High-momentum beamline projects at J-PARC

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Nuclear Structure and Dynamics at Short Distances (INT 13-52W)
February 11 - 22, 2013, INT, University of Washington, USA
http://www.int.washington.edu/PROGRAMS/13-52w/

February 22, 2013

Contents

I explain a general view without stepping into project details. It is up to you (users) to define the J-PARC hadron physics, especially at the high-momentum beamline.

Introduction

- J-PARC facility
- Hadron physics at J-PARC
- Theory activities at J-PARC

Hadron physics with high-momentum beams

- Hadron masses in nuclear medium
- Exotic hadrons, Charm physics
- Hard processes

  Unsolved mysteries of BNL-AGS, Origin of nucleon spin,

  Hadron tomography (somewhat my personal interest at this stage)

Summary and Prospects

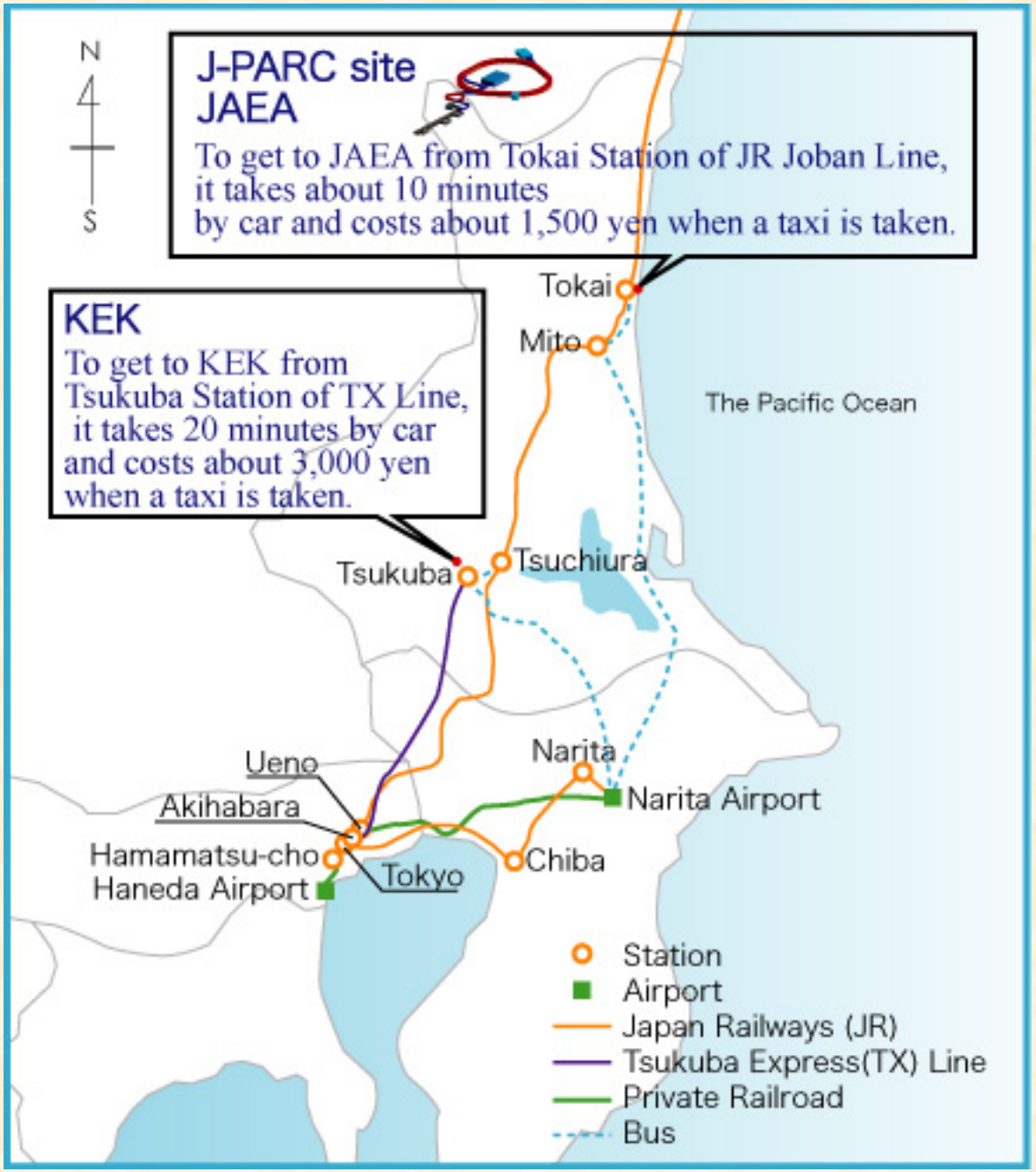
Introduction

J-PARC Facility

J-PARC location

J-PARC
(Japan Proton Accelerator Research Complex)

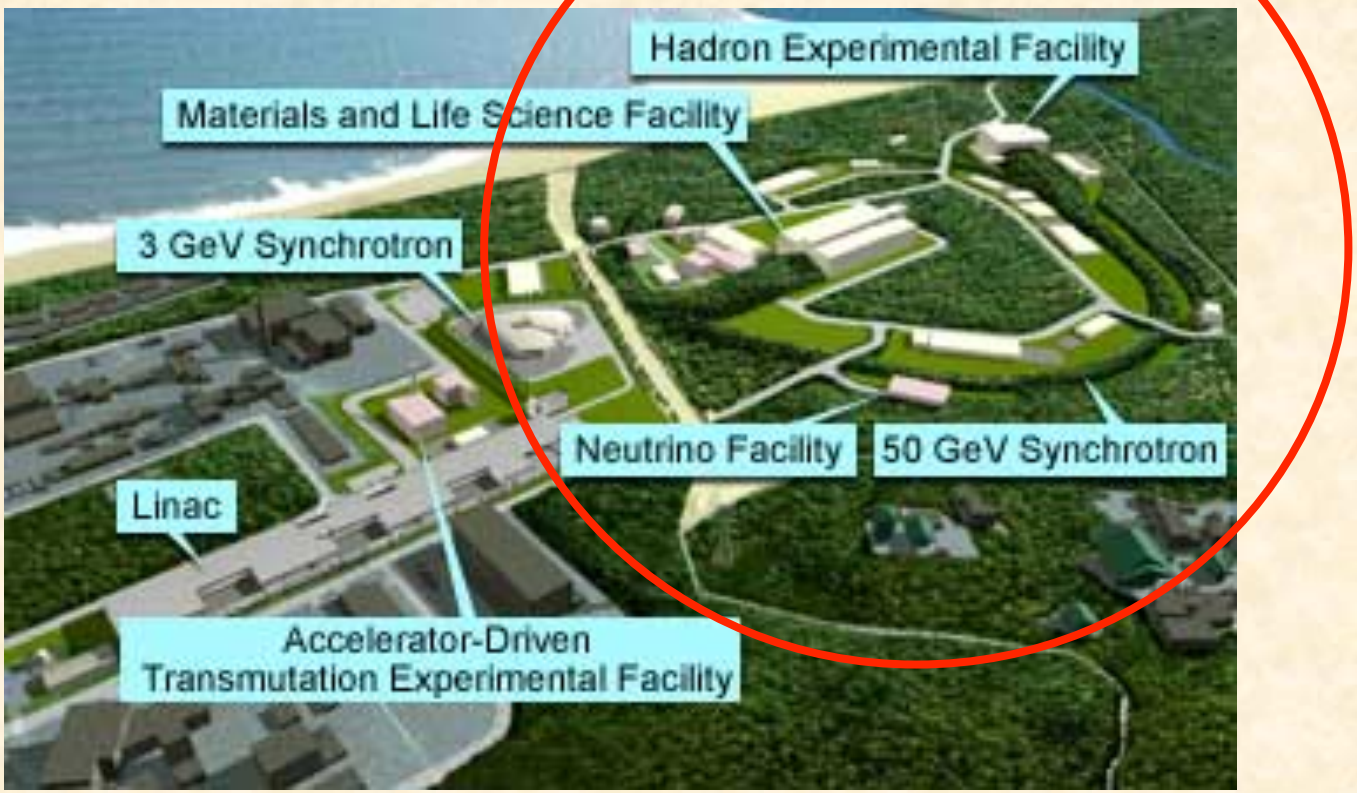
http://j-parc.jp/index-e.html



Bird's-eye view

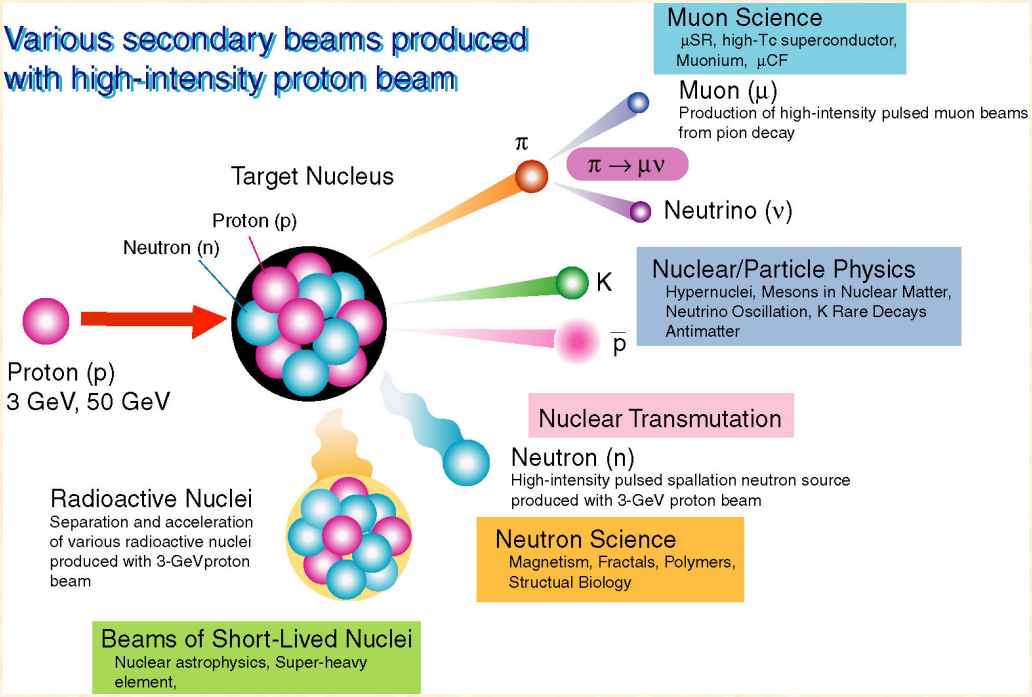
Particle and Nuclear Physics

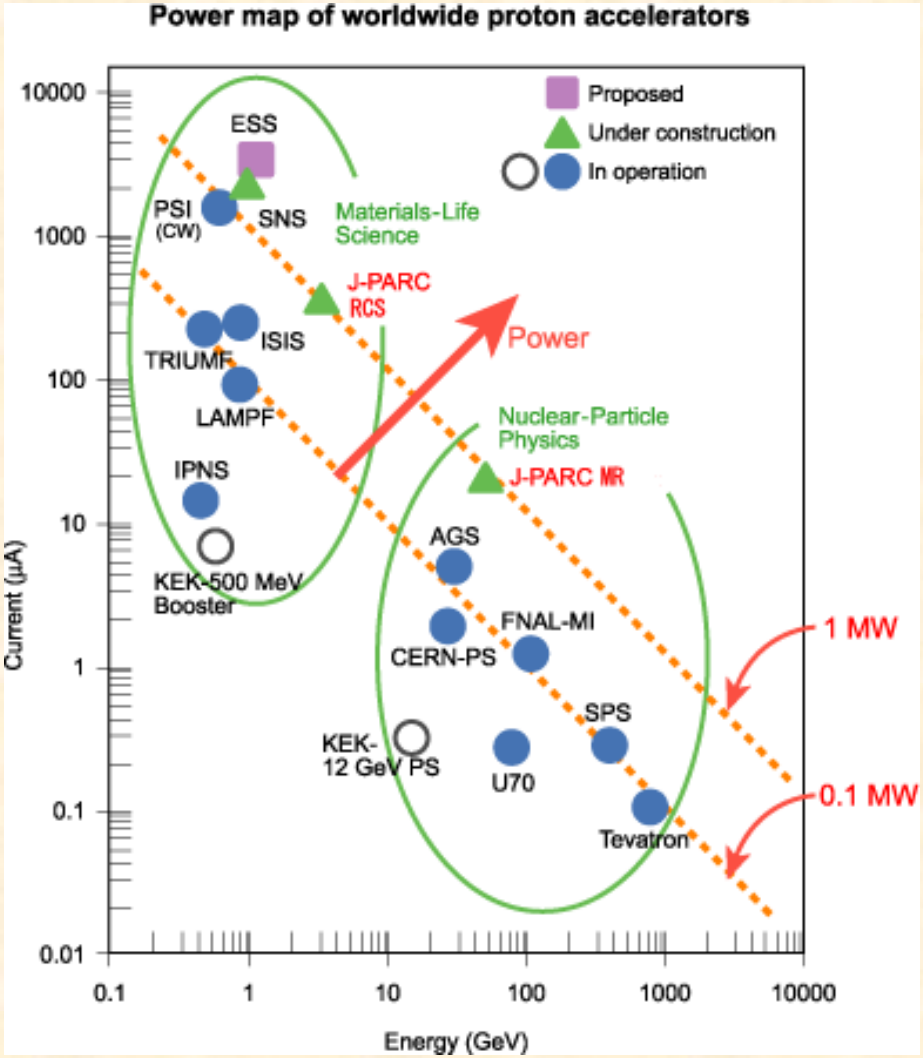
(KEK is in charge of this project.)



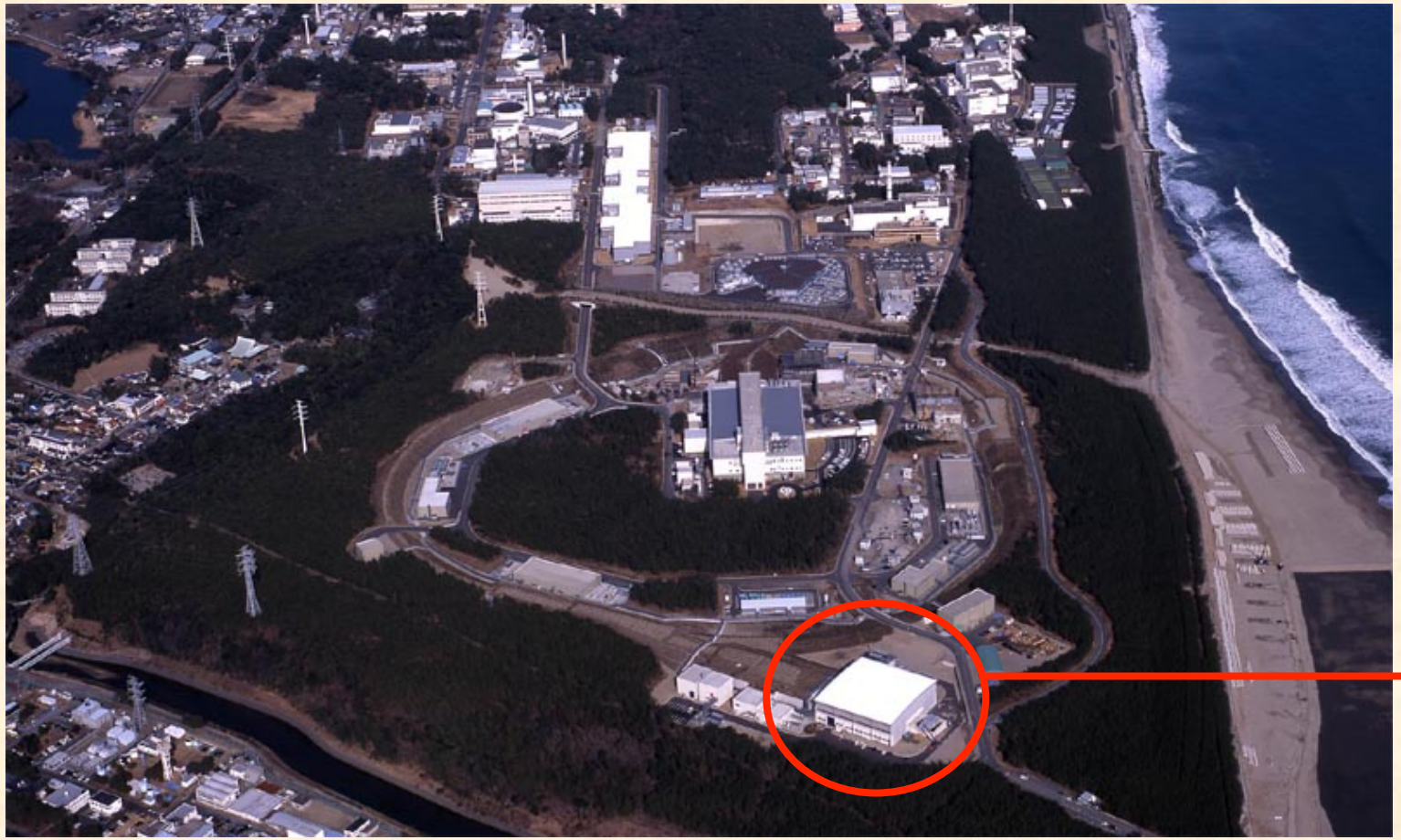
High-Intensity Frontier of Proton Accelerator

