Exploring the Light Anti-Quark Flavor Asymmetry in the Nucleon sea using SIDIS at higher energies

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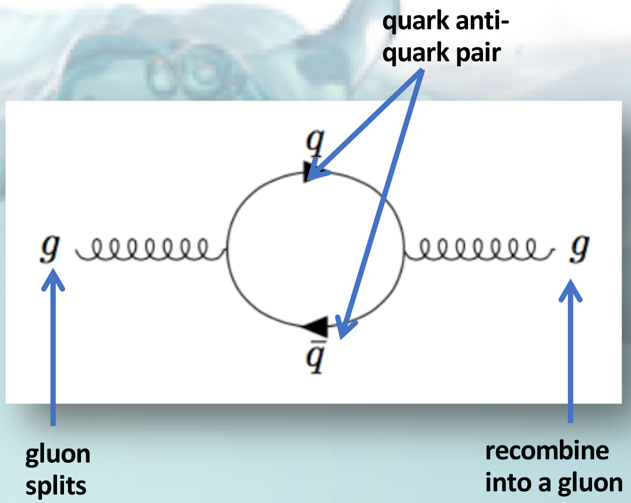
Nucleon sea (Flavor symmetric?)

- Nucleon sea naively assumed to be flavor symmetric and perturbatively generated

- Gluons don’t couple to flavor

- Masses of u and d quarks are small and similar, compared to QCD scale



Perturbative contributions calculated to be small!

D. A. Ross and C. T. Sachrajda, Nucl. Phys. B149, 497 (1979)

NMC (1991)

- Gottfried Sum Rule gives insight into the relative light quark flavor content of the nucleon

$$S_G = \frac{1}{3} + \int_0^1 \frac{2}{3}(\bar{u}^p(x) - \bar{d}^p(x))\,dx$$

- Symmetric sea implies S_G = 1/3

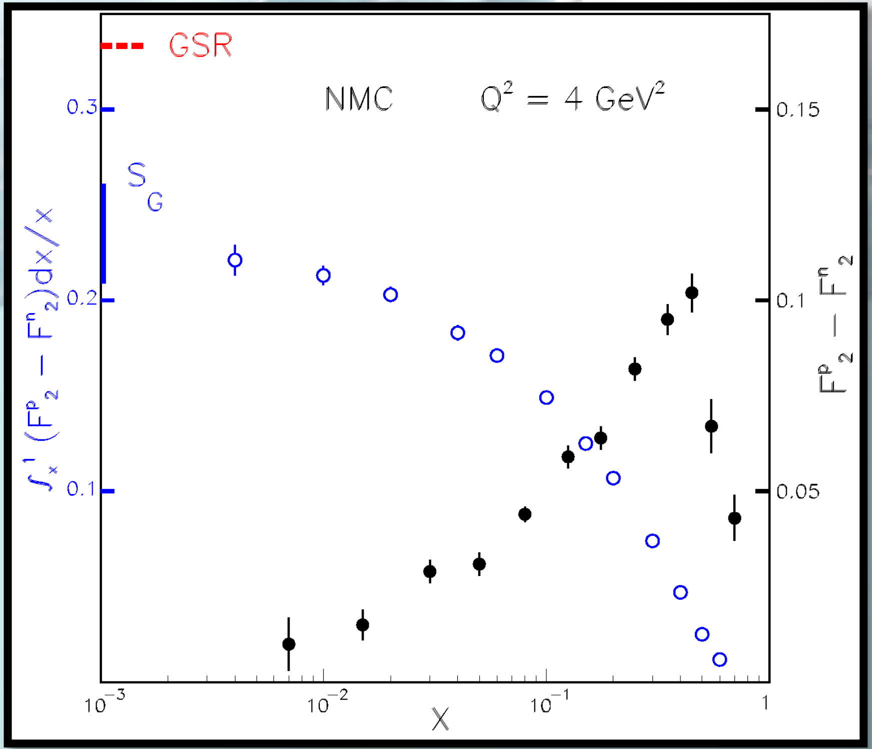
- NMC experiment (LD2, LH2, 90 GeV and 280 GeV muon beam)

$$S_G = \int_{0.004}^{0.8} (F_2^p - F_2^n)\,dx/x$$

$$= 0.221 \pm 0.008 \pm 0.019$$

- After extrapolation to 0 and 1

$$= 0.235 \pm 0.026$$



Amaudruz *et. al.* Phys. Rev. D 66, 21
Arneodo *et. al.* Phys. Rev. D 50, 1

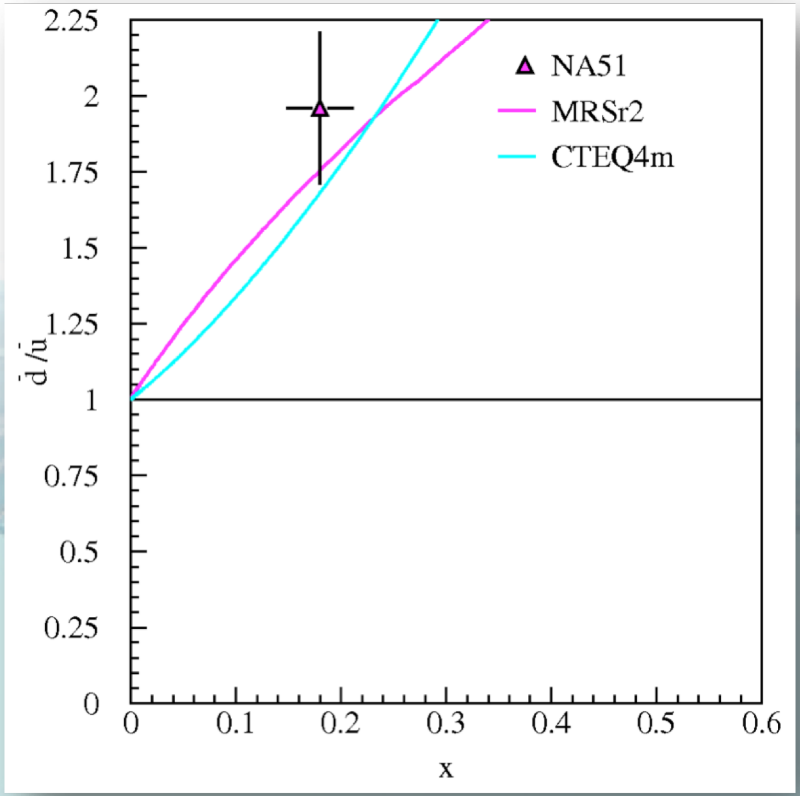
NA51 (1994)

