SeaQuest: Probing Protons and Nuclei with Dileptons

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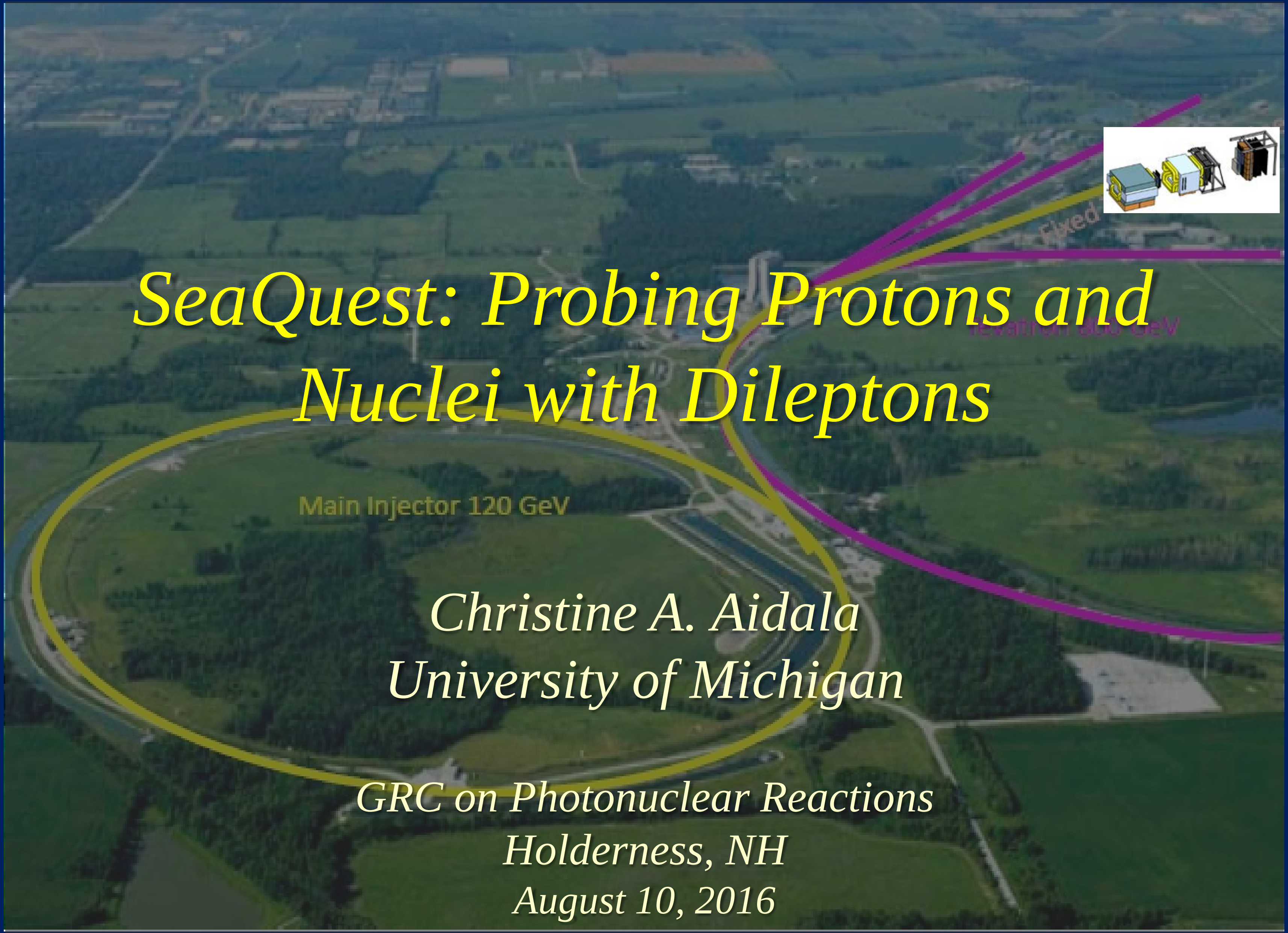
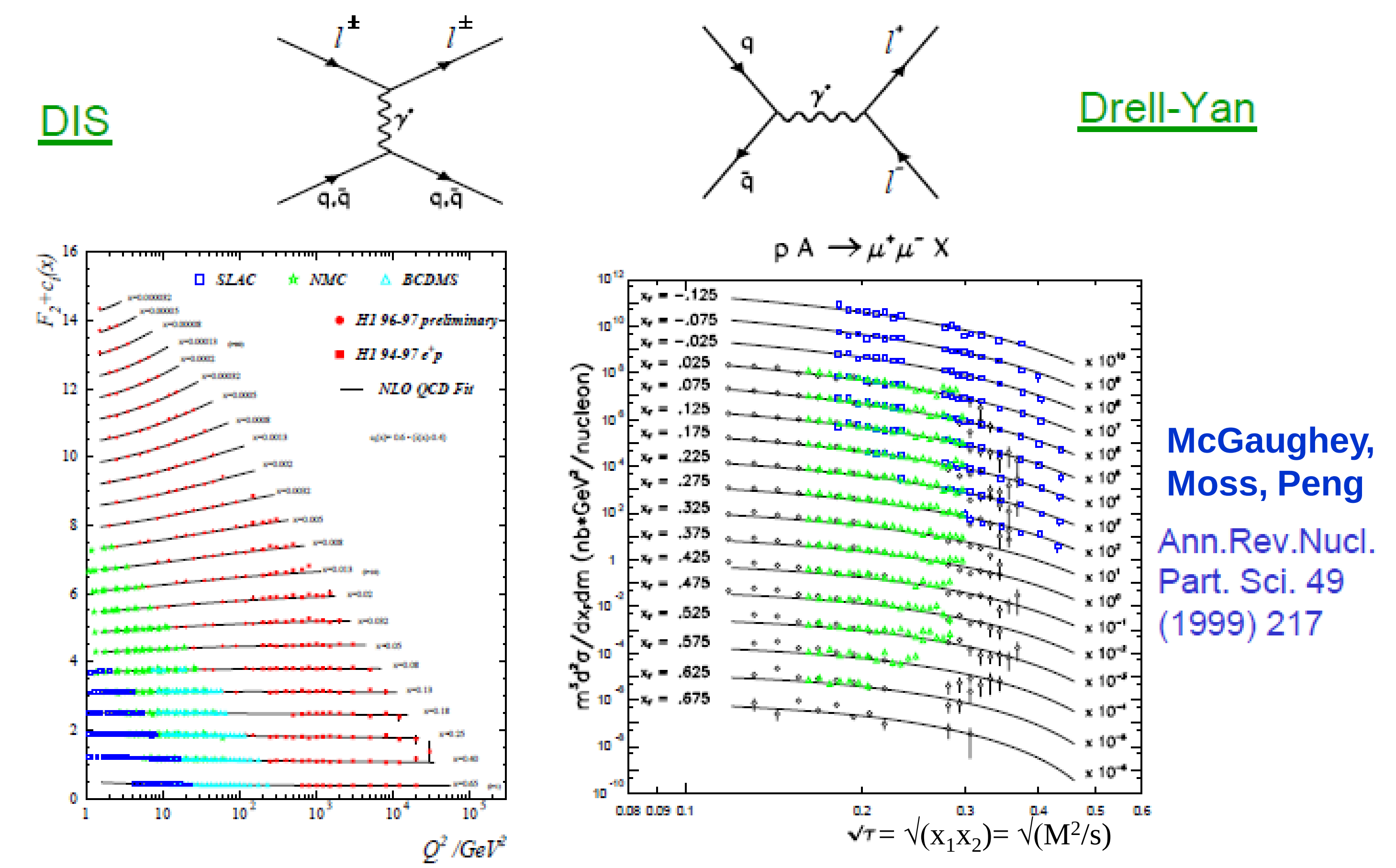
University of Michigan

GRC on Photonuclear Reactions
Holderness, NH
August 10, 2016



Complementarity of Drell-Yan and DIS



McGaughey, Moss, Peng

Ann.Rev.Nucl. Part. Sci. 49 (1999) 217

Both Drell-Yan and deep-inelastic scattering are tools to probe the quark and antiquark structure of hadrons

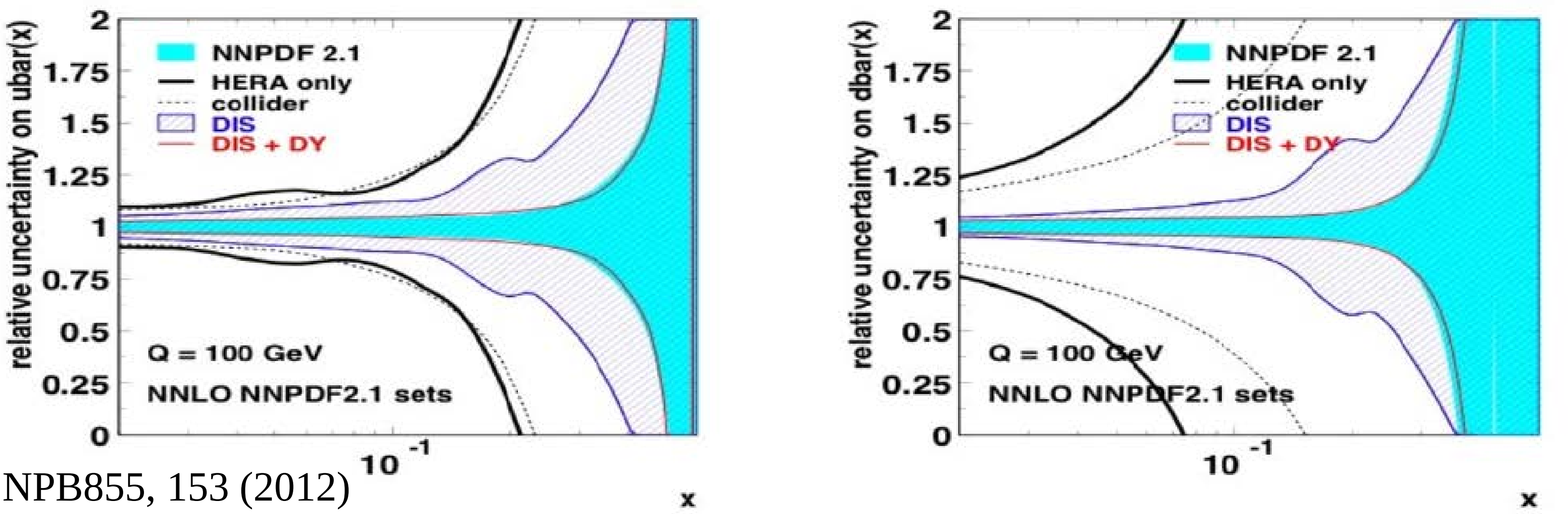
Drell-Yan with a proton beam: Tag antiquarks in target

- Fixed-target kinematics:
  - Large x_F (= $x_{beam} - x_{target}$)
  - $M^2 = x_{beam} x_{target} s$ plays role of Q^2 in DIS

$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9 x_b x_t} \sum_q e_q^2 [q(x_b)\bar{q}(x_t) + \xcancel{q(x_t)\bar{q}(x_b)}]$$

  - Proton beam: antiquark density negligible at large x, so first term dominates
  - Isolate *antiquarks in the target*
    - For pion beam instead have antiquark in beam, quark in target
  - Alter combinations of protons and neutrons—and therefore sea quark distributions—by changing targets

Sensitivity of Drell-Yan to sea antiquarks compared to DIS



NPB855, 153 (2012)

(Very high Q shown)

Deep-inelastic lepton-nucleon scattering – virtual photon couples only to electric charge of (anti)quark, insensitive to whether it's a quark or antiquark

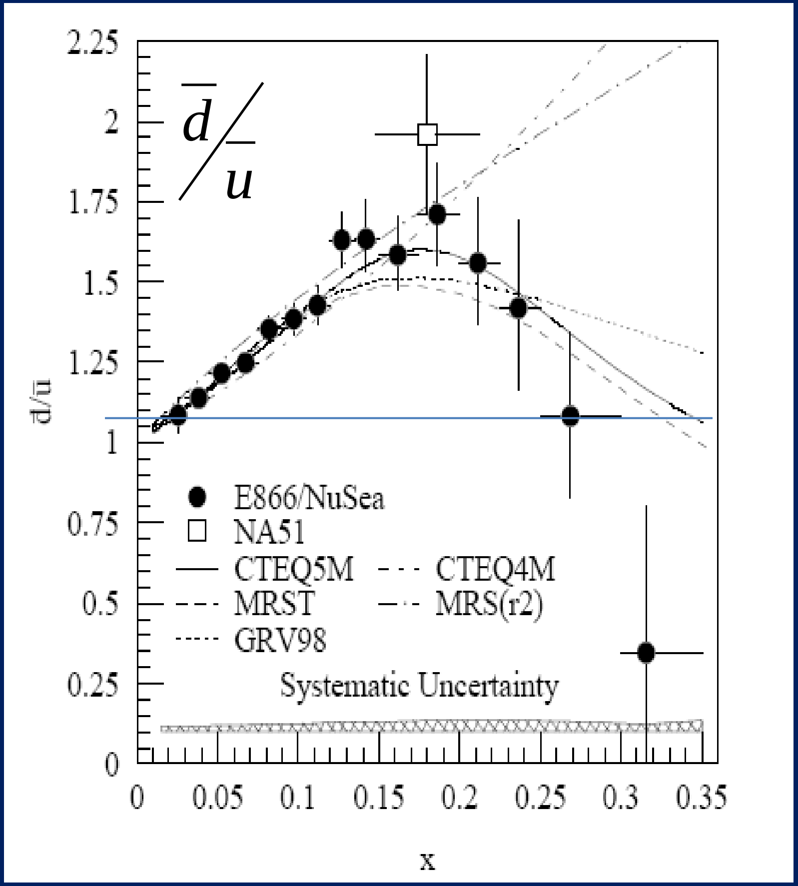
Setting the stage for E906/SeaQuest: Striking flavor asymmetry in sea mapped out by E866

- Proton-hydrogen and proton-deuterium collisions

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

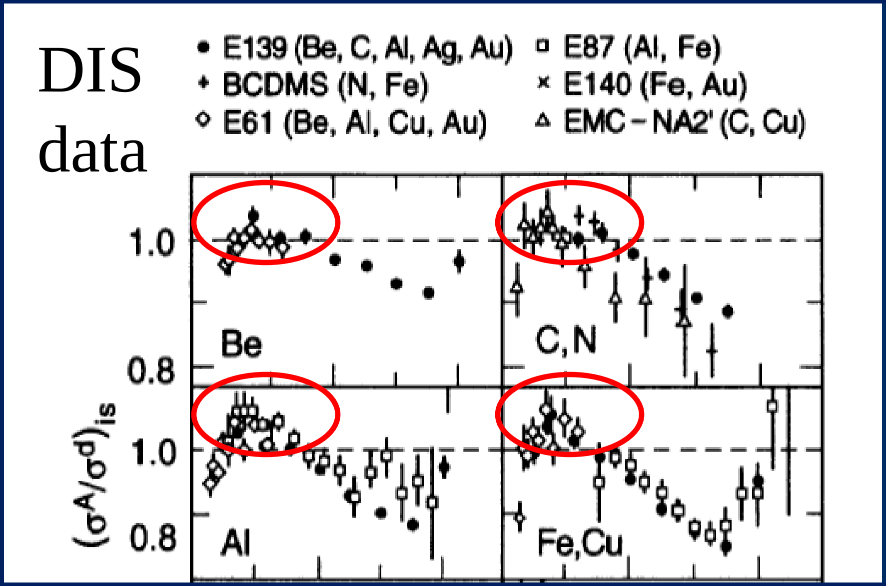
*simplest leading-order expression

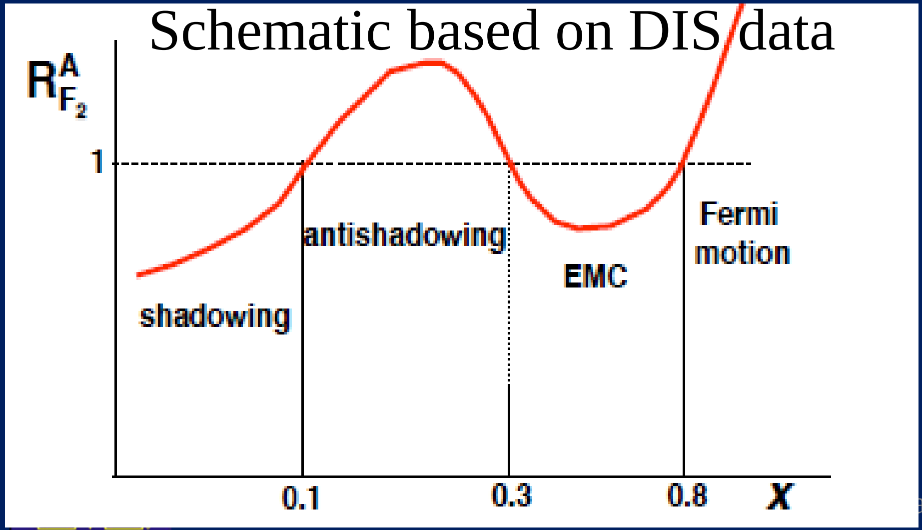
- Expect anti-down/anti-up ratio of 1 if sea quarks only generated dynamically by gluon splitting
  - Gluons don't couple to flavor
  - Up and down quark masses similar
- Indicates other mechanism(s) generating sea quarks—still not well understood!

