Prospects at J-PARC

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/

Hadronic Physics with Lepton and Hadron Beams
September 5-8, 2017, JLab, Newport News, USA
https://www.jlab.org/conferences/hadrons2017/

Note: Topics based on my personal view.
For a comprehensive overview on facility and experiments,
there was a Sawada's talk at Jlab-PAC45 on July 10, 2017.

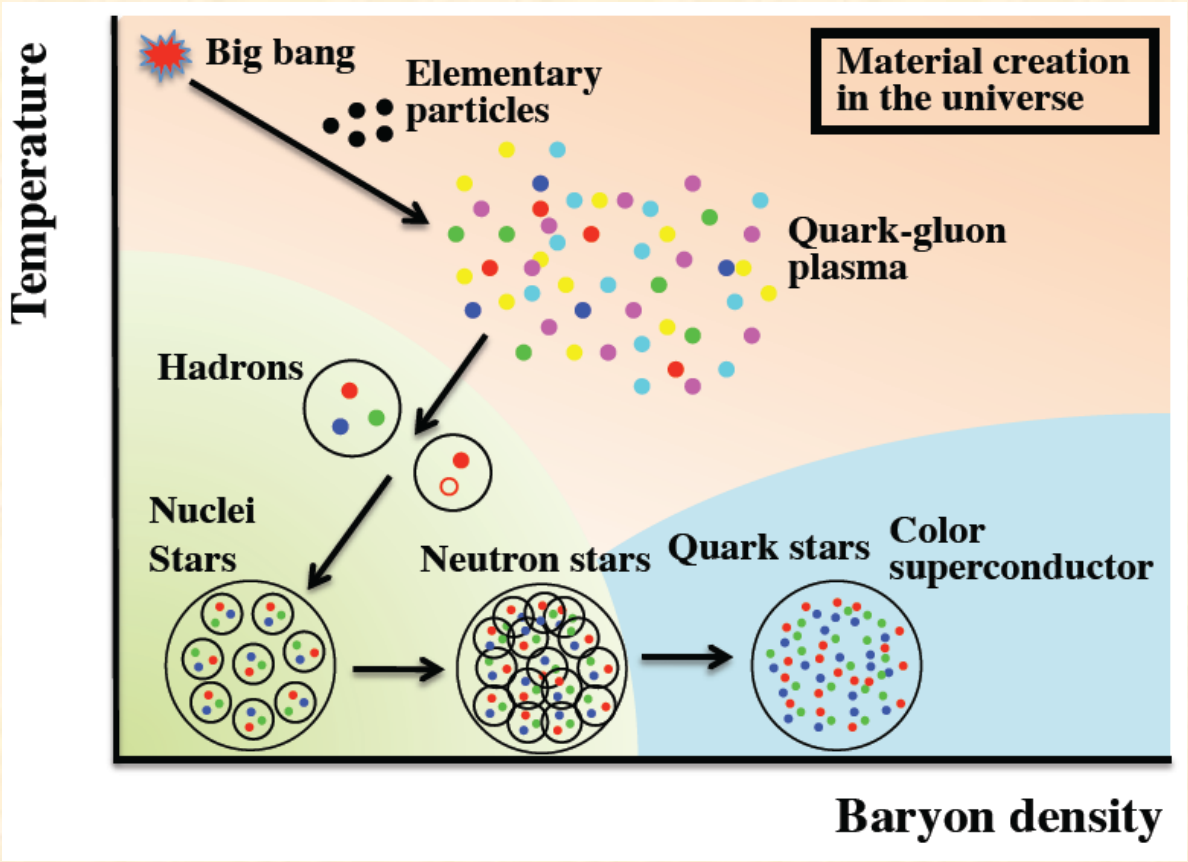
September 8, 2017

Contents

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

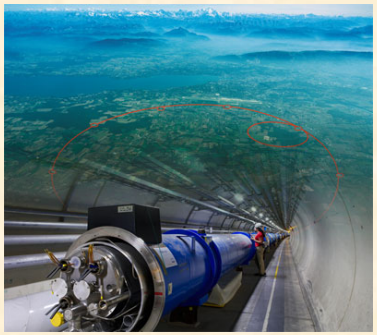
Nuclear physics is a field of investigating

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



Hadron-physics facilities

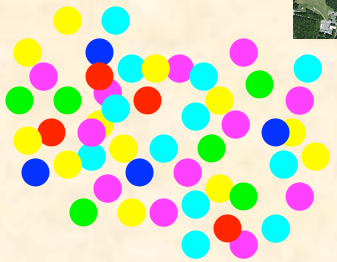
© BNL



© CERN

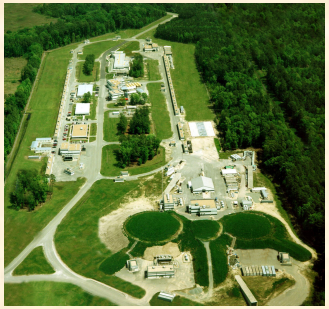
T

LHC
RHIC



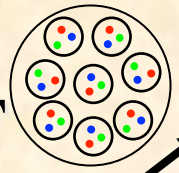
GSI-FAIR

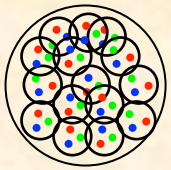
© GSI



© JLab

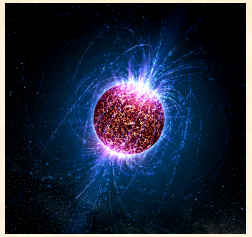
RIBF





Neutron star

μ



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JLab

J-PARC

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Q^2

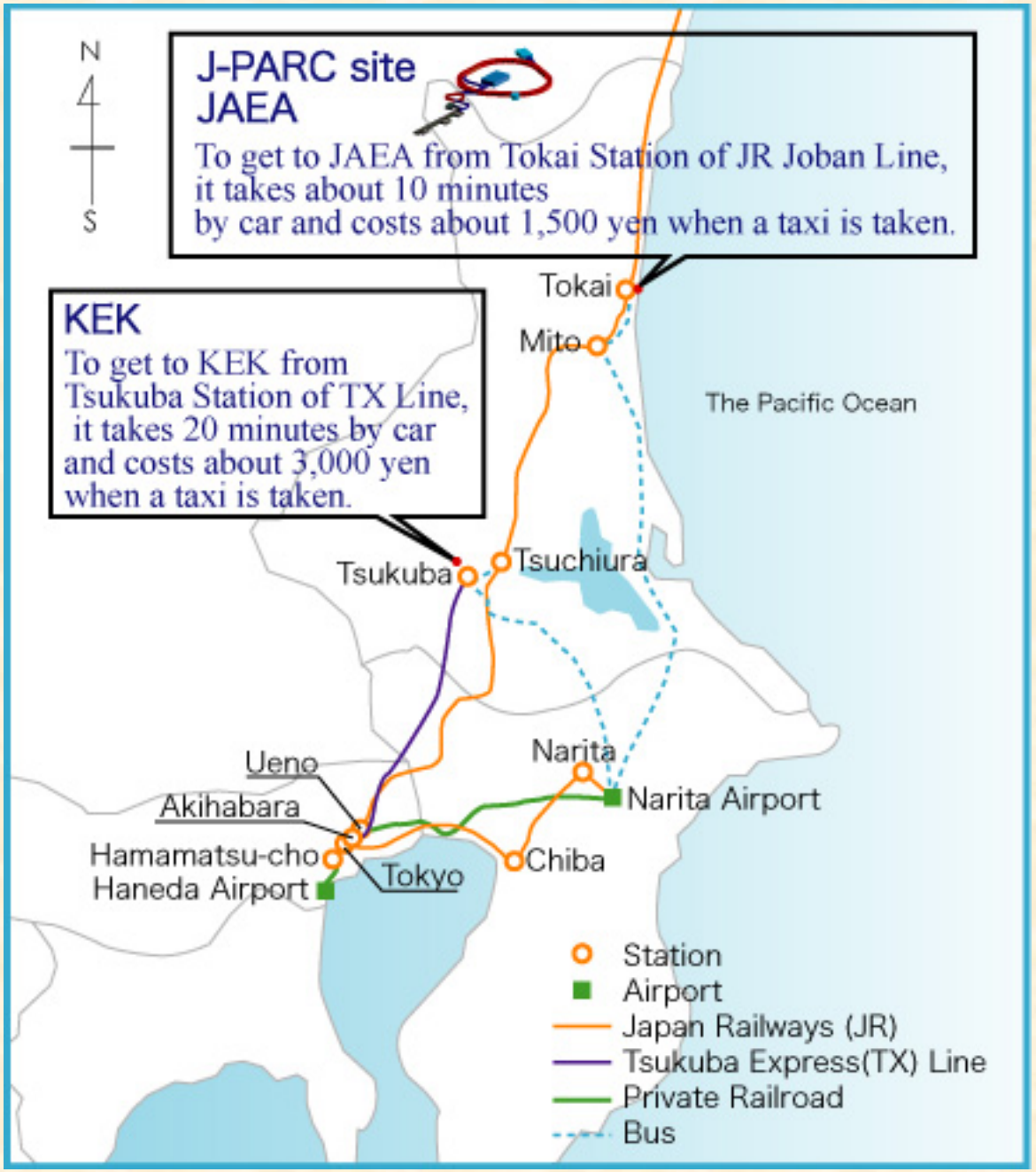
HERA, EIC
LHC, RHIC

J-PARC Facility

J-PARC location

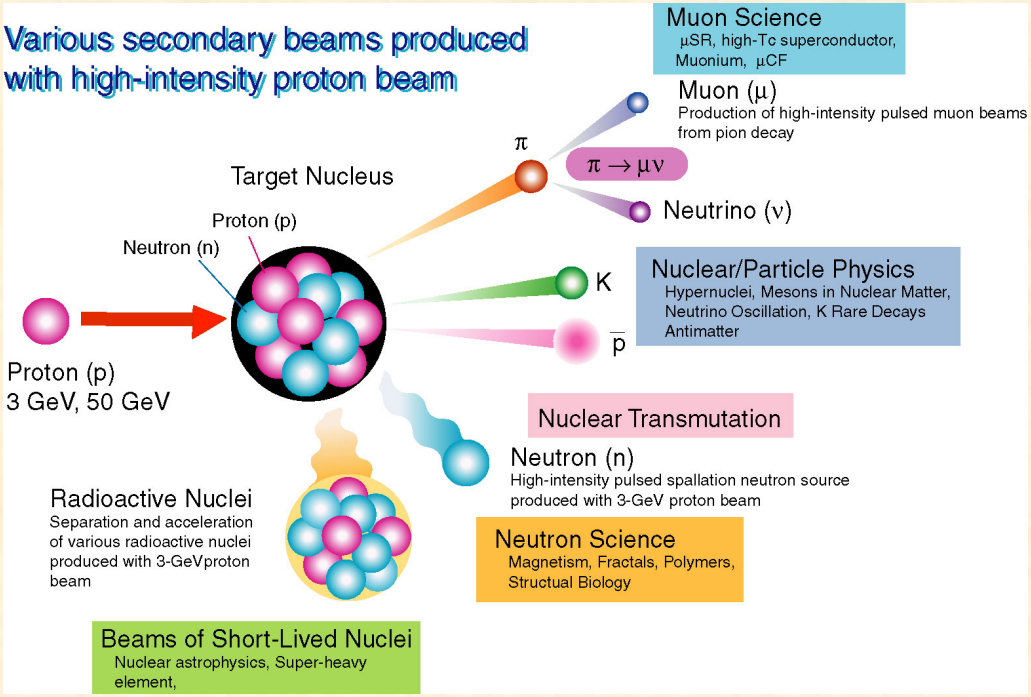
J-PARC
(Japan Proton Accelerator Research Complex)