- 450 GeV proton beam, LD2, LH2 targets

$$A_{DY} = \frac{\sigma_{pp} - \sigma_{pn}}{\sigma_{pp} + \sigma_{pn}} = 2\frac{\sigma_{pp}}{\sigma_{pd}} - 1$$

$$\sigma_{pd} \approx \sigma_{pp} + \sigma_{pn}$$

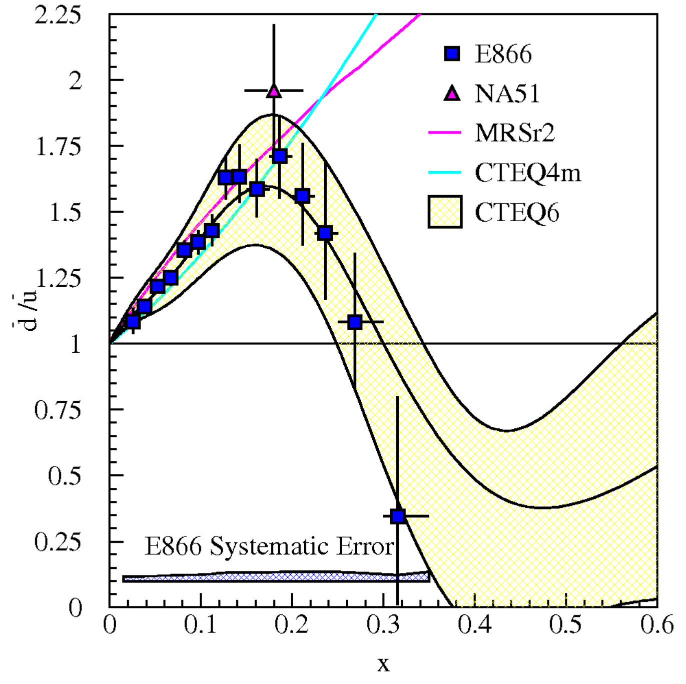
$$\left.\frac{\bar{d}}{\bar{u}}\right|_{\langle x\rangle=0.18} = 1.96 \pm 0.15 \pm 0.05$$



Baldit *et. al.* Phys. Lett. B 332, 244-250

E866 (1998)

- Mapped out the *x* dependence
- Overturn at 0.2
- Drop in the ratio below 1 at x_B = 0.25 (limited statistical uncertainty and bin on edge of acceptance)
- This asymmetry has to come from a non-perturbative origin!

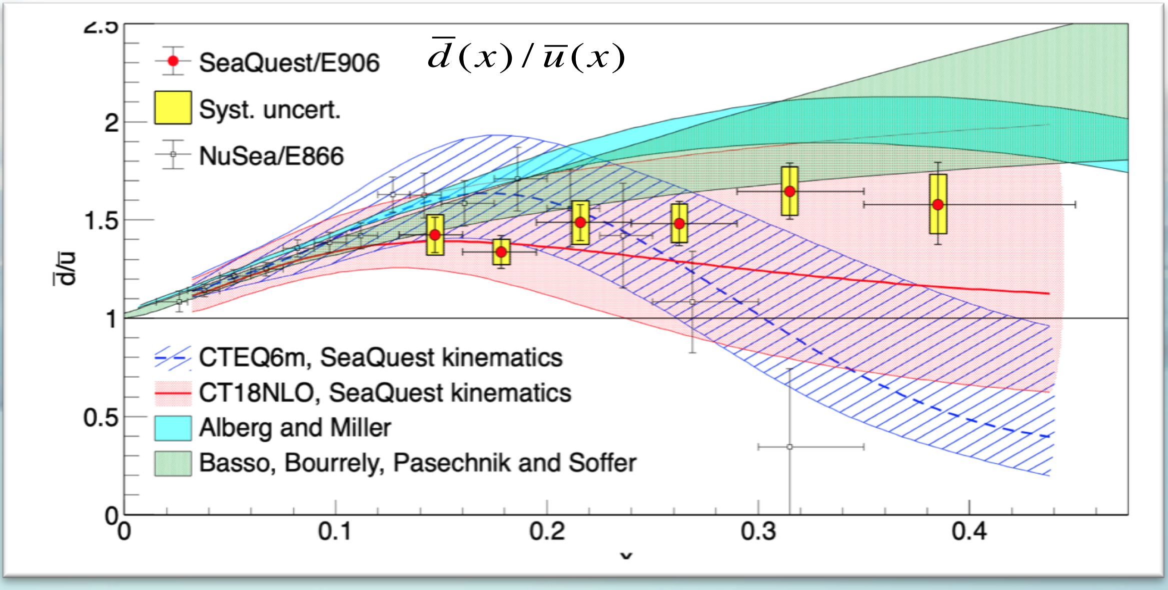


R.S. Towell *et. al.* Phys. Rev. D 64, 244-250

SeaQuest results

- SeaQuest results show that nature prefers dbar over ubar in the proton sea
- Non-perturbative mechanism other than gluon splitting must be the source
- Good agreement with meson baryon model and statistical parton distribution functions

Dove et. al. Nature 590, 561 – 565 (2021)



$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{(x_{beam}>>x_{targ})} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_{targ})}{\bar{u}(x_{targ})}\right]$$

Isospin distributions in the proton
and the Gottfried sum rule from leptoproduction of hadrons

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- Another method to investigate flavor asymmetry using SIDIS

- Assumes that in this model, the x and z dependencies factorize into distribution and fragmentation functions

2.1. Leptoproduction of pions

For charged pion production, isospin in addition to charge conjugation invariance reduces the number of independent fragmentation functions to three:

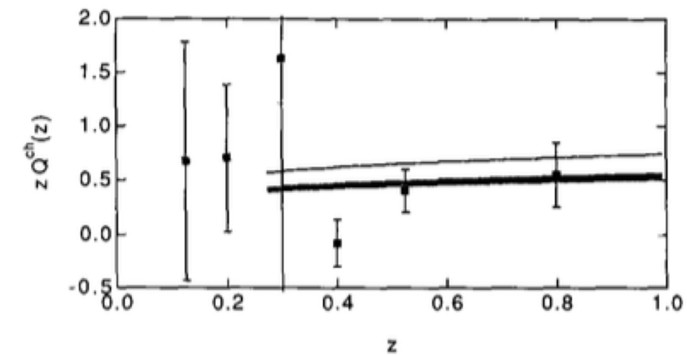
$$\text{favored:} \quad D \equiv D_u^{\pi^+} = D_{\bar{d}}^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-} ,$$

$$\text{non-favored:} \quad \tilde{D} \equiv D_d^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_u^{\pi^-} = D_{\bar{d}}^{\pi^-} ,$$

$$\tilde{D}_s \equiv D_s^{\pi^+} = D_{\bar{s}}^{\pi^+} = D_s^{\pi^-} = D_{\bar{s}}^{\pi^-} . \qquad (16)$$

The difference of leptoproduction of positively and negatively charged pions depends on the valence distributions. All dependence on the fragmentation functions disappears when taking the ratio of neutrons and protons, yielding a simple sum rule derived by Gronau, Ravndal and Zarmi [9],

$$\frac{\int dx [N^{n\pi^+}(x,z) - N^{n\pi^-}(x,z)]}{\int dx [N^{p\pi^+}(x,z) - N^{p\pi^-}(x,z)]} = \frac{2}{7} . \qquad (17)$$