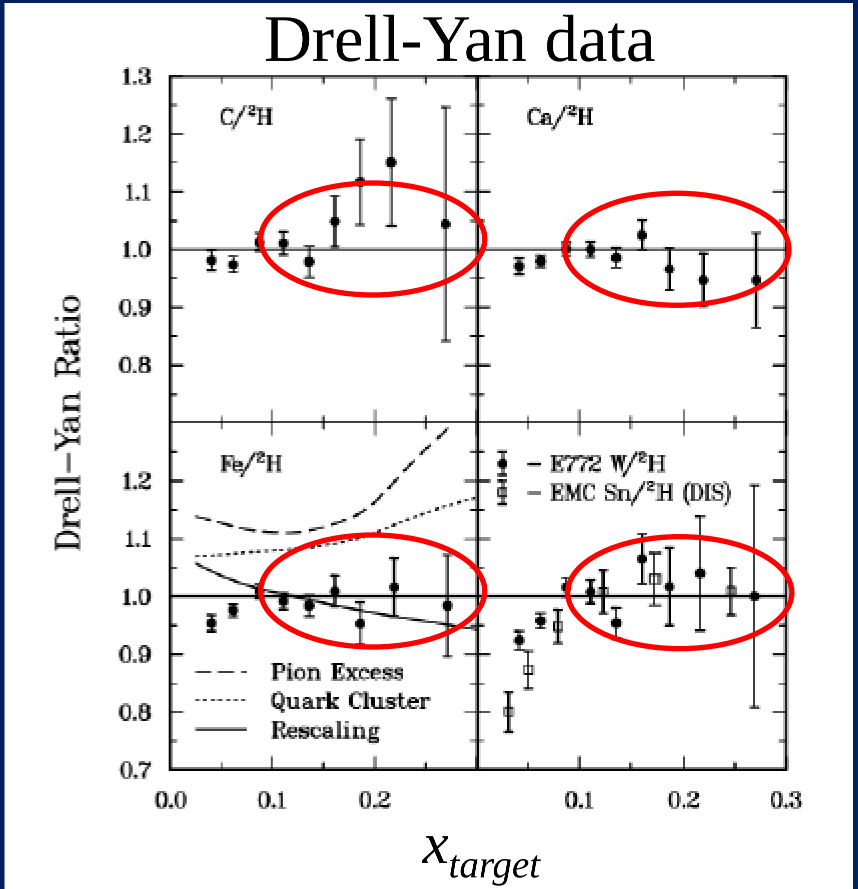


PRD64, 052002 (2001)

…And nuclear effects seen by E772 that differ from DIS







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

No clear "antishadowing" in Drell-Yan

Still lots to learn about nuclei!

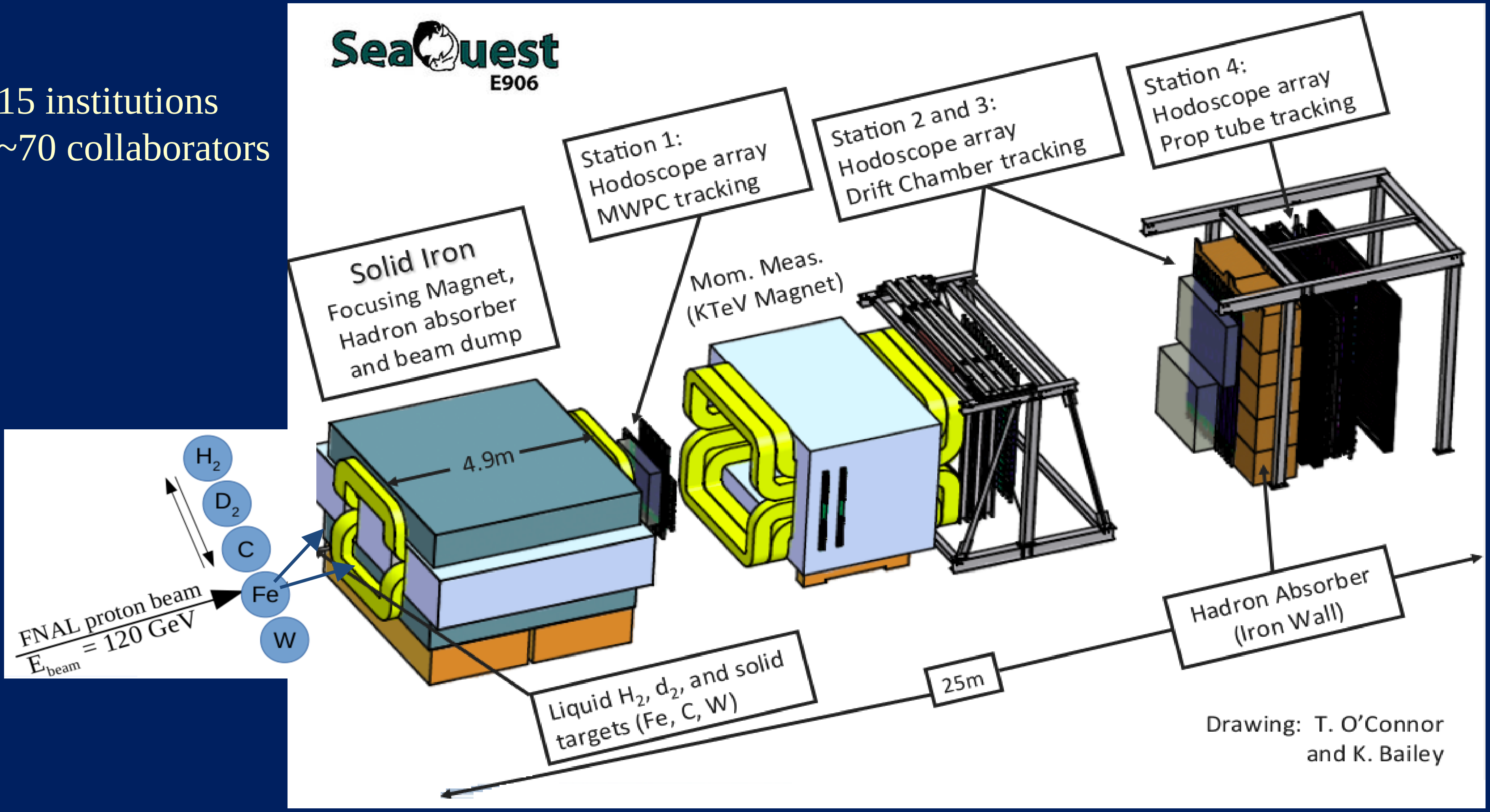
- But note—Drell-Yan results shown vs. x_{target}, which is x of sea quarks (proton rather than pion beam)
  - DIS instead dominated by valence for ~0.1<x< 0.3

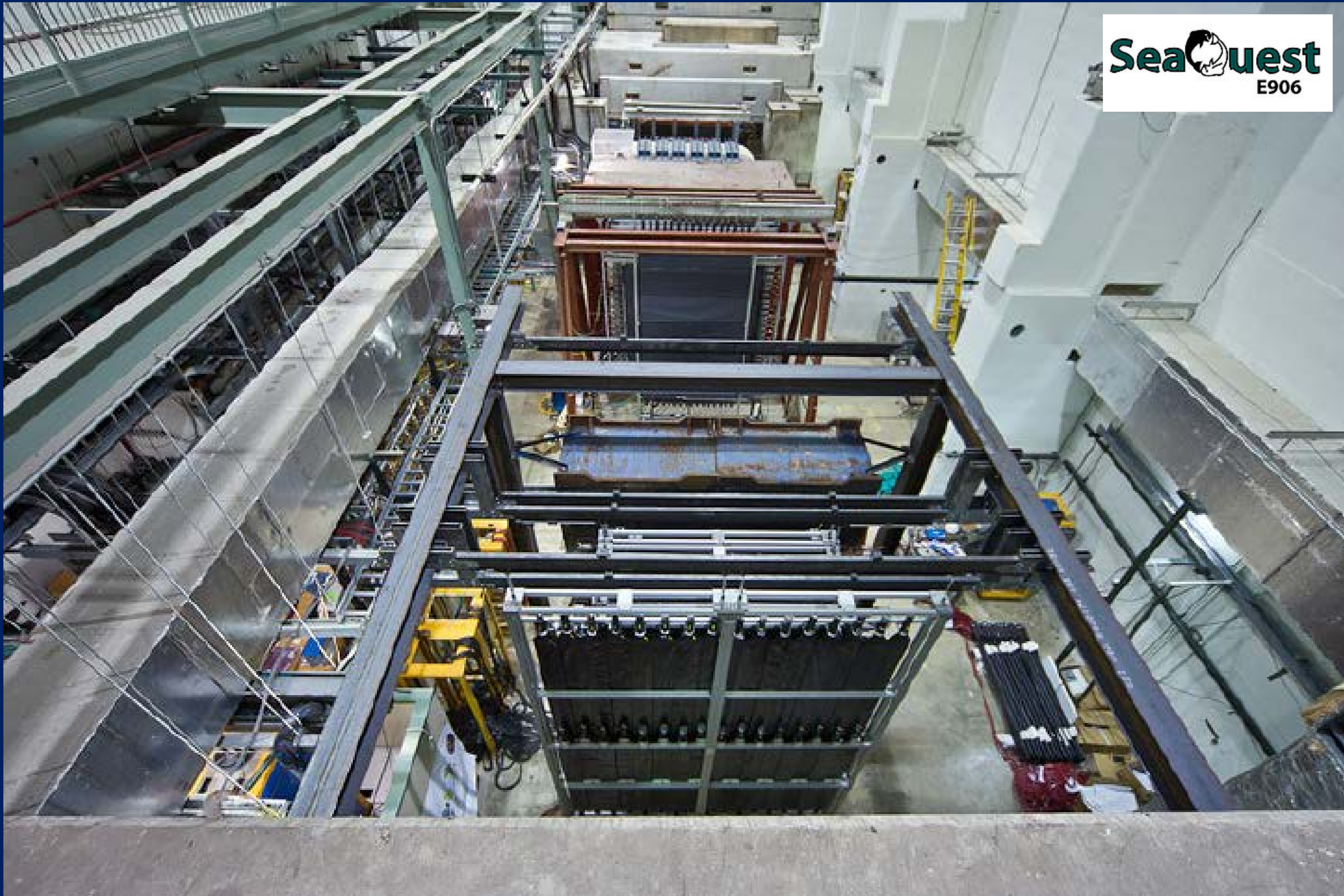
- If nuclear binding mediated by pions, why no clear excess of antiquarks in nuclei??

- Both DIS and D-Y data demonstrate rich and intriguing differences for nuclei compared to free nucleons, which vary with the linear momentum fraction probed (and likely transverse momentum, impact parameter, . . .)

Fermilab E906/SeaQuest

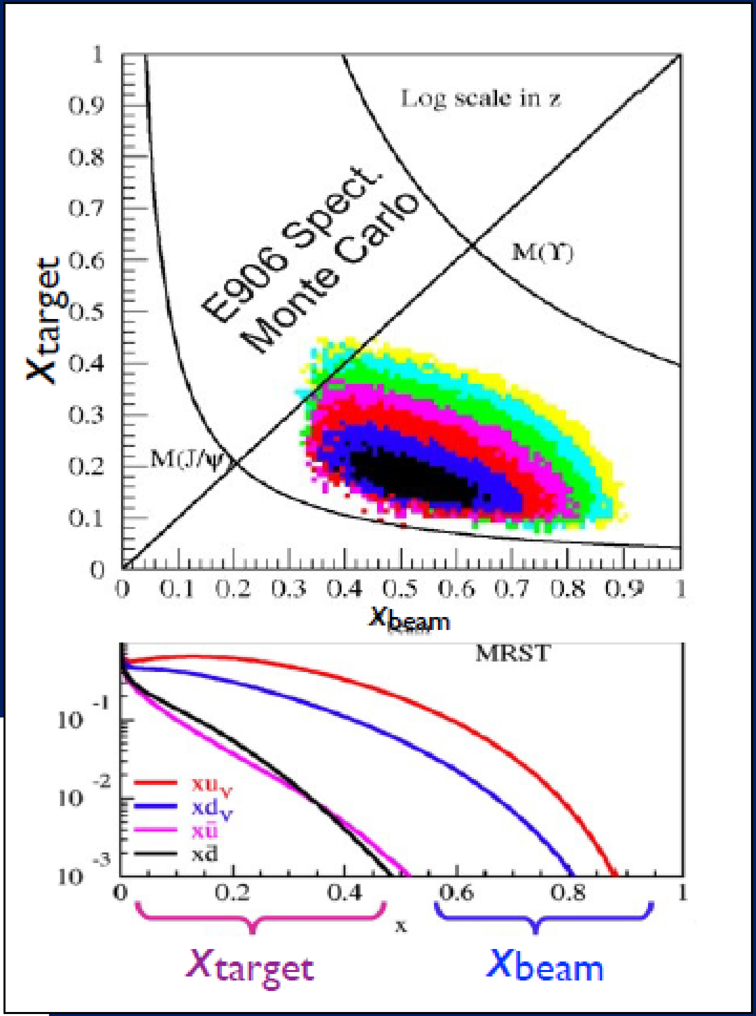
15 institutions
~70 collaborators

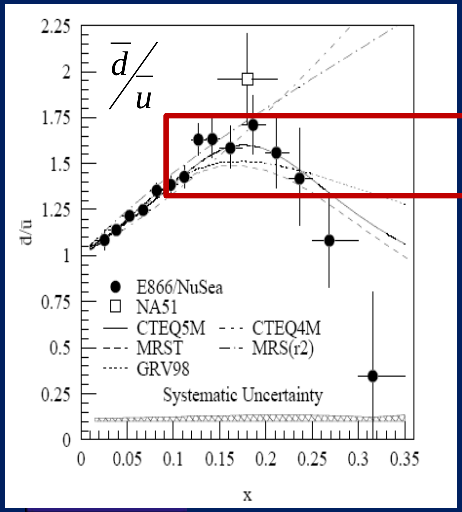


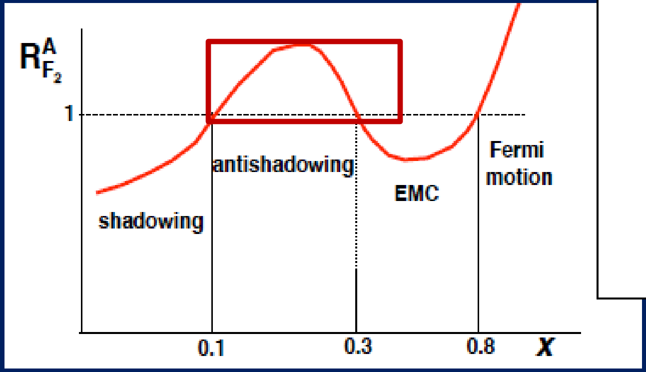


SeaQuest kinematics

- For masses between J/Psi and upsilon, most statistics near peak of dbar/ubar ratio ($\sim 0.15 < x_{target} < \sim 0.2$)
  - "Antishadowing" region for nuclei
- Max x_{target} ~0.5
  - Compare to 0.35 for E866
  - Into EMC region for nuclei







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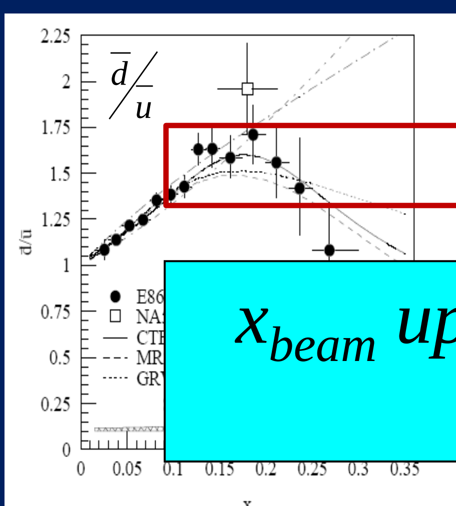
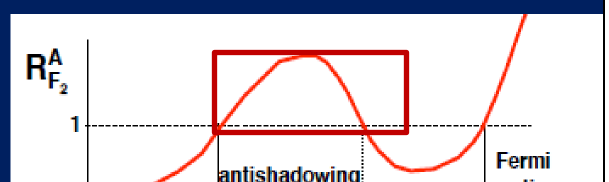
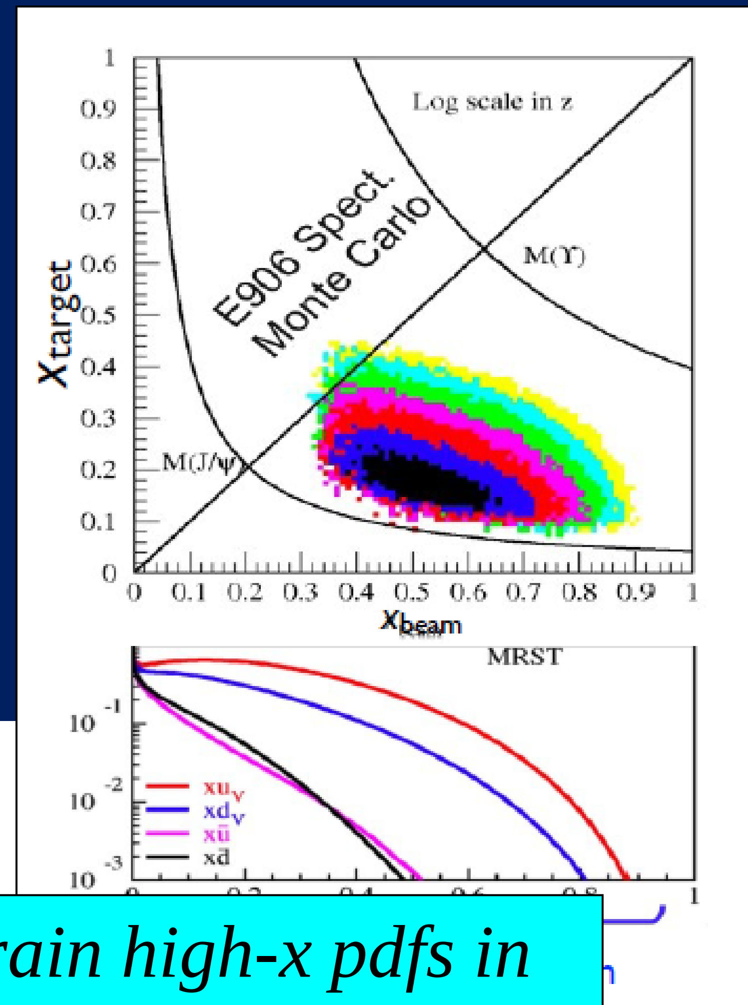


