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 $\rightarrow$ 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)
  - collaboration: Abilene Christian Univ., ANL, Duke Univ., KEK, UIUC, LANL, Pusan National Univ., RIKEN, Seoul National Univ., TokyoTech, Tokyo Univ. of Science, Yamagata Univ.
  - 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 $\Delta\Sigma = 12 \pm 9(\mathrm{stat}) \pm 14(\mathrm{syst})\%$ "proton spin crisis"
    - integration in x = 0 ~ 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 ? longitudinally 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

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$

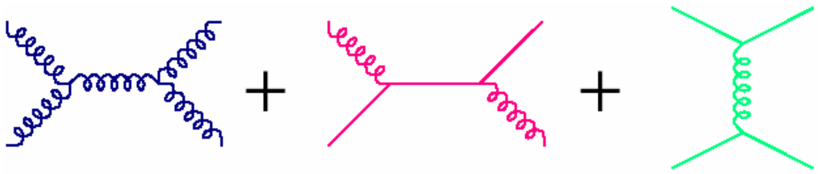
- Orbital angular momentum ?

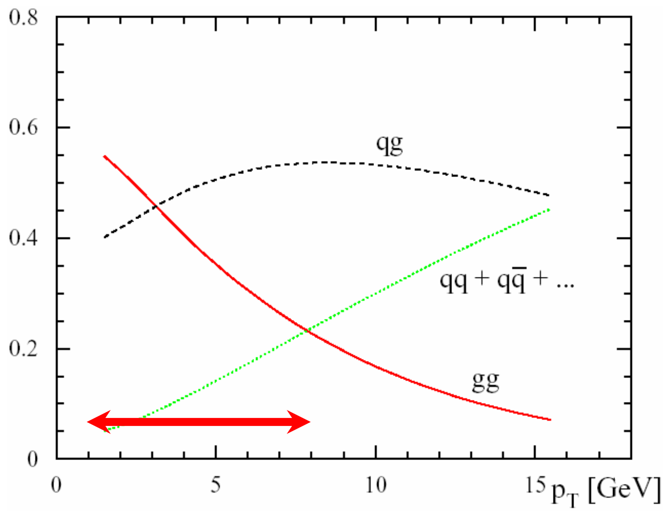
transversely polarized measurements

Gluon spin contribution

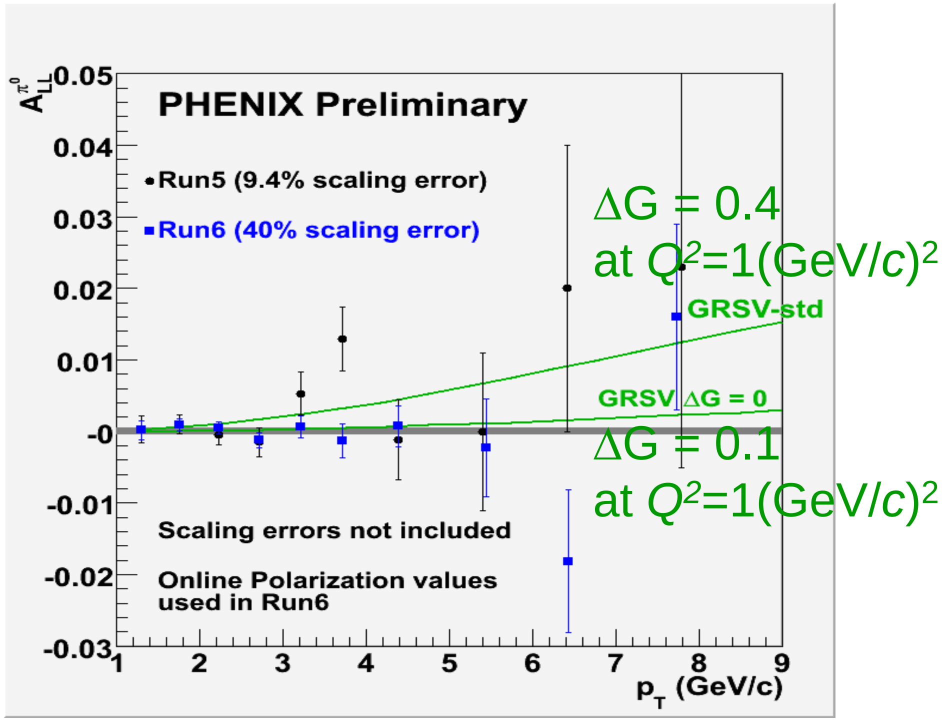
- A_{LL} in neutral pion production
  - mid-rapidity at RHIC, $\sqrt{s}$ = 200 GeV

$$A_{LL} = [\omega_{gg}]\Delta g \Delta g + [\omega_{gq}\Delta q]\Delta g + [\omega_{qq}\Delta q \Delta q]$$





gg + qg dominant
sensitive to the gluon reaction



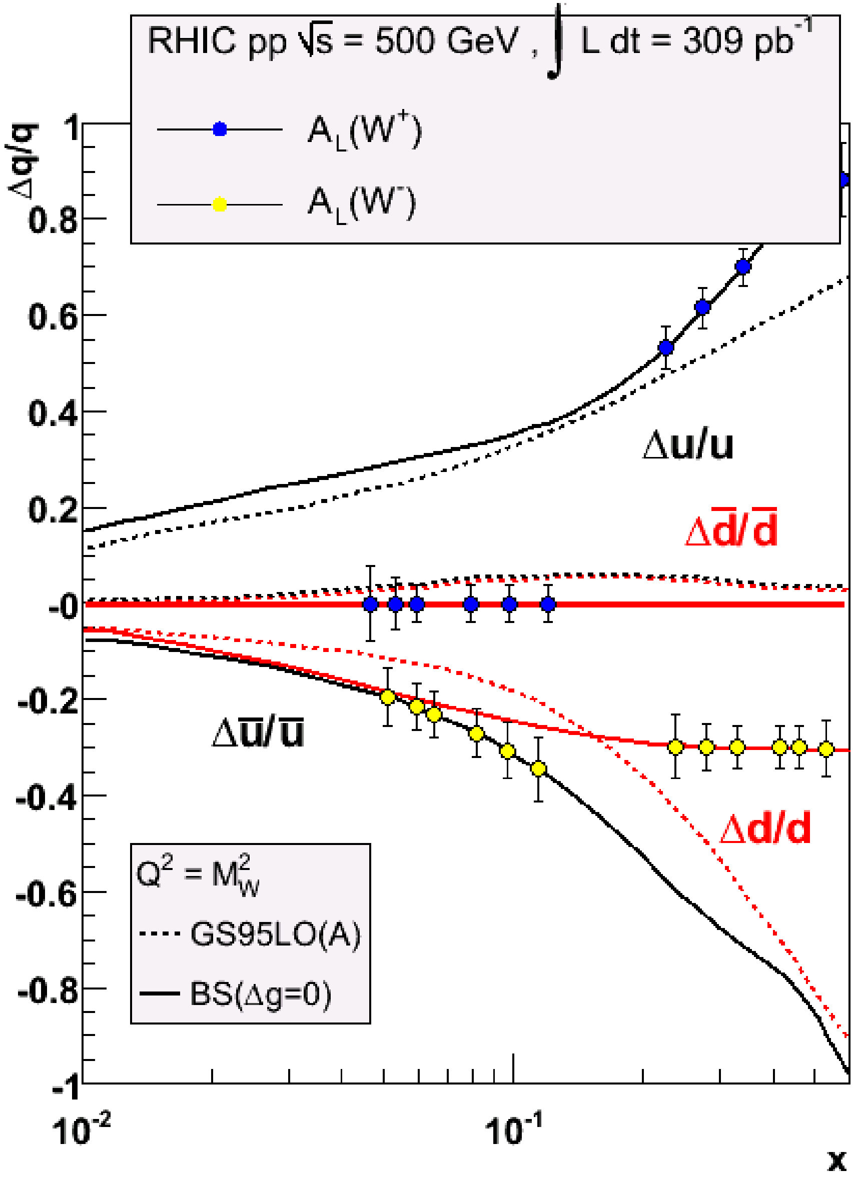
GRSV-std scenario, ΔG = 0.4 at Q^2 = 1(GeV/c)^2, excluded by data on more than 3-sigma level

Flavor-sorted quark polarization

- Weak boson production
  - RHIC spin
    - √s = 500 GeV
    - 2009 –
  - parity-violating asymmetry A_L

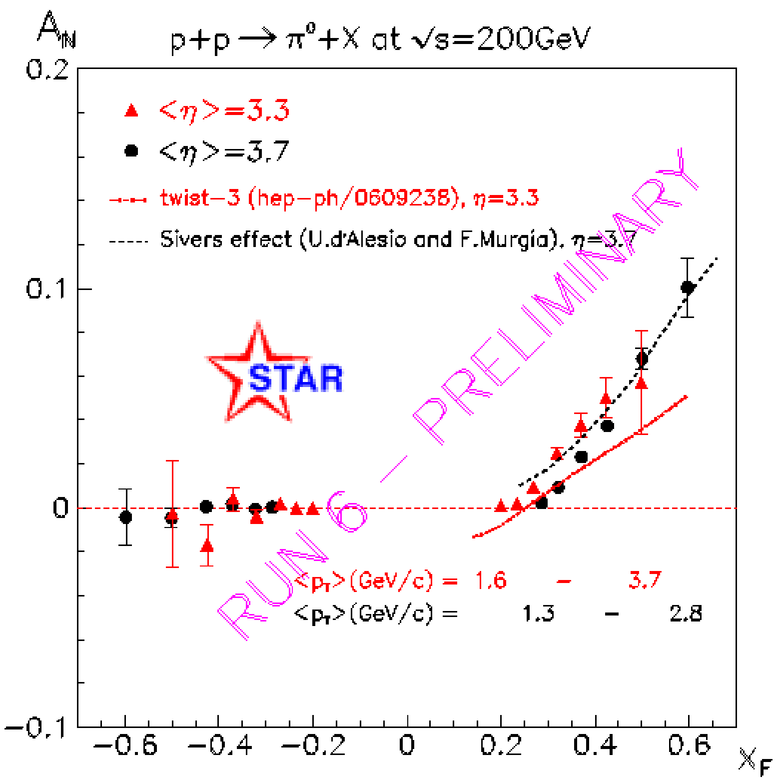
$$A_L^{W^+} = \frac{\Delta u(x_a)\bar{d}(x_b) - \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$

