

Hadron physics at J-PARC

(mainly with high-momentum beams)

Shunzo Kumano

**High Energy Accelerator Research Organization (KEK)
J-PARC Center (J-PARC)
Graduate University for Advanced Studies (GUAS)
<http://research.kek.jp/people/kumanos/>**

**Workshop on Cold dense nuclear matter
- from short-range nucleon correlations to neutron stars
October 13-16, 2015, GSI, Darmstadt, Germany
<https://indico.gsi.de/conferenceDisplay.py?ovw=True&confId=3738>**

October 16, 2015

Contents

Introduction

- Introduction to J-PARC facility

Hadron physics at high-momentum beamline

- Approved projects
- Future possibilities
- Activity toward a proposal

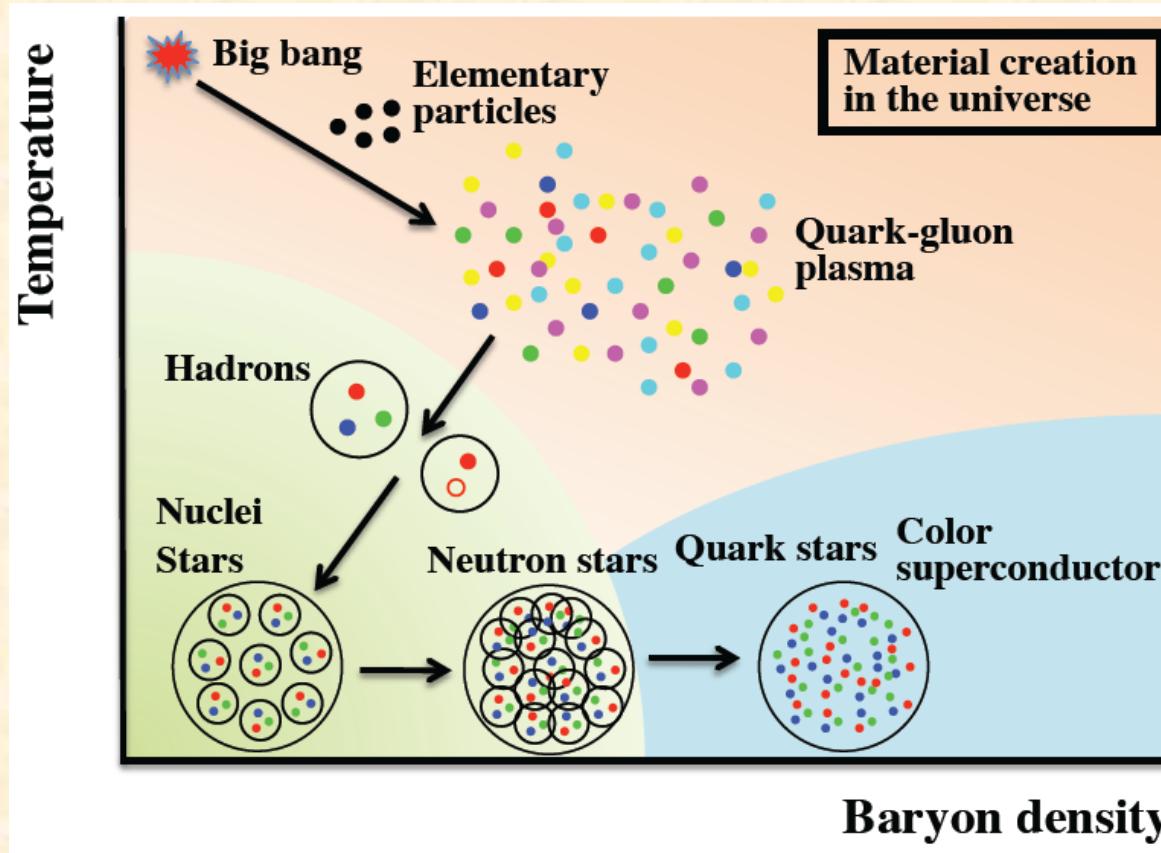
Summary

For the details of accelerator/experimental situation,
please look at N. Saito, Shinya (and Tanakhiro) Sawada's talks at the Spinfest 2015
<http://j-parc-th.kek.jp/workshops/2015/07-06/>.

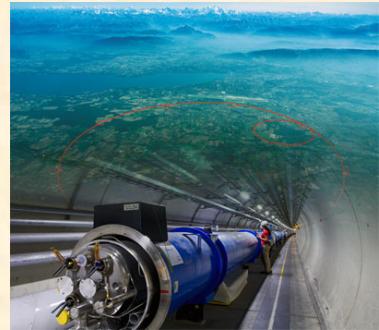
Nuclear Physics: Ultimate high-density quantum many-body system bound by strong interactions

Nuclear physics is a field of investigating

- matter generation of universe
- properties of quark-hadron many-body systems as ultimate materials.

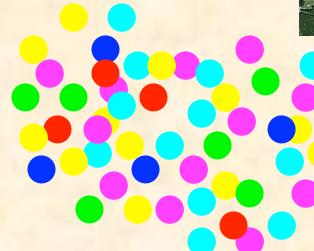


Hadron-physics facilities



T

LHC
RHIC

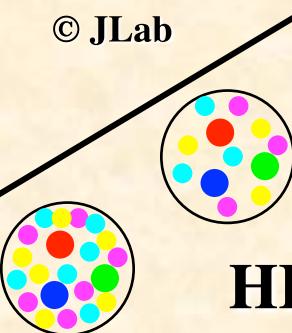


GSI-FAIR



© JLab

Q^2



HERA, EIC
LHC, RHIC

JLab

J-PARC



© J-PARC



© BNL



© GSI



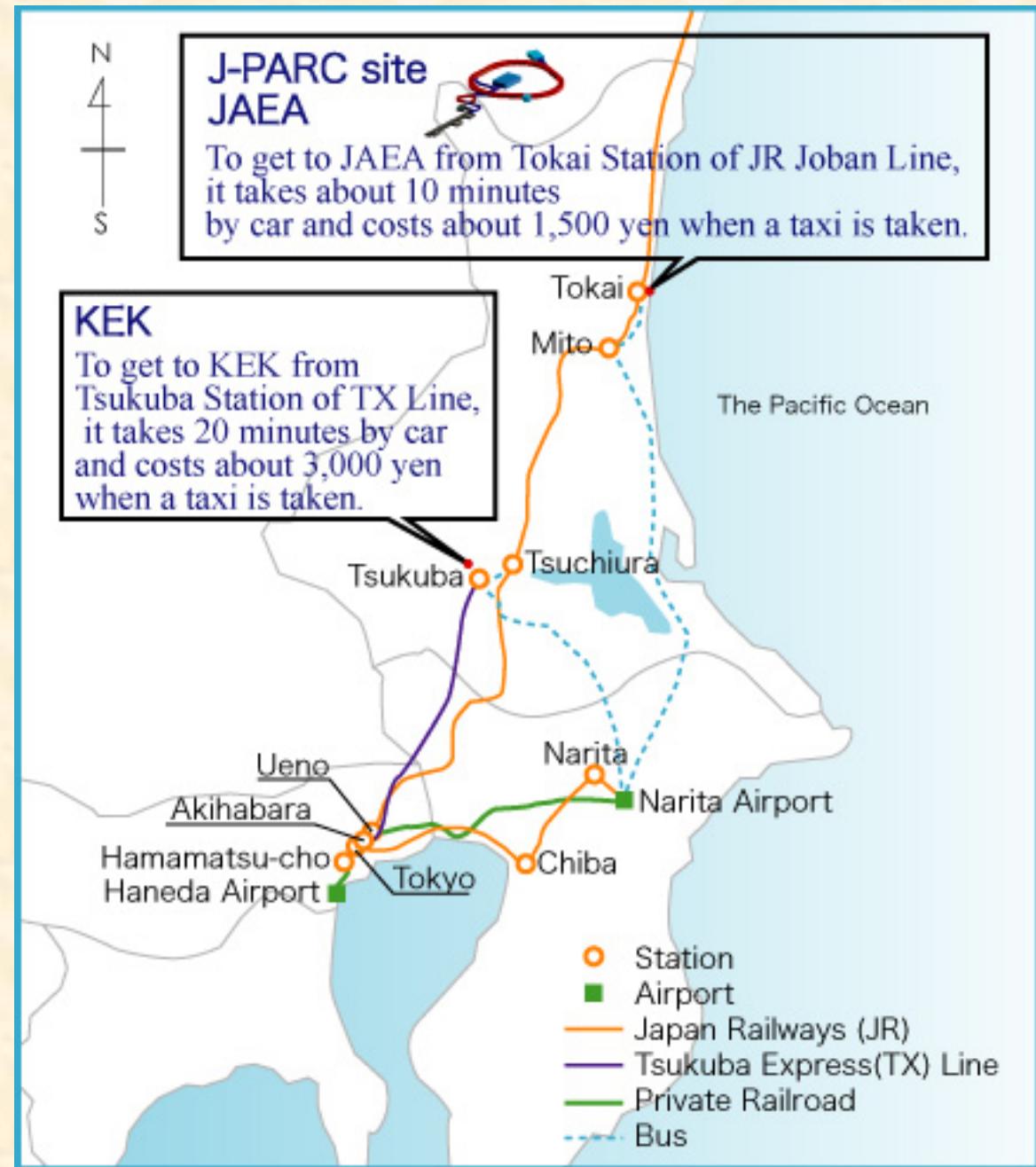
© C. Reed

J-PARC Facility

J-PARC location

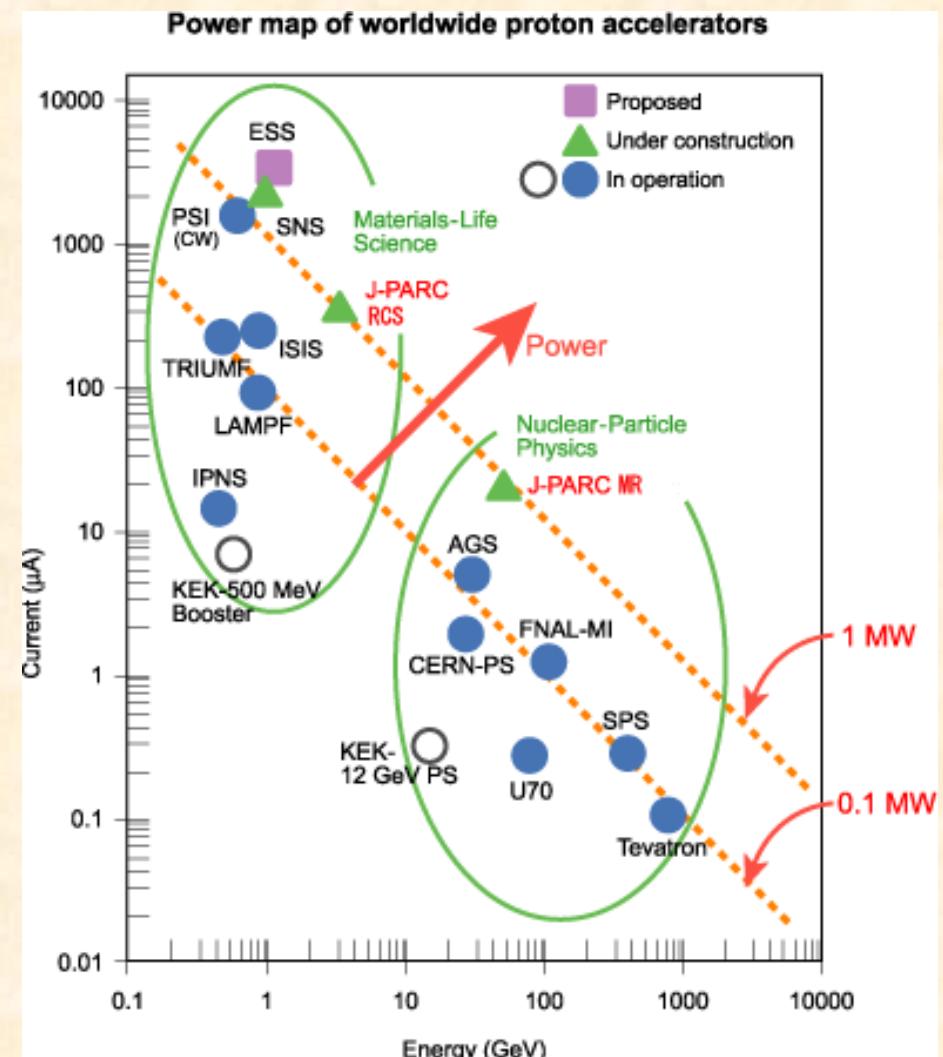
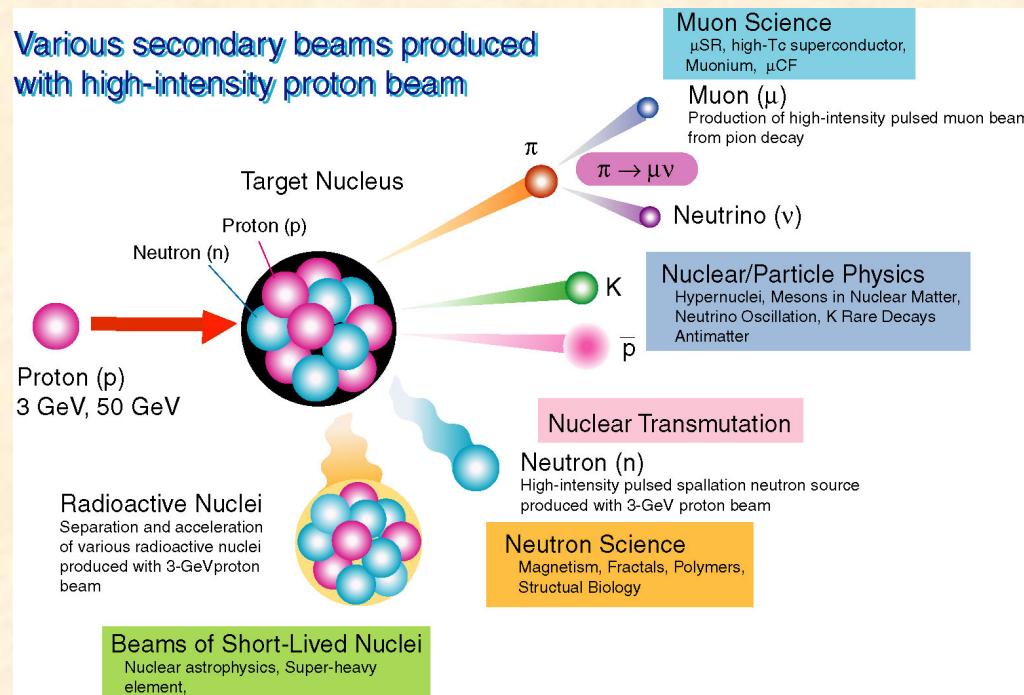
J-PARC
**(Japan Proton Accelerator
Research Complex)**

