Possible Spin Physics at J-PARC

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October 20-24, 2014
Peking University, Beijing, China
http://www.phy.pku.edu.cn/spin2014/

October 23, 2014

Related previous talks (focusing on fundamental particle physics)

N. Saito in Spin-2012

Updated information in 2014 at Lanzhou

In this talk, I focus mainly on possible hadron spin physics,
especially on 3-dimensional view of hadrons.

Contents

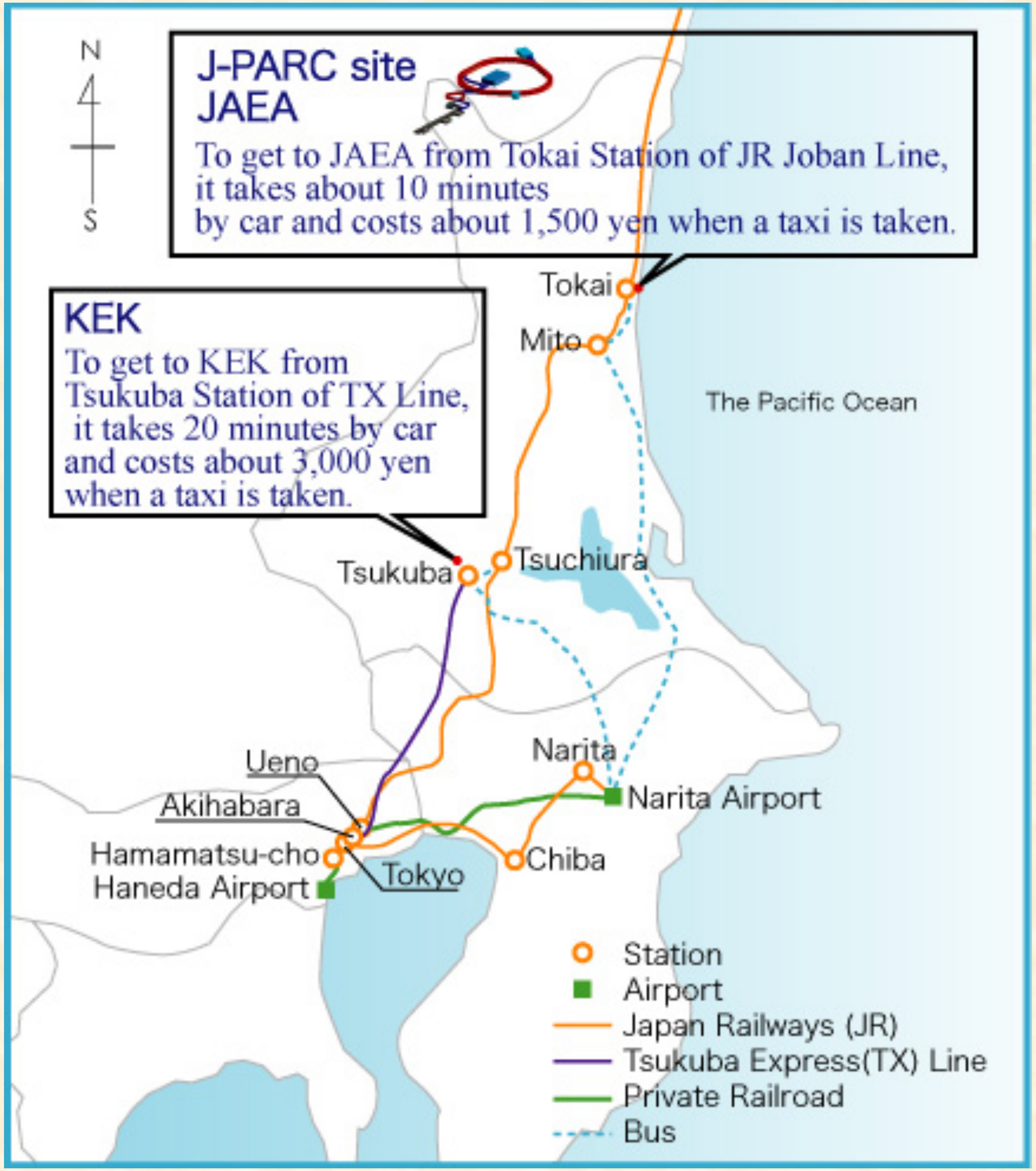
- **J-PARC projects**
  Introduction to J-PARC facility
  Spin in particle physics
  Possible J-PARC projects on high-energy hadron physics
- **Introduction to internal structure of hadrons**
- **Possible GPD studies at hadron facilities**
  GPD (Generalized Parton Distribution)
- **Constituent-counting rule for hadrons**
  old idea, but it could be valuable for finding internal configurations
- **GPDs and GDAs for exotic hadrons**
  GDA (Generalized Distribution Amplitude)
- **Comments on J-PARC hadron spin physics**
- **Summary**

J-PARC project

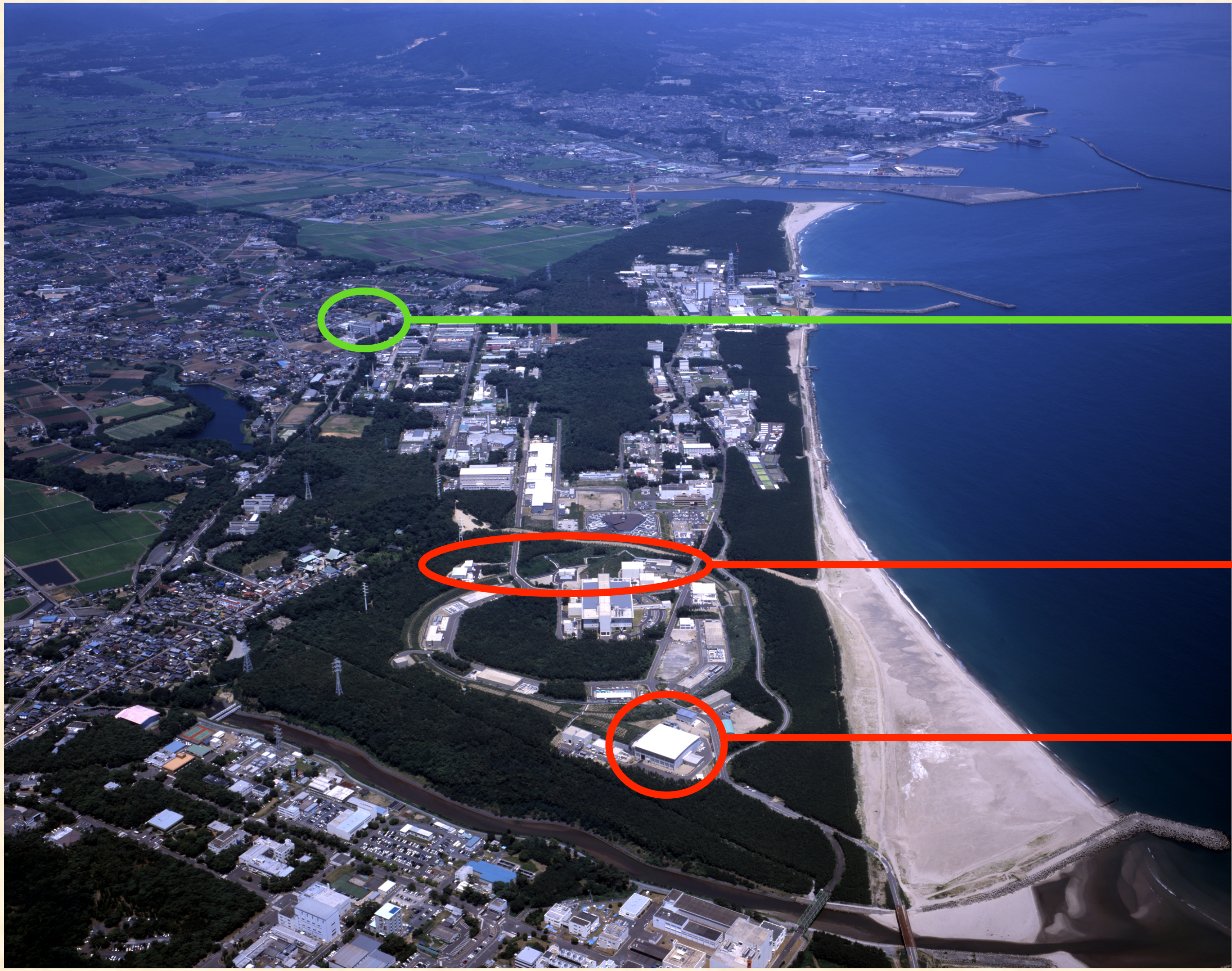
J-PARC location

J-PARC (Japan Proton Accelerator Research Complex)

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



Aerial photograph



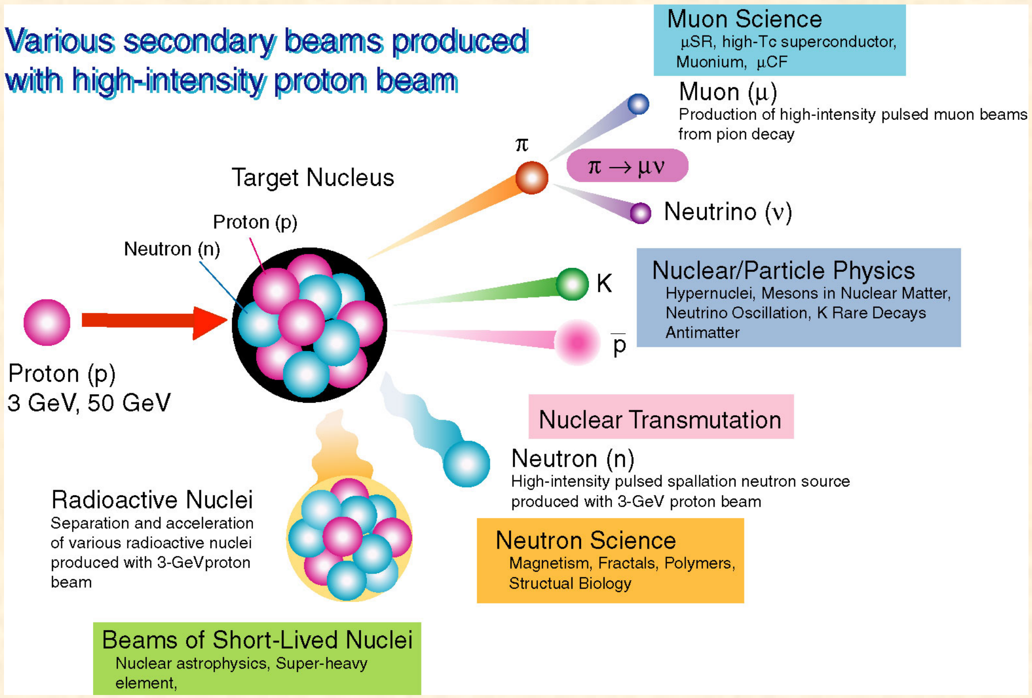
KEK Tokai building
(Theory activities)

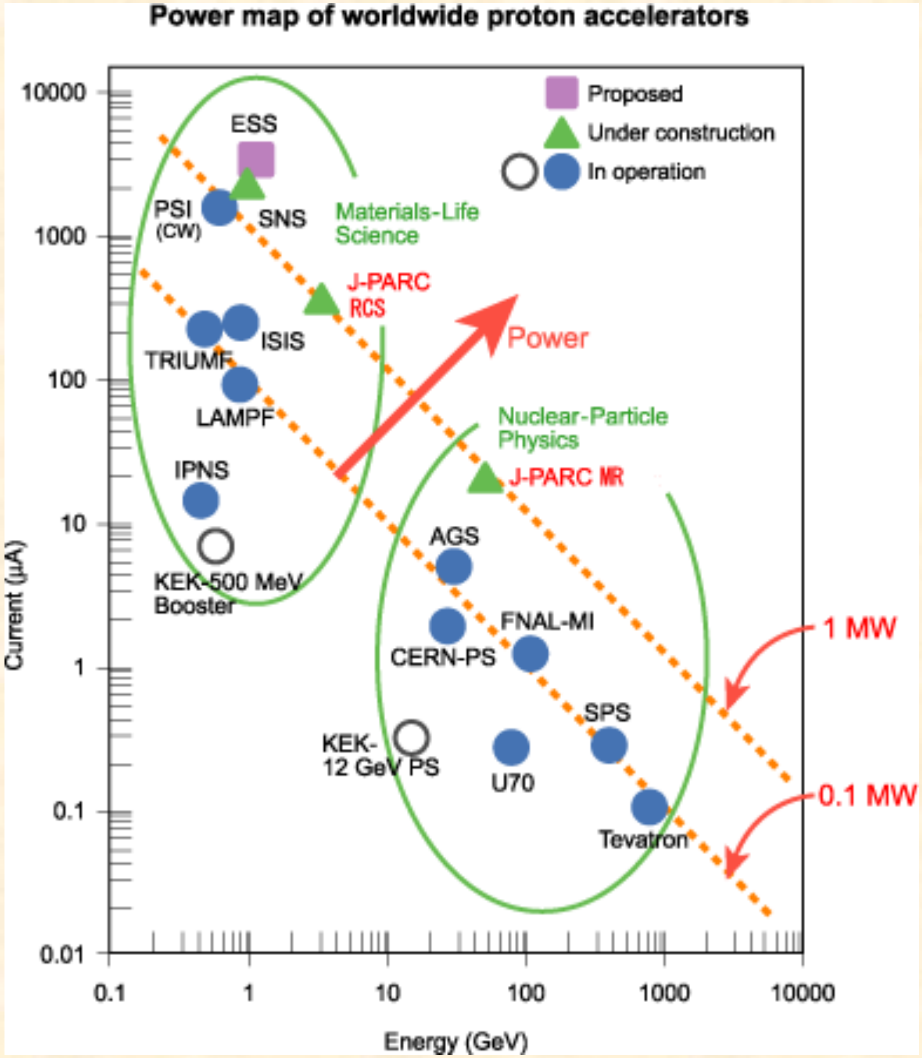
Neutrino
facility

Hadron
facility

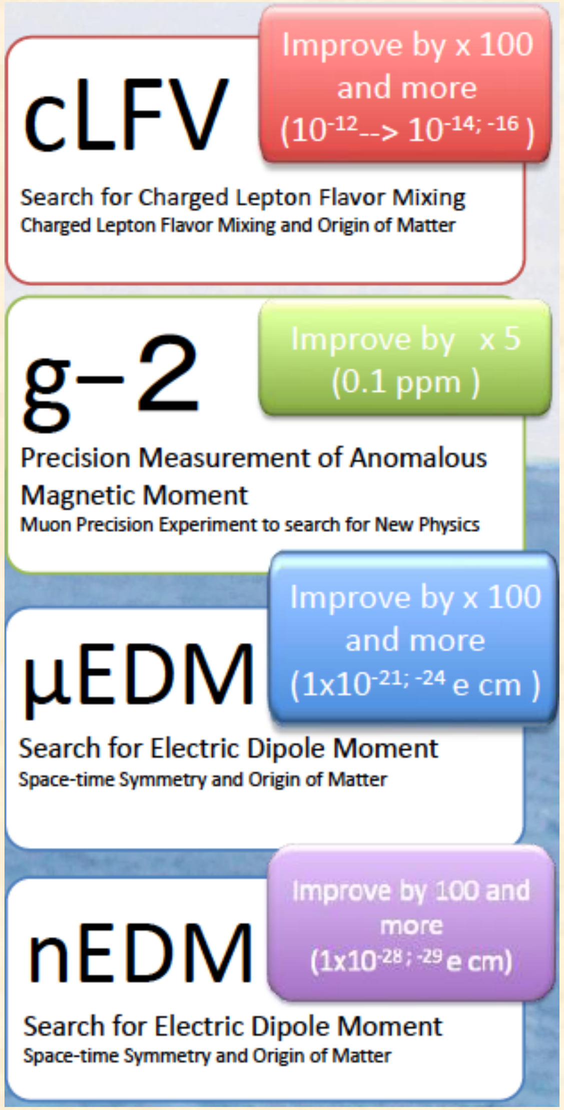
High-Intensity Frontier of Proton Accelerator

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





Spin in particle physics



N. Saito (2014)

general form of spin precession vector:

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

g−2

T. Mibe (2013)

BNL E821 approach
γ=30 (P=3 GeV/c)