VOLUME 81, NUMBER 25 PHYSICAL REVIEW LETTERS 21 DECEMBER 1998

Flavor Asymmetry of the Light Quark Sea from Semi-inclusive Deep-Inelastic Scattering

- HERMES published LO results with positrons on unpolarized hydrogen
  - 1 $< Q^2 <$ 10 GeV^2
  - 0.02 $< x <$ 0.3

- 25 years since the last lepton nucleon scattering results

$$r(x,z) = \frac{N_p^{\pi^-}(x,z) - N_n^{\pi^-}(x,z)}{N_p^{\pi^+}(x,z) - N_n^{\pi^+}(x,z)},$$

$$N^{\pi^\pm}(x,z) \propto \sum_i e_i^2 [q_i(x) D_{q_i}^{\pi^\pm}(z) + \bar{q}_i(x) D_{\bar{q}_i}^{\pi^\pm}(z)],$$

$$\frac{\bar{d}(x) - \bar{u}(x)}{u(x) - d(x)} = \frac{J(z)[1 - r(x,z)] - [1 + r(x,z)]}{J(z)[1 - r(x,z)] + [1 + r(x,z)]}.$$

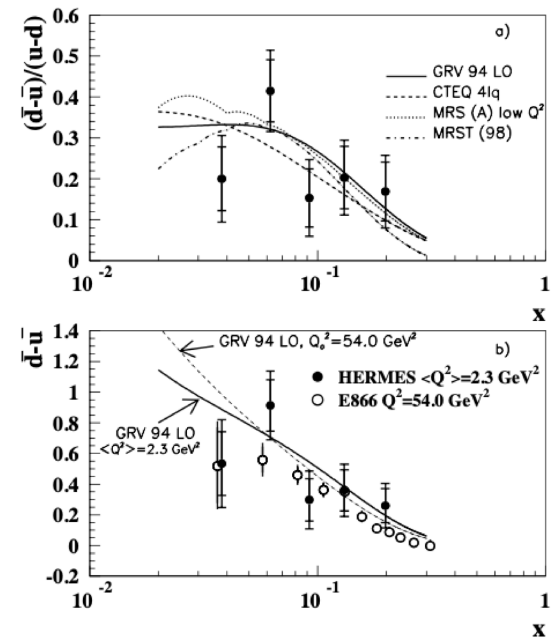


FIG. 2. (a) $(\bar{d} - \bar{u})/(u - d)$ as a function of x. Also included are the GRV 94 LO [9], CTEQ 4lq [10], MRS (A) [11] low Q^2, and MRST (98) [12] parametrizations calculated at the appropriate Q^2 for each x bin. (b) $\bar{d} - \bar{u}$ as a function of x. The open circles represent the E866 [15] determination of $\bar{d} - \bar{u}$ at $Q_0^2 = 54$ GeV^2. The solid (dashed) curve is the GRV 94 LO [9] parametrization, evaluated at the Q_0^2 values for the HERMES (E866) experiment. The inner error bars represent the statistical uncertainties while for all data including those from E866, the total error bars represent statistical and systematic uncertainties added in quadrature.

Origin of the Nucleon sea

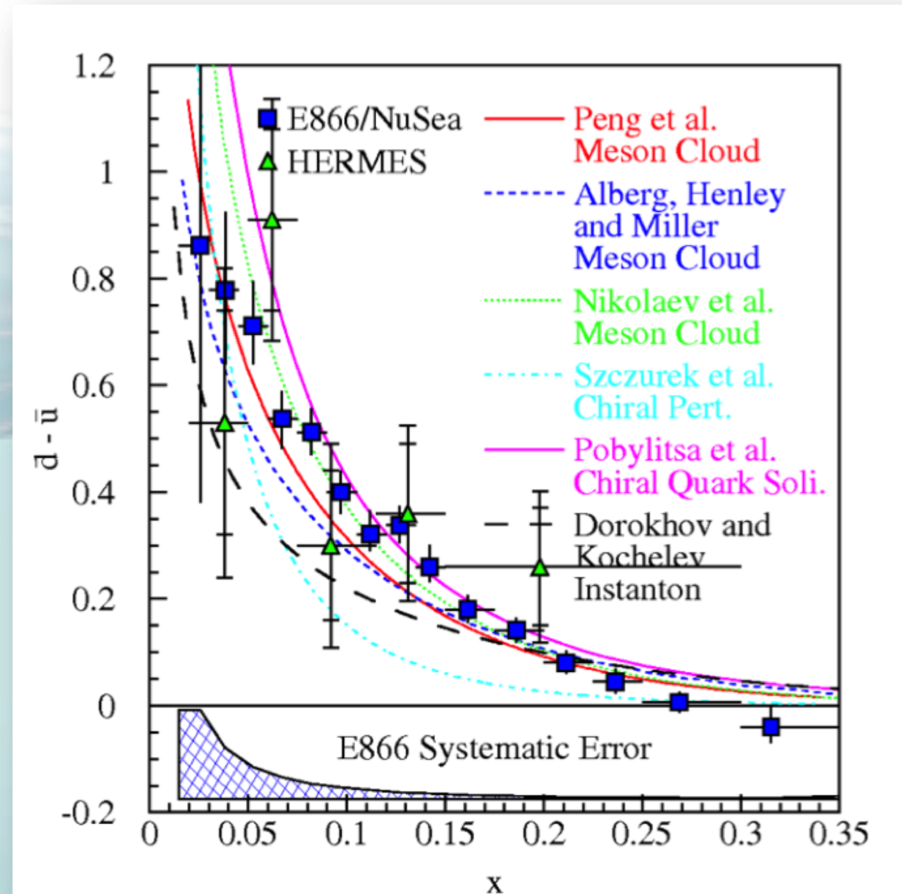
- Symmetric (perturbative and non-perturbative) component cancels away in the difference

- Non-perturbative models are motivated to explain the observed difference

x_{min}	x_{max}	$\int_{x_{min}}^{x_{max}}(\bar{d}-\bar{u})dx$	Q^2 (GeV^2)	Source	Ref.
0.0	1.0	0.147 ± .026	4	NMC	[8]
0.015	0.35	0.080 ± 0.011	54	NUSEA	[12]
0.0	1.0	0.118 ± 0.012	54	NUSEA	[12]
0.001	1.0	0.165	54	CT66nlo	[31]
0.001	1.0	0.114	54	CT10nlo	[16]
0.001	1.0	0.116	2	CT10nlo	[16]
0.01	1.0	0.090	54	CT14nlo	[17]
0.001	1.0	0.086	1	Stat. Mod.	[32]
0.	1.0	0.13	?	Det. Bal.	[33]
0.02	0.345	0.108	54	Chiral Soliton	[34]
0.0	1.0	0.13 ± 0.07	?	Lattice	[35]

Table I. Integrals of $(\bar{d}-\bar{u})$ from x_{min} to x_{max} from experiment (NMC and NUSEA) and from several global fits (CTEQ6.6, CTEQ10, CTEQ14), calculations (Lattice), and models (Statistical and Detailed Balance). The weak variation of the integral to the choice of scale is illustrated with the CTEQ10 comparison at 2 and 54 GeV^2. The scales of the detailed balance and lattice calculations are not explicitly reported in those references.