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

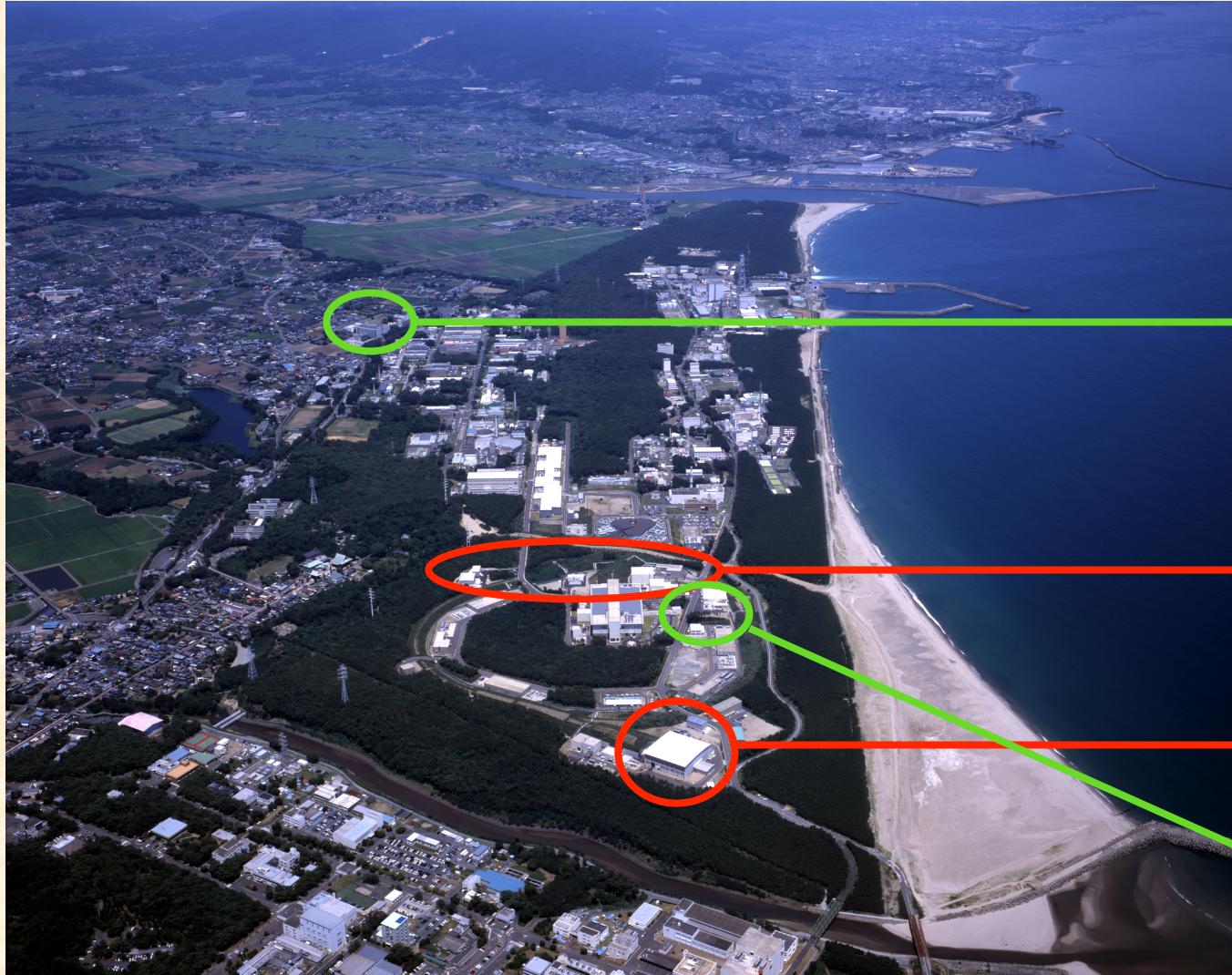


High-Intensity Frontier of Proton Accelerator

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



Aerial photograph



KEK Tokai campus,
J-PARC branch
KEK theory center

**Neutrino
facility**

**Hadron
facility**

New research
building

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>

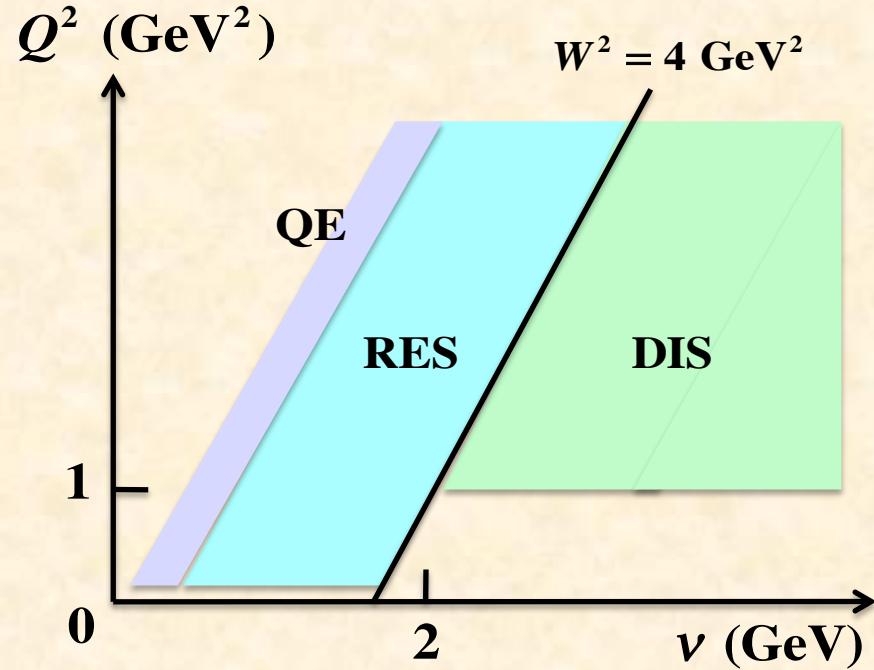
4 permanent KEK staffs (A. Dote, K. Itakura, S. Kumano, O. Morimatsu)
+ 1 research fellow (T. Marruyama)
+ 5 visiting staffs (S. Hirenzaki, A. Hosaka, T. Sato, S. Shinmura, K. Tanaka)

Hadron masses in medium Neutrino-nuclear interactions Structure functions
Charm physics Hyper-nuclear physics

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

Kinematical regions of neutrino-nucleus scattering

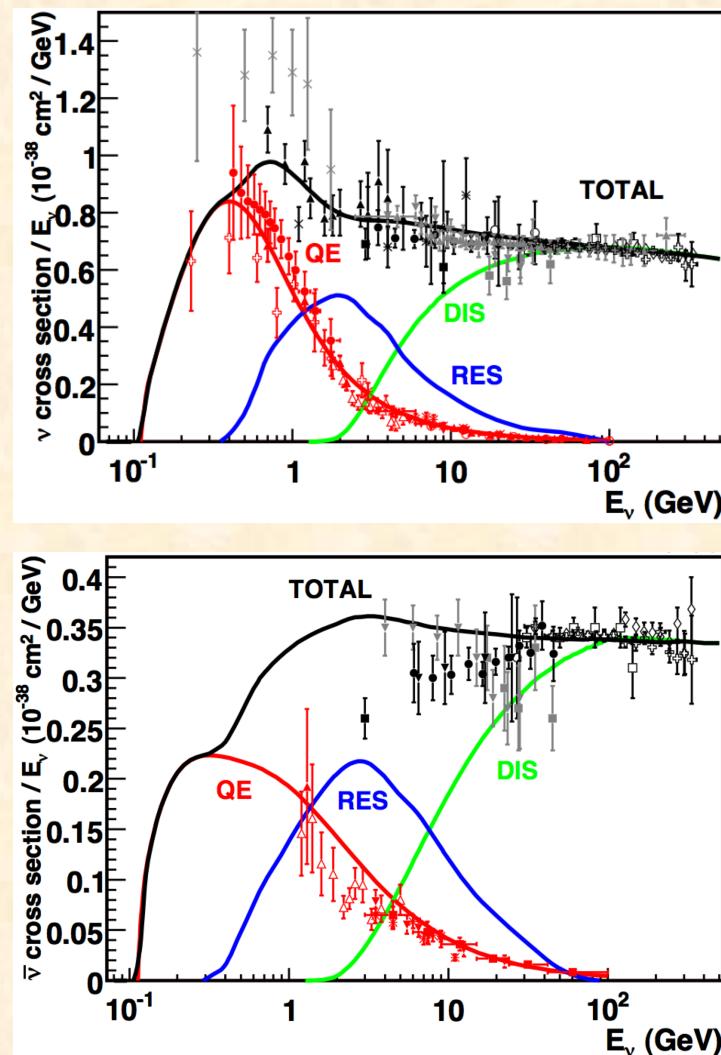
(related topic for this workshop audience)



Depending on the neutrino beam energy, different physics mechanisms contribute to the cross section.

- QE (Quasi elastic)
- RES (Resonance)
- DIS (Deep inelastic)

Activities at the J-PARC branch, KEK theory center
<http://j-parc-th.kek.jp/html/English/e-index.html>



J.L. Hewett *et al.*, arXiv:1205.2671,
Proceedings of the 2011 workshop
on Fundamental Physics at the Intensity Frontier

J-PARC hadron physics

J-PARC hadron physics

Possibilities

Approved proposals

- Strangeness nuclear physics (1st experiment)

• Exotic hadrons

• Hadrons in nuclear medium

• Hard processes

• Nucleon spin (beam polarization)

• Quark-hadron matter (heavy ion)