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

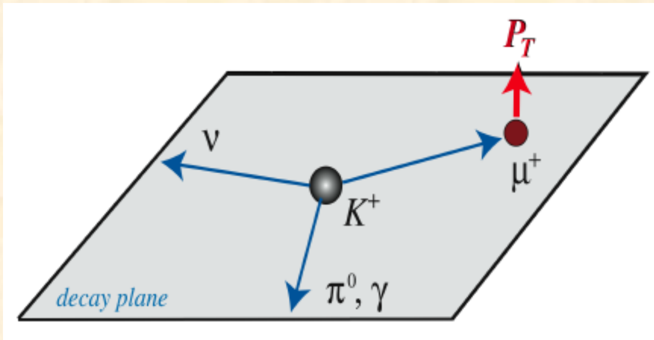
Continuation at FNAL with 0.1ppm precision

J-PARC approach
E = 0 at any γ

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

Proposed at J-PARC with 0.1ppm precision

TREK (Time Reversal violation Experiment with Kaons)

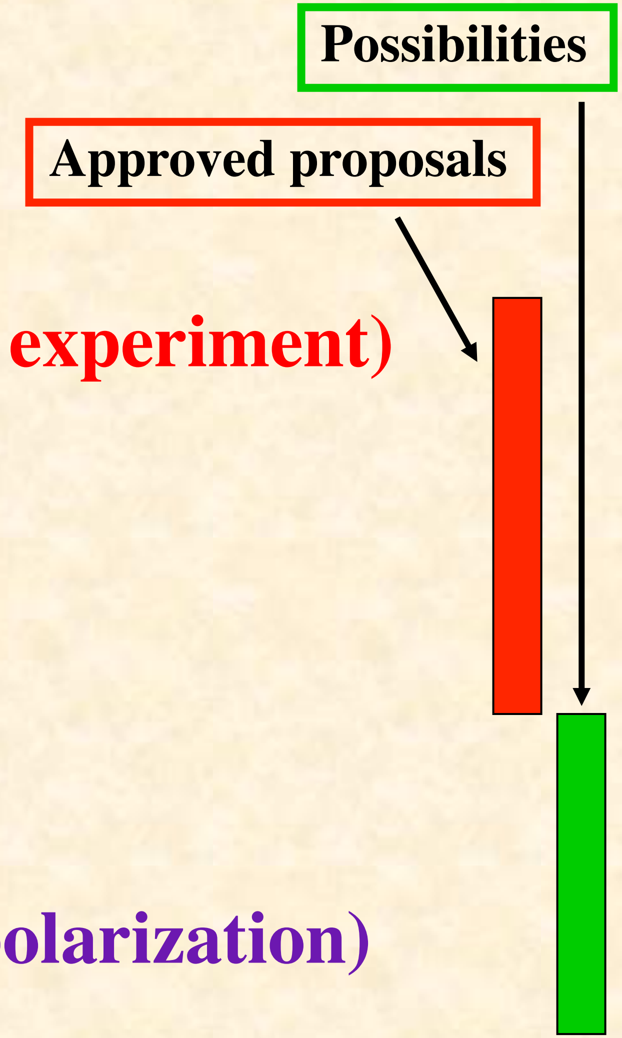


M. Kohl (2013)

- $K^+ \to \pi^0 \mu^+ \nu$
- Decay at rest
- T-odd correlation

$P_T \neq 0$ ⇒ T violation
(CPT theorem) ⇒ CP violation
Sakurai 1957

J-PARC hadron physics



1st project

- Strangeness nuclear physics (1st experiment)

Next projects

- Exotic hadrons
- Hadrons in nuclear medium
- Hard processes

Need major upgrades

- Nucleon spin (beam polarization)
- Quark-hadron matter (heavy ion)

Theory activities at J-PARC

J-PARC Branch, KEK Theory Center

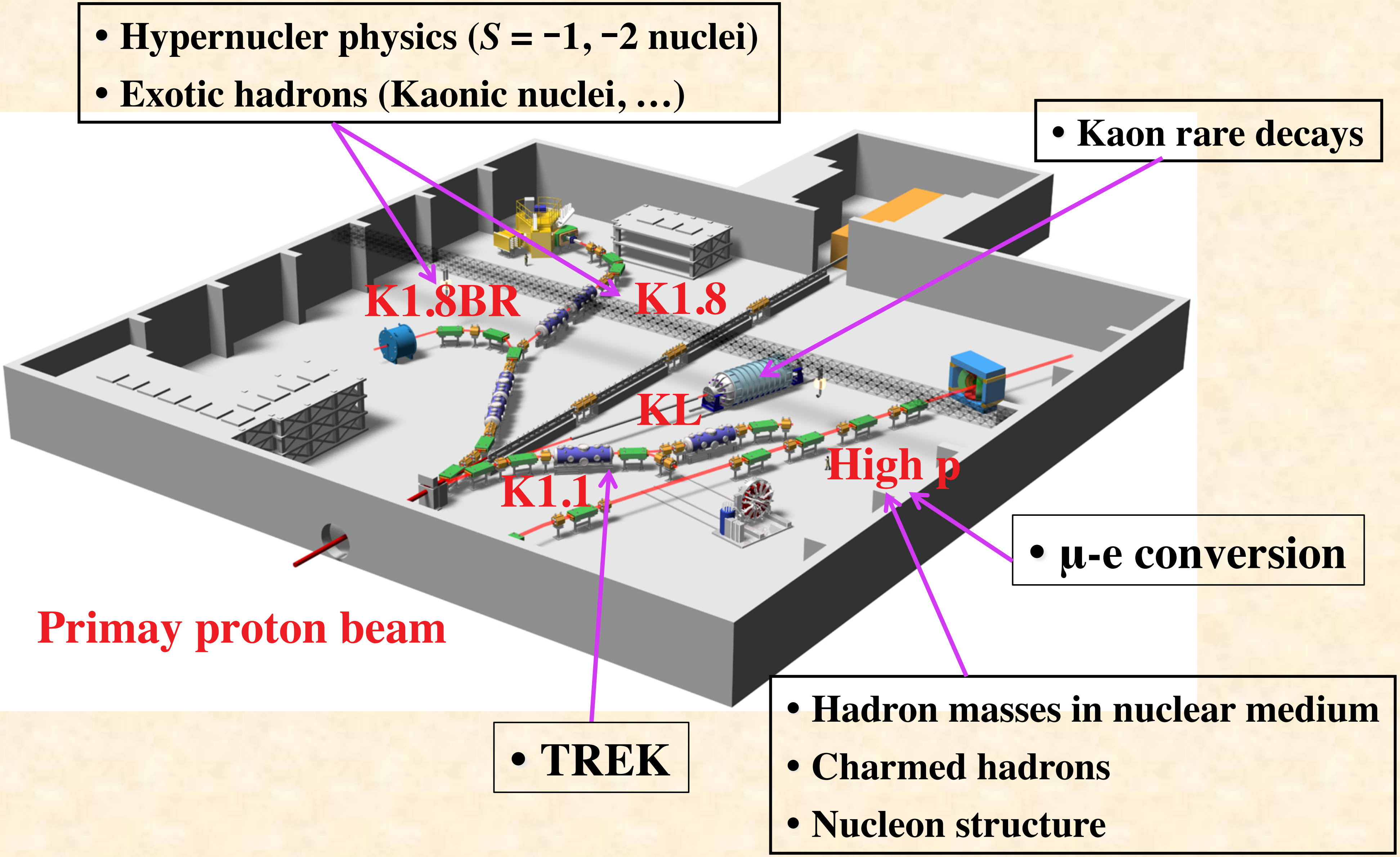
Institute of Particle and Nuclear Studies, KEK
203-1, Shirakata, Tokai, Ibaraki, 319-1106, Japan
http://j-parc-th.kek.jp

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

Hyper-nuclear physics (T. Harada)
Hadron masses in medium (S. Hirenzaki)
Charm physics (A. Hosaka)
Neutrino-nuclear interactions (K. Saito)
Structure functions (K. Tanaka)

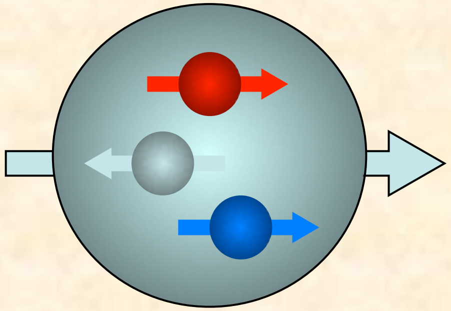
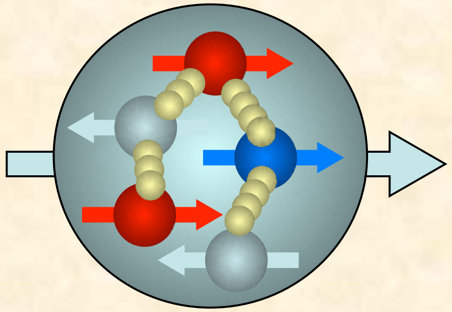
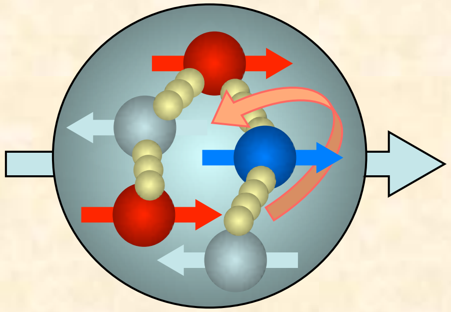
If you are interested in organizing a workshop or joining activities, please inform us.

Hadron facility



Introduction to
Internal structure of hadrons

Nucleon Spin

Naïve Quark Model

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

Electron / muon scattering

$\Delta\Sigma \approx 0.3$

Almost none of nucleon spin is carried by quarks!

QCD

Sea-quarks and gluons?

Gluon: ΔG

Sea-quarks: Δq_{sea}

ΔG **?**

Orbital angular momenta ?

L_q, L_g

3D view of nucleon (Tomography)

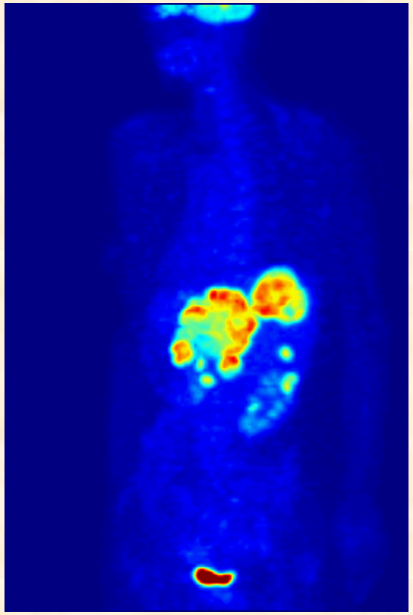
Nucleon Spin:

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

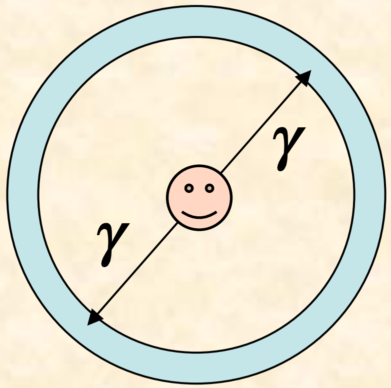
Tomography

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

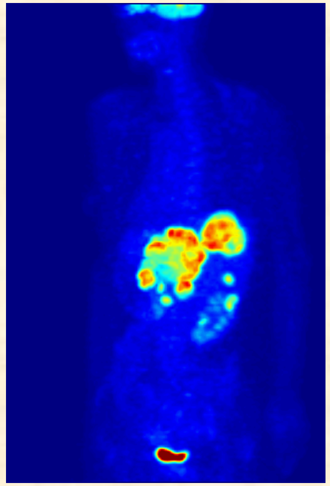
β^+ decay: $\ ^{18}_{9}\mathrm{F} \rightarrow \ ^{18}_{8}\mathrm{O} + e^+ + \nu_e \quad (\tau = 110 \text{ min})$



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



Nucleon (hadron) tomography



Classical density distribution

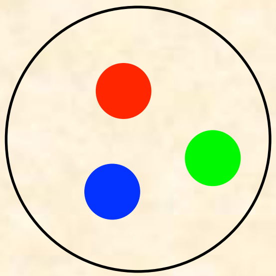
3D picture of nucleon

(Density distribution of quantum system: Quantum tomography)

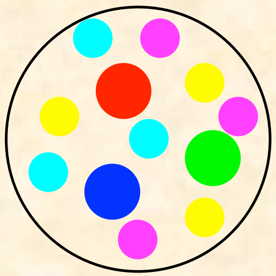
1D(Bjorken-*x*) picutre@HERA

© DESY

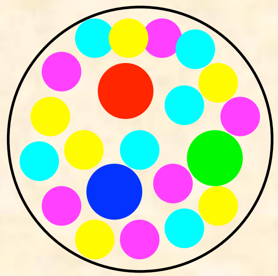
Low energy



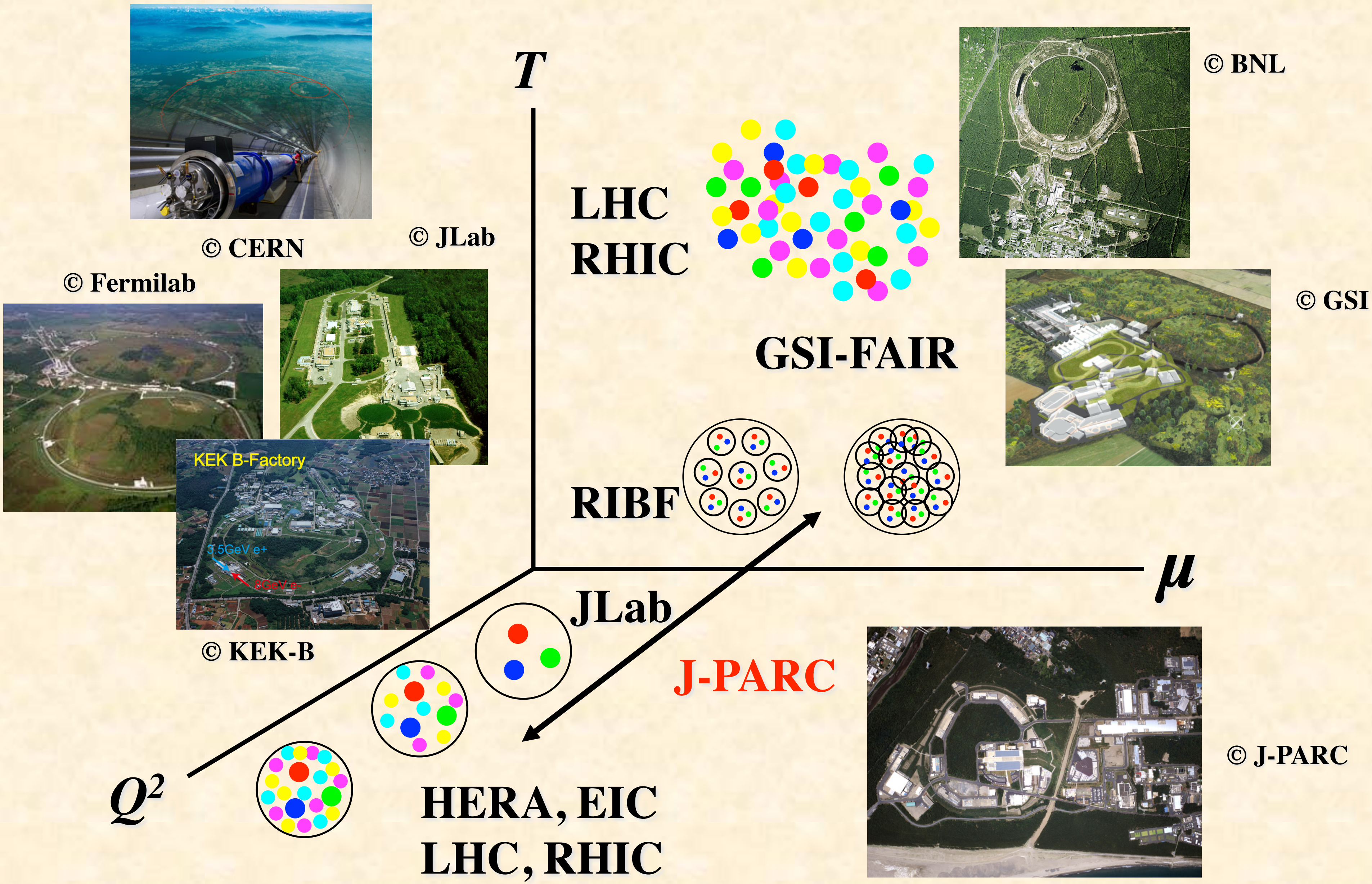
Intermediate energy



High energy



Test apparatus corresponds to "PET"



