The Abdus Salam International Centre for Theoretical Physics

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International Atomic Energy Agency

SMR.1751 - 57

Fifth International Conference on
PERSPECTIVES IN HADRONIC PHYSICS
Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

22 - 26 May 2006

Hadron Physics at J-PARC

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Hadron Physics at J-PARC

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Fifth International Conference on PERSPECTIVES IN HADRONIC PHYSICS: Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

Trieste, Italy, May 26, 2006

Contents

Many topics at this workshop could be covered by J-PARC!

1st project (also ν)

Next project

Need major upgrade

Purposes of J-PARC hadron physics

Understanding of strongly interacting matter
& Search for new state of matter

Quantum Chromodynamics (QCD)

- Asymptotic freedom, Factorization

  Perturbative QCD, Parton distribution functions,
  Nucleon spin, …
- Color confinement

  Hadron spectroscopy,
  Quark-hadron matter
- Chiral symmetry

  Hadrons in nuclear medium

Workshop on Hadron Structure at J-PARC
Nov. 30 – Dec. 2, 2005, KEK, Tsukuba, Japan

Presentations are available from
http://www-conf.kek.jp/J-PARC-HS05/program.html

This workshop is focused on hard processes, especially on first two days.

Thank speakers for their contributions.

Note: This talk is not a summary of this workshop.

My personal impression on the J-PARC project:

Although strangeness nuclear physics (and neutrino physics) is rather well investigated as a J-PARC project, the "hadron-physics" part is not well studied, especially by using the primary beam.

We need your suggestions and contributions for the success of the project. Please visit KEK for discussions!

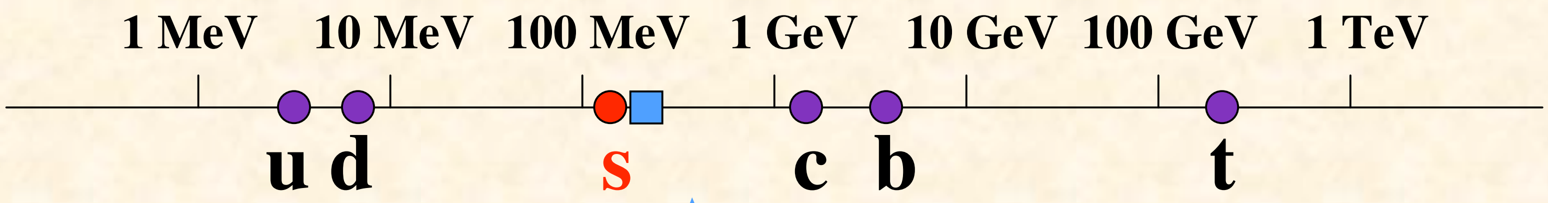
Strangeness Nuclear Physics

Exotic Hadrons

Hadrons in Nuclear Medium

Strangeness in hadron physics

(1) Probe of QCD dynamics



$m_s \ \Lambda_{QCD}$

Chiral symmetry
($m \ll \Lambda_{QCD}$)

$m_s \approx \Lambda_{QCD}$

Non-relativistic
quark model ($m \gg \Lambda_{QCD}$)

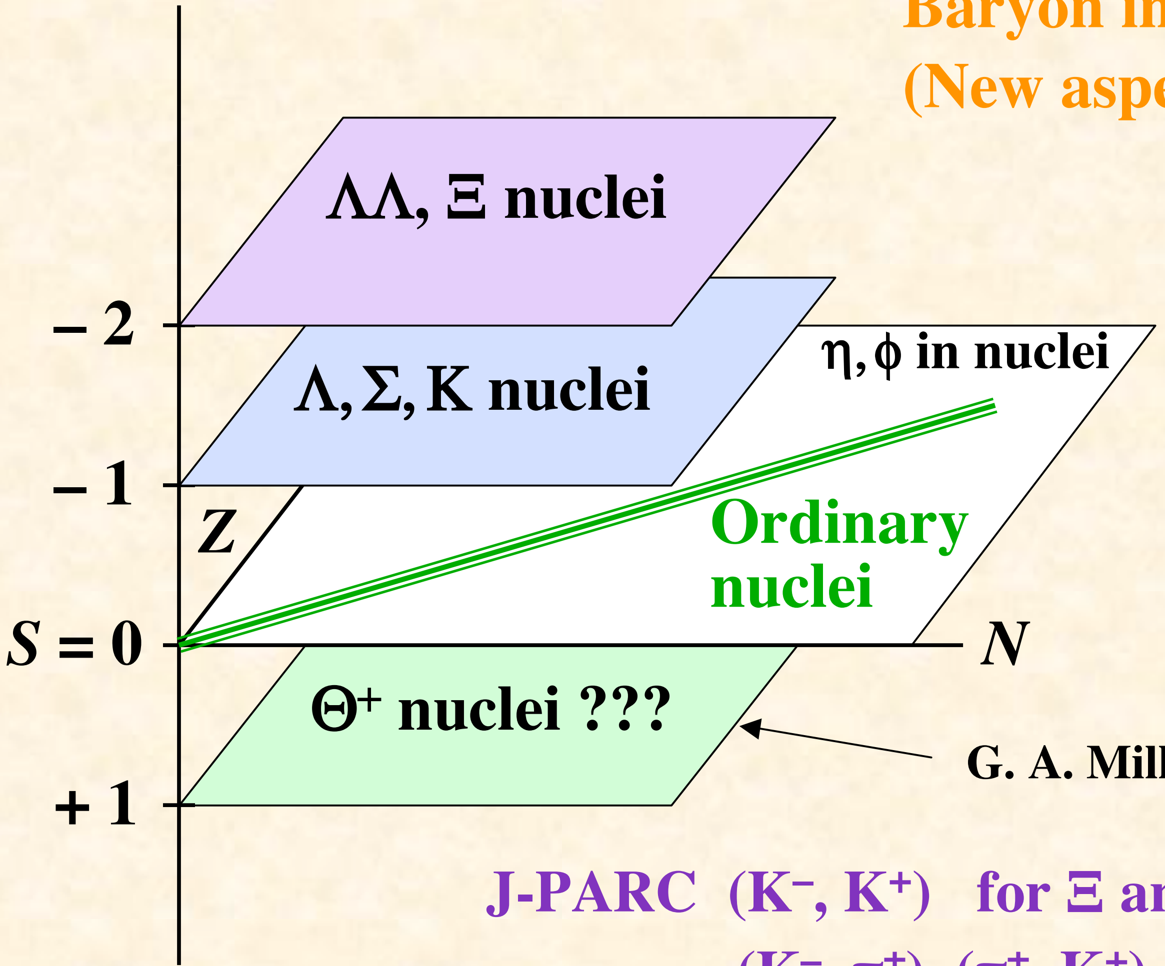
Bad point: It is difficult to describe hadrons with strangeness.

Good point: Strange quark could be a good probe of QCD dynamics.

(2) New particles and nuclei

New hadronic many-body system
by extending the flavor degrees of freedom.

Baryon interactions with strangeness
(New aspect of low-energy QCD)



- **No data for YY interactions**
- **Some data for YN interactions (~ 40)**
- **Plenty of data for NN interactions (~ 4,000)**

G. A. Miller, Phys. Rev. C70 (2004) 022202.

J-PARC (K⁻, K⁺) for Ξ and ΛΛ nuclei, YN scattering
(K⁻, π±), (π±, K⁺) for Λ nuclei, YN scattering

(3) Strangeness as impurity

No Pauli blocking with u, d → could penetrate deep inside a nucleus

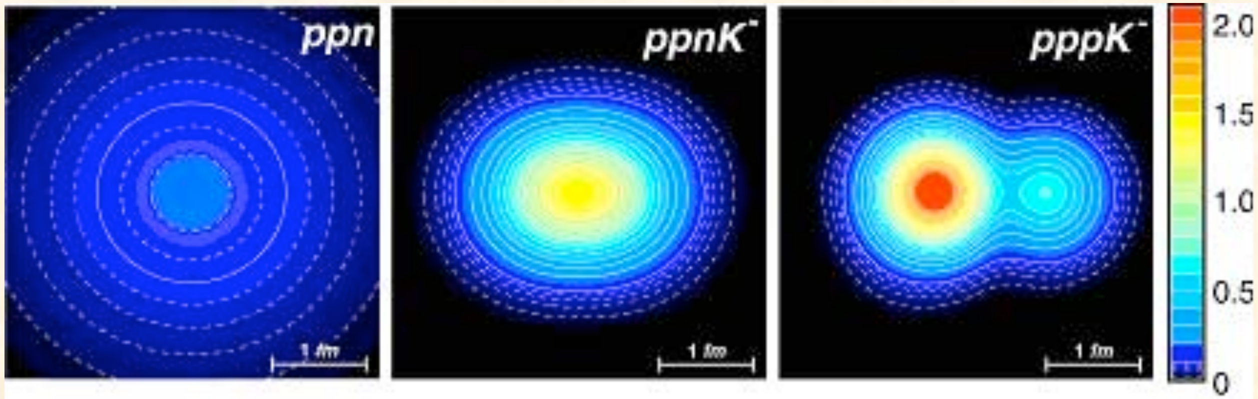
(probe inside a nuclear medium)

New YN interactions → could lead to new forms of nuclei

(possibly high-density nuclei)

Y. Akaishi, A. Dote, T. Yamazaki,
Phys. Lett. B613 (2005) 140.
See also Phys. Rev. C70 (2004) 044313.

- 1s atomic state of kaonic hydrogen
- $\bar{K}N$ scattering analysis
- Assume: $\Lambda(1405)$ = bound state of $\bar{K}N$
  → Predictions of new kaonic nuclei

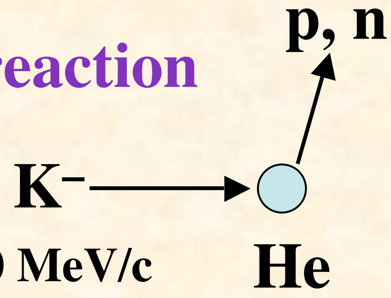


Density
(1/fm^3)

