The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1942-49

Sixth International Conference on Perspectives in Hadronic Physics

12 - 16 May 2008

High-energy hadron physics at J-PARC.

S. Kumano
KEK
Japan

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

High-Energy Hadron Physics at J-PARC

Shunzo Kumano

High Energy Accelerator Research Organization (KEK)

Graduate University for Advanced Studies (GUAS)

shunzo.kumano@kek.jp

http://research.kek.jp/people/kumanos/

Sixth International Conference on Perspectives in Hadronic Physics

ITCP, Trieste, Italy

May 12 – 16, 2008
(Talk on May 16)

Contents

1. **Introduction to high-energy hadron physics at J-PARC**
   - Introduction to the J-PARC facility
   - Possible projects with 30 – 50 GeV proton beam

2. **Structure functions**

   Possible roles of J-PARC projects in
   - Unpolarized and Polarized parton distribution functions (PDFs), Nuclear PDFs
   - Fragmentation functions
   - Tensor structure functions

Topics related to my studies

Part I

Introduction to
High-Energy Hadron Physics
at J-PARC

J-PARC Facility

J-PARC Location

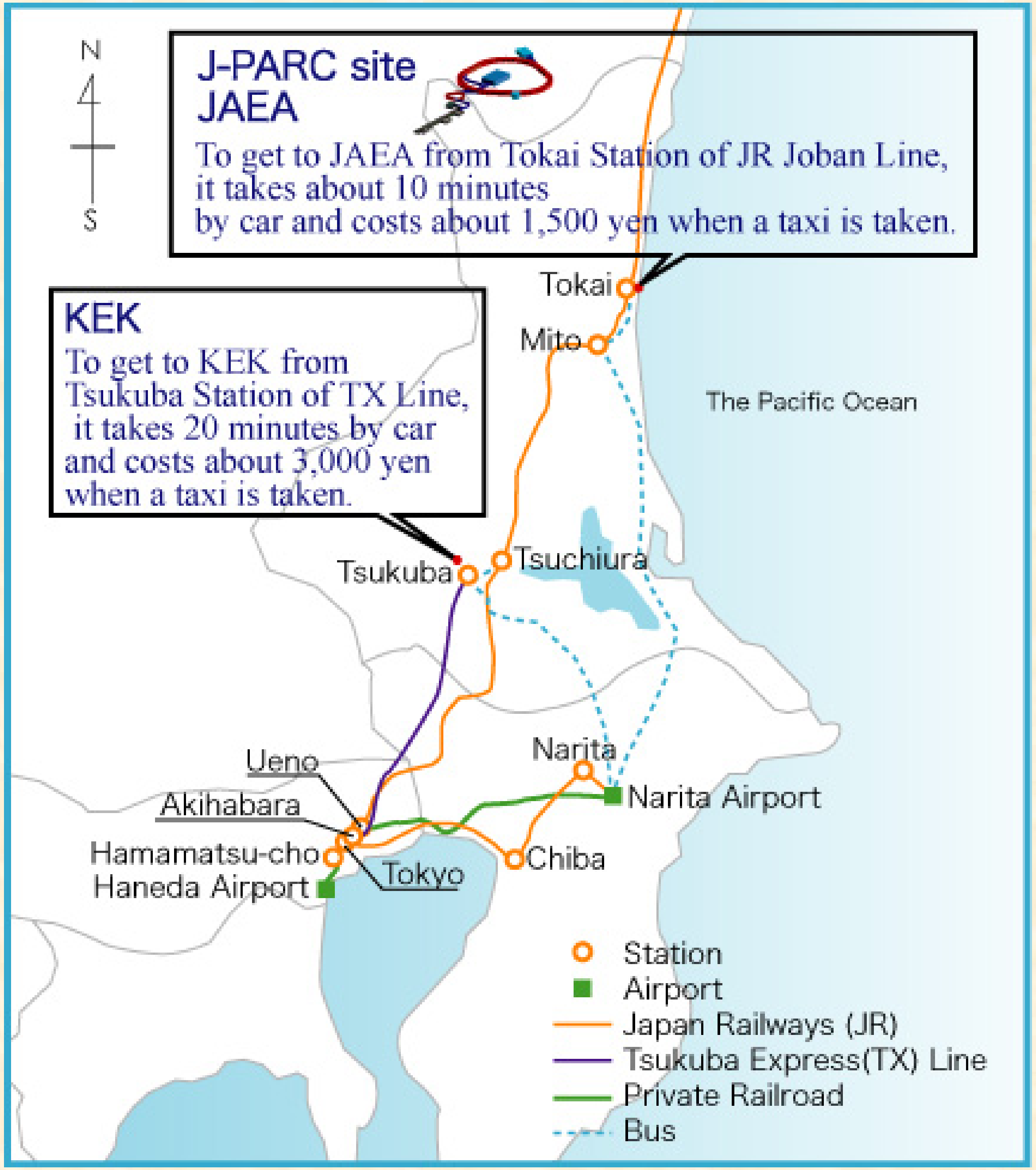
J-PARC
(Japan Proton Accelerator Research Complex)

http://j-parc.jp/index-e.html

Joint facility of JAEA and KEK.

JAEA (Japan Atomic Energy Agency)

KEK (High Energy Accelerator Research Organization)

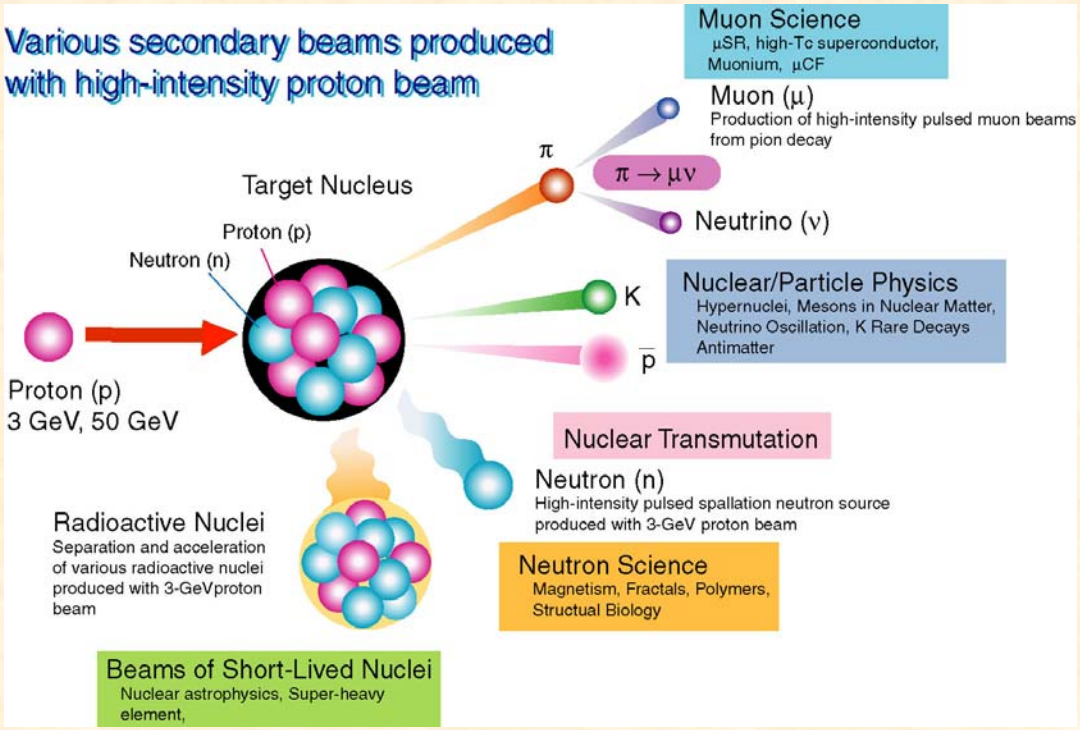


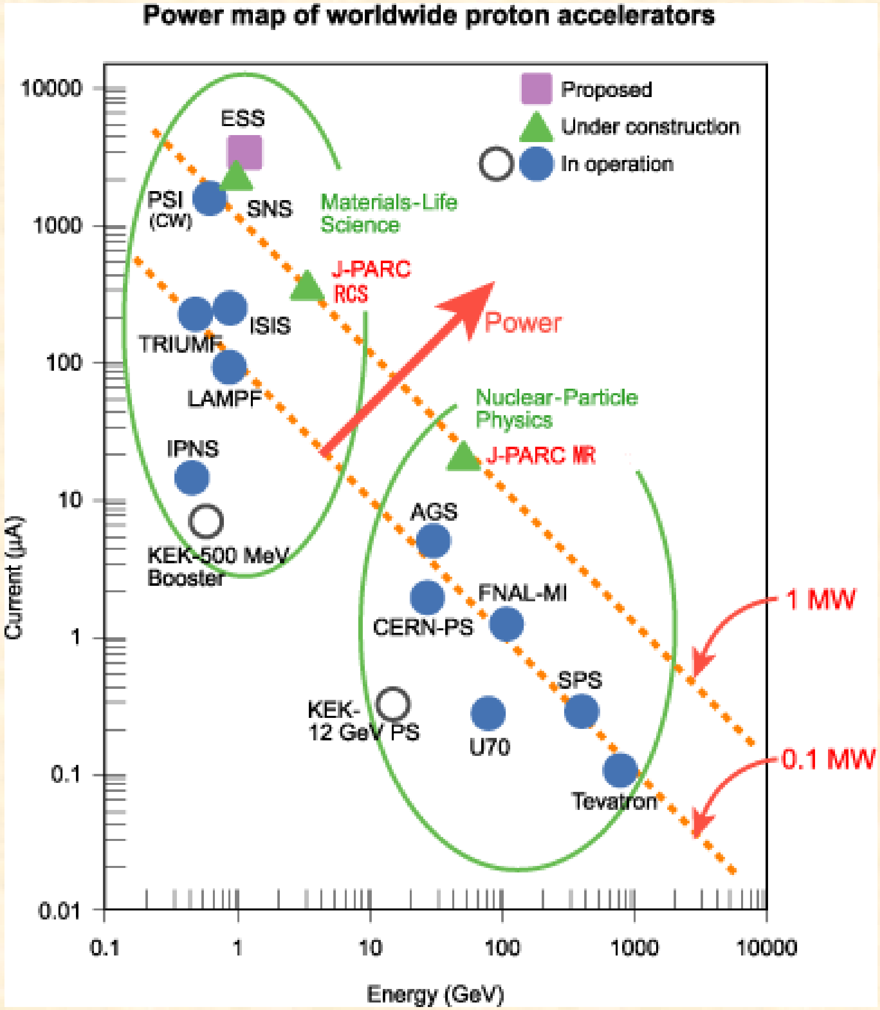
Bird’s-eye view

Particle and Nuclear Physics

High-Intensity Frontier of Proton Accelerator

High-intensity proton beam
→ High-intensity secondary beams
(Neutrino, Kaon, Pion, Neutron …)

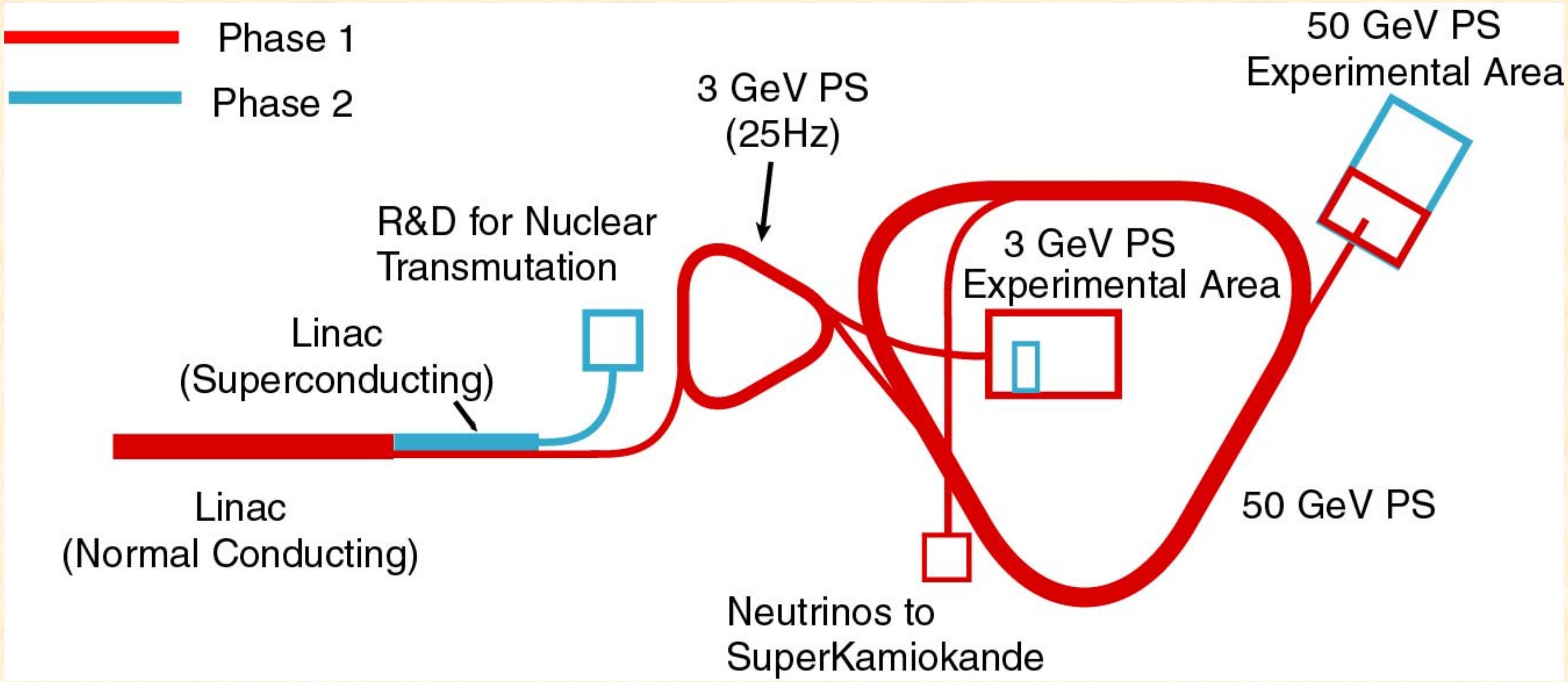




- Strangeness nuclear physics (1st experiment)
- Exotic hadrons
- Hadrons in nuclear medium
- Hard processes (50 GeV recovery)
- Nucleon spin (proton polarization)
- Quark-hadron matter (heavy ion)

