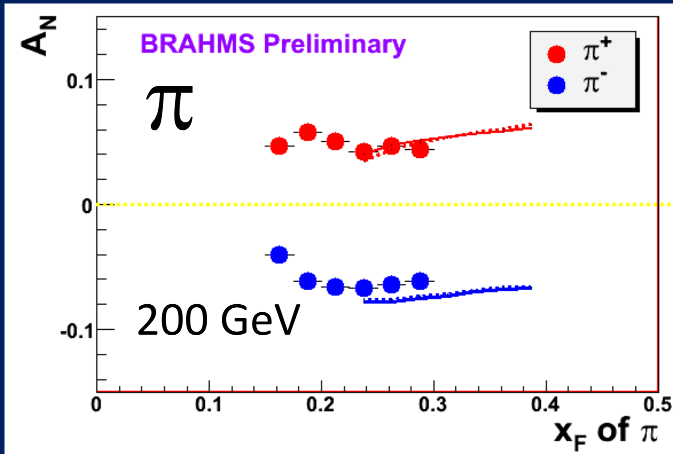
K^- $(\bar{u}s)$ asymmetries same as K^+ $(u\bar{s})$





Large antiproton asymmetry?? Unfortunately no 62.4 GeV measurement





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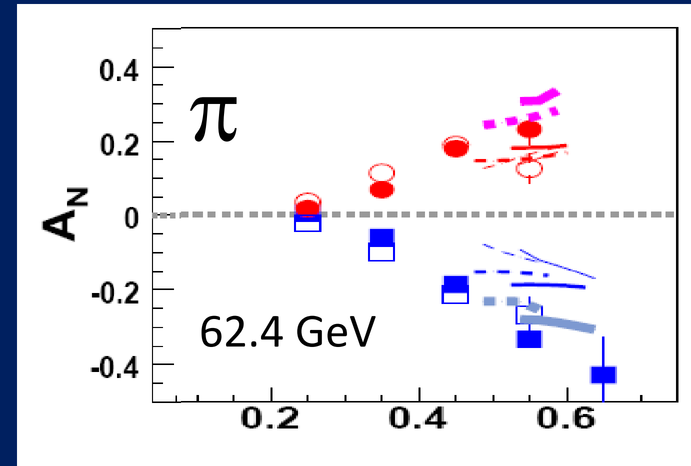

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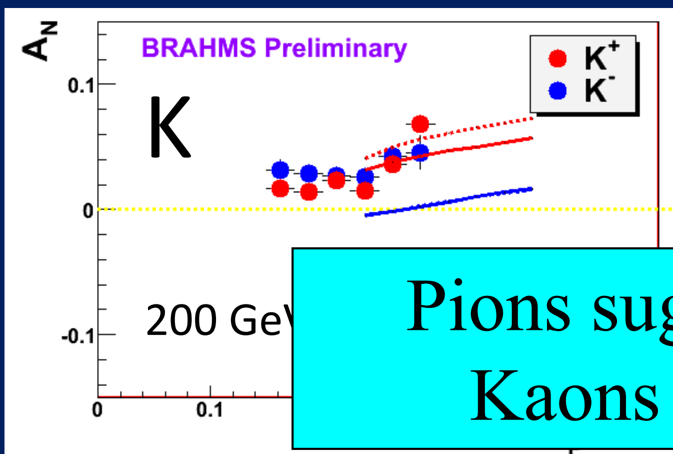

