E1039/SpinQuest: Polarized Drell-Yan Experiment at Fermilab

Abinash Pun

NMSU

INPP Seminar, Ohio University

March 23, 2021

About Me (past)

Abinash Pun

- Ohio University (2013-2019)
- Nepal
- Graduate Advisor: Dr. Justin Frantz

- Dissertation: "***Measurements of Di-Jet $\pi^0 - h^{\pm}$ Correlations in Light-Heavy Ion Collisions at RHIC-PHENIX***"
  - Study of possible jet energy loss (due to QGP) in light-heavy ion Collison
  - Analyzed: p+p, d+Au and He^3+Au collision systems
- **sPHENIX Electromagnetic calorimeter:**
  - Reconstructing performance, Energy leakage and New Calibration framework
- **Fun4All software framework:**
  - Modularized data analyzing framework (***C. Pinkenburg*** for PHENIX)
  - Being used in sPHENIX (also in EIC ?)

About Me (Currently)

- Post-Doctoral Research Associate at New Mexico State University (NMSU)
- SpinQuest Experiment at Fermilab
  - Reconstruction and Simulation Coordinator
  - Data management
- Currently stationed near Fermilab, IL

(NMSU) Group in SpinQuest

<u>Professors:</u>

Dr. Stephen Pate (PI): Deputy Chairman

Dr. Vassili Papavassiliou: Talks Committee

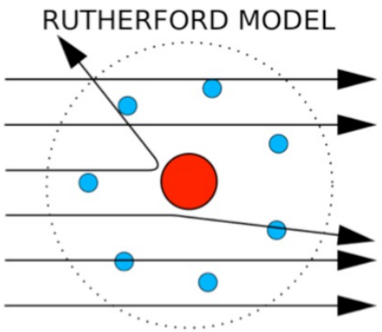
<u>Grad students</u>

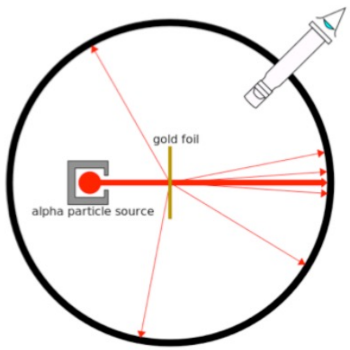
Forhad Hossain

Dinupa Nawarathne

Background

Proton Structure

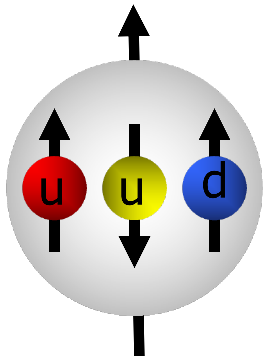




- Ernest Rutherford (1909):
  - "proton" : nucleus of lightest atom (hydrogen)
  - Considered to be elementary like electron
- Spin=1/2, charge = +1, Mass ≈ 938.28 MeV
- Magnetic moment:
  - $\mu = g\frac{q}{2m}\vec{s} \approx 2.79\frac{e}{2m_p} \approx$ 2.79 x point like fermions

First hint of internal structure of proton !!

- **Quark Model**: Gell-Mann and Zweig (1964)
  - Charge (+1)=$\frac{2}{3} + \frac{2}{3} - \frac{1}{3}$
  - Spin (1/2) = ½ ΔΣ = $\frac{1}{2} + \frac{1}{2} - \frac{1}{2}$



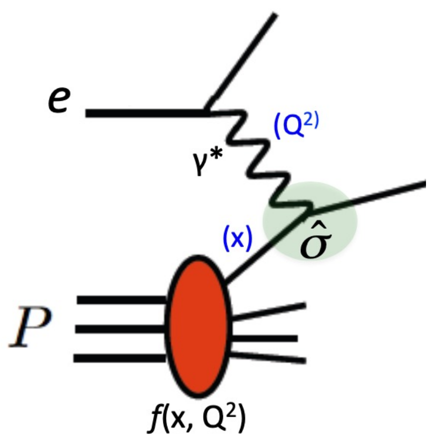
Probing Internal structure of nucleons

- Elastic electron-nucleon scattering
  - Cross-section parametrized in terms of electric and magnetic form factors (G_E, G_M)

- Deep Inelastic Scattering (DIS):

High Q2 proton breaks up

G_E, G_M → F1(x,Q2), F2(x,Q2) ; structure functions



$$F_2(x,Q^2) = \sum_i e_i^2 x f_i(x,Q^2)$$

f(x,Q2): Parton distribution function (PDF)

Factorization Theorem: $\sigma_{DIS} \propto \sum f(x,Q^2) \otimes \hat{\sigma}$

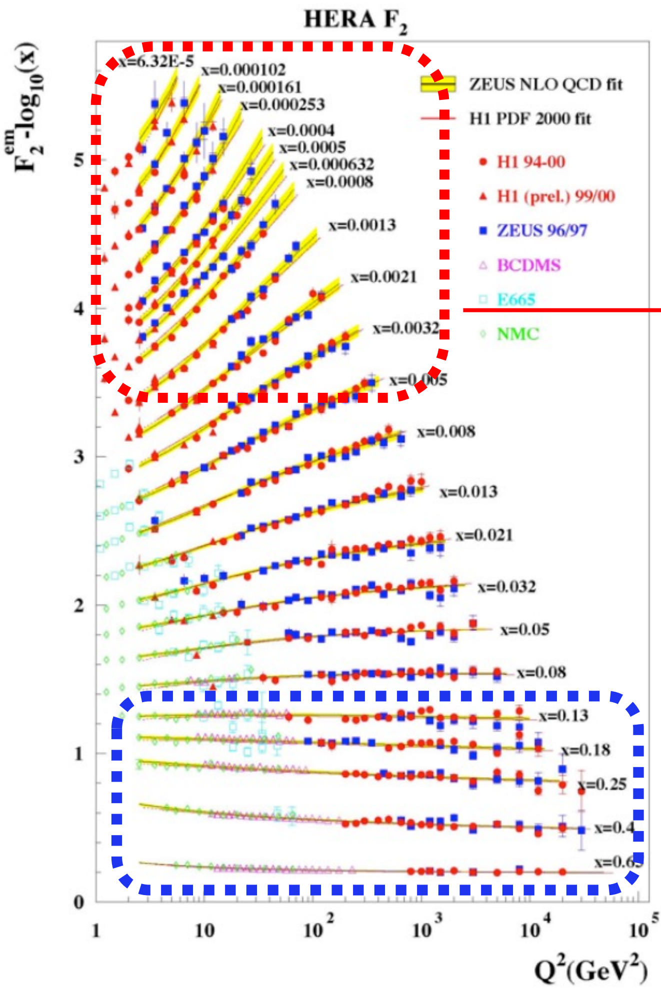
Determined from measurements

Can be calculated from perturbative QCD (pQCD)

Q^2: Squared momentum transfer to the lepton. Measure of resolution

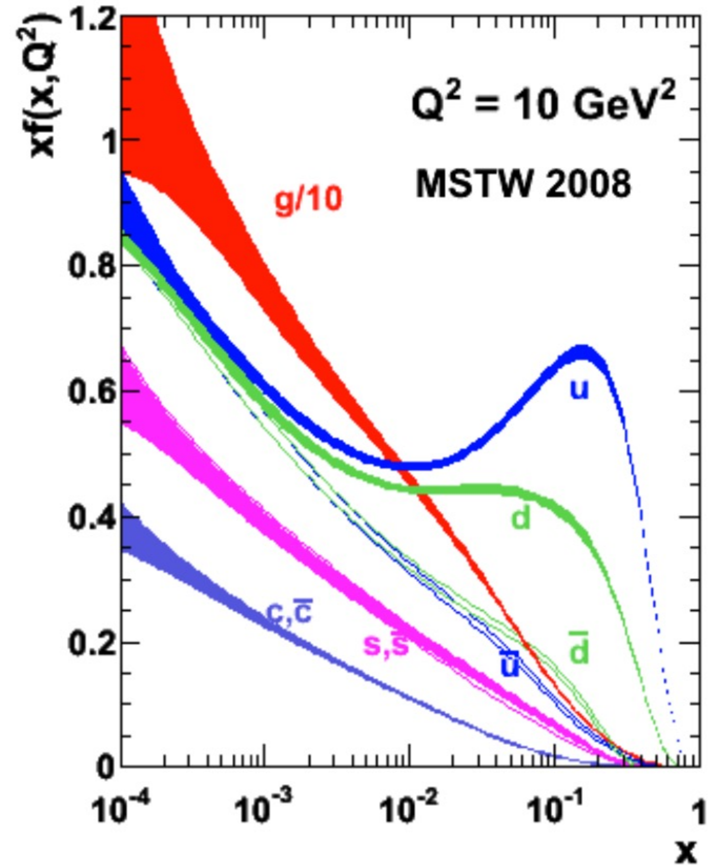
X: Momentum fraction of the struck parton in a proton

PDFs and QCD Parton Model

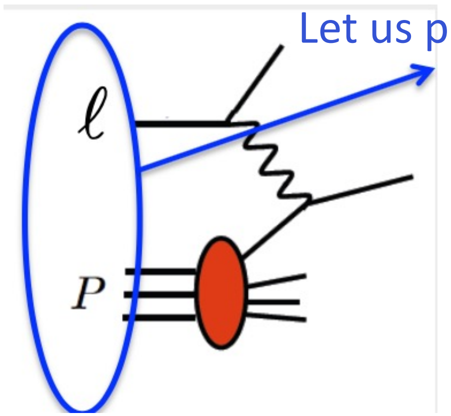


Scaling violation in low-x: Gluons !

Scaling behavior: $F_2(x, Q^2) \rightarrow F_2(x)$



Polarized DIS



Let us polarize them

Lepton, proton have different polarization direction

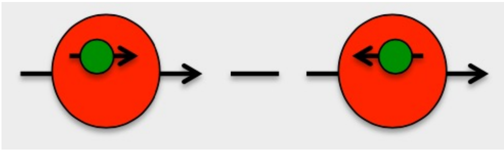
Lepton, proton have same polarization direction

$$\Delta\sigma = \left[\frac{d^2\sigma^{\rightleftarrows}}{dx\,dQ^2} - \frac{d^2\sigma^{\rightrightarrows}}{dx\,dQ^2}\right] \sim g_1(x,Q^2)$$

Spin dependent polarized Structure Function $g_1(x,Q^2)$:

$$g_1(x,Q^2) \sim \sum_q e_q^2 \Delta q(x,Q^2)$$

$$\Delta q(x,Q^2) \equiv q_+(x,Q^2) - q_-(x,Q^2)$$



$q_{+(-)}$: number density of quarks in the nucleon when the spin orientation of quarks is parallel (antiparallel) to the spin direction of the proton

Polarized DIS and Proton Spin

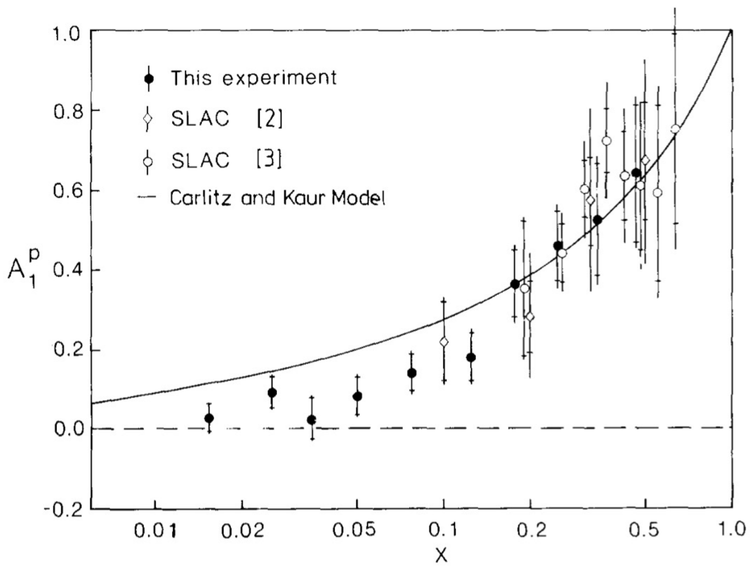
<u>European Muon Collaboration (EMC) : 1988</u>

DIS of a longitudinally polarized muon beam off a longitudinally polarized proton target over a large x range (0.01 < x < 0.7)