1st project

Next projects

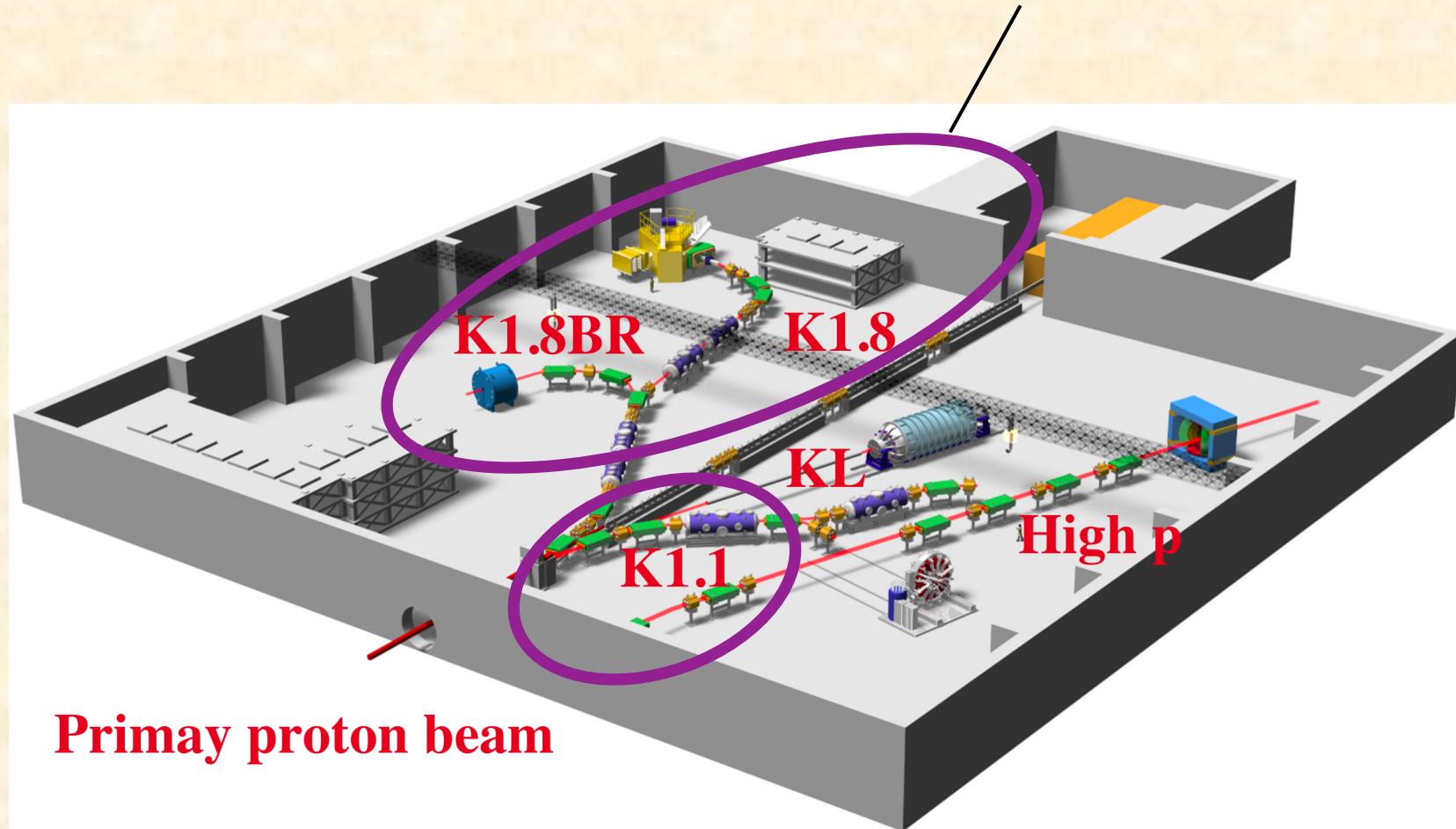
Need major
upgrades

“Possible” high-momentum beamline projects

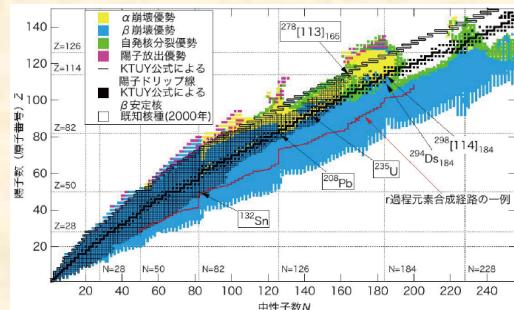


Hadron facility

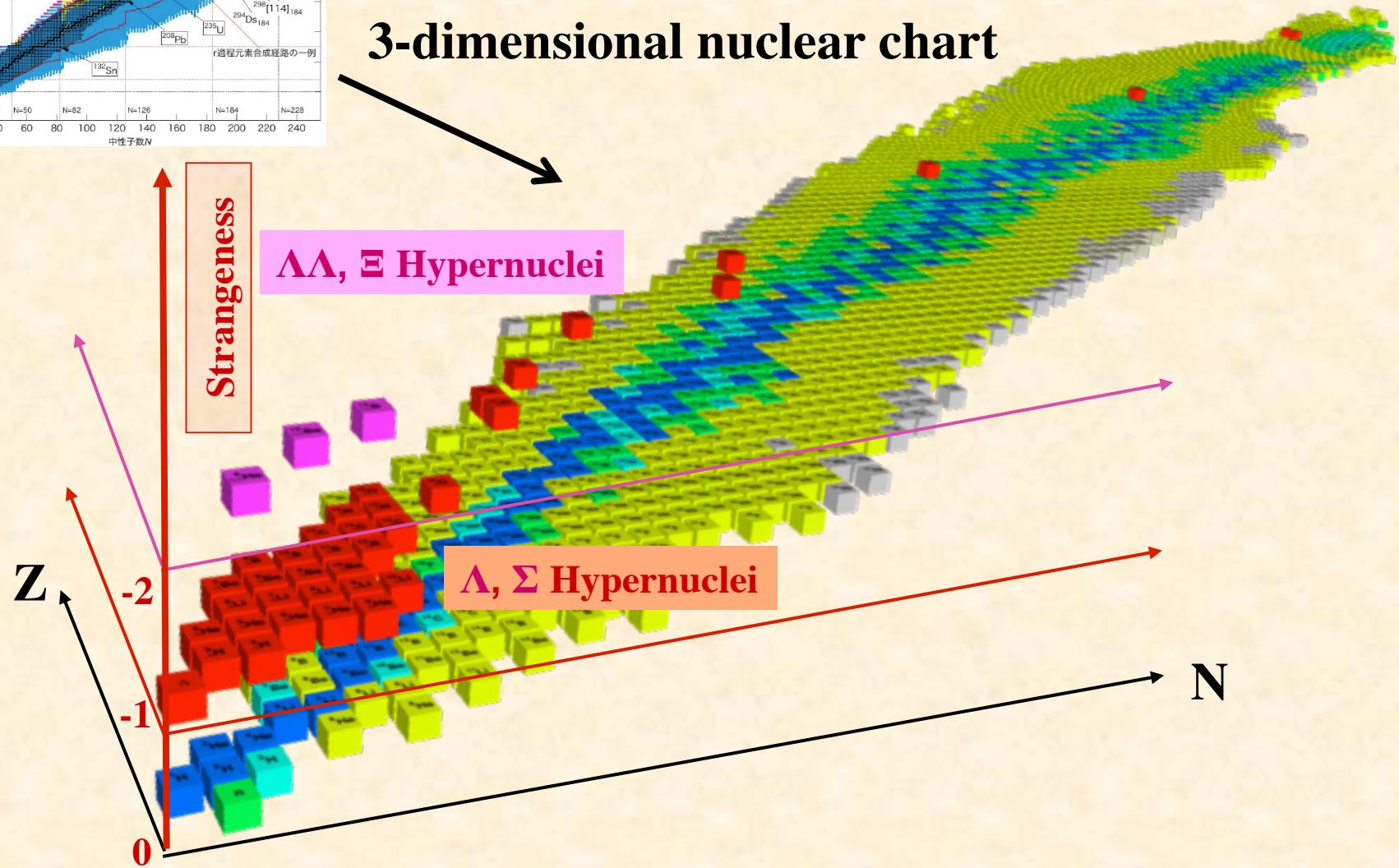
(Low energy) Kaon and pion experiments
are done at these beamlines.



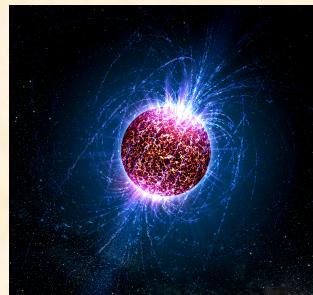
Strangeness nuclear physics



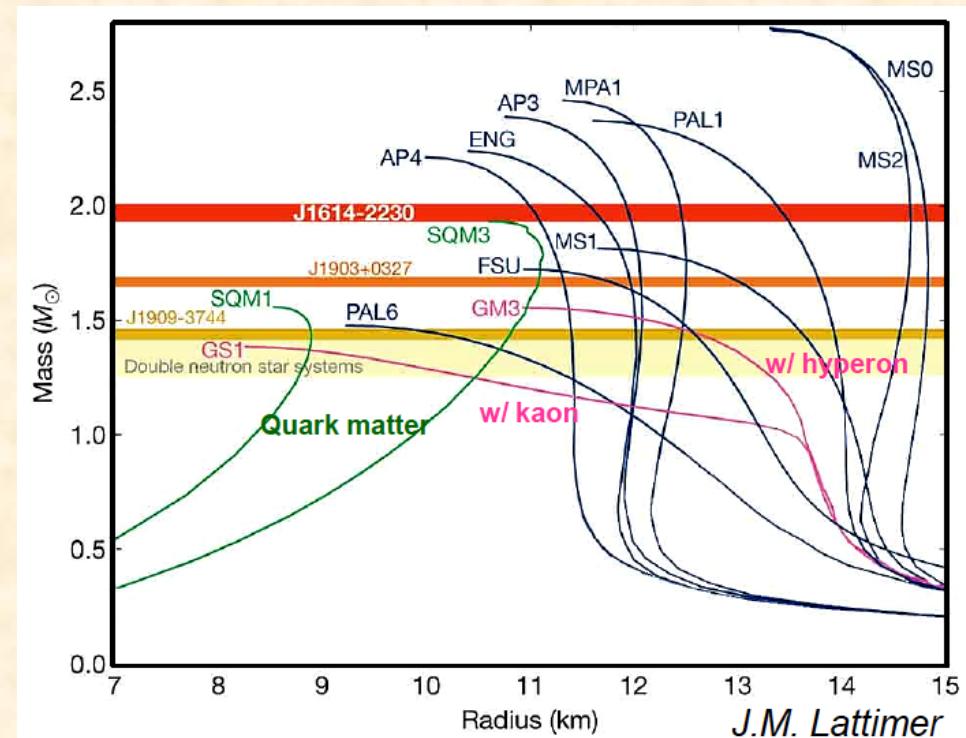
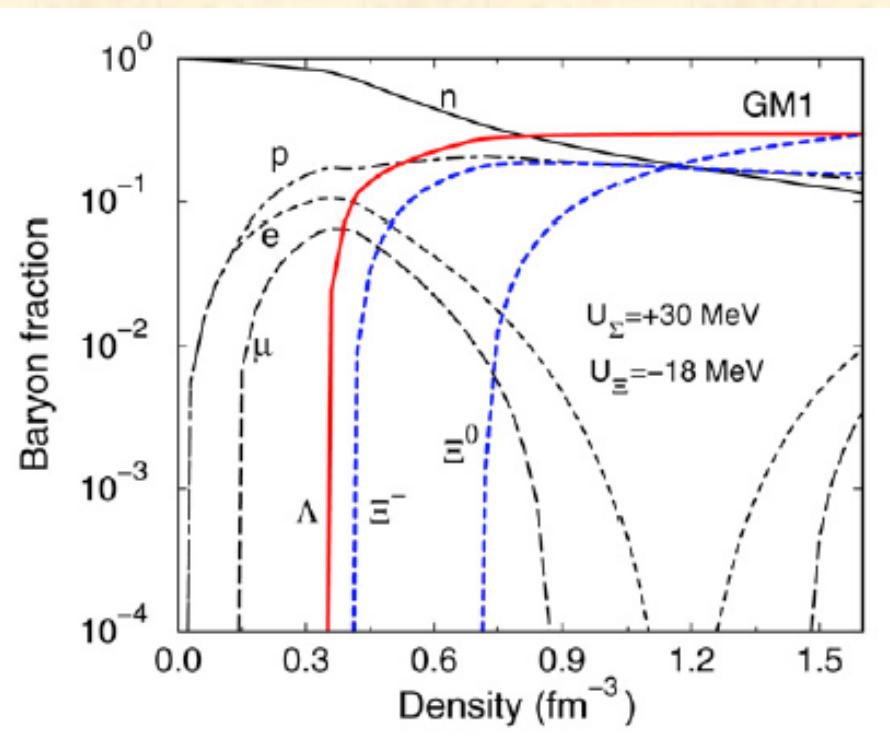
3-dimensional nuclear chart



Neutron stars



Precise YN, YY interactions are necessary for understanding neutron stars.