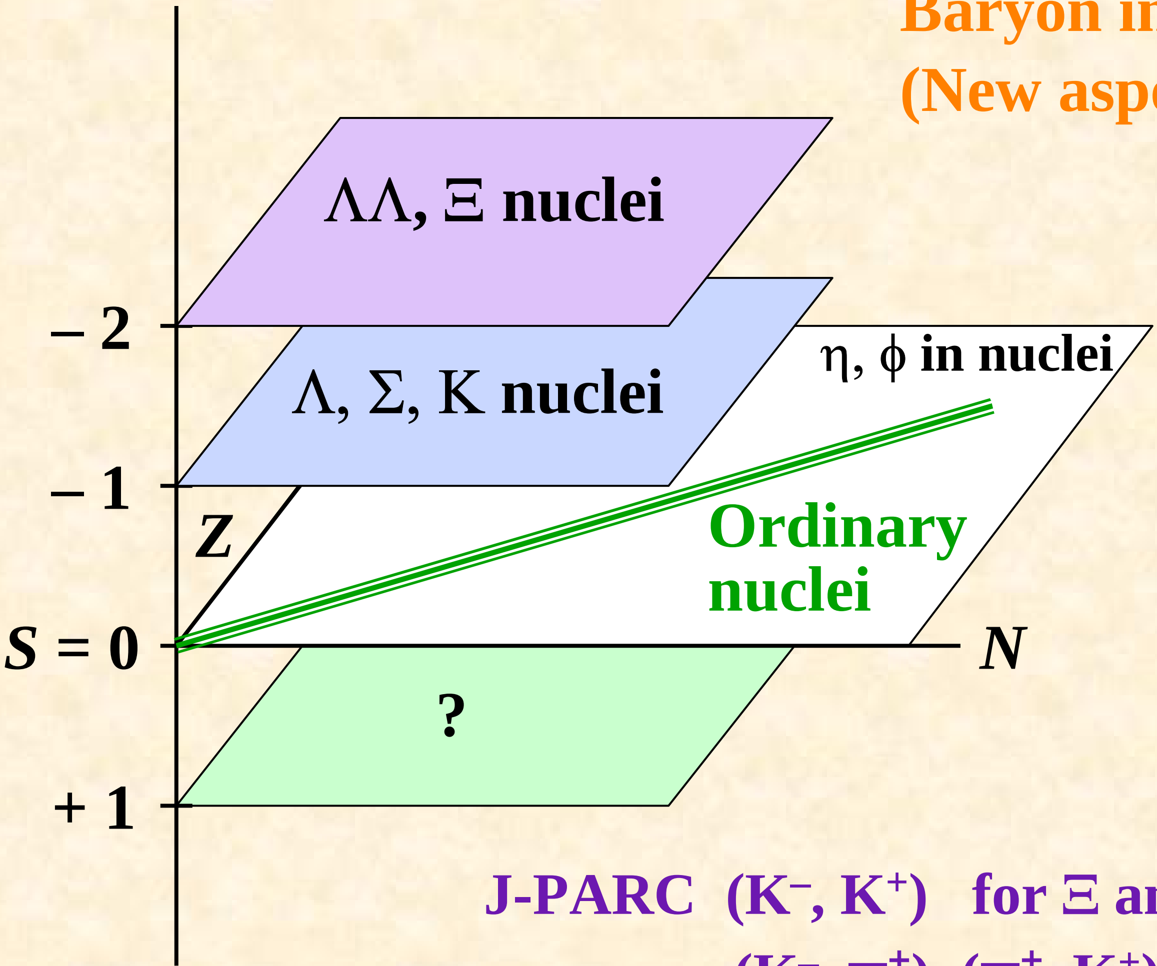
Efforts are needed to get approval for projects after strangeness physics.

Theorist's contributions are crucial for the 2nd projects.



New nuclei with strangeness

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



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

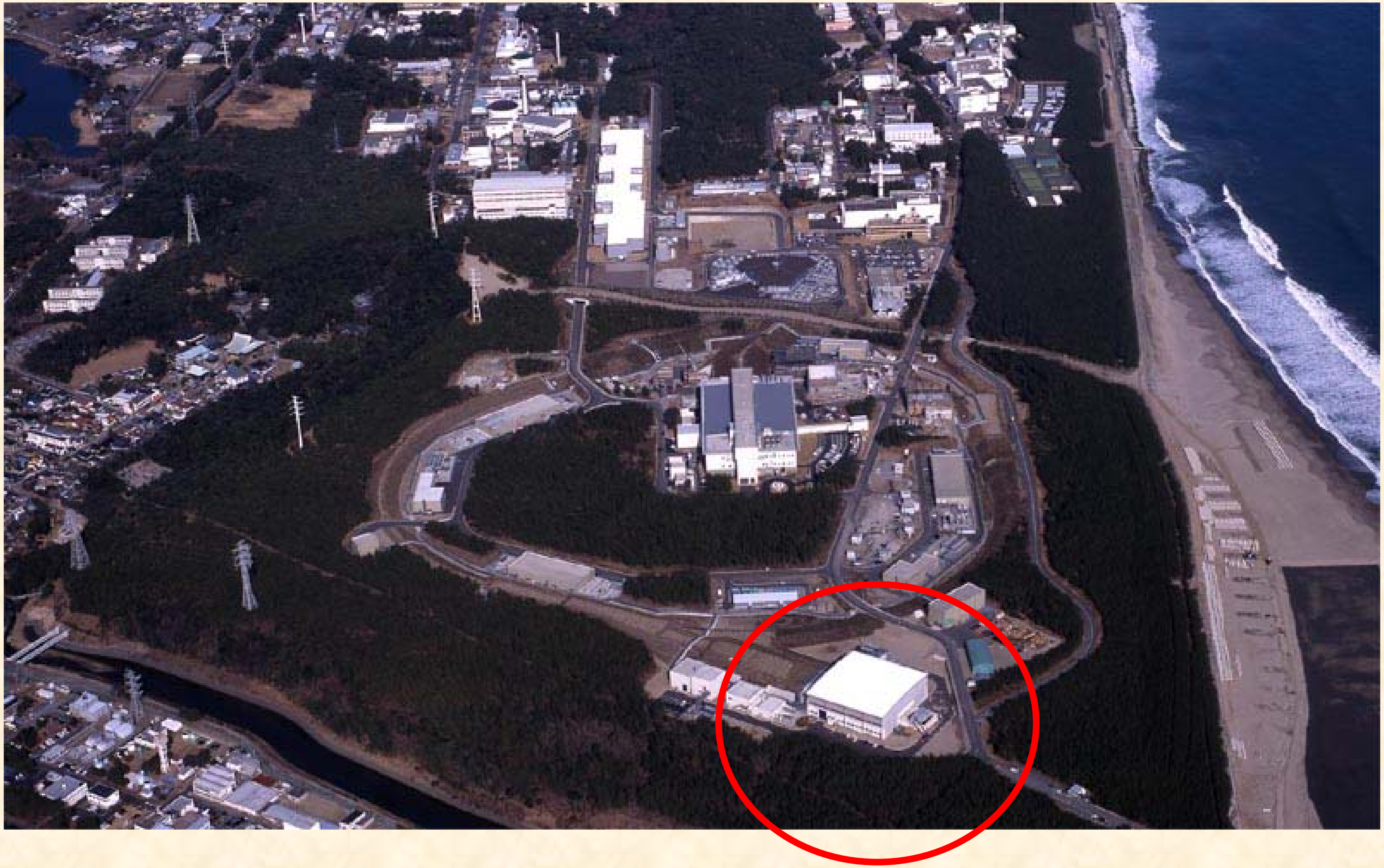
- **No data for YY interactions**

- **Some data for YN interactions (~ 40)**

- **Plenty of data for NN interactions (~ 4,000)**

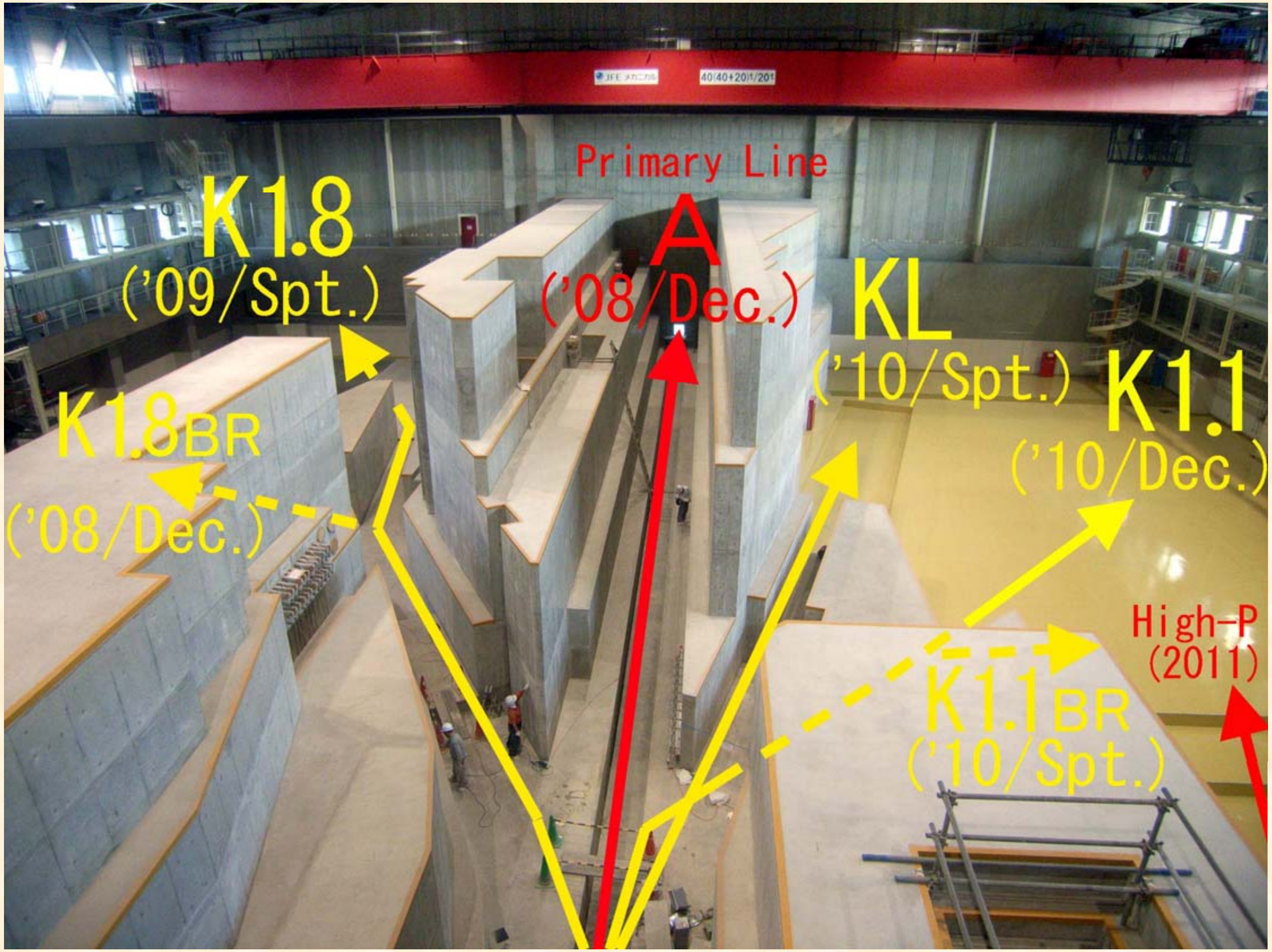
J-PARC (K^-, K^+) **for Ξ and ΛΛ nuclei, YN scattering**
$(K^-, \pi^\pm)$, $(\pi^\pm, K^+)$ **for Λ nuclei, YN scattering**