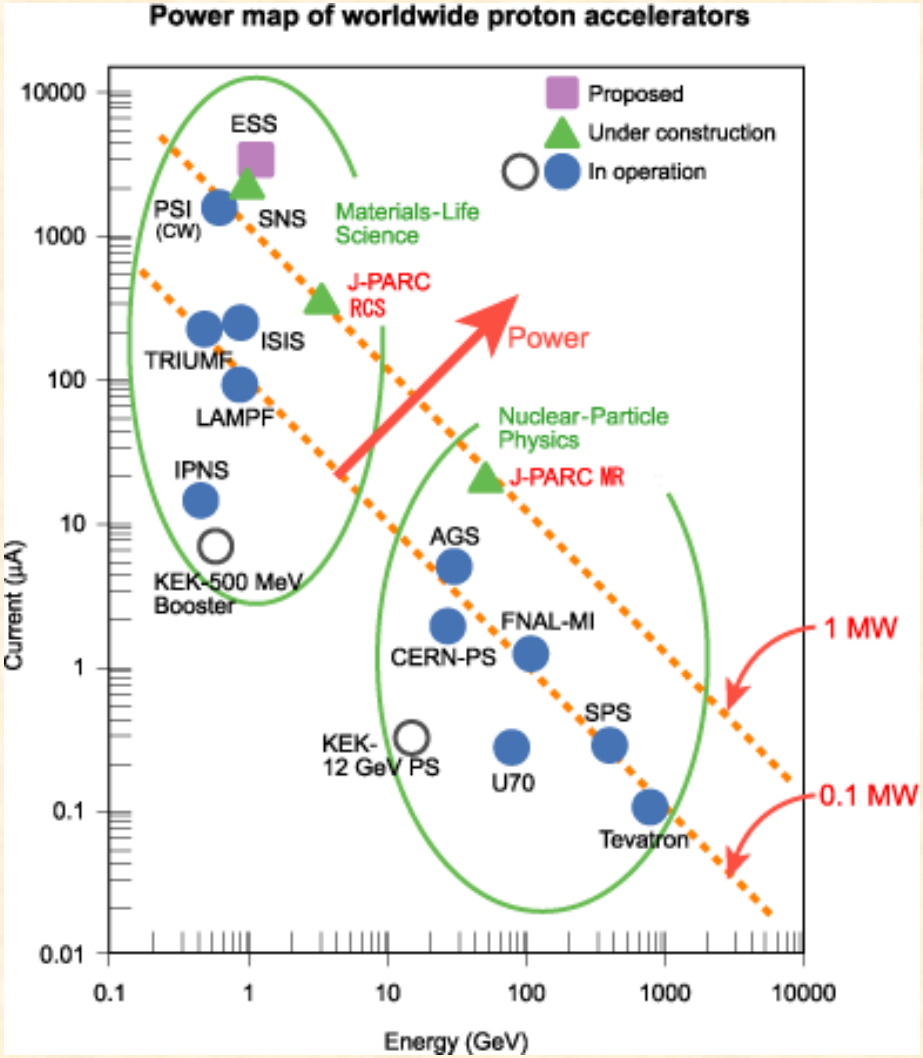
http://j-parc.jp/index-e.html



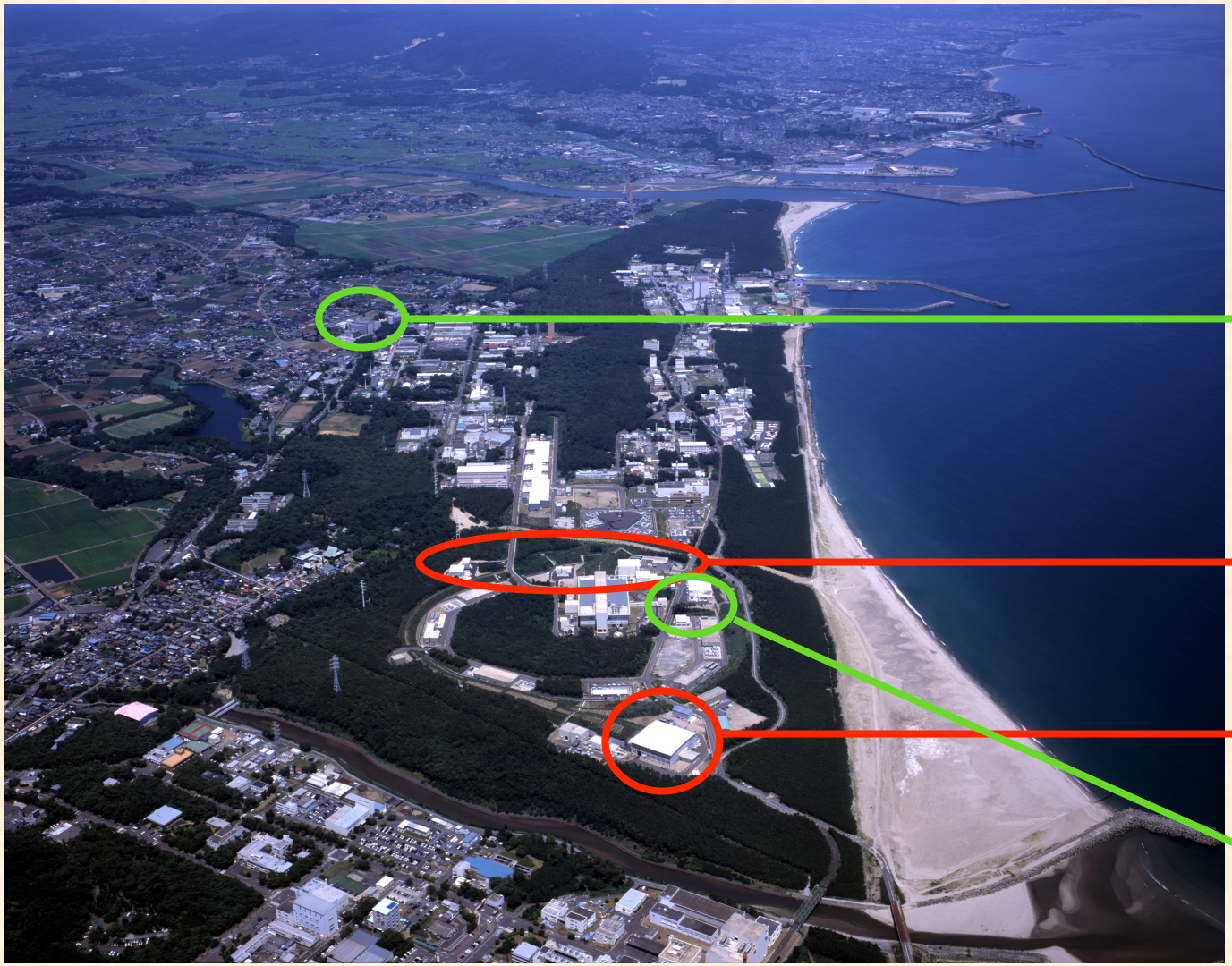
High-Intensity Frontier of Proton Accelerator

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

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

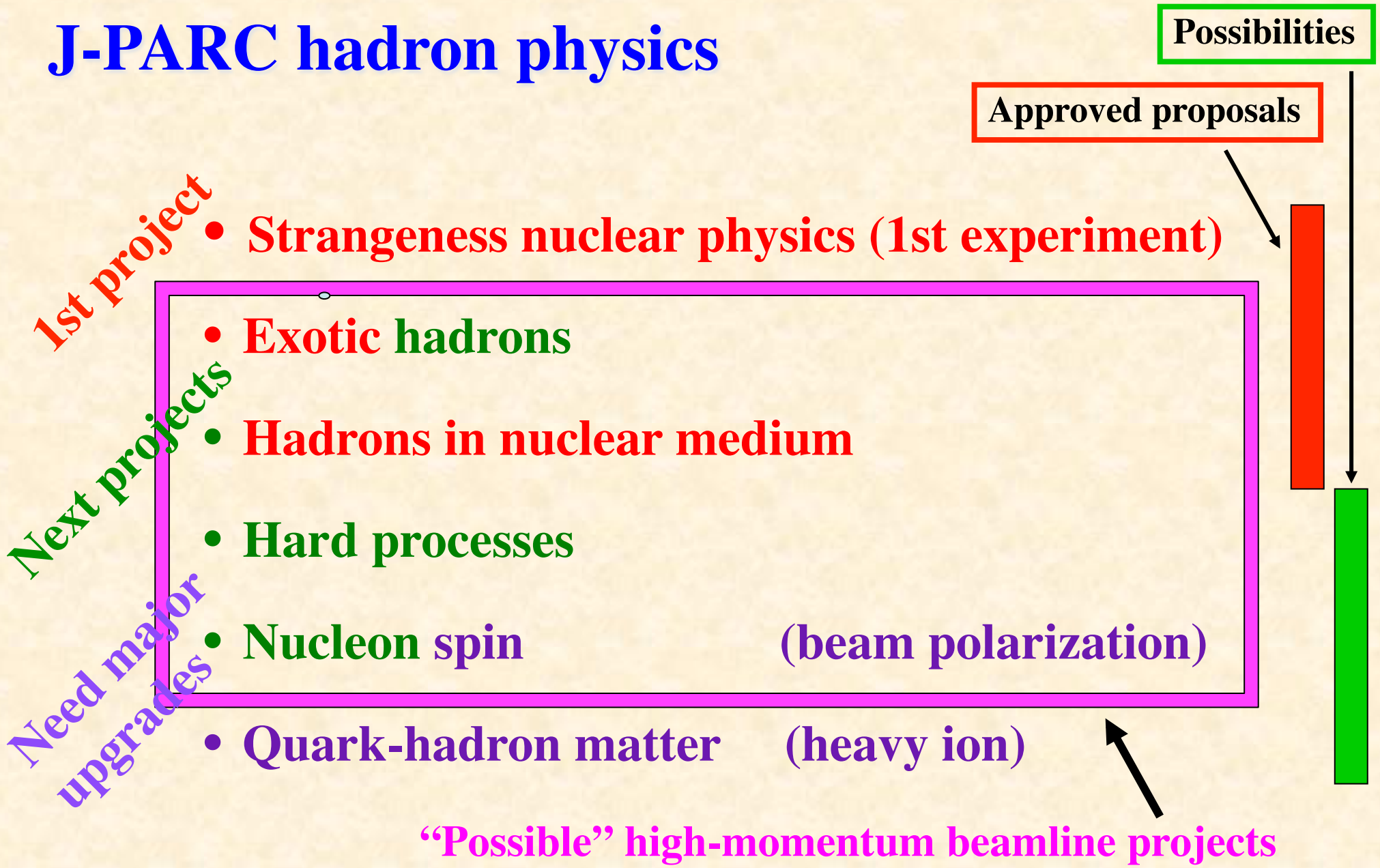
4 permanent KEK staffs (A. Dote, K. Itakura, S. Kumano, O. Morimatsu)
+ 5 visiting staffs (T. Harada, M. Kitazawa, T. Sato, M. Takizawa, K. Tanaka)

- **Hypernuclear physics**
- **Heavy-ion physics**
- **Neutrino-nuclear interactions**
- **Charm physics**
- **Structure functions**

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

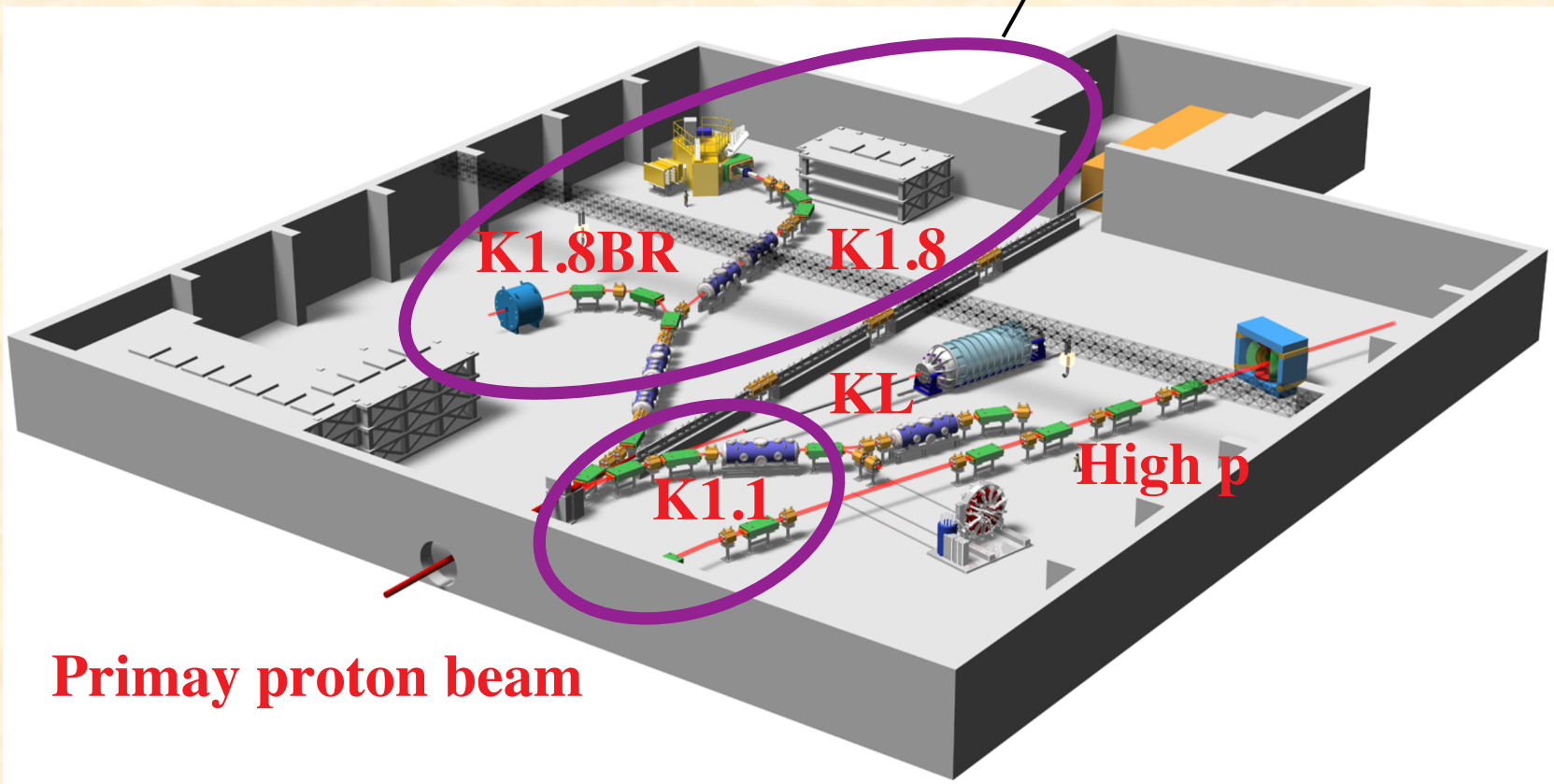
J-PARC hadron physics

J-PARC hadron physics

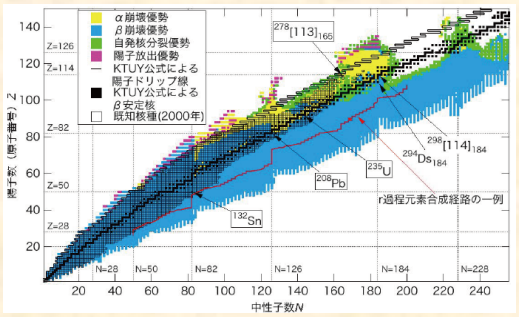


Hadron facility

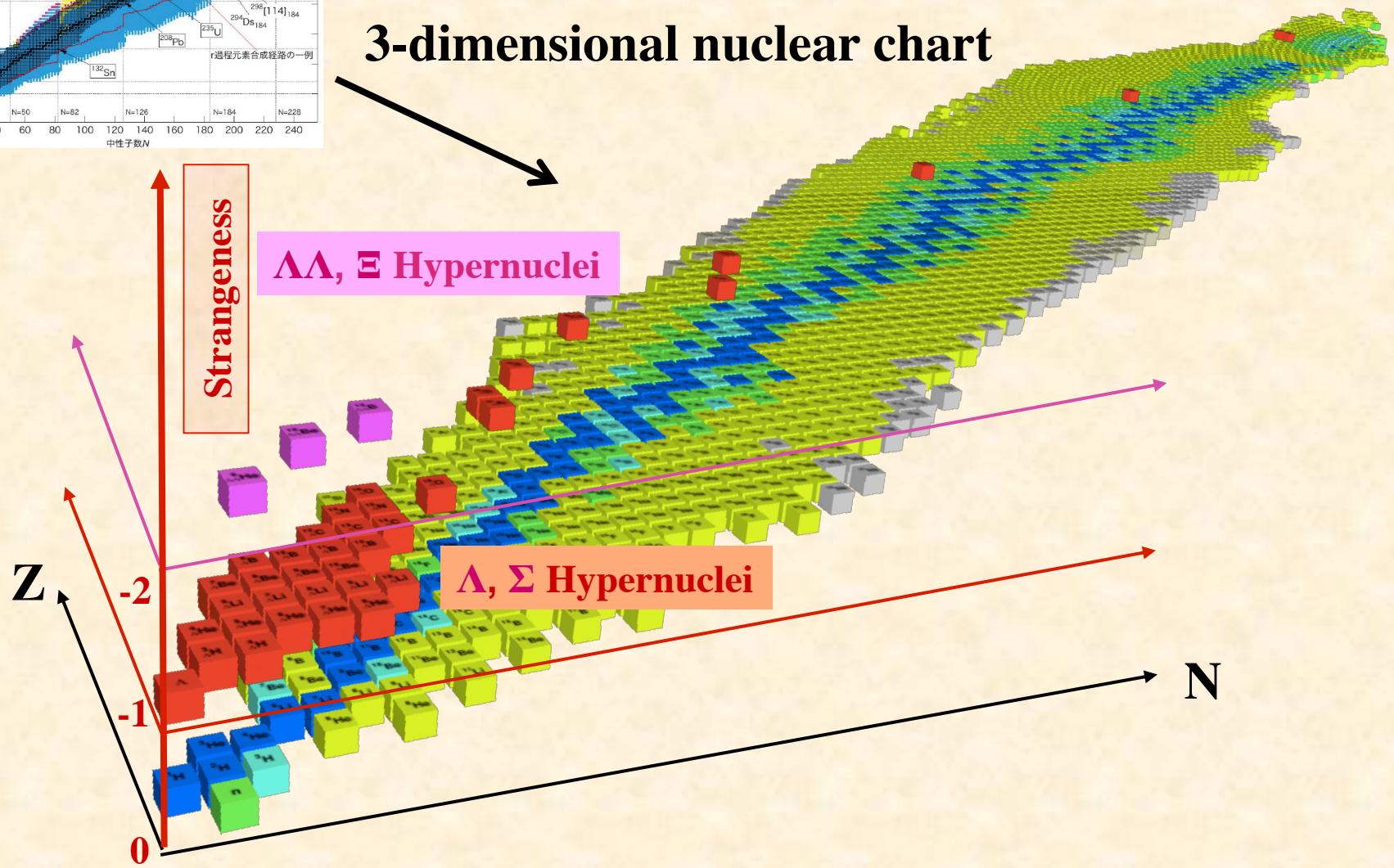
(Low energy) Kaon and pion experiments are done at these beamlines.