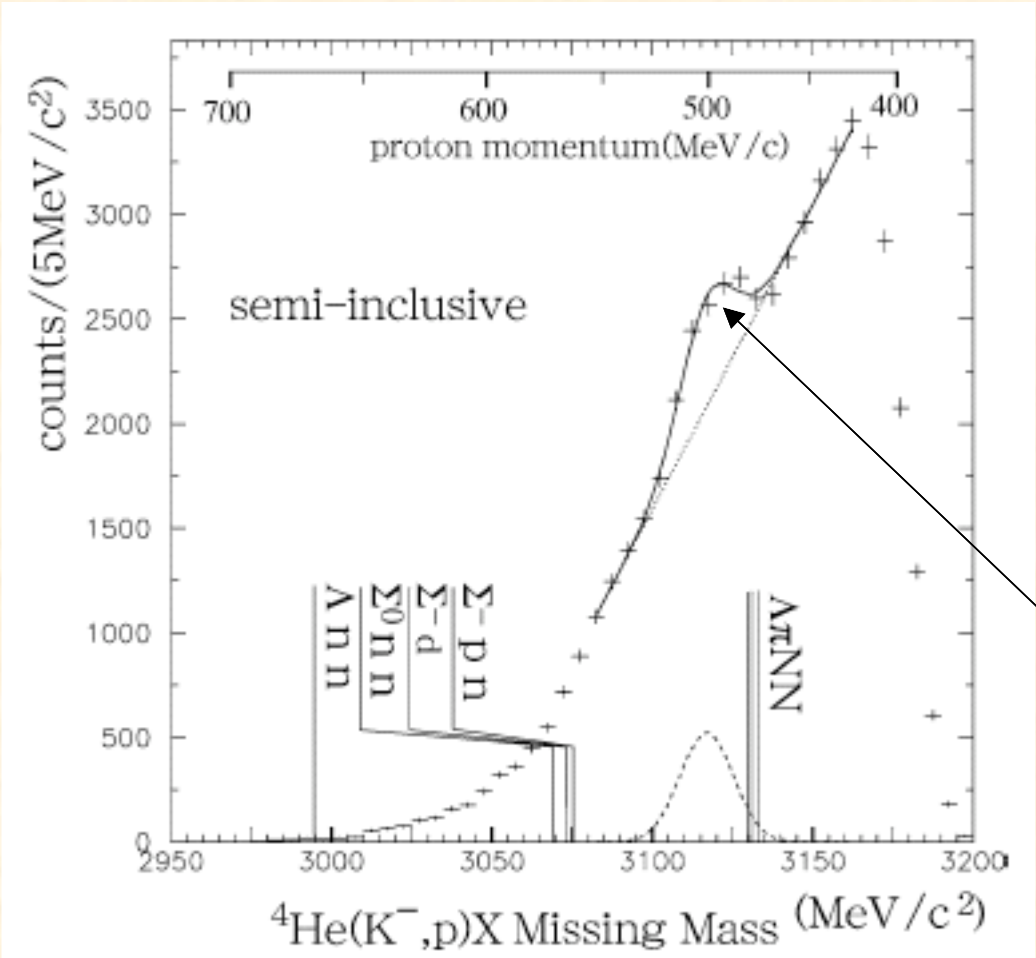
Recent criticisms in E. Oset and H. Toki, nucl-th/0509048: Treatment of $\Lambda(1405)$, …

KEK-E471 experiment

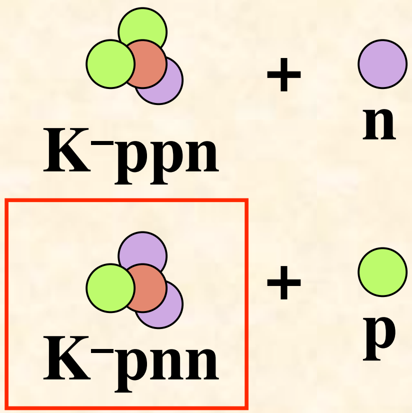
$^4He(K^-, p)$ reaction



T. Suzuki et al.,
Phys. Lett. B597 (2004) 263.



Final states



S⁰(3115)

- **K⁻pnn bound state?**
- **Absorption by two nucleons? ($K^-NN \rightarrow \Sigma N$)**

Something else?

Recent progress in exotic hadrons

$q\bar{q}$	Meson
q^3	Baryon
$q^2\bar{q}^2$	Tetraquark
$q^4\bar{q}$	Pentaquark
q^6	Dibaryon
…	
$q^{10}\bar{q}$	e.g. Strange tribaryon
…	
gg	Glueball
…	

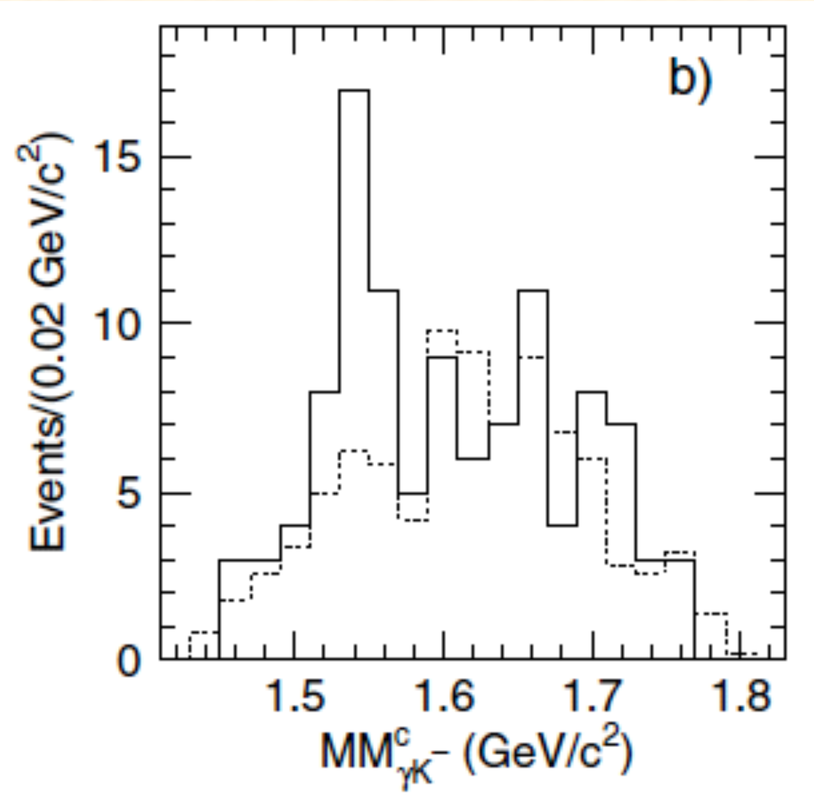
(Japanese ?) Exotics

- $\Theta^+(1540)$: LEPS
  Pentaquark?
- $S^0(3115)$, $S^+(3140)$: KEK-PS
  Strange tribaryons?
- X (3872), Y(3940): Belle
  Tetraquark, $D\bar{D}$ molecule
- $D_{sJ}(2317)$, $D_{sJ}(2460)$: BaBar, CLEO, Belle
  Tetraquark, DK molecule

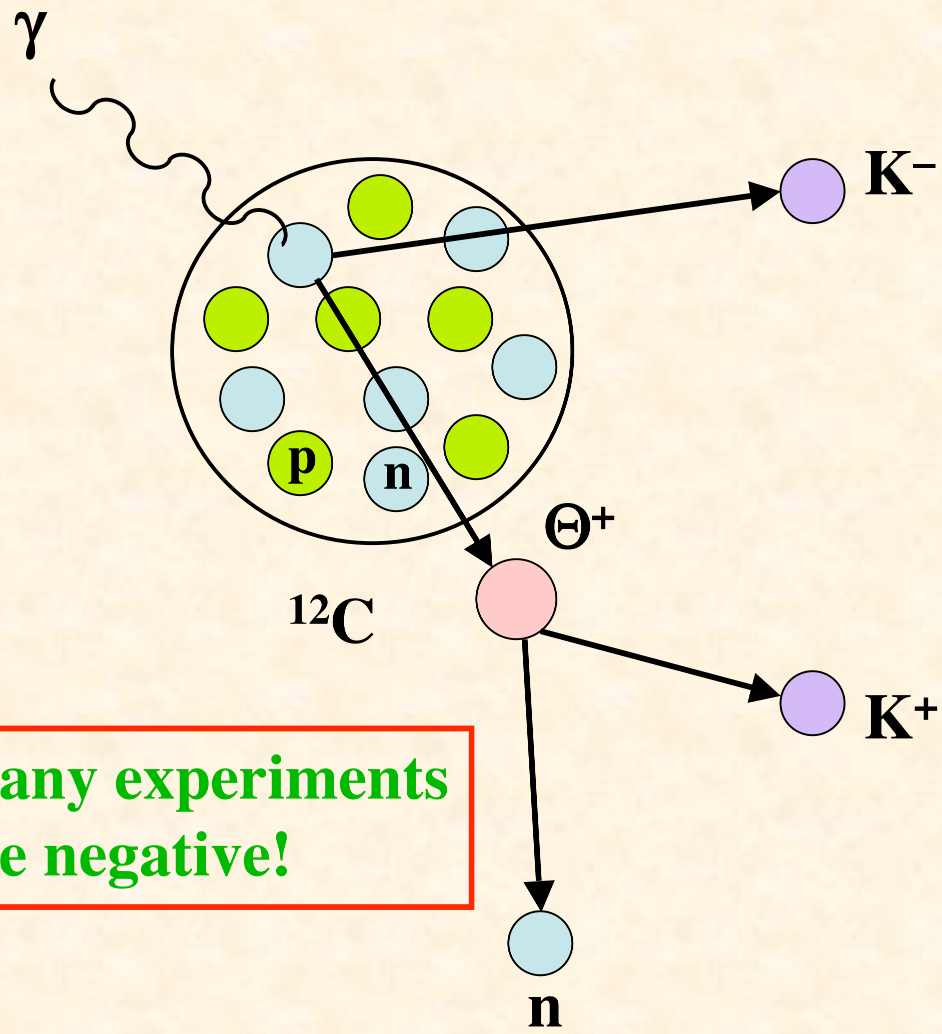
Pentaquark Θ^+

LEPS Collaboration (T. Nakano et al.), Phys. Rev. Lett. 91 (2003) 012002.

