Recent Results and Future Plans for Drell-Yan Measurements at Fermilab

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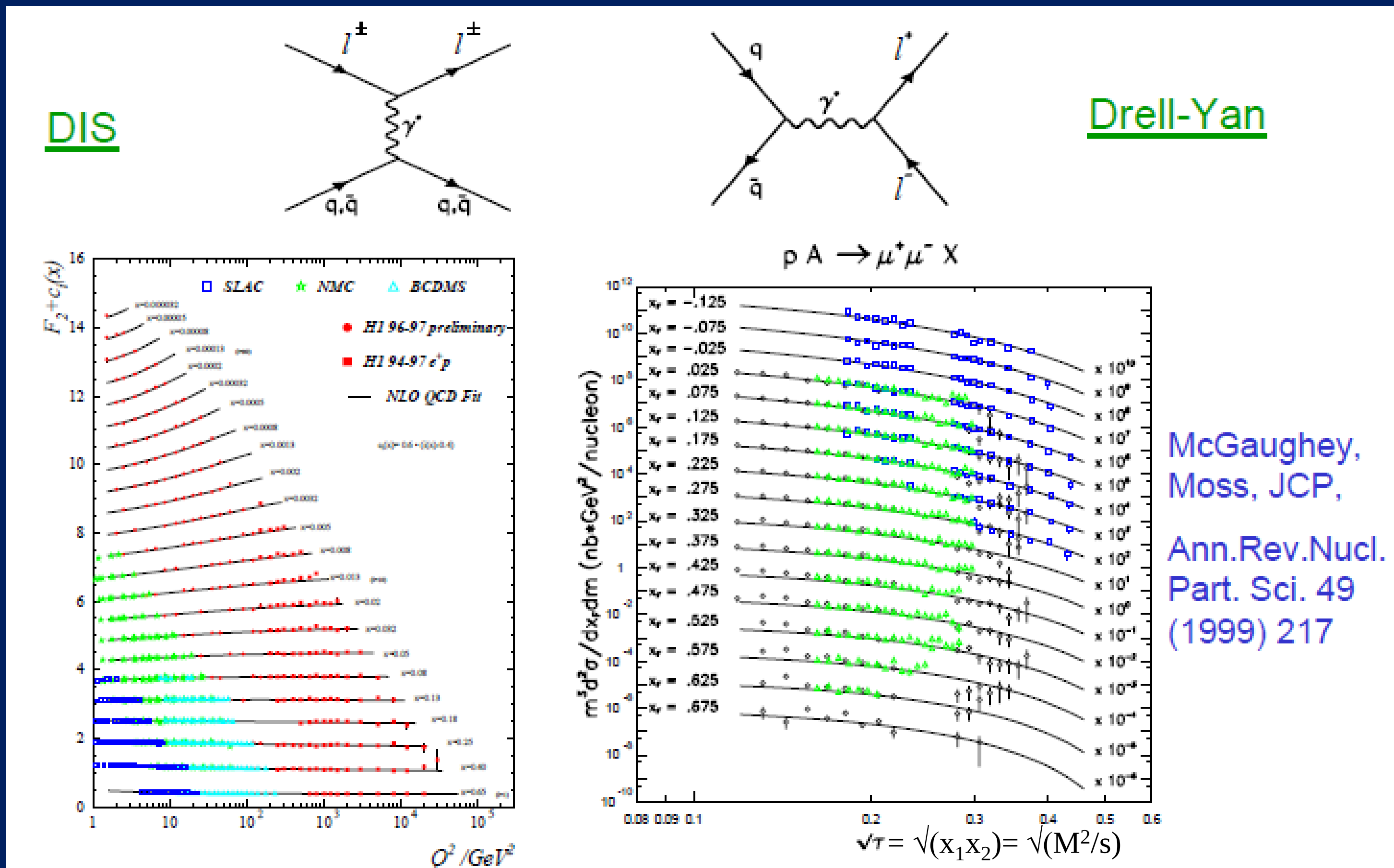
Complementarity of Drell-Yan and DIS



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

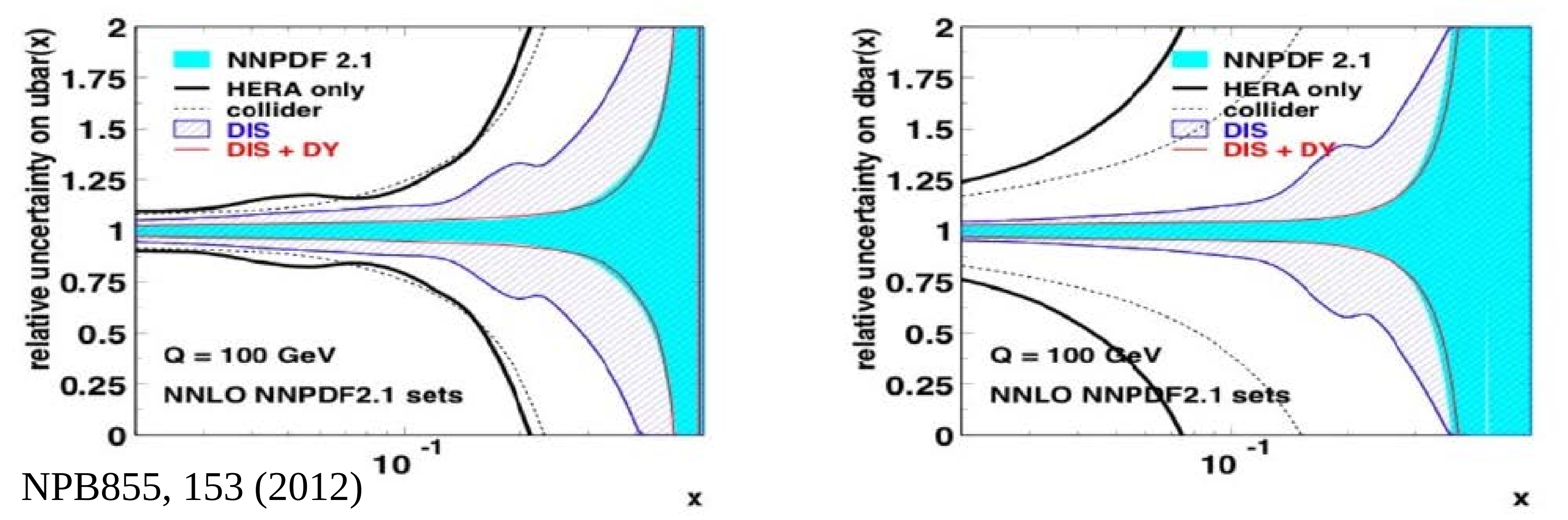
Drell-Yan with a proton beam: Tag antiquarks in target

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

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

  - 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

Sensitivity of Drell-Yan to sea antiquarks compared to DIS



NPB855, 153 (2012)

(Very high Q shown)

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 – Currently running!*

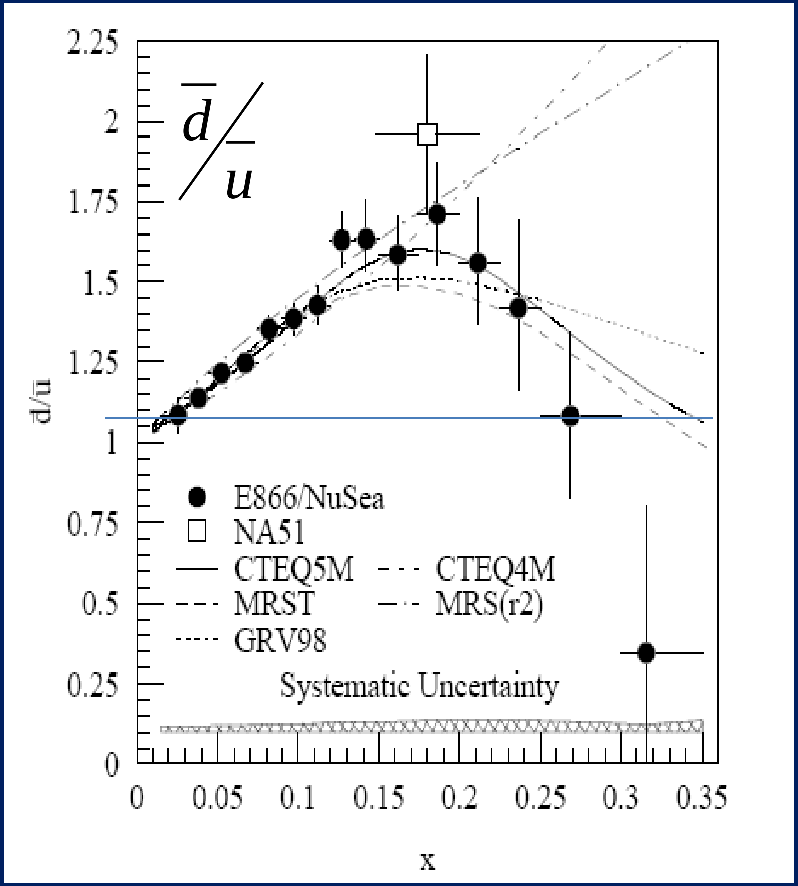
Setting the stage for E906/SeaQuest: Striking flavor asymmetry in sea mapped out by E866

- Proton-hydrogen and proton-deuterium collisions

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

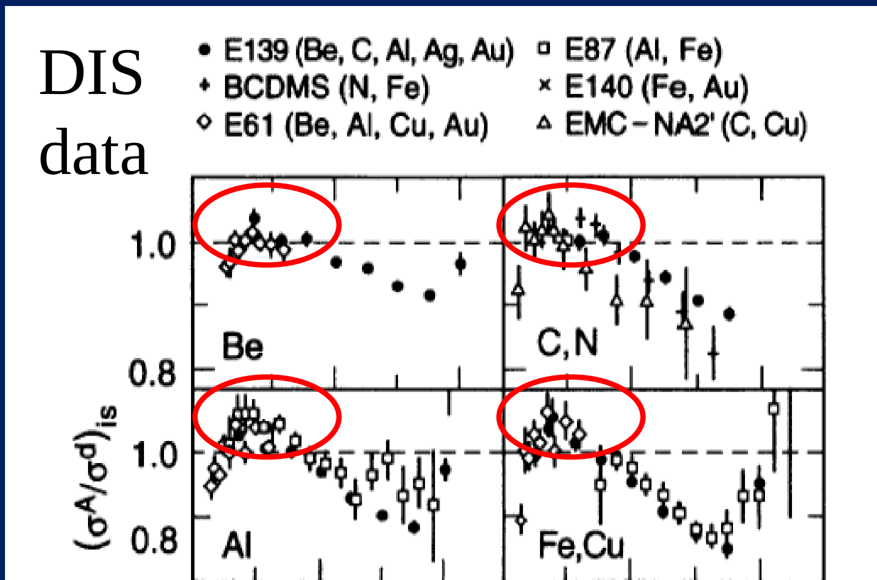
*simplest leading-order expression

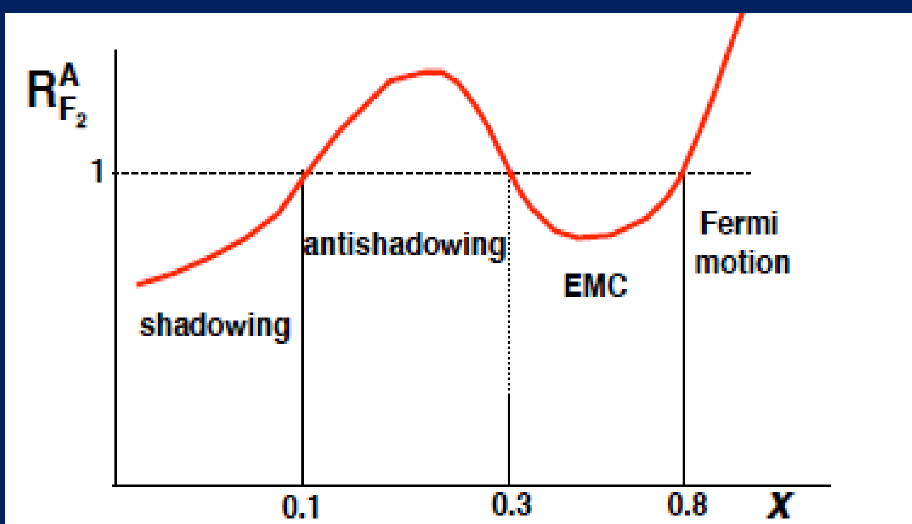
- Expect anti-down/anti-up ratio of 1 if sea quarks only generated dynamically by gluon splitting
- Indicates "primordial" sea quarks—still not well understood!