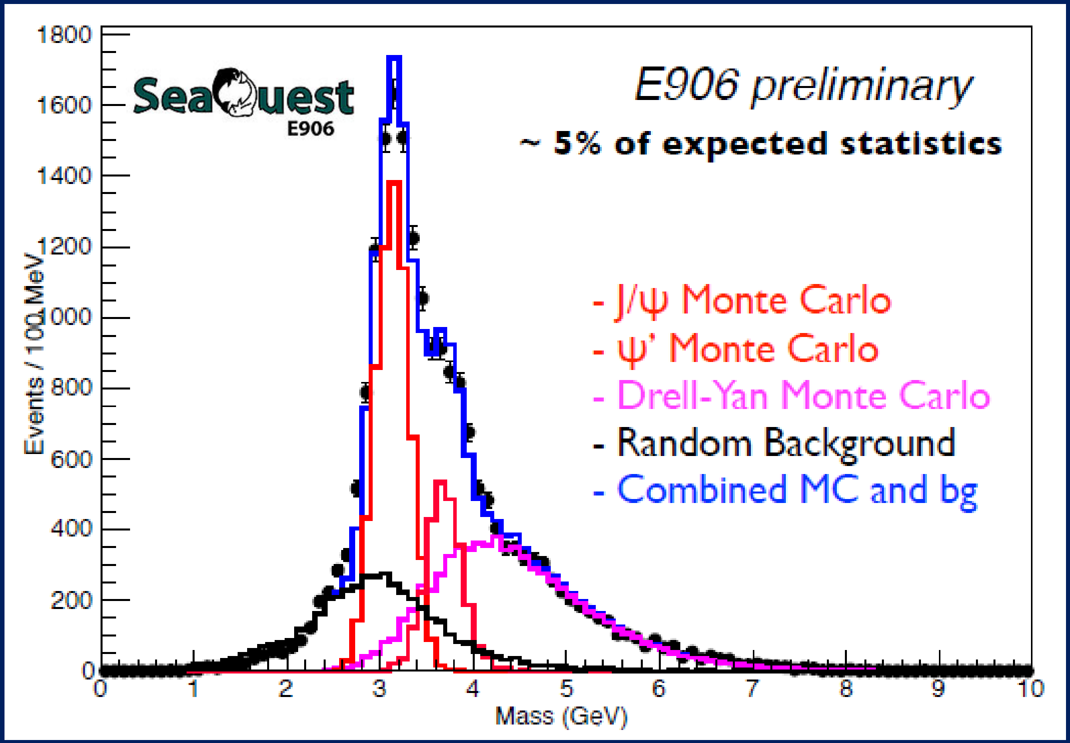




x_{beam} up to ~0.9. Help constrain high-x pdfs in conjunction with JLab program

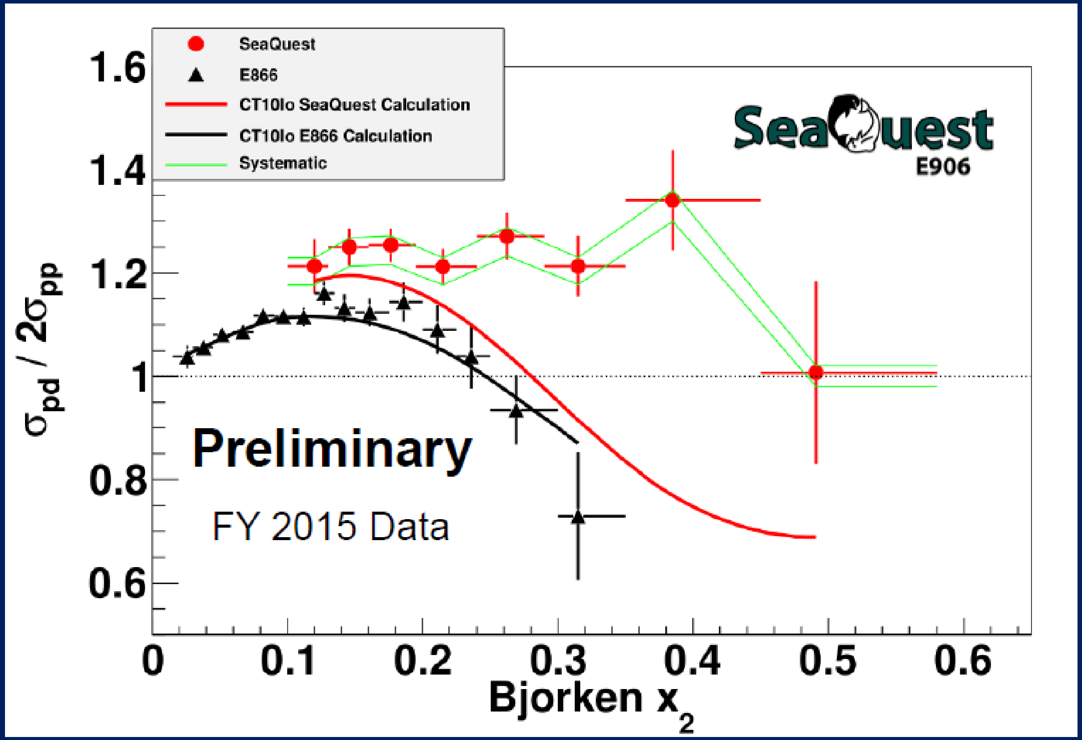
Invariant mass distribution

- Mass resolution ~180 MeV/c^2
  - Better than expected!
- Data agree well with simulation



Results for cross section ratio sensitive to light sea asymmetry

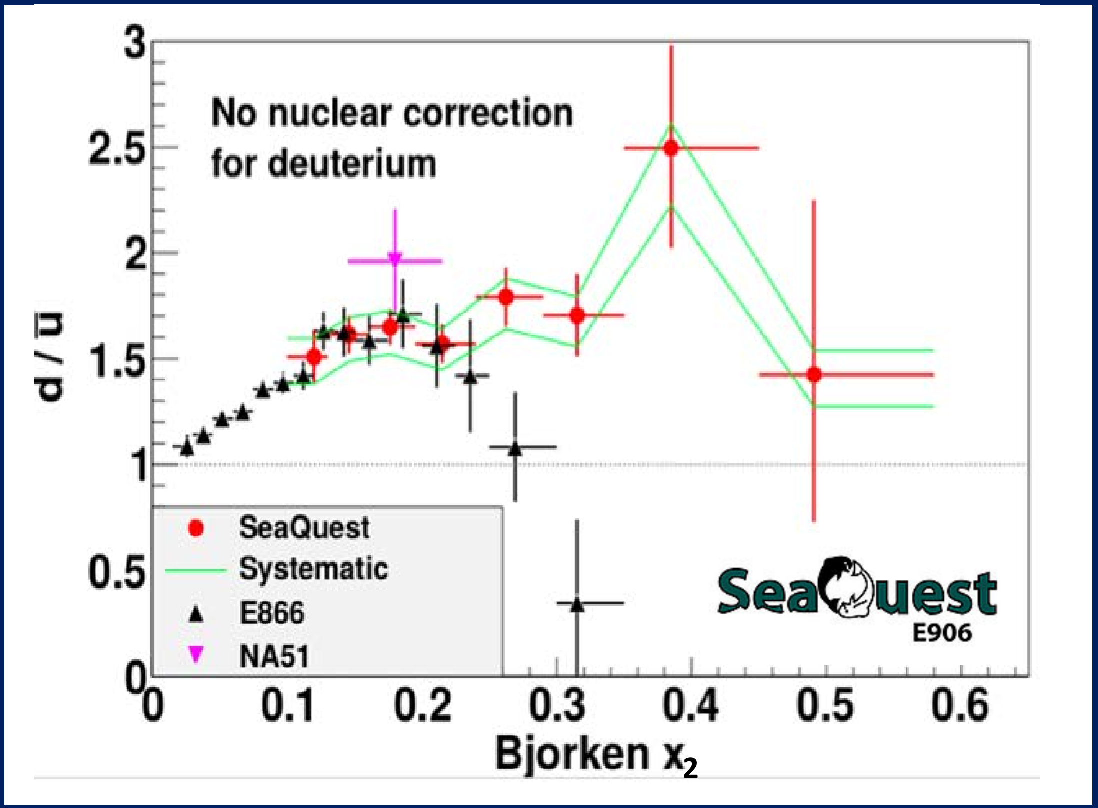
- <50% of anticipated data
- Suggests ratio does not drop off sharply as observed by E866
- Curves are calculations based on CT10 pdfs (include E866 data) and experiment kinematics



See poster #52 by Arun Tadepalli

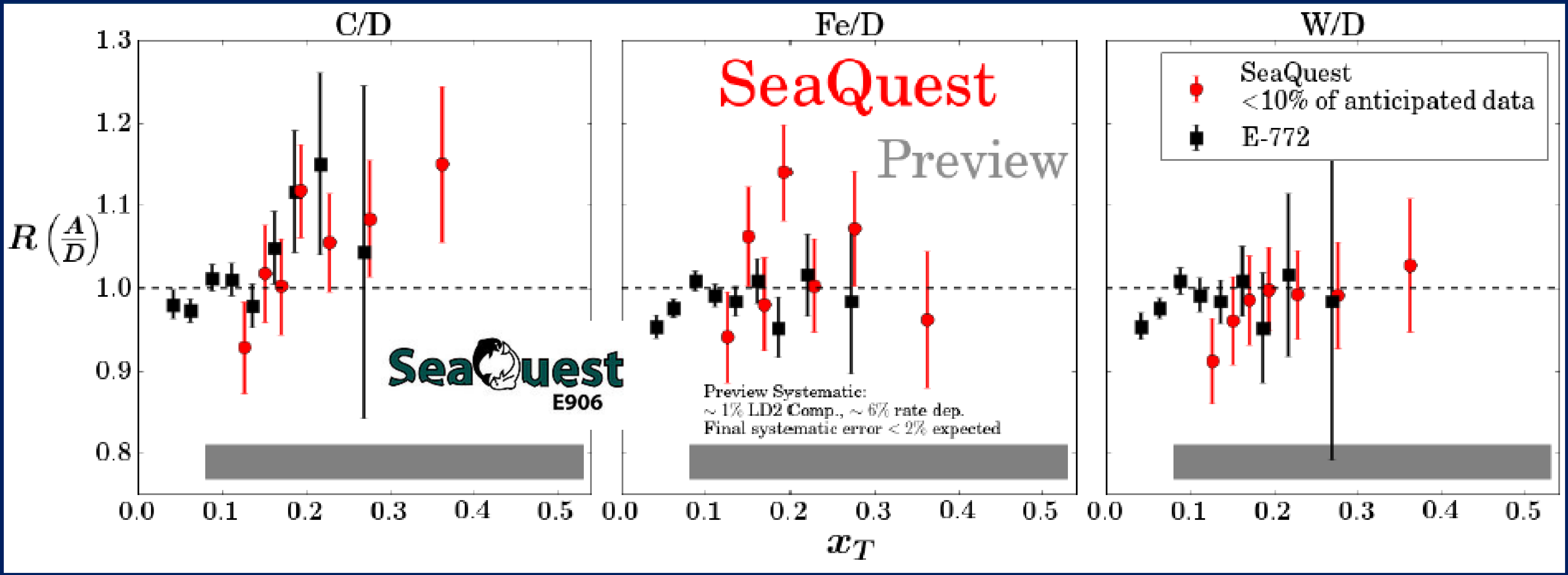
Extracted light sea asymmetry

- Preliminary SeaQuest results above last two points from E866
- Statistical and systematic uncertainties will be reduced for final results
- No strong conclusion yet . . .

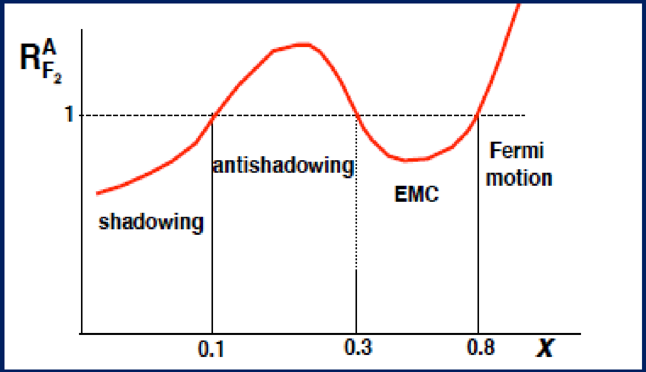


See poster #52 by Arun Tadepalli

Probing sea quark distributions in nuclei

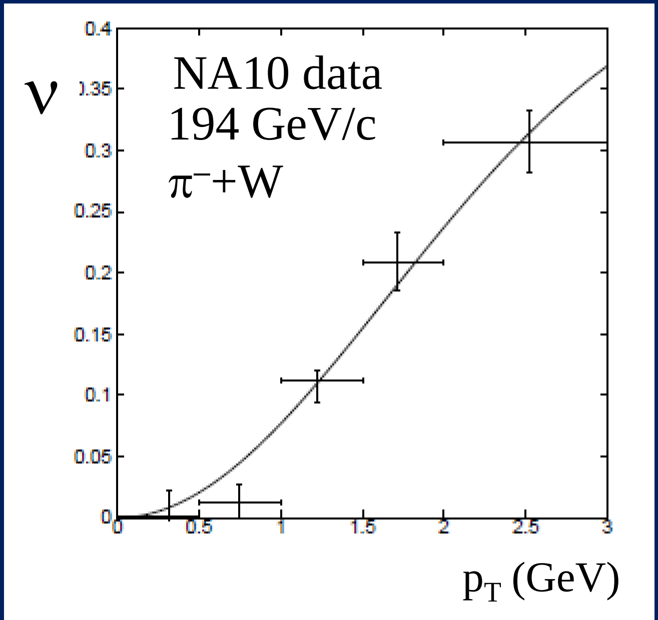


- <10% of anticipated data
- Consistent with E772, no clear evidence for "antishadowing" of sea quark distributions (yet?)
- Pushing into x range (0.3<x<0.8) where DIS sees a depletion of the valence densities ("EMC effect")
- Can high-x sea measurements shed light on mechanisms generating these nuclear effects?



Probing (anti)quark spin-momentum correlations in unpolarized Drell-Yan

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



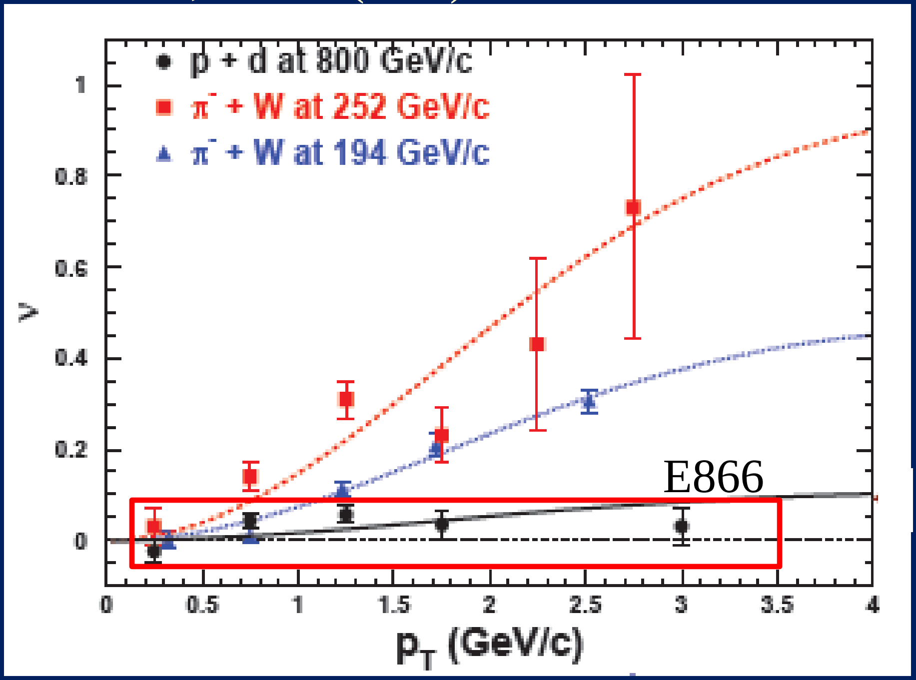
D. Boer, PRD60, 014012 (1999)

- $\cos 2\phi$ term sensitive to *correlations between quark transverse spin and quark transverse momentum* → Boer-Mulders transverse-momentum-dependent (TMD) pdf
- Evidence for such correlations also in semi-inclusive DIS data
- Large $\cos 2\phi$ dependence seen in pion-induced Drell-Yan from multiple experiments

See poster #35 by R. Evan McClellan on D-Y angular distributions

What about proton-induced Drell-Yan?