Some results already from J-PARC

PHYSICAL REVIEW C 90, 035205 (2014)

High-resolution search for the Θ^+ pentaquark via a pion-induced reaction at J-PARC

M. Moritsu,^{1,*} S. Adachi,¹ M. Agnello,^{2,3} S. Ajimura,⁴ K. Aoki,⁵ H. C. Bhang,⁶ B. Bassalleck,⁷ E. Botta,^{3,8} S. Bufalino,³ N. Chiga,⁹ H. Ekawa,¹ P. Evtoukhovitch,¹⁰ A. Feliciello,³ H. Fujioka,¹ S. Hayakawa,¹¹ F. Hiruma,⁹ R. Honda,⁹ K. Hosomi,^{9,†} Y. Ichikawa,¹ M. Ieiri,⁵ Y. Igarashi,⁵ K. Imai,¹² N. Ishibashi,¹¹ S. Ishimoto,⁵ K. Itahashi,¹³ R. Iwasaki,⁵ C. W. Joo,⁶ S. Kanatsuki,¹ M. J. Kim,⁹ S. J. Kim,⁶ R. Kiuchi,^{6,‡} T. Koike,⁹ Y. Komatsu,¹⁴ V. V. Kulikov,¹⁵ S. Marcello,^{8,§} S. Masumoto,¹⁴ Y. Matsumoto,⁹ K. Matsuoka,¹¹ K. Miwa,⁹ T. Nagae,¹ M. Naruki,^{5,¶} M. Niiyama,¹ H. Noumi,⁴ Y. Nozawa,¹ R. Ota,¹¹ K. Ozawa,⁵ N. Saito,⁵ A. Sakaguchi,¹¹ H. Sako,¹² V. Samoilov,¹⁰ M. Sato,⁹ S. Sato,¹² Y. Sato,⁵ S. Sawada,⁵ M. Sekimoto,⁵ K. Shirotori,^{9,12,||} H. Sugimura,^{1,†} S. Suzuki,⁵ H. Takahashi,⁵ T. N. Takahashi,^{13,14,¶} H. Tamura,⁹ T. Tanaka,¹¹ K. Tanida,^{6,12} A. O. Tokiyasu,^{1,§} N. Tomida,¹ Z. Tsamalaidze,¹⁰ M. Ukai,⁹ K. Yagi,⁹ T. O. Yamamoto,⁹ S. B. Yang,⁶ Y. Yonemoto,⁹ C. J. Yoon,⁶ and K. Yoshida¹¹
(J-PARC E19 Collaboration)

Physics Letters B 729 (2014) 39–44

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb



ELSEVIER

Search for ${}^6_{\Lambda}\text{H}$ hypernucleus by the ${}^6\text{Li}(\pi^-, K^+)$ reaction at $p_{\pi^-} = 1.2 \text{ GeV}/c$

J-PARC E10 Collaboration

H. Sugimura^{a,b,*}, M. Agnello^{c,d}, J.K. Ahn^e, S. Ajimura^f, Y. Akazawa^g, N. Amano^a, K. Aoki^h, H.C. Bhangⁱ, N. Chiga^g, M. Endo^j, P. Evtoukhovitch^k, A. Feliciello^d, H. Fujioka^a, T. Fukuda^l, S. Hasegawa^b, S. Hayakawa^j, R. Honda^g, K. Hosomi^g, S.H. Hwang^b, Y. Ichikawa^{a,b}, Y. Igarashi^h, K. Imai^b, N. Ishibashi^j, R. Iwasaki^h, C.W. Jooⁱ, R. Kiuchi^{i,b}, J.K. Lee^e, J.Y. Leeⁱ, K. Matsuda^j, Y. Matsumoto^g, K. Matsuoka^j, K. Miwa^g, Y. Mizoi^l, M. Moritsu^f, T. Nagae^a, S. Nagamiya^b, M. Nakagawa^j, M. Naruki^a, H. Noumi^f, R. Ota^j, B.J. Roy^m, P.K. Saha^b, A. Sakaguchi^j, H. Sako^b, C. Samantaⁿ, V. Samoilov^k, Y. Sasaki^g, S. Sato^b, M. Sekimoto^h, Y. Shimizu^l, T. Shiozaki^g, K. Shirotori^f, T. Soyama^j, T. Takahashi^h, T.N. Takahashi^o, H. Tamura^g, K. Tanabe^g, T. Tanaka^j, K. Tanidaⁱ, A.O. Tokiyasu^f, Z. Tsamalaidze^k, M. Ukai^g, T.O. Yamamoto^g, Y. Yamamoto^g, S.B. Yangⁱ, K. Yoshida^j

PTEP

Prog. Theor. Exp. Phys. 2015, 021D01 (8 pages)
DOI: 10.1093/ptep/ptv002

Letter

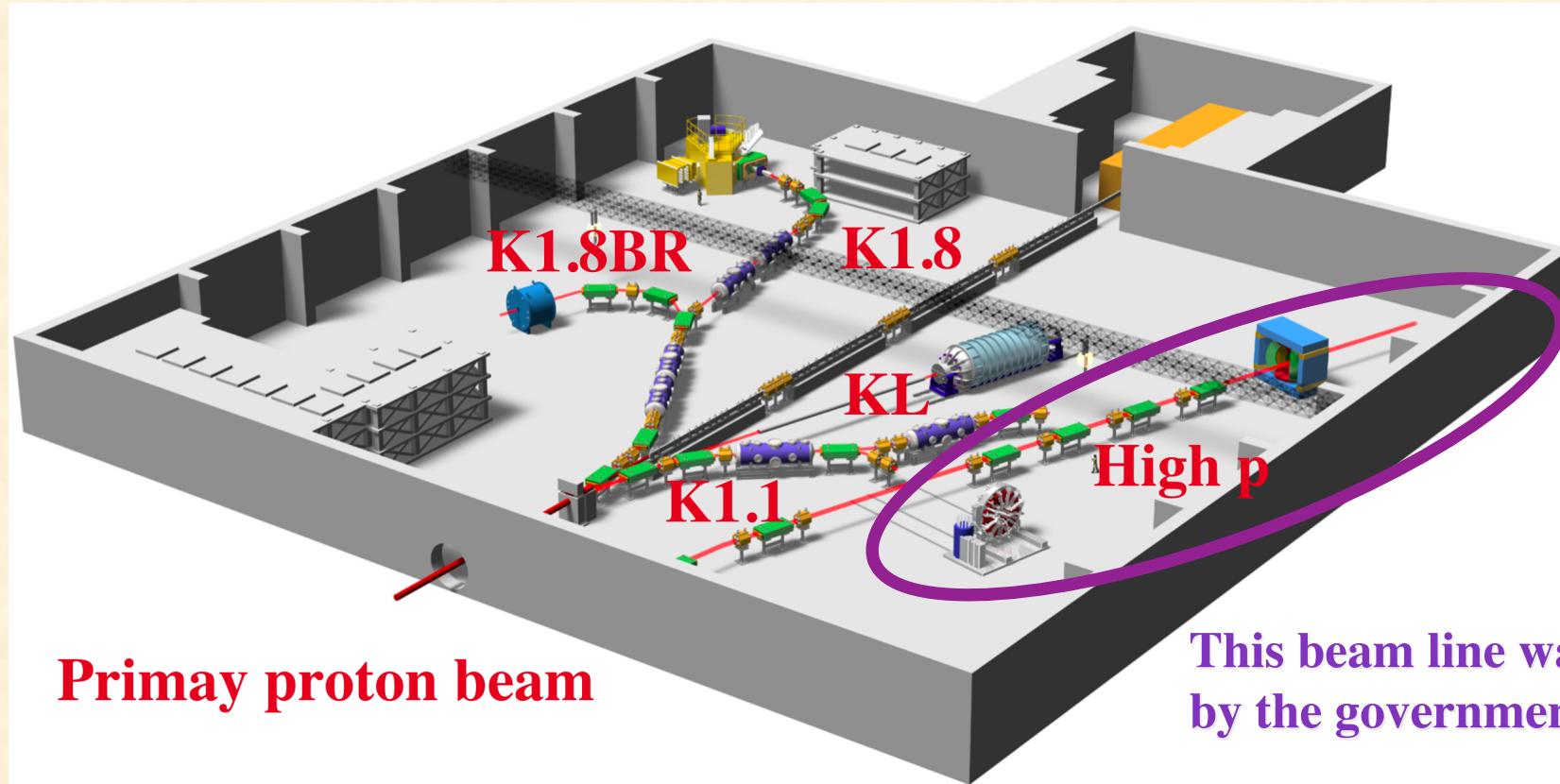
Observation of the “ $K^- pp$ ”-like structure in the $d(\pi^+, K^+)$ reaction at $1.69 \text{ GeV}/c$

Yudai Ichikawa^{1,2}, Tomofumi Nagae^{1,*}, Hiroyuki Fujioka¹, Hyoungchan Bhang³, Stefania Bufalino⁴, Hiroyuki Ekawa^{1,2}, Petr Evtoukhovitch⁵, Alessandro Feliciello⁴, Shoichi Hasegawa², Shuhei Hayakawa⁶, Ryotaro Honda⁷, Kenji Hosomi², Ken'ichi Imai², Shigeru Ishimoto⁸, Changwoo Joo³, Shunsuke Kanatsuki¹, Ryuta Kiuchi², Takeshi Koike⁷, Harphool Kumawat⁹, Yuki Matsumoto⁷, Koji Miwa⁷, Manabu Moritsu¹⁰, Megumi Naruki¹, Masayuki Niiyama¹, Yuki Nozawa¹, Ryosuke Ota⁶, Atsushi Sakaguchi⁶, Hiroyuki Sako², Valentin Samoilov⁵, Susumu Sato², Kotaro Shirotori¹⁰, Hitoshi Sugimura², Shoji Suzuki⁸, Toshiyuki Takahashi⁸, Tomonori N. Takahashi¹⁰, Hirokazu Tamura⁷, Toshiyuki Tanaka⁶, Kiyoshi Tanida³, Atsushi O. Tokiyasu¹⁰, Zviadi Tsamalaidze⁵, Bidyut Roy⁹, Mifuyu Ukai⁷, Takeshi O. Yamamoto⁷, and Seongbae Yang³

J-PARC projects on high-momentum beamline

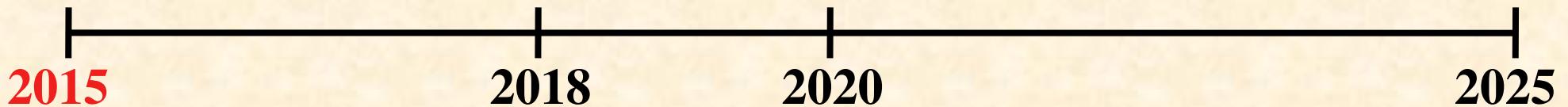
Hadron facility

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

Physics of J-PAC high-momentum beamline



Construction

**Hadron masses
in nuclear
medium**

E16

Proposal

Electron pair spectrometer at the J-PARC
50-GeV PS to explore the chiral symmetry in
QCD

April 28, 2006
June 07, 2006 rev.1

S. Yokkaichi¹, H. En'yo, M. Naruki, R. Muto, T. Tabaru
RIKEN

K. Ozawa, H. Hamagaki

Center for Nuclear Study, Graduate School of Science, University of Tokyo

K. Shigaki

Graduate School of Science, Hiroshima University

S. Sawada, M. Sekimoto

High Energy Accelerator Research Organization (KEK)

F. Sakuma, K. Aoki

Department of Physics, Kyoto University

KEK/J-PARC-PAC 2012-19

Charmed Baryon Spectroscopy via the (π, D^-) reaction

Y. Morino, T. Nakano,^{*} H. Noumi,[†] K. Shirotori, Y. Sugaya, and T. Yamaga
Research Center for Nuclear Physics (RCNP), Osaka University,
10-1, Mihogaoka, Ibaraki, Osaka, 567-0047, Japan

K. Ozawa[‡]

Institute of Particle and Nuclear Studies(IPNS),
High Energy Accelerator Research Organization (KEK),
1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

T. Ishikawa

Reserach Center for Electron Photon Science,
Tohoku University, 1-2-1, Mikamine,
Taihaku-ku, Sendai, Miyagi 982-0826, Japan

V. Miyachi

Physics Department, Yamagata University, 1-4-12,
Kojirakawa-machi, Yamagata 990-8560, Japan

K. Tanida

Department of Physics and Astronomy,
Seoul National University, Seoul 151-747, Korea

**High-energy
hadron???**



**There is a possibility
for high-energy hadron physics,
including nucleon structure,
short-range NN correlations.**

Hadron masses in nuclear medium

Origin of the nucleon mass:

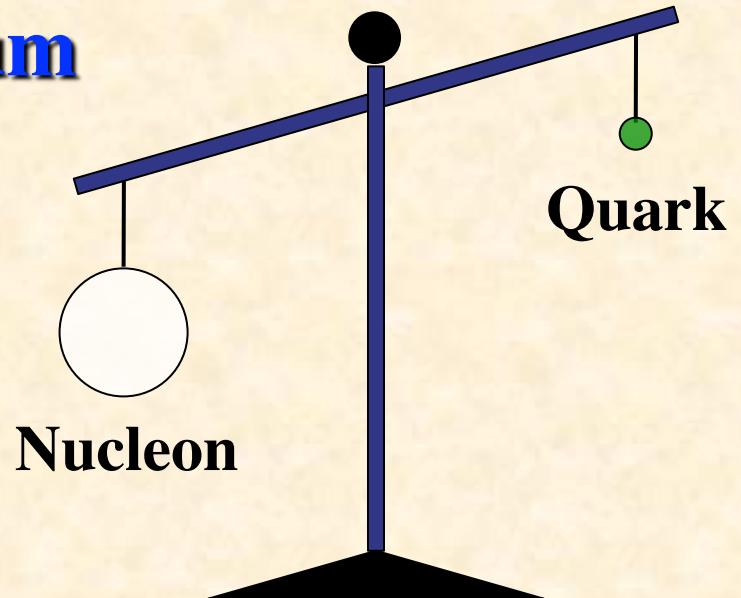
Why $m_{\text{quark}} \ll m_{\text{nucleon}}$?

