Fermilab SeaQuest 実験

第 4 回 高エネルギー QCD・核子構造 勉強会
2014.11.01 @ 東工大

中野健一

東工大

Outline

- E906/SeaQuest 実験の目的
  - Drell-Yan 反応を用いた核子構造の測定
  - Sea queark のフレーバー非対称性 ($\bar{d}/\bar{u}$)
  - Boer-Mulders 分布関数 ($h_1^{\perp}$)
  - 等々…
- セットアップ & スケジュール
  - 最初の物理ラン (Run-2) が終わり、次の物理ランが始まる時期
- 状況 & 将来予測
  - Run-2 データの解析に基づいて
- 次世代 偏極 Drell-Yan 実験 (E1027 & E1039 @ Fermilab)
- まとめ

Drell-Yan Process @ Forward

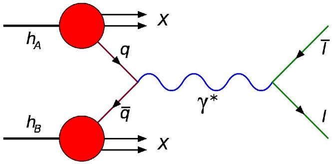
- Cross section @ LO

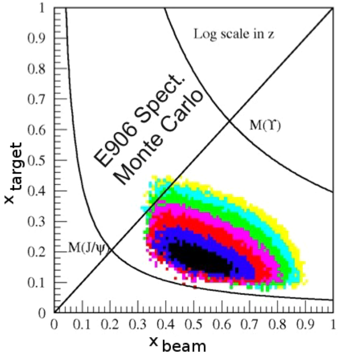
$$\frac{d^2\sigma}{dx_B dx_T} = \frac{4\pi\alpha^2}{9x_B x_T}\frac{1}{s}\sum_i {e_i}^2$$
$$\times \left\{ q_i^{\mathrm{B}}(x_B)\bar{q}_i^{\mathrm{T}}(x_T) + \bar{q}_i^{\mathrm{B}}(x_B) q_i^{\mathrm{T}}(x_T) \right\}$$

(B: beam, T: target)

- Always involve anti quark ... cf. DIS
- Quark @ beam & anti-quark @ target since $x_\mathrm{B} \gg x_\mathrm{T}$ & $q(x) \gg \bar{q}(x)$ at large x

$$q + \bar{q} \to \gamma^* \to \mu^+ + \mu^-$$



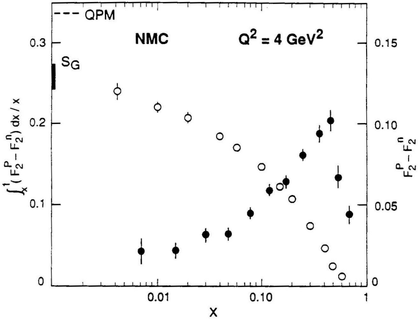


Flavor Asymmetry in Anti-Quark ($\bar{u}$ vs $\bar{d}$) Dist.

- Symmetric?
  - Simple assumption: $\bar{d}(x) = \bar{u}(x)$, which gives $\int \bar{d}(x)dx = \int \bar{u}(x)dx$
  - Gottfried Sum Rule:

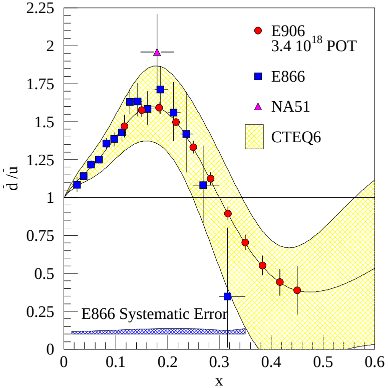
$$\begin{aligned} S_G &= \int_0^1 \frac{dx}{x} \{F_{2p}(x) - F_{2n}(x)\} \\ &= \frac{1}{3} \int \{(u(x) - \bar{u}(x)) - (d(x) - \bar{d}(x))\} dx - \frac{2}{3} \int (\bar{d}(x) - \bar{u}(x))\, dx \\ &= \frac{1}{3} \quad \text{if} \quad \int \bar{d}(x)dx = \int \bar{u}(x)dx \end{aligned}$$

- CERN NMC ('90):
  - $S_G = 0.2281(65) \neq 1/3$ at $x \in (0.004, 0.8)$ & $Q^2 = 4\ \text{GeV}^2$
  - Not symmetric!
    - $\int \bar{d}(x)dx > \int \bar{u}(x)dx$
    - $\bar{d}(x) > \bar{u}(x)$ in at least a certain x region



Sea-Quark Flavor Asymmetry ($\bar{d}/\bar{u}$)

- x-dependence of $\bar{d}/\bar{u}$ first measured by Drell-Yan exp.