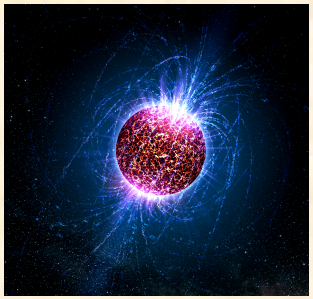
Strangeness nuclear physics



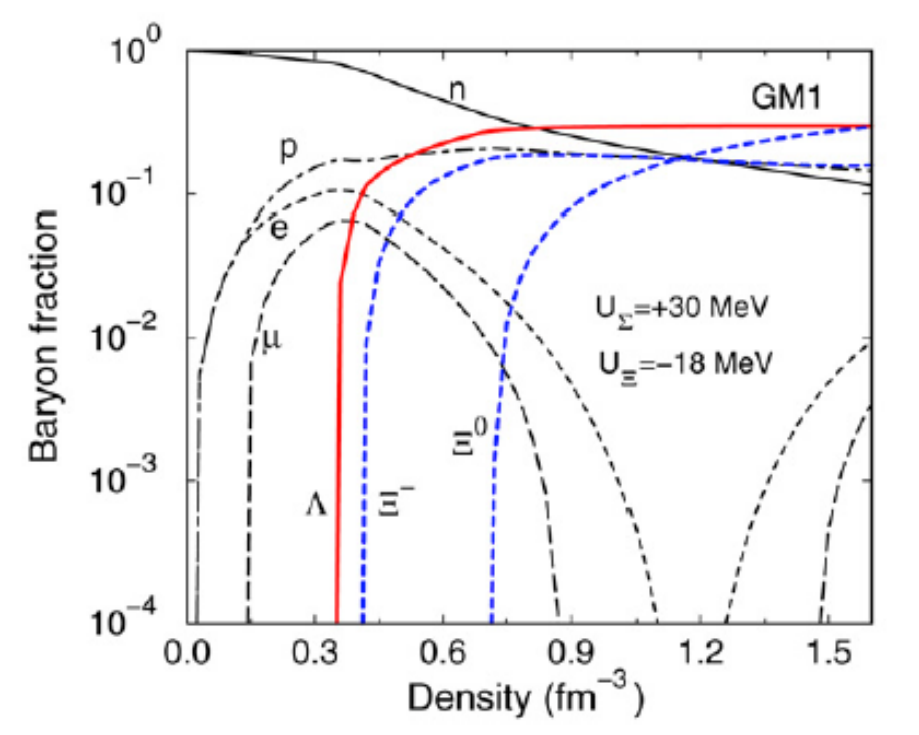
3-dimensional nuclear chart

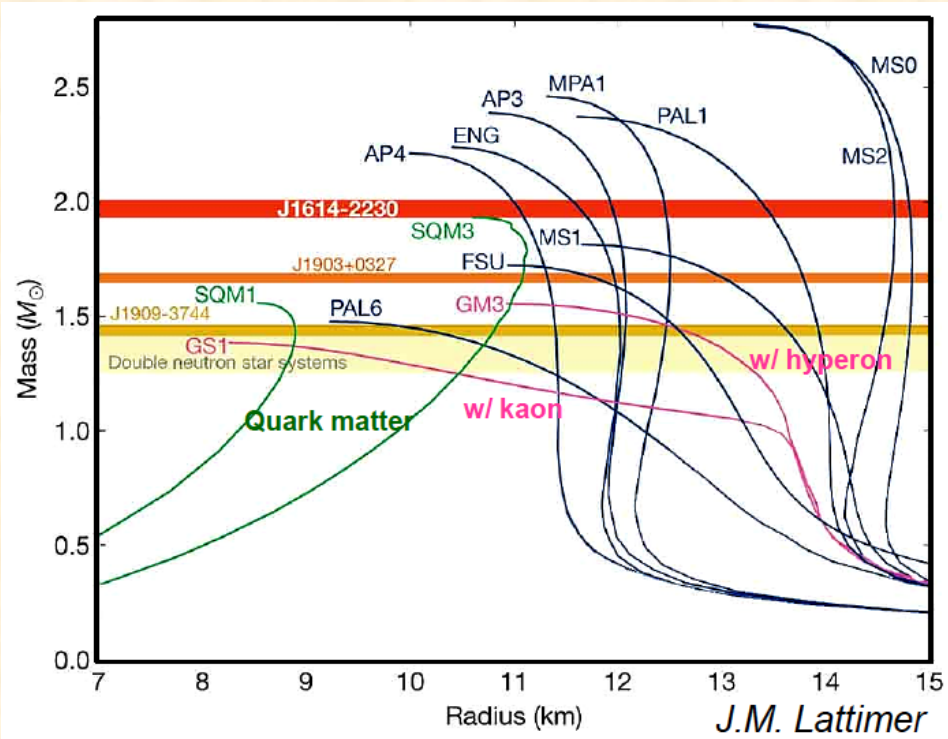


Neutron stars

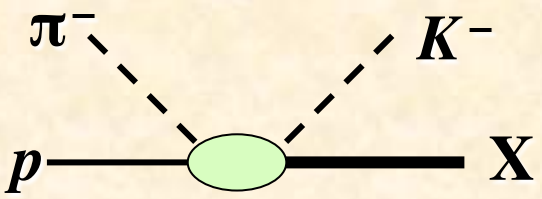


Precise YN, YY interactions are necessary for understanding neutron stars.





Some results already from J-PARC

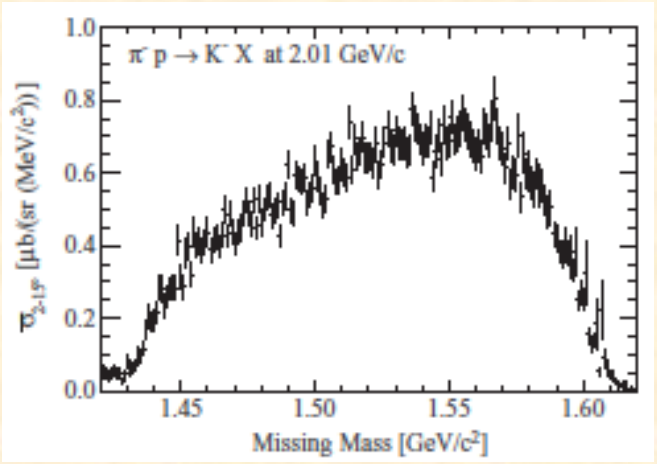


PRL 109, 132002 (2012); PRC 90, 035205 (2014)

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,[6] S. J. Kim,[6] R. Kiuchi,[6,‡] T. Koike,[9] Y. Komatsu,[14] V. V. Kulikov,[15] S. Marcello,[8,3] 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. 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. Yoshida[11]
(J-PARC E19 Collaboration)



PLB729, 39 (2014)

Physics Letters B 729 (2014) 39–44

Contents lists available at ScienceDirect

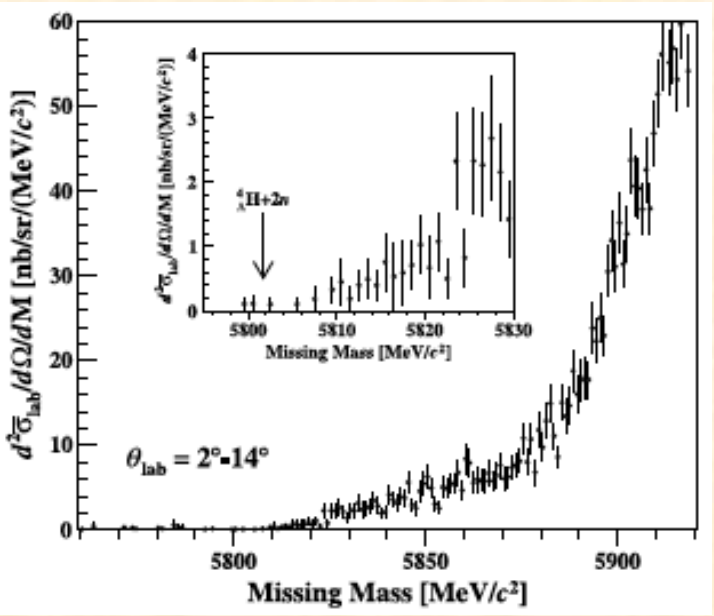
Physics Letters B

www.elsevier.com/locate/physletb

Search for ${}^{6}_{\Lambda}$H hypernucleus by the ^{6}Li(π^-, K^+) reaction at $p_{\pi^-} = 1.2$ 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. Bhang [i], 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. Joo [i], R. Kiuchi [i,b], J.K. Lee [e], J.Y. Lee [i], 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. Samanta [n], 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. Tanida [i], A.O. Tokiyasu [f], Z. Tsamalaidze [k], M. Ukai [g], T.O. Yamamoto [g], Y. Yamamoto [g], S.B. Yang [i], K. Yoshida [j]



PTEP 2015, 021D01 (2015)

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 GeV/c

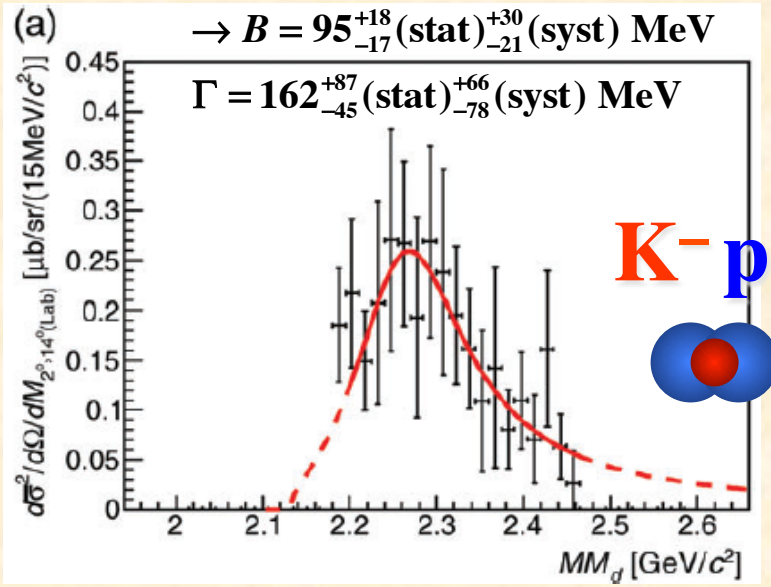
Yudai Ichikawa[1,2], Tomofumi Nagae[1,*], Hiroyuki Fujioka[1], Hyoungchan Bhang[3], Stefania Bufalino[4], Hiroyuki Ekawa[1,2], Petr Evtoukhovitch[5], Alessandro Feliciello[4], Shoichi Hasegawa[2], Shuhei Hayakawa[6], Ryotaro Honda[7], Kenji Hosomi[2], Ken'ichi Imai[2], Shigeru Ishimoto[8], Changwoo Joo[3], Shunsuke Kanatsuki[1], Ryuta Kiuchi[2], Takeshi Koike[7], Harphool Kumawat[9], Yuki Matsumoto[7], Koji Miwa[7], Manabu Moritsu[10], Megumi Naruki[1], Masayuki Niiyama[1], Yuki Nozawa[1], Ryosuke Ota[6], Atsushi Sakaguchi[6], Hiroyuki Sako[2], Valentin Samoilov[5], Susumu Sato[2], Kotaro Shirotori[10], Hitoshi Sugimura[2], Shoji Suzuki[8], Toshiyuki Takahashi[8], Tomonori N. Takahashi[10], Hirokazu Tamura[7], Toshiyuki Tanaka[6], Kiyoshi Tanida[3], Atsushi O. Tokiyasu[10], Zviadi Tsamalaidze[5], Bidyut Roy[9], Mifuyu Ukai[7], Takeshi O. Yamamoto[7], and Seongbae Yang[3]

$\pi^+ + d \rightarrow K^+ + X$

$M = 2275^{+17}_{-18}(\text{stat})^{+21}_{-30}(\text{syst})$ MeV

$\rightarrow B = 95^{+18}_{-17}(\text{stat})^{+30}_{-21}(\text{syst})$ MeV

$\Gamma = 162^{+87}_{-45}(\text{stat})^{+66}_{-78}(\text{syst})$ MeV



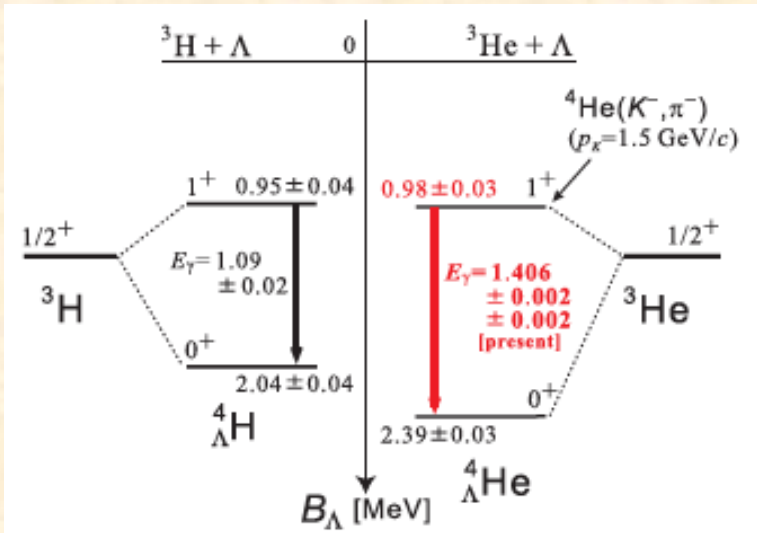
PRL 115, 222501 (2015)

PRL **115,** 222501 (2015) PHYSICAL REVIEW LETTERS week ending 27 NOVEMBER 2015

Observation of Spin-Dependent Charge Symmetry Breaking in ΛN Interaction: Gamma-Ray Spectroscopy of $^4_\Lambda$He