Wigner distribution

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

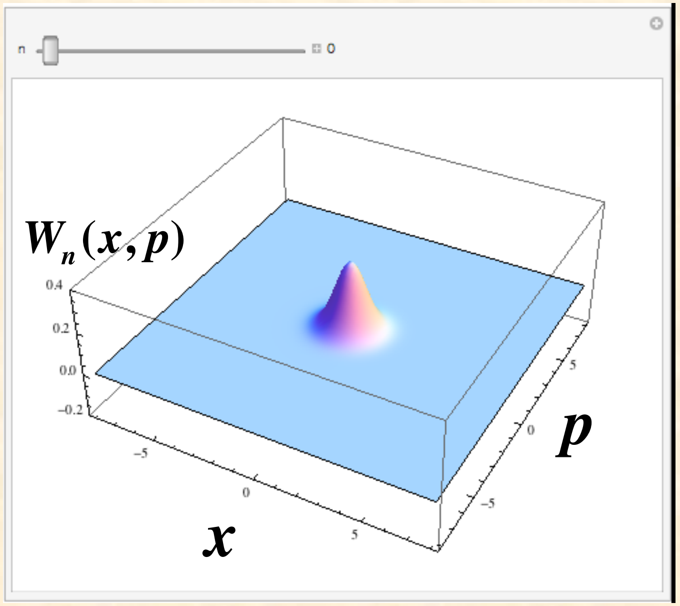
The Wigner distribution is defined by

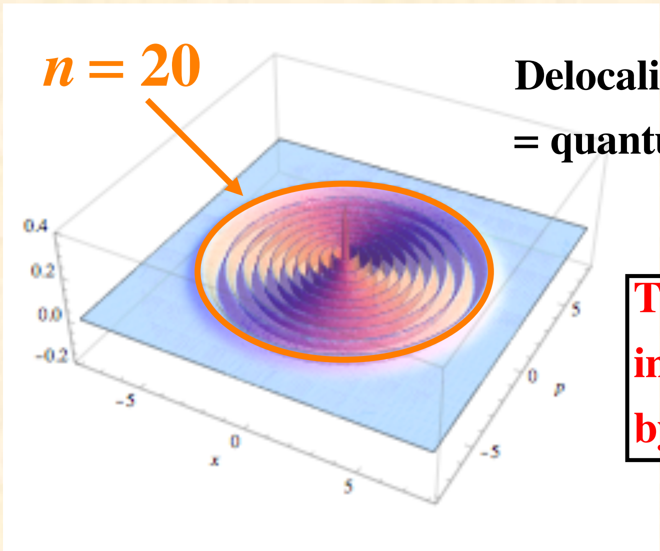
$$W(x,p) \equiv \int d\xi\, e^{ip\xi/\hbar} \psi^*(x-\xi/2)\psi(x+\xi/2) = \text{ phase-space distribution}$$

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

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

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





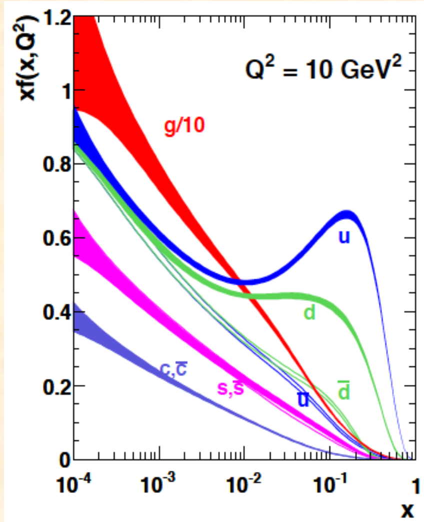
Delocalization of the Wigner distribution
= quantum effect (uncertainty principle)

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

Wigner distribution and various structure functions

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

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



Form factor ← $\int dx\, d^2k_\perp$

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

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

3D world

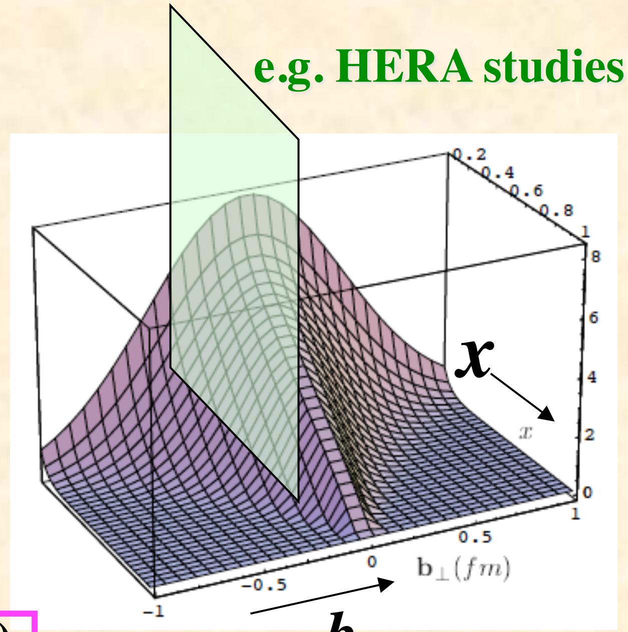
$\int d^3r$ → TMD (Transverse Momentum Dependent) parton distribution

$\int d^2k_\perp dz$ → GPD (Generalized Parton Distribution)

s-*t* crossing →

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

e.g. HERA studies



Exotic hadrons

Clarification of internal structure

of exotic-hadron candidates

by hadron tomography

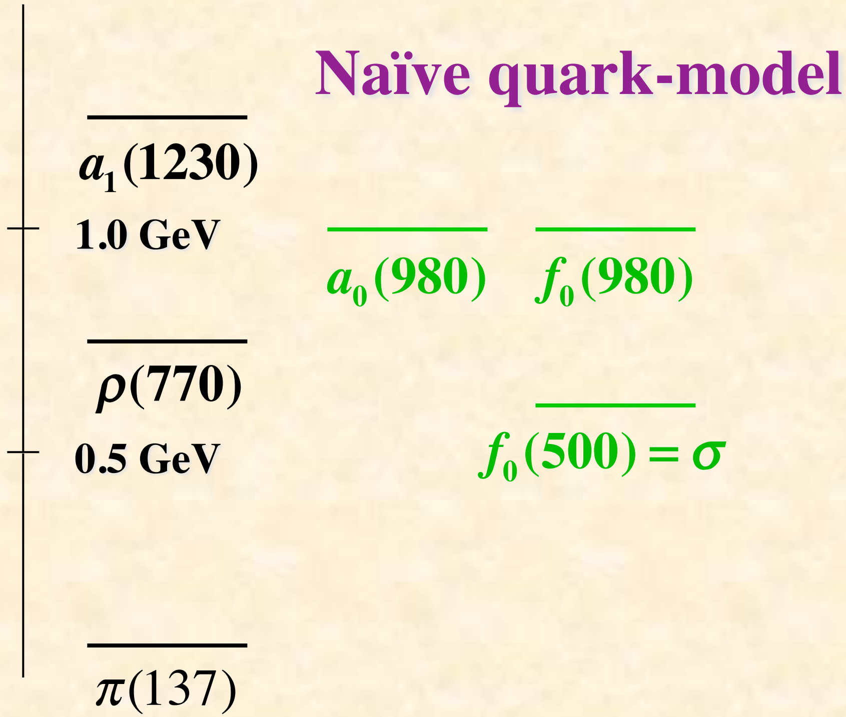
Progress in exotic hadrons

$q\bar{q}$ 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
…

- Θ^+(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?
- …

Scalar mesons $J^P=0^+$ at $M\sim 1$ GeV



$$\sigma = f_0(500) = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$$

$$f_0(980) = s\bar{s}$$

$$a_0(980) = u\bar{d},\quad \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}),\quad d\bar{u}$$

Naive model: $m(\sigma) \sim m(a_0) < m(f_0)$

⇕ contradiction

Experiment: $m(\sigma) < m(a_0) \sim m(f_0)$

Strong-decay issue: The experimental widths $\Gamma(f_0, a_0) = 40 - 100$ MeV are too small to be predicted by a typical quark model.
SK and V. R. Pandharipande, PRD38 (1988) 146.

These issues could be resolved
if f_0 (a_0) is a tetraquark ($qq\bar{q}\bar{q}$)
or a $K\bar{K}$ molecule,
namely an "exotic" hadron.

Radiative decay: F. E. Close, N. Isgur, and SK,
Nucl. Phys. B389 (1993) 513.

$f_0 - a_0$ mixing $\Leftrightarrow$ $K\bar{K}$
T. Sekihara, SK, arXiv:1409.2213

Exotic hadrons by fragmentation functions

"Favored" and "disfavored" (unfavored) fragmentation functions

Possibility of finding exotic hadrons in high-energy processes

Hirai, SK, Oka, Sudoh, PRD 77 (2008) 017504.

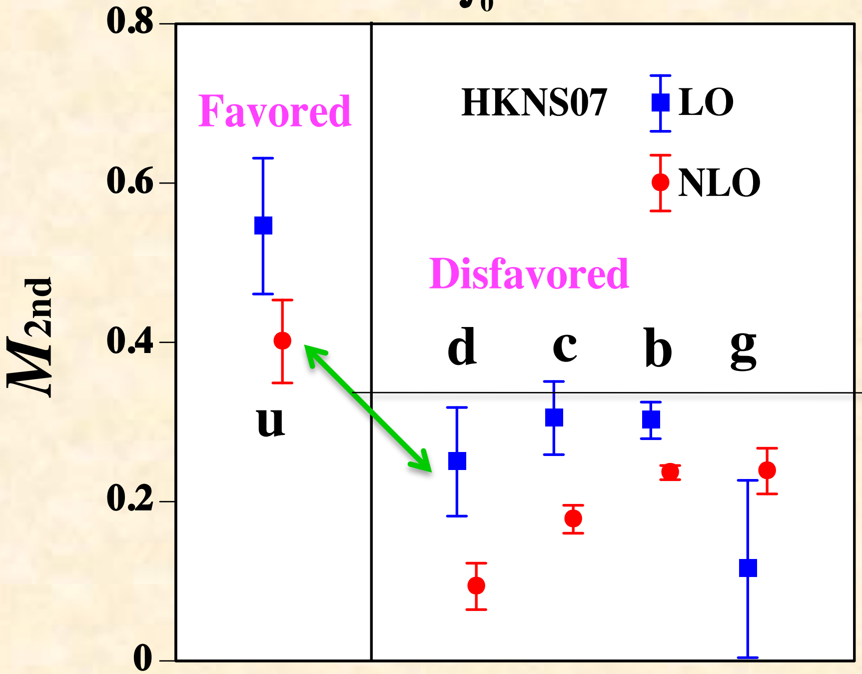
Possibilities for $f_0(980)$: $\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$, $s\bar{s}$, $\frac{1}{\sqrt{2}}(u\bar{u}s\bar{s}+d\bar{d}s\bar{s})$, $K\bar{K}$, or gg

$e.g.$ if $f_0(980) = s\bar{s}$: favored $s, \bar{s} \to f_0$; disfavored $u, d, \bar{u}, \bar{d} \to f_0, \cdots$

$f_0(980)$: Belle analysis is possible in principle.

Pion case

$$M_{2nd} = \int_0^1 dz\, z\, D_i^{\pi^+}(z)$$



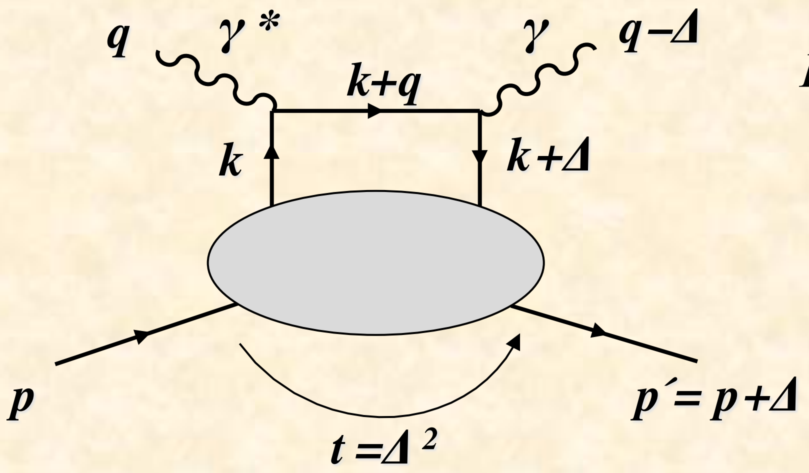
2nd moments of M. Hirai, SK, T.-H. Nagai, K. Sudoh, PRD 75 (2007) 094009.

There are distinct differences between the favored and disfavored 2nd moments.

→ It could be used for exotic-hadron studies.

GPDs in the ERBL region at hadron facilities

Generalized Parton Distributions (GPDs)



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

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

Momentum transfer squared $t=\Delta^2$

Skewdness 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

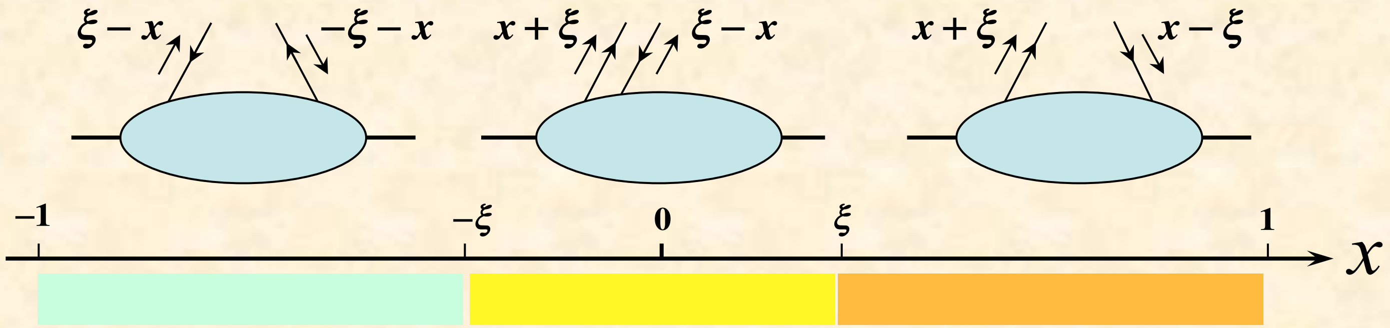
Dirac and Pauli form factors F_1, F_2

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

Second moments: Angular momenta

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

GPDs in different x regions and GPDs at hadron facilities



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

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

Quark distribution

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

Meson-like distribution amplitude

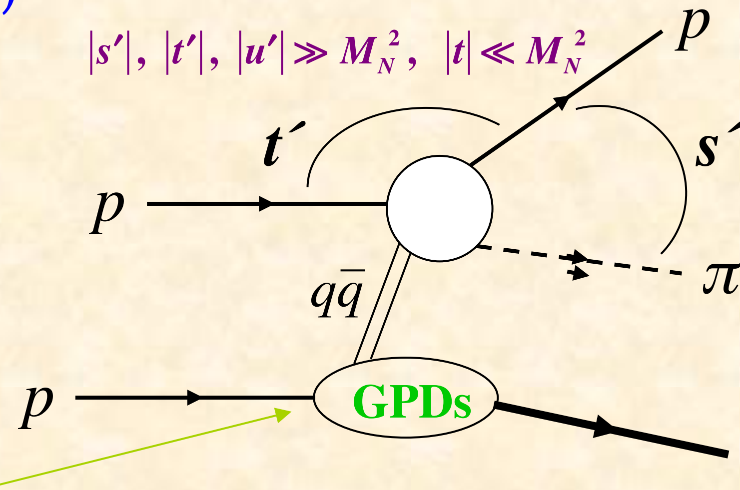
Emission of quark with momentum fraction $x+\xi$
Emission of antiquark with momentum fraction $\xi-x$