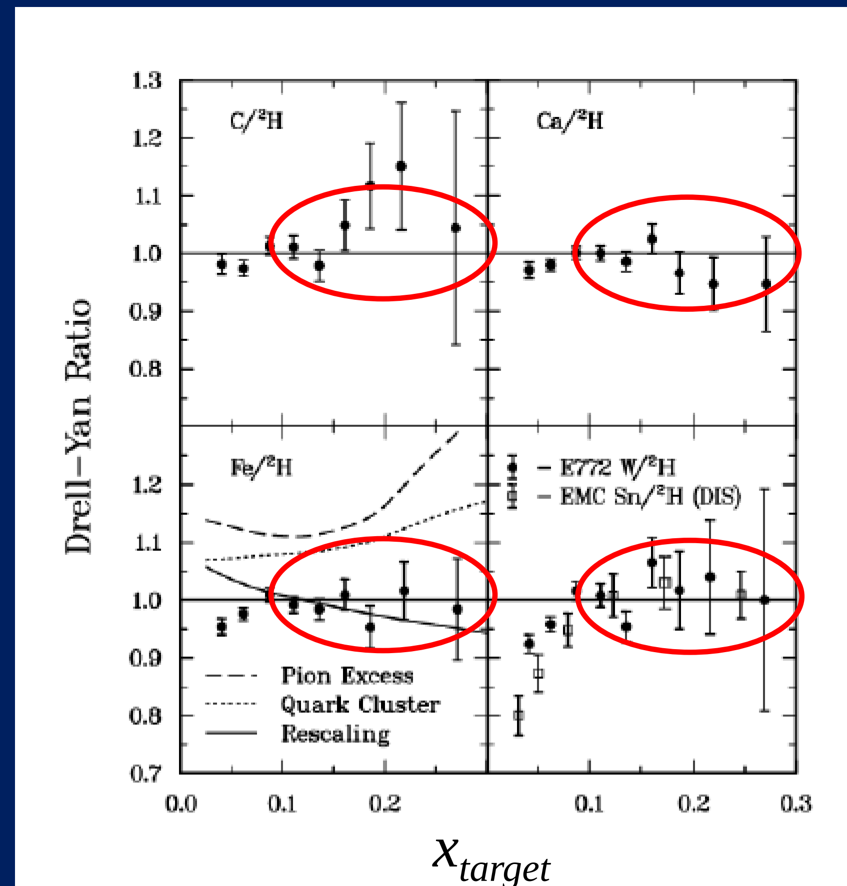


PRD64, 052002 (2001)

…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

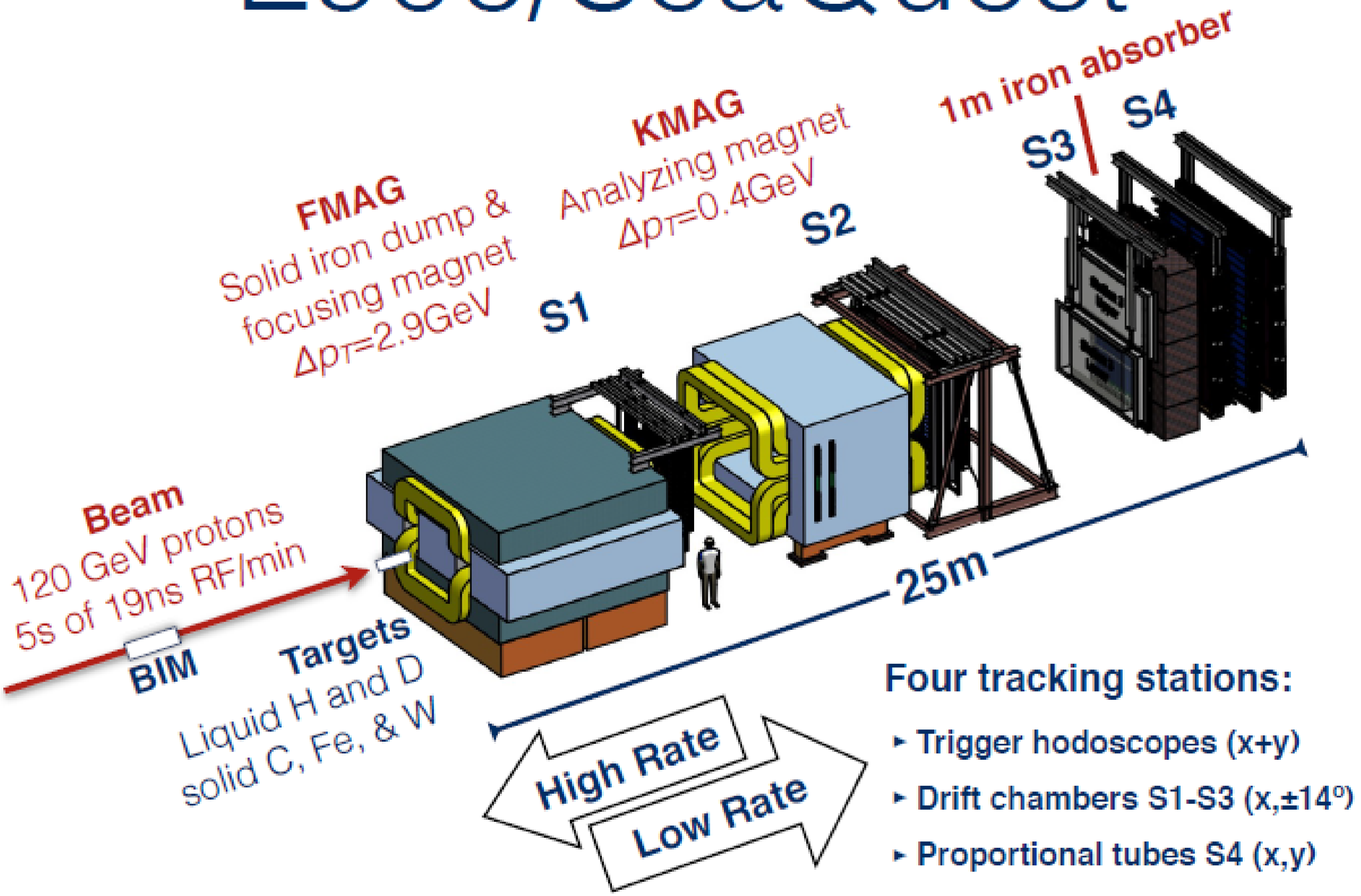
Still lots to learn about nuclei!

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

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

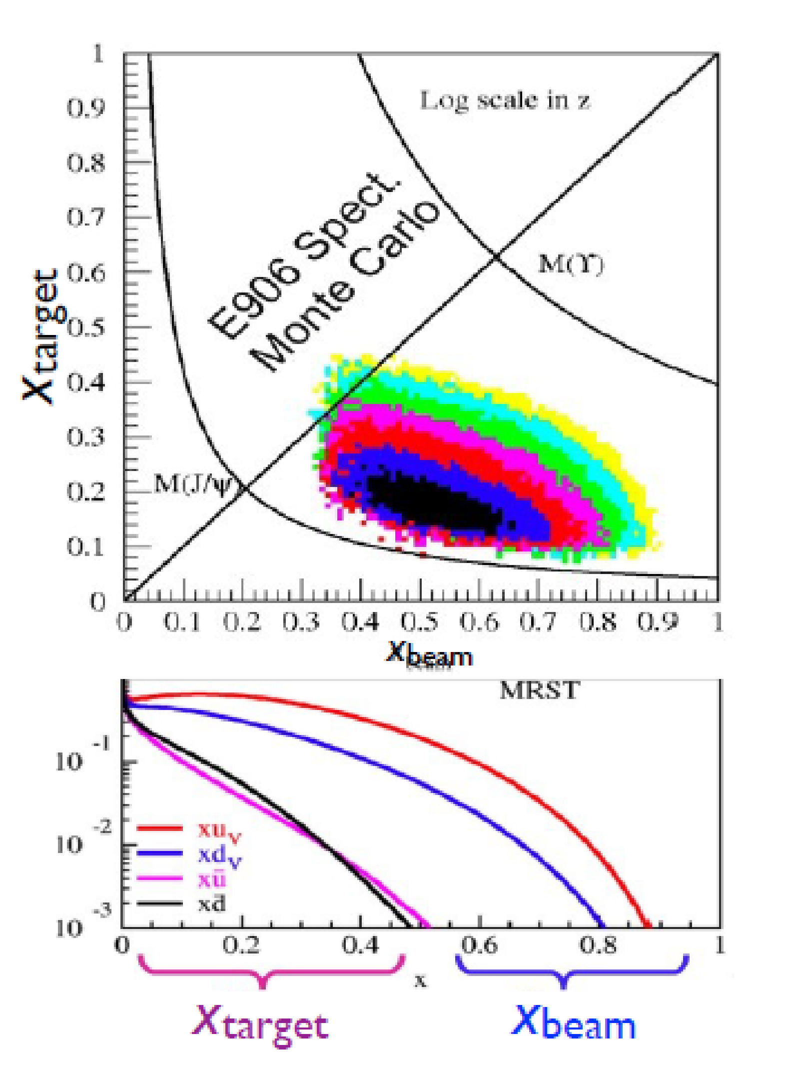
- Both DIS and D-Y data demonstrate rich and intriguing differences for nuclei compared to free nucleons, which vary with the linear momentum fraction probed (and likely transverse momentum, impact parameter, . . .)

E906/SeaQuest



SeaQuest kinematics

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



E906/SeaQuest collaboration

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University of Colorado
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Fermi National Accelerator Laboratory
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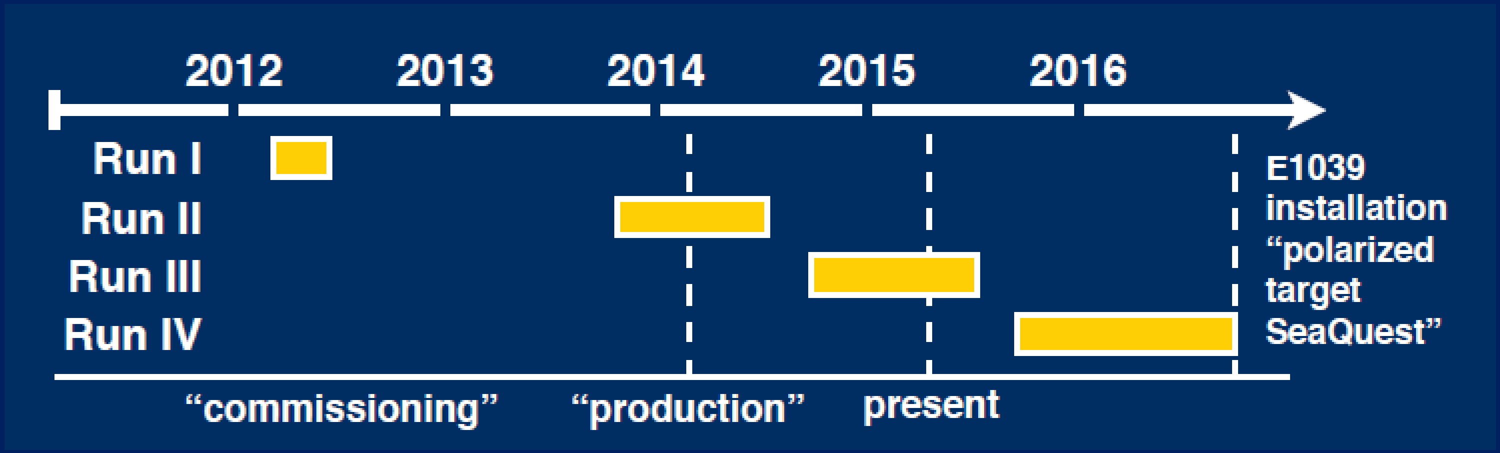
Yuya Kudo, Yoshiyuki Miyachi, Shumpei Nara

* Co-spokespersons

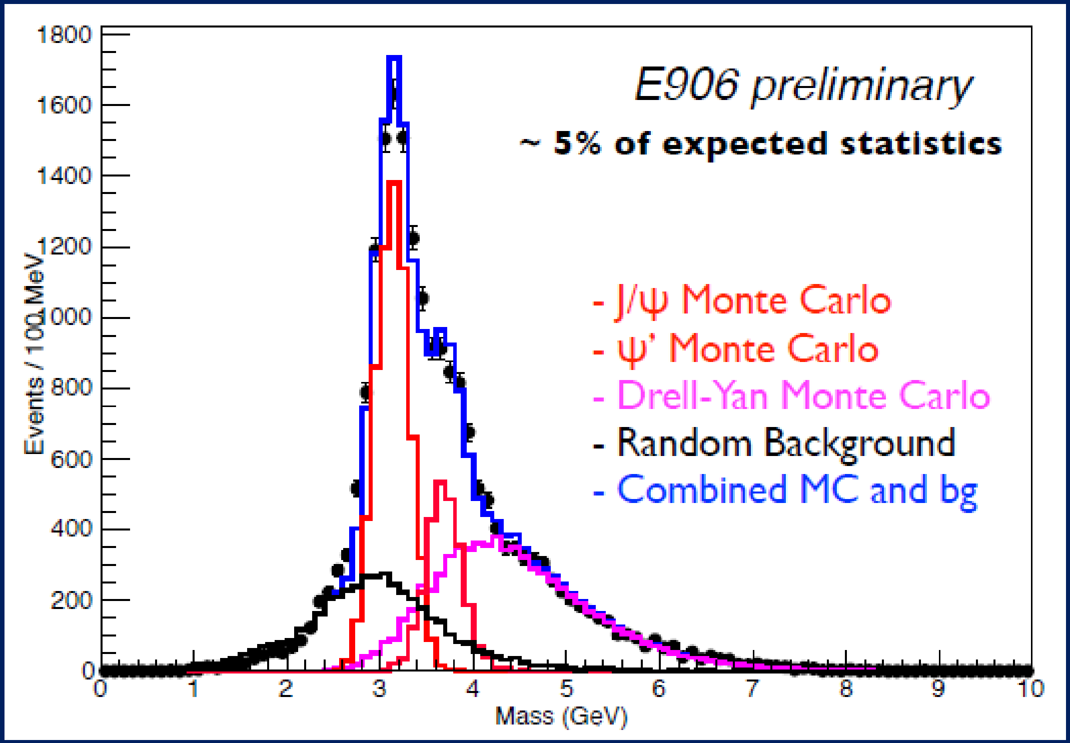
SeaQuest timeline



- (Original proposal 1999! . . .)
- Run I – Commissioning. Observed huge intensity fluctuations
- Run II – Installed beam intensity monitor and new Station-3 drift chamber
- Run III – Installed additional shielding to enable higher intensity running
- Run IV – Will install new Station 1 drift chamber with improved acceptance and plane spacing

Target mass distribution

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



First results! Light sea flavor ratio

- Only 5% of anticipated data
- Systematic uncertainty dominated by target-dependent variation in collection efficiency with beam intensity—expected to drop to ~1% after corrections
- Already comparable high-x_{target} statistics to E866 result
- Suggests ratio does not drop off sharply
- Installation of new Station 1 chamber will enhance high-x_{target} acceptance

During the workshop, SeaQuest Preview results on the antidown-to-antiup ratio were shown. These results are not publicly available.

Please contact SeaQuest spokesperson Paul Reimer (reimer@anl.gov) if you would like a copy of these results.

MICHIGAN

First results! Nuclear effects

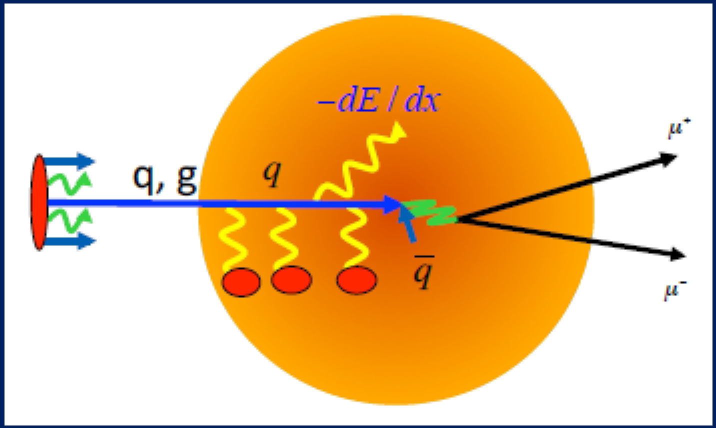
During the workshop, SeaQuest Preview results on ratios of Drell-Yan production in carbon, iron, and tungsten to deuterium as a function of x_{target} were shown. These results are not publicly available.

