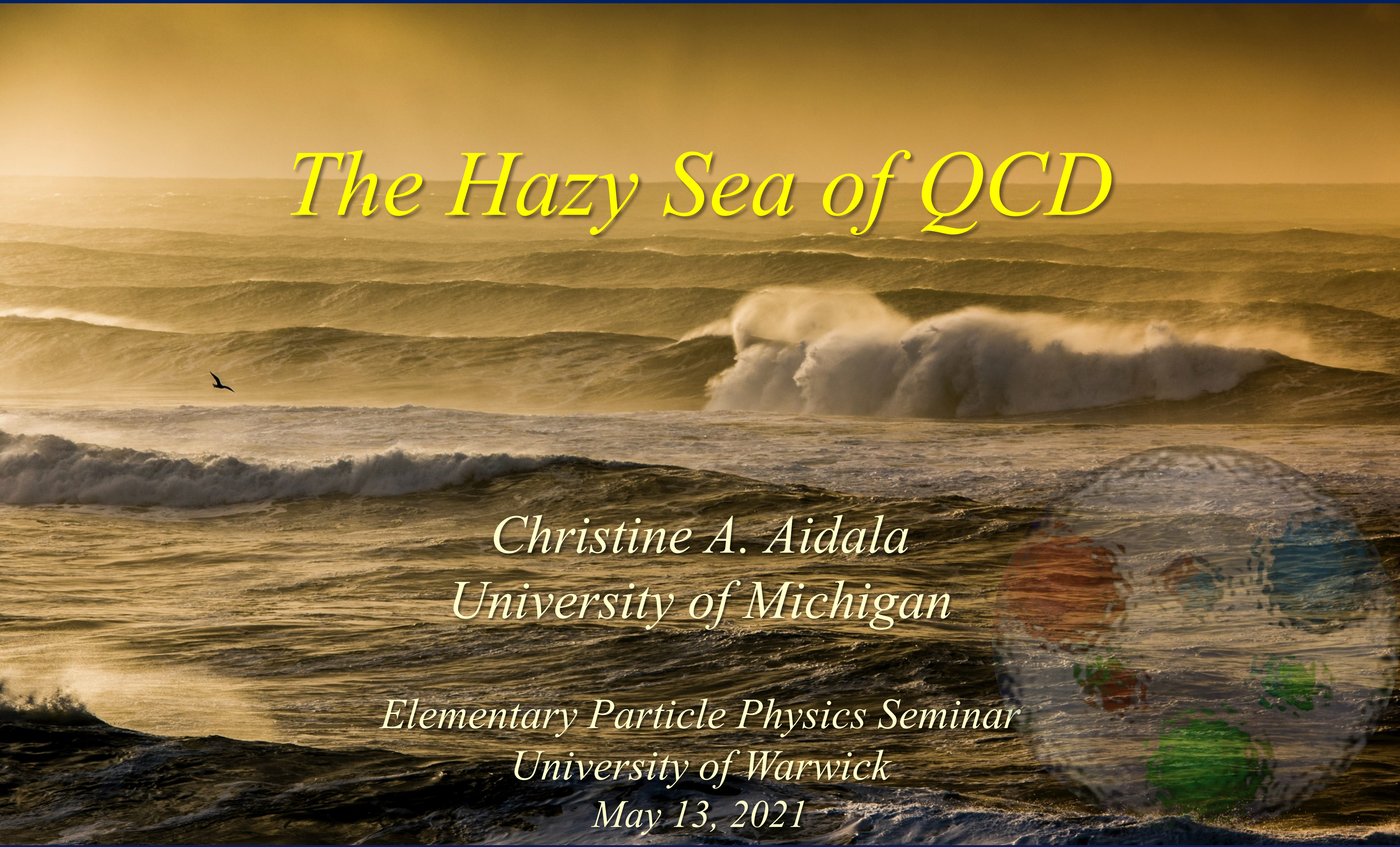


The Hazy Sea of QCD

Christine A. Aidala

University of Michigan

Elementary Particle Physics Seminar

University of Warwick

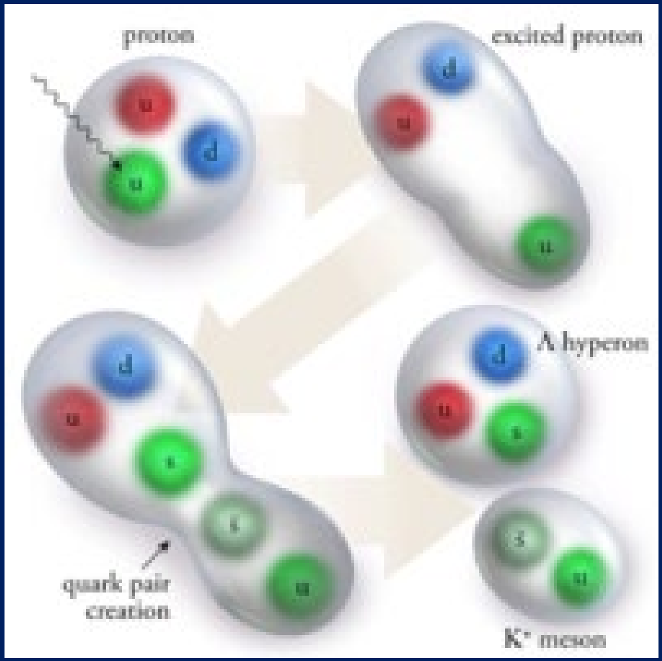
May 13, 2021

Photo by Payton Bissell on Unsplash

Quantum Chromodynamics: Theory of strong interactions

- Fundamental field theory in hand since the early 1970s—BUT . . .
- Quark and gluon degrees of freedom in the theory cannot be observed or manipulated directly in experiment!

Color *confinement*—quarks and gluons are confined to color-neutral bound states



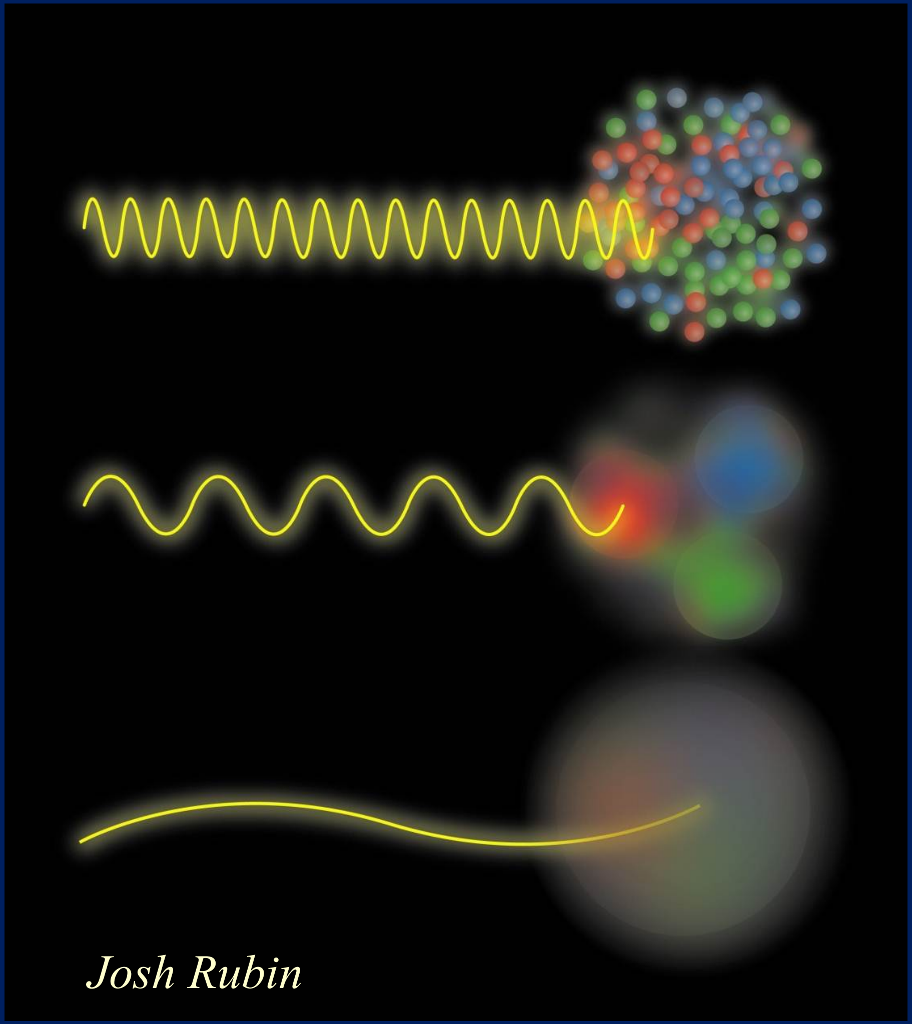
CLAS Collaboration
PRL 113, 152004 (2014)

How do we understand the visible matter in our universe in terms of the quark and gluon degrees of freedom of quantum chromodynamics?

How can studying QCD systems teach us more about fundamental aspects of QCD as a theory?

The proton as a "laboratory" for studying QCD

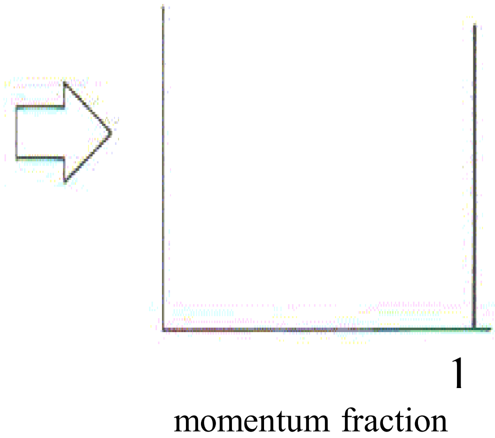
- Proton: simplest stable QCD bound state
- Different energy scales offer information on different aspects of proton internal structure



Parton distribution functions inside the proton: The language we've developed (so far!)

What momentum fraction would the scattering particle carry if the proton were made of …

A point-like particle



Halzen and Martin, "Quarks and Leptons", p. 201

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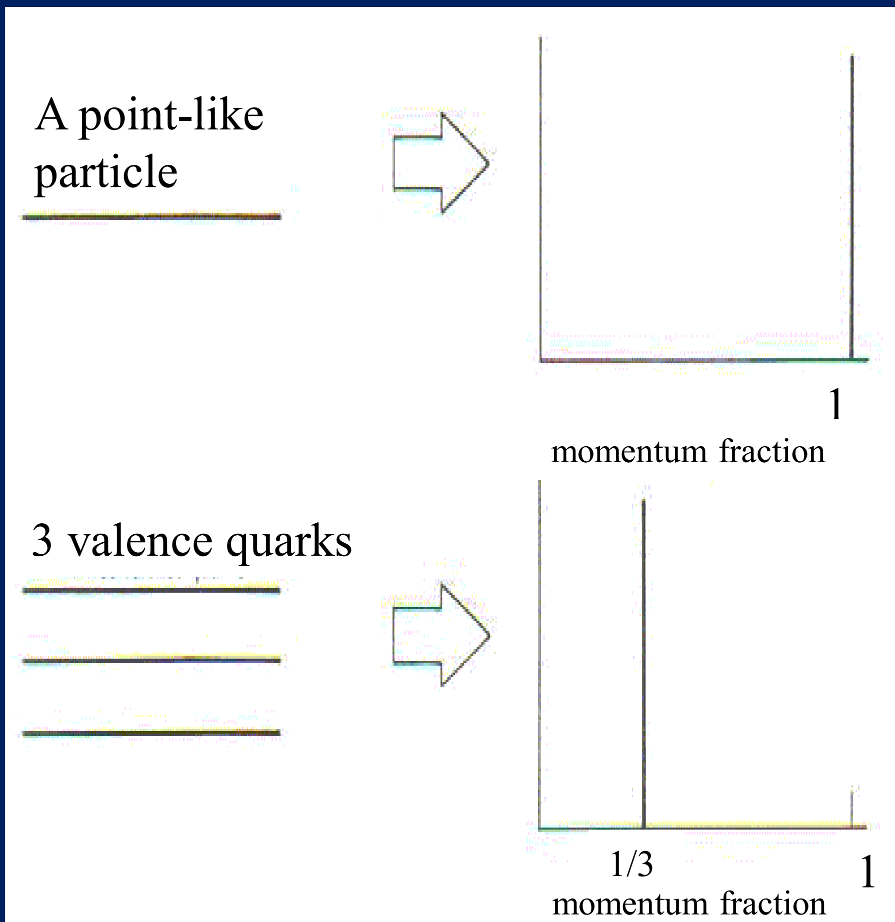

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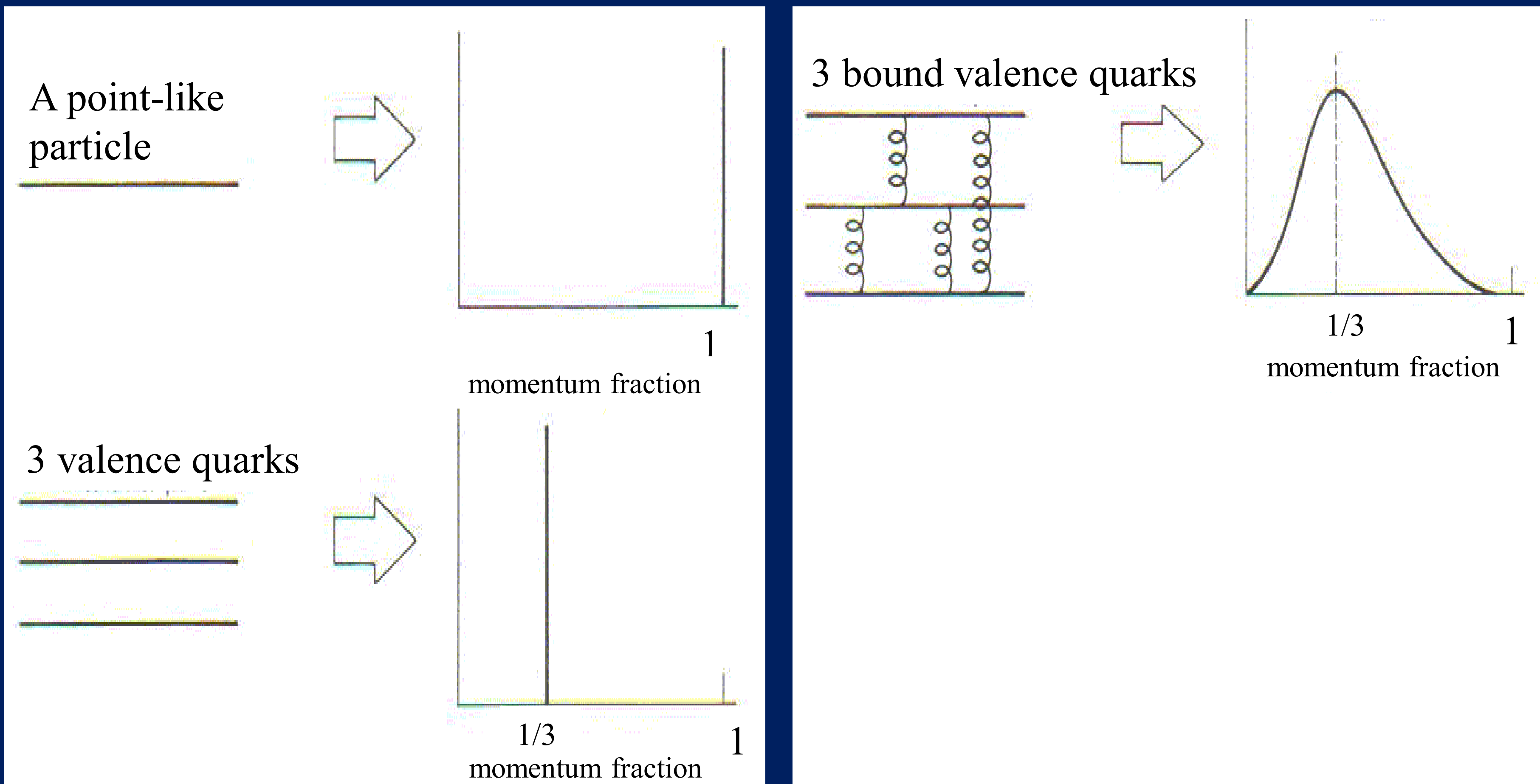

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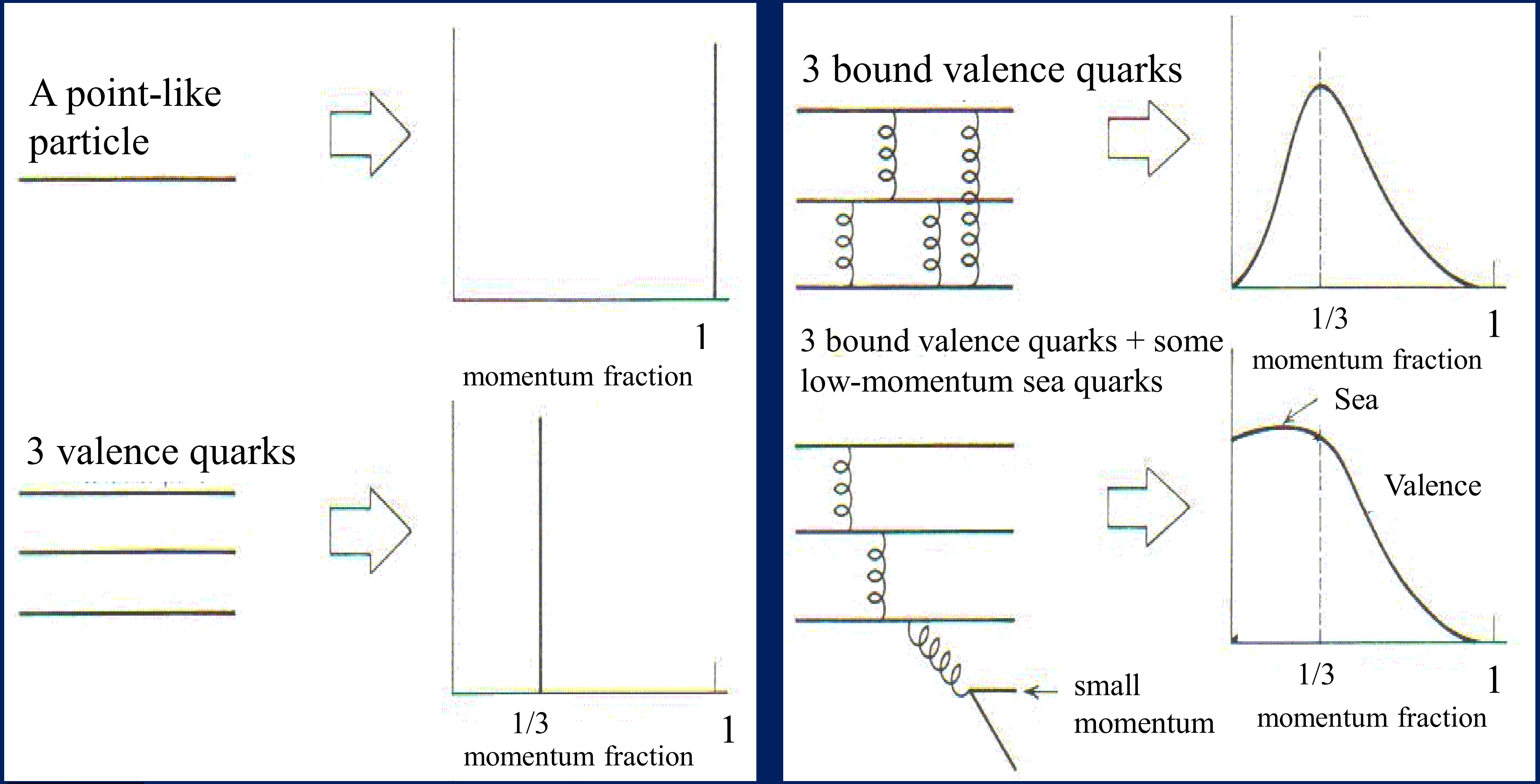
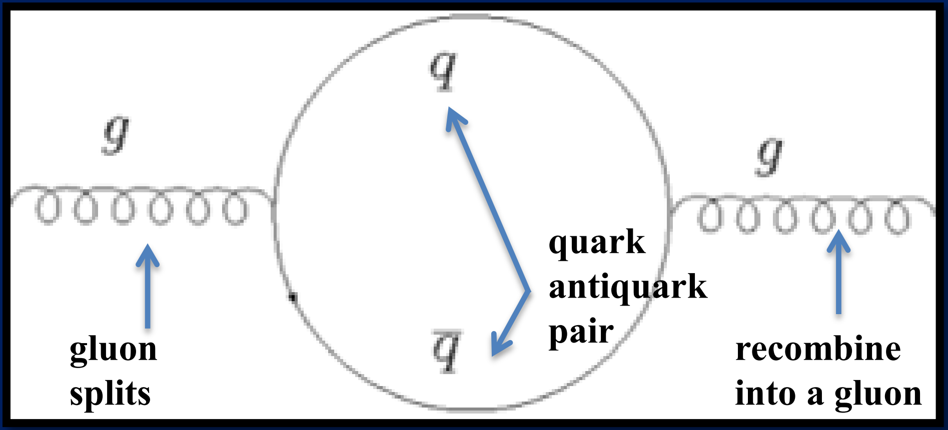


Halzen and Martin, "Quarks and Leptons", p. 201

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)

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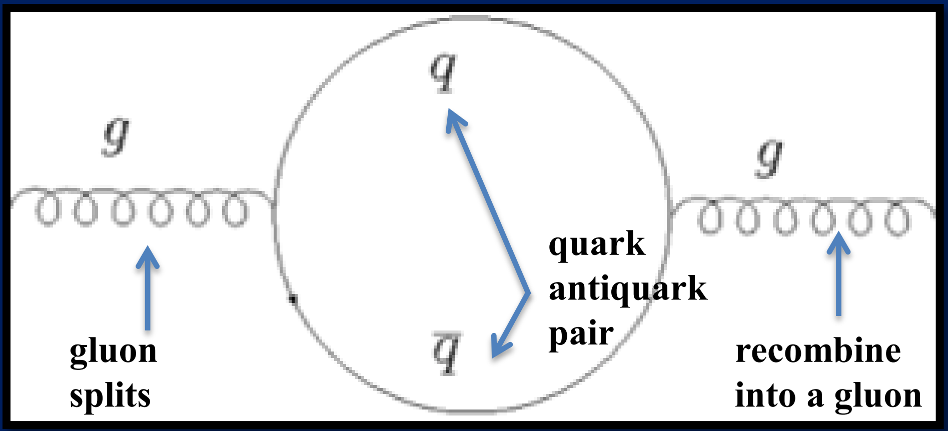


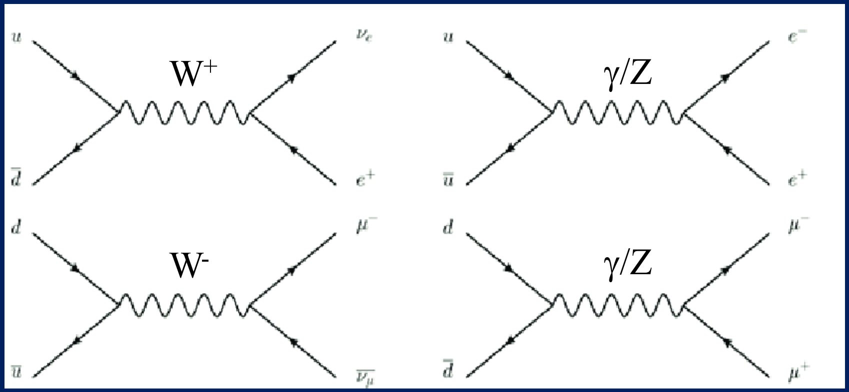
- Perturbative calculation differences between u and d are very small!
  - D. A. Ross and C. T. Sachrajda, Nucl. Phys. B149, 497 (1979)

But experiments have shown that the nucleon sea is not that simple!