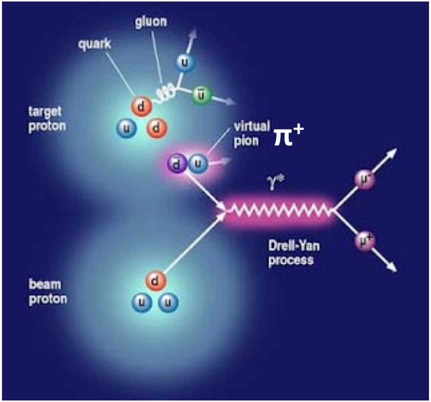


  - Examined with theory models (meson cloud model etc.)
  - Unique data on $\bar{u}(x) \neq \bar{d}(x)$

- SeaQuest will measure $\bar{d}/\bar{u}$ @ $0.2 \lesssim x_{Bj} \lesssim 0.4$ w/ $p+p$ & $p+d$
  - x_{Bj} dependence is the key to understand $\bar{d}/\bar{u}$ asym.
  - Particularly $\bar{d} \gtrsim \bar{u}$ @ $x_{Bj} \sim 0.3$??

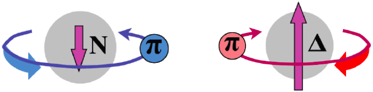
The meson cloud model explains the flavor asymmetry in the sea, and requires quarks to carry angular momentum.

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



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

Need **L=1** to get proton's $J^P=\frac{1}{2}^+$

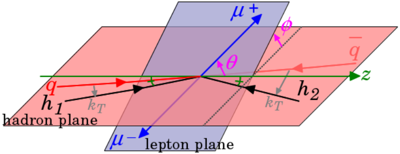


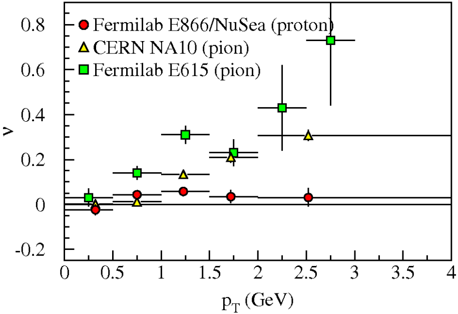
Sea quarks should carry orbital angular momentum.

Boer-Mulders Function ($h_1^\perp(x, k_T)$)

- Via measurement of angular distribution with $p+p$ & $p+d$

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

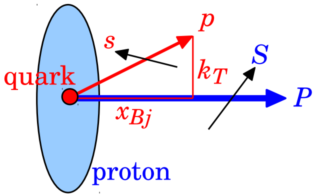




  - $\nu \equiv$ size of $\cos(2\phi)$ modulation
  - Break of Lam-Tung relation: $1-\lambda \neq 2\nu$
- Convolution of two $h_1^\perp$
  - $\nu \propto \left[\, h_1^\perp \text{ of } \bar{q}\,\right] \times \left[\, h_1^\perp \text{ of } q\,\right]$
  - $h_1^\perp$ of q @ $x \sim 0.5$
  - $h_1^\perp$ of $\bar{q}$ @ $x \sim 0.3$
  - Extraction of $h_1^\perp$ from E866/NuSea data ... PRD 81, 034023 (2010), PRD 82, 114025 (2010)

Origin of Violation of Lam-Tung Relation??