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



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

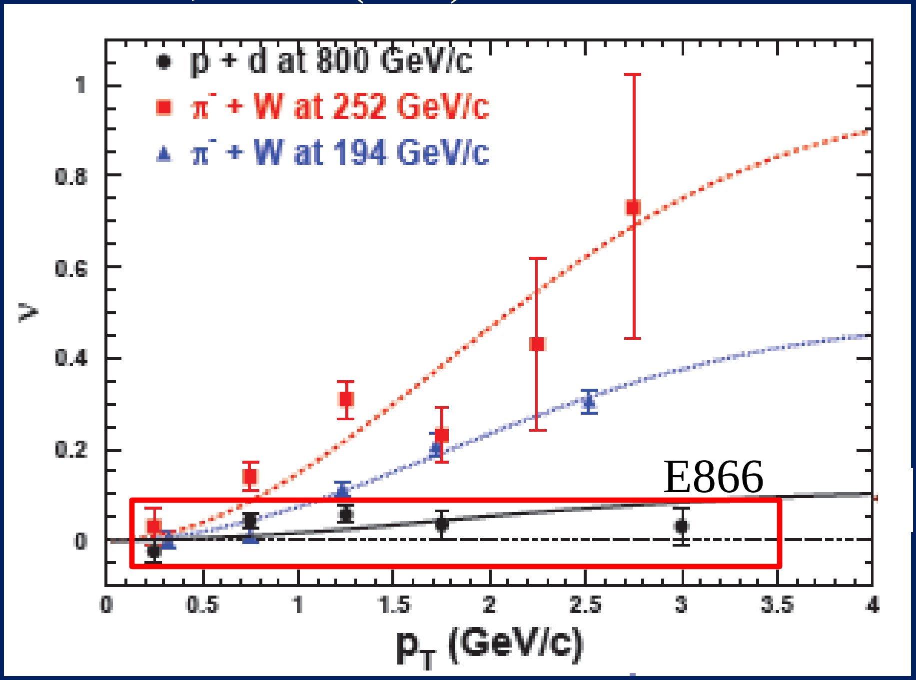
$\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim$ [valence $h_1^{\perp}(\pi)$] * [valence $h_1^{\perp}(p)$]

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

- Significantly reduced but nonzero cos2ϕ dependence in proton-induced D-Y
- Suggests sea quark transverse spin-momentum correlations small?
- What about higher-*x* sea quarks in SeaQuest??
  - SeaQuest statistics dominated by x_{target} near flavor asymmetry peak
  - Probe flavor asymmetry origins via sea quark *dynamics*

What about proton-induced Drell-Yan?

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



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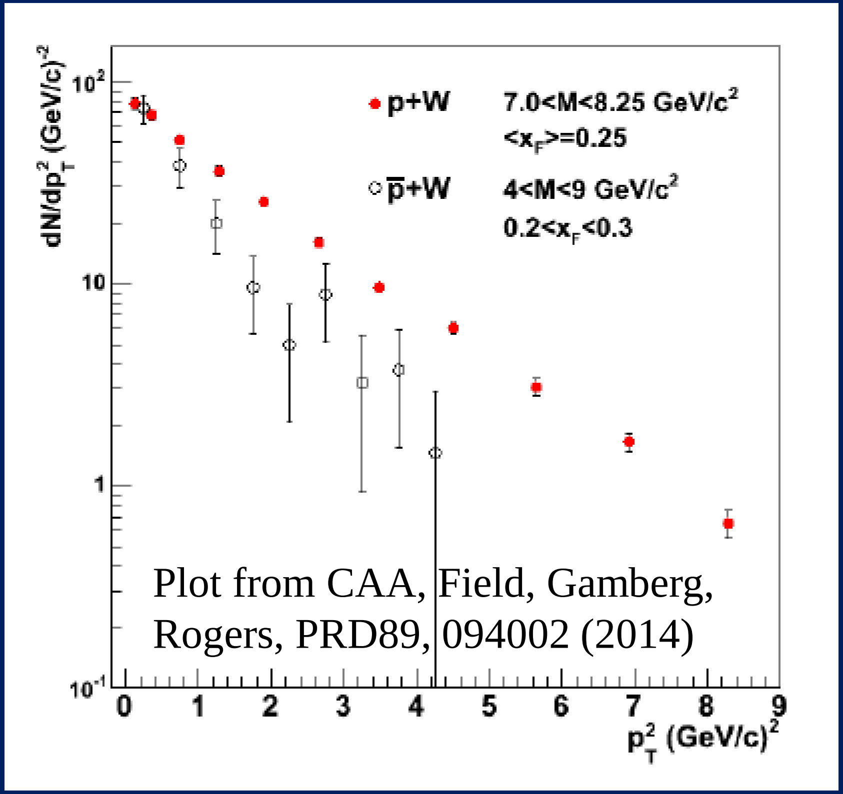
So Drell-Yan with a proton beam is useful for probing sea quarks in your target . . . But do we have many reasons to expect sea quarks to be interesting?

Sea quarks—many hints of interesting behavior already!

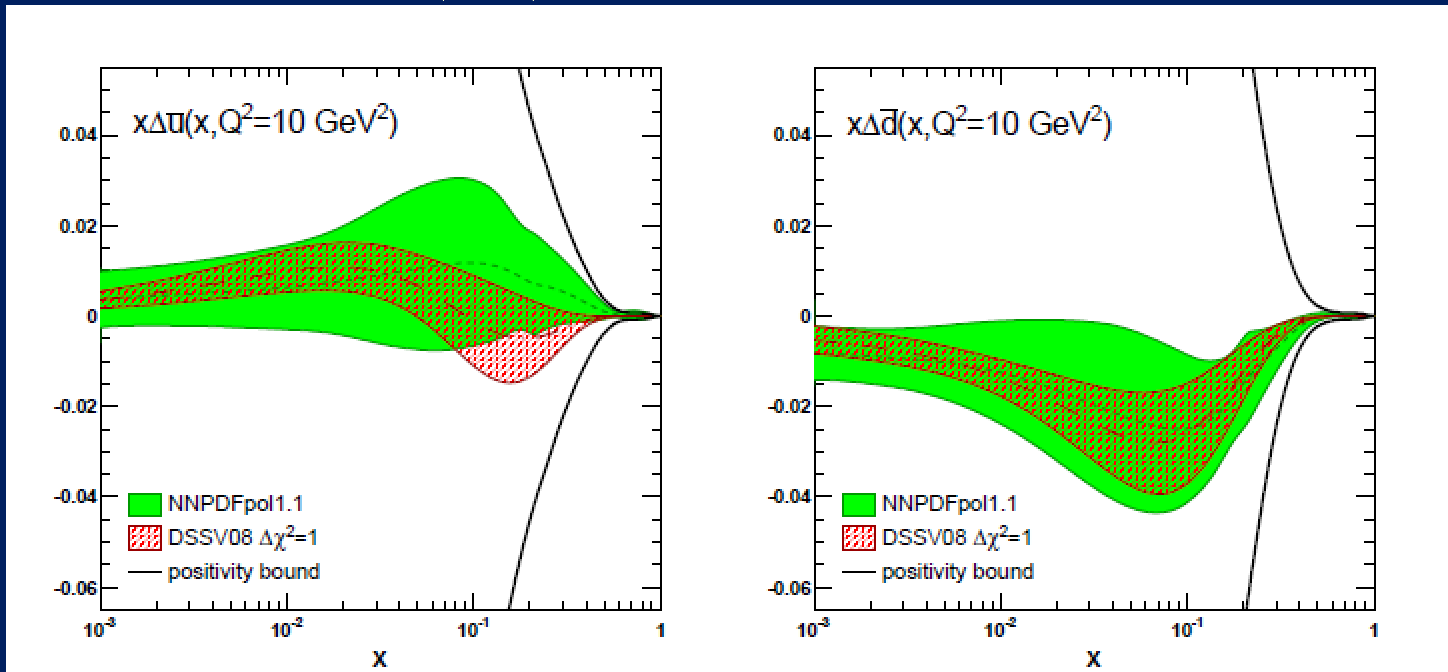


- p+W: (Valence) quark from p, (sea) antiquark from W
- pbar+W: (Valence) quark from W, (valence) antiquark from pbar
- (Valence × sea) spectrum harder → Larger mean k_T for sea than valence quarks?
  - Agrees with chiral soliton model predictions (e.g. Schweitzer, Strikman, Weiss 2013)
  - Consistent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

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

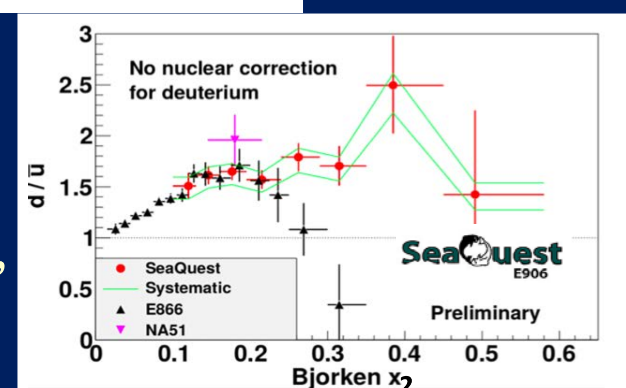
Flavor asymmetry in the sea helicity distributions

NNPDF, NPB 887.276 (2014)

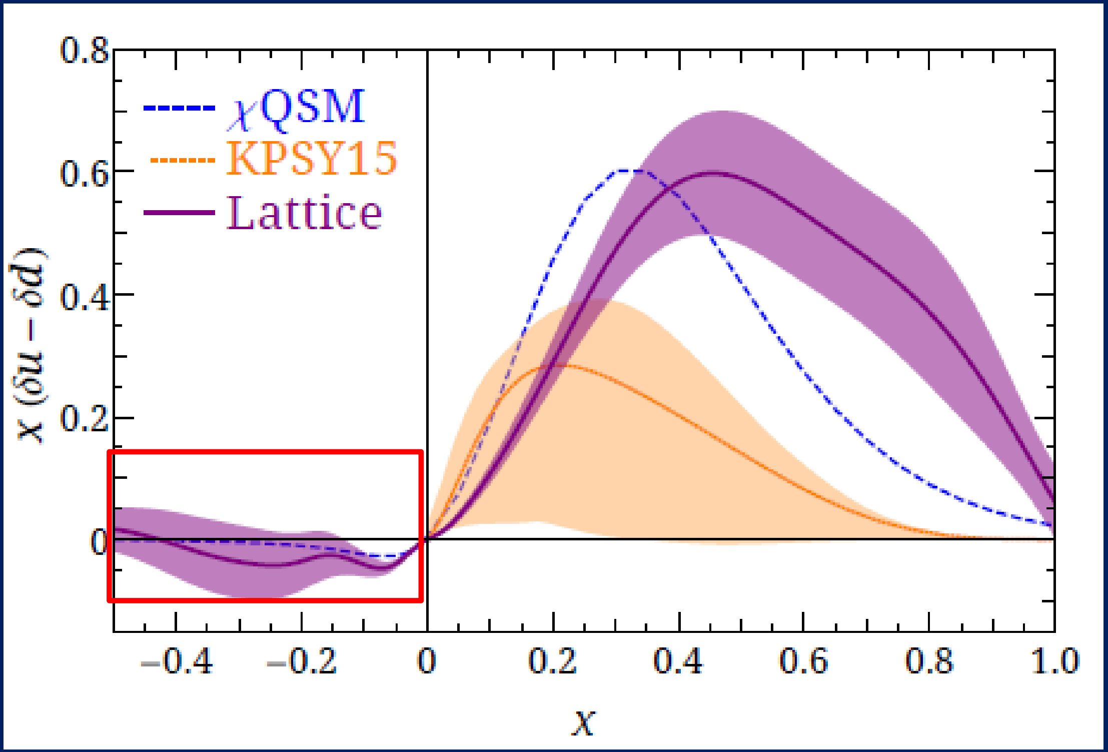


(DSSV08: Before RHIC W data)

And of course flavor asymmetry in unpolarized, collinear sea



Transversity for sea quarks nonzero and flavor-asymmetric?



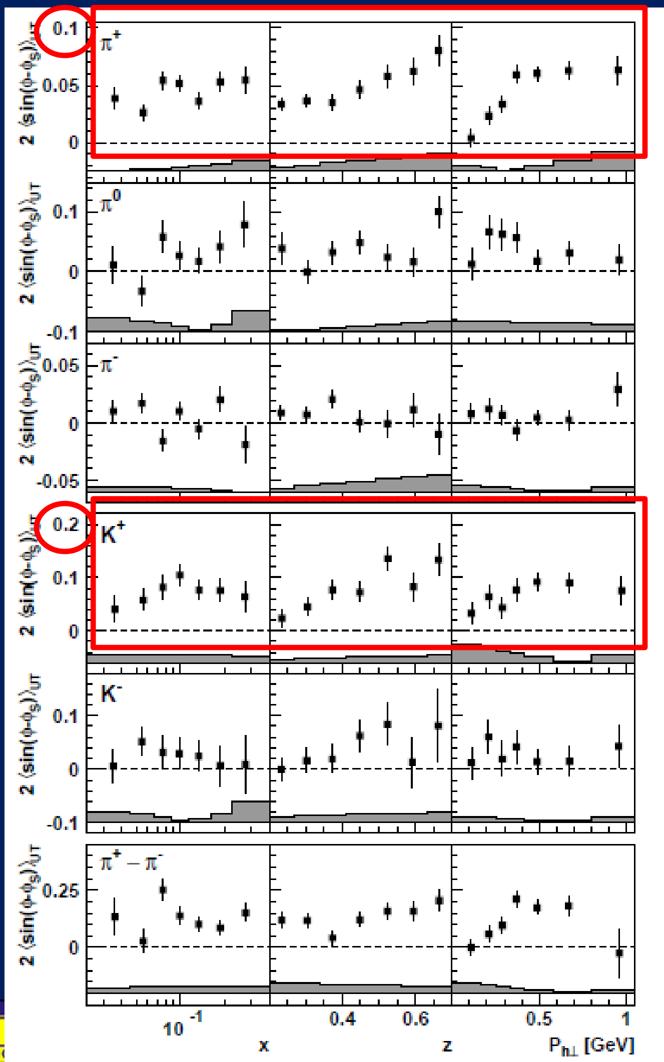
Initial lattice calculation finds transversity for sea nonzero and flavor-asymmetric! Chen et al., arXiv:1603.06664

Also chiral quark soliton model Schweitzer et al., PRD64, 034043 (2001)

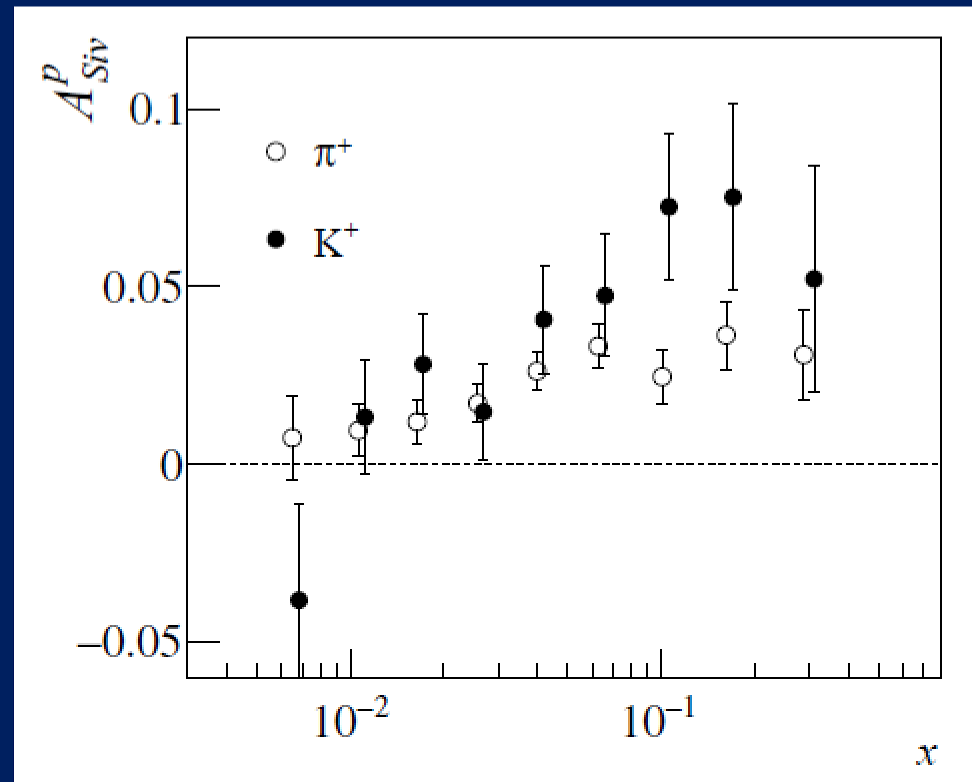
$\delta\bar{q}(x) = -\delta q(-x)$

No constraining measurements yet

SIDIS Sivers transverse single-spin asymmetries larger for K^+ than π^+

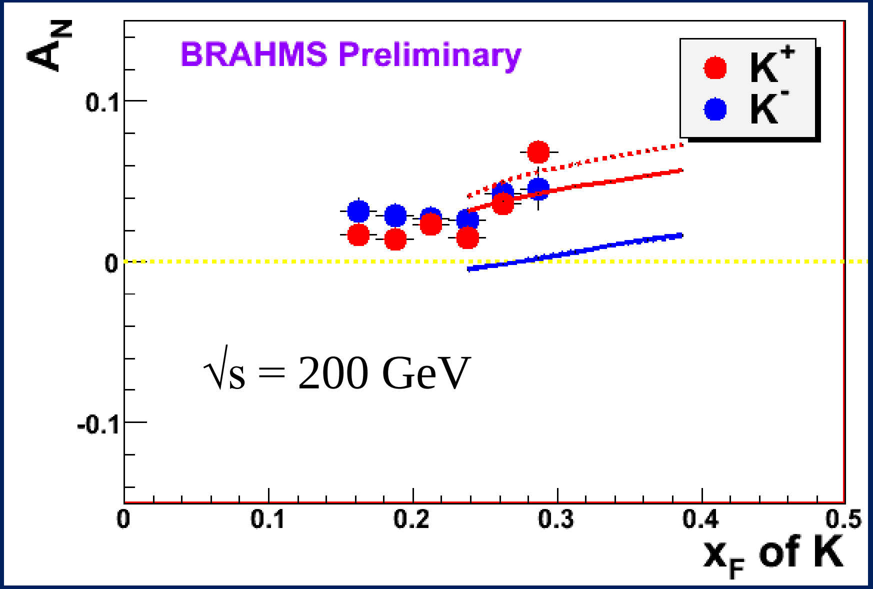


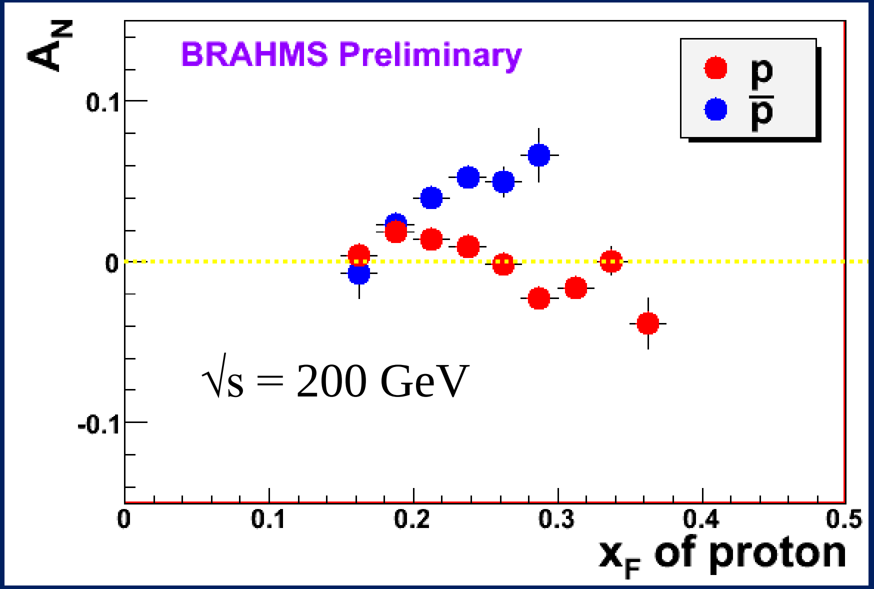
HERMES, PRL103, 152002 (2009)



COMPASS, PLB744, 250 (2015)

Large K^- and antiproton transverse single-spin asymmetries in p+p at RHIC





We have a lot to learn about the nucleon and nuclear sea!