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



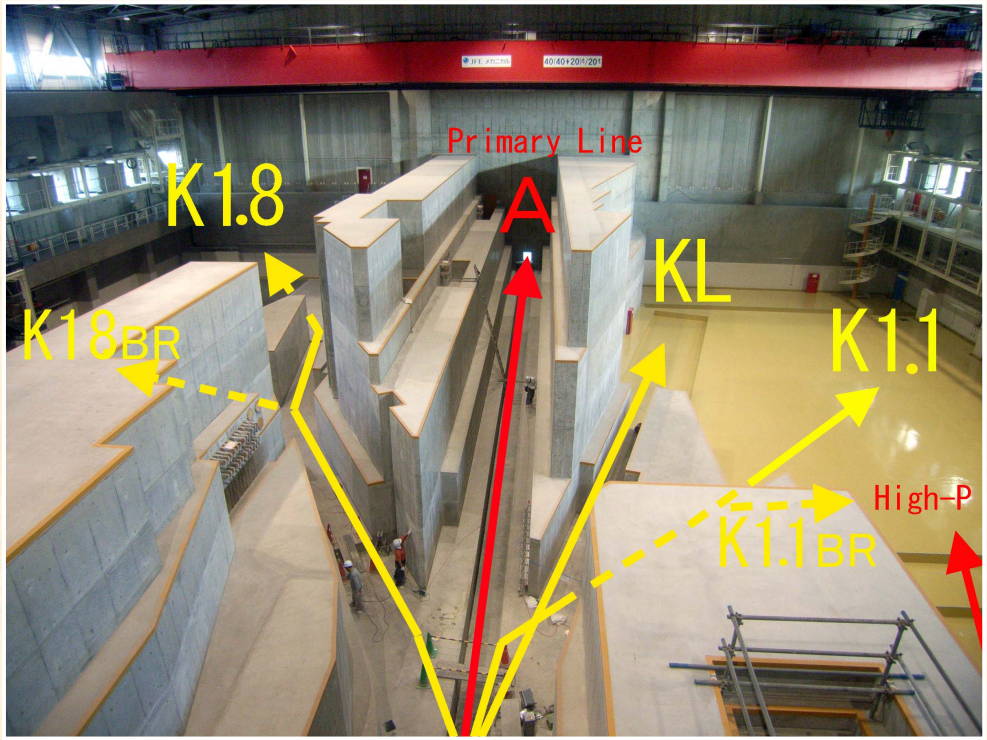


Aerial photograph on January 28, 2008



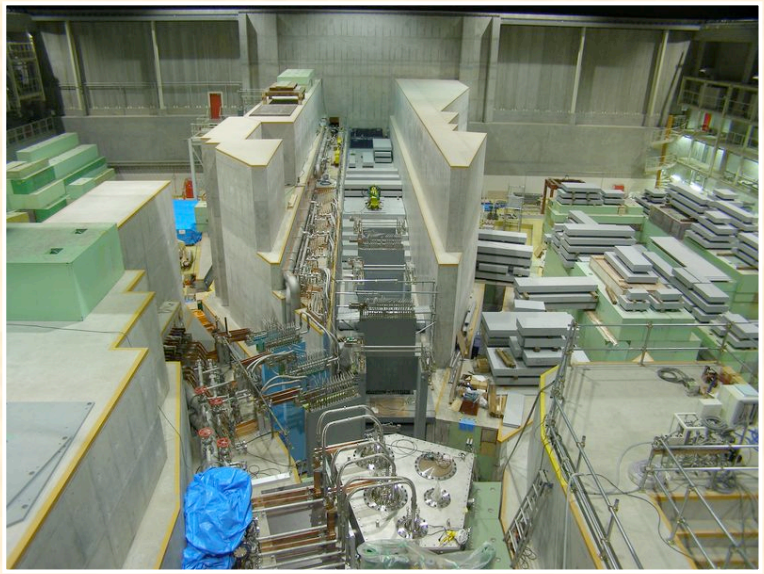
May, 2008: Injection to Main Ring
January, 2009: Acceleration to 30 GeV
March, 2009: Kaon beam
April, 2009: Neutrino beam

Hadron facility



July 2007

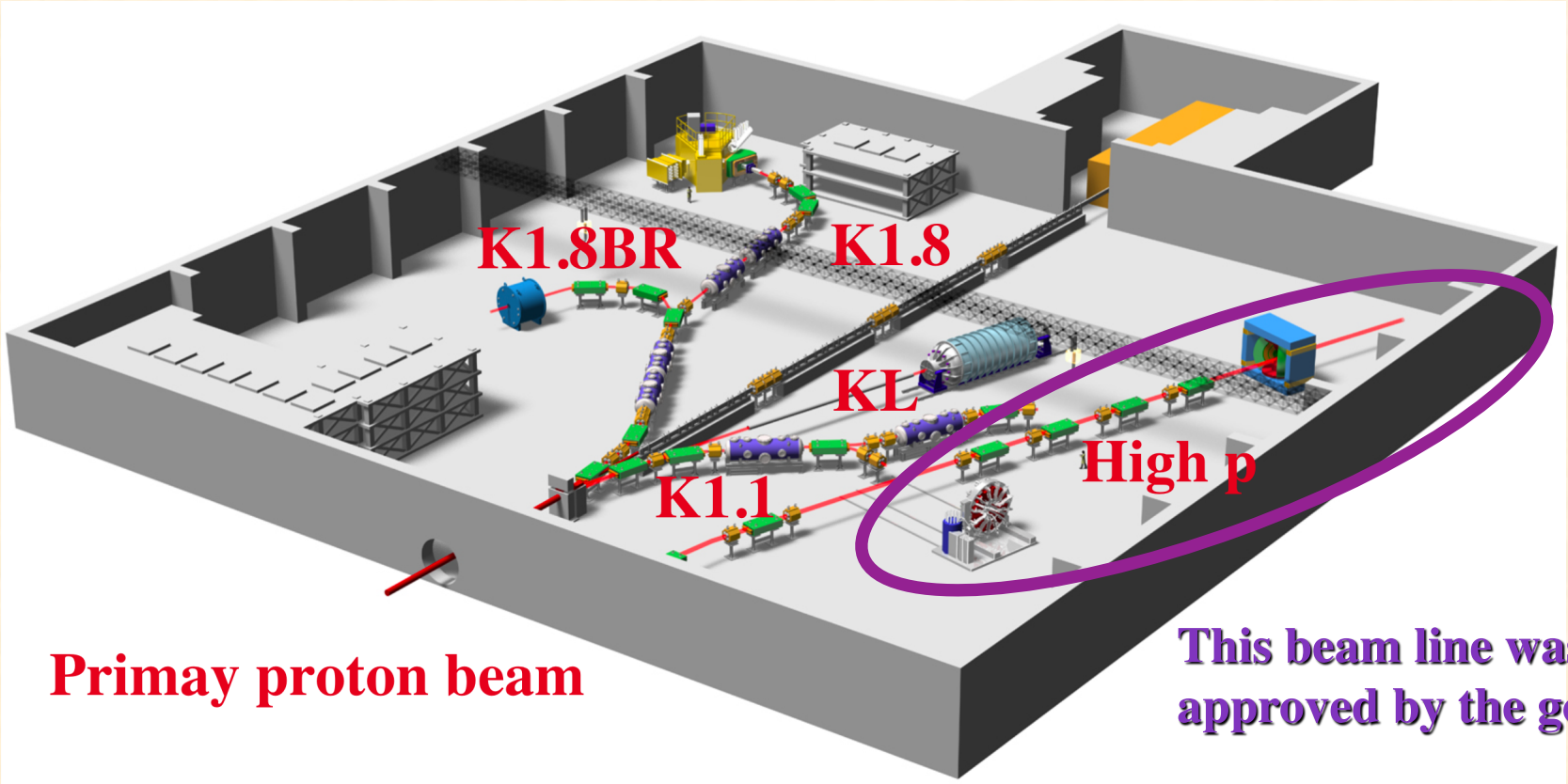
November 2008



January 2009

Hadron facility

Recent workshop on high-momentum beamline physics,
January 15 - 18, 2013, KEK,
http://www-conf.kek.jp/hadron1/j-parc-hm-2013/



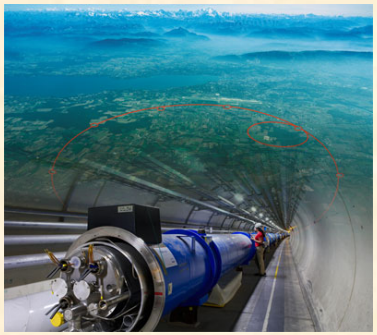
- Proton beam up to 30 GeV
- Unseparated hadron (pion, …) beam up to 15~20 GeV

Hadron Physics at J-PARC

Ref. SK, J. Phys. Conf. Series
312 (2011) 032005.

Diversity of hadron physics

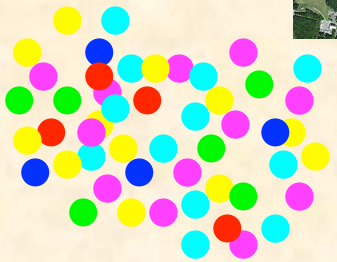
© BNL



© CERN

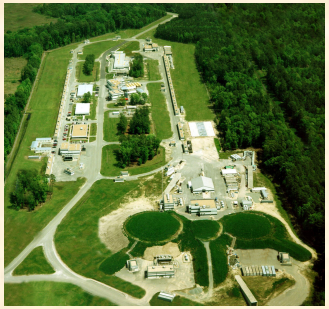
T

LHC
RHIC



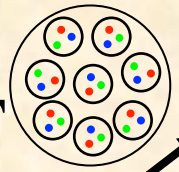
GSI-FAIR

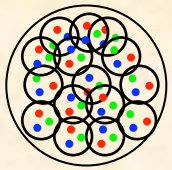
© GSI



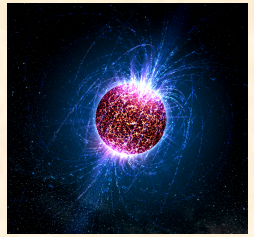
© JLab

RIBF





Neutron star



© C. Reed

B

JLab

J-PARC

© J-PARC

Q^2

HERA, EIC
LHC, RHIC

Purposes of J-PARC hadron physics

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

Quantum Chromodynamics (QCD)

- **New forms of matter and their interactions**

  Hadron physics by extending flavor degrees of freedom (strangeness, charm)

- **Color confinement**

  Hadron spectroscopy, Quark-hadron matter

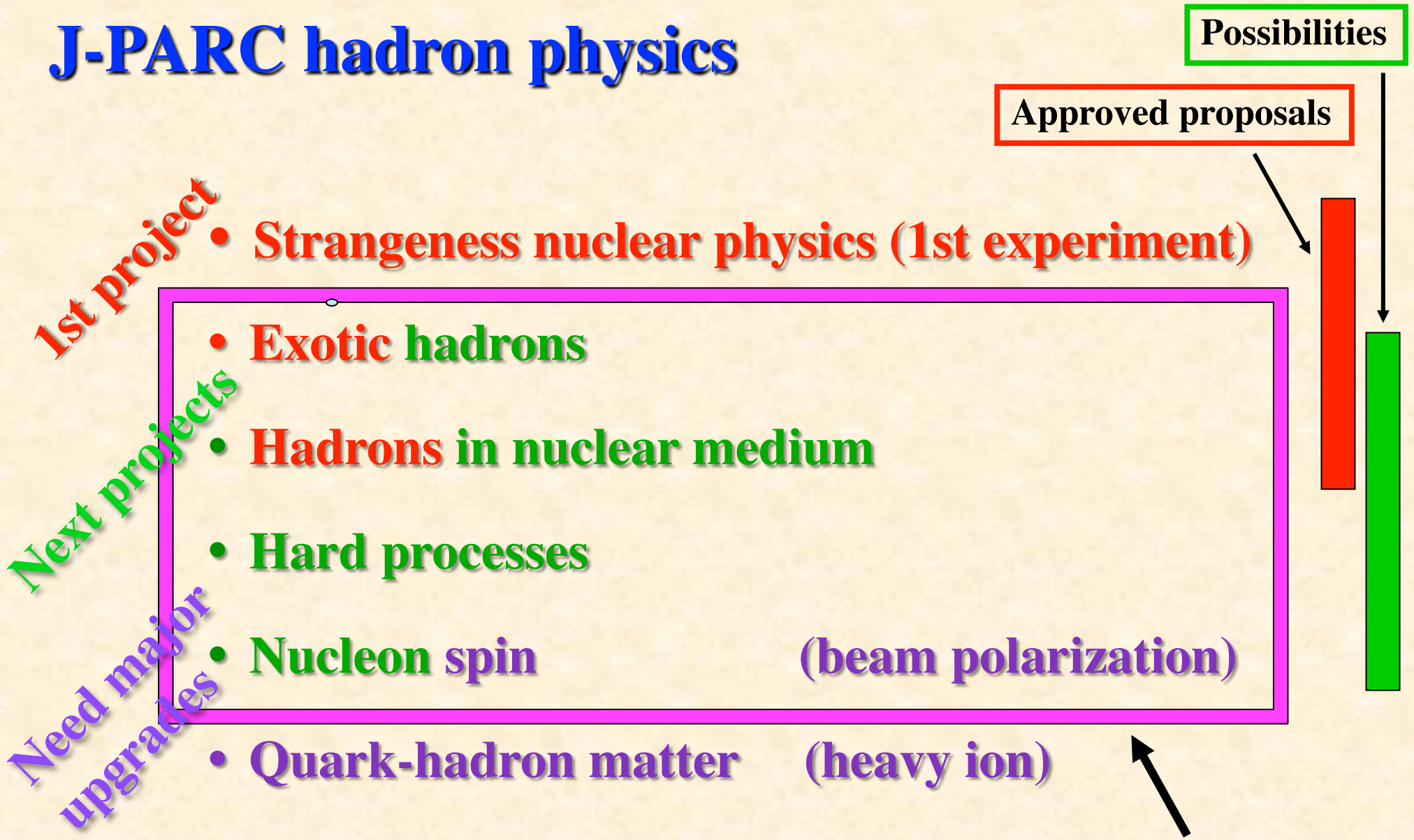
- **Chiral symmetry**

  Hadrons in nuclear medium

- **Asymptotic freedom, Partonic structure**

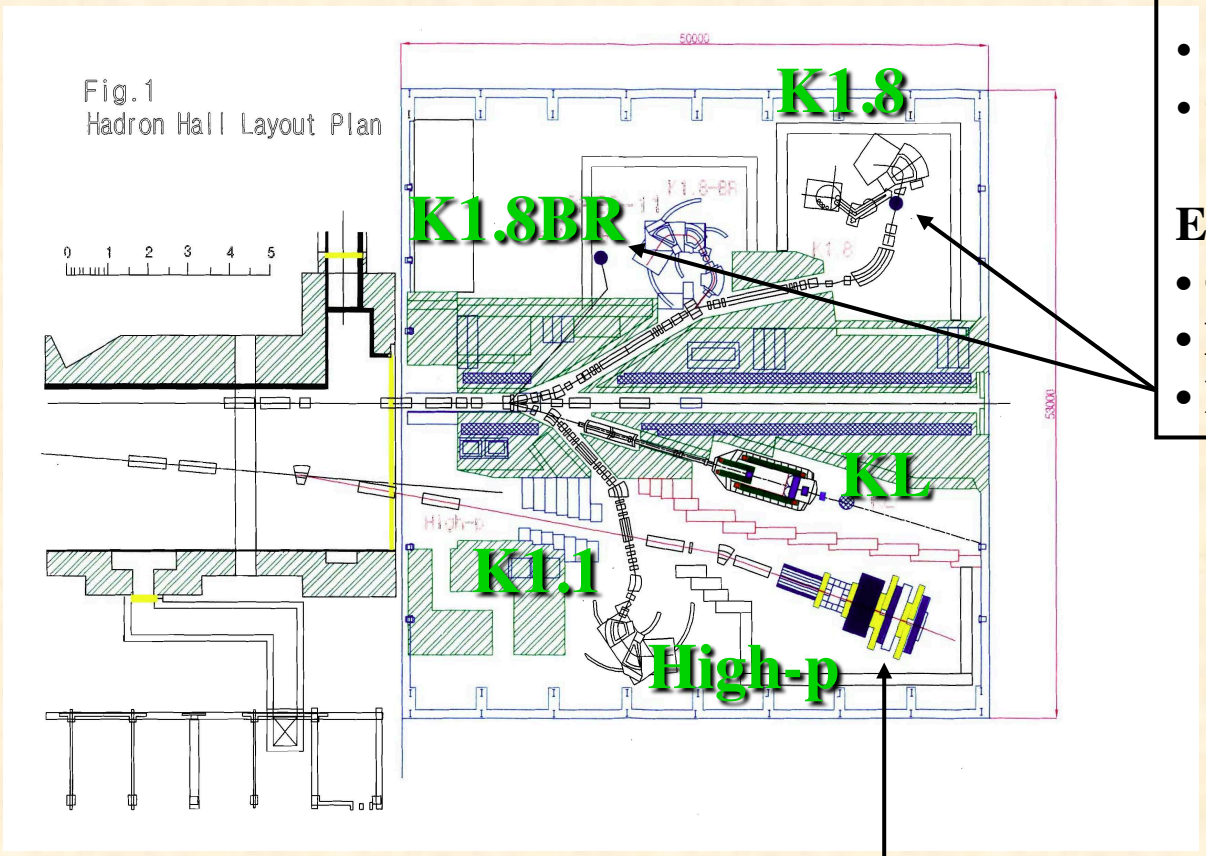
  Perturbative QCD, Parton distribution functions, Nucleon spin, …

J-PARC hadron physics



Speakers are selected from these topics (next page)

Approved experiments



Hypernucler Physics
- γ ray spectroscopy for S= – 1 systems
- Ξ hypernuclei
- weak decay etc.