Accessing sea quarks

In proton-proton collisions

- Drell-Yan process of quark-antiquark annihilation to dileptons
- W boson production



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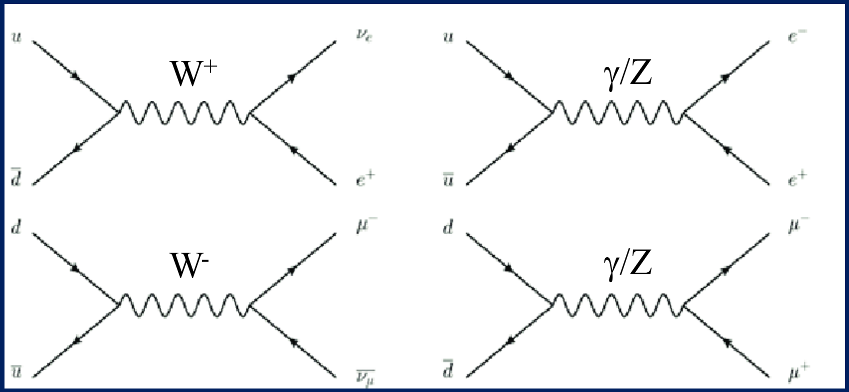
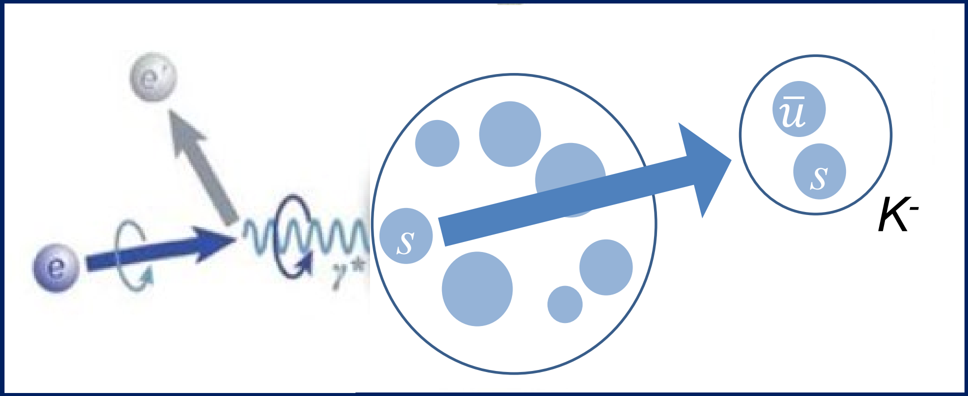
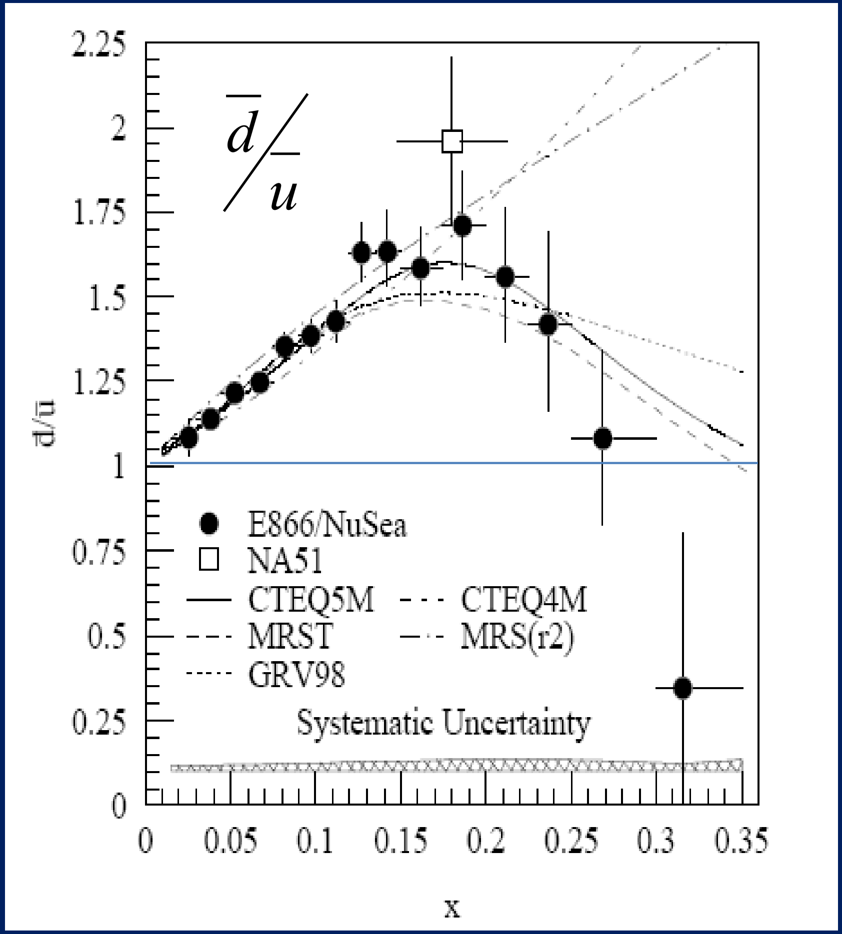


In lepton-proton collisions

- Semi-inclusive deep-inelastic scattering (DIS) with identified hadrons
  - Statistically enhance sensitivity to sea quarks by selecting certain hadrons, e.g. kaons to access strange quarks



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

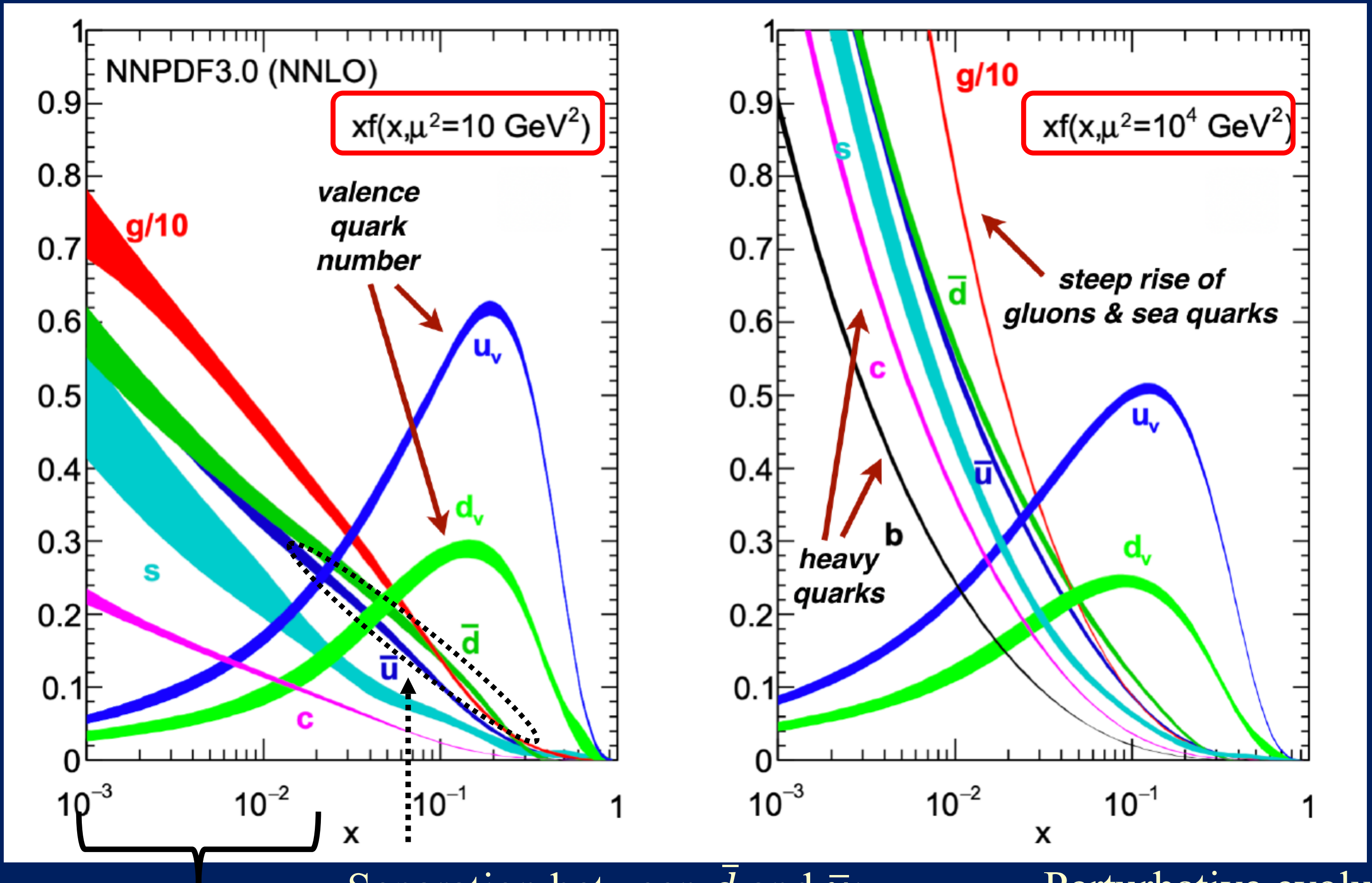


Fermilab E866 data: PRD64, 052002 (2001)
CERN NA51 data: PLB332, 244 (1994)

- Ratio deviates 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

Parton distribution function fits

J. Rojo, arXiv:1910.03408

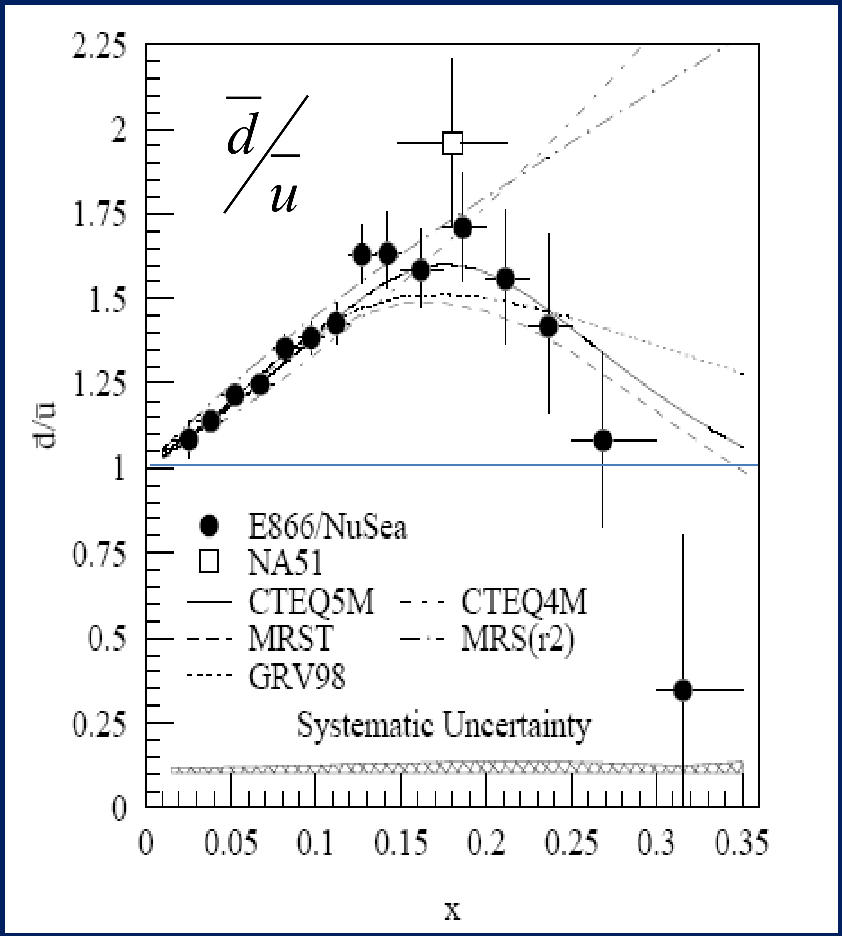


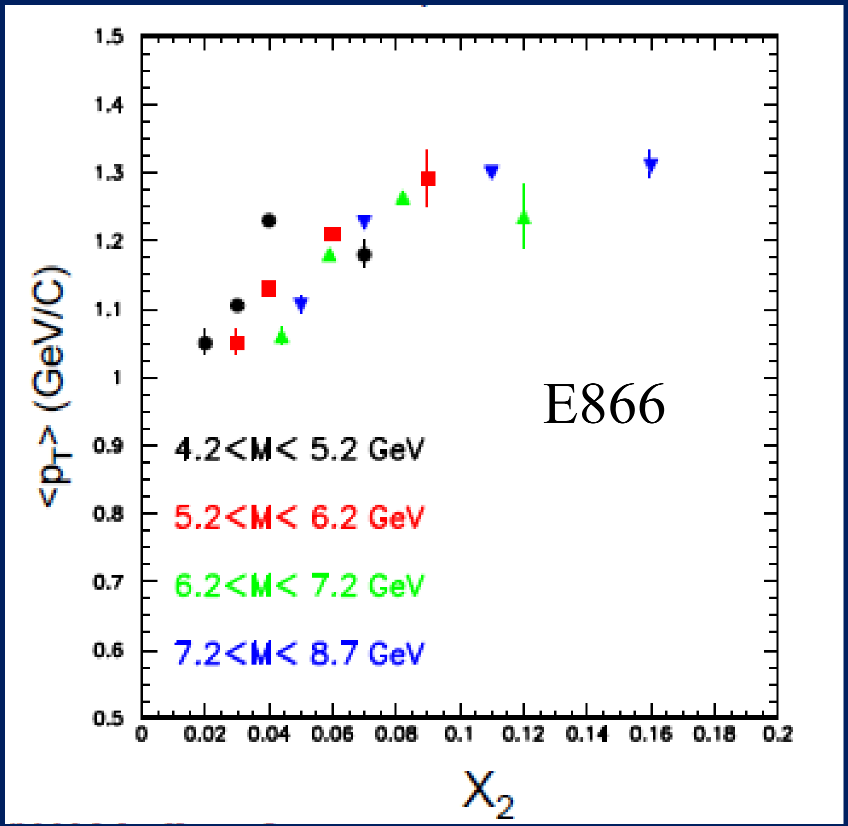
Perturbative sea

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

Perturbative evolution to other energy scales

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

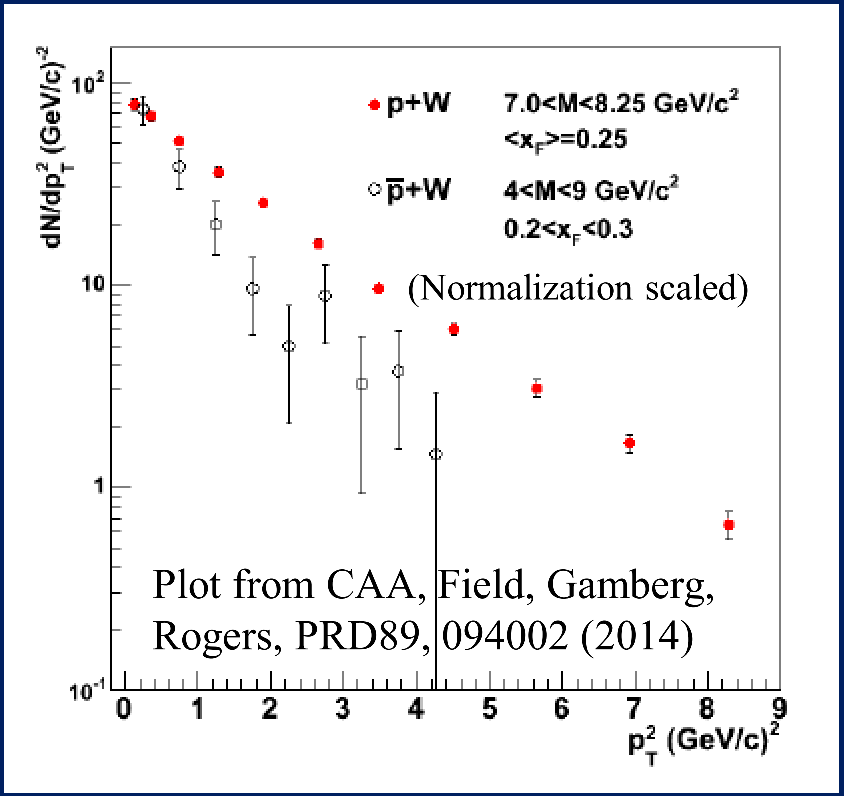




Fermilab E866 data: PRD64, 052002 (2001)
CERN NA51 data: PLB332, 244 (1994)

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

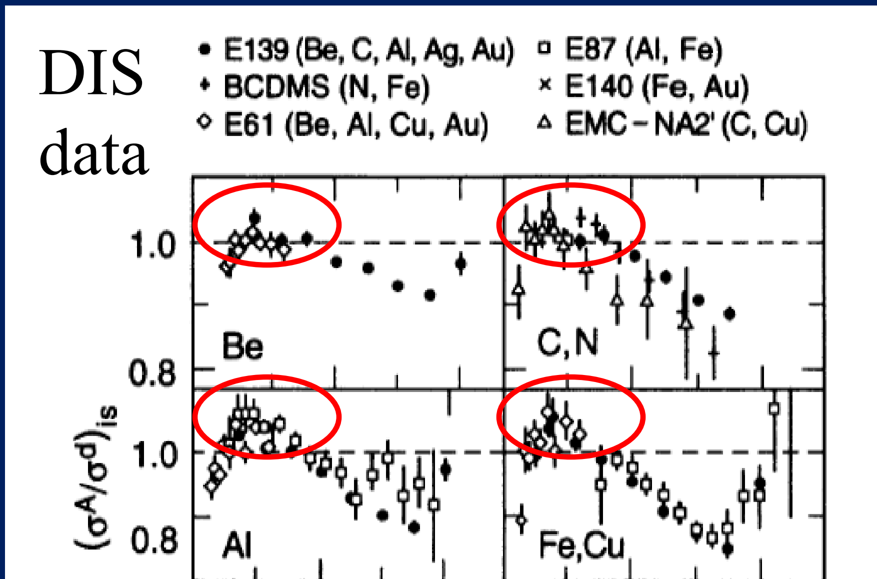
Dynamics: Transverse momentum of valence vs. sea quarks

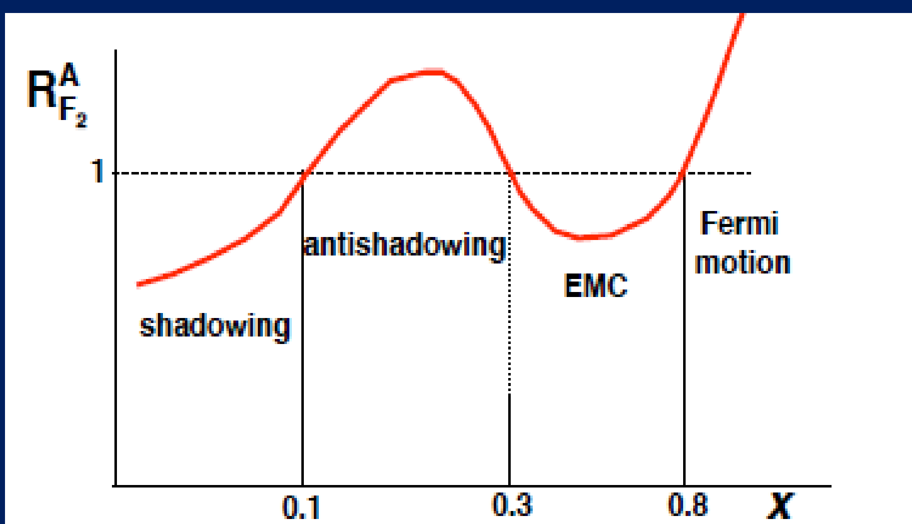


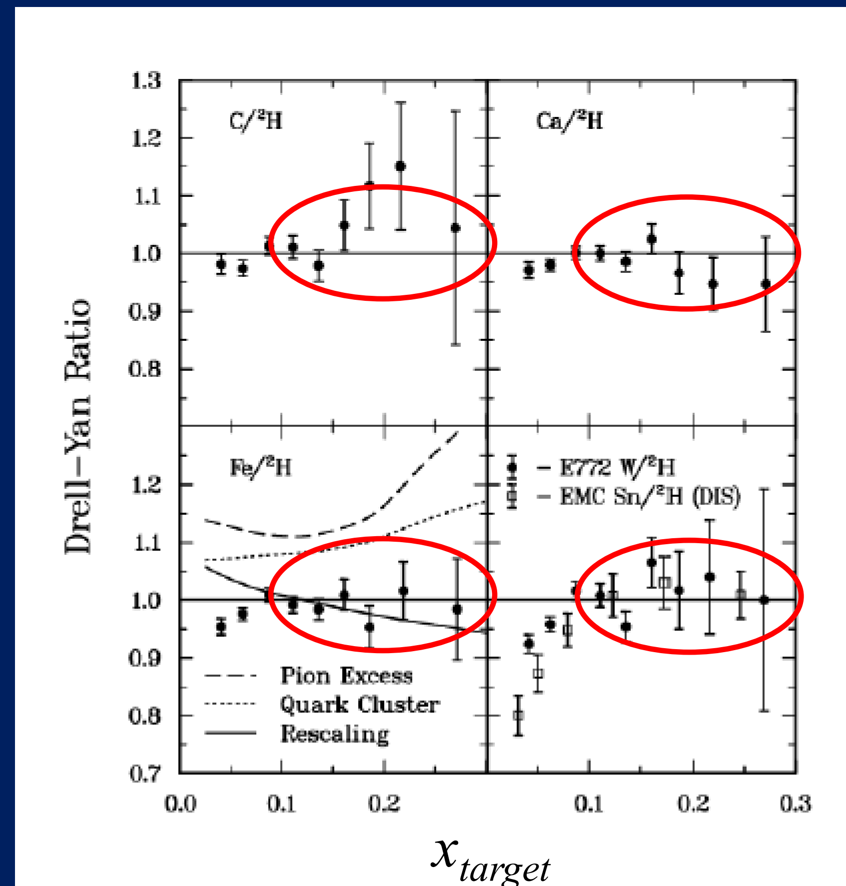
Data from E537 (pbar+W): PRD38, 1377 (1988)
E439: (p+W): AIP Conf. Proc. 45, 93 (1978)

- p+W: (Valence) quark from p, (sea) antiquark from W
- pbar+W: (Valence) quark from W, (valence) antiquark from pbar
- (Valence × 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







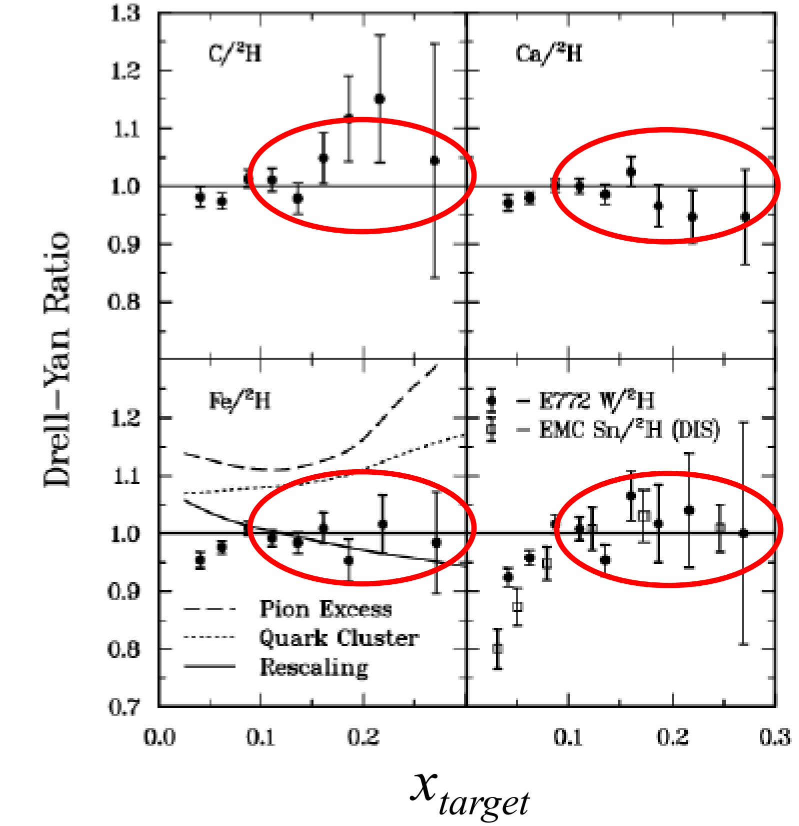
Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

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??



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

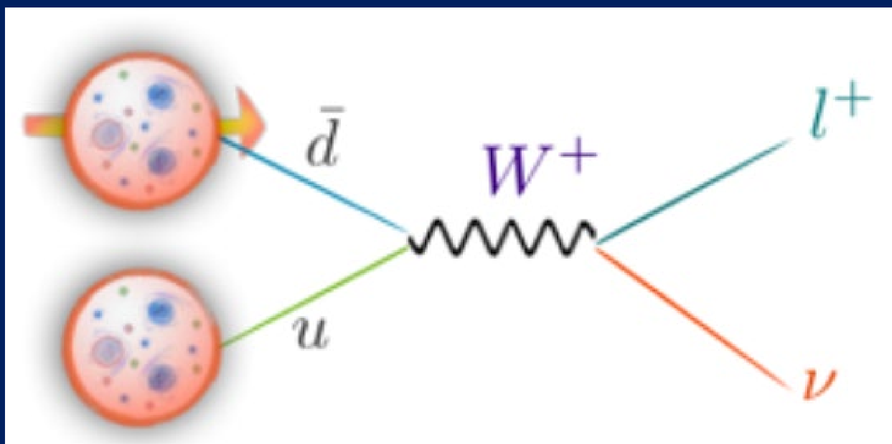
No clear "antishadowing" in Drell-Yan

Sea quark spin-spin correlations (helicity distributions)

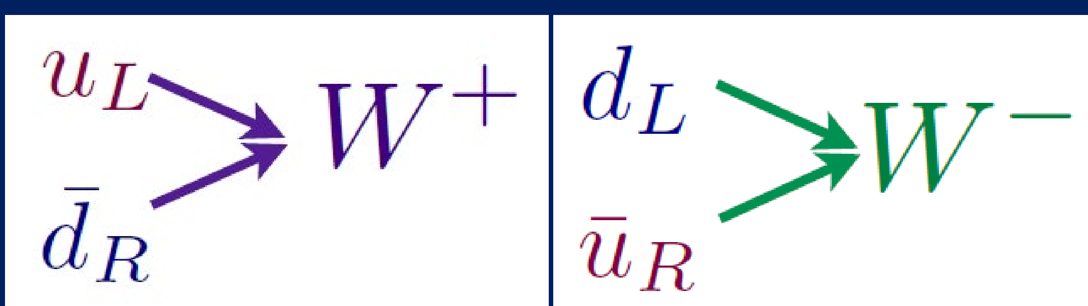
$\Delta q(x), \Delta\bar{q}(x)$

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

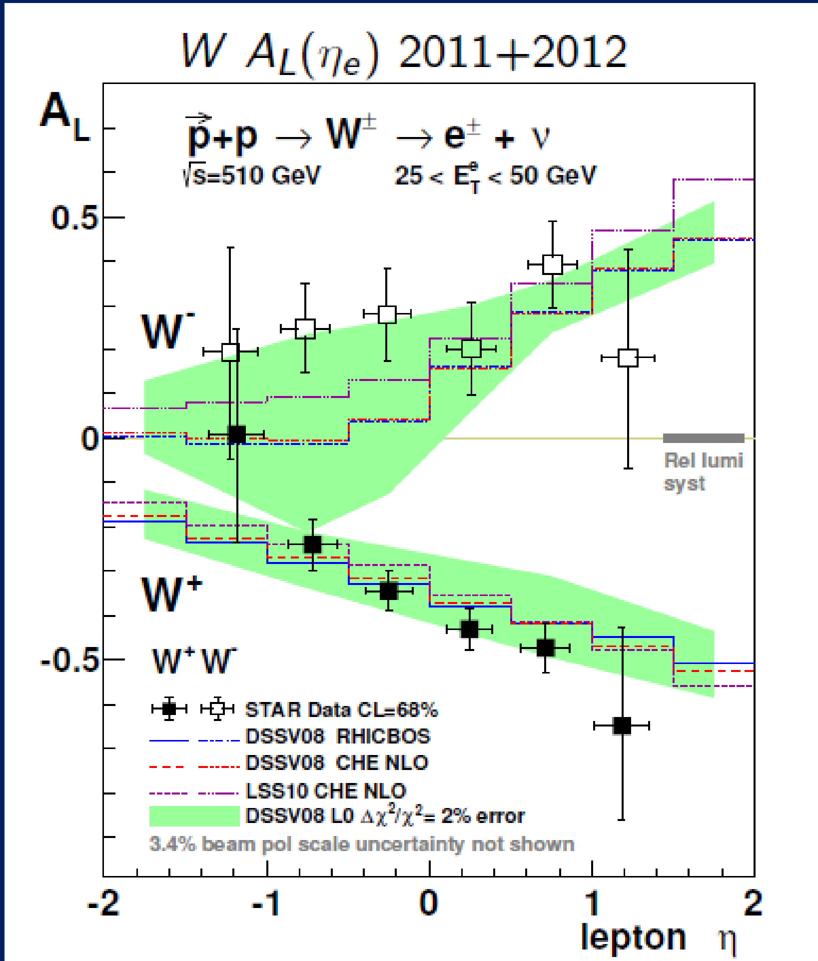
$$A_L^{W^-} \approx -\frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) - \bar{u}(x_1)d(x_2)}$$



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



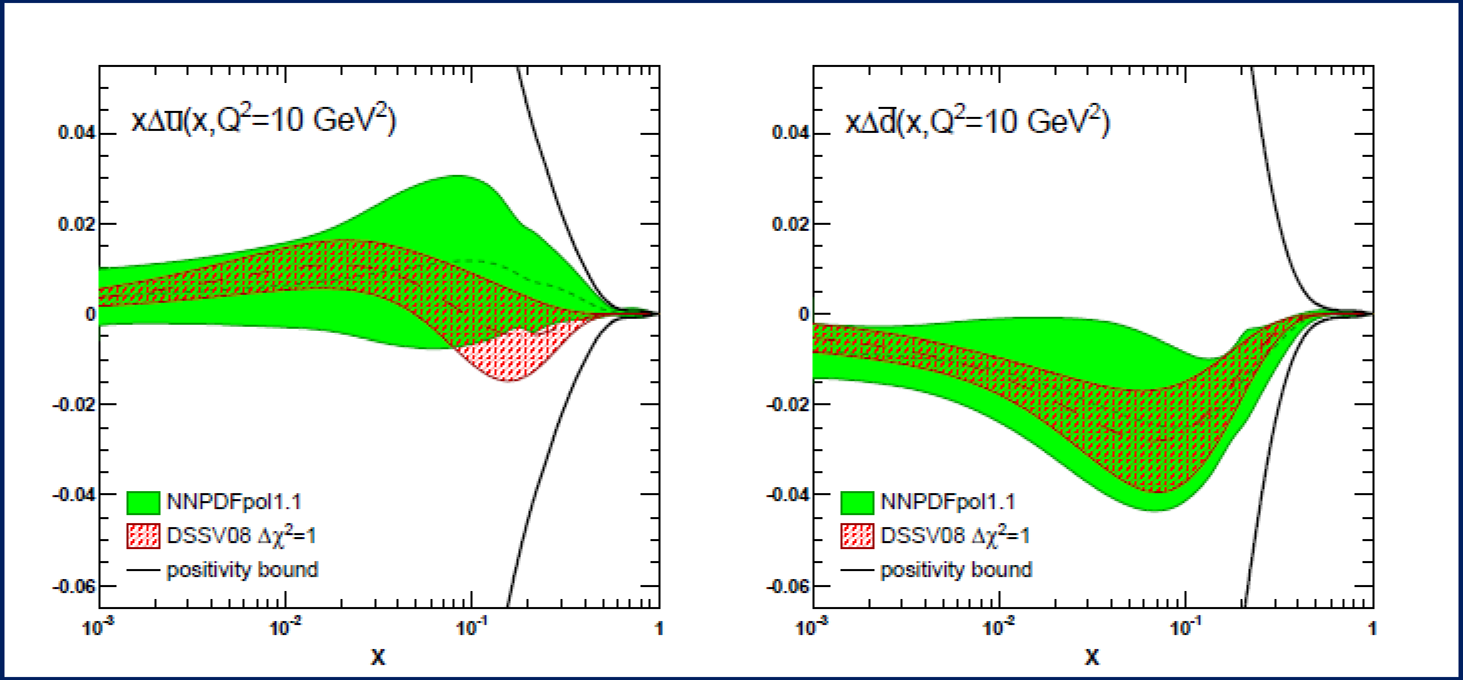
PRL 113, 072301 (2014)