Aerial photograph on January 28, 2008

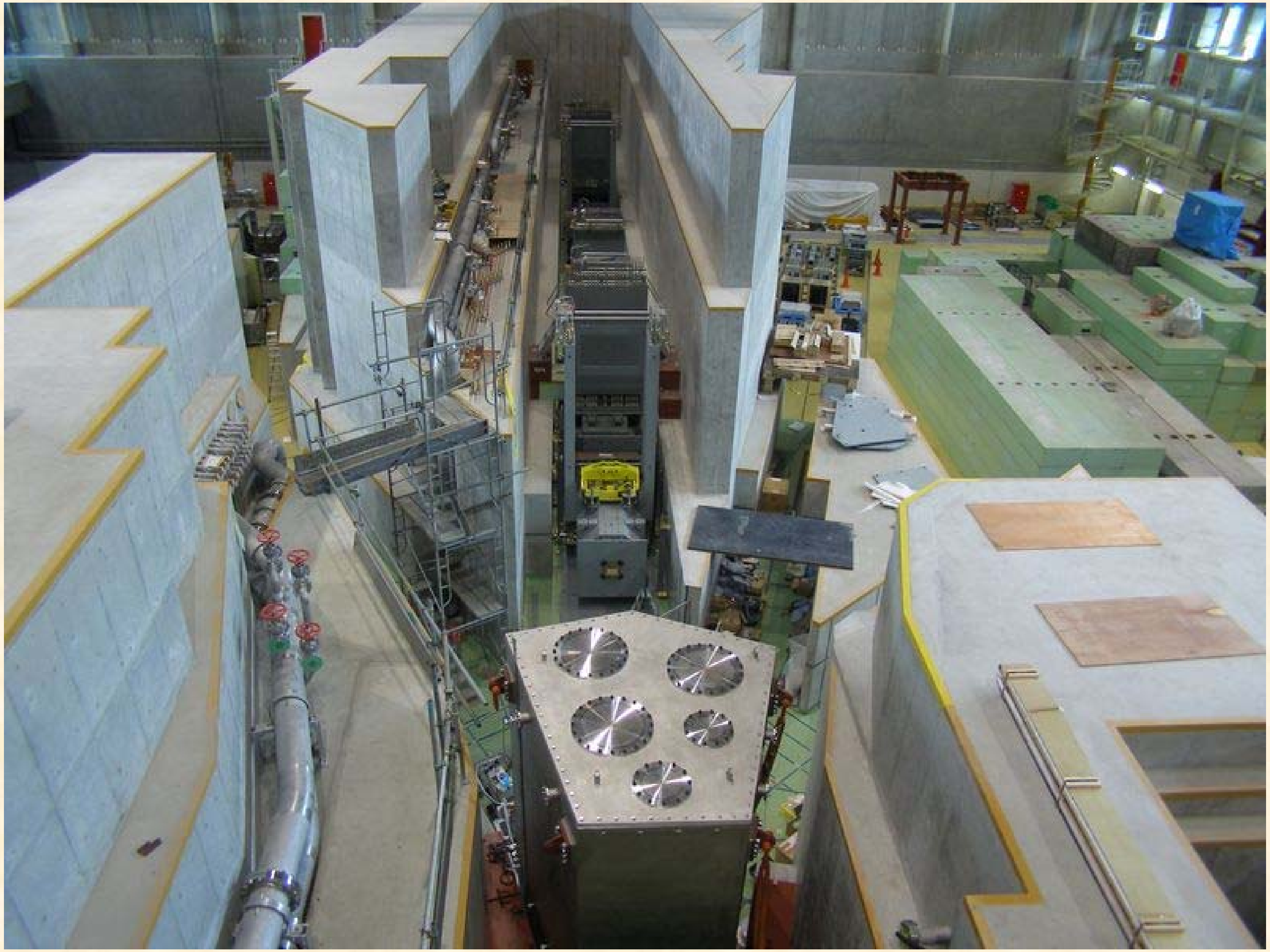


Hadron facility

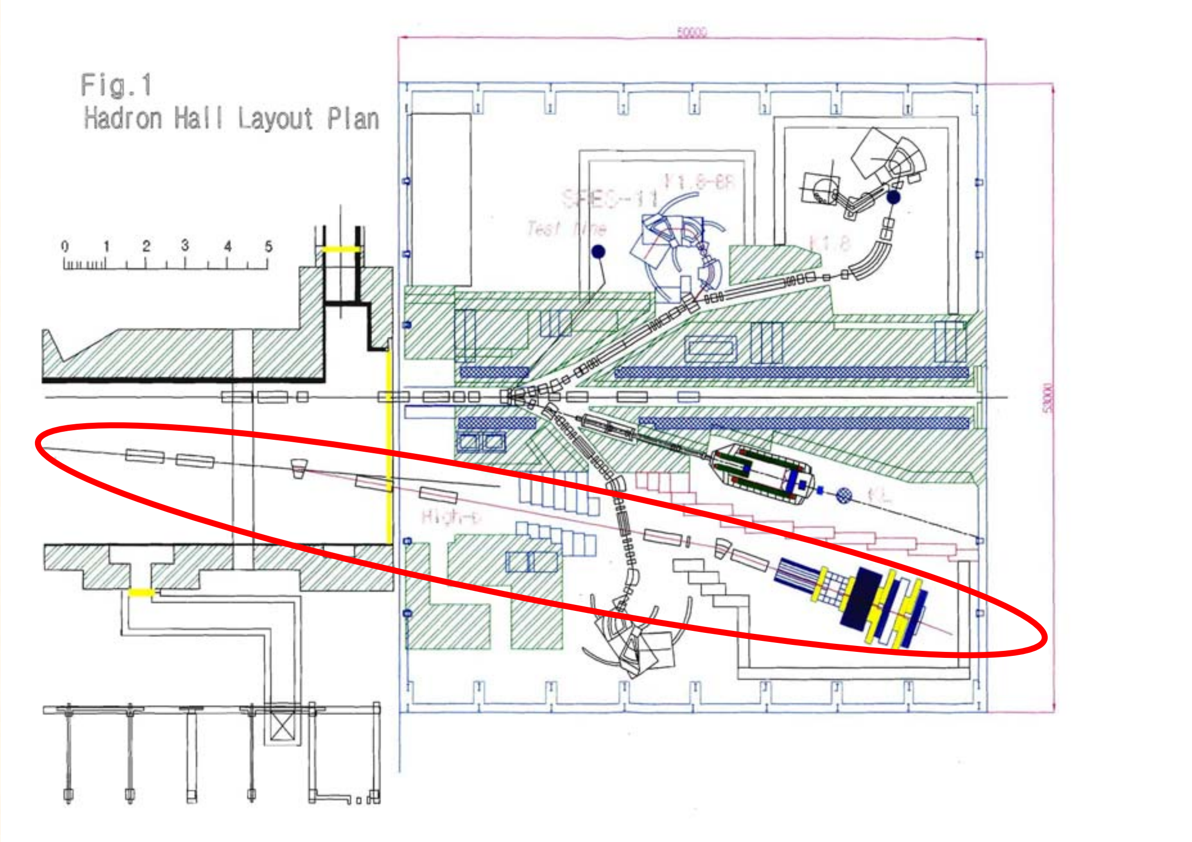
Hadron Facility in May 2007
and a possible schedule for beam lines



Hadron Facility on April 11, 2008



High-Momentum Beam Line (30, 50 GeV Proton)



This beam line should be interesting for the audience of this workshop.

General comments on J-PARC projects with 30 – 50 GeV proton beam

J-PARC workshops on hadron physics

- **J-PARC-HS05,**
  http://www-conf.kek.jp/J-PARC-HS05/program.html
- **J-PARC-NP07,**
  http://www-conf.kek.jp/NP_JPARC/program.html
- **J-PARC-NP08, http://j-parc.jp/NP08/**

Refs. My talks on "Possible Hadron Physics at J-PARC"

in Trieste (2006) http://www.pg.infn.it/hadronic06/

in Ghent (2007) http://inwpent5.ugent.be/workshop07/

in Mito (2008) http://j-parc.jp/NP08/

Haron Physics at J-PARC

1st project (also ν)

- Strangeness nuclear physics (1st experiment)

Kaon and pion beams

Next projects

- Exotic hadrons
- Hadrons in nuclear medium

Proton beam

- Hard processes (50 GeV recovery)
- Nucleon spin (proton polarization)

Need major upgrades

- Quark-hadron matter (heavy ion)

My talk is related to

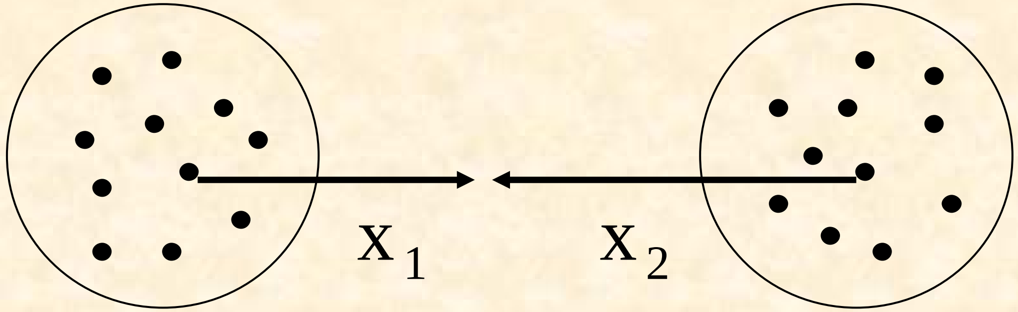
Hadron physics with 30 – 50 GeV proton beam

30 GeV
- J/ψ production
  - Transition: Hadron → Quark degrees of freedom
  - Hadron interactions in nuclear medium
  - Short-range *NN* interactions
  - GPDs
  - …

50 GeV
- Drell-Yan (unpolarized PDFs)
  - Single spin asymmetries
  - Tensor structure at 50 GeV (Spin-1 hadrons)
  - Fragmentation functions (Hadron productions)
  - …

Proton-beam polarization
  - Drell-Yan: Double asymmetries (Polarized PDFs)
  - Complimentary to RHIC-Spin (large-*x* physics)
  - …

Hadron facilities



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

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

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

- $s = (p_1 + p_2)^2$
- $m_{\mu\mu} \geq 3$ GeV

J-PARC: $\sqrt{s} = 10$ GeV

RHIC: $\sqrt{s} = 200$ GeV

LHC: $\sqrt{s} = 14$ TeV

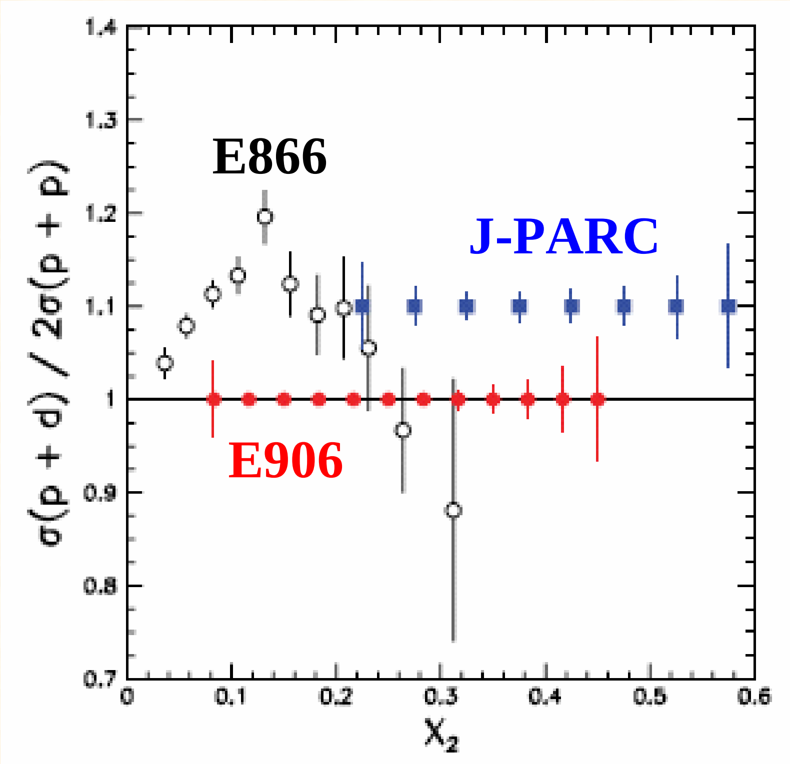
$x \sim \frac{\sqrt{m_{\mu\mu}^2}}{\sqrt{s}} \geq \frac{3}{10} = 0.3$ J-PARC **Large-*x* facility (Medium-*x*)**

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

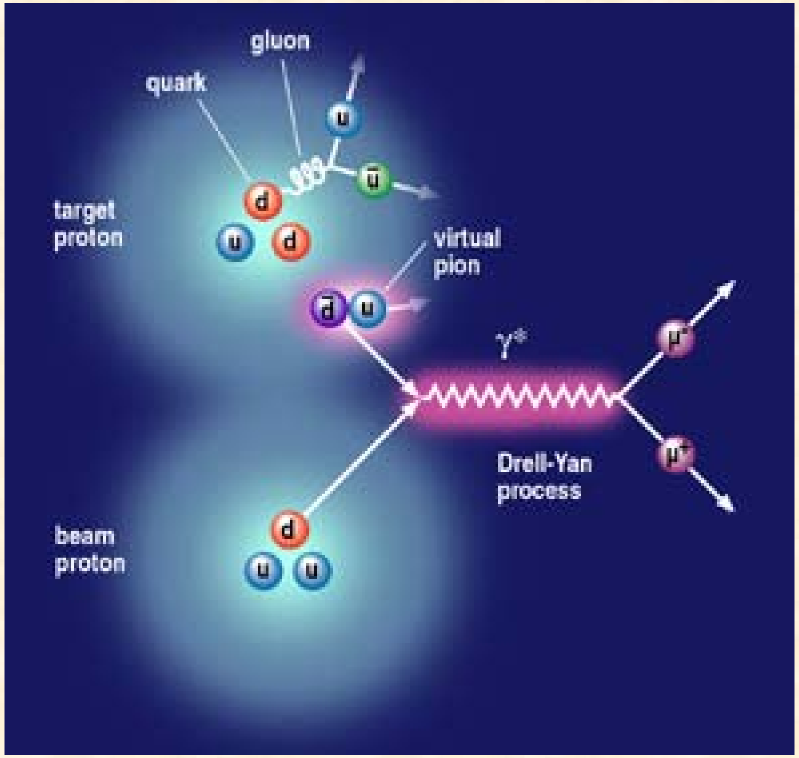
$\geq \frac{3}{14000} = 0.0002$ LHC **Small-*x* facility**

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

J.-C. Peng's talk



J-PARC proposal, M. Bai *et al.* (2007)



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

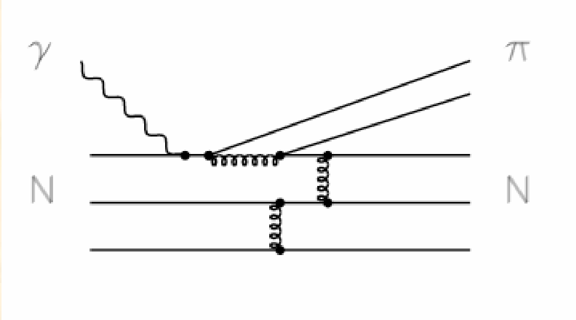
This project is suitable for probing "peripheral structure" of the nucleon.

SK, Phys. Rep. 303 (1998) 183;
G. T. Garvey and J.-C. Peng, Prog. Part. Nucl. Phys. 47 (2001) 203.

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.



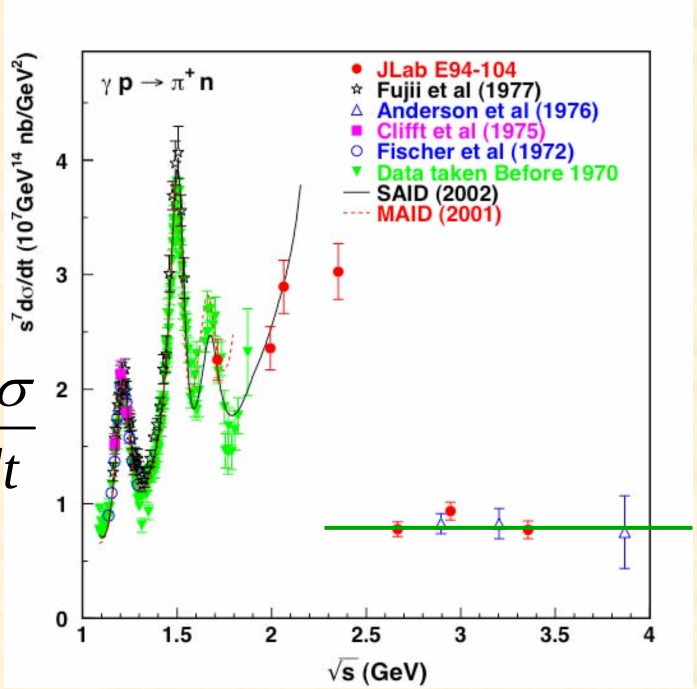
$\gamma p \to \pi^+ n$ **H. Gao**

Constituent counting rule

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

$n = n_A + n_B + n_C + c_D$
(total number of interacting elementary particles)

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



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

J-PARC: p + p → p + p

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

Investigate p A → p p (A-1)

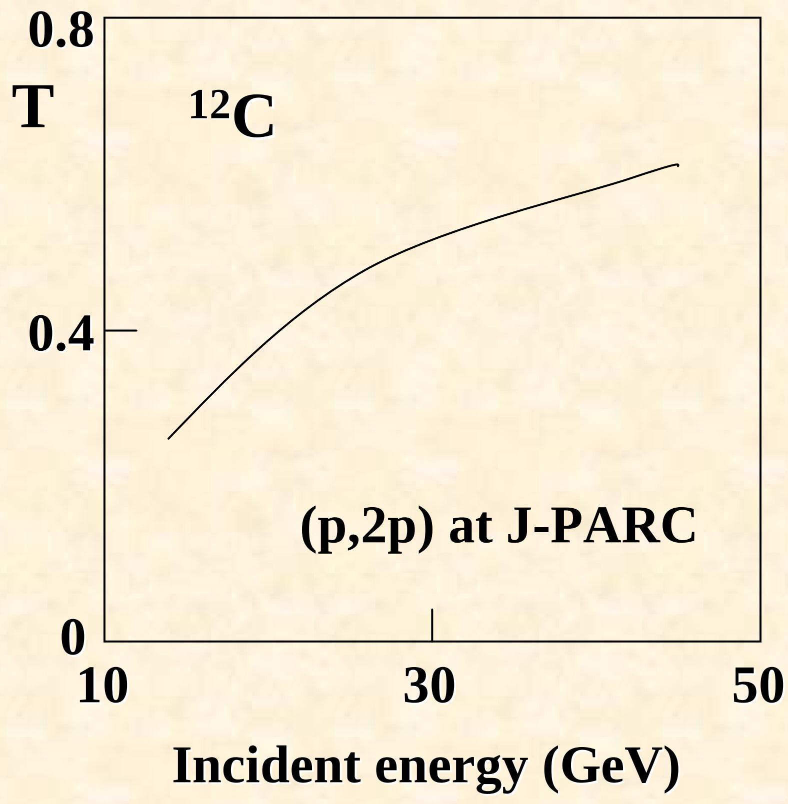
Nuclear transparency: $T = \dfrac{\sigma_A}{A\sigma_N}$

Hadron size ~ 1 / hard scale

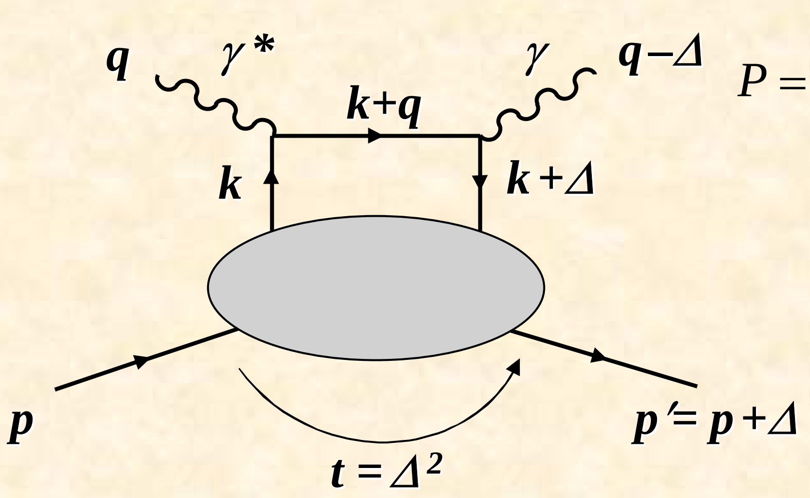
Color transparency:
T → larger, as the hard scale → larger

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

Possibility at J-PARC



Generalized Parton Distributions (GPDs)



$$P = \frac{p + p'}{2}, \quad \Delta = p' - p$$

GPDs are defined as correlation of off-forward matrix.