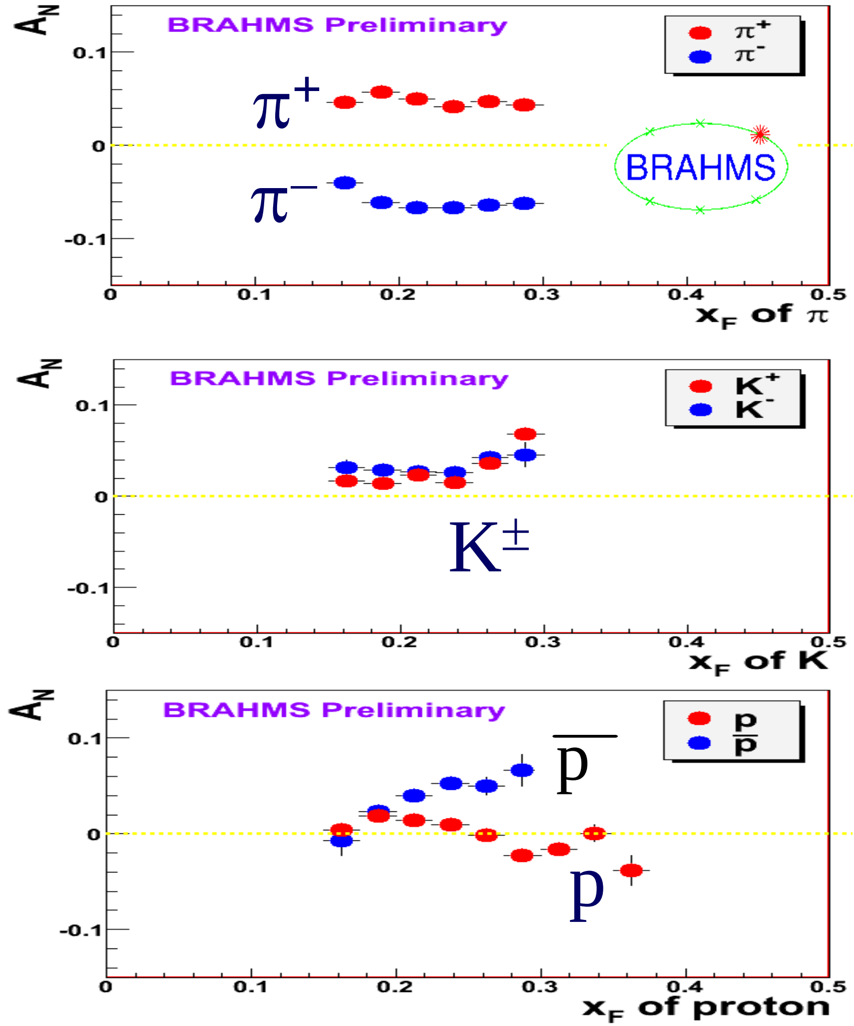
  - reduction of uncertainties to determine the quak spin contribution ΔΣ and gluon spin contribution ΔG to the proton spin



Transverse single-spin asymmetry (SSA)

- Link to orbital angular momentum in the nucleon
  - forward rapidity
    - Fermilab E704, √s = 20 GeV
    - RHIC, √s = 200 GeV



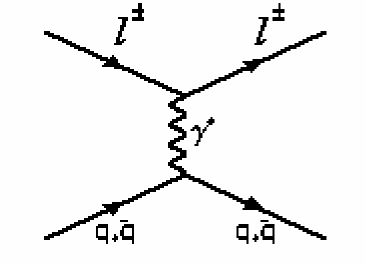


explained by many undetermined distribution and fragmentation functions: transversity, Sivers function, Collins function

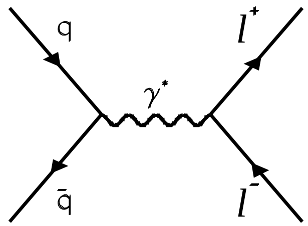
Drell-Yan experiment

- The simplest process in hadron-hadron reactions

DIS



Drell-Yan



  - 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

$$p \to p\pi^0, n\pi^+, \Delta\pi$$

  - chiral quark model

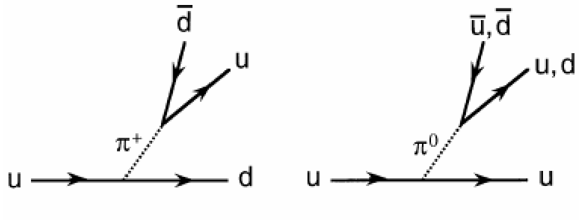
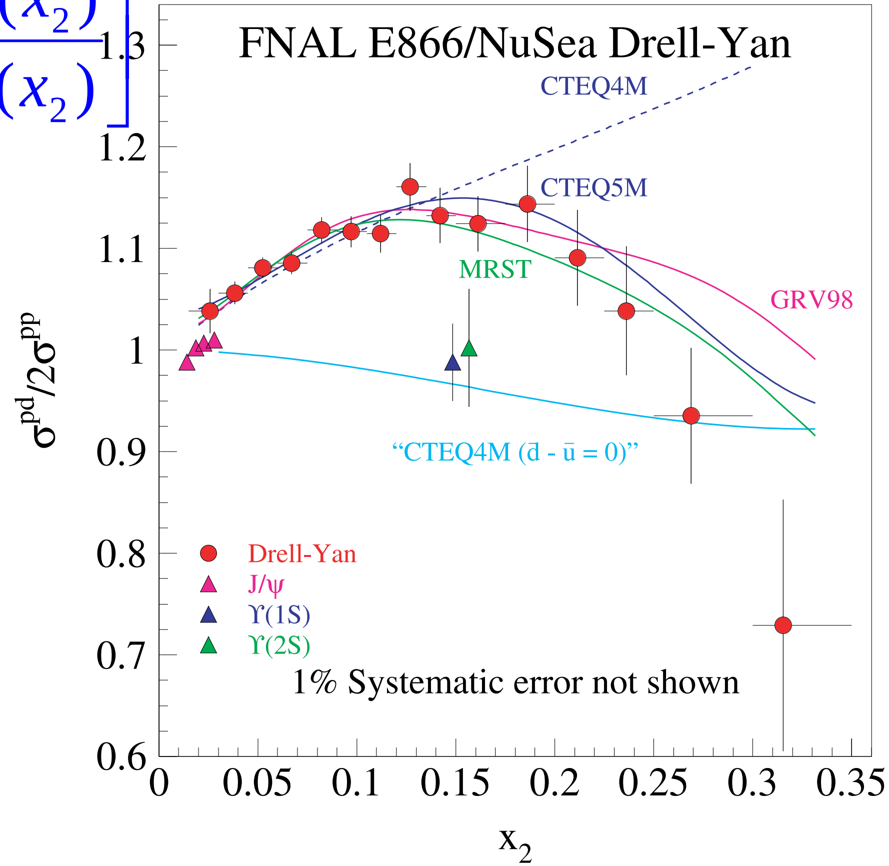


Fig. 17. Valence *u* quark splitting.

  - instanton model
  - chiral quark soliton model
- Is π^+ the origin of $\bar{d}$ -quark excess in the proton?



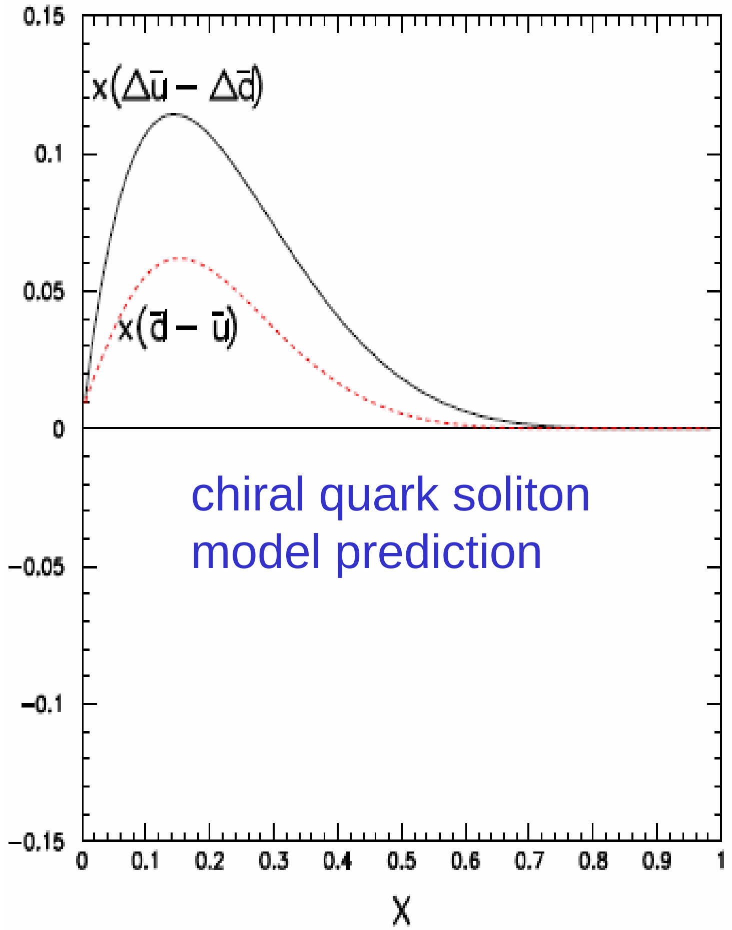
with CTEQ5M

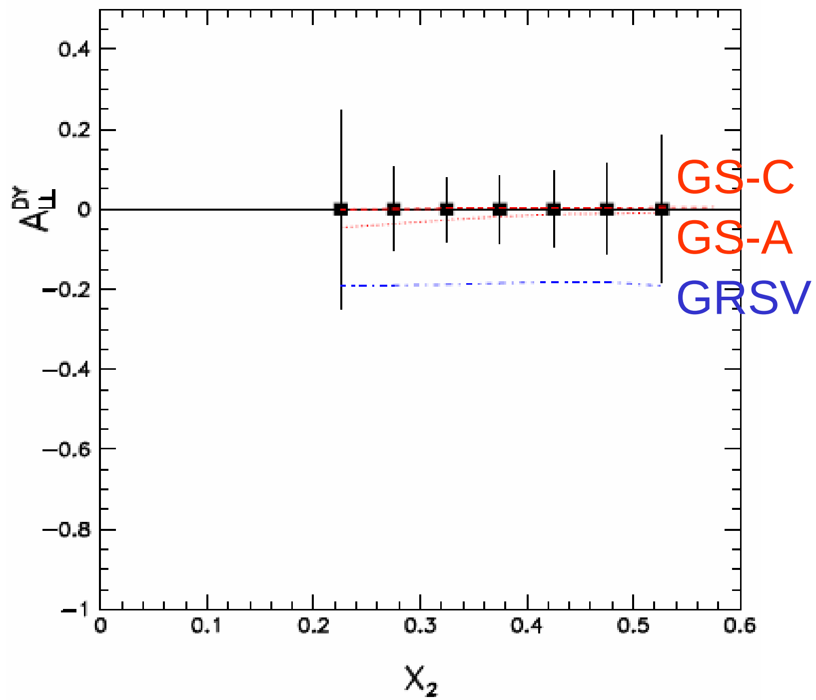
$$\int_{0.015}^{0.35} dx[\bar{d}(x)-\bar{u}(x)] = 0.0803 \pm 0.011$$