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

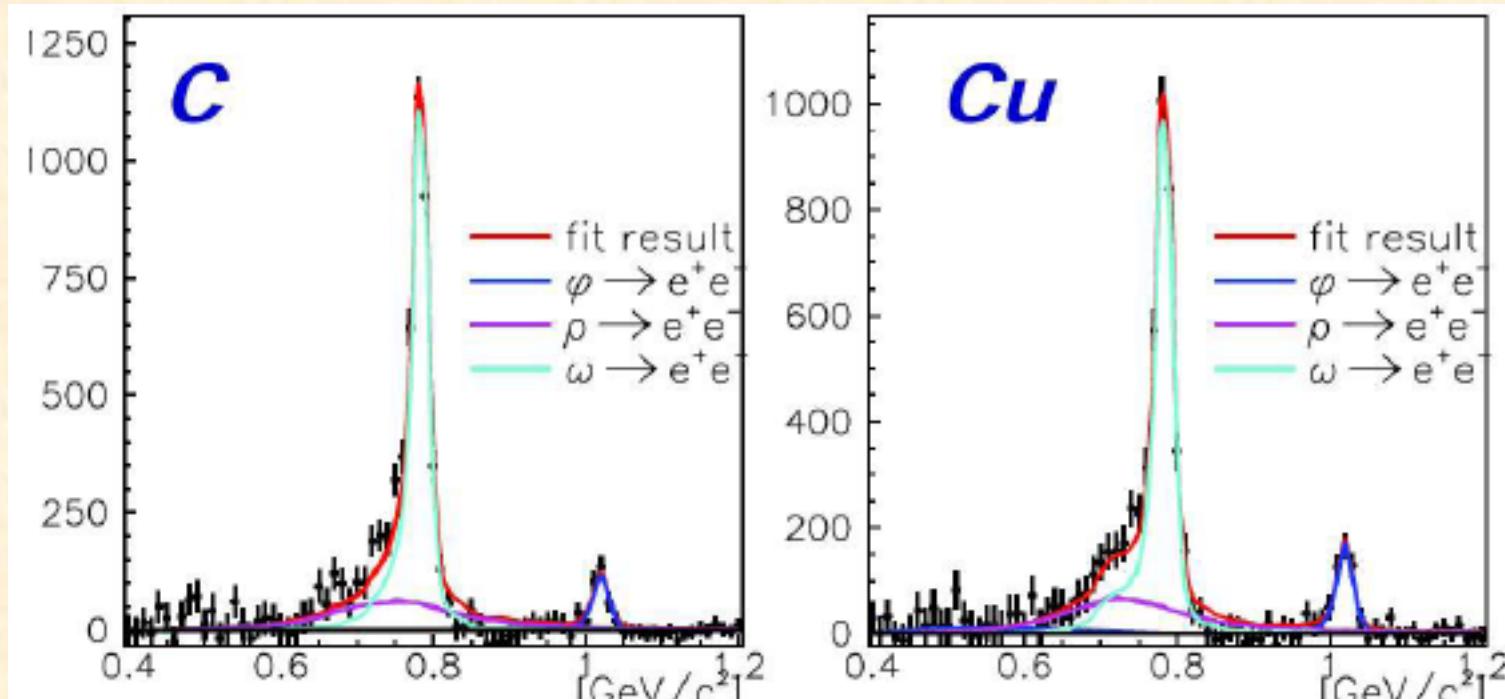
Modifications even
at “normal nuclear density”

Reduction in ρ , ω masses
at normal nuclear density

KEK-E325 Collaboration

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

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

$$m(\varrho) / m(0) = 1 - k \varrho / \varrho_0 \quad k = 0.092 \pm 0.002 \text{ for } \rho, \omega \quad 9\%, 3\% \text{ mass shifts}$$
$$= 0.034^{+0.006}_{-0.007} \quad \text{for } \phi$$

→ continued at J-PARC (E16)

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, Λ , Σ , Ξ , ...
(many theoretical studies)

Future experiments: J/ ψ , D, ...,
(need further studies)

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

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

Possibilities of J-PARC projects at high-momentum beamline

(high-energy hadron physics)

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

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



Topics:

- Quarks/Hadrons in nuclear medium
- Exotic hadrons, Charm physics
- Baryon interactions, Short-range correlations
- Nucleon structure

Related talks

Mark Strikman, High-energy hadron interactions in nuclear medium

Dipangkar Dutta, Experiments on high-energy hadron interactions in nuclear medium

Jianwei Qiu, Parton energy loss in nuclear medium

Kenneth Hicks, Experiments on parton energy loss in cold nuclear medium

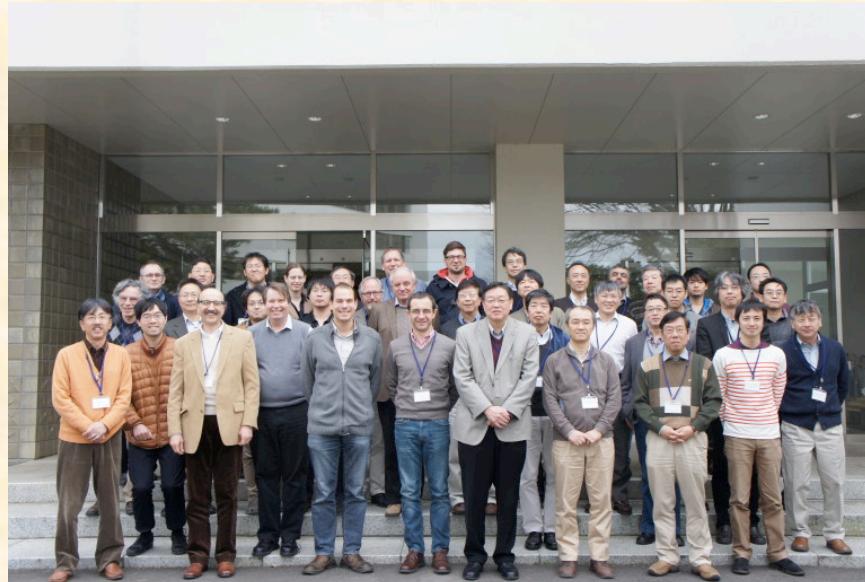
Claudio Ciofi degli Atti, Short-range NN correlations

Eliezer Piasetzky, Experiments on short-range NN correlations

Hadron physics with high-momentum hadron bemas at J-PARC in 2015

<http://research.kek.jp/group/hadron10/j-parc-hm-2015/>

March 13-16, 2015, KEK, Tsukuba, Japan



Related talks

Mark Strikman: High-energy hadron interactions in nuclear medium

Misak Sargsian: Probing quark correlations in hard hadronic processes

William Brooks: Parton energy loss in cold nuclear medium

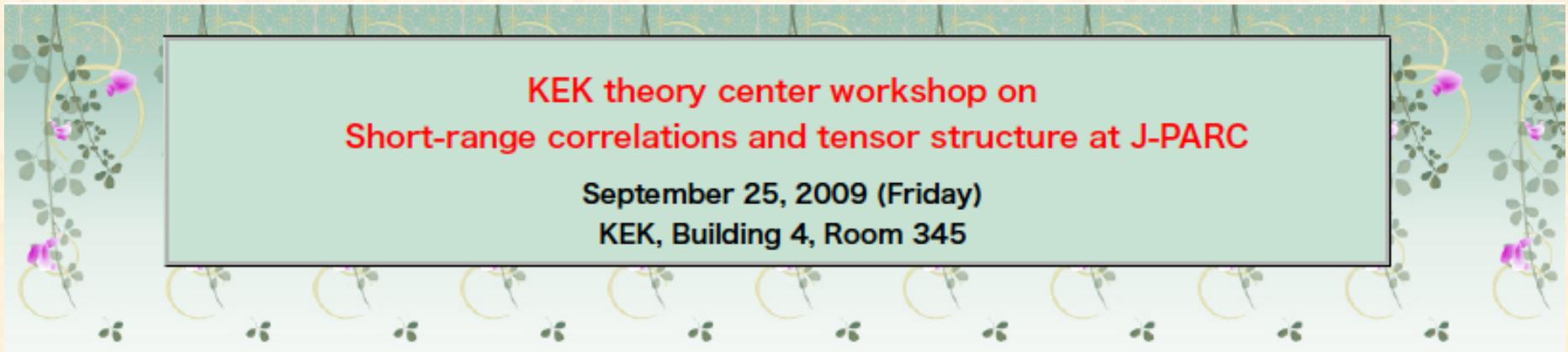
J-PARC possibility on short-range correlations (2009)

Workshop on Short-range correlations and tensor structure at J-PARC

<http://www-conf.kek.jp/past/hadron1/j-parc-src09/>

September 26, 2009

with Claudio Ciofi degli Atti



At that time, the high-momentum beamline was not financially approved,
so the discussions did not develop into a realistic experimental proposal.
→ Situation is now different for the facility.

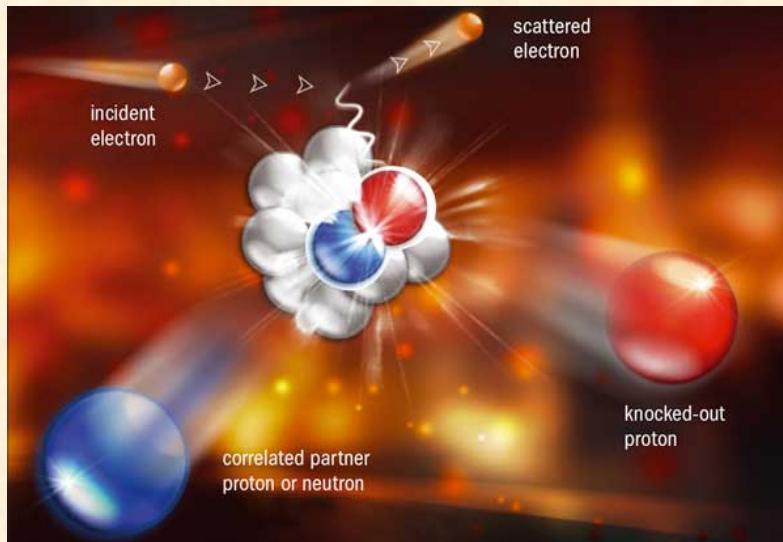
The J-PARC high-momentum beamline will be ready in 2018.

→ ...

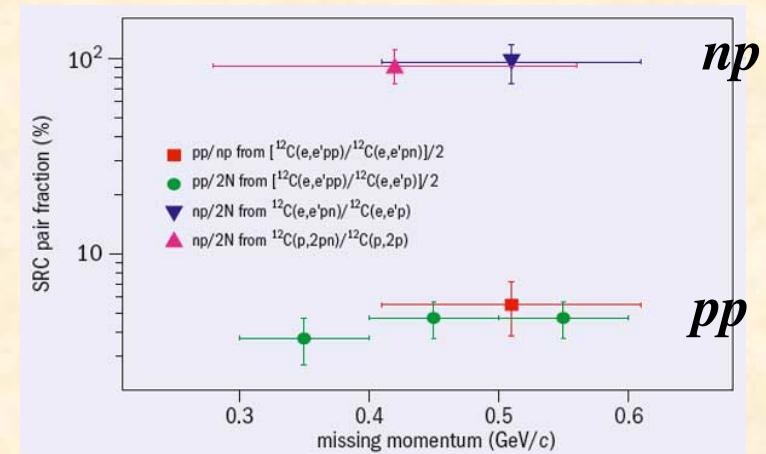
Short-range NN interaction

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

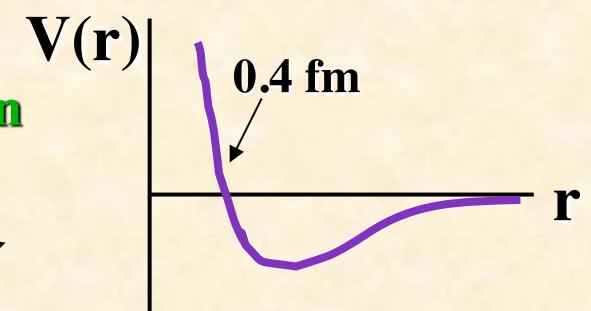
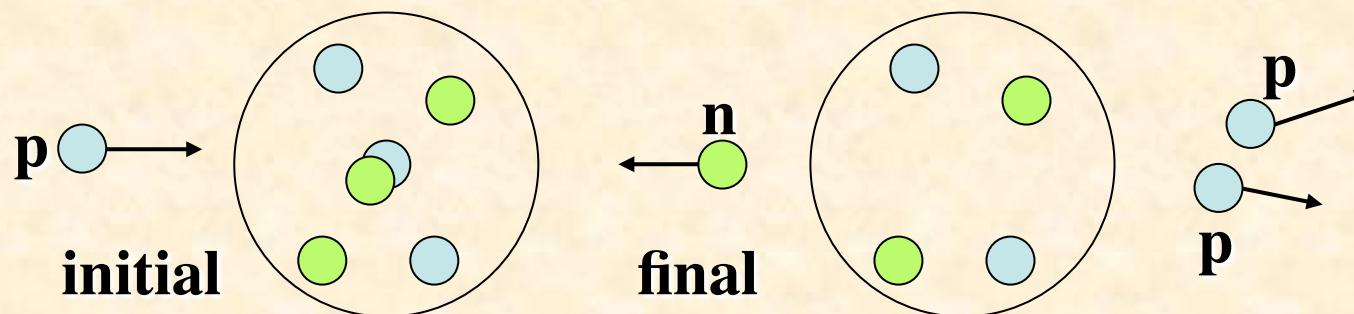
D. Higinbotham, E. Piasetzky, and M. Strikman
CERN Courier 49 (2009) 22.



