Tomography of hadrons in high-energy exclusive processes

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February 28, 2014

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- GPDs at hadron facilities

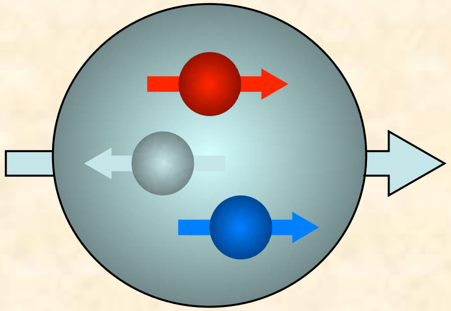
  SK, M. Strikman, K. Sudoh, PRD 80 (2009) 074003.
- Constituent-counting rule for exotic hadrons

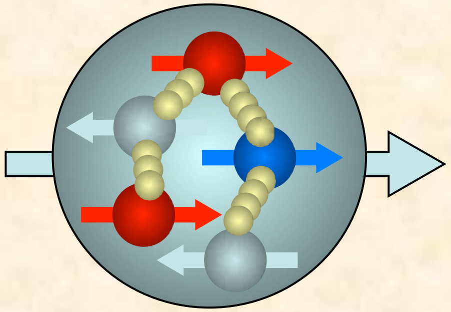
  H. Kawamura, SK, T. Sekihara, PRD 88 (2013) 034010.
- GPDs and GDAs for exotic hadrons

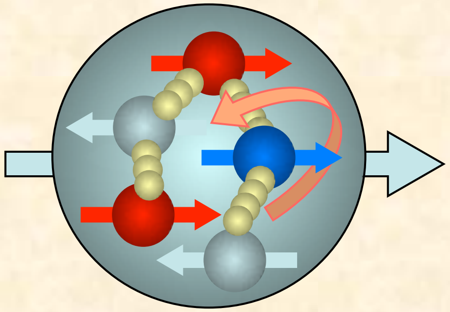
  H. Kawamura, SK, arXiv:1312.1596, Phys. Rev. D in press (2014).
- Comments on J-PARC project
- Summary

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}

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

Orbital angular momenta ?

$L_q,\ L_g$

Future experiments

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

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

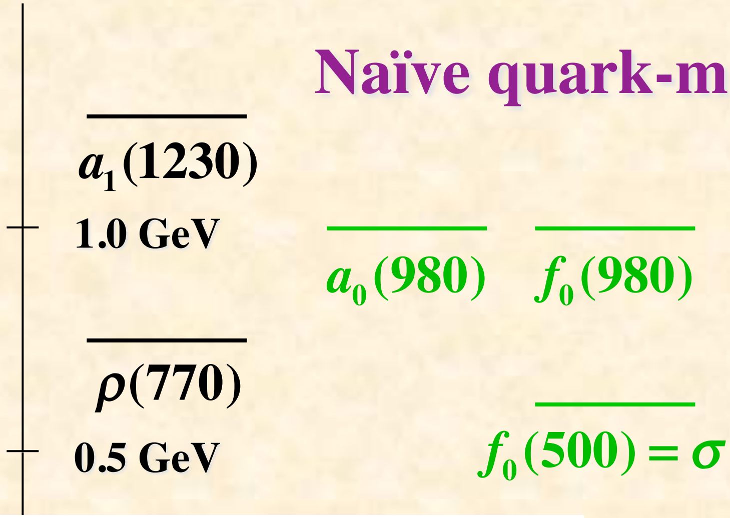
$c\bar{s}$
$D^0(c\bar{u})K^+(u\bar{s})$
$D^+(c\bar{d})K^0(d\bar{s})$?

- Z (4430): Belle
  Tetraquark, …

$c\bar{c}u\bar{d}$, D molecule?

- …

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



Naïve quark-model

$a_1(1230)$

1.0 GeV

$a_0(980)$ $f_0(980)$

$\rho(770)$

0.5 GeV

$f_0(500) = \sigma$

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

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

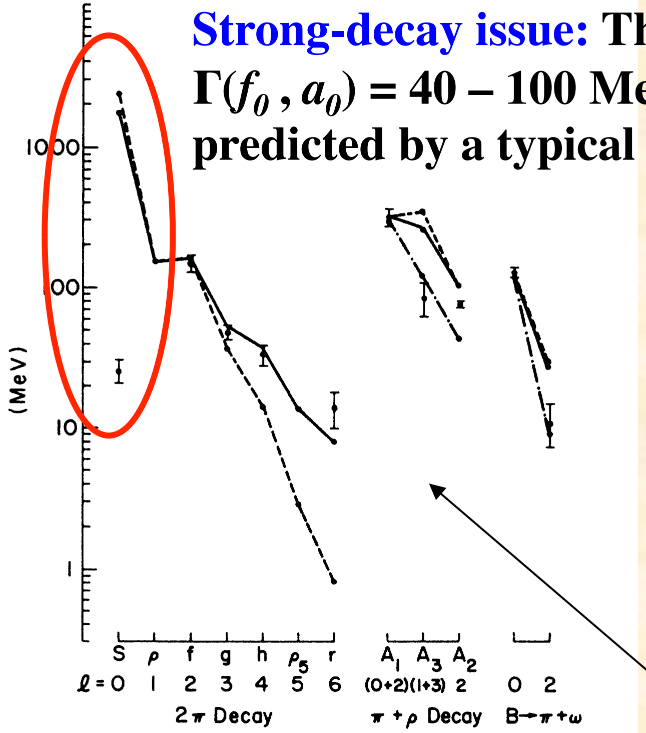
$$a_0(980) = u\bar{d},\ \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}),\ d\bar{u}$$