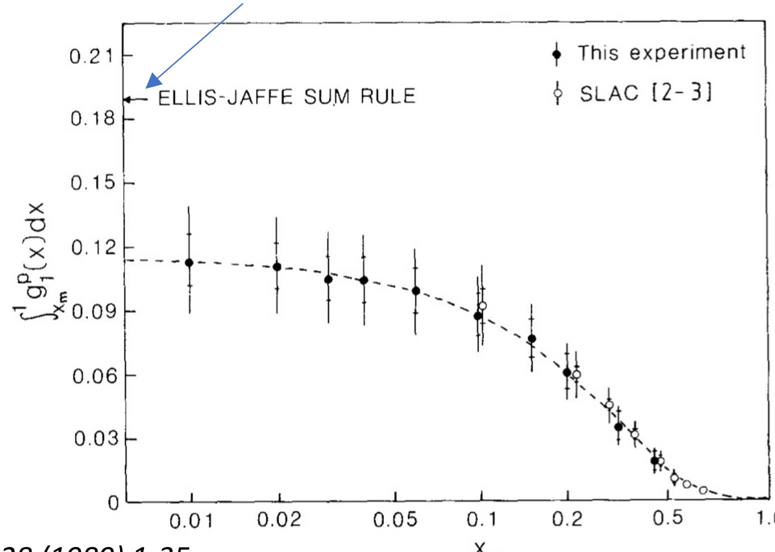
$$A_1 \cong \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} \approx \frac{g_1(x)}{F_1(x)}$$

$$\int_0^1 g_1^p \, dx = 0.123 \pm 0.013 \pm 0.019,$$

Quarks' contribution only ~12%: SPIN CRISIS



Violation of Ellis-Jaffe sum rules –



<u>Nuc. Phy. B328 (1989) 1-35</u>

Gluon contribution: RHIC

Measuring the the **asymmetry of jets and pions** in longitudinally polarized proton-proton collision

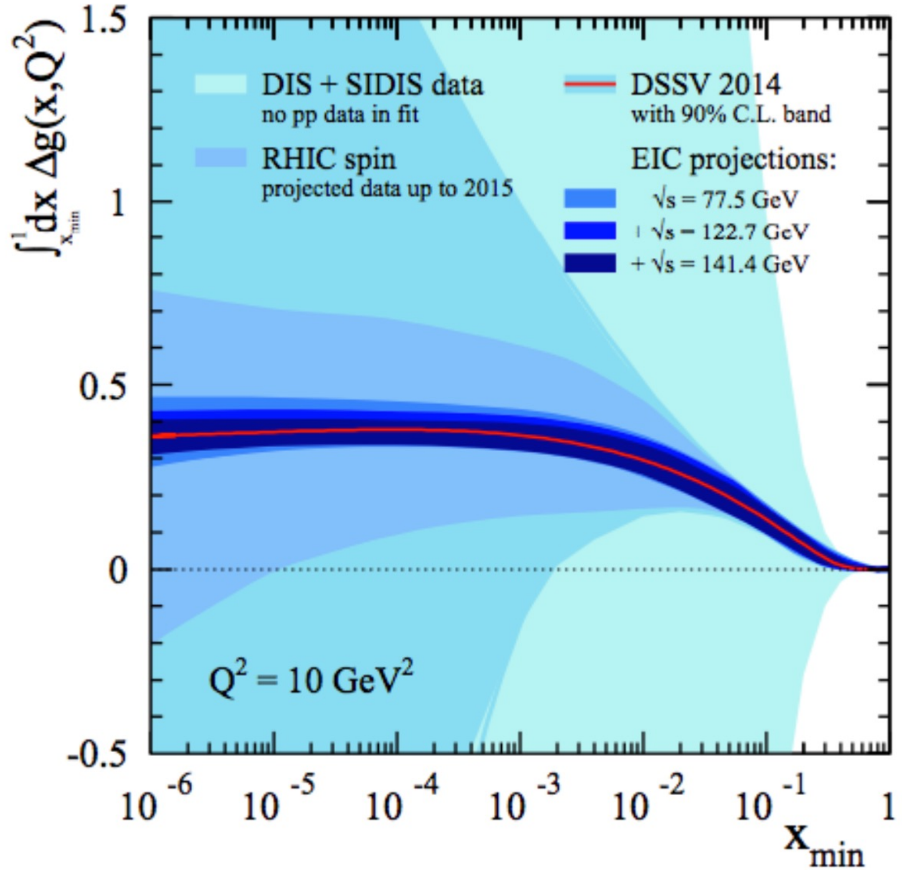
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\sum_{a,b} \Delta f_a \Delta f_b \hat{a}_{LL}}{\sum_{a,b} f_a f_b}$$

RHIC data=> Non-zero gluon contribution

$$\int_{0.05}^{1} dx \Delta g(x) = 0.2^{+0.06}_{-0.07}$$

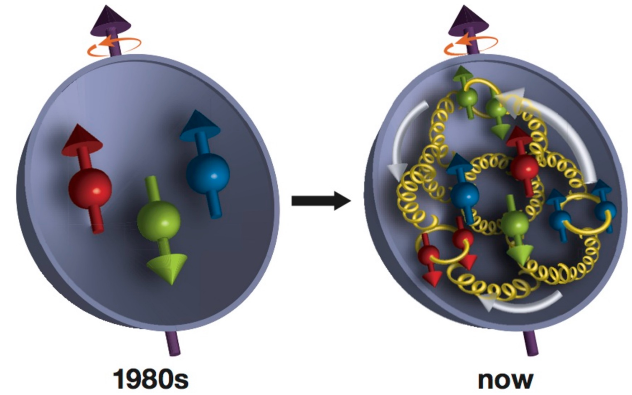
Still huge uncertainty in the unmeasured region (x<0.05)

EIC is expected to provide a conclusive answer (?)



Making the case for E1039 Experiment

Spin puzzle



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + Lg$$

Quarks +anti-quarks
$\Delta\Sigma = (\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s})$
Well known ~0.3

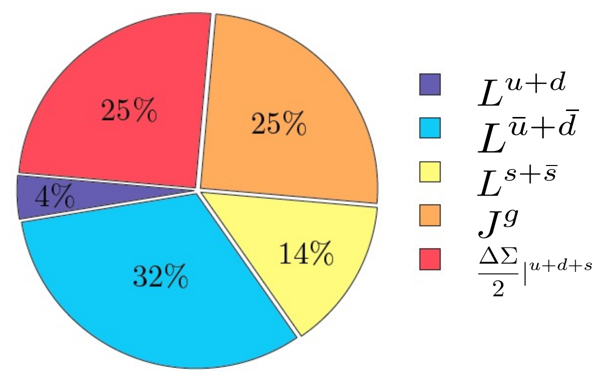
Gluon Contribution
Started understanding

Orbital angular Contribution
Unknown

Lattice Calculation

$\Rightarrow$ Large fraction of proton spin comes from light anti quarks OAM

$\Rightarrow$ Need to understand it experimentally and theoretically



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

How to access quark OAM ?

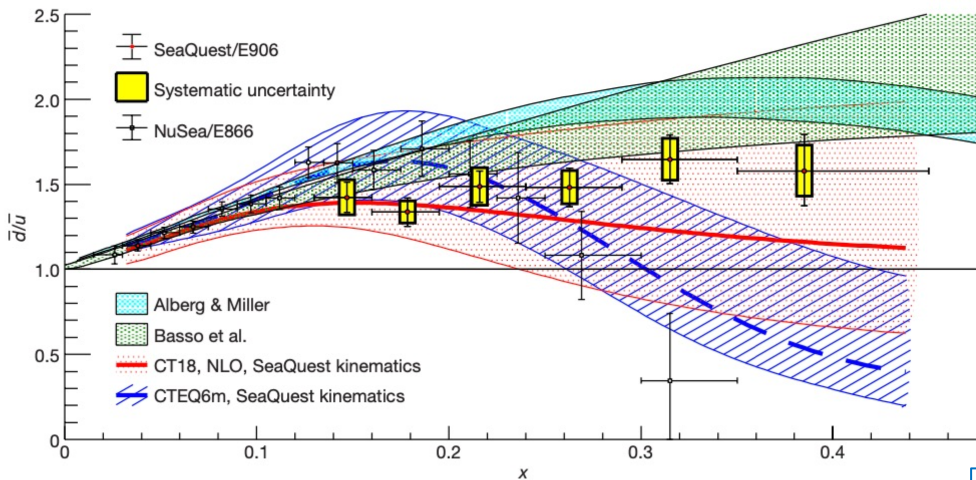
$\Delta\Sigma_q \approx 25\%$ $\quad L_u \approx - L_d$

$2\ L_q \approx 46\%$ (0%(valence)+46%(sea))

$2\ J_g \approx 25\%$

Light anti-quark flavor asymmetry: $\frac{\bar{d}}{\bar{u}}$

<u>*Nature 590, 561–565 (2021)*</u>

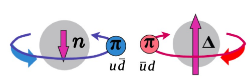


$$S_G = \int_0^1 \frac{dx}{x}[F_2^p(x) - F_2^n(x)] = \frac{1}{3} + \frac{2}{3}\int_0^1 dx[\bar{u}(x) - \bar{d}(x)]$$
$$= 0.235 \pm 0.026$$

Gottfried Sum Rule: S_G =**1/3**

$$\int_0^1 dx[\bar{d}(x) - \bar{u}(x)] = 0.147 \pm 0.039$$

Pion cloud model



$$|p\rangle \propto |p_0\rangle + |n\pi^+\rangle + |\Delta^{++}\pi^-\rangle + \ldots$$

Pions $J^p=0^-$ Negative Parity
Need **L=1** to get proton's $J^p=½^+$

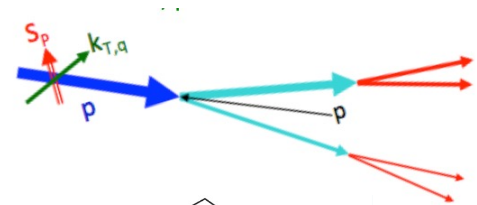
Light sea quarks should carry orbital angular momentum

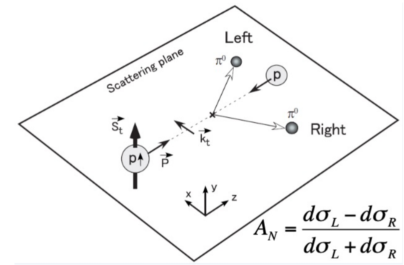
- Data reasonably agrees with the models (statistical parton distribution and meson-baryon)
- But the models have different predictions for the spin contribution from the anti quarks

Measure the spin contribution from light sea quarks to differentiate the models

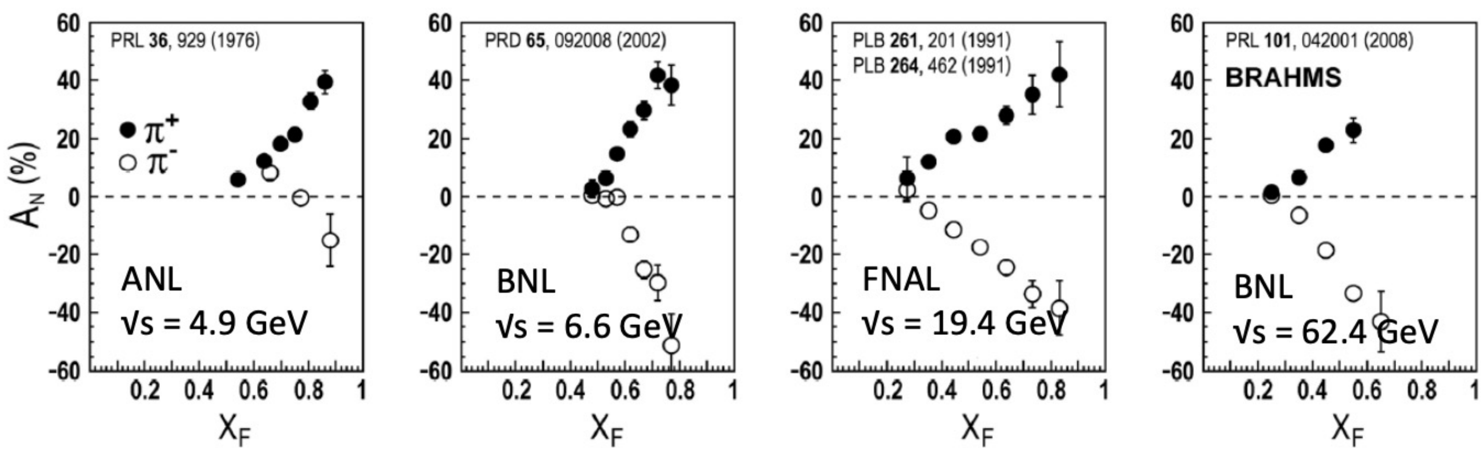
Sivers Function

$f_{1T}^{\perp}(x, k_T)$ =





- Correlation between proton spin (S_p) and intrinsic parton transverse momentum $k_{T,q}$
- Introduced to explain transverse single spin asymmetries of pions in $pp^{\uparrow} \rightarrow \pi X$
- One of the eight leading order Transverse Momentum Dependent Distribution functions (TMDs)

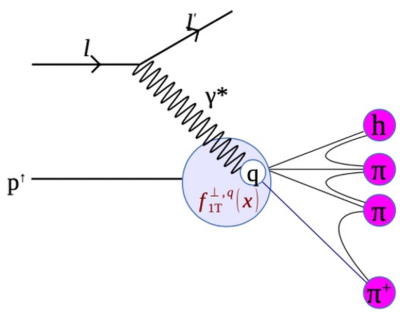


Nonzero Sivers function => Nonzero OAM contribution of parton on proton spin?