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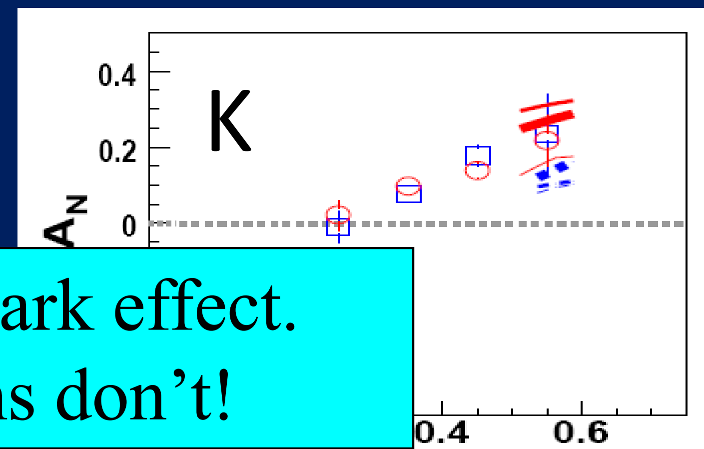
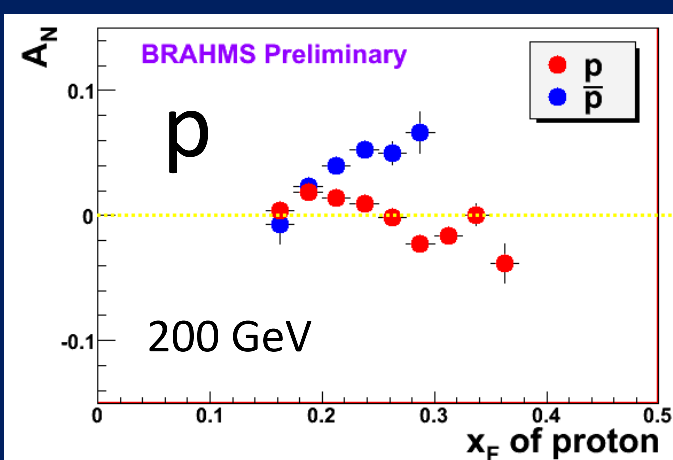


Pions suggest valence quark effect.
Kaons and (anti)protons don't!



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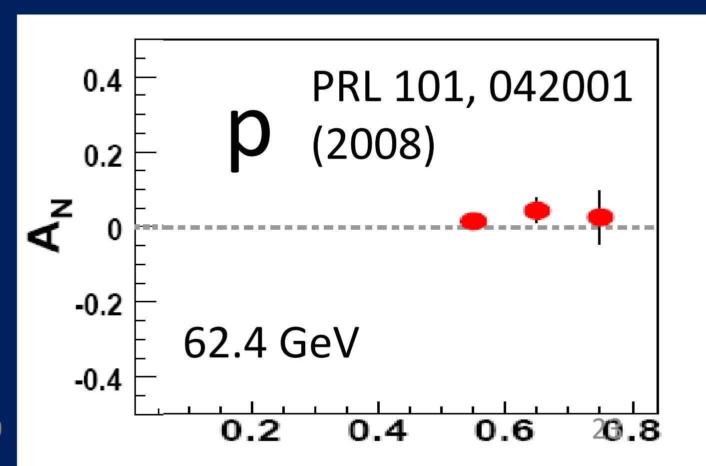

Baryon vs. meson sea

- 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?

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?
  - transverse-momentum-dependent 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?

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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- At any given instant, the proton has a net up content of 2 and net down content of 1, which determines the +1 charge.
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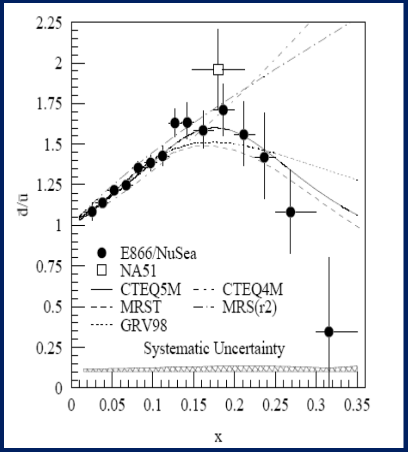
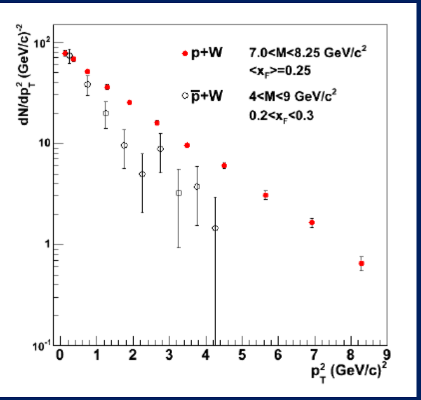
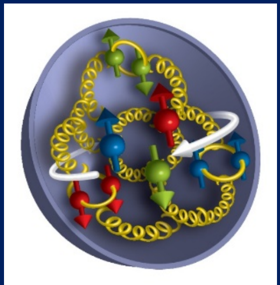
- We talk about "the valence quarks" being at large x, but experiments have already measured (sea) antiquarks up to 0.35.
  Is it meaningful to think also of sea *quarks* at these high x values, i.e. up or down sea quarks rather than antiup or antidown?
  – If we measure an up or down quark at x~0.35, 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?





