Probing Anti-Quark Structure of Proton with Drell-Yan at FNAL

BARYONS'10 @ Osaka
Structure of Hadrons (SH1)
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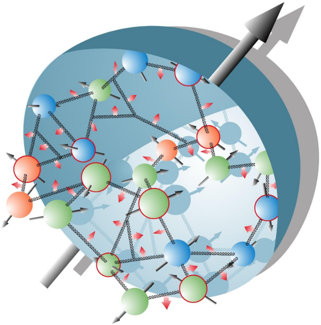
Contents

Introduction

- Proton @ small scale
  - Dynamic bound system by strong force (QCD)
  - Breakdown of proton momentum ... $q : g \sim 50\% : 50\%$ @ $Q^2 \gtrsim 100$ GeV^2
  - Well described with DGLAP evolution equation



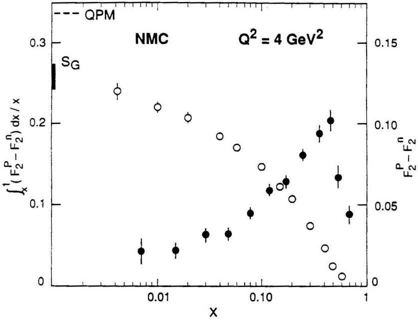
- Recent developments in measurement & theory are revealing rich features
  - Anti-quark distribution
  - Proton spin problem ... quark-spin contribution is only 30%
  - 3-dim. structure ... generalized PDF = form factor $\otimes$ parton dist. function

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

- Symmetry?
  - Naive assumption: $\bar{d} = \bar{u}$
  - Gottfried Sum Rule:

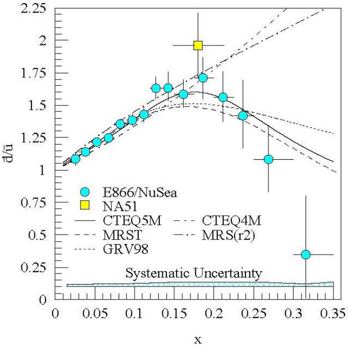
$$S_G = \int_0^1 \frac{dx}{x} \{F_{2p}(x) - F_{2n}(x)\}$$
$$= \frac{1}{3}\{(u - \bar{u}) - (d - \bar{d})\} - \frac{2}{3}(\bar{d} - \bar{u})$$
$$= \frac{1}{3} \quad \text{if} \quad \bar{d} = \bar{u}$$

- CERN NMC ('90):
  $S_G = 0.2281(65) \neq 1/3$
  at $x \in (0.004, 0.8)$ & $Q^2 = 4\ \mathrm{GeV}^2$



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

- CERN NMC ('90): $S_G = 0.2281(65) \neq 1/3$
- CERN NA51 ('94): $\bar{d} > \bar{u}$ at $x \sim 0.18$
- FNAL E866/NuSea ('98): $\bar{d}/\bar{u}$ for $x \in (0.015, 0.35)$



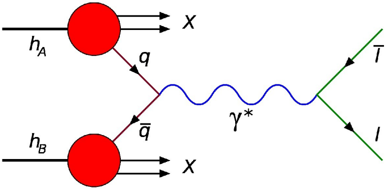
70% asymmetry!

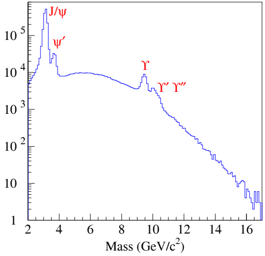
- ▷ Much larger than the effect by Pauli principle

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

- Precise measurement of $\bar{d}/\bar{u}$ with Drell-Yan process:

$$p + A \to \mu^+ + \mu^- + X \ , \quad A = p, d, Fe, etc.$$

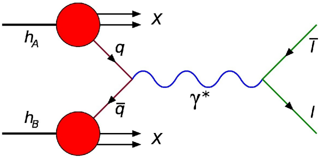


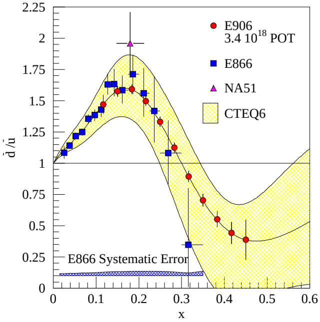


  - Advantage
    - Anti-quark always involved $\Longrightarrow$ Highly sensitive to $\bar{q}(x_{Bj})$
    - Simple final state & kinematics $\Longrightarrow$ x_{Bj} & Q^2 controllable

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

- Current understanding of $\bar{d}/\bar{u}$
  - $\bar{d}/\bar{u} > 1$ (asymmetric) @ $x_{Bj} \lesssim 0.25$
  - Model interpretations
    - Pion cloud model: $u \to u + (\bar{d} + d) \to \pi^{+} + d$
    - Chiral soliton model, Instanton model, etc
    - $\bar{d} > \bar{u}$ caused by $u > d$ in all models
    - Hard to explain $\bar{d} < \bar{u}$ at $x \gtrsim 0.3$
- E906/SeaQuest aims to reveal $\bar{d}/\bar{u}$ at $0.25 \lesssim x_{Bj} \lesssim 0.45$
  - x_{Bj} dependence is the key to investigate the mechanisum of $\bar{d}/\bar{u}$ asymmetry
  - Size reversal ($\bar{d} \gtrless \bar{u}$) at $x_{Bj} \sim 0.3$?





