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SeaQuest and SpinQuest Experiment: Fixed-target Drell-Yan Program at Fermilab

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12th Workshop on Hadron Physics and Opportunities Worldwide
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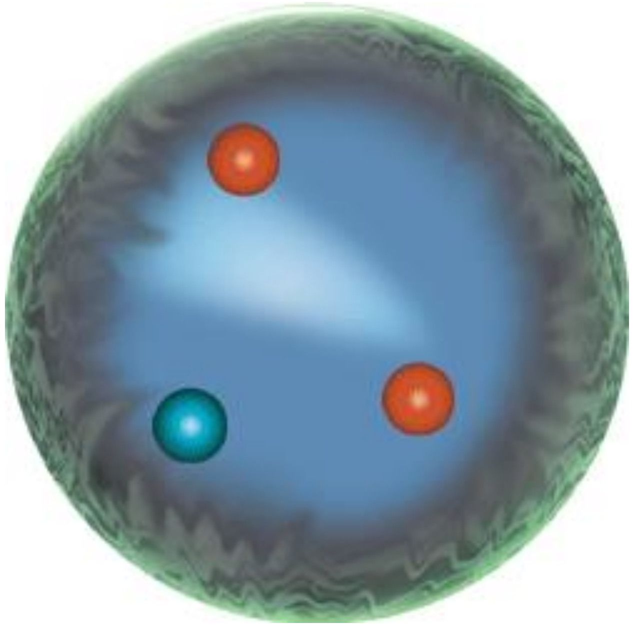
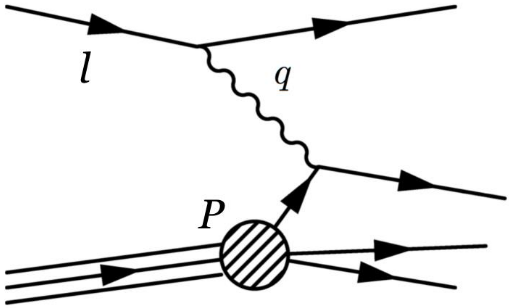
Outline

- Introduction to physics motivation
- SeaQuest results
- SpinQuest status
- Summary and future prospects

Intro to Physics Motivation

The inner structure of proton





Other than charge, valence quarks only contribute to part of the proton's properties: *mass, momentum, spin*

Investigation(s) of the proton structure

- QCD
- Lattice QCD
- Experimental probs:
  - ❑ Deep Inelastic Scattering
  - ❑ Drell-Yan - ***focus of our Fermilab experiments***

Describing quarks inside the proton

- Parton model
- Parton distribution function *f(x)*
- Structure functions

$$F_2^p(x) = \sum_i x Q_i^2 f_i(x)$$

Intro to Physics Motivation
Looking into the light quark sea

- **Proton as a sum of quarks:**

$$P = q_u^1 + q_u^2 + q_d^3 + \sum_i q_{sea}^i \bar{q}_{sea}^i$$

Valence Sea

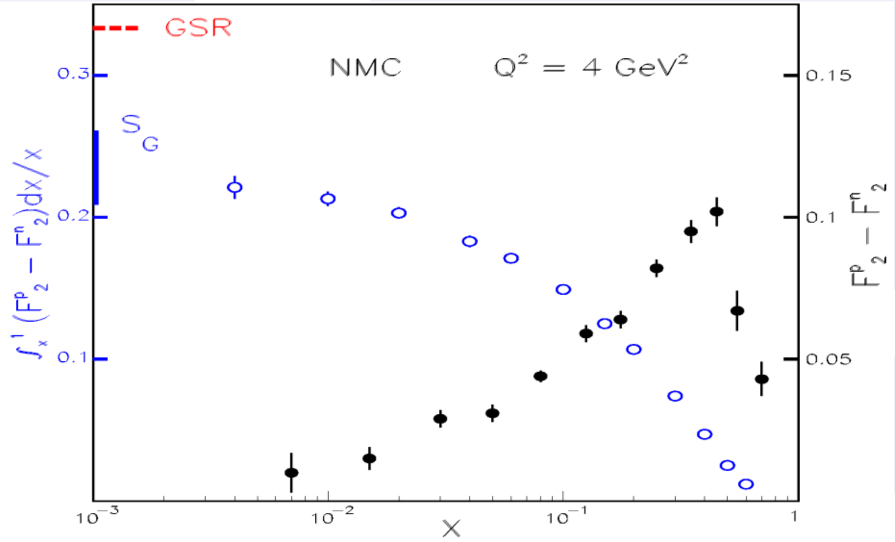
- **Separate the sea from the valence**

$$\int_0^1 [F_2^p(x) - F_2^n(x)]\frac{dx}{x} = \frac{1}{3} - \frac{2}{3}\int_0^1 [\bar{d}_p(x) - \bar{u}_p(x)]dx$$

Gottfried Sum Rule

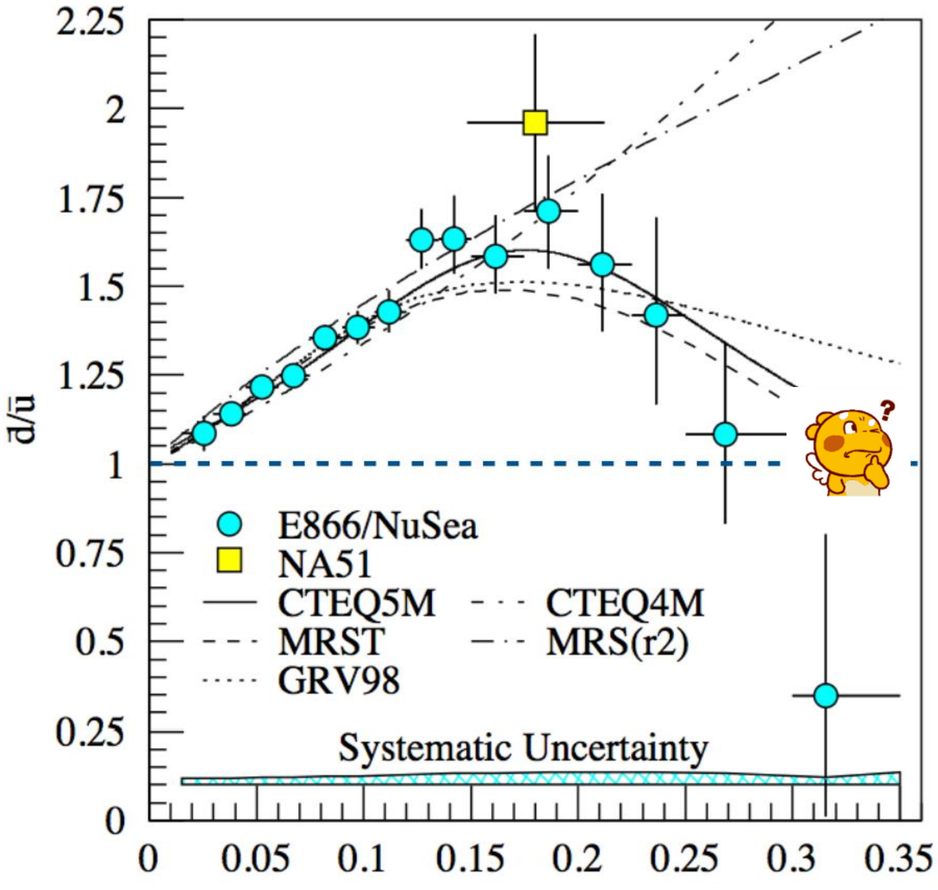
- **NMC tested the Gottfried Sum Rule by muon DIS on hydrogen and deuterium**

$$\int_0^1 [F_2^p(x) - F_2^n(x)]\frac{dx}{x} = 0.235 \pm 0.026$$



Intro to Physics Motivation

Sea quark flavor asymmetry



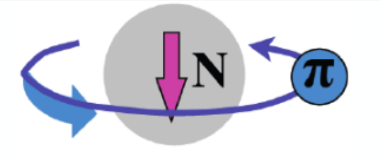
All models introduce a dbar excess, however the data beyond x ~ 0.3 is hard to be incorporated

- Assuming charge symmetry, ignoring the nuclear effects and heavy quark contributions:

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_1 \gg x_2} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$

- NA51 and NuSea/E866 revealed a striking asymmetry of the anti-quarks at moderate *x*

- Many models proposed to explain the anti-matter asymmetry:
    - Meson cloud
    - Pauli blocking
    - Chiral quark model
    - Instantons
    - Statistical parton distributions
    - …

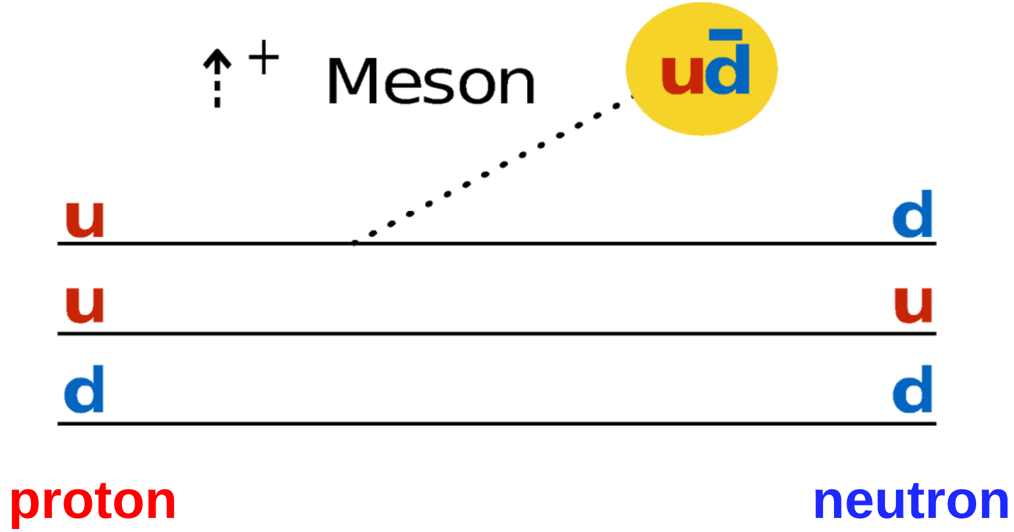


Intro to Physics Motivation

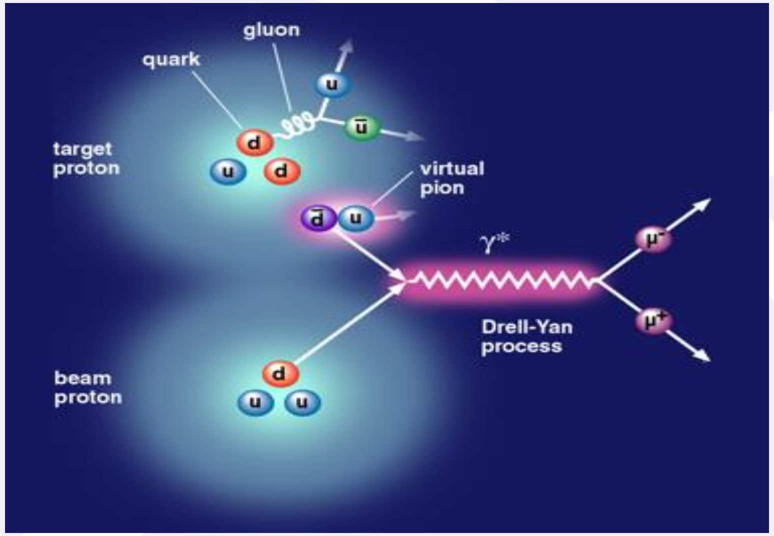
Sea-quark's orbital motion

Pion cloud model

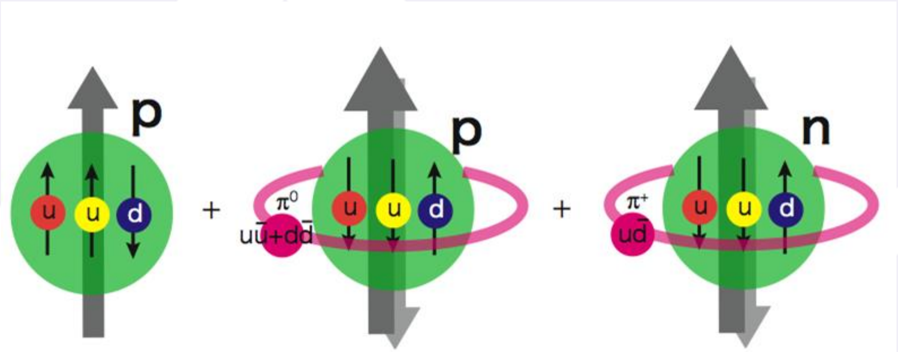
- Sea-quark flavor asymmetry
- Sea-quark orbital angular motion
- Expect large Sivers function at x = 0.1 - 0.4



Pion cloud and Drell-Yan process

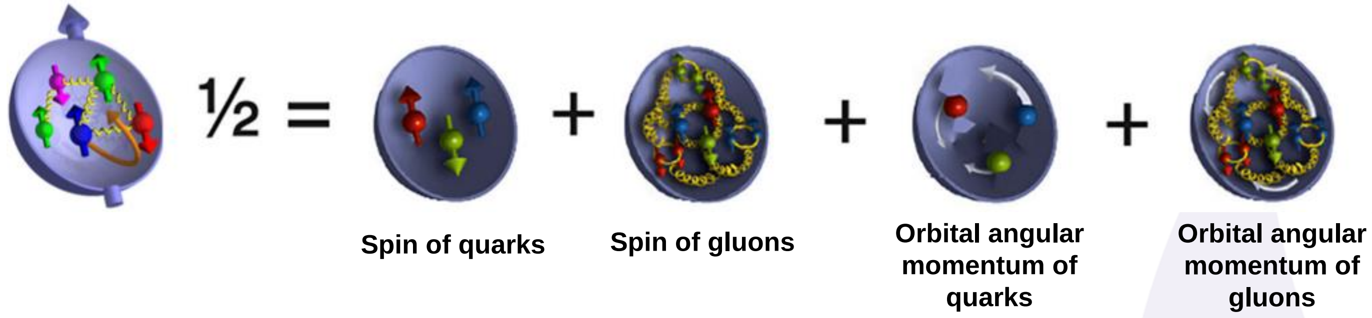


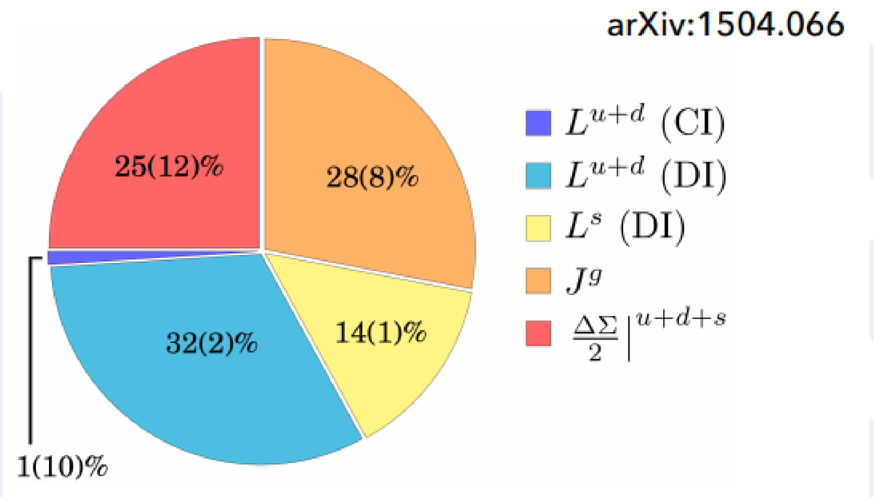
$|p\rangle = a_1|p_0\rangle + a_2|p_0 + pi^0\rangle + a_3|n+pi^+\rangle + \ldots$