Exotic Hadrons
- Θ^+ via (π^-, K^-)
- Xrays from Kaonic Atom
- K^-pp bound State

Hadron Masses in Nuclear Medium
- Modification of vector meson mass in nuclear medium

Baryon resonances by $\pi N \rightarrow \pi\pi N$, KY

Many other ideas are needed for effective use of this new beamline.

Theory activities at J-PARC

Started in 2011

J-PARC Branch, KEK Theory Center

Institute of Particle and Nuclear Studies, KEK

203-1, Shirakata, Tokai, Ibaraki, 319-1106, Japan

http://j-parc-th.kek.jp

Theory activities at J-PARC

J-PARC Branch, KEK Theory Center

Institute of Particle and Nuclear Studies, KEK
203-1, Shirakata, Tokai, Ibaraki, 319-1106, Japan
http://j-parc-th.kek.jp

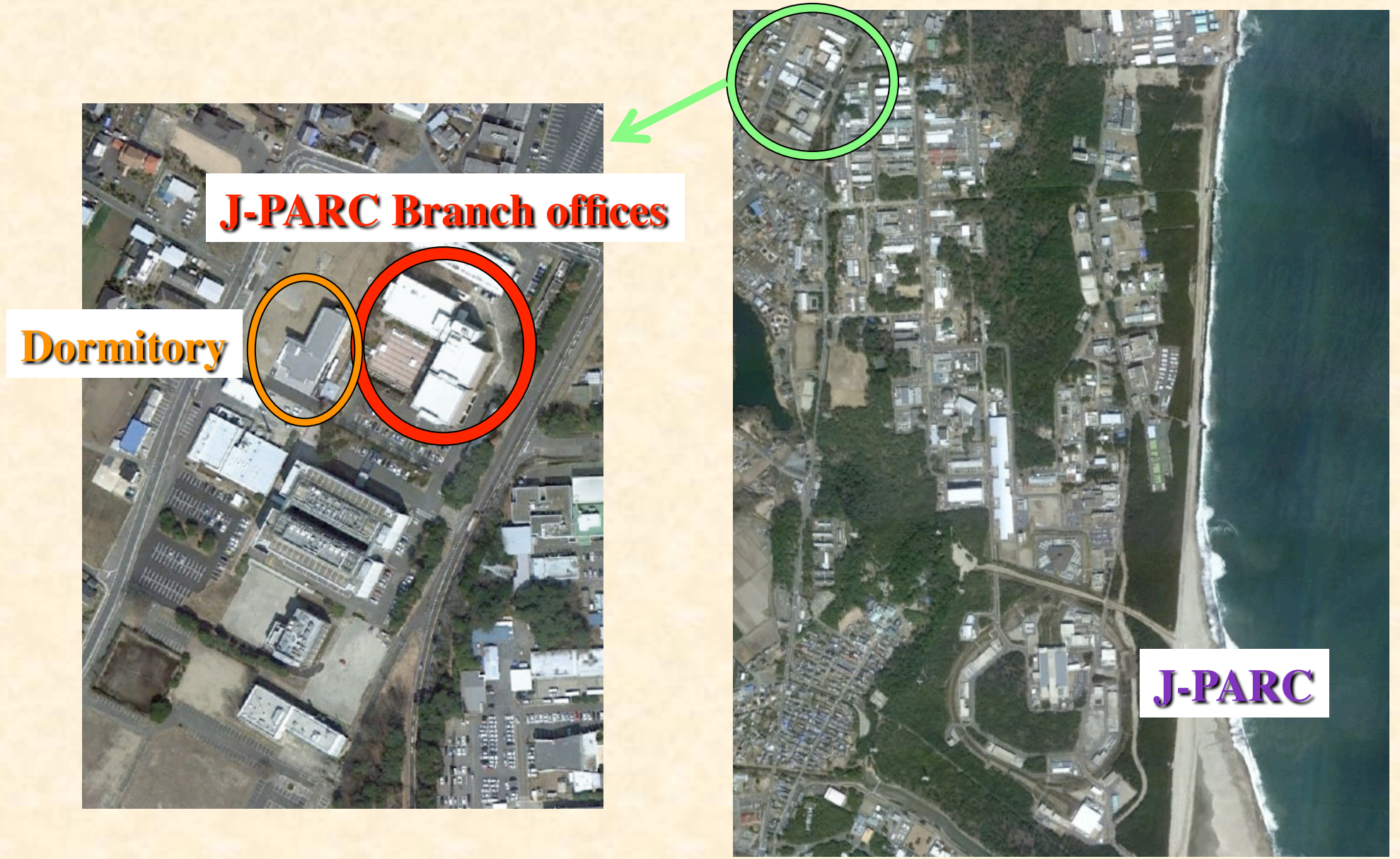
4 permanent KEK staffs (A. Dote, K. Itakura, S. Kumano, O. Morimatsu)
+ 1 research fellow (T. Marruyama)
+ 5 visiting staffs (T. Harada, E. Hiyama, D. Jido, M. Oka, T. Sato)

In 2011 & 2012, they are on strangeness hadron-nuclear physics and neutrino-nucleus interactions (on first experimental projects).

In future, we may invite theorists on different fields of hadron physics even from foreign countries.

If you are interested in organizing a workshop or joining activities, please inform us.

J-PARC Theory Branch Location



J-PARC theory activities

- 4 KEK staff members in hadron-nuclear theory
- 5 KEK visiting staff members on strangeness, exotics, neutrino
- 1 research fellow

Start from hadron-nuclear theory (particle theory?).

Staff and visitor rooms are ready

You are welcome to join the activities on J-PARC theory.

Purposes: of J-PARC theory branch

- Communications between theorists and experimentalists
- Promotion of J-PARC projects from theory side

Activities:

1. Workshops

   Small (~20 participants), Medium (50~100), …

2. Collaboration meetings

   Theoretical studies related to J-PARC projects,
   New ideas for letters of intent and proposals,
   Discussions on experimental results, …

3. Regular seminars

The activities are listed at http://j-parc-th.kek.jp .

Workshops among hadron and computational physicists

Discuss J-PARC hadron physics projects among

• Theorists • Computational Physicists • Experiemtalists

February 9-11, 2012
http://j-parc-th.kek.jp/workshops/2012/02-09/program.html

February 11-13, 2013
http://j-parc-th.kek.jp/workshops/2013/02-11/Program.html

We hope to have your cooperation in activating theoretical activities at this J-PARC site for the success of the J-PARC project!

Possibilities with US

- **Exchange project ?!**
- **Joint workshop with JLab/INT ?!**
- **Any ideas?**

Possible

High-momentum beamline projects

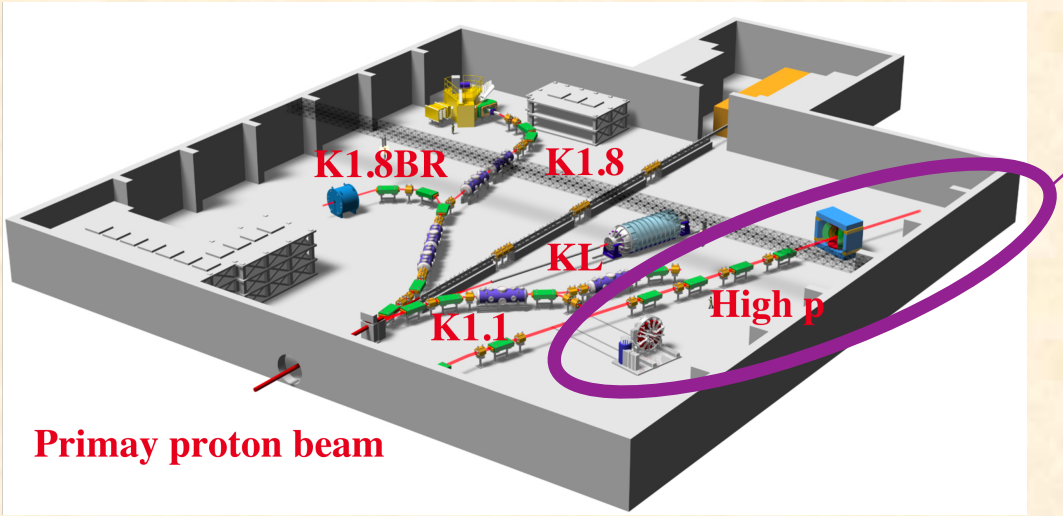
Introduction to Hadron Physics with High-Momentum Hadron Beams

This hadron physics is not defined,
so that you could create interesting topics
by writing theory papers and
by submitting experimental proposals.
It is up to you!

The following introduction is my personal view.

KEK workshop on "Hadron physics with high-momentum hadron bemas at J-PARC in 2013"

January 15 - 18, 2013, KEK,
http://www-conf.kek.jp/hadron1/j-parc-hm-2013/



Discussions on possible topics at this beam line.

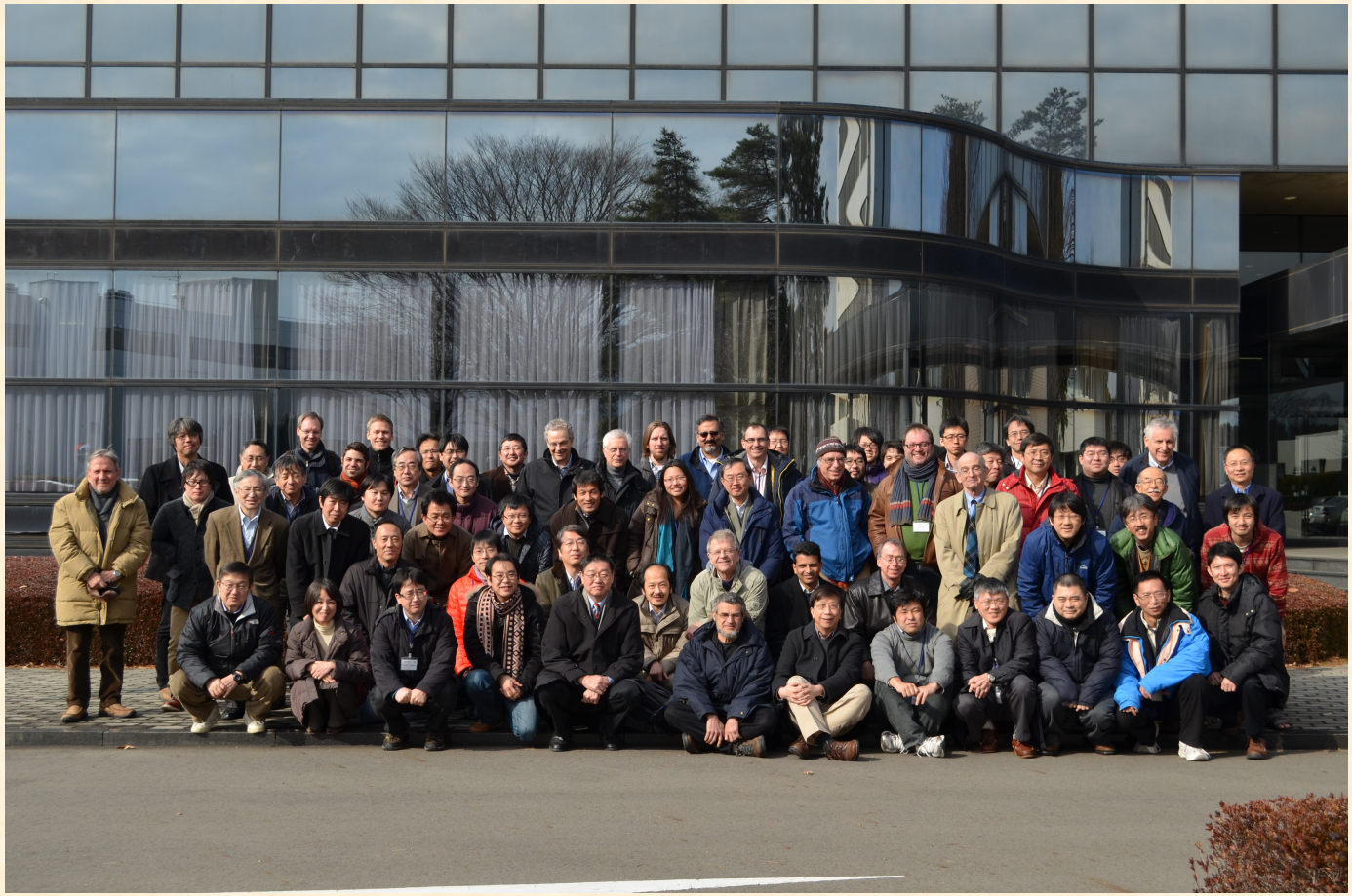
- **Proton beam up to 30 GeV**
- **Unseparated hadron (pion, …) beam up to 15~20 GeV**

*** hadron properties in nuclear medium** *** pQCD, partonic structure of nucleon and nuclei**
*** charmed-hadron physics** *** exotic hadrons and nuclei**
*** N* physics** *** high-energy spin physics**
*** transition form hadron to quark degrees of freedom**
*** short-range NN correlations** *** exclusive processes (GPD, quark counting, ...)**
*** quark/hadron interactions in nuclear medium (parton-energy loss, color transparency)**
*** J/psi production mechanisms and its interactions in nuclear medium**
*** hadron distribution amplitude** *** intrinsic charm and strange** *** any new ideas!**

Hadron physics with high-momentum hadron bemas at J-PARC in 2013

http://www-conf.kek.jp/hadron1/j-parc-hm-2013/

88 participants (~100 including non-registered ones)



High-momentum beamline workshop, Jan. 2013

- **J-PARC facility, Introduction**
  (Jan.15) Sawada, Brodsky, Kumano
- **Hard processes**
  (Jan.15) Kawamura, Peng, Maas, Chang, Li
- **Exotic hadrons, Charm physics**
  (Jan.16) Eichten, Qiu, Peters, Uehara, Oka, Ozawa, Sato
- **Quarks / Hadrons in nuclear medium**
  (Jan.17) Morimatsu, Metag, Yokkaichi, Strikman, Dutta, Qiu, Hicks
- **Nucleon spin, Baryon interactions, Summary**
  (Jan.18) Boer, Deshpande, Goto, Wakamatsu,
  Aoki, Ciofi degli Atti, Piasetzky, Imai

Talk files are at http://www-conf.kek.jp/hadron1/j-parc-hm-2013/.