Summary: Lecture 4



- We typically think of the sea simply being perturbatively generated through gluon splitting, but a number of experimental measurements indicate a richer picture

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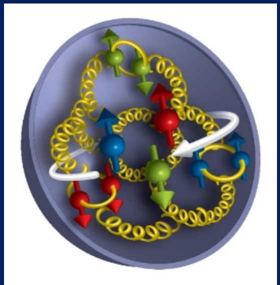

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- Need more experimental data!
- And with more measurements to provide meaningful constraints, will need consistent treatment of sea quarks in theory/phenomenology

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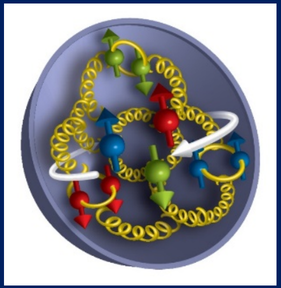

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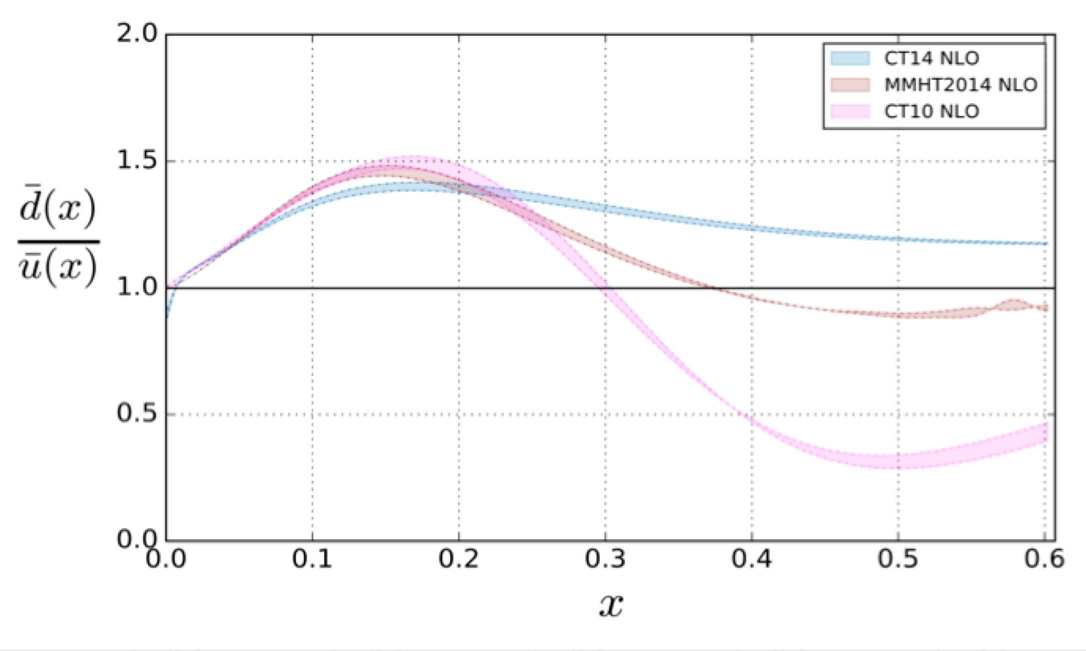
- Need more experimental data!
- And with more measurements to provide meaningful constraints, will need consistent treatment of sea quarks in theory/phenomenology
- Understanding the *dynamics* of sea quarks, which probe beyond static pictures of antiquarks in the nucleon and nucleus, will be crucial to understanding the way(s) in which the sea is generated