Accessing Sea Quark Sivers Function

Polarized Semi-Inclusive DIS (SIDIS)

$$e + p^{\uparrow} \rightarrow e'\pi\, X$$

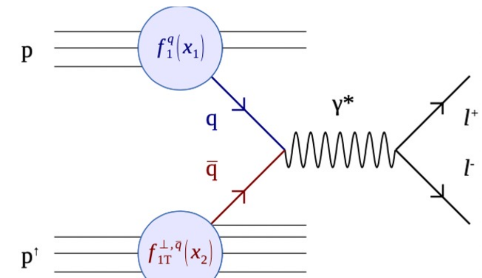


$$A_{UT}^{SIDIS} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x)\otimes D_1^q(z)}{\sum_q e_q^2 f_1^q(x)\otimes D_1^q(z)}$$

- L-R asymmetry in hadron production
- Quark to hadron fragmentation function
- Valence-sea quark: mixed

Polarized Drell-Yan

$$p + p^{\uparrow} \rightarrow \mu^+\mu^- X$$



$$A_N^{DY} \propto \frac{\sum_q e_q^2\left[f_1^q(x_1)\cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2\right]}{\sum_q e_q^2\left[f_1^q(x_1)\cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2\right]}$$

- L-R asymmetry in Drell-Yan production
- ✓ No fragmentation function
- ✓ Valence-sea quark: isolated

So far …

- Spin Crisis to Spin puzzle: Yet to be solved
- Lattice Calculation

  ⇒Significant contribution from OAM of sea quark
- Light antiquark flavor asymmetry in E866 and E906

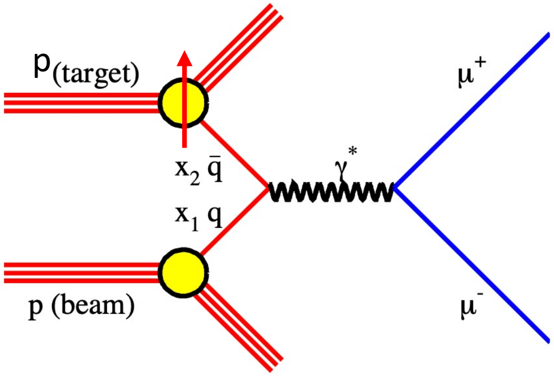
  ⇒Need for the measurement of spin contribution to differentiate existing models
- Non-vanishing sea quark Sivers distribution

  =>might establish the contribution of sea quark in nuclear spin
- Drell-Yann process allows direct measurement of Sivers Function
  - without complication of fragmentation function and final state interaction
  - Sensitive to sea quarks

E1039/SpinQuest experiment

- Polarized Fixed Target DY at experiment Fermilab
- Unpolarized proton beam of 120 GeV with Polarized $\mathbf{NH_3}$ or $\mathbf{ND_3}$ target
- Goals:
    - measure azimuthal asymmetry in dimuons from Drell-Yan and
    - extract the magnitude and sign of Sivers function of sea quarks ($\boldsymbol{\bar{u}}$ and $\boldsymbol{\bar{d}}$)

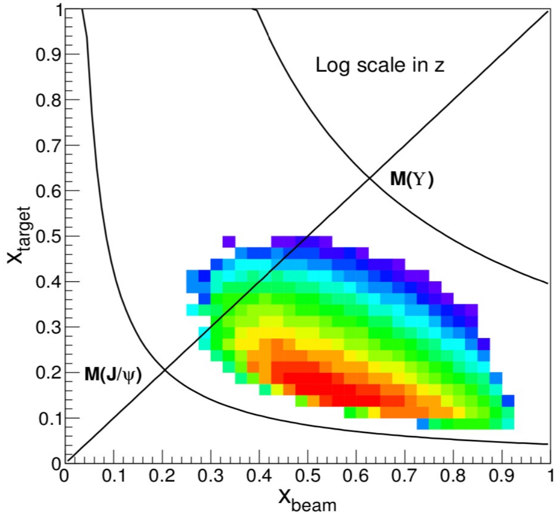
Polarized Drell-Yan in E1039



- Cross section at LO

$$\frac{d^2\sigma}{dx_{beam}dx_{target}} = \frac{4\pi\alpha^2}{9x_{beam}x_{target}}\frac{1}{s}\sum_{i=u,d,\cdots} e_i{}^2 \cdot \{q_i(x_{beam})\bar{q}_i(x_{target}) + \bar{q}_i(x_{beam})q_i(x_{target})\}$$

  - "$\boldsymbol{q(xbea_m)\bar{q}(x_{target})}$" survives @forward rapidity



https://arxiv.org/abs/1901.09994v2

Polarized Drell-Yan in E1039

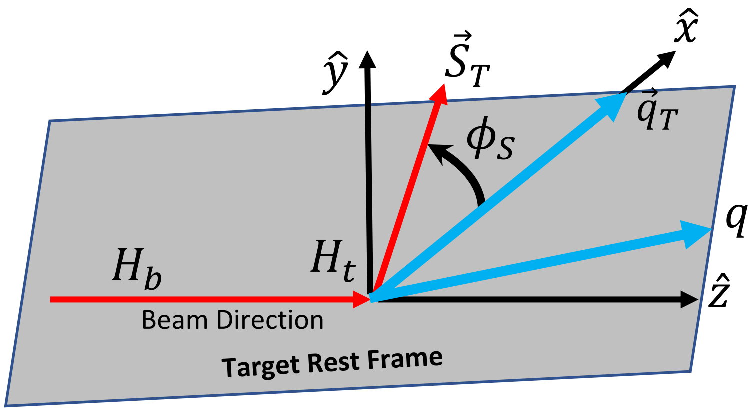
The Drell-Yan cross section in terms of Sivers asymmetry

Phys. Rev. D 79, 034005 (2009), PRL 119, 112002 (2017)

$$\frac{d\,\sigma^{LO}}{d^4q\ \ d\phi_S} \propto 1 \pm |\mathrm{S_T}|\ \ sin\,\phi_S\ \ A_T^{\sin\phi_S}$$

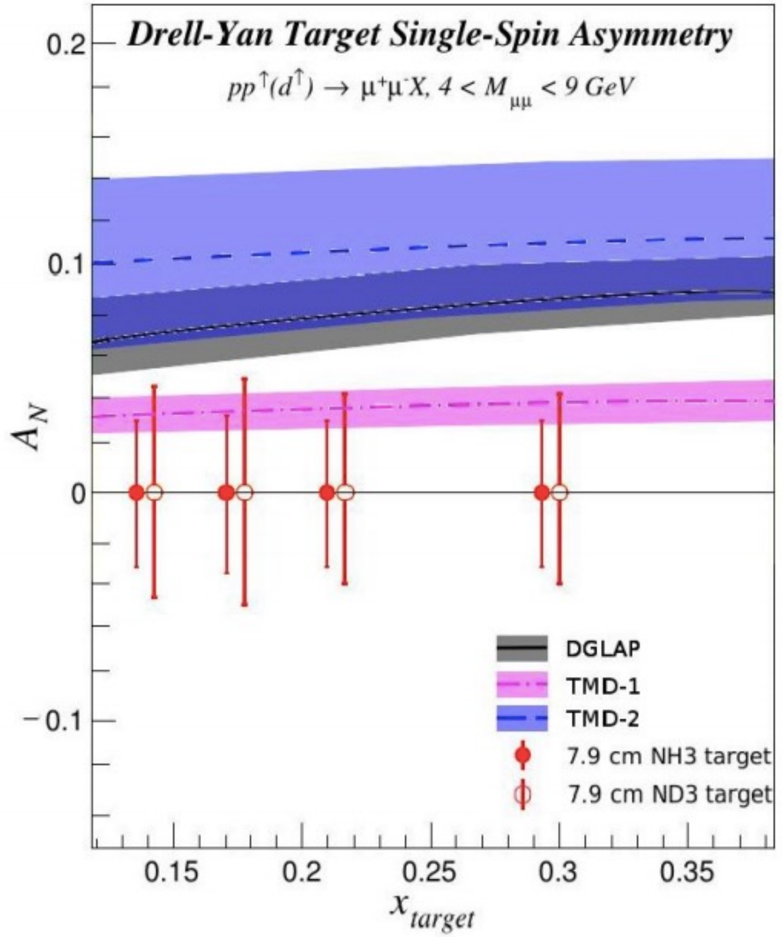
$$A(\phi_S) = \frac{1}{|S_T|}\,\frac{\sigma_{DY}^{\uparrow} - \sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow} + \sigma_{DY}^{\downarrow}} = \ \sin\phi_S\ A_T^{\sin\phi_S} \propto \frac{f_{1T}^{\perp,\bar{u}}(x_t)}{f_1^{\bar{u}}(x_t)}$$

1. $A_T^{\sin\phi_S}$ is the Sivers asymmetry .
2. $\vec{S}_T$= Target spin vector
3. $\vec{q}_T$= Dimuon's transverse momentum
4. Azimuthal angle ϕ_S in Target Rest Frame

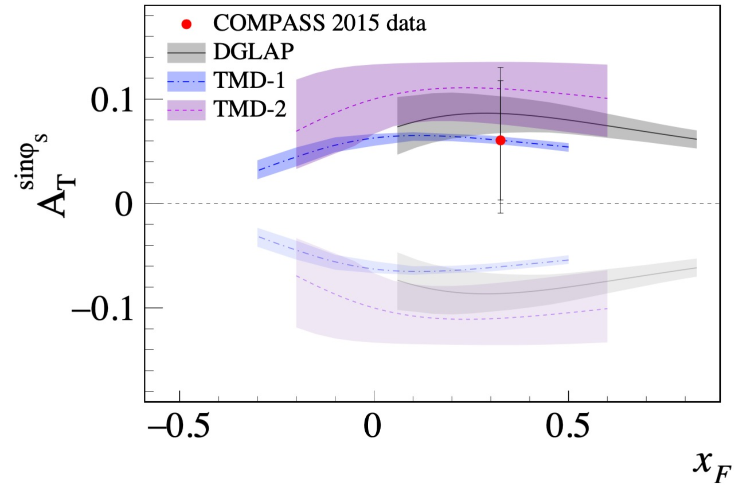


Sketch: F. Hossain

Anticipated Sensitivity of E1039



DGLAP: M. Anselmino et al arXiv:1612.06413
TMD-1: M. G. Echevarria et al arXiv:1401.5078
TMD-2: P. Sun and F. Yuan arXiv:1308.5003



PRL 119, 112002 (2017)

$$\Delta A_N = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N}}$$

f: dilution factor
P: Polarization
N: event yield

Range x_2	Mean x_2	N events p	ΔA % p	N events n	ΔA % n
0.1-0.16	.139	5.0×10^4	3.2	5.8×10^4	5.4
0.16-0.19	0.175	4.5×10^4	3.3	5.2×10^4	5.7
0.19-0.24	0.213	5.7×10^4	2.0	6.6×10^4	5.0
0.24-0.6	0.295	5.5×10^4	3.0	6.4×10^4	5.1

About SpinQuest/E1039 Collaboration

- Relatively small collaboration
  - 51 Full members,
    - 12 grad students, 10 postdocs, 29 faculties
  - 50 Affiliate members
  - 17 institutions from 5 countries (Armenia, China, Srilanka, Japan, USA)
- **Spokespersons:**
  - Kun Liu (liuk@fnal.gov): LANL
  - Dustin Keller (dustin@jlab.org): UVA (OU Alumni)
- Official webpage: https://spinquest.fnal.gov