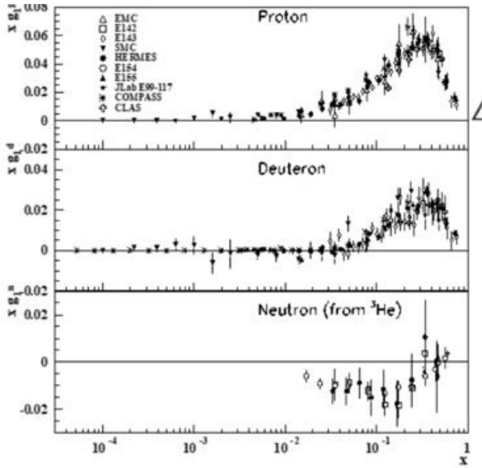


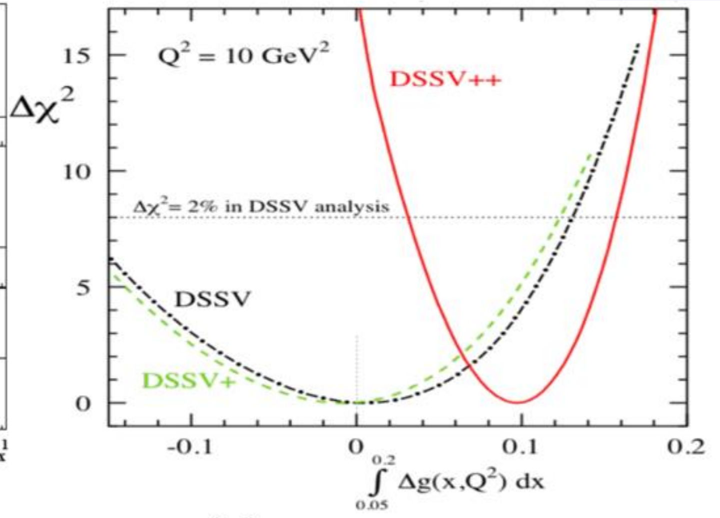
Intro to Physics Motivation

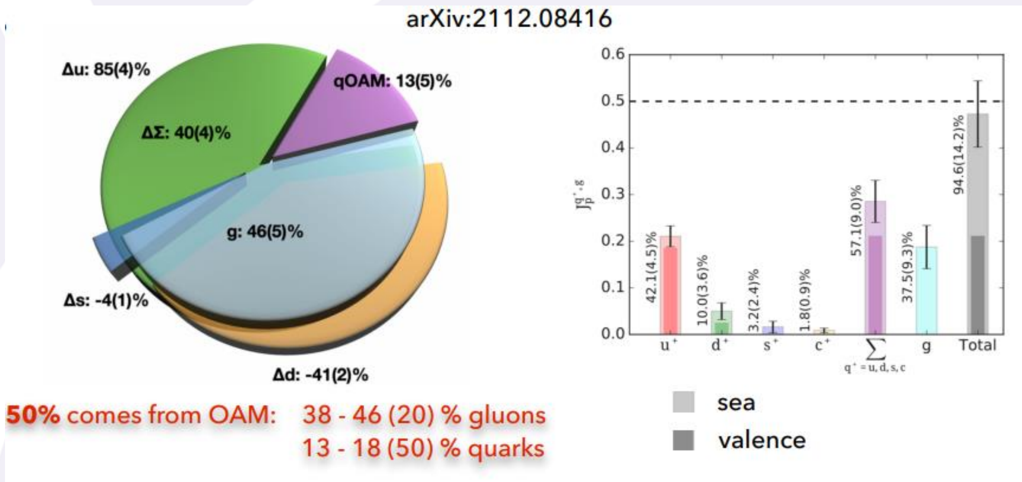
Proton spin puzzle/crisis and sea-quark OAM











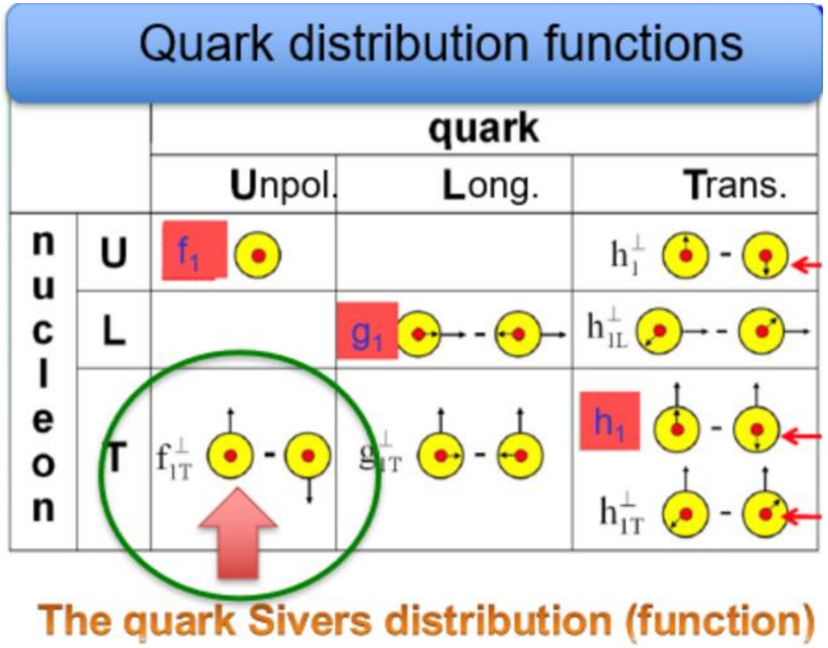
$$\Delta\Sigma \sim 0.25 \pm \ldots$$

$$\int_{0.05}^{0.2} dx \Delta g(x) = 0.2 \pm 0.06$$

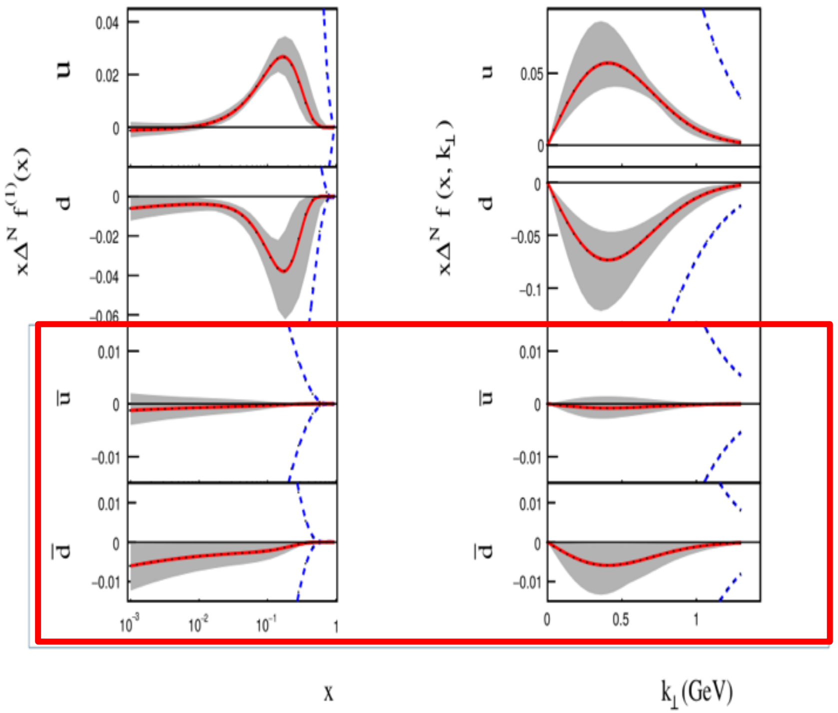
Intro to Physics Motivation

Probe the proton spin through TMDs and Sivers function

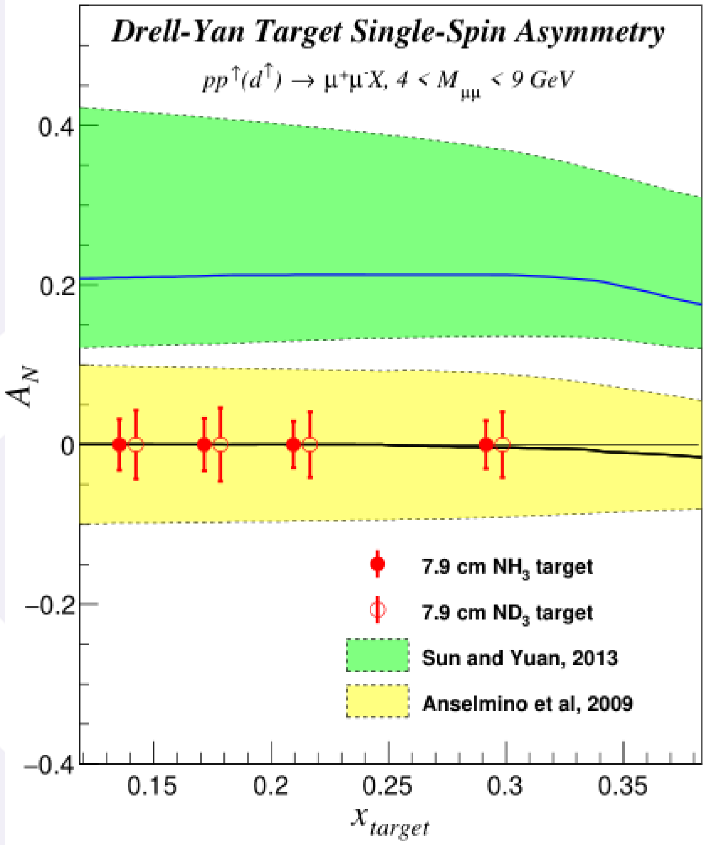
***TMD** = **T**ransverse **M**omentum **D**ependent PDF*



The Sivers function vanishes if the quarks have no ***orbital motion***



Anselmino, M. et. all, https://doi.org/10.1007/JHEP04(2017)046



Simultaneous measurement of both ubar and dbar

Statistics shown for 2 calendar years of running

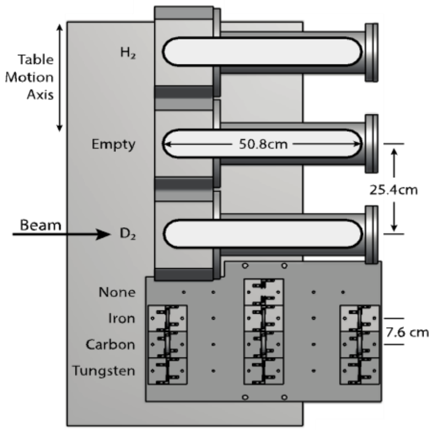
SeaQuest/SpinQuest Experiment at Fermilab

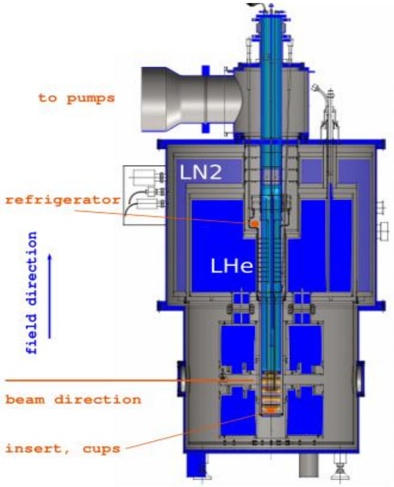
E906/SeaQuest: 2012 – 2017

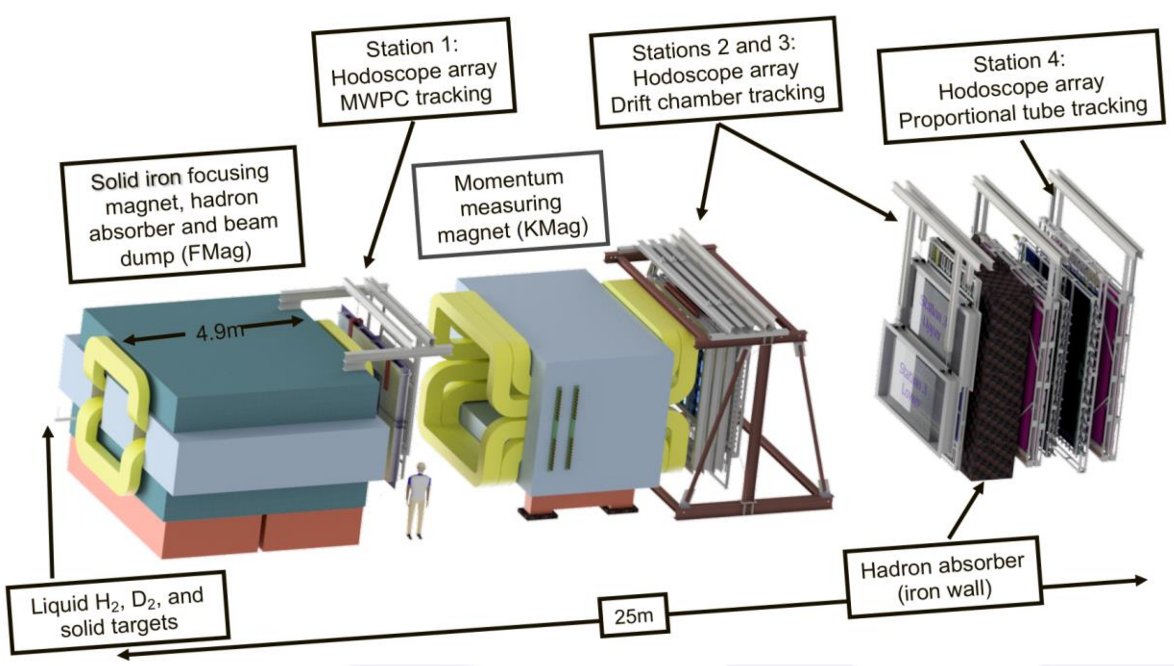
- 120 GeV proton beam with unpolarized proton/deuteron, and nuclear targets

E1039/SpinQuest: 2018 – now

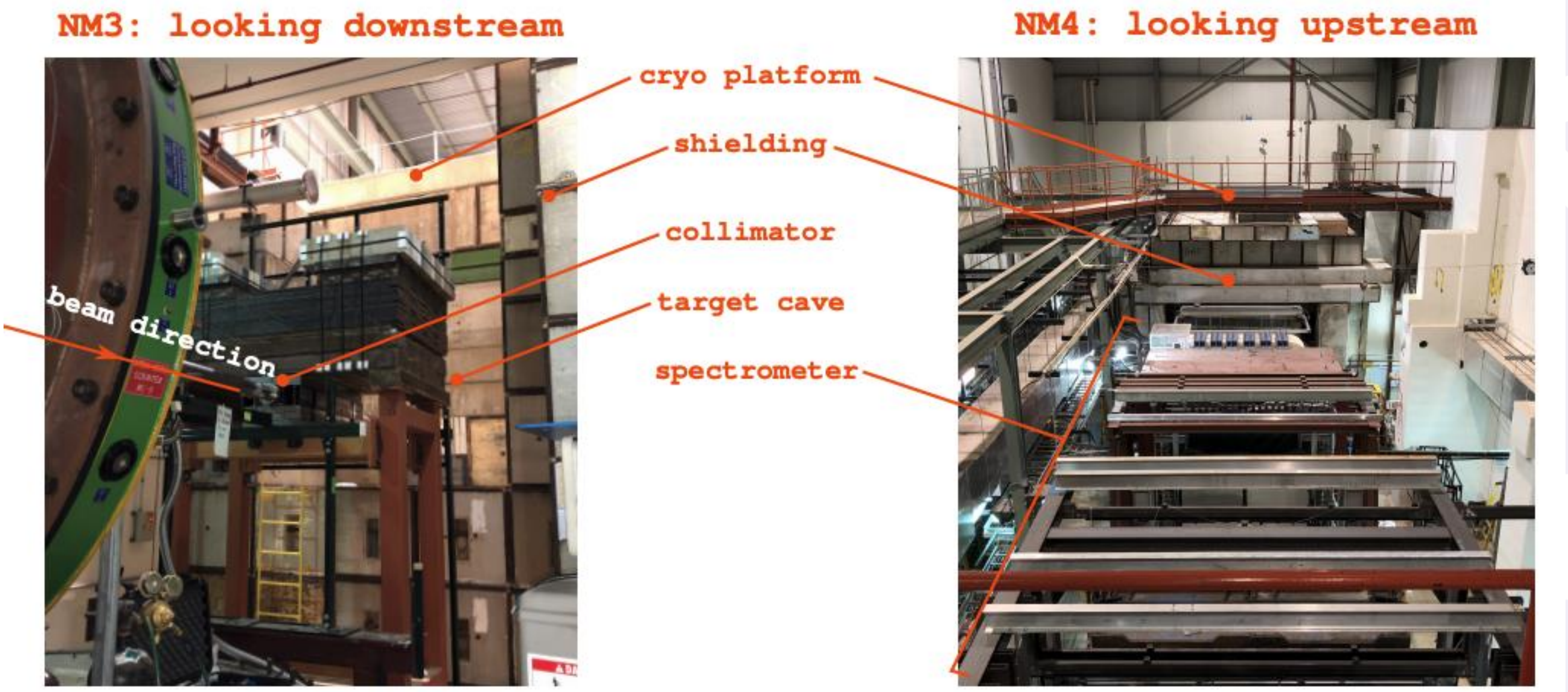
- 120 GeV proton beam with polarized proton/deuteron target