J-PARC after BNL-AGS

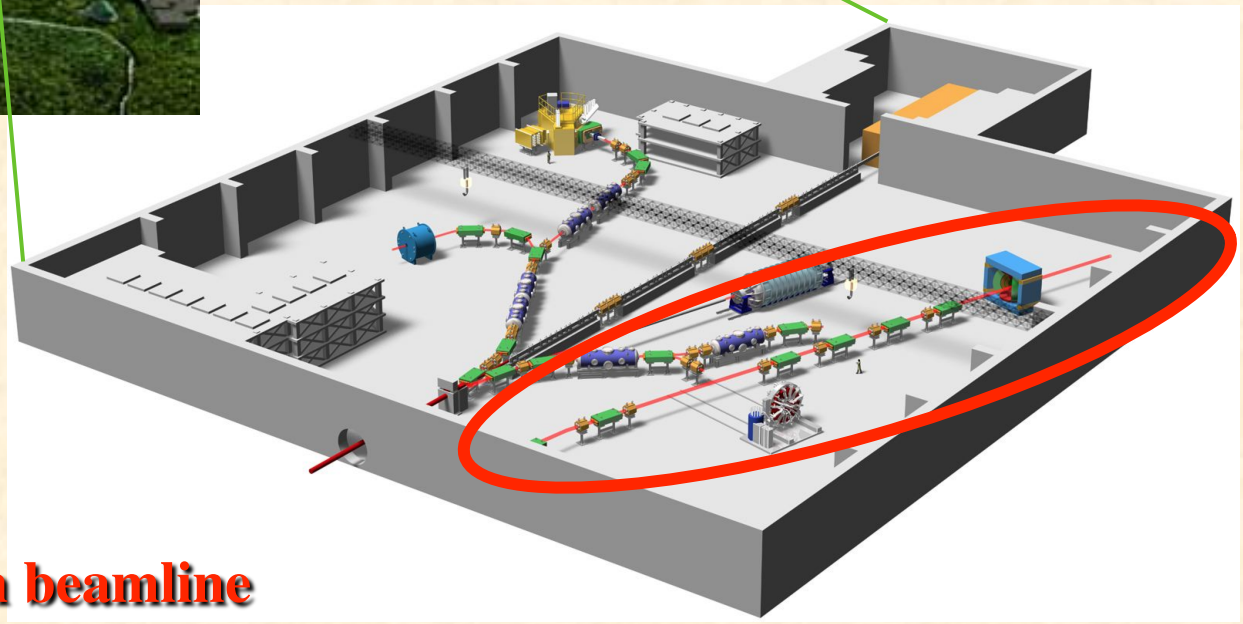
Unsolved mysteries at AGS

- Color transparency
- Spin asymmetries in polarized pp elastic
- …

Physics developed after the AGS era

- High-energy spin physics
- 3D picture of hadrons (GPD, TMD)
- Hard exclusive reactions and quark counting
- Short-range NN interactions
- Parton-energy loss
- Hadron → Quark transition, Duality
- Intrinsic charm, strange
- …

High-momentum beamline of J-PARC

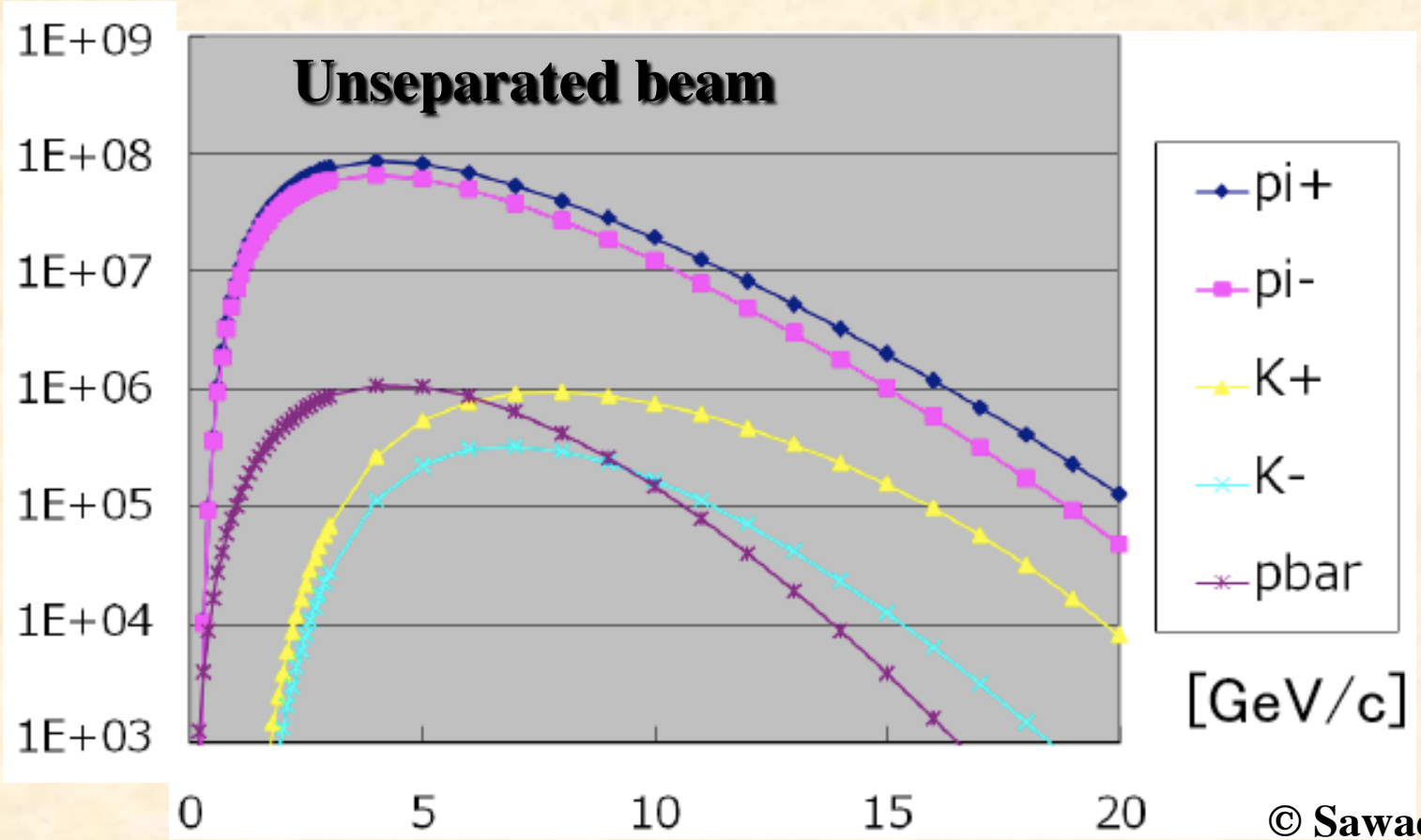


High-momentum beamline

- **30 GeV proton**
- **~15 GeV unseparated (mainly pions)**

High-momentum beamline of J-PARC

- Primary proton beam (30 GeV) with the intensity of 10^{10} - 10^{12}/sec
- Unseparated secondary beams such as pions *etc*. with 10^{7}/sec (10^{6}/sec) for 10 GeV/c (15 GeV/c) pions.



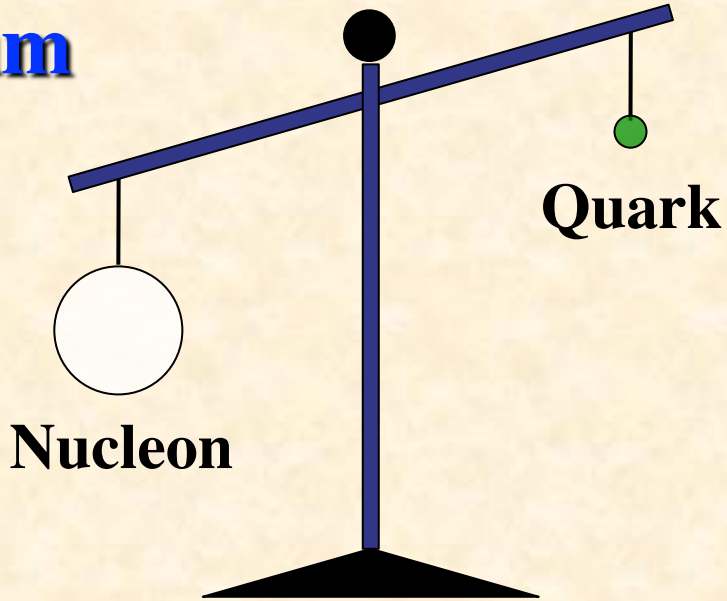
© Sawada (2013-Jan)

“Possible” topics

Hadrons in Nuclear Medium

Discussions in the morning of Jan. 17

Hadron masses in nuclear medium



Origin of the nucleon mass:

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

Chiral-symmetry breaking

Order parameter:
"quark condensate $<q\bar{q}>$"

$<q\bar{q}>$ depends temperature and density

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

Vector-meson masses vs. density

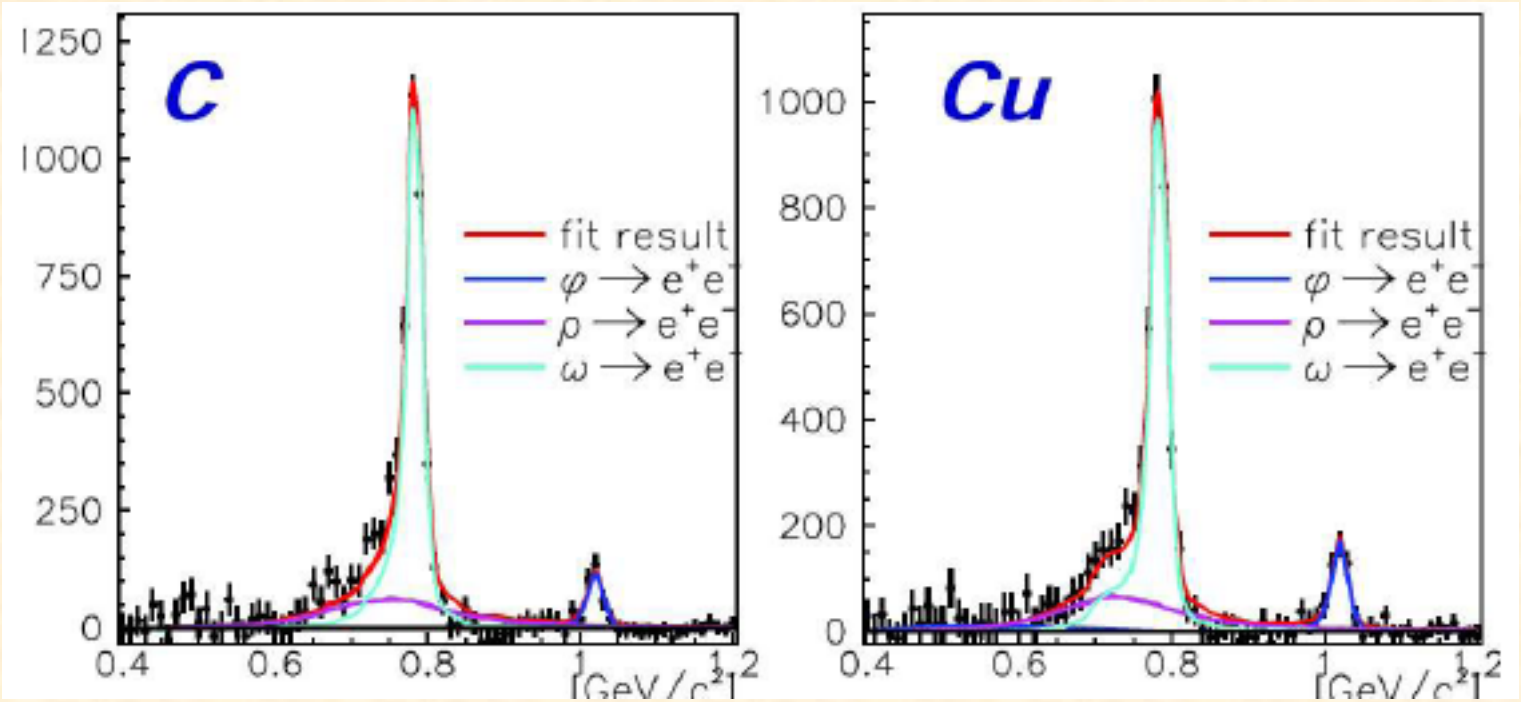
Modifications even at "normal nuclear density"

Reduction in ρ, ω masses at normal nuclear density

KEK-E325 Collaboration

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

After background subtraction



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

R. Muto et al.,
PRL 98 (2007) 042501

T. Tabaru et al.,
PRC 74 (2006) 025201

$m(\varrho) / m(0) = 1 - k\,\varrho/\varrho_0$ $\quad k = 0.092 \pm 0.002$ for ρ, ω

$= 0.034^{+0.006}_{-0.007}$ for ϕ

9%, 3% mass shifts

→ continued at J-PARC

Exotic Hadrons

Discussions in the morning of Jan. 17

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
…	

- $\Theta^+(1540)$???: LEPS
  Pentaquark?
  $uudd\bar{s}$?
- Kaonic nuclei?: KEK-PS, …
  Strange tribaryons, …
  $K^- pnn$, $K^- ppn$?
  $K^- pp$?
- X (3872), Y(3940): Belle
  Tetraquark, $D\bar{D}$ molecule
  $c\bar{c}$
  $D^0(c\bar{u})\bar{D}^0(\bar{c}u)$
  $D^+(c\bar{d})D^-(\bar{c}d)$?
- $D_{sJ}(2317)$, $D_{sJ}(2460)$: BaBar, CLEO, Belle
  Tetraquark, DK molecule
  $c\bar{s}$
  $D^0(c\bar{u})K^+(u\bar{s})$
  $D^+(c\bar{d})K^0(d\bar{s})$?
- Z (4430): Belle
  Tetraquark, …
  $c\bar{c}u\bar{d}$, D molecule?
- …

Charm physics

From "strangeness hadron physics"
to "charm hadron physics"

J-PARC is a facility to create new states of hadrons by extending flavor degrees of freedom.

First experiments: $K, \Lambda, \Sigma, \Xi, \ldots$
(many theoretical studies)

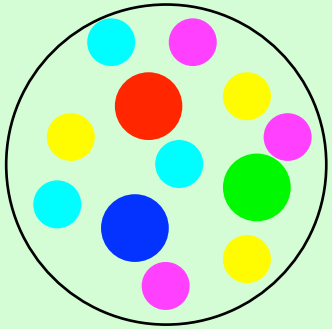
Future experiments: why not $J/\psi, D, \ldots,$
(not so well studied?)

J-PARC: 30 GeV
$\rightarrow \sqrt{s} = 8$ GeV

Comparisons with other projects of Belle/BaBar, GSI, COMPASS, …

Hard Processes
Hadron Interactions

Discussions on Jan. 15, 17, 18



J-PARC after BNL-AGS

There were some studies at Brookhaven AGS in the same energy range. What do we need to study?