$\gamma\, n \rightarrow K^+ K^- n$



Missing mass spectrum



Many experiments are negative!

Decisive test of Θ^+ at J-PARC

s-channel formation with K^+ beam

$K^+ n \rightarrow \Theta^+ \rightarrow K^0 p$

Hadron masses in nuclear medium

Origin of the nucleon mass:

Why $m_{quark} << m_{nucleon}$?

Chiral-symmetry breaking

Order parameter:
"quark condensate $\langle q\bar{q}\rangle$"

$\langle q\bar{q}\rangle$ depends temperature and density

$\langle q\bar{q}\rangle$ is not a direct observable, so look at nuclear-medium modification of hadron masses.

Vector-meson masses vs. density

Modifications even at "normal nuclear density"

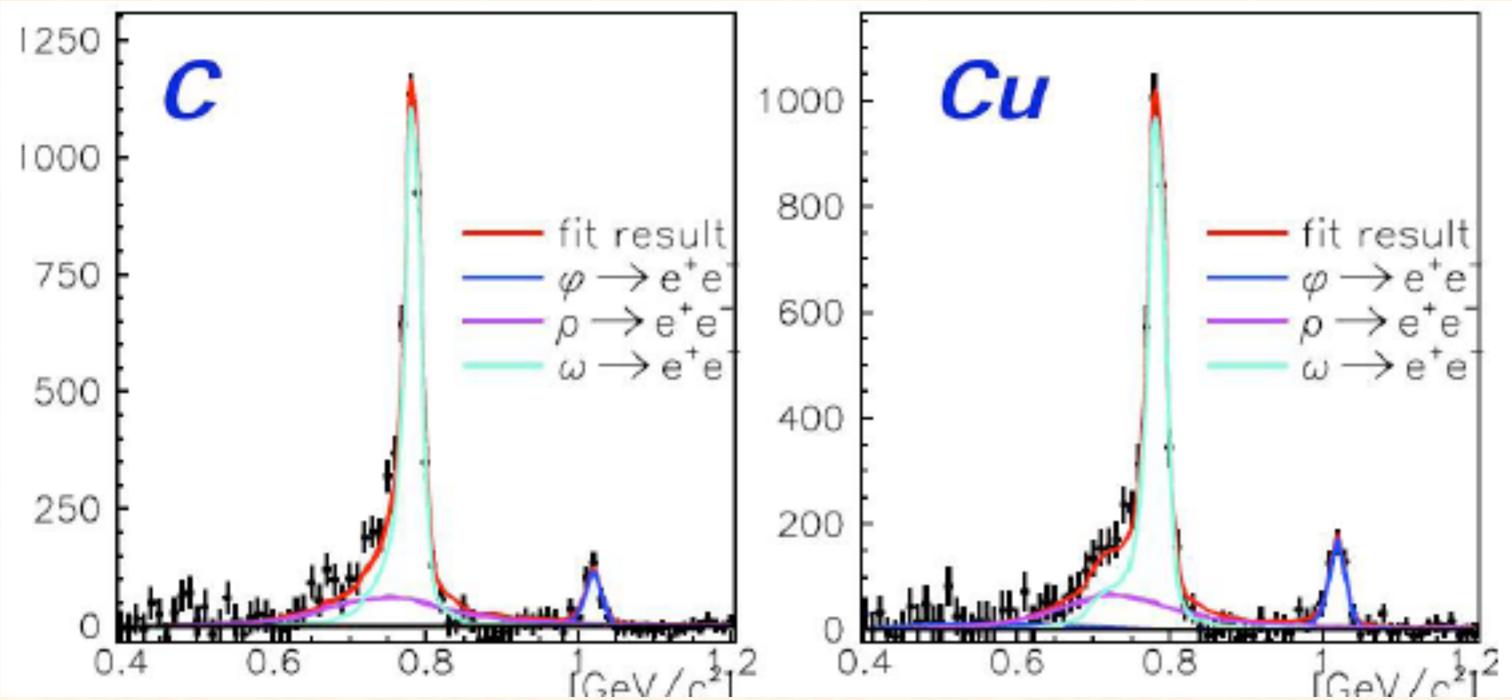
Brown-Rho, Hatsuda-Lee

18% reduction in ρ, ω masses at normal nuclear density

KEK-E325 Collaboration

$$(12\ \text{GeV})\ p + A \rightarrow \rho,\ \omega,\ \phi + X \quad (\rho,\ \omega,\ \phi \rightarrow e^{+} + e^{-})$$

After background subtraction



T. Tabaru et al., nucl-ex/0603013

R. Muto et al., nucl-ex/0511019

M. Naruki et al., PRL 96 (2006) 092301

$m(\rho) / m(0) = 1 - k\, \rho / \rho_0$ $\quad$ $k = 0.092 \pm 0.002$ $\quad$ **9% mass shifts**

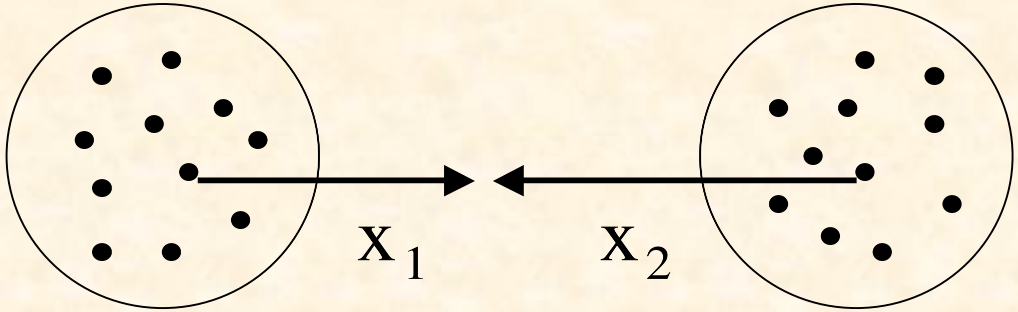
→ continued at J-PARC

Hard Processes

Structure Functions

Neutrino Reactions

Hadron facilities



e.g. Drell-Yan: $x_1 x_2 = \frac{m_{\mu\mu}^2}{s}$

$\longrightarrow \quad x \sim \frac{\sqrt{m_{\mu\mu}^2}}{\sqrt{s}}$

$p + p(A) \rightarrow \mu^+\mu^- + X \quad (q\bar{q} \rightarrow \mu^+\mu^-)$

- $s = (p_1 + p_2)^2$

J-PARC: $\sqrt{s} = 10$ GeV
RHIC: $\sqrt{s} = 200$ GeV
LHC: $\sqrt{s} = 14$ TeV

- $m_{\mu\mu} \geq 3$ GeV

$x \sim \frac{\sqrt{m_{\mu\mu}^2}}{\sqrt{s}} \geq \frac{3}{10} = 0.3$ J-PARC **Large-x facility** **(Medium-x)**

$\geq \frac{3}{200} = 0.02$ RHIC

$\geq \frac{3}{14000} = 0.0002$ LHC **Small-x facility**

Flavor asymmetric antiquark distributions: $\bar{u}/\bar{d}$

SK, Phys. Rep. 303 (1998) 183

Perturbative QCD contribution

$$q^{\pm} = q \pm \bar{q}, \quad P_{q^{\pm}} = P_{qq} \pm P_{q\bar{q}}$$

$$\frac{\partial}{\partial(\ln Q^2)} q^{\pm}(x,Q^2) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y} P_{q^{\pm}}\left(\frac{x}{y}\right) q^{\pm}(y,Q^2) \quad \text{(+ gluon term)}$$

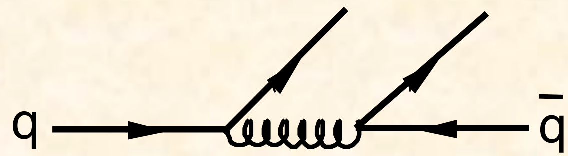
$$\bar{q} = (q^+ - q^-)/2$$

$$\downarrow$$

$$\frac{\partial}{\partial(\ln Q^2)}\left[\bar{u}(x,Q^2) - \bar{d}(x,Q^2)\right] = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}\left(\frac{x}{y}\right)\left\{\bar{u}(y,Q^2)-\bar{d}(y,Q^2)\right\} + P_{\bar{q}q}\left(\frac{x}{y}\right)\left\{u(y,Q^2)-d(y,Q^2)\right\}\right]$$

$P_{\bar{q}q} = 0$ in LO

$\neq 0$ in NLO



Therefore, $(\bar{u} - \bar{d})_{pQCD} = 0$ in LO

$\neq 0$ in NLO

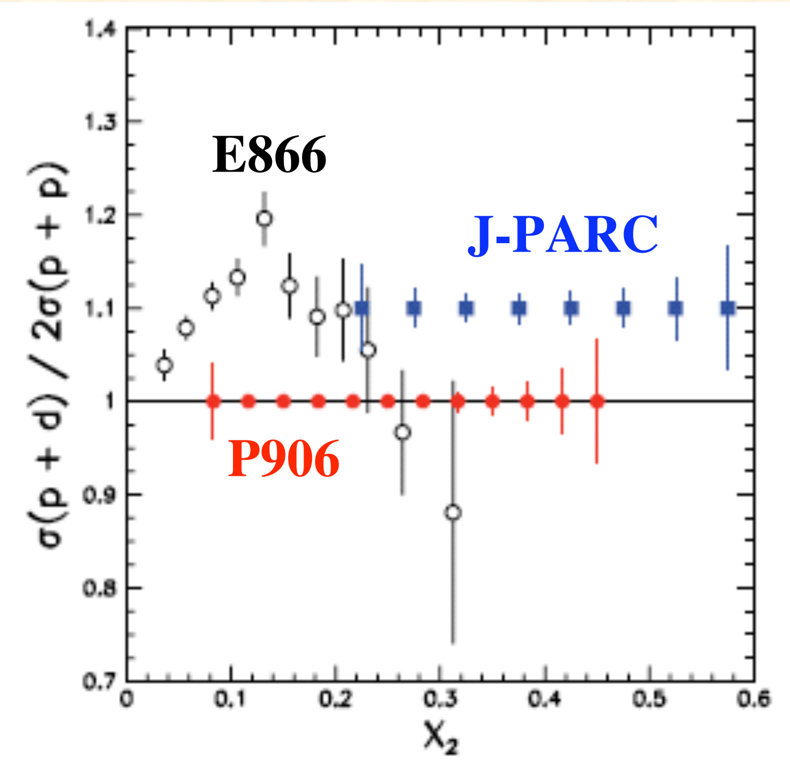
$$(\bar{u} - \bar{d})_{pQCD} \ll (\bar{u} - \bar{d})_{nonperturbative}$$

Of course, it depends on the initial scale for the evolution.