Bjorken variable $x = \dfrac{Q^2}{2p \cdot q}$

Momentum transfer squared $t = \Delta^2$

Skewdness parameter $\xi = \dfrac{p^+ - p'^+}{p^+ + p'^+} = -\dfrac{\Delta^+}{2P^+}$

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p' | \bar{\psi}(-z/2)\gamma^+\psi(z/2) | p \rangle \Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[H(x,\xi,t)\bar{u}(p')\gamma^+u(p) + E(x,\xi,t)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u(p) \right]$$

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p' | \bar{\psi}(-z/2)\gamma^+\gamma_5\psi(z/2) | p \rangle \Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[\tilde{H}(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5u(p) + \tilde{E}(x,\xi,t)\bar{u}(p')\frac{\gamma_5\Delta^+}{2M}u(p) \right]$$

Forward limit: PDFs

$$H(x,\xi,t)\big|_{\xi=t=0} = f(x), \quad \tilde{H}(x,\xi,t)\big|_{\xi=t=0} = \Delta f(x)$$

There is no analog in E and $\tilde{E}$.

First moments: Form factors

Dirac and Pauli form factors F_1, F_2

$$\int dx\, H(x,\xi,t) = F_1(t), \quad \int dx\, E(x,\xi,t) = F_2(t)$$

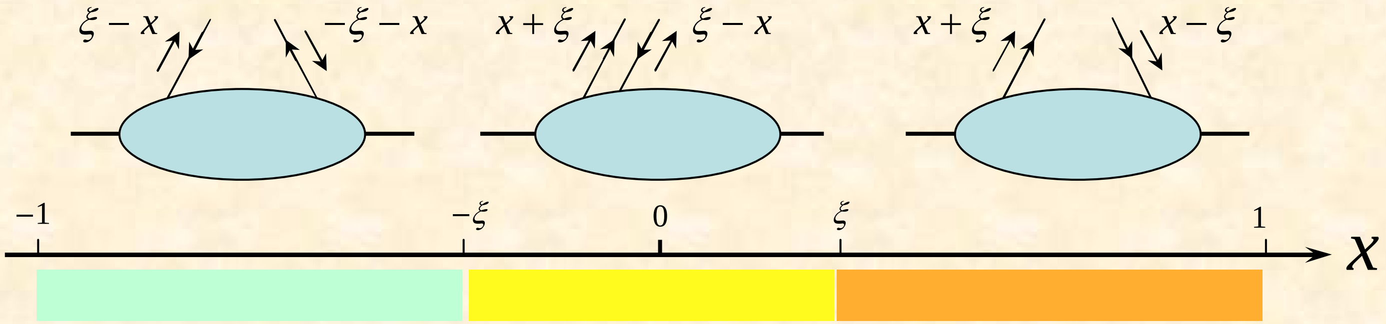
Axial and Pseudoscalar form factors G_A, G_P

$$\int dx\, \tilde{H}(x,\xi,t) = G_A(t), \quad \int dx\, \tilde{E}(x,\xi,t) = G_P(t)$$

Second moments: Angular momenta

Sum rule: $J_q = \dfrac{1}{2}\displaystyle\int dx\, x\left[H_q(x,\xi,t=0) + E_q(x,\xi,t=0) \right]$, $\quad J_q = \dfrac{1}{2}\Delta q + L_q$

GPDs in different *x* regions and GPDs at J-PARC



$-1 < x < \xi \quad (x+\xi < 0,\ x-\xi < 0)$ $\qquad$ $\xi < x < 1 \quad (x+\xi > 0,\ x-\xi > 0)$

$-\xi < x < \xi \quad (x+\xi > 0,\ x-\xi < 0)$

Quark distribution

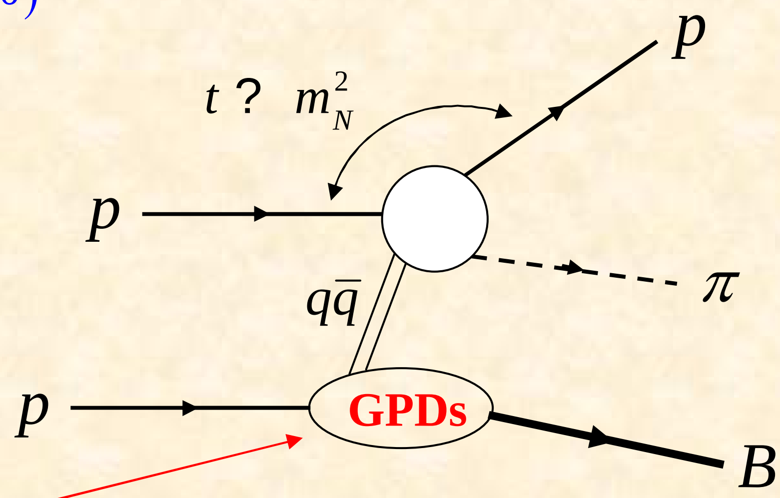
Emission of quark with momentum fraction $x+\xi$
Absorption of quark with momentum fraction $x-\xi$

Meson distribution amplitude

Emission of quark with momentum fraction $x+\xi$
Emission of antiquark with momentum fraction $\xi-x$

Antiquark distribution

Emission of antiquark with momentum fraction $\xi-x$
Absorption of antiquark with momentum fraction $-x-\xi$



GPDs at J-PARC:
SK, M. Strikman, K. Sudoh,
in progress.

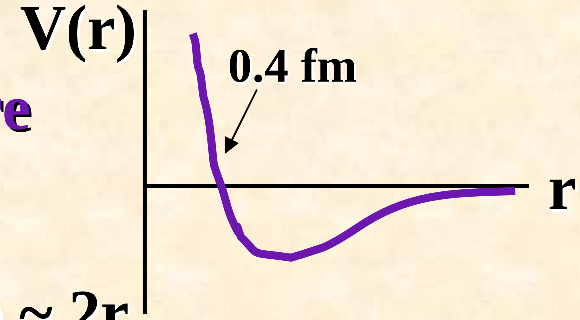
Short-range NN interaction

Ciofi degli Atti@J-PARC-NP07

Strikman@INPC07

E. Piasetzky et al.,
PRL97 (2006) 162504

- Short-range repulsive core, Tensor force
- Quark degrees of freedom
- Cold dense nuclear matter, Neutron star



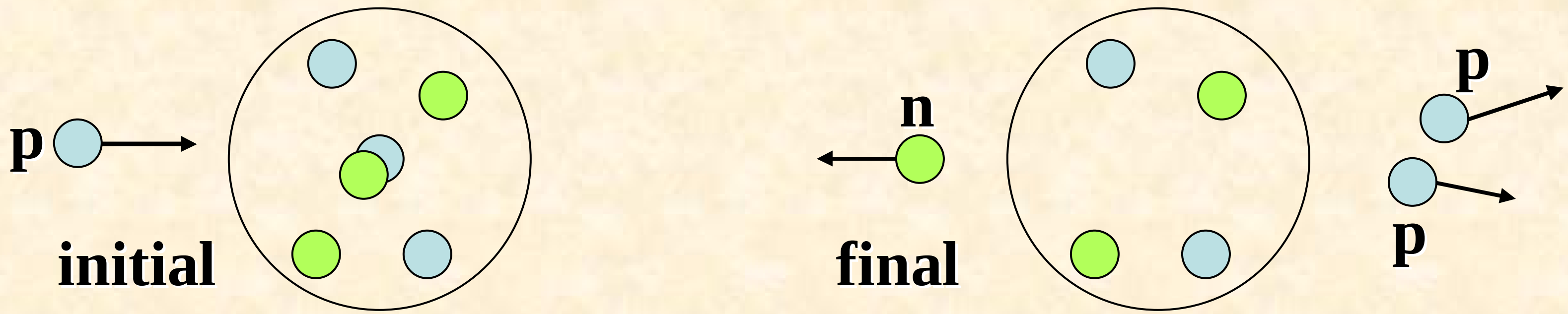
Nuclei do not collapse → Short-range repulsive core

Nucleon size r ≈ 0.8 fm

Average nucleon separation in a nucleus: R ≈ 2 fm ~ 2r

→The short-range part is important as the density becomes larger (neutron star).

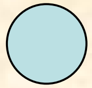
A(p, 2pN)X experiment for short range correlation



Single spin asymmetry

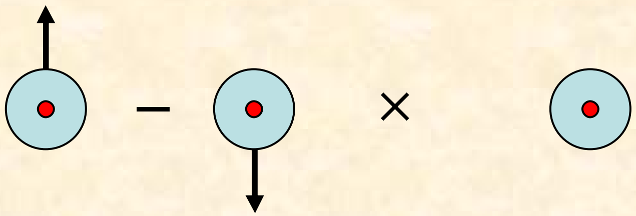
(No polarized proton beam is needed!)

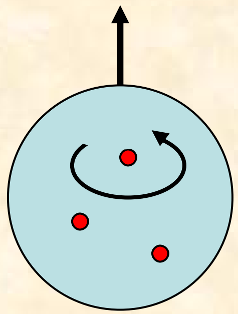
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

 **Nucleon**  **Quark**

- Sivers effect

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



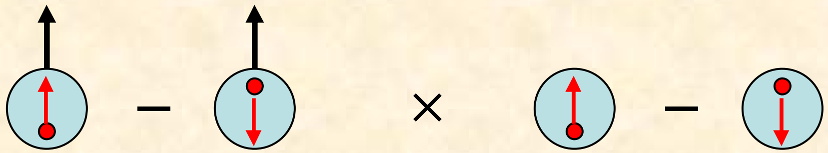


Burkardt @J-PARC-HS05

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

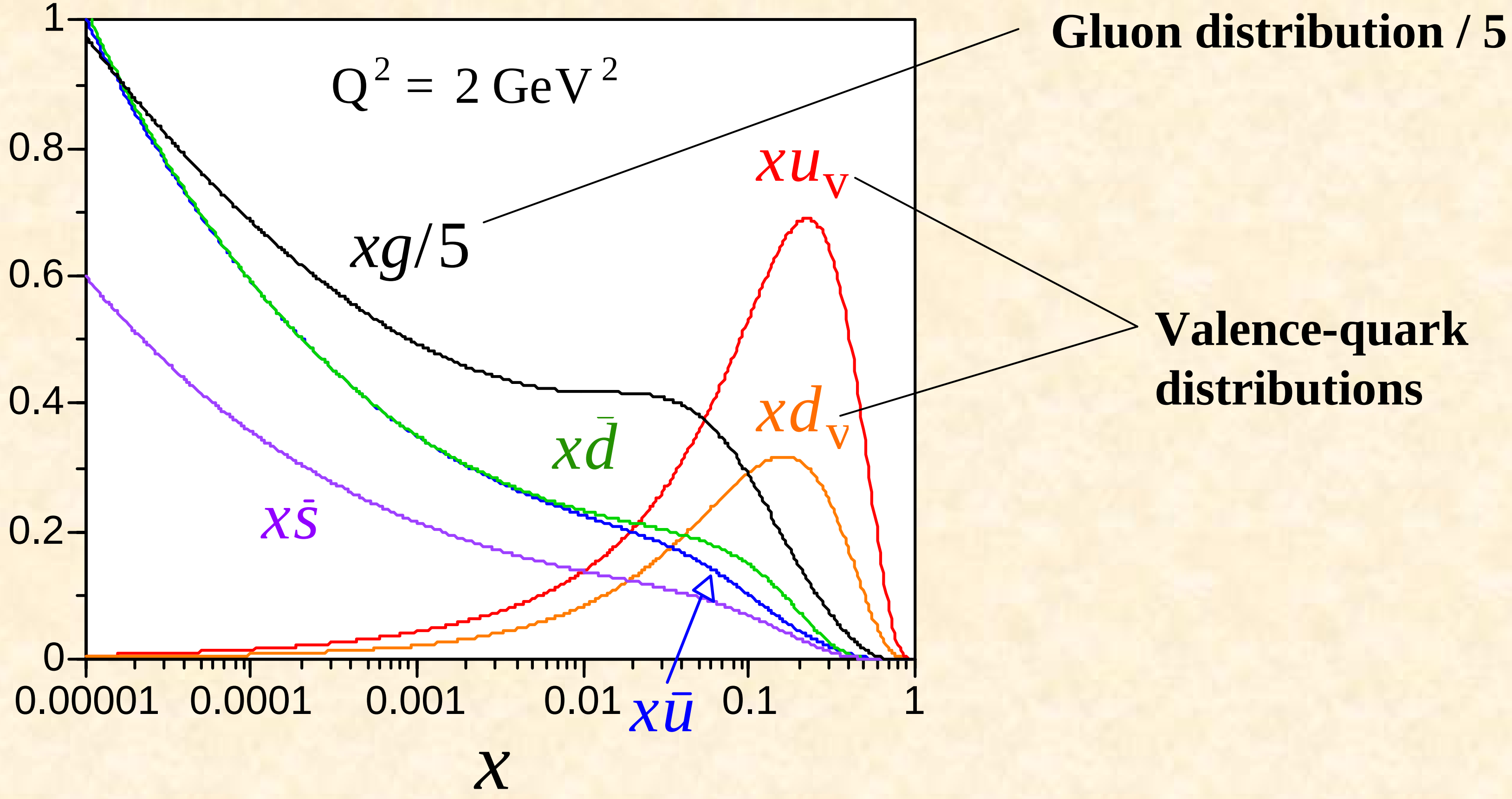
Part II

Parton Distribution Functions
and
Fragmentation Functions

in connection with J-PARC

Unpolarized Parton Distribution Functions (PDFs) in the nucleon

The PDFs could be obtained from
http://durpdg.dur.ac.uk/hepdata/pdf.html



PDF uncertainty

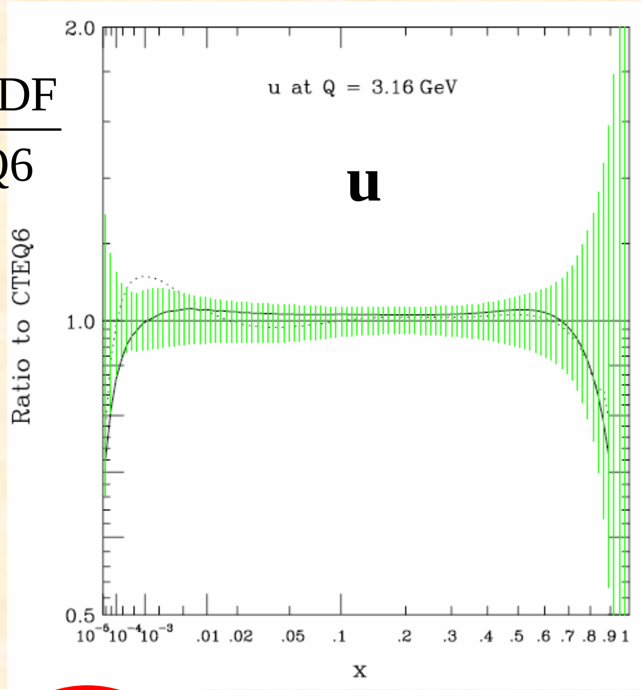
$\frac{\text{other PDF}}{\text{CTEQ6}}$

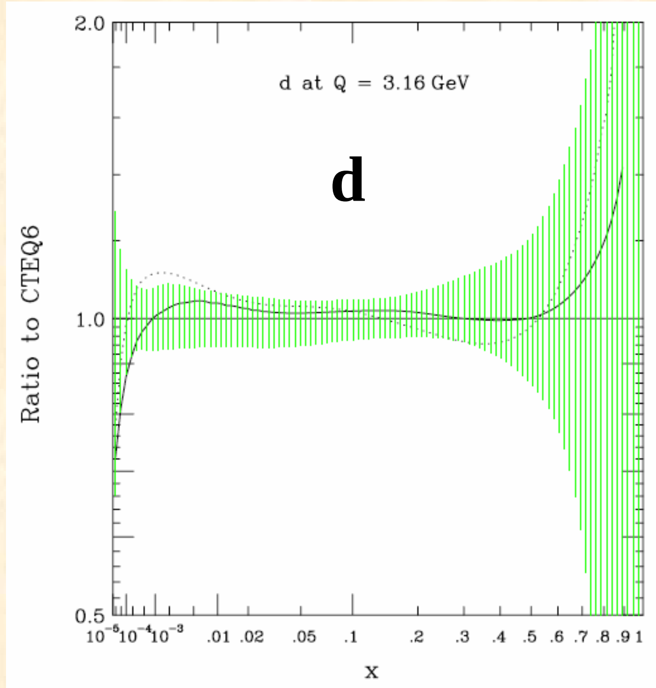
CTEQ6 (J. Pumplin *et al.*), JHEP 0207 (2002) 012