- Transverse Momentum Dependent (TMD) parton distribution
- Boer-Mulders effect ... $\propto s \cdot (P \times k_T)$

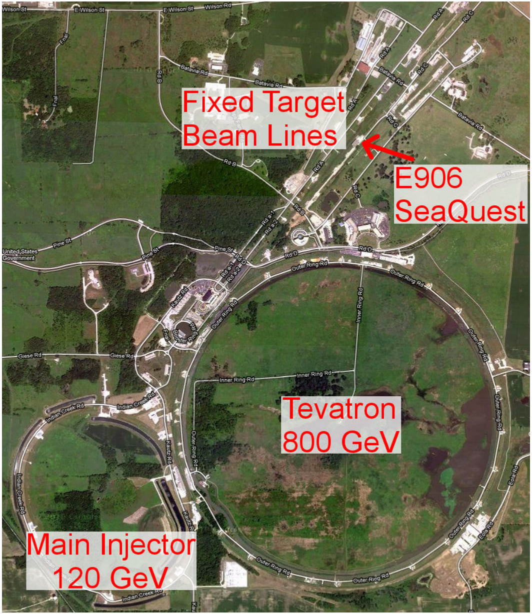


  - Arise from correlation between quark spin (s) & transverse momentum (k_T) ... if no correlation, no effect is seen
  - Boer-Mulders distribution function

  - cf. Sivers effect ... $\propto S \cdot (P \times k_T)$
- Non-zero $h_1^\perp \Longleftrightarrow$ non-zero orbital angular mom. $\Longleftrightarrow$ non-zero spatial dist.

E906/SeaQuest 実験の
セットアップ & スケジュール

Fermilab Proton Beam

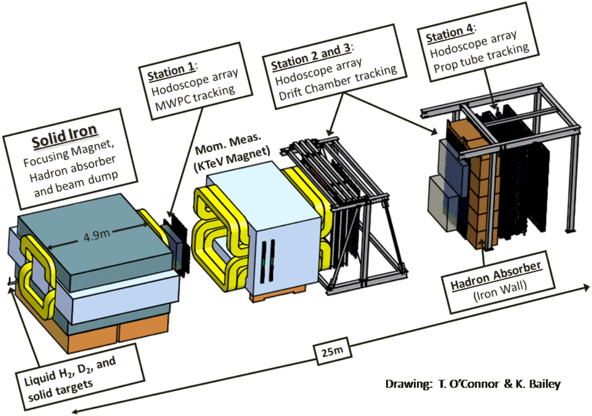


- Energy $E = 120$ GeV ($\sqrt{s} = 15$ GeV)
- Duty cycle
  - 60 sec per cycle
  - 5 sec for E906 with slow extraction
  - The rest for neutrino exp.
- Bunch
  - Length: 1 nsec
  - Interval: 19 nsec (53 MHz)
  - 10^{13} protons in 5 sec in spot size

FNAL E906/SeaQuest Collaboration

- Institutes
  - Abilene Christian Univ.
  - Argonne National Lab
  - Fermi National Accelerator Lab
  - KEK $_{\mathrm{Jp}}$
  - Los Alamos National Lab
  - Univ. of Michigan
  - RIKEN $_{\mathrm{Jp}}$
  - Tokyo Tech $_{\mathrm{Jp}}$
  - Academia Sinica $_{\mathrm{Tw}}$
  - Univ. of Colorado
  - Univ. of Illinois
  - Ling-Tung Univ. $_{\mathrm{Tw}}$
  - Univ. of Maryland
  - National Kaohsiung Normal Univ.
  - Rutgers Univ.
  - Yamagata Univ. $_{\mathrm{Jp}}$

E906/SeaQuest Spectrometer



- Targets ... LH_2, LD_2, C, Fe, W (& empty flask, none) in rotation
- Di-muon trigger with hodoscopes @ St. 1...4
- Tracking with drift chambers @ St. 1...3 & prop. tubes @ St. 4
- Detect $\mu^{+/-}$ with $p \sim 40$ GeV/c

SeaQuest Schedule

Year	Month	Event
2009	04	Start of building spectrometer
2011	08	Complete spectrometer
2012	03-04	Commissioning run (Run 1)
		(1st beam on March 08)
2012	05...	Detector & DAQ upgrade
2013	11	Start of Physics run (Run 2)
		(1st beam on November 08)
2014	09-10	Accelerator maintenance ← Now
2014	11	Re-start of Physics run (Run 3)
2016	*X*	End