Please contact SeaQuest spokesperson Paul Reimer (reimer@anl.gov) if you would like a copy of these results.

- 10% of anticipated data
- Systematic uncertainty will also be greatly reduced
- Consistent with E772
- Pushing into x range ($0.3<x<0.8$) where DIS sees a depletion of the valence densities ("EMC effect"). *What will the sea do??*

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



Parton energy loss in cold nuclear matter

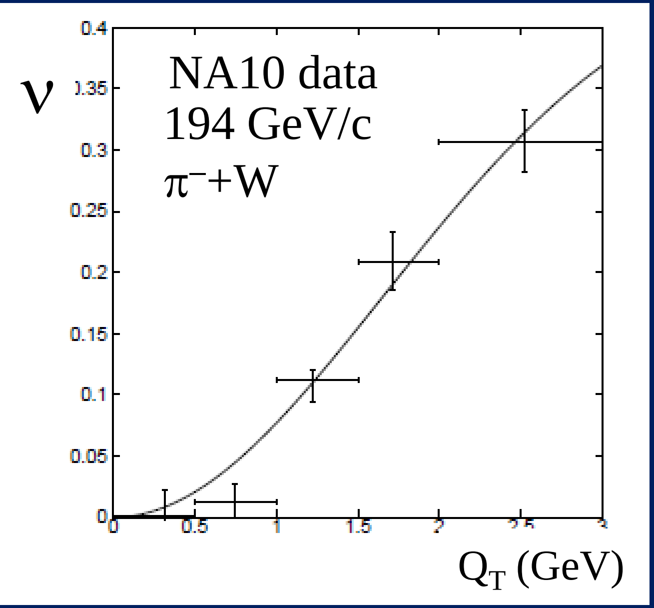
During the workshop, SeaQuest Preview results on ratios of Drell-Yan production in carbon, iron, and tungsten to deuterium as a function of x_{beam} were shown. These results are not publicly available.

Please contact SeaQuest spokesperson Paul Reimer (reimer@anl.gov) if you would like a copy of these results.

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

Probing quark spin in unpolarized Drell-Yan

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

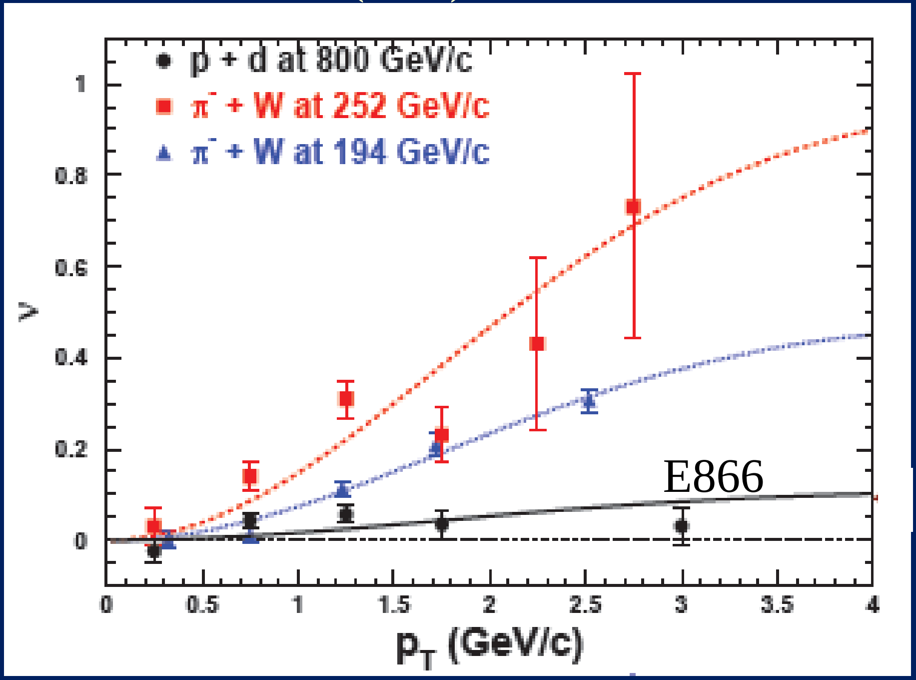


D. Boer, PRD60, 014012 (1999)

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

What about proton-induced Drell-Yan?

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



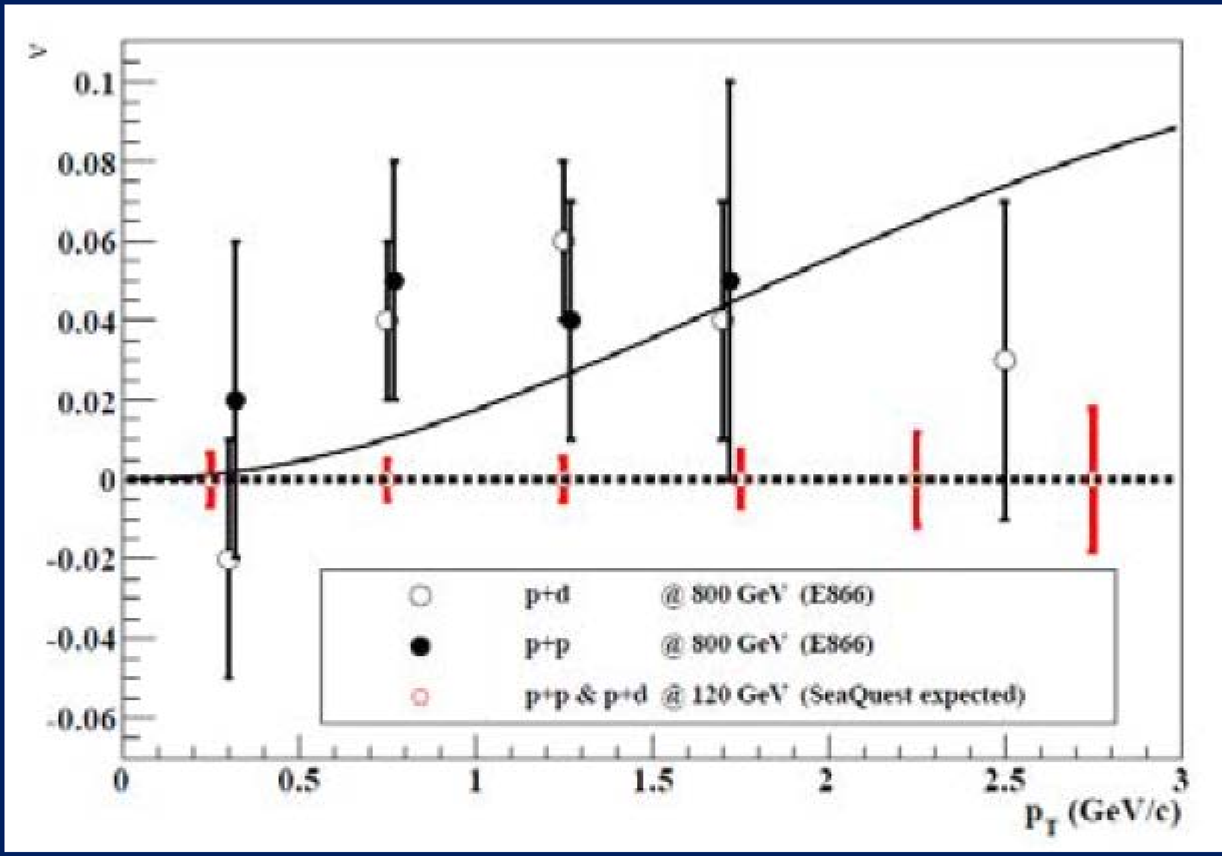
- Significantly reduced cos2ϕ dependence in proton-induced D-Y
- Suggests sea quark transverse spin-momentum correlations small?
- What about higher-*x* sea quarks in E906??
  - E906 statistics dominated by x_{target} near flavor asymmetry peak
  - Probe flavor asymmetry origins via sea quark *dynamics*

Boer - Mulders function $h_1^\perp$

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

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

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



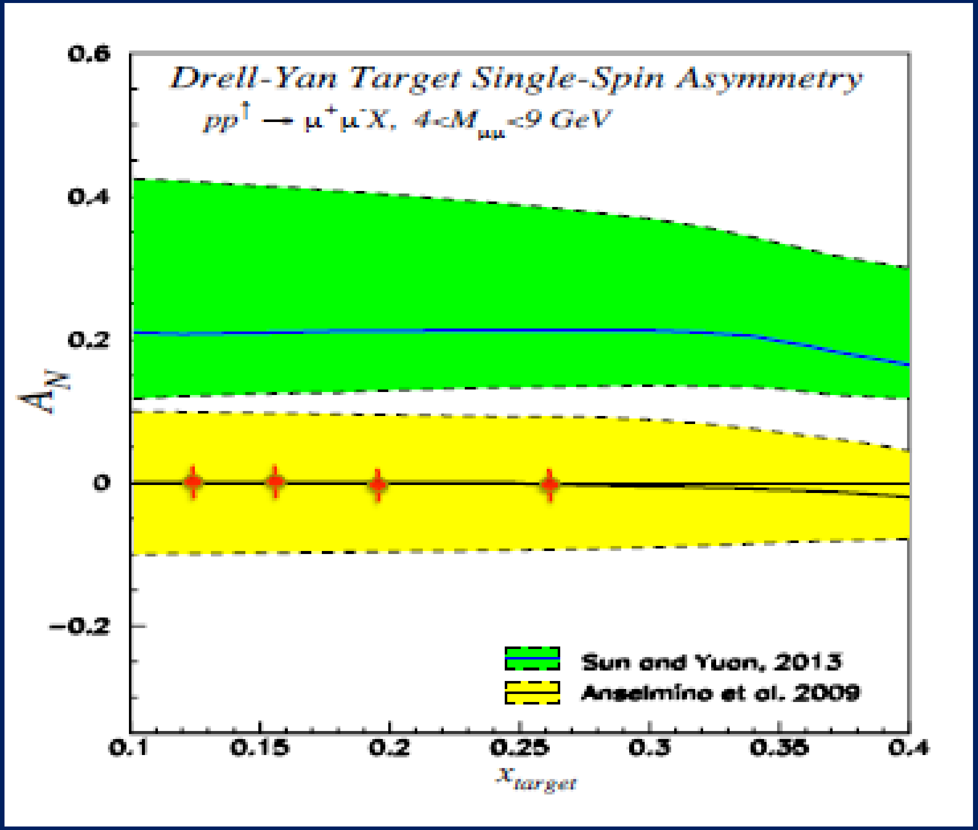
- Significantly reduced uncertainties expected compared to E866

After E906/SeaQuest: Polarized target experiment E1039

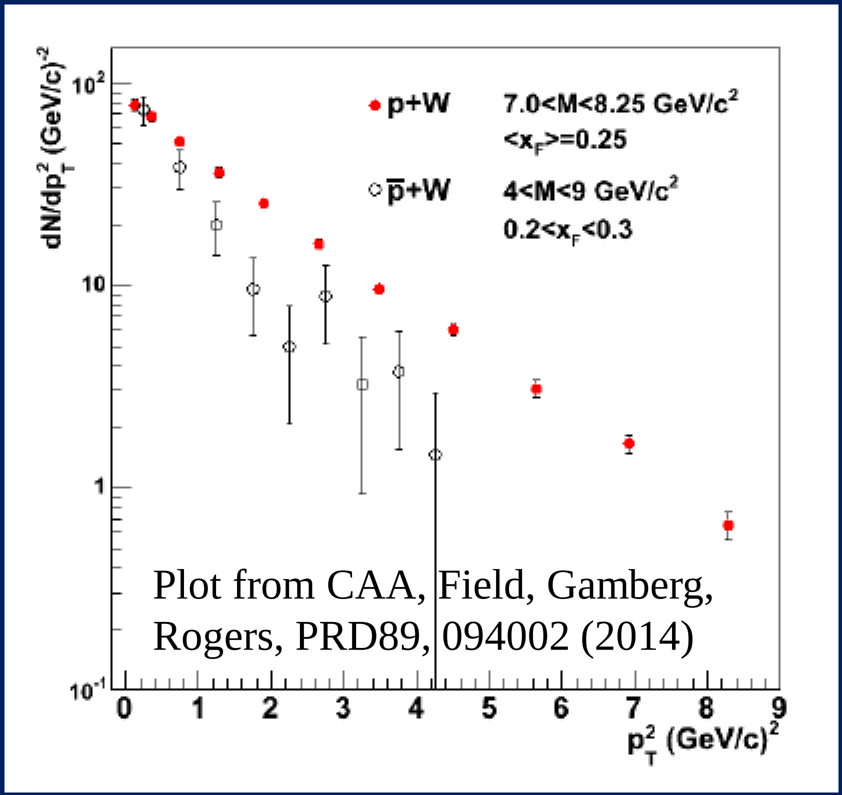
- Transversely polarized frozen NH_3 target
  - Los Alamos National Lab, U. Virginia
- Dynamic nuclear polarization
  - Prototype working, already existing 5 T magnet reconfigured for transverse polarization
- Shutdown second half of 2016
  - Remove unpolarized targets
  - Beam line optics and shielding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



Sea quarks—many hints of interesting behavior already!



Plot from CAA, Field, Gamberg, Rogers, PRD89, 094002 (2014)

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

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

Transversity for sea quarks large and flavor-asymmetric??