Unsolved mysteries at AGS

- Color transparency
- Spin asymmetries in polarized pp elastic
- …

Physics developed after the AGS era

- High-energy spin physics
- 3D picture of hadrons (GPD, TMD)
- Hard exclusive reactions and quark counting
- Short-range NN interactions
- Parton-energy loss
- Hadron → Quark transition, Duality
- Intrinsic charm, strange
- …

Existing proposals on this topic

P04: Measurement of High-Mass Dimuon Production at the 50-GeV Proton Synchrotron
Spokespersons: J.C. Peng (U. Illinois), S. Sawada (KEK)

P12-LoI: Letter of Intent to J-PARC PAC for Study of Parton Distribution Function of Mesons vis Drell-Yan Process at J-PARC at High-p beamline
Spokesperson: S. Choi (Seoul National U. Korea)

P24: Polarized Proton Acceleration at J-PARC
Spokespersons: Y. Goto (RIKEN), H. Sato (KEK)

Measurement of High-Mass Dimuon Production at the 50-GeV Proton Synchrotron

April 28, 2006

J. Chiba[1], D. Dutta[2], H. Gao[2], Y. Goto[3], L. D. Isenhower[4], T. Iwata[11], S. Kato[11], M. J. Leitch[5], M. X. Liu[5], P. L. McGaughey[5], J. C. Peng[6†], P. Reimer[7], M. Sadler[4], N. Saito[8], S. Sawada[9†], T. -A. Shibata[10], K. H. Tanaka[9], R. Towell[4], and H. Y. Yoshida[11]

Polarized Proton Acceleration at J-PARC

November 30, 2007

M. Bai[1], M. Brooks[5], J. Chiba[11], N. Doshita[12], Y. Fukao[7], Y. Goto[7,8†], M. Grosse Perdekamp[2], K. Hatanaka[6], H. Huang[1], K. Imai[4], T. Iwata[12], S. Ishimoto[3], X. Jiang[5], K. Kondo[12], G. Kunde[5], K. Kurita[9], M. J. Leitch[5], M. X. Liu[5], A. U. Luccio[1], P. L. McGaughey[5], A. Molodojentsev[3], C. Ohmori[3], J.-C. Peng[2], T. Roser[1], N. Saito[3], H. Sato[3†], S. Sawada[3], R. Seidl[2], T.-A. Shibata[10], J. Takano[3], A. Taketani[7,8], M. Togawa[8], and A. Zelenski[1]

Study of Parton Distribution Function of Mesons via Drell-Yan Process at J-PARC at High-p beamline

S. Sawada
High Energy Accelerator Research Organization
Ibaraki 305-0801 Japan

J.-K. Ahn
Department of Physics
Pusan National University
Pusan 609-735 Korea

H.-C. Bhang, Seonho Choi (Spokesperson, contact)
Department of Physics and Astronomy
Seoul National University
Seoul 151-747 Korea

Contact: Seonho Choi (choi@phya.snu.ac.kr)

April 28, 2006

Unsolved Mysteries at Brookhaven-AGS

Discussions on Jan. 17, 18

Color Transparency

At large momentum transfer, a small-size hadron could freely pass through nuclear medium. (Transparent)

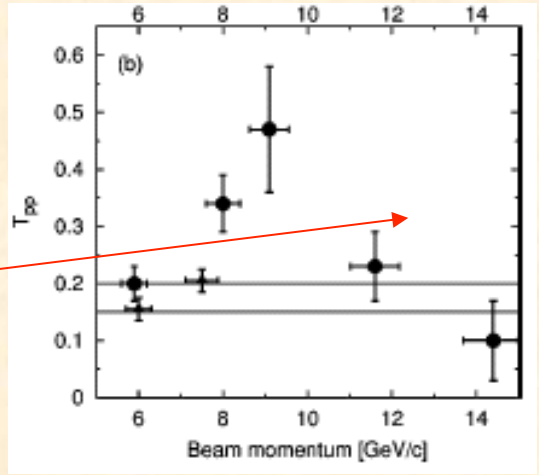
Investigate $pA \rightarrow pp(A-1)$

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

Color transparency:

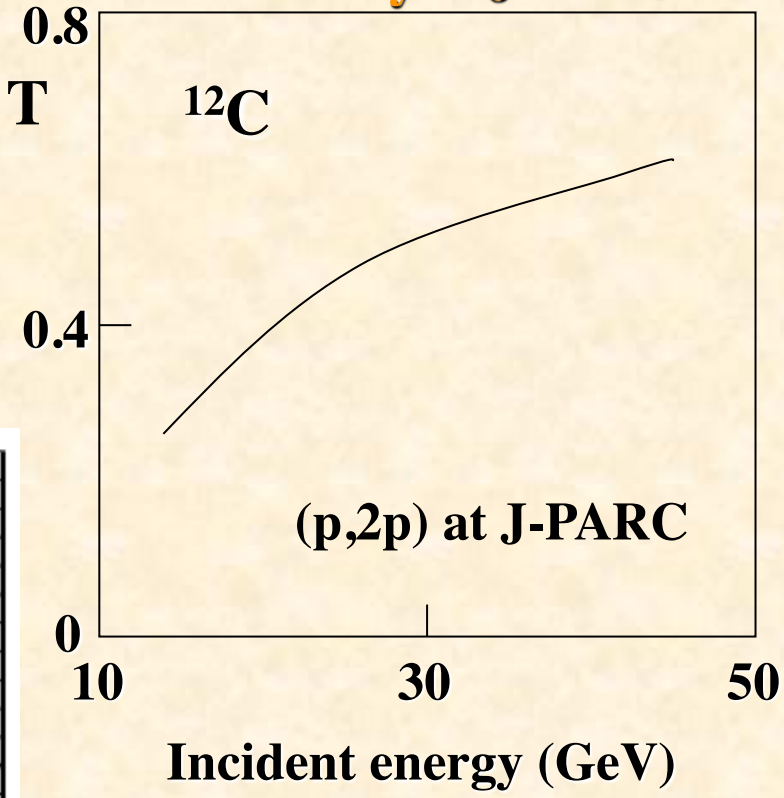
$T \rightarrow$ larger, as the hard scale $\rightarrow$ larger

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



reason for this drop?

Possibility at J-PARC



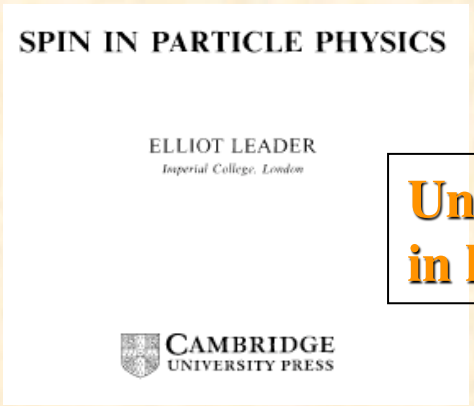
Spin asymmetry in pp elastic scattering

Single spin asymmetry in $p\vec{p}$ elastic: $A_n = \dfrac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$

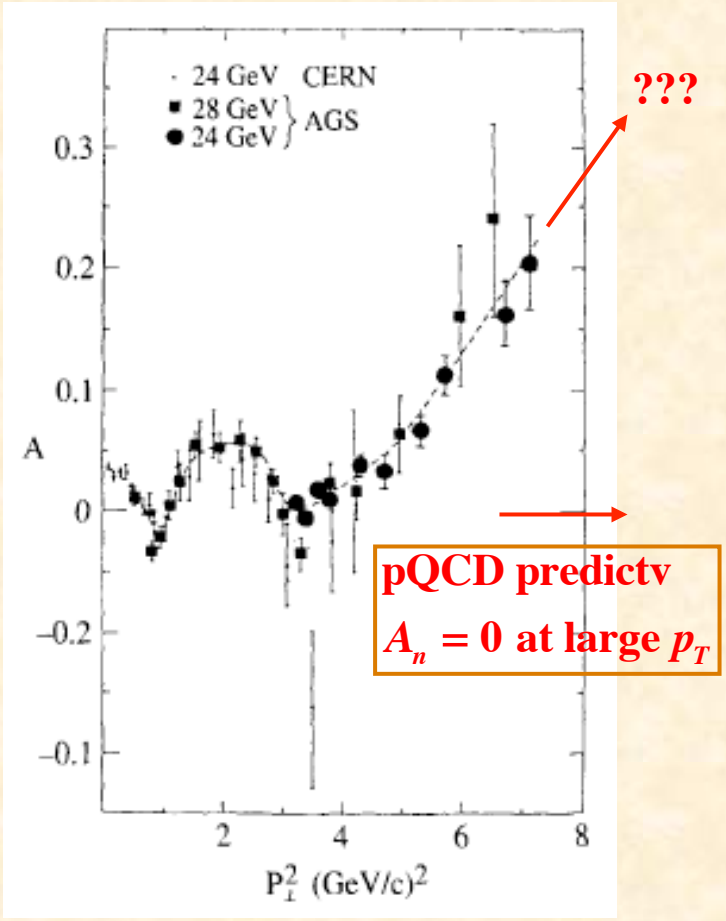
J-PARC 30 GeV is the same as the AGS energy.
(The kinematical range is similar.)

For a possible J-PARC experiment,

- **New observable should be investigated for providing a clue to pin down a possible mechanism of producing the asymmetry at large p_T.**



Unsolved problem in high-energy spin physics



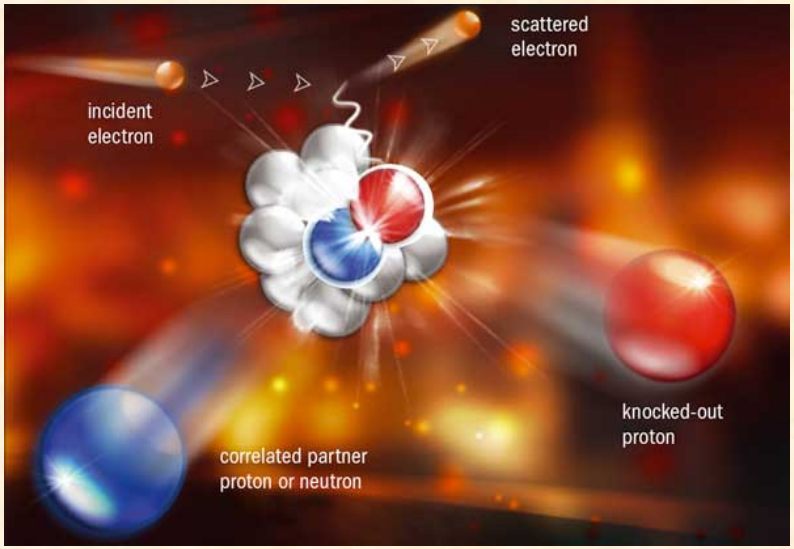
From Spin in Particle Physics, E. Leader, Cambridge University press (2001);
D. G. Crabb et al., PRL65 (1990) 3241.

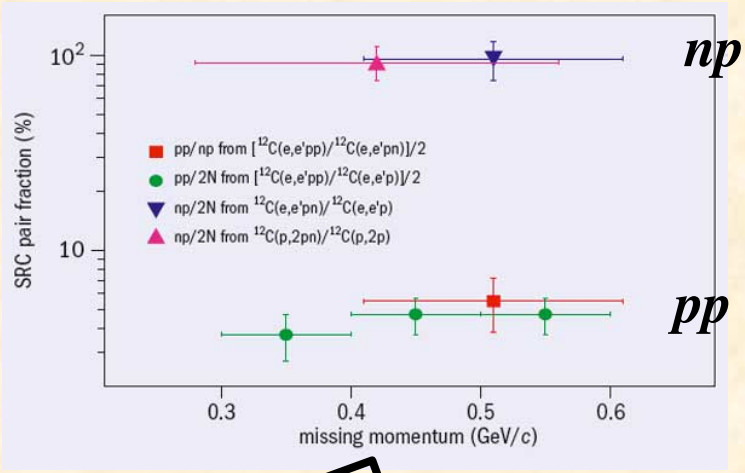
Short-range NN interaction

High-momentum $\frac{np}{pp} \simeq 20$!

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

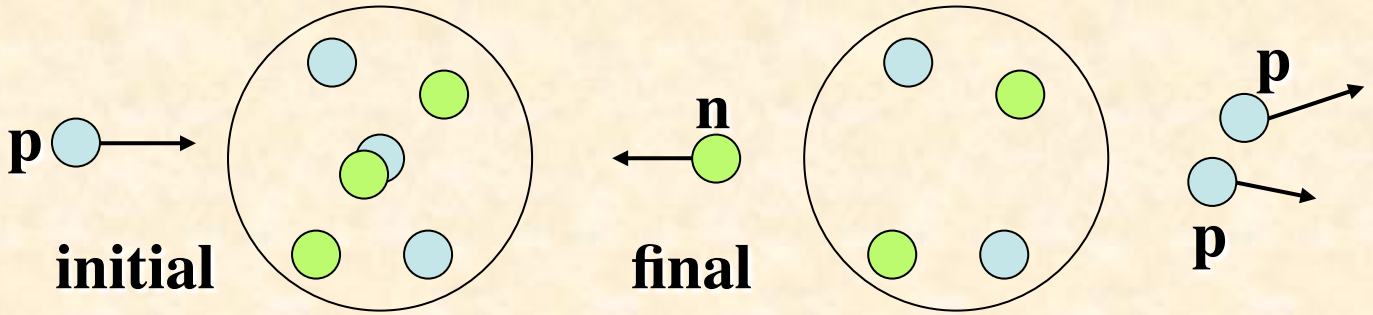
D. Higinbotham, E. Piasetzky, and M. Strikman
CERN Courier 49 (2009) 22.

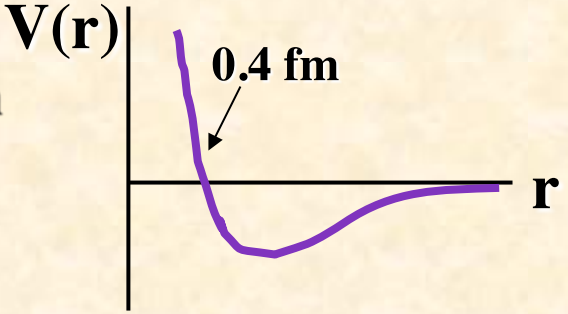




No longer, a mystery

J-PARC: A(p, 2pN)X experiment for short-range correlation



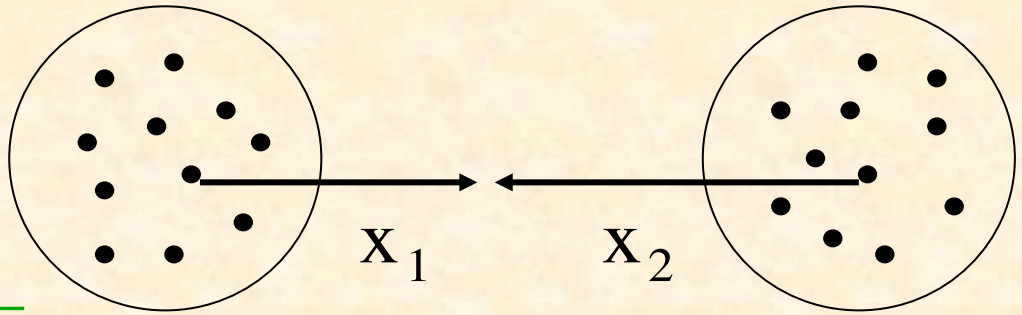


Antiquark distributions

Intrinsic charm, strange

Discussions on Jan. 15

Hadron facilities



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

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

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

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

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

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

e.g. Quark spin content: $\Delta q = \int_0^1 dx \Delta q(x)$
= Integral from small x (RHIC)
to large x (J-PARC).

$$x \sim \frac{\sqrt{m_{\mu\mu}^2}}{\sqrt{s}} \geq \frac{3}{10} = 0.3$$ J-PARC (Fermilab-120 GeV)

$$\geq \frac{3}{200} = 0.02$$ RHIC (COMPASS)

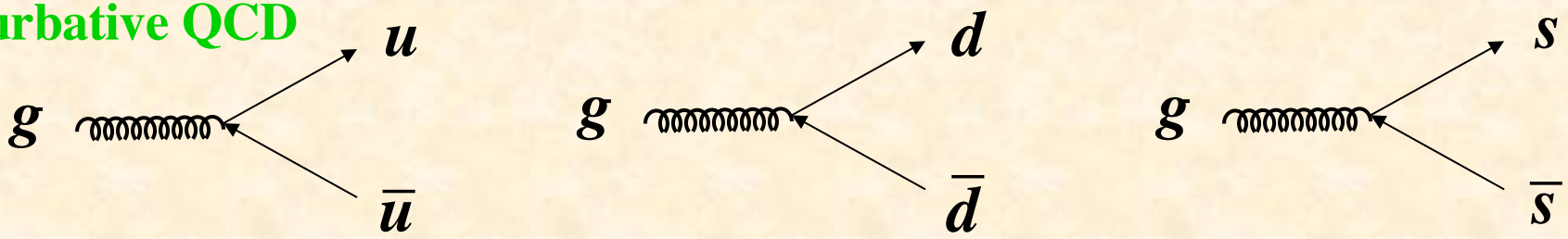
$$\geq \frac{3}{14000} = 0.0002$$ LHC

Large-x facility

Small-x facility

Flavor dependence of antiquark distributions

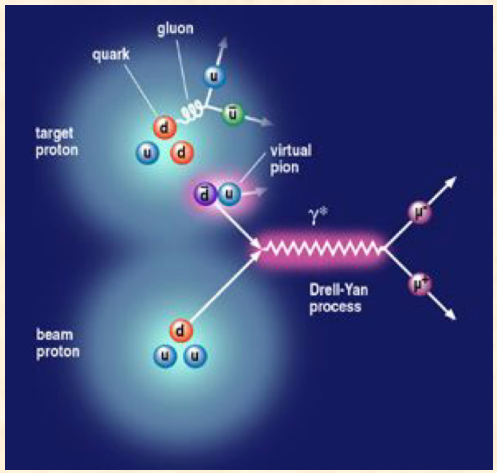
Perturbative QCD



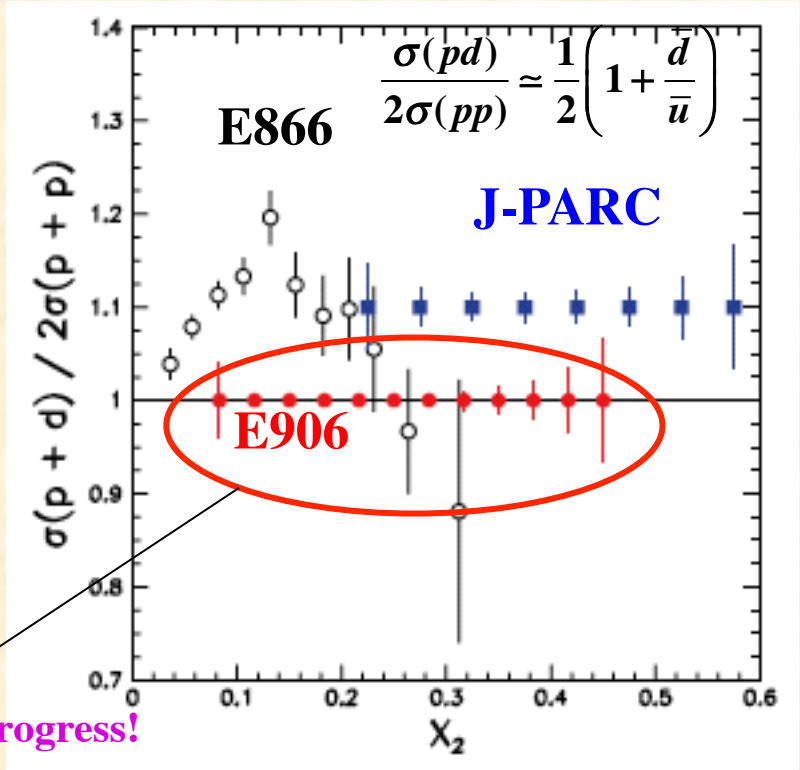
Because of $m_u^2, m_u^2, m_u^2 \ll Q^2$, we expect $\bar{u} = \bar{d} = \bar{s}$ from the antiquark creaction by the gluon splitting $g \to q\bar{q}$ in perturbative QCD.