Peng *et al.* Phys. Rev. D 58 092004



D.F. Geesaman, P.E. Reimer Rept.Prog.Phys. 82 (2019) 4, 046301

SeaQuest results

- In agreement with HERMES and E866
- 25 years since lepton nucleon scattering data
- More precise complementary data from SIDIS is necessary for a global picture of flavor asymmetry as a function of x and Q^2

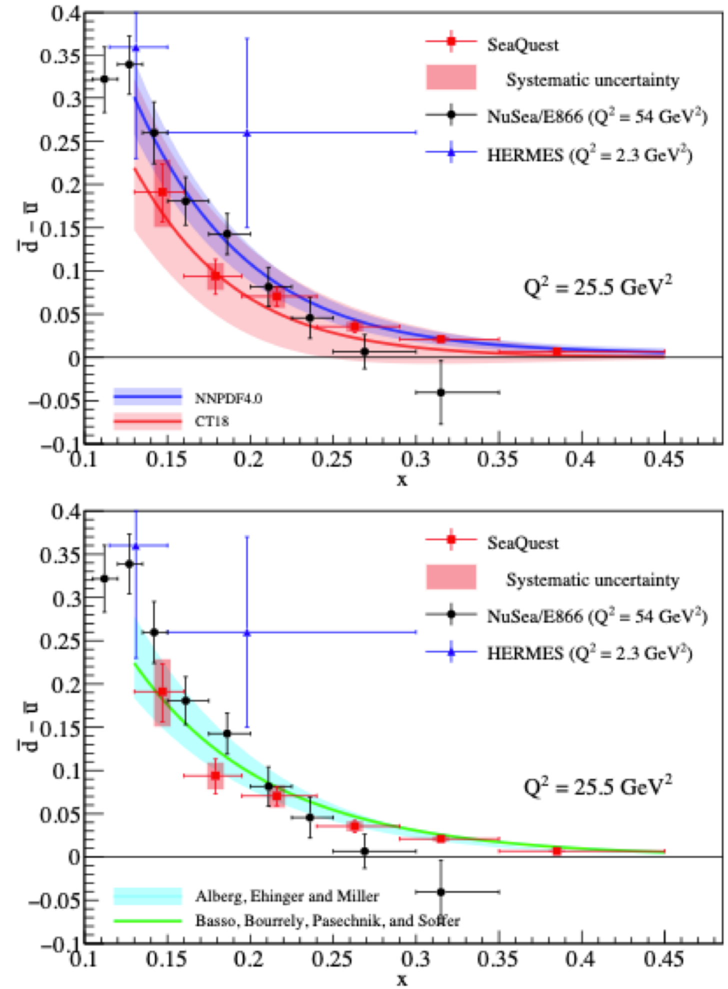


FIG. 12. The SeaQuest $\bar{d}(x) - \bar{u}(x)$ results compared with data from HERMES [16] and E866 [13, 14] with calculations based on PDFs of CT18, NNPDF4.0 (top) and with the statistical models of Bourrely and Soffer [29, 30, 55], and of Alberg, Ehinger and Miller [53, 54].

arxiv: 2212.12160

Exploring the Light Anti-Quark Flavor Asymmetry in the Nucleon Sea using Semi Inclusive Charged Pion Production in Hall C

A Letter of Intent for PAC50

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LOI submitted to PAC50

Old proposal: PR 12-06-111
LOI: 12-22-01
Reader: Alessandro Bachetta

Goals of the LOI

- 12 GeV e^- beam on LH2 and LD2 targets
- To explore the region $0.1 < x < 0.25$ using SIDIS to establish consistency with previous Drell-Yan measurements confirming process independence
- To explore the high-x ($0.25 < x < 0.4$) region where there is apparent tension between NuSea and SeaQuest results using sensitivity to charged pion yield ratios

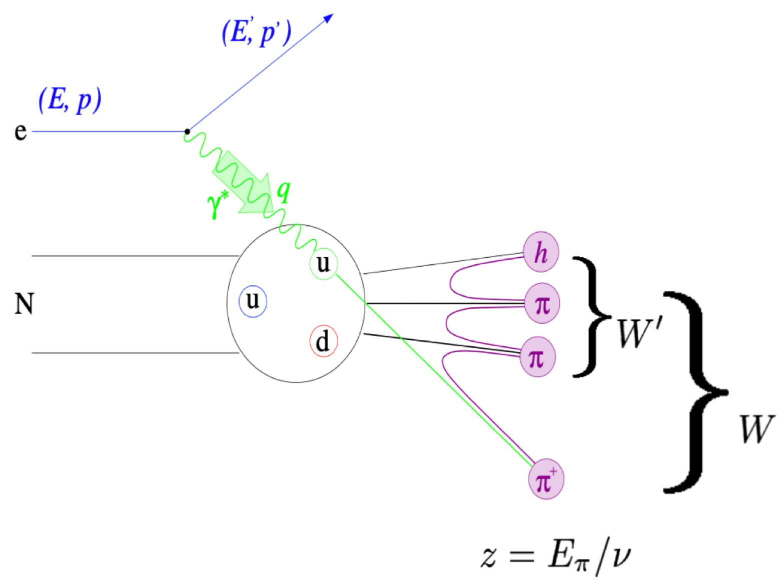
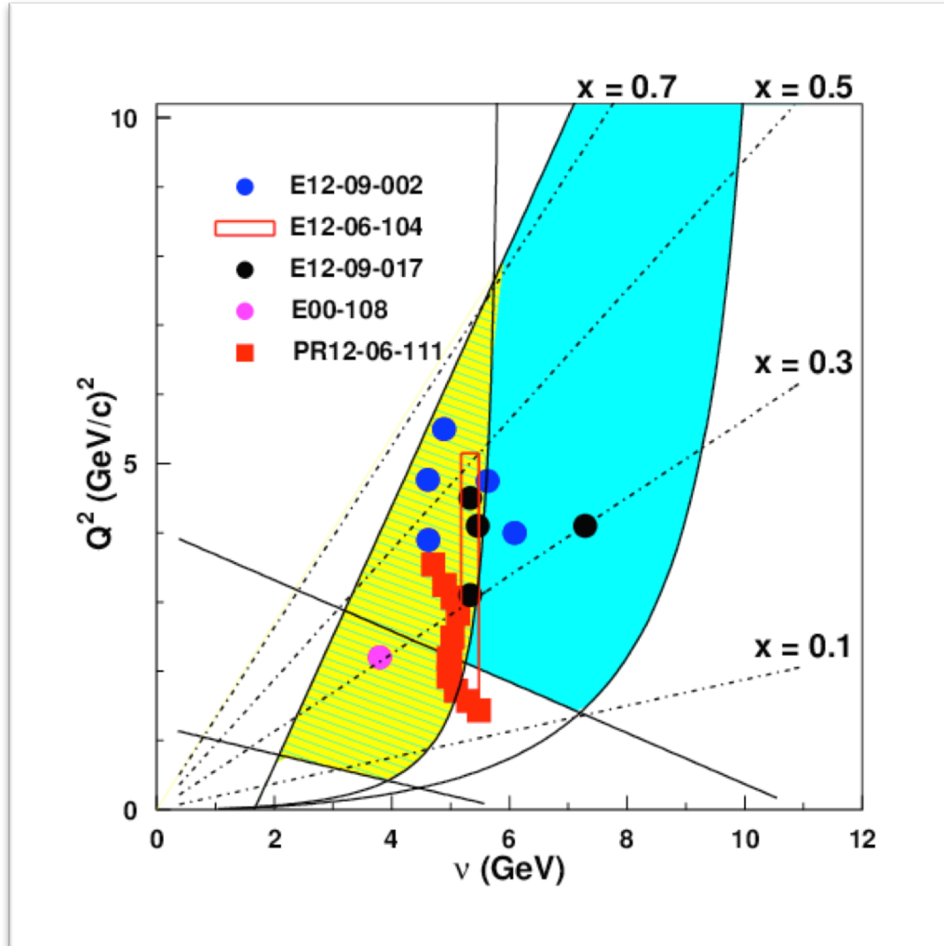