Antiquark distribution

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

Consider a hard reaction with

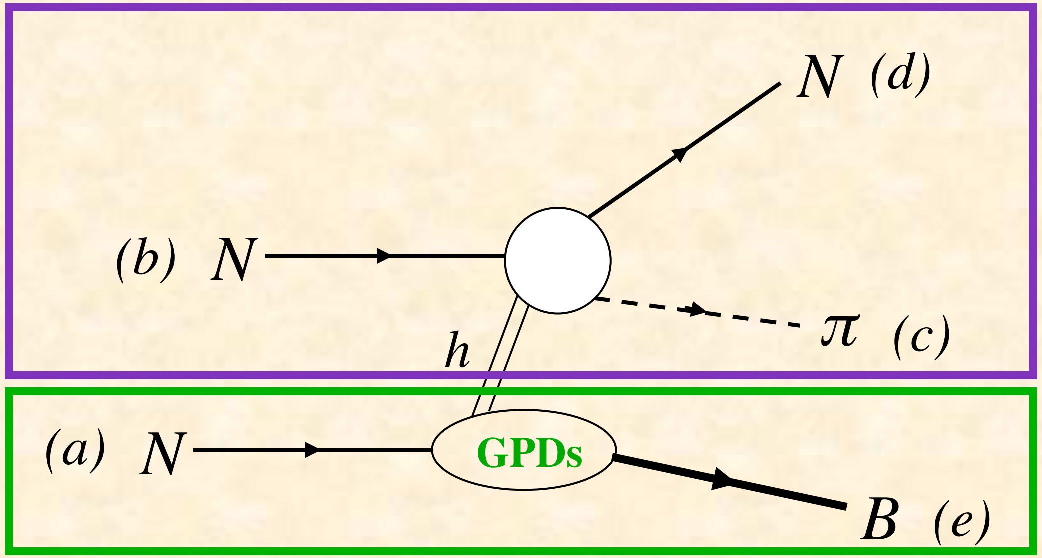
$|s'|,\ |t'|,\ |u'| \gg M_N^2,\quad |t| \ll M_N^2$



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

Efremov-Radyushkin -Brodsky-Lepage (ERBL) region

Cross section estimates



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

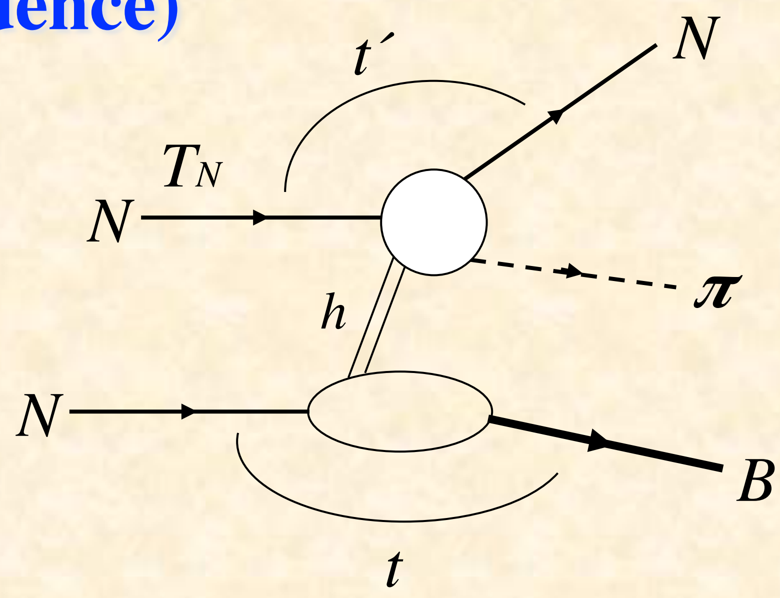
This part is expressed by GPDs.

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.

Cross section estimate (ξ dependence)

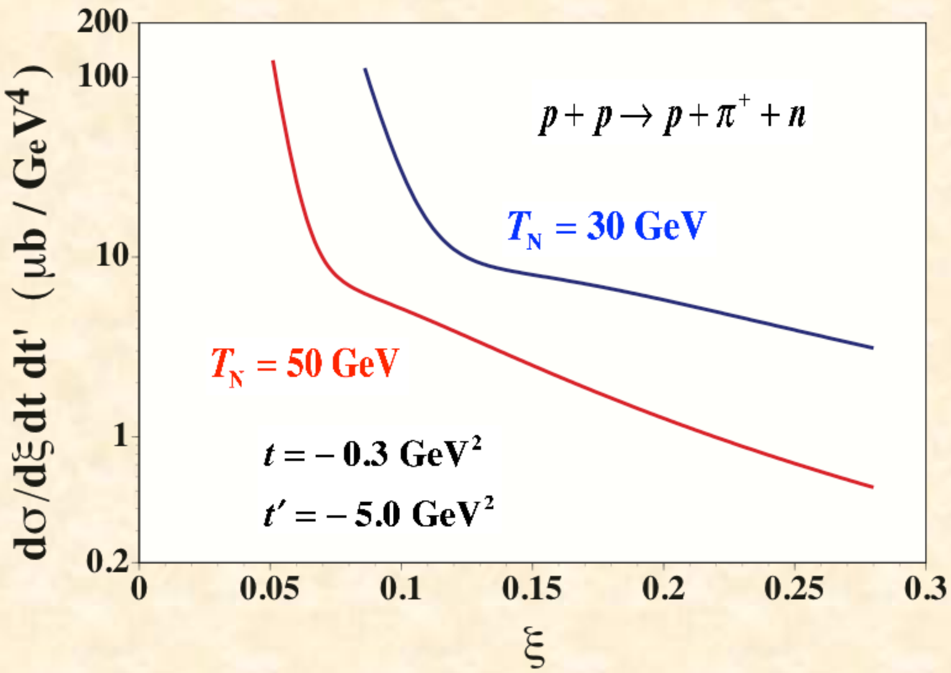


Skewdness parameter: $\xi = \dfrac{p_N^+ - p_B^+}{p_N^+ + p_B^+}$

$\dfrac{d\sigma}{d\xi\, dt\, dt'} \left(\dfrac{\mu b}{GeV^2}\right)$ as a function of ξ

at fixed $T_N = 30\ (50)$ GeV,

$t = -0.3\ GeV^2, \quad t' = -5\ GeV^2.$

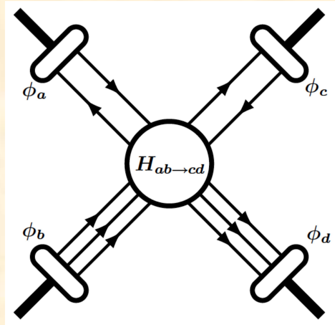


At this stage, our numerical results are for rough order of magnitude estimates on cross sections by assuming π- and ϱ-like intermediate states.

Constituent-counting rule

for exotic hadrons

Constituent-counting rule in perturbative QCD: Hard exclusive processes $a + b \to c + d$



Consider the hard exclusive hadron reaction $a + b \to c + d$

$$M_{ab\to cd} = \int d[x_a]d[x_b]d[x_c]d[x_d]\phi_c([x_c])\phi_d([x_d])H_M([x_a],[x_b],[x_c],[x_d],Q^2)\phi_a([x_a])\phi_b([x_b])$$

ϕ_p = proton distribution amplitude, H_M = hard amplitude (calculated in pQCD)

Rule for estimating $M_{ab\to cd}$

(1) Feynman diagram: Draw leading and connected Feynman diagram by connecting $n/2$ quark lines by gluons.

(2) Gluon propagators: The factor $1/P^2$ is assigned for each gluon propagator.

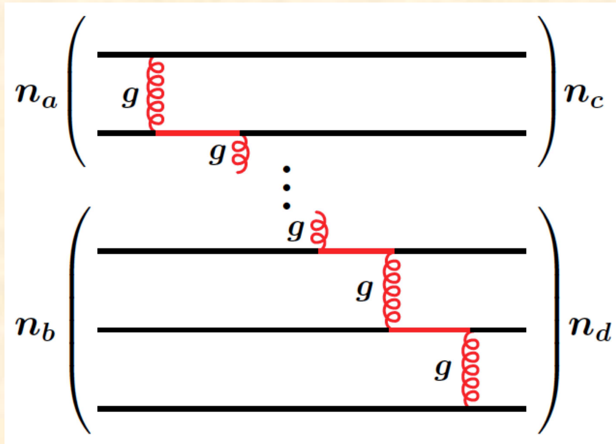
There are $n/2-1$ gluon propagators $\sim 1/(P^2)^{n/2-1}$.

(3) Quark propagators: The factor $1/P$ is assigned for each quark propagator.

There are $n/2-2$ gluon propagators $\sim 1/(P)^{n/2-2}$.

(4) External quarks: The factor $\sqrt{P}$ is assigned for each external quark.

There are n gluon propagators $\sim (\sqrt{P})^n$.



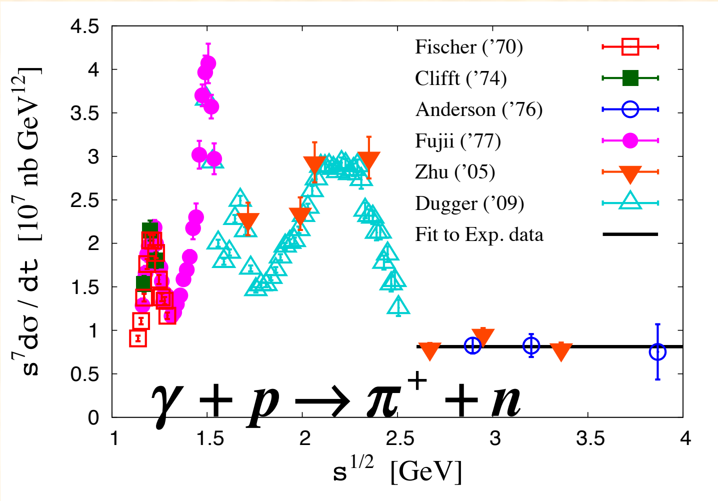
$$M_{ab\to cd} \sim \frac{1}{(P^2)^{n/2-1}}\frac{1}{(P)^{n/2-2}}(\sqrt{P})^n = \frac{(P)^{n/2}}{(P)^{n-2}(P)^{n/2-2}} = \frac{1}{(P)^{n-4}} \sim \frac{1}{s^{n/2-2}}$$

Cross section: $$\frac{d\sigma_{ab\to cd}}{dt} \simeq \frac{1}{16\pi^2}\overline{\sum_{spol}}|M_{ab\to cd}|^2 \sim \frac{1}{s^{n-2}}$$

Constituent-counting rule, Transition from hadron degrees of freedom to quark-gluon ones

Typical current situation

- Transition from hadron d.o.f to quark d.o.f.
- (Looks like) Constituent-counting scaling



BNL: C. White it et al., PRD 49 (1994) 58.

No.	Interaction	Cross section E838	Cross section E755	n-2 ($\frac{d\sigma}{dt} \sim 1/s^{n-2}$)
1	$\pi^+ p \to p \pi^+$	132 ± 10	4.6 ± 0.3	6.7 ± 0.2
2	$\pi^- p \to p \pi^-$	73 ± 5	1.7 ± 0.2	7.5 ± 0.3
3	$K^+ p \to p K^+$	219 ± 30	3.4 ± 1.4	$8.3^{+0.6}_{-1.0}$
4	$K^- p \to p K^-$	18 ± 6	0.9 ± 0.9	≥ 3.9
5	$\pi^+ p \to p \rho^+$	214 ± 30	3.4 ± 0.7	8.3 ± 0.5
6	$\pi^- p \to p \rho^-$	99 ± 13	1.3 ± 0.6	8.7 ± 1.0
13	$\pi^+ p \to \pi^+ \Delta^+$	45 ± 10	2.0 ± 0.6	6.2 ± 0.8
15	$\pi^- p \to \pi^+ \Delta^-$	24 ± 5	≤ 0.12	≥ 10.1
17	$pp \to pp$	3300 ± 40	48 ± 5	9.1 ± 0.2
18	$\bar{p}p \to \bar{p}p$	75 ± 8	≤ 2.1	≥ 7.5

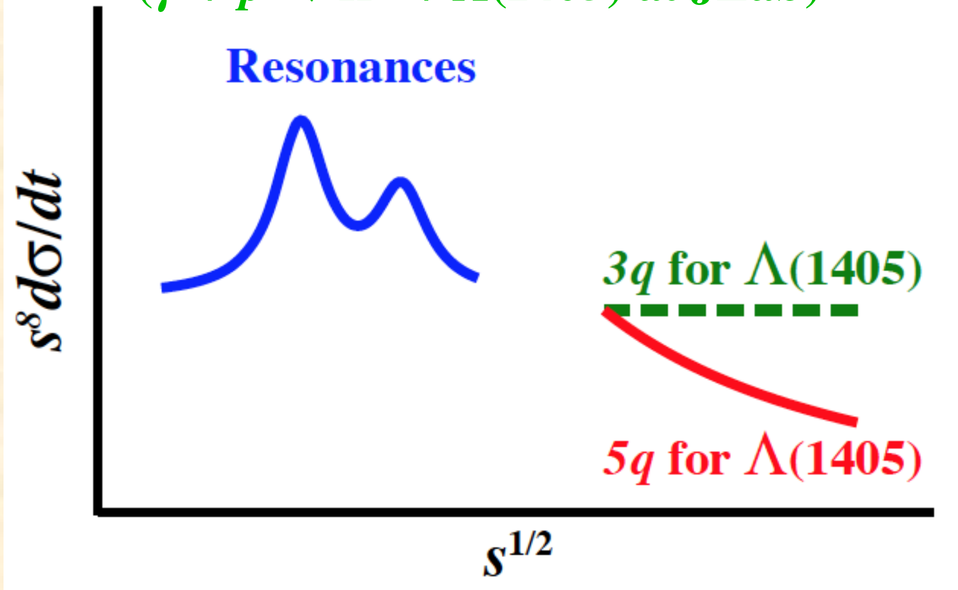
Our idea

- Transition from hadron d.o.f to quark d.o.f. for exotic-hadron production
- Internal structure of exotic hadrons by constituent-counting scaling

Exotic hadron production

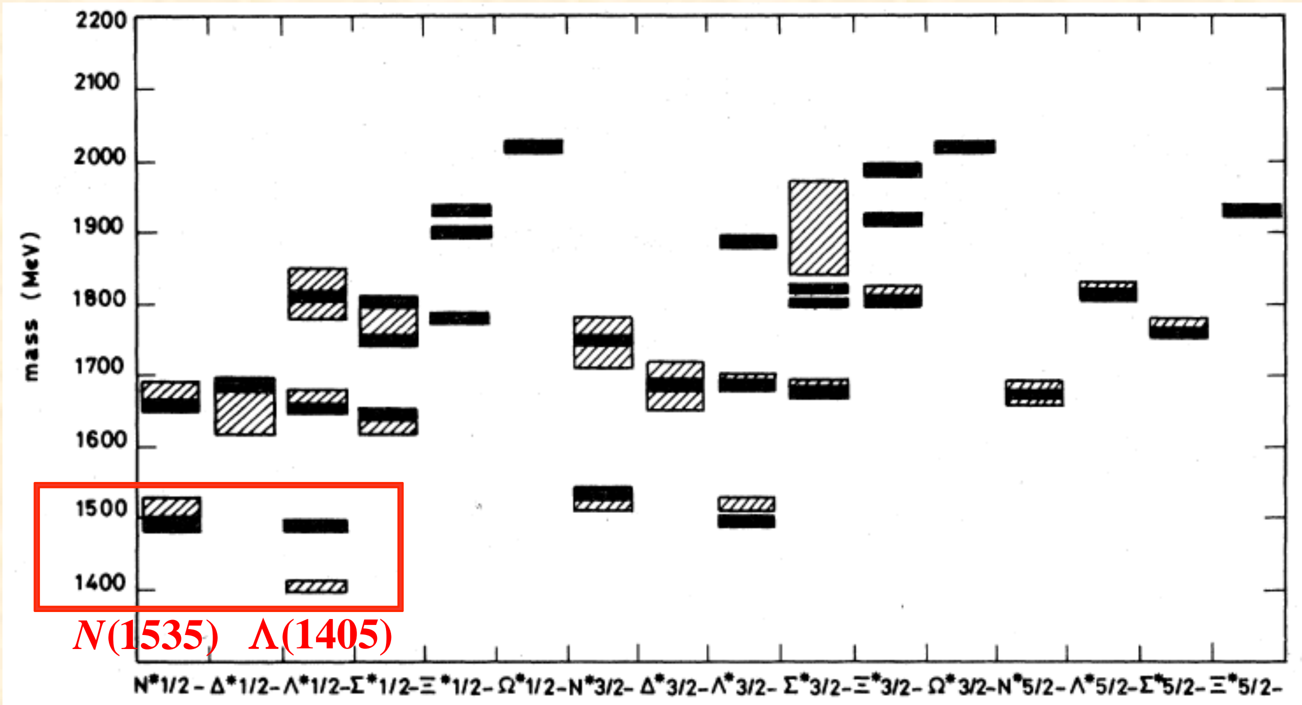
$\pi^- + p \to K^0 + \Lambda(1405)$

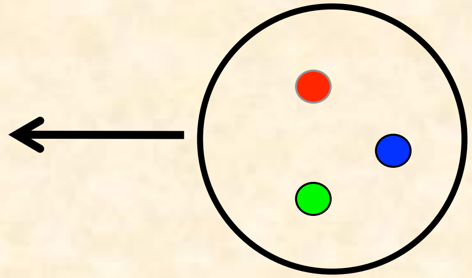
($\gamma + p \to K^+ + \Lambda(1405)$ at JLab)

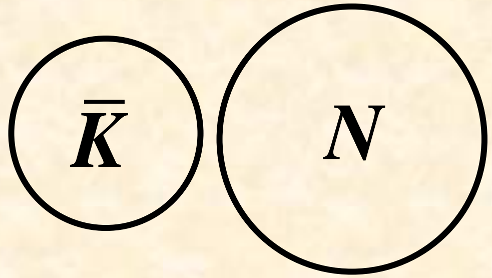


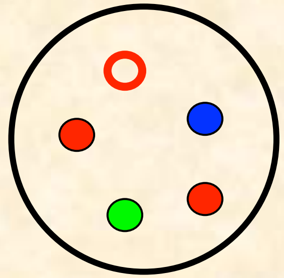
Λ(1405): exotic hadron?