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



J-PARC: $\text{A}(\text{p}, 2\text{pN})\text{X}$ experiment for short-range correlation



Color Transparency

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

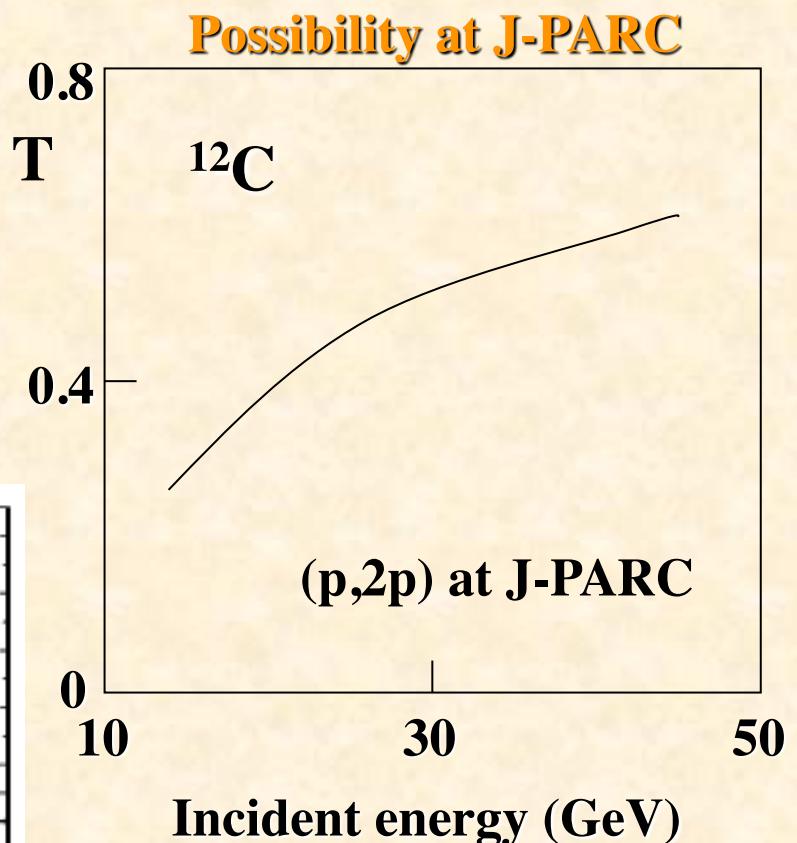
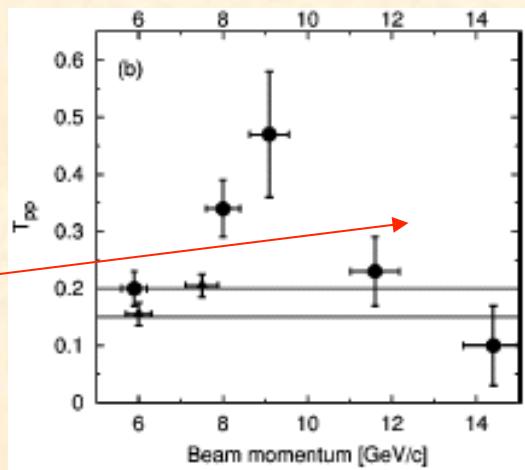
Investigate $pA \rightarrow pp$ ($A=I$)

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

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?



Past proposals and prospects

Proposals on high-energy hadron physics

http://j-parc.jp/researcher/Hadron/en/Proposal_e.html

J. C. Peng, S. Sawada *et al.*

Proposal

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

S. Choi *et al.*

Letter of Intent to J-PARC PAC
for

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

Y. Goto *et al.*

Proposal

Polarized Proton Acceleration at J-PARC

**The high-momentum had not been approved financially until 2013,
so these proposals were deferred.**

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

**New proposal
under consideration!**

Hadron facilities

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

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

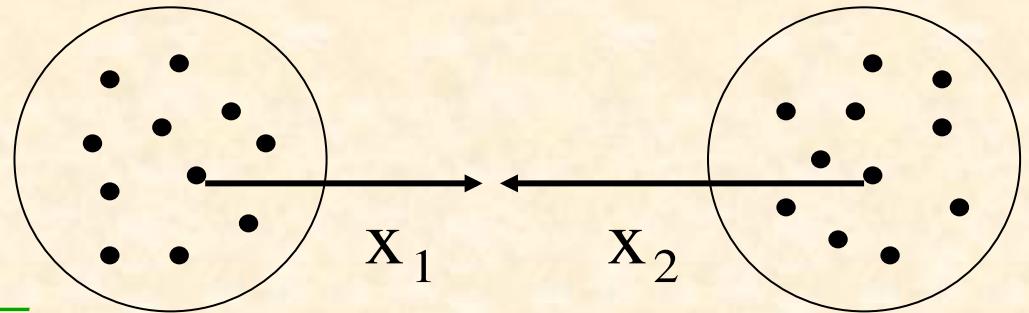
- $s = (p_1 + p_2)^2$

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).

$$\begin{aligned} x \sim \frac{\sqrt{m_{\mu\mu}^2}}{\sqrt{s}} &\geq \frac{3}{10} = 0.3 \\ &\geq \frac{3}{200} = 0.015 \\ &\geq \frac{3}{14000} = 0.0002 \end{aligned}$$

J-PARC (Fermilab-120 GeV)

RHIC (COMPASS)

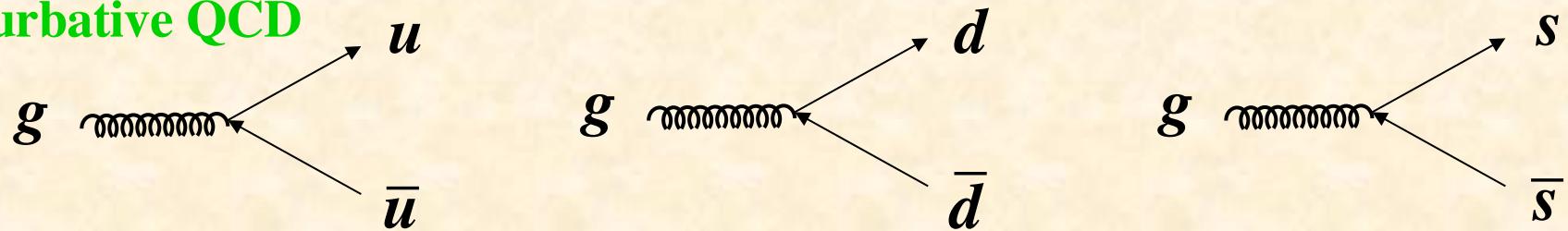
LHC

Large- x facility

Small- x facility

Flavor dependence of antiquark distributions

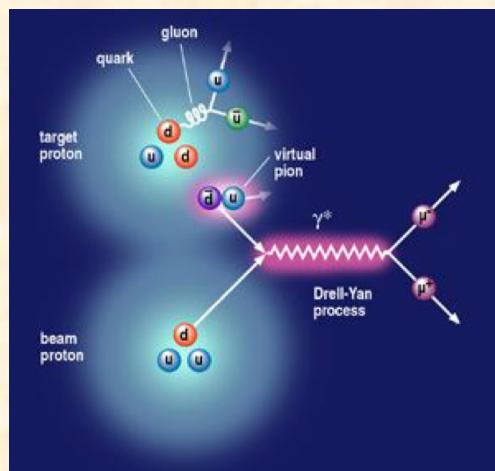
Perturbative QCD



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

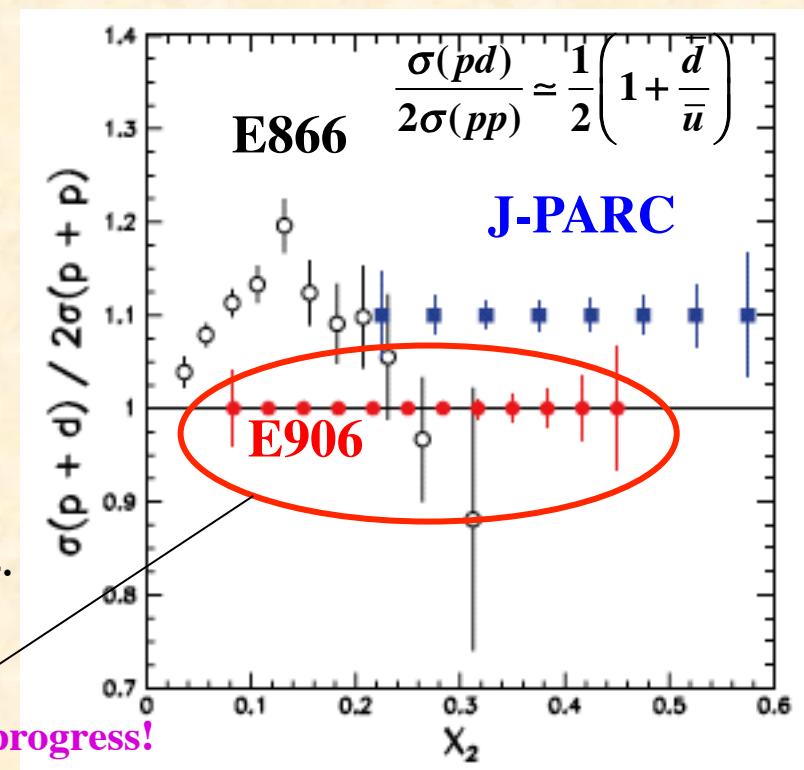
$$\Rightarrow \text{Experimentally, } \frac{\bar{s}}{(\bar{u} + \bar{d})/2} \sim 0.4, \quad \frac{\bar{d}}{\bar{u}} = 1 \sim 1.4$$

Non-perturbative mechanism for the asymmetries?



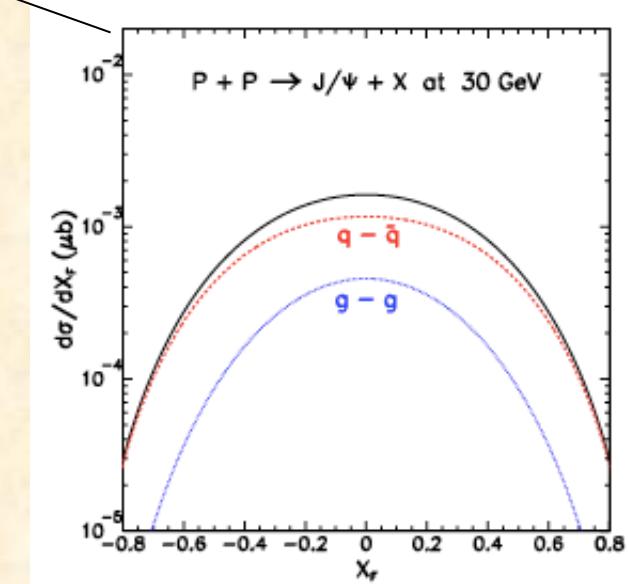
- SK, Phys. Rep. 303 (1998) 183;
 J. Speth, A. W. Thomas,
 Adv.Nucl.Phys. 24 (1997) 83;
 G. T. Garvey and J.-C. Peng,
 Prog. Part. Nucl. Phys. 47 (2001) 203.
 J.-C. Peng, J.-W. Qiu, arXiv:1401.0934.

Fermilab experiment in progress!



Comments about J-PARC after Fermilab-E906

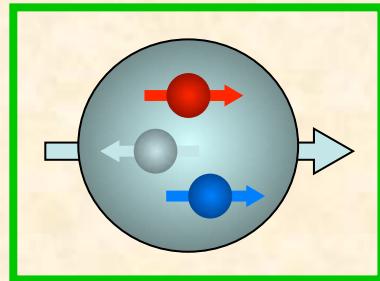
- Energy is not high (30 GeV) → 40, 50 GeV operation ???
 $m_{\mu\mu}$ below J/ψ at J-PARC → feasibility studies are needed
soft-gluon contributions → K-factor is large but seems to be managed theoretically.
- hadron strucutre with J/ψ production → OK, pQCD corrctions?
- physics topics by considering E906 results
→ We may also consider other possibilities.
e.g. exclusive processes



P04 (Peng *et al.*)

Origin of nucleon spin

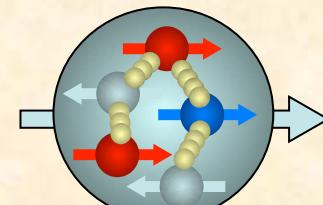
“old” standard model



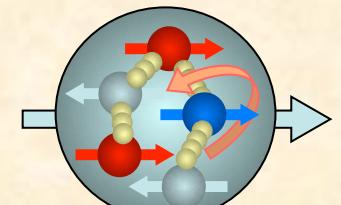
$$p_\uparrow = \frac{1}{3\sqrt{2}} (uud [2 \uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow] + \text{permutations})$$

$$\Delta q(x) \equiv q_\uparrow(x) - q_\downarrow(x)$$

$$\Delta\Sigma = \sum_i \int dx [\Delta q_i(x) + \Delta \bar{q}_i(x)] \rightarrow 1 \text{ (100%)}$$