- Improve constraints on light antiquark helicity distributions

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

And suggest 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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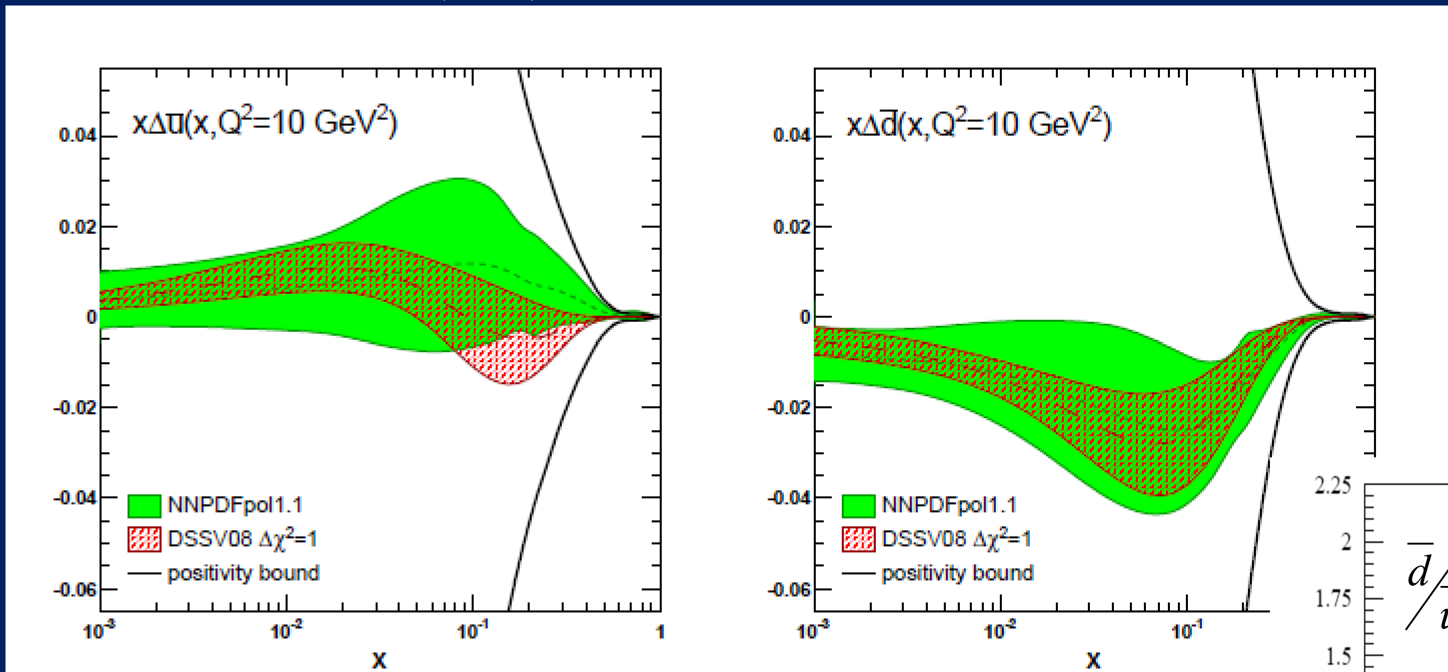

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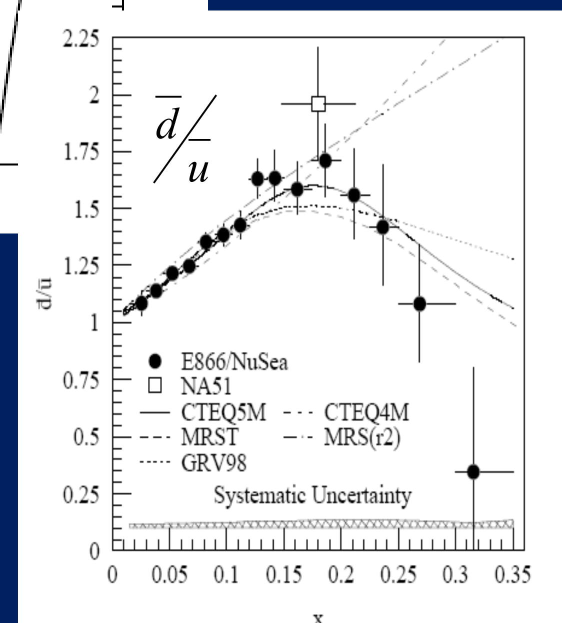
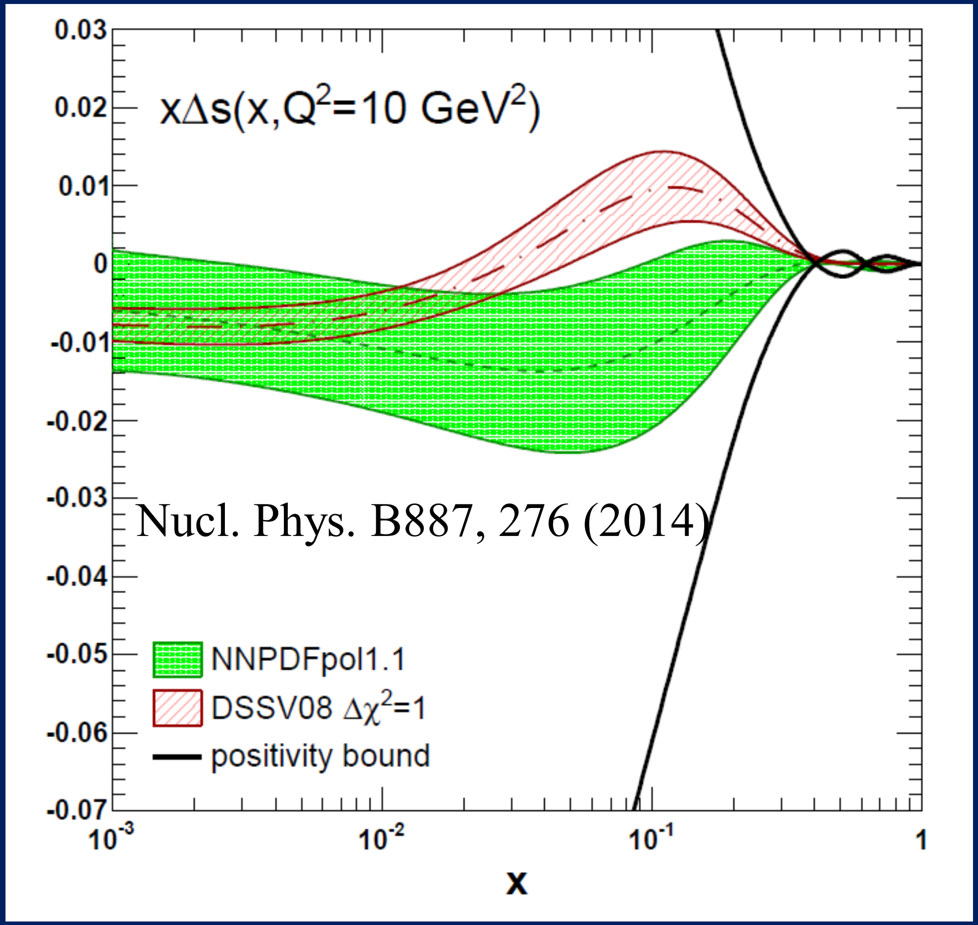


Shouldn't be surprising given flavor asymmetry in unpolarized sea? Or unrelated??

Strangeness helicity distribution from inclusive vs. semi-inclusive DIS

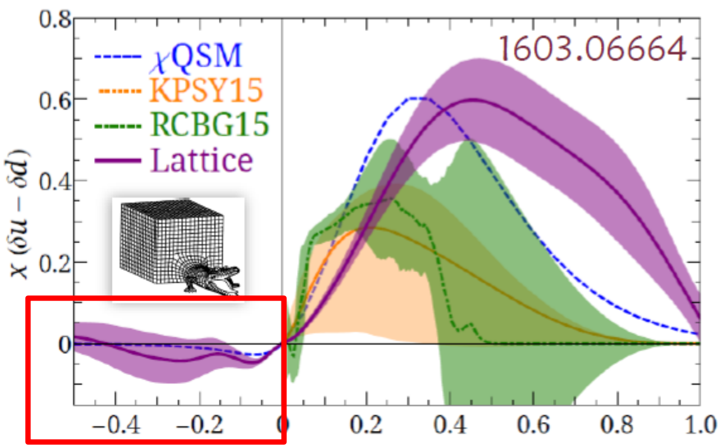
- NNPDF fit an indirect extraction of strangeness using only inclusive DIS
- DSSV includes semi-inclusive DIS kaon data
- Is the strange sea polarized, and if so, with or against the proton??
  - Need more data!



Theory: Transverse spin-spin correlations 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, …

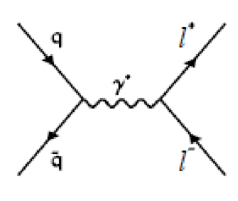
MICHIGAN STATE UNIVERSITY

Huey-Wen Lin — The Flavor Structure of Nucleon Sea

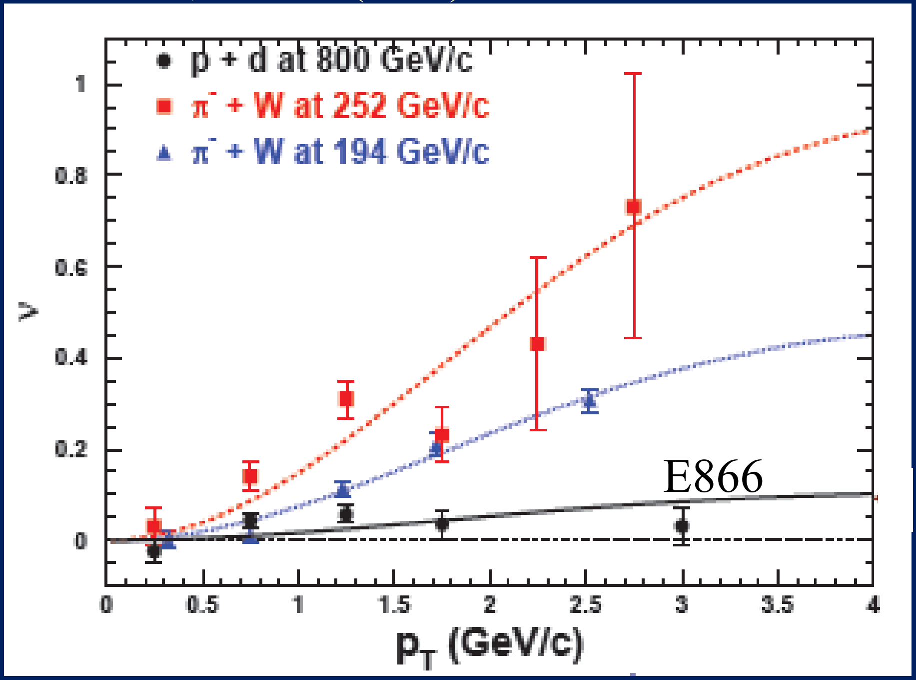
Slide from Huey-Wen Lin, INT Workshop Oct 2017

Lattice calculation agrees with chiral quark-soliton model calculation

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



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



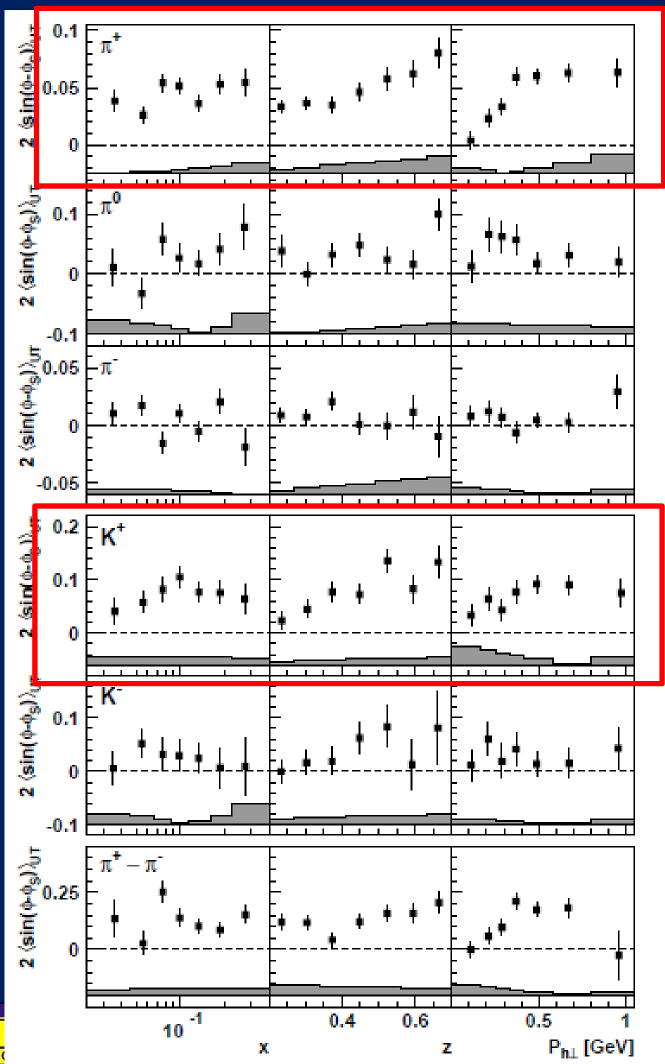
Boer - Mulders function $h_1^{\perp}$

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

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

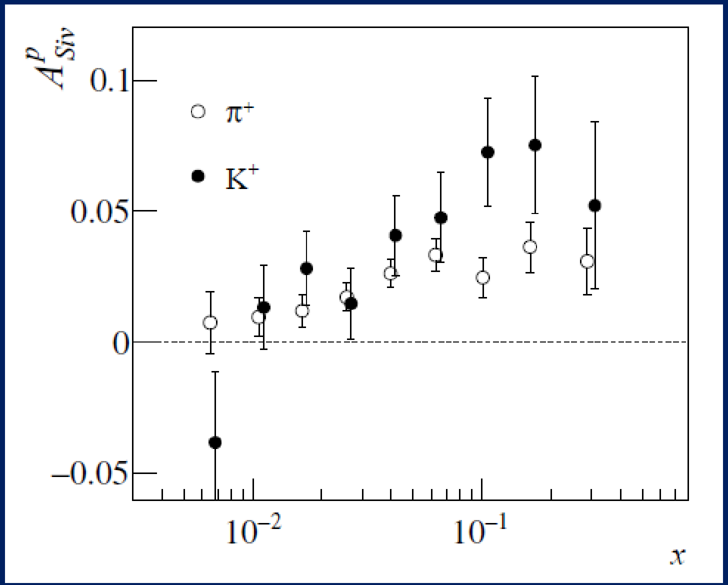
- Significantly reduced cos2ϕ dependence in *proton*-induced Drell-Yan compared to *pion*-induced Drell-Yan
- Suggests this spin-orbit correlation for sea quarks is small?
  - Boer-Mulders transverse-momentum-dependent PDF: describes correlation between orbital motion of quark and the quark's own transverse spin, in an unpolarized hadron

Spin-orbit coupling for sea quarks in ***transversely 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??



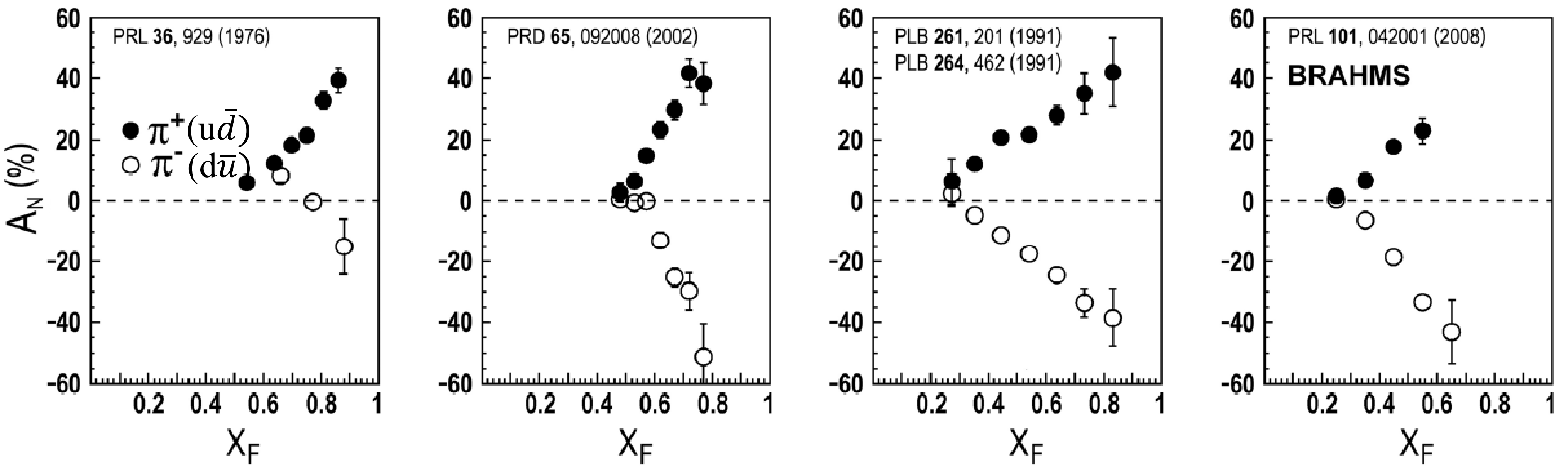
COMPASS, PLB744, 250 (2015)

HERMES, PRL103, 152002 (2009)

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

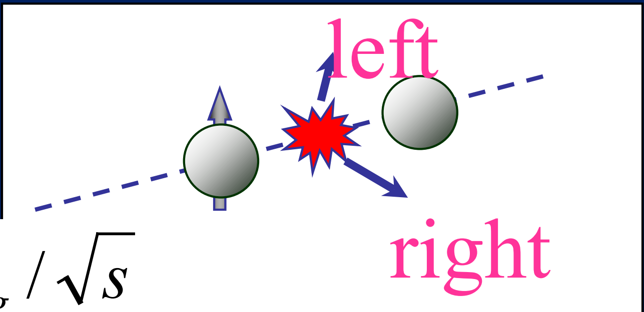
Huge spin-momentum correlations observed in hadronic collisions involving transversely polarized protons

ANL	BNL	FNAL	RHIC
$\sqrt{s}$=4.9 GeV	$\sqrt{s}$=6.6 GeV	$\sqrt{s}$=19.4 GeV	$\sqrt{s}$=62.4 GeV



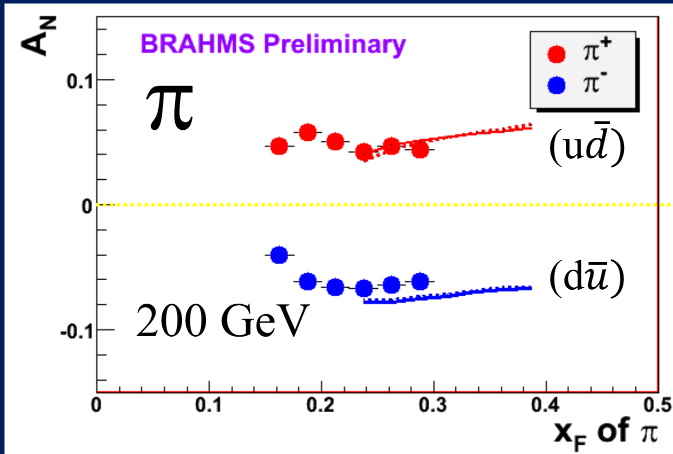
CAA, Bass, Hasch, Mallot, Rev. Mod. Phys. 85, 655 (2013)

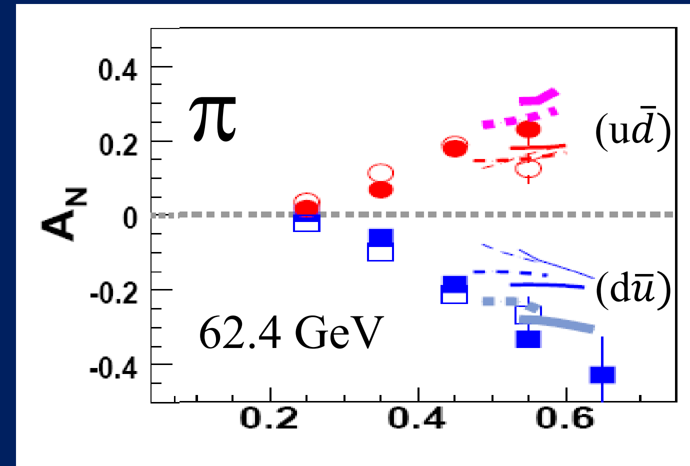
Large asymmetries for more forward pion production with respect to polarized beam and opposite sign for π^+ and π^- suggest valence quark effect with opposite sign spin-momentum correlation for u vs. d



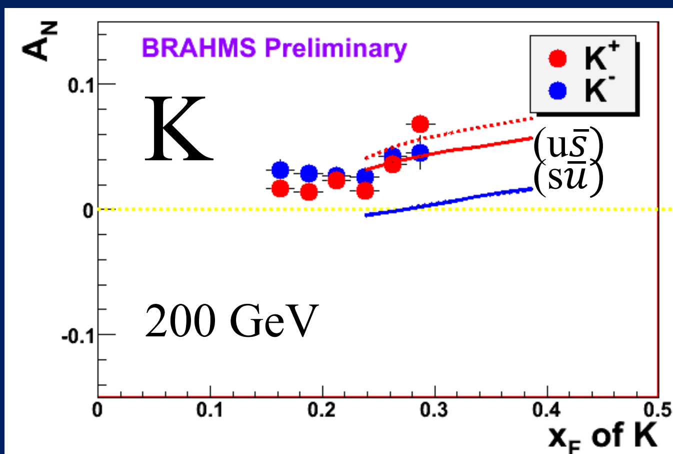
$$x_F = 2p_{long}/\sqrt{s}$$

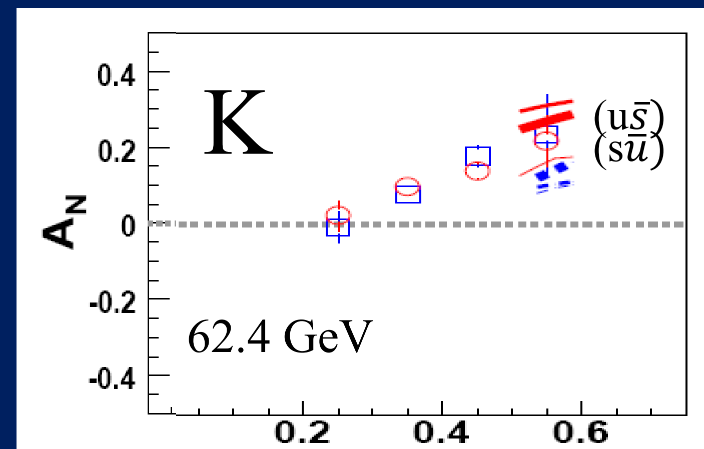
π, K, p at 200 and 62.4 GeV



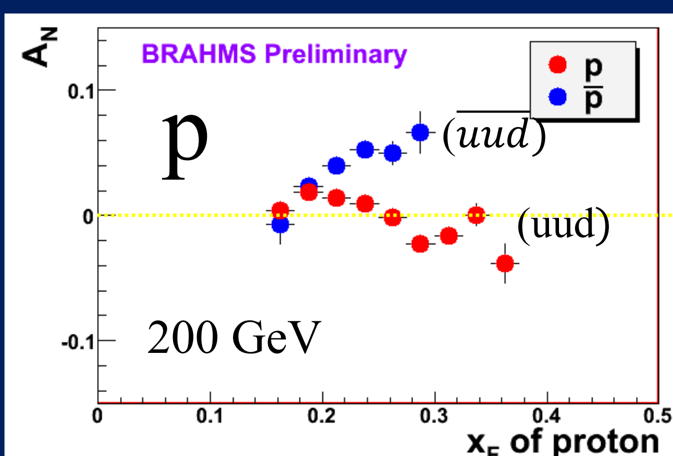


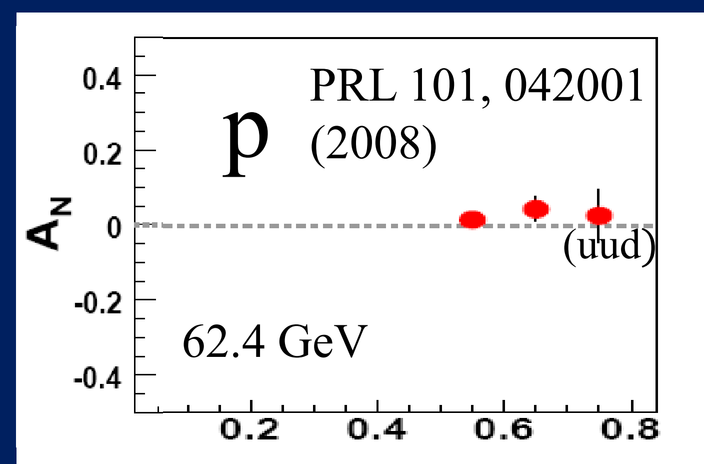
Note different scales →



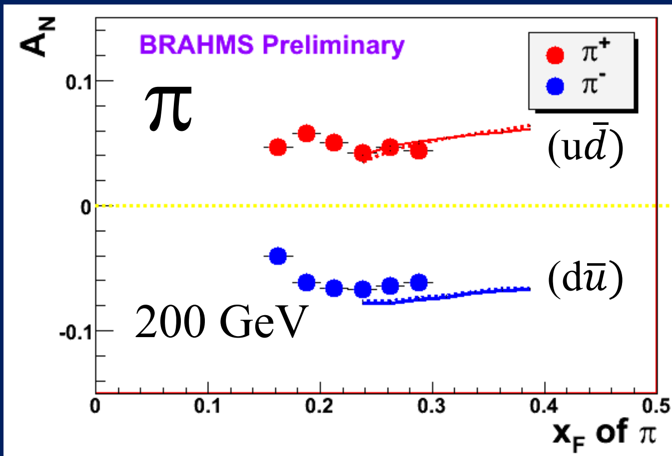


K^- $(\bar{u}s)$ asymmetries same as K^+ $(u\bar{s})$





Large antiproton asymmetry?? Unfortunately no 62.4 GeV measurement



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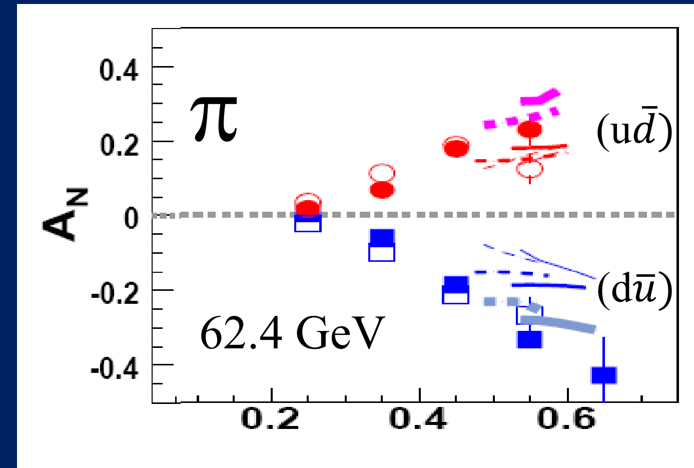

