Probing Parton Distributions and Nucleon Structure in the SeaQuest and SpinQuest Experiments at Fermilab

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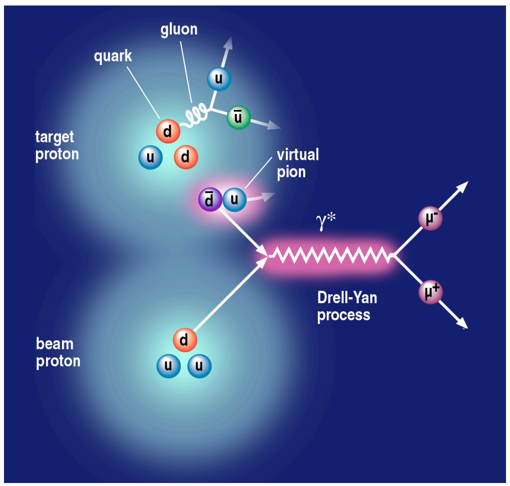
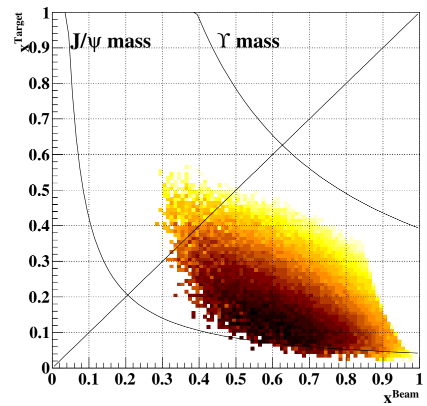
Outline

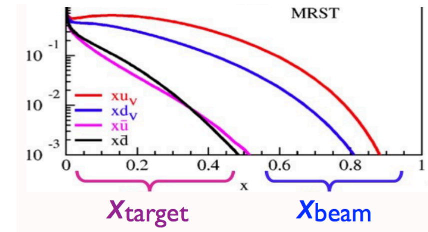
- **Drell-Yan (DY) Fixed Target Experiments at Fermilab**
  - E-906/SeaQuest (unpolarized targets)
  - E-1039/SpinQuest (polarized targets)
  - The Spectrometer
- **Highlight of SeaQuest Physics Topic**
  - Anti-quark Asymmetry
- **Highlight of SpinQuest Physics Topics and Status**
- **Summary and Outlook**

The Drell-Yan Process

<u>DY process</u>: $p + p \rightarrow \Upsilon^* \rightarrow \mu^+ + \mu^-$







Spectrometer acceptance for experiments

<u>Cross section at Leading Order (LO)</u>:

Distinguishable event-by-event

Small!

$$\frac{d^2\sigma}{dM^2dx_F} = \frac{4\pi\alpha^2}{9M^4}\frac{x_{beam}x_{target}}{x_{beam}+x_{target}}\sum_{i\in\{u,d,s,...\}}^{n} e_i^2[f_i(x_{beam})\bar{f}_i(x_{target}) + \cancel{\bar{f}_i(x_{beam})f_i(x_{target})}]$$

Definitions:

$x_F \approx x_{beam} - x_{target}$ α = *fine structure constant* $\tau = M^2 / s = x_{beam}x_{target}$

M = *mass of dimuon pair* e_i = *charge of quark* $\sqrt{s} = E_{CM} = \sqrt{(2E_{beam}m_p)}$

DY Fixed-Target Experiments at Fermilab

- 120 GeV proton beam ($\sqrt{s}$ = 15 GeV) from Main Injector
  - Intensity ~ 10^{12} protons/sec
- **E-906/SeaQuest**
  - Targets (unpolarized):
    - Liquid hydrogen and deuterium (LH2, LD2)
    - Solid carbon, iron, tungsten
  - Data taking: 2013-2017
  - Some physics topics
    - Flavor asymmetry in the proton sea*
    - Nuclear effects via DY process
    - Nuclear effects via J/ψ production

AND MORE!

