Dimuon Measurement with Polarized Beam at J-PARC

NP08 in Mito
March 6th, 2008
Yuji Goto (RIKEN/RBRC)
Outline

• Origin of the nucleon spin 1/2
  – introduction
    • history
  – Drell-Yan measurement
    • unpolarized measurement → polarized measurement
  – quark spin, gluon spin, and orbital angular momentum of quark and gluon
    • longitudinal and transverse spin measurements

• Polarized proton acceleration at J-PARC
J-PARC proposals

• P04: measurement of high-mass dimuon production at the 50-GeV proton synchrotron
  – spokespersons: Jen-Chieh Peng (UIUC) and Shinya Sawadas (KEK)
  – including polarized physics program, but not seriously discussed
  – “deferred”

• P24: polarized proton acceleration at J-PARC
  – contact persons: Yuji Goto (RIKEN) and Hikaru Sato (KEK)
  – collaboration: ANL, BNL, UIUC, KEK, Kyoto Univ., LANL, RCNP, RIKEN, RBRC, Rikkyo Univ., TokyoTech, Tokyo Univ. of Science, Yamagata Univ.
  – polarized Drell-Yan included as a physics case
  – “no decision”

• Next proposal for the polarized physics program
  – to be submitted
Origin of the nucleon spin $1/2$?

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta g + L \]

- EMC experiment at CERN  
  J. Ashman et al., NPB 328, 1 (1989).
  - total quark spin constitutes a small fraction of the nucleon spin
    \[ \Delta \Sigma = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\% \]  
    “proton spin crisis”
    - integration in $x = 0 \sim 1$ makes uncertainty
    - more data to cover wider $x$ region with more precise data necessary
  - SLAC/CERN/DESY/JLAB experiments
    \[ \Delta \Sigma \sim 20\% \]

- Gluon spin contribution?  
  longitundinally polarized measurements
  - scaling violation in polarized DIS
    - success of the evolution equation of the perturbative QCD
    - limited sensitivity due to a limited range of $Q^2$
  - semi-inclusive polarized DIS
  - polarized hadron collision

- Orbital angular momentum? 
  transversely polarized measurements
**Gluon spin contribution**

- $A_{LL}$ in neutral pion production
  - mid-rapidity at RHIC, $\sqrt{s} = 200$ GeV
  
  \[ A_{LL} = [\omega_{gg}] \Delta g \Delta g + [\omega_{gq}] \Delta g + [\omega_{qq}] \Delta q \Delta q \]

  \[ \Delta G = 0.4 \text{ at } Q^2 = 1(\text{GeV}/c)^2 \]

  \[ \Delta G = 0.1 \text{ at } Q^2 = 1(\text{GeV}/c)^2 \]

  GRSV-std scenario, $\Delta G = 0.4$ at $Q^2 = 1(\text{GeV}/c)^2$, excluded by data on more than 3-sigma level

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Flavor-sorted quark polarization

- Weak boson production
  - RHIC spin
    - $\sqrt{s} = 500$ GeV
    - 2009 –
  - parity-violating asymmetry $A_L$
    \[ A_L^{W^+} = \frac{\Delta u(x_a)\bar{d}(x_b) - \Delta \bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} \]
  - reduction of uncertainties to determine the quark spin contribution $\Delta \Sigma$ and gluon spin contribution $\Delta G$ to the proton spin
Transverse single-spin asymmetry (SSA)

- Link to orbital angular momentum in the nucleon
  - forward rapidity
    - Fermilab E704, $\sqrt{s} = 20$ GeV
    - RHIC, $\sqrt{s} = 200$ GeV

explained by many undetermined
distribution and fragmentation
functions: transversity, Sivers function,
Collins function
**Drell-Yan experiment**

- The simplest process in hadron-hadron reactions
  - no QCD final-state effect
  - no polarized Drell-Yan experiment done yet
  - flavor asymmetry of the sea-quark distributions
    - unpolarized and longitudinally-polarized measurements
  - orbital angular momentum in the nucleon
    - Sivers effect (no Collins effect)
  - transversity distribution function, etc.