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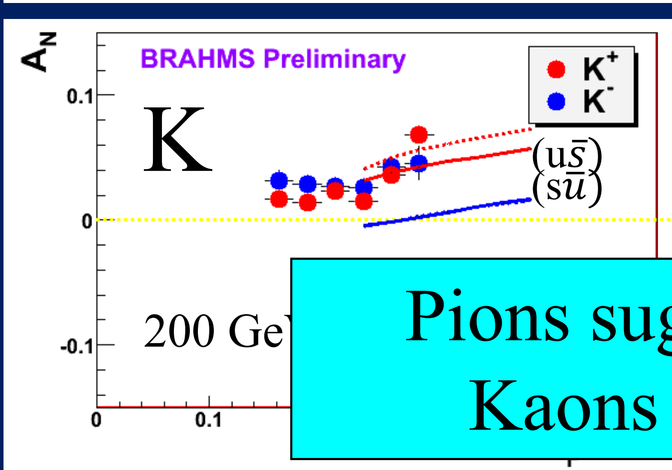

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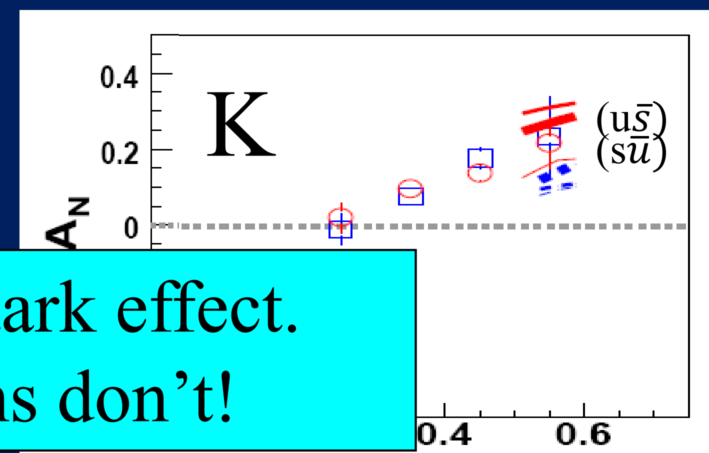
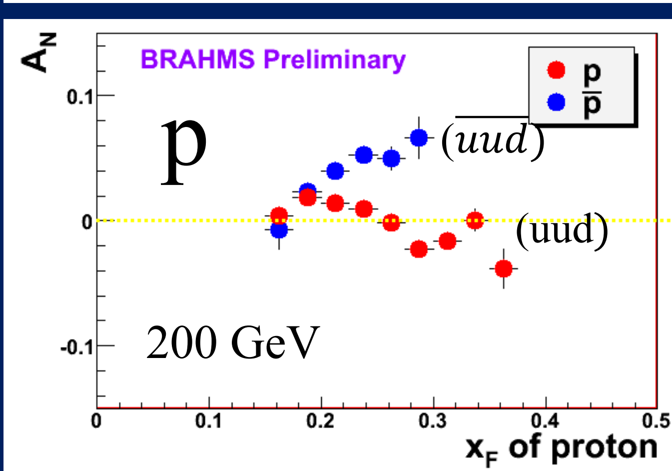


Pions suggest valence quark effect. Kaons and (anti)protons don't!



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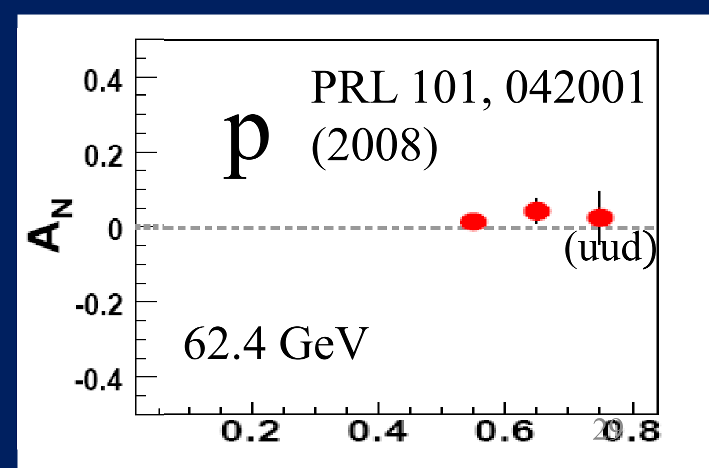
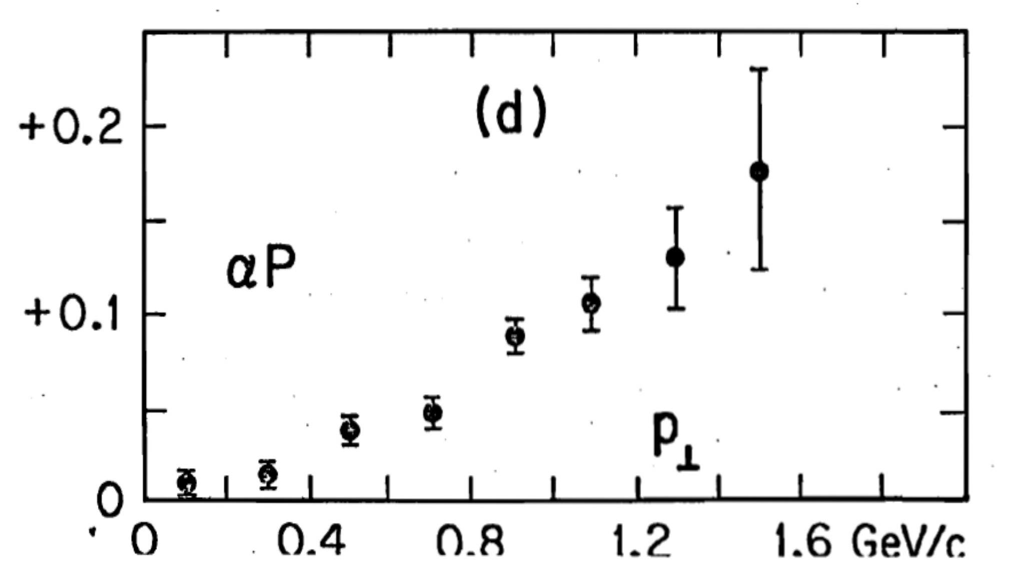


Hyperon polarization from unpolarized collisions

(uds)

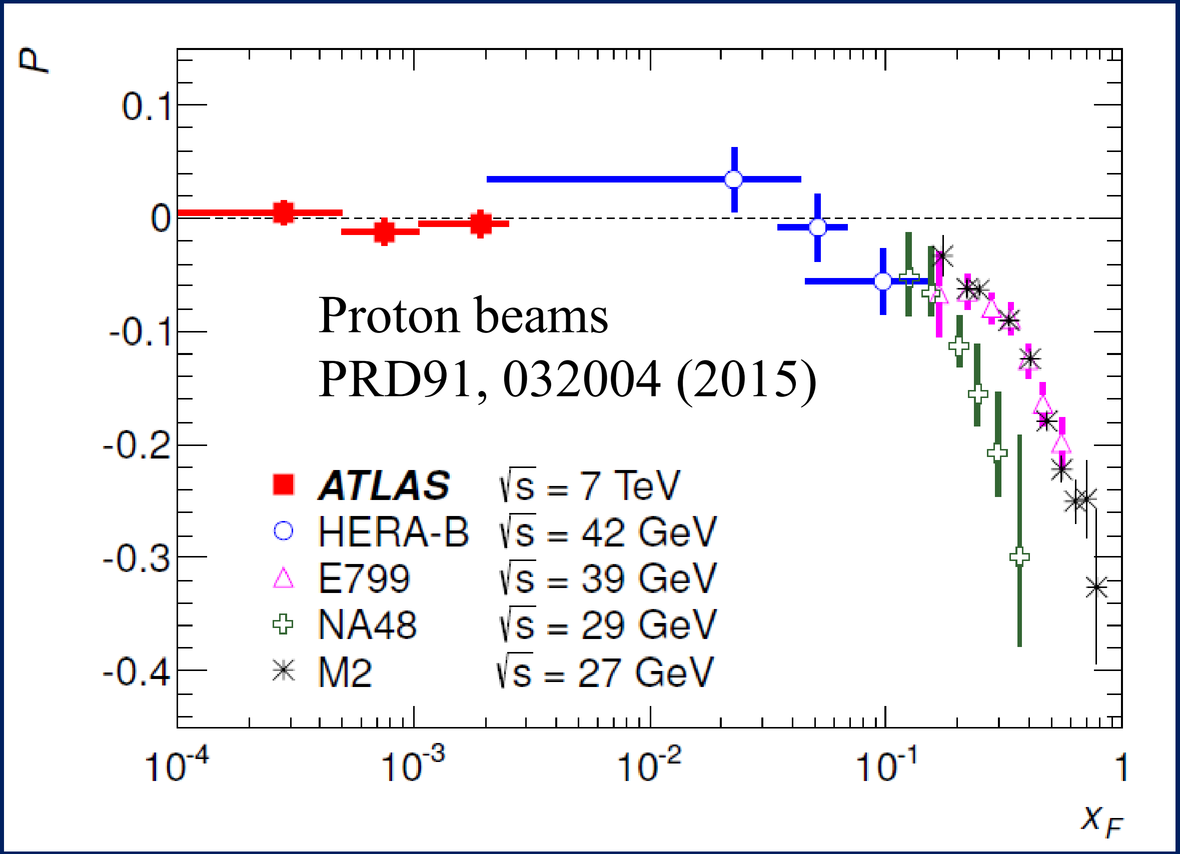
Λ^{0} Hyperon Polarization in Inclusive Production by 300 GeV Protons on Beryllium

PRL36, 1113 (1976)



- 1976 lambda polarization discovery: p+Be, 300 GeV beam
- Polarization transverse to production plane up to ~20% for forward-angle lambda production
- Confirmed 1977 at CERN, p+Pt, 24 GeV beam (and by various proton-nucleus and proton-proton experiments afterwards . . .)

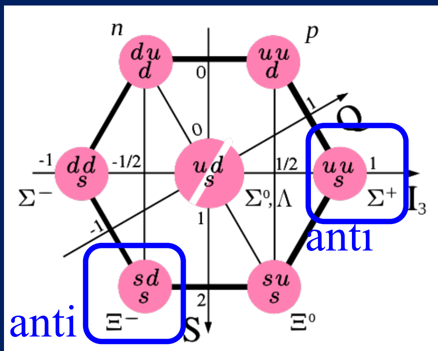
Observed for forward lambda production: large Feynman-x (x_F)

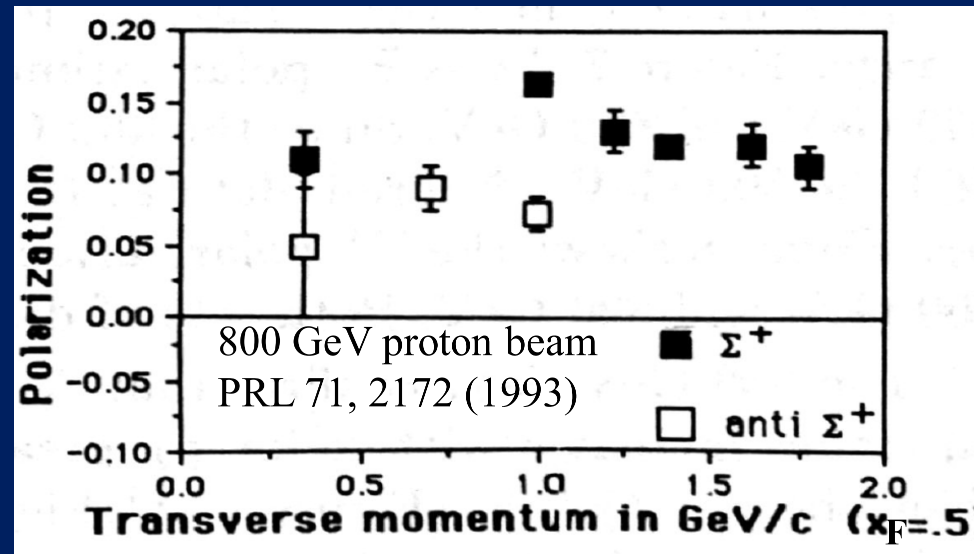


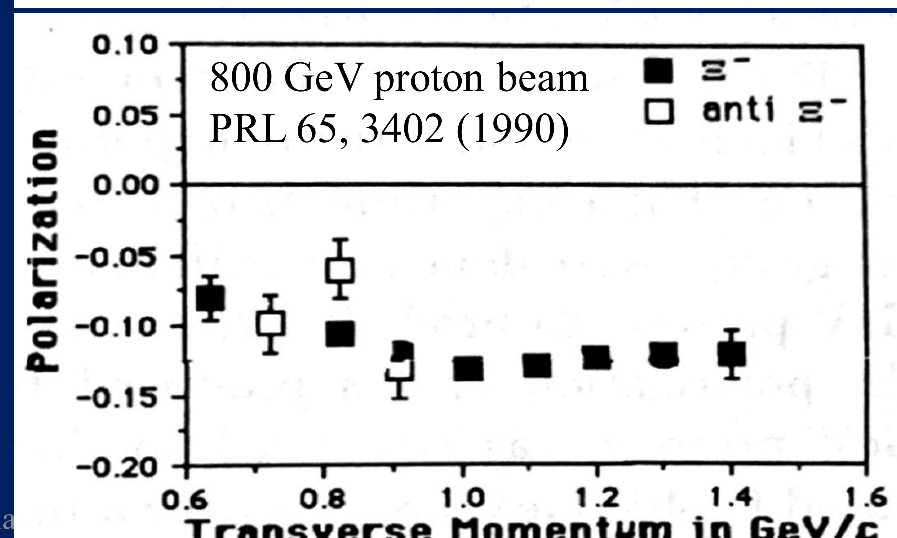
$$x_F = \frac{p_L}{|\max p_L|} \text{ in c.m. frame}$$

Note that sign convention is reversed from original discovery on previous slide!

But also some polarized antibaryons from (unpolarized) proton beams!







No valence quarks in produced baryons same as valence quarks in proton beam, but polarization still observed for particles produced in the more forward region

K. Heller, Proceedings, 12th International Symposium on Spin Physics, Amsterdam, 1996

Baryon vs. meson sea

- Would naively expect dynamics of valence quarks in baryons vs. mesons to be different. Also dynamics of sea quarks?
  - Three-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 vs. decay from another hadron 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 . . .

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.
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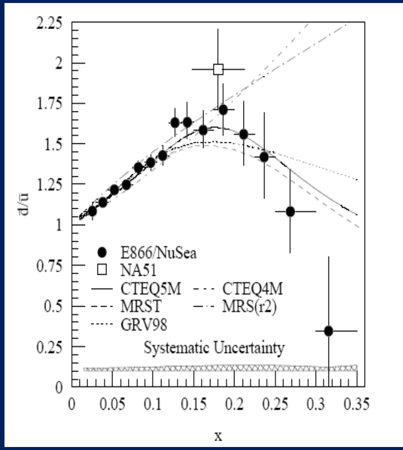
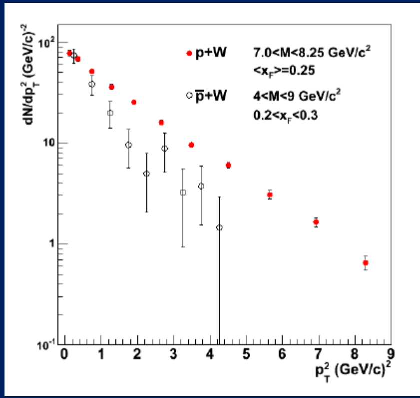
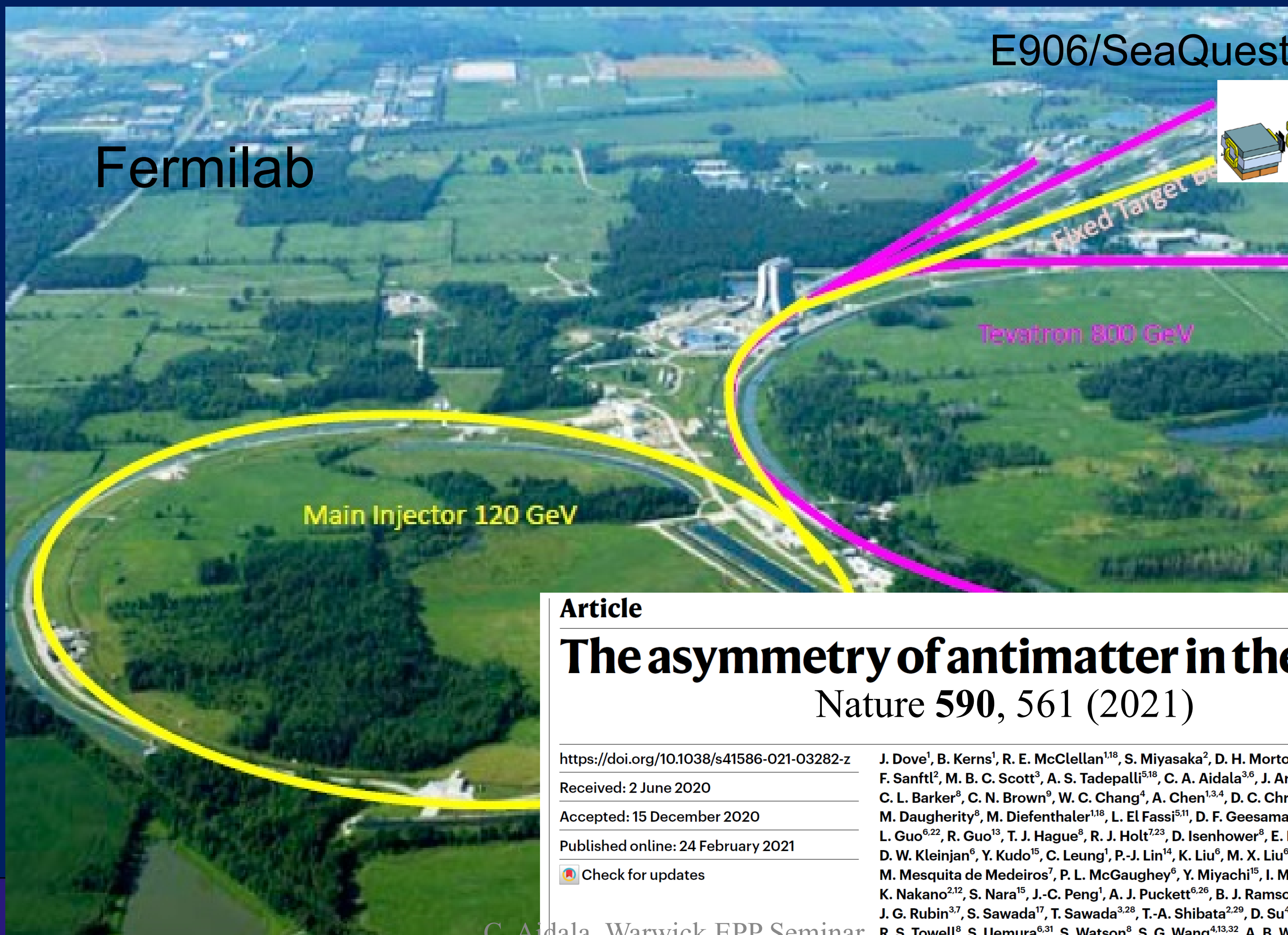
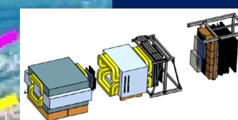


- We talk about "the valence quarks" being at large momentum fraction *x*, but Fermilab E866 measured (sea) antiquarks up to $x = 0.35$.
  Is it meaningful to think also of sea *quarks* at these high *x* values, i.e. up or down sea quarks rather than antiup or antidown?
  - If we measure an up or down quark at $x \sim 0.35$, 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?



New results on the light flavor asymmetry of the proton sea from SeaQuest





Article

The asymmetry of antimatter in the proton

Nature **590**, 561 (2021)

https://doi.org/10.1038/s41586-021-03282-z

Received: 2 June 2020

Accepted: 15 December 2020

Published online: 24 February 2021

Check for updates

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

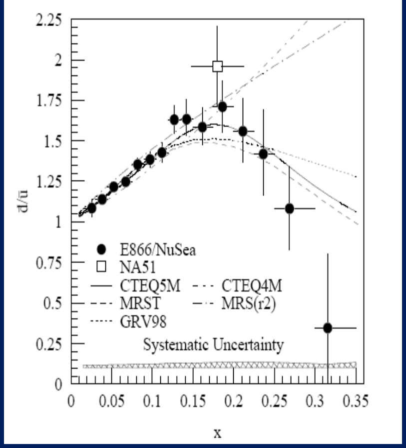
- Fixed-target kinematics:
  - Large x_F (= $x_{beam} - x_{target}$)
  - $M^2 = x_{beam} x_{target} s$ plays role of Q^2

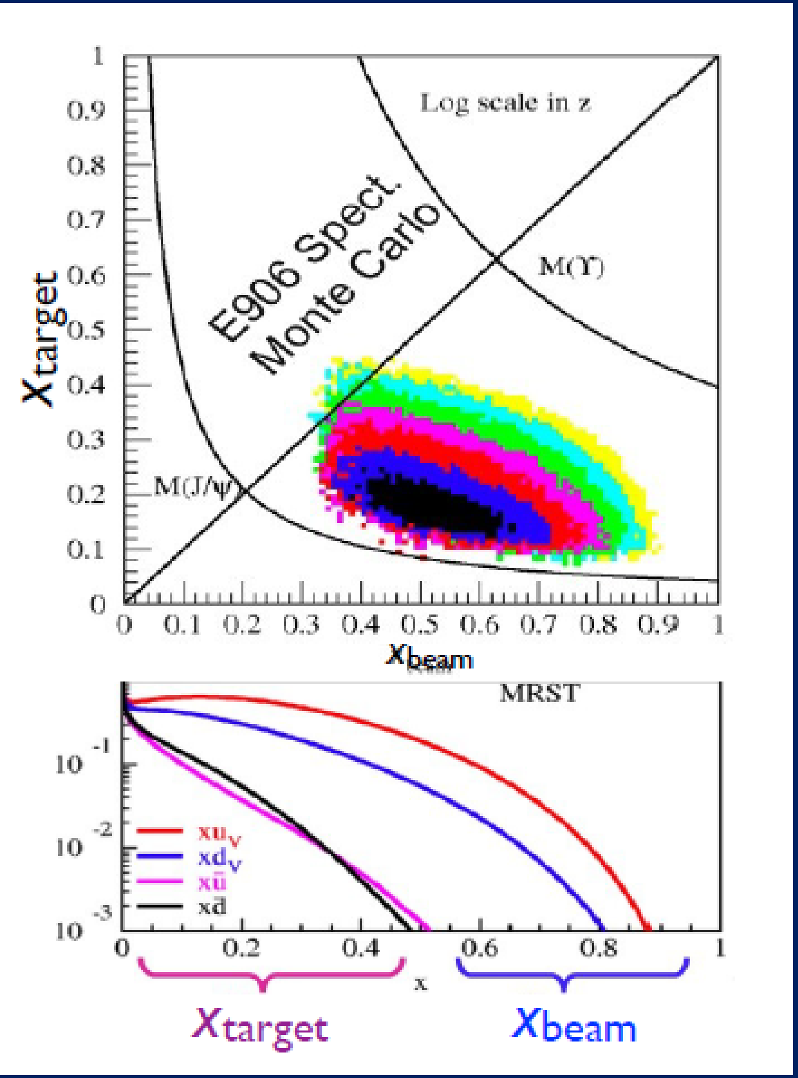
$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_t} \sum_q e_q^2 [q(x_b)\bar{q}(x_t) + q(x_t)\bar{q}(x_b)]$$

  - Proton beam: antiquark density negligible at large x, so first term dominates
  - Isolate *antiquarks in the target*
  - Alter combinations of protons and neutrons—and therefore sea quark distributions—by changing targets
- Same strategy as Fermilab E866/NuSea, but different kinematics → access higher x

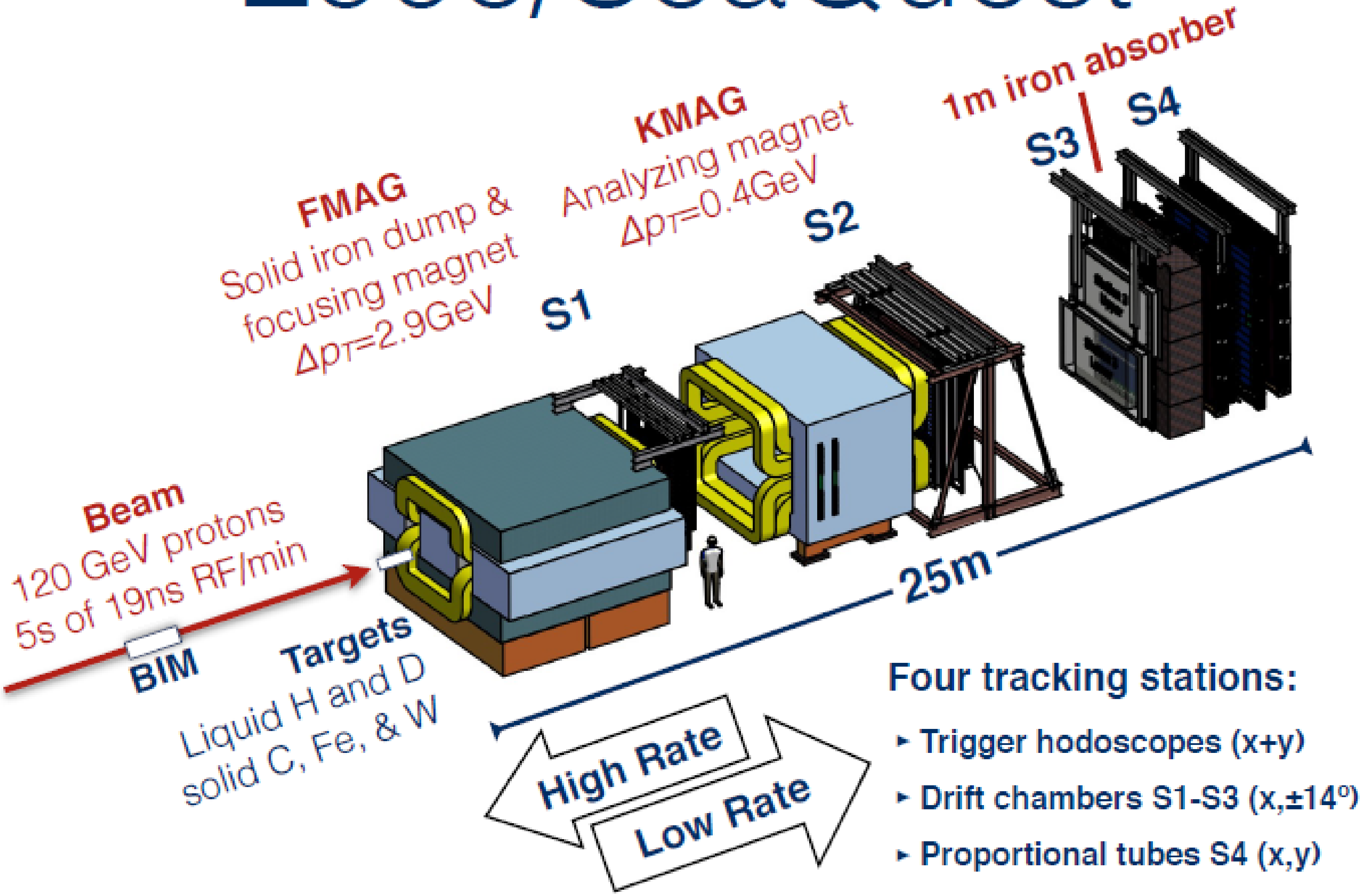
SeaQuest kinematics

- For invariant masses between J/Psi and upsilon, most statistics near peak of $\bar{d}/\bar{u}$ (~0.15<x_{target}<~0.2)
- Max x_{target} ~0.45
  - Compare to 0.35 for E866