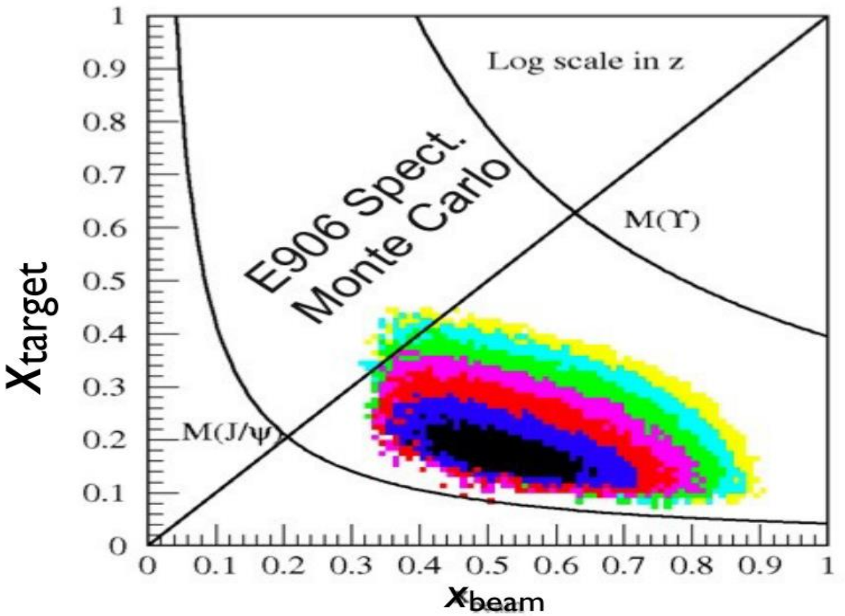


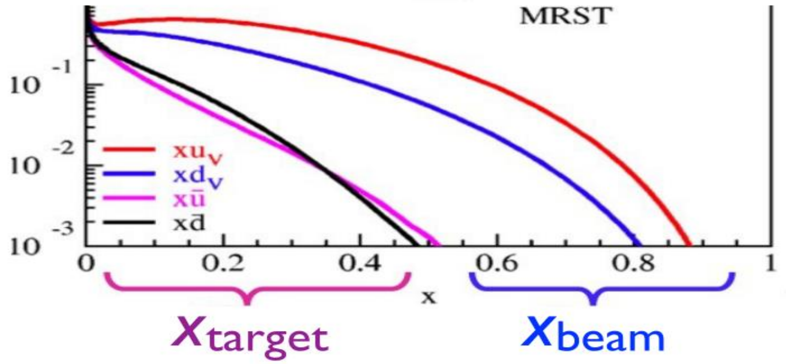
SeaQuest/SpinQuest Experiment Setup

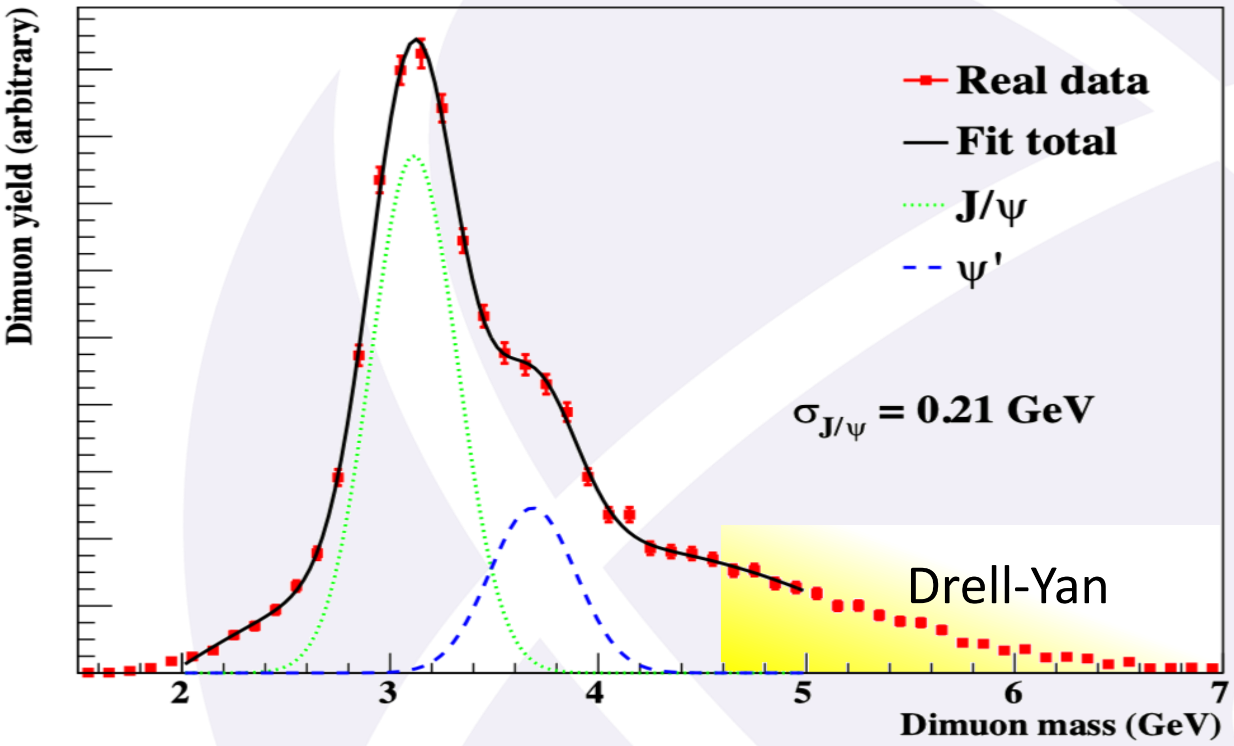


SeaQuest Results

Typical mass spectrum and kinematic coverage





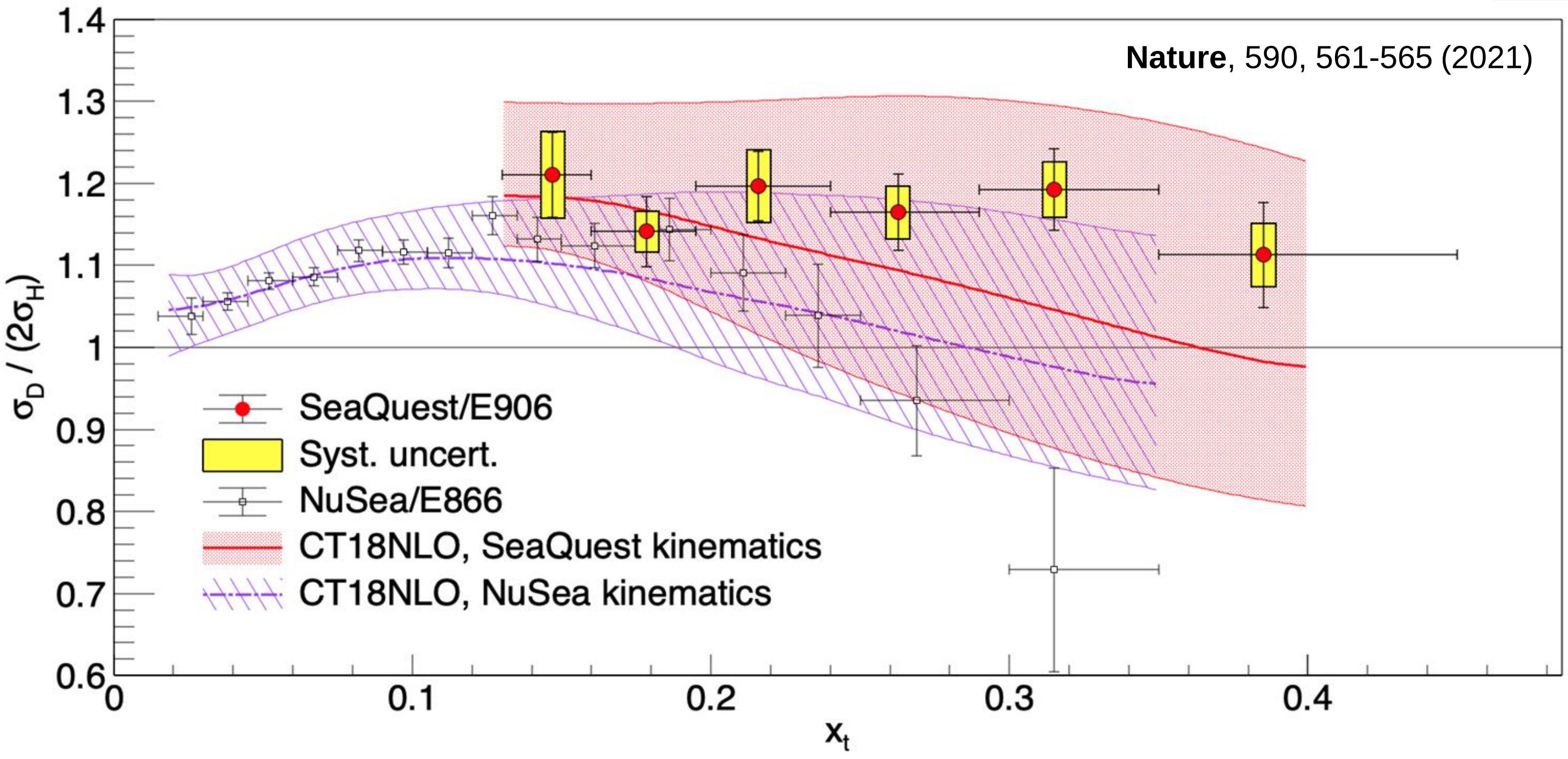


$$\frac{d^2\sigma}{dx_b\,dx_t} = \frac{4\pi\alpha^2}{9x_b\,x_t}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_t(x_t)q_b(x_b) + \cancel{q_t(x_t)\bar{q}_b(x_b)}\right]$$

small

SeaQuest Results

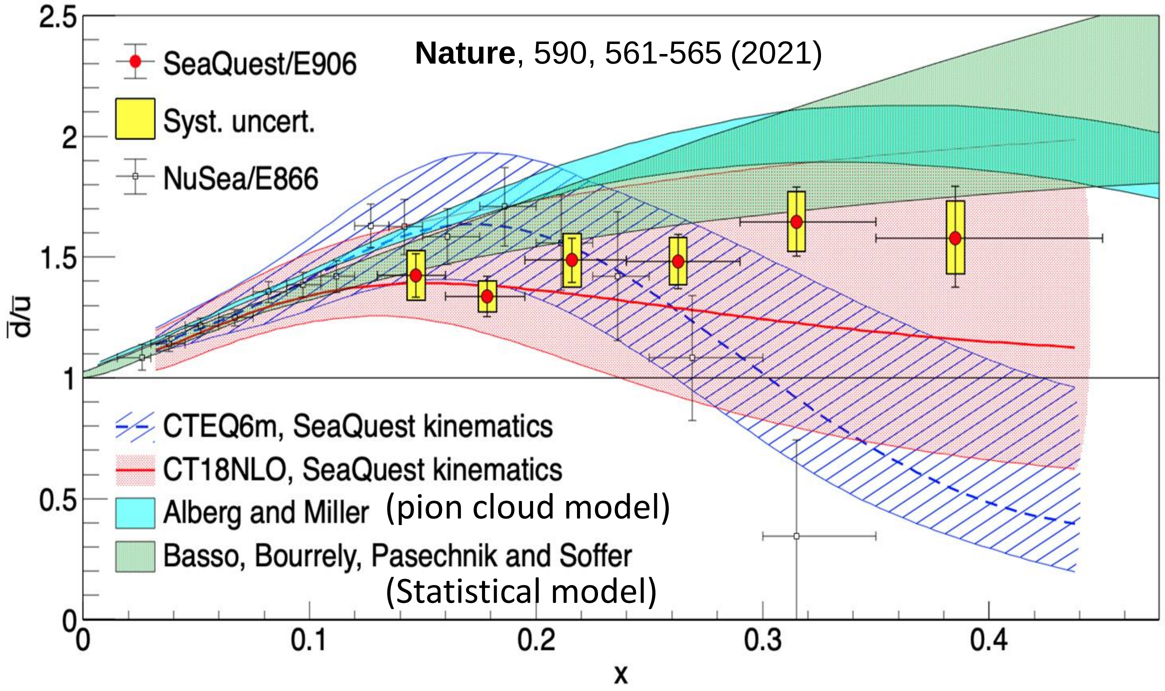
Drell-Yan cross-section ratio



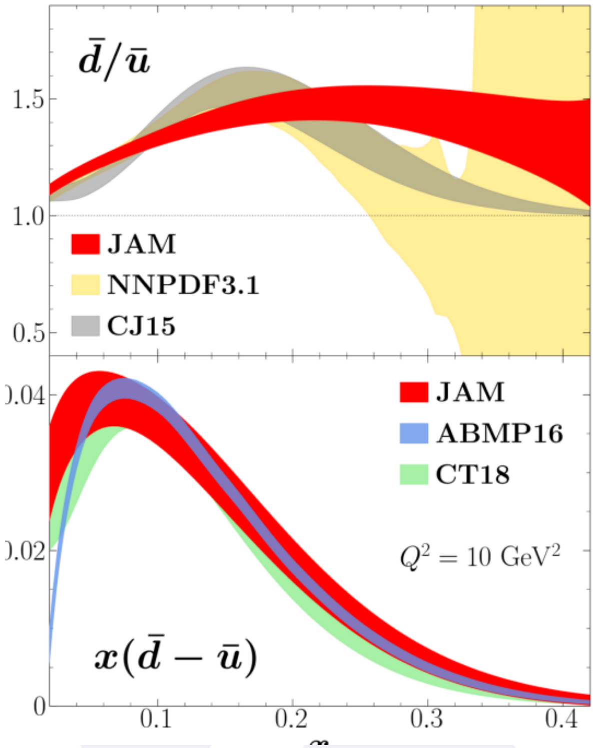
- SeaQuest results compared with E866/NuSea data shows discrepancy at higher *x*
- Effects of experimental kinematics (120 GeV vs. 800 GeV beam) has been studied
  - Shown by the calculation using CT18 NLO
  - Account for the difference at *x* ~ 0.15