Transversity Distribution

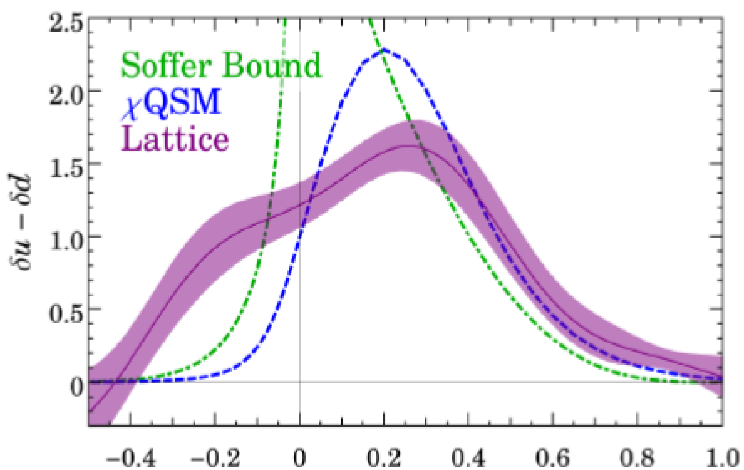
§ Exploratory study

- We found $\delta\bar{u} < \delta\bar{d}$ with large sea asymmetry

$$\int dx\,(\delta\bar{u}(x) - \delta\bar{d}(x)) \approx -0.26(10)$$

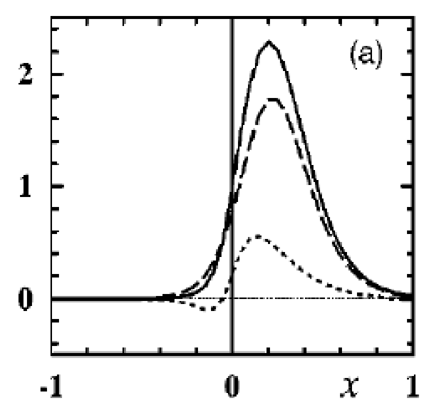
- Chiral quark-soliton model

$$\int dx\,(\delta\bar{u}(x) - \delta\bar{d}(x)) \approx -0.082$$



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

CQS model



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

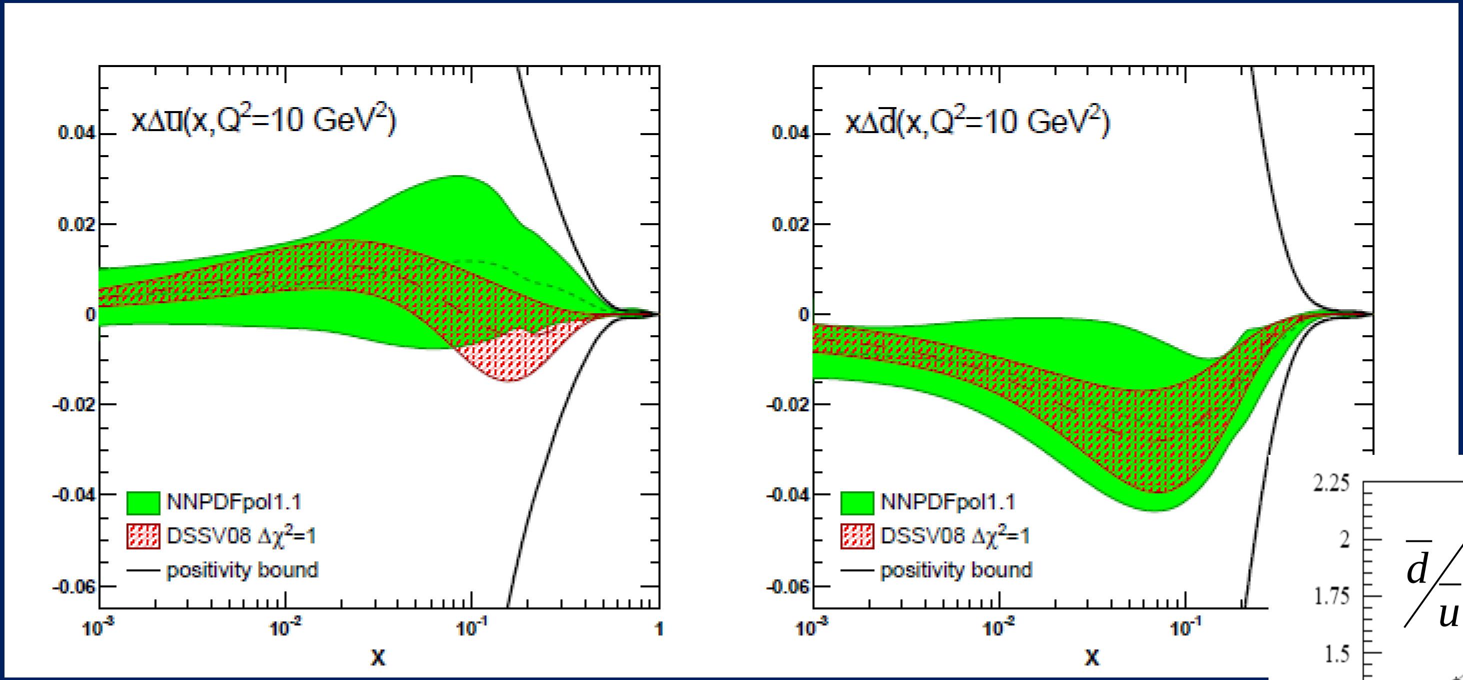
UNIVERSITY OF WASHINGTON

Huey-Wen Lin — Light Cone 2014

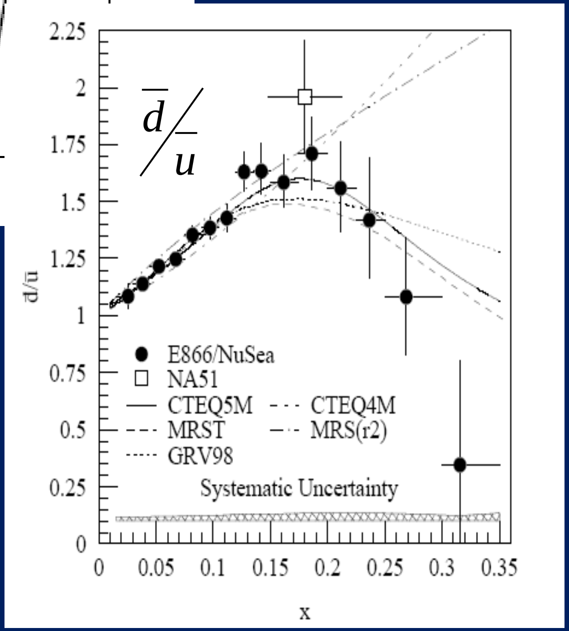
Preliminary lattice calculation finds transversity for sea large and flavor-asymmetric!

Flavor asymmetry in the sea helicity distributions

NNPDF, NPB 887.276 (2014)

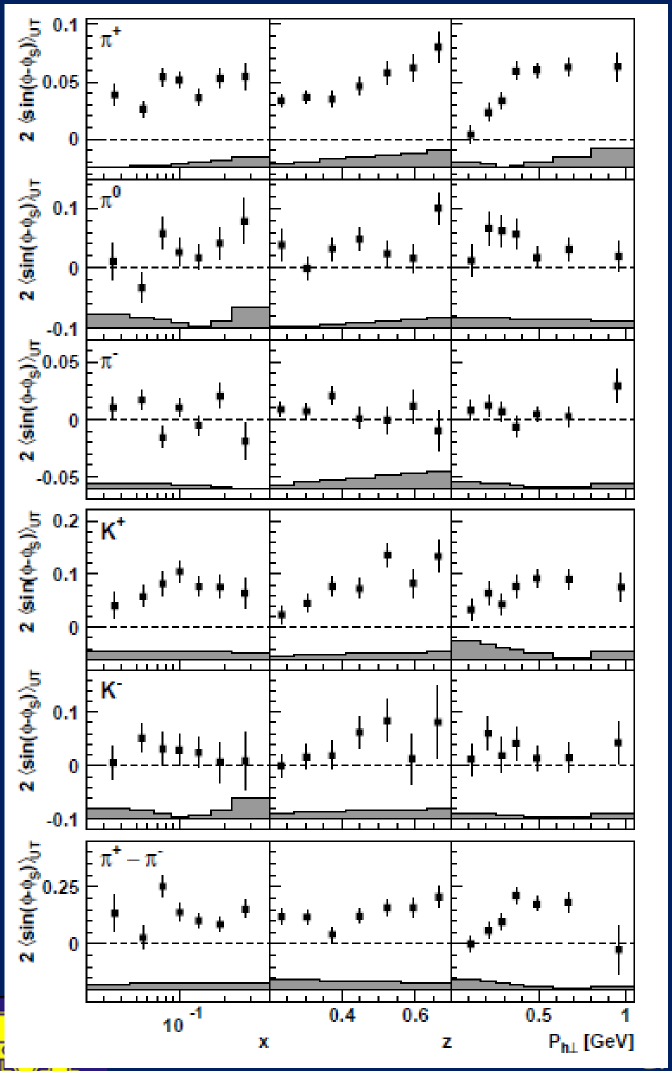


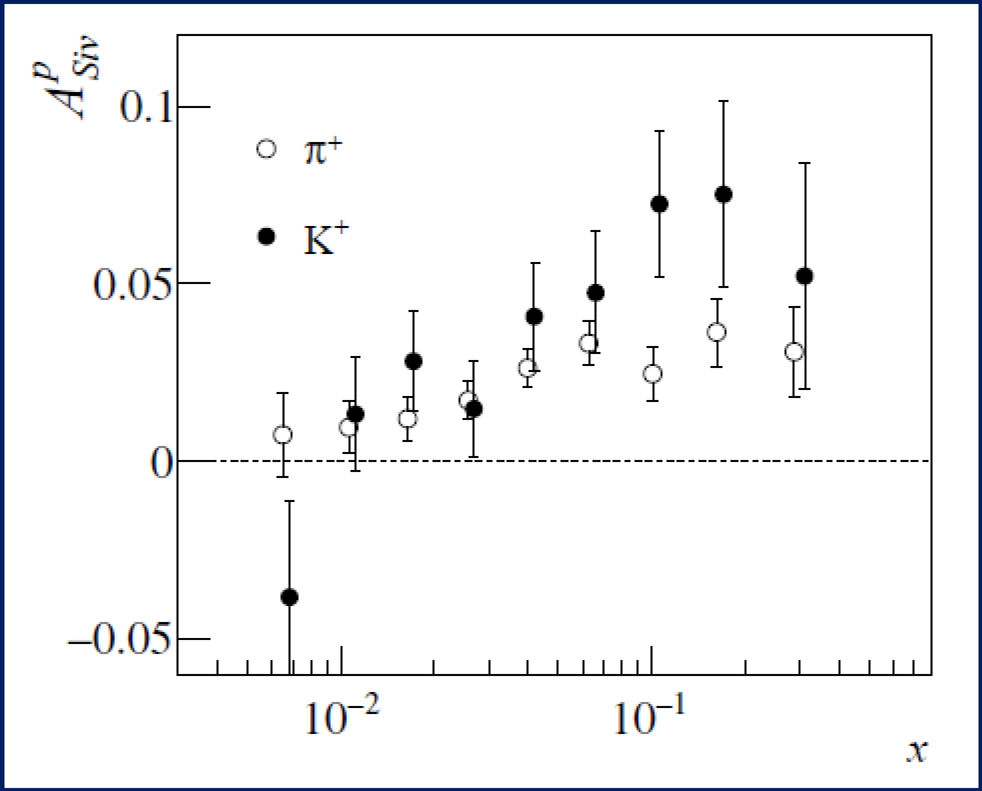
(DSSV08: Before RHIC W data)



And of course flavor asymmetry in unpolarized sea

SIDIS Sivers asymmetries larger for K^+ than π^+

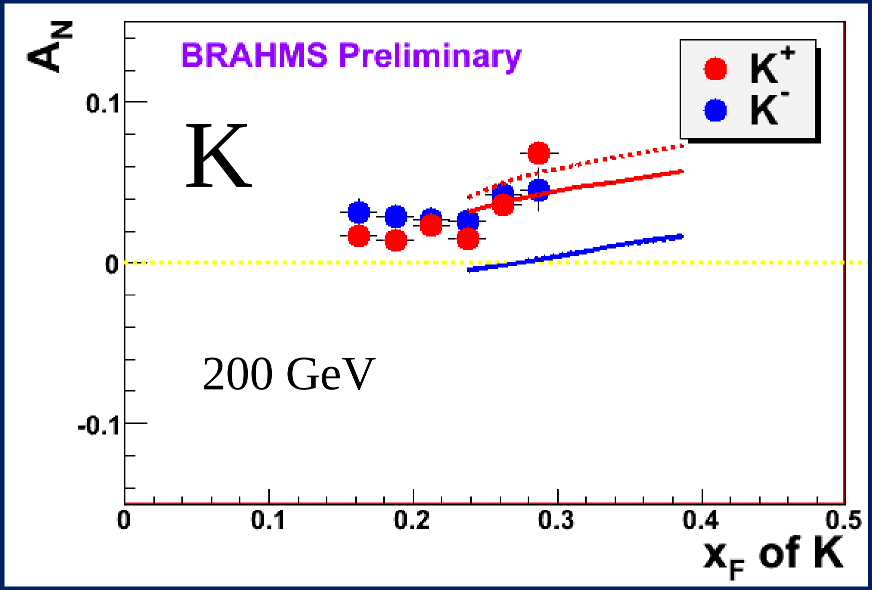


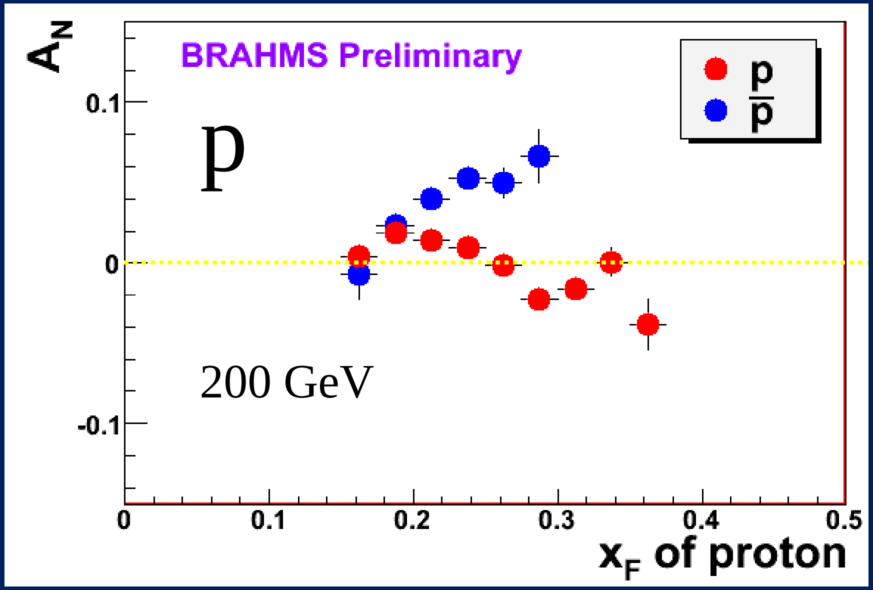


COMPASS, PLB744, 250 (2015)

HERMES, PRL103, 152002 (2009)

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

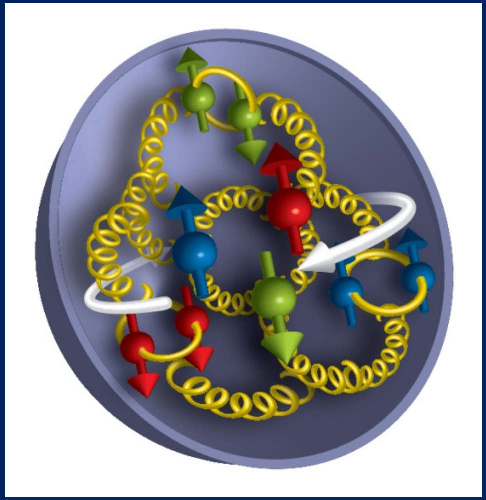




BRAHMS

Need more experimental data!