Extra

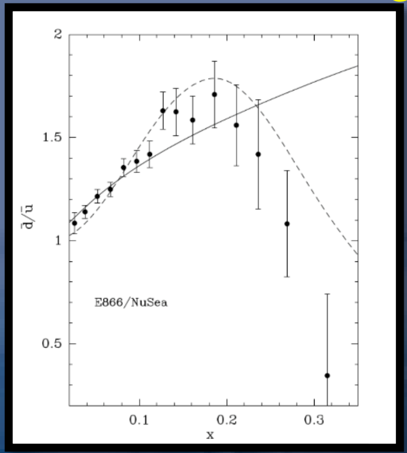
dbar(x)/ubar(x) for PDFs



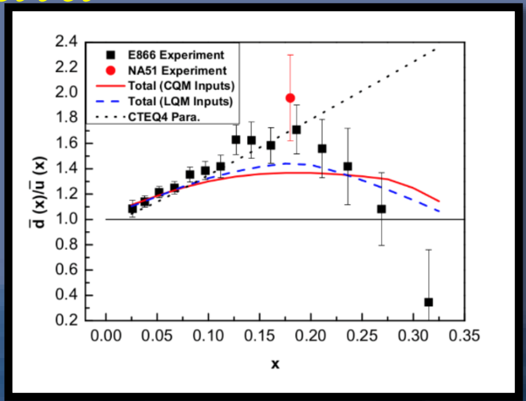
Plot credit: Shivangi Prasad

- Q value between 4.2 and 8.7 GeV

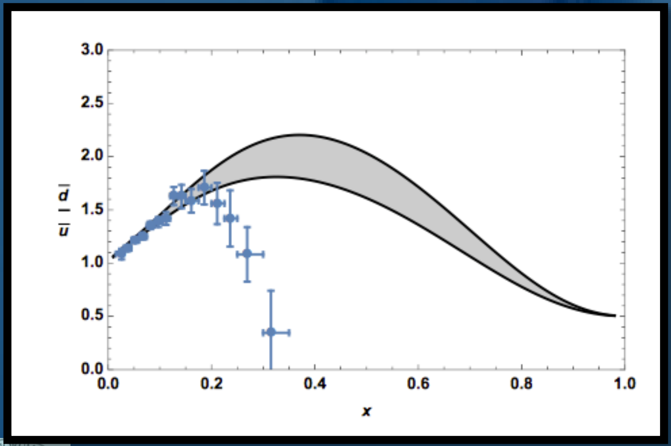
Many models for light sea quark flavor asymmetry…none match the shape of the existing data