- Why at J-PARC?
  - polarized beam feasible in discussions with J-PARC and BNL accelerator physicists
  - high intensity/luminosity for small Drell-Yan cross section
Flavor asymmetry of sea-quark distribution

- Fermilab E866
  \[ \frac{\sigma^{pd}}{2\sigma^{pp}} \sim \frac{1}{2} \left[ 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \right] \]

- Possible origins
  - meson-cloud model
    - virtual meson-baryon state
      \[ p \rightarrow p \pi^0, n \pi^+, \Delta \pi \]
  - chiral quark model
    - instanton model
  - chiral quark soliton model

- Is \( \pi^+ \) the origin of \( \bar{d} \)-quark excess in the proton?

\[ \int_{0.015}^{0.35} dx [\bar{d}(x) - \bar{u}(x)] = 0.0803 \pm 0.011 \]
\[ \int_{0}^{1} dx [\bar{d}(x) - \bar{u}(x)] = 0.118 \pm 0.012 \]
Polarized Drell-Yan experiment at J-PARC

- Longitudinally-polarized measurement
  - $A_{LL}$ measurement
  - flavor asymmetry of sea-quark polarization

120-day run
75% polarization for a $5 \times 10^{11}$ protons/spill polarized solid NH3 target, 75% hydrogen polarization and 0.15 dilution factor
Flavor asymmetry of sea-quark polarization

- Polarized Drell-Yan experiment at J-PARC
  - $x = 0.25 - 0.5$
- $W^\pm$ production at RHIC
  - $x = 0.05 - 0.1$

Reduction of uncertainties to determine the quark spin contribution $\Delta \Sigma$ and gluon spin contribution $\Delta G$ to the proton spin.

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**Polarized Drell-Yan experiment at J-PARC**

- Orbital angular momentum
  - in hadron-hadron reaction, no direct link between measurement and theory (yet)
  - but, any partonic transverse motion and correlation should be related
    - Sivers effect / higher-twist effect
- SSA \((A_N)\) measurement
  - Sivers effect and higher-twist effect provide the same description of SSA on Drell-Yan and semi-inclusive DIS at moderate \(q_T\): \(\Lambda_{QCD} << q_T << Q\)
  - Sivers function in Drell-Yan should have a sign opposite to that in DIS
    - sensitive QCD test between e+p data and p+p data

1000 fb-1 (120-day run), 75% polarization, no dilution factor
Theory calculation by Ji, Qiu, Vogelsang and Yuan based on Sivers function fit of HERMES data
Polarized Drell-Yan experiment at J-PARC

- $A_{TT}$ measurement
  - $h_1(x)$: transversity
    - remaining leading-order distribution function of the nucleon
  \[
  A_{TT} = \hat{a}_{TT} \cdot \frac{\sum_{q} e_{q}^2 (\bar{h}_{1q}(x_1)h_{1q}(x_2) + (1 \leftrightarrow 2))}{\sum_{q} e_{q}^2 (\bar{r}_{1q}(x_1)r_{1q}(x_2) + (1 \leftrightarrow 2))}
  \]
  \[
  \hat{a}_{TT} = \frac{\sin^2 \theta \cos(2\phi - \phi_S - \phi_{S_2})}{1 + \cos^2 \theta}
  \]

- SSA measurement, $\sin(\phi + \phi_S)$ term
  - $h_1(x)$: transversity
  - $h_{1\perp}^{(1)}(x)$: Boer-Mulders function (1st moment of)
  \[
  \hat{A} = -\frac{1}{2} \frac{\sum_{q} e_{q}^2 (\bar{h}_{1q}^{\perp(1)}(x_1)h_{1q}(x_2) + (1 \leftrightarrow 2))}{\sum_{q} e_{q}^2 (\bar{r}_{1q}(x_1)\bar{f}_{1q}(x_2) + (1 \leftrightarrow 2))}
  \]
Polarized proton acceleration at AGS/RHIC