Spacial Distribution of (Anti-) Quarks

- Second(?) interest of E906/SeaQuest
- Angular distribution of lepton pair production (PRD 18, 2447 (1978))

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

- Lam-Tung relation:

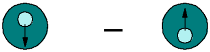
$$1 - \lambda = 2\nu$$

  - Spin-1/2 nature of quarks (similar to Callen-Gross relation in DIS)
  - No NLO corrections ($\mathcal{O}(\alpha_s)$)
  - Small NNLO corrections ($\mathcal{O}(\alpha_s^2)$)

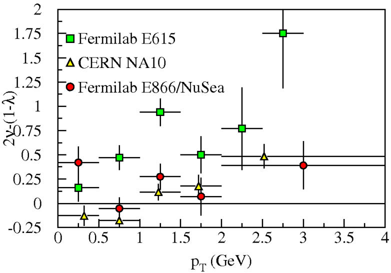
Lam-Tung Relation

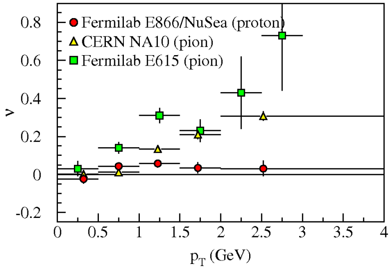
- With π beam
  - Lam-Tung relation violated!
  - Large ν = large $\cos 2\phi$ dep.
  - Stronger at larger p_T
- With p beam
  - Lam-Tung relation holds?
- Interpretation with Boer-Mulder dist. function:

$h_1^\perp$ =



  - With π beam:
    $\nu \propto$ valence $h_1^\perp(\pi) \times$ valence $h_1^\perp(p)$
  - With p beam:
    $\nu \propto$ valence $h_1^\perp(p) \times$ sea $h_1^\perp(p)$
- Non-zero angular momentum (= spacial distribution)?



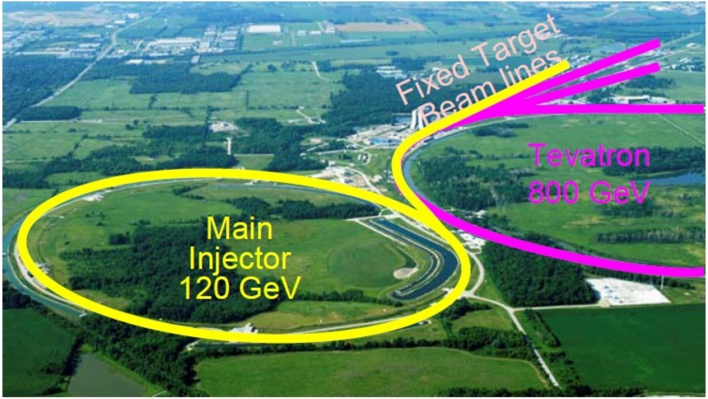


FNAL E-906/SeaQuest Collaboration

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

Proton Beam @ FNAL

- Beam energy $E = 120$ GeV, $\sqrt{s} = 15$ GeV
- Slow extraction: bunch length 1 nsec, interval 19 nsec (53 MHz)
- Proton rate: 2×10^{12}/sec in spot size



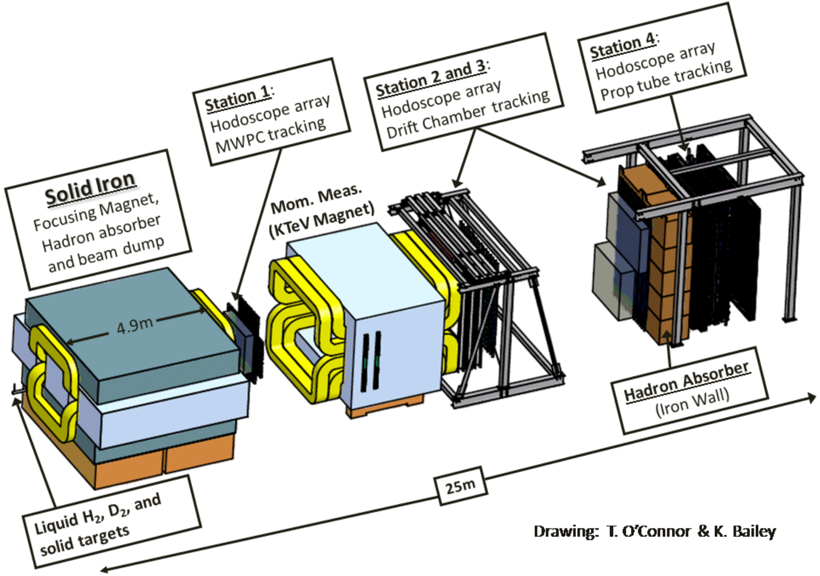
Proton Beam @ FNAL

- Advantage of 120-GeV Main Injector
  - Past: FNAL-E866/NuSea
    - Data in 1996–1997
    - ^{1}H, ^{2}H & nuclear targets
    - 800-GeV proton beam
  - Present: FNAL-E906/SeaQuest
    - Data in 2010
    - ^{1}H, ^{2}H & nuclear targets
    - 120-GeV proton beam
  - Drell-Yan rate scales as 1/s