Other thoughts on SeaQuest Drell-Yan measurements

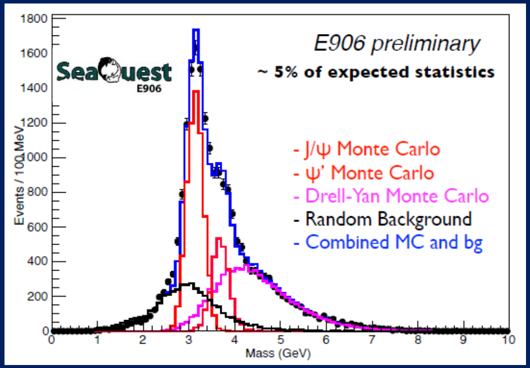
SeaQuest: 120 GeV p beam on p, d, C, Fe, W

- Constraints on unpolarized TMD pdfs and their evolution via multidifferential Drell-Yan cross sections
- Nuclear modification of unpolarized TMD pdfs for sea quarks via ratios of p_T-dependent yields
- Will be able to compare p+W directly with previous pi- + W and pbar+W
  - Lowest pion beam energies 125, 194 GeV, not far from 120 GeV
  - Pion-tungsten data measured large angular modulations
  - Antiproton beam energy 125 GeV

- Quark energy loss traversing nuclear matter – preview result in backup slides

Physics with J/Ψ at SeaQuest

- J/Ψ multidifferential cross section and polarization in p+p, p+A → J/Ψ production mechanism(s)



- Probe QCD phase diagram(?)
  - $\sqrt{s}$ = 15.4 GeV, near phase transition, between RHIC beam energy scan energies of 14.5 and 19.6 GeV

- Search for TMD factorization breaking effects – check if nonperturbative p_T width for J/Ψ not in line with Drell-Yan p_T width as a function of mass

Summary

- Proton-induced Drell-Yan provides unique tagging of sea quarks in the nucleon and nuclei

- Early results now coming out from Fermilab SeaQuest!

- 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/nuclei, will be crucial to understanding how the nucleon/nuclear sea is generated

Extra material

Long history of fixed-target Drell-Yan at Fermilab

- E288 – 200, 300, and 400 GeV p beams on Be, Cu, and Pt targets
- E325 – 200, 300, and 400 GeV p beams on Cu target
- E326 – 225 GeV π- beam on W target
- E439 – 400 GeV p beam on W target
- E444 – 225 GeV, π+/-, K+, proton/antiproton beams on C, Cu, W targets
- E537 – 125 GeV antiproton and π^- beams on W target
- E605 – 800 GeV p beam on Cu target
- E615 – 252 GeV π- beam on W target
- E772 – 800 GeV p beam on deuterium, C, Ca, Fe, W targets
- E866/NuSea – 800 GeV p beam on hydrogen, deuterium targets
- *E906/SeaQuest – 120 GeV p beam on hydrogen, deuterium, C, Fe, W targets – Running since 2014*

E906/SeaQuest collaboration

Abilene Christian University
Ryan Castillo, Michael Daugherity, Donald Isenhower, Noah Kitts, Lacey Medlock, Noah Shutty, Rusty Towell, Shon Watson, Ziao Jai Xi

Academia Sinica
Wen-Chen Chang, Ting-Hua Chang, Shiu Shiuan-Hao

Argonne National Laboratory
John Arrington, Don Geesaman*, Kawtar Hafidi, Roy Holt, Harold Jackson, David Potterveld, Paul E. Reimer*, Brian Tice

University of Colorado
Ed Kinney, Joseph Katich, Po-Ju Lin

Fermi National Accelerator Laboratory
Chuck Brown, Dave Christian, Su-Yin Wang, Jin-Yuan Wu

University of Illinois
Bryan Dannowitz, Markus Diefenthaler, Bryan Kerns, Hao Li, Naomi C.R Makins, Dhyaanesh Mullagur R. Evan McClellan, Jen-Chieh Peng, Shivangi Prasad, Mae Hwee Teo, Mariusz Witek, Yangqiu Yin

KEK
Shin'ya Sawada

Los Alamos National Laboratory
Gerry Garvey, Xiaodong Jiang, Andreas Klein, David Kleinjan, Mike Leitch, Kun Liu, Ming Liu, Pat McGaughey

Mississippi State University
Lamiaa El Fassi

University of Maryland
Betsy Beise, Yen-Chu Chen, Kazutaka Nakahara

University of Michigan
Christine Aidala, McKenzie Barber, Catherine Culkin, Vera Loggins, Wolfgang Lorenzon, Bryan Ramson, Richard Raymond, Joshua Rubin, Matt Wood

National Kaohsiung Normal University
Rurngsheng Guo, Su-Yin Wang

RIKEN
Yoshinori Fukao, Yuji Goto, Atsushi Taketani, Manabu Togawa

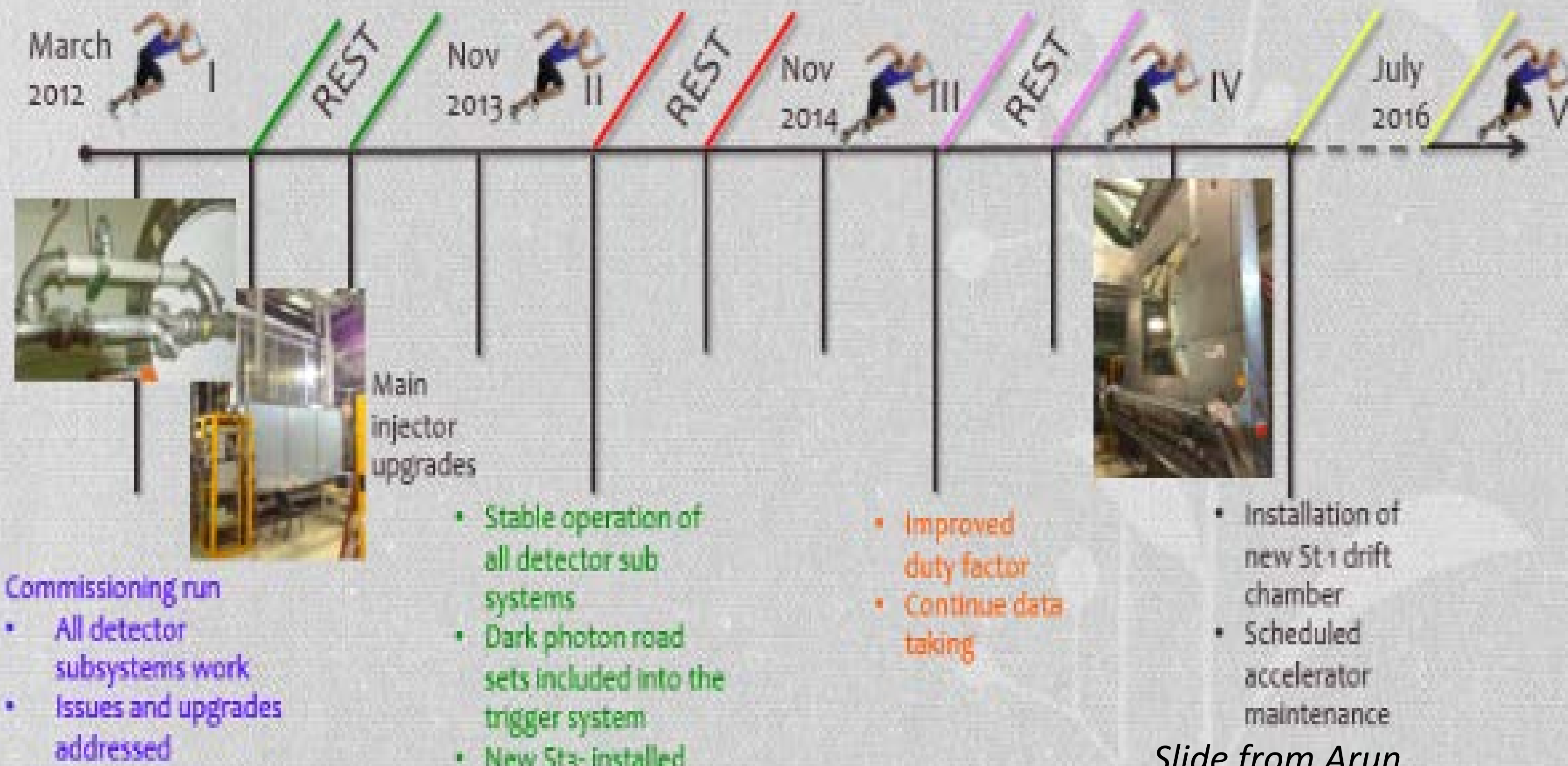
Rutgers, The State University of New Jersey
Ron Gilman, Ron Ransome, Arun Tadepalli

Tokyo Tech
Shou Miyaska, Kei Nagai, Kenichi Nakano, Shigeki Obata, Florian Sanftl, Toshi-Aki Shibata

Yamagata University
Yuya Kudo, Yoshiyuki Miyachi, Shumpei Nara

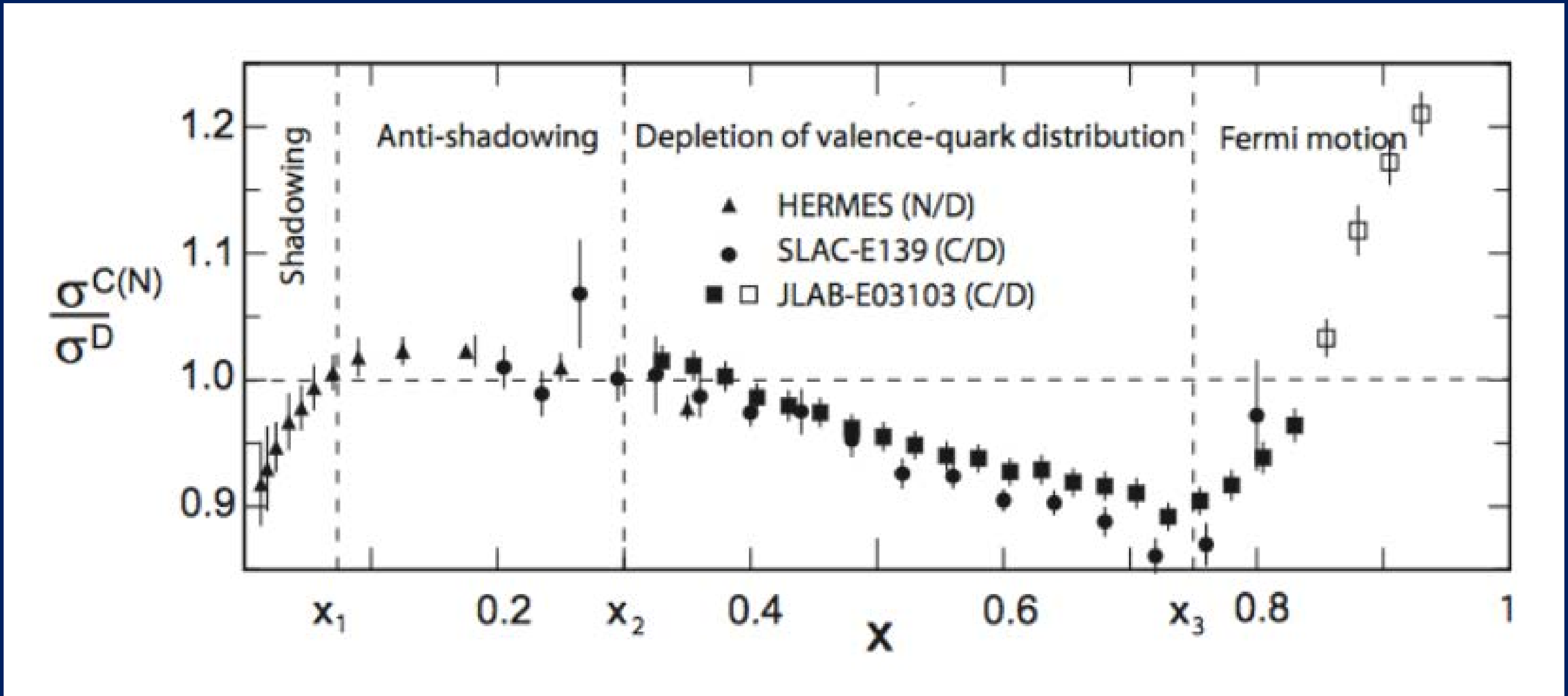
* Co-spokespersons

Timeline of SeaQuest



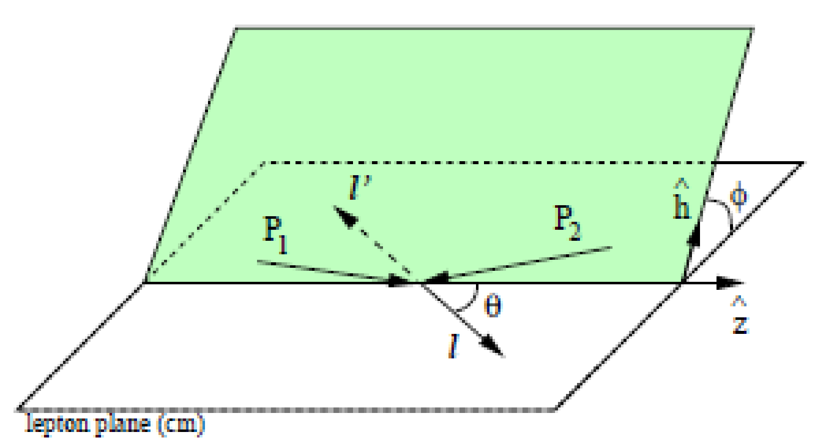
Slide from Arun Tadepalli

DIS data on nuclear targets



- Klaus Rith, *Present status of the EMC effect.* arXiv:1402.5000

Drell-Yan decay angular distributions



θ and ϕ are the decay polar and azimuthal angles of the μ^+ in the dilepton rest frame: Collins-Soper frame