- Proposed scheme for the polarized proton acceleration at J-PARC is based on the successful experience of accelerating polarized protons to 25 GeV at BNL AGS.
Polarized proton acceleration at J-PARC

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Accelerating polarized protons in the MR

- AGS 25% superconducting helical snake

helical dipole coil

correction solenoid and dipoles

measured twist angle 2 deg/cm in the middle ~4 deg/cm at ends
Accelerating polarized protons in the MR

• Possible location of partial helical snake magnets in the MR
Summary

• Polarized Drell-Yan experiment with dimuon measurement using polarized proton beam at J-PARC has a rich physics programs
  – flavor asymmetry of sea-quark polarization → higher precision for $\Delta \Sigma$ and $\Delta G$
  – SSA measurements for Sivers and higher-twist effects and transversity → link to orbital-angular momentum

• We propose to make the J-PARC facility allow acceleration of polarized proton beams to 30-50 GeV
  – feasible in discussion with J-PARC and BNL accelerator physicists
  – technically, there is no showstopper
Backup slides
**Gluon spin contribution**

- **PHENIX** $A_{LL}$ of $\pi^0$
  - GRSV-std scenario, $\Delta G = 0.4$ at $Q^2 = 1\text{(GeV/c)}^2$, excluded by data on more than 3-sigma level, $\chi^2(\text{std}) - \chi^2_{\text{min}} > 9$
  - only experimental statistical uncertainties included (the effect of systematic uncertainties expected to be small in the final results)
  - theoretical uncertainties not included

Calc. by W. Vogelsang and M. Stratmann

[Diagram showing chi-squared distribution with curves for different scenarios: $\Delta G_{\text{GRSV}}$, $\Delta G = 0$, $\Delta G = G_{\text{GRSV}}$, and $\chi^2(\text{std}) - \chi^2_{\text{min}} > 9$.]

Run5: hep-ex-0704.3599
Run6: Preliminary
Distribution and fragmentation functions

• Transversity distribution function
  \[ \delta q(x) = h_{1T}(x) \]
  – distribution of the transverse-spin of a parton inside the transversely polarized proton

• Sivers distribution function
  \[ f_{1T}^{\perp}(x, p_T^2) \]
  – correlation between the transverse-spin of the proton and the transverse-momentum of an unpolarized parton inside the proton \( (p_T^2) \)

• Collins fragmentation function
  \[ H_{1}^{\perp}(z, k_T^2) \]
  – correlation between the transverse spin of a fragmenting quark and the transverse momentum of the outgoing hadron relative to the quark \( (k_T^2) \)
**Dimuon experiment at J-PARC (P04)**

- based on the Fermilab spectrometer for 800 GeV
- length to be reduced but the aperture to be increased
- two vertically bending magnets with $p_T$ kick of 2.5 GeV/c and 0.5 GeV/c
- tracking by three stations of MWPC and drift chambers
- muon id and tracking

**tapered copper beam dump and Cu/C absorbers placed within the first magnet**
**Dimuon experiment at J-PARC (P04)**

- Unpolarized measurement
  - with proton and deuterium targets
Unpolarized Drell-Yan experiment at J-PARC

- Boer-Mulders function $h_1^\perp(x, k_T^2)$
  
  - angular distribution of unpolarized Drell-Yan
    $\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right) = \left[\frac{3}{4\pi}\right]\left[1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi\right]$ 
  
  - Lam-Tung relation reflect the spin-1/2 nature of quarks
    $1 - \lambda = 2\nu$
    $\nu \neq 0, 1 - \lambda \neq 2\nu$
  
  - violation of the Lam-Tung relation suggests non-perturbative origin
  
  - correlation between transverse quark spin and quark transverse momentum

With Boer-Mulders function $h_1^\perp$:

$\nu (\pi^- W \rightarrow \mu^- \mu^+ X) \sim \text{valence } h_1^\perp(\pi^-)$
$\nu (pd \rightarrow \mu^- \mu^+ X) \sim \text{valence } h_1^\perp(p)$
$\nu (pd \rightarrow \mu^- \mu^+ X) \sim \text{sea } h_1^\perp(p)$


hep-ex/0609005
Physics at 30 GeV

- **J/ψ**
  - gluon fusion or quark-pair annihilation
  - quark-pair annihilation dominant
    - must be confirmed experimentally…
    - similar physics topics as Drell-Yan process

Calculations by color-evaporation model
Physics at 30 GeV

- SSA measurement of open charm production
  - no single-spin transfer to the final state
  - sensitive to initial state effect: Sivers effect
  - collider energies: gluon-fusion dominant
    - sensitive to gluon Sivers effect
  - fixed-target energies: quark-pair annihilation dominant
    - sensitive to quark Sivers effect

Polarized proton acceleration

• How to keep the polarization given by the polarized proton source
  – depolarizing resonance
    • imperfection resonance
      – magnet errors and misalignments
    • intrinsic resonance
      – vertical focusing field
  – weaken the resonance
    • fast tune jump
    • harmonic orbit correction
  – intensify the resonance and flip the spin
    • rf dipole
    • snake magnet

• How to monitor the polarization
  – polarimeters
Modes of operation

• Operation mode of the J-PARC MR should be:
  – 50 GeV maximum energy
  – $10^{12}$ proton/spill ($\sim 10^{36}\text{cm}^{-2}\text{s}^{-1}$ luminosity with a $\sim 5\%$ interaction target)
    • 8 bunches
    • $2\times 10^{11}$ proton/bunch at RCS
  – 0.5 s spill length (working assumption)
  – 80% polarization
  – $10\pi\ \text{mm}\cdot\text{mrad}$ normalized 95% emittance and 0.3 eVs longitudinal emittance
High-intensity polarized $H^-$ source

- OPPIS parameters required:
  - 0.16 mA peak $H^-$ ion current in 500 $\mu$sec pulse
    - $5 \times 10^{11}$ $H^-$ ion/pulse
  - 50Hz repetition rate
  - $1.0\pi$ mm·mrad normalized emittance
  - 35 keV beam energy
  - 85% polarization
High-intensity polarized $H^-$ source

- RHIC OPPIS
  - built at KEK and upgraded at TRIUMF
  - 0.5-1.0 mA (max. 1.6 mA) $H^-$ ion current in 400 $\mu$sec pulse
    - 1.2-2.4\times10^{12} H^- ion/pulse
  - 7 Hz max. repetition rate
    - 1 Hz routine repetition
  - 82-85% polarization
**High-intensity polarized H\(^-\) source**

- **Issues**
  - where to locate the polarized H\(^-\) source
  - how to merge the polarized beam to the existing beam line
    - may require RFQ
  - maintenance of the laser system
From source to RCS

• Polarimeter
  – at the end of the linac
  – proton-Carbon inclusive polarimeter similar to that at BNL

• Stripping foil
  – 300-500 $\mu$g/cm$^2$ stripping foil for injection to RCS
  – need to be replaced by 100 $\mu$g/cm$^2$ foil to have better $dp/p$
Accelerating polarized protons in the RCS

- Kinetic energy from 0.18 GeV to 3 GeV
  - $G\gamma = 2.2 \sim 7.5$
  - betatron tune $\nu_y = 6.35$

by Mei Bai (BNL)
Accelerating polarized protons in the RCS

- 5 imperfection resonances
  - \( G_\gamma = 3, 4, 5, 6, 7 \)
  - corrected by harmonic orbit correction
- 4 intrinsic resonances
  - betatron tune \( \nu_y = 6.35 \)
  - \( G_\gamma = 2.65 (9-\nu_y), 3.35 (-3+\nu_y), 5.65 (12-\nu_y), 6.35 (0+\nu_y) \)
  - first small resonance is corrected by fast tune jump
  - latter three strong resonances are completely (> 99%) spin-flipped by a rf dipole
    - 20 Gm vertical rf dipole
    - smaller size of beam (comparing to 7cm painting beam) required: operational issue
Accelerating polarized protons in the RCS