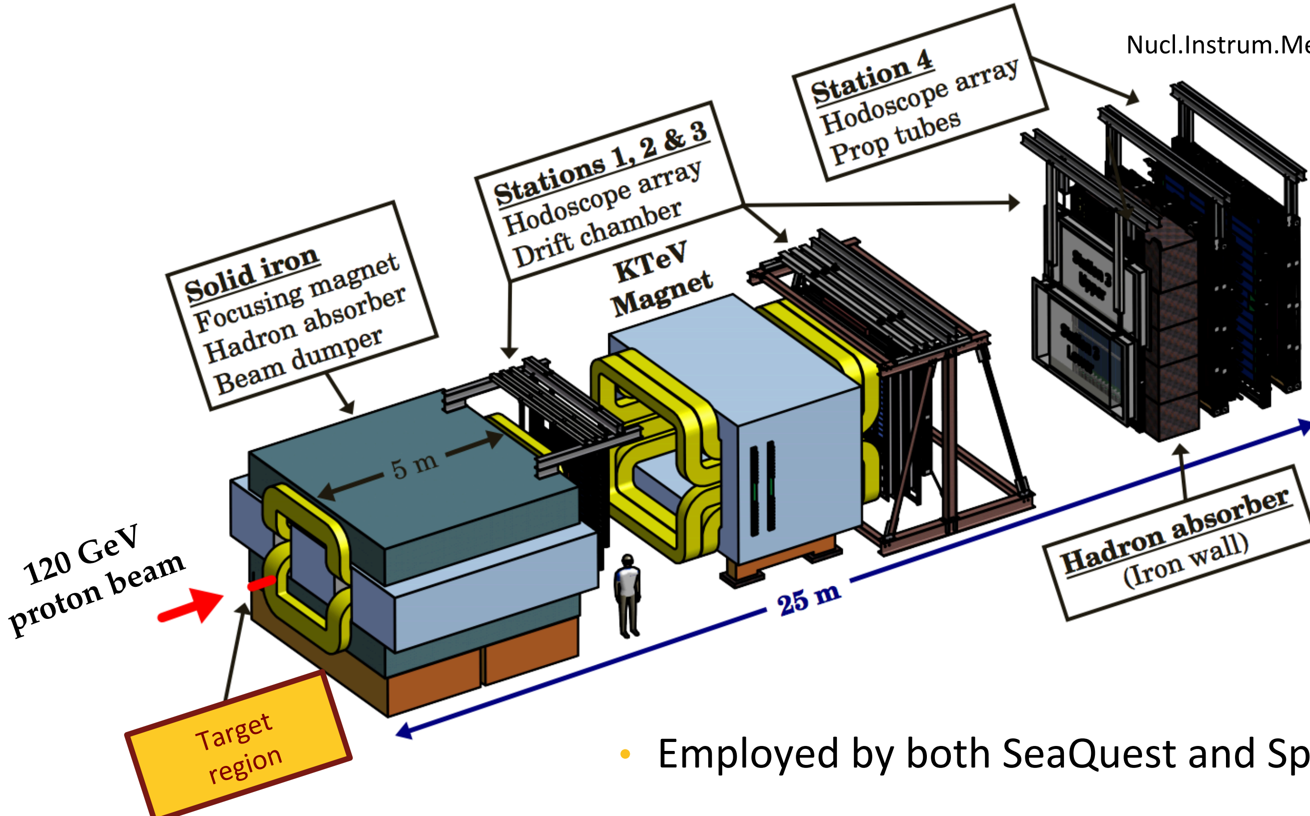
DY Fixed-Target Experiments at Fermilab

- 120 GeV proton beam ($\sqrt{s}$ = 15 GeV) from Main Injector
  - Intensity ~ 10^{12} protons/sec
- **E-1039/SpinQuest**
  - Targets (transversely-polarized):
    - NH_3 and ND_3
  - Expected data taking: 2021-2023
  - Some physics topics
    - Anti-quarks Sivers asymmetry
    - Gluonic Sivers asymmetry*

AND MORE!

The Spectrometer

Nucl.Instrum.Meth.A 930 (2019)



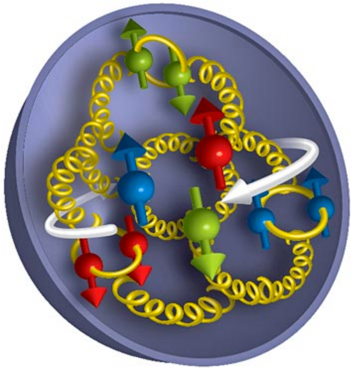
Located in NM4 enclosure at Fermilab

- Employed by both SeaQuest and SpinQuest
- SpinQuest polarized cryogenic targets:
  - Dynamic nuclear polarization (~ 80% target polarization at 4% uncertainty)
  - Kept at 1K in 5 T field, polarization flip every 8 hours

Highlight of SeaQuest Physics Topics:

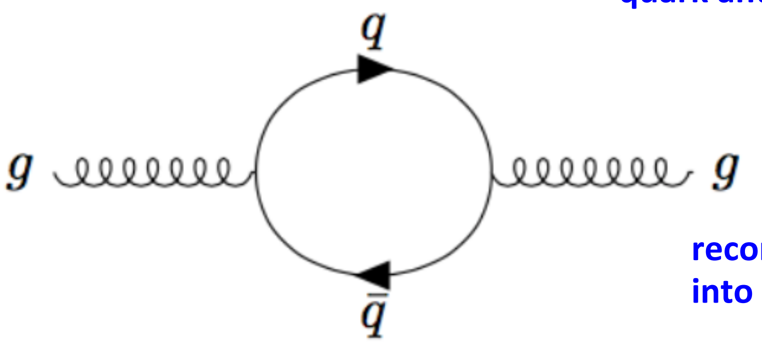
Anti-quark Asymmetry

Nucleon Sea



- Nucleon sea naively assumed to be flavor symmetric
  - Gluons don't couple to flavor
  - Masses of u and d quarks are similar and small, compared to QCD scale

quark anti-quark pair



gluon splits

recombine into a gluon

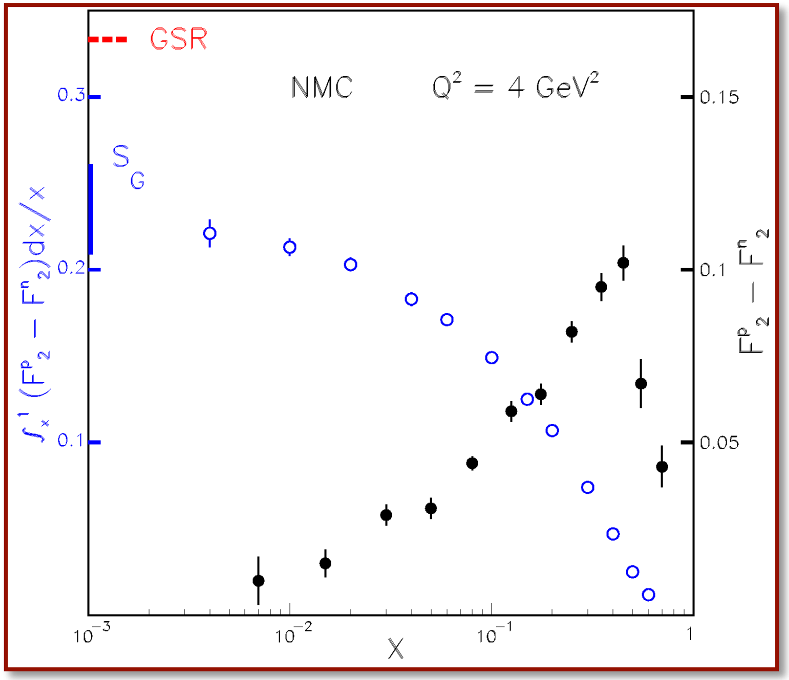
Perturbative contributions calculated to be small!

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

NMC (1991)

- Gottfried Sum Rule:

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



- Symmetric sea implies S_G = 1/3
- NMC experiment (LD2, LH2, 90 GeV and 280 GeV μ-beam)

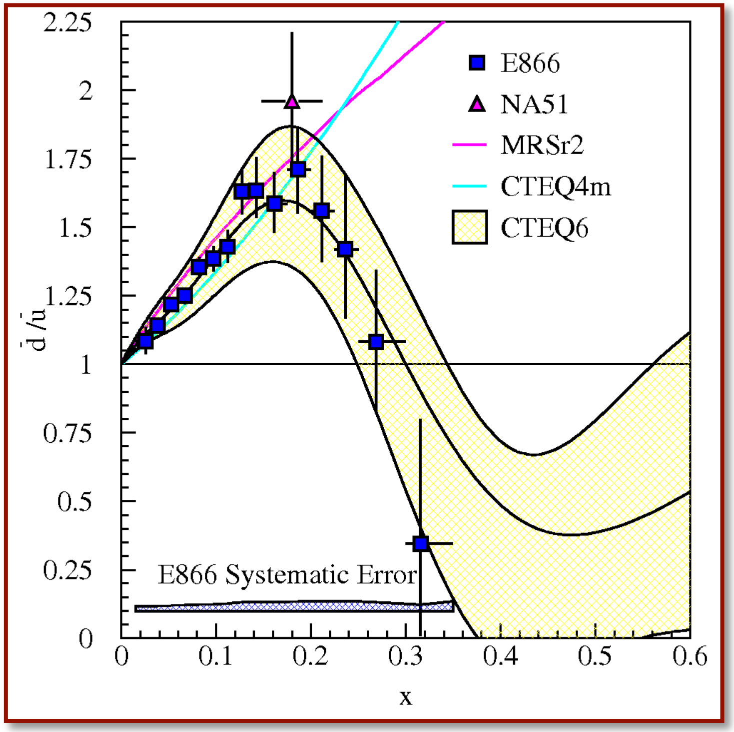
$$S_G = \int_0^1 (F_2^p - F_2^n)\,dx/x = 0.235 \pm 0.026$$