$$\int_{0}^{1} dx[\bar{d}(x)-\bar{u}(x)] = 0.118 \pm 0.012$$

Polarized Drell-Yan experiment at J-PARC

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

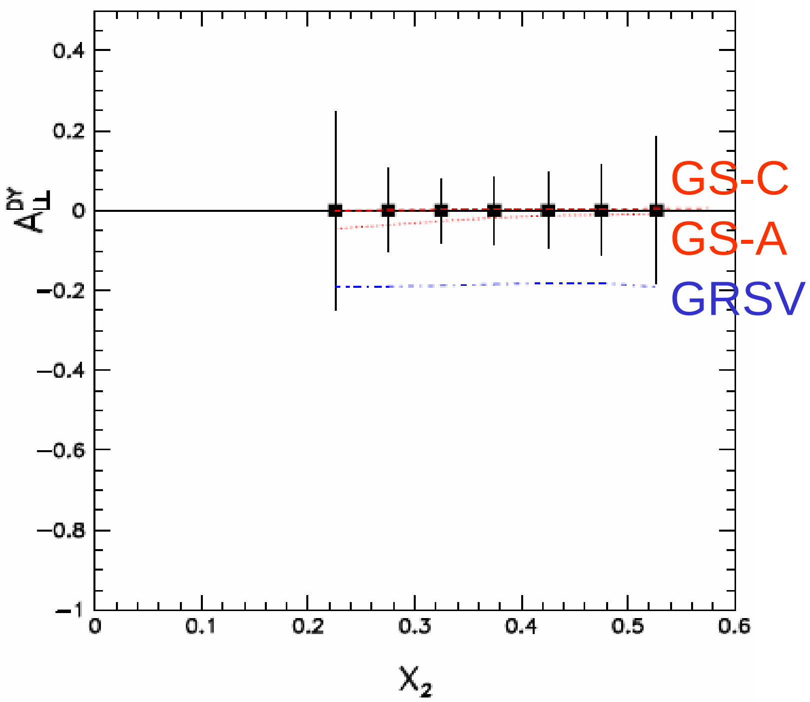


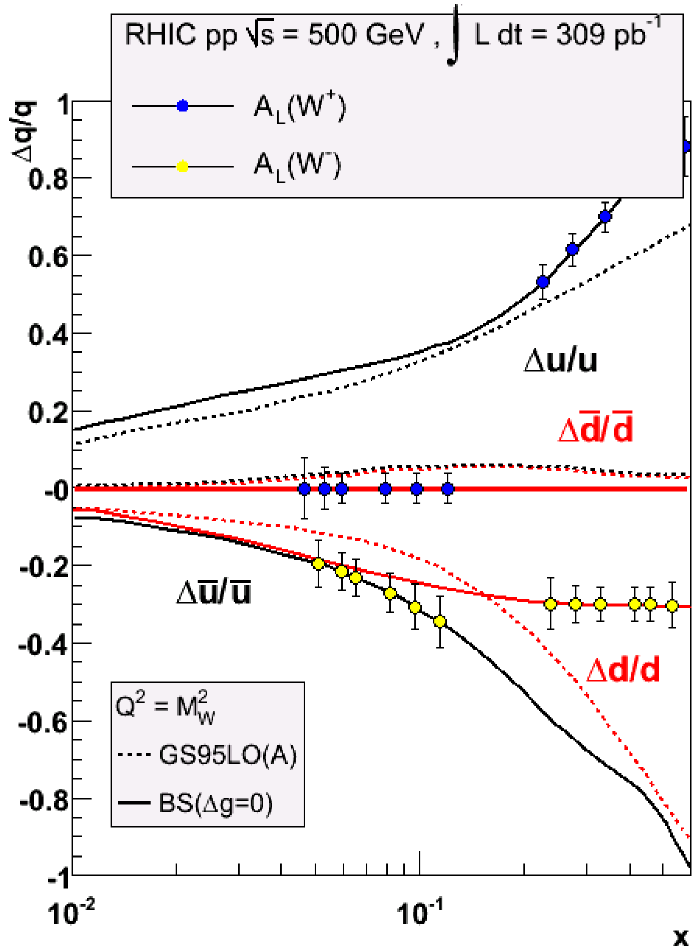


120-day run
75% polarization for a 5×10[11] protons/spill
polarized solid NH3 target, 75% hydrogen
polarization and 0.15 dilution factor

Flavor asymmetry of sea-quark polarization

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

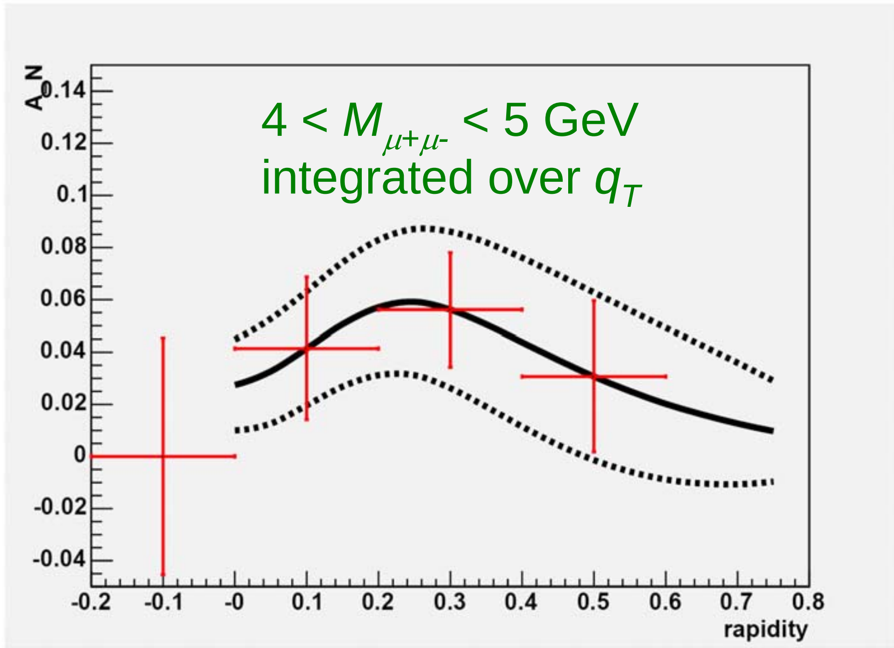




reduction of uncertainties to determine the quak spin contribution ΔΣ and gluon spin contribution ΔG to the proton spin

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

$$A_{TT} = \hat{a}_{TT} \cdot \frac{\sum_q e_q^2 (\bar{h}_{1q}(x_1) h_{1q}(x_2) + (1 \leftrightarrow 2))}{\sum_q e_q^2 (\bar{f}_{1q}(x_1) f_{1q}(x_2) + (1 \leftrightarrow 2))}$$

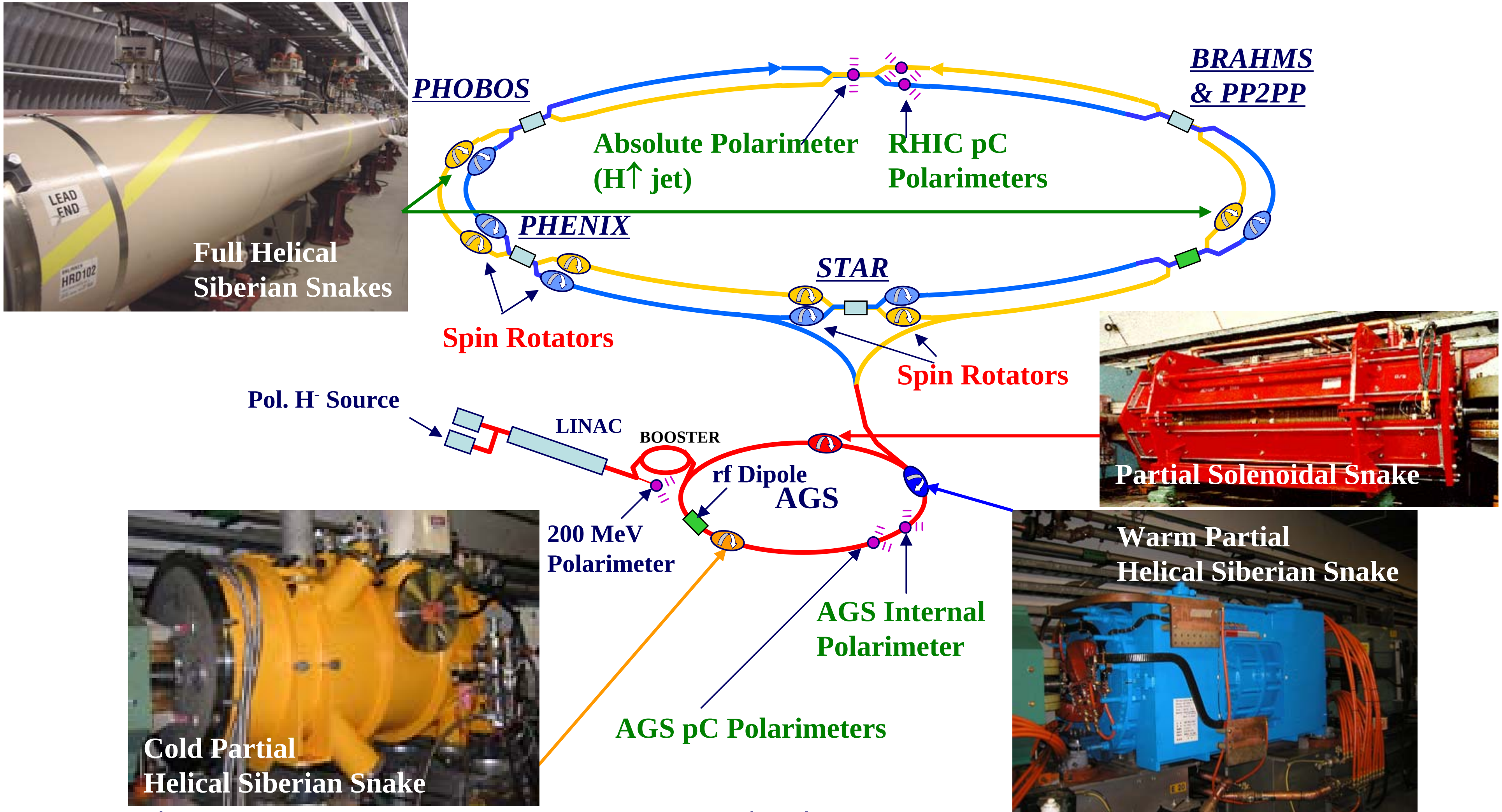
$$\hat{a}_{TT} = \frac{\sin^2\theta \cos(2\phi - \phi_{S_1} - \phi_{S_2})}{1 + \cos^2\theta}$$