A general expression for Drell-Yan decay angular distributions

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos2\phi\right]$$

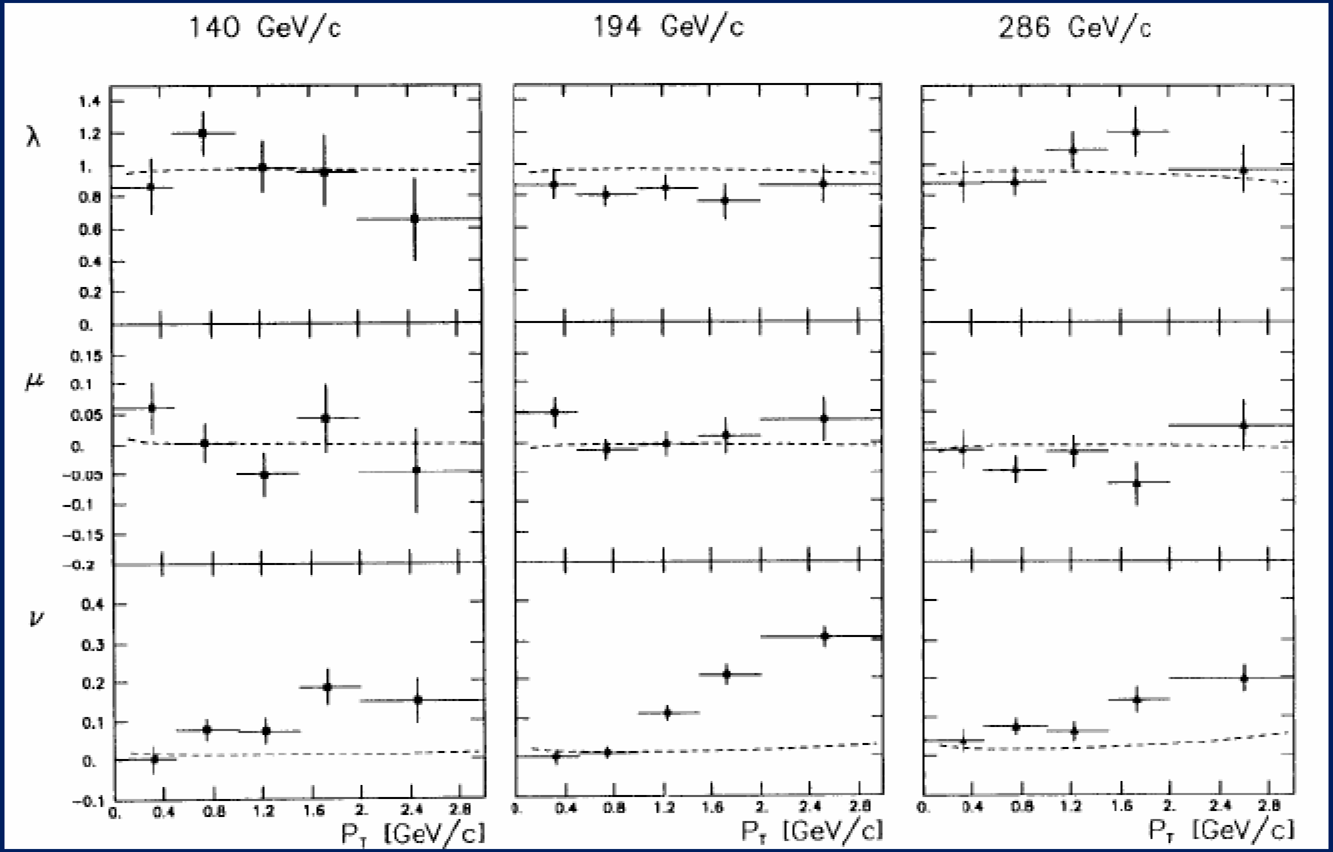
- Lam-Tung relation: 1- $\lambda = 2\nu$
  - Reflects the spin-1/2 nature of (anti)quarks
  - Analog of the Callan-Gross relation in deep-inelastic scattering

Lam-Tung relation

- Lam and Tung, PRD18, 2447 (1978)
- Theoretically robust
  - Unaffected by NLO [O(α_s)] corrections
  - NNLO [O(α_s^2)] corrections small
    - Mirkes and Ohnemus, PRD 51, 4891 (1995)
  - Preserved under resummation of soft gluons
    - Berger, Qiu, and Rodrigues-Pedraza, arXiv:0707.3150 and PRD 76, 074006 (2007)

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

Measured angular dependences



CERN NA10
$\pi^- + W$

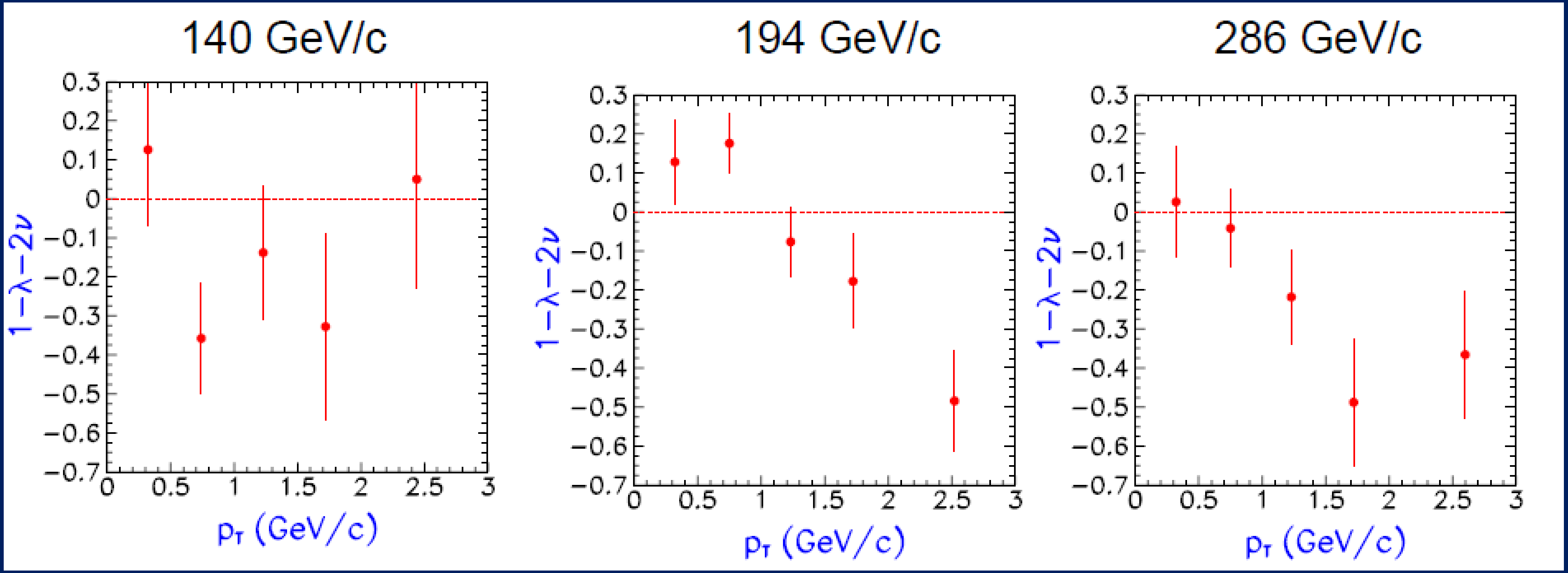
Z. Phys. 37, 545 (1988)

Dashed curves from pQCD calculations

***ν* non-zero, increases with p_T**

Lam-Tung relation violated!

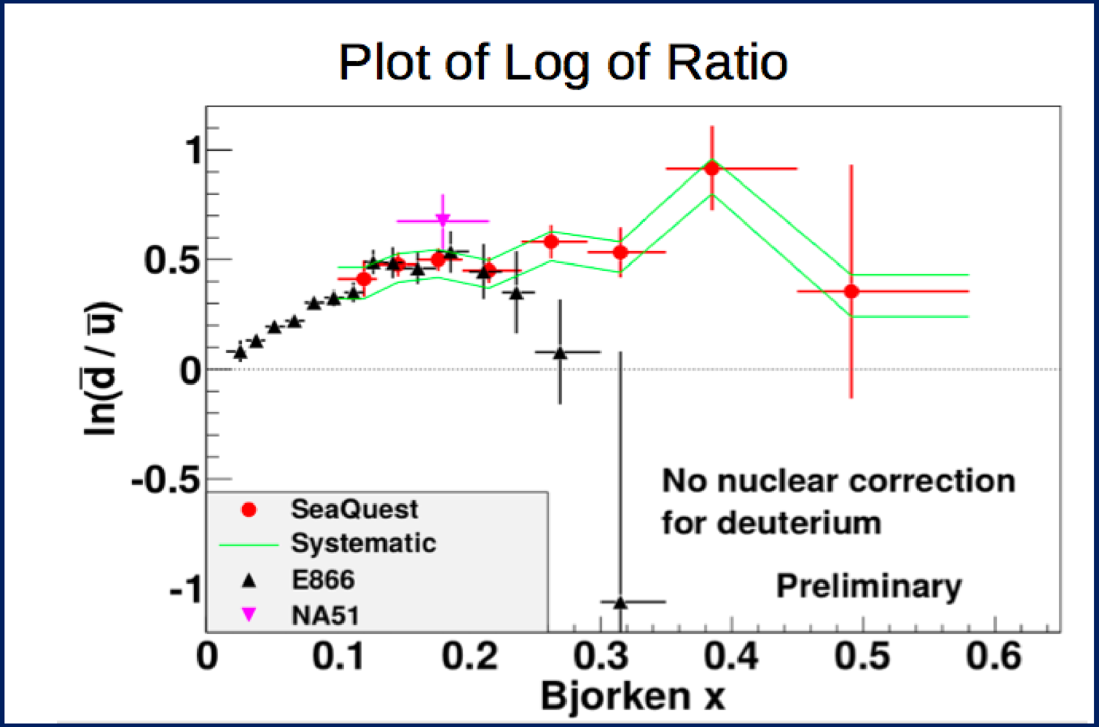
NA10, Z. Phys. 37, 545 (1988)

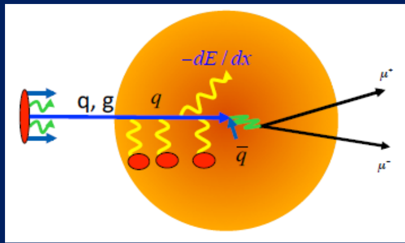


*Violation of the Lam-Tung relation suggests new mechanisms with **non-perturbative** origin!*

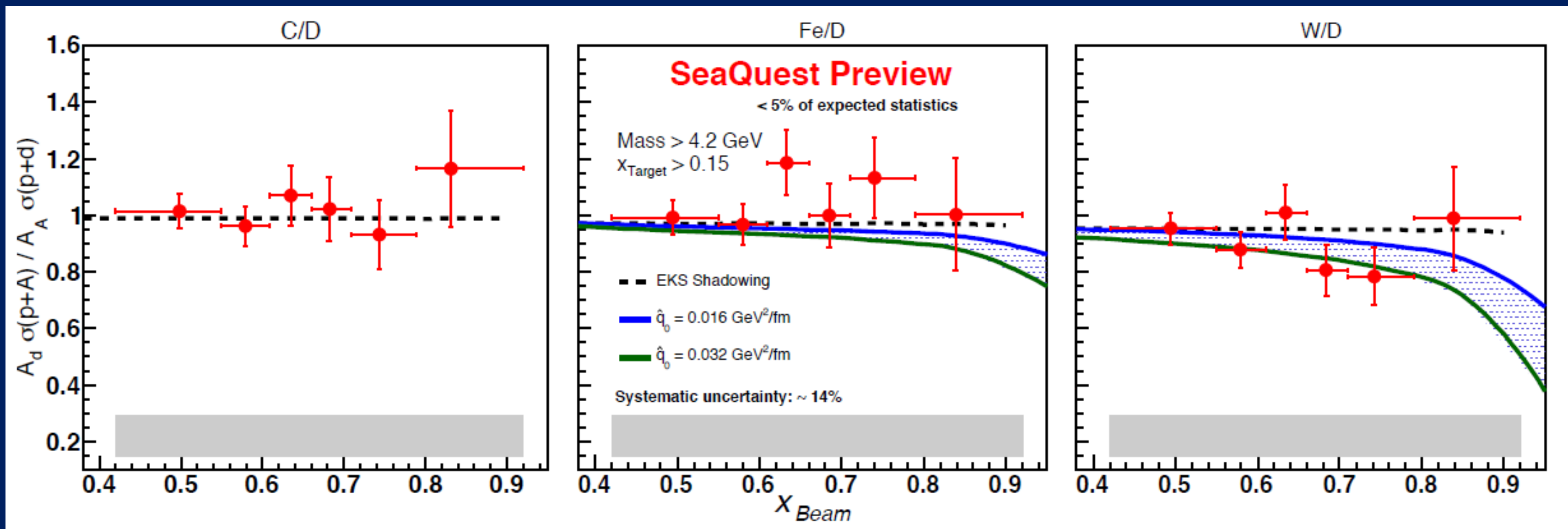
Log of light sea ratio

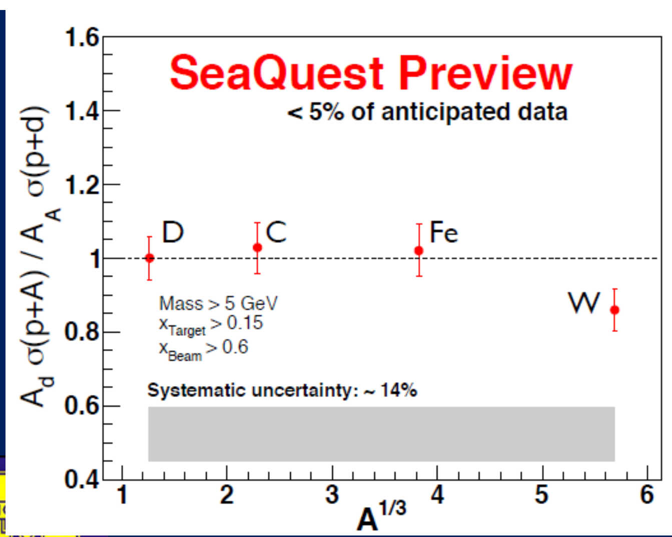
- Treats dbar and ubar on equal footing
- More meaningful uncertainty on last E866 data point
  - Can't imply (unphysically) negative ratio as in linear plot





Parton energy loss in cold nuclear matter





- Very little predicted shadowing—any modification should be energy loss
- Statistics-limited so far
- With 20x more statistics, will be able to distinguish
  - dE ∝ $A^{1/3}$ (or L)
  - dE ∝ $A^{2/3}$ (or L^2)

After E906/SeaQuest: Polarized target experiment E1039

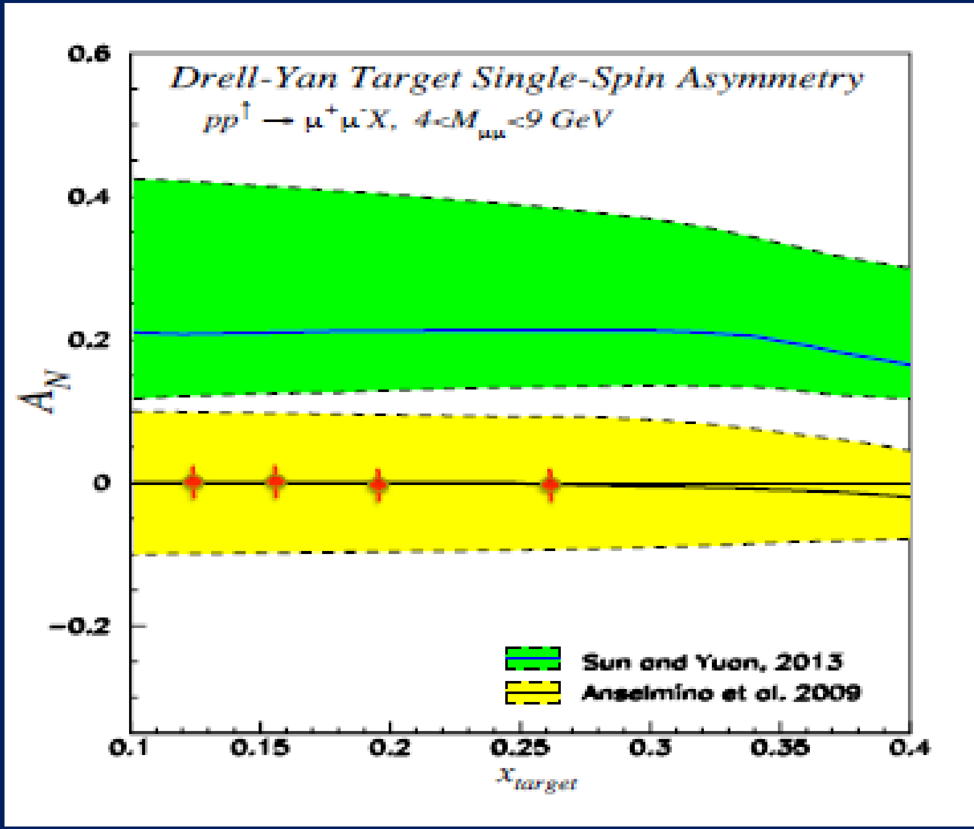
- Transversely polarized frozen NH_3 target
  - Los Alamos National Lab, U. Virginia
- Dynamic nuclear polarization
  - Prototype working, already existing 5 T magnet reconfigured for transverse polarization
- Shutdown second half of 2016
  - Remove unpolarized targets
  - Beam line optics and shielding
  - Install polarized target and cryo
- Take data for 2 years, 2017-18

Probe Sivers asymmetry for sea quarks

- Completely unknown! (despite convincing some theory groups to give us calculations to include in the proposal . . .)

- Often we neglect the sea completely . . . Sometimes (like here) we focus our attention on it explicitly

- But is the time right to perform an experiment focused on TMD pdfs of sea quarks??



Longer-term future: Polarize the Main Injector beam?