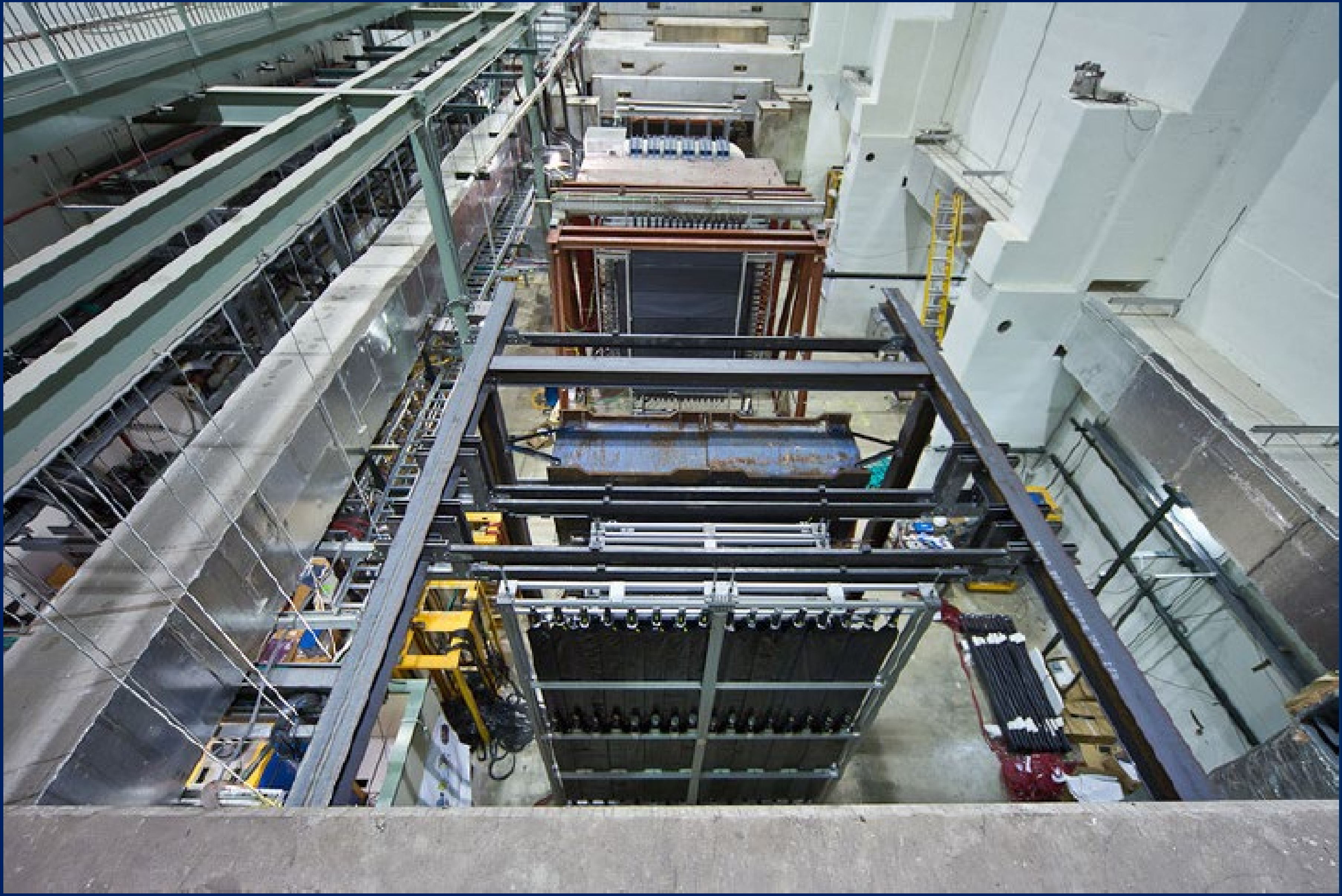


E906/SeaQuest

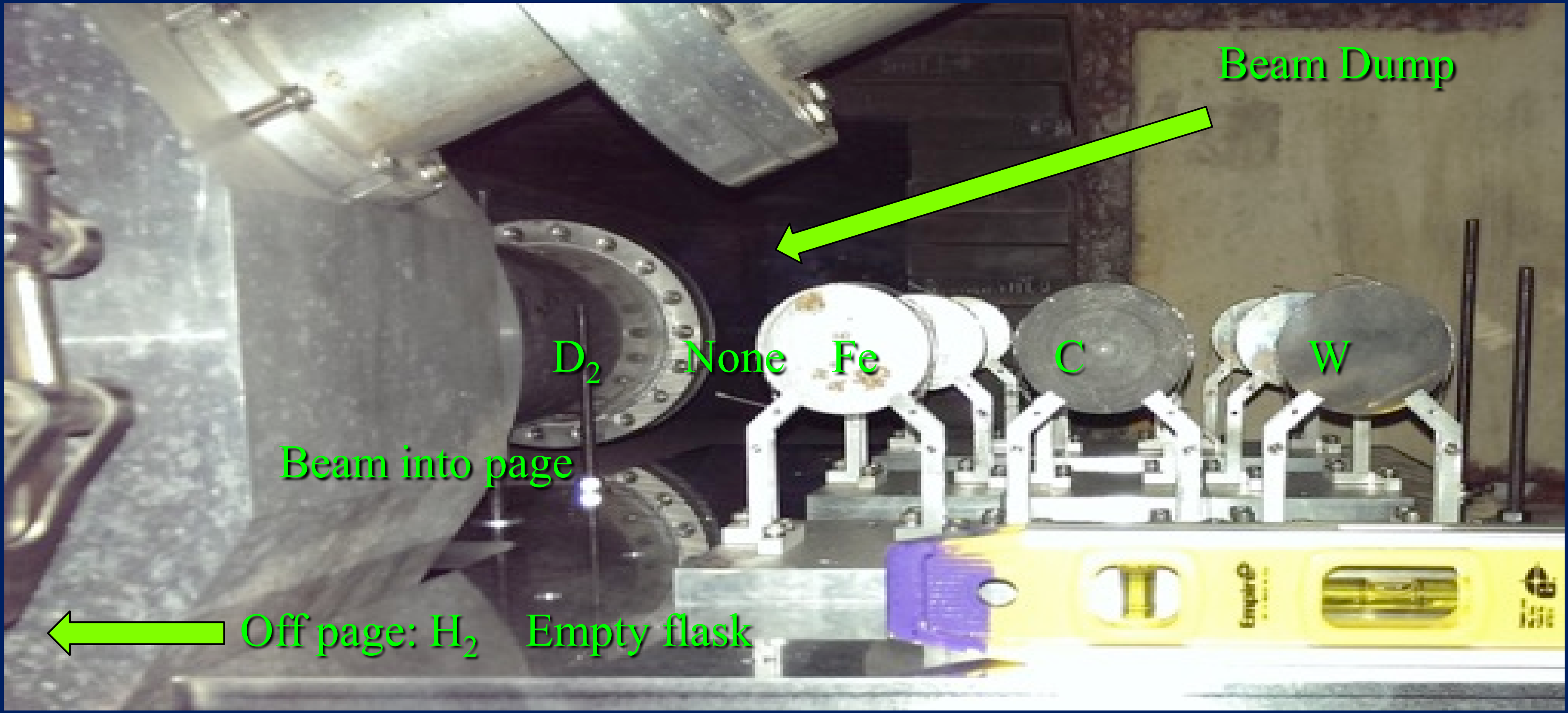


Four tracking stations:

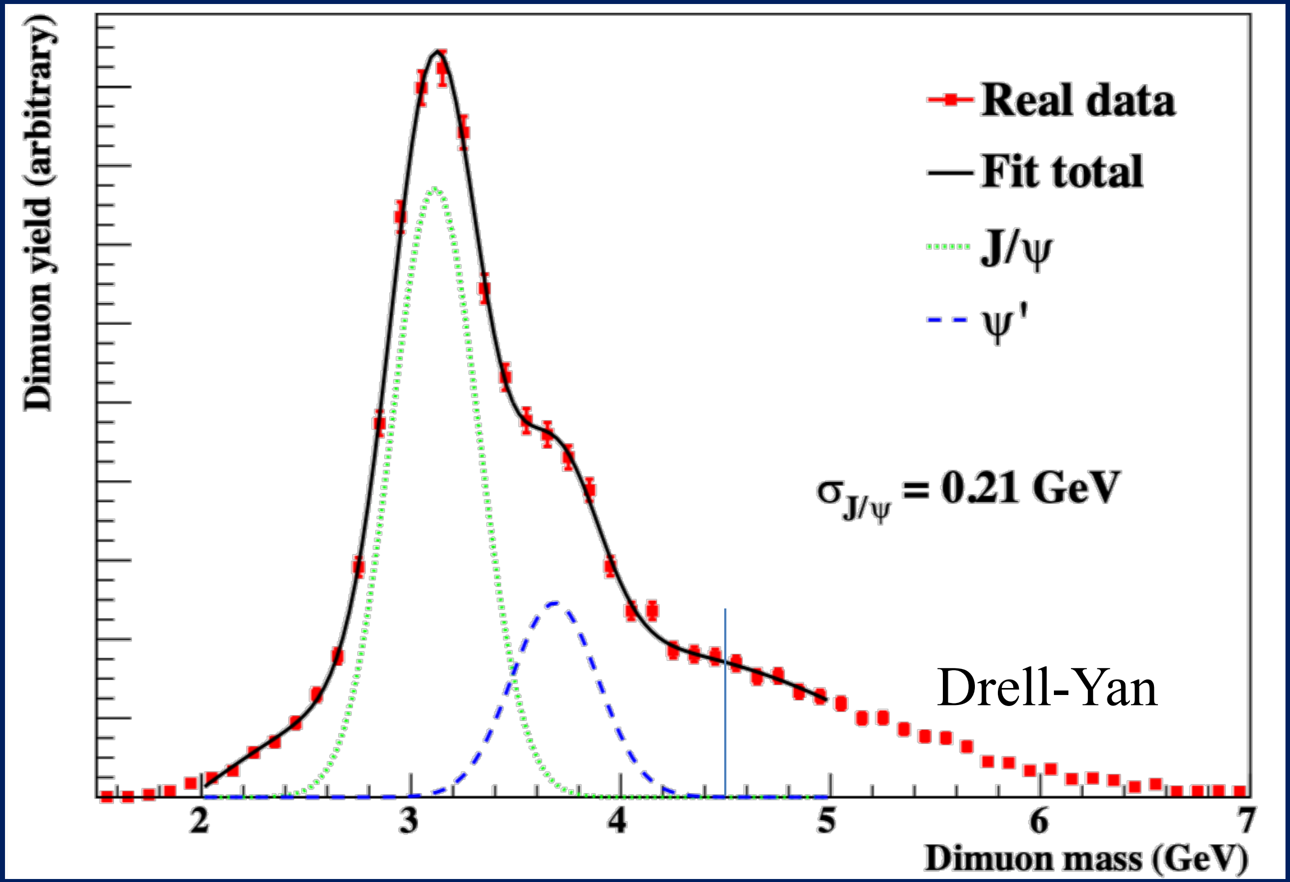
- Trigger hodoscopes (x+y)
- Drift chambers S1-S3 (x,±14°)
- Proportional tubes S4 (x,y)

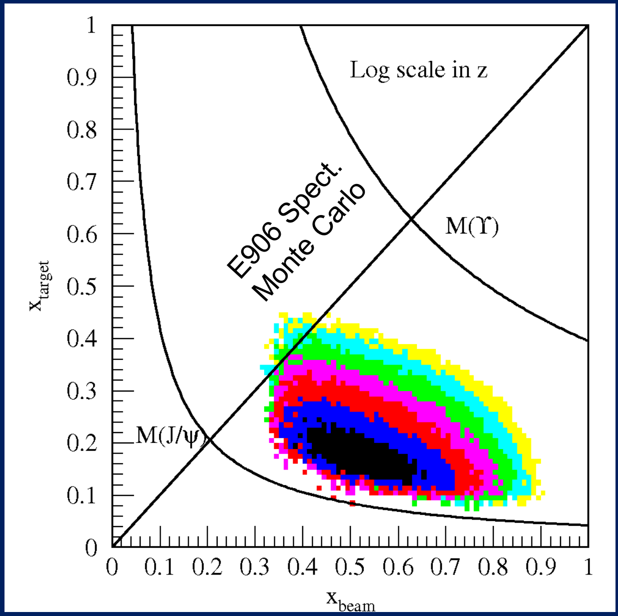


Liquid hydrogen, liquid deuterium, and solid targets

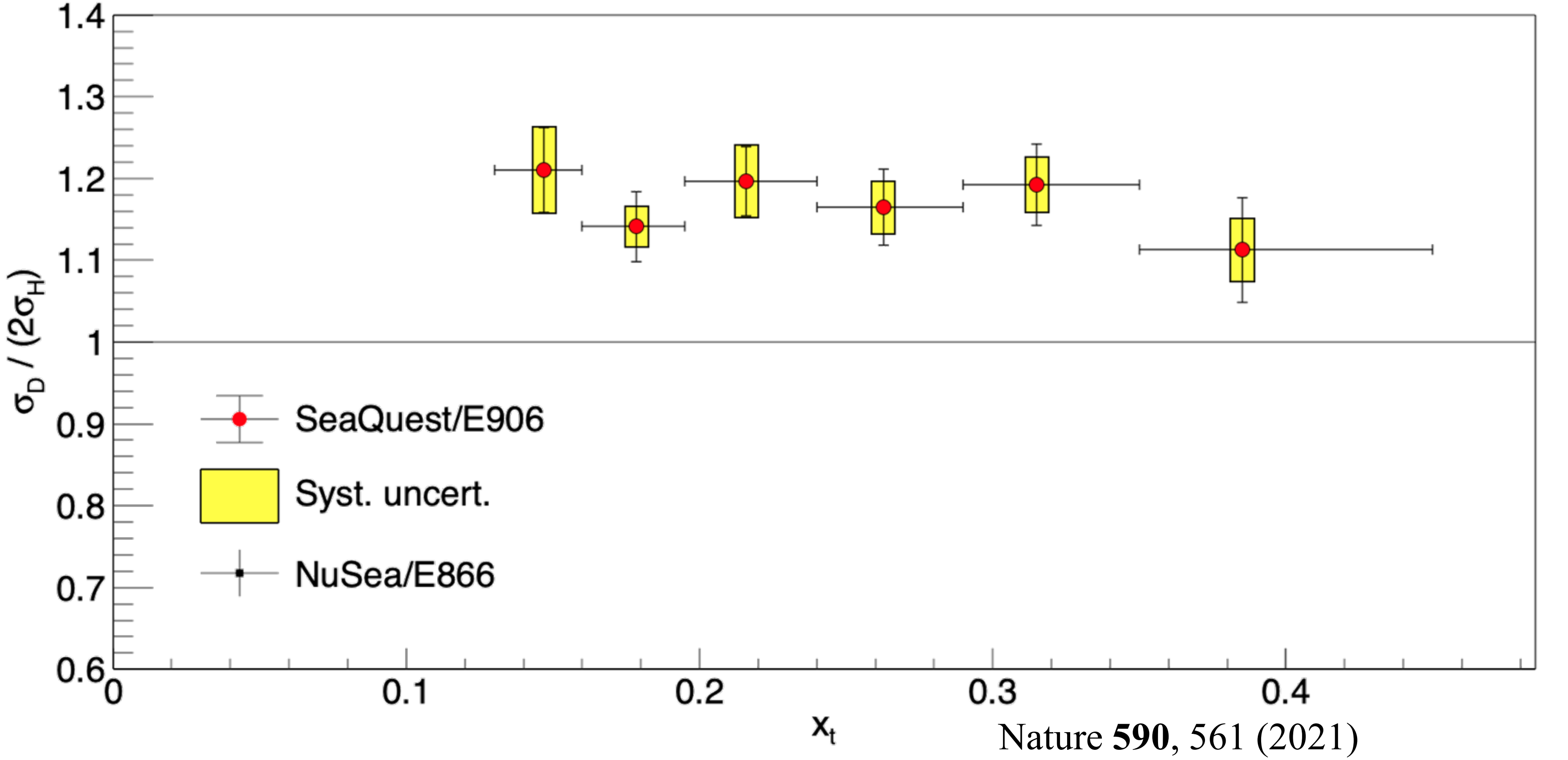


Dimuon mass spectrum





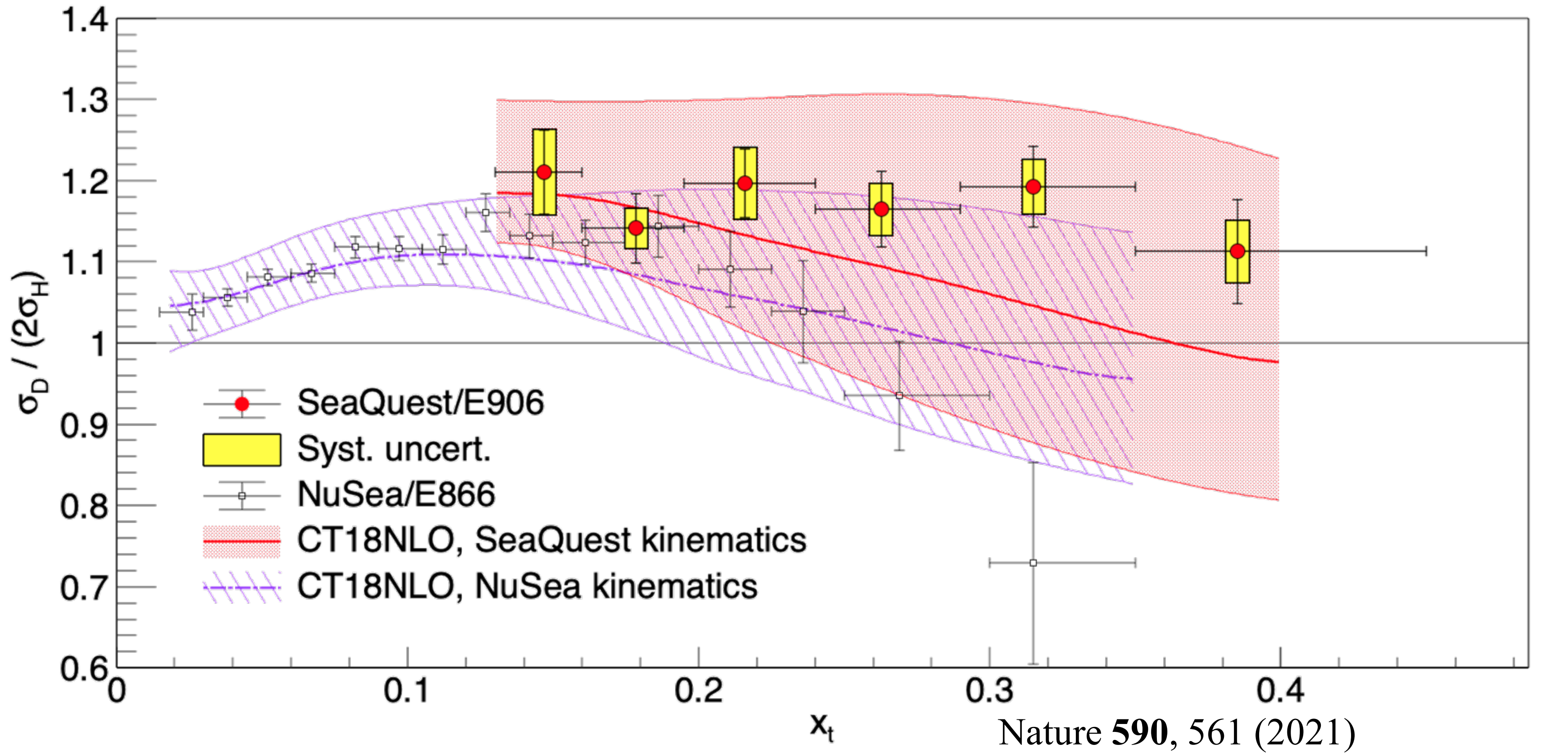
Drell-Yan cross-section ratio: Deuterium to hydrogen



Nature **590**, 561 (2021)

SeaQuest data: $\frac{\boldsymbol{\sigma^{pd}}}{\boldsymbol{2\sigma^{pp}}} > \mathbf{1}$ over entire range

Cross-section ratio compared to E866/NuSea



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Different kinematics suggest that SeaQuest should be slightly higher

SeaQuest's extraction of $\bar{d}/\bar{u}$

Correct way to extract quark distributions is within the context of a global fit to all relevant world data!

$$\frac{\sigma^D}{2\,\sigma^H} \approx \frac{1}{2}\left[1 + \frac{\bar{d}}{\bar{u}}\right]$$

What we have done in the meantime:

- Fix PDFs in a current global fit except for $\bar{d}/\bar{u}$
  - The sum $\bar{d}(x) + \bar{u}(x)$ is also fixed
  - Used CT10, CT14, CT18, MMHT2014, all NLO
- Compute

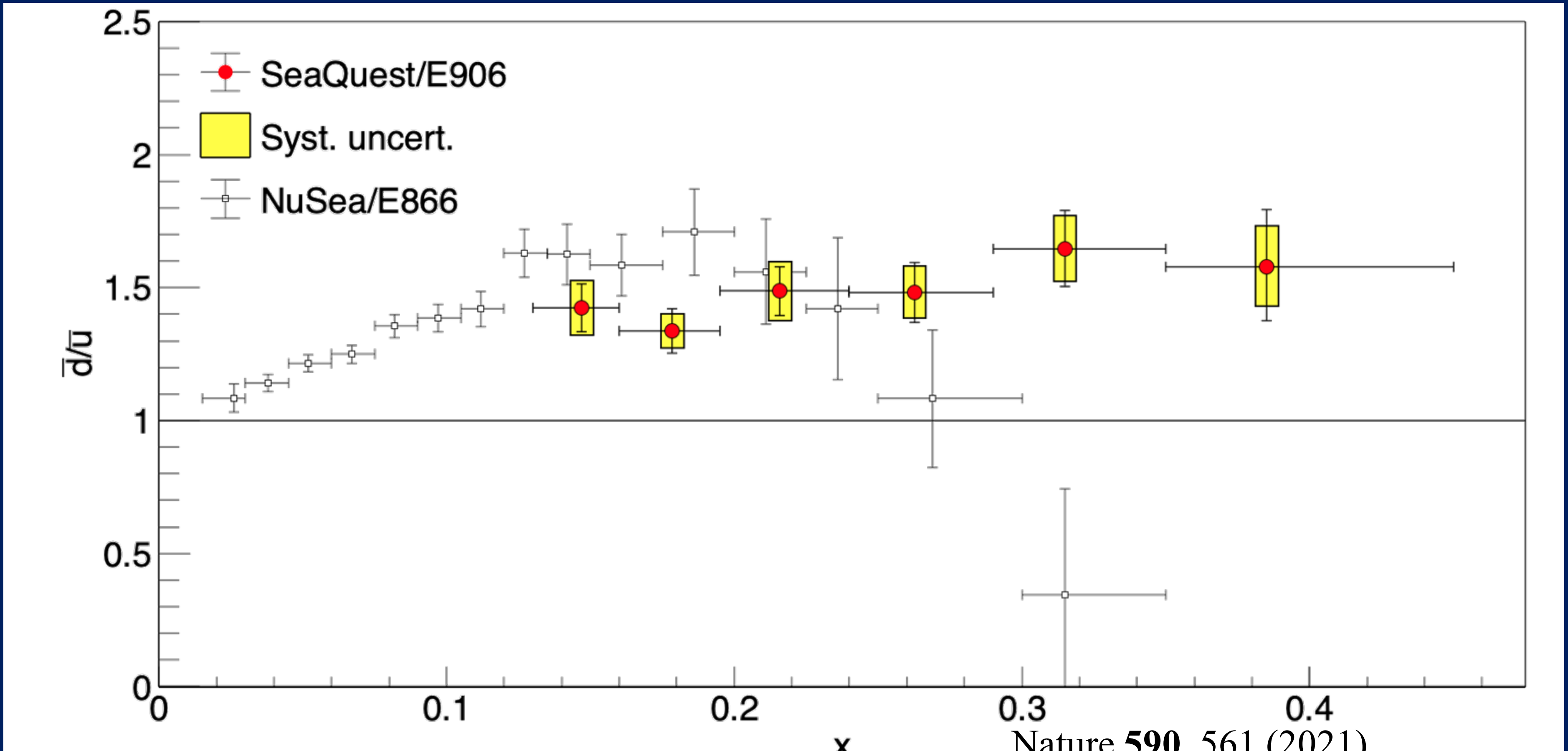
$$\frac{\sigma^D}{2\sigma^H} = \frac{\iint \frac{d\sigma^D_{NLO}}{dx_1 dx_2} dx_1\, dx_2}{2\iint \frac{d\sigma^H_{NLO}}{dx_1 dx_2} dx_1\, dx_2} \text{ with } \bar{d}/\bar{u}\,\big]_i$$

with the integrals over the experimental acceptance

- Compare with measured $\frac{\sigma^D}{2\sigma^H}$, and iterate on $\bar{d}/\bar{u}\,\big]_{i+1}$

SeaQuest extracted $\bar{d}/\bar{u}$ compared with E866

SeaQuest extraction starting from CT18 shown



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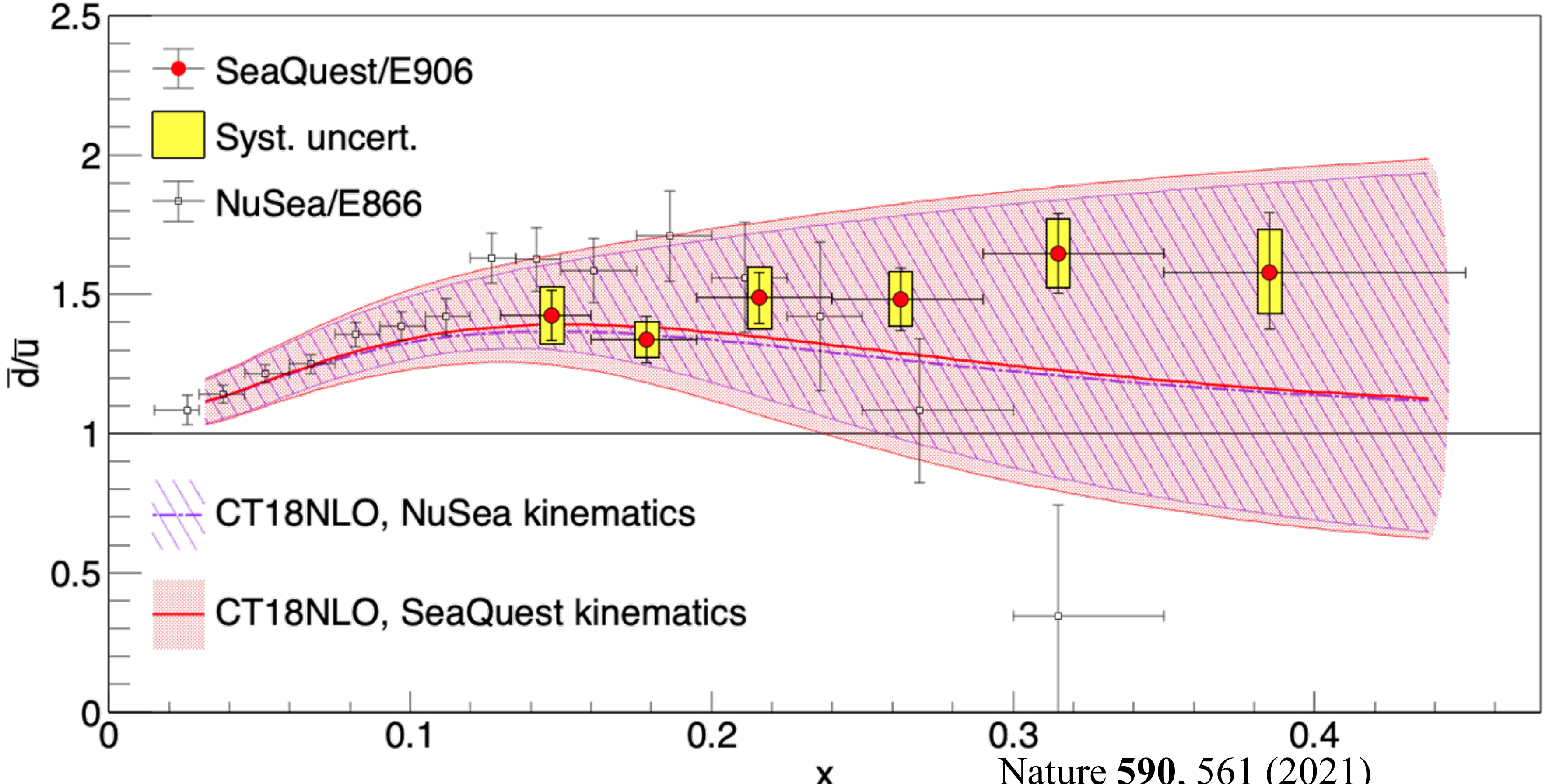
SeaQuest $\bar{d}(x)/\bar{u}(x) > 1$ for entire measured range. Some tension with E866.