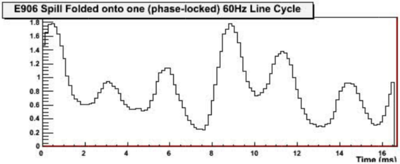
- Two years for 10^{19} protons delivered
  (10^{13} protons/spill $\times$ 1 spill/min $\times$ 2 years)

E906/SeaQuest 実験の状況 & 将来予測

Status — Beam

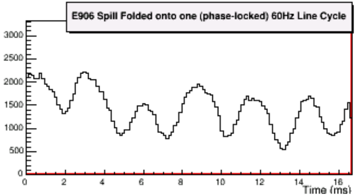
- Intensity
  - $\sim 4\times10^{12}$ delivered protons/spill at Run-2 end
  - To be 1×10^{13} in Run 3
- Duty factor
  - $\langle I\rangle^2 / \langle I^2\rangle$ ... how uniform the number of protons/bucket is
  - Less protons/bucket $\Longrightarrow$ less fake di-muons
  - 60% at minimum in MoU
  - Improvement @ accelerator

Commissioning run (Run 1)



D.F. = 30% @ 7.5 kHz

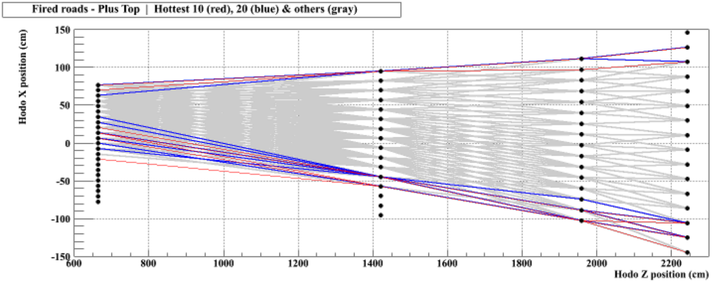
Run 2



D.F. = 60% @ 7.5 kHz,
25% @ 53 MHz

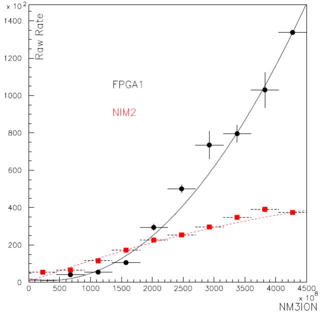
Status — Trigger & Hodoscope

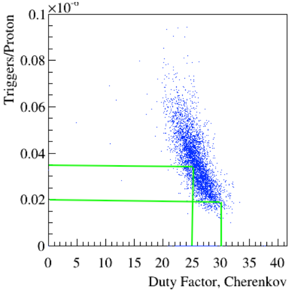
- Flexible trigger logic on FPGA
  - Trigger road = combination of hodoscope hits @ St. 1, 2, 3 & 4
  - Pair of trigger roads = di-muon
  - Large opening angle with straight roads = high mass



Trigger Rate (R) & Beam Intensity (I)

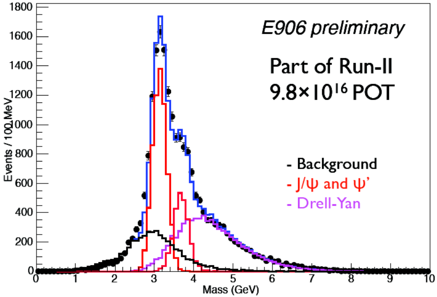
- Primary issue at Run-2 start
- R was much higher (>10 kHz) than DAQ bandwidth (5 kHz)
  - Observed $R \propto I^2$
  - Due to fake high-p tracks
- Solution
  - Measured & improved beam duty factor ($\langle I \rangle^2 / \langle I^2 \rangle$)
  - Found & removed "hot" trigger patterns in real data & simulation
- 4×10^{12} delivered protons/spill at Run-2 end (to be 1×10^{13} in Run 3)





Status of Run-2 Data Analysis

- Di-muon mass distribution (preliminary)