SeaQuest Results

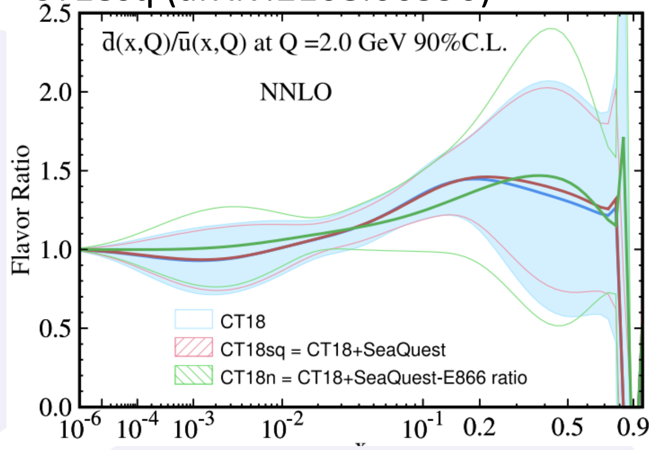
Sea-quark flavor asymmetry



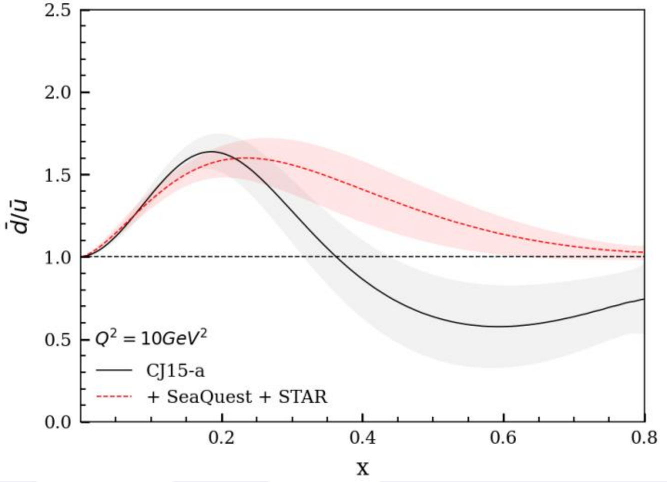
JAM (PRD 104, 074031)



CT18sq (arXiv:2108.06596)



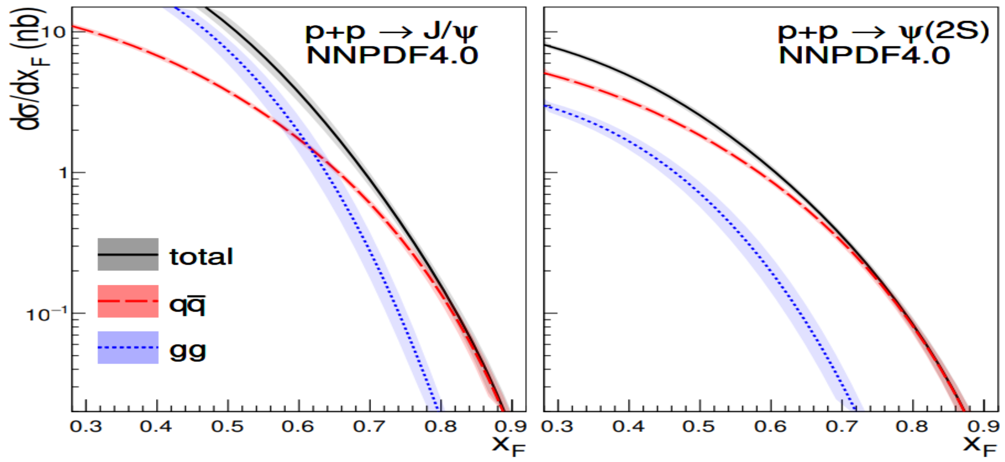
CJ15-a+ (arXiv:2108.05786)



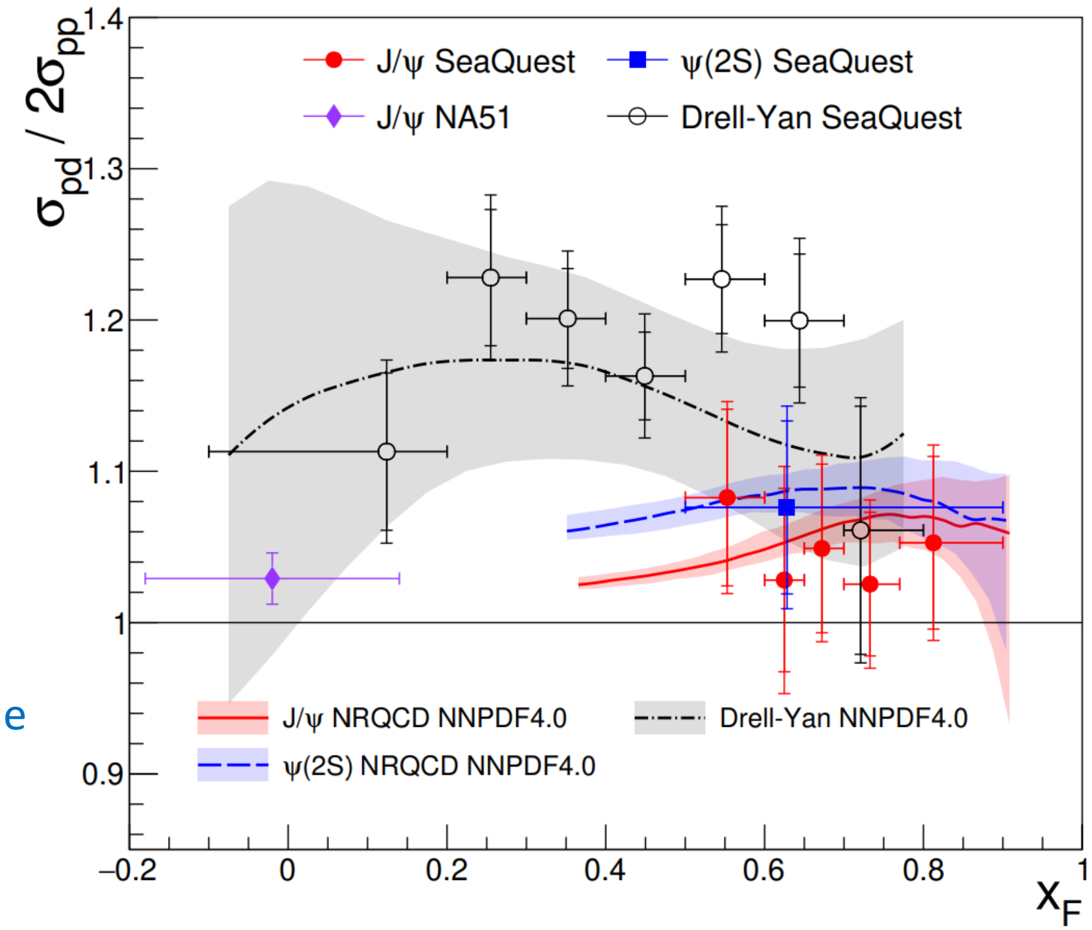
- Reasonably described by two theoretical predictions
- Included in multiple global analysis
- Improved analysis with more data is ongoing

Other SeaQuest Results

J/ψ and ψ(2s) cross section



arXiv:2406.11459, submitted to PLB



- NRQCD with NNPDF4.0 described the data pretty well
- At SeaQuest energy (√s = 15 GeV), both J/ψ and ψ(2s) have sizable qqbar contributions and are sensitive to the sea quark flavor asymmetry

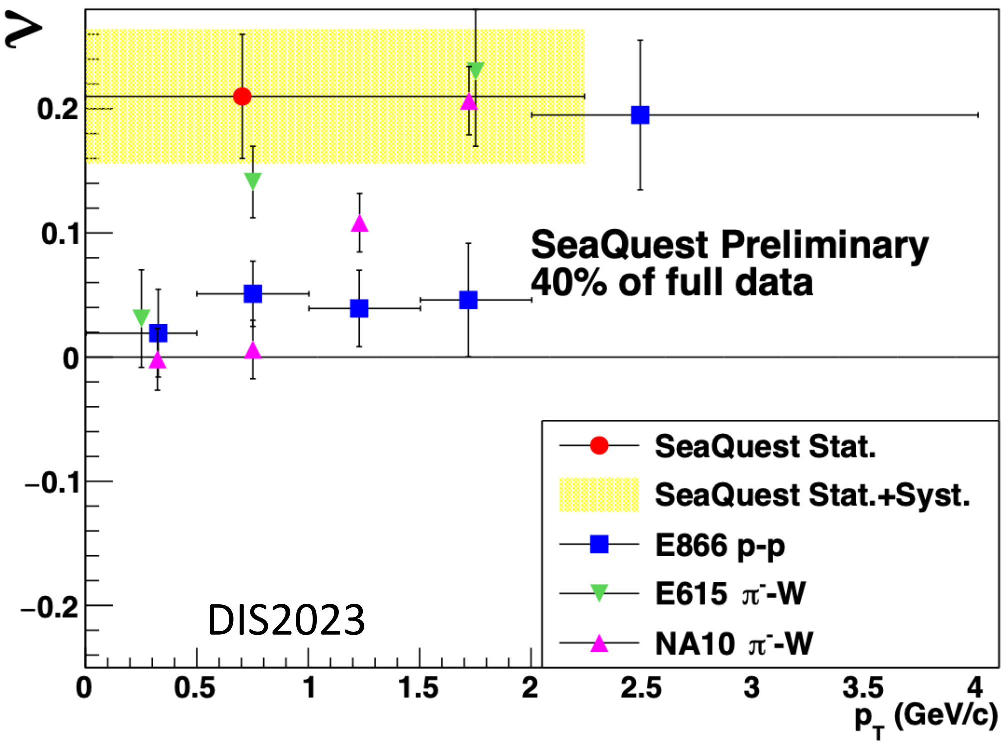
Other SeaQuest Results

Extraction of Boer-Mulders function

- Drell–Yan angular distribution is essential to access Boer–Mulders function:

$$d\sigma/d\Omega \propto 1 + \lambda\cos^2\theta + \mu\sin2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos2\phi,$$

$\nu/2 \propto h_{1,\mathrm{beam}}^{\perp} h_{1,\mathrm{target}}^{\perp}$, where $h_1^{\perp}$ is Boer–Mulders function



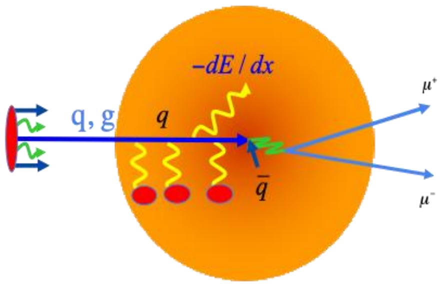
- A large ν value was obtained
  - ❑ Similar to π-induced Drell–Yan results
  - ❑ We may need to re-consider an assumption that the Boer–Mulders functions of sea-quarks are small

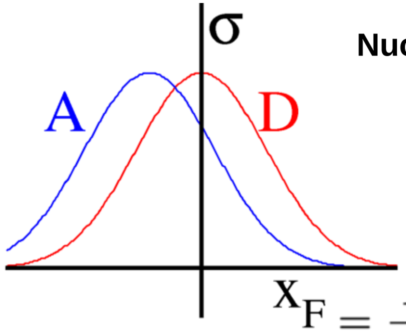
- Preliminary result presented at DIS2023, paper draft under preparation

Other SeaQuest Results

Initial-state energy loss in cold nuclear medium

Nuclei targets:
p+p, p+d, p+C, p+Fe and p+W



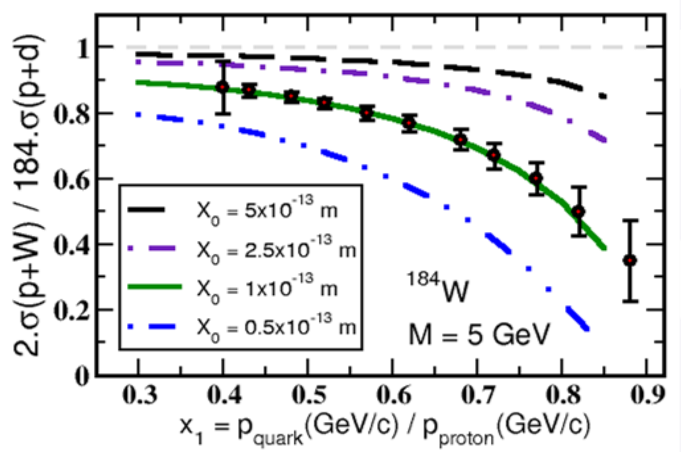


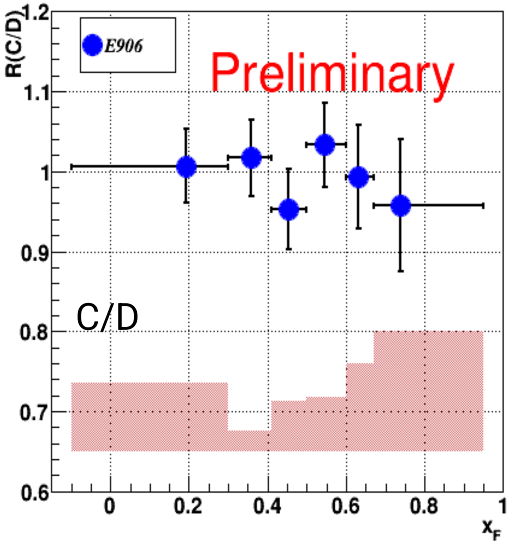
$$x_F = \frac{P_{DY}}{P_{beam}}$$

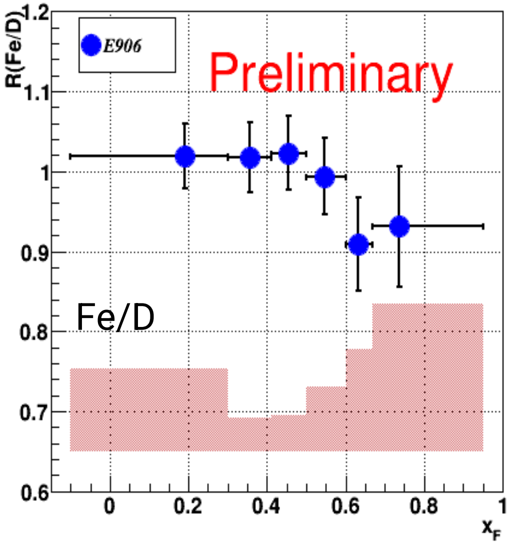
Nuclear modification factor:

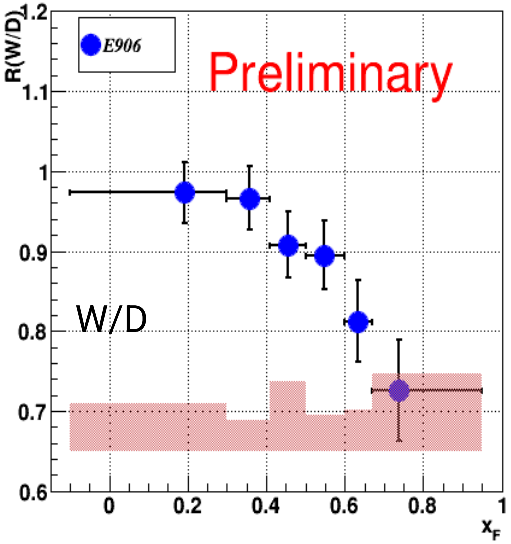
$$R_{pA} = \frac{2\sigma^{pA}}{A \times \sigma^{pD}}$$