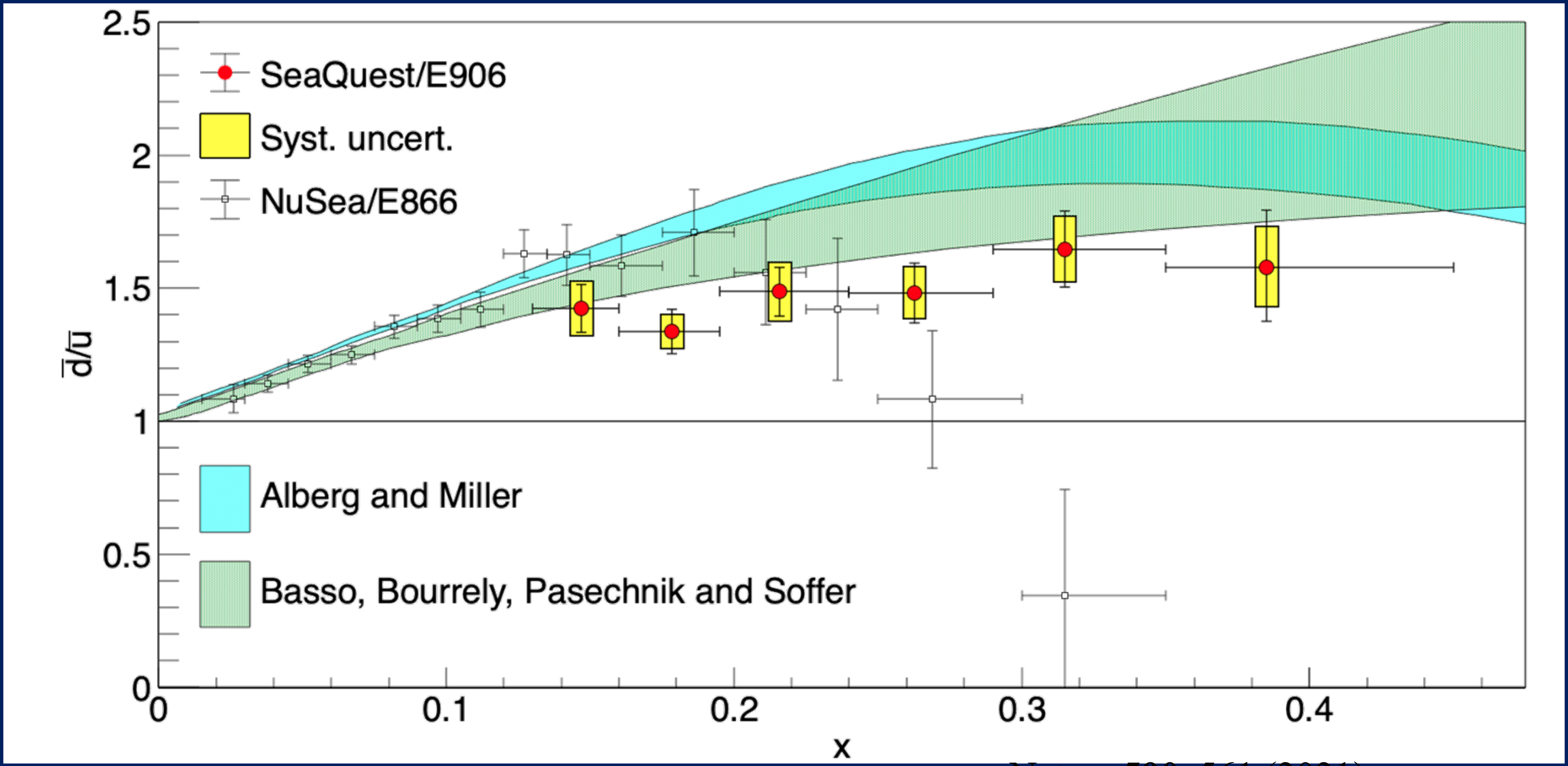
E866: $< M^2 > \sim 54$ GeV^2 SeaQuest: $< M^2 > \sim 20 - 40$ GeV^2

SeaQuest extracted $\bar{d}/\bar{u}$ compared with CT18NLO global PDF fit



Nature **590**, 561 (2021)

SeaQuest extracted $\bar{d}/\bar{u}$ compared with nonperturbative models



Nature **590**, 561 (2021)

Alberg and Miller – a pion cloud model from chiral effective perturbation theory – PRC100, 035205 (2019)

Basso et al. – based on a statistical model – Nuc. Phys. A948, 63, (2016)

NATURE PODCAST · 24 FEBRUARY 2021

The quark of the matter: what's really inside a proton?

NEWS RELEASE 24-FEB-2021

Nature's funhouse mirror: understanding asymmetry in the proton

DOE/ARGONNE NATIONAL LABORATORY

Quanta magazine

QUANTUM PHYSICS

Decades-Long Quest Reveals Details of the Proton's Inner Antimatter

27

Twenty years ago, physicists set out to investigate a mysterious asymmetry in the proton's interior. Their results, published today, show how antimatter helps stabilize every atom's core.

reddit

Posted by u/m3prx 18 days ago

487 The asymmetry of antimatter in the proton

nature.com/articl...

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NEWS PARTICLE PHYSICS

Protons' antimatter is even more lopsided than we thought

In the sloshing sea of particles within a proton, down antiquarks outnumber up antiquarks

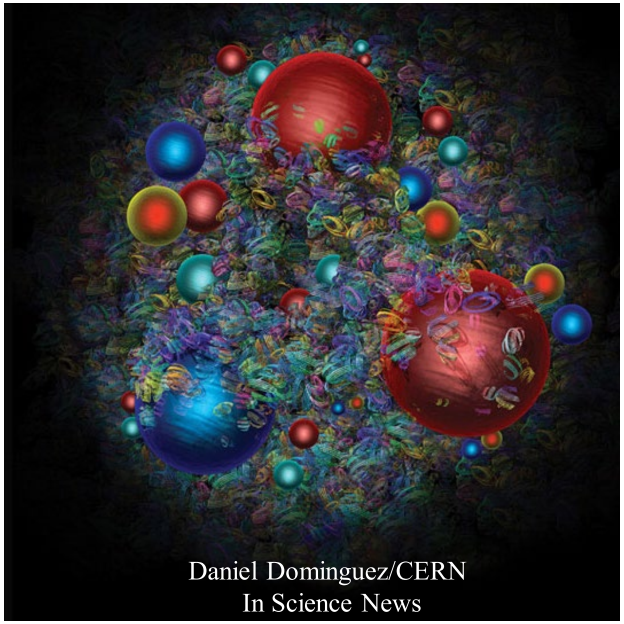
Le Monde

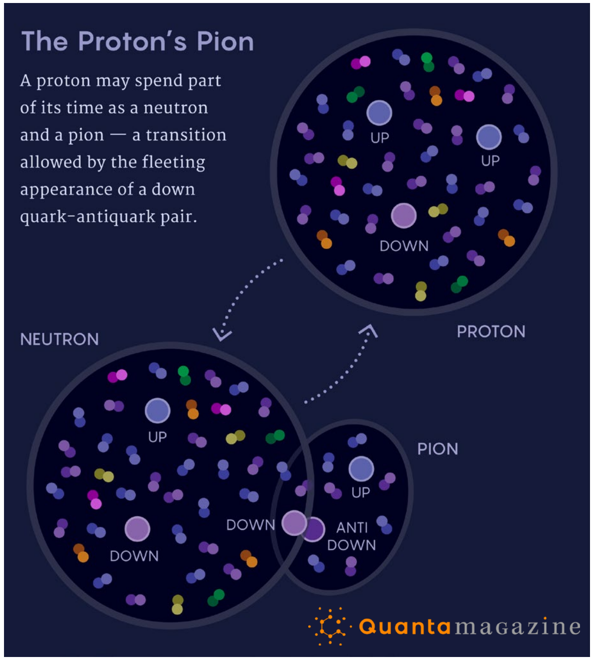
SCIENCE & MÉDECINE

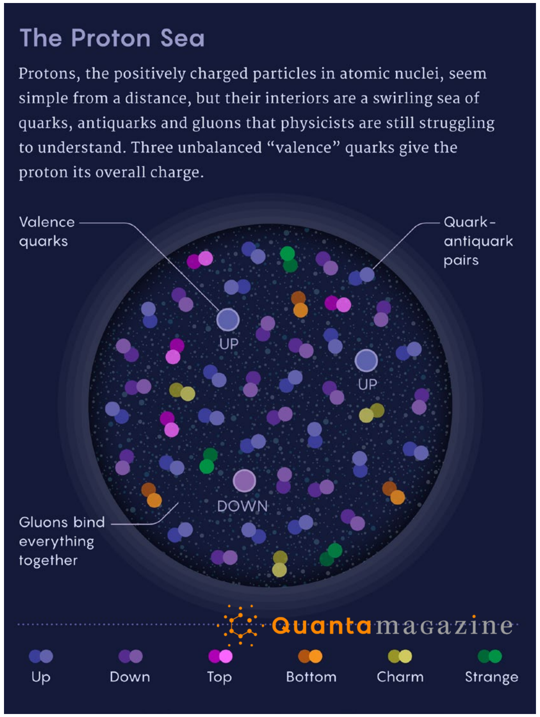
Le proton, cette particule essentielle et mal définie de la matière

PHYSIQUE - Le constituant principal du noyau des atomes se révèle être un sac de nœuds complexe, qui échappe encore à l'entendement

Graphic art from the media!







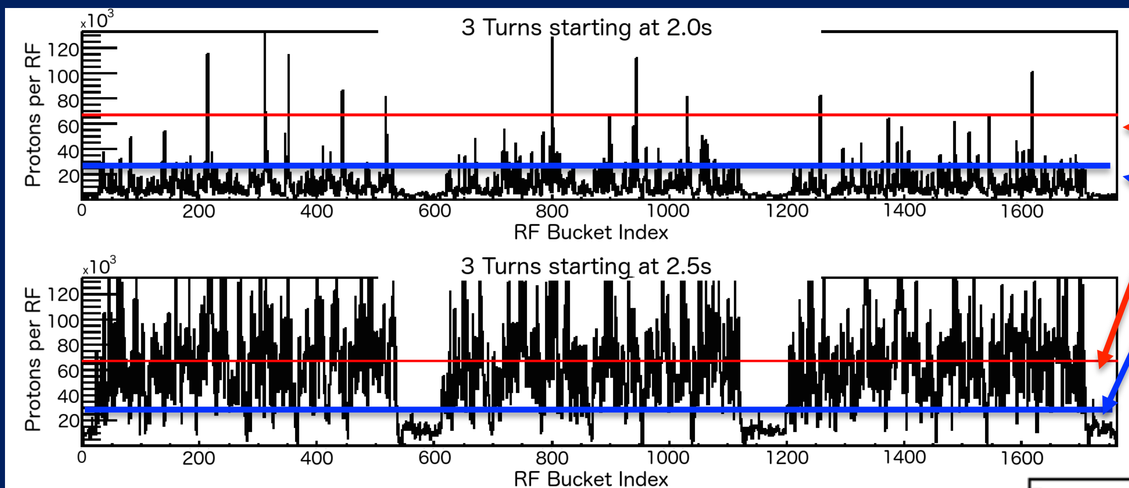
Conclusions and outlook

- Still trying to peer through the haze to understand the sea within hadrons!
- New SeaQuest results extend constraints on the light flavor nucleon sea to higher x
  - $\bar{d}$ enhancement persists
  - No conclusive theoretical understanding thus far
- Future measurements from SeaQuest, LHC, SpinQuest, Relativistic Heavy Ion Collider, and Electron-Ion Collider, with the latter three polarized, will help shed further light on the sea of nucleons and nuclei
- Understanding in particular the *dynamics* of sea quarks, which probe beyond static pictures of antiquarks in the nucleon, will be crucial to understanding how the nucleon sea is generated (and what in fact it is!)

Extra material

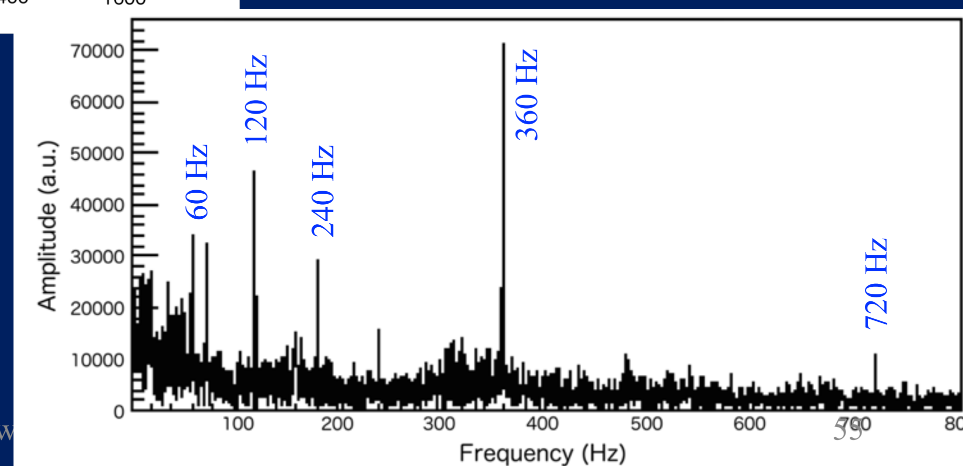
Issues with beam intensity fluctuations

- Slow-spill extraction from the Main Injector for 4 s every 60 s
- Bunch spacing 19 ns
- Saw bunch-to-bunch intensity fluctuations of factor >1000 during 2012 commissioning!



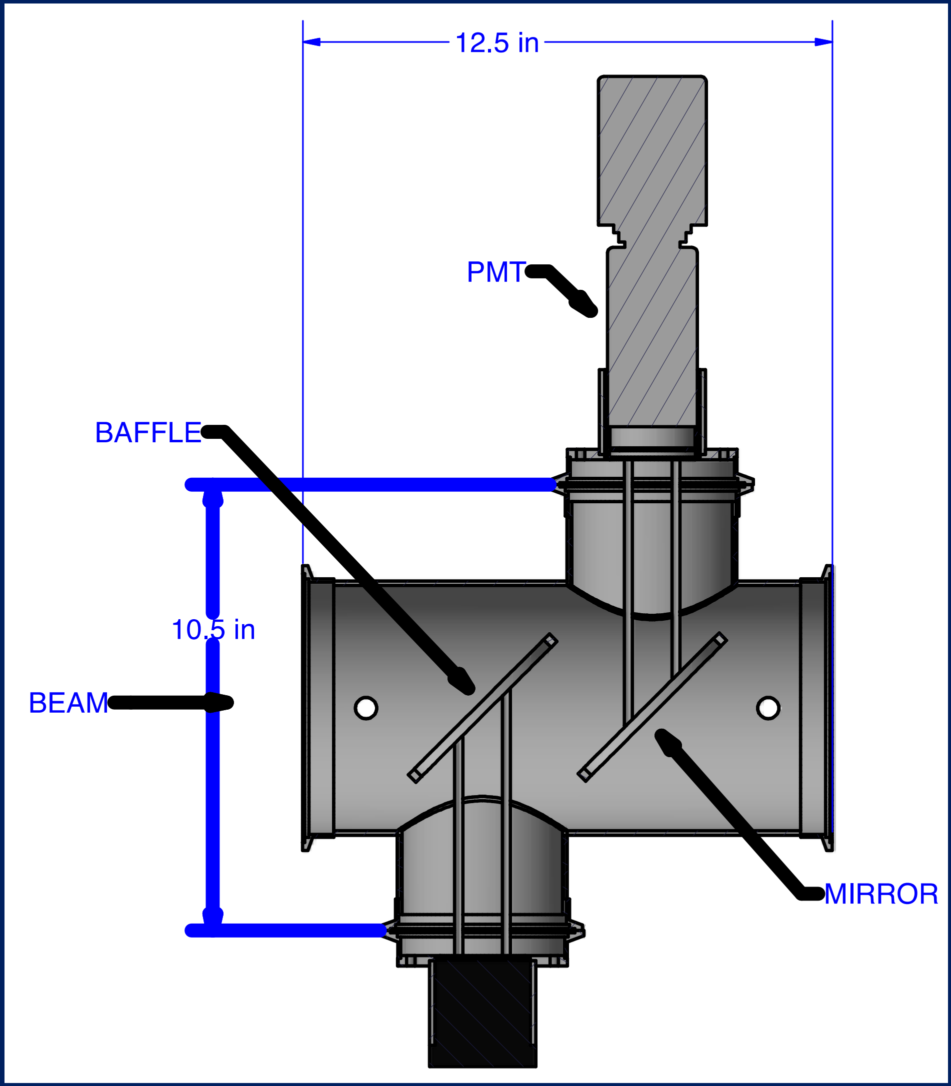
- Each bin is 19 ns
- Veto Level
- Even beam distribution

FOURIER TRANSFORM



Beam Cherenkov detector to veto high-intensity bunches

- <16 ns time resolution
- Approx. 30 to 3×10^{16} protons/RF cycle
- Calibrated every minute against beam line SEM

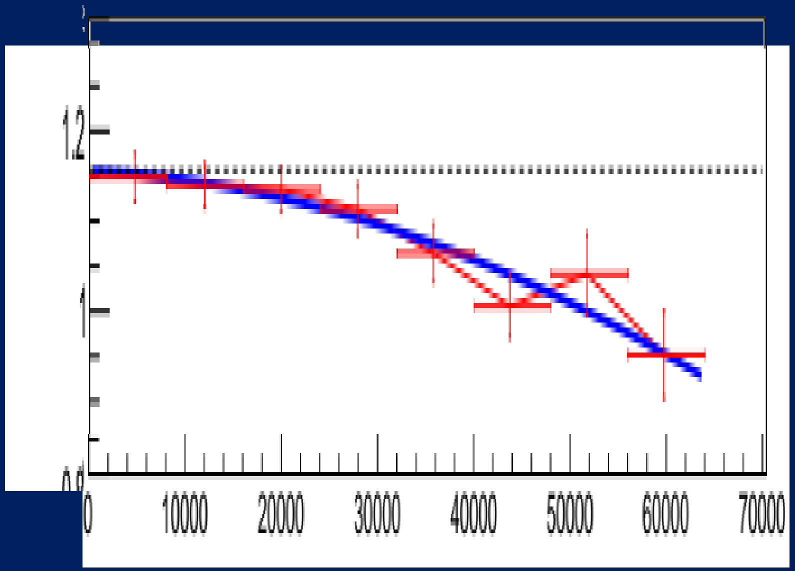


Intensity dependence

Plot $^{\sigma_D}/_{2\sigma_H}$ as a function of the # of protons in the triggered bucket

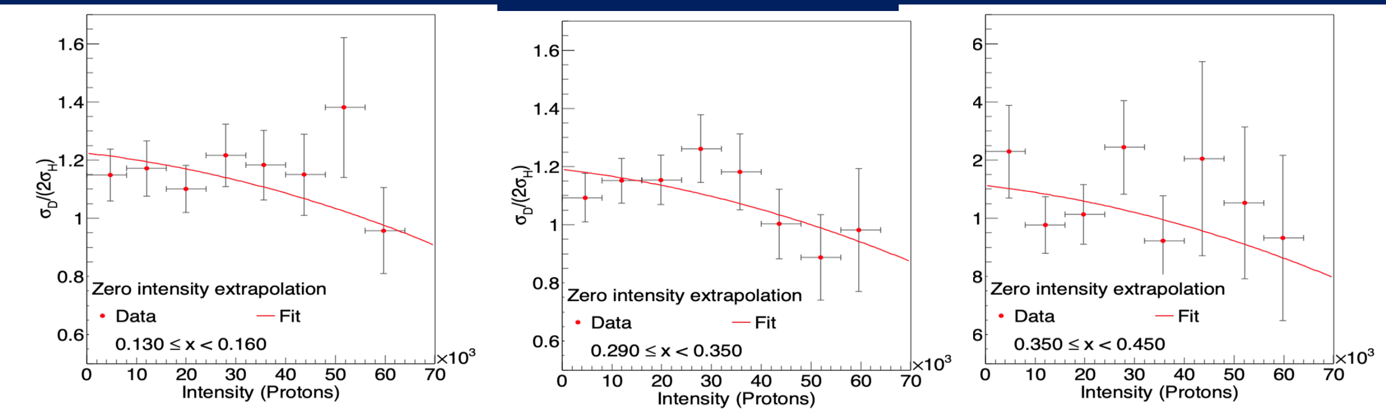
Possible sources:

- Trigger inefficiency at high rates
- Increased triggering on noise events
- Reconstruction inefficiency at high occupancy
- . . . .
- Cut on beam intensity
  - Lose statistical power of the data
- Model-based corrections
  - Fit data w/model of source
  - Monte Carlo to verify
  - Used by E866/NuSea
  - Becomes difficult with multiple effects

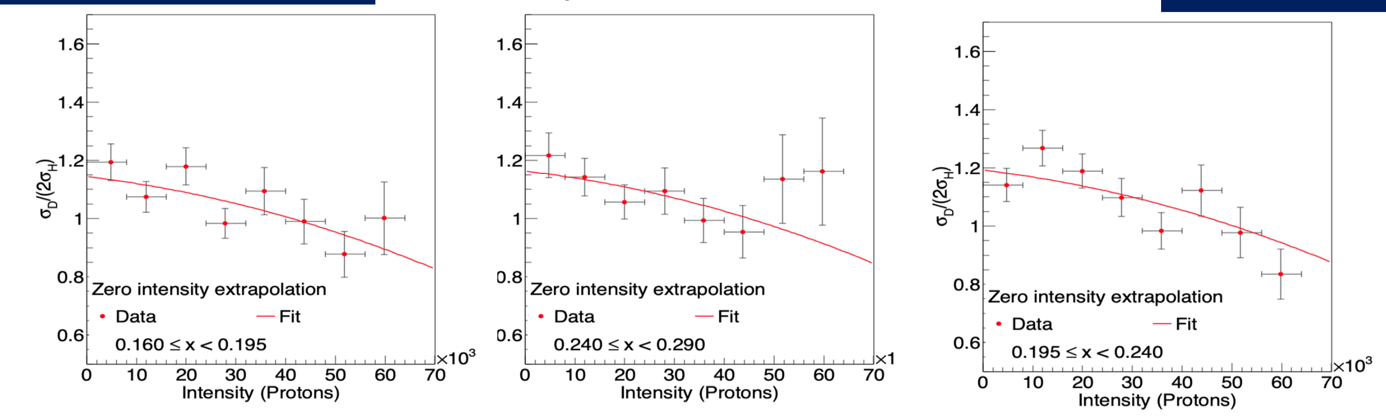


→ Fit rate dependence and extract intercept at 0. (Technically want cross-section ratio for beam intensity at 1, i.e. 1 beam proton interacting with target)