More Evidence of Flavor Asymmetry

- **CERN NA51** (1994): 450 GeV p-beam, LD2, LH2 targets

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

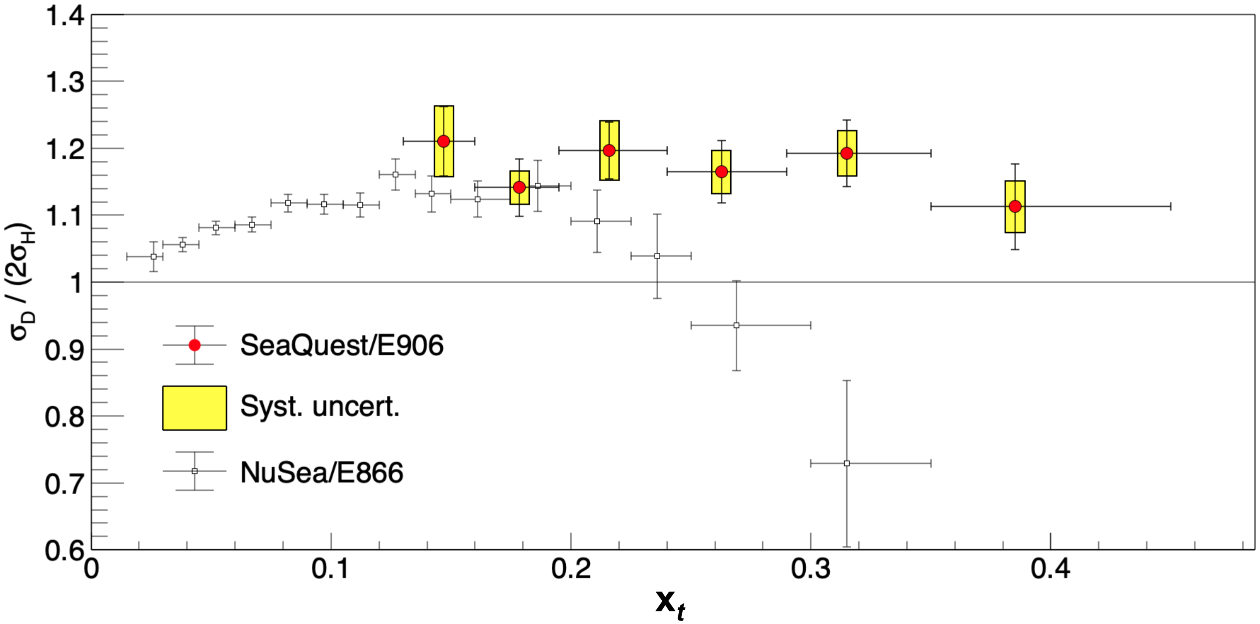
- **FNAL E866/NuSea** (1998): 800 GeV p beam LD2, LH2 targets
- Studied actively by effective QCD models & lattice QCD
  - Precise measurement at large x was needed