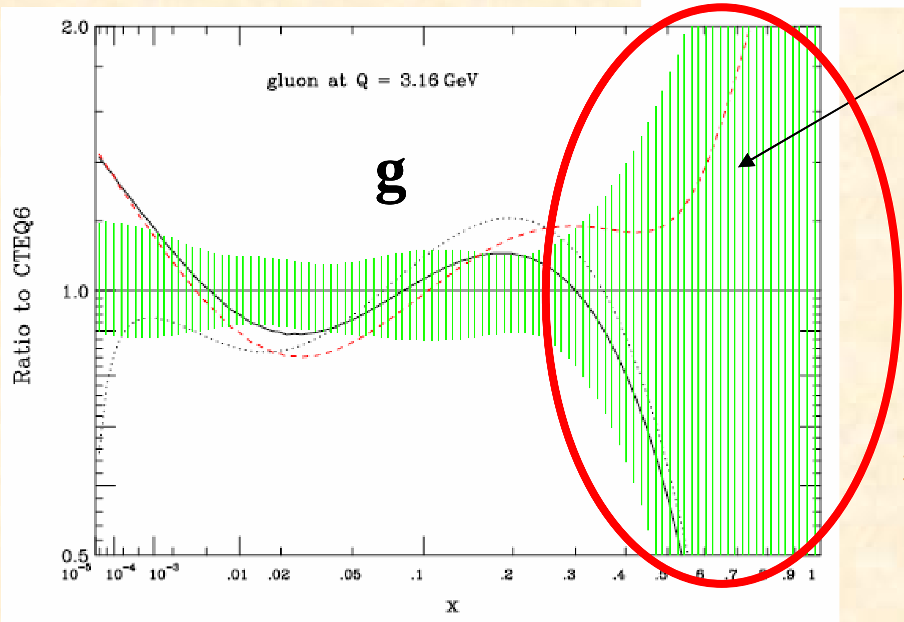
CTEQ5M1 (solid line)

MRS2001 (dotted line)

CTEQ5HJ (dashed line)







Important *x* region for finding an "exotic event" in a high-p_T region at LHC

J-PARC *x* region

If processes are well understood theoretically including pQCD terms, J-PARC measurements are important for finding new physics at LHC or possibly in cosmic rays.

Nuclear
Parton Distribution Functions

http://research.kek.jp/people/kumanos/nuclp.html

Experimental data: total number = 1241

(1) F_2^A / F_2^D 896 data

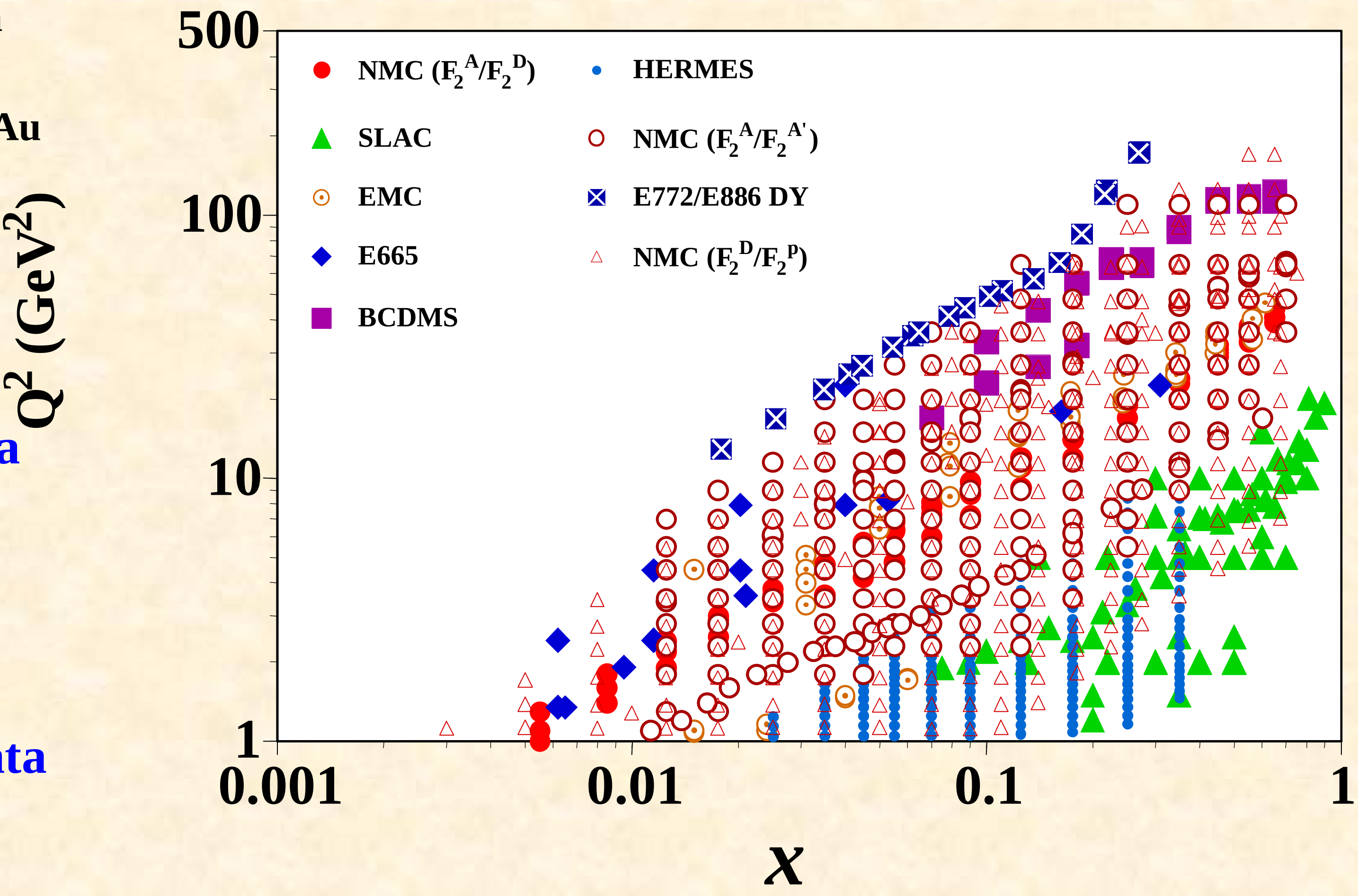
NMC: p, He, Li, C, Ca
SLAC: He, Be, C, Al, Ca, Fe, Ag, Au
EMC: C, Ca, Cu, Sn
E665: C, Ca, Xe, Pb
BCDMS: N, Fe
HERMES: N, Kr

(2) $F_2^A / F_2^{A'}$ 293 data

NMC: Be / C, Al / C, Ca / C, Fe / C, Sn / C, Pb / C, C / Li, Ca / Li

(3) $\sigma_{DY}^A / \sigma_{DY}^{A'}$ 52 data

E772: C / D, Ca / D, Fe / D, W / D
E866: Fe / Be, W / Be



Functional form

Nuclear PDFs "per nucleon"

If there were no nuclear modification

$$Au^A(x) = Zu^p(x) + Nu^n(x), \quad Ad^A(x) = Zd^p(x) + Nd^n(x) \qquad p = \text{proton}, \quad n = \text{neutron}$$

Isospin symmetry： $u^n = d^p \equiv d, \qquad d^n = u^p \equiv u$

$$\rightarrow \quad u^A(x) = \frac{Zu(x) + Nd(x)}{A}, \qquad d^A(x) = \frac{Zd(x) + Nu(x)}{A}$$

Take account of nuclear effects by $w_i(x, A)$

$$u_v^A(x) = w_{u_v}(x,A)\frac{Zu_v(x) + Nd_v(x)}{A}, \quad d_v^A(x) = w_{d_v}(x,A)\frac{Zd_v(x) + Nu_v(x)}{A}$$

$$\bar{u}^A(x) = w_{\bar{q}}(x,A)\frac{Z\bar{u}(x) + N\bar{d}(x)}{A}, \qquad \bar{d}^A(x) = w_{\bar{q}}(x,A)\frac{Z\bar{d}(x) + N\bar{u}(x)}{A}$$

$$\bar{s}^A(x) = w_{\bar{q}}(x,A)\bar{s}(x)$$

$$g^A(x) = w_g(x,A)g(x)$$

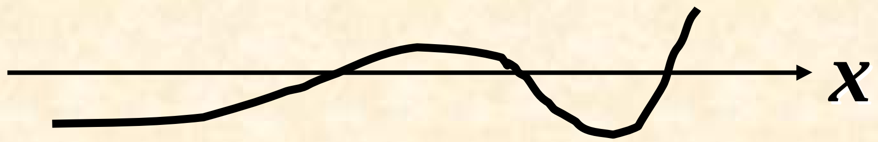
at Q^2=1 GeV^2 ($\equiv Q_0^2$)

Functional form of $w_i\,(x, A)$

$$f_i^A(x,Q_0^2) = w_i(x,A)\,f_i(x,Q_0^2) \qquad i = u_v,\ d_v,\ \bar{u},\ \bar{d},\ \bar{s},\ g$$

$$w_i(x,A) = 1 + \left(1 - \frac{1}{A^\alpha}\right)\frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^\beta}$$

Note: The region $x > 1$ cannot be described by this parametrization.



A simple function = cubic polynomial

Three constraints

Nuclear charge: $$Z = A\int dx\left[\frac{2}{3}\left(u^A - \bar{u}^A\right) - \frac{1}{3}\left(d^A - \bar{d}^A\right) - \frac{1}{3}\left(s^A - \bar{s}^A\right)\right] = A\int dx\left[\frac{2}{3}u_v^A - \frac{1}{3}d_v^A\right]$$

Baryon number: $$A = A\int dx\left[\frac{1}{3}\left(u^A - \bar{u}^A\right) + \frac{1}{3}\left(d^A - \bar{d}^A\right) + \frac{1}{3}\left(s^A - \bar{s}^A\right)\right] = A\int dx\left[\frac{1}{3}u_v^A + \frac{1}{3}d_v^A\right]$$

Momentum: $$A = A\int dx\left[u^A + \bar{u}^A + d^A + \bar{d}^A + s^A + \bar{s}^A + g\right]$$

$$= A\int dx\left[u_v^A + d_v^A + 2\left(\bar{u}^A + \bar{d}^A + \bar{s}^A\right) + g\right]$$

Analysis conditions

· **Nucleonic PDFs:** **MRST98** **[Λ_{QCD} = 174 MeV (LO), 300 MeV (NLO)]**

· **Total number of parameter : 12**

· **Total number of data : 1241 ($Q^2 \geqq 1$ GeV^2)**

896 (F_2^A/F_2^D) + 293 ($F_2^A/F_2^{A'}$) + 52 (Drell-Yan)

· **Subroutine for χ^2 analysis : CERN-Minuit**

$$\chi^2 = \sum_i \frac{\left(R_i^{data} - R_i^{theo}\right)^2}{\left(\sigma_i^{data}\right)^2}$$

$$R = \frac{F_2^A}{F_2^D}, \quad \frac{F_2^A}{F_2^{A'}}, \quad \frac{\sigma^{pA}}{\sigma^{pA'}}$$

$$\sigma_i^{data} = \sqrt{\left(\sigma_i^{sys}\right)^2 + \left(\sigma_i^{stat}\right)^2}$$

χ^2_{min} (/d.o.f.) = 1653.3 (1.35) ….. LO

= 1485.9 (1.21) ….. NLO

· **Error estimate : Hessian method**

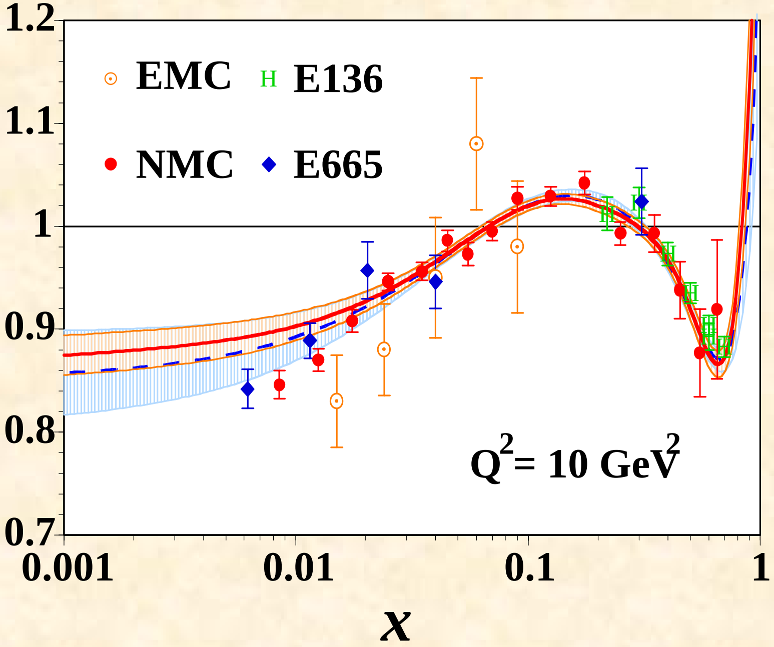
$$\left[\delta F(x)\right]^2 = \Delta\chi^2 \sum_{i,j} \frac{\partial F(x)}{\partial \xi_i} H_{ij}^{-1} \frac{\partial F(x)}{\partial \xi_j}$$