T. O. Yamamoto,[1] M. Agnello,[2,3] Y. Akazawa,[1] N. Amano,[4] K. Aoki,[5] E. Botta,[3,6] N. Chiga,[1] H. Ekawa,[7] P. Evtoukhovitch,[8] A. Feliciello,[3] M. Fujita,[1] T. Gogami,[7] S. Hasegawa,[9] S. H. Hayakawa,[10] T. Hayakawa,[10] R. Honda,[10] K. Hosomi,[9] S. H. Hwang,[9] N. Ichige,[1] Y. Ichikawa,[9] M. Ikeda,[1] K. Imai,[9] S. Ishimoto,[5] S. Kanatsuki,[7] M. H. Kim,[11] S. H. Kim,[11] S. Kinbara,[12] T. Koike,[1] J. Y. Lee,[13] S. Marcello,[3,6] K. Miwa,[1] T. Moon,[13] T. Nagae,[7] S. Nagao,[1] Y. Nakada,[10] M. Nakagawa,[10] Y. Ogura,[1] A. Sakaguchi,[10] H. Sako,[9] Y. Sasaki,[1] S. Sato,[9] T. Shiozaki,[1] K. Shirotori,[14] H. Sugimura,[9] S. Suto,[1] S. Suzuki,[5] T. Takahashi,[5] H. Tamura,[1] K. Tanabe,[1] K. Tanida,[9] Z. Tsamalaidze,[8] M. Ukai,[1] Y. Yamamoto,[1] and S. B. Yang[13]

(J-PARC E13 Collaboration)

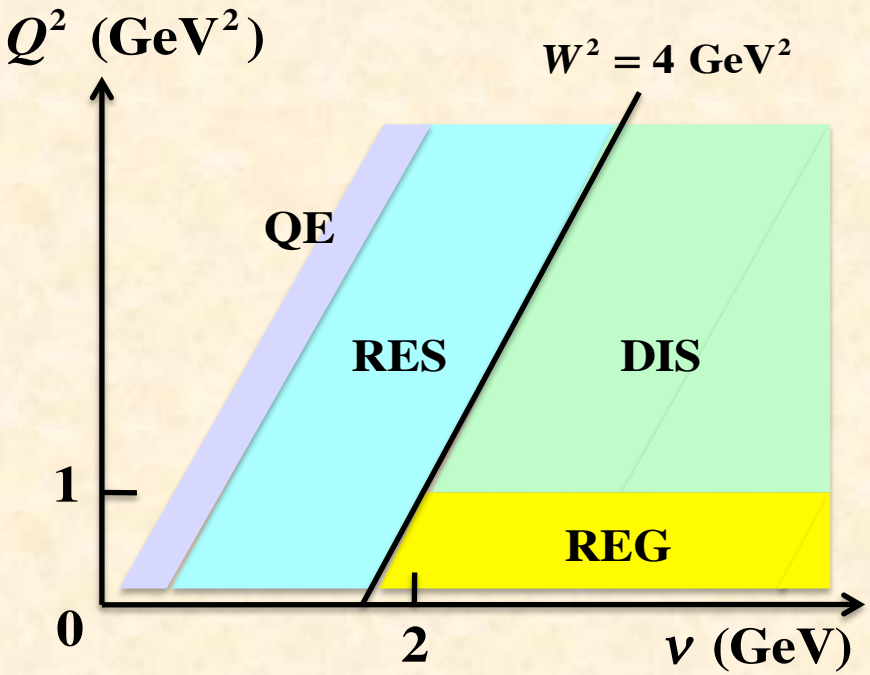


Comments on

Neutrino-nucleus interactions

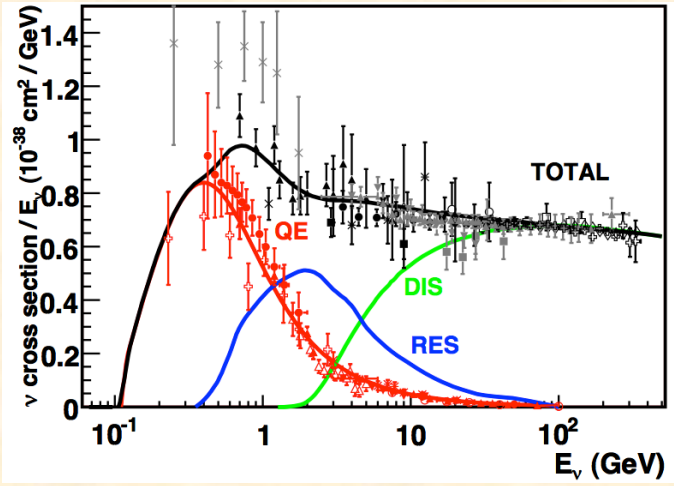
Neutrino-nucleus interactions: Motivation

Kinematical regions of neutrino-nucleus scattering



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

- **QE (Quasi elastic)**
- **RES (Resonance)**
- **DIS (Deep inelastic scattering)**
- **REG (Regge)**



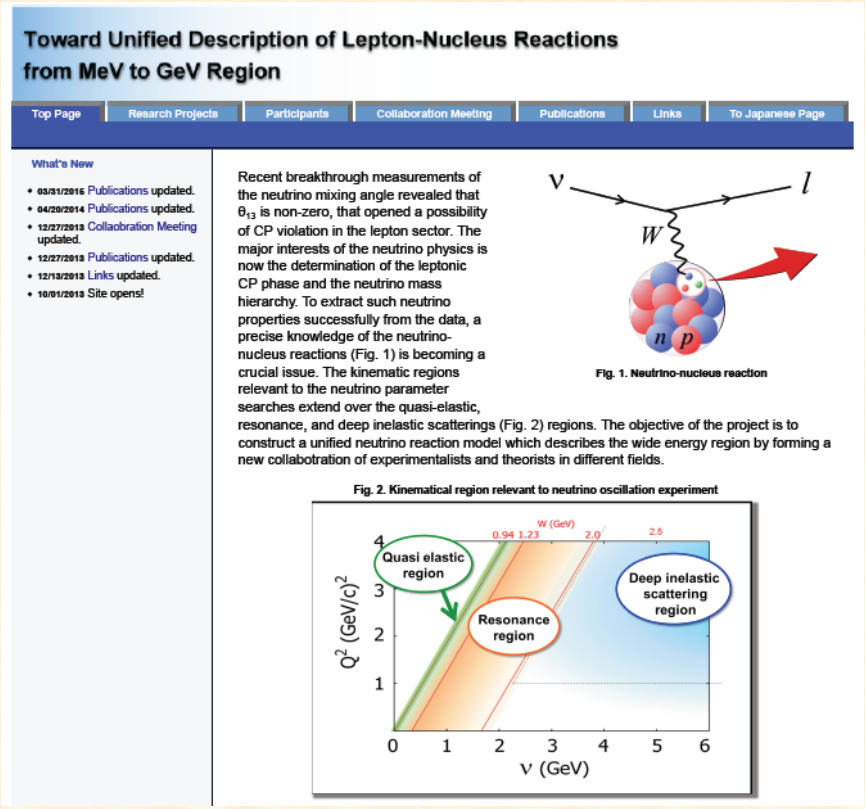
J.L. Hewett *et al.*, arXiv:1205.2671, Proceedings of the 2011 workshop on Fundamental Physics at the Intensity Frontier

ν flux		16%
ν flux and cross section	w/o ND measurement	21.8%
	w/ ND measurement	2.7%
ν cross section due to difference of nuclear target btw. near and far		5.0%
Final or Secondary Hadronic Interaction		3.0%
Super-K detector		4.0%
total	w/o ND measurement	23.5%
	w/ ND measurement	7.7%

ν interactions

A.K.Ichikawa@KEK workshop 2015

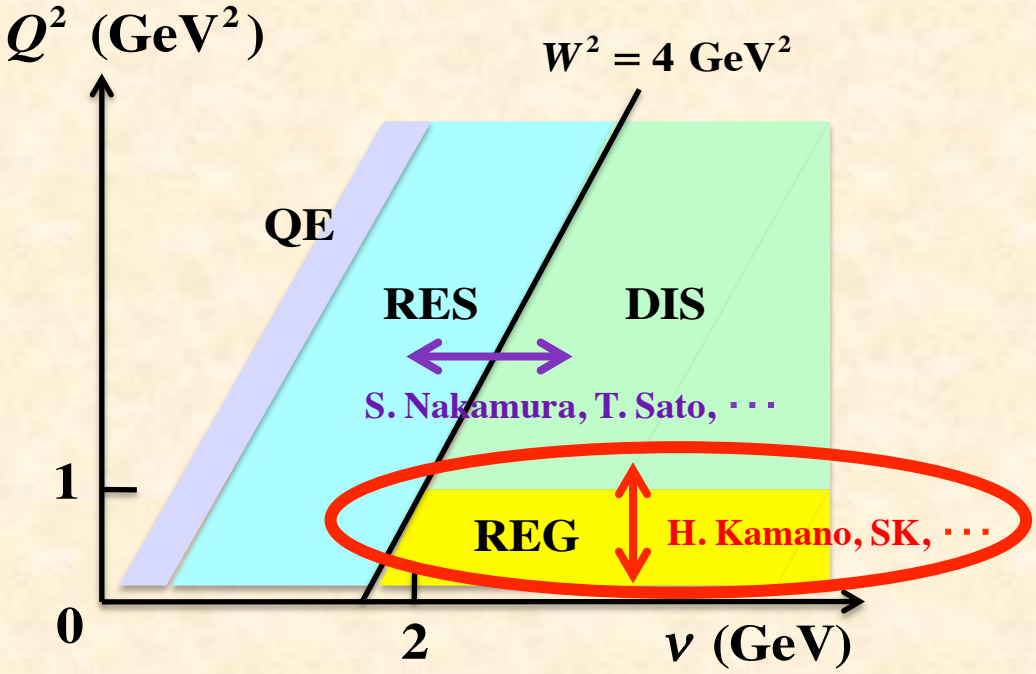
ν-interaction collaboration at J-PARC



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

Y. Hayato, M. Hirai, W. Horiuchi, H. Kamano, S. Kumano, T. Murata, S. Nakamura, K. Saito, M. Sakuda, T. Sato

http://nuint.kek.jp/index_e.html



For the details, see

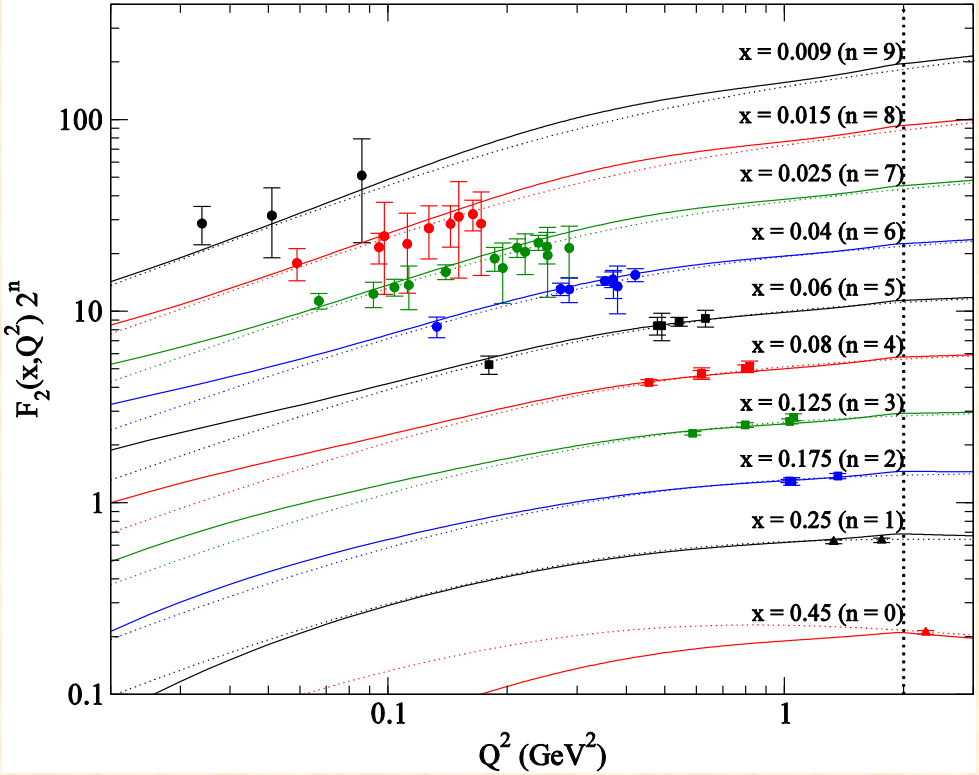
Towards a unified model of neutrino-nucleus reactions for neutrino oscillation experiments,
S. X. Nakamura, H. Kamano, Y. Hayato, M. Hirai, W. Horiuchi,
S. Kumano, T. Murata, K. Saito, M. Sakuda, T. Sato, and Y. Suzuki,
Rep. Prog. Phys. 80 (2017) 056301.