Intensity extrapolation



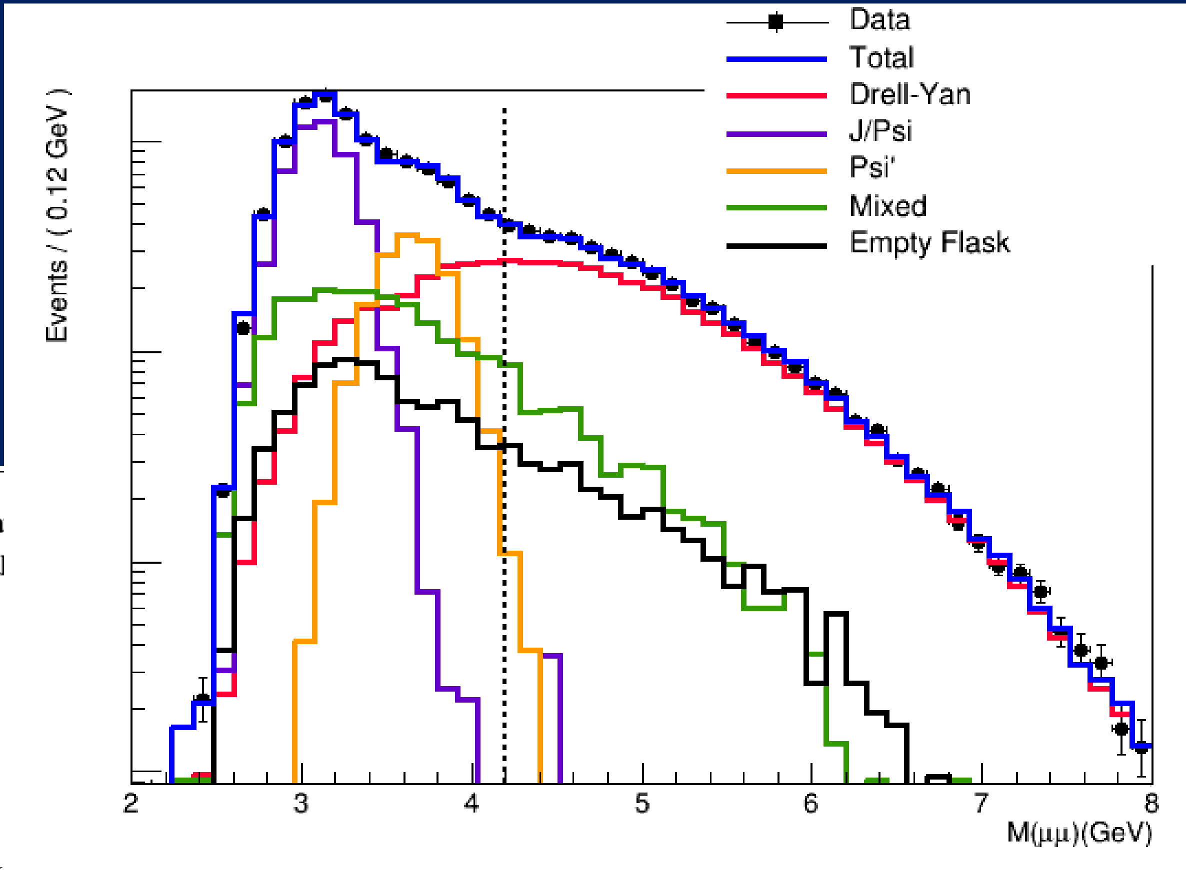
$$\frac{Y_D(x_t, I)}{2Y_H(x_t, I)} = R_{x_t} + a\,I + b\,I^2$$

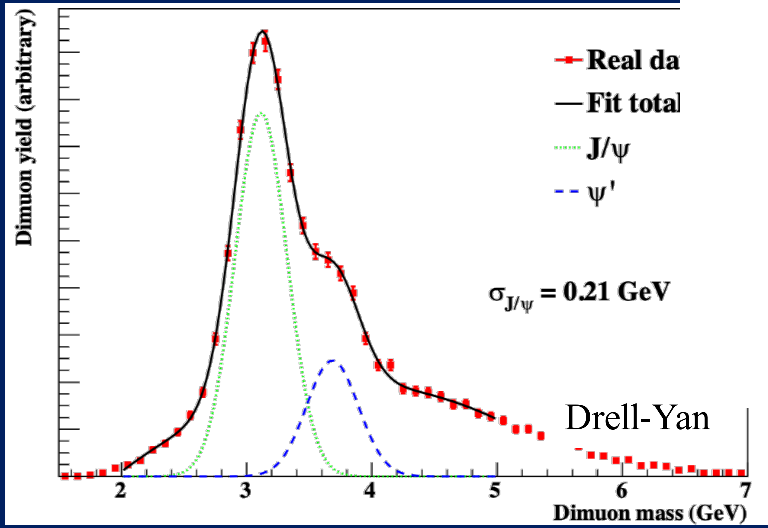


Intensity = 0 intercept from simultaneous fits gives ${}^{\sigma_d}/_{2\sigma_p}$ for different x_T bins

Cross Check of Rate Dependence

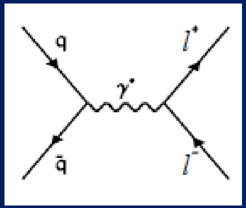
- Multi-component mass fit
- Combinatorial background via mixed events





Light flavor sea: Experimental surprises

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



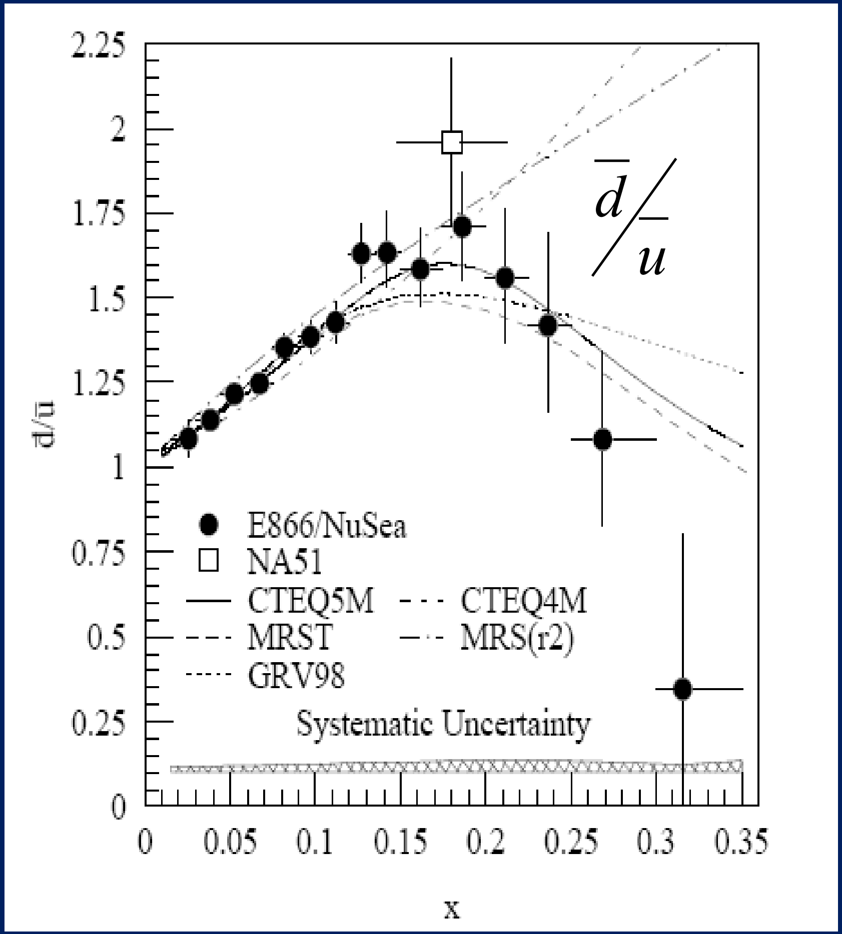
- Proton-hydrogen and proton-deuterium collisions

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

*simplest leading-order expression

- Indicates additional nonperturbative mechanism to generate sea quarks—not just gluon splitting!

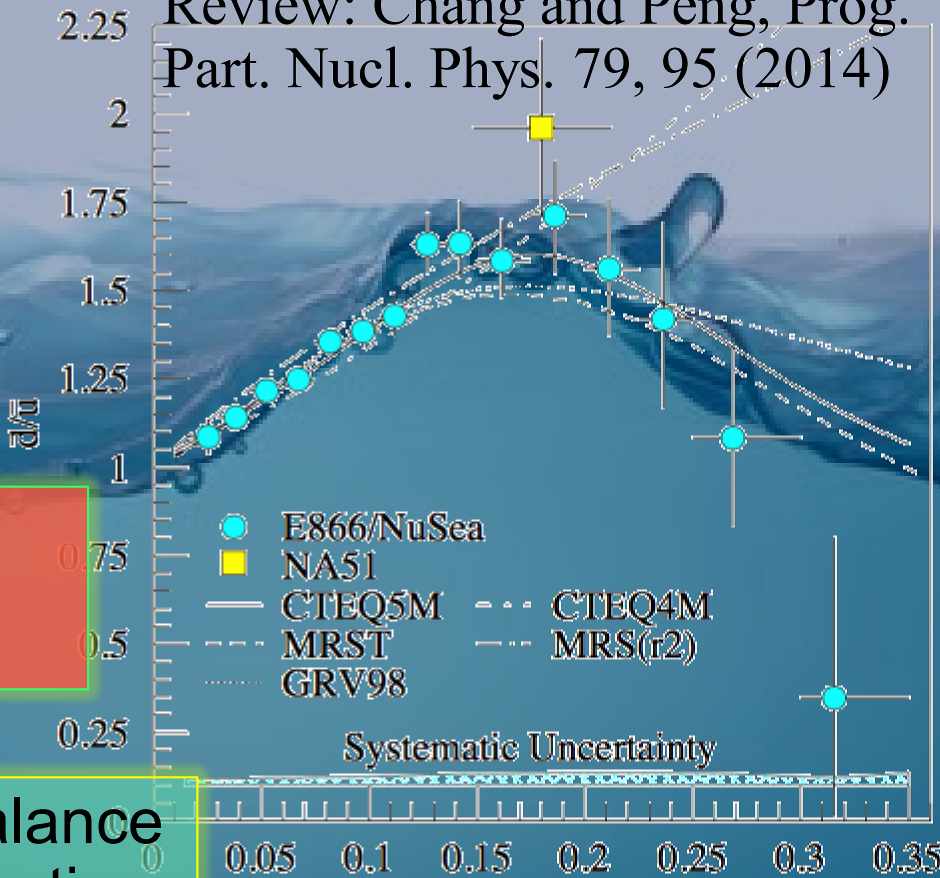
$$\int \left(\bar{d}(x,Q^2) - \bar{u}(x,Q^2)\right) dx = 0.118 \pm 0.012$$



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?

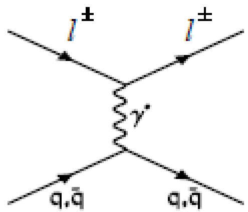
Instanton model?

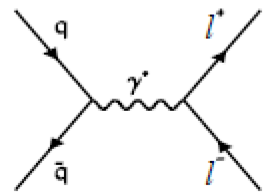
Your model??

Slide from Arun Tadepalli

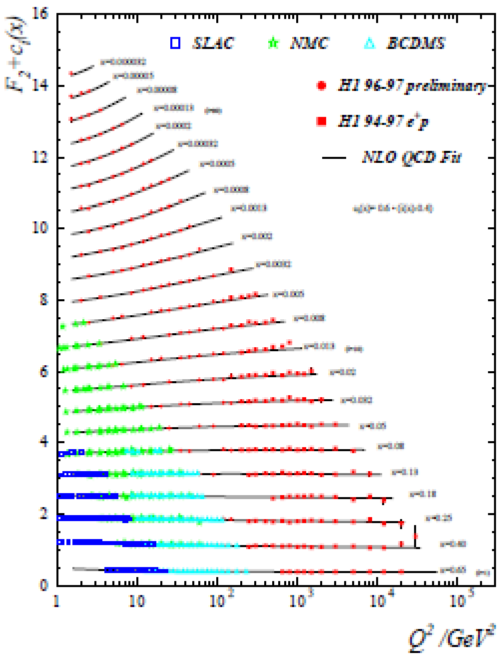
Complementarity of Drell-Yan and DIS

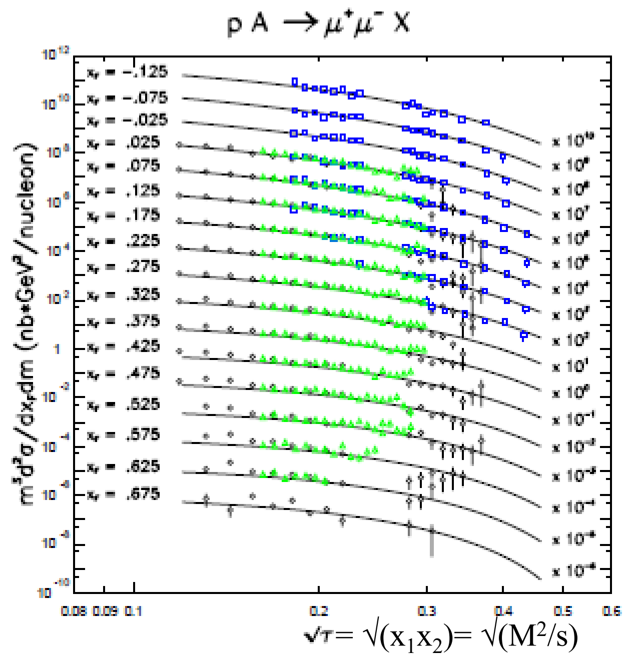
DIS





Drell-Yan





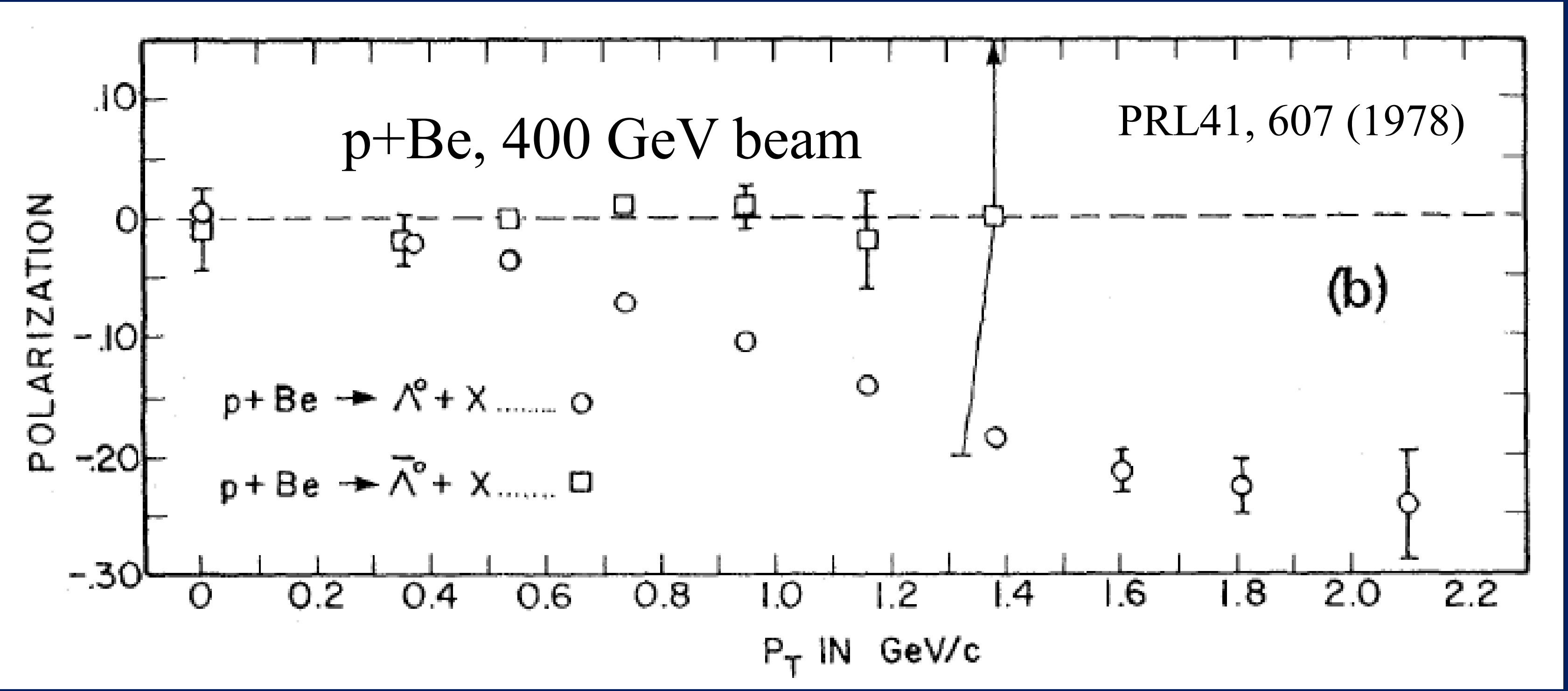
McGaughey, Moss, JCP, Ann.Rev.Nucl. Part. Sci. 49 (1999) 217

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

Long history of fixed-target Drell-Yan at Fermilab

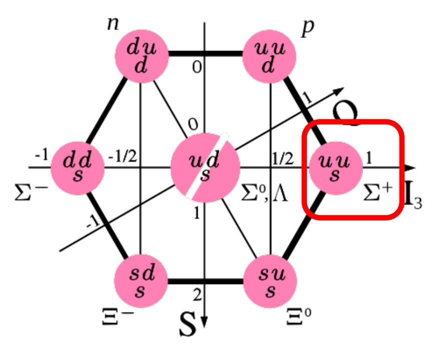
- E288 – 200, 300, and 400 GeV p beams on Be, Cu, and Pt targets
- E325 – 200, 300, and 400 GeV p beams on Cu target
- E326 – 225 GeV π- beam on W target
- E439 – 400 GeV p beam on W target
- E444 – 225 GeV, π+/-, K+, proton/antiproton beams on C, Cu, W targets
- E537 – 125 GeV antiproton and π^- beams 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*

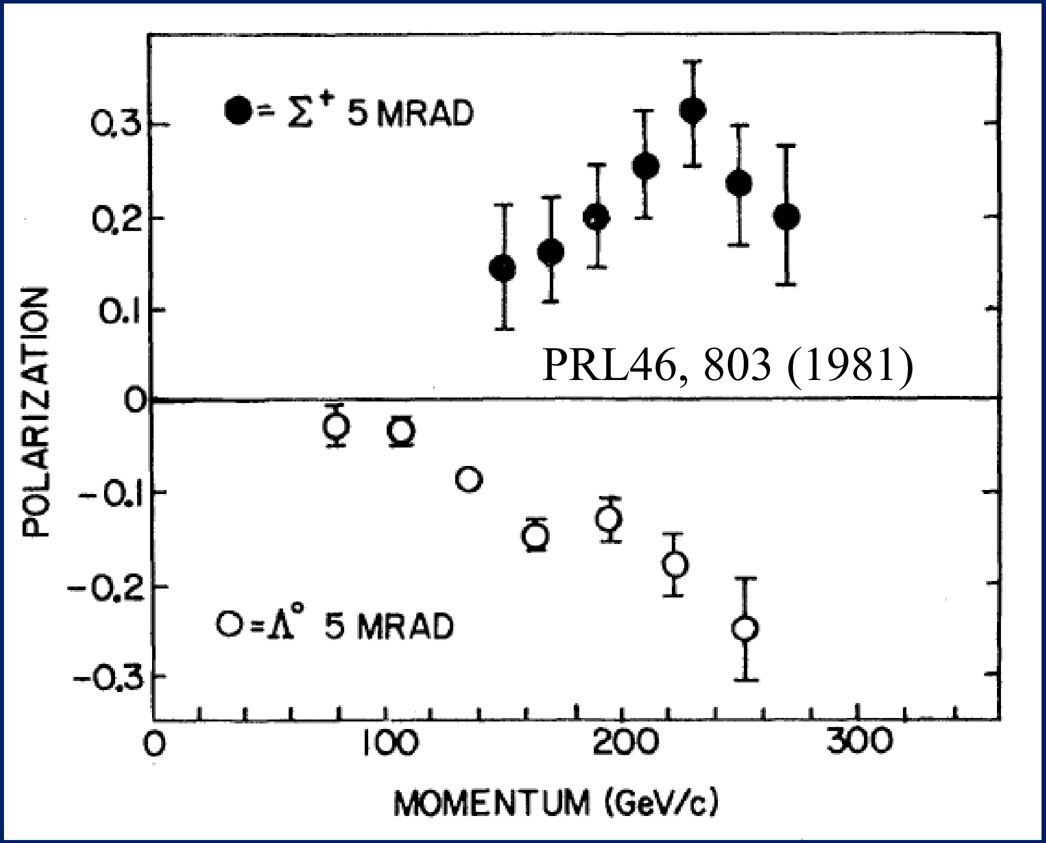
No observed antilambda polarization



- 1978: No antilambda polarization
- And lambda polarization now measured up to p_T = 2.2 GeV, polarization ~25%. (Same sign convention as compilation of measurements in ATLAS paper)

Σ^+ polarized with opposite sign

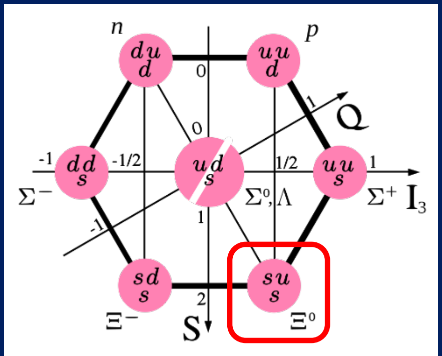


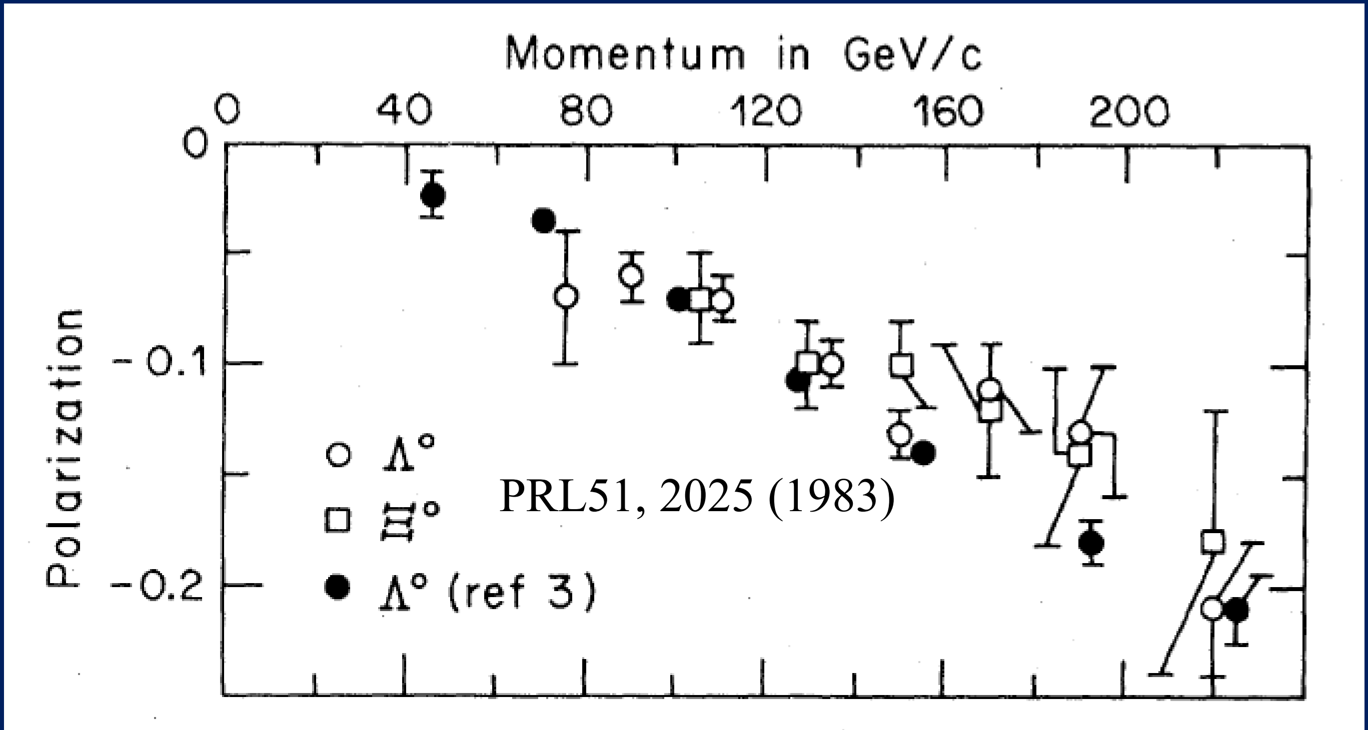


PRL46, 803 (1981)