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

$\Updownarrow$ 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.



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.

SK and V. R. Pandharipande, Phys. Rev. D38 (1988) 146.

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.

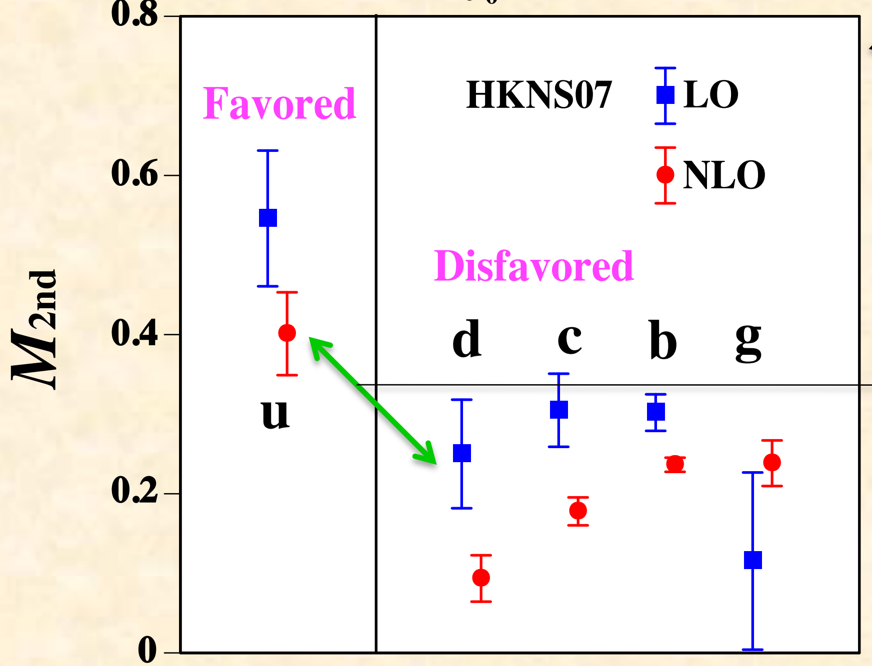
Possibilities for $f_0(980)$: $\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$, $s\bar{s}$, $\frac{1}{\sqrt{2}}(u\bar{u}s\bar{s}+d\bar{d}s\bar{s})$, $K\bar{K}$, or gg

$e.g.$ 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.

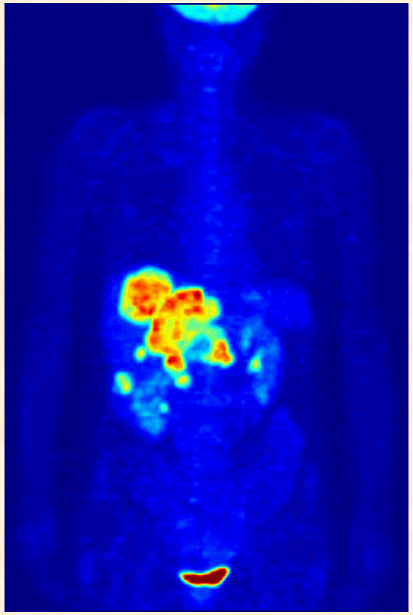
→ It could be used for exotic-hadron studies.

Tomography

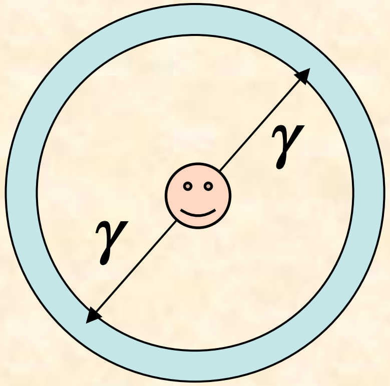
- CT (Computed Tomography)
- PET (Positron Emission Tomography)