SPIN QUEST

ACU: Donald Isenhower (PI), Michael Daugherity, Shon Watson
ANL: Paul Reimer (PI), Donald Geesaman
FNAL: Rick Tesarek (PI), Carol Johnstone, Charles Brown, Cristina Suarez
KEK: Shin'ya Sawada (PI)
LANL: Kun Liu (PI, SP), Ming Liu, Astrid Morreale, Mikhail Yurov, Kei Nagai, Zongwei Zhang
MSU: Lamiaa El Fassi (PI), Dipangkar Dutta, Catherine Ayuso, Nuwan Chaminda
NMSU: Stephen Pate (PI), Vassili Papavassiliou, Abinash Pun, Forhad Hossain, Dinupa Nowarathne
RIKEN: Yuji Goto (PI)
Shandong U: Qinghua Xu (PI), Zhaohuizi Ji
TokyoTech: Kenichi Nakano (PI), Toshi-Aki Shibata
U. Colo: Darshana Perera(PI), Harsha Sirilal, Vibodha Bandara
UIUC: Jen-Chieh Peng (PI), Jason Dove, Ching-Him Leung
U. Mich: Wolfgang Lorenzon (PI), Ievgen Lavrukhin, Minjung Kim, Noah Wuerfel
UNH: Karl Slifer (PI), David Ruth
UVA: Dustin Keller (PI, SP), Ishara Fermando, Zulkaida Akbar, Liliet Diaz, Anchit Arora, Arthur Conover
Yamagata U: Yoshiyuki Miyachi (PI), Norihito Doshita
YerPhI: Hrachya Marukyan (PI)

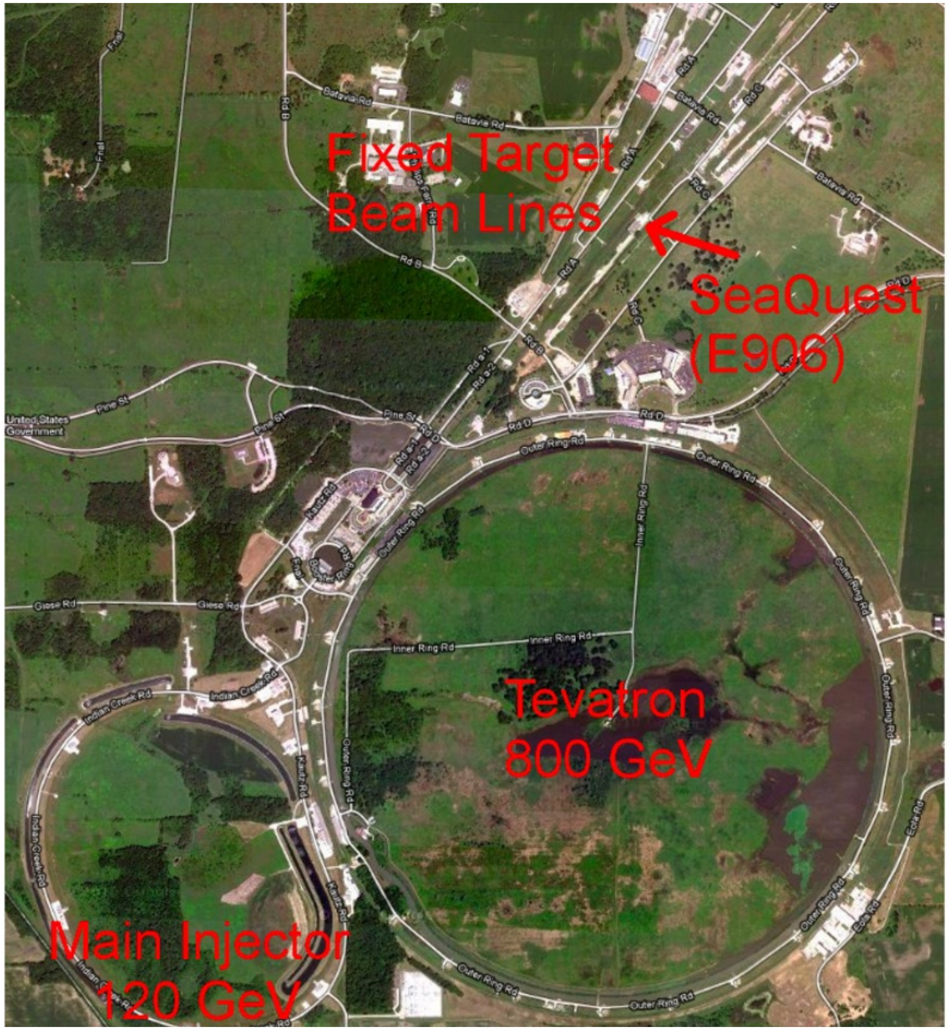
- Postdocs *- Grad students*

Fermilab: Proton Beam

- Energy E = 120 GeV

$(\sqrt{s} = 15\ GeV)$

- Duty Cycle (60 sec)
    - 4 sec for SpinQuest
    - Rest for neutrino experiments
- Bunch
    - Length: 1 n sec
    - Interval: 19 n sec (53 MHz)
    - $\mathbf{4 \times 10^{12}}$ **protons in 4 sec**

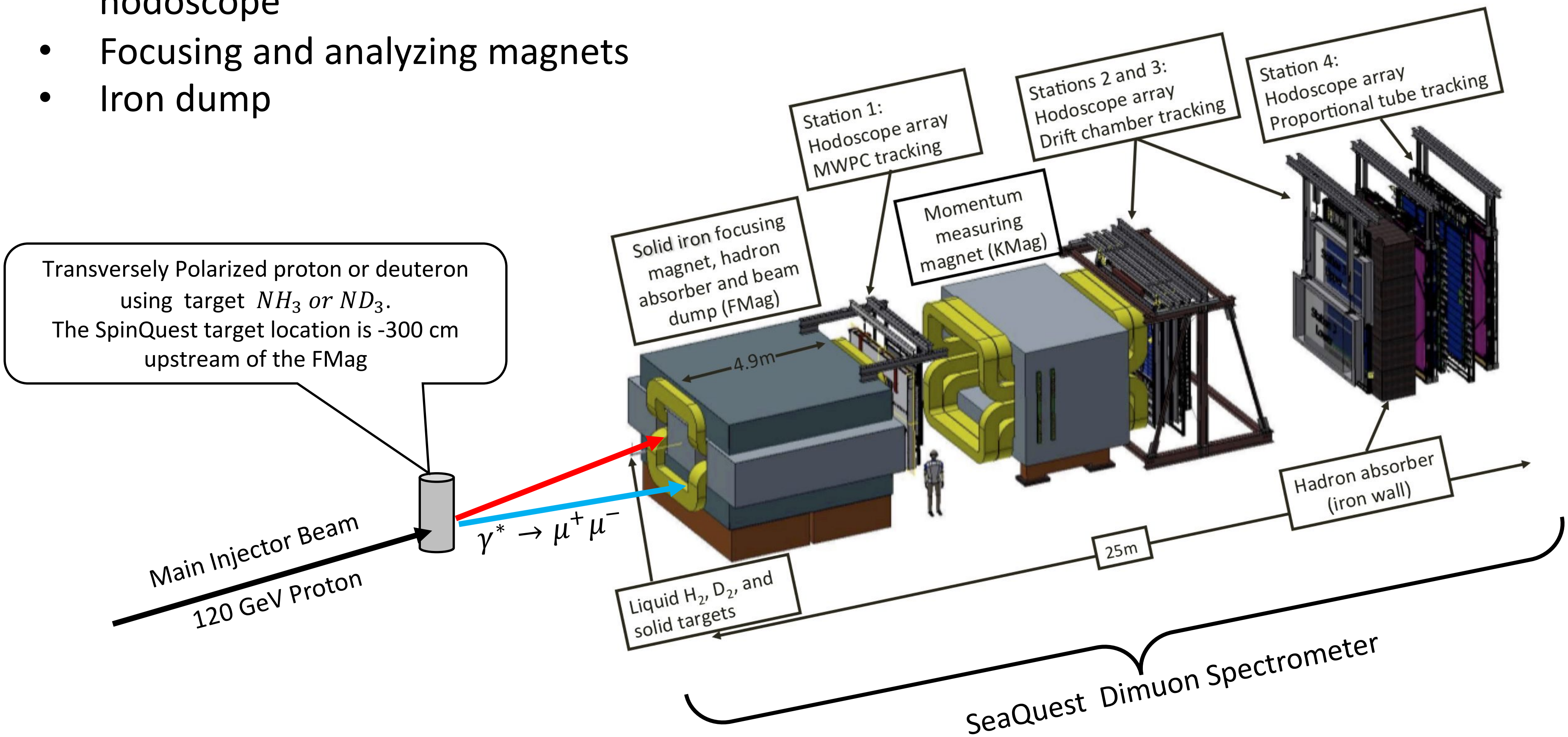


Kenichi

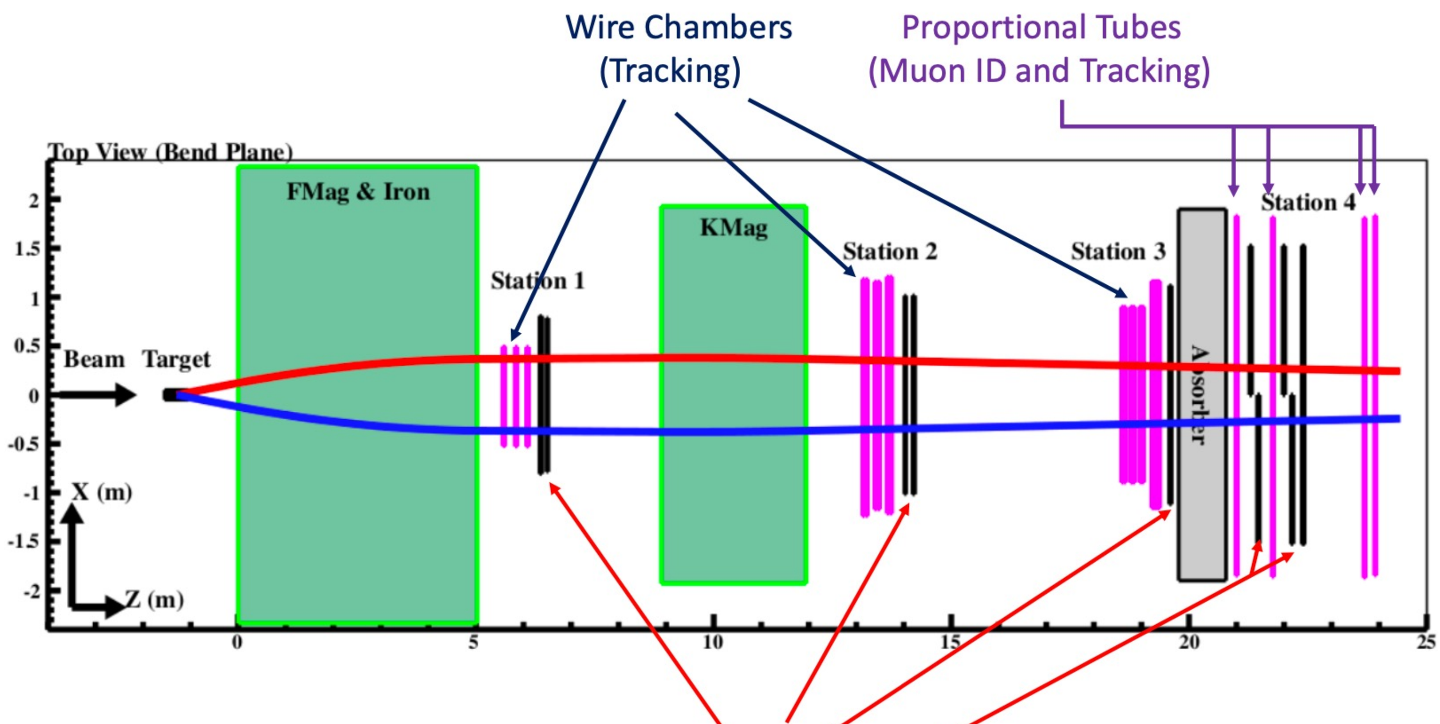
E1039/SpinQuest Spectrometer

SeaQuest/E906 spectrometer

- 4 tracking stations, trigger hodoscope
- Focusing and analyzing magnets
- Iron dump