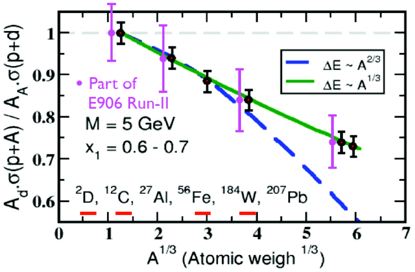


  - With ~1/3 of Run-2 data
  - Events on all targets (LH_2, LD_2, C, Fe & W) are summed up here
  - Detectors work nicely as expected
  - Good J/ψ mass resolution (~180 MeV)
    - Drell-Yan dominates @ $M \gtrsim 4$ GeV
    - Can separate J/ψ & ψ'
  - Resonable MC/data agreement on mass dependence of acceptance

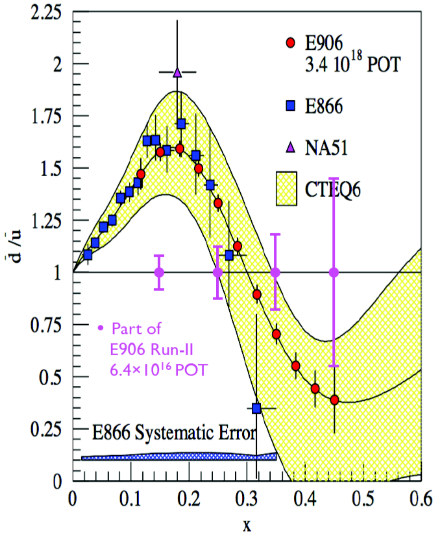
Measurement Precision at Present

- With part of Run-2 data = ~5% of expected luminosity
- Flavor asymmetry ($\bar{d}/\bar{u}$) → & nuclear dependence ↓
- The anticipated precision is achievable!

(error size only)

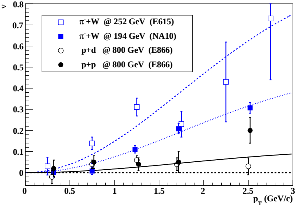


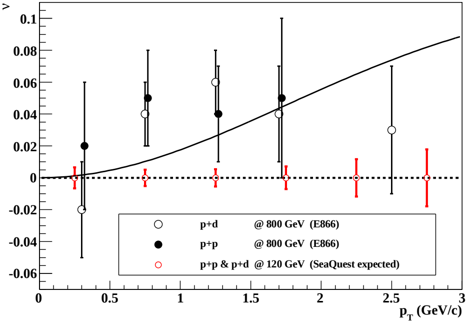
(error size only)



Expected Precision on Angular Distribution

- Data analysis is ongoing
- Estimate with MC
  - Assuming the full luminosity (3.4×10^{18} recorded protons)
  - $\nu \equiv$ size of $\cos(2\phi)$ modulation $\propto \left[\, h_1^\perp \text{ of } \bar{q} \right] \times \left[\, h_1^\perp \text{ of } q \right]$



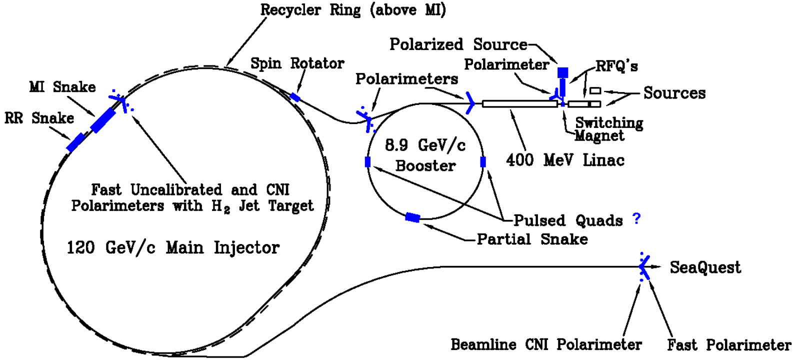


  - Probably $h_1^\perp$ of $\bar{q}$ is smaller than q,
    but E906/SeaQuest will measure it with enough accuracy

次世代 偏極 Drell-Yan 実験
(E1027 & E1039 @ Fermilab)