Negative-parity baryons
N. Isgur and G. Karl,
PRD 18 (1978) 4187.







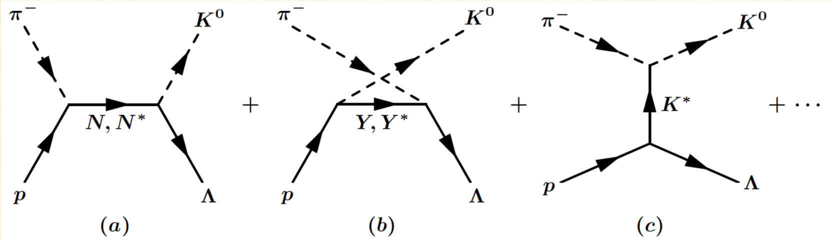


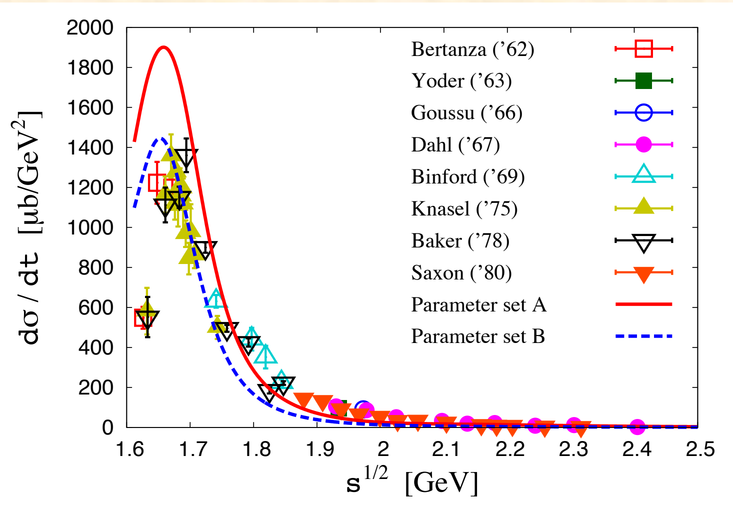
Most spectra agree with the ones by a $3q$-picture

- Only Λ(1405) deviates from the measurement.
- Difficult to understand the small mass of Λ(1405) in comparison with N(1535).
  $\rightarrow \bar{K}N$ molecure or penta-quark ($qqqq\bar{q}$)?

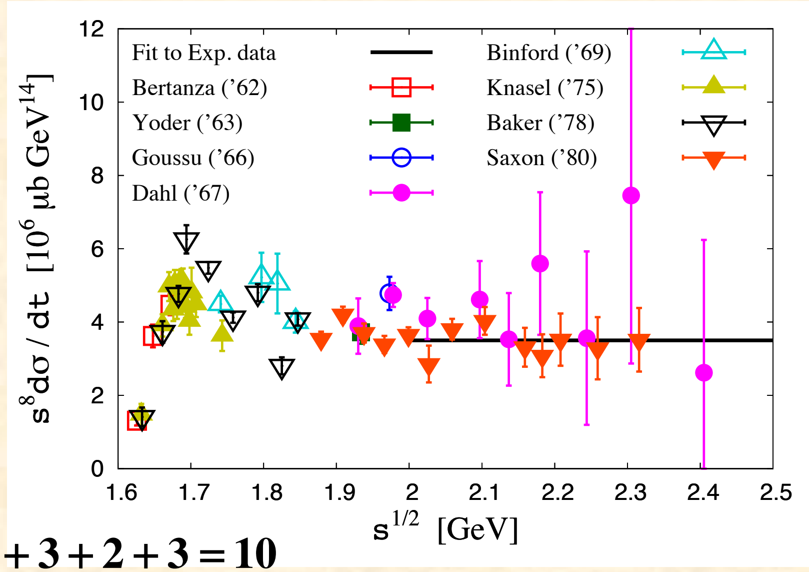
Ordinary-hadron production $\pi^- + p \to K^0 + \Lambda$ as a reference

At low energies





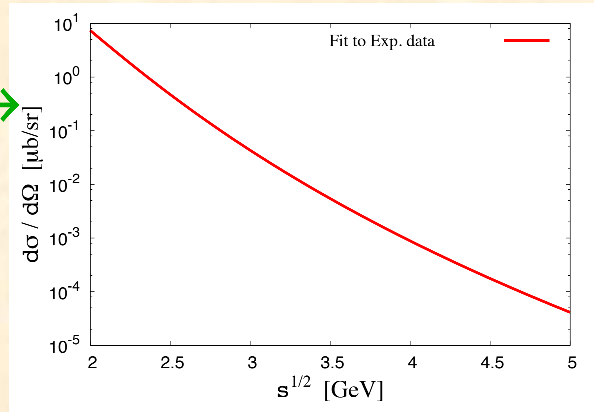
From low to higher energies



$$n = 2 + 3 + 2 + 3 = 10$$

$$\frac{d\sigma_{ab\to cd}}{dt} = \frac{\text{const}}{s^{n-2}}, \quad n = 10.1 \pm 0.6,$$ **encouraging!**

Our prediction at high energies →



Exotic-hadron production $\pi^- + p \to K^0 + \Lambda(1405)$

Theoretical and experimental situation
is no as good as the one for the ground Λ.

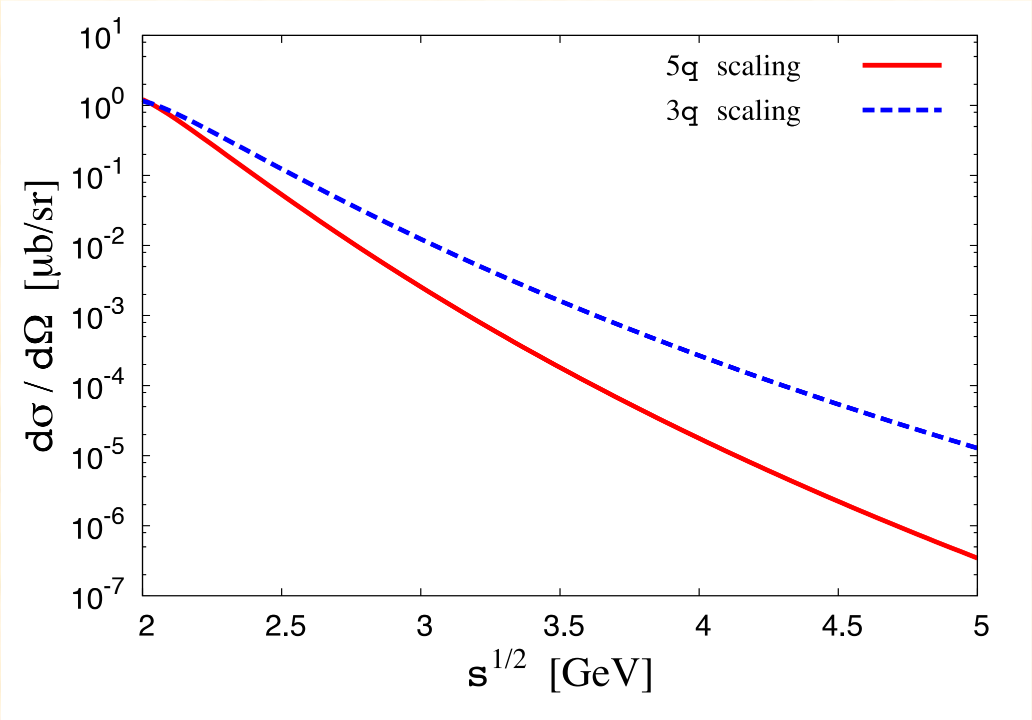
$n = 2+3+2+3 = 10$ **if Λ(1405) = three-quark state**

$\quad = 2+3+2+5 = 12$ **if Λ(1405) = five-quark state**

(including $\bar{K}N$ molecule)

$$\frac{d\sigma_{ab\to cd}}{dt} = \frac{\text{const}}{s^{n-2}}, \quad n = 10 \text{ or } 12$$

Our prediction at high energies



See H. Kawamura, SK, T. Sekihara, PRD 88 (2013) 034010.

GPDs and GDAs

for exotic hadrons

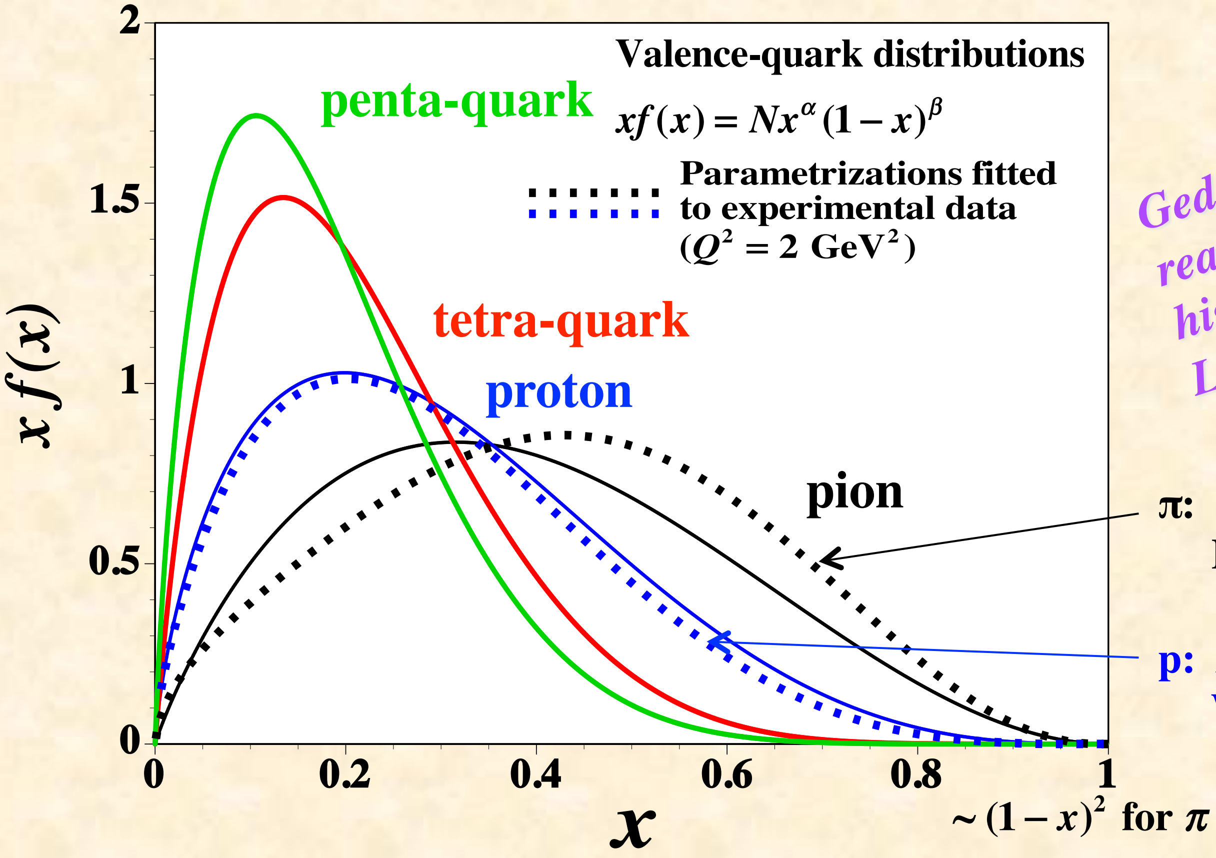
Simple function of GPDs

$$H_q^h(x,t) = f(x)F(t,x)$$

M. Guidal, M.V. Polyakov, A.V. Radyushkin, M. Vanderhaeghen, PRD 72, 054013 (2005).

Longitudinal-momentum distribution (PDF) for valence quarks: $f(x) = q_v(x) = c_n x^{\alpha_n}(1-x)^{\beta_n}$

- **Valence-quark number sum rule (charge and baryon numbers):** $\int_0^1 dx\, f(x) = n$
- **Constituent conting rule at** $x \to 1$: $\beta_n = 2n - 3 + 2\Delta S$ **(**n **= number of constituents)**
- **Momentum carried by quarks** $\langle x \rangle_q \simeq \int_0^1 dx\, x f(x)$



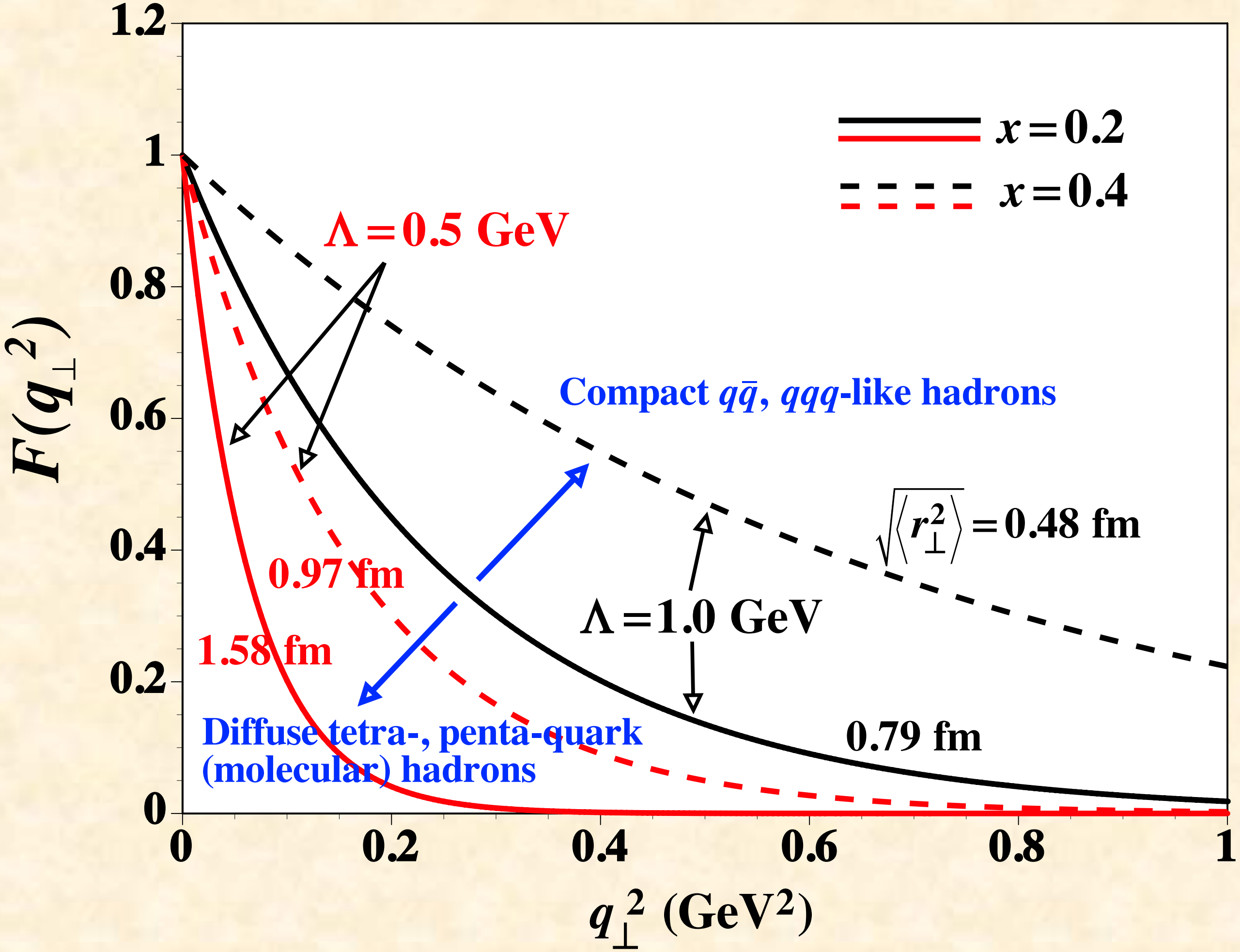
Gedankenexperiment, but …
read our paper for studying exotics in high-energy processes at KEK-B, Linear Collider, ….