Figure 7: Diagram of (e,e'π) reaction on nucleon.

SIDIS landscape of JLab experiments

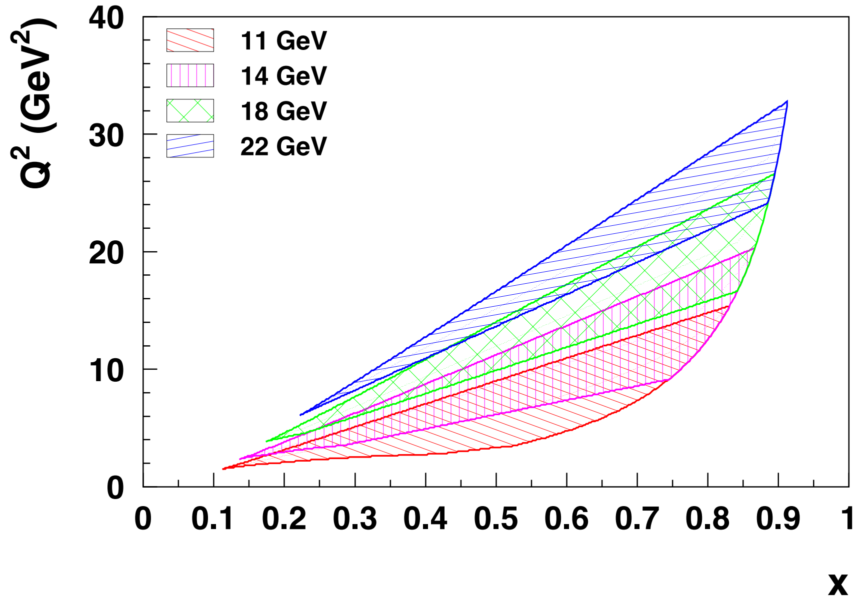
- Some opportunistic R_{SIDIS} kinematics overlap
    - 11 GeV $e-$ beam
    - $0.1 < x < 0.48$
    - $1.2 < Q^2 < 4.3$ (GeV/c)^2
    - $0.3 < z < 0.7$
  - Same targets (LH2 and LD2)
  - Standard detector package (HMS and SHMS)
- Will avoid considerable overhead due to the above mentioned factors
- Region of kinematics where factorization is believed to work well
- Emphasis of impactful kinematic x regions will be worked out for the full proposal



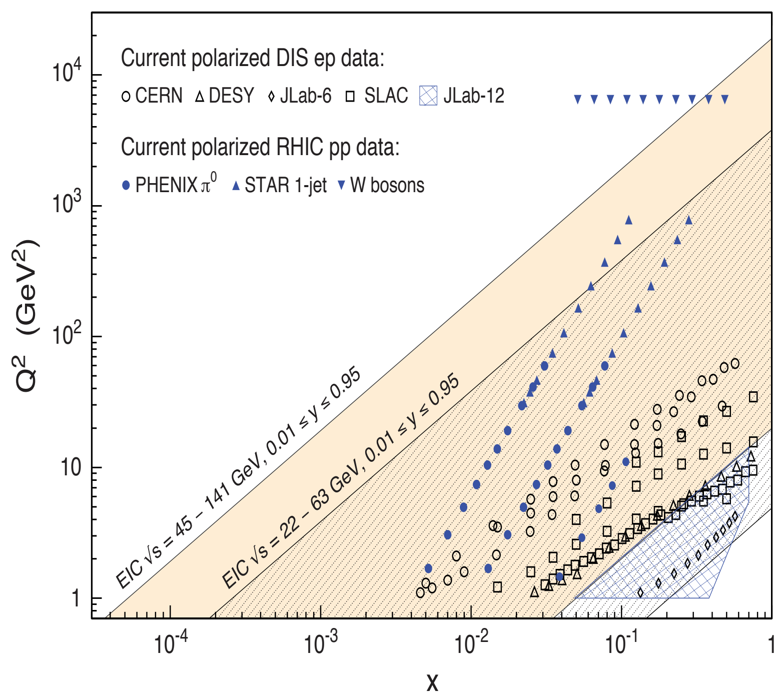
Plot credit: Dave Gaskell

Complementarity and uniqueness

Experiment/Facility	x	Q^2
HERMES/DESY	0.02 – 0.3	1 - 10 GeV^2
NuSea/Fermilab	0.015 – 0.3	54 GeV^2
SeaQuest/Fermilab	0.13 – 0.45	29.5 GeV^2
JLab12	0.1 - 0.45	1.43 – 3.54 GeV^2
JLab22	0.1 – 0.45	> 6 GeV^2
EIC	Low – 0.45	1 – 10^3 GeV^2



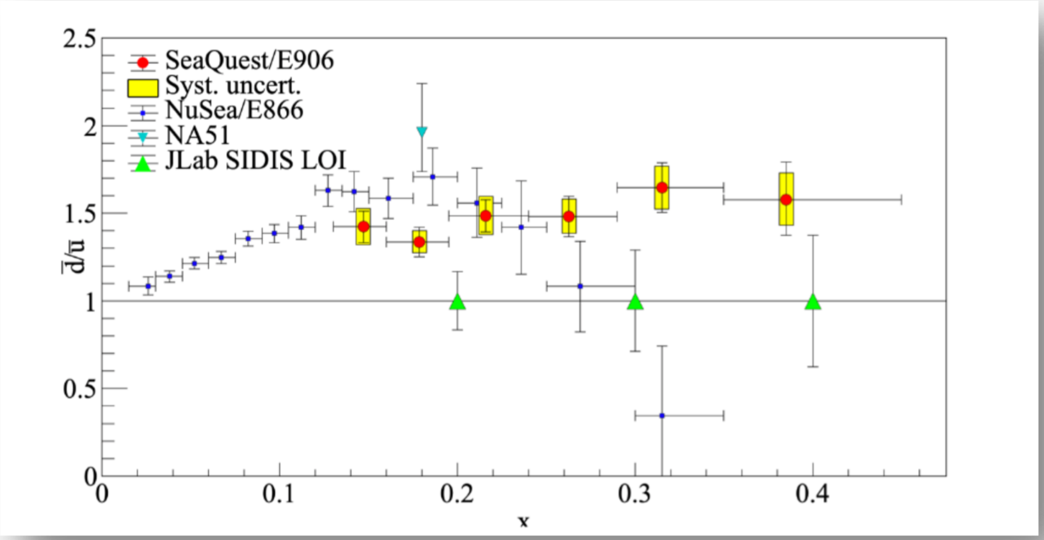
arXiv:1212.1701



Complementary information on process independence and Q^2 evolution of PDFs with Fermilab and EIC