Comparison with JLab/SLAC data

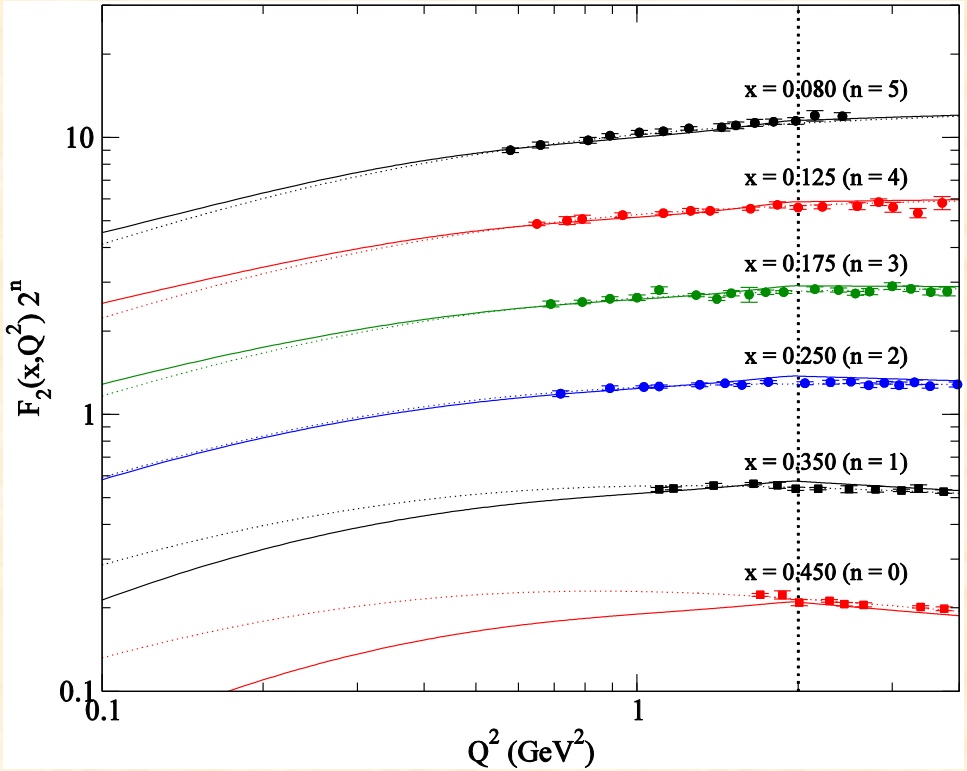
——— our

····· ALLM-97

JLab



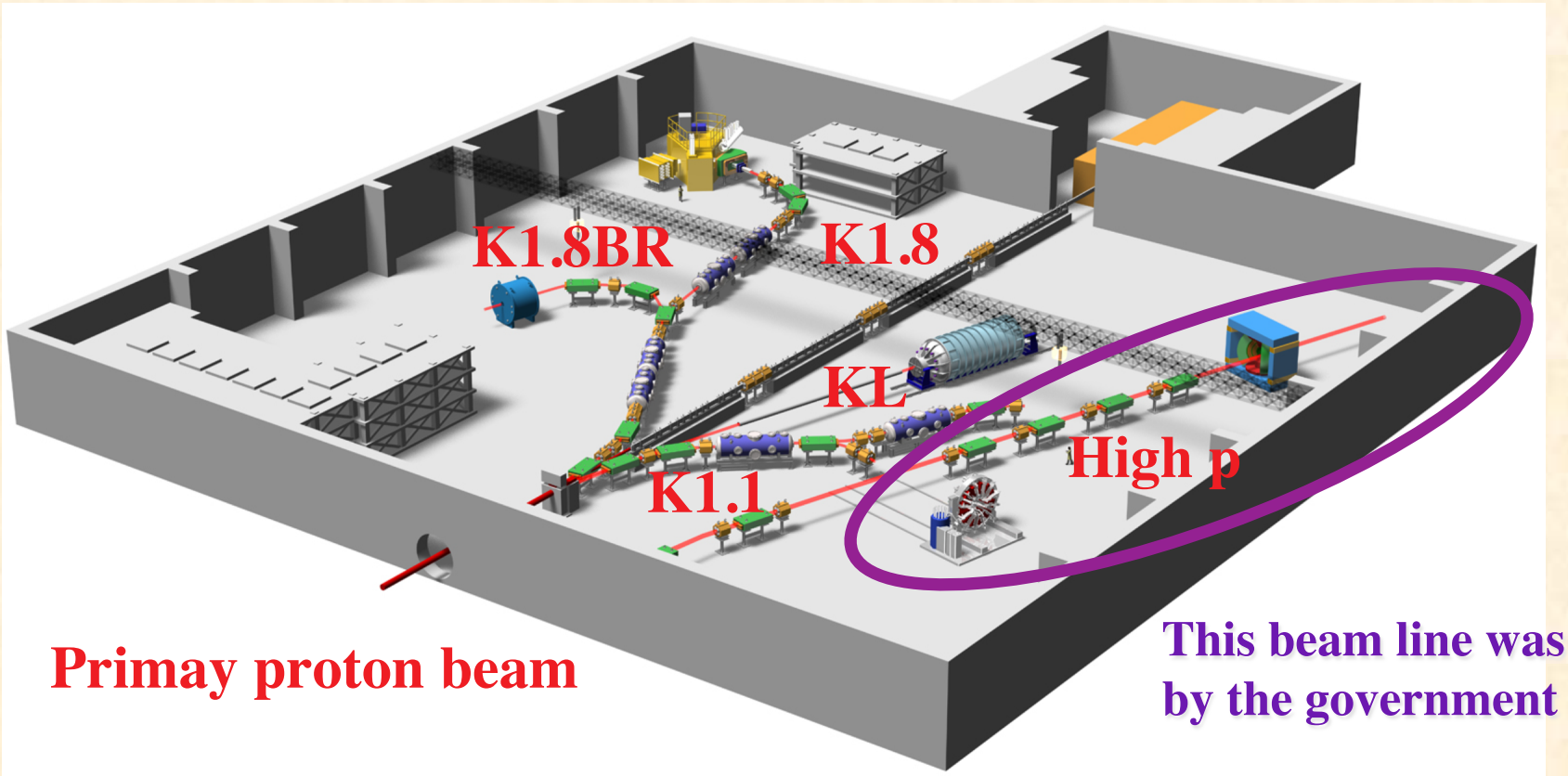
SLAC



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

2017 — 2019 — 2021

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. Yokkaichi[1], 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

E50

Charmed baryons

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
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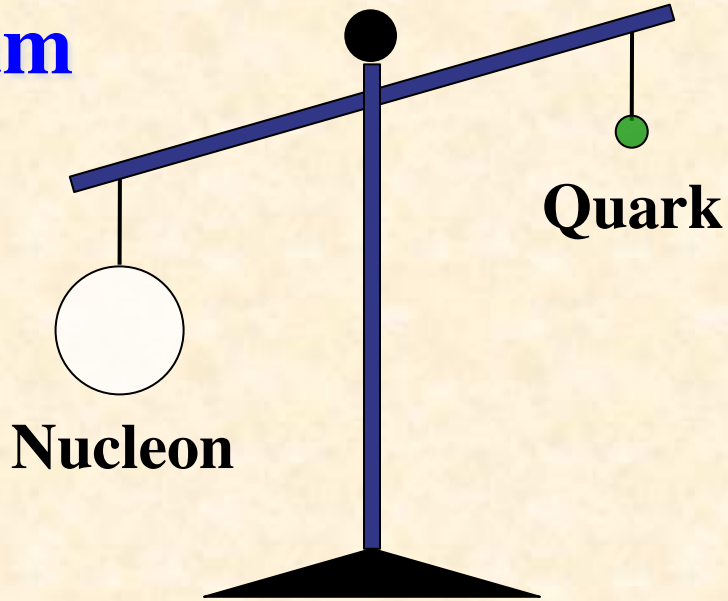
High-energy hadron???

↑

There is a possibility for high-energy hadron physics, including nucleon structure, ...

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

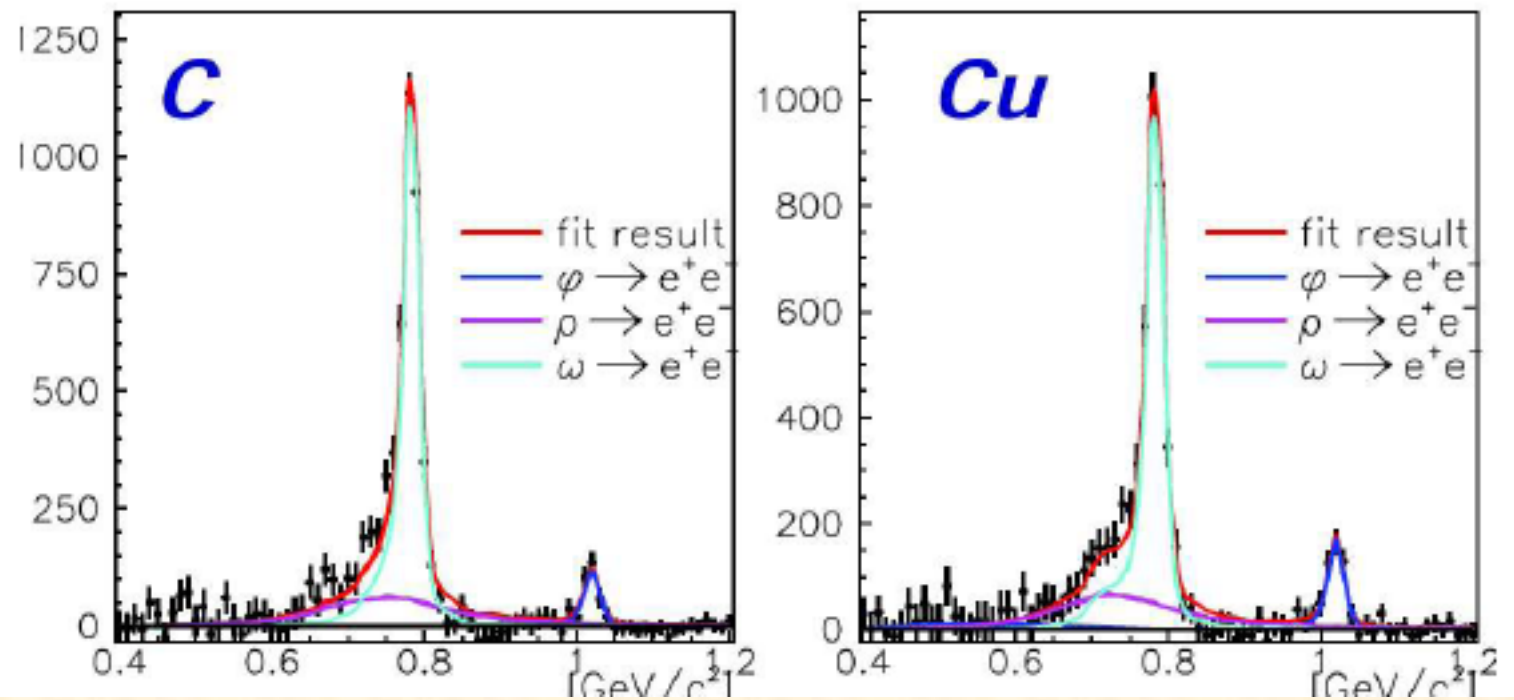
Modifications even at "normal nuclear density"

Reduction in ϱ, ω masses at normal nuclear density

KEK-E325 Collaboration

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

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

$m(\varrho) / m(0) = 1 - k\,\varrho/\varrho_0$

$k = 0.092 \pm 0.002$ for ρ, ω

$= 0.034^{+0.006}_{-0.007}$ for ϕ

9%, 3% mass shifts

→ continued at J-PARC (E16)

Progress in exotic hadrons

$q\bar{q}$ Meson
q^3 Baryon

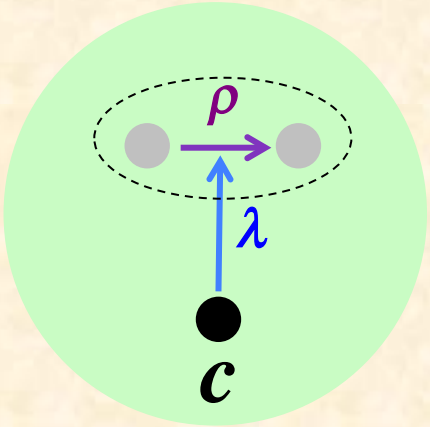
$q^2\bar{q}^2$ Tetraquark
$q^4\bar{q}$ Pentaquark
q^6 Dibaryon
…
$q^{10}\bar{q}$ e.g. Strange tribaryon
…
gg Glueball
…

- $\Theta^+(1540)$???: 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?
- $P_c(4380)$, $P_c(4450)$: LHCb
- …
  $u\bar{c}udc$, $\bar{D}(u\bar{c})\Sigma_c^*(udc)$, $\bar{D}^*(u\bar{c})\Sigma_c(udc)$ molecule?

Charmed-baryon physics

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

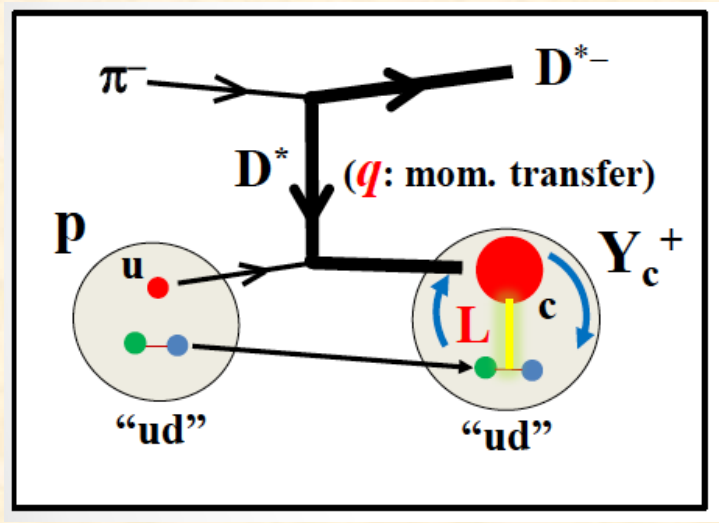
From "strangeness hadron physics" to "charm hadron physics"



- one heavy quark: ρ and λ modes
- roles of diquark

E50 experiment: $\pi^- + p \to D^{*-} + Y_c^+$

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

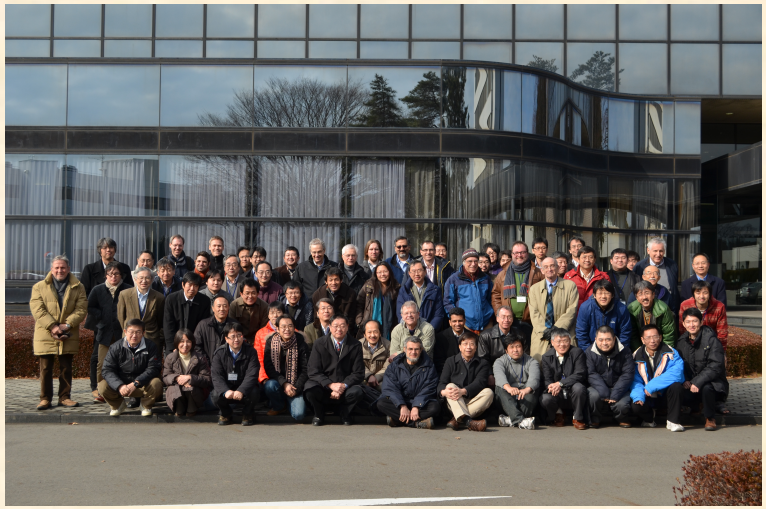


Possibilities of J-PARC projects at high-momentum beamline

(high-energy hadron physics)

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

http://www-conf.kek.jp/hadron1/j-parc-hm-2013/
http://research.kek.jp/group/hadron10/j-parc-hm-2015/



Topics:

- **Quarks/Hadrons in nuclear medium**
- **Exotic hadrons, Charm physics**
- **Baryon interactions, Short-range correlations**
- **Nucleon structure** ← **Today, I comment on this topic.**

For other projects, please look at the conference web pages.

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!