π: M. Aicher, A. Schafer, W. Vogelsang, PRL 105 (2010) 252003.

p: A. D. Martin, R. G. Roberts, W. J. Stirling, PLB 636, 259 (2006)

Two-dimensional form factor

$$H_q^h(x,t) = f(x)F(t,x), \quad F(t,x) = e^{(1-x)t/(x\Lambda^2)}, \quad \langle r_\perp^2 \rangle = \frac{4(1-x)}{x\Lambda^2}$$



GPDs for exotic hadrons !?

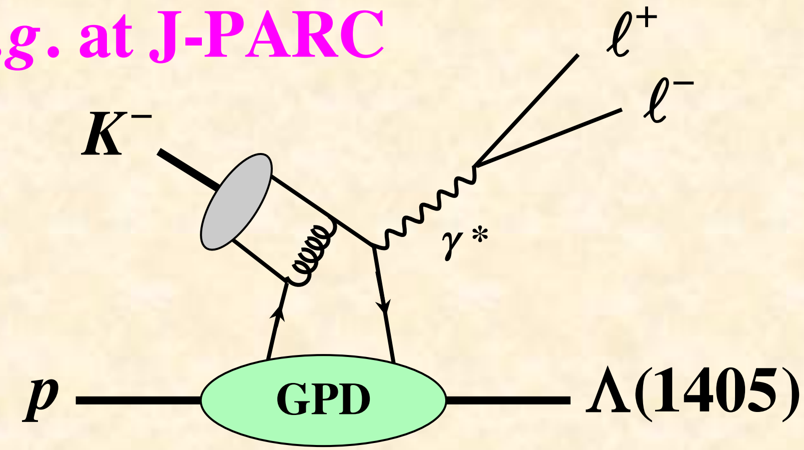
Because stable targets do not exit for exotic hadrons,
it is not possible to measure their GPDs in a usual way.

→ Transition GPDs

or

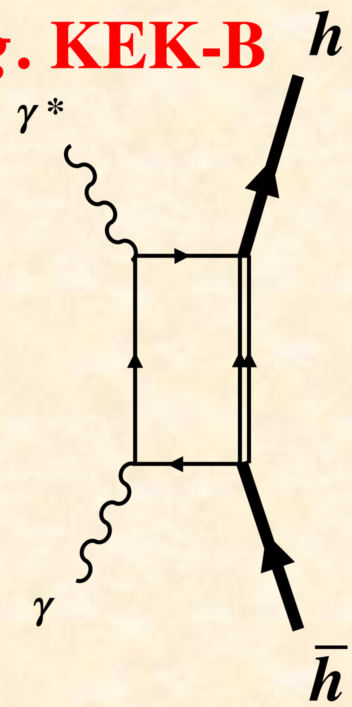
→ $s \leftrightarrow t$ crossed qunatity = GDAs at KEK-B, Linear Collider

e.g. at J-PARC



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

e.g. KEK-B



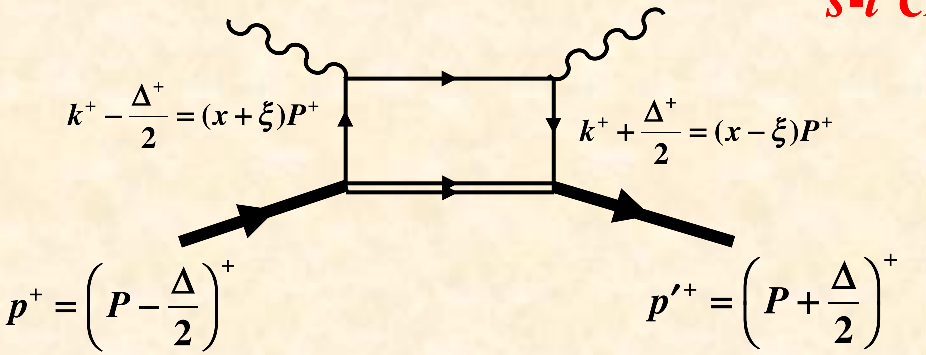
GPD $H_q^h(x,\xi,t)$ and GDA $\Phi_q^{h\bar{h}}(z,\zeta,W^2)$

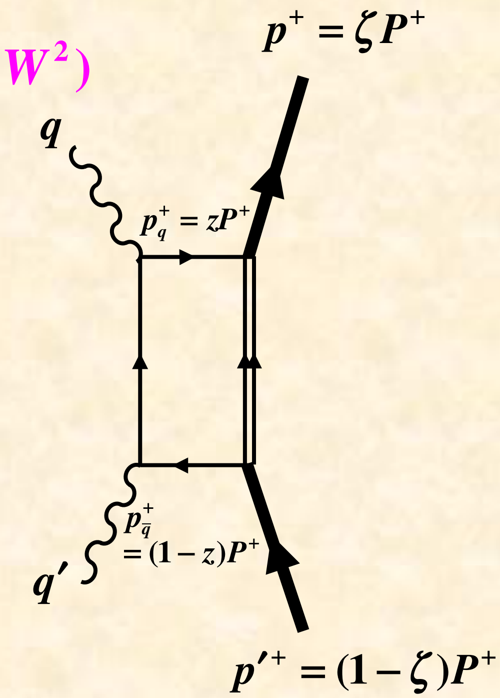
GPD: $H_q(x,\xi,t) = \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \langle h(p')|\bar{\psi}(-y/2)\gamma^+\psi(y/2)|h(p)\rangle\Big|_{y^+=0,\vec{y}_\perp=0}$, $\quad P^+ = \frac{(p+p')^+}{2}$

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

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

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





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

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

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

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

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

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

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

Cross section: form factor dependence

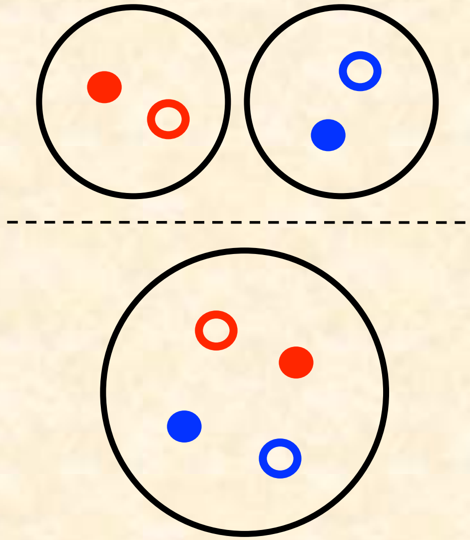
$$\Phi_q^{h\bar{h}(I=0)}(z,\zeta,W^2) \propto F_h(W^2)$$

$$F_h(W^2) = \frac{1}{\left[1+(W^2-4m_h^2)/\Lambda^2\right]^{n-1}}$$

See H. Kawamura and SK
Phys. Rev. D 89 (2014) 054007.

Ordinal $q\bar{q}$

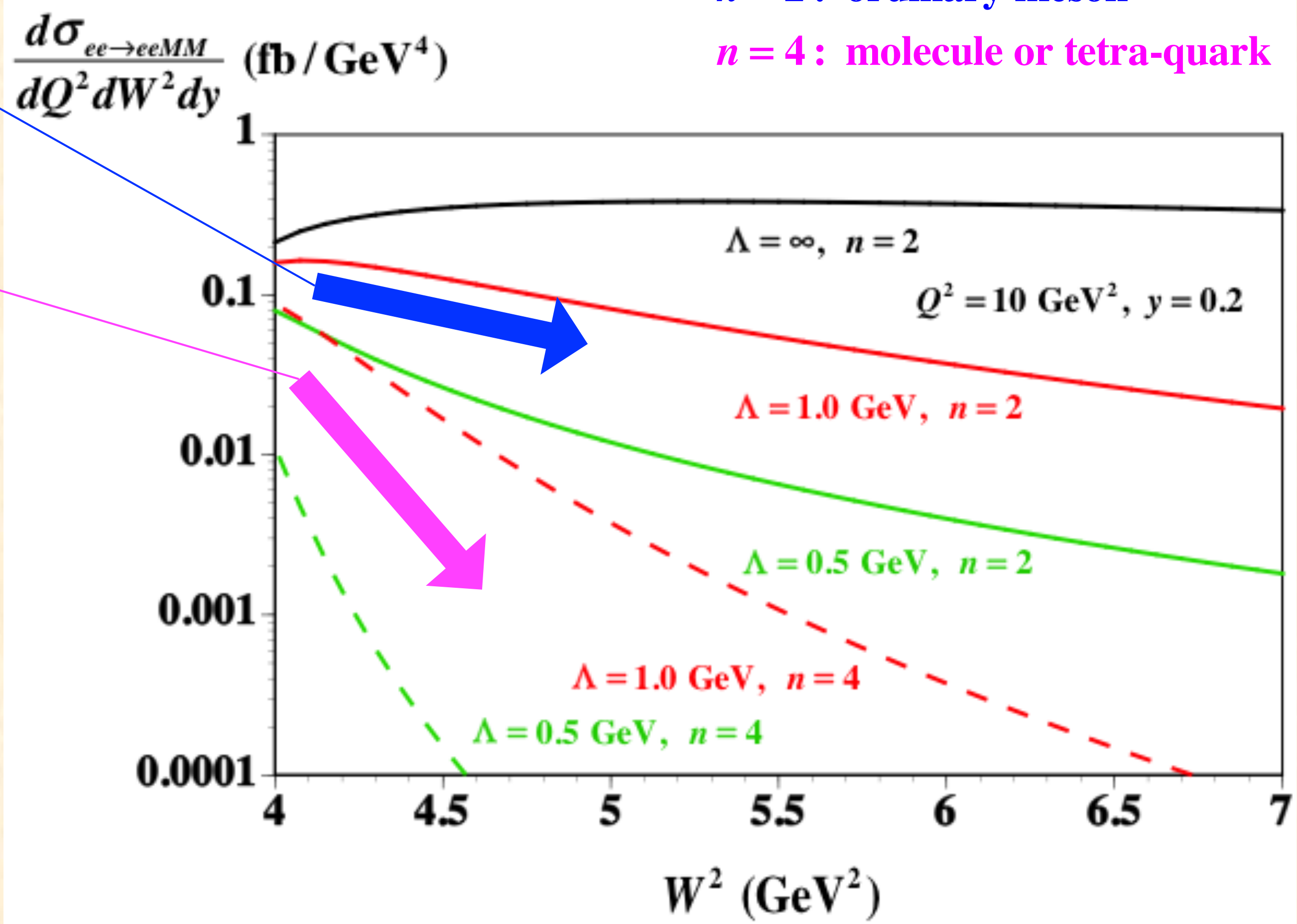
Molecule $K\bar{K}$ or tetra-quark $qq\bar{q}\bar{q}$



Constituent-counting rule

$n = 2$: ordinary meson

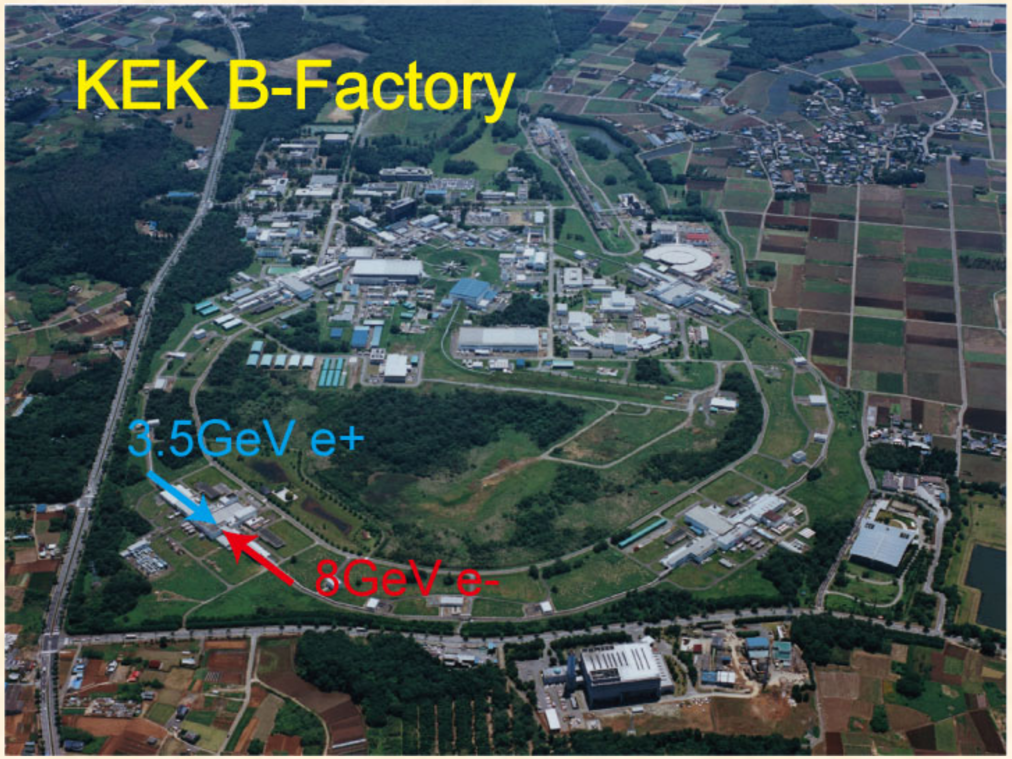
$n = 4$: molecule or tetra-quark



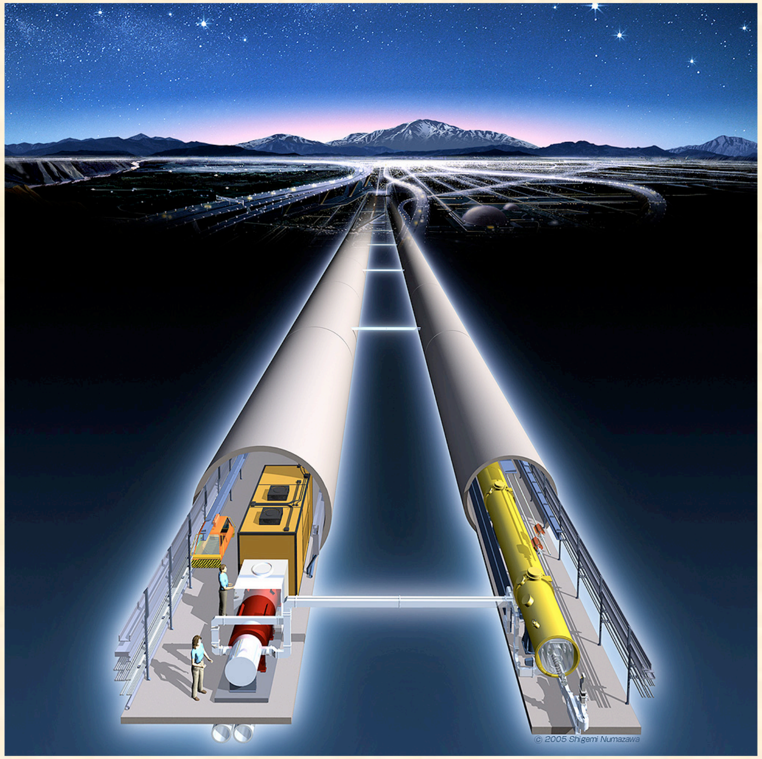
Experimental studies of GDAs in future

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

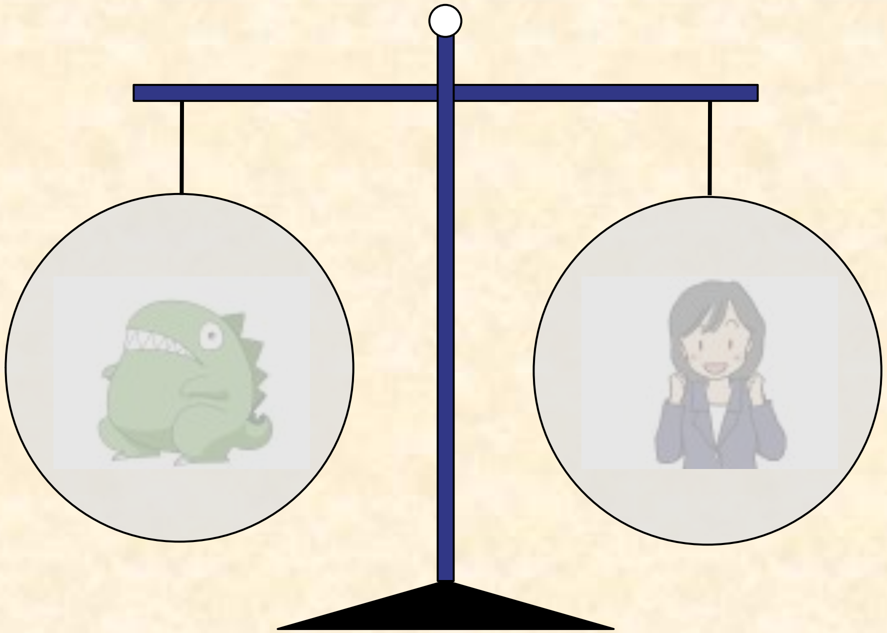
KEK B-factory



Linear Collider ?