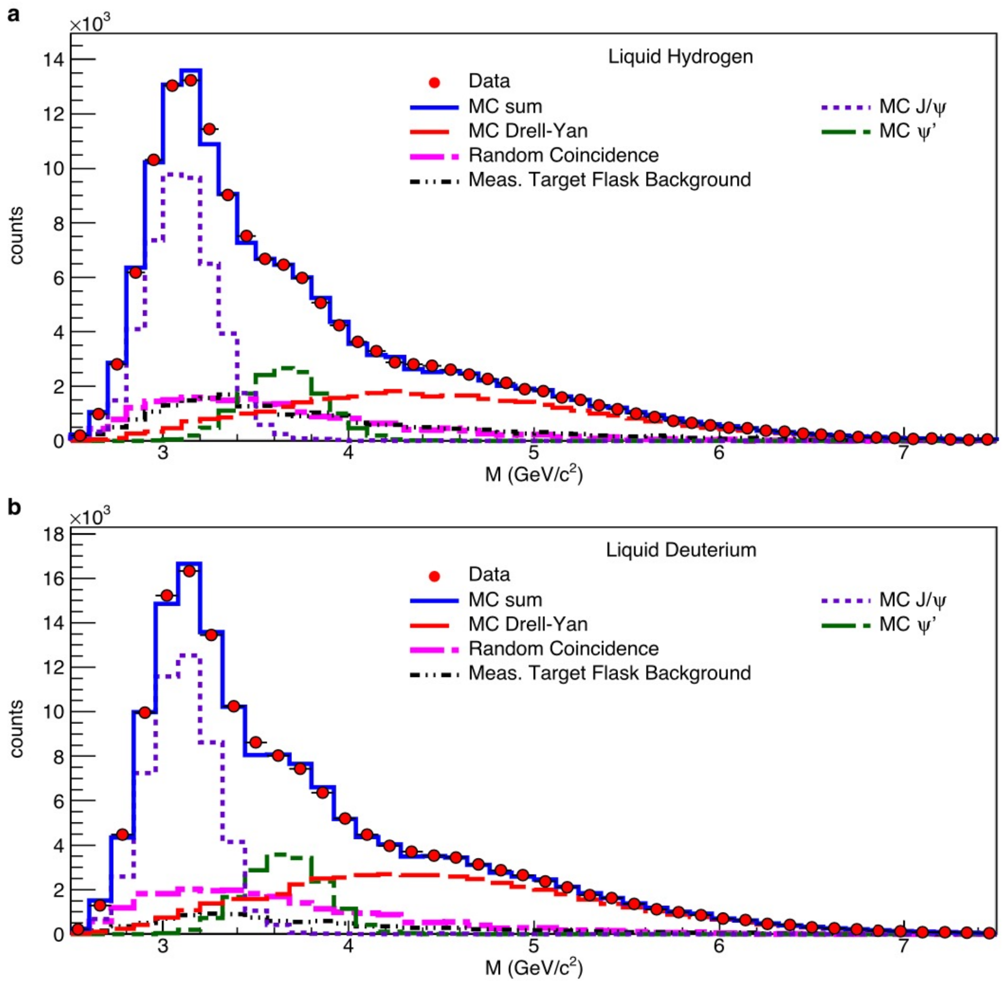


Typical Drell-Yan event in E1039/SpinQuest



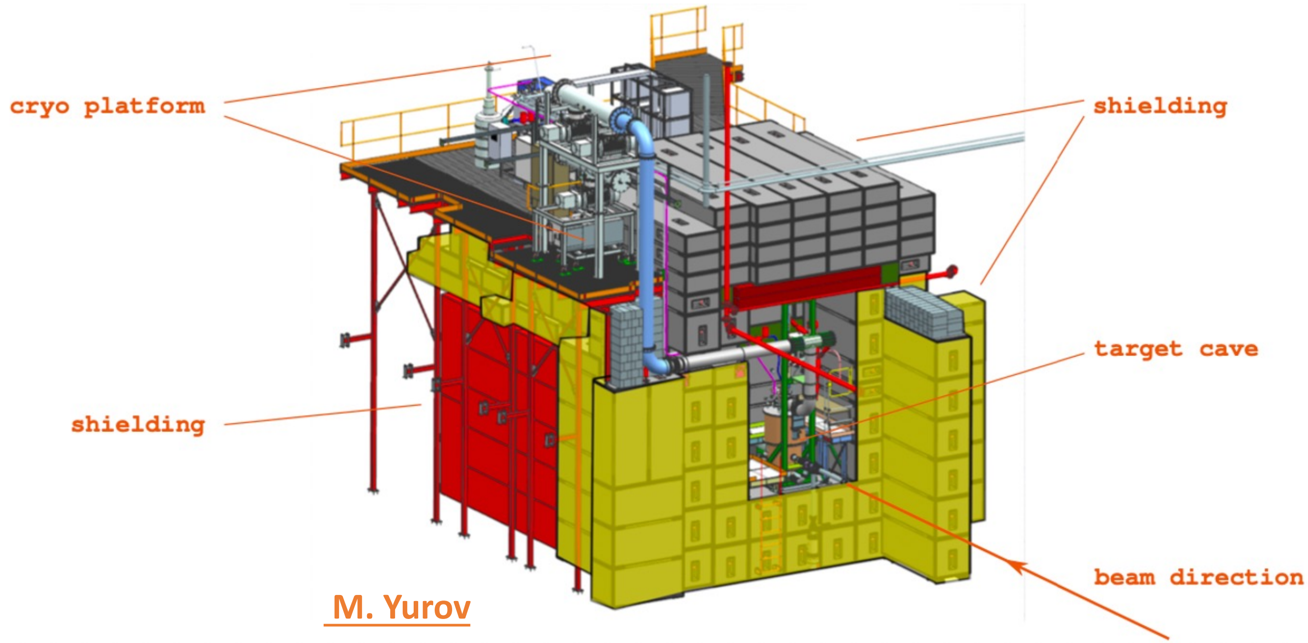
- Muon momenta ∼ 40 GeV/c
- <u>Detection of dimuons:</u>
  - Trigger with hodoscopes at station 1 – 4
  - Tracking with drift chambers at station 1-3
  - Muon identification with drift tubes at station 4
  - Resolution: $dM/M \lesssim 10\ \%$ (dominated by the multiple scattering in FMag)

Dimuon mass distribution from E906



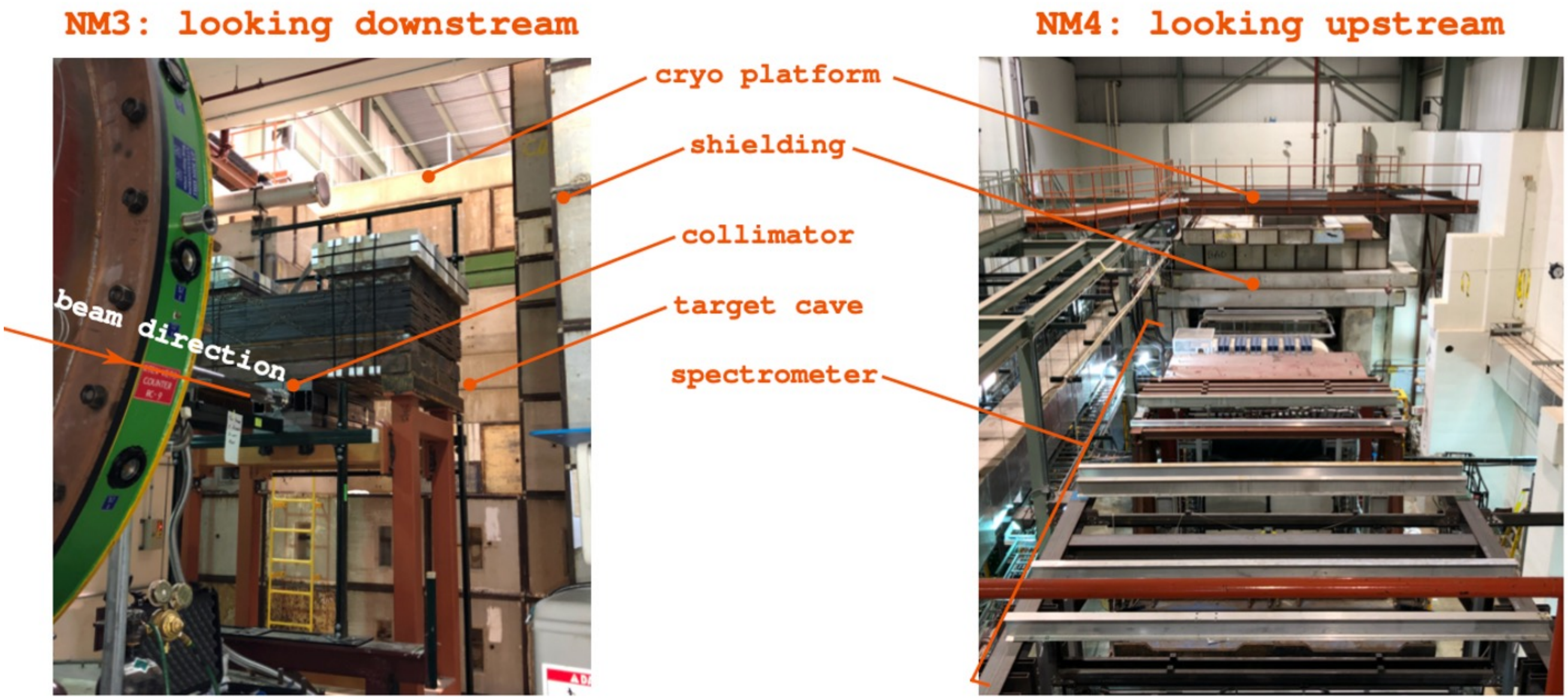
Nature 590, 561–565 (2021)

Beamline and Shielding



- Major modification around target (compared to E906): Thanks to Fermilab Accelerator Division
  - More radiation shielding
  - New cryo platform for target infrastructure
  - New location of target cave (300 cm upstream of Fmag)
  - New collimator on beam line

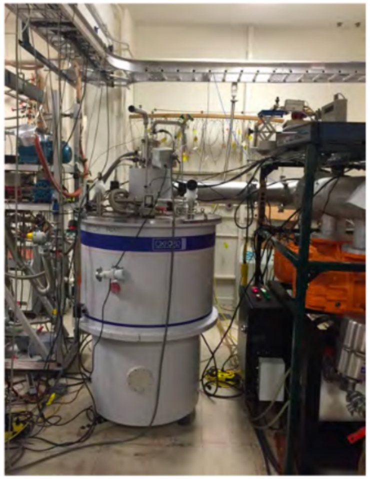
E1039-Experimental Hall

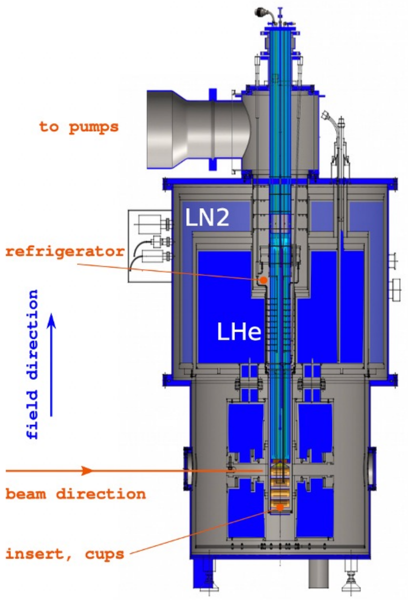


M. Yurov

Polarized Target

- Designed for high intensity proton beam (4 × 10^12 proton/ 4 sec) by **LANL-UVA group**
- 8 cm long solid NH3 and ND3 targets
- Magnetic Field: B = 5 T with $dB/B < 10^{-4}$ over 8 cm
- ^{4}He evaporation refrigerator (3 W of maximum cooling power)
- 140 GHz microwave source





Source: Zulkaida, Joshua

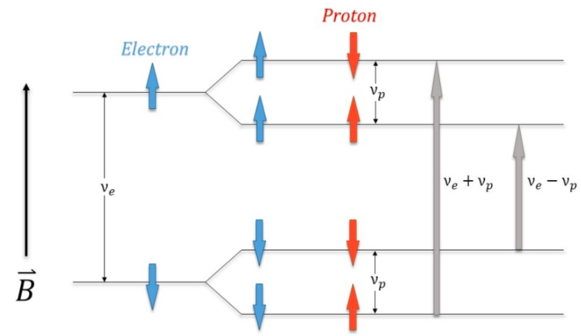
Material	Density	Dilution factor	Packing fraction	Polarization	Interaction length
NH_3	0.867 g/cm^3	0.176	0.60	80%	5.3%
ND_3	1.007 g/cm^3	0.300	0.60	32%	5.7%