© Jens Langner

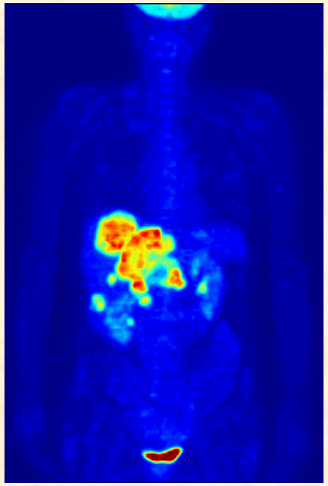
$$\beta^+ \text{ decay:} \quad {}^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + e^+ + \nu_e \quad (\tau = 110 \text{ min})$$



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



Nucleon (hadron) tomography



Classical density distribution

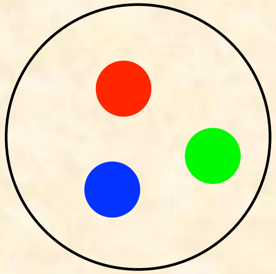
3D picture of nucleon

(Density distribution of quantum system: Quantum tomography)

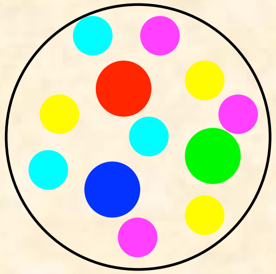
1D(Bjorken-x) picutre@HERA

© DESY

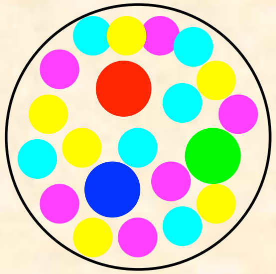
Low energy



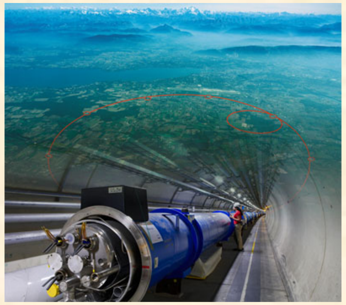
Intermediate energy



High energy



Test apparatus corresponds to “PET”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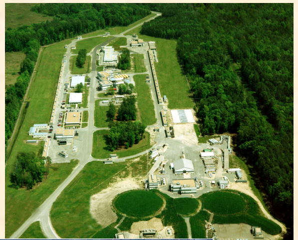
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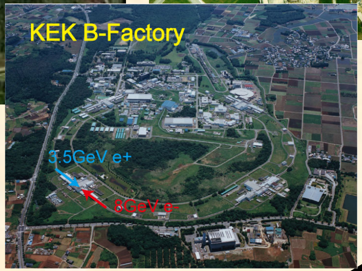

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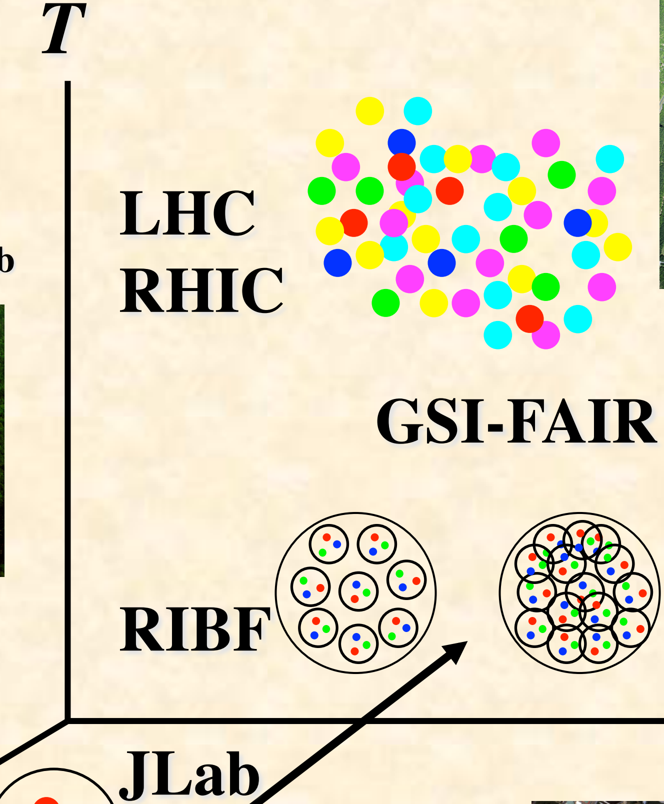