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



- Understanding the *dynamics* of sea quarks, which probe beyond static pictures of antiquarks in the nucleon, will be crucial to understanding how the nucleon sea is generated (and what in fact it is!)

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)*

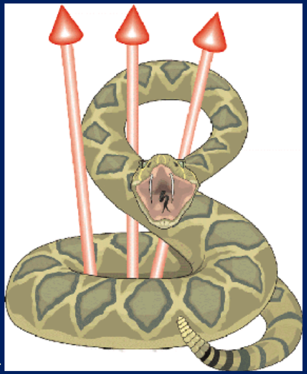
**not constrained by SIDIS data* / # rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams)

W. Lorenzon (U-Michigan)

Polarizing the Fermilab Main Injector: History

- In 1991-95 Fermilab Director John Peoples commissioned studies to examine what would be needed to polarize the (planned) Main Injector (as well as the already existing Tevatron)
  - Spin@Fermi collaboration, led by A. Krisch
- August 2011 - Update of 1995 report submitted by Spin@Fermi collaboration to Fermilab
  - arXiv:1110.3042
- Spring 2012 - Formal experiment proposal submitted to Fermilab
- Spring 2012 - Impact study and cost estimate by Fermilab
- 2012-13 long shutdown – No longer space for 2 snakes after accelerator modifications!

History, cont.



- 2012-13 - Development of novel single-snake design
  - arXiv:1309.1063
  - Concept proposed decades ago by Kondratenko (published in SPIN proceedings), but never implemented
- May 2013 – Workshop at Fermilab
- Fall 2013 - Stage-1 approval by Fermilab directorate based on single-snake design

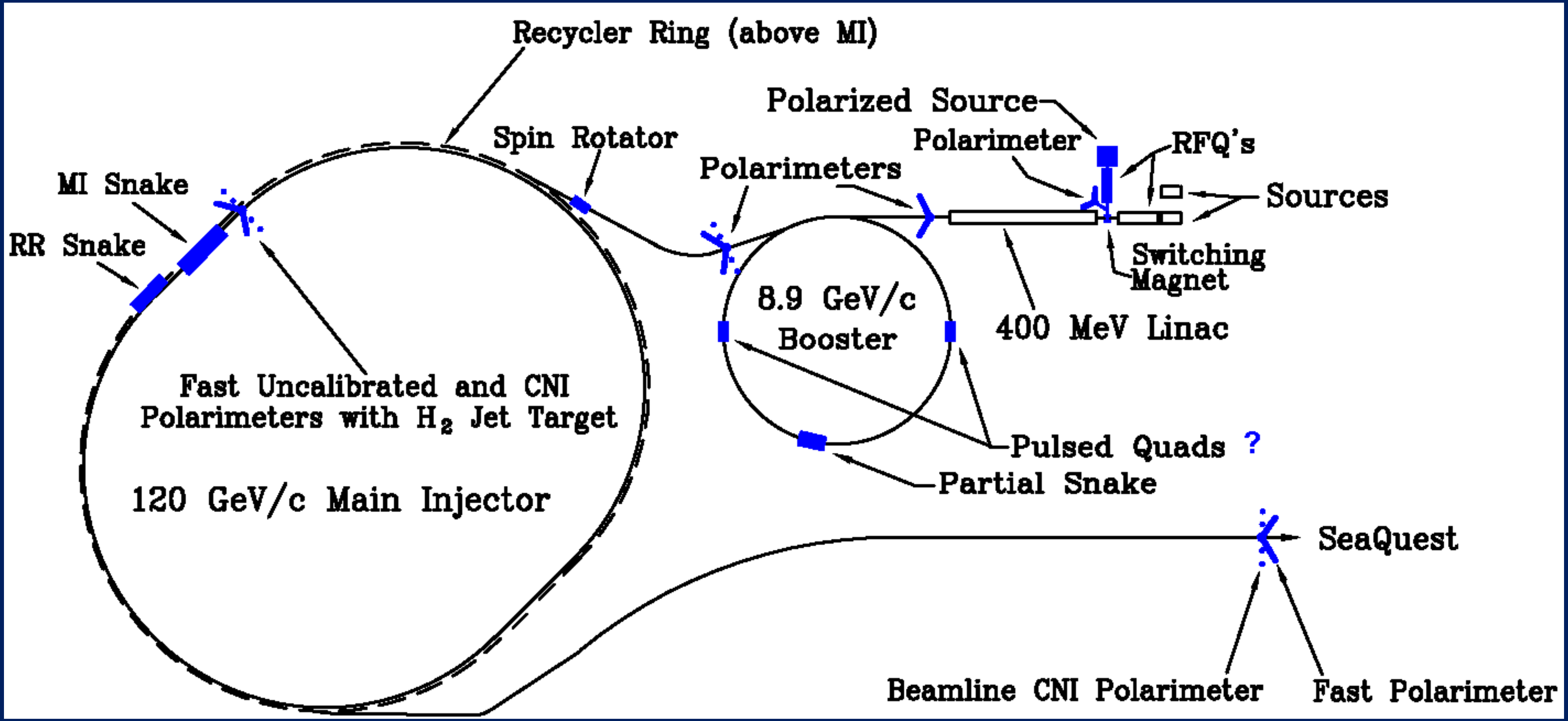
- Current status: Have conceptual design that works *at least for a perfect machine*—perfect magnet alignment, perfect orbits, no momentum spread, etc.
- Now: Starting to perform detailed spin-tracking simulations with more realistic parameters

Single snake with single, 4-twist helical dipole

- Compared to RHIC with 2 snakes, each 4 single-twist helical dipoles - Reduced space requirement
- More flexible placement around machine
  - Doesn’t need to be 180 degrees from a second snake
  - Potentially useful for non-circular accelerator geometries—JPARC?? (triangular configuration)

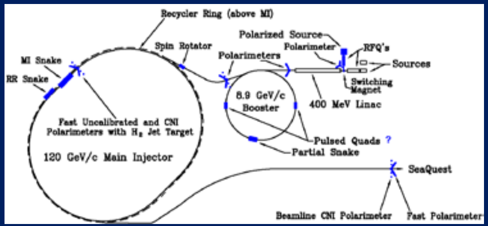
- Smaller excursions—allow wider dynamic range from injection to top energy
- Reduction in cost—1 helical dipole instead of 8, correspondingly reduced cryogenic needs

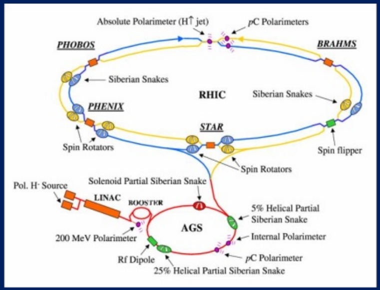
Proposed modifications for polarized beam



Differences compared to RHIC

- **Most significant difference**: Ramp time of Main Injector < 0.7 s, at RHIC 1-2 min
  - Warm magnets at MI vs. superconducting at RHIC
  - *Pass through all depolarizing resonances much more quickly*
- Beam remains in MI 5 s, in RHIC ~8 hours
  - Extracted beam vs. storage ring
  - Much less time for cumulative depolarization

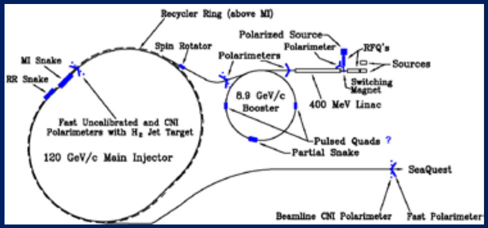


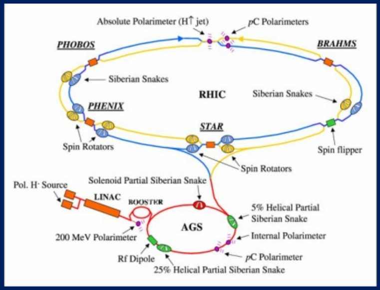


Differences compared to RHIC (cont.)

- Additionally, Main Injector runs ~48 weeks/year. Plan is for polarized protons 6 s/minute or 1 min/10 min (unpolarized source for neutrino experiments for 90% of time). Can work on polarization development continuously.

- Disadvantage compared to RHIC—no institutional history of accelerating polarized proton beams
  - Fermilab E704 used hyperon decays





Next steps and prospects

- Need full, detailed accelerator simulations to get to a point where a technical design review could be performed
- Collaborating with accelerator physicist Mike Syphers at Michigan State U.
- Fermilab Accelerator Division staff scientist will contribute part-time starting in the fall
- Stay tuned . . .

Summary

- E906/SeaQuest continues a long tradition of Drell-Yan experiments at Fermilab
- Very first results out!

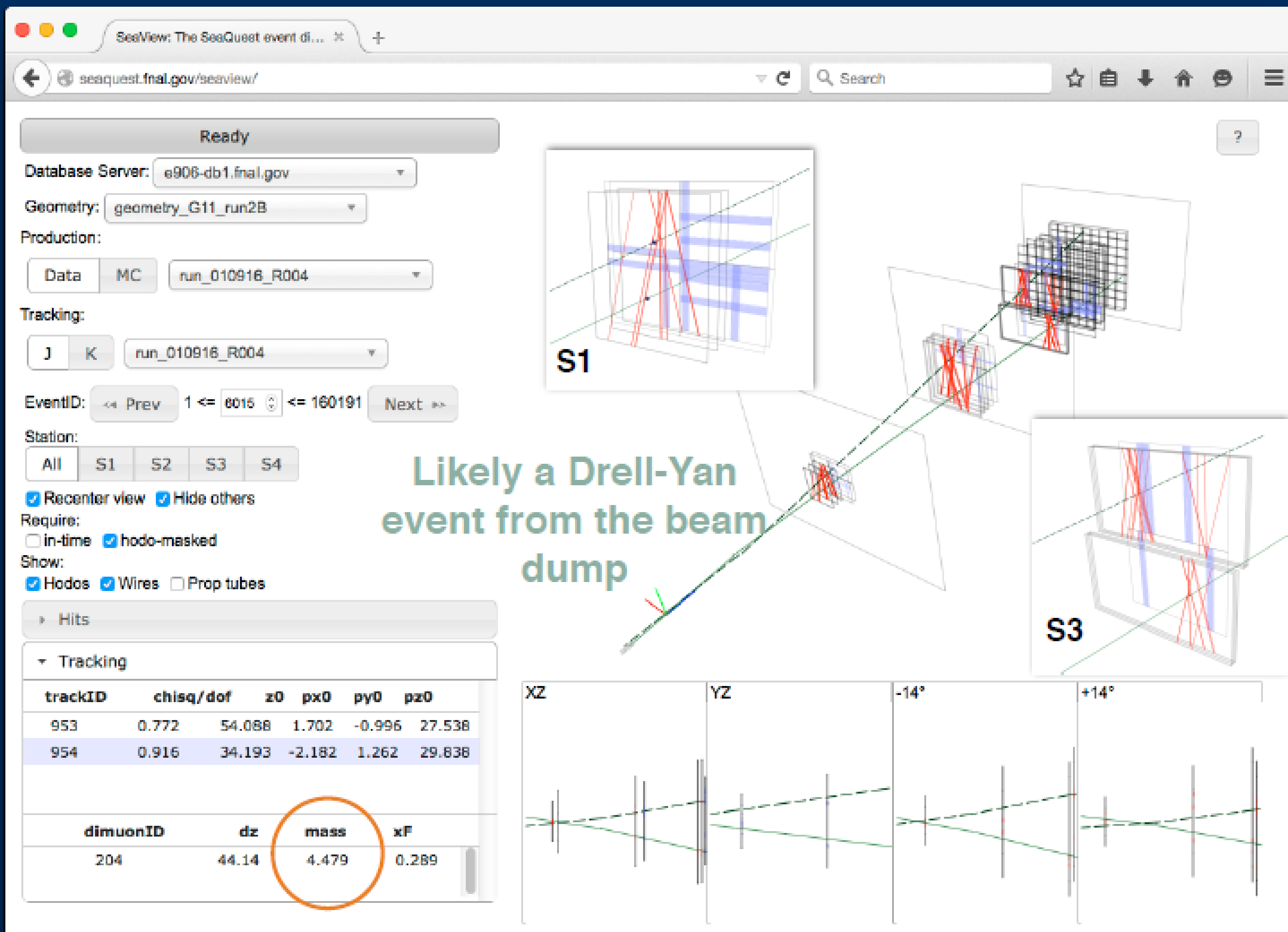
  - dbar/ubar, nuclear cross section ratios, parton energy loss

- E1039 will run with polarized NH_3 target 2017-18
  - Measure Sivers asymmetry for sea quarks
- Possibility for future polarized proton beam
  - High-statistics measurement of Sivers asymmetry in valence region, overlapping existing semi-inclusive DIS measurements → test predicted sign change