Polarized Target

$$H = -\mu_e B - \mu_p B + H_{SS}$$

Dynamic Nuclear Polarization (DNP)

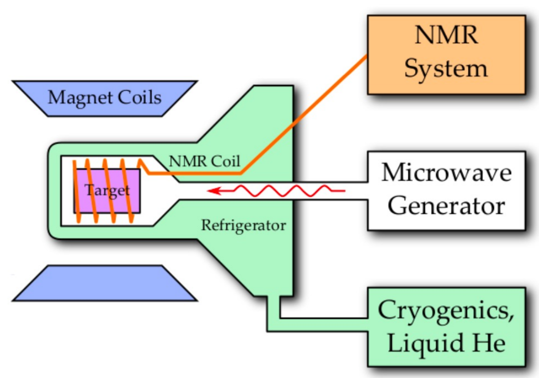
- The coupling between (unpaired) electron & proton introduces hyper- fine splitting
- Applying an RF-signal at the correct frequency, we can drive the nucleons into preferential state
- The disparity in relaxation times between the electron (ms) and proton (tens of minutes) at 1K is crucial to continue proton polarization



Aligned: $\nu_e - \nu_p$
Anti-aligned: $\nu_e + \nu_p$

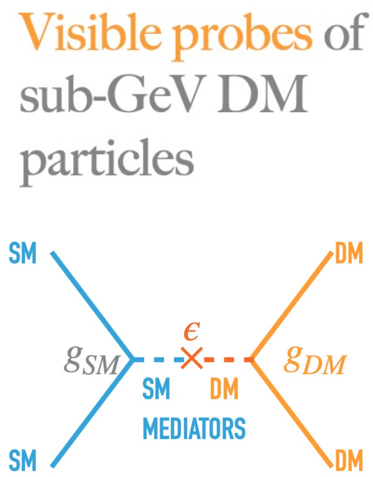
Target systems

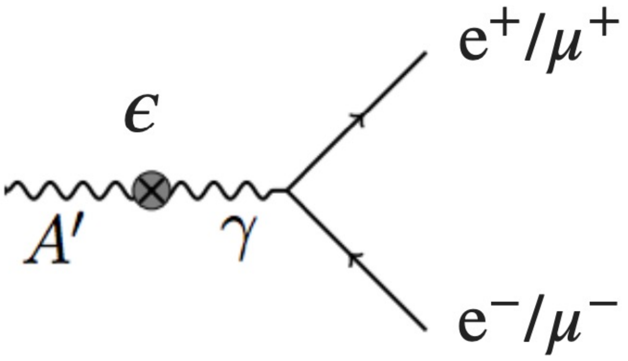
1. Microwave system: pumps the spin polarization of the target
2. NMR system: measures the target polarization
3. Cryogenics and pumping system: cools the solid target and magnet coils

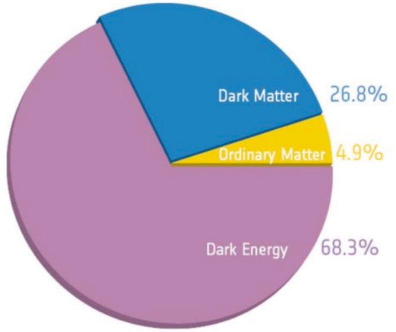


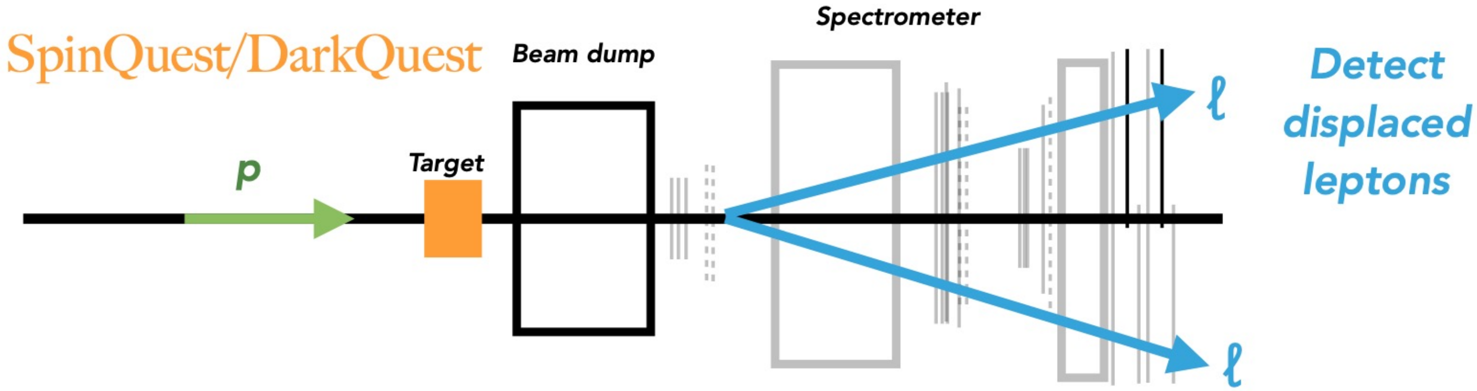
Source: Zulkaida, Joshua

Parasite Run for Dark Photon Search









Slide: C. M. Suarez

(Un)Polarized Drell Yan Experiments

Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2}\, s^{-1}$)		P_b or P_t (f)	rFOM#	Timeline
COMPASS (CERN)	$\pi^- + p^\uparrow$	160 GeV $\sqrt{s} = 17$	$x_t = 0.1 – 0.3$	2×10^{33}		$P_t = 90\%$ f = 0.22	1.1×10^{-3}	2015-2016, 2018
J-PARC (high-p beam line)	$\pi^- + p$	10-20 GeV $\sqrt{s} = 4.4\text{-}6.2$	$x_b = 0.2 – 0.97$ $x_t = 0.06 – 0.6$	2×10^{31}		---	---	>2020? under discussion
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	$\sqrt{s} = 200$ $\sqrt{s} = 510$	$x_b = 0.1 – 0.5$ $x_b = 0.05 – 0.6$	8×10^{31} 6×10^{32}		$P_b = 60\%$ $P_b = 50\%$	4.0×10^{-4} 2.1×10^{-3}	>2021?
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 – 2017
Pol tgt DY‡ (FNAL: E-1039)	$p + p^\uparrow$ $p + d^\uparrow$	120 GeV $\sqrt{s} = 15$	$x_t = 0.1 – 0.45$	3.0×10^{35} 3.5×10^{35}		$P_t = 85\%$ f = 0.176	0.15	2021-2023+
Pol beam DY§ (FNAL: E-1027)	$p^\uparrow + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 – 0.9$	2×10^{35}		$P_b = 60\%$	1	> 2023+ ???

‡ *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, f=0.22 for π^- beam on NH_3)

W. Lorenzon (U-Michigan)

E1039 Status and Timeline

2018
March: DOE approval

2018
May: Fermilab stage-2 approval

2018
June: E906 decommissioned

2019
May: Transferred the polarized target from UVA to Fermilab

Now
commission all components using cosmic rays

Fall of 2021
Polarized target to be installed by fall of 2021

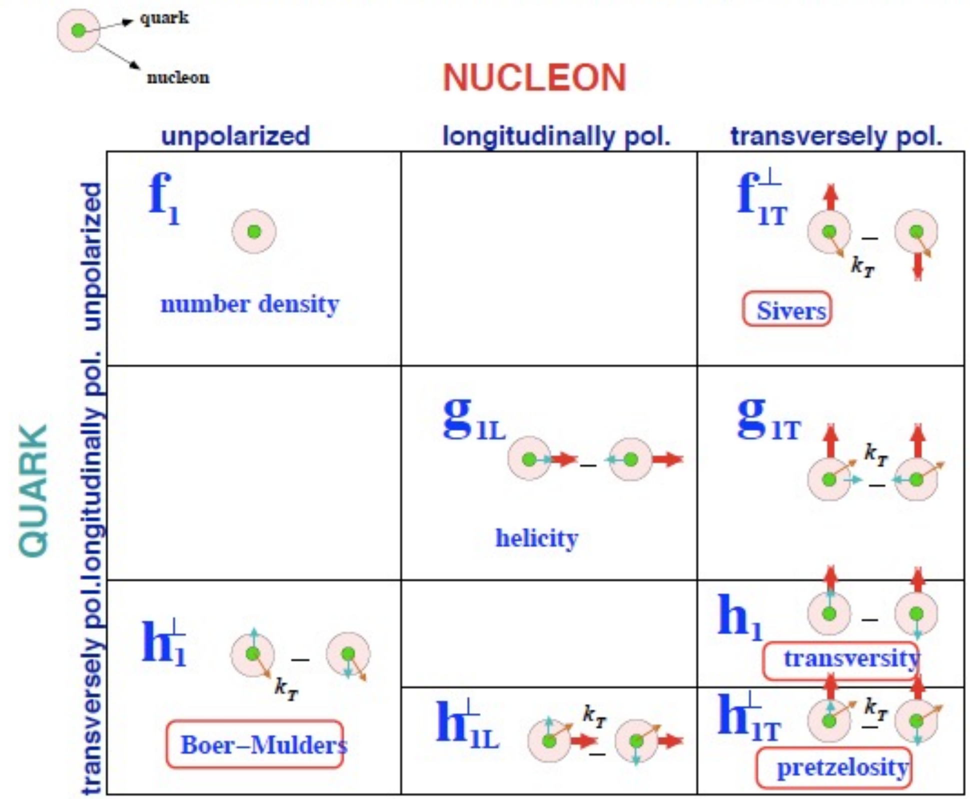
Late 2021
E1039 commissioning starts in late 2021
- Run for 2+ years, 2021-2023+

Summary

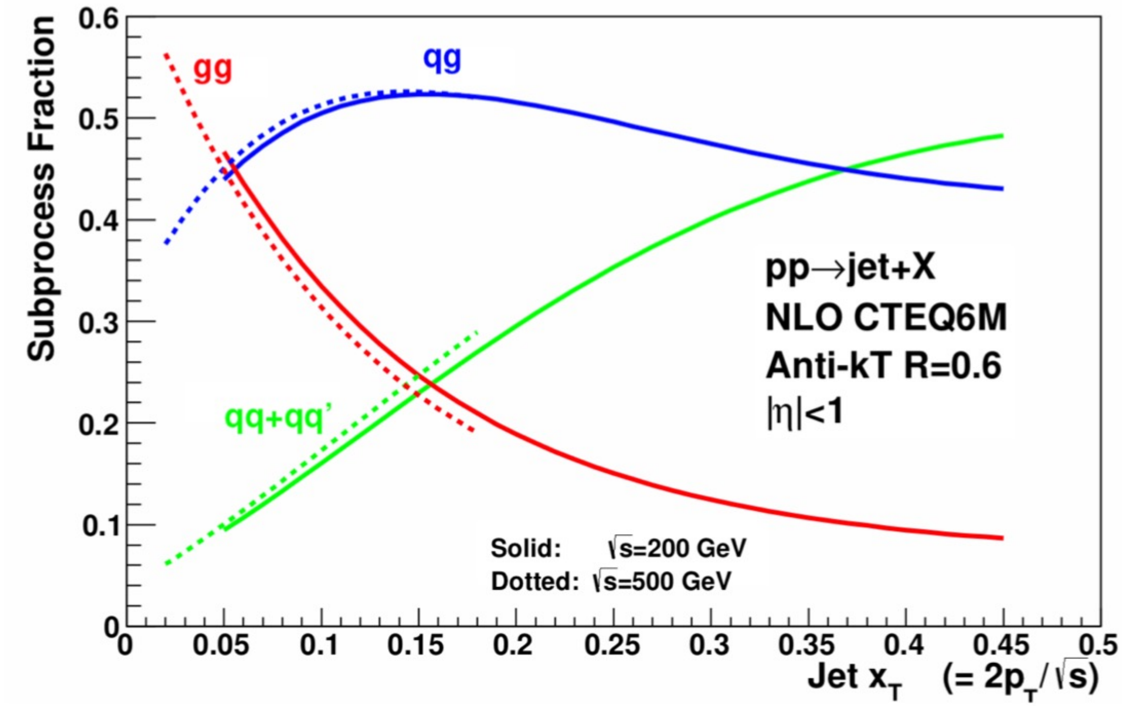
- The Spin puzzle is yet to solved
  - Angular momentum contribution is least understood
- E1039 intend to measure
  - Sivers asymmetry in Drell-Yan process using polarized NH_3 and ND_3 target
  - Magnitude and sign of Sivers function of sea quarks ($\bar{\boldsymbol{u}}$ and $\bar{\boldsymbol{d}}$)
  - Anticipated statistical accuracy $\sim 3 - 5\ \%$
- Non-zero Sivers asymmetry => Non-zero OAM for light anti-quarks (Major discovery!)
- Data taking starts by 2021 Fall
  - Expected to run for two years of beam time