- 1981: p+Be, 400 GeV beam

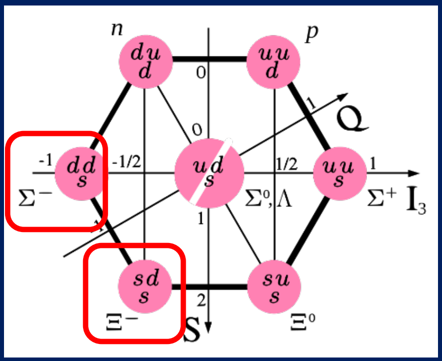
Ξ^0 polarization similar to Λ^0





- 1983: p+Be, 400 GeV beam
- Similar results for p+Cu and p+Pb

Σ^- polarized similarly to Σ^+; Ξ^- similarly to Ξ^0



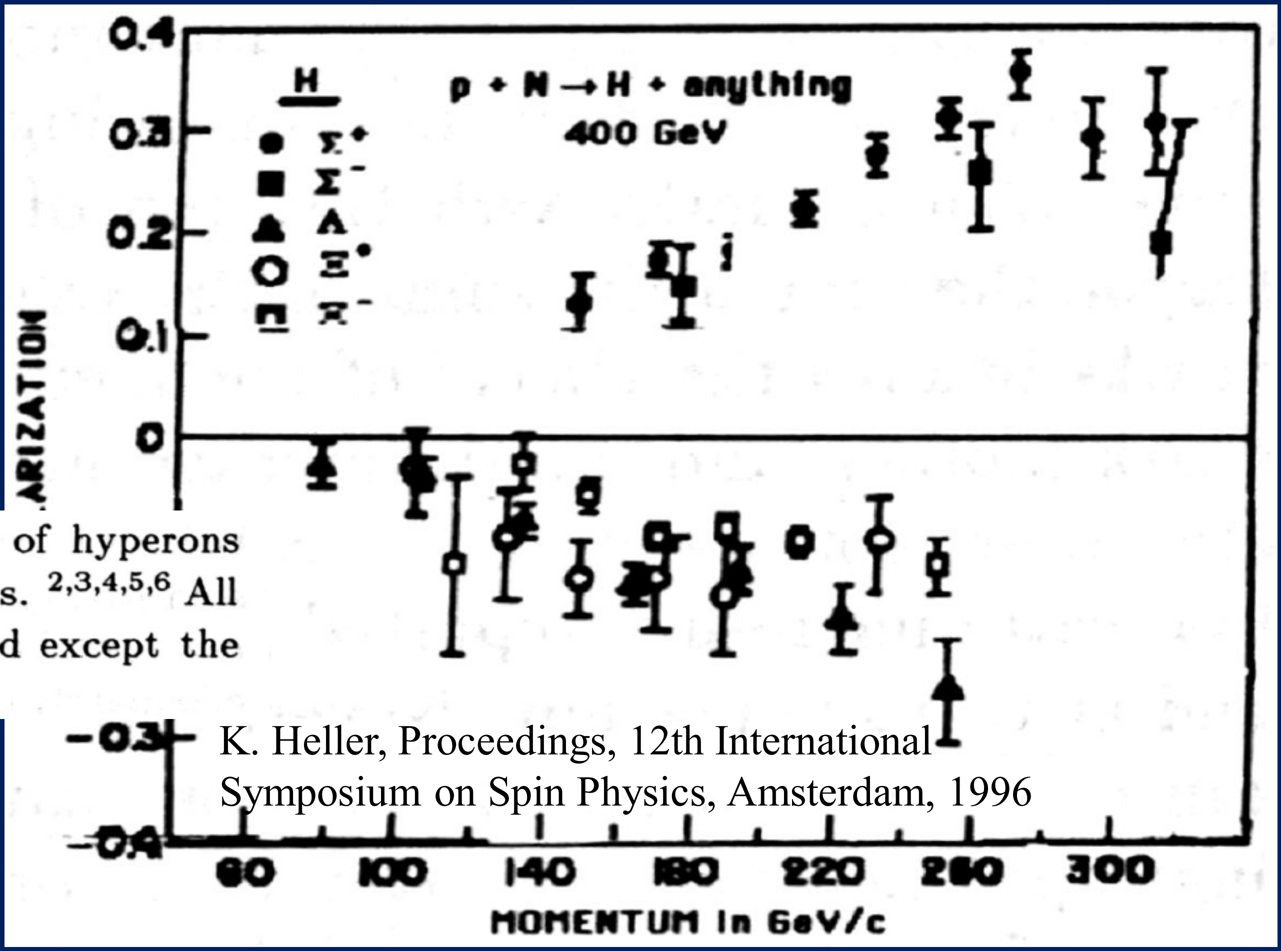
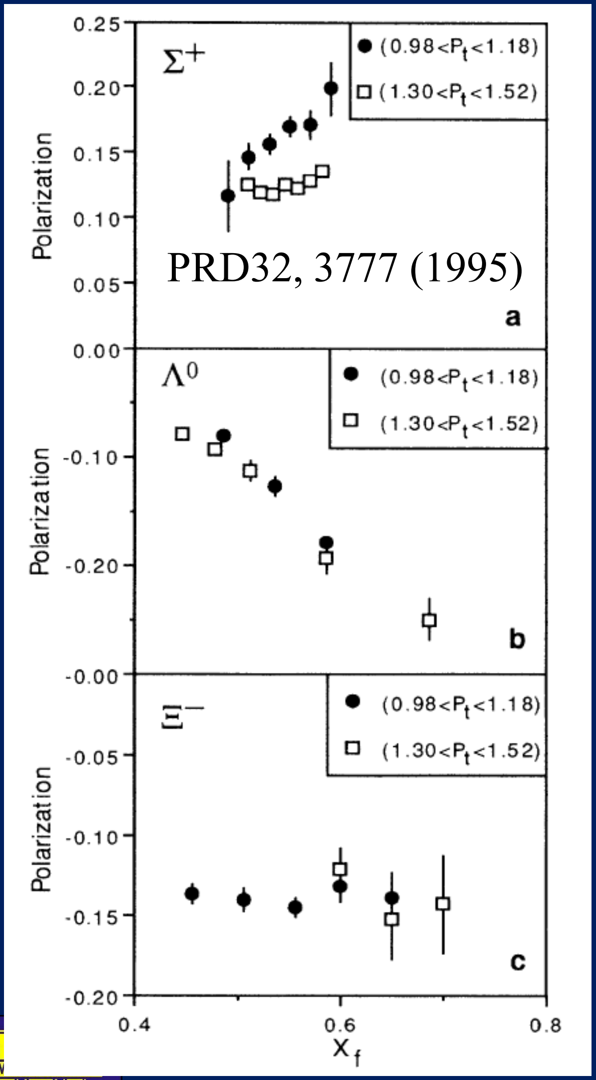
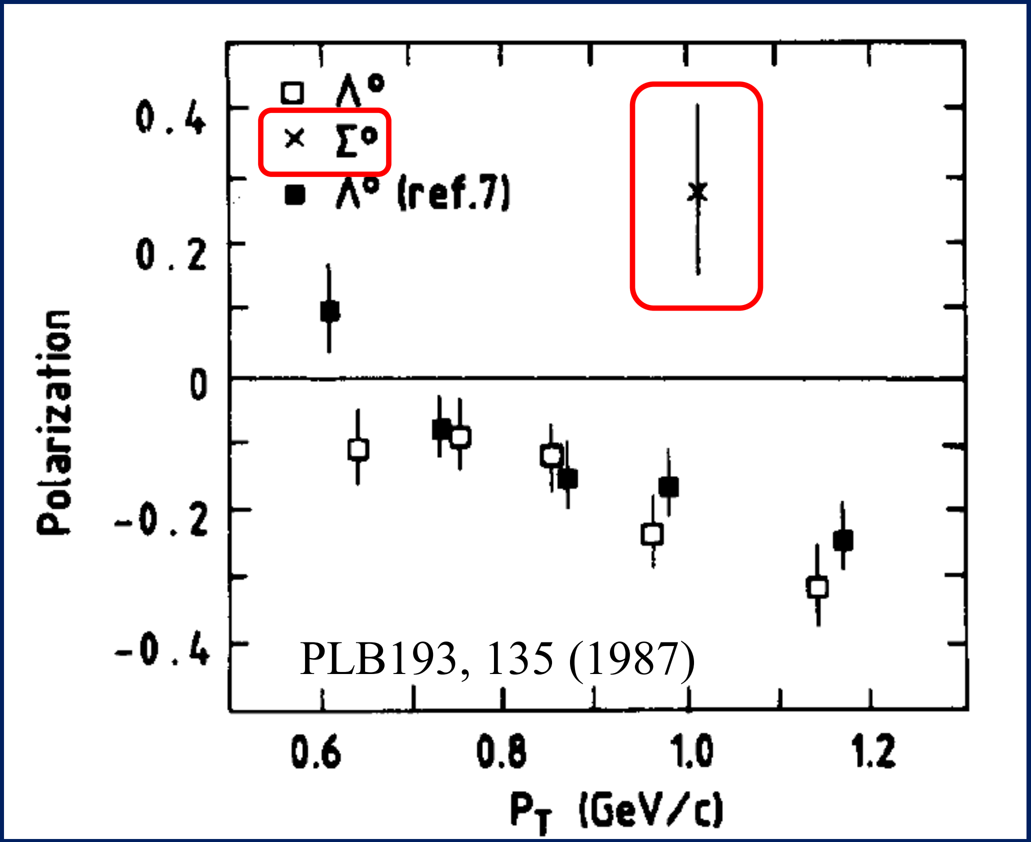


Figure 1: The polarization of hyperons produced by 400 GeV protons.[2,3,4,5,6] All production angles are 5 mrad except the Ξ^o which is 3.5 mrad.

K. Heller, Proceedings, 12th International Symposium on Spin Physics, Amsterdam, 1996

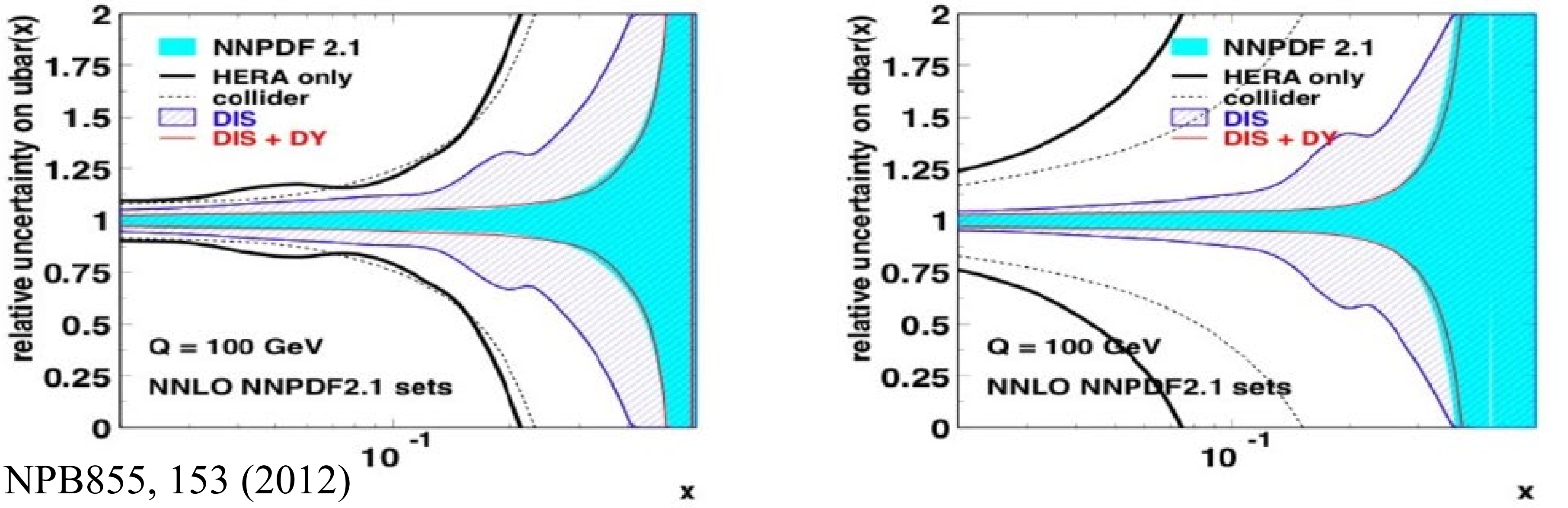
Other hyperon polarization measurements





- p_T dependence for Σ^+ but not Λ^0 or Ξ^-
- Σ^0 appears to have same sign polarization as Σ^+, Σ^- but opposite from Λ (both uds)

Sensitivity of Drell-Yan to sea antiquarks compared to inclusive DIS

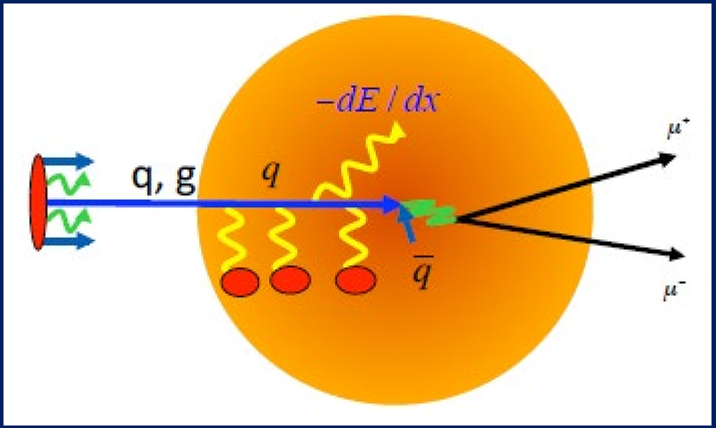


NPB855, 153 (2012)

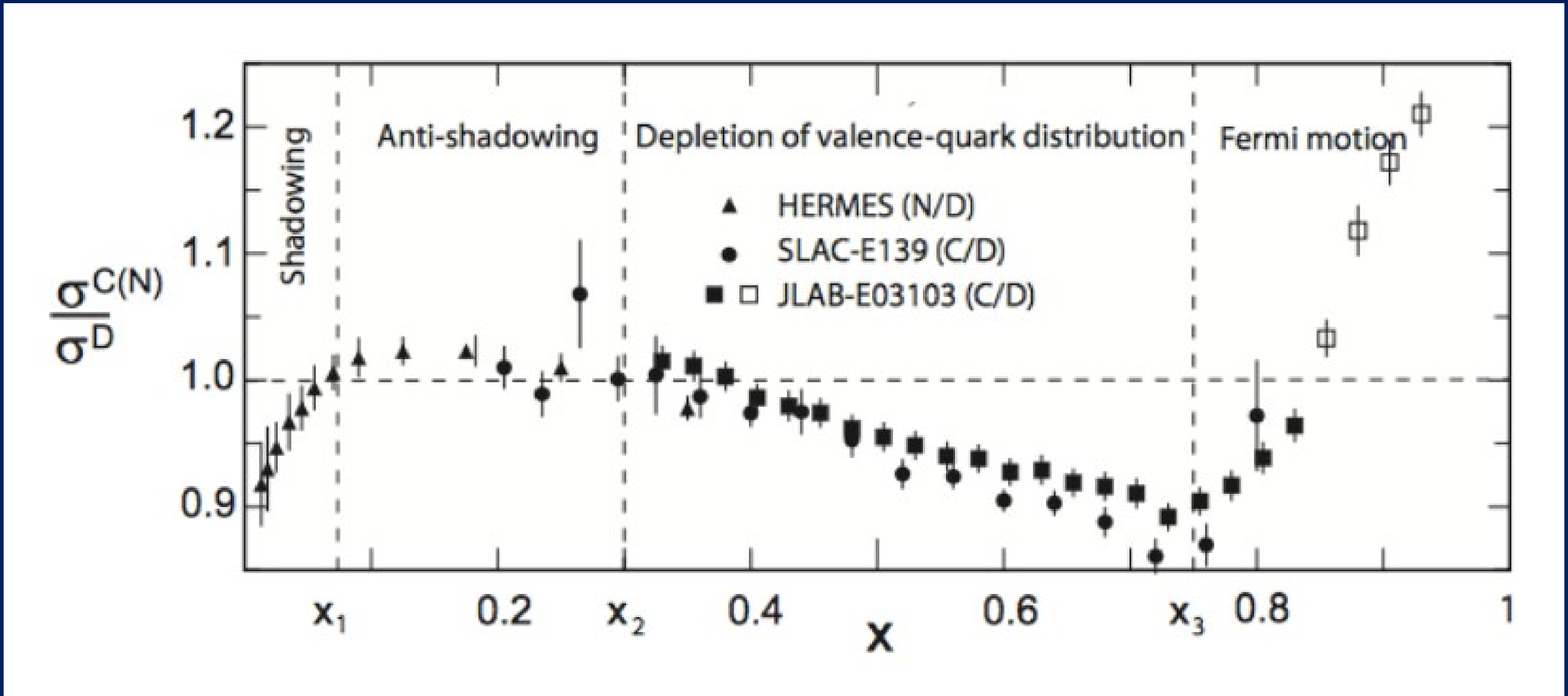
(Very high Q shown)

Parton energy loss in cold nuclear matter

- Understanding parton energy loss in hot, dense nuclear matter (quark-gluon plasma) of great interest in heavy ion community
- Drell-Yan provides clean reference for energy loss in cold nuclear matter—only minimal final-state interactions



DIS data on nuclear targets



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

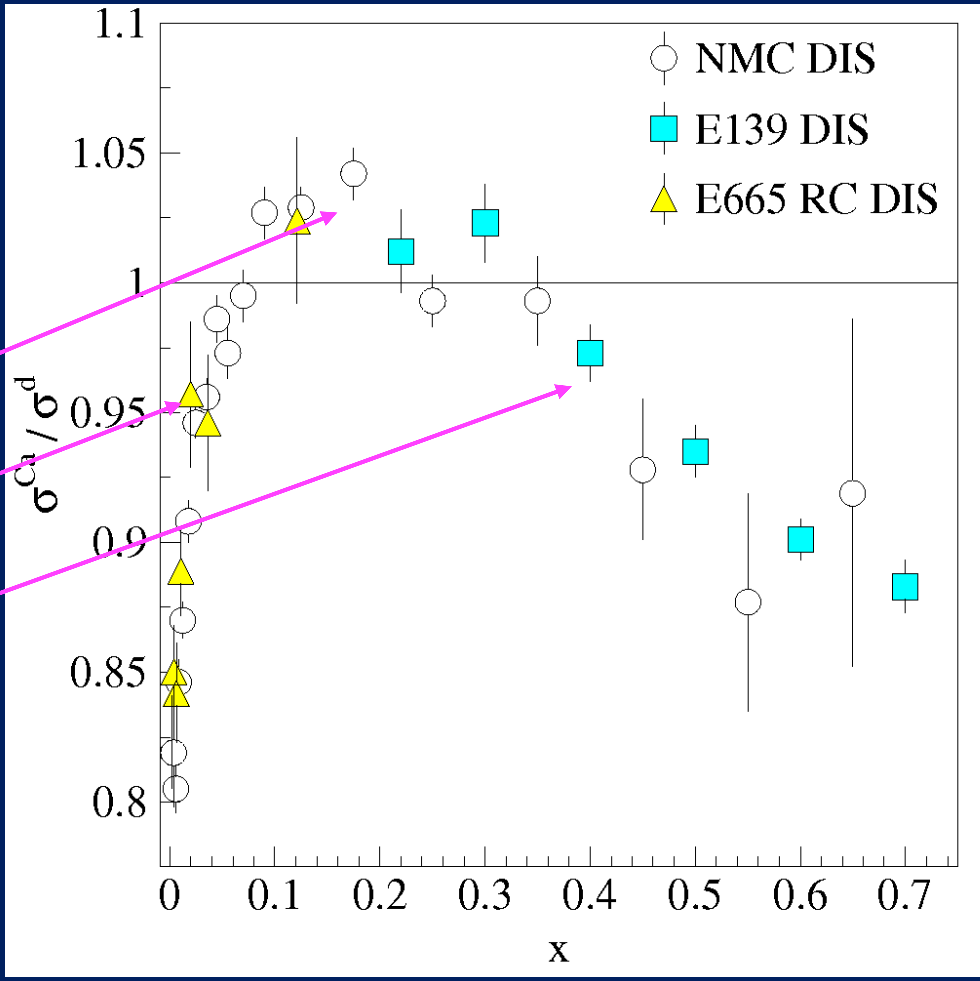
EMC effect with antiquarks?

- DIS results establish nuclear dependence of quark distributions.
- Expectations of large antiquark effects

Anti-Shadowing

Shadowing

EMC Effect



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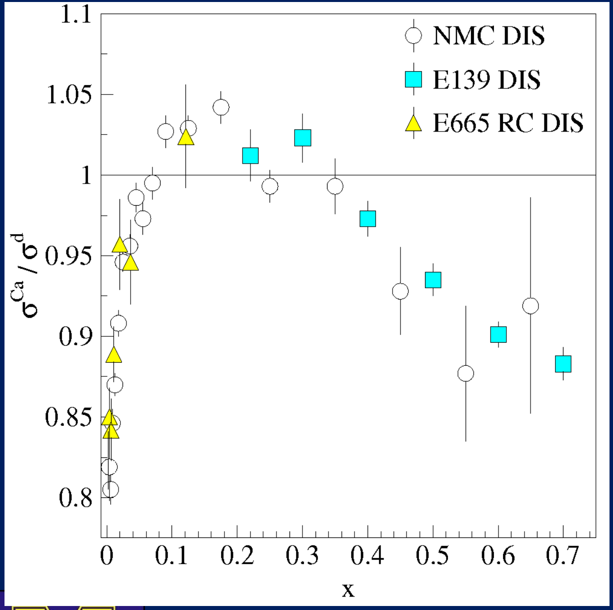
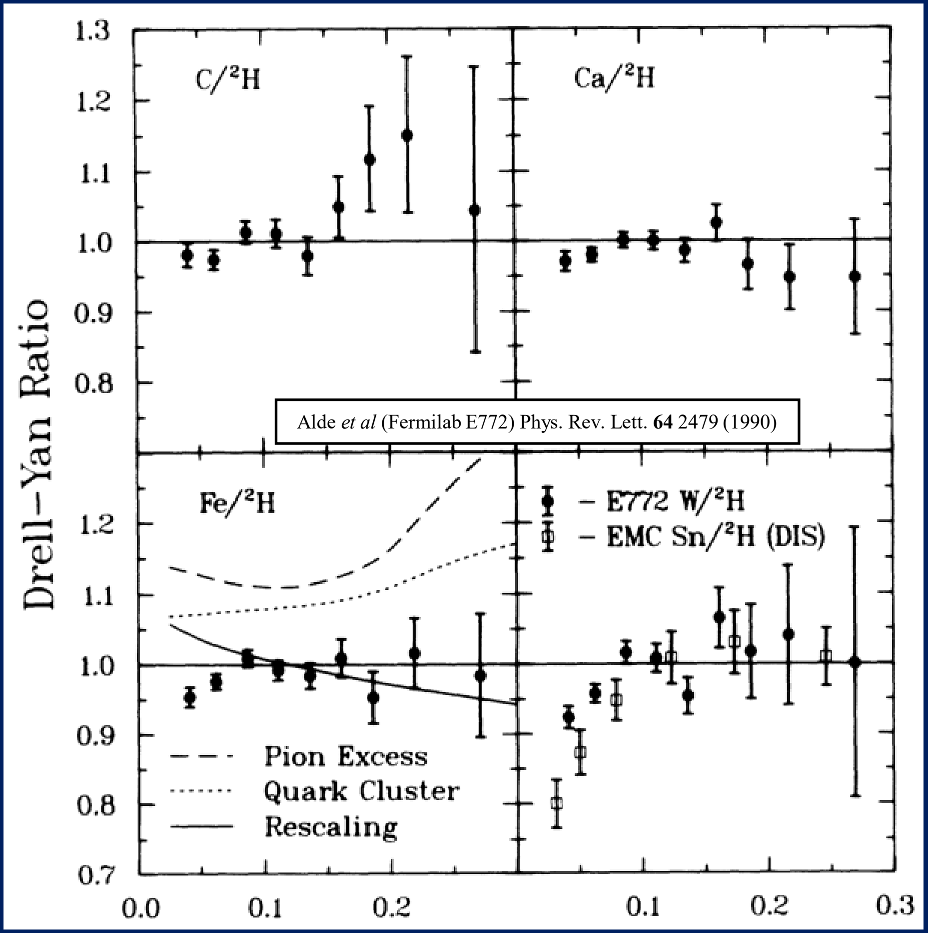
- **No effects were seen in E772 Drell-Yan experiment**





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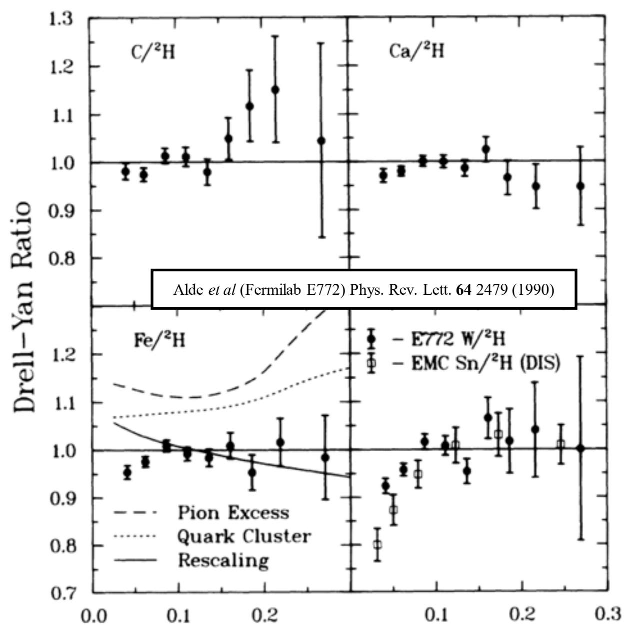
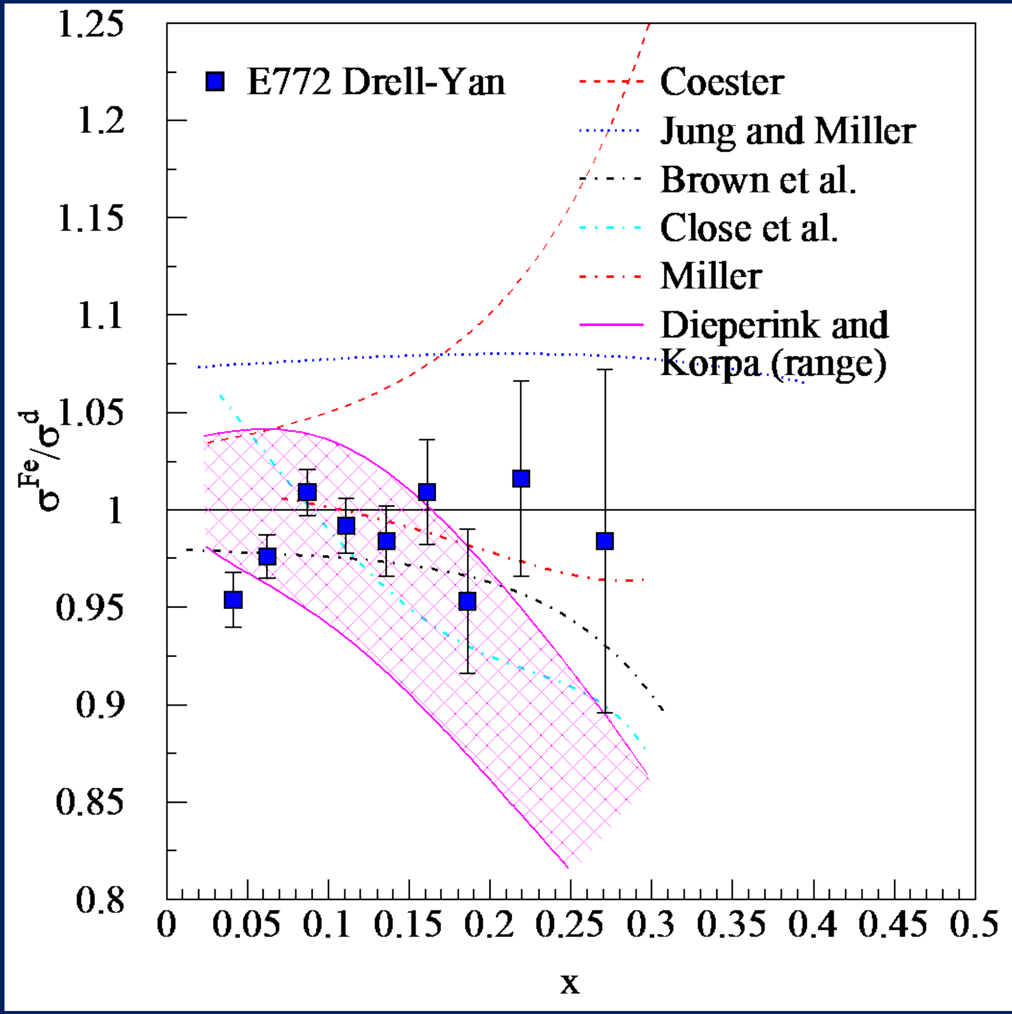
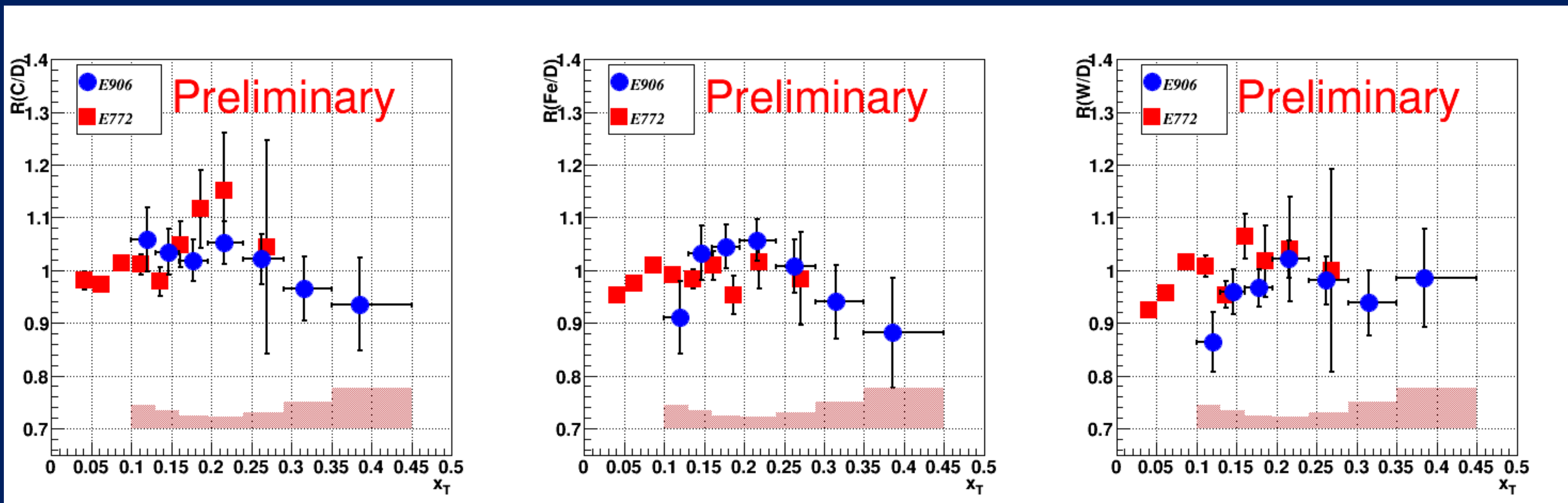




SeaQuest EMC effect nuclear dependence



- No enhancement seen as in the case of a pion excess model!
- Caveat—**partonic energy loss is important**
- In agreement with E772 results in the overlap region