Search for exotic hadrons …



It is difficult to determine whether or not a hadron is exotic by low-energy observables, masses, decay widths, …

(Already, history of a half century)

By the tomography, we may determine

 or  .

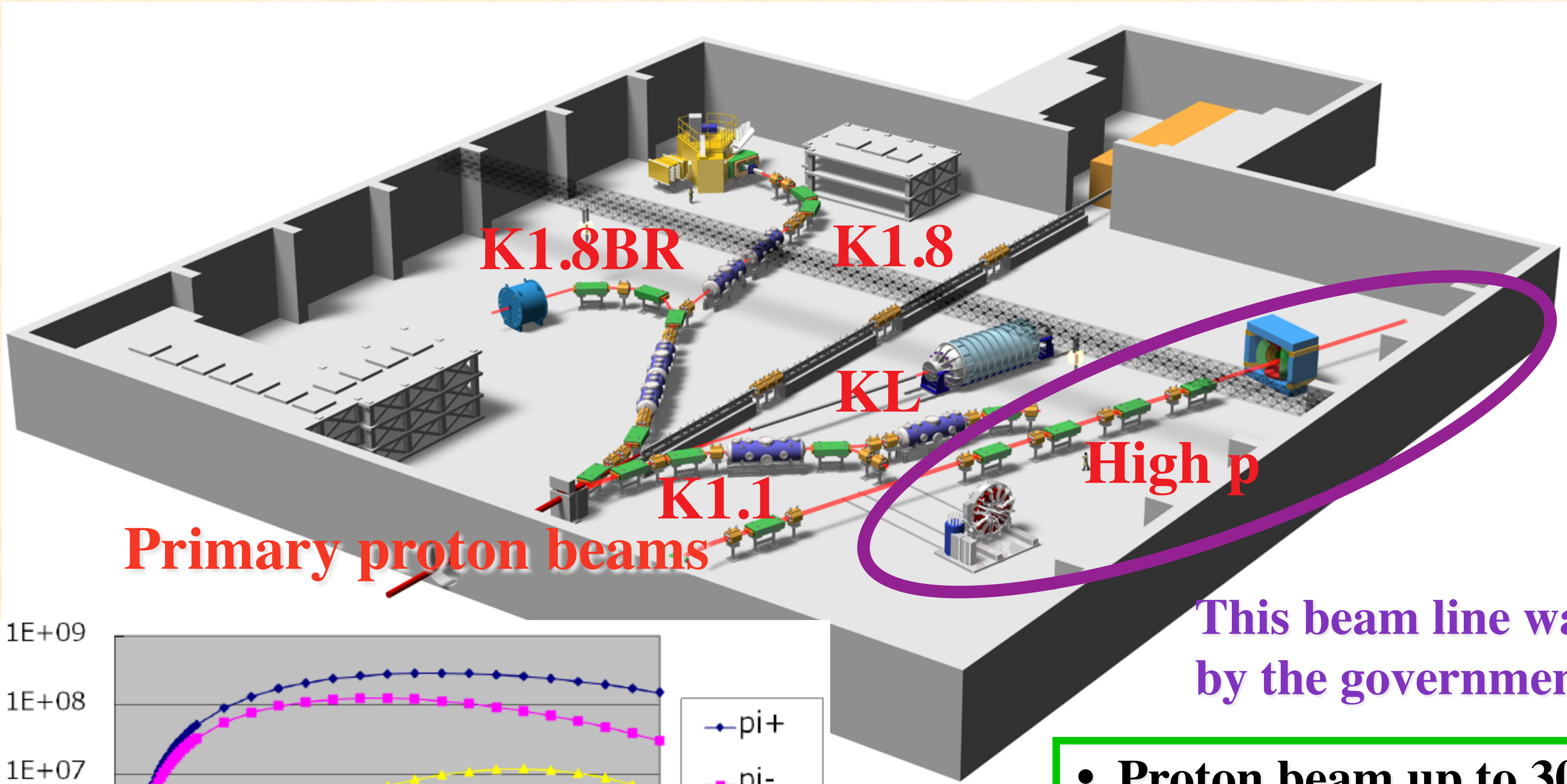
Discussions in progress toward J-PARC project

Recent efforts of
Wen-Chen Chang, Takahiro Sawada (Academia Sinica)
Jen-Chieh Peng (U. Illinois)

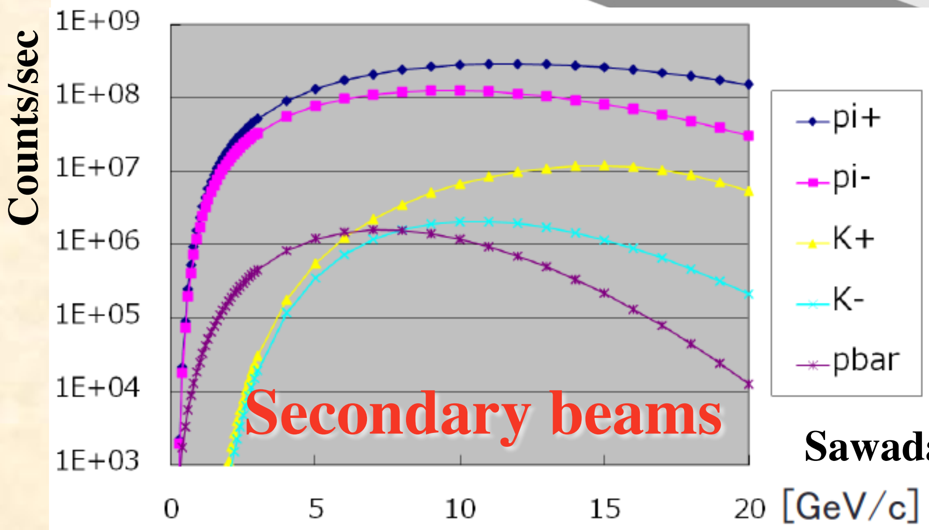
Refs. (1) Wen-Chen Chang at the J-PARC workshop in 2014:
http://j-parc-th.kek.jp/workshops/2014/02-10/
(2) Peng, Tanaka, Kawamura's talks on Feb. 13, 2014:
http://j-parc-th.kek.jp/collabo/2014/02-13/hadron-sf-2014-02-13.html.
(3) Peng, Sawada, Tanaka's talks on Oct. 7, 2014
at the APS-JPS join meeting in Hawaii.

Hadron facility

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



This beam line was approved by the government in 2013.



Sawada (2014)

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

You may propose your experiments!

J-PARC hadron physics

Possibilities

Approved proposals

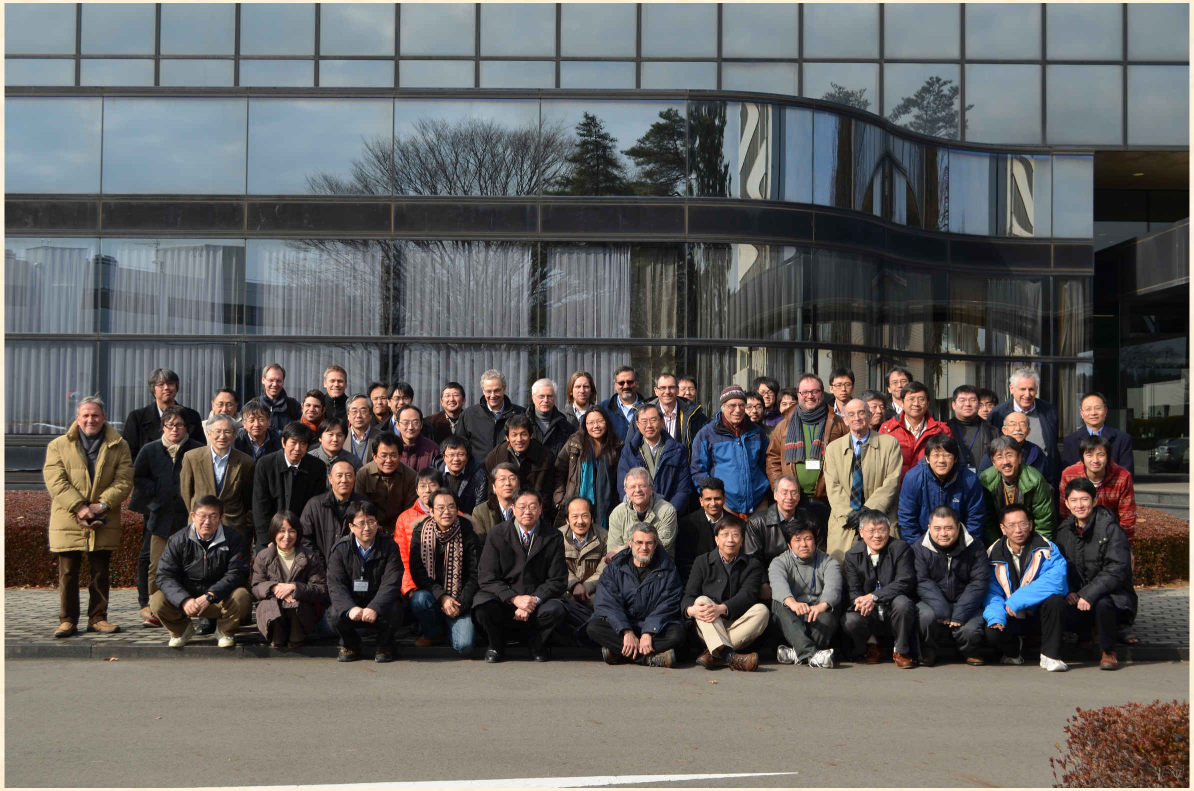
- Strangeness nuclear physics (1st experiment)
- Exotic hadrons
- Hadrons in nuclear medium
- Hard processes
- Nucleon spin (beam polarization)
- Quark-hadron matter (heavy ion)

"Possible" high-momentum beamline projects

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

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

88 participants (~100 including non-registered ones)



Next workshop on March 13-16 (→3 days), 2015.

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

Y. Goto *et al.*

Proposal

Polarized Proton Acceleration at J-PARC

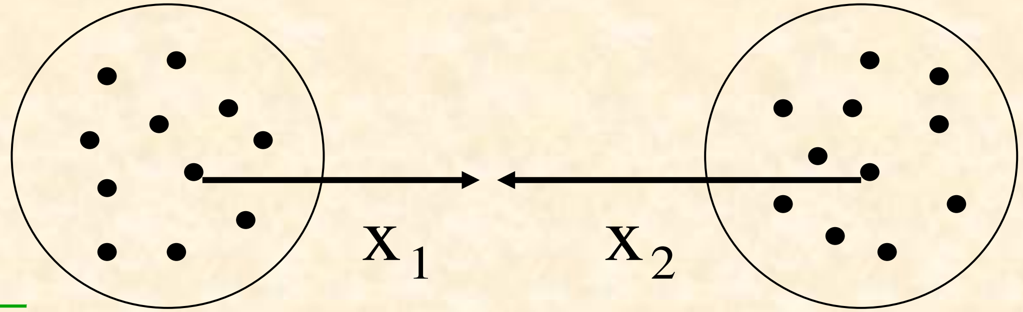
The high-momentum had not been approved financially until 2013, so these proposals were deferred.

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

New LoI / proposal under consideration!

Hadron facilities

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



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

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

  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).

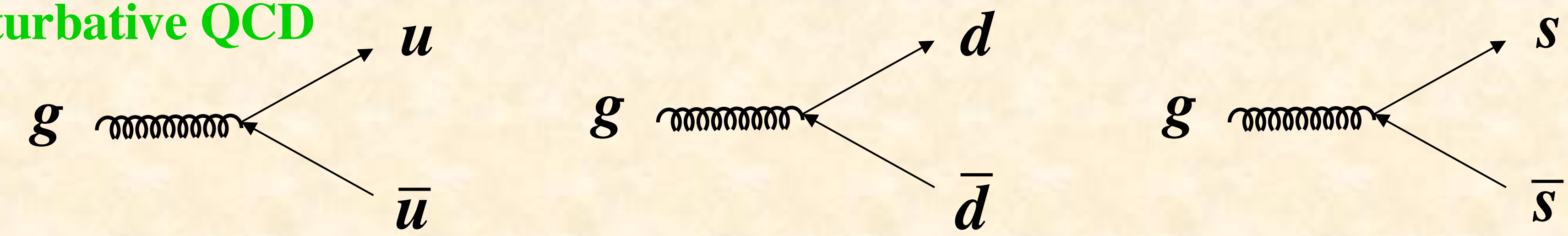
$x \sim \frac{\sqrt{m_{\mu\mu}^2}}{\sqrt{s}} \geq \frac{3}{10} = 0.3$ J-PARC (Fermilab-120 GeV) **Large-x facility**

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

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

Flavor dependence of antiquark distributions

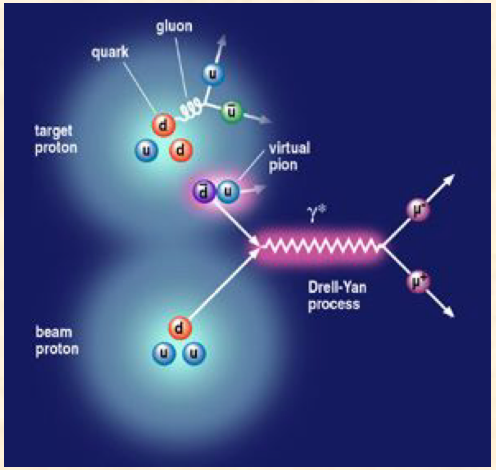
Perturbative QCD



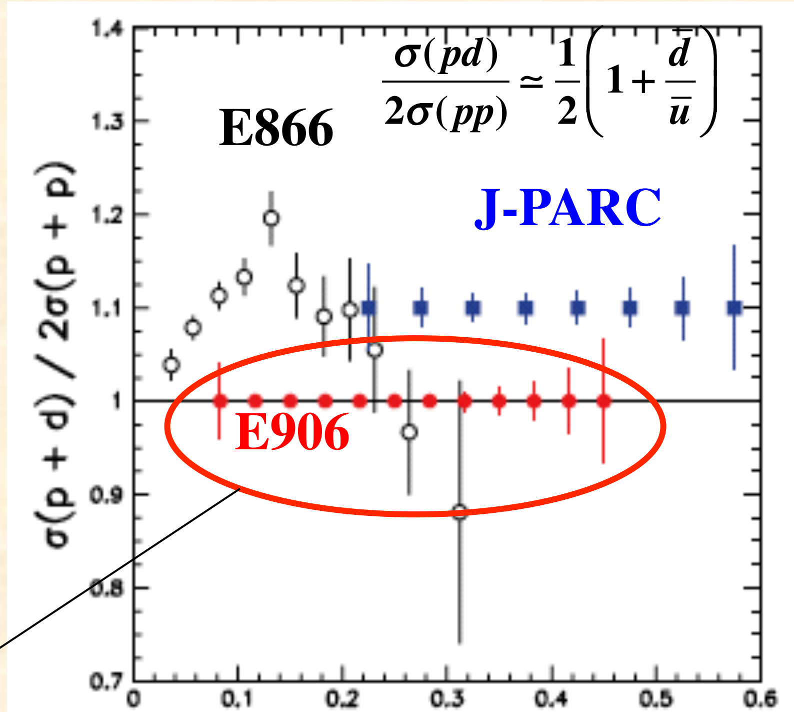
Because of $m_u^2, m_u^2, m_u^2 \ll Q^2$, we expect $\bar{u} = \bar{d} = \bar{s}$ from the antiquark creaction by the gluon splitting $g \to q\bar{q}$ in perturbative QCD.

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

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!