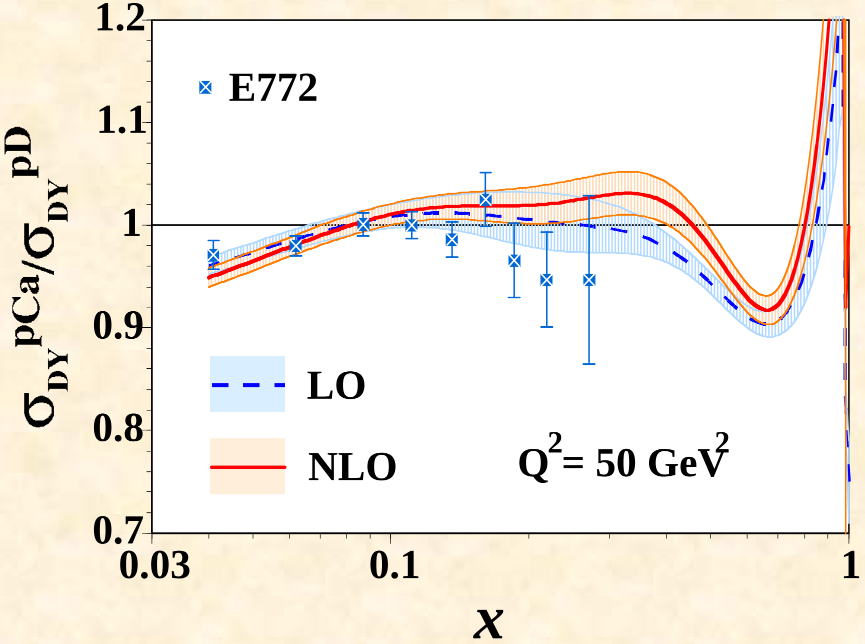
H_{ij} = Hessian

ξ_i = parameter

Comparison with F_2^{Ca}/F_2^{D} & $\sigma_{DY}^{pCa}/\sigma_{DY}^{pD}$ data

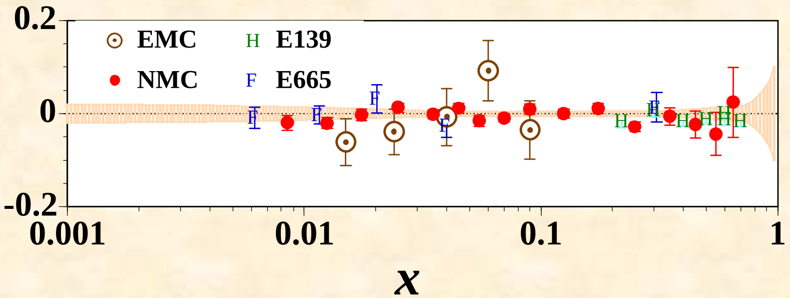
LO analysis **NLO analysis**

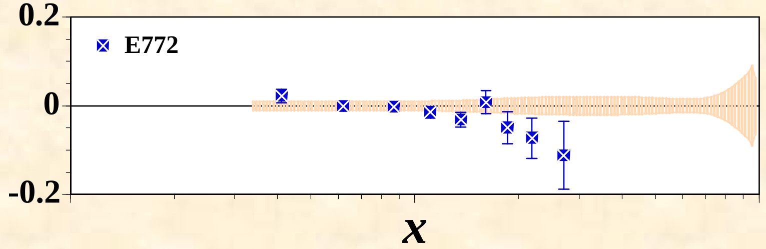




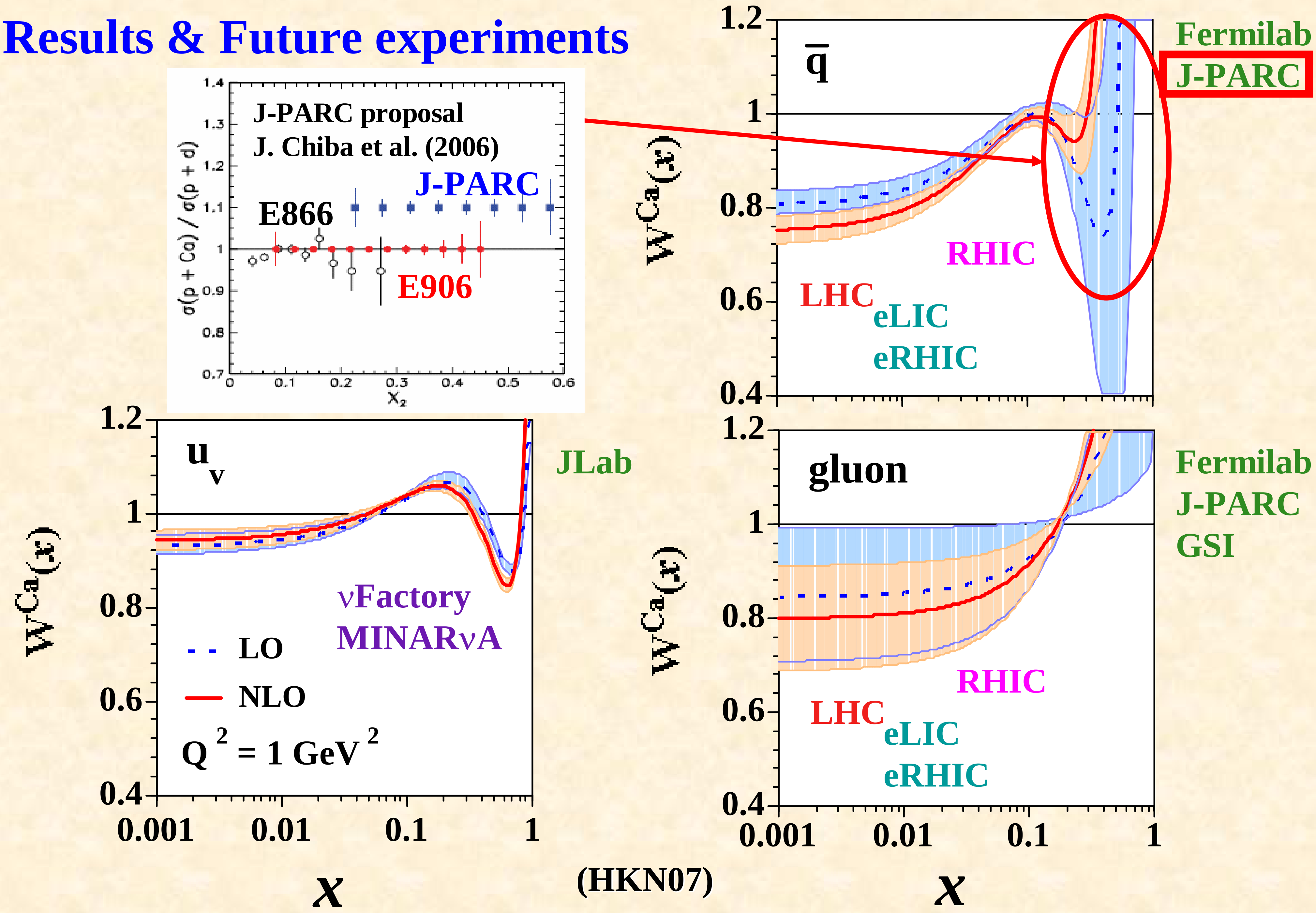
$(R^{exp}-R^{theo})/R^{theo}$ at the same Q^2 points

$R= F_2^{Ca}/F_2^{D},\ \sigma_{DY}^{pCa}/\sigma_{DY}^{pD}$





Results & Future experiments

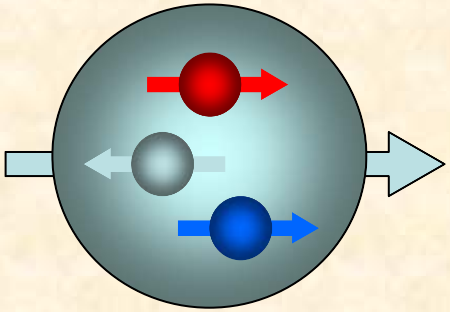


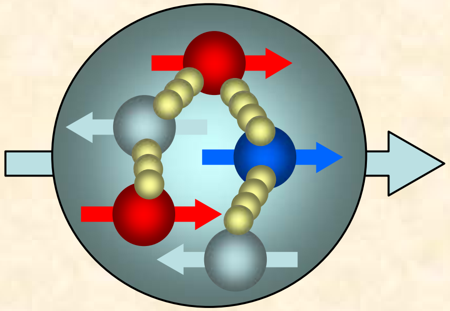
(HKN07)

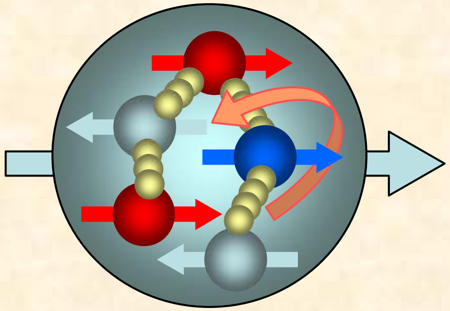
Polarized
Parton Distribution Functions

http://spin.riken.bnl.gov/aac/

Nucleon Spin







Naïve Quark Model

$$\Delta\Sigma = \Delta u_v + \Delta d_v = 1$$

Electron / muon scattering

$$\Delta\Sigma \approx 0.1 \sim 0.3$$

Almost none of nucleon spin is carried by quarks!

QCD

Sea-quarks and gluons?

Gluon: ΔG

Sea-quarks: Δq_{sea}

Recent data indicate ΔG is small at x ~ 0.1.

Orbital angular momenta ?

$$L_q, L_g$$

Future experiments

Nucleon Spin: $$\frac{1}{2} = \frac{1}{2}\underbrace{\left(\Delta u_v + \Delta d_v + \Delta q_{sea}\right)}_{\Delta\Sigma} + \Delta G + L_q + L_g$$

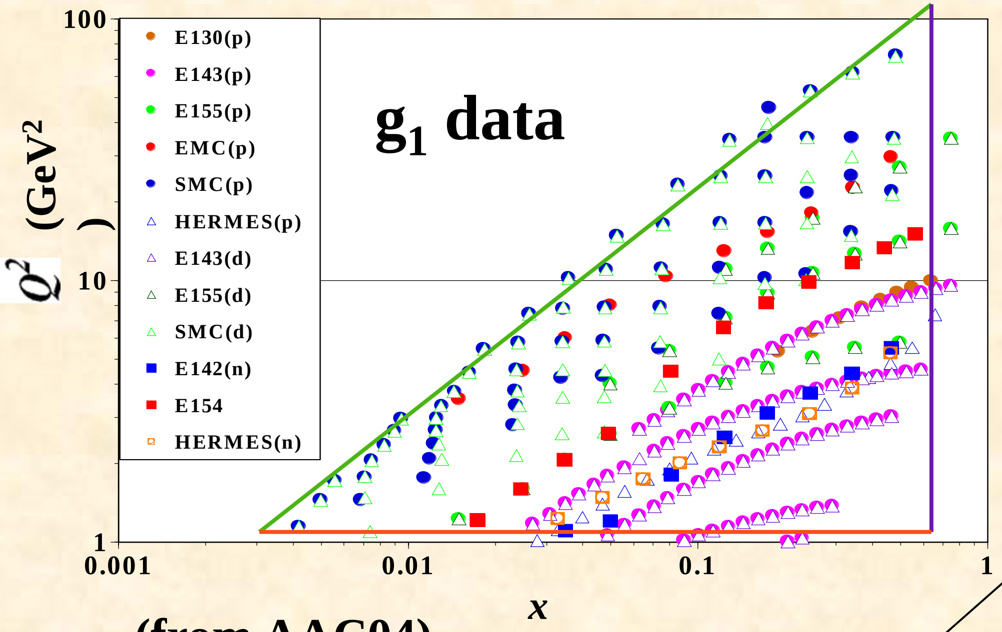
Current polarized data are kinematically limited.

$$x = \frac{Q^2}{2\,p \cdot q}\;;\;\frac{Q^2}{ys}$$

fixed target: $\min(x) = \dfrac{Q^2}{2M_N E_{lepton}} \le \dfrac{1}{2E_{lepton}(\text{GeV})}$

if $Q^2 \ge 1\ \text{GeV}^2$

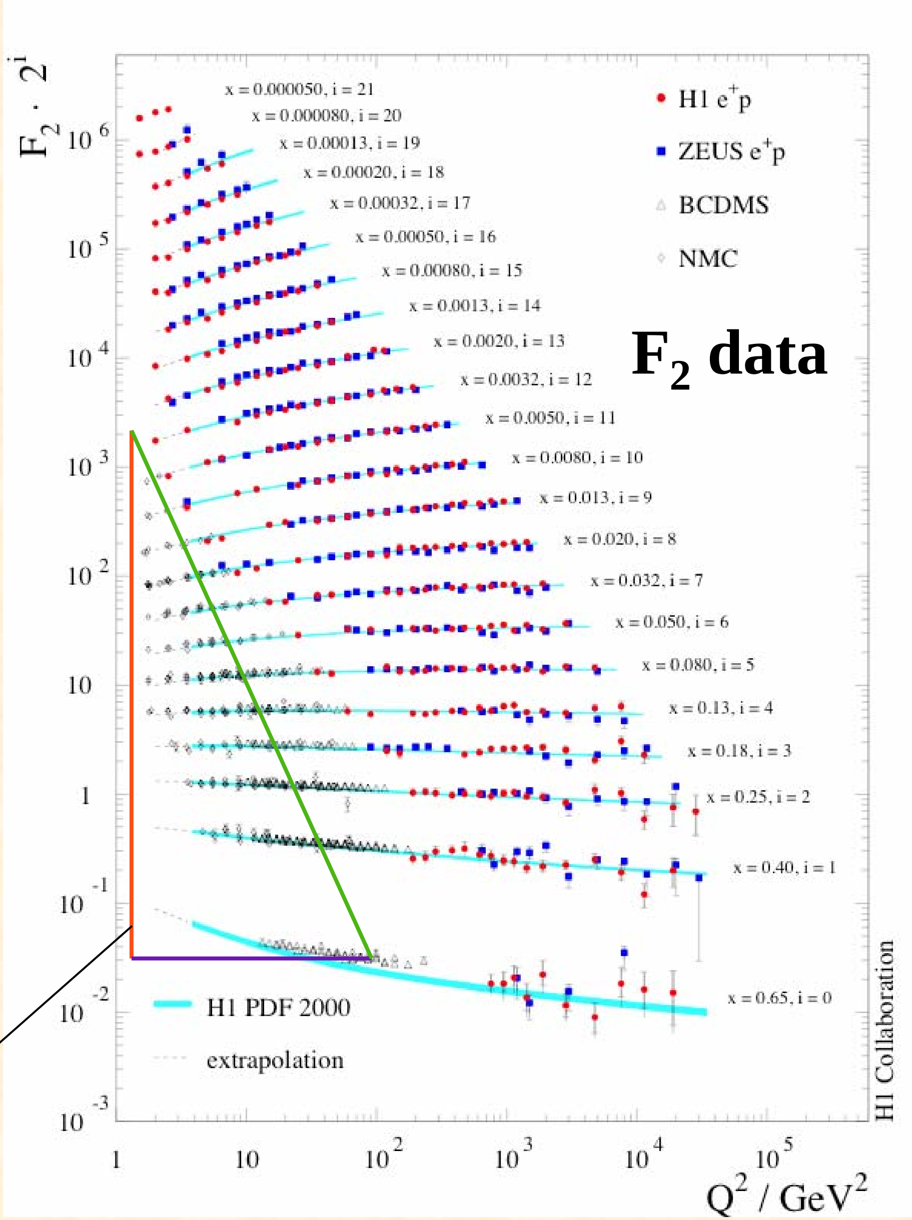
for $E_{lepton}(\text{SMC}) = 190\ \text{GeV},\ \min(x) = \dfrac{1}{400} = 0.003$