- Why polarize the proton beam in the Main Injector?
  - High luminosity: higher than collider experiment because of density of liquid or solid targets, and higher than pion-induced D-Y on fixed targets because of primary rather than secondary beam
  - Long window of opportunity—high-intensity proton beam will be available at Fermilab as long as there’s a neutrino program

Planned or proposed polarized Drell-Yan measurements

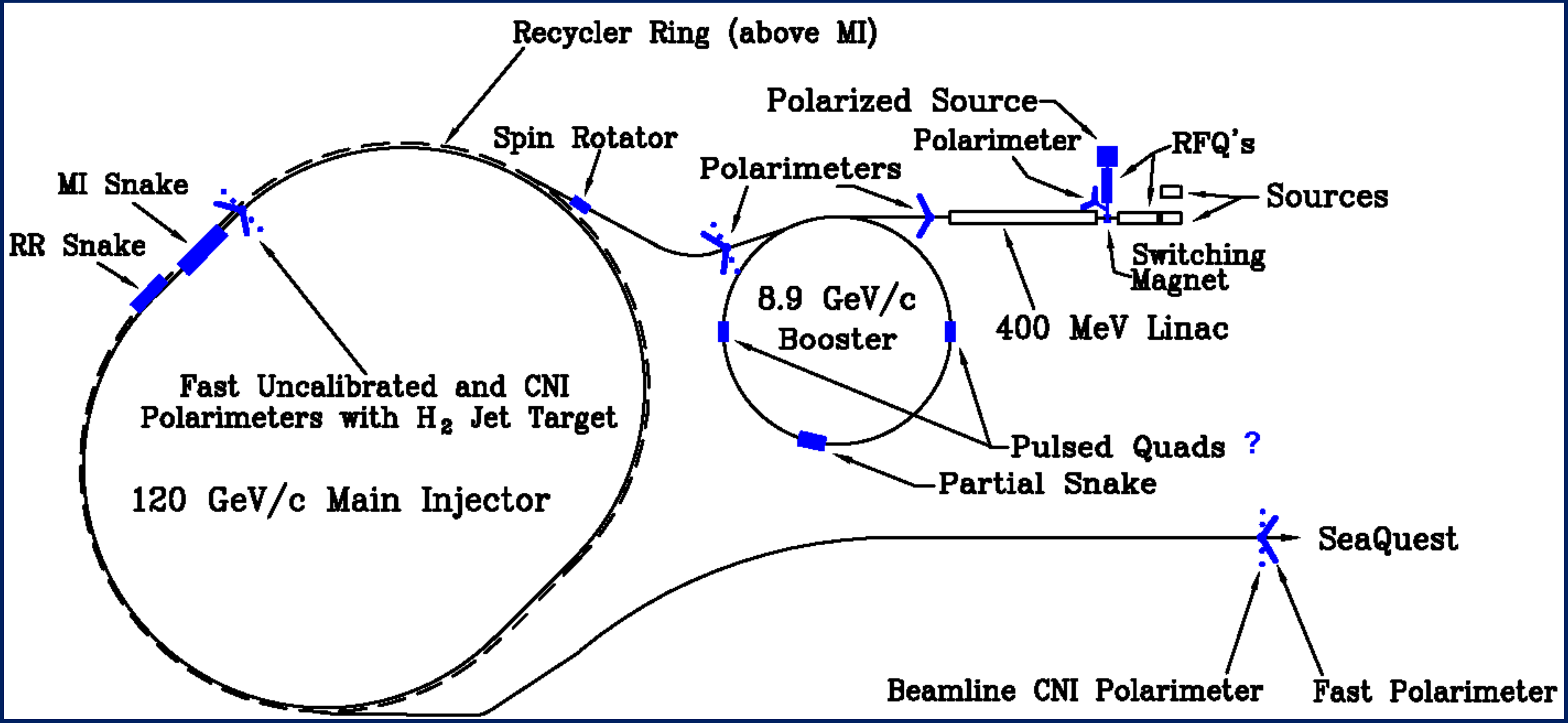
Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2} s^{-1}$)	$A_T^{\sin\phi_S}$	P_b or P_t (f)	rFOM#	Timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s} = 17$	$x_t = 0.2 - 0.3$	2×10^{33}	0.14	$P_t = 90\%$ f = 0.22	1.1×10^{-3}	2014, 2018
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	15 GeV $\sqrt{s} = 5.5$	$x_t = 0.2 - 0.4$	2×10^{32}	0.07	$P_t = 90\%$ f = 0.22	1.1×10^{-4}	>2018
PAX (GSI)	$p^{\uparrow} + \bar{p}$	collider $\sqrt{s} = 14$	$x_b = 0.1 - 0.9$	2×10^{30}	0.06	$P_b = 90\%$	2.3×10^{-5}	>2020?
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s} = 26$	$x_b = 0.1 - 0.8$	1×10^{31}	0.04	$P_b = 70\%$	6.8×10^{-5}	>2018
PHENIX (RHIC)	$p^{\uparrow} + p$	collider $\sqrt{s} = 500$	$x_b = 0.05 - 0.1$	2×10^{32}	0.06	$P_b = 60\%$	3.6×10^{-4}	>2018
SeaQuest (FNAL: E-906)	$p + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 - 0.9$ $x_t = 0.1 - 0.45$	3.4×10^{35}	---	---	---	2012 - 2015
Pol tgt DY‡ (FNAL: E-1039)	$p + p^{\uparrow}$	120 GeV $\sqrt{s} = 15$	$x_t = 0.1 - 0.45$	4.0×10^{35}	0 – 0.2*	$P_t = 88\%$ f = 0.176	0.13	2016
Pol beam DY§ (FNAL: E-1027)	$p^{\uparrow} + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 - 0.9$	2×10^{35}	0.04	$P_b = 60\%$	1	2018

‡ *8 cm NH_3 target* § *$L = 1 \times 10^{36}$ $cm^{-2} s^{-1}$ (LH_2 tgt limited) / $L = 2 \times 10^{35}$ $cm^{-2} s^{-1}$ (10% of MI beam limited)*

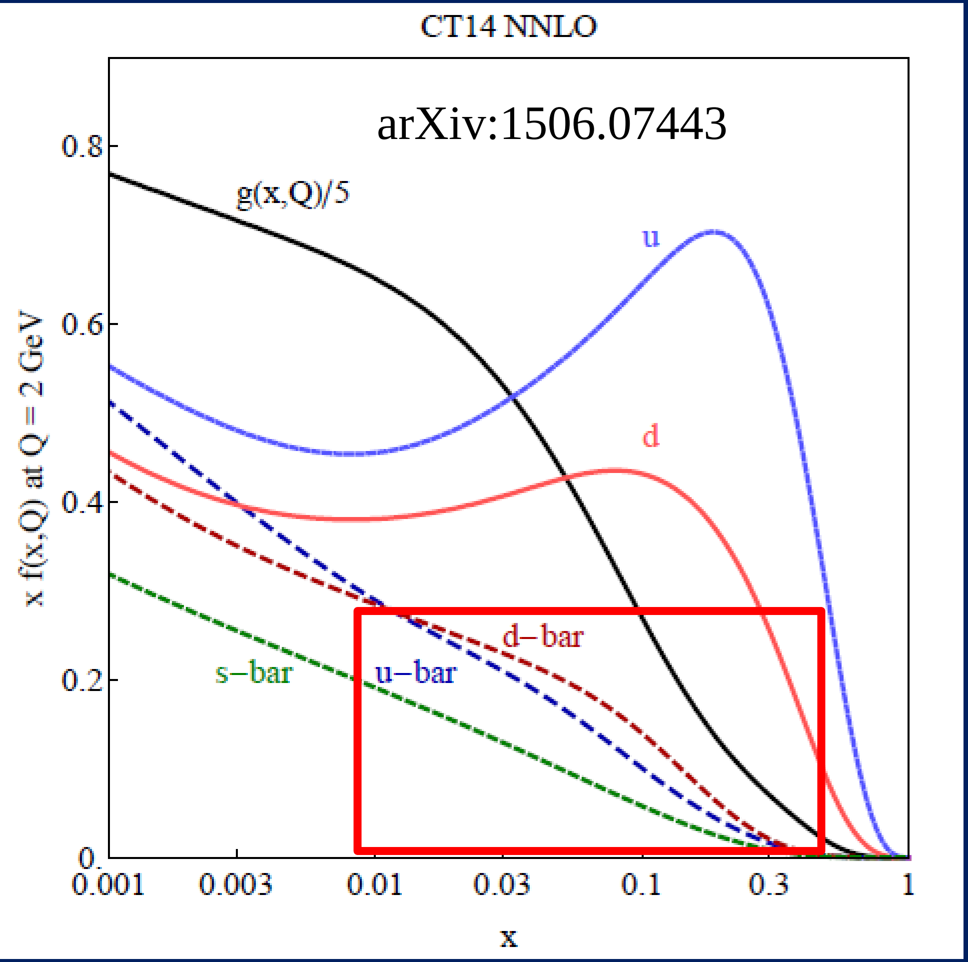
* *not constrained by SIDIS data* / # rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams)

W. Lorenzon (U-Michigan)

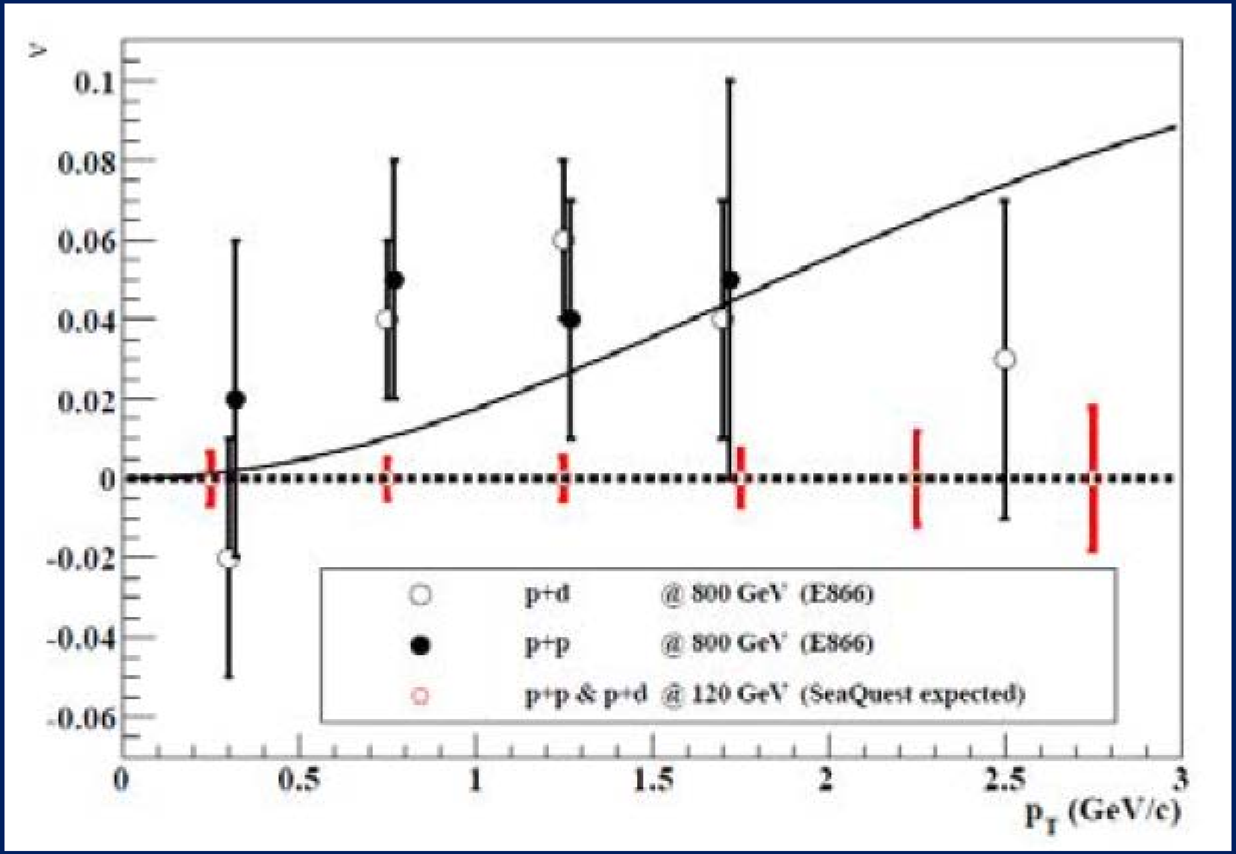
Proposed modifications for polarized beam



dbar/ubar asymmetry in CT14



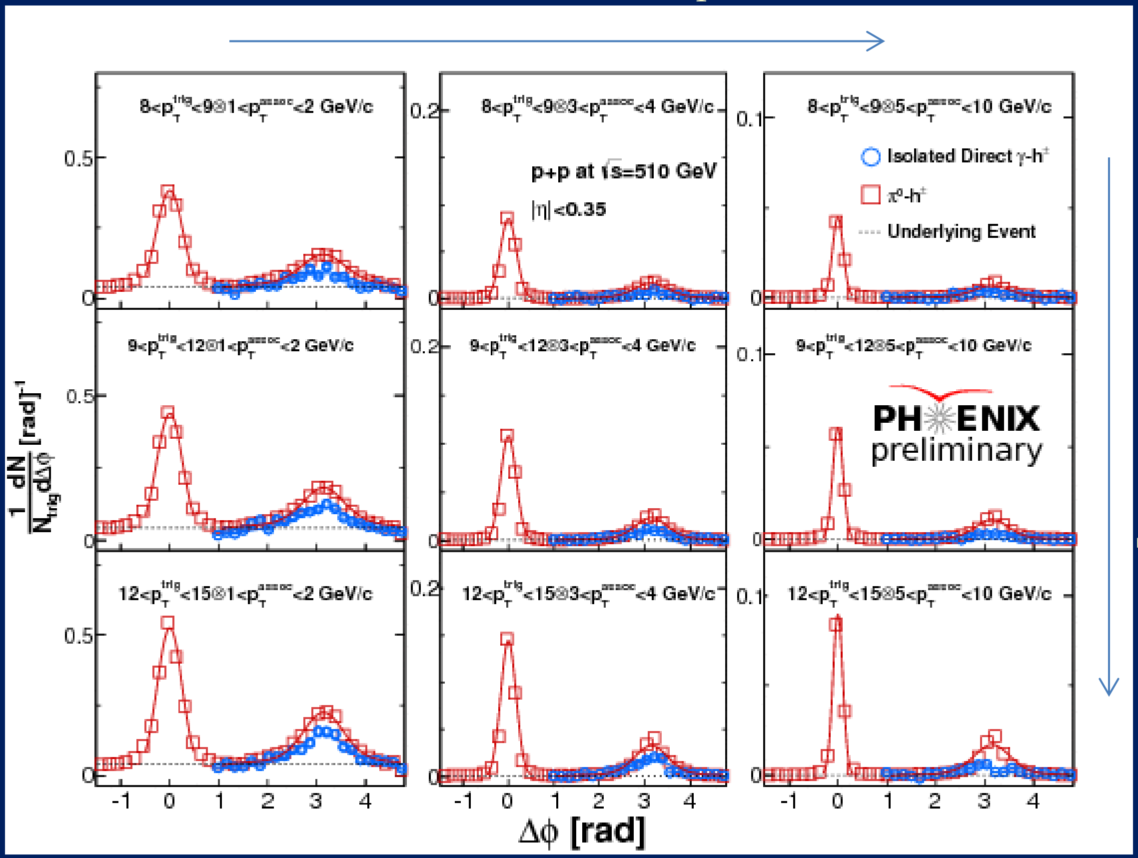
SeaQuest projections for coefficient of $\cos 2\phi$ modulation



- Significantly reduced uncertainties expected compared to E866

Two-particle azimuthal angular correlations in p+p collisions at RHIC

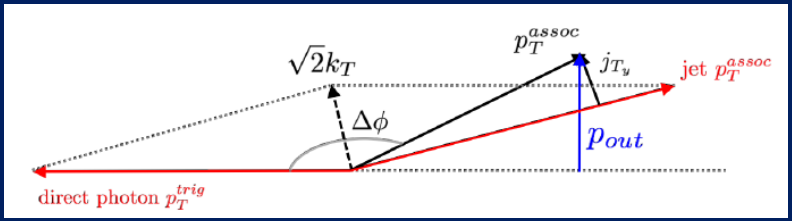
Associated charged hadron p_T increasing

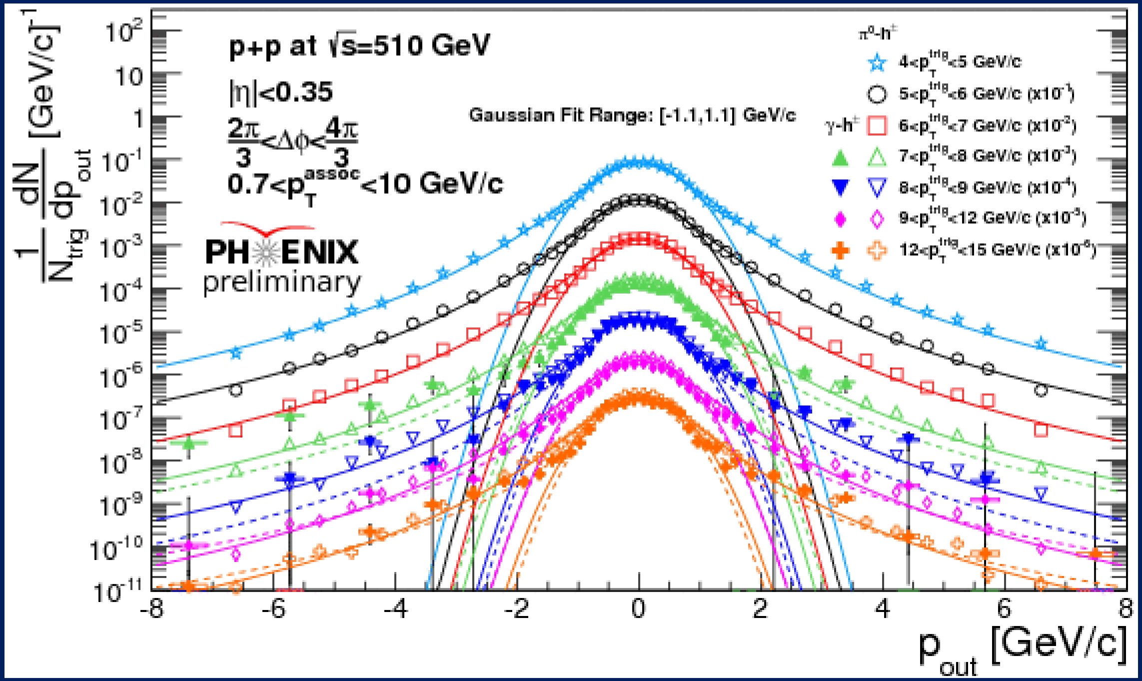


Trigger photon or pion p_T increasing

- Angular distribution of "associated" charged hadrons around a "trigger" photon or π^0
- Two-jet structure seen for pion-hadron correlations
- Away-side jet structure seen for direct photon – hadron correlations
  - Isolation cut on near side
- Trigger particle p_T shown here ranges from 8-15 GeV/c → hard scale