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

SeaQuest Result

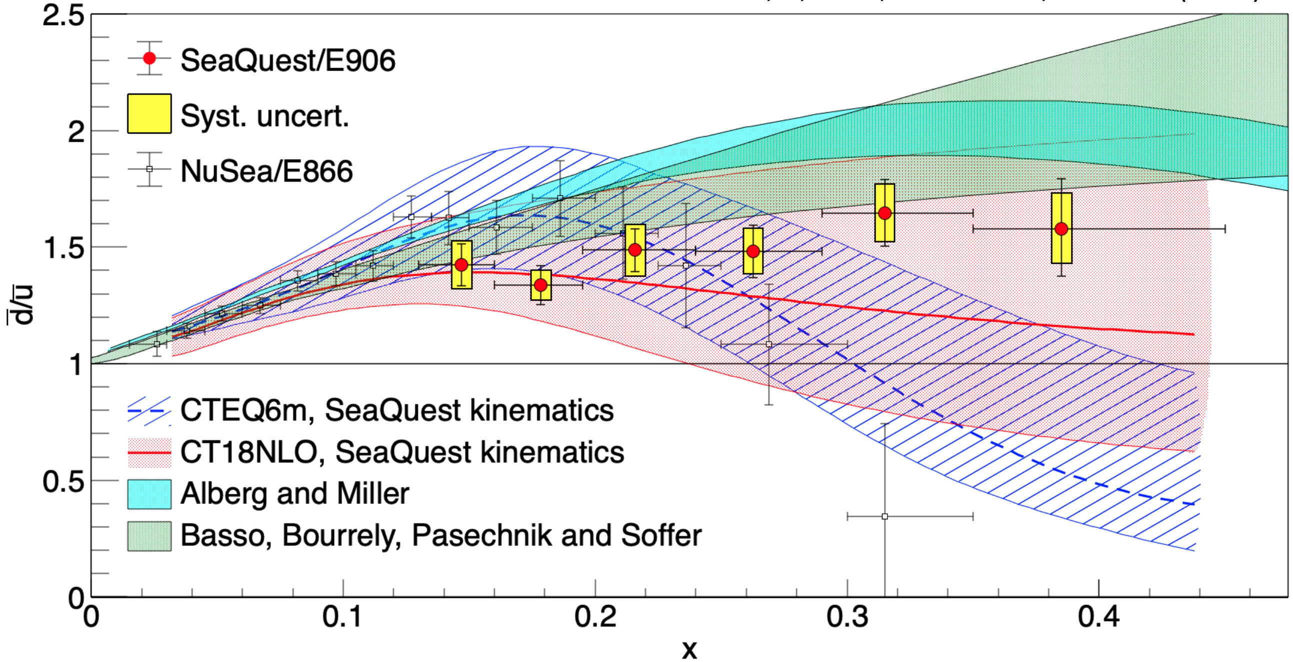
Dove, J., et al., Nature 590, 561–565 (2021)



- Large asymmetry over entire range measured
- Discrepancy with NuSea could be due to: different beam energy, acceptance and kinematic coverage
  - Discrepancy at high x is not well understood

Model Calculation Comparison

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



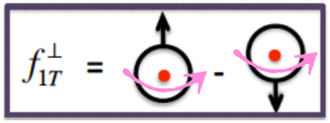
- Reasonably described by the predictions of
  - "Pion cloud model" (Alberg & Miller)

$$|p\rangle = (1 - \sum a_i)|p_0\rangle + a_{|N\pi\rangle}|N\pi\rangle + a_{|\Delta\pi\rangle}|\Delta\pi\rangle + a_{|\Lambda K\rangle}|\Lambda K\rangle + \cdots$$

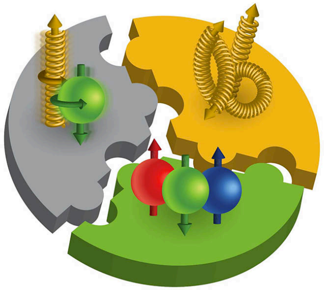
  - "Statistical model" (Basso et al.)

SpinQuest Motivation

- Explore the **anti-quark** and **gluon Sivers functions,** $\boldsymbol{f_{1T}^{\perp}}$:

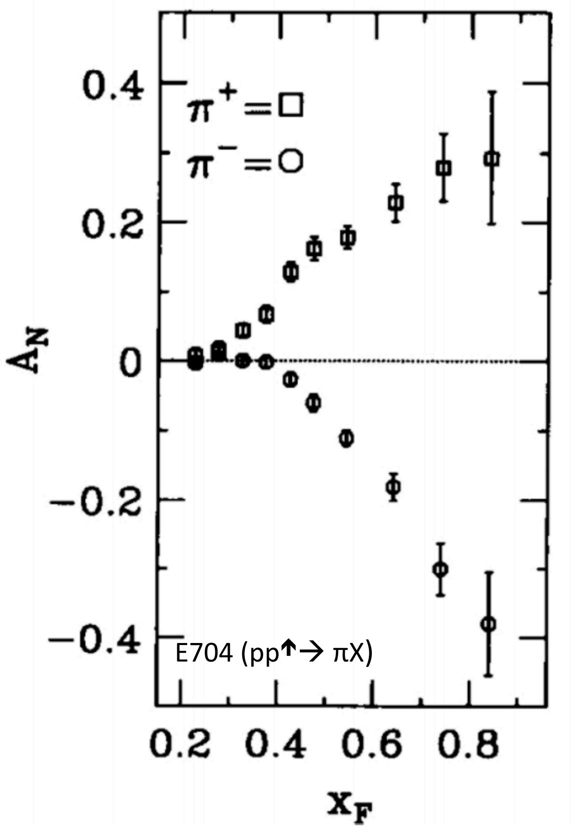


  - Large transverse single spin asymmetries (TSSAs), $A_N (\propto \boldsymbol{f_{1T}^{\perp}})$, observed in polarized pp-collisions
  - Study/constrain antiquark and gluon orbital angular momentum contributions to proton spin

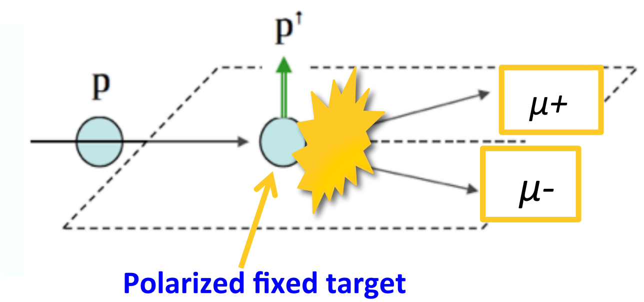


$$A_N = \frac{d\sigma^{\Uparrow} - d\sigma^{\Downarrow}}{d\sigma^{\Uparrow} + d\sigma^{\Downarrow}}$$

Phys. Lett. B 264, 462 (1991)



Sivers Function at SpinQuest



$x_{Bjorken} = x = p_{parton}/p_{proton}$
$x_2 = x_{target}$, $x_1 = x_{beam}$
$x_F = x_1 - x_2$

$N_{u\ (or\ d)}$ = # of dimuons for spin 🡅(🡇)
$L_{u\ (or\ d)}$ = live protons for spin 🡅(🡇)

i.e. The Drell-Yan Process

$$A_n = \frac{\frac{N_u}{L_u} - \frac{N_d}{L_d}}{\frac{N_u}{L_u} + \frac{N_d}{L_d}} \propto \frac{\sum_q e_q^2\left[f_1^q(x_1)\cdot f_{1T}^{\perp,\bar{q}}(x_2) + \cancel{1 \leftrightarrow 2}\right]}{\sum_q e_q^2\left[f_1^q(x_1)\cdot f_1^{\bar{q}}(x_2) + \cancel{1 \leftrightarrow 2}\right]}$$

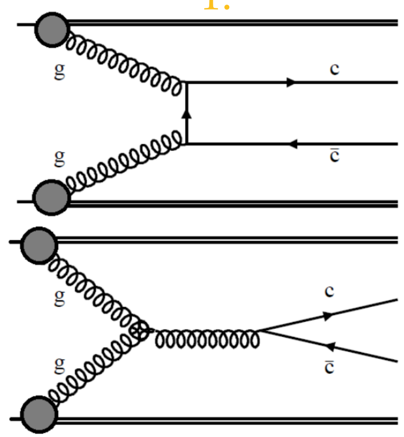
Small due to SpinQuest acceptance!

- Measure azimuthal asymmetry in:
  - DY dimuon production → study anti-quark Sivers
  - **J/ψ meson dimuon decay → study gluon Sivers**

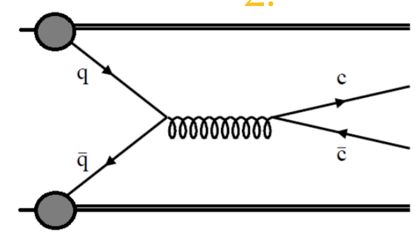
J/ψ Production

- The SpinQuest experiment: access to dimuon decay of the J/ψ meson (charm, anti-charm bound state)
- Mechanisms:
  1. gluon-gluon (g-g) fusion
  2. quark anti-quark (q-q-) annihilation

1.



2.