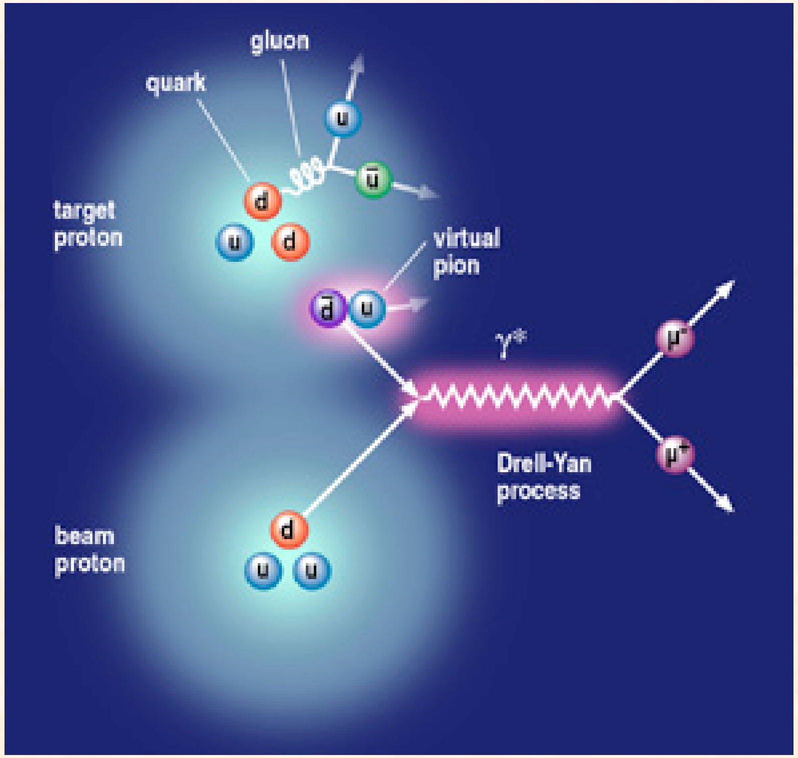
$\bar{u}/\bar{d}$ could be an appropriate quantity for testing nonperturbative aspects.

Flavor asymmetric antiquark distributions: $\bar{u}$ / $\bar{d}$

Sawada@J-PARC-HS05



J-PARC proposal, J. Chiba et al. (2006)



http://www.acuonline.edu/academics/cas/physics/research/e906.html

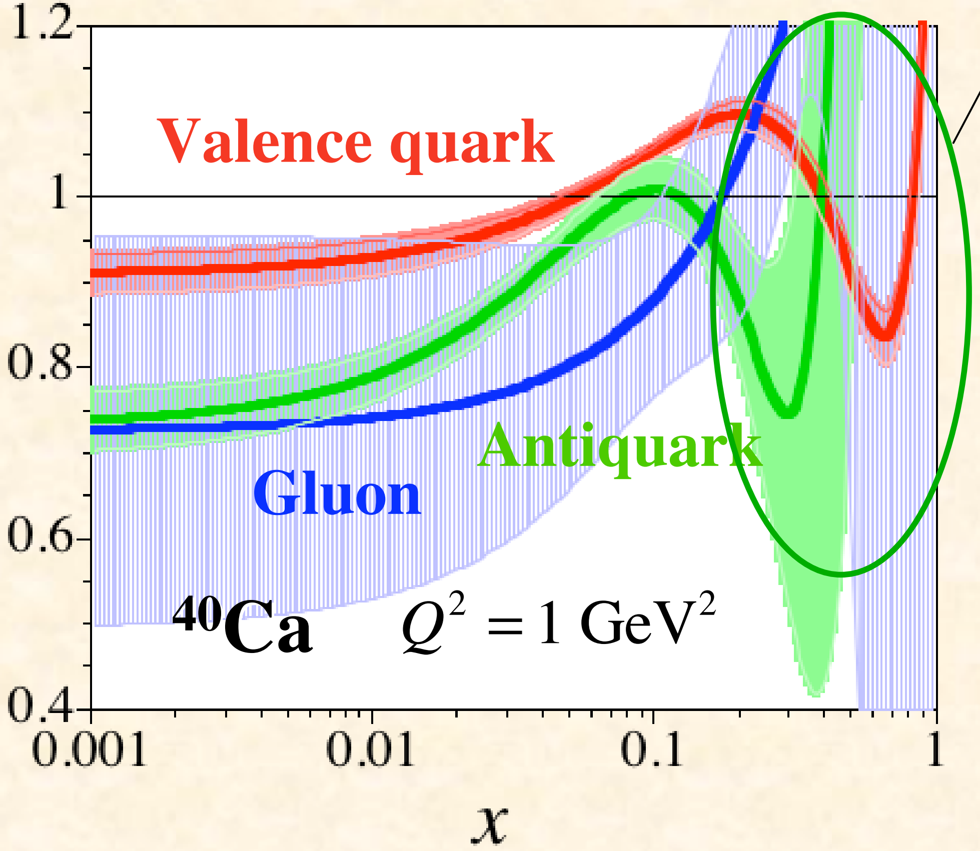
This project is suitable for probing "peripheral structure" of the nucleon.

Nuclear corrections on parton distribution functions

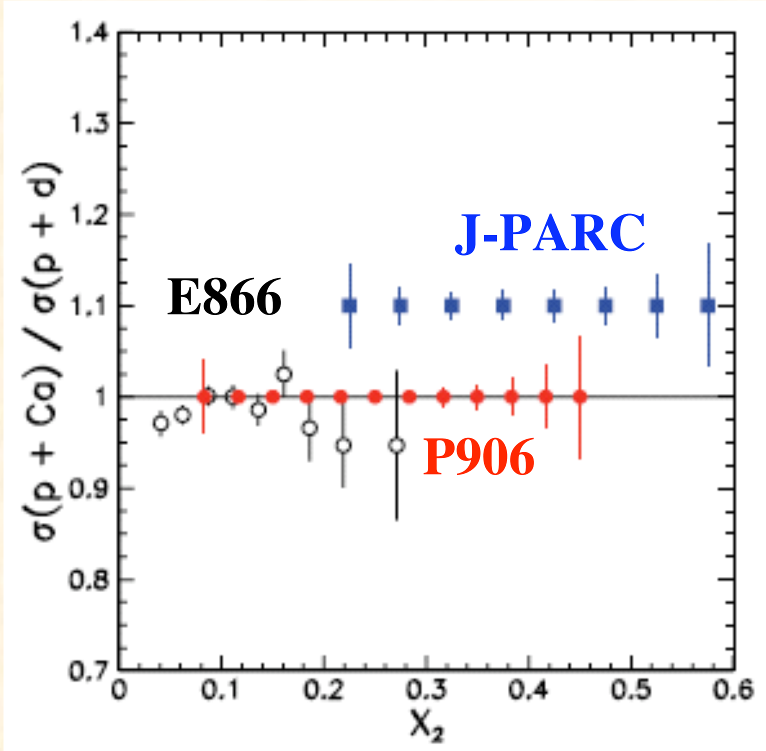
This region could be investigated by J-PARC.

$$\frac{f^{Ca}(x,Q^2)}{f^N(x,Q^2)}$$

Global NPDF analysis result



J-PARC proposal
J. Chiba et al. (2006)



Yokoya, Stratmann@J-PARC-HS05

PDF-library code: http://research.kek.jp/people/kumanos/nuclp.html

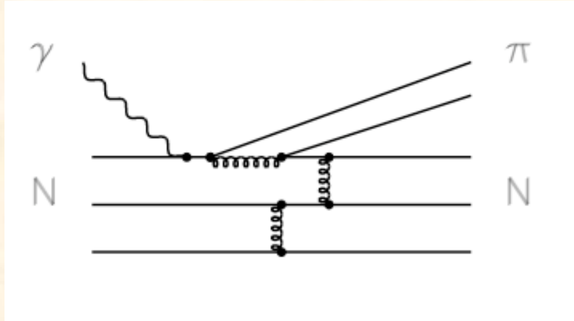
PR D64 (2001) 034003
C70 (2004) 044905

- Higher-order α_s corrections
- Soft-gluon resummation

Elastic Scattering: A+B → C+D at large p_T

Brodsky@J-PARC-HS05

Transition from hadron degrees of freedom to quark-gluon d.o.f.