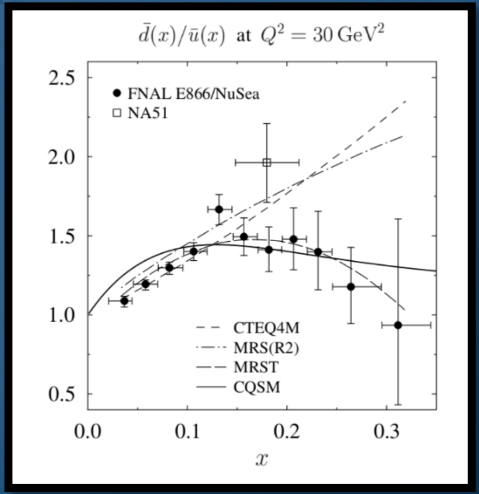
Statistical parton model



Chiral Quark model



Meson cloud model

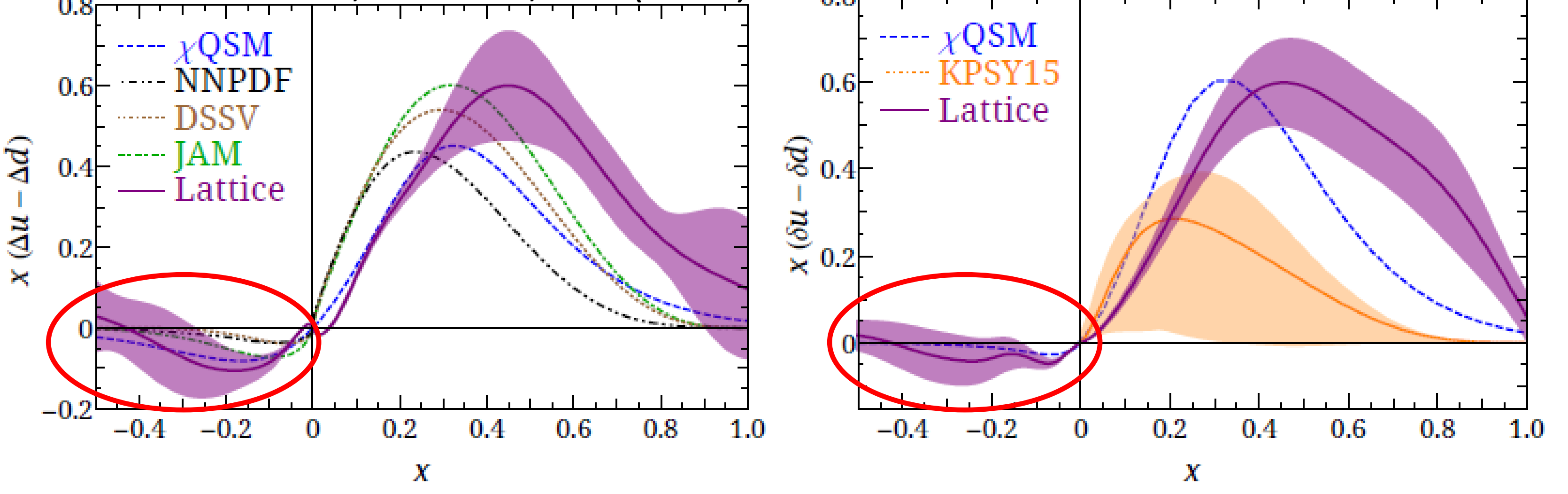


Chiral Quark Soliton model

Slide from Arun Tadepalli

Helicity and transversity distributions for sea quarks from lattice QCD(!)

Chen et al., NPB 911, 246 (2016)



$\Delta\overline{q}(x) = \Delta q(-x)$

$\delta\overline{q}(x) = -\delta q(-x)$

- Lattice calculations of x-dependent PDFs, rather than integrated moments, just starting to be published!
- Lattice confirms experimental evidence for flavor asymmetry in sea helicity distributions
  - "Negative" momentum fraction x indicates x for sea quarks here.
- Lattice calculation finds transversity for sea nonzero and flavor-asymmetric . . .
- x-dependent unpolarized sea distributions: PRD91, 054510 (2015)

Oct 2017: Institute for Nuclear Theory 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