Parton distribution functions

Taking into account the intrinsic transverse momentum k_T of quarks, at LO **8 PDFs** are needed for a full description of the nucleon:

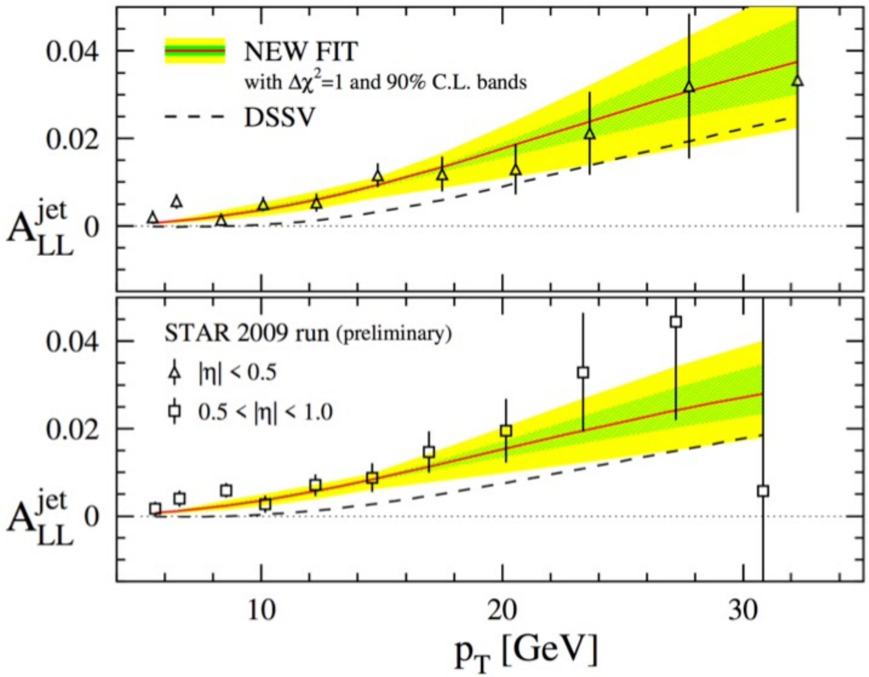


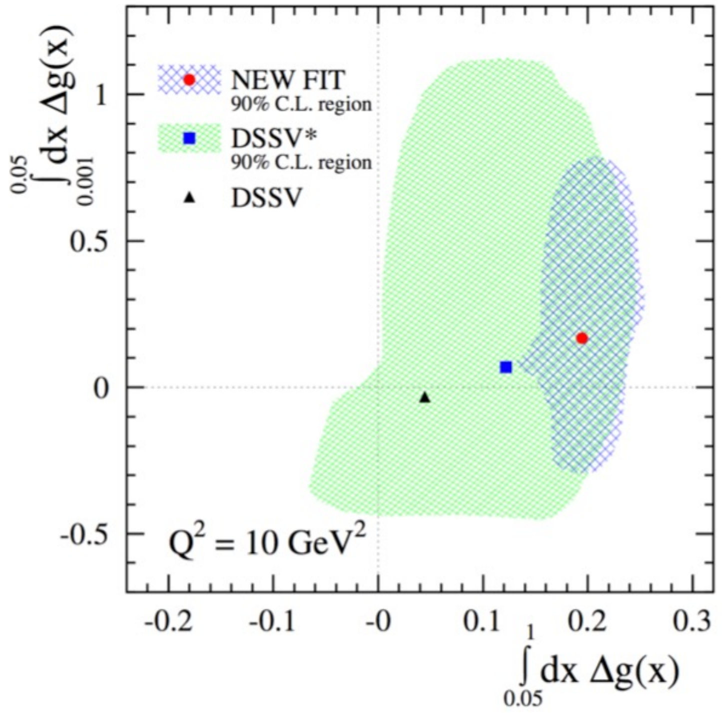
Polarized Drell-Yan measurements in COMPASS C. Quintans – p.2



- longitudinally polarized protons at RHIC can access $\Delta g(x,Q_2)$ directly through quark-gluon and gluon-gluon scattering.
- gluon scattering processes dominate at low xT

Gluon contribution: RHIC





$$\int_{0.05}^{1} dx \Delta g(x) = 0.20^{+0.06}_{-0.07}$$

Unexplored x<0.05 and significant uncertainties

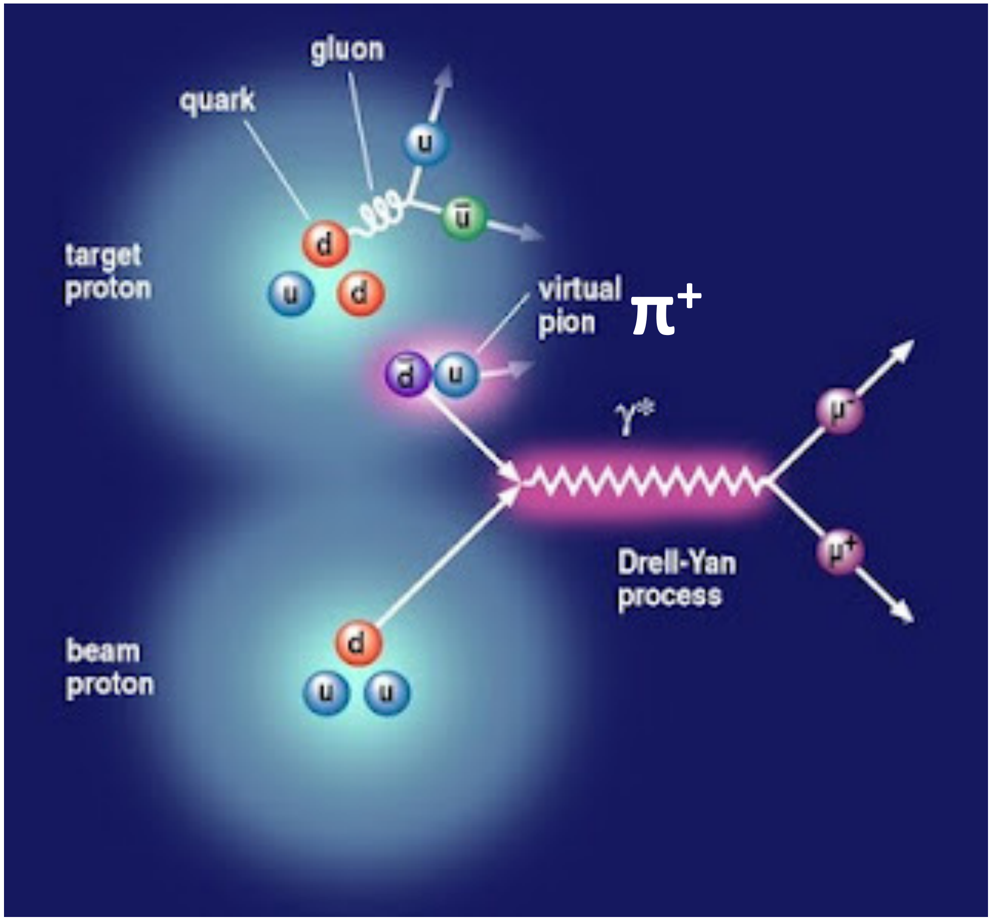
Meson Cloud Model

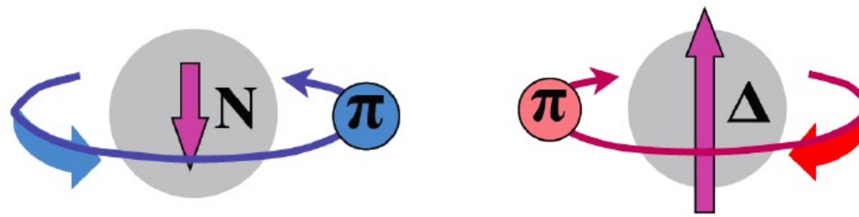
The meson cloud model explains the flavor asymmetry in the sea and requires quarks to carry angular momentum.

$|p\rangle = p + N\pi + \Delta\pi + \ldots$

Pions $J^p=0^-$ Negative Parity

Need **L=1** to get proton's $J^p=½^+$





Sea quarks should carry orbital angular momentum.

Sivers Effect in the Nucleon

Reasons for the Asymmetry

Phys. Rev. D **70**, 117504 (2004)
Phys. Rev. D **67**, 074010 (2003)

The number density of unpolarized quarks in a transeverly polarized proton:

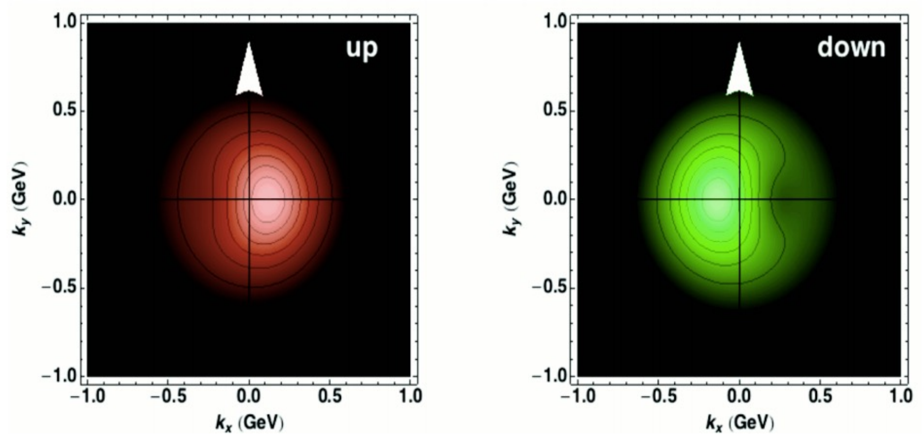
$$f_{q/p^{\uparrow}}(x_B, \vec{k}_T) = f_1^q(x_b, k_T^2) - \boldsymbol{f_{1T}^{\perp q}(x_B, k_T^2)} \frac{(\hat{P} \times \vec{k}_T) \cdot \vec{S}}{m_p}$$

Gives correlation between $\vec{k}_T$ and $\vec{S}$

The $\vec{k}_T$ distribution of quarks in a transversely polarized proton can be **asymmetric** and known as "**Sivers effect**".

f_1^q = Unpolarized quark density.
$\boldsymbol{f_{1T}^{\perp q}(x_B, \vec{k}_T)}$ = *Sivers function.*
$\vec{S}$ = Spin polarization vector.
$\vec{P}$ = Three momentum of the proton.
$\vec{k}_T$ = Intrinsic transverse momentum of unpolarized quarks.