H. Gao

Constituent counting rule

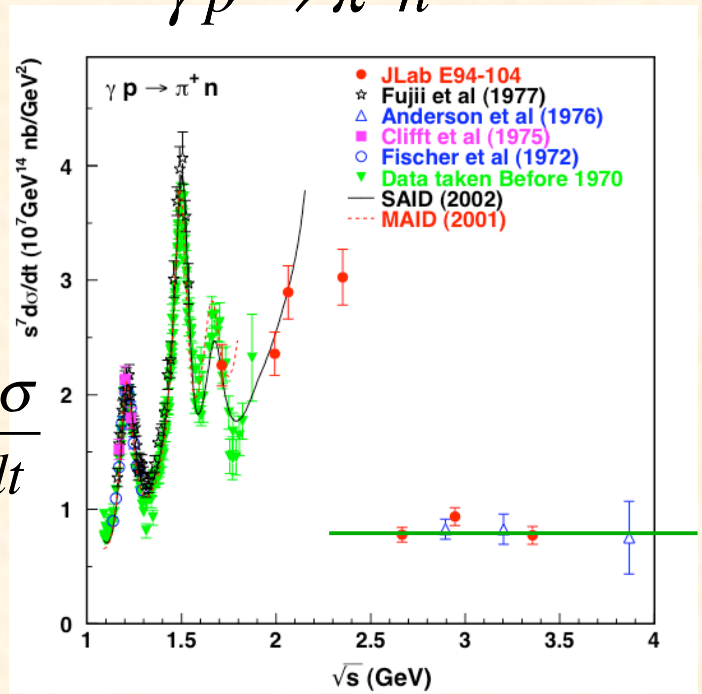
$$\frac{d\sigma}{dt}(AB \to CD) \sim s^{2-n} f(\theta_{c.m.})$$

$n = n_A + n_B + n_C + c_D$

(total number of interacting elementary particles)

$\gamma p \to \pi^+ n$

$s^7 \frac{d\sigma}{dt}$



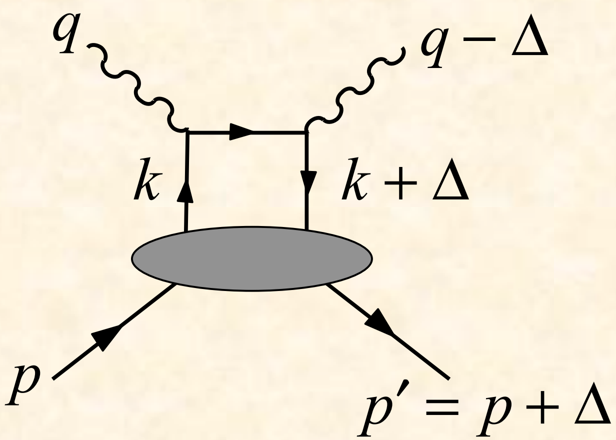
L.Y. Zhu et al., PRL 91 (2003) 022003

J-PARC: p + p → p + p

Generalized Parton Distributions (GPDs)

GPDs are defined by off-forward matrix element

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \left\langle p' \middle| \bar{q}(-z/2)\gamma^+ q(z/2) \middle| p \right\rangle_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2p^+}\left[H(x,\xi,\Delta^2)\,\bar{u}(p')\gamma^+ u(p) + E(x,\xi,\Delta^2)\,\bar{u}(p')\frac{i\sigma^{+\mu}\Delta_\mu}{2M}u(p) \right]$$

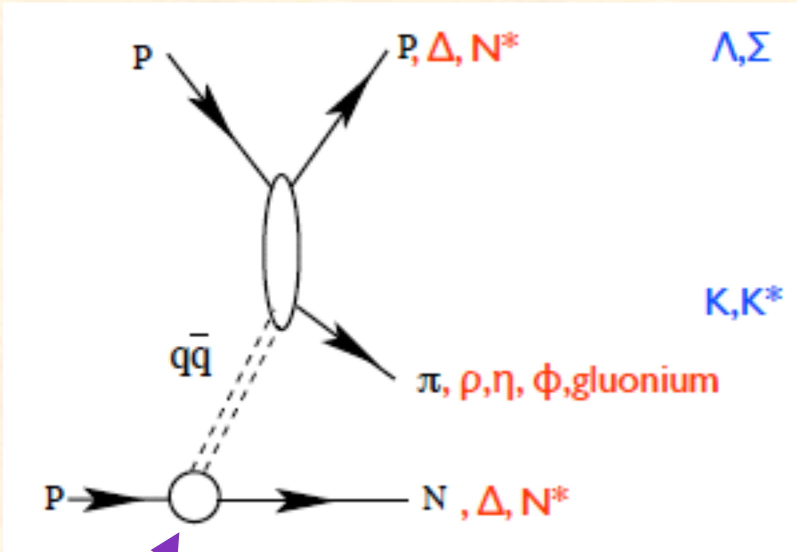


Forward limit: PDFs

First moments: Form factors

Second moments: Angular momentum

$$k^+ = xp^+, \quad P = \frac{1}{2}(p+p'), \quad \xi = -\frac{\Delta^+}{2P^+}$$



Strikman@J-PARC-HS05

L. L. Frankfurt et al., PRL 84 (2000) 2589

Extension of GPDs to N → Δ, π, …

Color Transparency

"Probe of dynamics of elementary reactions"

At large momentum transfer, a small-size component of the hadron wave function should dominate. This small-size hadron could freely pass through nuclear medium. (Transparent)

Brodsky, Strikman@J-PARC-HS05

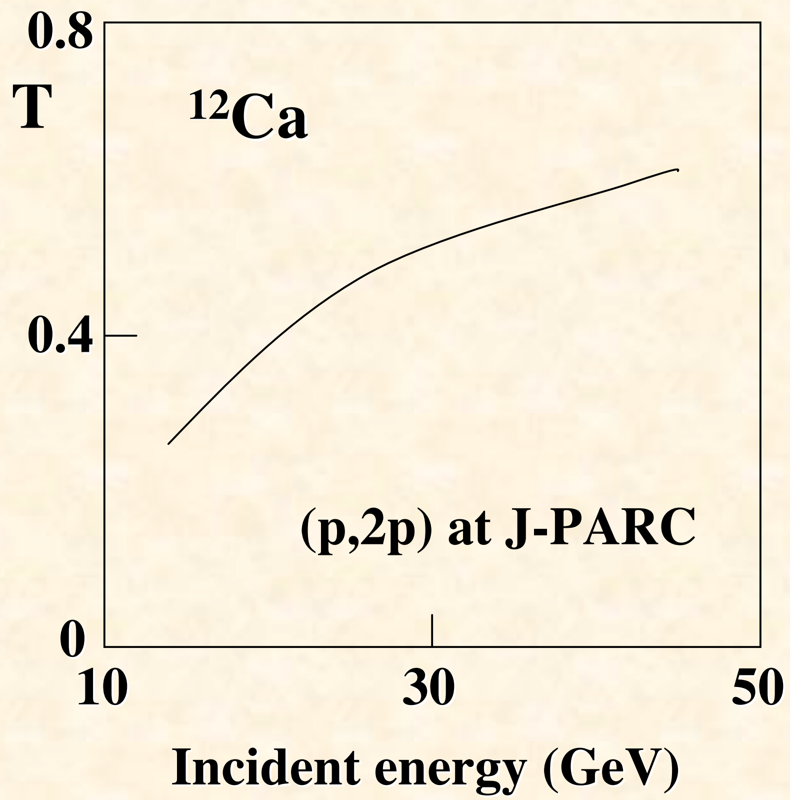
Possibility at J-PARC

Investigate $p\,A \rightarrow p\,p\,(A\text{-}1)$

Nuclear transparency: $T = \dfrac{\sigma_A}{A\sigma_N}$

Hadron size ~ 1 / hard scale

Color transparency:
$T \rightarrow$ larger, as the hard scale $\rightarrow$ larger



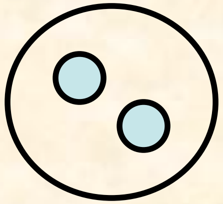
(BNL-EVA) J. Aclander et al., PRC 70 (2004) 015208

Tensor Structure in Proton-Deuteron Drell-Yan

SK@J-PARC-HS05

(Note: No polarized proton beam is needed!)

b_1 for spin-1 particles



only in S-wave $\quad$ **$b_1 = 0$**

1st measurement of b_1:
(HERMES) A. Airapetian et al., PRL 95 (2005) 242001.

Spin asymmetries

$$A_{LL} = \frac{\sum_a e_a^2 \left[\Delta q_a(x_A) \Delta \bar{q}_a(x_B) + \Delta \bar{q}_a(x_A) \Delta q_a(x_B) \right]}{\sum_a e_a^2 \left[q_a(x_A) \bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B) \right]}$$

M. Hino and SK, PR D59 (1999) 094026; D60 (1999) 054018.

$$A_{TT} = \frac{\sin^2\theta \cos(2\phi)}{1+\cos^2\theta} \frac{\sum_a e_a^2 \left[\Delta_T q_a(x_A) \Delta_T \bar{q}_a(x_B) + \Delta_T \bar{q}_a(x_A) \Delta_T q_a(x_B) \right]}{\sum_a e_a^2 \left[q_a(x_A) \bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B) \right]}$$

$$A_{UQ_0} = \frac{\sum_a e_a^2 \left[q_a(x_A) \delta \bar{q}_a(x_B) + \bar{q}_a(x_A) \delta q_a(x_B) \right]}{\sum_a e_a^2 \left[q_a(x_A) \bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B) \right]}$$

$$\delta q_i = q_i^{\,0} - \frac{q_i^{\,+1} + q_i^{\,-1}}{2}$$

Note: $\delta \neq$ transversity in my notation

Advantage of the hadron reaction ($\delta\bar{q}$ measurement)

$$A_{UQ_0}(\text{large } x_F) \approx \frac{\sum_a e_a^2 q_a(x_A) \delta \bar{q}_a(x_B)}{\sum_a e_a^2 q_a(x_A) \bar{q}_a(x_B)}$$

$$\delta\bar{q} \leftrightarrow \int dx \; b_1$$

F. E. Close and SK, PRD42, 2377 (1990).

Neutrino beam: Elastic νN scattering and Δs

Axial part of weak neutral current

$$\langle N|A_\mu^Z|N\rangle = -\left(\frac{G_F}{\sqrt{2}}\right)^{1/2}\frac{1}{2}\langle N|\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d - \bar{s}\gamma_\mu\gamma_5 u|N\rangle$$

$$= -\left(\frac{G_F}{\sqrt{2}}\right)^{1/2}\frac{1}{2}\langle N| - G_A(Q^2)\gamma_\mu\gamma_5\tau_z + G_A^S(Q^2)\gamma_\mu\gamma_5|N\rangle$$