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum_i {e_i}^2 \left\{ q_i^{\mathrm{T}}(x^{\mathrm{T}})\bar{q}_i^{\mathrm{B}}(x^{\mathrm{B}}) + \bar{q}_i^{\mathrm{T}}(x^{\mathrm{T}})q_i^{\mathrm{B}}(x^{\mathrm{B}}) \right\}$$

$\Longrightarrow \times 7$ stat. at a fixed luminosity
  - Background rate (primarily from J/ψ decays) scales as s
$\Longrightarrow \times 7$ luminosity at a fixed detector rate
  - Thus $\times 50$ stat. at the same detector rate

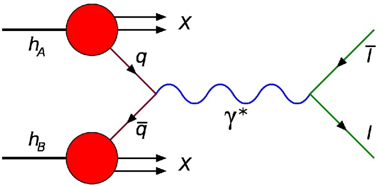
E906/SeaQuest Spectrometer



- Detect $\mu^+\mu^-$ pairs with $p \sim 30$ GeV/c

Measurement Techniques

- Drell-Yan kinematics
  - $M^2 = x_{beam} x_{target} s$,
    $\exp Y = \sqrt{x_{beam}/x_{target}}$
  - $x_{beam} = \frac{M}{\sqrt{s}} e^{Y}$, $x_{target} = \frac{M}{\sqrt{s}} e^{-Y}$



- Accessing $\bar{d}/\bar{u}$ at large x_{Bj}
  - Forward ($Y \gg 0$, i.e. $x_{beam} > x_{target}$)
    $\Longrightarrow x_{beam} = x_q, x_{target} = x_{\bar{q}}$ since $q(x) \gg \bar{q}(x)$ at large x ($\gtrsim 0.5$),

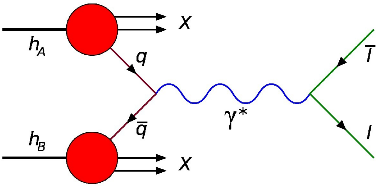
$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum_i e_i{}^2 \left\{ q_i^{\mathrm{T}}(x^{\mathrm{T}})\bar{q}_i^{\mathrm{B}}(x^{\mathrm{B}}) + \bar{q}_i^{\mathrm{T}}(x^{\mathrm{T}})q_i^{\mathrm{B}}(x^{\mathrm{B}}) \right\}$$

$\Longrightarrow$ By measuring $p+p$ & $p+d$ scatterings, $\frac{\sigma_{pd}}{2\sigma_{pp}} \approx \frac{1}{2}\left(1 + \frac{\bar{d}}{\bar{u}}\right)$

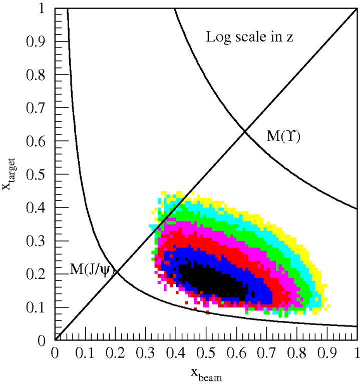
  - Larger $M \Longrightarrow$ larger x_{target}

Measurement Techniques

- Drell-Yan kinematics
  - $M^2 = x_{beam} x_{target} s$,
    $\exp Y = \sqrt{x_{beam}/x_{target}}$
  - $x_{beam} = \frac{M}{\sqrt{s}} e^{Y}$, $x_{target} = \frac{M}{\sqrt{s}} e^{-Y}$

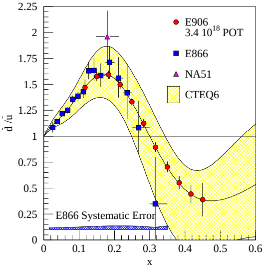


- Concentrated acceptance with focus magnet
  - Steering high-mass $\mu^{\pm}$ pairs into detector acceptance
    $\Longrightarrow$ Enhancing high-x_{Bj} event
  - Sweeping out low-mass & low-mom. μ
    $\Longrightarrow$ Reducing background



Final Remarks

- Anti-quarks in proton
  - Flavor asymmetry ($\bar{d}/\bar{u}$)
  - Boer-Mulder dist. function ($h_1^\perp$)
    $\Longrightarrow$ Angular momentum & spacial distribution



- E906/SeaQuest, a Drell-Yan Experiment at FNAL
  - With 120-GeV proton beam + p/d targets
  - $\bar{d}/\bar{u}$ at large x_{Bj} ($\gtrsim 0.25$)
  - About to start
    - Beam commissioning from Jan. 2011
    - Three-year running
  - In future
    - Polarized target and/or beam at FNAL?
    - Experiment w/ E906 spectrometer at RHIC or J-PARC?