Extra material

E906/SeaQuest dimuon event

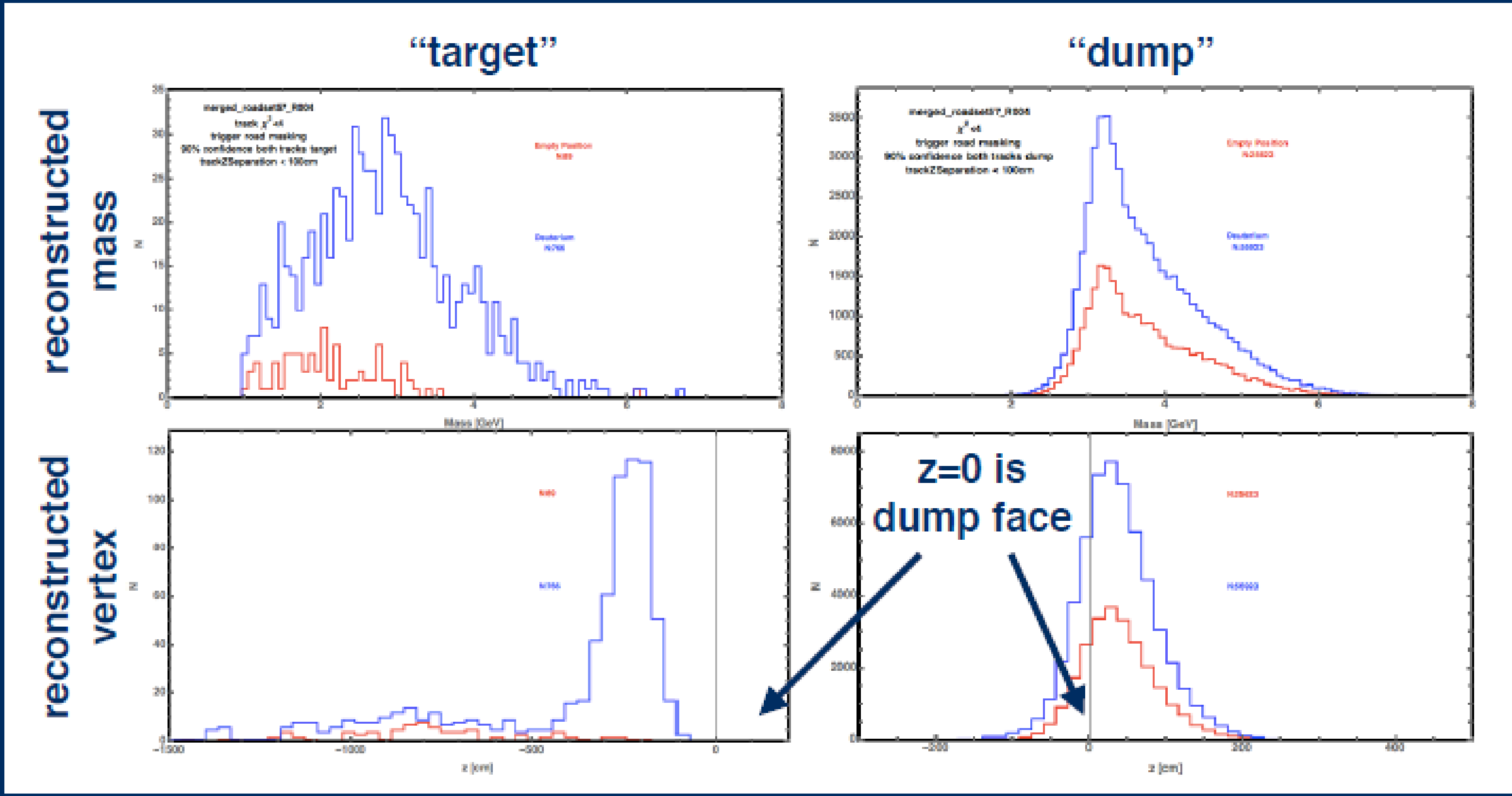
Here's a real dimuon event in our web-based event display



Likely a Drell-Yan event from the beam dump

Target Dump Separation

- Tiny data sample for demonstration
- “target”/“dump” using Matt parameterization (tuned of 90%/muon purity)

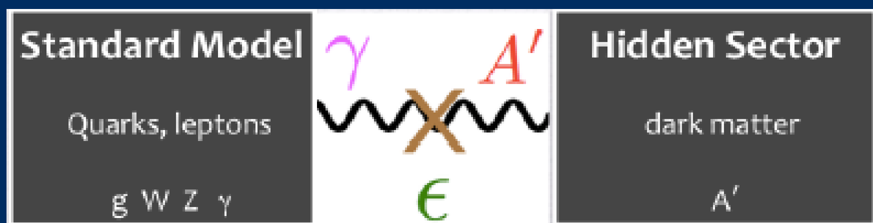


- Virtually no high mass pairs identified as “target” in target-out position (red)
- Dimuon pairs identified as “target” on D2. Ratio on dump makes sense

Slide from J.G. Rubin

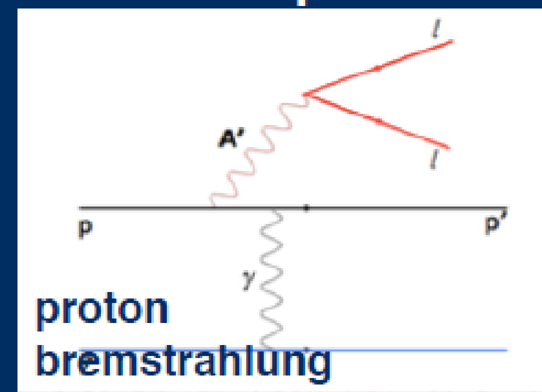
Searching for dark matter at SeaQuest

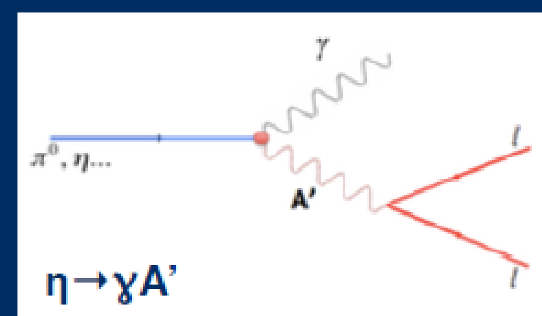
- One hypothesis, a dark photon A' that couples to the real sector with strength ϵ:



- 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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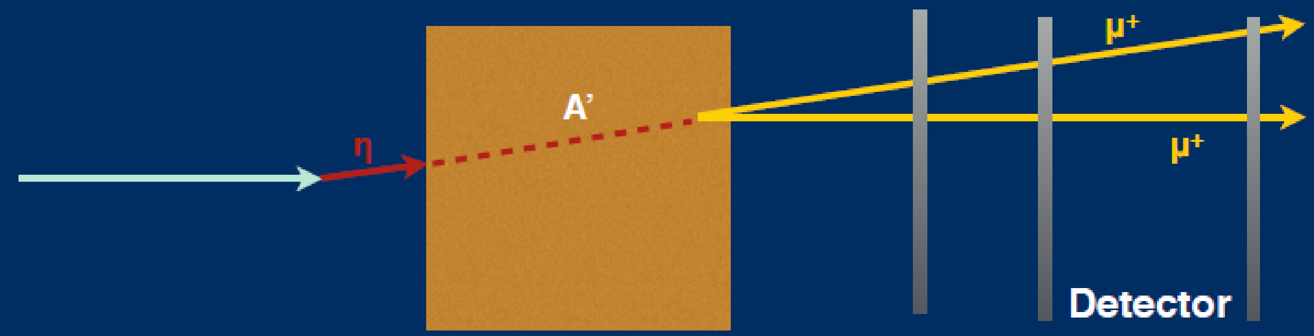
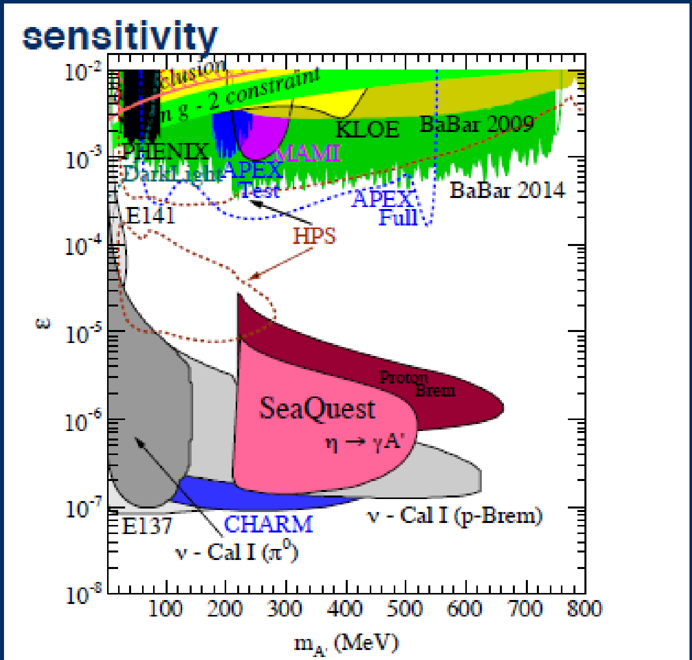
From J.G. Rubin

Searching for dark matter at SeaQuest

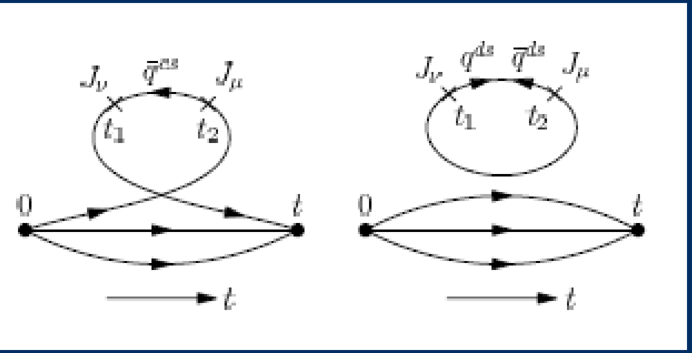


- Analysis details being studied
- Trigger already contains ≈63% of possible dark photon acceptance. More can be added in exchange for background rate.

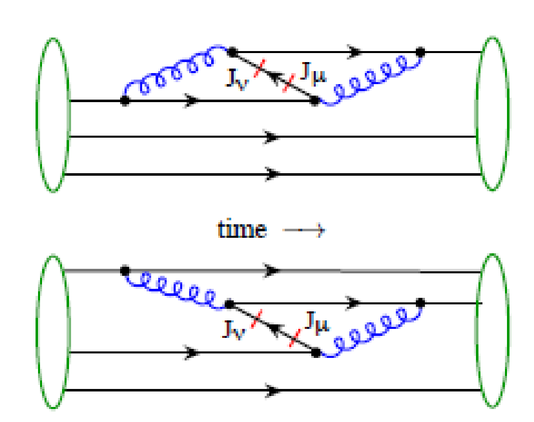


From J.G. Rubin

One possible explanation for ū at larger-x



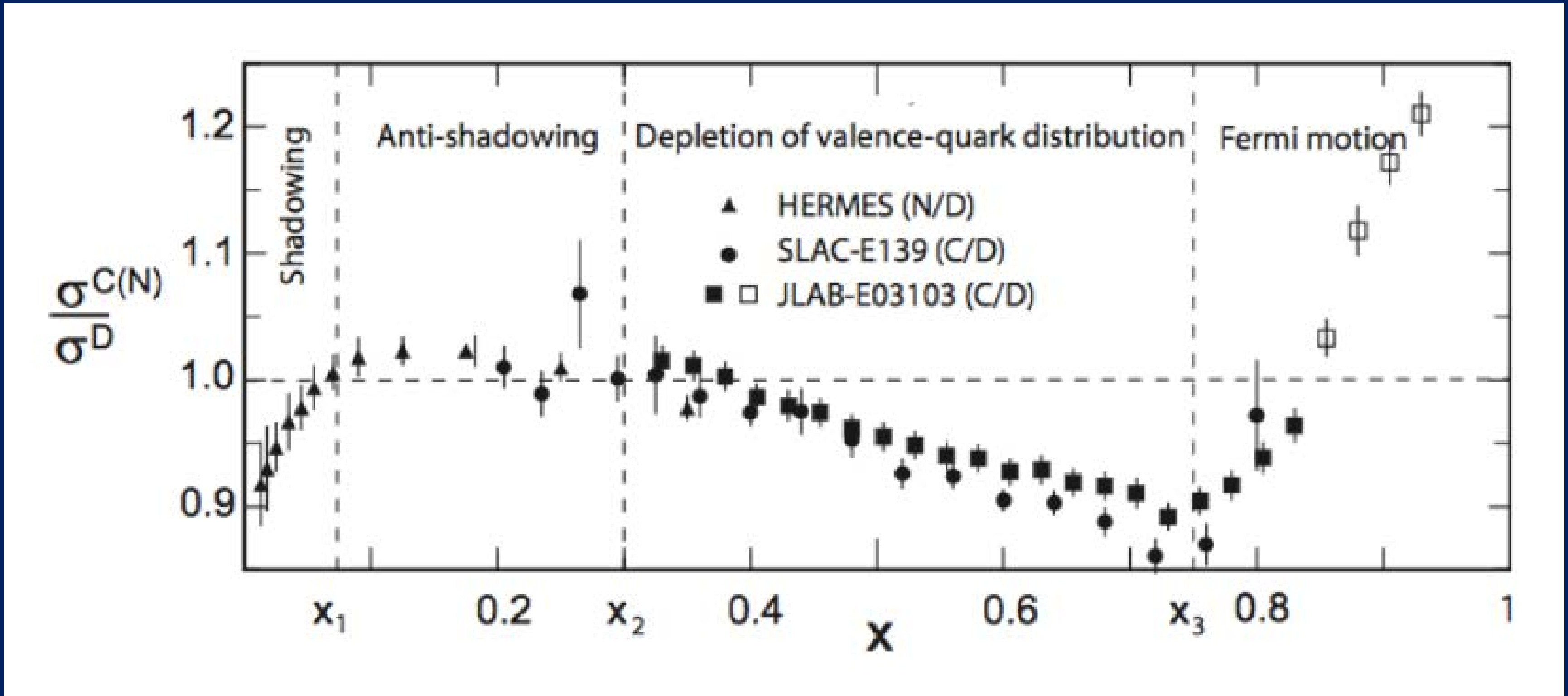
- The path integral formulation of QCD distinguishes between a connected sea (cs) and a disconnected sea (ds) as depicted on the right. There are unambiguous topological differences.
- Connected sea quarks are space-time loop trajectories created by valence quarks.
- Because of this, they create an enhancement of parton densities for quarks and antiquarks matching the flavor of the valence sector and with valence-like momentum distribution



non-trivial five-quark fluctuations. i.e. not vacuum polarization

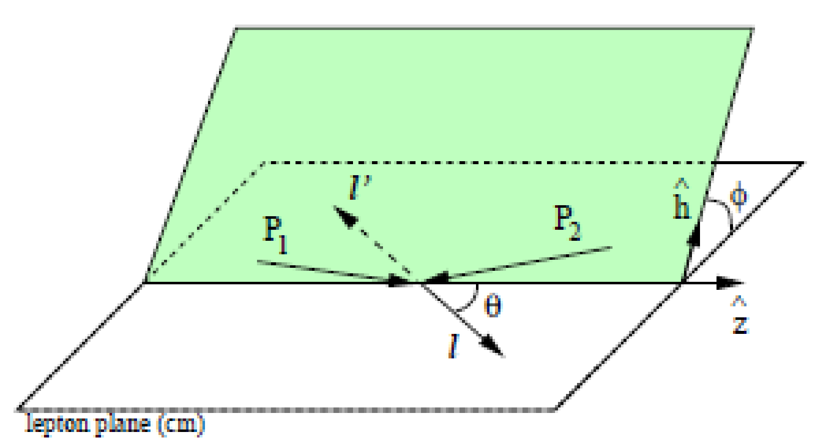
Jen-Chieh Peng, Wen-Chen Chang, Hai-Yang Cheng, Tie-Jiun Hou, Keh-Fei Liu, Jian-Wei Qiu
http://arxiv.org/abs/1401.1705v1 (January 2014)