- SSA measurement, $\sin(\phi + \phi_S)$ term
  - $h_1(x)$: transversity
  - $h_1^{\perp(1)}(x)$: Boer-Mulders function (1st moment of)

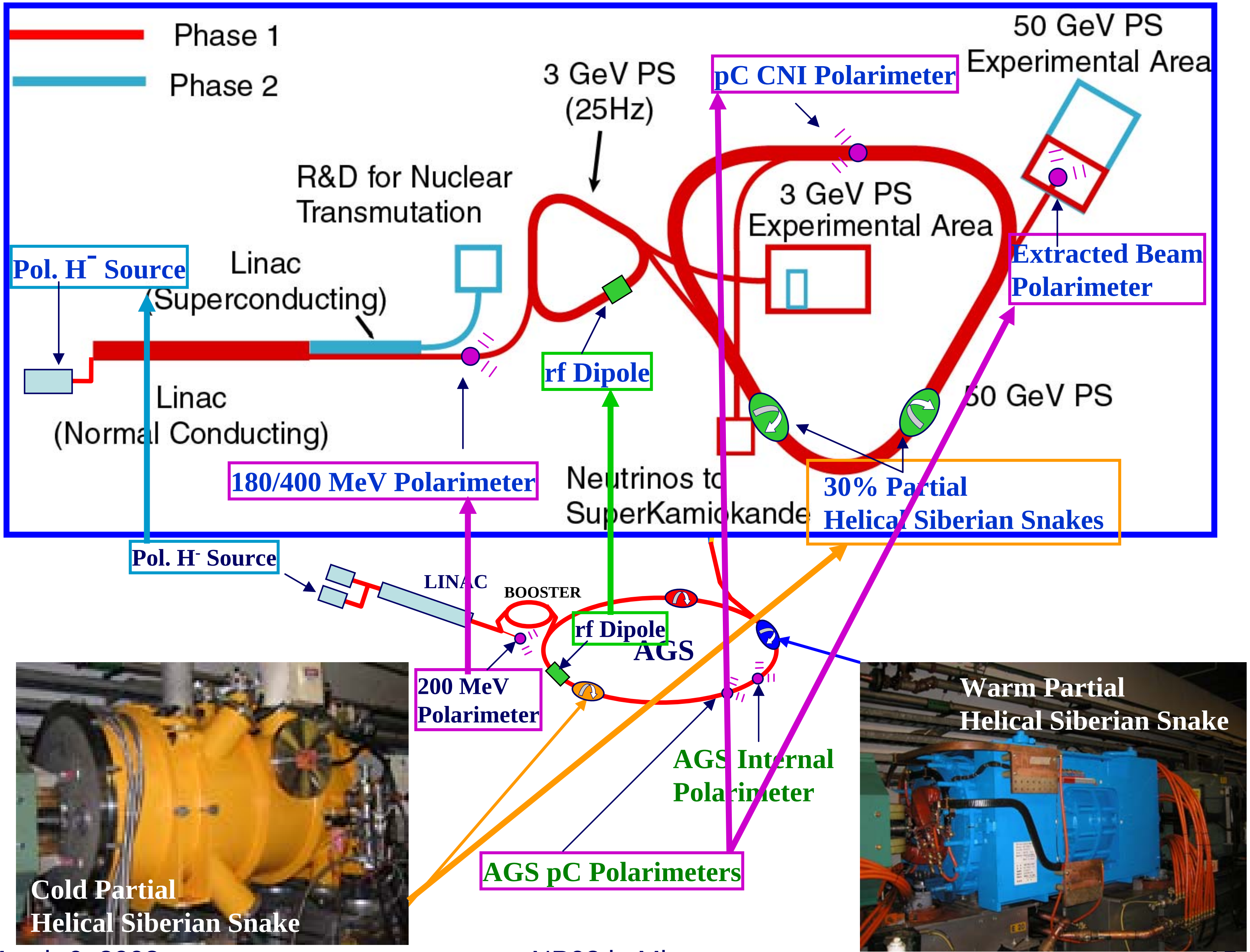
$$\hat{A} = -\frac{1}{2} \frac{\sum_q e_q^2 (\bar{h}_{1q}^{\perp(1)}(x_1) h_{1q}(x_2) + (1 \leftrightarrow 2))}{\sum_q e_q^2 (\bar{f}_{1q}(x_1) f_{1q}(x_2) + (1 \leftrightarrow 2))}$$