(Quasi-) Elastic cross section

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2}{2\pi}\frac{Q^2}{E_\nu^2}\left(A \pm BW + CW^2\right)$$

$+$ for ν, $-$ for $\bar{\nu}$

$$W = 4(E_\nu / M_p - \tau), \quad \tau = Q^2 / 4M_p^2$$

$$A = \frac{1}{4}\left[G_1^2(1+\tau) - \left(F_1^2 - \tau F_2^2\right)(1-\tau) + 4\tau F_1 F_2\right]$$

$$B = -\frac{1}{4}\left[G_1\left(F_1 + \tau F_2\right)\right] \qquad C = \frac{1}{16}\frac{M_p^2}{Q^2}\left[G_1^2 + F_1^2 + \tau F_2^2\right]$$

Axial vector form factor

$$G_1(Q^2) = \frac{1}{2}\left[-G_A(Q^2)\tau_z + G_A^s(Q^2)\right]$$

Nonstrange part: $G_A(Q^2 = 0) = 1.2673 \pm 0.0035$ from neutron β decay

$$G_1^s(Q^2 = 0) = \Delta s$$

J-PARC **Miyachi@J-PARC-HS05**

Liquid scintillators with different mixtures of hydrogen / carbon
→ Remove nuclear effects

$Q^2 \approx 0.15 - 0.75\ \text{GeV}^2$

$\Delta s = ?\ \pm 0.03$

[E734: $\delta(\Delta s)=0.08$]

Neutrino-Nucleus Interactions in the Few-GeV Region (T2K)

Sakuda@J-PARC-HS05

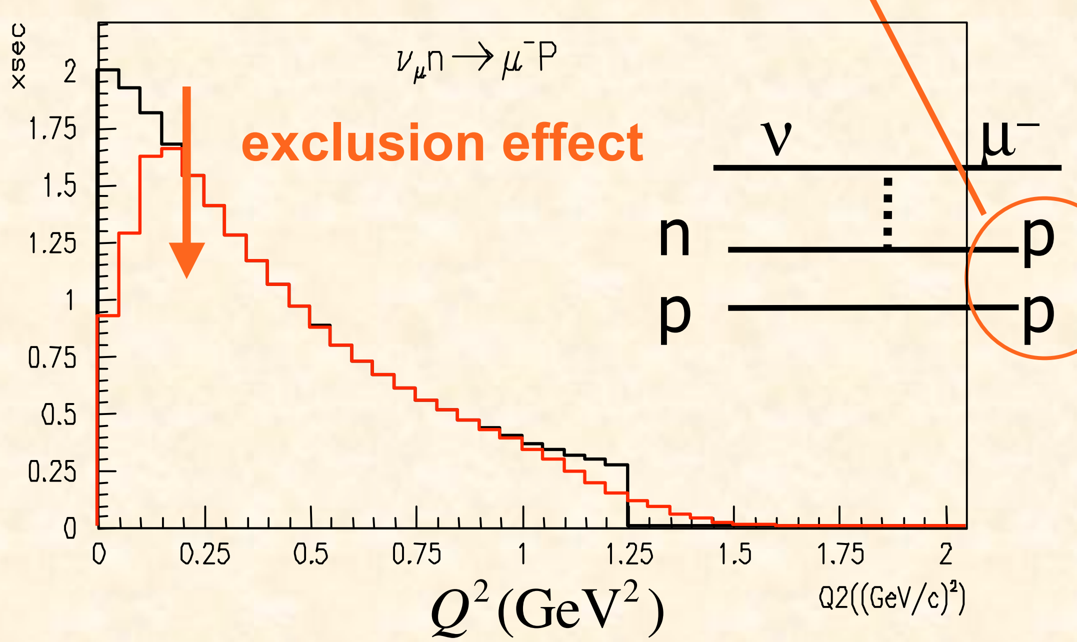
ν-nucleus cross sections are not well known at E_ν=0.5-20 GeV. **(20% accuracy)**

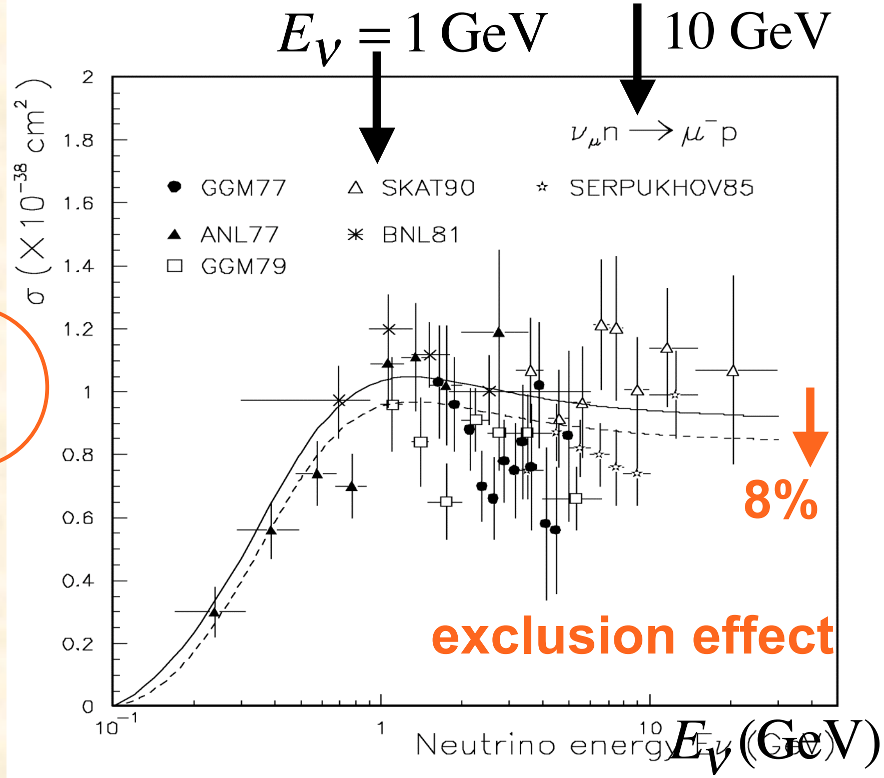
For accurate oscillation measurements, a few % accuracy is needed.

⟶ Nuclear corrections in ^{16}O are important!

Binding, Fermi motion, Pauli exclusion, NN correlation, PDF modification, …

$d\sigma/dQ^2$ **M. Sakuda, NP, B112 (2002) 109.**





Attempt to describe DIS & resonance region

Empirical formula

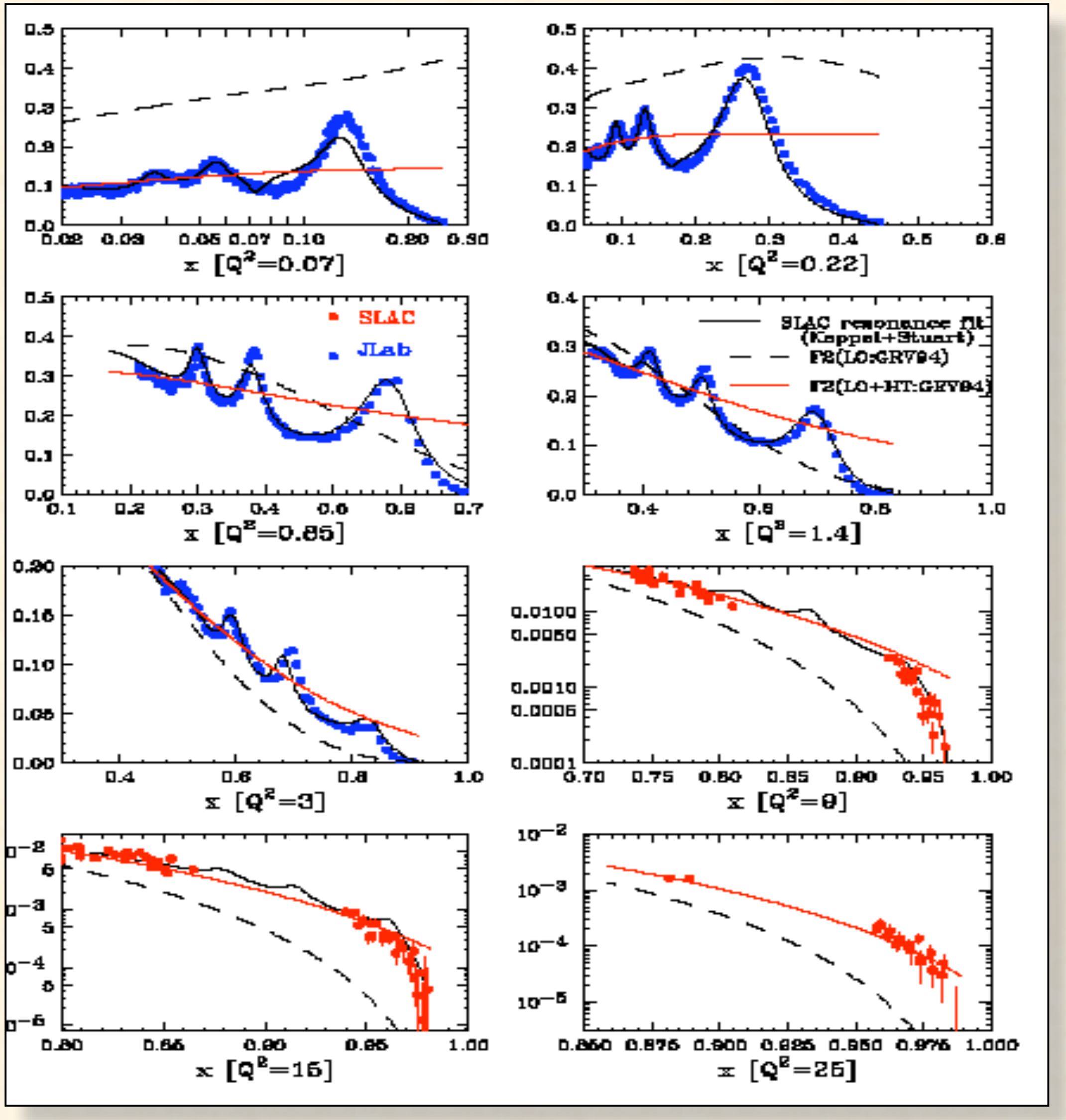
$$F_2(x) = \frac{Q^2}{Q^2 + 0.188} F_2(x_W)$$

where $$x_W = x \frac{Q^2 + 0.624}{Q^2 + 1.735\,x}$$

- - - - - - - - - - **GRV94**

———— **Bodek-Yang**

NP B112 (2002) 70



Quark-Hadron Duality: The details are explained in W. Melnitchouk, R. Ent, C. Keppel, Phys. Rept. 406 (2005) 127.