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

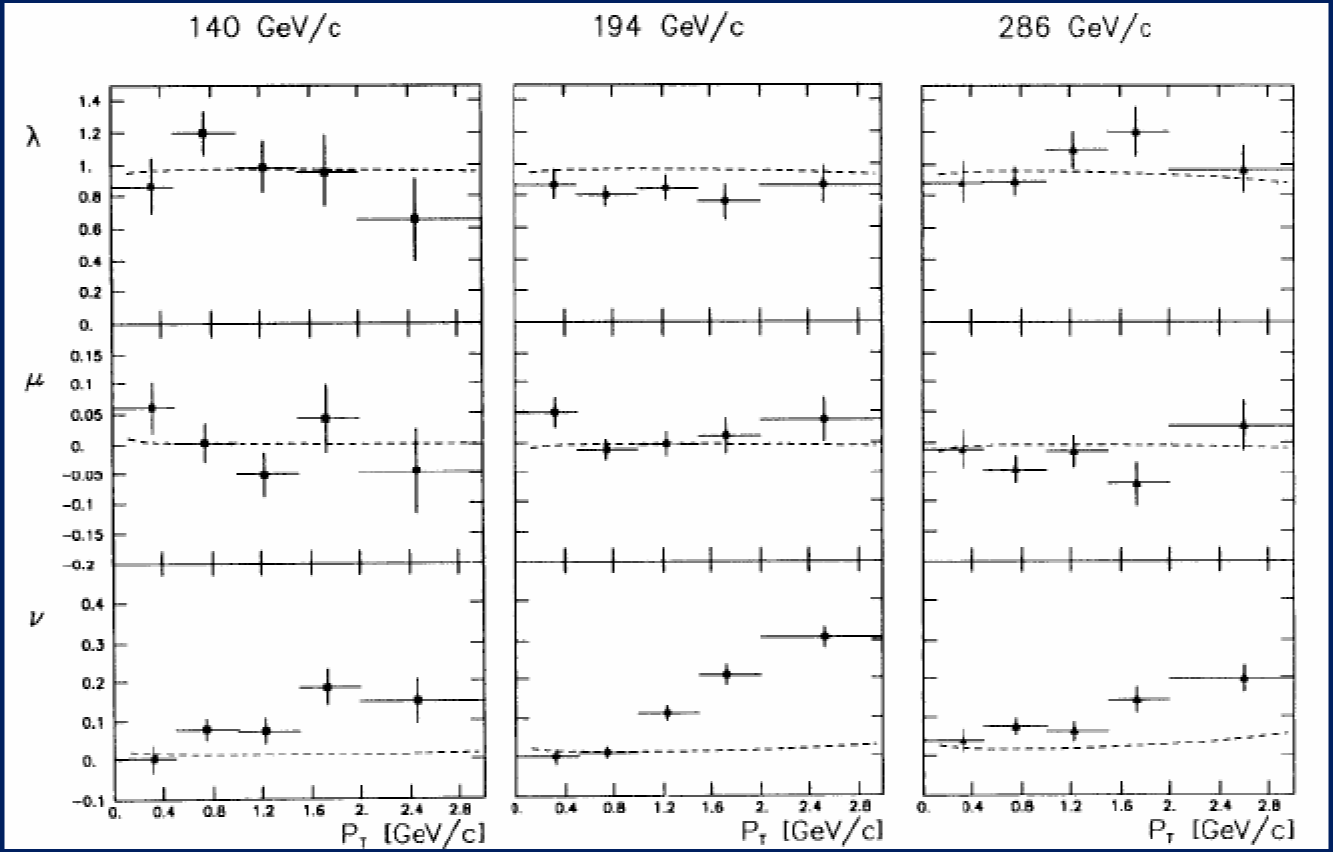
Lam-Tung relation

- 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)

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

What do the data show?

Measured angular dependences



CERN NA10
$\pi^- + W$

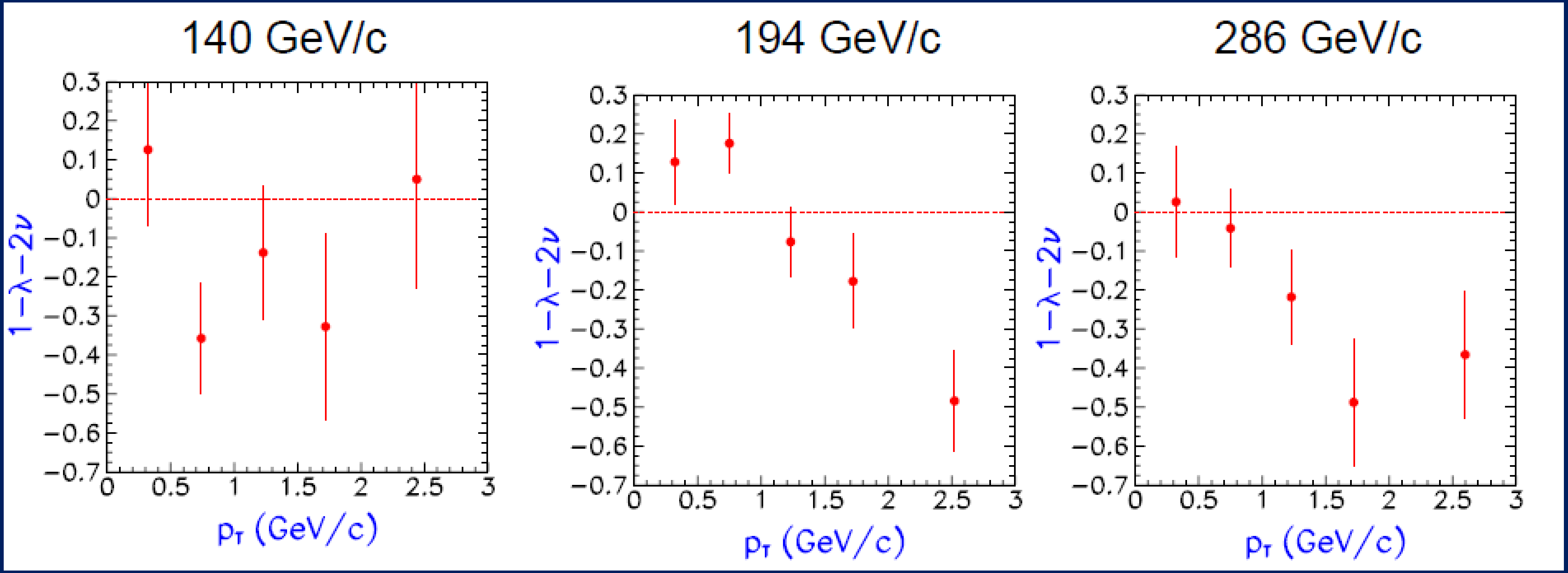
Z. Phys. 37, 545 (1988)

Dashed curves from pQCD calculations

ν non-zero, increases with p_T

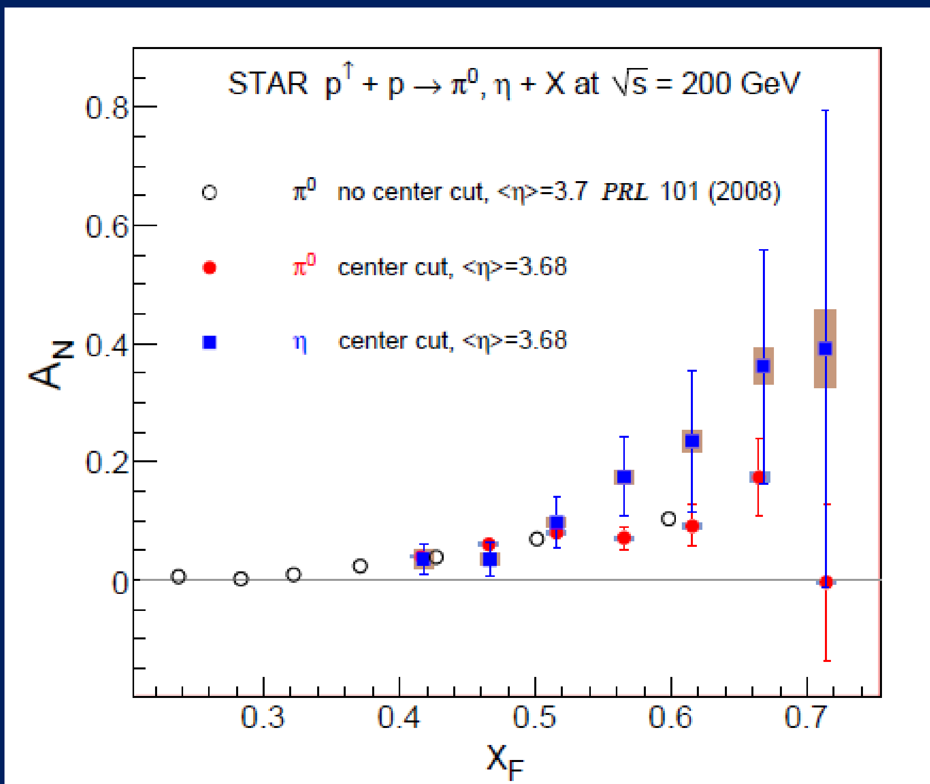
Lam-Tung relation violated!

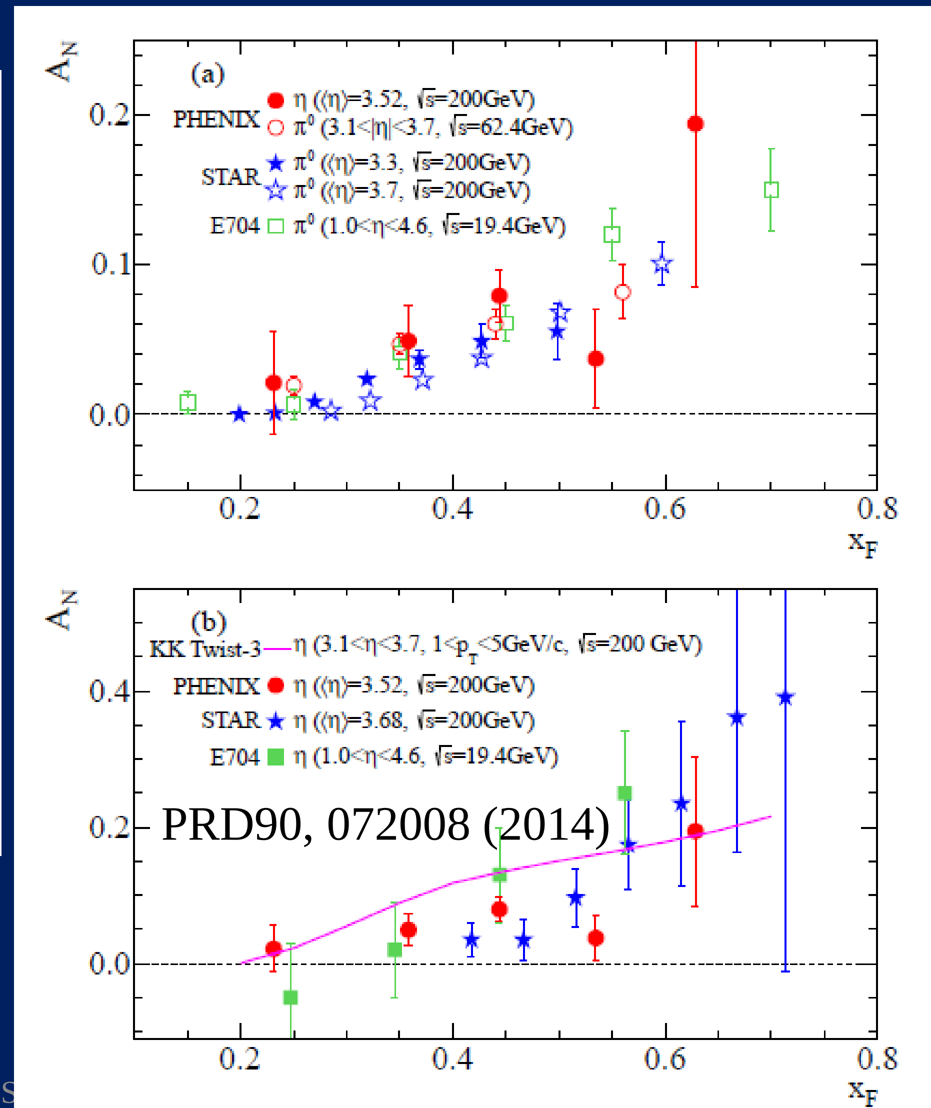
NA10, Z. Phys. 37, 545 (1988)