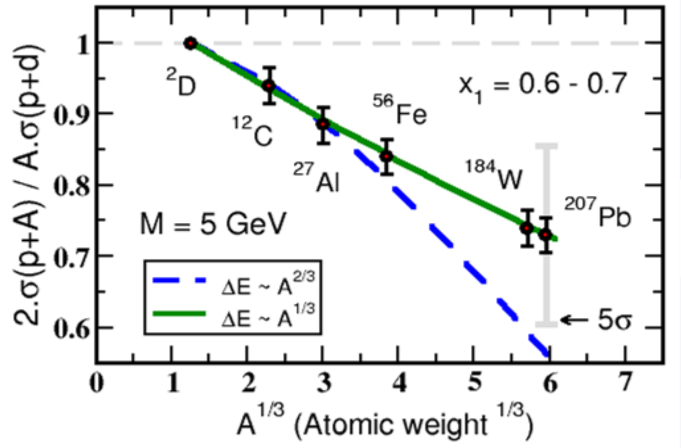
I. Vitev et al





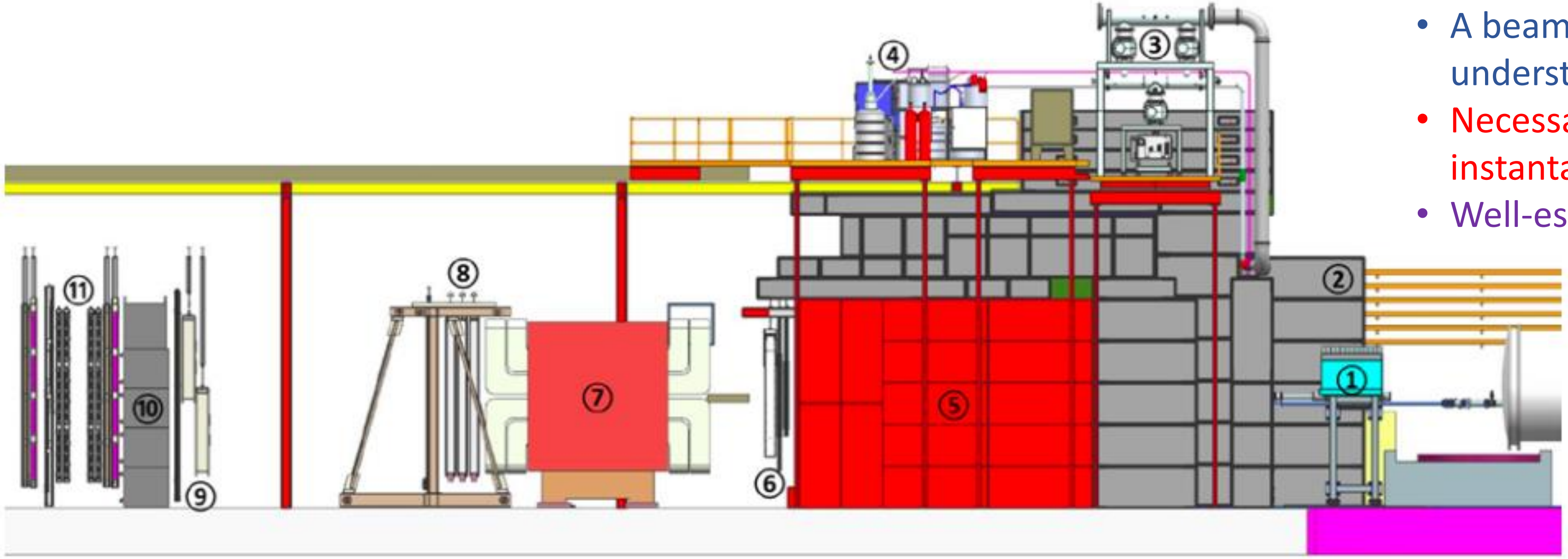






SpinQuest Status

Transition from SeaQuest to SpinQuest



① Beam Collimator ② Target Shielding ③ ROOTS Vacuum Pump ④ Helium Liquefier
⑤ Beam Dump/FMag ⑥ Station-1 Hodoscope & Tracking ⑦ KMag
⑧ Station-2 hodoscope & tracking ⑨ Station-3 Hodoscope & Tracking ⑩ Absorber
⑪ Station-4 Hodoscope & Muon Identification

Inherited from SeaQuest (5 – 11)

- A beam/spectrometer combination with well-understood capabilities and limitations
- Necessary instrumentation to cope with high instantaneous intensity environment
- Well-established analysis procedure

New polarized target system (1 – 4)

- Tighter beam requirements (better shielding and new collimator)
- Cryogenic infrastructure (liquefier, pump, service platforms, etc.)
- Larger operation and maintenance overhead
- Additional systematic uncertainties

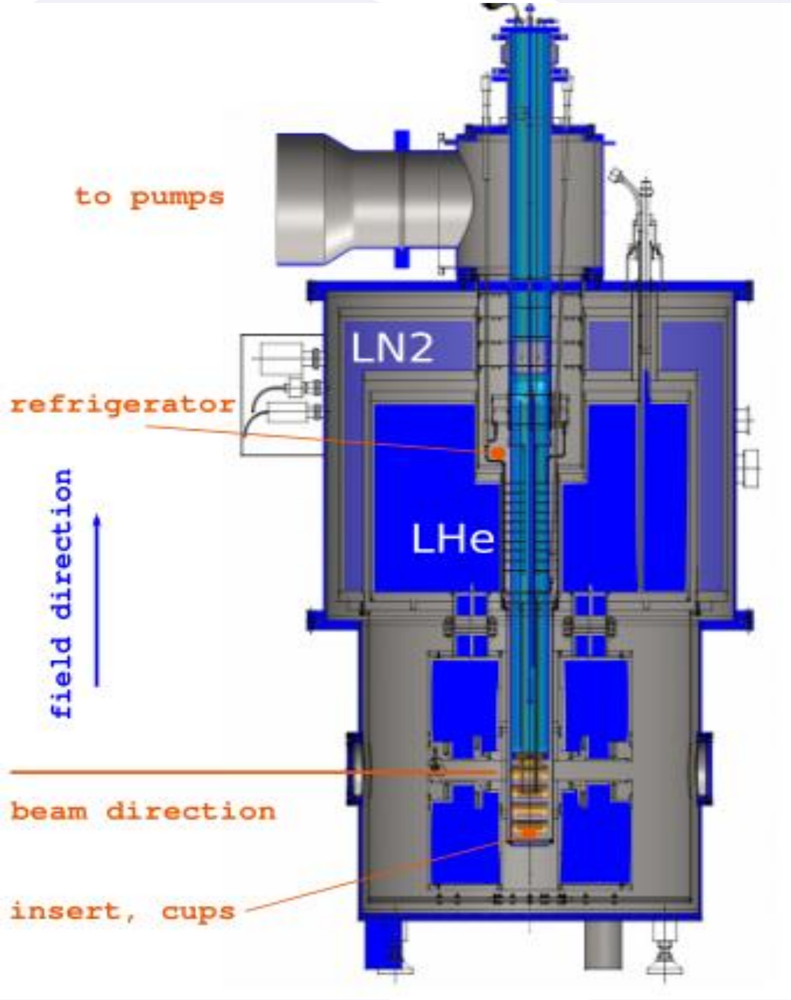
SpinQuest Status

Polarized target

- Refurbished from a longitudinal polarized target used at SLAC and rotated the magnet to be a transversely polarized target
- Dynamic Nuclear Polarization process to get nucleon polarization

Key specs

- Material: frozen beads of NH_3/ND_3 (7.9 cm long caps)
- 5T vertical superconducting magnet ($<10^{-4}$ homogeneity)
- High cooling capacity 1K ^4He evaporation refrigerator
- High power microwave system
- 3 NMR coils per cup
- >90% polarization for proton and >40% polarization for deuteron

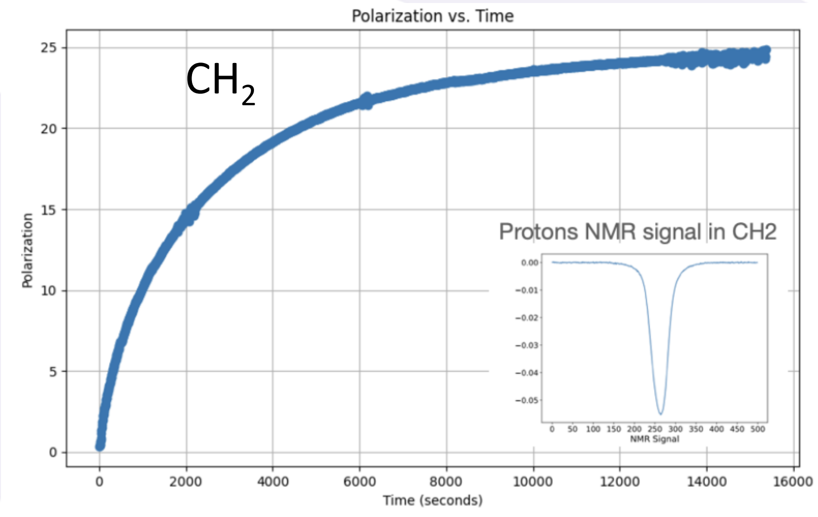


Unparalleled high luminosity and polarization

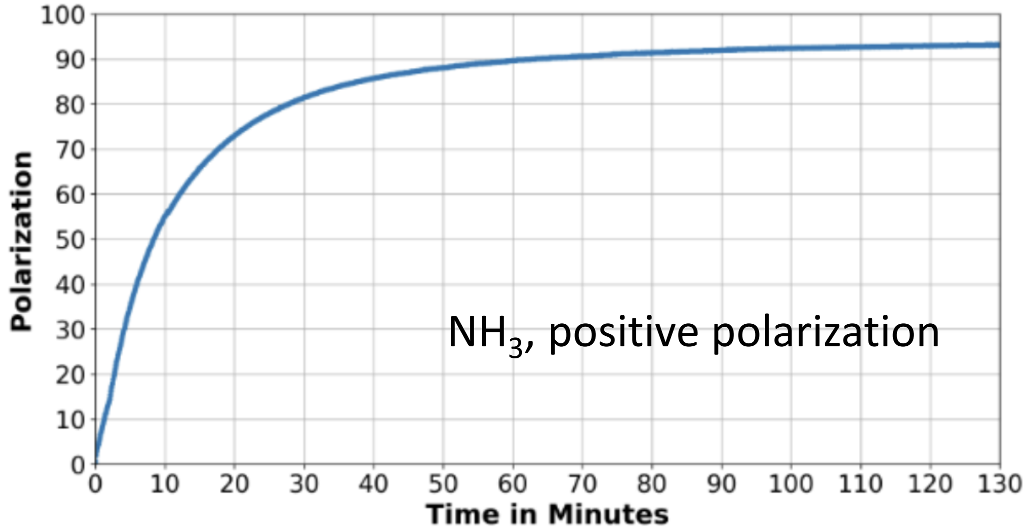
SpinQuest Status

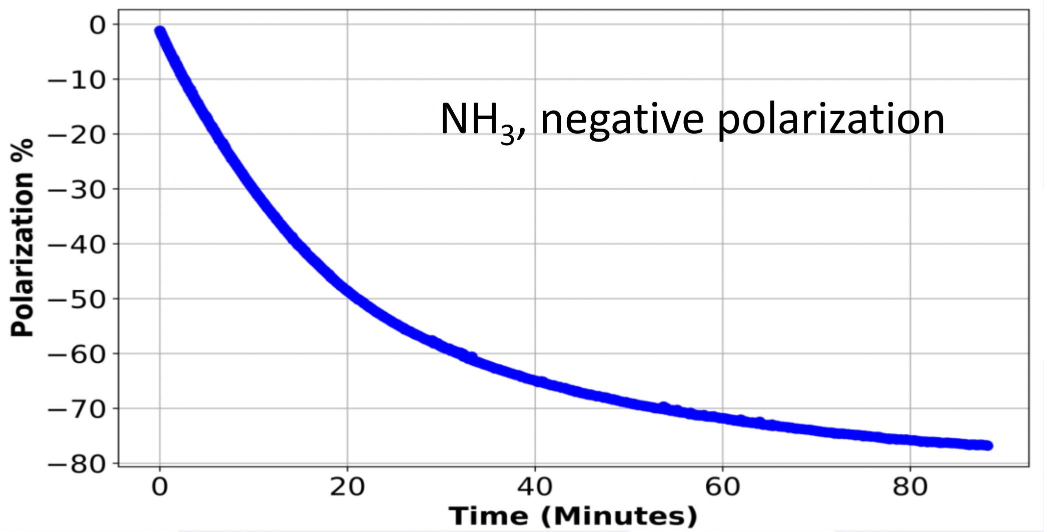
Polarized target successfully tested with beam

- After many years of installation and delays, we finally took the first commissioning and short production run in June
- Successful operation of polarized target in high-intensity proton beam up to 3E12 protons per pulse
- Reached 26% polarization with CH_2 target
- Reached 90% polarization with NH_3 target