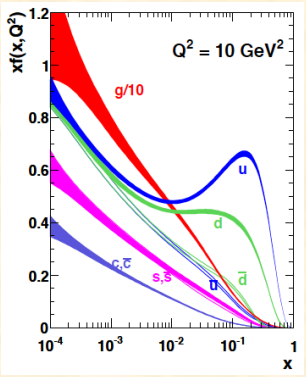
Wigner distribution and various structure functions

Form factor

$\int dx\, d^2k_T$

PDF (Parton Distribution Function)

$\int d^2k_T, \Delta \to 0$



GTMD $W(x, \vec{k}_T, \Delta) \xrightarrow[\Delta^+ \to 0]{} \text{Wigner } W(x, \vec{k}_T, \vec{r}_T)$

$\Delta = p' - p$

$\int d^2k_T$

3D world

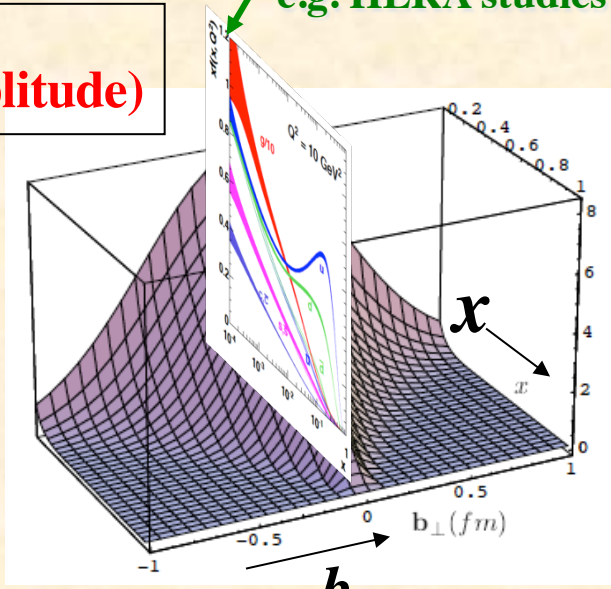
GPD (Generalized Parton Distribution)

$\xrightarrow{s \leftrightarrow t}$ GDA (Generalized Distribution Amplitude)

e.g. HERA studies

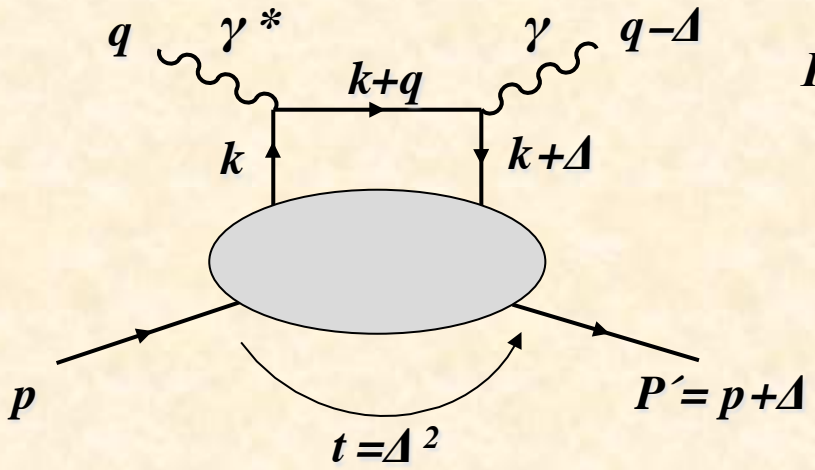
$\Delta \to 0$

TMD (Transverse Momentum Dependent) parton distribution



Our work by the two-photon process $\gamma\gamma \to h\bar{h}$.

Generalized Parton Distributions (GPDs)



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

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

Momentum transfer squared $t = \Delta^2$

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

GPDs are defined as correlation of off-forward matrix:

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

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

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

First moments: Form factors

Dirac and Pauli form factors F_1, F_2 $\int_{-1}^{1} dx\, H(x,\xi,t) = F_1(t), \quad \int_{-1}^{1} dx\, E(x,\xi,t) = F_2(t)$

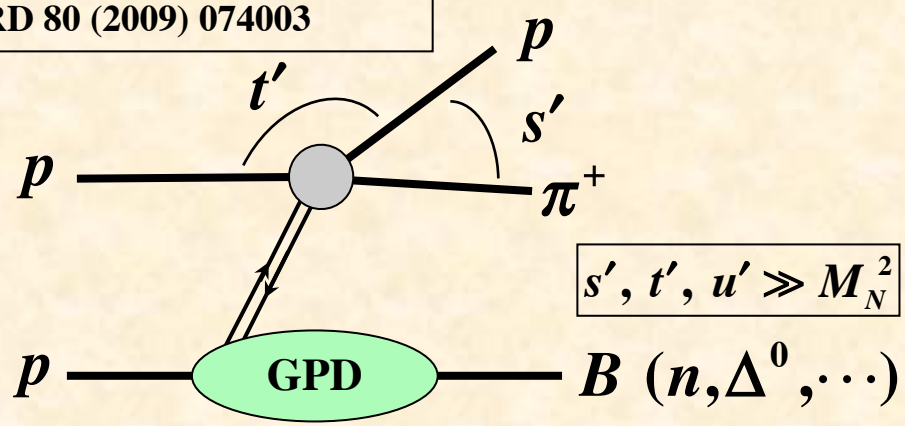
Axial and Pseudoscalar form factors G_A, G_P $\int_{-1}^{1} dx\, \tilde{H}(x,\xi,t) = g_A(t), \quad \int_{-1}^{1} dx\, \tilde{E}(x,\xi,t) = g_P(t)$

Second moments: Angular momenta

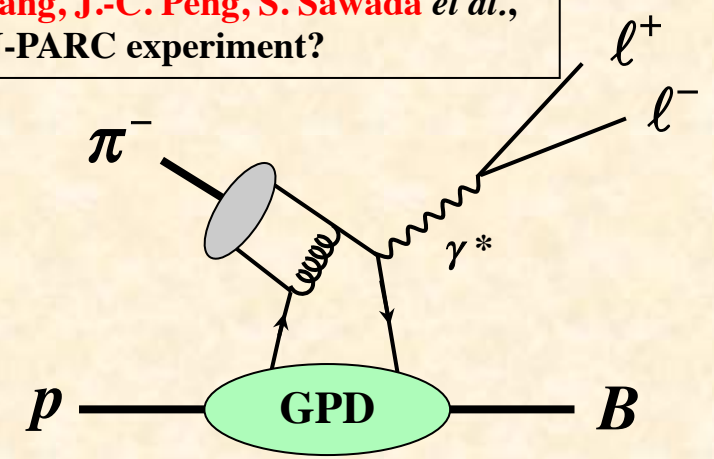
Sum rule: $J_q = \dfrac{1}{2}\int_{-1}^{1} dx\, x\left[H_q(x,\xi,t=0) + E_q(x,\xi,t=0)\right], \quad J_q = \dfrac{1}{2}\Delta q + L_q$

Possibilities of hadron tomography at J-PARC

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

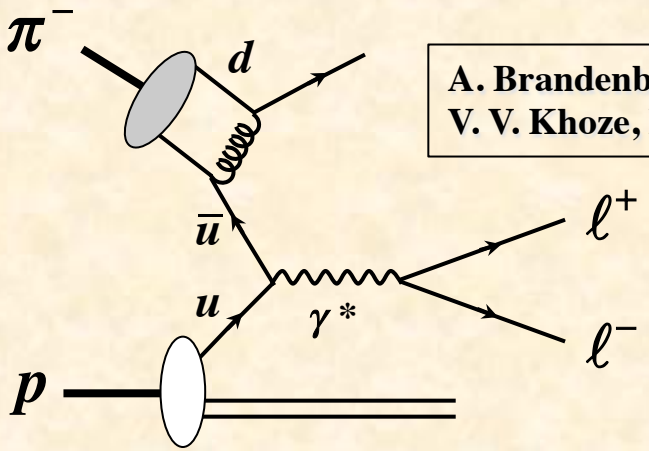


W.-C. Chang, J.-C. Peng, S. Sawada *et al.*,
possible J-PARC experiment?



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

Pion distribution

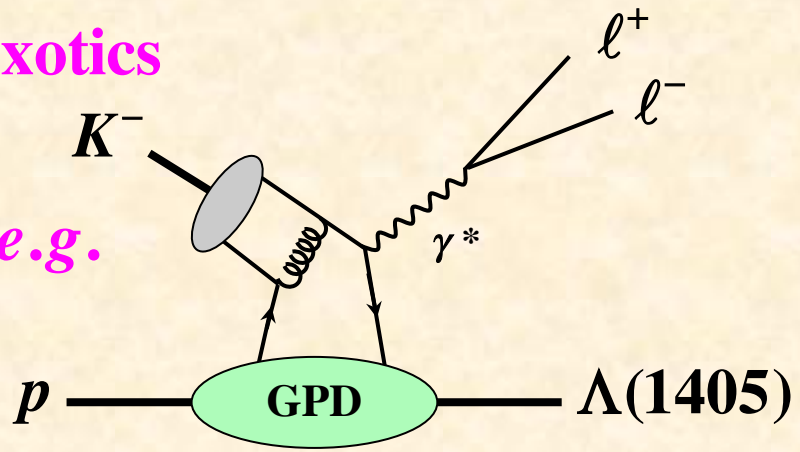


A. Brandenburg, S. J. Brodsky,
V. V. Khoze, D. Müller (1994)

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

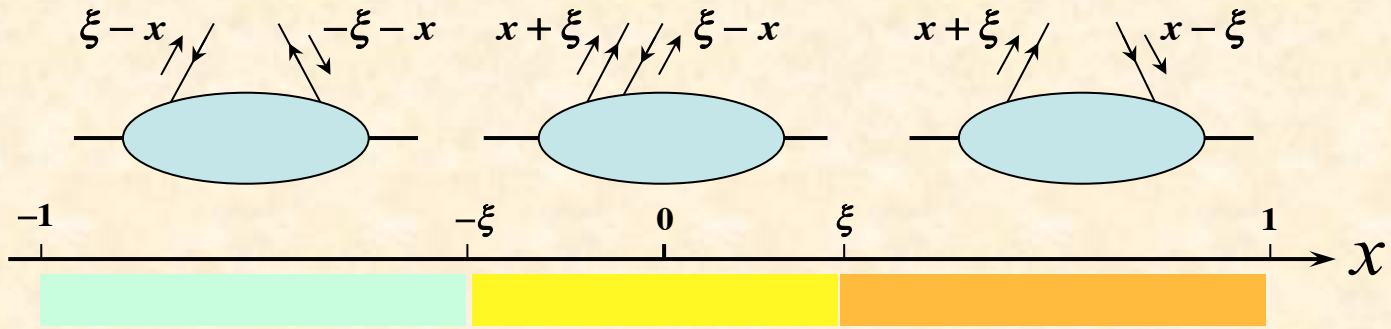
exotics

e.g.



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

GPDs in different x regions and GPDs at hadron facilities



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

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

Quark distribution

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

$q\bar{q}$(meson)-like distribution amplitude

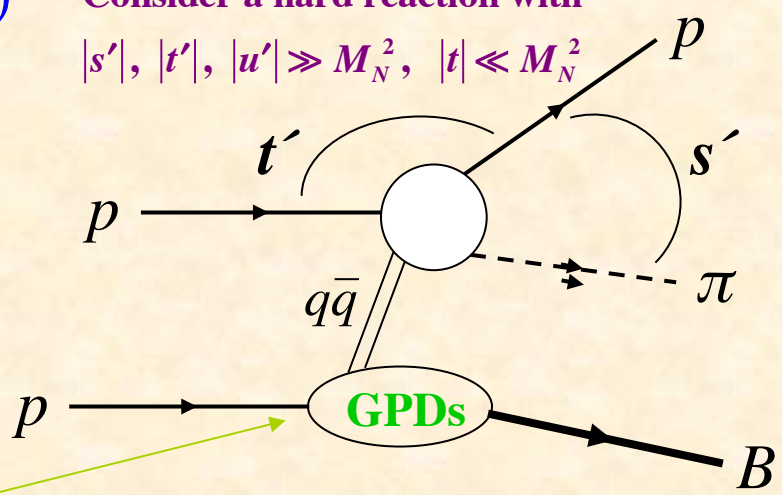
Emission of quark with momentum fraction $x+\xi$
Emission of antiquark with momentum fraction $\xi-x$

Antiquark distribution

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

Consider a hard reaction with

$|s'|, |t'|, |u'| \gg M_N^2, \quad |t| \ll M_N^2$



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

Efremov-Radyushkin -Brodsky-Lepage (ERBL) region

Toward a new proposal at J-PARC

T. Sawada, W.-C. Chang, S. Kumano, J.-C. Peng, S. Sawada, and K. Tanaka, PRD93 (2016) 114034.

Exclusive Drell-Yan: $\pi^- + p \to \mu^+\mu^- + n$

PHYSICAL REVIEW D 93, 114034 (2016)

Accessing proton generalized parton distributions and pion distribution amplitudes with the exclusive pion-induced Drell-Yan process at J-PARC

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(Received 15 May 2016; published 29 June 2016)

Generalized parton distributions (GPDs) encoding multidimensional information of hadron partonic structure appear as the building blocks in a factorized description of hard exclusive reactions. The nucleon GPDs have been accessed by deeply virtual Compton scattering and deeply virtual meson production with lepton beam. A complementary probe with hadron beam is the exclusive pion-induced Drell-Yan process. In this paper, we discuss recent theoretical advances on describing this process in terms of nucleon GPDs and pion distribution amplitudes. Furthermore, we address the feasibility of measuring the exclusive pion-induced Drell-Yan process $\pi^- p \to \mu^+\mu^- n$ via a spectrometer at the High Momentum Beamline being constructed at J-PARC in Japan. Realization of such measurement at J-PARC will provide a new test of perturbative QCD descriptions of a novel class of hard exclusive reactions. It will also offer the possibility of experimentally accessing nucleon GPDs at large timelike virtuality.

Exclusive Drell-Yan $\pi^- + p \to \mu^+\mu^- + n$ and GPDs

$$\frac{d\sigma_L}{dQ'^2 dt} = \frac{4\pi\alpha^2}{27}\frac{\tau^2}{Q'^2} f_\pi^2 \left[(1-\xi^2)\left|\tilde{H}^{du}(-\xi,\xi,t)\right|^2 - 2\xi^2\,\mathrm{Re}\left\{\tilde{H}^{du}(-\xi,\xi,t)^*\,\tilde{E}^{du}(-\xi,\xi,t)\right\} - \xi^2\frac{t}{4m_N^2}\left|\tilde{E}^{du}(-\xi,\xi,t)\right|^2 \right]$$

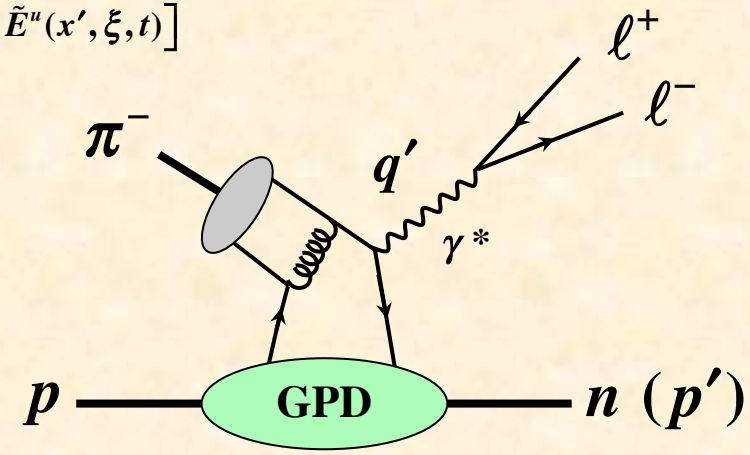
$$Q'^2 = q'^2,\ \ t = (p-p')^2,\ \ \tau = \frac{Q'^2}{2p\cdot q_\pi} \simeq \frac{Q'^2}{s-m_N^2}$$