Proton polarization

Y. Goto *et al.*

Proposal

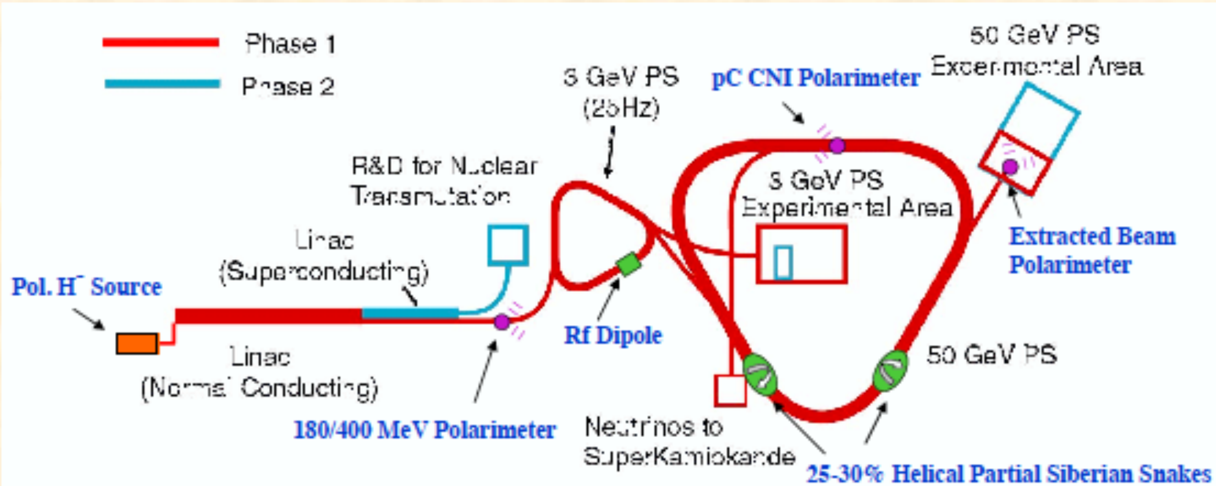
Polarized Proton Acceleration at J-PARC

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]

Proton beam polarization is technically possible.

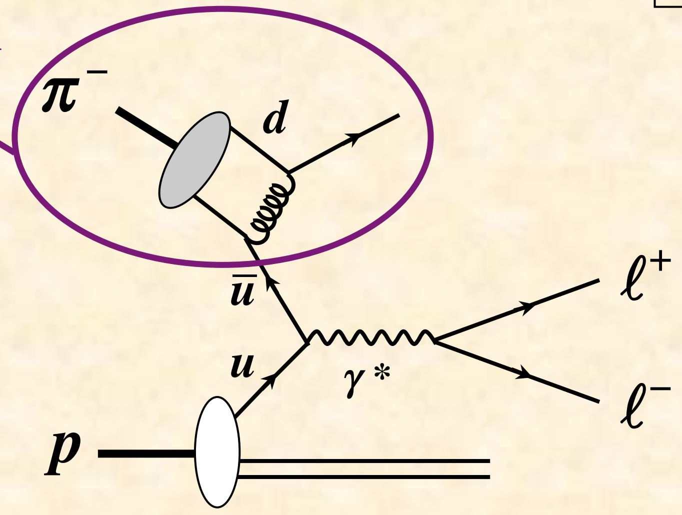
The J-PARC PAC deferred decision.



Toward a new proposal

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

pion distribution



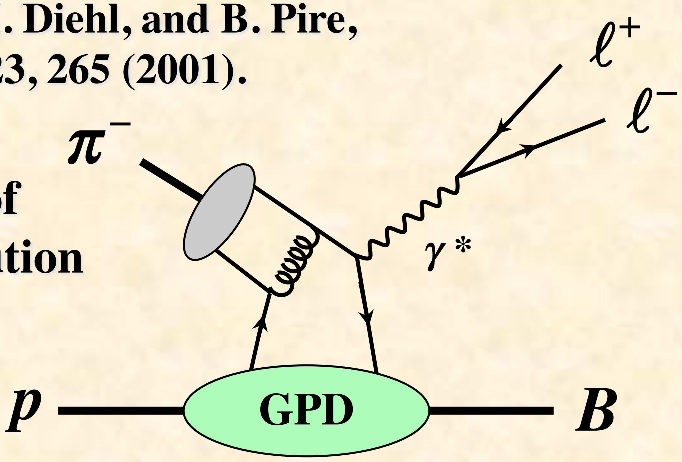
A. Brandenburg, S. J. Brodsky,
V. V. Khoze, and D. Müller,
Phys. Rev. Lett. 73 (1994) 939.

Investigation of
- Pion distribution amplitude

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

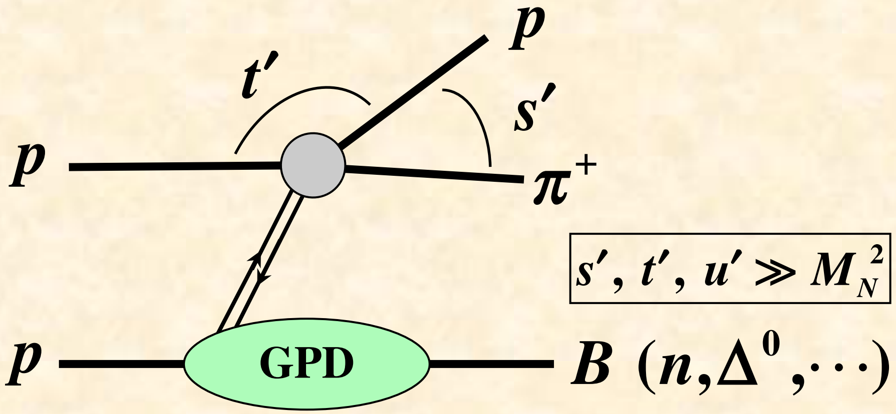
E. R. Berger, M. Diehl, and B. Pire,
Phys. Lett. B 523, 265 (2001).

Investigation of
- Pion distribution amplitude
- GPDs



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

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



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

In progress for LoI / proposal

Wen-Chen Chang (Academia Sinica),
Jen-Chieh Peng (U. Illinois), Sinya Sawada (KEK) …

See the slides of J-PARC workshops in 2014:

http://research.kek.jp/people/kumanos/conf/conf14.html
http://j-parc-th.kek.jp/collabo/2014/02-13/hadron-sf-2014-02-13.html

Physics to be investigated in the high momentum beam line of hadron hall at J-PARC

Wen-Chen Chang
Institute of Physics, Academia Sinica, Taipei 11529, Taiwan

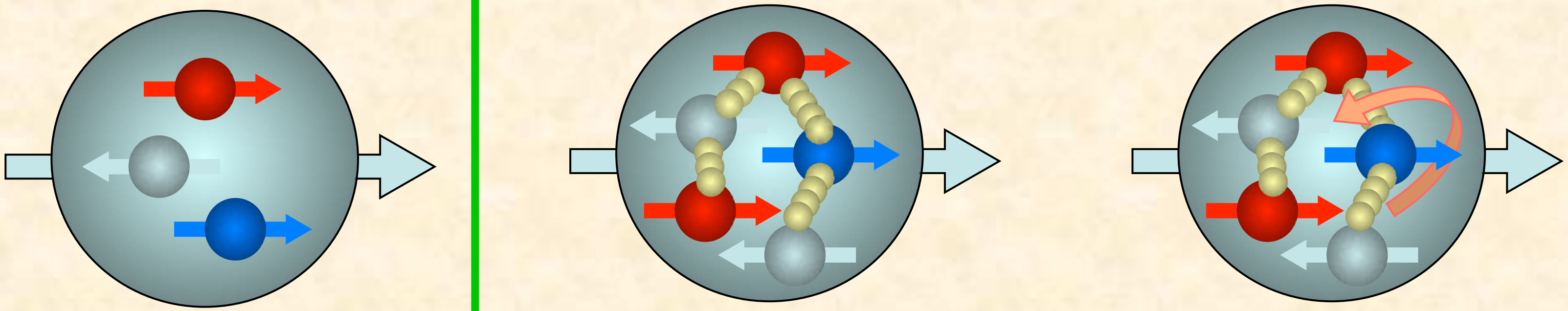
Hiroyuki Kawamura and Shunzo Kumano
KEK Theory Center, Institute of Particle and Nuclear Studies,
High Energy Accelerator Research Organization (KEK)

Jen-Chieh Peng
Department of Physics, University of Illinois at
Urbana-Champaign, Urbana, Illinois 61801, USA

Shin'ya Sawada
Institute of Particle and Nuclear Studies,
High Energy Accelerator Research Organization (KEK)

Nucleon spin

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

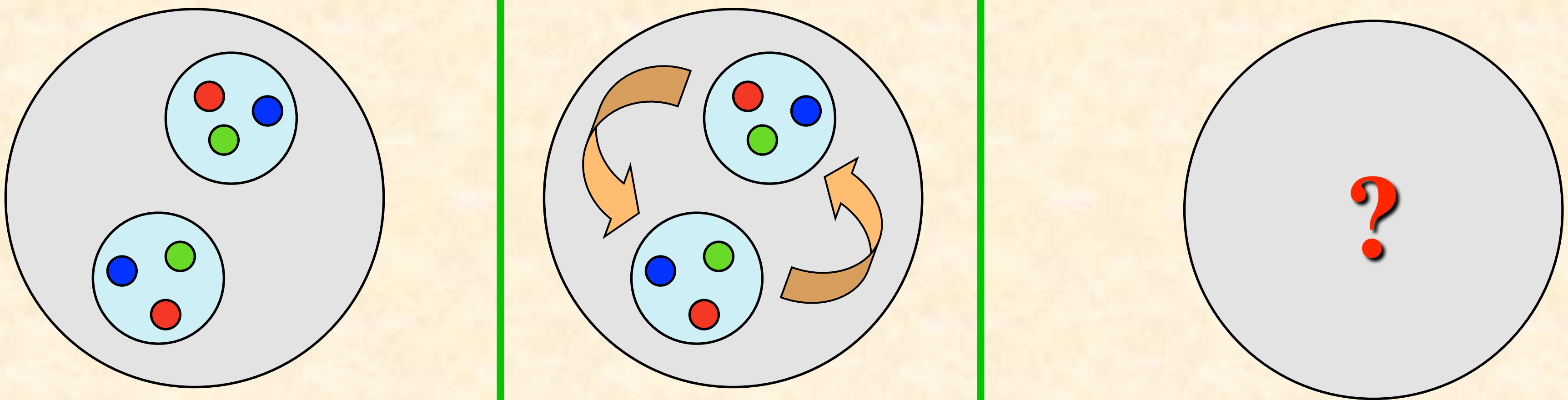


Naïve Quark Model | Sea-quarks and gluons? | Orbital angular momenta ?

"old" standard model

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

Tensor-structure crisis!?



only S wave

$b_1 = 0$

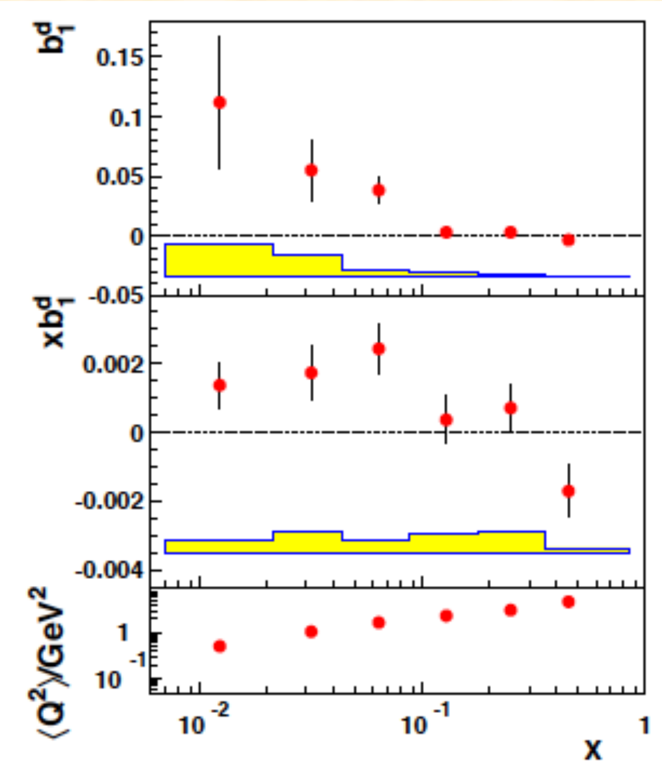
S + D waves

standard model $b_1 \neq 0$

$b_1^{\text{experiment}} \neq b_1^{\text{"standard model"}}$

HERMES measurements on b_1

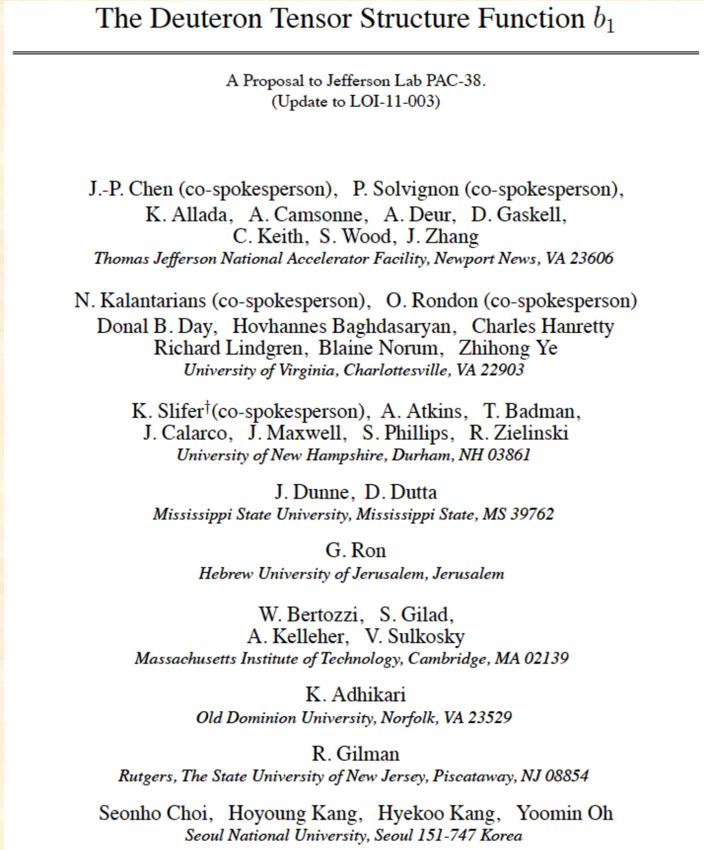
A. Airapetian *et al.* (HERMES), PRL 95 (2005) 242001.



b_1 measurements in the kinematical region

$0.01 < x < 0.45, \;\; 0.5 \text{ GeV}^2 < Q^2 < 5 \text{ GeV}^2$

Jlab proposal, PR12-11-110 (approved!)



The Deuteron Tensor Structure Function b_1

A Proposal to Jefferson Lab PAC-38.
(Update to LOI-11-003)

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Related talk by O. Teryaev on Oct.21
GPD and b_1: Y.B. Dong, C. Liang, Int. J. Mod. Phys. Conf. Ser. 29 (2014) 1460229.
For the details, see SK, arXiv:1407.3852.

Spin asymmetries in the parton model

unpolarized: q_a, longitudinally polarized: Δq_a,
transversely polarized: $\Delta_T q_a$, tensor polarized: δq_a

Unpolarized cross section

$$\left\langle \frac{d\sigma}{dx_A dx_B d\Omega} \right\rangle = \frac{\alpha^2}{4Q^2}\left(1+\cos^2\theta\right)\frac{1}{3}\sum_a e_a^2\left[q_a(x_A)\bar{q}_a(x_B)+\bar{q}_a(x_A)q_a(x_B)\right]$$

Spin asymmetries

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

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

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

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

$$A_{LT} = A_{TL} = A_{UT} = A_{TU} = A_{TQ_0} = A_{UQ_1}$$
$$= A_{LQ_1} = A_{TQ_1} = A_{UQ_2} = A_{LQ_2} = A_{TQ_2} = 0$$

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

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

Fermilab? Xiaodong Jiang, personal communications (2014)

Summary

J-PARC Fundamental physics with high-intensity beams

GPDs at hadron facilities

GPDs can be investigated by not only DVCS at lepton facilities but also exclusive reactions at hadron facilities.

Constituent-counting rule for exotic hadrons

High energies = Quark and gluon degrees of freedom
Exclusive processes for probing internal configurations.

GPDs and GDAs for exotic hadrons

3D structure of hadrons can be investigated by GPDs and GDAs.

Comments on spin-1 deuteron (b_1)

JLab experiment, Drell-Yan at hadron facilities, …

J-PARC: Propose your experiments, joint workshops, …

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

Topics

- **High-energy hadron physics (including spin physics)**
- **Charm-hadron physics**
- **Hadron-mass modifications in nuclear medium**
- **New ideas …**

March 13-16 (date should be fixed next week), 2015,
Tsukuba campus of KEK, Japan

→ If you are interested in the workshop,
please inform shunzo.kumano @ kek.jp.

The End

The End