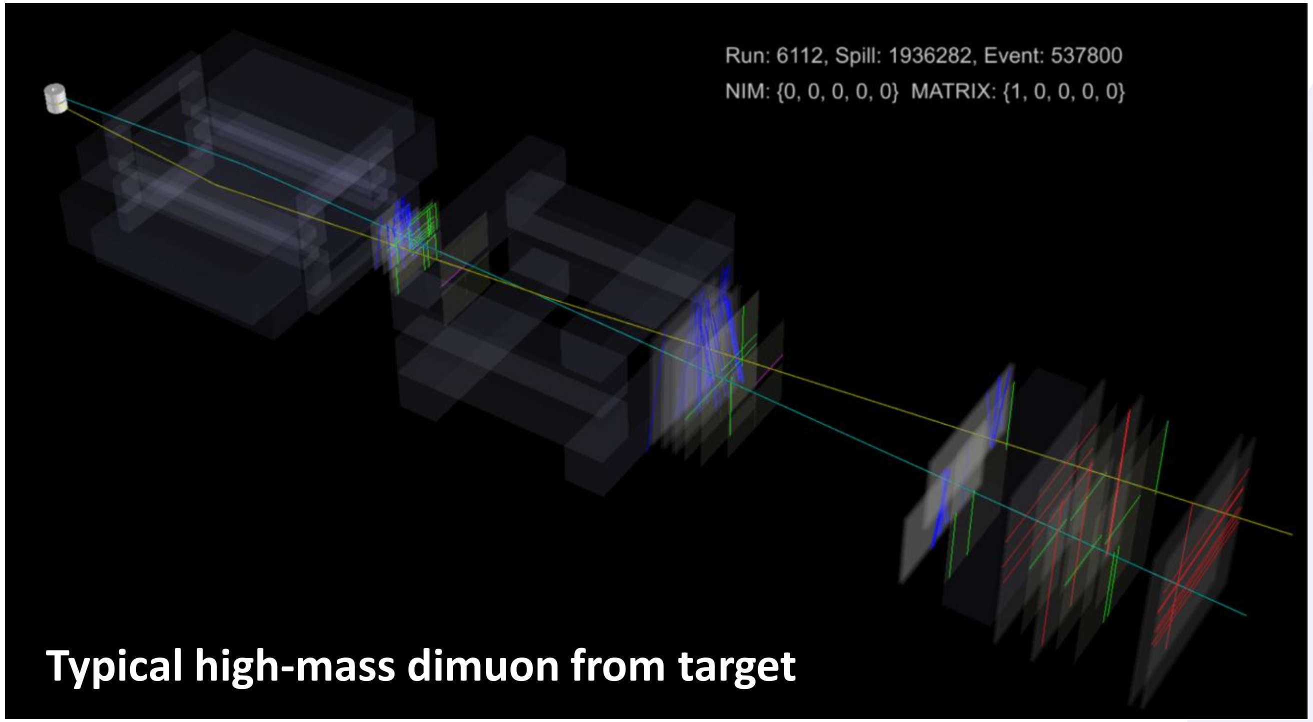
Proton Polarization



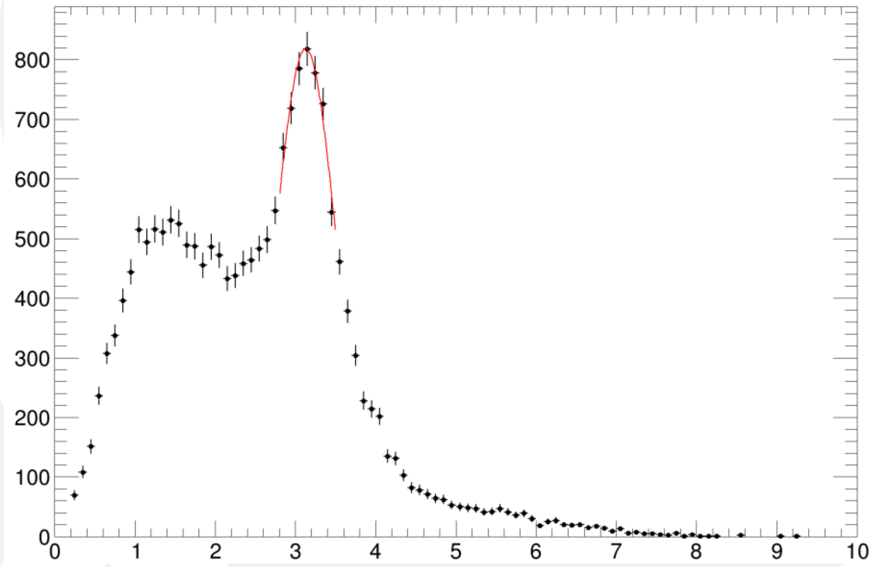


SpinQuest Status

First short production run



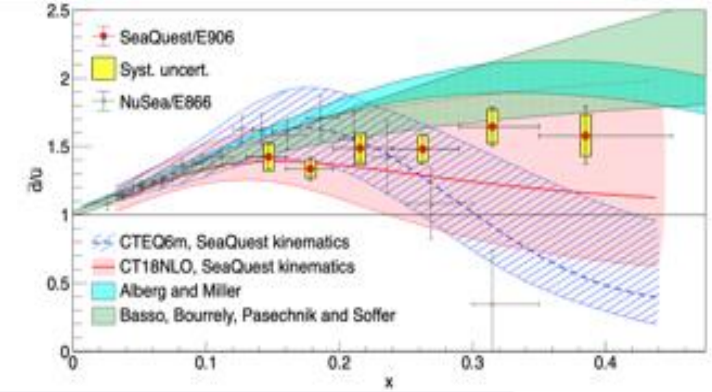
Online reconstruction

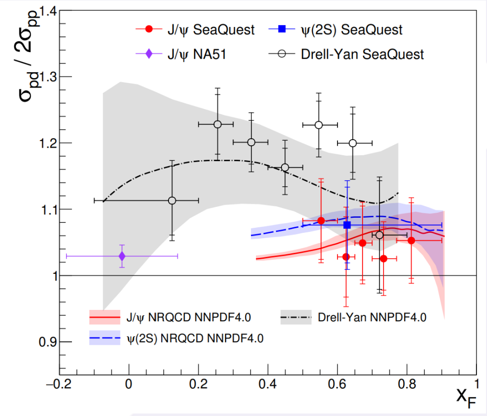


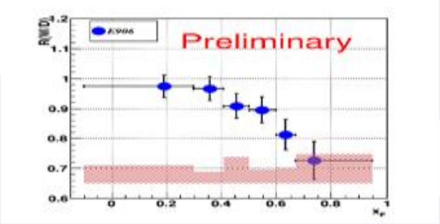
- The first short production run with 4E15 protons on polarized target – roughly a few hundred J/ψ events are expected for the first peek on the J/ψ TSSA measurement
- Clear J/ψ and high-mass dimuon events (dominated by beam dump events) observed in the online plots
- Offline analysis of the production data is ongoing

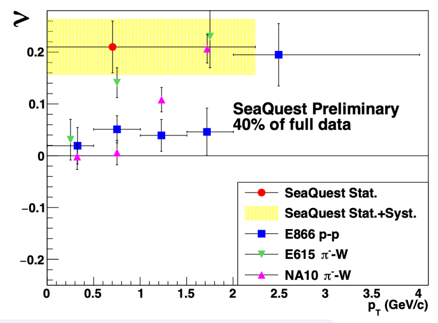
Summary and Future Prospects

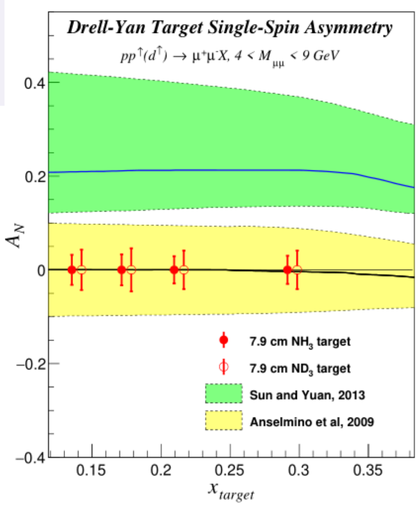
- Very rich QCD dynamics and sea-quark distributions inside the proton
- Anti-quark flavor asymmetry remains large at intermediate x, no sign of getting smaller as indicated in the previous statistics-limited data
  - ❑ Excludes some early proton models
- SpinQuest started data-taking this summer, with two years of production data taking planned
  - ❑ Expect first determination of sea-quark Sivers functions, probing OAM from sea-quarks
  - ❑ Shed new light on the proton structure, spin puzzle, and potentially constrains the future EIC nucleon structure physics program
  - ❑ ***Now is the time to join us!***





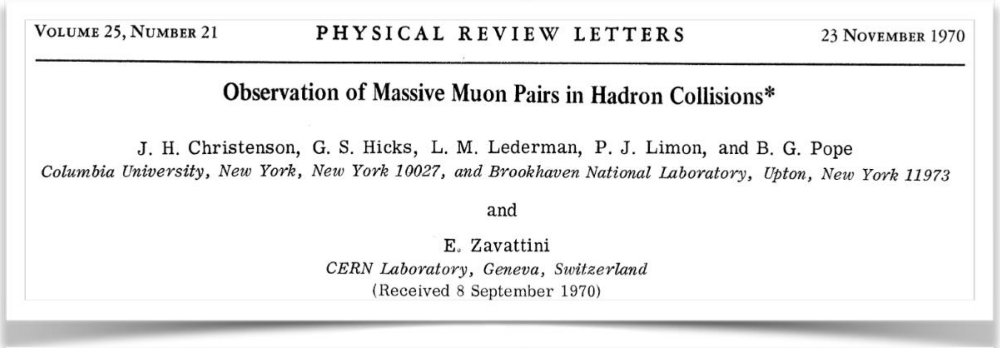






Backups

Drell-Yan process

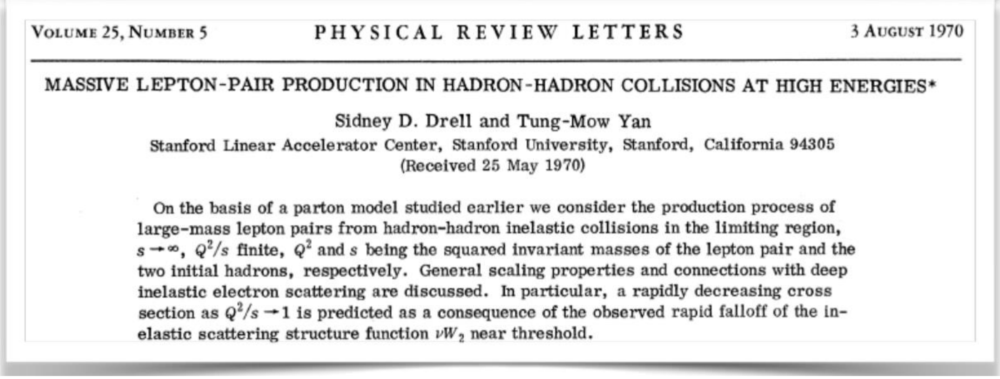

VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

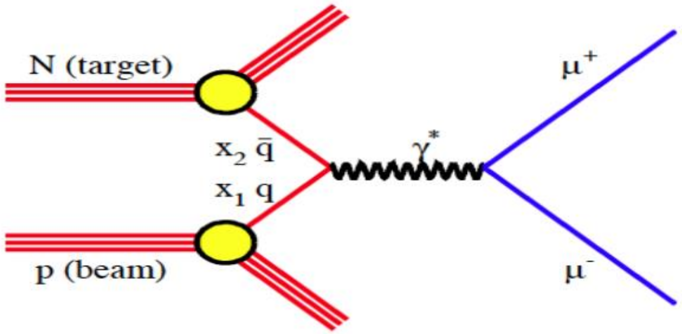
E. Zavattini
CERN Laboratory, Geneva, Switzerland
(Received 8 September 1970)

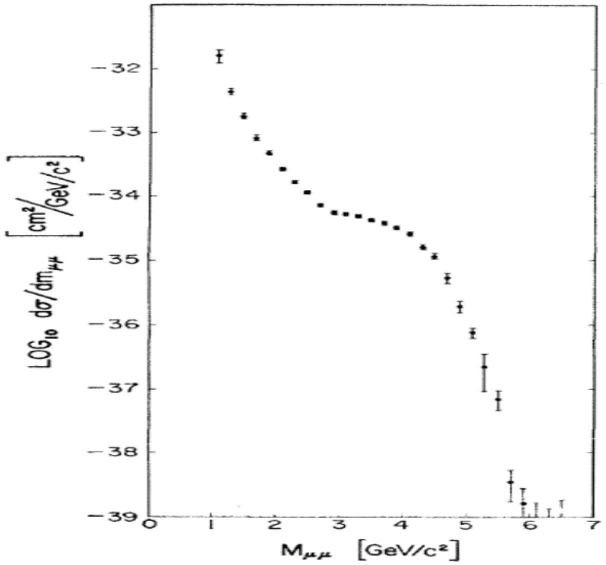

VOLUME 25, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1970

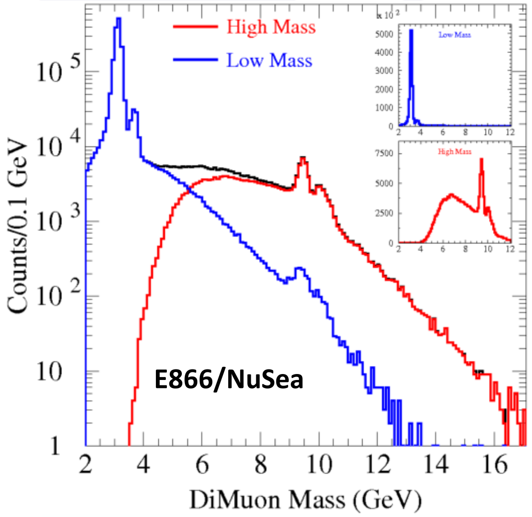
MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \to \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.

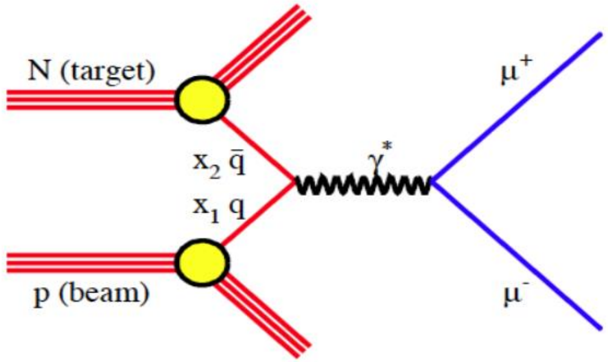






Unique sensitivity to sea-quarks

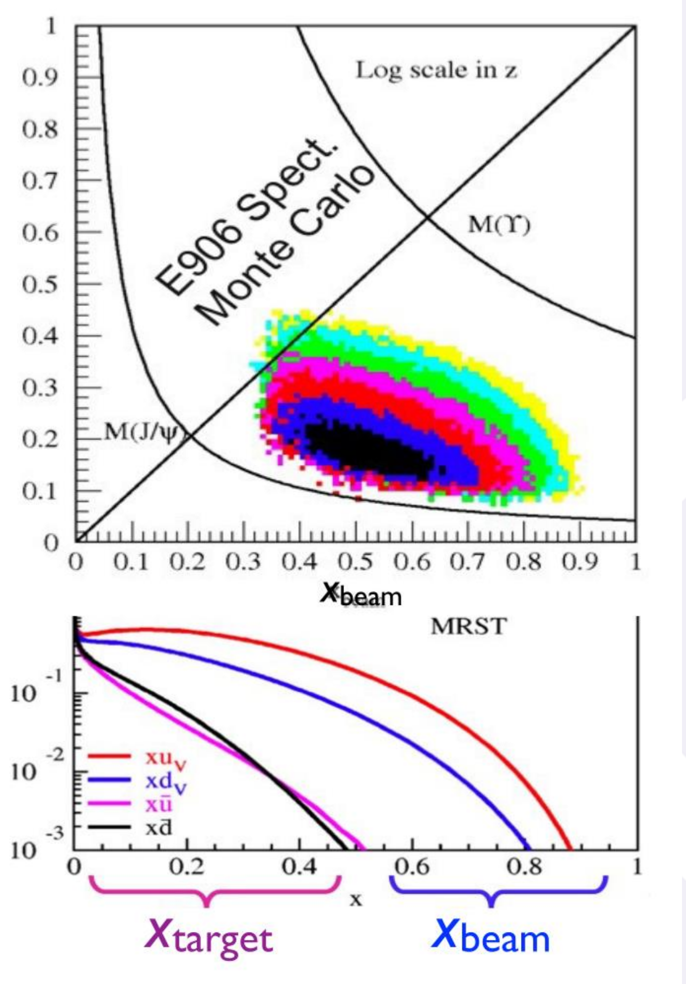
The Drell-Yan Process:



$$\frac{d^2\sigma}{dx_b\,dx_t} = \frac{4\pi\alpha^2}{9x_b\,x_t}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$

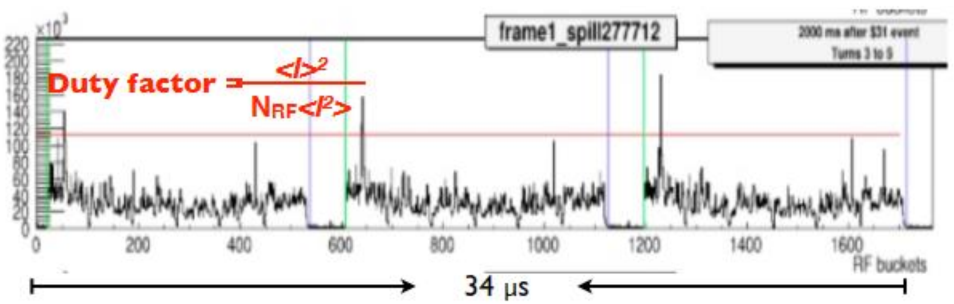
small

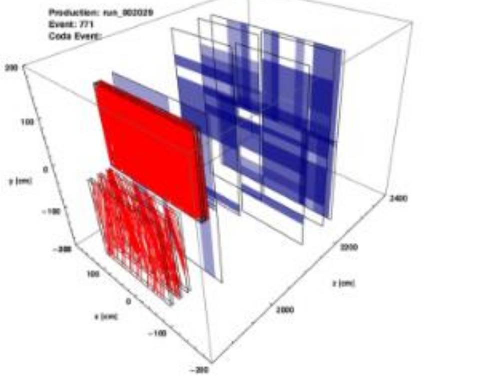
Unique sensitivity to sea quarks!