Sivers Effect: Intrinsic k_T imbalance leads to the asymmetry



Source: A. Bacchetta et al. Il Nuovo Saggiatore

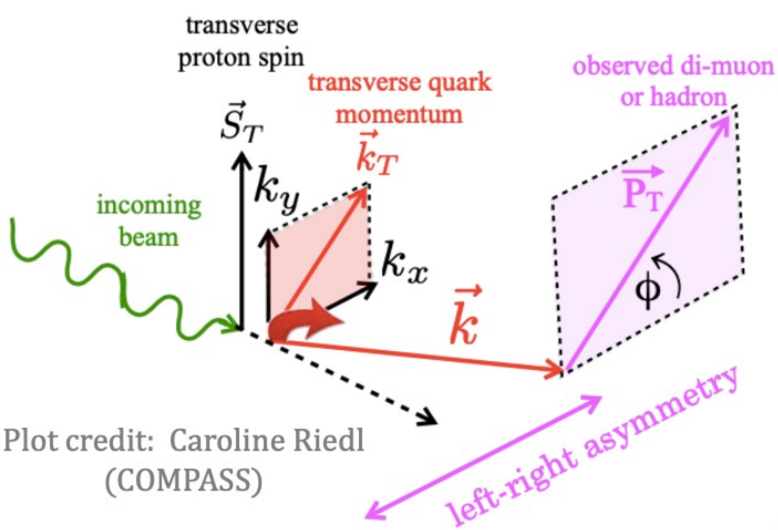
Sea-quark Sivers Asymmetry from Polarized Drell-Yan

The Drell-Yan cross section in terms of Sivers asymmetry:

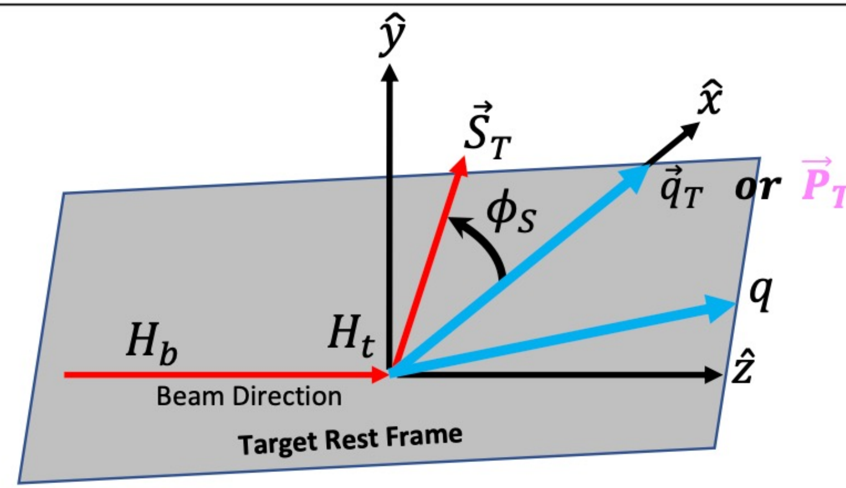
$$\sigma_{DY}^{\uparrow\downarrow}(x_a, x_b, q_T, \phi_S) = \frac{d\,\sigma^{LO}}{d^4q\ \ d\phi_S} \propto 1 \pm |S_T|\ \sin\phi_S\ A_T^{\sin\phi_S}$$

Phys. Rev. D 79, 034005 (2009),
PRL 119, 112002 (2017)

$$A(\phi_S) = \frac{1}{|S_T|}\ \frac{\sigma_{DY}^{\uparrow}-\sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow}+\sigma_{DY}^{\downarrow}} = \ \sin\phi_S\ A_T^{\sin\phi_S}$$



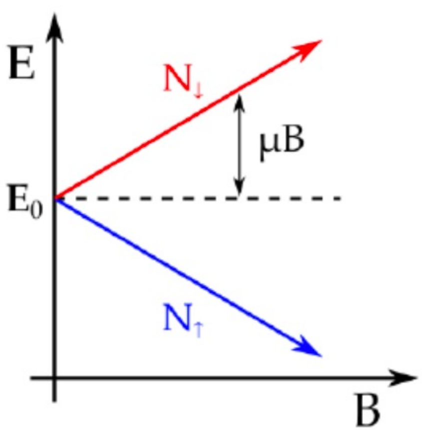
Plot credit: Caroline Riedl (COMPASS)



1. $\sigma_{DY}^{\uparrow\downarrow}$ is the Drell-Yan cross section when spin is vertically up(down.)
2. $A_T^{\sin\phi_S}$ is the Sivers asymmetry that SpinQuest will measure.
3. Azimuthal angle ϕ_S in target rest frame can be written in terms of azimuthal angle ϕ defined in detector rest frame : $\phi_S = \left(\frac{\pi}{2} - \phi\right)$.

Brute-Force Method:

- Use high-B at low-T via zeeman-splitting mechanism



Courtesy of James Maxwell

- Degree of polarization at thermal equilibrium

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

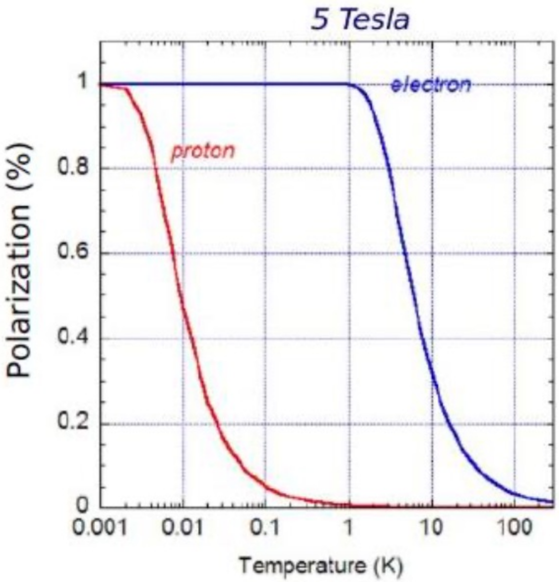
- Proton has small magnetic moment

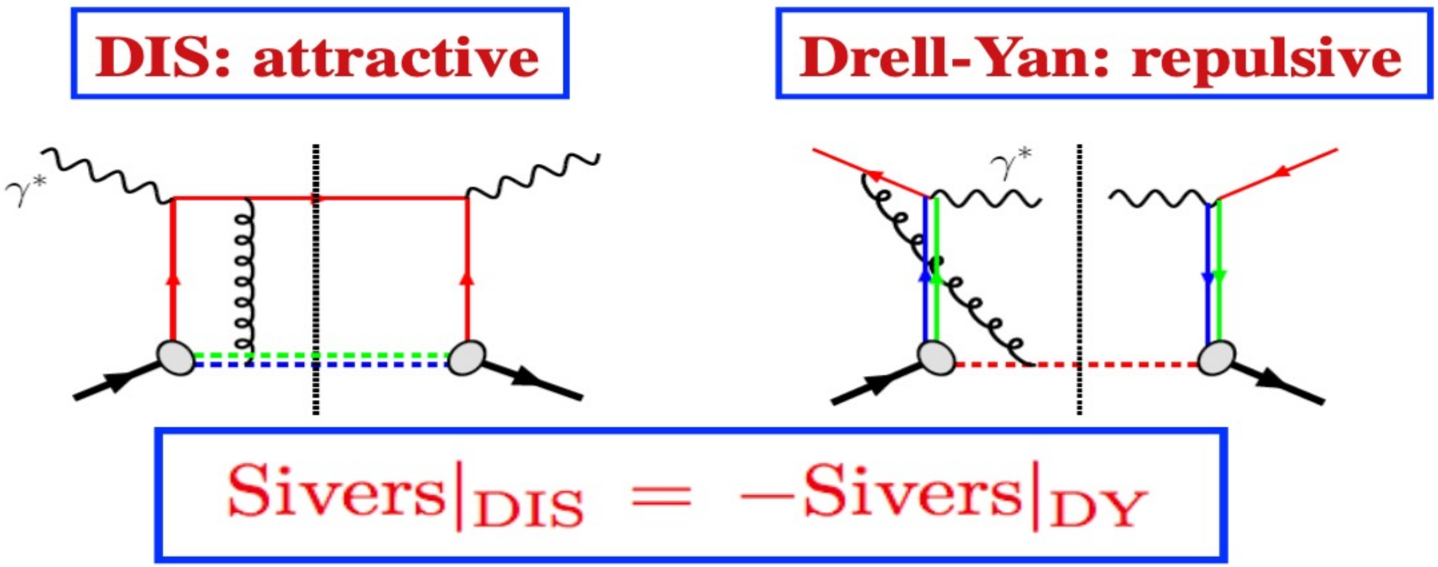
$$\mu_e \approx 660\mu_p$$

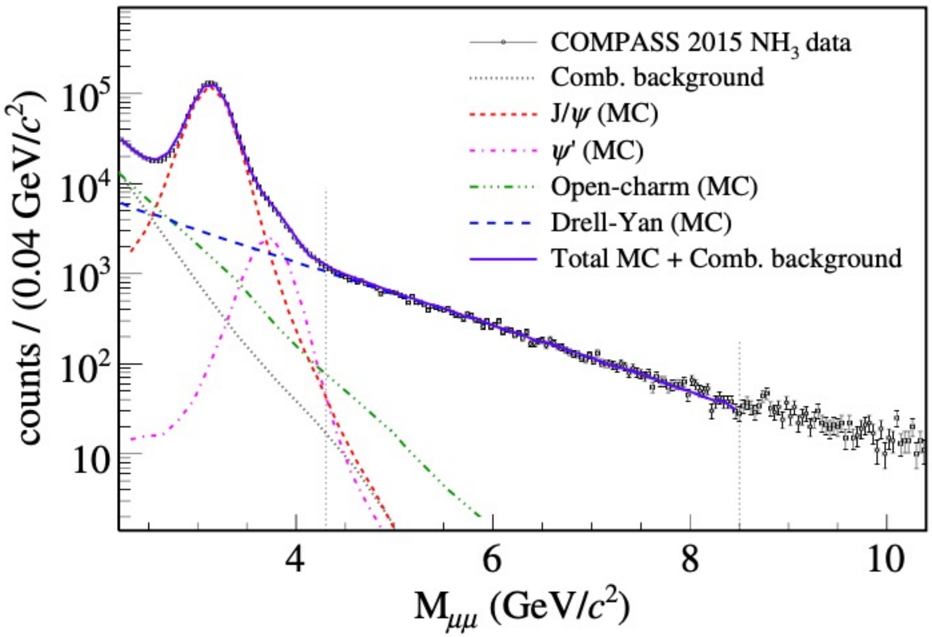
- At B = 5 Tesla & T = 1 K

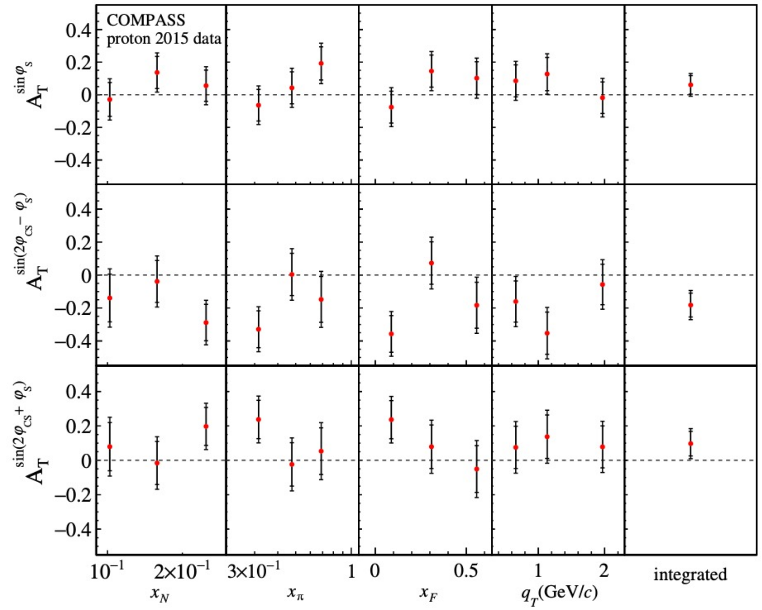
$$P_e = \sim 98\%, P_p = 0.51\%$$

- We need a better method!

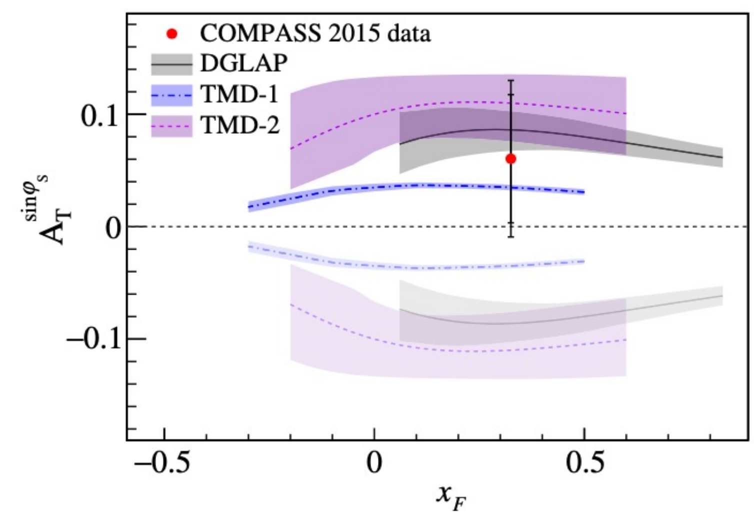



DIS: attractive
Drell-Yan: repulsive
γ^*
γ^*
$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$





average Sivers asymmetry $A_T^{\sin\varphi_S} = 0.060 \pm 0.057(\text{stat}) \pm 0.040(\text{sys})$ is found to be above 0 at about one standard



Fundamental Properties

Property	Value
Muon Mass	105.6583668 ± 0.0000038 MeV
Muon Electric Charge	e^-, e^+ (anti-muon)
Mean Life	2.19703 ± 0.00004 μ seconds
Spin	1/2
Magnetic Moment Ratio, μ/p	3.18334539 ± 0.00000010
Electric Dipole Moment	$3.7 \pm 3.4\ (10^{-19}\,\mathrm{ecm})$