T

LHC
RHIC

GSI-FAIR

RIBF

μ

JLab

J-PARC

Q^2

HERA, EIC
LHC, RHIC


© BNL

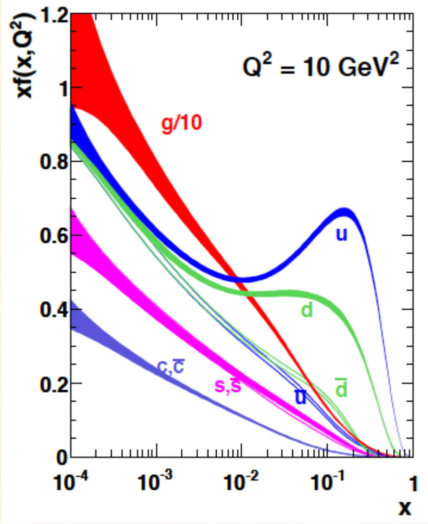

© GSI


© J-PARC

Wigner distribution and various structure functions

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

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

$\int d^3r$

$\int d^2k_\perp dz$

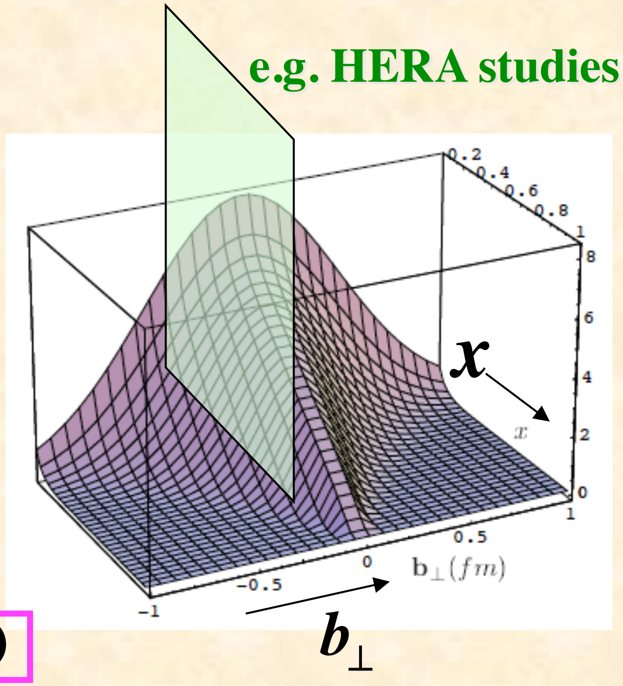
TMD (Transverse Momentum Dependent) parton distribution

GPD (Generalized Parton Distribution)

s-*t* crossing →

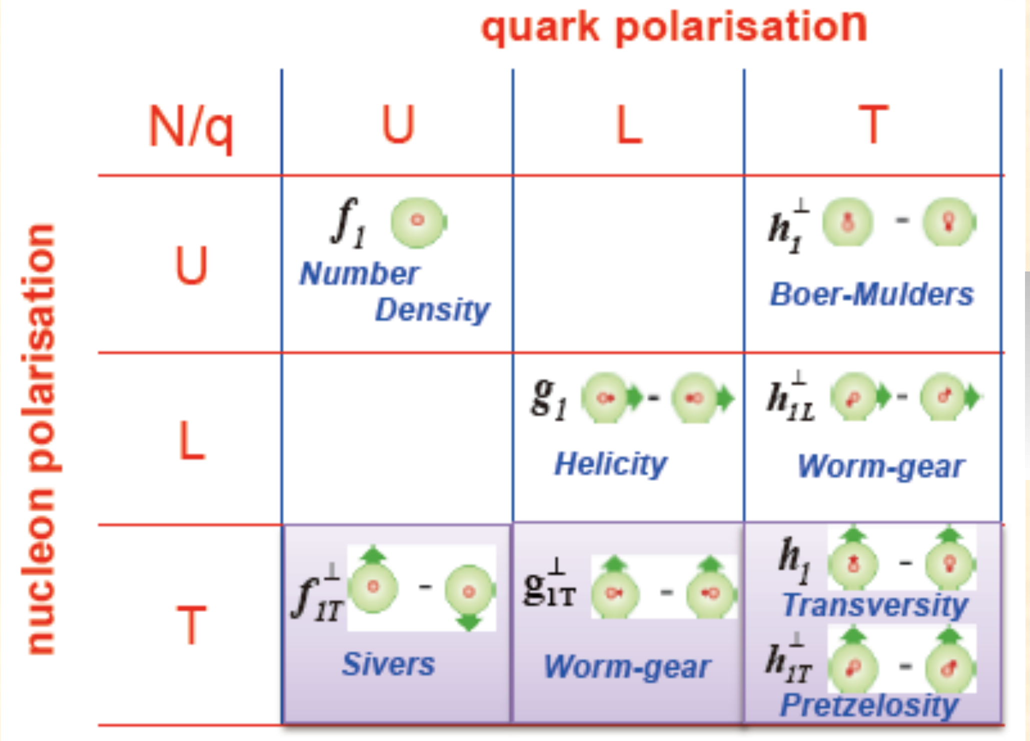
$\gamma\gamma \to h\bar{h}$ GDA (Generalized Distribution Amplitude)