Preliminary projections exercise for JLab12

- As an exercise we considered 17 PAC days total at x = 0.2, 0.3 and 0.4
- We would need more statistical precision in the high-x region in order to resolve the tension between NuSea and SeaQuest
- Emphasis on impactful kinematic regions will be worked out for the full proposal
- Interpretation more straight forward for a region with higher Q^2 which is accessible through an energy upgrade



PRELIMINARY EXERCISE PROJECTIONS

Summary

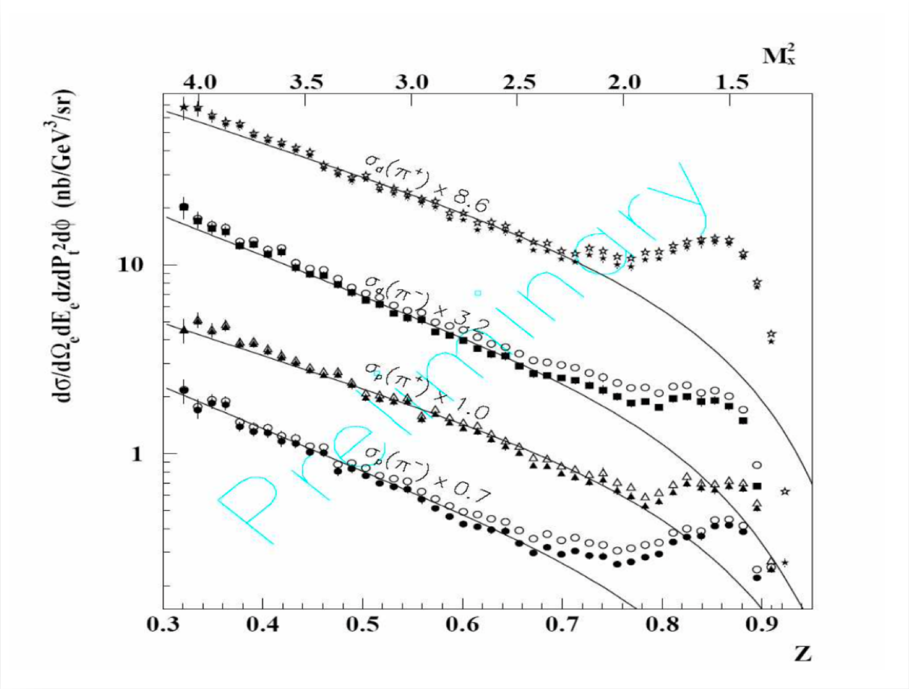
- Exploring the nucleon sea region with higher precision is one of the central themes of the Jefferson lab energy upgrade
- Models of nucleon structure are driven to explain the anti-quark flavor asymmetry in the nucleon sea
- Charged pion yield ratios have sensitivity to the light quark flavor asymmetry
- After results from various experiments (HERMES, NuSea and SeaQuest), a high statistics data sample with good control over systematic uncertainties using SIDIS reactions will provide an independent study of the region of overlap with previous Drell-Yan measurements establishing process independence
- Energy upgrade will open up the phase space as we get complementarity with Fermilab and EIC in a broad range of Q^2

BACK UP

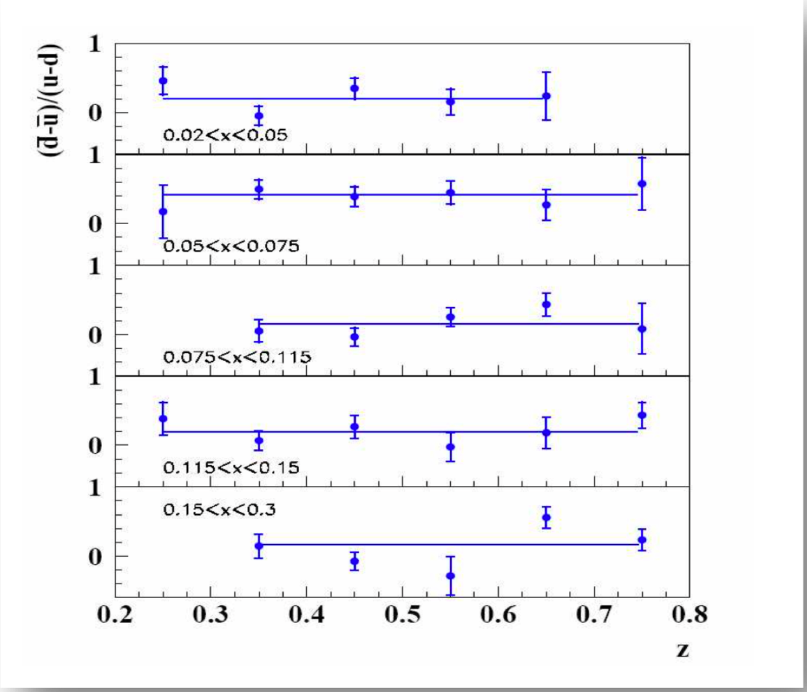
Previously proposed kinematics

x	Q^2 (GeV^2/c^2)	z	W (GeV)	W' (GeV)
0.139	1.43	0.415	3.12	2.43
0.158	1.57	0.431	3.04	2.34
0.180	1.72	0.448	2.96	2.26
0.206	1.92	0.452	2.88	2.19
0.235	2.19	0.458	2.82	2.14
0.264	2.49	0.456	2.79	2.12
0.294	2.83	0.451	2.76	2.10
0.324	3.06	0.459	2.69	2.04
0.353	3.24	0.462	2.61	1.98
0.401	3.54	0.473	2.48	1.87