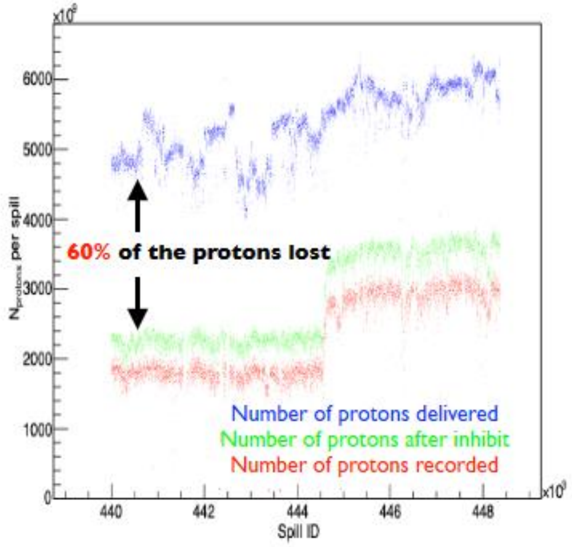
Tracking software challenges for SeaQuest

Huge variations in the instantaneous beam intensity → high hit rate/detector occupancy



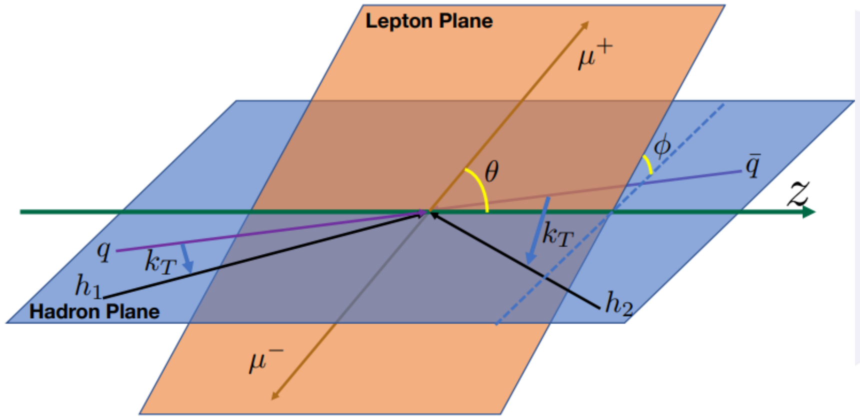


- This is the first time extracting beam from Fermilab Main Injector, duty factor initially < 10%
  - ➢ high intensity (super) buckets saturates the detector
  - ➢ completely kills DAQ
  - ➢ huge background poses serious challenge to reconstruction
- Partial solution: bucket-by-bucket beam intensity monitor
  - ➢ inhibit trigger at super bucket just to keep DAQ alive
  - ➢ measure the proton lost due to DAQ busy
- *Christmas miracle* (in 2014): turning on one forgotten switch significantly improves the duty factor



Angular Distribution for Drell-Yan

- Collins–Soper frame
  - Virtual photon rest frame
  - θ: polar angle of positive lepton
  - ϕ: azimuthal angle of positive lepton



- Drell–Yan cross section

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

  - Naively, $\lambda = 1,\ \mu = \nu = 0$ ($d\sigma \propto 1 + \cos^2\theta$) at leading order
    - ★ No transverse momentum on quarks
    - ★ No gluon emission
  - NLO: $\lambda \neq 1,\ \mu,\ \nu \neq 0$, but λ and ν still satisfy $1 - \lambda = 2\nu$ (**Lam–Tung relation**)

- Lam–Tung relation
  - Analogue of Callan–Gross relation (scattering of spin 1/2 particles)
  - Satisfied when the quark-antiquark axis is coplanar to hadron plane

Dynamic Nuclear Polarization

Given the small magnetic moment of the proton we can not reach a significant polarization just by using a large B field and a low T.

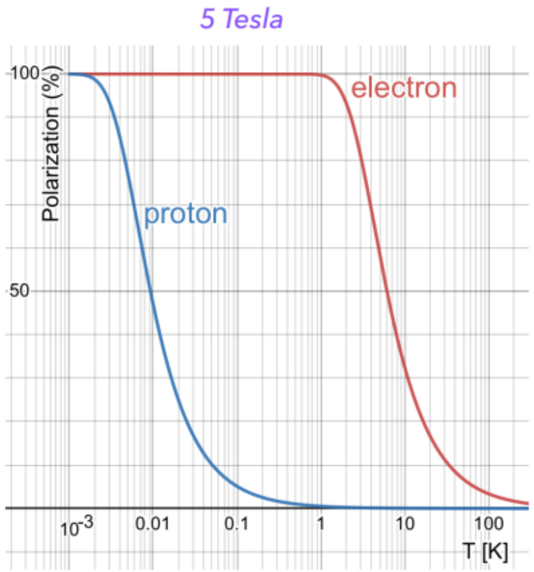
$$P = tanh\left(\frac{\mu B}{kT}\right)$$

- Proton has small magnetic moment

$$\mu_e \approx 660\mu_p$$

- At B = 5 Tesla & T = 1 K

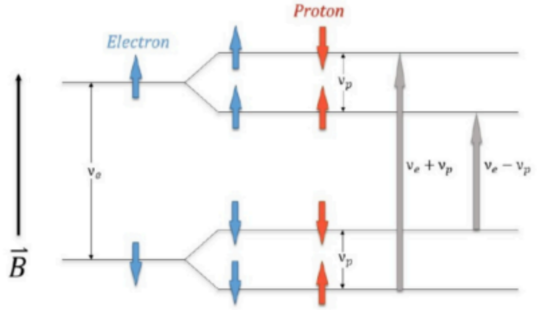
$$P_e = {\sim}98\%,\ P_p = 0.51\%$$



- Dynamic Nuclear Polarization
  - Dope target material with paramagnetic centers:

    chemical or irradiation doping to just the right density (10^{19} spins/cm^3)
  - Polarize the centers: Just stick it in a magnetic field
  - Use microwaves to transfer this polarization to nuclei:

    mutual electron-proton spin flips re-arrange the nuclear Zeeman populations to favor one spin state over the other



The disparity in relaxation times between the electron (ms) and proton (tens of minutes) at 1K is crucial to continue proton polarization.

Allows to achieve proton polarization of > 90%

SpinQuest Collaboration

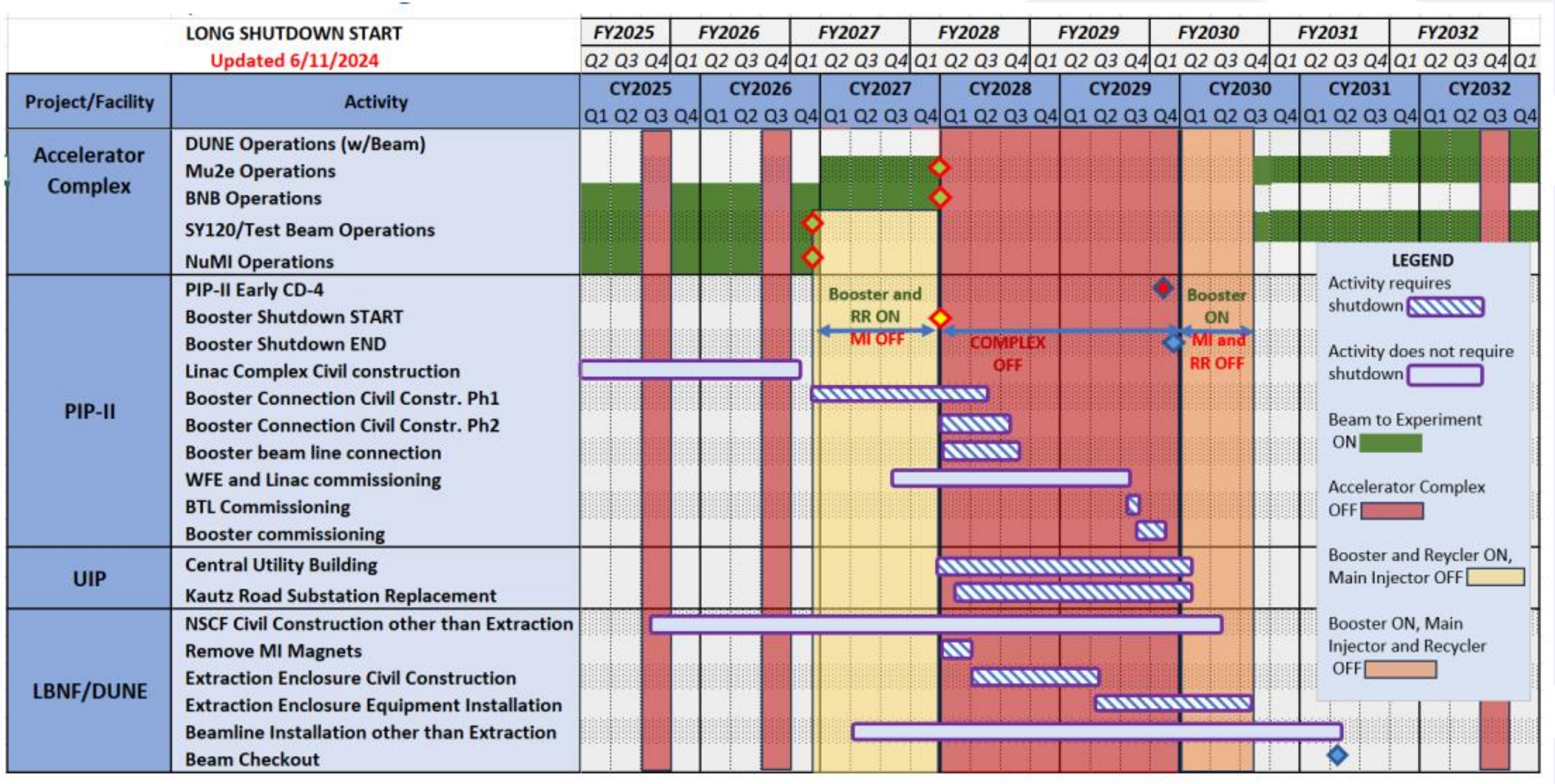
- 22 institutions from 7 countries (Armenia, China, India, Sri Lanka, Pakistan, Japan, USA)
- 50 active collaborators
  - ❑ 13 grad students
  - ❑ 7 postdocs
  - ❑ 30 faculties
- 18 collaborators reside in or near Fermilab

ACU: Donald Isenhower (PI), Michael Daugherity, Shon Watson
ANL: Paul Reimer (PI), Donald Geesaman
Aligarh Muslim University: Huma Haider* (PI)
Boston University: David Sperka (PI), Zijie Wan
FNAL: Rick Tesarek (PI), Carol Jong
KEK: Shin'ya Sawada (PI)
LANL: Kun Liu (PI, SP), Ming Liu, Kei Nagai
MIT: Phil Harris (PI), Noah Paladino
MSU: Lamiaa El Fassi (PI), Eric Fuchey
NMSU: Stephen Pate (PI), Vassili Papavassiliou, Abinash Pun, Huma Haider Forhad Hossain, Dinupa Nowarathen, Harsha Sirilal
RIKEN: Yuji Goto (PI)
Shandong U: Qinghua Xu (PI)
TokyoTech: Toshi-Aki Shibata (PI)
U. Colombo: Hansika Atapattu (PI), Vibodha Bandara
UIUC: Jen-Chieh Peng (PI)
U. Mich: Wolfgang Lorenzon (PI), Ievgen Lavrukhin, Noah Wuerfel
UNH: Karl Slifer (PI)
Tsinghua University: Zhihong Ye (PI)
UVA: Dustin Keller (PI, SP), Kenichi Nakano, Ishara Fermando, Zulkaida Akbar, Ernesto Diaz, Amal Pattividana, Jay Roberts, Devin Seay, Liliet Diaz, Arthur Conover
Yamagata U: Yoshiyuki Miyachi (PI), Yoshiki Hiruma
YerPhI: Hrachya Marukyan (PI)
National Center for Physics: Waqar Ahmed (PI), Farooq Muhammad

- Postdocs - Grad students

** Current on leave and full time postdoc at NMSU*

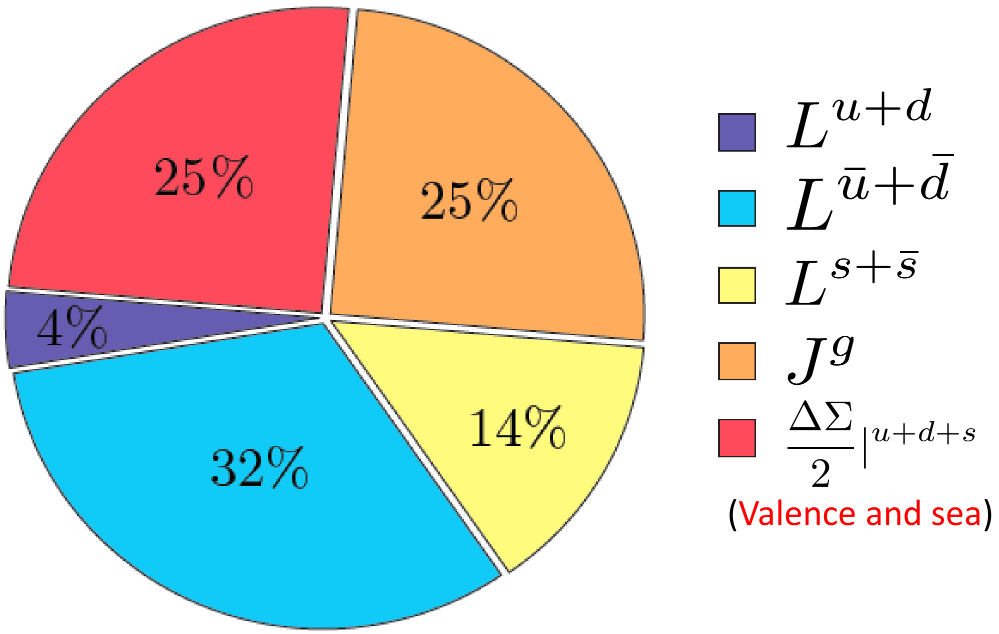
Fermilab accelerator schedule



Importance of sea-quarks in the proton spin

Recent lattice QCD results

K.-F. Liu *et al* arXiv:1203.6388



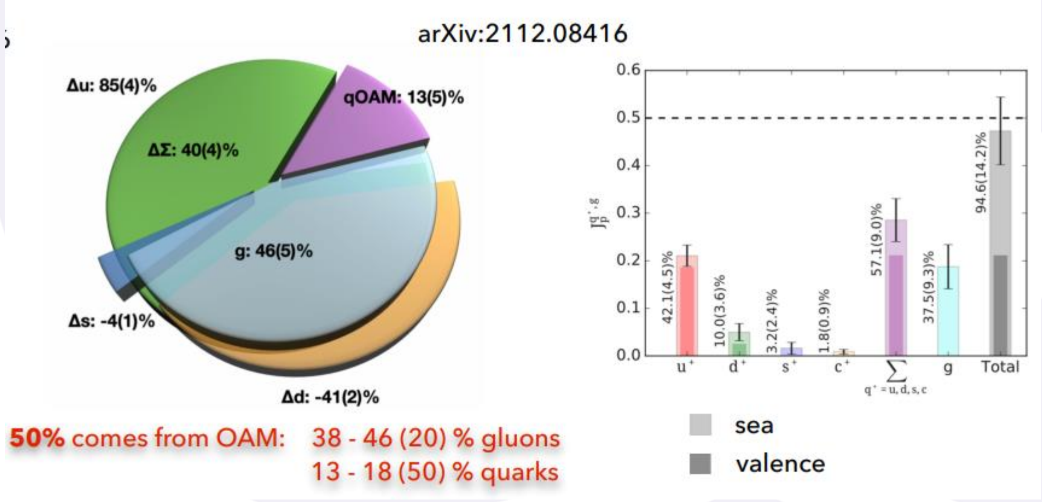
DS_q » 25% $L_u \approx - L_d$

$2\ L_q$ » 46% (0%(valence)+46%(sea))

$2\ J_g$ » 25% $J_g = DG + L_g$

Orbital angular momentum ? Sea quarks' angular momentum could be a major part of the "missing spin".