e.g. HERA studies



TMD distributions

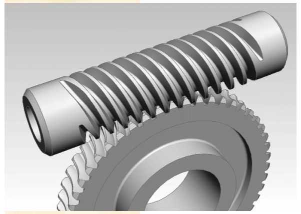
Contalbrigo@Jlab-PAC-2011

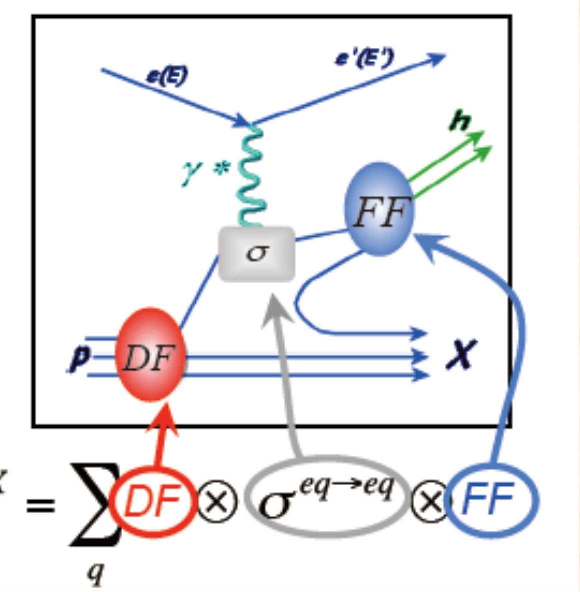


quark polarisation

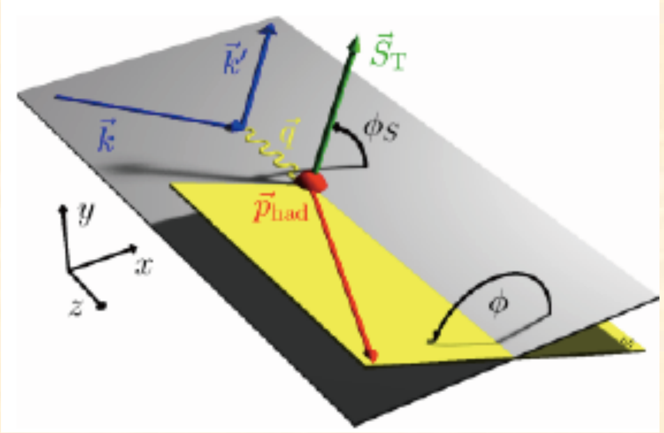
nucleon polarisation

N/q	U	L	T
U	f_1 Number Density		$h_1^\perp$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^\perp$ Worm-gear
T	$f_{1T}^\perp$ Sivers	$g_{1T}^\perp$ Worm-gear	h_1 Transversity $h_{1T}^\perp$ Pretzelosity





$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$



SIDIS cross section:

$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi\,dP_{h\perp}^2} \underset{Twist}{\overset{Leading}{\propto}} S_T\left\{\sin(\phi-\phi_S)F_{UT,T}^{\sin(\phi-\phi_S)}\right\}$$

$$+S_T\left\{\varepsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\right\}$$

$$+S_T\lambda_e\left\{\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right\}+\dots$$

$h_1 \otimes H_1^\perp$

$f_{1T}^\perp \otimes D_1$

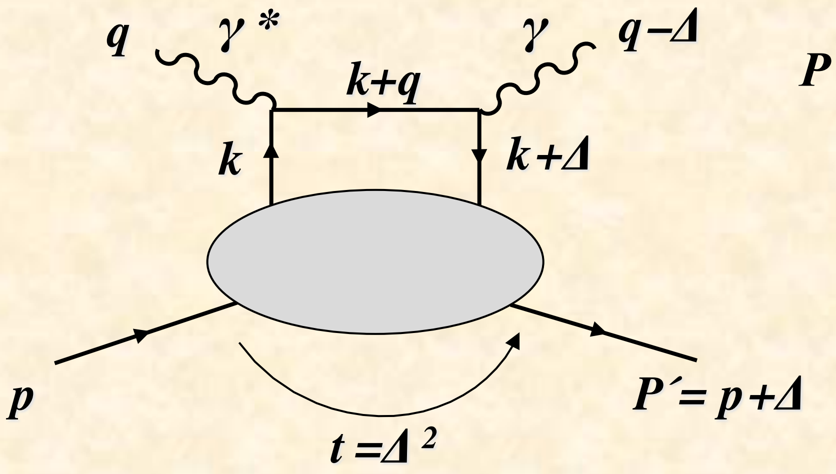
$h_{1T}^\perp \otimes H_1^\perp$

$g_{1T}^\perp \otimes D_1$

GPDs in the ERBL region
at hadron facilities

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

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:

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

Forward limit: PDFs

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

First moments: Form factors

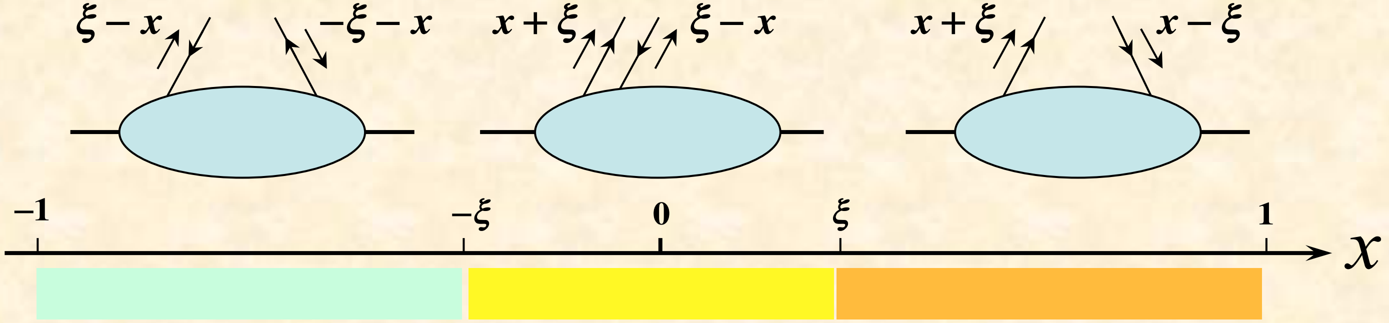
Dirac and Pauli form factors F_1, F_2

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

Second moments: Angular momenta

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

GPDs in different *x* regions and GPDs at hadron facilities



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

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

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

Quark distribution

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

Meson-like distribution amplitude

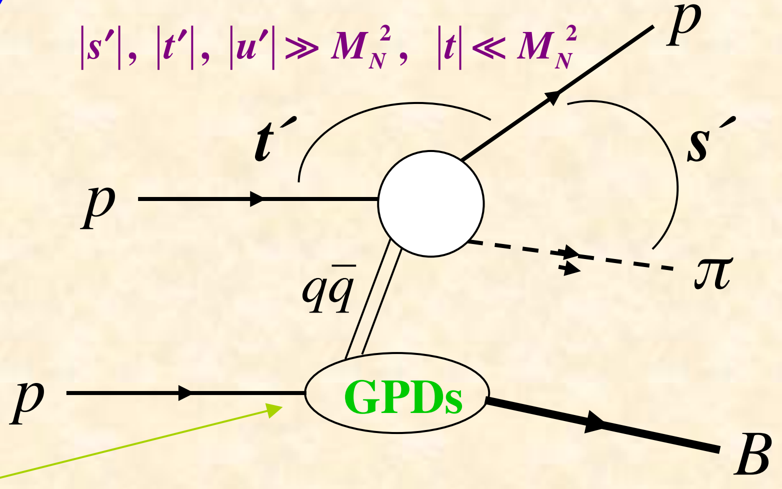
Emission of quark with momentum fraction $x+\xi$
Emission of antiquark with momentum fraction $\xi-x$

Antiquark distribution

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

Consider a hard reaction with

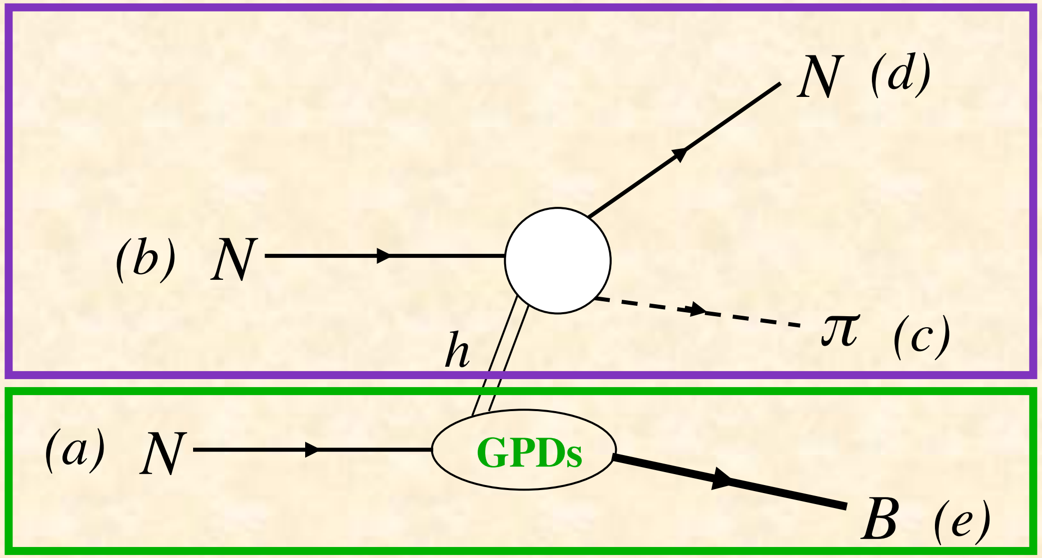
$|s'|,\ |t'|,\ |u'| \gg M_N^2,\ \ |t| \ll M_N^2$



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

Efremov-Radyushkin -Brodsky-Lepage (ERBL) region

Cross section estimates



$\dfrac{d\sigma(s',t')}{dt'}$ so as to explain AGS experimental data on

$\pi + p \to \pi + p, \;\; \pi + p \to \rho + p$

This part is expressed by GPDs.