Factorization tests

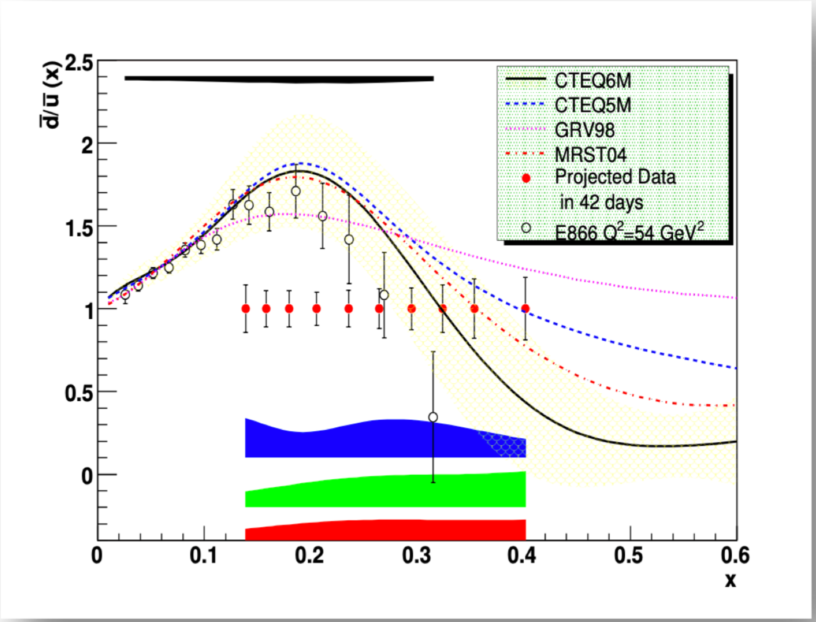


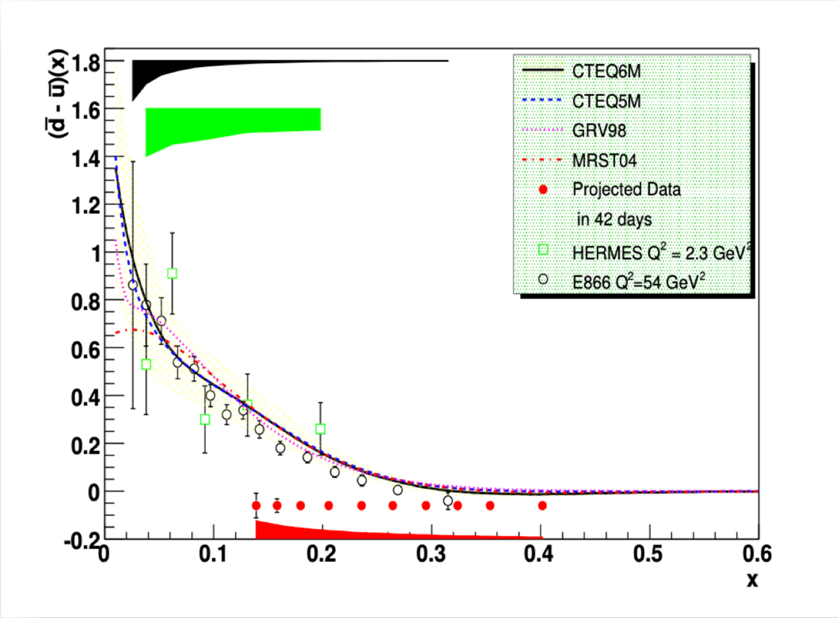
Jlab 6 GeV kinematics



HERMES experiment

Projections of deferred PR12-06-111





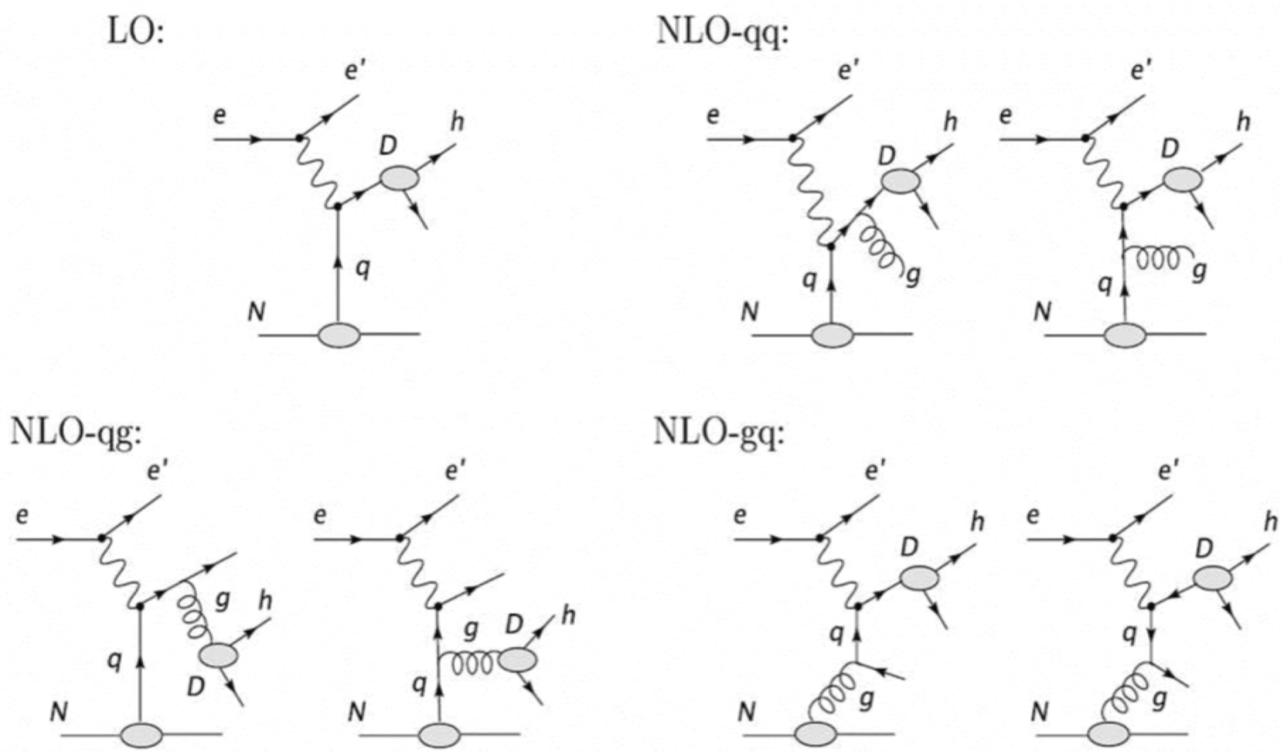


Figure 3: Semi-inclusive deep inelastic scattering diagrams at leading order (LO) and the next-to-leading order (NLO).

PAC50 LOI 12-22-002 Communications

D. Dutta, H. Gao, D. Gaskell, H. Mkrtchyan, R. Montgomery, P.E.Reimer, A.S. Tadepalli

1. As noted in the TAC-PHY report, you make a request for 52 days, but then you speak about 17 days of beam. Could you please clarify this discrepancy?
52 days was taken as a guide from the previous proposal PR12-06-111. 17 days was assumed in Figure 7 - given the uncertainties, we will certainly request more than 17 days in the final proposal.