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

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

$$\tilde{H}^{du}(x,\xi,t) = \frac{8}{3}\alpha_s\int_{-1}^{1}dz\frac{\phi_\pi(z)}{1-z^2}\int_{-1}^{1}dx'\left[\frac{e_d}{x-x'-i\varepsilon} - \frac{e_u}{x+x'-i\varepsilon}\right]\left[\tilde{H}^d(x',\xi,t) - \tilde{H}^u(x',\xi,t)\right]$$

$$\tilde{E}^{du}(x,\xi,t) = \frac{8}{3}\alpha_s\int_{-1}^{1}dz\frac{\phi_\pi(z)}{1-z^2}\int_{-1}^{1}dx'\left[\frac{e_d}{x-x'-i\varepsilon} - \frac{e_u}{x+x'-i\varepsilon}\right]\left[\tilde{E}^d(x',\xi,t) - \tilde{E}^u(x',\xi,t)\right]$$

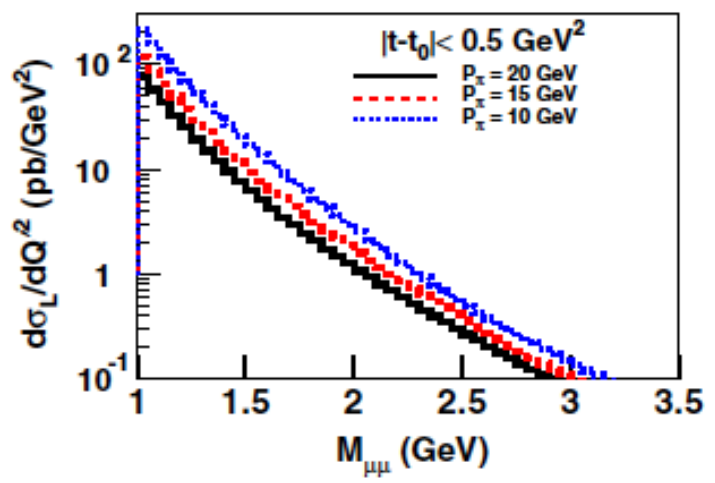


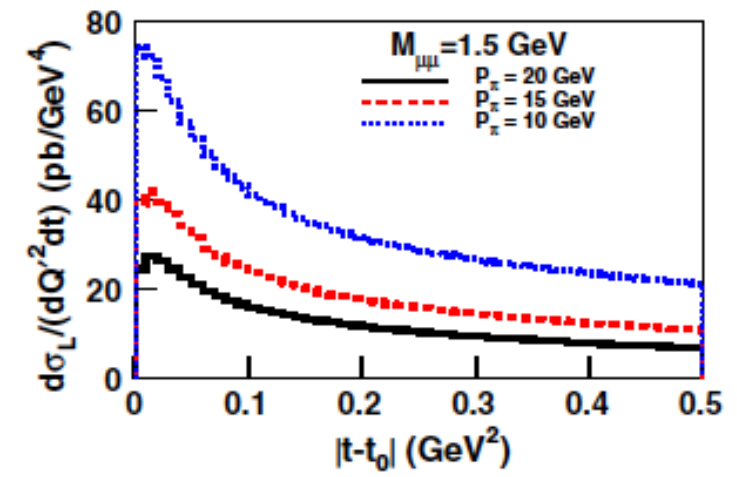
$$\pi^-(\bar{u}d) + p(uud) \to n(udd) + \gamma^*(\to \ell^+\ell^-)$$

Expected Drell-Yan events at J-PARC

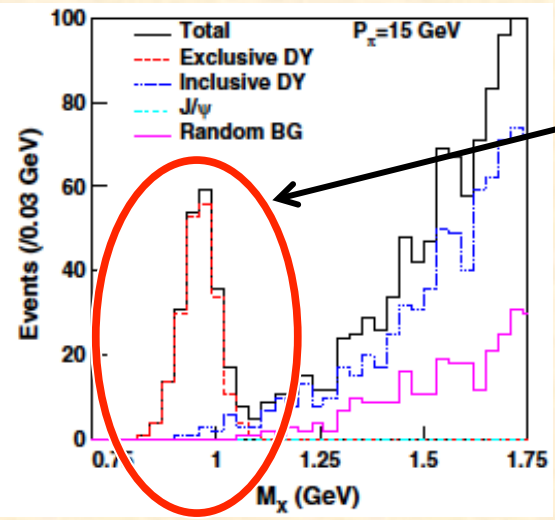
$$Q'^2 = q'^2,\ t = (p-p')^2,\ \tau = \frac{Q'^2}{2p\cdot q_\pi} \simeq \frac{Q'^2}{s-m_N^2}$$

$$\frac{d\sigma_L}{dQ'^2 dt} = \frac{4\pi\alpha^2}{27}\frac{\tau^2}{Q'^2} f_\pi^2 \left[(1-\xi^2)\left|\tilde{H}^{du}(-\xi,\xi,t)\right|^2 - 2\xi^2\,\mathrm{Re}\left\{\tilde{H}^{du}(-\xi,\xi,t)^*\,\tilde{E}^{du}(-\xi,\xi,t)\right\} - \xi^2\frac{t}{4m_N^2}\left|\tilde{E}^{du}(-\xi,\xi,t)\right|^2 \right]$$

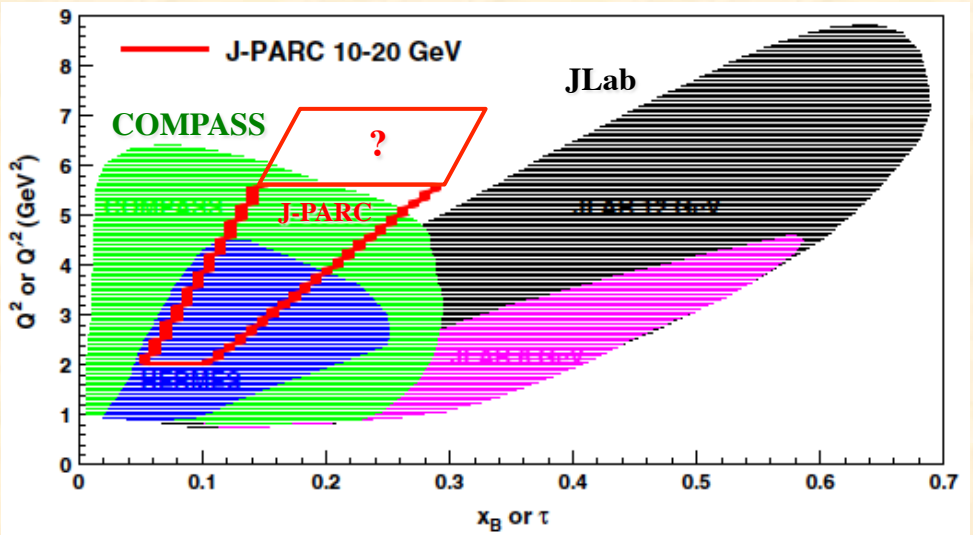




Missing mass



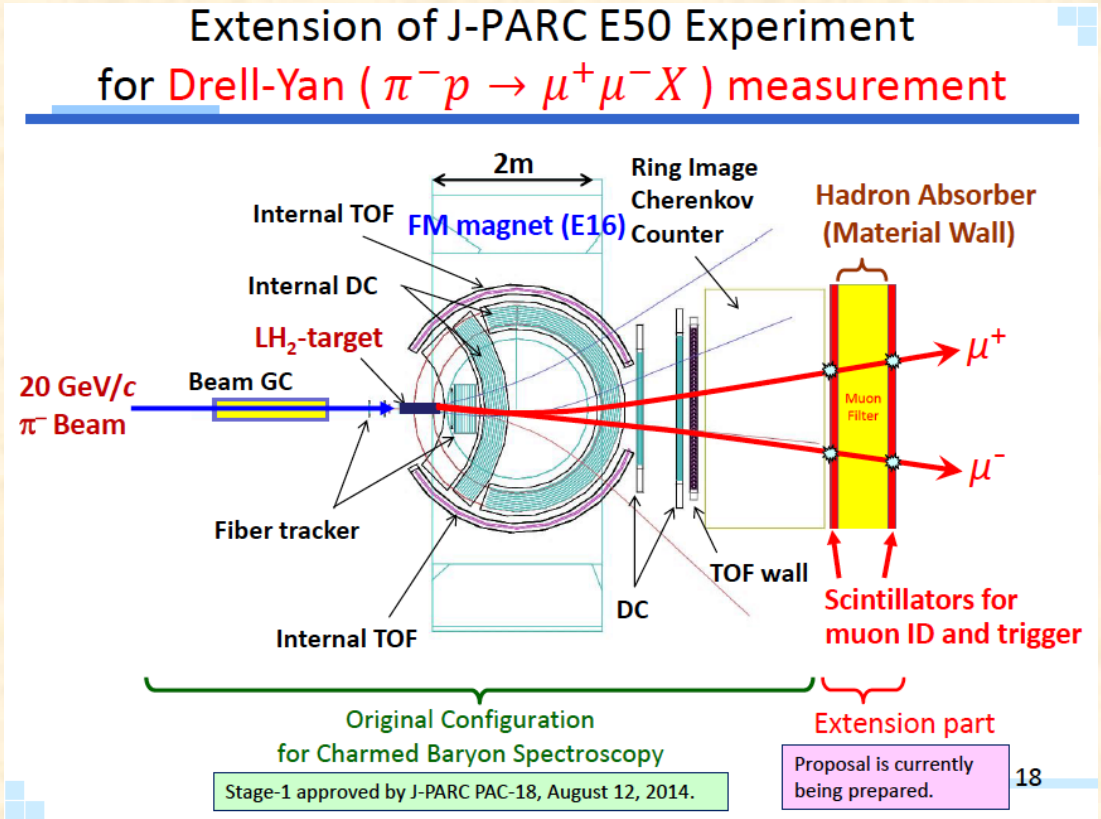
Exclusive Drell-Yan



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

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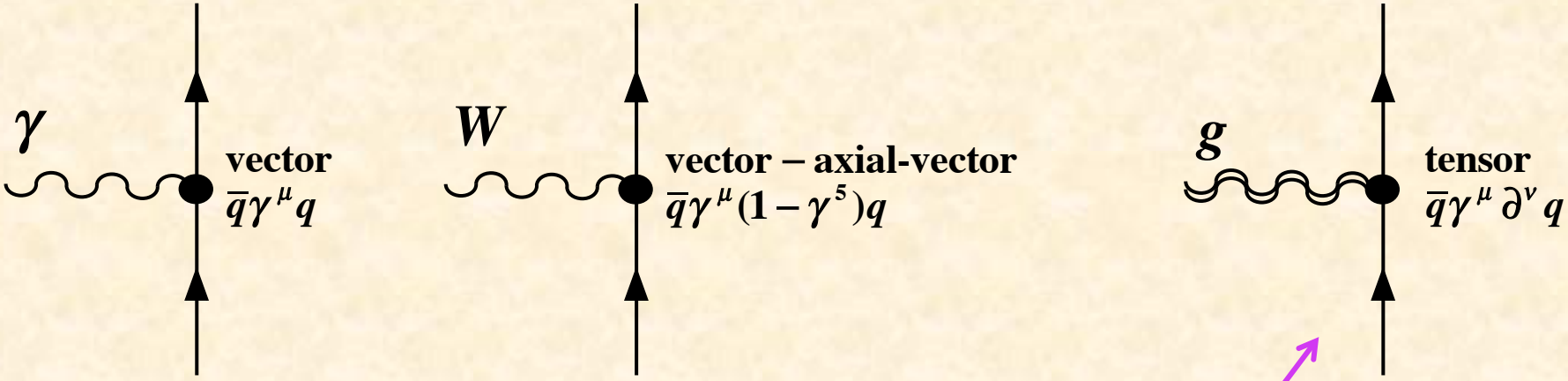
Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea

There is a possibility to join the E50 group for efforts toward a proposal.

Why gravitational interactions with hadrons ?



Electron-proton elastic scattering cross section:

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2 E_f\cos^2\frac{\theta}{2}}{4E_i^3\sin^4(\theta/2)}\left[\frac{G_E^2+\tau G_M^2}{1+\tau}+2\tau G_M^2\tan^2\frac{\theta}{2}\right],\quad \tau=-\frac{q^2}{4M^2}$$

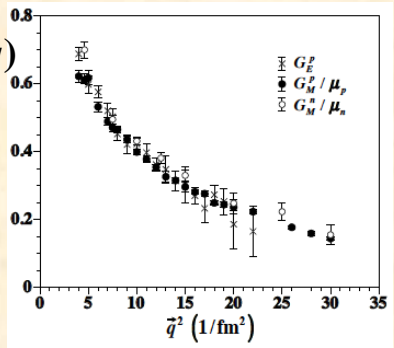
$$F(\vec{q})=\int d^3x\, e^{i\vec{q}\cdot\vec{x}}\rho(\vec{x})=\int d^3x\left[1-\frac{1}{2}(\vec{q}\cdot\vec{x})^2+\cdots\right]\rho(\vec{x})$$

$$\langle r^2\rangle=\int d^3x\, r^2\rho(\vec{x}),\quad r=|\vec{x}|$$

$\sqrt{\langle r^2\rangle}$ = root-mean-square (rms) radius

$$F(\vec{q})=1-\frac{1}{6}\vec{q}^{\,2}\langle r^2\rangle+\cdots,\quad \langle r^2\rangle=-6\left.\frac{dF(\vec{q})}{d\vec{q}^{\,2}}\right|_{\vec{q}^{\,2}\to 0}$$

$F(q)$



$$\rho(r)=\frac{\Lambda^3}{8\pi}e^{-\Lambda r}\ \Leftrightarrow\ \text{Dipole form: } F(q)=\frac{1}{\left(1+|\vec{q}|^2/\Lambda^2\right)^2},\quad \Lambda^2\simeq 0.71\ \text{GeV}^2$$

How about gravitational radius?