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

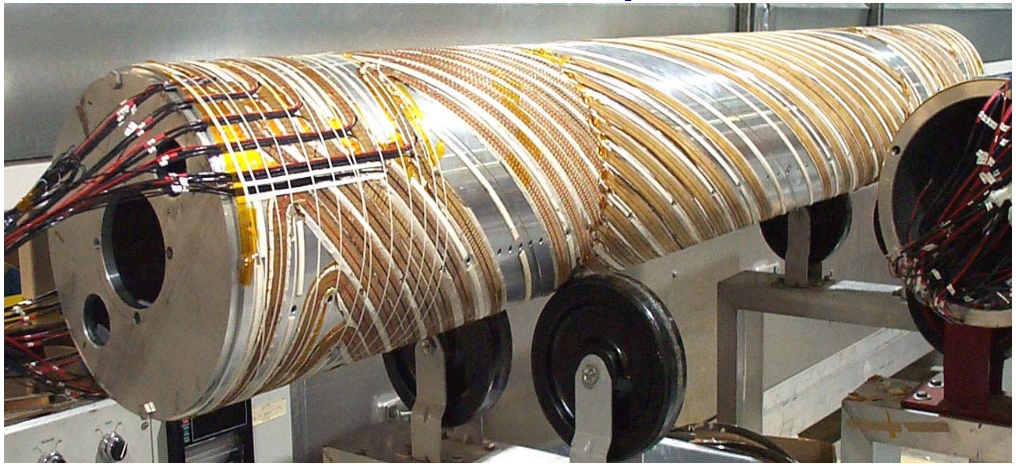


Polarized proton acceleration at J-PARC

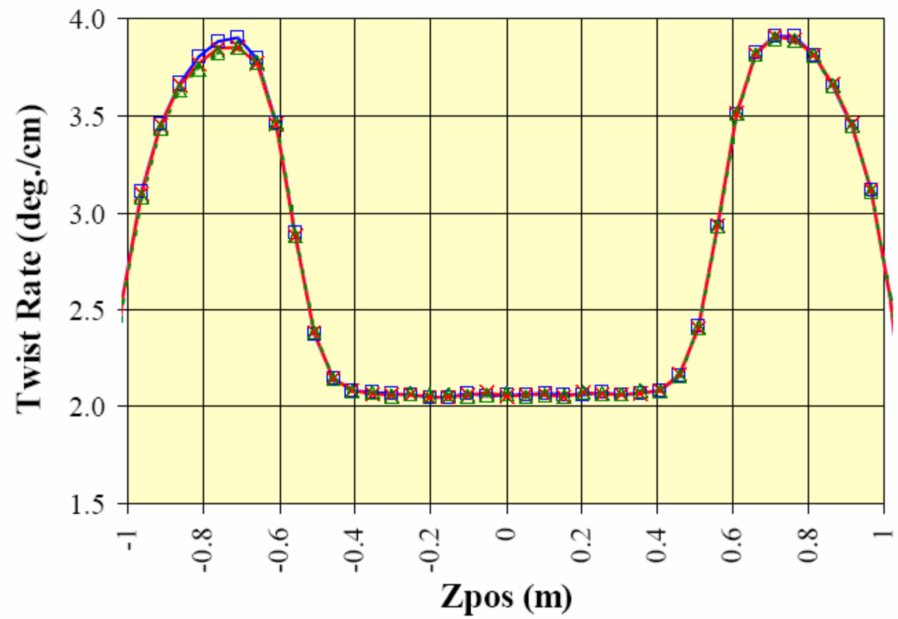


Accelerating polarized protons in the MR

- AGS 25% superconducting helical snake



helical dipole coil

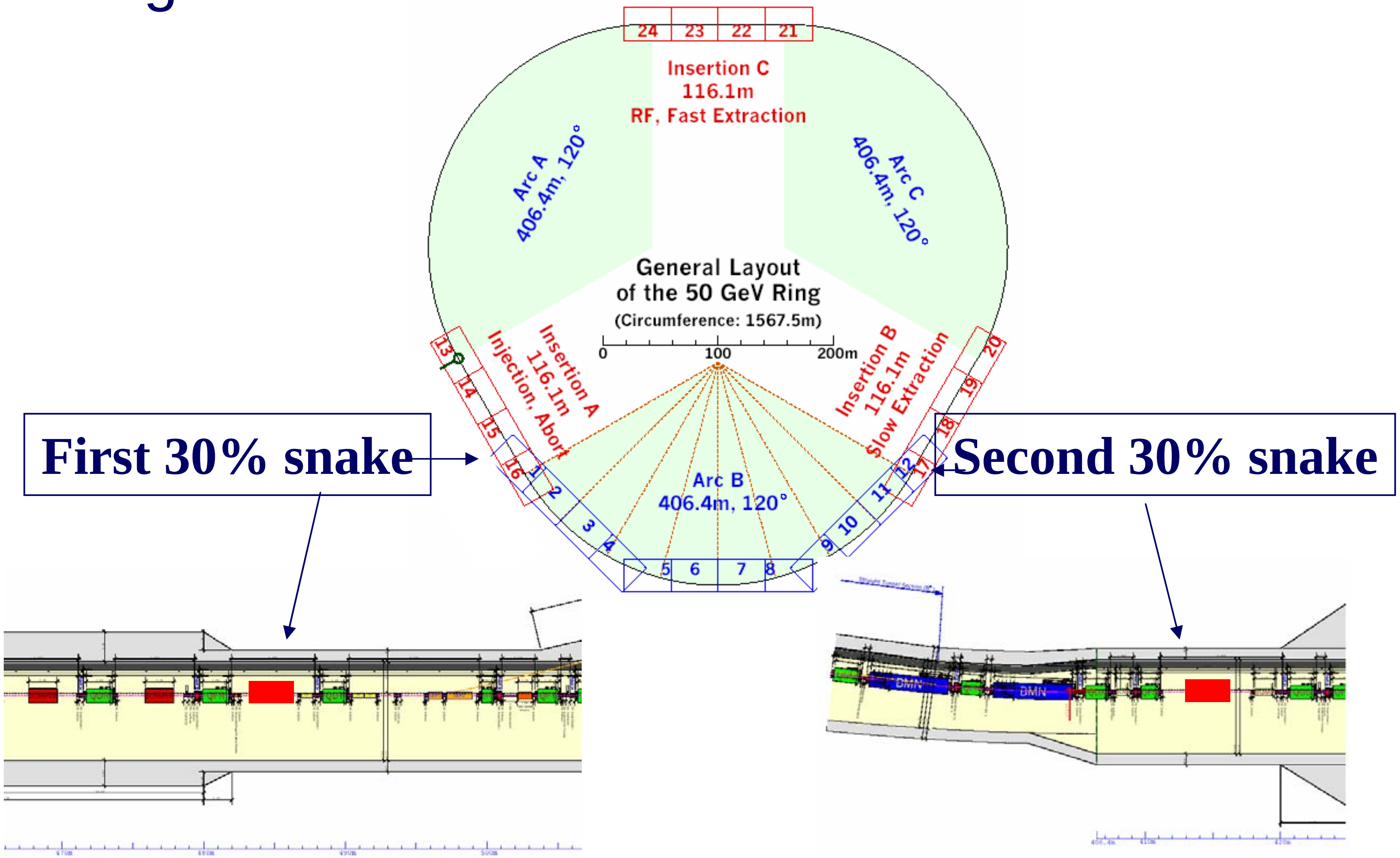


measured twist angle 2 deg/cm
in the middle ~4 deg/cm at ends

correction solenoid and dipoles

Accelerating polarized protons in the MR

- Possible location of partial helical snake magnets in the MR



Summary

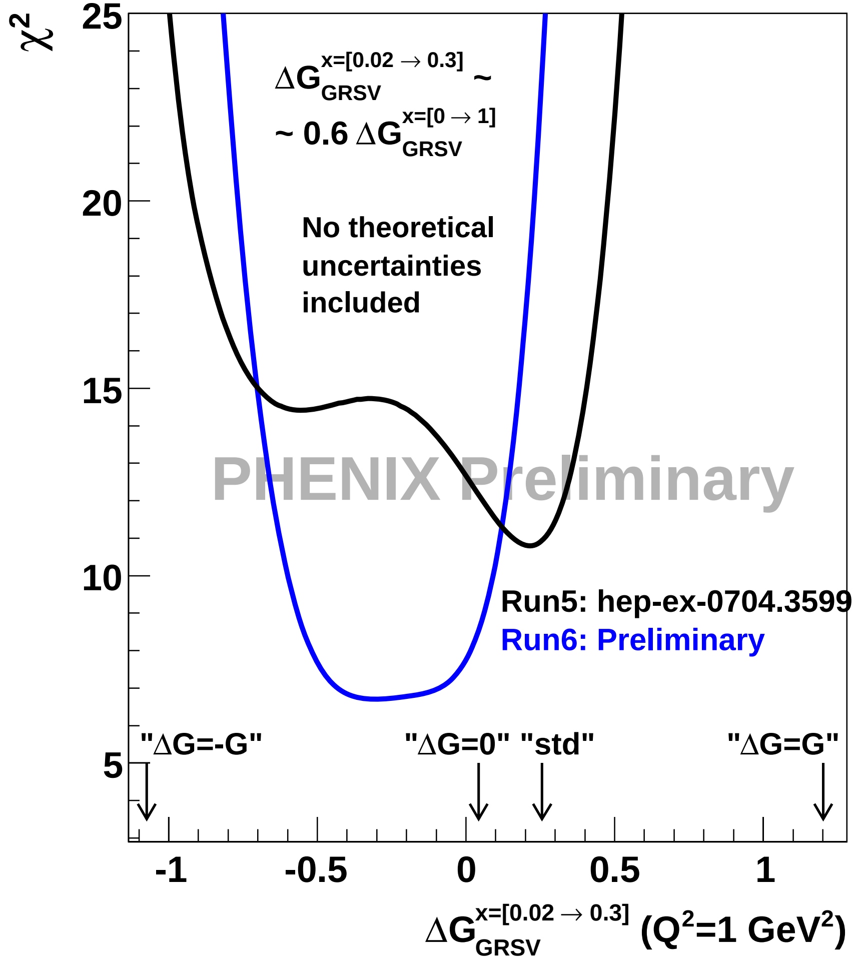
- Polarized Drell-Yan experiment with dimuon measurment using polarized proton beam at J-PARC has a rich physics programs
  - flavor asymmetry of sea-quark polarization $\rightarrow$ higher precision for $\Delta\Sigma$ and ΔG
  - SSA measurements for Sivers and higher-twist effects and transversity $\rightarrow$ 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 π^0
  - GRSV-std scenario, ΔG = 0.4 at $Q^2 = 1(\text{GeV/c})^2$, excluded by data on more than 3-sigma level, $\chi^2(\text{std})-\chi^2_{min} > 9$
    - 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



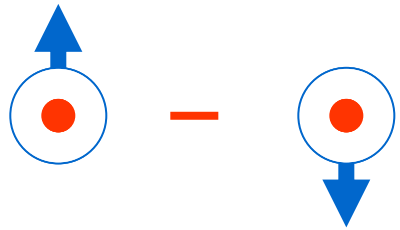
Distribution and fragmentation functions

- 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

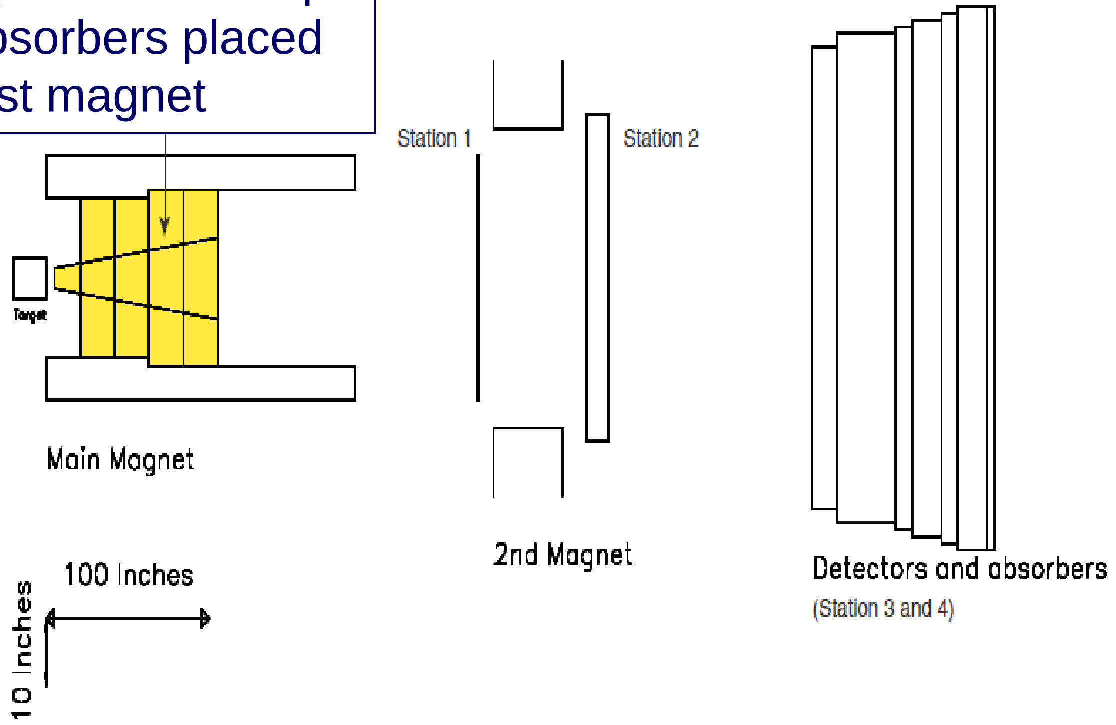
$$H_1^{\perp}(z, k_T^2)$$

  - 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)

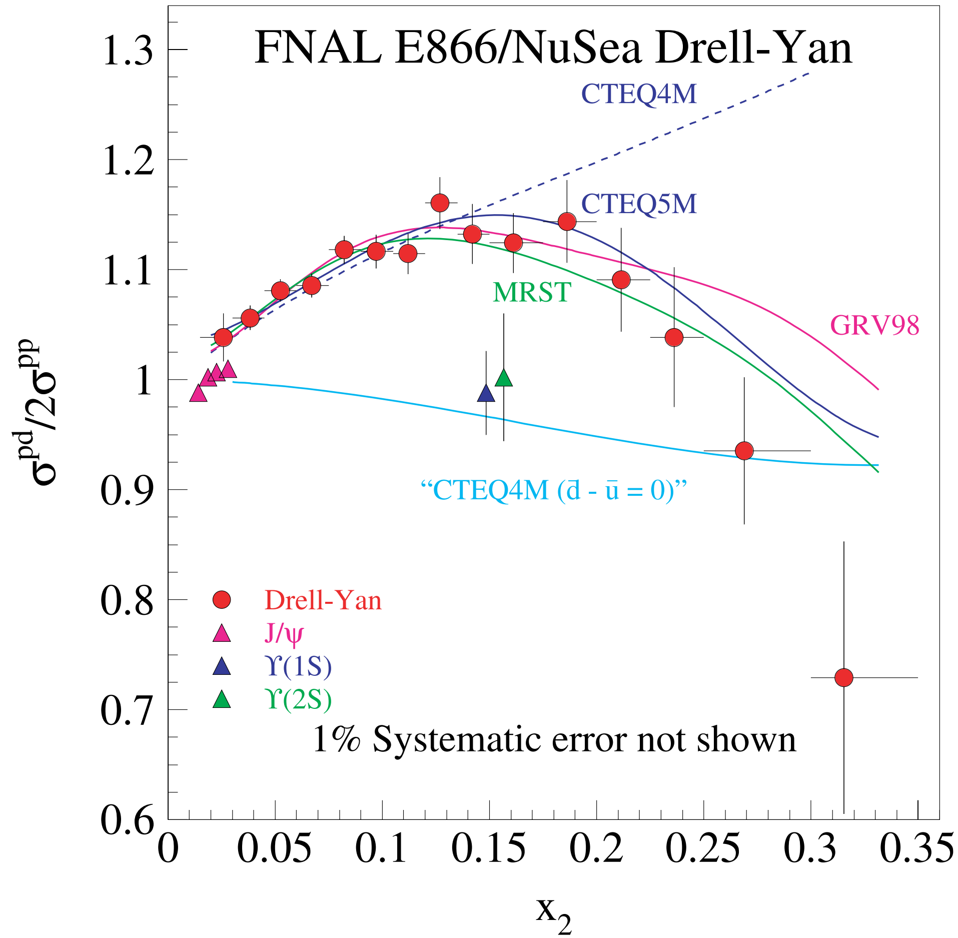
- based on the Fermilab spectrometer for 800 GeV
- length to be reduced but the aperture to be increased
- two vertically bending magnets with p_T kick of 2.5 GeV/c and 0.5 GeV/c
- tracking by three stations of MWPC and drift chambers
- muon id and tracking