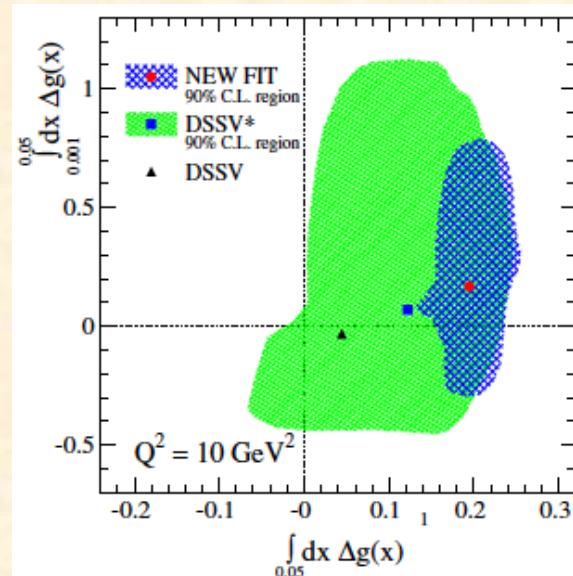


gluon spin



angular momentum

next page



$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta g + L_{q,g}$$

Wigner distribution and various structure functions

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

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

Form factor

PDF (Parton Distribution Function)

$$\int dx d^2 k_\perp$$

$$\int d^2 k_\perp d^3 r$$

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

3D world



**TMD (Transverse Momentum Dependent)
parton distribution**

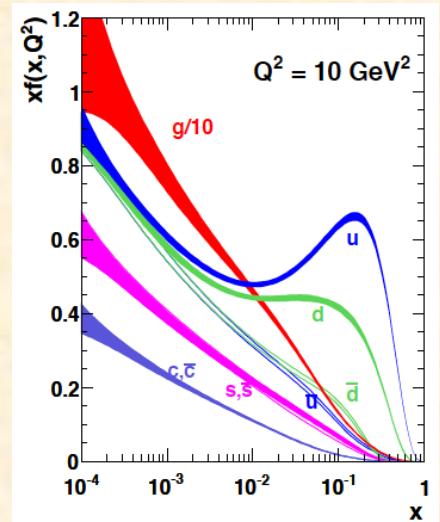
$$\int d^3 r$$

$$\int d^2 k_\perp dz$$

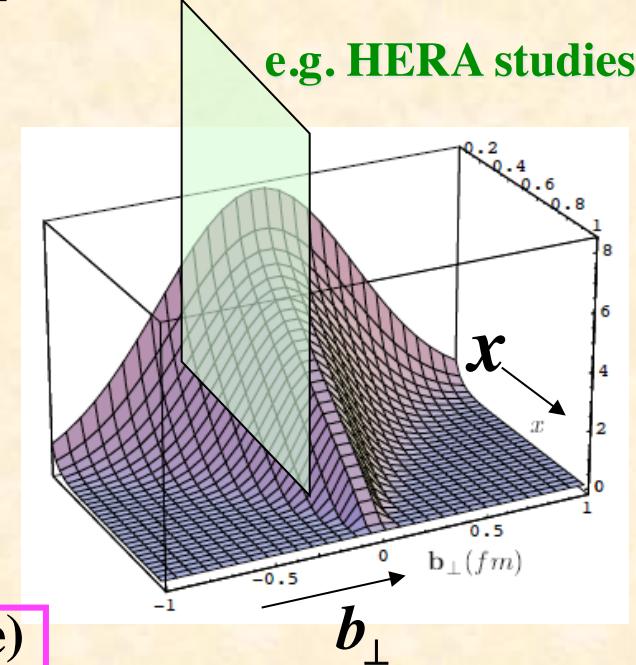
GPD (Generalized Parton Distribution)

$s-t$ crossing \rightarrow

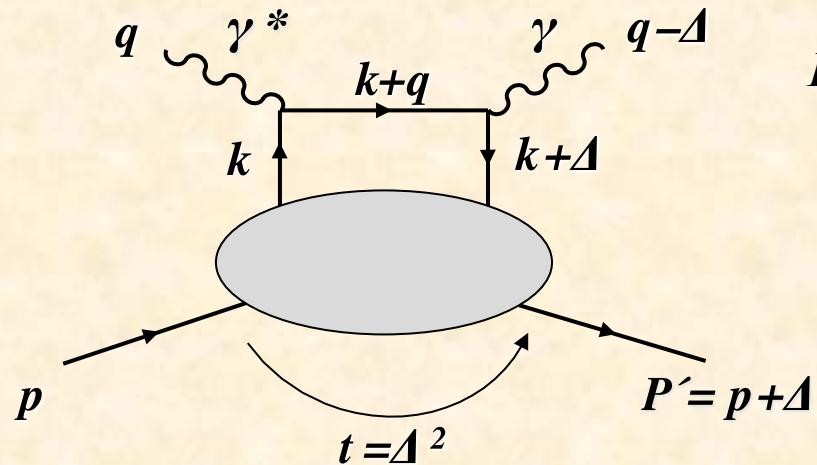
$\gamma\gamma \rightarrow h\bar{h}$ **GDA (Generalized Distribution Amplitude)**



e.g. HERA studies



Generalized Parton Distributions (GPDs)



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

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

Momentum transfer squared $t = \Delta^2$

Skewness parameter $\xi = \frac{p^+ - p'^+}{p^+ + p'^+} = -\frac{\Delta^+}{2P^+}$

GPDs are defined as correlation of off-forward matrix:

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

Forward limit: PDFs $H(x, \xi, t) \Big|_{\xi=t=0} = f(x)$

First moments: Form factors

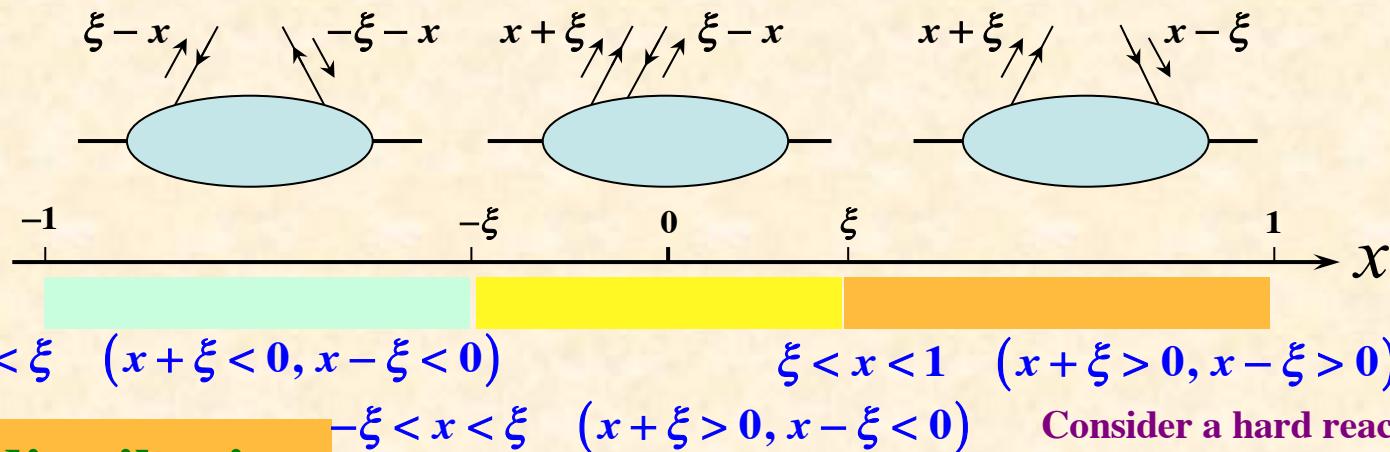
Dirac and Pauli form factors F_1, F_2

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

Second moments: Angular momenta

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

GPDs in different x regions and GPDs at hadron facilities



Quark distribution

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

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

Meson-like distribution amplitude

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

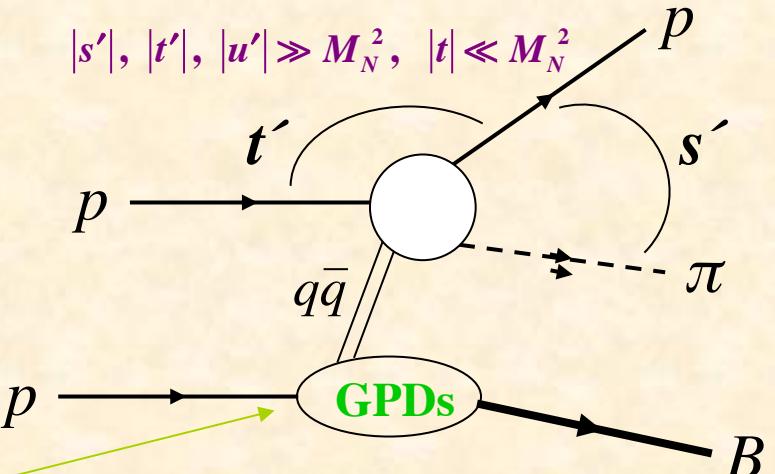
Emission of antiquark with momentum fraction $\xi-x$

Antiquark distribution

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

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

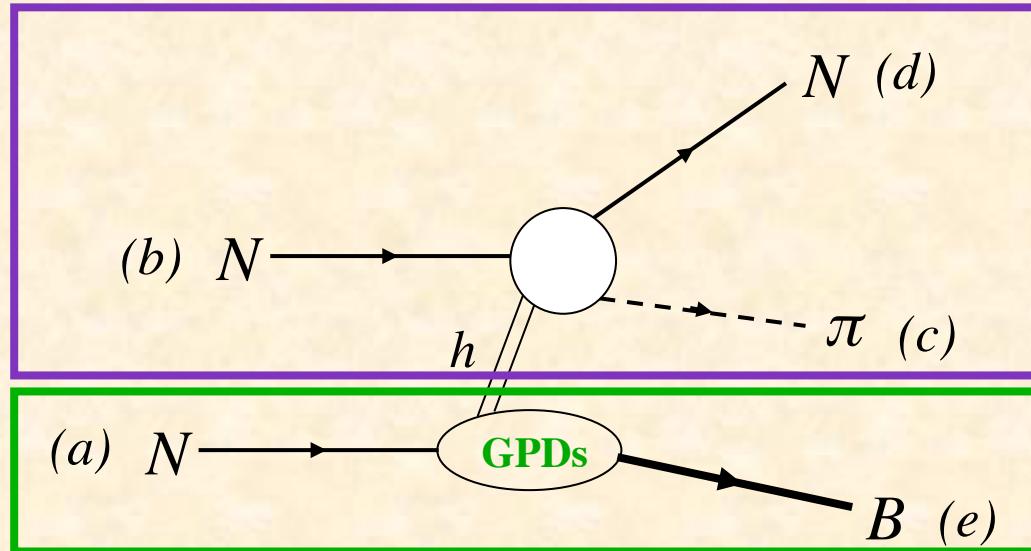
Consider a hard reaction with
 $|s'|, |t'|, |u'| \gg M_N^2, |t| \ll M_N^2$



GPDs at J-PARC: S. Kumano, M. Strikman,
and K. Sudoh, PRD 80 (2009) 074003.

**Efremov-Radyushkin
-Brodsky-Lepage (ERBL) region**

Cross section estimates



$\frac{d\sigma(s',t')}{dt'}$ so as to explain
AGS experimental data on
 $\pi + p \rightarrow \pi + p, \ \pi + p \rightarrow \rho + p$

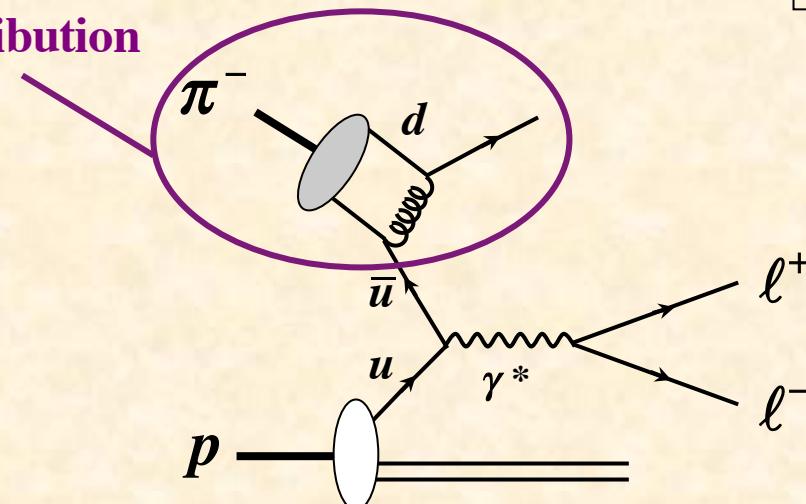
This part is expressed by GPDs.

Purposes of our studies:

- (1) The ultimate purpose is to extract the GPDs in the ERBL region by measurements at hadron facilities in addition to lepton ones.
- (2) Since our work is the first one to point out the GPD studies at hadron reactions, we estimate the order of magnitude of cross sections simply by using meson-pole expressions of the GPDs.
For experimental feasibility studies.