$\Rightarrow$ Experimentally, $\dfrac{\bar{s}}{(\bar{u}+\bar{d})/2} \sim 0.4$, $\dfrac{\bar{d}}{\bar{u}} = 1 \sim 1.4$

Non-perturbative mechanism for the asymmetries?



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

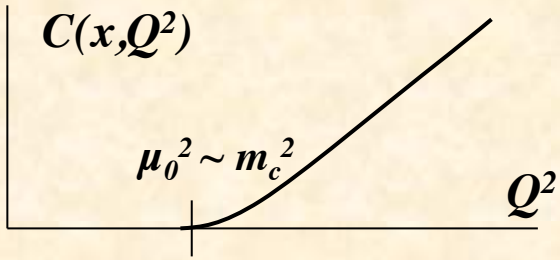


Fermilab experiment in progress!

Intrinsic charm distribution

- **pQCD (radiatively generated charm)**

  The charm distribution is simply generated by Q^2 evolution.



- **Light-cone Fock space picture**

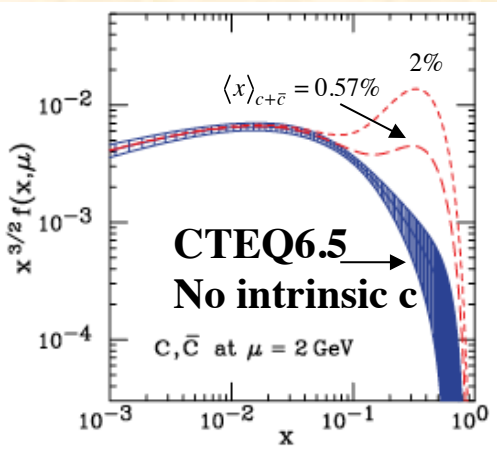
$$|p\rangle = |uud\rangle + \cdots + |uudc\bar{c}\rangle + \cdots$$

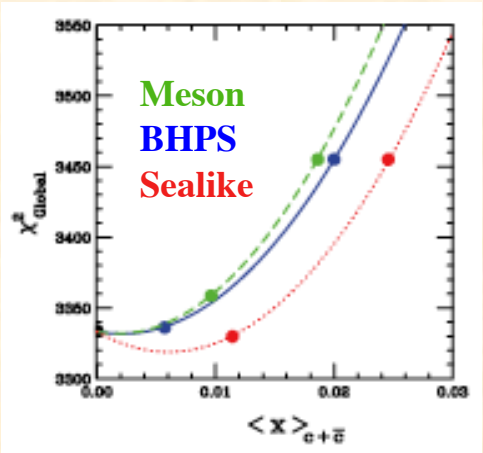
Brodsky, Hoyer, Peterson, Sakai (BHPS), PLB93 (1980) 451

- **Meson-cloud picture**

$$p(uud) \to \bar{D}^0(u\bar{c})\Lambda_c^+(udc), \quad p(uud)J/\psi(c\bar{c})$$

- **Global analysis** **CTEQ, PRD75 (2007) 054029**





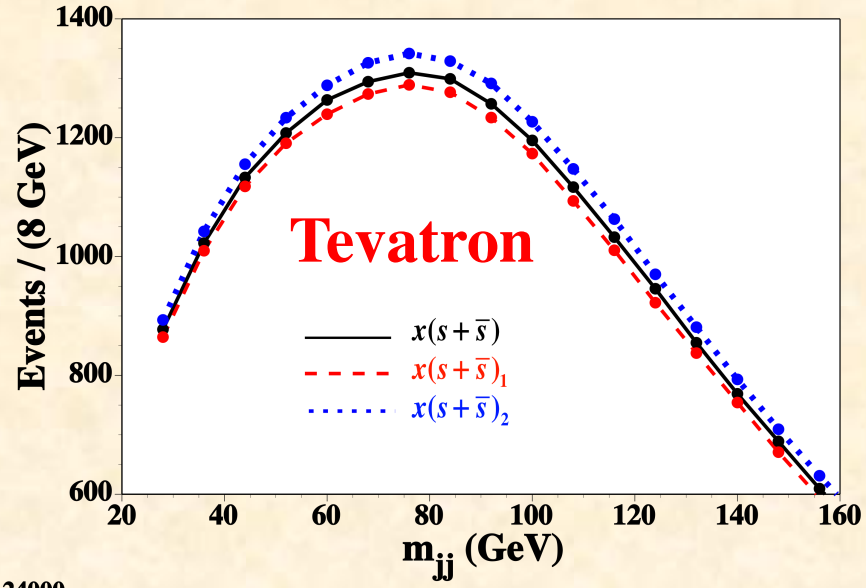
0~1% intrinsic charm is consistent with the data

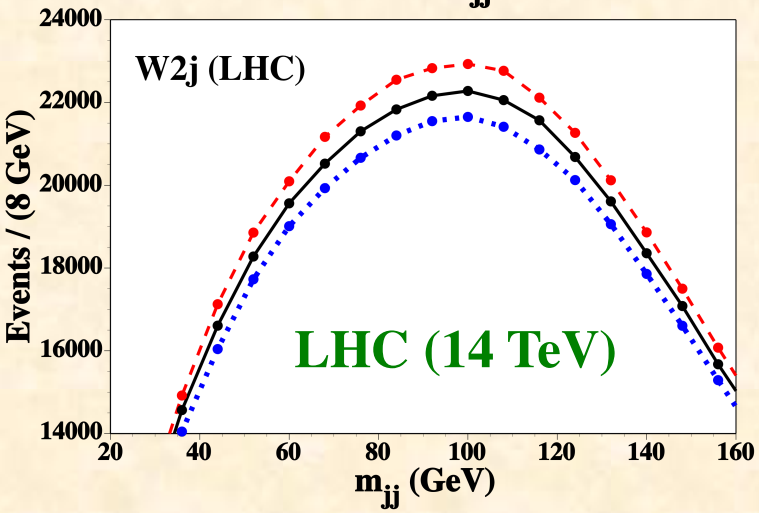
S. J. Brodsky (SLAC), at J-PARC

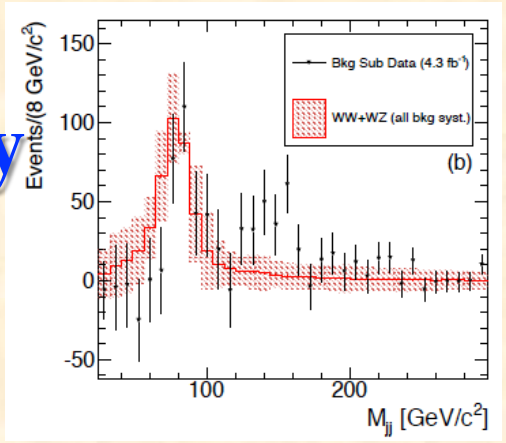
$$pp \to J/\psi(c\bar{c})X,\ \Lambda_c^+(udc)X,$$
$$\Sigma_c(usc)X,\ \Omega_c(ssc)X$$

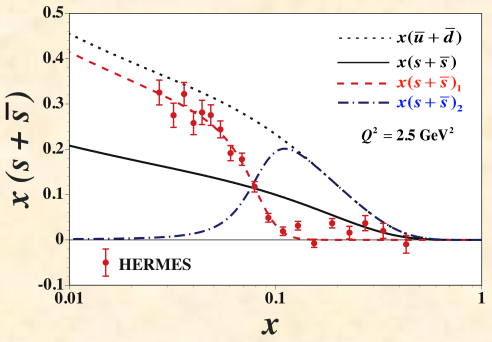
Intrinsic strange: $s(x)$ effects on CDF anomaly

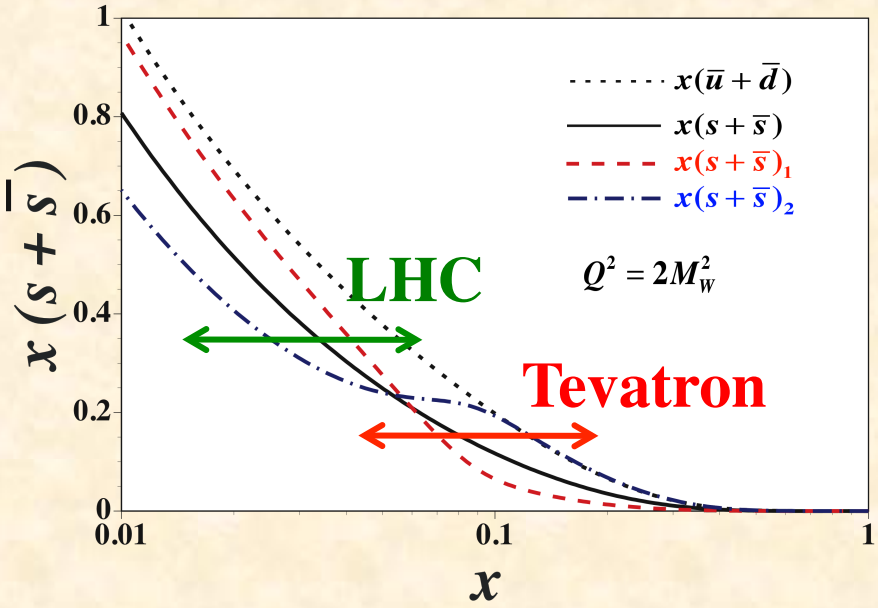
H. Kawamura, SK, Y. Kurihara,
PRD 84 (2011) 114003.









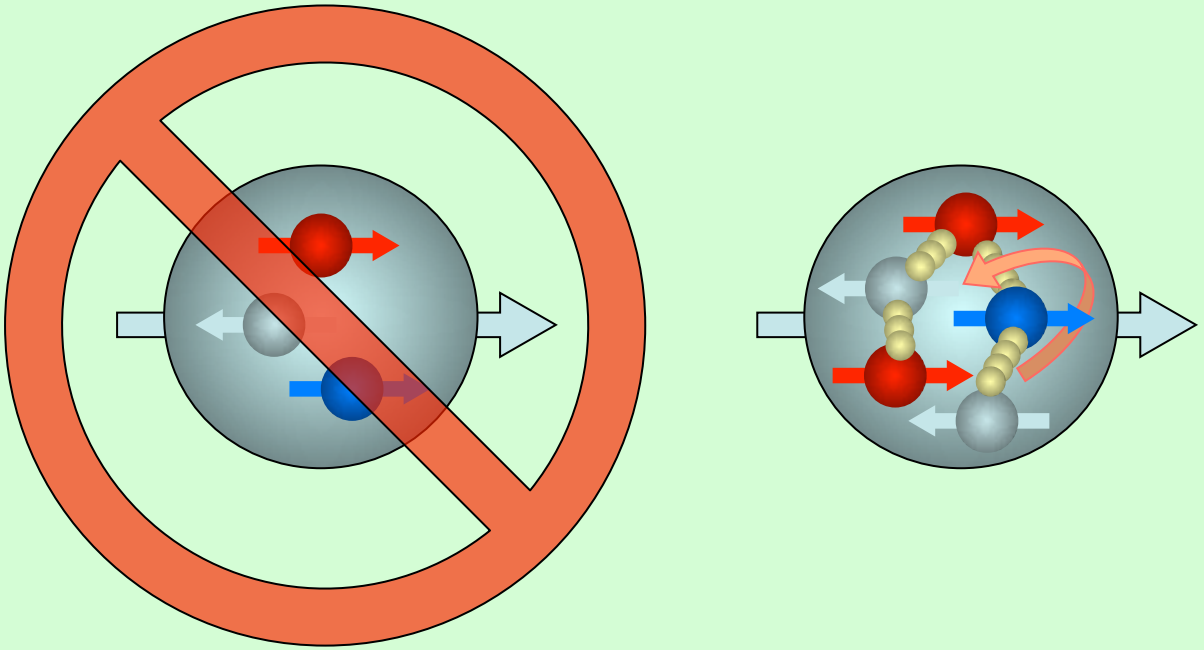


$s(x)$ modifications affect the ℓ+2j distribution

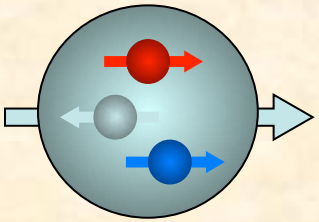
W.-C. Chang and J.-C. Peng,
PRL 106 (2011) 252002 (2011).

Origin of Nucleon Spin

Discussions in the morning of Jan. 18

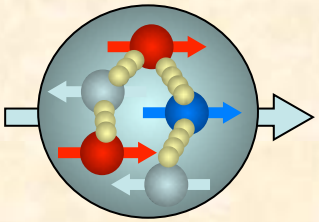


Nucleon spin



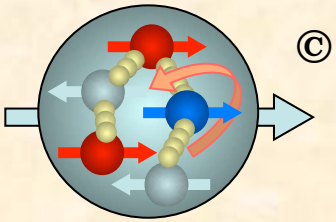
Naïve Quark Model

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



Sea-quarks and gluons?

Recent data indicate ΔG is small at $x \sim 0.1$.