2. You mention more than once in the LOI the importance of multidimensional binning, but as far as I see in the proposal you discussed only x binning. Could you please specify what kind of binning you plan to do and what kind of precision you expect to achieve in the case of multidimensional binning?
In this short LOI, our focus was on the simplest extraction of $\bar{d}(x)/\bar{u}(x)$ assuming ideal factorization. In the full experiment, we would make measurements in multiple bins in z to verify the expected $x-z$ factorization of the result (i.e., $\bar{d}(x)/\bar{u}(x)$ should be independent of z). In addition, our measurements would primarily be sensitive to pions emitted along or close to the q-vector, at relatively small P_t. In the absence of full P_t coverage, the multiplicities must be inferred from the P_t dependence of the cross sections and/or ratios. So to the extent possible (where there is full azimuthal coverage), we will measure the P_t dependence.

We will attempt to extract $\bar{d}(x)/\bar{u}(x)$ in a simple LO factorized approach, but in the end, it is likely that a full multi-dimensional analysis will be required. We will provide cross sections and ratios as a function of x, z, P_t, and ϕ for that purpose. When preparing the full proposal we expect to have a complete set of simulations to help determine the expected bin size and precision for the multidimentional binning.

3. You mention the fact that you could partially run in parallel with E12-06-104. First of all, could you please clarify what is the status of that experiment (I could check myself, but I would be grateful if you could spare me this effort)? Secondly, most importantly, could you make the effort of making a larger overlap with the experiment, so that both of you could increase the beam time? Maybe, can you consider organizing a Run Group proposal? Also a study with kaons could fit in this Run Group

Experiment E12-06-104 is approved but not yet scheduled. It is being considered as one of a few experiments that might run after March 2024 (after the running of NPS experiments).

The kinematics we explored in the LOI overlapped the R_{SIDIS}, large epsilon settings at $x = 0.2$, 0.3, and 0.4 exactly. We could also take data at their proposed $x = 0.15$ setting. Since E12-06-104 will measure L-T separated cross sections, they will make measurements at lower beam energies, and we could certainly make use of that data as well. However, we

require better statistical precision, so will require more beam time than already allocated. This means we can't form a Run Group proposal in the usual sense - we need to request additional beam time.

We will also be able to access kaons with this data - we welcome collaboration on efforts in that direction.

4. I am not sure I understand the relation between Fig. 7 and Fig. 8: is Fig. 7 showing the expected precision of the LOI measurement? Would you be able to prepare a version of Fig. 7 similar to Fig. 8, i.e., with updated PDF extractions and with updated colored bands?
Figure 8 was reproduced to answer one of the questions by PAC30. Figure 7 was just an exercise to see how the statistical error bars would look like with 17 days of beam time at the same kinematics for the R_{SIDIS} experiment. For the full proposal, a figure will be made with updated PDF extractions with updated color bands.

LOI - Communications

LOI-22-002: *Exploring the Light Anti-Quark Flavor Asymmetry in the Nucleon Sea using Semi Inclusive Charged Pion Production in Hall C*

N. Sato, A. Accardi

This proposal aims at measuring the unpolarized SIDIS cross sections of final state charged pions with proton and deuteron targets. The major physics goal is to access the $\bar{d}-\bar{u}$ nucleon asymmetry in order to (1) test the universality of the results compare with other measurements such as those from DY experiments at FNAL, and (2) clarify the potential disagreement between NuSea and SeaQuest at high x.

The proposed experiment is certainly important since it would provide the community with a measurement of the light sea asymmetry with a different colliding system from that employed in the Drell-Yan measurements, and can also leverage other JLab 12 GeV measurements. However we are concerned with th level of precision that is required to make an impact, and with a proper evaluation of theoretical systematics. In particular, the LOI has not addressed a few important points:

- The LO arguments by the HERMES analysis shows that one has direct access to $\bar{d}-\bar{u}$ by combining cross sections of protons and neutrons. However, the LOI mention the using a deuteron target as a proxy for a neutron. Therefore it is not clear if the potential background associated with nuclear effects can potentially restricts the impact of the measurements on the sea asymmetry. For the pull proposal, it is advisable to also study the actual sensitivity of the sea asymmetry at the cross section level with state-of-the art theory calculations with nuclear effects, and to quantify the associated systematic uncertainties. These are probably not very large in the proposed $0.1 < x < 0.5$ kinematics, and will be at least partially cancelled in the cross section ratios, but should not be a-priori neglected.

- Cancellation of fragmentation fucntions in the proposed SIDIS ratios only happens at LO and when Hadron Mass Corrections are neglected. While pion masses can be to a good extent ignored at HERMES energies, they may still yield non-negligible effects at JLab energies, hence entangling PDFs and FFs at numerator and denominator independently [1]. At the level of precision needed to make an impact on the large $0.25 < x < 0.5$ region, these effects may have to be carefully accounted for.

- The estimated uncertainties from the LOI in Fig. 7 requires to be contrasted with the most recent global analysis of sea quark pdfs by the JAM, CJ and or the CT groups who specifically included the recent STAR $W^{\pm}$ differential cross sections along with the SeaQuest data, and addressed the large-x tension between the latter and NuSea. For example, in Fig. 5 of [2] the uncertainties on $\bar{d}/\bar{u}$ are currently ~ 0.2 at $x = 0.3$ while the projected uncertainties of the LOI are about 0.3 at the same kinematics. Giving that nuclear effects have not been considered nor the uncertainty from fragmentation functions, it is not clear if the proposed measurements will be able to substantially change the current knowledge of the sea asymmetries.

- Although strangeness extraction is not considered in this proposal, it is to be noted that the HERMES and COMPASS analyses differ significantly in their extraction of the s-quark even after Hadron Mass corrections are taken into account [5]. This discrepancy has been attributed in how binning is performed in phase space by either collaboration. With high statistics, as advocated in this proposal, it would be possible to address this by using higher-dimensional semi-inclusive observables than possible at HERMES, which was also the approach utilized by COMPASS. We suggest carefully considering these issue in a full proposal.

Due to these observations, we advise to revisit the projections to make certain the required precision is achievable, and formulate and experimental program that can significantly improve our current knowledge on the nucleon $\bar{d}-\bar{u}$ asymmetries. Taking into account the latest developments in global QCD analysis of the involved PDFs will also be important [1-5]. The CJ and JAM collaborations will certainly be available to provide support and theoretical guidance on this.

[1] A. Accardi, T. Hobbs and W. Melnitchouk, JHEP **11** (2009), 084 doi:10.1088/1126-6708/2009/11/084 [arXiv:0907.2395 [hep-ph]].

[2] C. Cocuzza *et al.* [Jefferson Lab Angular Momentum (JAM)], Phys. Rev. D **104**, no.7, 074031 (2021) doi:10.1103/PhysRevD.104.074031 [arXiv:2109.00677 [hep-ph]].

[3] S. Park, A. Accardi, X. Jing and J. F. Owens, [arXiv:2108.05786 [hep-ph]].

[4] M. Guzzi, T. J. Hobbs, T. J. Hou, X. Jing, K. Xie, A. Courtoy, S. Dulat, J. Gao, J. Huston and P. M. Nadolsky, *et al.* [arXiv:2108.06596 [hep-ph]].

[5] J. V. Guerrero and A. Accardi, PoS **QCDEV2017** (2017), 055 doi:10.22323/1.308.0055 [arXiv:1712.04571 [hep-ph]].

LOI - Theory