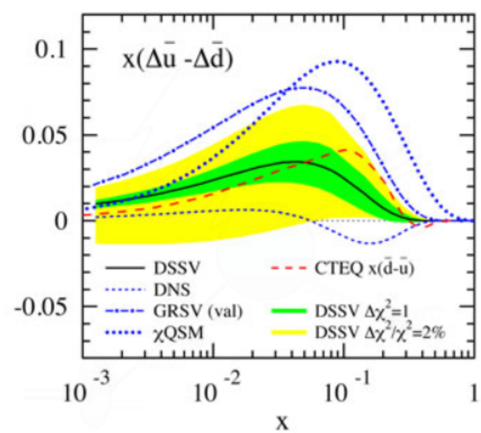
Talks Online

Exit Survey

INT Workshop INT-17-68W

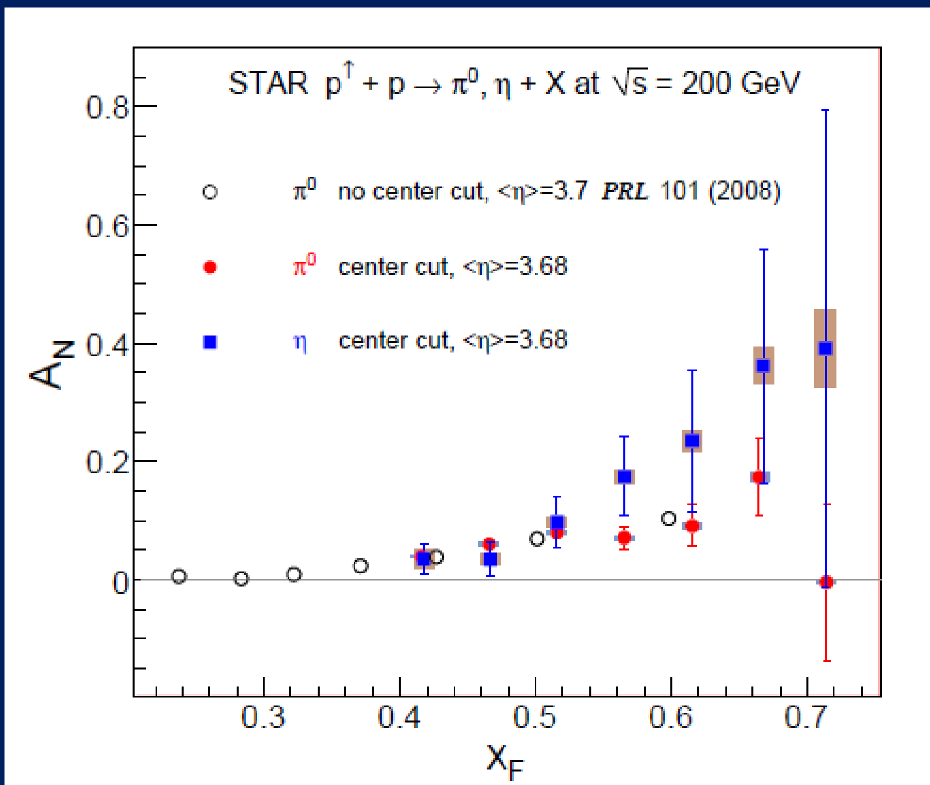
The Flavor Structure of Nucleon Sea

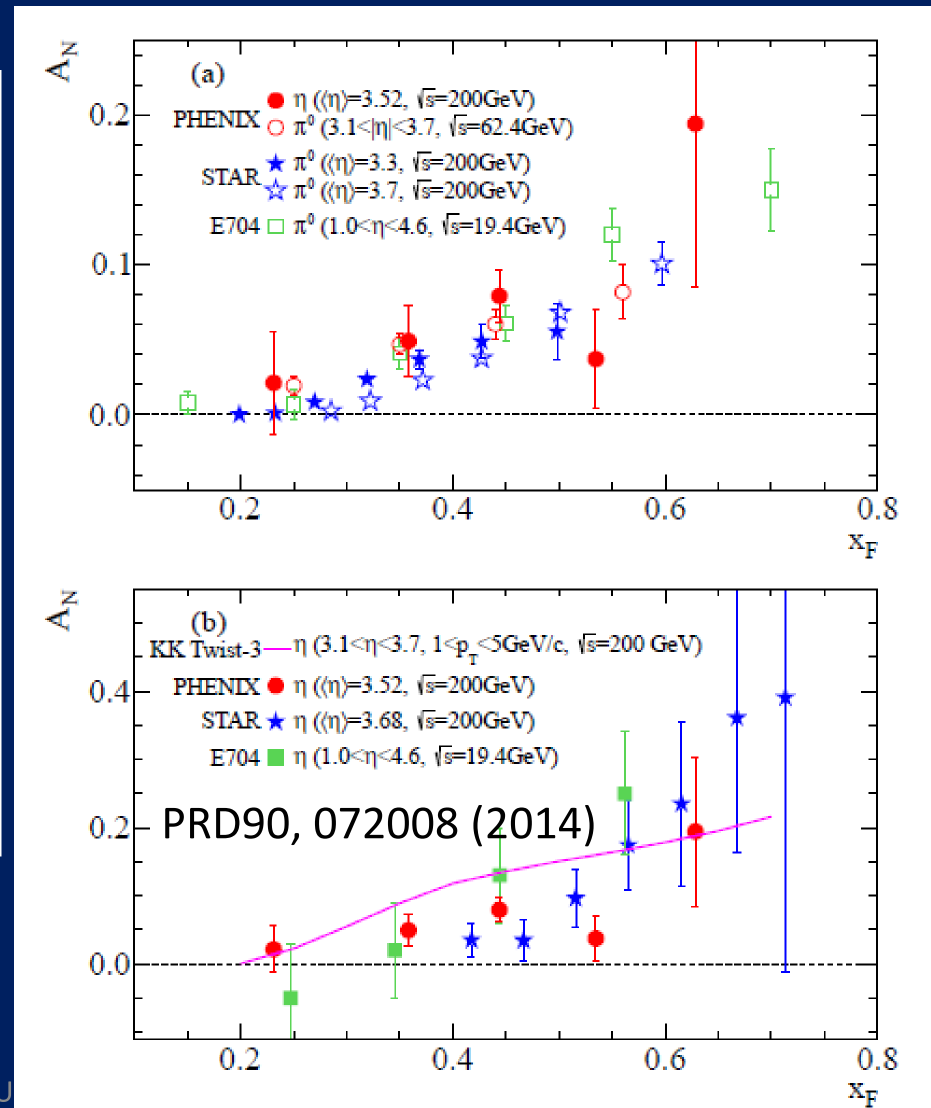
October 2-13, 2017



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.

$p+p$ η A_N larger than π^0?? Same?





Any difference should be due to isospin, strangeness, or mass