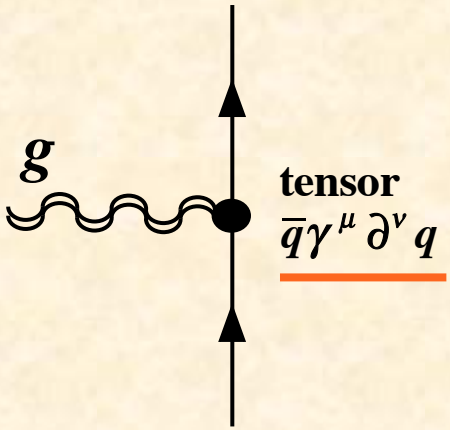
Proton-charge-radius puzzle:

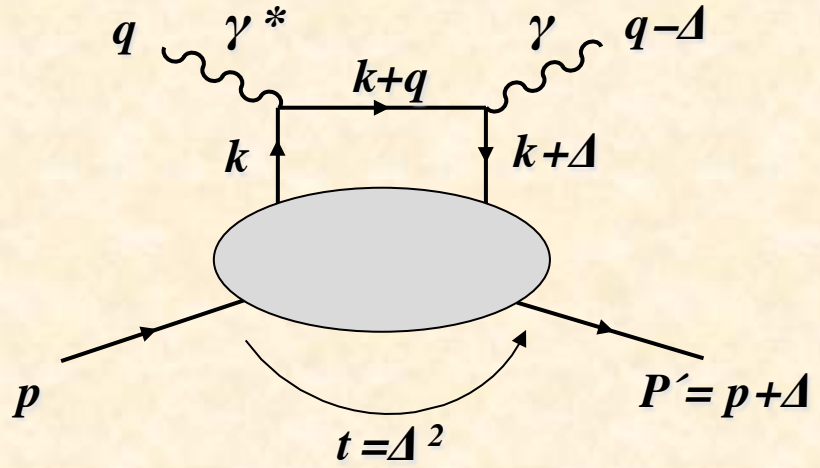
$R_{\text{electron scattering}} = 0.8775$ fm

⇕

$R_{\text{muonic atom}} = 0.8418$ fm

Gravitational interactions and 3D structure functions





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

Angular momentum: $J_q = \frac{1}{2}\int_{-1}^{1} dx\, x\left[H_q(x,\xi,t=0) + E_q(x,\xi,t=0)\right], \quad J_q = \frac{1}{2}\Delta q + L_q$

Non-local operator of GPDs/GDAs:

$$\left(P^+\right)^n \int dx x^{n-1} \int \frac{dz^-}{2\pi} e^{ixP^+z^-}\left[\bar{q}(-z/2)\gamma^+q(z/2)\right]_{z^+=0,\vec{z}_\perp=0} = \left(i\frac{d}{dz^-}\right)^{n-1}\left[\bar{q}(-z/2)\gamma^+q(z/2)\right]_{z=0}$$

$$= \bar{q}(0)\gamma^+\left(i\overleftrightarrow{\partial}^+\right)^{n-1}q(0)$$

= energy-momentum tensor of a quark for $n=2$ (electromagnetic for $n=1$)

= source of gravitiy

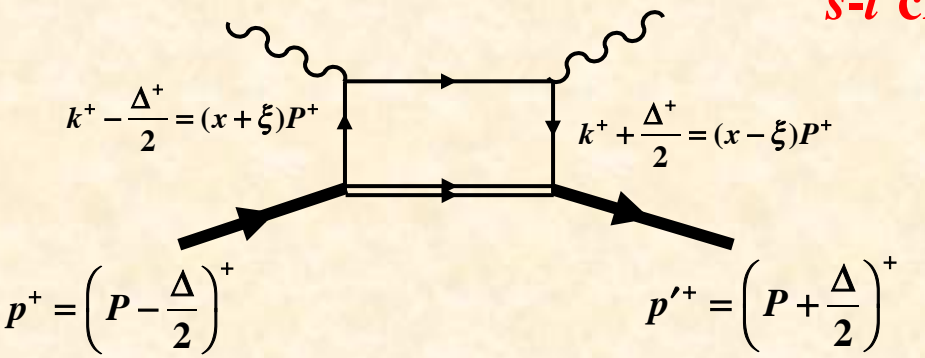
GPD $H_q^h(x,\xi,t)$ and GDA $\Phi_q^{h\bar{h}}(z,\zeta,W^2)$

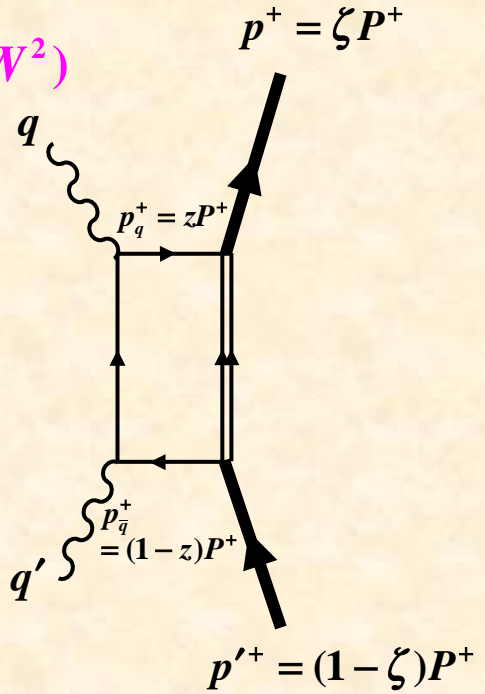
GPD: $$H_q(x,\xi,t)=\int\frac{dy^-}{4\pi}\,e^{ixP^+y^-}\left\langle h(p')\left|\bar{\psi}(-y/2)\gamma^+\psi(y/2)\right|h(p)\right\rangle\Big|_{y^+=0,\vec{y}_\perp=0},\qquad P^+=\frac{(p+p')^+}{2}$$

GDA: $$\Phi_q(z,\zeta,s)=\int\frac{dy^-}{2\pi}\,e^{izP^+y^-}\left\langle h(p)\bar{h}(p')\left|\bar{\psi}(-y/2)\gamma^+\psi(y/2)\right|0\right\rangle\Big|_{y^+=0,\vec{y}_\perp=0}$$

DA: $$\Phi_q^h(z,\zeta,s)=\int\frac{dy^-}{2\pi}\,e^{izP^+y^-}\left\langle h(p)\left|\bar{\psi}(-y/2)\gamma^+\gamma_5\psi(y/2)\right|0\right\rangle\Big|_{y^+=0,\vec{y}_\perp=0}$$

$H_q^h(x,\xi,t)$ $\longleftrightarrow$ ***s-t* crossing** $\longleftrightarrow$ $\Phi_q^{hh}(z,\zeta,W^2)$





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

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

Momentum transfer squared: $t=\Delta^2$

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

Bjorken variable for $\gamma\gamma^*$: $z=\dfrac{Q^2}{2q\cdot q'}$

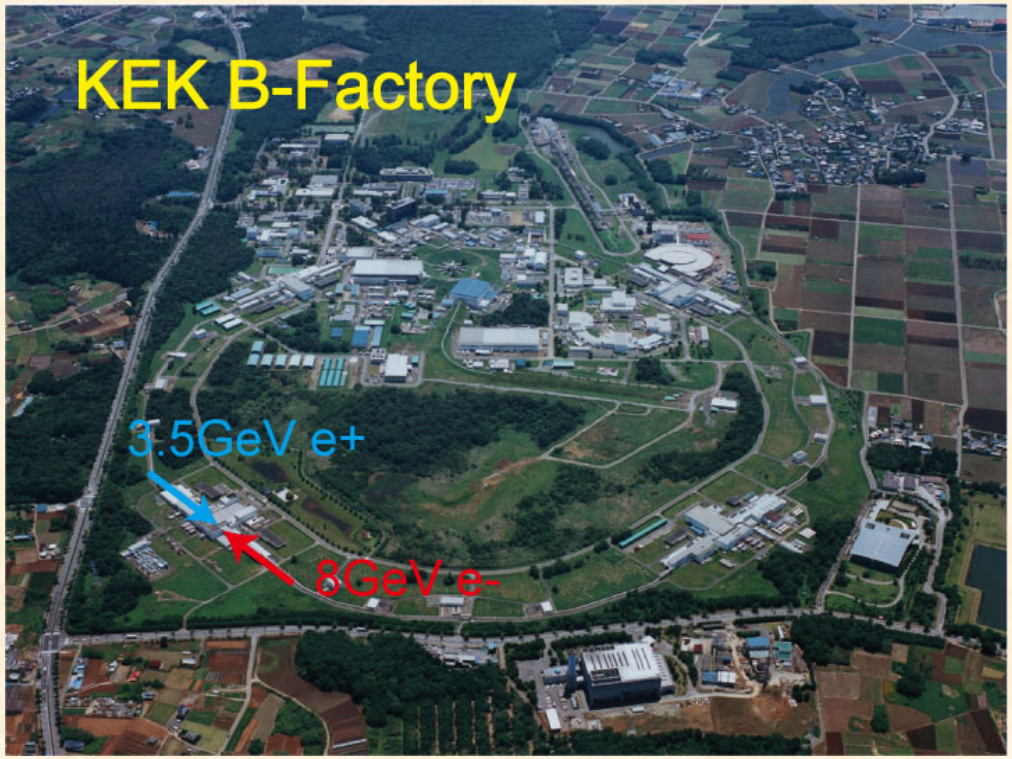
Light-cone momentum ratio for h in $h\bar{h}$: $\zeta=\dfrac{p^+}{P^+}=\dfrac{1+\beta\cos\theta}{2}$

Invariant mass of $h\bar{h}$: $W^2=(p+p')^2$

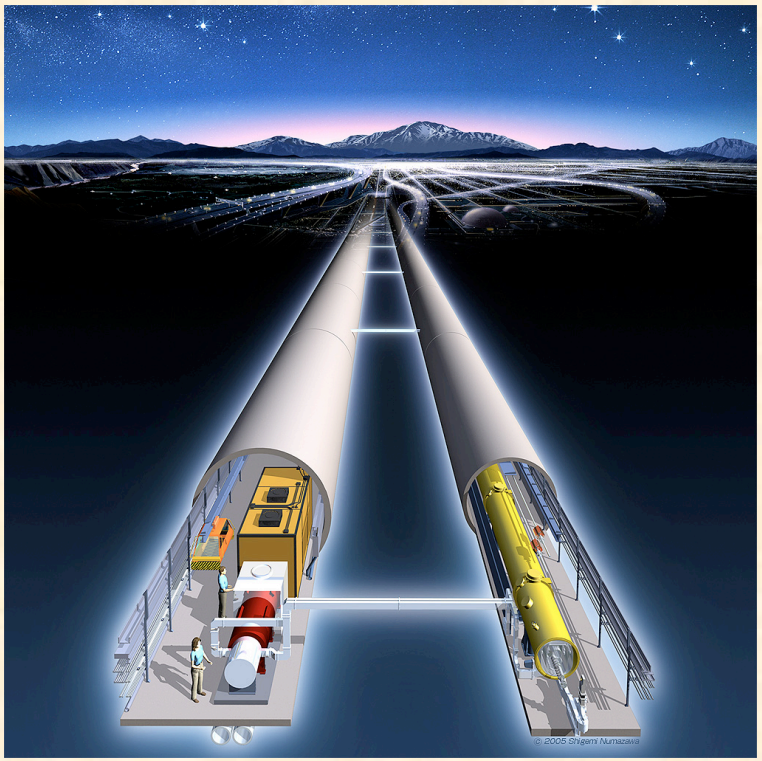
Experimental studies of GDAs in future

$\gamma\gamma \to h\bar{h}$ for internal structure of exotic hadron candidate h

KEK B-factory



Linear Collider ?



Future facility update possibilities

Hadron-hall extension

arXiv: 1706.07916

Extension of
the J-PARC Hadron Experimental Facility
- summary report -

April 30, 2017

Committee for the study of the extension of
the Hadron Experimental Facility

Heavy-ion acceleration?

8th International Conference on Quarks and Nuclear Physics

November 13-17, 2018, Tsukuba, Japan
http://www-conf.kek.jp/qnp2018/

Quark and gluon structure of hadrons:
- parton distribution functions, generalized parton distributions,
- transverse momentum distributions, high-energy hadron reactions, …

Hadron spectroscopy:
- heavy quark physics, exotics, N*, ...

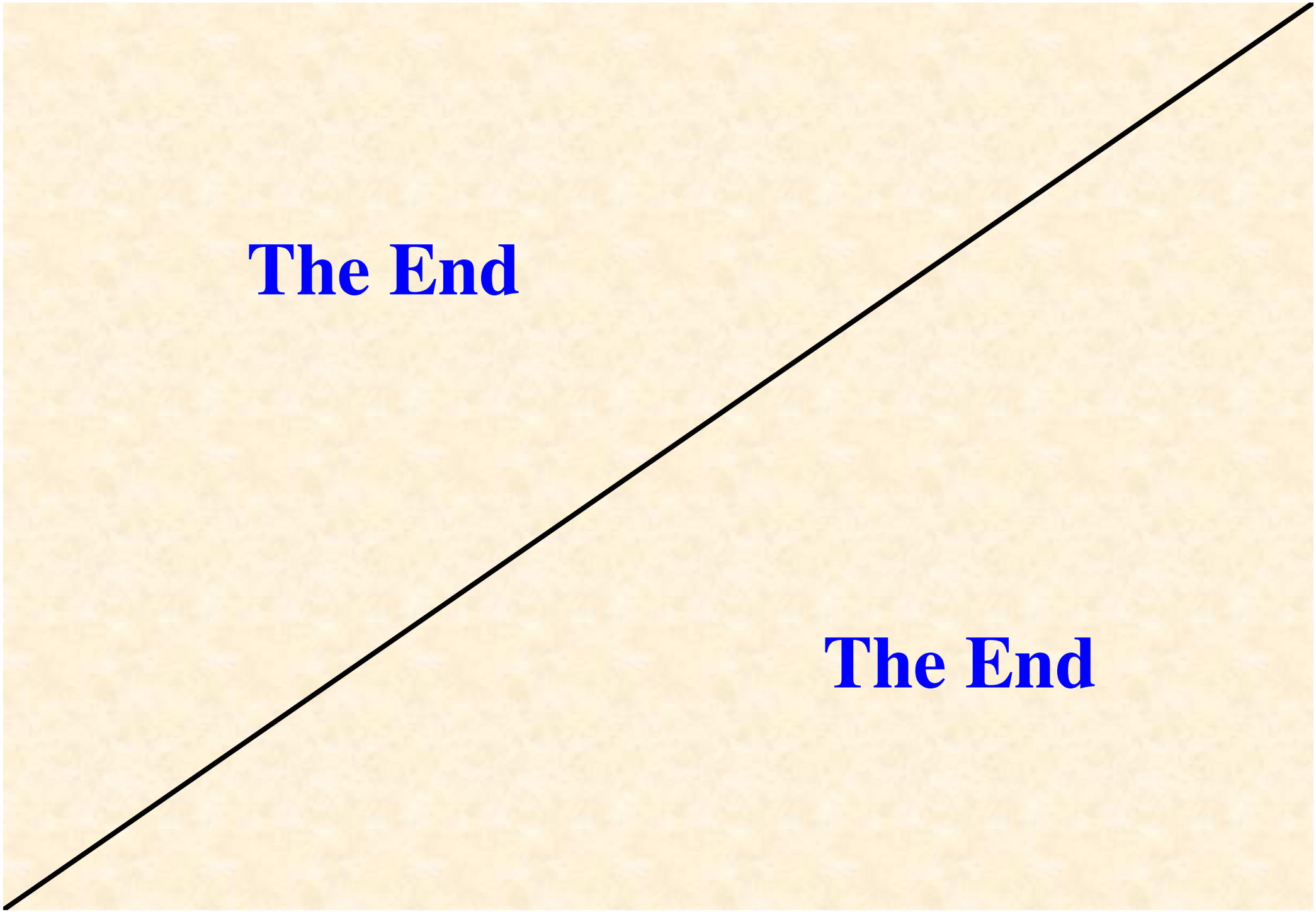
Hadron interactions and nuclear structure:
- hypernuclear physics, kaonic nuclei, baryon interactions, ...

These topics are closely related to Jlab/GSI projects. You are welcome!

Summary

- **J-PARC started producing data**
  on strangeness hadron/nuclear physics.
- **The high-momentum beamline (p, π, ...) will be ready soon.**
- **Common physics interests among GSI, JLab, J-PARC:**
  strangeness and charm hadron physics, N*,
  structure functions, nuclear medium effects, ...

It is nice if we have joint efforts and communications!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