(from AAC04)

region of g_1 data

(from H1 and ZEUS, hep-ex/0502008)



General strategies for determining polarized PDFs

Spin asymmetry $A_1 \; ; \; g_1 \dfrac{2x\left(1+R\right)}{F_2}$ $\qquad R \equiv \dfrac{F_L}{2xF_1} = \dfrac{F_2 - 2xF_1}{2xF_1}$

$$g_1(x,Q^2) = \frac{1}{2}\sum_q e_q^2 \int_x^1 \frac{dy}{y}\left[\Delta q(x/y,Q^2) + \Delta\bar{q}(x/y,Q^2)\right]\left[\delta(1-y) + \frac{\alpha_s(Q^2)}{2\pi}\Delta C_q(y) + \cdots\right]$$

$$+\frac{1}{2}\left\langle e_q^2 \right\rangle \int_x^1 \frac{dy}{y}\Delta g(x/y,Q^2)\left[n_f \frac{\alpha_s(Q^2)}{2\pi}\Delta C_g(y) + \cdots\right] \qquad \left\langle e_q^2 \right\rangle = \frac{1}{n_f}\sum_q e_q^2$$

Leading Order (LO) **Next to Leading Order (NLO)**

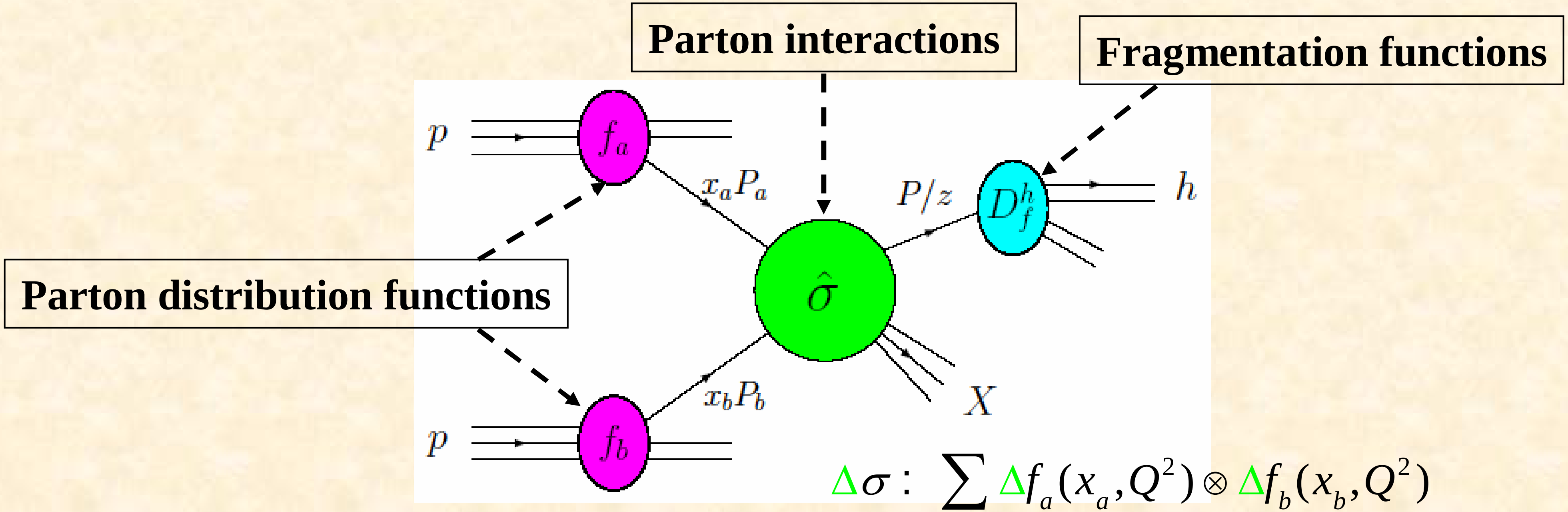
ΔC_q (ΔC_g) = quark (gluon) coefficient function

$$F_2(x,Q^2) = x\sum_q e_q^2 \int_x^1 \frac{dy}{y}\left[q(x/y,Q^2) + \bar{q}(x/y,Q^2)\right]\left[\delta(1-y) + \frac{\alpha_s(Q^2)}{2\pi}C_q^{(2)}(y) + \cdots\right]$$

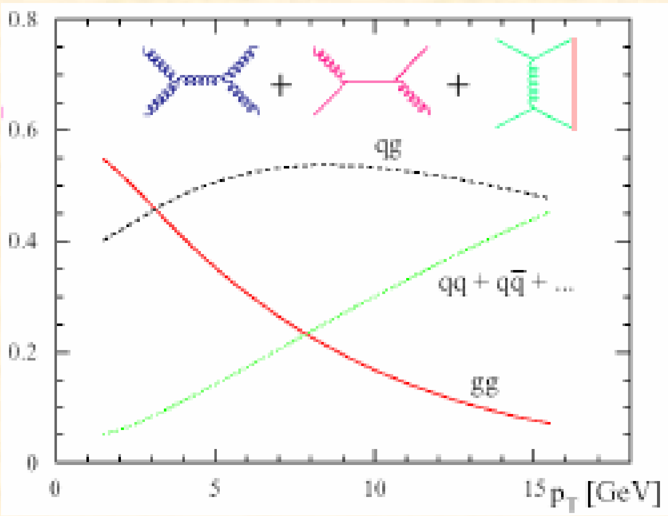
$$+\,x\left\langle e_q^2 \right\rangle \int_x^1 \frac{dy}{y}\, g(x/y,Q^2)\left[n_f \frac{\alpha_s(Q^2)}{2\pi}C_g^{(2)}(y) + \cdots\right]$$

Unpolarized PDFs

Description of π^0 production



$$\Delta\sigma : \sum_{a,b,c} \Delta f_a(x_a, Q^2) \otimes \Delta f_b(x_b, Q^2) \otimes \Delta\hat{\sigma}(ab \to cX) \otimes D_c^{\pi}(z, Q^2)$$



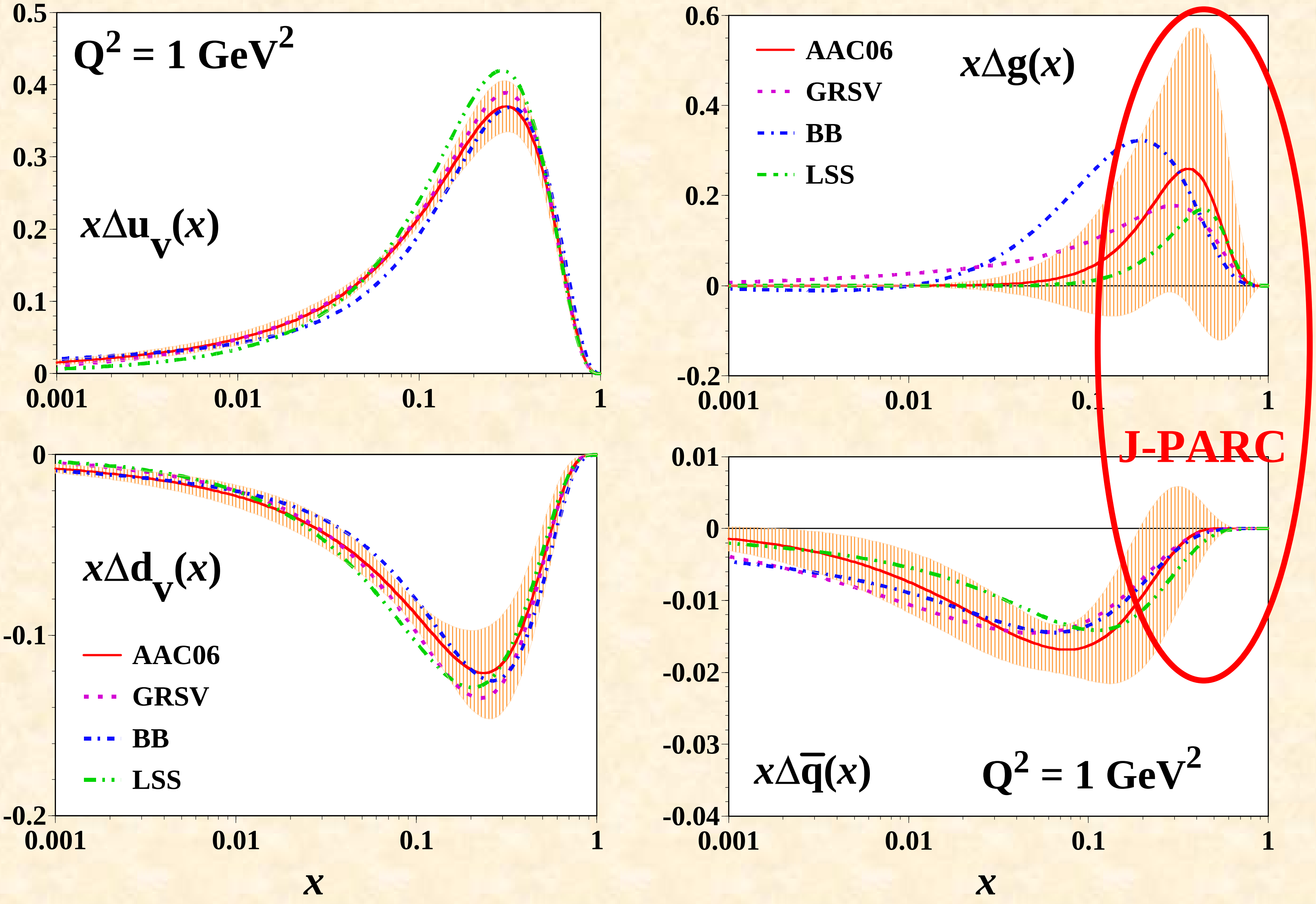
$g + g \to q(g) + X$ processes are dominant at small p_T

$q + g \to q(g) + X$ at large p_T

The π^0 production process is suitable for finding the gluon polarization Δg.

Situation of polarized PDFs

Gluon and antiquark distributions have large uncertainties at large *x*.



Fragmentation Functions

http://research.kek.jp/people/kumanos/ffs.html

Purposes of investigating fragmentation functions

Semi-inclusive reactions have been used for investigating

- **origin of proton spin**

  $\vec{e} + \vec{p} \to e' + h + X$ (e.g. HERMES), $\vec{p} + \vec{p} \to h + X$ (RHIC-Spin)

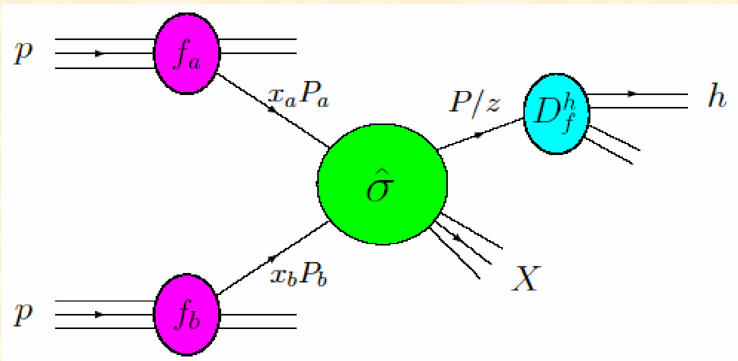
  Quark, antiquark, and gluon contributions to proton spin

  (flavor separation, gluon polarization)

- **properties of quark-hadron matters** $A + A' \to h + X$ (RHIC, LHC)

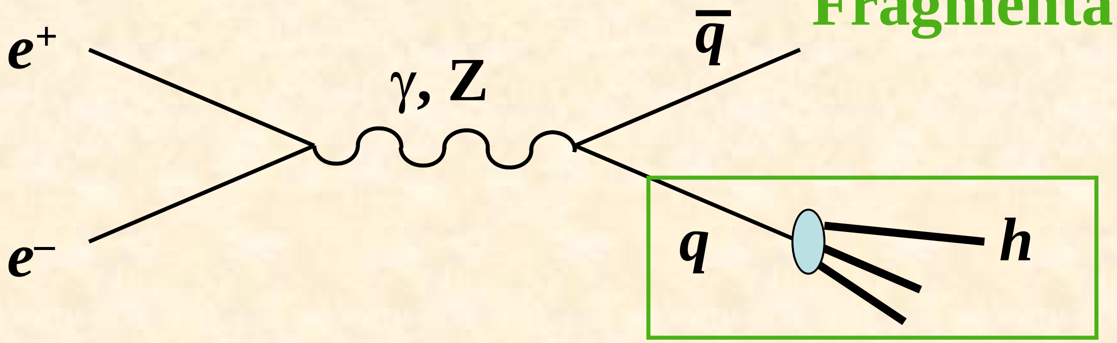
  Nuclear modification

  (recombination, energy loss, …)



$$\sigma = \sum_{a,b,c} f_a(x_a, Q^2) \otimes f_b(x_b, Q^2) \otimes \hat{\sigma}(ab \to cX) \otimes D_c^{\pi}(z, Q^2)$$

Fragmentation Function



Fragmentation: **hadron production from a quark, antiquark, or gluon**

$$z \equiv \frac{E_h}{\sqrt{s}/2} = \frac{2E_h}{Q} = \frac{E_h}{E_q}, \quad s = Q^2$$

Fragmentation function is defined by

$$F^h(z,Q^2) = \frac{1}{\sigma_{tot}} \frac{d\sigma(e^+e^- \to hX)}{dz}$$

σ_{tot} = total hadronic cross section

Variable *z*
- **Hadron energy / Beam energy**
- **Hadron energy / Primary quark energy**

A fragmentation process occurs from quarks, antiquarks, and gluons, so that F^h is expressed by their individual contributions:

$$F^h(z,Q^2) = \sum_i \int_z^1 \frac{dy}{y} C_i\left(\frac{z}{y},Q^2\right) D_i^h(y,Q^2)$$