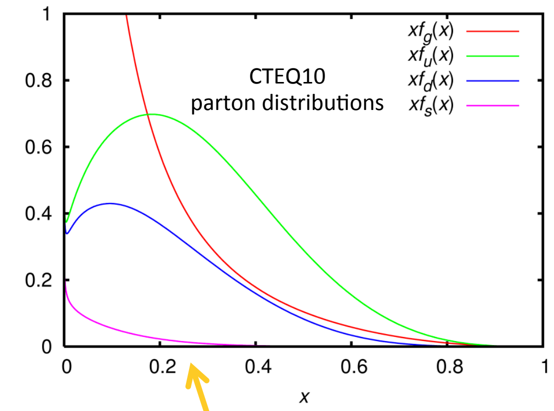
$$H_{beam,target}(x_{target}, x_{beam}; M^2) = \overbrace{g(x_{beam})g(x_{target})\sigma(gg \to c\bar{c}; M^2)}^{1.}$$

$$+ \sum_{i \in \{u,d,s,...\}}^{n} [f_i \underbrace{(x_{beam})\bar{f}_i(x_{target}) + \bar{f}_i(x_{beam})f_i(x_{target})]\sigma(q\bar{q} \to c\bar{c}; M^2)}_{2.}$$

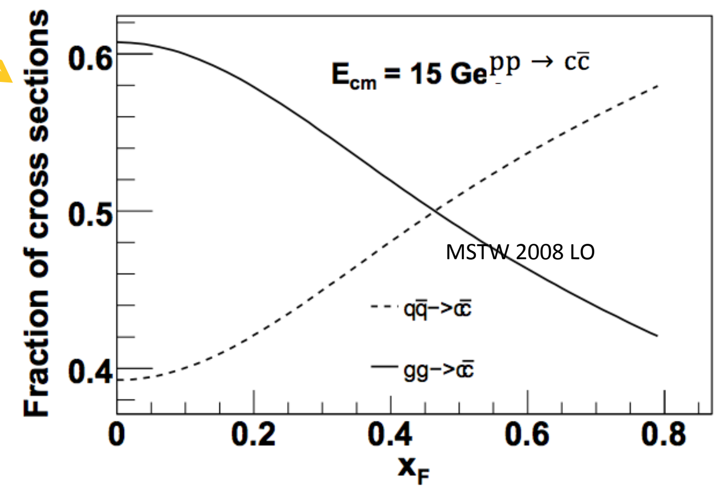
$$\frac{d^2\sigma}{d\tau dx_F} = \frac{2\tau}{\sqrt{{x_F}^2 + 4\tau^2}} H_{beam,target}(x_{target}, x_{beam}; x_{target}x_{beam}s)$$

J/ψ TSSAs

- TSSAs (up to ~40%) observed in light hadron production in $0.1 < x < 0.5$
- **g-g fusion**: dominant mechanism for J/ψ production at SpinQuest
  - Acceptance $x_F \gg 0$ at J/ψ mass
  - q-q- vs. g-g / Σ cross sections → gg mechanism dominant at SpinQuest's E_{cm} (=15GeV) for $x_F > 0.42$
- J/ψ TSSA: study of gluon Sivers and QCD dynamics in hadron production with **improved statistics** in higher x_F region!



Many gluons below 0.22!