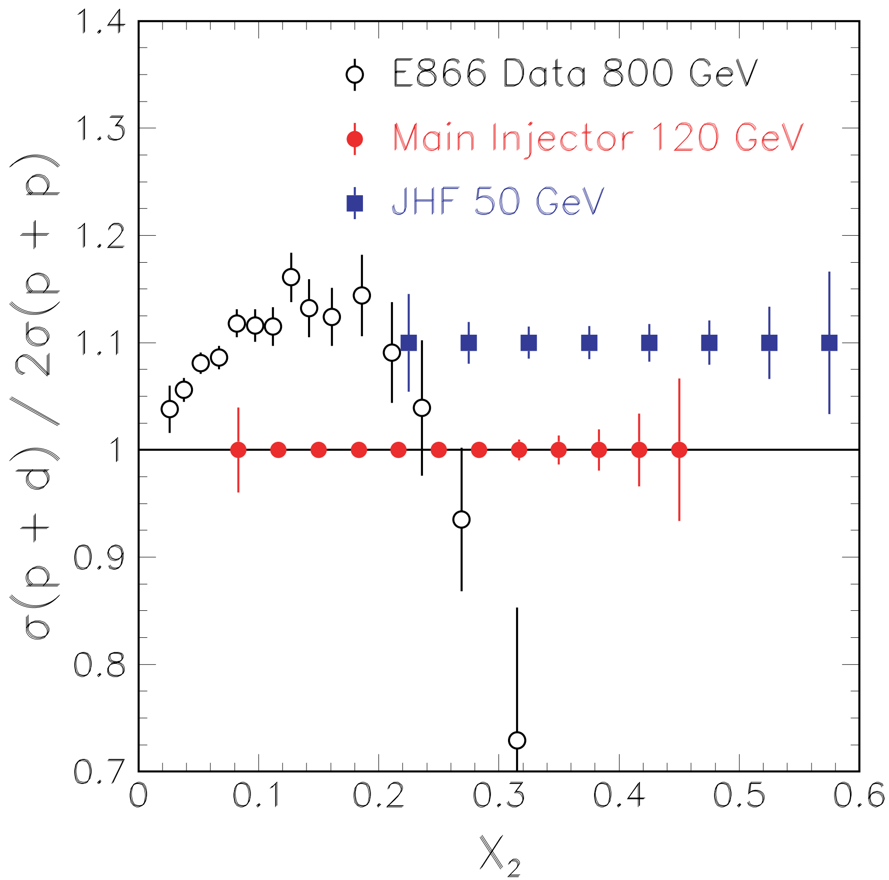
tapered copper beam dump and Cu/C absorbers placed within the first magnet



Dimuon experiment at J-PARC (P04)

- Unpolarized measurement
  - with proton and deuterium targets



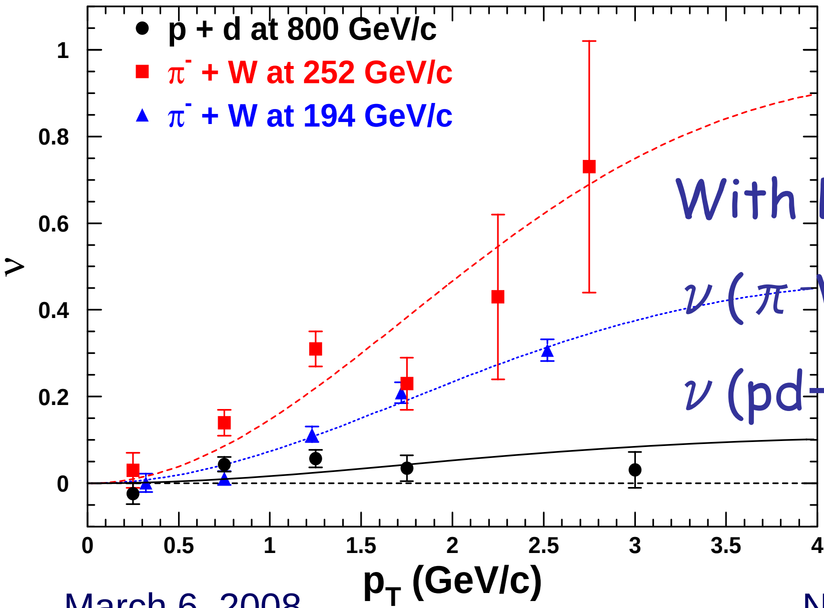


Unpolarized Drell-Yan experiment at J-PARC

- 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 $1-\lambda=2\nu$
  - violation of the Lam-Tung relation suggests non-perturbative origin $\nu\neq 0, 1-\lambda\neq 2\nu$
  - correlation between transverse quark spin and quark transverse momentum



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

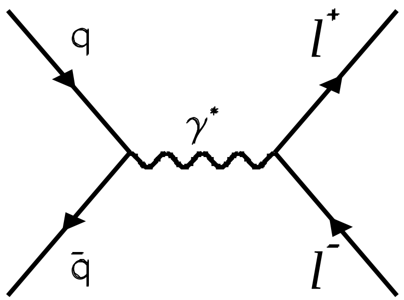
$\nu(\pi^- W\rightarrow\mu^+\mu^- X)$~valence $h_1^{\perp}(\pi)$*valence $h_1^{\perp}(p)$

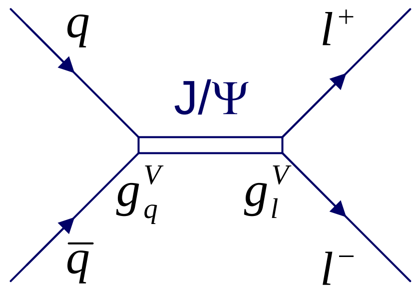
$\nu(pd\rightarrow\mu^+\mu^- X)$~valence $h_1^{\perp}(p)$*sea $h_1^{\perp}(p)$

L.Y. Zhu, J.C. Peng, P. Reimer et al.
hep-ex/0609005

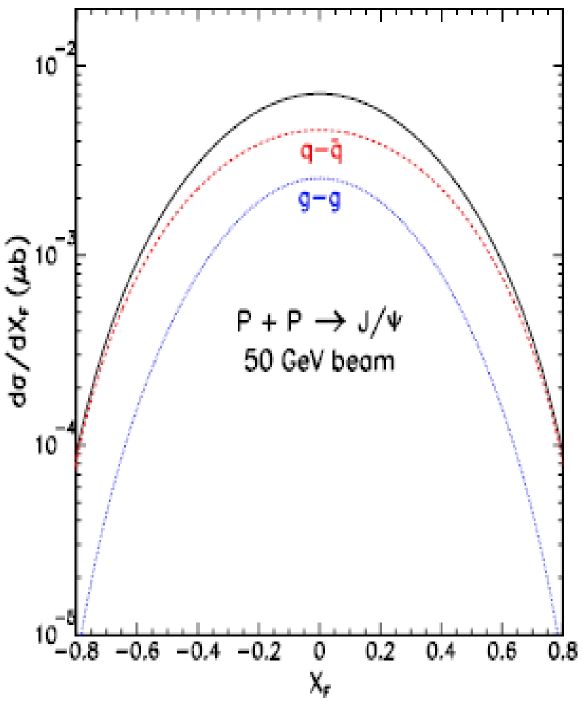
Physics at 30 GeV

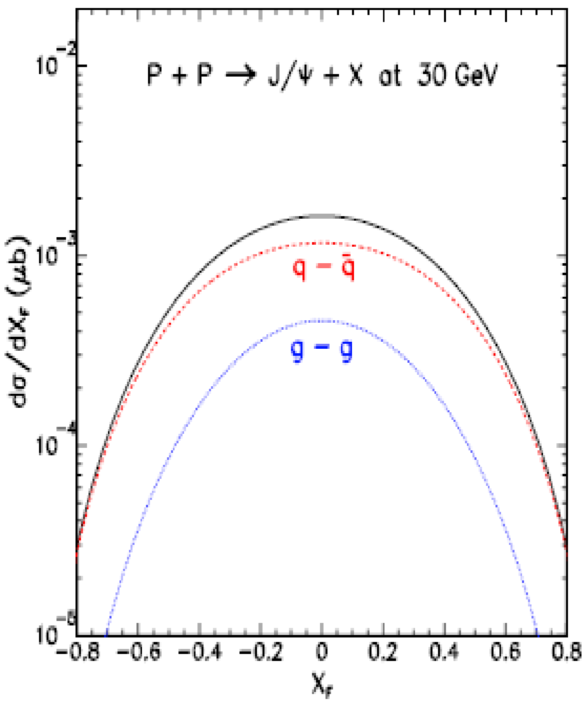
- J/ψ
  - gluon fusion or quark-pair annihilation
  - quark-pair annihilation dominant
    - must be confirmed experimentally…
    - similar physics topics as Drell-Yan process