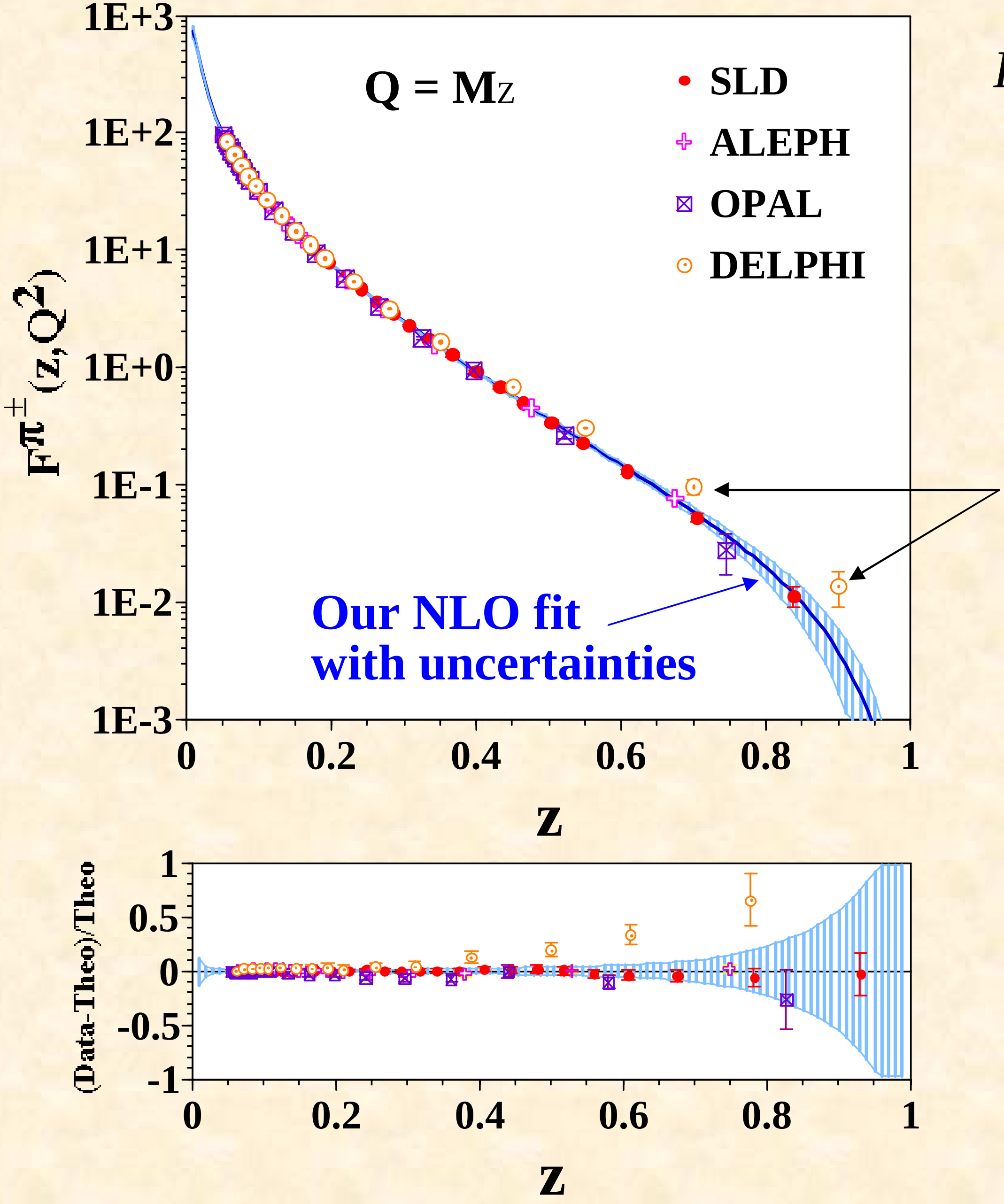
Calculated in perturbative QCD

Non-perturbative (determined from experiments)

$C_i(z,Q^2)$ = coefficient function

$D_i^h(z,Q^2)$ = fragmentation function of hadron *h* from a parton *i*

Comparison with pion data



$$F^{\pi^\pm}(z,Q^2) = \frac{1}{\sigma_{tot}} \frac{d\sigma(e^+e^- \to \pi^\pm X)}{dz}$$

Our fit is successful to reproduce the pion data.

The DELPHI data deviate from our fit at large z.

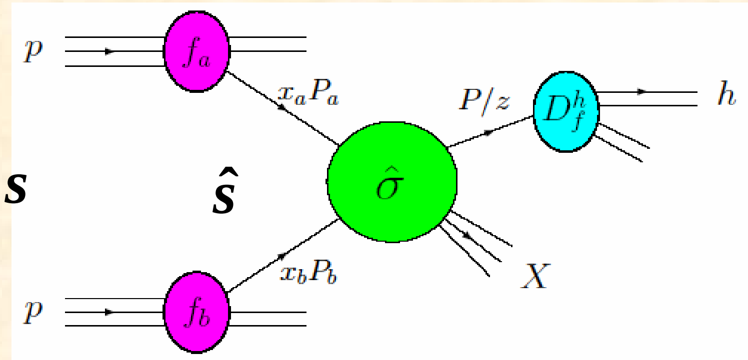
Rational difference between data and theory

$$\frac{F^{\pi^\pm}(z,Q^2)_{data} - F^{\pi^\pm}(z,Q^2)_{theory}}{F^{\pi^\pm}(z,Q^2)_{theory}}$$

Fragmentation functions at J-PARC

Gluon and light-quark fragmentation functions have large uncertainties.

Large differences between the functions of various analysis groups.

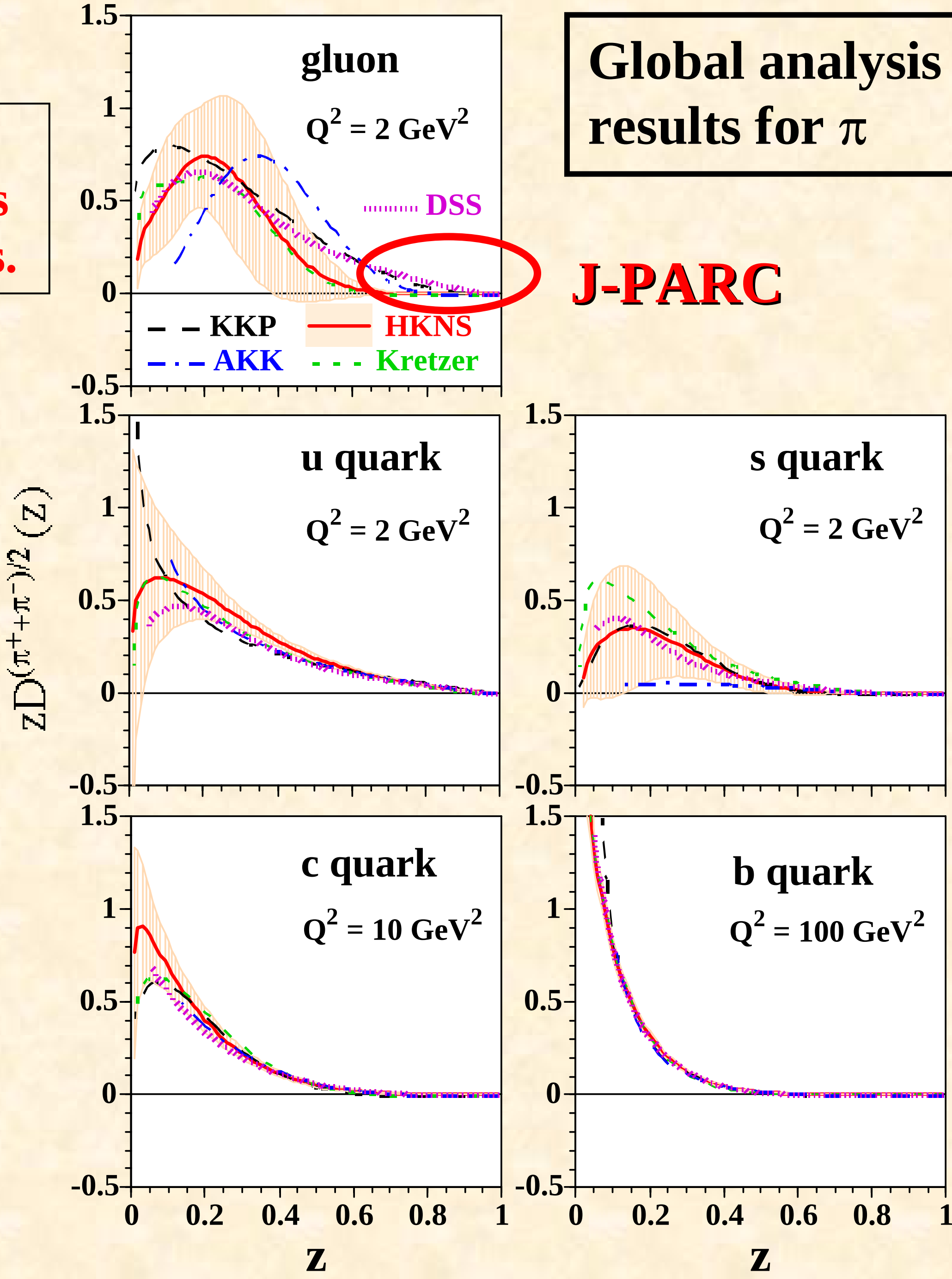


$$\hat{s} = x_a x_b s \sim (0.4)^2 (10\ \text{GeV})^2$$

$$\sqrt{\hat{s}} = 0.4 \cdot 10 = 4\ \text{GeV}$$

$$z \sim \frac{p_T}{\sqrt{\hat{s}}/2} = \frac{p_T}{2} \sim 1 \quad (\text{large } z)$$

Global analysis results for π



Exotic hadron search
by fragmentation functions

f_0(980) as an example

Criteria for determining f_0 structure by its fragmentation functions

Possible configurations of $f_0(980)$

(1) ordinary u, d - meson $\quad \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$

Contradicts with experimental widths

$\Gamma_{\text{theo}}(f_0 \to \pi\pi) = 500 - 1000 \text{ MeV}$

$? \quad \Gamma_{\text{exp}} = 40 - 100 \text{ MeV}$

$\Gamma_{\text{theo}}(f_0 \to \gamma\gamma) = 1.3 - 1.8 \text{ keV}$

$? \quad \Gamma_{\text{exp}} = 0.205 \text{ keV}$

(2) strange meson, $\quad s\bar{s}$

(3) tetraquark ($K\bar{K}$), $\quad \frac{1}{\sqrt{2}}(u\bar{u}s\bar{s} + d\bar{d}s\bar{s})$

(4) glueball $\quad gg$

Contradicts with lattice-QCD estimate

$m_{\text{lattice}}(f_0) = 1600 \text{ MeV}$

$? \quad m_{\text{exp}} = 980 \text{ MeV}$

Discuss 2nd moments and functional forms (peak positions) of the fragmentation functions for f_0 by assuming the above configurations, (1), (2), (3), and (4).

Tensor Structure at High-Energies For Spin-1 Hadrons

Note: Proton-beam polarization is not needed.
Polarized deuteron target is enough at J-PARC!

http://www-conf.kek.jp/J-PARC-HS05/program.html

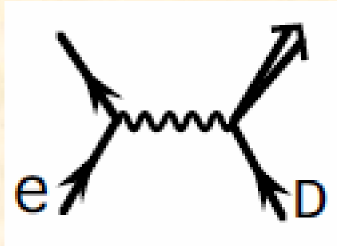
Tensor Structure in High-energy Reactions

(Note: No polarized proton beam is needed!)

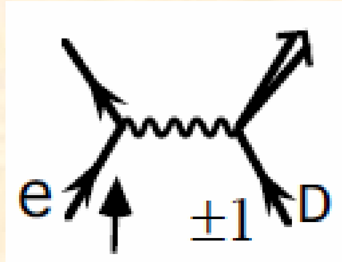
L. L. Frankfurt and M. I. Strikman, NP A405 (1983) 557.
P. Hoodbhoy, R. L. Jaffe, and A. Manohar, NP B312 (1989) 571.

Structure Functions (in e scattering)

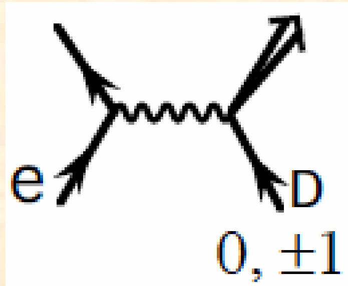
$$F_1 \propto \langle d\sigma \rangle$$



$$g_1 \propto d\sigma(\uparrow, +1) - d\sigma(\uparrow, -1)$$



$$b_1 \propto d\sigma(0) - \frac{d\sigma(+1) + d\sigma(-1)}{2}$$



Parton Model

$$F_1 = \frac{1}{2}\sum_i e_i^2 \left(q_i + \bar{q}_i\right) \qquad q_i = \frac{1}{3}\left(q_i^{+1} + q_i^{0} + q_i^{-1}\right)$$

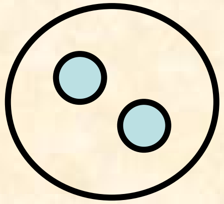
$$g_1 = \frac{1}{2}\sum e_i^2 \left(\Delta q_i + \Delta\bar{q}_i\right) \qquad \Delta q_i = q_{i\uparrow}^{+1} - q_{i\downarrow}^{+1}$$

$$\left[q_\uparrow^H\left(x, Q^2\right)\right] \qquad b_1 = \frac{1}{2}\sum_i e_i^2 \left(\delta q_i + \delta\bar{q}_i\right) \qquad \delta q_i = q_i^{0} - \frac{q_i^{+1} + q_i^{-1}}{2}$$

Tensor Structure in Proton-Deuteron Drell-Yan

b_1 for spin-1 particles

(Note: No polarized proton beam is needed!)



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

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

Spin asymmetries

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

Polarized proton-deuteron Drell-Yan
(Theory) S. Hino and SK,
PR D 59 (1999) 094026,
D 60 (1999) 054018.
(Experiment) None → J-PARC

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

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

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

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

Unpolarized proton
+ Tensor polarized deuteron

Unique advantage of J-PARC ($\delta\bar{q}$ measurement)

$$\int dx\, b_1^D(x) = 0 + \frac{1}{9}\left(\delta Q + \delta \bar{Q}\right)_{sea}$$

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

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

Gottfried: $$\int \frac{dx}{x} \left[F_2^p(x) - F_2^n(x) \right] = \frac{1}{3} + \frac{2}{3} \int dx \left[\bar{u} - \bar{d} \right]$$

Our works related to this talk

(1) Overview on "Possible Hadron Physics at J-PARC"
SK, Nucl. Phys. A782 (2007) 442.

(2) ubar/dbar
SK, Phys. Rep. 303 (1998) 183.

(3) Nuclear PDFs
M. Hirai, SK, and M. Miyama, Phys. Rev. D 64 (2001) 034003;
M. Hirai, SK, and T.-H. Nagai, Phys. Rev. C 70 (2004) 044905; C 76 (2007) 065207.

(4) Polarized PDFs, Asymmetry Analysis Collaboration (AAC)
Y. Goto *et al.*, Phys. Rev. D 62 (2000) 034017;
M. Hirai, SK, N. Saito, Phys. Rev. D 69 (2004) 054021; D 74 (2006) 014015.

(5) Global analyses for FFs of π, K, and p + their uncertainties
M. Hirai, SK, T.-H. Nagai, and K. Sudoh, Phys. Rev. D75 (2007) 094009;
Exotic hadron search by using FFs *e.g.* for $f_0(980)$
M. Hirai, SK, M. Oka, and K. Sudoh, Phys. Rev. D77 (2008) 017504.

(6) Sum rule for $b_1(x)$
F. E. Close and SK, Phys. Rev. D 42 (1990) 2377.
General formalism for polarized proton+deuteron Drell-Yan
S. Hino and SK, Phys. Rev. D 59 (1999) 094026; D 60 (1999) 054018.

Summary

J-PARC will be an important facility in hadron and nuclear physics communities.

In high-energy hadron physics

- **Structure functions of hadrons**
- **Fragmentation**
- **Hadron interactions in nuclear medium**
- **Short-range NN interactions**
- **Hadron $\rightarrow$ Quark degrees of freedom**
- **Hadron spin**
- **…**

I introduced some topics. More contributions are needed for the hadron project at J-PARC!

Need to discuss possible topics with 30 GeV, 50 GeV, and 50 GeV polarized proton beams.

The End

The End