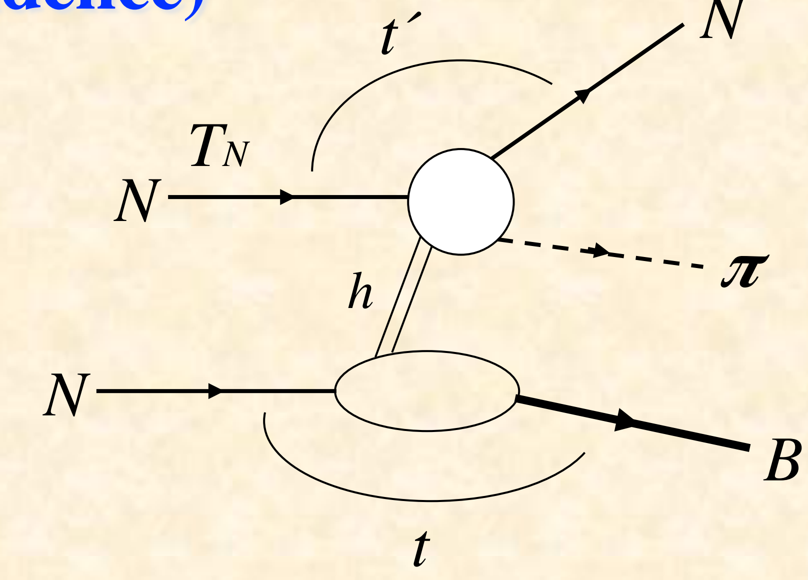
Purposes of our studies:

(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)



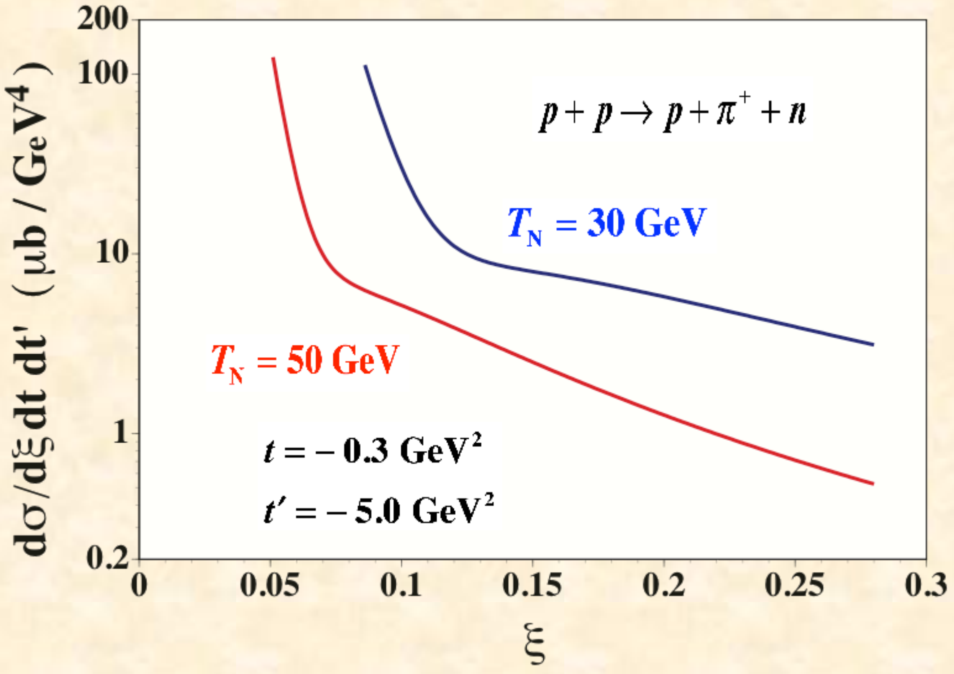
Skewdness parameter: $\xi = \dfrac{p_N^+ - p_B^+}{p_N^+ + p_B^+}$

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

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

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

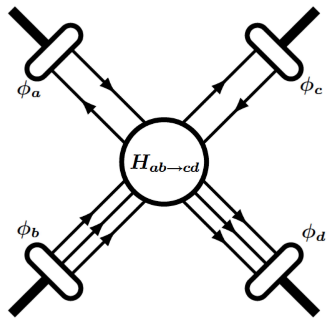
At this stage, our numerical results are for rough order of magnitude estimates on cross sections by assuming π- and ϱ-like intermediate states.



Constituent-counting rule for exotic hadrons

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

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



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

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

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.