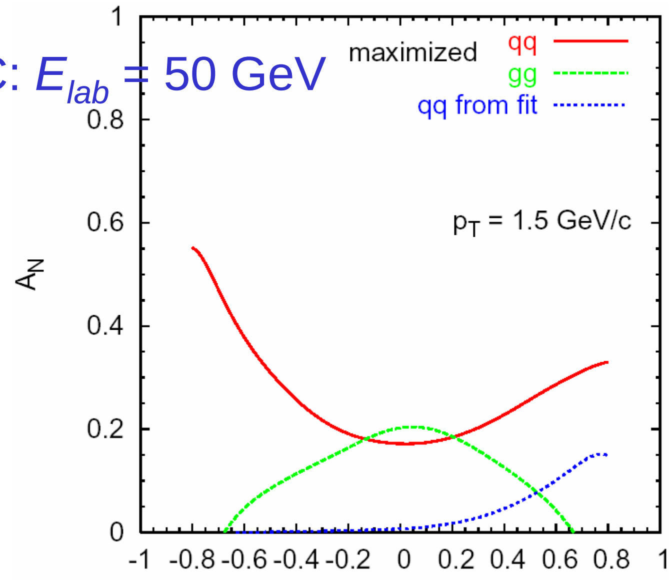
calculations by color-evaporation model

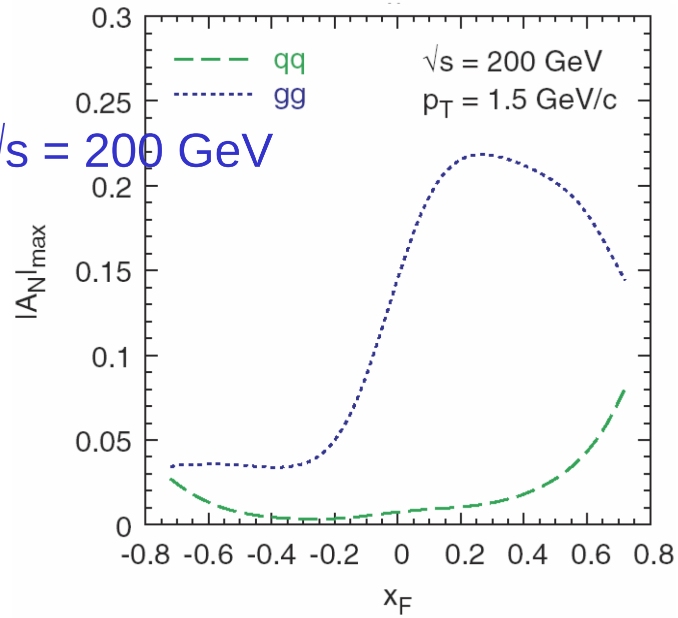




Physics at 30 GeV

- 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





M. Anselmino, U. D'Alesio, F. Murgia, et al.

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

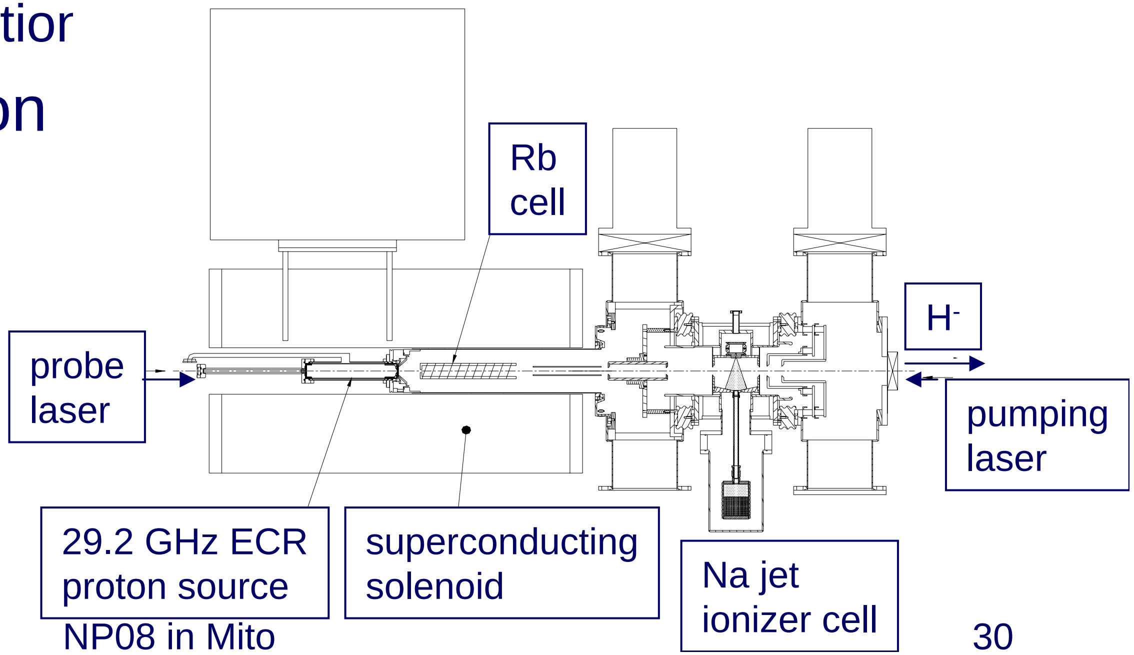
- Operation mode of the J-PARC MR should be:
  - 50 GeV maximum energy
  - 10^{12} proton/spill (~10^{36}cm^{-2}s^{-1} luminosity with a ~5% interation target)
    - 8 bunches
    - 2×10^{11} proton/bunch at RCS
  - 0.5 s spill length (working assumption)
  - 80% polarization
  - 10π mm·mrad normalized 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 μsec pulse
    - 5×10^{11} H^- ion/pulse
  - 50Hz repetition rate
  - 1.0π 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 μsec pulse
    - $1.2\text{-}2.4\times10^{12}$ H$^-$ ion/pulse
  - 7 Hz max. repetition rate
    - 1 Hz routine repetitior
  - 82-85% polarization



High-intensity polarized H^- source

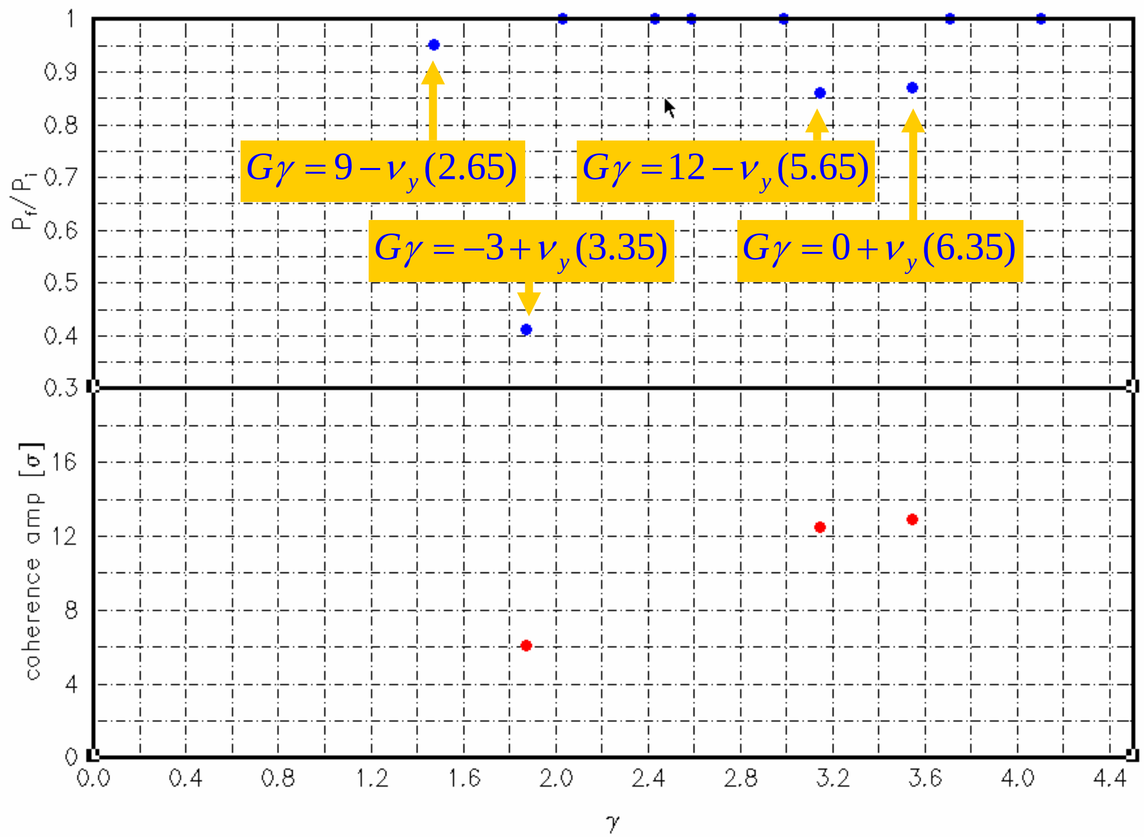
- Issues
  - where to locate the polarized H^- source
  - how to merge the polarized beam to the existing beam line
    - may require RFQ
  - maintenance of the laser system

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 ~ 7.5
  - betatron tune ν_y = 6.35



by Mei Bai (BNL)