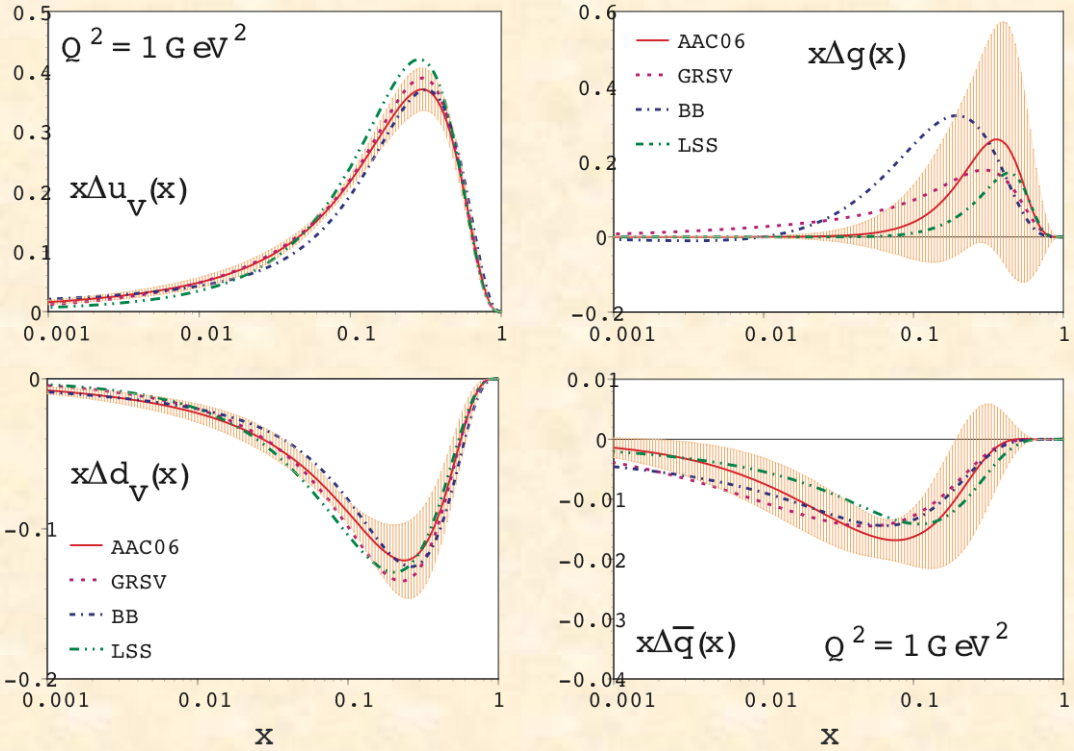
Orbital angular momenta ?

Electron / muon scattering

$\Delta\Sigma \approx 0.2 \sim 0.3$

Almost none of nucleon spin is carried by quarks!

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



Single spin asymmetry

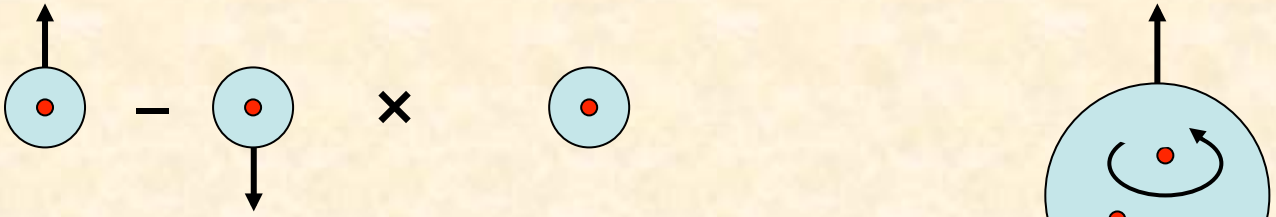
(No polarized proton beam is needed!)

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

- Sivers effect

Nucleon **Quark**

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



Probe of angular momentum

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

- Collins effect

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

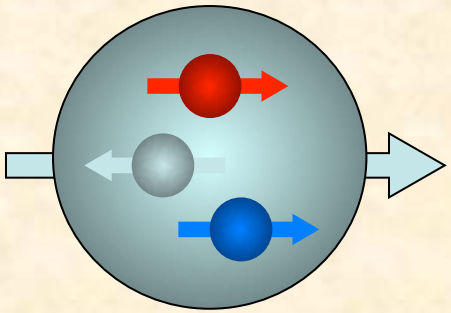
The transversity distribution describes transverse quark polarization in the transversely polarized nucleon.

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

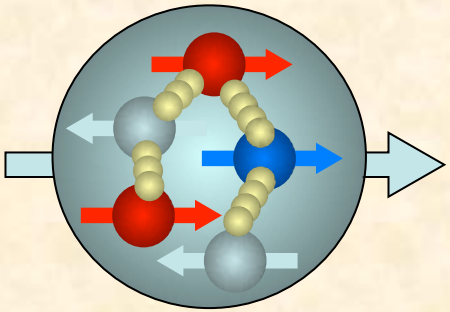
Higher-twist

Nucleon spin

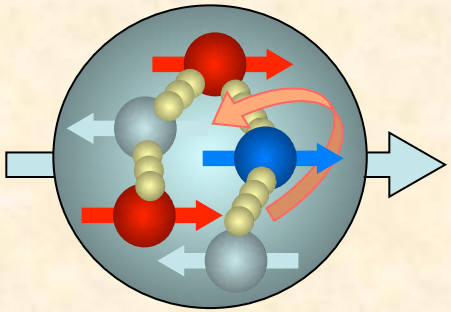
Almost none of nucleon spin is carried by quarks! → Nucleon spin crisis!?



Naïve Quark Model



Sea-quarks and gluons?



Orbital angular momenta ?

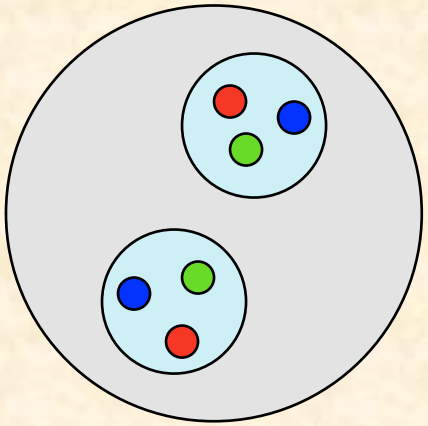
"old" standard model

SK, PRD82 (2010) 017501

Tensor structure b_1 (*e.g.* deuteron)

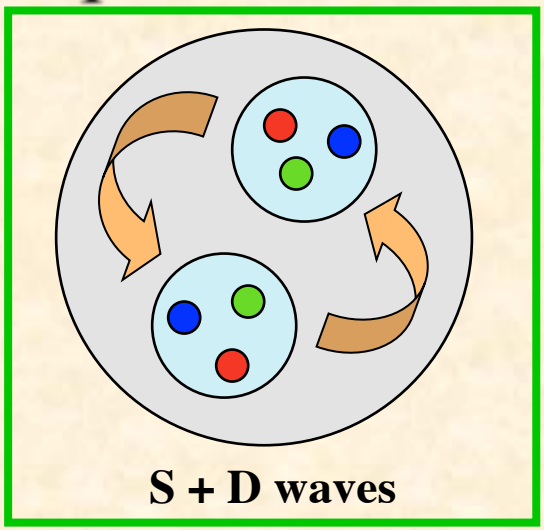
Tensor-structure crisis!?

JLab proposal, PR12-11-110



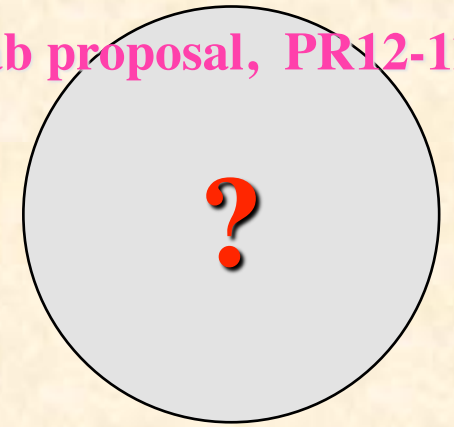
only S wave

$b_1 = 0$



S + D waves

standard model $b_1 \neq 0$



b_1 experiment

$\neq b_1$ "standard model"

Hadron Tomography

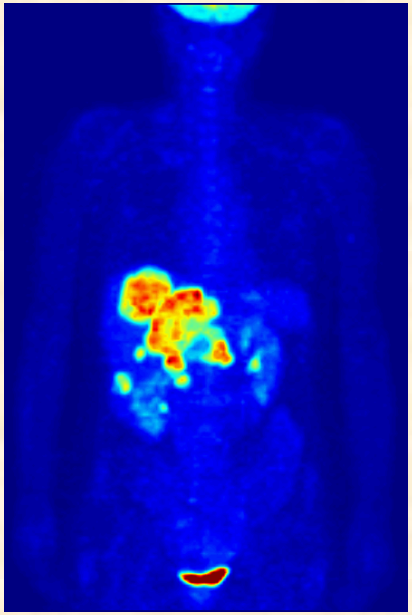
Discussions on Jan. 15, 18

Tomography

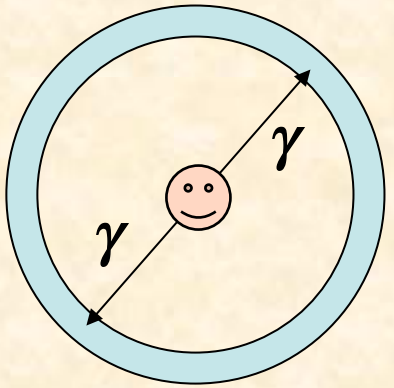
- CT (Computed Tomography)
- PET (Positron Emission Tomography)

© Jens Langner

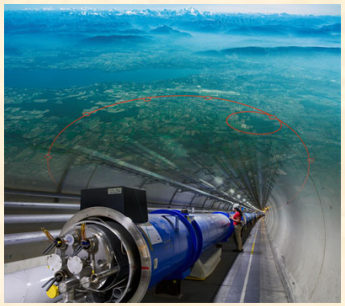
β^+ decay: $^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + e^+ + \nu_e \quad (\tau = 110\ \mathrm{min})$



$e^+ + e^- \rightarrow \gamma + \gamma \quad (E_\gamma = 511\ \mathrm{keV})$



Test apparatus corresponds to "PET"



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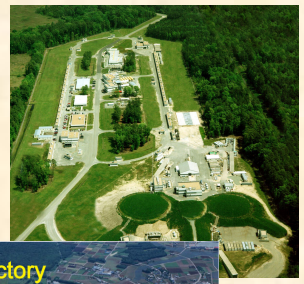
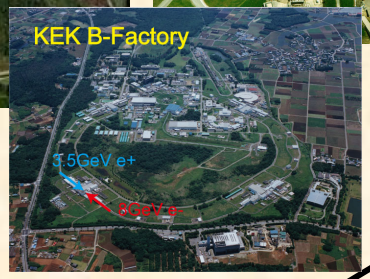




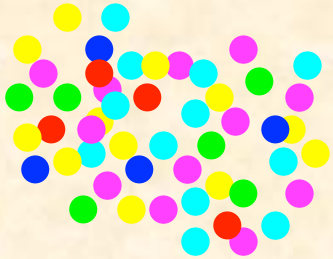
© KEK-B

© BNL

© GSI

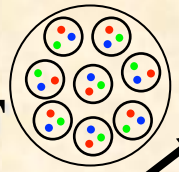
T

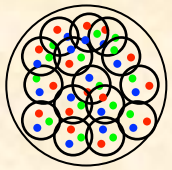
LHC
RHIC



GSI-FAIR

RIBF





μ

JLab

J-PARC

© J-PARC

Q^2

HERA, EIC
LHC, RHIC

Hadron tomography

Establishment of 3-dimentional structure of hadrons

$\rightarrow$ Determination of Wigner distributions of hadrons

Wigner distribution

© Nobel Foundation

One-dimentional quantum mechanics with wave function $\psi(x)$.

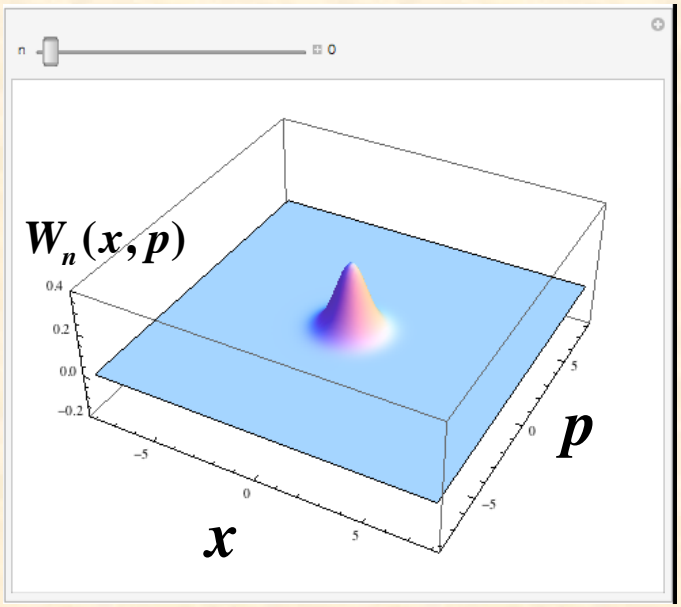
The Wigner distribution is defined by

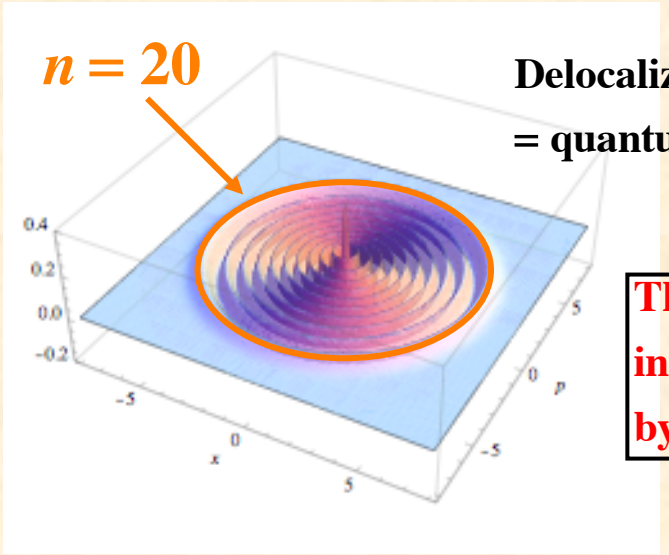
$$W(x,p) \equiv \int d\xi\, e^{ip\xi/\hbar} \psi^*(x-\xi/2)\psi(x+\xi/2) = \text{phase-space distribution}$$

Example: One-dimentional harmonic oscillator: $H(x,p) = \dfrac{p^2}{2m} + \dfrac{1}{2}m\omega^2 x^2$

$$W_n(x,p) = \frac{(-1)^n}{\pi\hbar} e^{-2H/(\hbar\omega)} L_n\left(\frac{4H}{\hbar\omega}\right), \quad E_n = \hbar\omega\left(n+\frac{1}{2}\right), \quad L_n = \text{Laguerre polynomials}$$

$$\to \delta\left(H(p,x) - E_n\right) \text{ as } \hbar \to 0,\ n \to \infty \quad \text{Classical trajectory with } E_n.$$





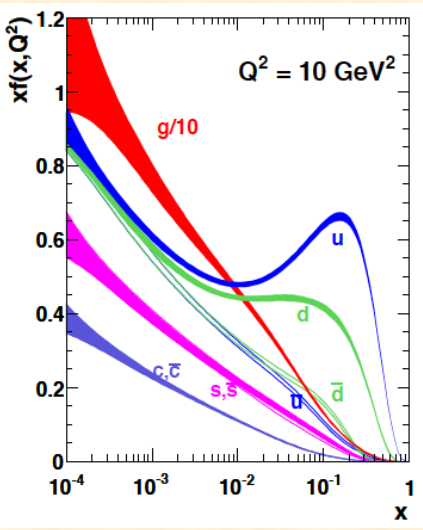
Delocalization of the Wigner distribution = quantum effect (uncertainty principle)

The Wigner distribution provides information on qunatum states by using phase-space concept.