- All of the quark orbital momentum comes from the sea quark contribution
- Important to understand it experimentally ad theoretically



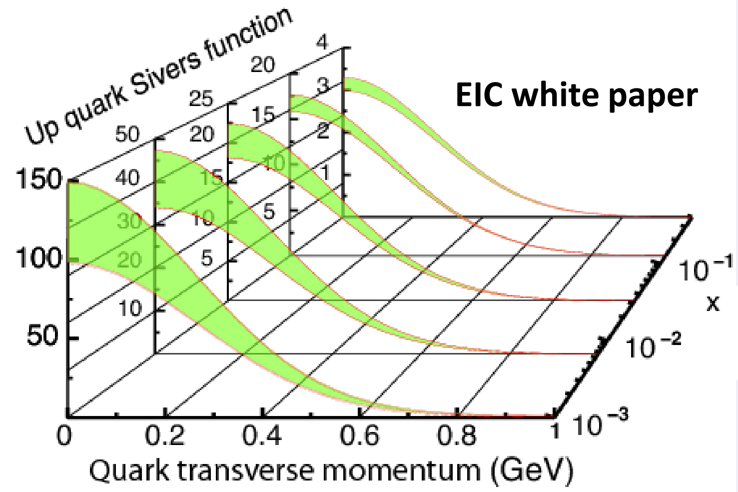
TMDs – Sivers function

Quark distribution functions

		quark		
		Unpol.	**L**ong.	**T**rans.
nucleon	**U**	f_1		$h_1^{\perp}$
	L		g_1	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$

The quark Sivers distribution (function)

Expected dramatic increase at lower x

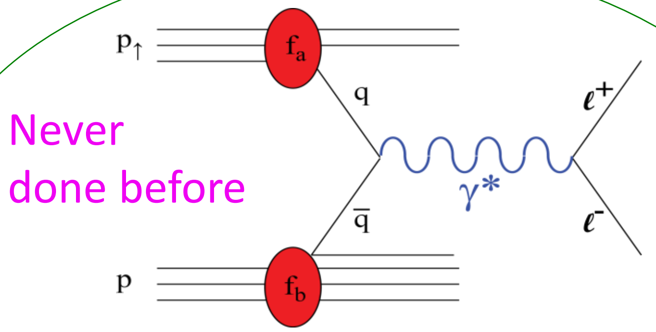


- Focus on transverse momentum – 3D structure of the nucleon

$$f_{1T}^{\perp[\mathcal{C}]}(x,k_T^2)\,(\vec{S}_T \times \vec{k}_T) = \frac{M}{2}\,\mathrm{F.T.}\,\langle P,S_T|\,\overline{\psi}(0)\,\mathcal{L}_{\mathcal{C}}(0,\xi)\,\not{n}_-\,\psi(\xi)\,|P,S_T\rangle\big|_{\xi^+=0}$$

The Sivers function vanishes if the quarks have no orbital motion

Sivers asymmetry in polarized Drell-Yna

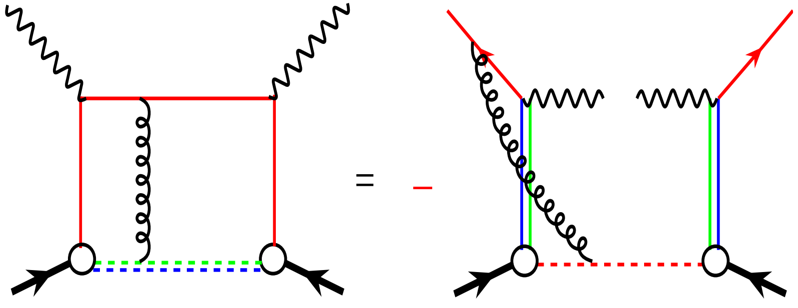


$$pp^\uparrow \to \mu^+\mu^- X$$

Left-right asymmetry in Drell-Yan di-muon production on a polarized nucleon

Cornerstone prediction of QCD factorization

$$f_{1T}^{\perp q}\,|_{SIDIS} = -f_{1T}^{\perp q}\,|_{DY}$$



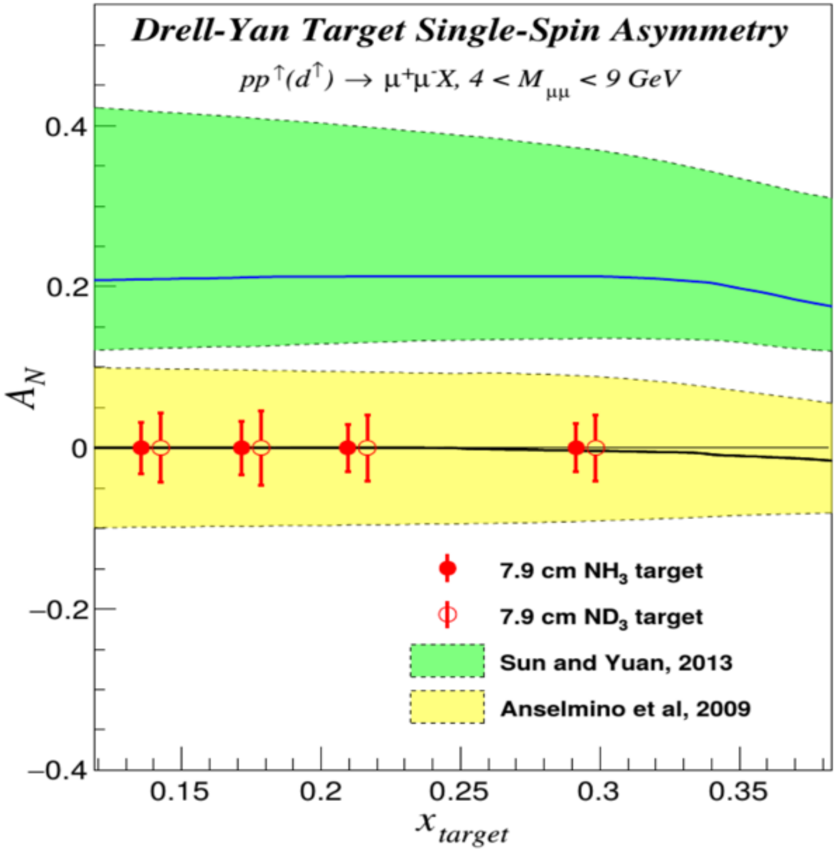
SIDIS = – DY

- The same quark Sivers distribution in both processes, but with an opposite sign

Deeply rooted in the gauge invariance in QCD

DOE Milestone: “Test unique QCD predictions for relations between single-spin phenomena in p-p scattering and those observed in deep-inelastic scattering”

SpinQuest Expected Results and Impact



Simultaneous measurement of both ubar and dbar
Statistics shown for 2 calendar years of running

$$A_N^{DY} \propto \frac{u(x_b) \cdot f_{1T}^{\perp,\bar{u}}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}$$

Existing data do not put enough constraints on the sea quark Sivers distribution, neither sign nor value

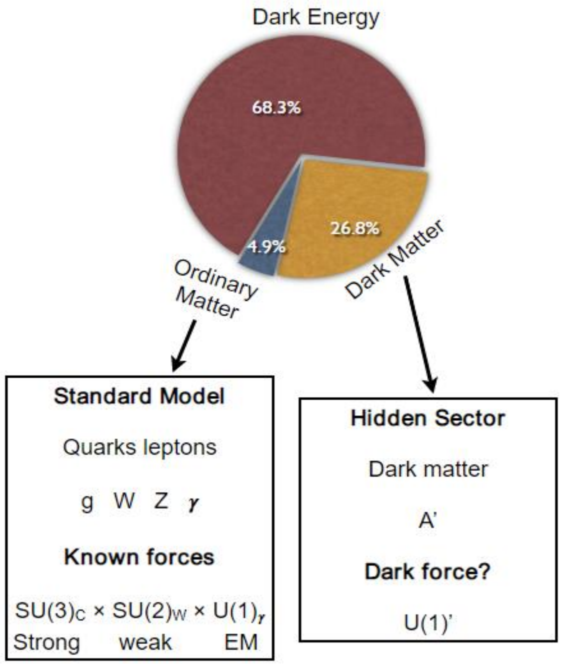
If $A_N \neq 0$, major discovery:

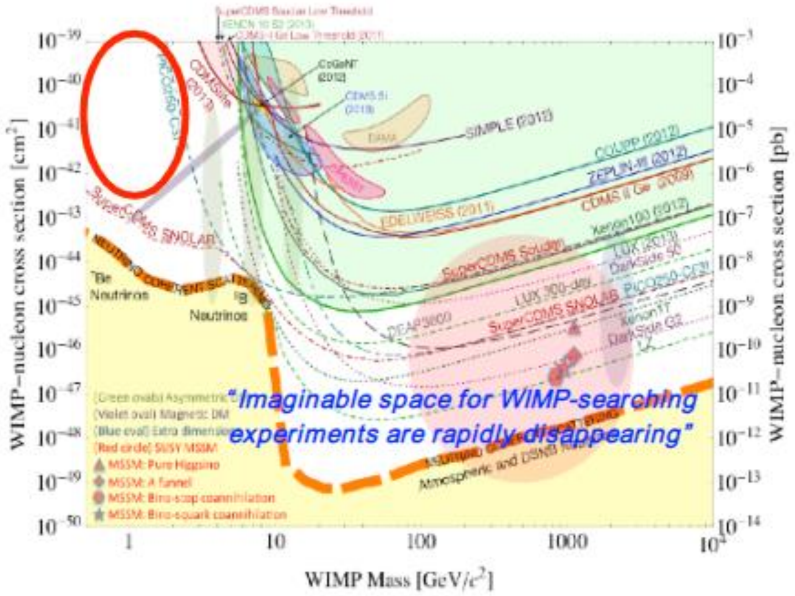
- “Smoking gun” evidence for $L_{sea} \neq 0$
- Determine sign and value for sea quark Sivers function
- Confirm global analysis expectations

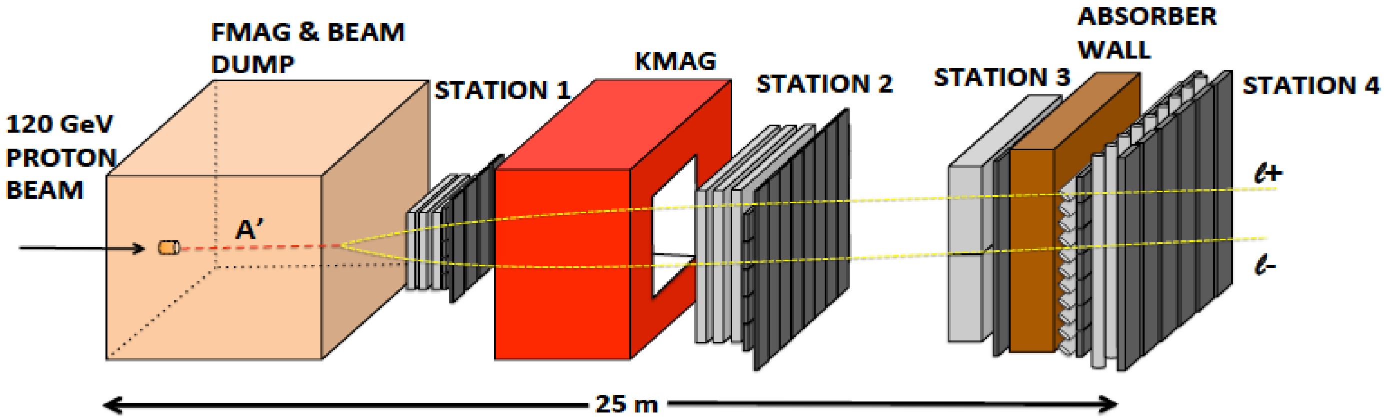
If $A_N = 0$:

- $L_{sea} = 0$, spin puzzle more dramatic?
- Sea quark flavor asymmetry hard to explain

Dark Sector Physics Extension





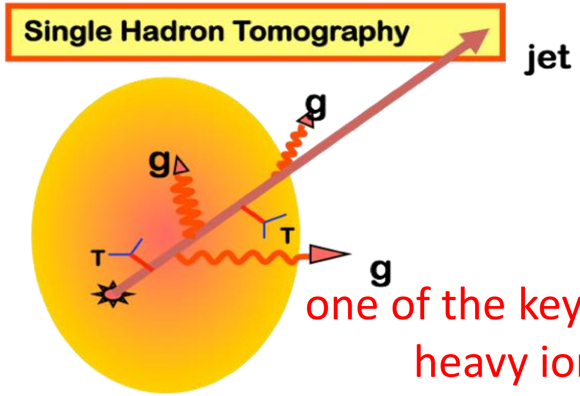


Understanding Jet quenching at RHIC/LHC

Energy loss of partons from hard scattering through re-scattering in the hot and dense medium (Quark Gluon Plasma)

- nuclear modification factor $R_{AA} << 1$ at high p_T

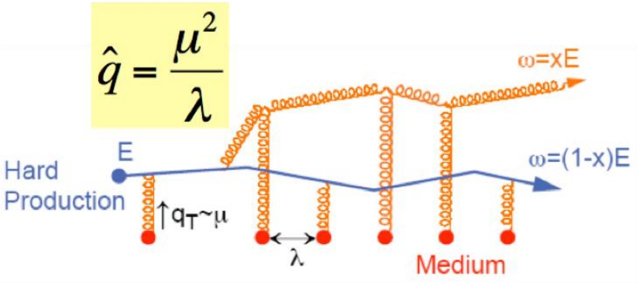
$$R_{AA} = \frac{\text{Yield}_{AA}/\langle N_{binary}\rangle_{AA}}{\text{Yield}_{pp}} \sim 1 - \int \rho \otimes \frac{dE}{dx}$$



one of the key questions in heavy ion today

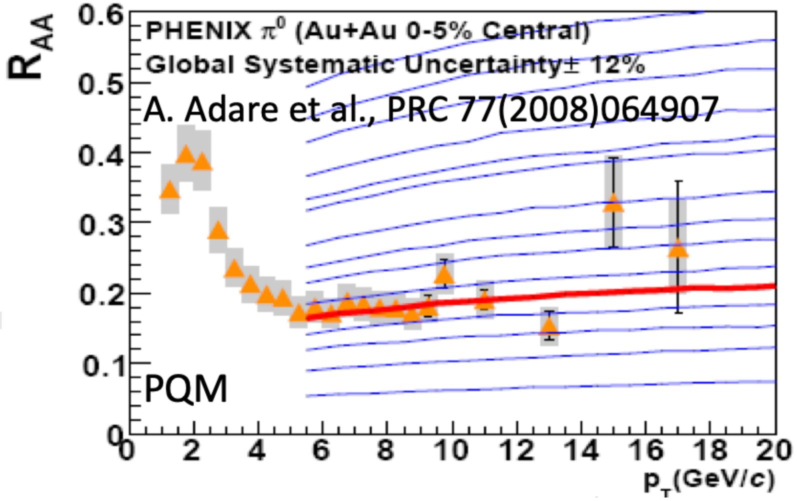
Recent JET collaboration progress (PRC 90, 014909 (2014)) fo 10 GeV quark:

- qhat = 1.2 ± 0.3 GeV^2/fm for RHIC
- qhat = 1.9 ± 0.7 GeV^2/fm for LHC



Access medium properties through statistical analysis:

- example: transport coefficient
- **model dependent**



Measurement of Cold Nuclear Medium will help pin down the model uncertainty

Dark Sector Expected Results

First data taking parasitically with SpinQuest/E1039: FY24 – FY25