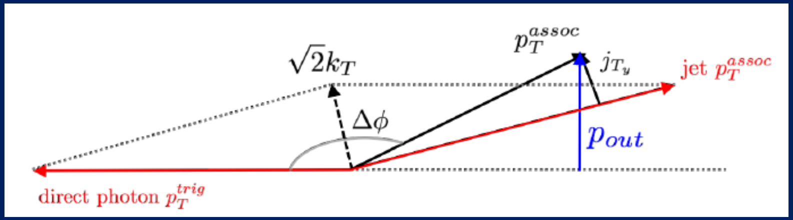
Out-of-plane momentum component distributions

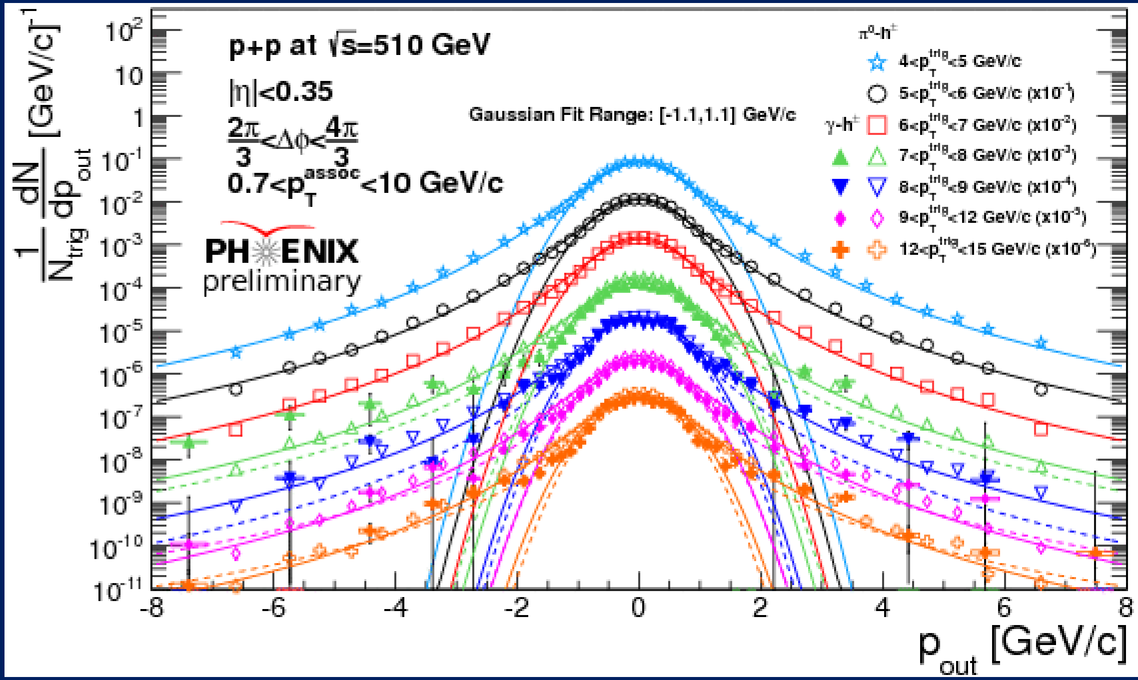




- Out-of-plane momentum distribution for charged hadrons in the away-side peak
- Associated charged hadron p_T from 0.7-10 GeV/c
  - Underlying event (hadrons not associated with jet structure) statistically subtracted
- Different colors for different photon or pion p_T bins, ranging from 4-15 GeV/c
- Open points for pion-hadron correlations
- Filled points for photon-hadron correlations

Out-of-plane momentum component distributions

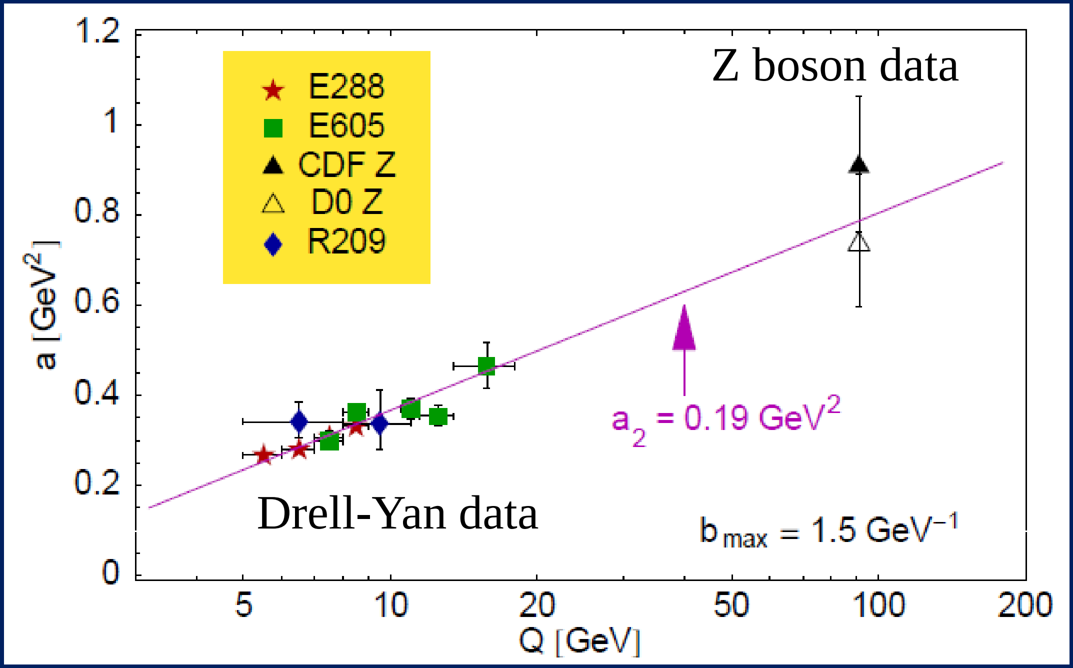




- Clear two-component distribution observed
  - Gaussian around $p_{out} = 0$ → sensitive to nonperturbative transverse momentum
  - Power law tails → due to perturbative gluon radiation
- Curves are fits, not calculations

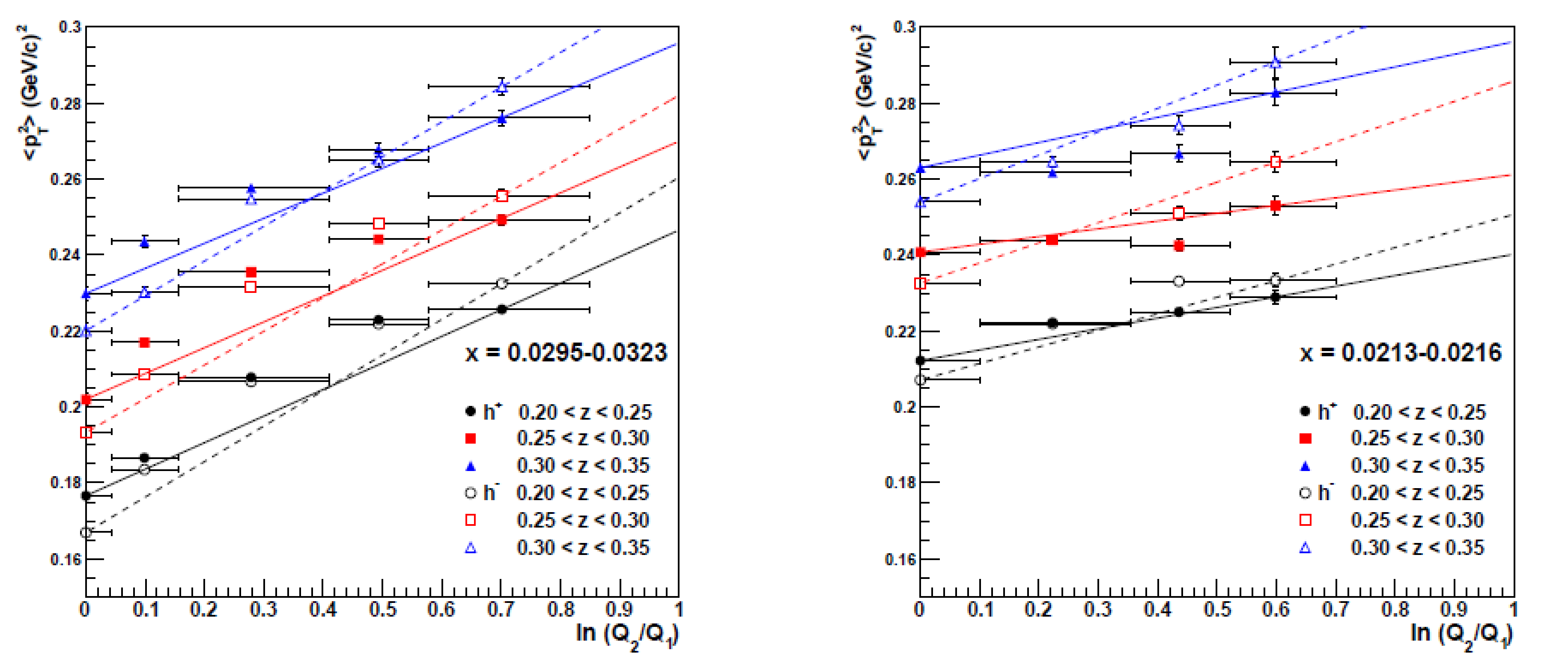
CSS evolution predicts nonperturbative transverse momentum widths increase with Q

- Can be understood intuitively as broadening of phase space for gluon radiation
- Confirmed experimentally



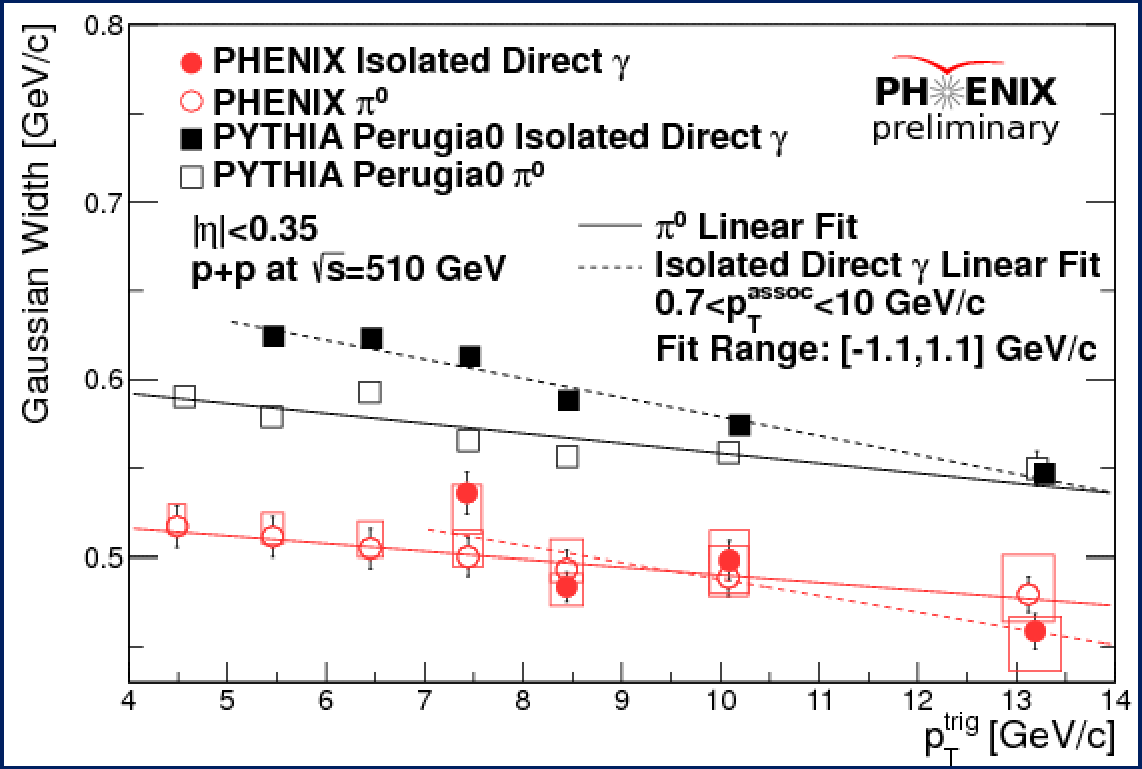
Konychev + Nadolsky, PLB633, 710 (2006)

Broadening with hard scale also confirmed experimentally in SIDIS data



CAA, Field, Gamberg, Rogers, PRD89, 094002 (2014)
Data from COMPASS, EPJ C73, 2531 (2013)

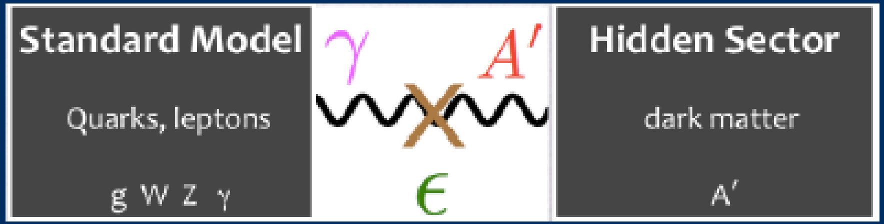
p+p data: Widths <u>decrease</u> as function of hard scale!



- Clear *qualitative* deviation from CSS evolution!
- CS evolution equation comes directly out of derivation of TMD factorization
- Deviation from CSS evolution implies breaking of factorization: *scattering partons correlated across colliding protons*

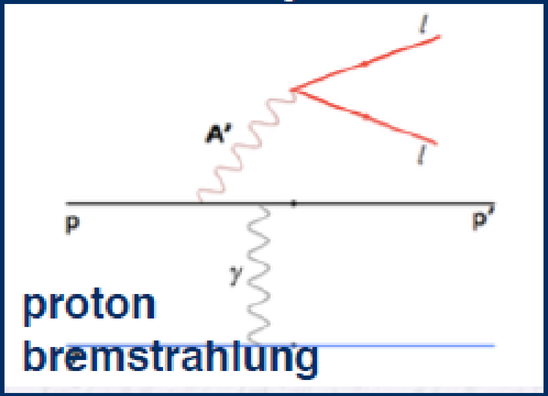
Searching for dark matter at SeaQuest

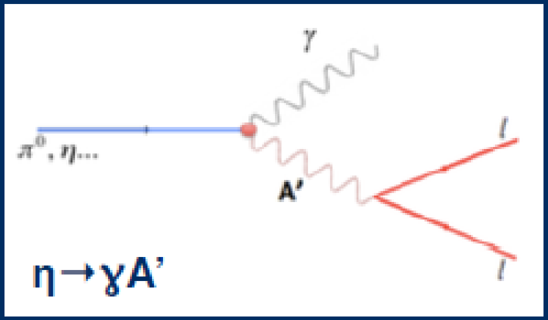
- One hypothesis, a dark photon A' that couples to the real sector with strength ϵ:



- Due to weakness of the interaction, A' travels through the SeaQuest beam dump (5m) and decays to two leptons downstream.

Examples:





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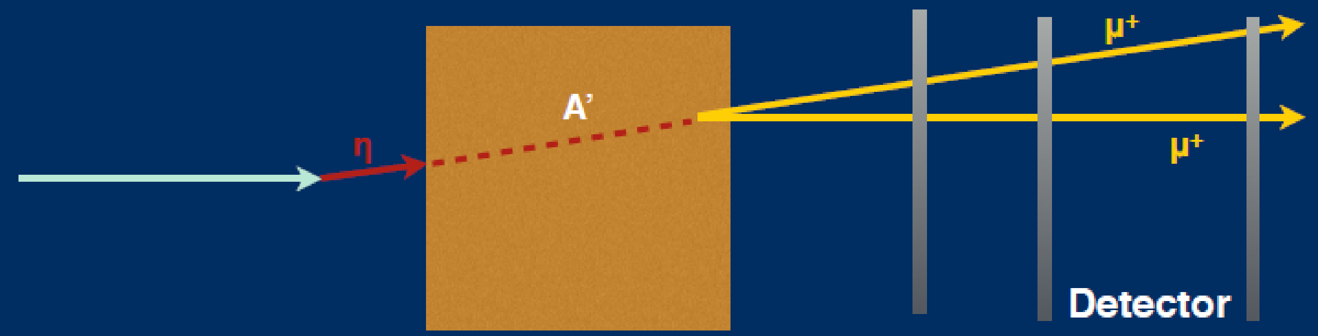
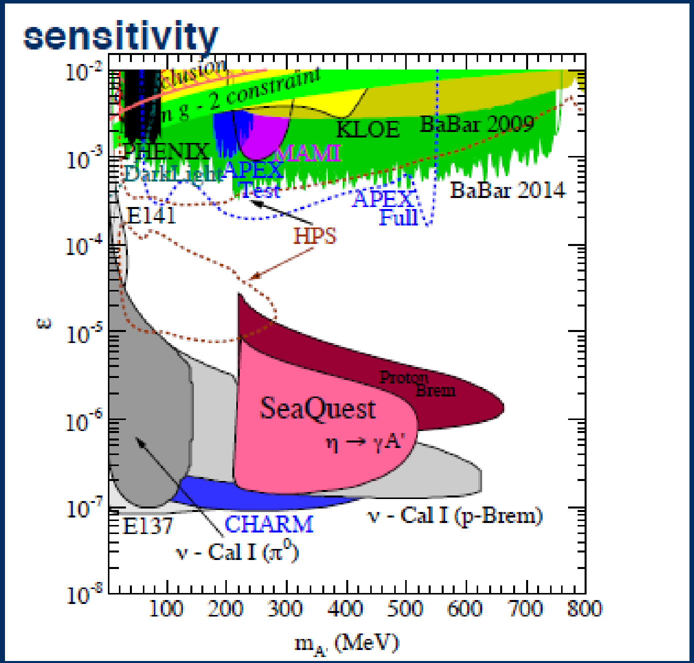
From J.G. Rubin

Searching for dark matter at SeaQuest



- Analysis details being studied
- Trigger already contains ≈63% of possible dark photon acceptance. More can be added in exchange for background rate.



From J.G. Rubin