Current status on nucleon spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$$

Orbital angular momenta

Gluon spin

Quark and antiquark spin

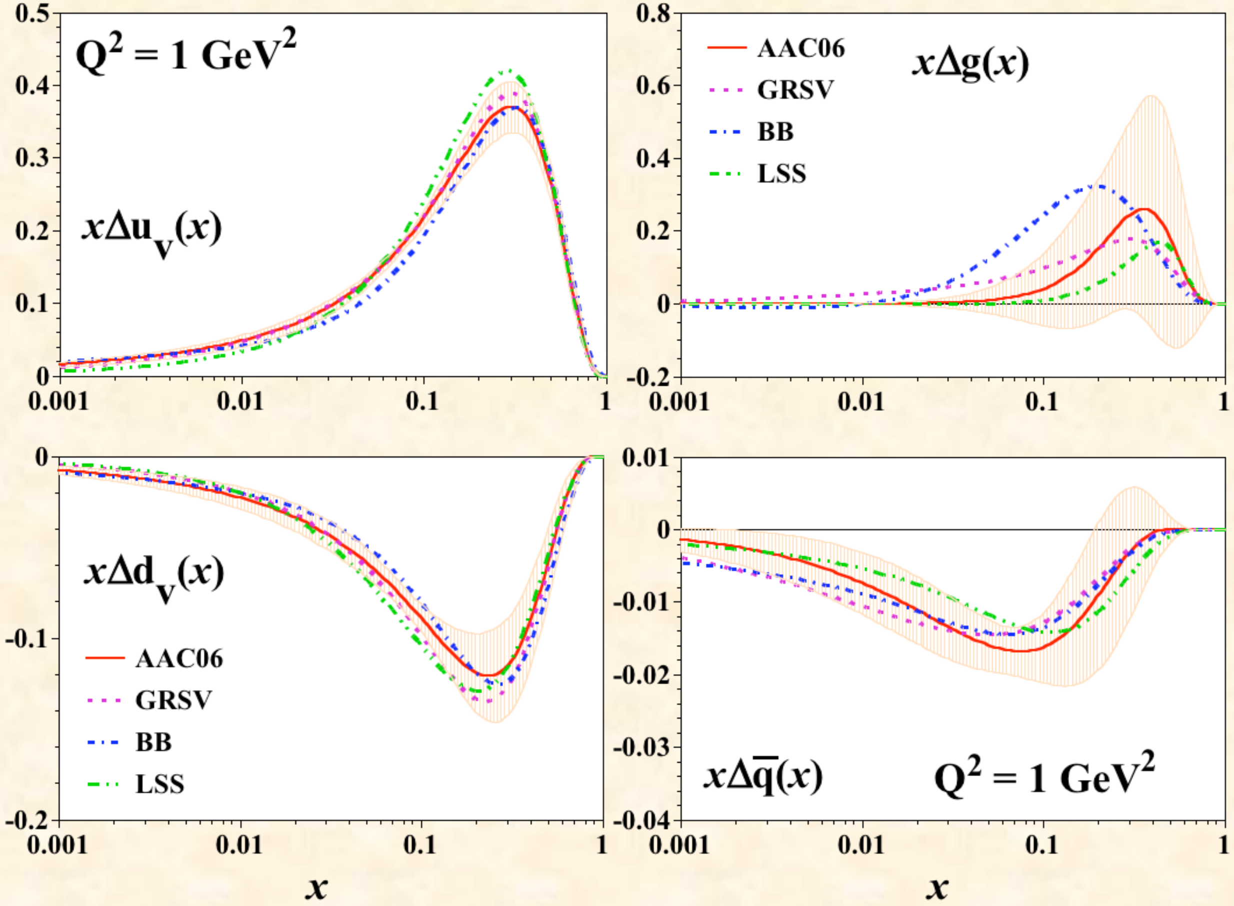
Global analysis of DIS and RHIC data (AAC, hep-ph/0603213)

$\Delta\Sigma = 0.27 \pm 0.07$

$\Delta g = 0.31 \pm 0.32$

Gluon polarization is not determined.

Orbital angular momenta could be important.



Single spin asymmetry

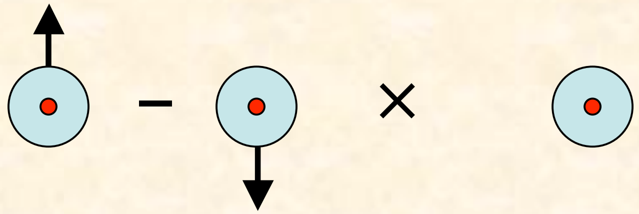
(No polarized proton beam is needed!)

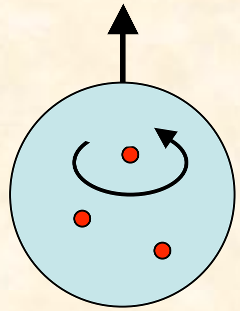
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Nucleon • Quark

- Sivers effect

$$A_N \sim f_{1T}^{\perp} \cdot D_1 \quad \text{(Sivers function} \times \text{ Unpolarized fragmentation)}$$





Burkardt @J-PARC-HS05

Probe of angular momentum

The Sivers function describes unpolarized quark in the transversely polarized nucleon.

- Collins effect

$$A_N \sim \delta_T q \cdot H_1^{\perp} \quad \text{(Transversity } \times \text{ Collins fragmentation function)}$$

The transversity distribution describes transverse quark polarization in the transversely polarized nucleon.

The Collins fragmentation function describes a fragmentation of polarized quark into unpolarized hadron.

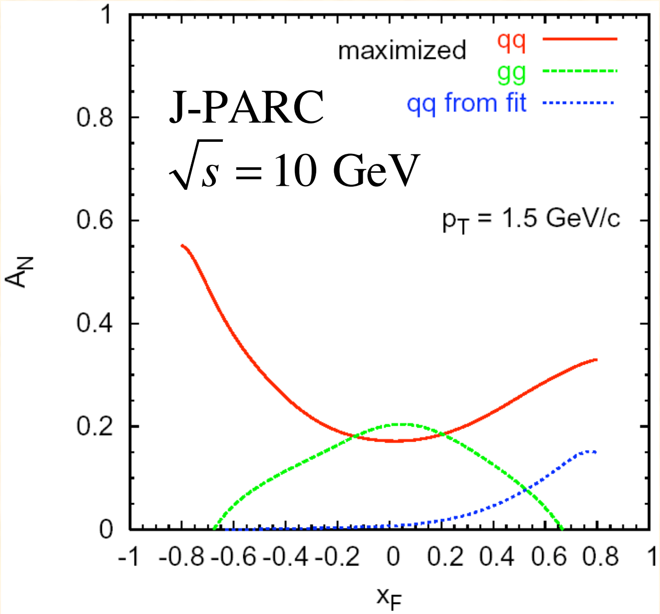
- Higher-twist

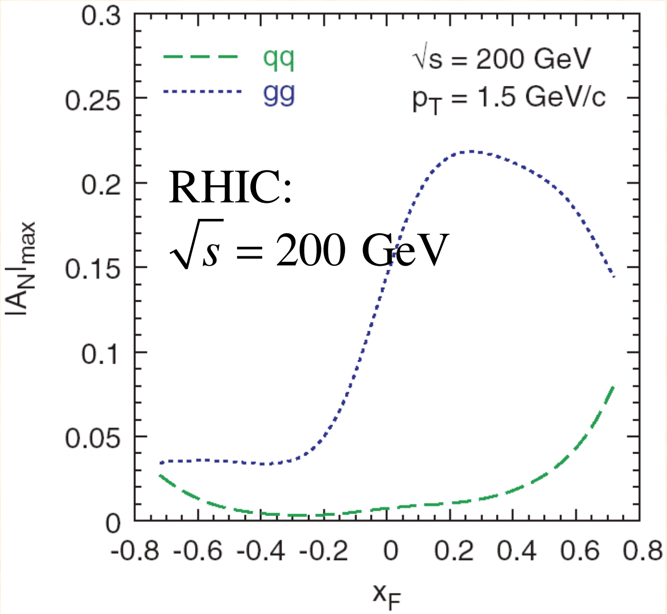
Qiu, Sterman; Koike@J-PARC-HS05

Single spin asymmetry D-meson production

No single spin transfer: $gg \to c\bar{c}, \quad q\bar{q} \to c\bar{c}$

$\to c$ & $\bar{c}$ are not polarized (no Collins mechanism)