arXiv:1110.4268

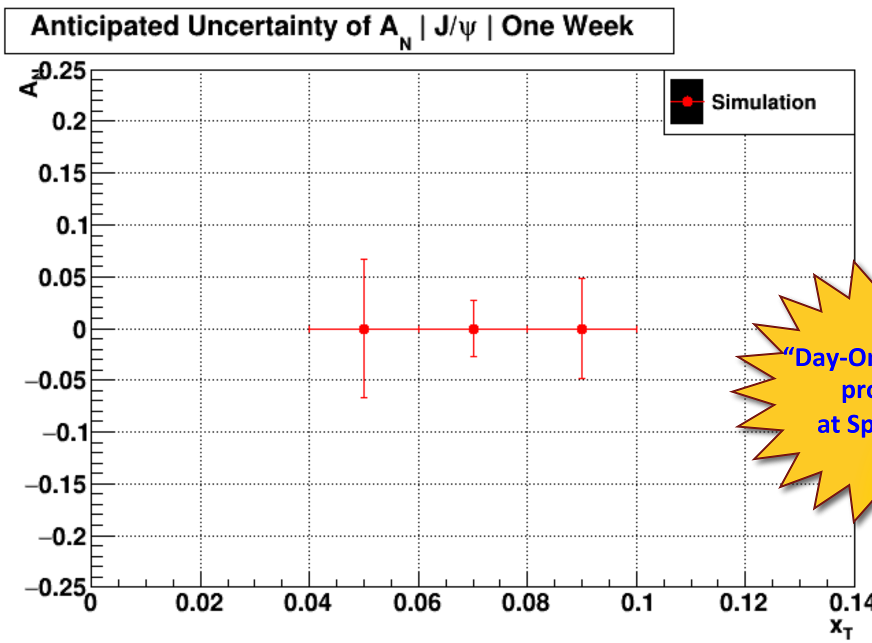
Anticipated Uncertainty for J/ψ TSSAs

- Rate of in-acceptance dimuons estimated by GMC:
  - PYTHIA8 charmonium production
  - Geometric acceptance considered
- **One week** of dedicated data taking was assumed
  - Integrated luminosity: L_{1w} = 1.75e4 pb^{-1} & L_{sim} = 6567 pb^{-1}
  - Dilution factor: f = 0.176
  - Polarization: P = 0.8

φ_S = azimuthal angle b/t target spin & hadron plane

Binning in (x_T, ϕ_{S_i})

$$A_N = \frac{2}{f}\frac{\sum_i N(x_T,\phi_{S_i})\sin\phi_{S_i}}{\sum_i N(x_T,\phi_{S_i})}$$



"Day-One Physics" program at SpinQuest

$$\delta^{1w}_{AN} = 1/f \cdot 1/P \cdot \delta^{sim}_{AN} \cdot \sqrt{L^{sim}/L^{1w}} = 3.3 \cdot \delta^{sim}_{AN}$$

$$\delta^{sim}_{AN} \sim 1/\sqrt{N_{measured}}$$

Timeline for SpinQuest

Year	Month	Event
2018	May	Granted Stage-2 approval from Fermilab Decommissioned SeaQuest components
2019	June	Transferred the pol. target from UVA to Fermilab Sanity checking/debugging detector components using cosmic rays
2020		Testing spectrometer components with cosmic ray data (limited access due to COVID-19)
2021	January	Testing/debugging spectrometer components
	November	Commission target and detector
December 2021- 2023		Production runs

Summary and Outlook

- SeaQuest and SpinQuest aim to probe nucleonic structure and parton distributions in newer kinematic regions and higher accuracy
- E-906/SeaQuest with unpolarized targets
  - Large anti-down vs. anti-up asymmetry at high x was observed
  - Also investigating nuclear effects via DY and J/ψ and more topics!
- SpinQuest polarized DY and J/ψ data will constrain anti-quark and gluon Sivers functions
  - SpinQuest measurement on J/ψ TSSA is anticipated to be the first published results.

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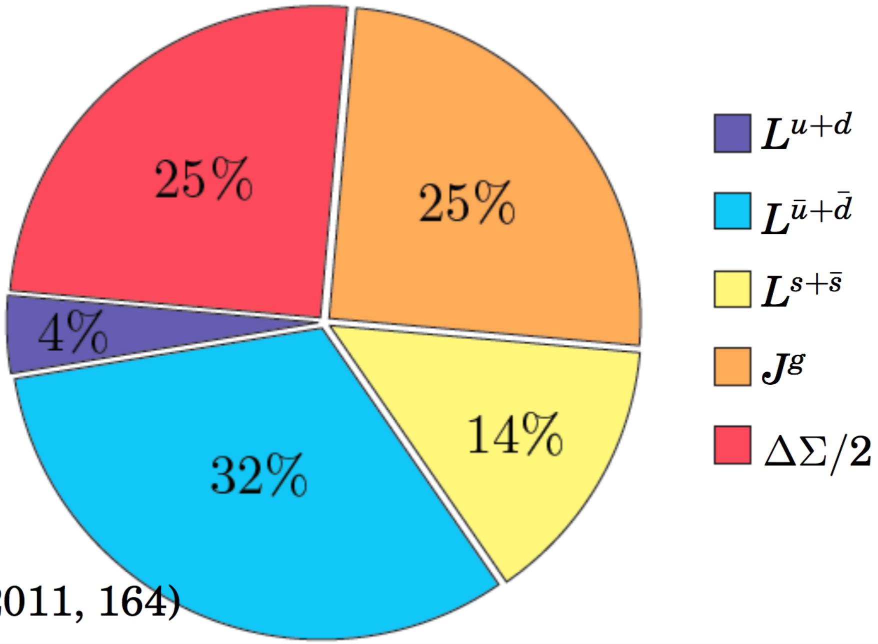
Backup Slides

Importance of Gluons and Seaquarks

- Proton spin puzzle:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + J_G + L_q + L_{\bar{q}}$$



Lattice QCD
(PoS LATTICE2011, 164)