Toward a new proposal

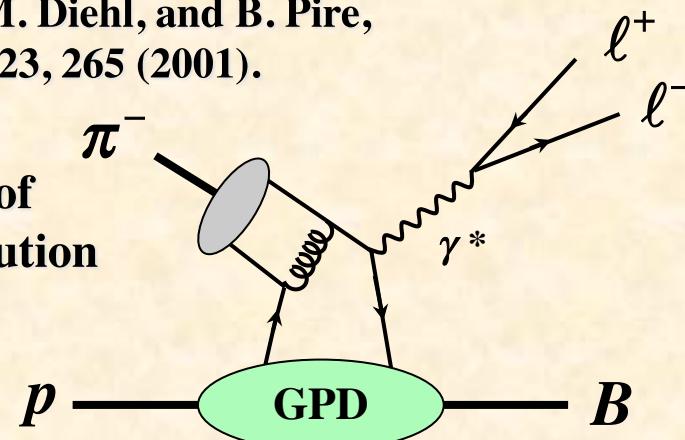
pion distribution



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

E. R. Berger, M. Diehl, and B. Pire,
Phys. Lett. B 523, 265 (2001).

Investigation of
 • Pion distribution
 amplitude
 • GPDs



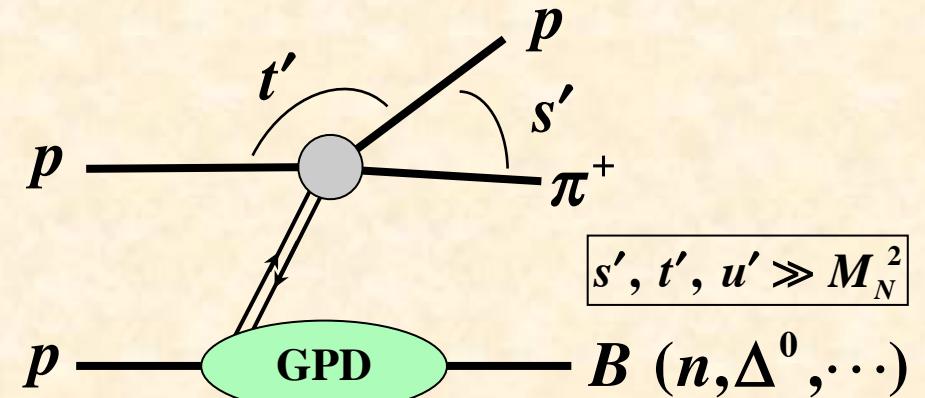
$$\pi^-(\bar{u}d) + p(uud) \rightarrow B(udd) + \gamma^* (\rightarrow \ell^+ \ell^-)$$

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

A. Brandenburg, S. J. Brodsky,
V. V. Khoze, and D. Müller,
Phys. Rev. Lett. 73 (1994) 939.

Investigation of
 • Pion distribution amplitude

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



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

Hadron physics with high-momentum hadron beams at J-PARC in 2015

<http://research.kek.jp/group/hadron10/j-parc-hm-2015/>
March 13-16, 2015, KEK, Tsukuba, Japan

March 12 (Thursday) pre-workshop meeting

Discussions on J-PARC proposal on high-energy hadron physics

13:00-17:00

Wen-Chen Chang (Academia Sinica)

Plan for a proposal in high-energy hadron physics at J-PARC ([Chang-discussion.pdf](#))

* GPDs from exclusive Drell-Yan process

Peter Kroll (University of Wuppertal) ([Kroll-discussion.pdf](#))

Oleg Teryaev (Joint Institute for Nuclear Research) ([Teryaev-discussion.pdf](#))

Kazuhiro Tanaka (Juntendo University/KEK) ([Tanaka-discussion.pdf](#))

* Ideas on hadron physics with J-PARC high-momentum beam

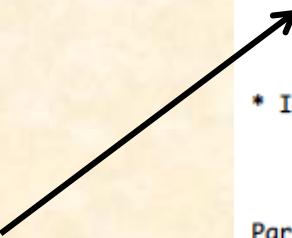
Jen-Chieh Peng (University of Illinois) ([Peng-discussion.pdf](#))

Feng Yuan (Lawrence Berkeley National Laboratory) ([Yuan-discussion.pptx](#))

Participants: William Brooks, Wen-Chen Chang, Seonho Choi,
Yubing Dong, Shoichi Hasegawa, Yoshihiko Kondo, Peter Kroll,
Shunzo Kumano, Takayuki Matsuki, Hiroyuki Noumi, Jen-Chieh Peng,
Jianwei Qiu, Paul Reimer, Shin'ya Sawada, Katharina Schmidt,
Ralf Seidl, Kazuhiro Tanaka, Oleg Teryaev, Feng Yuan, ...

Contact persons: Shunzo Kumano and Kazuhiro Tanaka

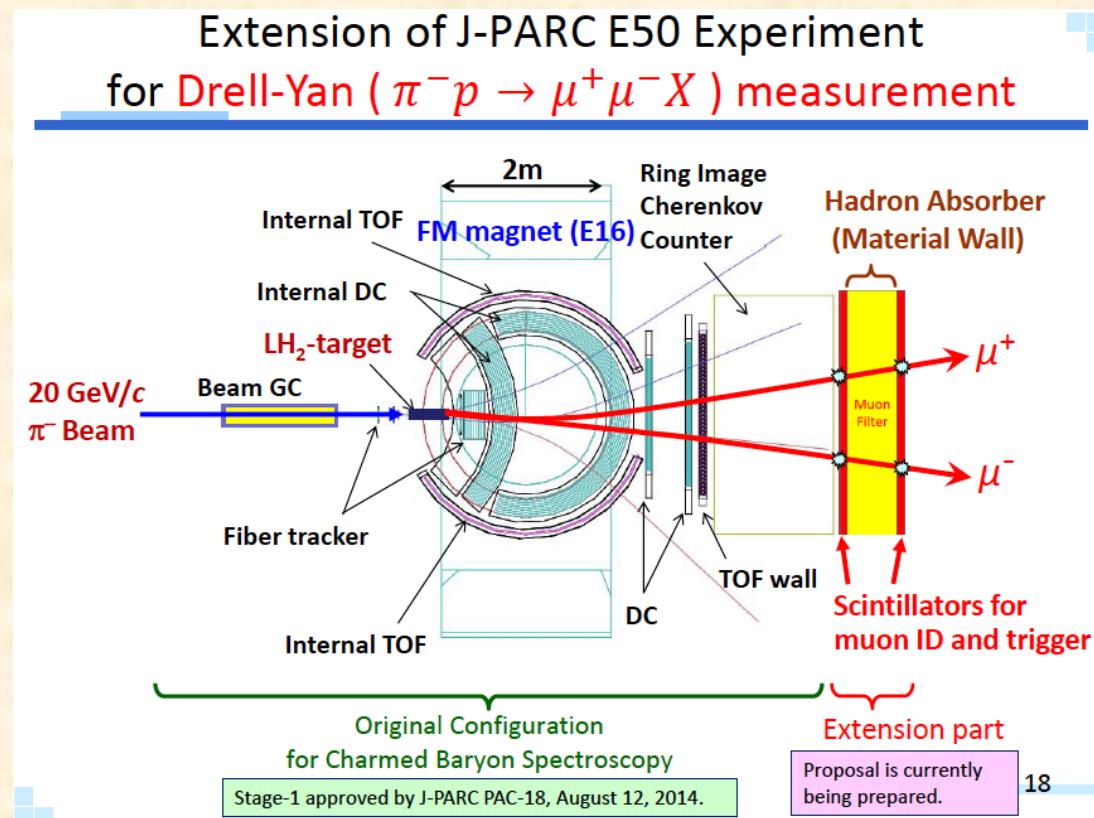
Exclusive Drell-Yan
and GPDs



Join the approved E50 experiment?

Wen-Chen Chang in Spinfest, July 13, 2015
<http://j-parc-th.kek.jp/workshops/2015/07-06/>

Takahiro Sawada in Pacific spin, Oct. 6, 2015
<http://www.phys.sinica.edu.tw/PacSPIN2015/>



KEK/J-PARC-PAC 2012-19

Charmed Baryon Spectroscopy via the (π, D^{*-}) reaction

Y. Morino, T. Nakano,^{*} H. Noumi[†], K. Shirotori, Y. Sugaya, and T. Yamaga
Research Center for Nuclear Physics (RCNP), Osaka University,
10-1, Mihogaoka, Ibaraki, Osaka, 567-0047, Japan

K. Ozawa[‡]
Institute of Particle and Nuclear Studies(IPNS),
High Energy Accelerator Research Organization (KEK),
1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

T. Ishikawa
Reserach Center for Electron Photon Science,
Tohoku University, 1-2-1, Mikamine,
Taihaku-ku, Sendai, Miyagi 982-0826, Japan

Y. Miyachi
Physics Department, Yamagata University, 1-4-12,
Kojirakawa-machi, Yamagata 990-8560, Japan

K. Tanida
Department of Physics and Astronomy,
Seoul National University, Seoul 151-747, Korea

There will be a meeting with E50 people
for joint efforts toward a proposal
in December, 2015.
→ You may get in touch with
Wen-Chen Chang (Academia Sinica),
Jen-Chieh Peng (U. Illinois).

Summary

The high-momentum beamline (protons, pions, kaons, ...) will be ready soon in 2018.

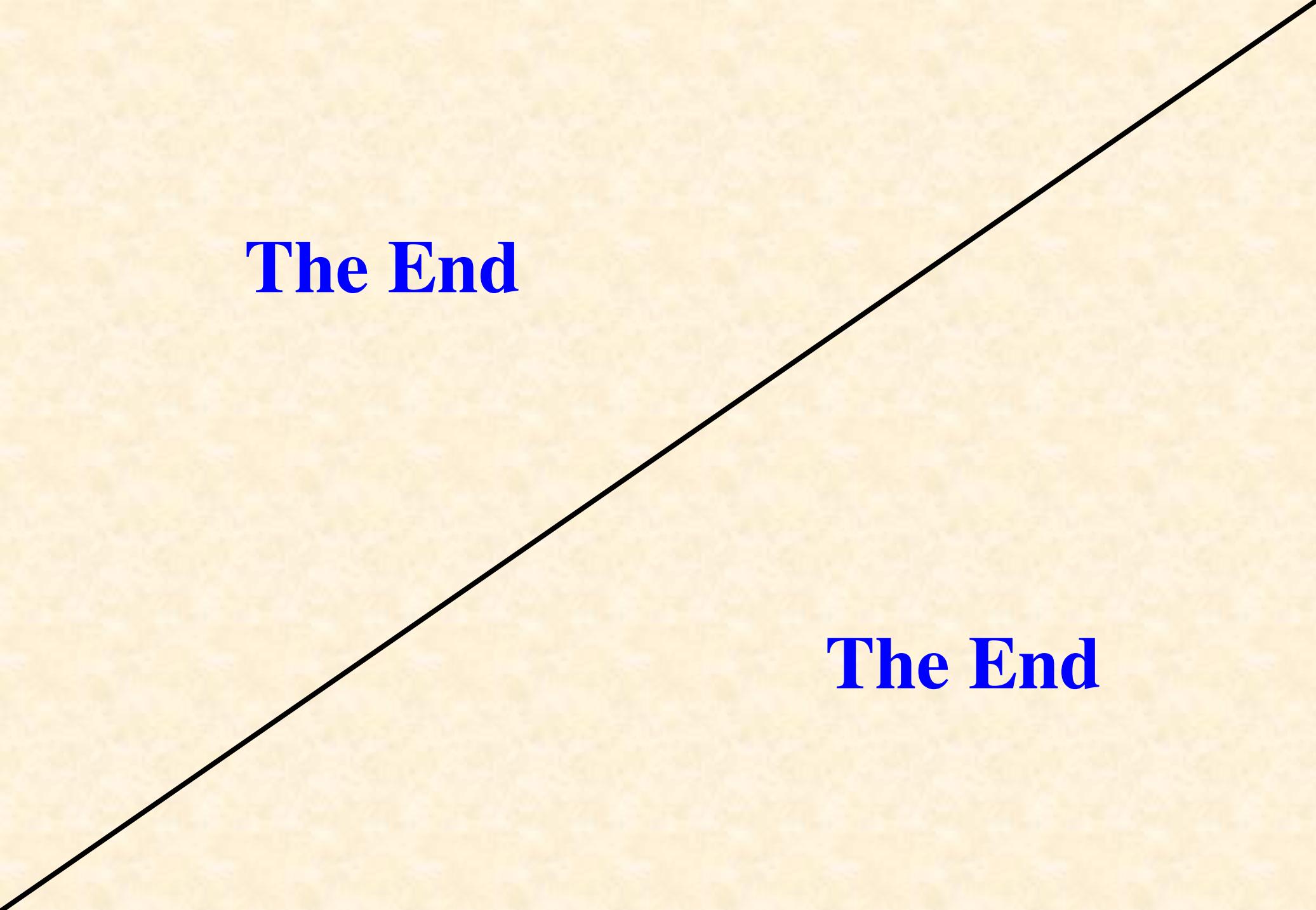
It can be used for high-energy hadron physics,
including nucleon structure and short-range correlations.

You are welcome to

- (experimentalists) propose an experiment,
→ S. Sawada/K. Ozawa (KEK), J.-C. Peng (Illinois),
W.-C. Chang (Academia Sinica)
- (theorists/experimentalists) propose a joint workshop.
→ me (S. Kumano) or KEK theory-center members, experimentalists.

Common physics interests among GSI, JLab, J-PARC

It is nice if we have joint efforts and communications.



The End

The End