Y. Goto @J-PARC-HS05

U. D'Alesio @BNL, 2005

M. Anselmino et al., PRD 70 (2004) 074025.

In the region $x_F < 0$

J-PARC: sensitive to quark Sivers effect

RHIC: sensitive to gluon Sivers effect

J-PARC Hadron Physics

"after major upgrades"

- **Spin Physics**
- **Heavy-Ion Physics**
- **Neutrino Factory (~30 GeV)**

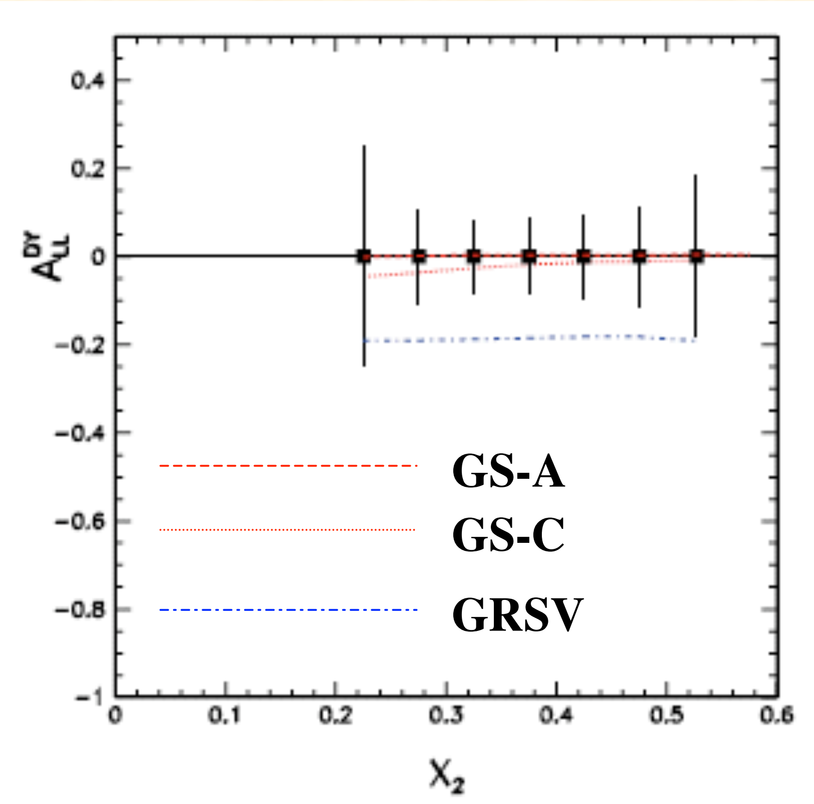
I explain just a few examples.

Polarized Drell-Yan

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

$$\vec{p} + \vec{d} \rightarrow \mu^+\mu^- + X$$

$\Delta\bar{u} / \Delta\bar{d}$ asymmetry



J-PARC proposal, J. Chiba et al. (2006)

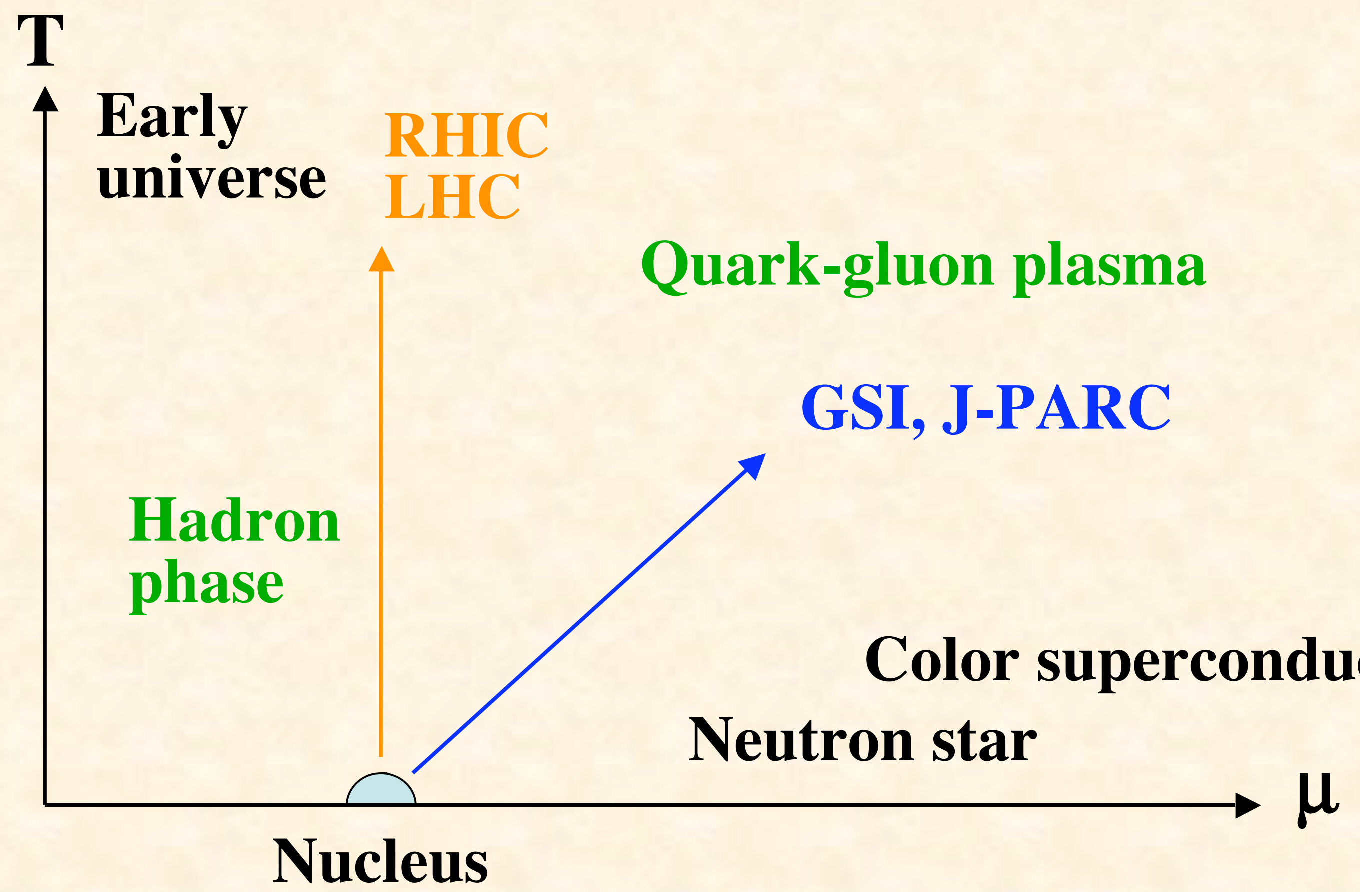
The small-x part of the $\bar{u} / \bar{d}$ asymmetry has been established.

→ No information for polarized asymmetry for the light antiquark distributions

(Model predictions are very different.)

J-PARC could contribute in the medium-x region.

Quark-hadron matter



Low-temperature & high-density region:
J-PARC could investigate a different region of the phase diagram from the ones for RHIC and LHC.

Neutrino factory ~ 30 GeV (~15 years later?)

Polarized neutrino-proton scattering (CC)

$$W_{\mu\nu} = (-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}) F_1 + \frac{\hat{p}_\mu \hat{p}_\nu}{p\cdot q} F_2 - i\,\varepsilon_{\mu\nu\lambda\sigma} \frac{q^\lambda p^\sigma}{2p\cdot q} F_3$$

where $\hat{p}_\mu = p_\mu - \frac{p\cdot q}{q^2} q_\mu$

$$+ i\,\varepsilon_{\mu\nu\lambda\sigma} \frac{q^\lambda s^\sigma}{p\cdot q} g_1 + i\,\varepsilon_{\mu\nu\lambda\sigma} \frac{q^\lambda (p\cdot q\, s^\sigma - s\cdot q\, p^\sigma)}{(p\cdot q)^2} g_2$$

$$+ \left[\frac{\hat{p}_\mu \hat{s}_\nu + \hat{s}_\mu \hat{p}_\nu}{2p\cdot q} - \frac{s\cdot q\, \hat{p}_\mu \hat{p}_\nu}{(p\cdot q)^2} \right] g_3 + \frac{s\cdot q\, \hat{p}_\mu \hat{p}_\nu}{(p\cdot q)^2} g_4 + (-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}) \frac{s\cdot q}{p\cdot q} g_5$$

new structure functions g_3, g_4, g_5

$$g_5^{\nu p} + g_5^{\bar{\nu} p} \simeq -(\Delta u_v + \Delta d_v)$$

be careful about "various" definitions of g_3, g_4, g_5 !

$$\frac{d(\sigma^{CC}_{\lambda_p=-1} - \sigma^{CC}_{\lambda_p=+1})}{dx\,dy} = \frac{G_F^2 Q^2}{\pi(1+Q^2/M_W^2)^2 xy} \Big\{ [-\lambda_\ell y(2-y) x g_1^{CC} - (1-y) g_4^{CC} - y^2 x g_5^{CC}]$$

$$+ 2xy \frac{M^2}{Q^2} \Big[\lambda_\ell x^2 y^2 g_1^{CC} + \lambda_\ell 2x^2 y\, g_2^{CC} + \left(1 - y - x^2 y^2 \frac{M^2}{Q^2}\right) x\, g_3^{CC}$$

$$- x\left(1 - \frac{3}{2} y - x^2 y^2 \frac{M^2}{Q^2}\right) g_4^{CC} - x^2 y^2 g_5^{CC} \Big] \Big\}$$

→ 0 at $Q^2 \gg M^2$

Summary

J-PARC will be a flagship facility in (Japanese) hadron and nuclear physics communities.

- **Hypernuclear physics**
- **Hadron spectroscopy**
- **Hadrons in nuclear medium**
- **Structure functions**
- **Nucleon spin**
- **Heavy-ion physics**

Your support is important for success of the hadron project at J-PARC!