Wigner distribution and various structure functions

Wigner operator: $\hat{w}(k_+,\vec{k}_\perp,\vec{r}) \equiv \int d\xi_- d^2\xi_\perp e^{i\left(\xi_- k_+ - \vec{\xi}_\perp\cdot\vec{k}_\perp\right)} \bar{\psi}\left(\vec{r}-\vec{\xi}/2\right)\psi\left(\vec{r}+\vec{\xi}/2\right)$

Wigner distribution: $W(x,\vec{k}_\perp,\vec{r}) \equiv \int \frac{d^3q}{(2\pi)^3}\left\langle \vec{q}/2\middle|\hat{w}(\vec{r},k_+,\vec{k}_\perp)\middle|-\vec{q}/2\right\rangle, \quad x = k_+ / p_+$



Form factor $\int dx\, d^2k_\perp\, dz$

PDF (Parton Distribution Function) $\int d^2k_\perp d^3r$

Wigner distribution $W(x,\vec{k}_\perp,\vec{r})$

3D world

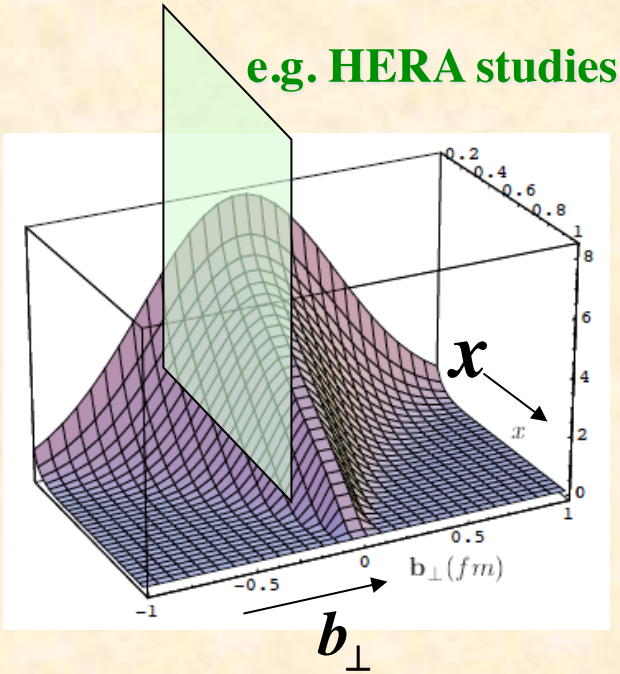
$\int d^3r$

$\int d^2k_\perp dz$

TMD (Transverse Momentum Dependent) parton distribution

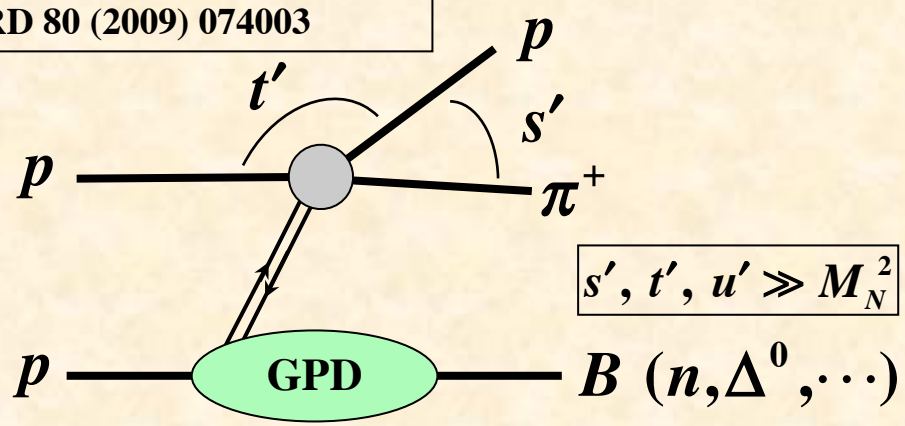
GPD (Generalized Parton Distribution)

e.g. HERA studies



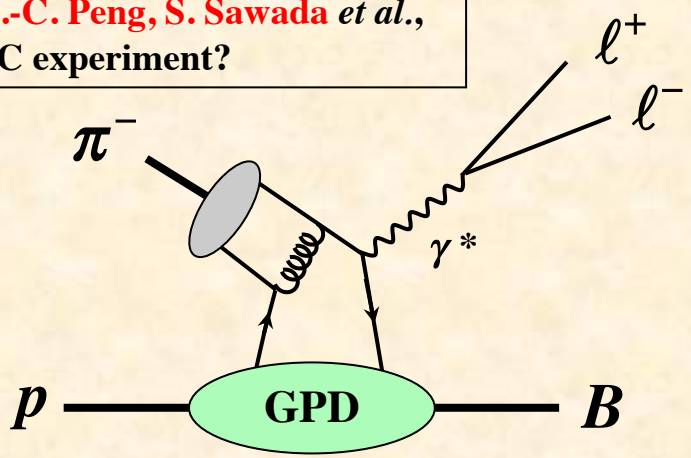
Hadron tomography at J-PARC

SK, M. Strikman, K. Sudoh,
PRD 80 (2009) 074003



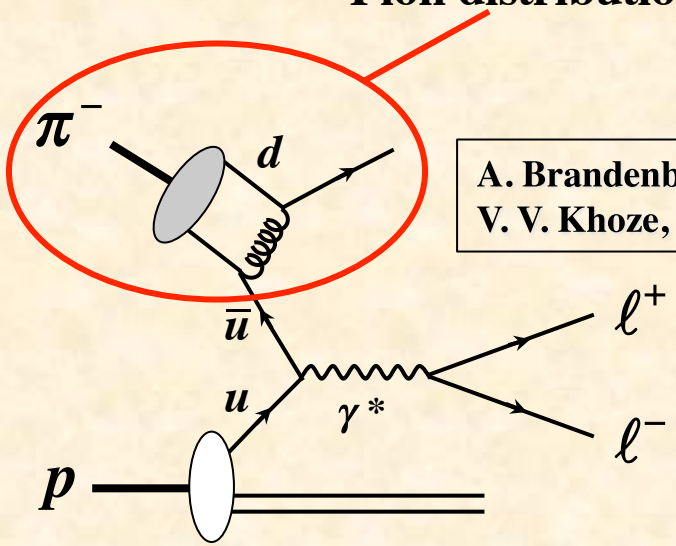
$s', t', u' \gg M_N^2$

W.-C. Chang, J.-C. Peng, S. Sawada *et al.*,
possible J-PARC experiment?



$$\pi^-(\bar{u}d) + p(uud) \to B(udd) + \gamma^*(\to \ell^+\ell^-)$$

Pion distribution

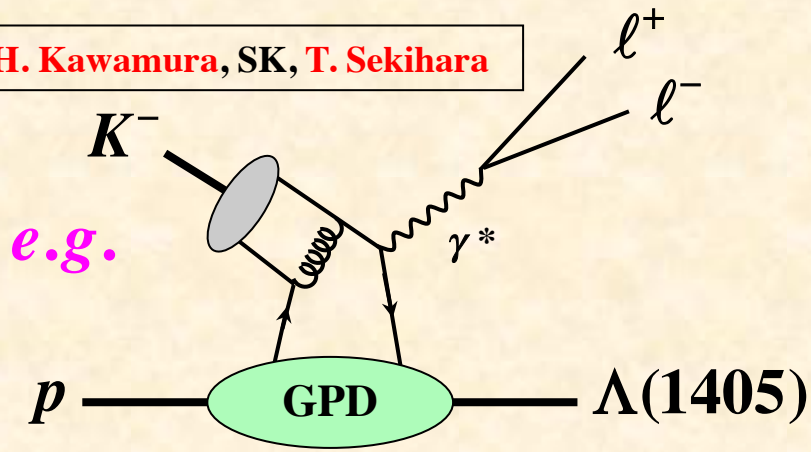


A. Brandenburg, S. J. Brodsky,
V. V. Khoze, D. Müller (1994)

$$\pi^-(\bar{u}s) + p(uud) \to \ell^+\ell^- + X$$

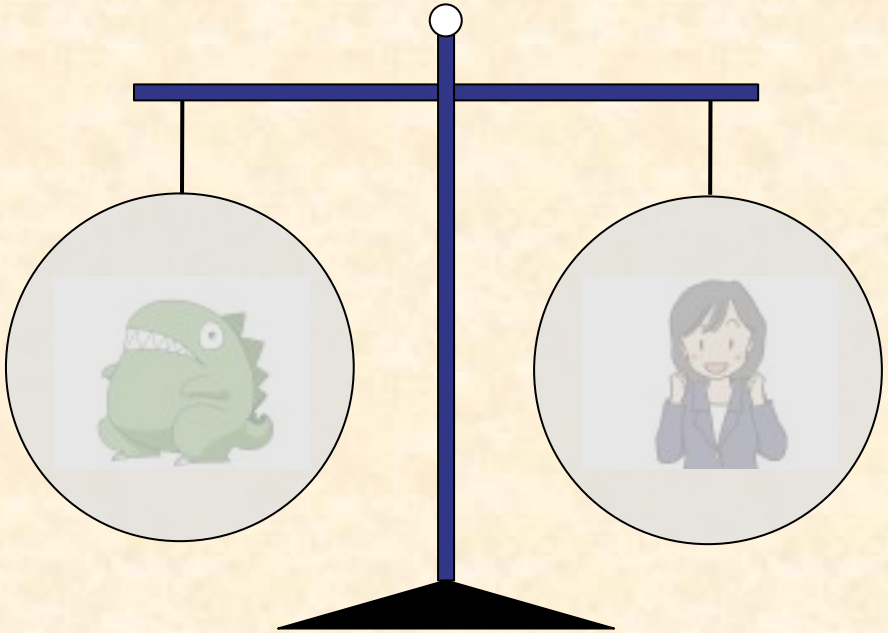
J-PARC exotics

H. Kawamura, SK, T. Sekihara



$$K^-(\bar{u}s) + p(uud) \to \Lambda_{1405}(uud\bar{u}s) + \gamma^*$$

Search for exotic hadrons …



It is difficult to determine
whether or not a hadron is exotic.

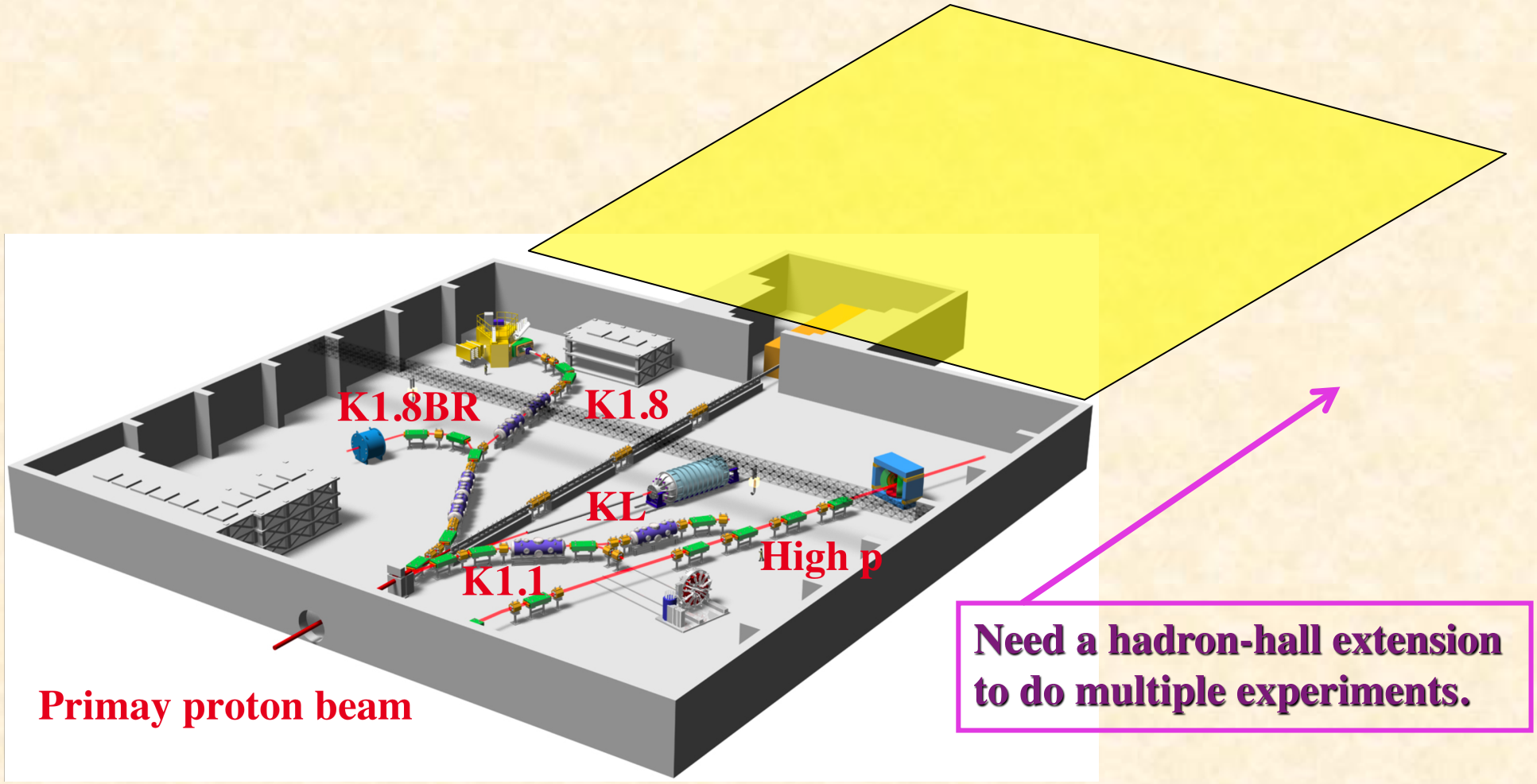
(Already, history of a half century)

By the tomography, we may determine


or

.

Hadron-hall extension?



Summary

J-PARC is a flagship facility in hadron and nuclear physics

- **Hypernuclear physics, Exotic hadrons**
- **Quarks/hadrons in nuclear medium**
- **Partonic structure of hadrons, Spin physics, …**

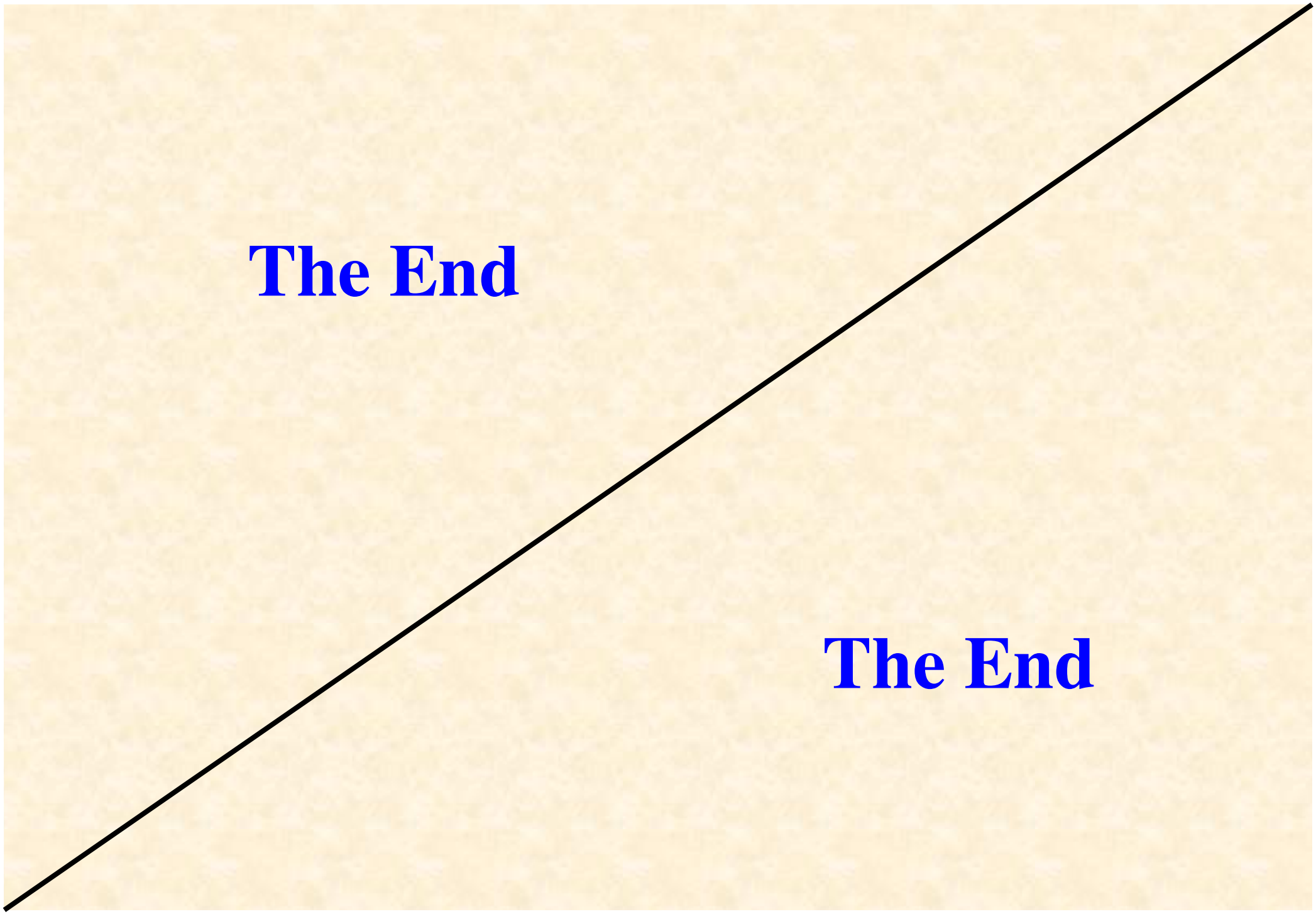
Many researchers in Japan

Manpower ? in Japan

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

The high-momentum beamline physics is like a white canvas, on which you can draw your own picture.

The End



The End