• Issues
  – where to locate the rf dipole
  – design of the rf dipole
  – beam monitor system to cover a wide dynamic range between high-intensity unpolarized beam ($4 \times 10^{13}$/bunch) and polarized beam ($1.5 \times 10^{11}$/bunch)
    • position monitor necessary to calculate the magnetic field error and correct it by the harmonic orbit correction
  – spin tracking to be done
Accelerating polarized protons in the MR

- Kinetic energy from 3 GeV to 50 GeV
  - $G_\gamma = 7.5 \sim 97.5$
  - betatron tune $\nu_x = 22.339, \nu_y = 20.270$
**Accelerating polarized protons in the MR**

- Two superconducting 30% partial helical Siberian snakes separated by 120 degree installed in two of the three straight sections:
  - avoid all vertical depolarizing resonances
- Two quadrupole doublets
  - to compensate perturbation of the lattice by the snakes at low energies

![Graph](image)  
full spin flip at all imperfection and strong intrinsic resonances using partial Siberian snake and rf dipole at AGS
Accelerating polarized protons in the MR

- Spin tracking
  - $\nu_x = 22.128$, $\nu_y = 20.960$
  - average of 12 particles on an ellipse of $8\pi$ mm mrad

by A.U. Luccio (BNL)
Primary beam extraction

• No serious issues

• Issues
  – operational issues
    • tune change for the extraction
    • vertical bend of the beam line
  – beam profile monitor system for the stability of beam intensity, position, and spot size to provide a systematical control of the experimental data quality
  – spin rotator magnet necessary to manipulate a direction of beam polarization
Proton-carbon elastic-scattering polarimeter

• Requirements
  – known analyzing power $A_N$
  – small systematic error
  – quick measurement (~1 min)

• AGS/RHIC pC CNI polarimeter
  – elastic scattering in the coulomb-nuclear interference region
  – micro-ribbon carbon target in the circulating beam
  – detecting recoil carbon nucleus
    • arrival time from time-zero to Si sensors

WFD image provided by K. Kurita (Rikkyo)
Proton-carbon elastic-scattering polarimeter

- Proton-carbon CNI polarimeter at J-PARC
  - no time-zero information
  - coincidence measurement between the recoiled carbons and the forward going protons with the extracted beam
  - economical solution which provides a quick turn-around to optimize machine parameters to achieve maximum polarization
**Absolute polarimeter**

- Proton-proton and proton-carbon elastic scattering at 31.2 GeV of the RHIC beam
  - measured analyzing power data at 31.2 GeV of the RHIC beam
  - available for calibration of absolute polarimeter of the main ring (gas jet) and/or extracted beam (solid target)
Cost for polarized proton acceleration

- Rough estimation based on the cost at BNL
  - 200 million yen high-intensity polarized H⁻ source
    - OPPIS / RFQ / polarimeter
  - 50 million yen from source to RCS
    - proton-carbon inclusive polarimeter / stripping foil upgrade
  - 100 million yen acceleration at RCS
    - rf dipole magnet / beam monitor system upgrade
  - 500 million yen acceleration at MR
    - two superconducting 30% partial helical Siberian snakes / two quadrupole doublets
  - 250 million yen primary beam extraction
    - beam profile monitor system / spin rotators
  - 100 million yen proton-carbon CNI polarimeter
  - 100 – 300 million yen absolute polarimeter
    - gas jet in the main ring and/or solid target with the extracted beam
- Total 1,300 – 1,500 million yen
Polarized target

- Michigan polarized target
  - existing at KEK
  - target thickness \( \sim 3 \text{ cm} \) (1% target)
  - maybe operational with \( 10^{11} \) ppp (luminosity \( \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1} \))