Accelerating polarized protons in the RCS

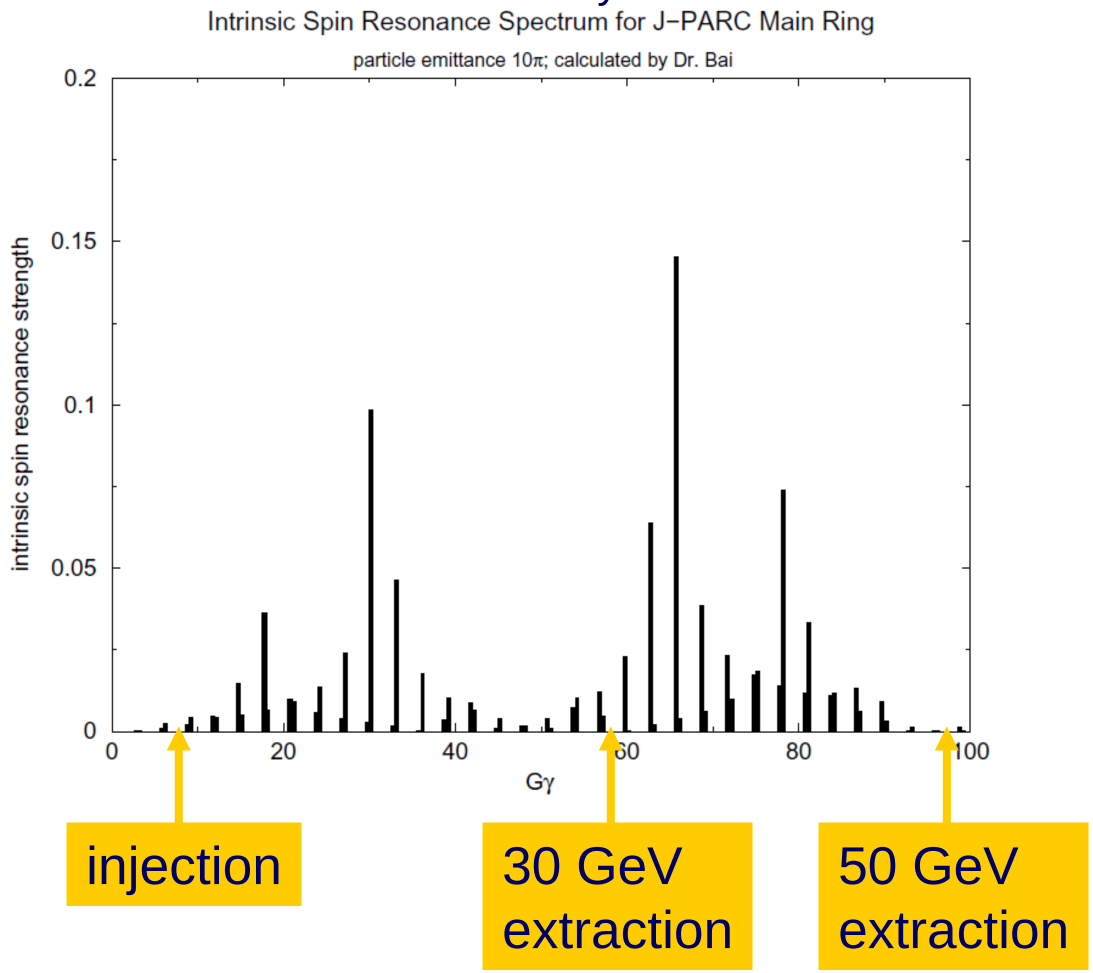
- 5 imperfection resonances
  - $G\gamma$ = 3, 4, 5, 6, 7
  - corrected by harmonic orbit correction
- 4 intrinsic resonances
  - betatron tune $\nu_y = 6.35$
  - $G\gamma$ = 2.65 ($9-\nu_y$), 3.35 ($-3+\nu_y$), 5.65 ($12-\nu_y$), 6.35 ($0+\nu_y$)
  - first small resonance is corrected by fast tune jump
  - 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 (4×10^{13}/bunch) and polarized beam (1.5×10^{11}/bunch)
    - position monitor necessary to calculate the magnetic field error and correct it by the harmonic orbit correction
  - spin tracking to be done

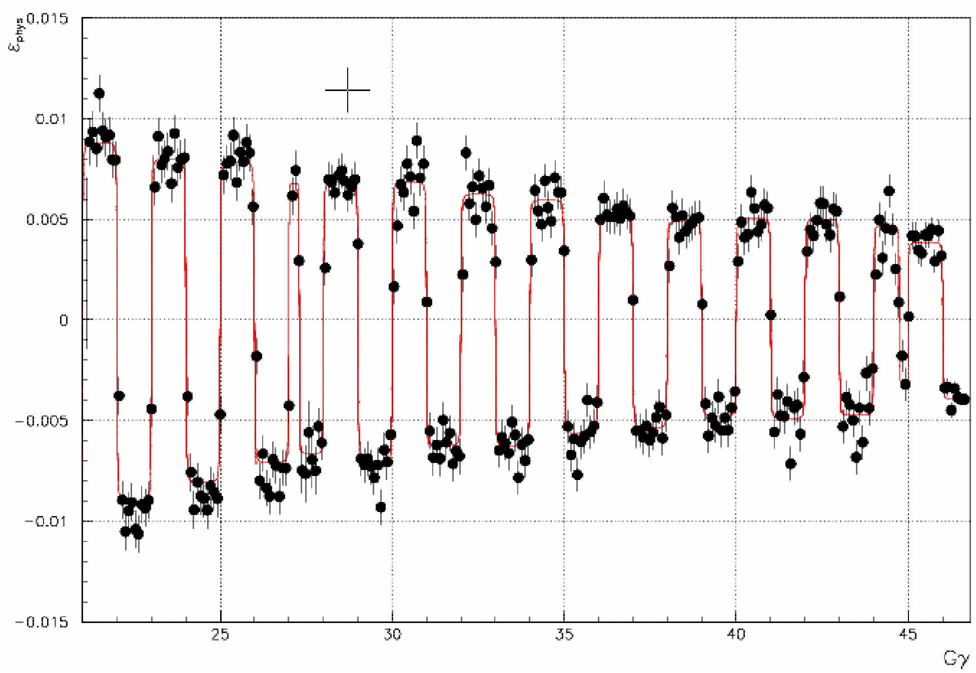
Accelerating polarized protons in the MR

- Kinetic energy from 3 GeV to 50 GeV
  - $G\gamma$ = 7.5 ~ 97.5
  - betatron tune $\nu_x = 22.339$, $\nu_y = 20.270$



Accelerating polarized protons in the MR

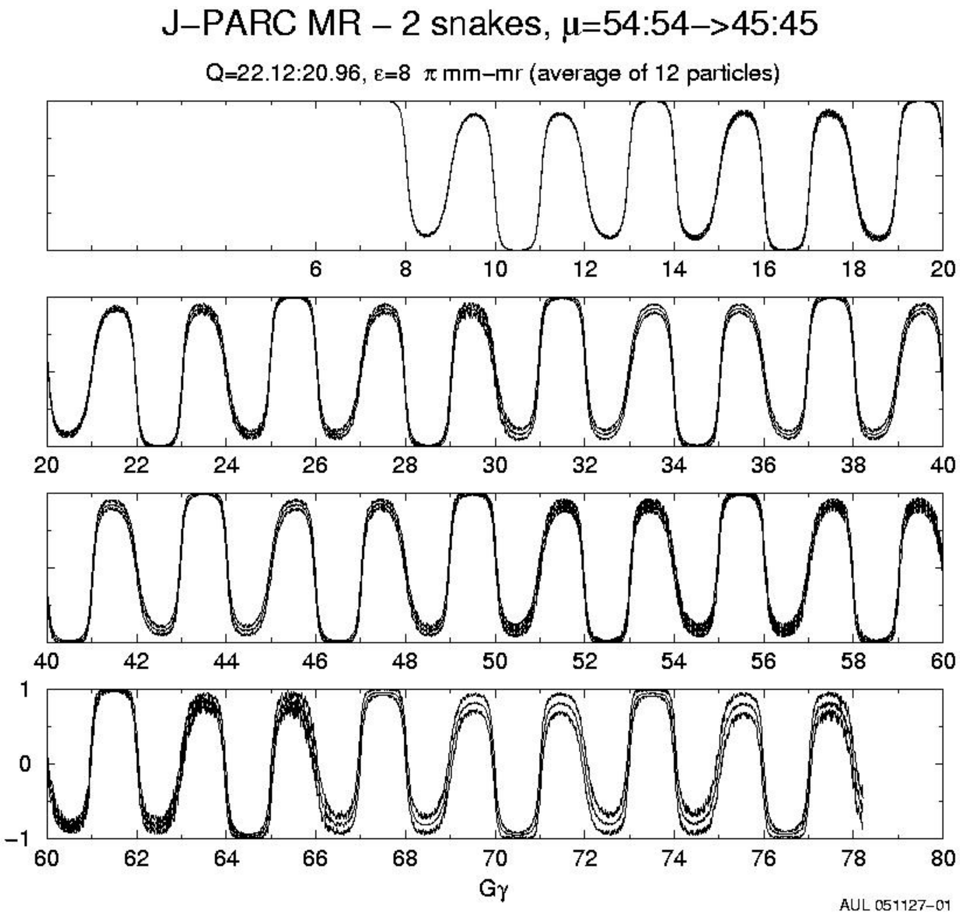
- Two superconducting 30% partial helical Siberian snakes separated by 120 degree installed in two of the three straight sections:
  – avoid all vertical depolarizing resonances
- Two quadrupole doublets
  – to compensate perturbation of the lattice by the snakes at low energies



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
  - ν_x = 22.128, ν_y = 20.960
  - average of 12 particles on an ellipse of 8π mm mrad



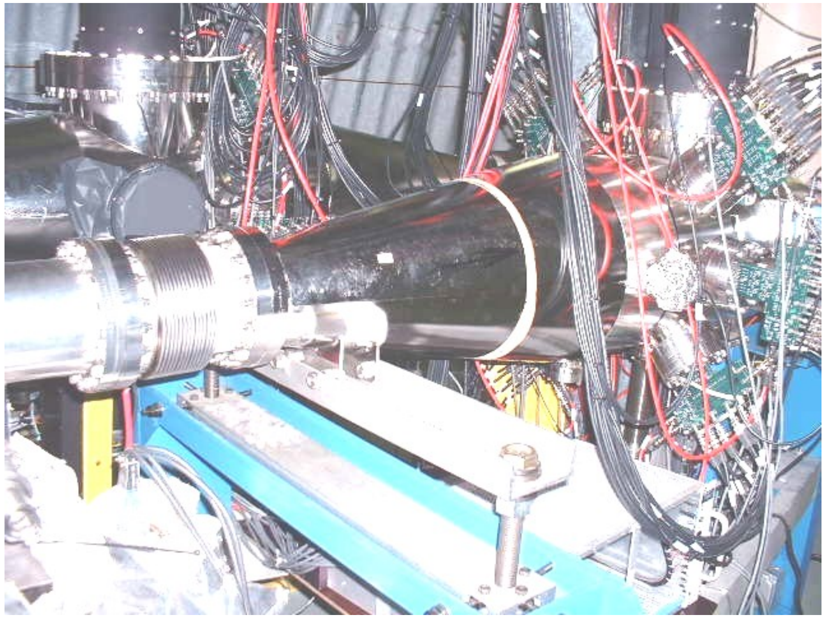
by A.U. Luccio (BNL)

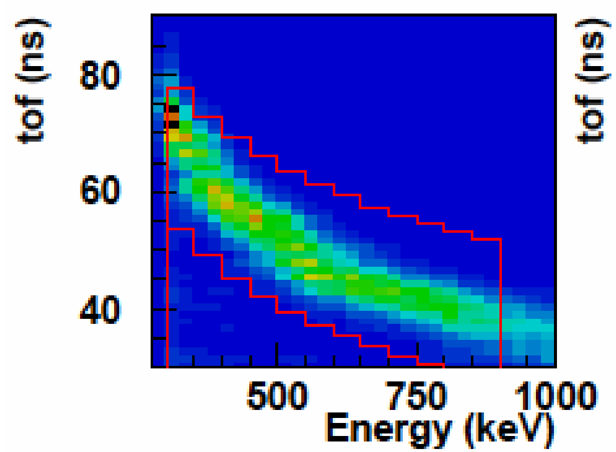
Primary beam extraction

- 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 ~3 cm (1% target)
  - maybe operational with 10^{11} ppp (luminosity ~10^{34} $cm^{-2}s^{-1}$)