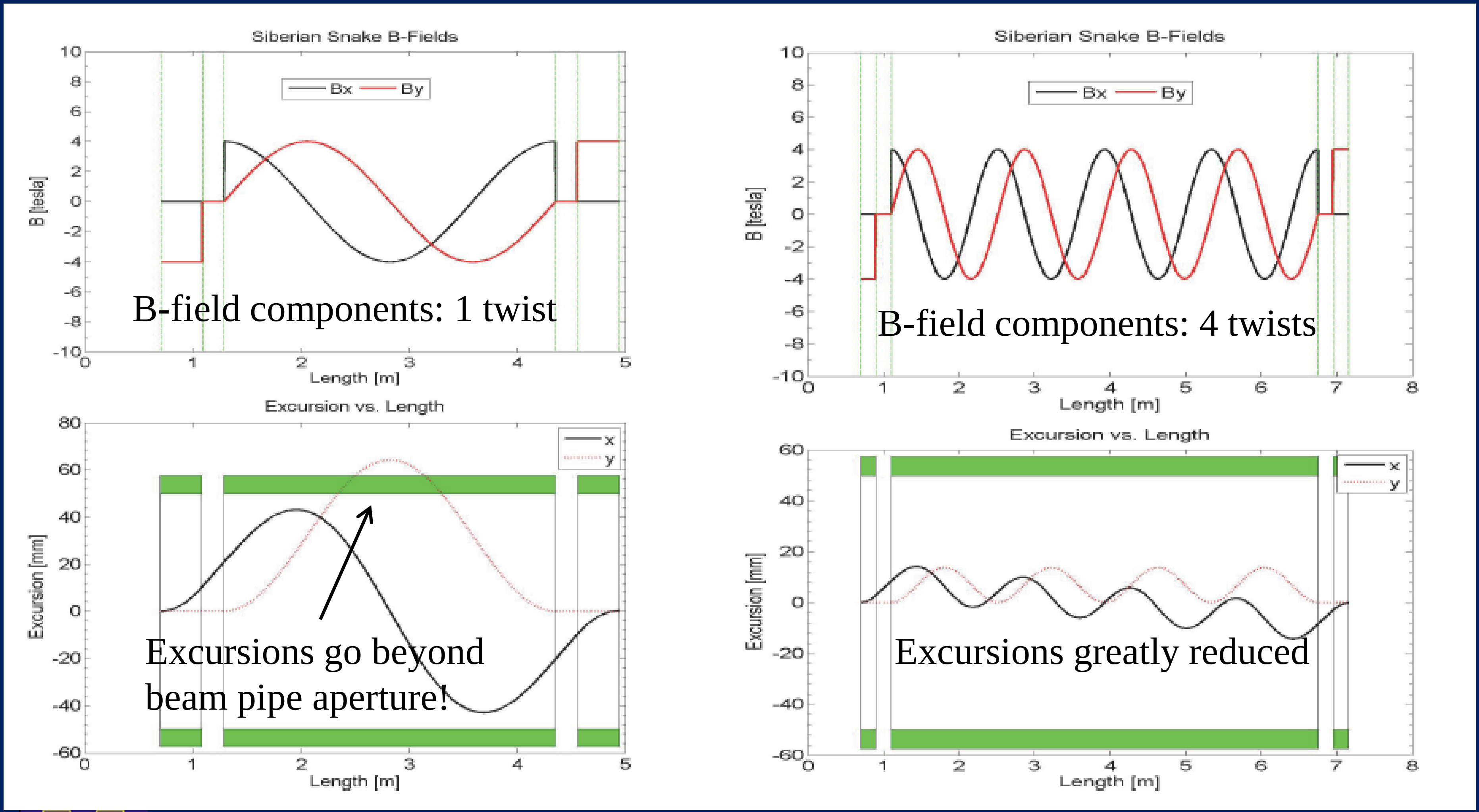
*Violation of the Lam-Tung relation suggests new mechanisms with **non-perturbative** origin!*

$p+p\ \eta\ A_N$ larger than π^0?? Same?

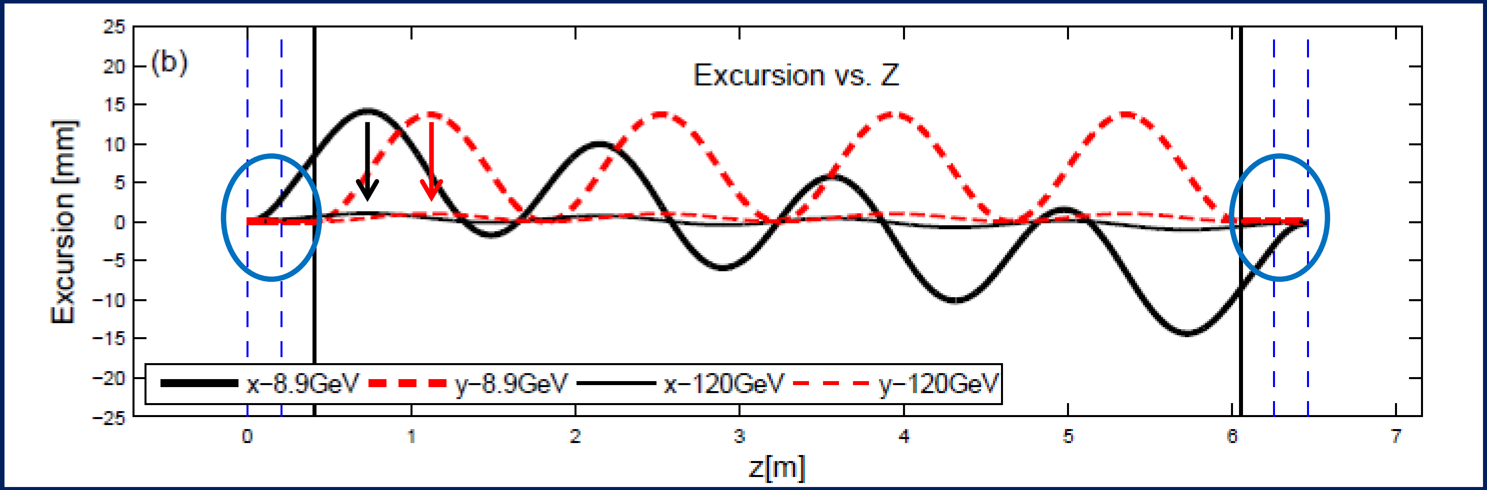




Excursions at 8.9 GeV injection: 1-twist vs. 4-twist

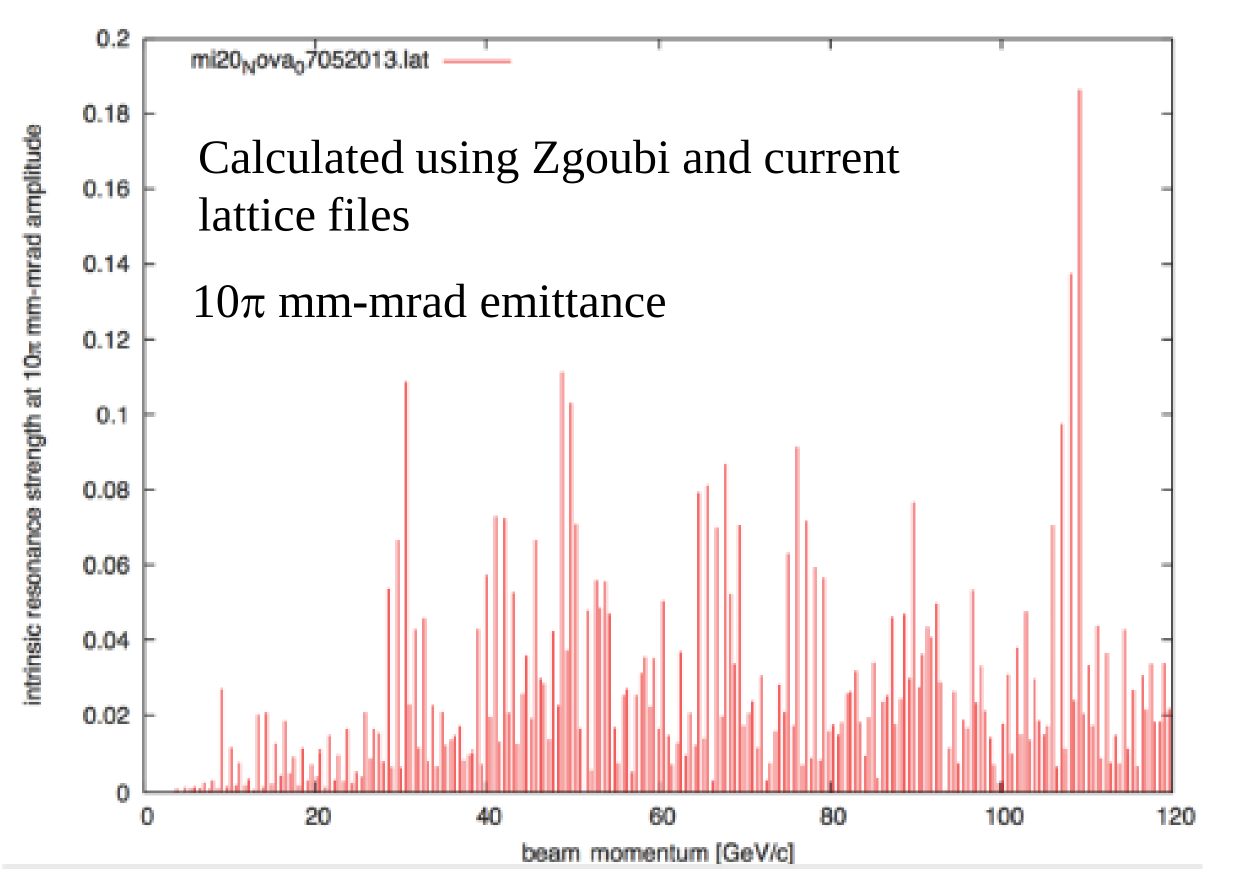


Excursions at 8.9 vs. 120 GeV



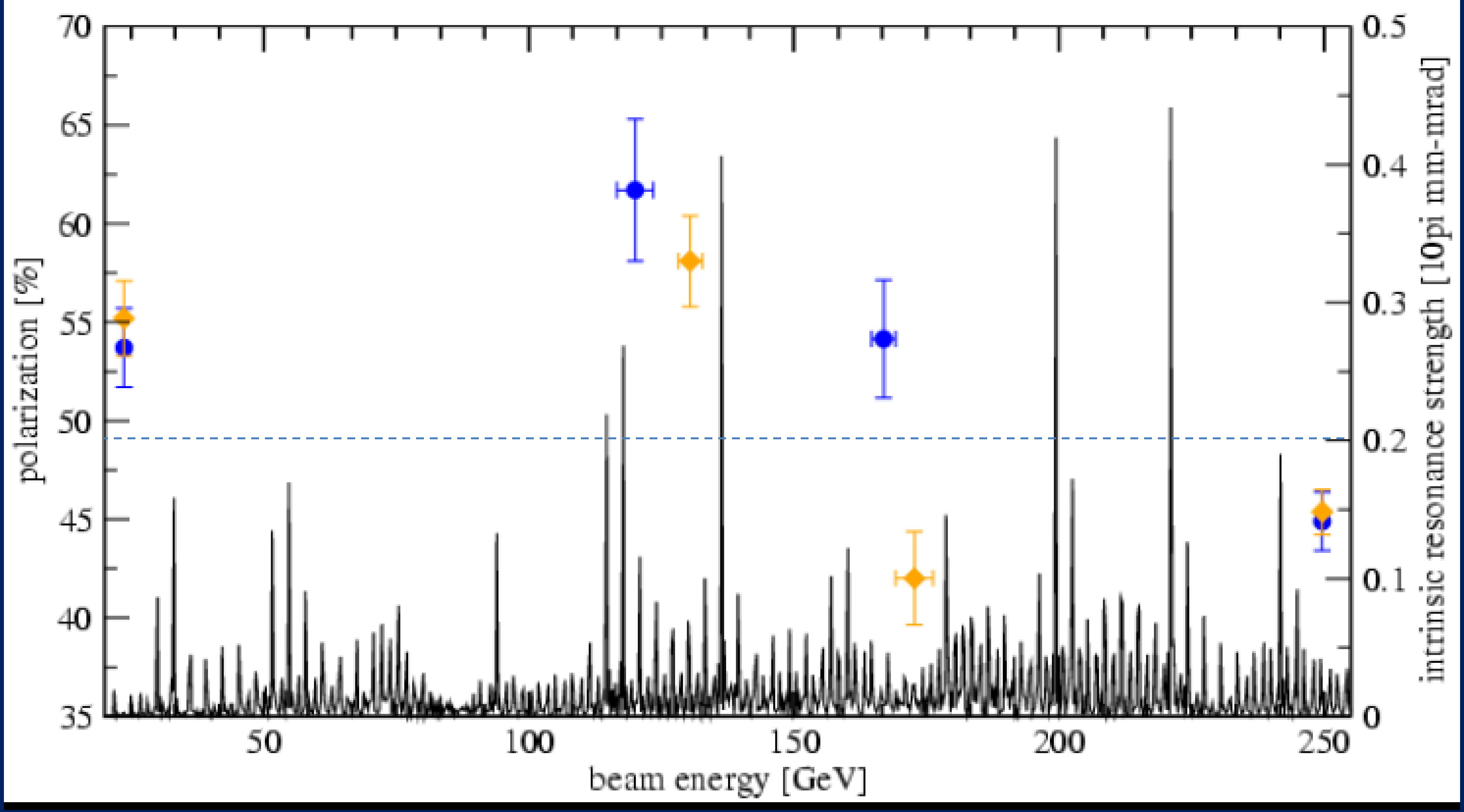
- Excursions decrease with increasing energy
  – Most stringent constraints at 8.9 GeV injection
- Dipoles at ends of helix for optical transparency

Intrinsic depolarizing resonances in Main Injector



- Strongest intrinsic depolarizing resonance < 0.2

RHIC intrinsic depolarizing resonances



Modifications to accelerator chain: Source to LINAC

- Source—Dubna interested
  - Switching magnet—to go between polarized and unpolarized sources—would use unpolarized source (higher intensity) for neutrino program
- 35 keV transport line from polarized source to RFQ
- RFQ - new
- 750 keV transport line from new RFQ to LINAC—no modifications necessary
- LINAC – acceleration from 750 keV up to 400 MeV
  - No depolarization in LINACs—no modifications necessary
- 400 MeV transport line—no modifications necessary

Modifications to accelerator chain: Booster to Recycler Ring

- Booster – acceleration from 400 MeV to 8.9 GeV
  - 4% partial snake – solenoid – to overcome 15 weak imperfection resonances
  - One weak intrinsic resonance—3-μs pulsed quads for tune jumping
- 8.9 GeV transport line to Recycler Ring – need to study if spin rotator needed—vertical and horizontal bends
- Recycler Ring – warm partial snake?
- 8.9 GeV transport line to Main Injector—no modifications necessary

Modifications to accelerator chain: Main Injector to Experimental Hall

- Main Injector – single, 4-twist superconducting helical dipole snake
- Transport line to NM4 experimental hall
  - Has vertical as well as horizontal bends—likely need spin rotator