FNAL E-1027 with Polarized Beam

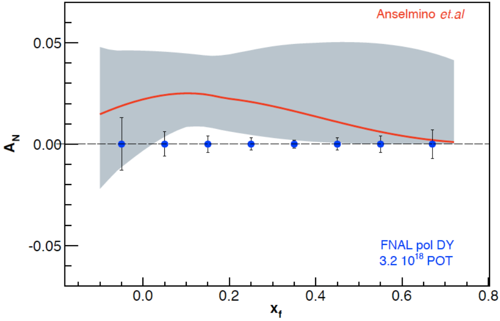
- Proposal @ http://inspirehep.net/record/1216817
- Stage-1 approved
- Use E906/SeaQuest spectrometer (w/ magnetic field adjusted)
- Upgrade source, booster & main injector
  - Based on design & experience of BNL RHIC
  - Detailed design & construction under study



Prospect of E-1027 with Polarized Beam

- Sivers TMD PDF of quark
- Observable: $A_N \equiv \dfrac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \propto \dfrac{f_{1T}^{\perp,u}(x_B) \cdot \bar{u}(x_T)}{u(x_B) \cdot \bar{u}(x_T)}$

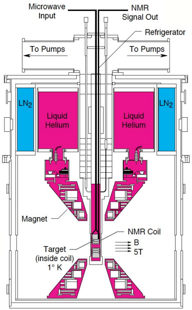
  ... similar to ν (cos(2ϕ) modulation)



  - Red line ... prediction with SIDIS (HERMES & COMPASS) result
  - "Can measure not only sign, but also the size & maybe shape of the Sivers function"

FNAL E-1039 with Polarized Target

- LoI @ http://www.fnal.gov/directorate/program_planning/June2013PACPublic/P-1039_LOI_polarized_DY.pdf
- Stage-1 approved
- Use E906/SeaQuest spectrometer
- Build polarized target
  - LANL LDRD project (approved for FY2013-2016)
  - Existing NH_3 target (UVa or Hall-C polarized target)
  - Modification (pol. direction, cryostat, etc) & Re-commissioning



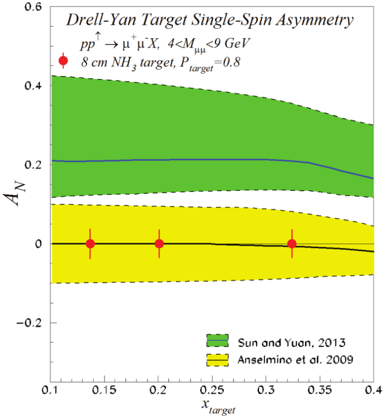
Prospect of E-1039 with Polarized Target

- Sivers TMD PDF of anti-quark
- Observable:

$$A_N \equiv \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \propto \frac{u(x_B) \cdot f_{1T}^{\perp,\bar{u}}(x_T)}{u(x_B) \cdot \bar{u}(x_T)}$$

… similar to ν ($\cos(2\phi)$ modulation)

  - Zero or non-zero?
  - Improve the present accuracy (yellow band, by SIDIS)
  - Compare also with blue line, which takes into account scale evolution (Collins-Soper-Sterman evolution)



Phys. Rev. D88, 034016 (2013)

Eur. Phys. J. A39, 89 (2009)

まとめ

- Purpose of E906/SeaQuest @ Fermilab
  - Investigate the nucleon structure with the Drell-Yan process
  - Measure the sea-quark flavor asymmetry, $\bar{d}/\bar{u}$
  - Measure the Boer-Mulders function, $h_1^{\perp}(x, k_T)$
  - Measure the nuclear dependence, $\sigma_{p+A}/\sigma_{p+d}$
    - Not only physics but also to limit the nuclear correction on $\bar{d}/\bar{u}$.
- First physics run (Run-2) has finished
  - Data analyses are on-going
  - Preliminary result has confirmed that
    the data are being accumulated as anticipated
- Second physics run (Run-3) will start in November 2014
- Future polarized Drell-Yan experiments at Fermilab,
  i.e. E-1027 & E-1039