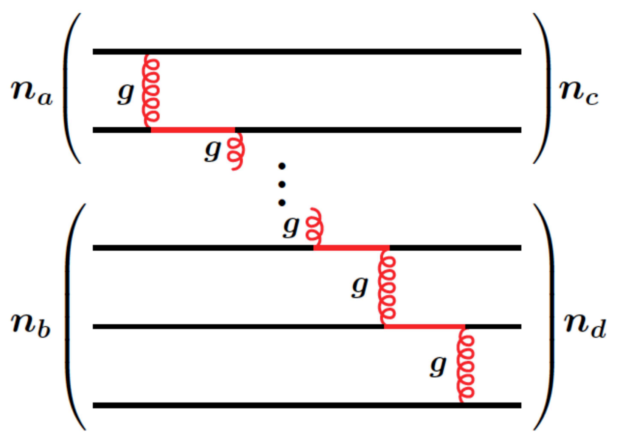
There are $n/2-1$ gluon propagators $\sim 1/(P^2)^{n/2-1}$.

(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 $\sim (\sqrt{P})^n$.



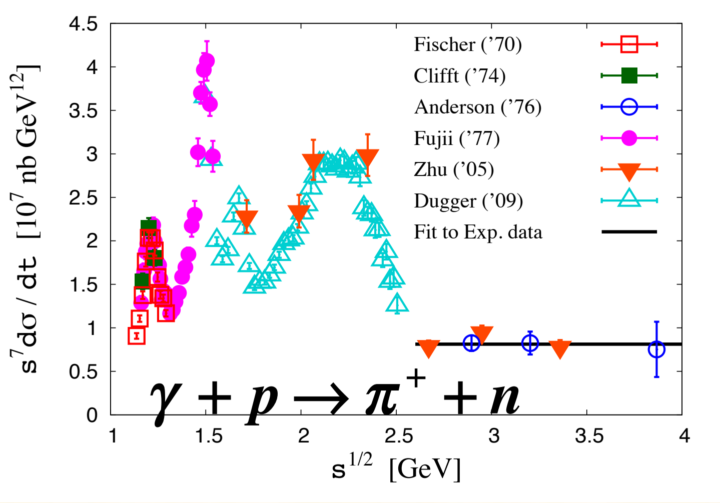
$$M_{ab\to cd} \sim \frac{1}{(P^2)^{n/2-1}}\frac{1}{(P)^{n/2-2}}(\sqrt{P})^n = \frac{(P)^{n/2}}{(P)^{n-2}(P)^{n/2-2}} = \frac{1}{(P)^{n-4}} \sim \frac{1}{s^{n/2-2}}$$

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

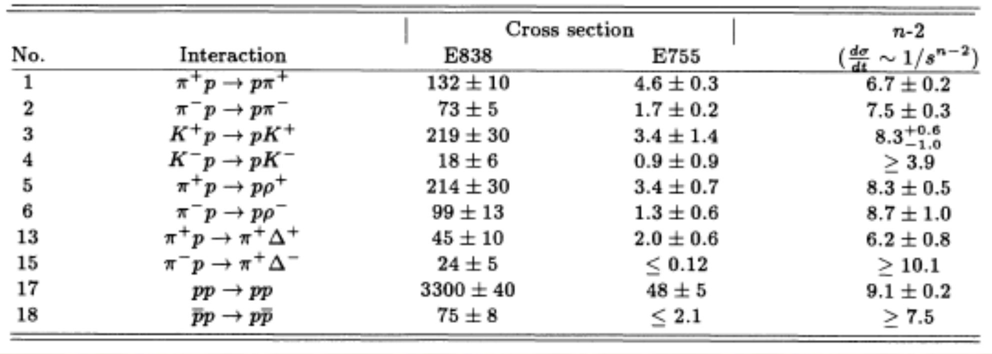
Constituent-counting rule, Transition from hadron degrees of freedom to quark-gluon ones

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	$\pi^+ p \rightarrow p\pi^+$	132 ± 10	4.6 ± 0.3	6.7 ± 0.2
2	$\pi^- p \rightarrow p\pi^-$	73 ± 5	1.7 ± 0.2	7.5 ± 0.3
3	$K^+ p \rightarrow pK^+$	219 ± 30	3.4 ± 1.4	$8.3^{+0.6}_{-1.0}$
4	$K^- p \rightarrow pK^-$	18 ± 6	0.9 ± 0.9	≥ 3.9
5	$\pi^+ p \rightarrow p\rho^+$	214 ± 30	3.4 ± 0.7	8.3 ± 0.5
6	$\pi^- p \rightarrow p\rho^-$	99 ± 13	1.3 ± 0.6	8.7 ± 1.0
13	$\pi^+ p \rightarrow \pi^+ \Delta^+$	45 ± 10	2.0 ± 0.6	6.2 ± 0.8
15	$\pi^- p \rightarrow \pi^+ \Delta^-$	24 ± 5	≤ 0.12	≥ 10.1
17	$pp \rightarrow pp$	3300 ± 40	48 ± 5	9.1 ± 0.2
18	$\bar{p}p \rightarrow p\bar{p}$	75 ± 8	≤ 2.1	≥ 7.5

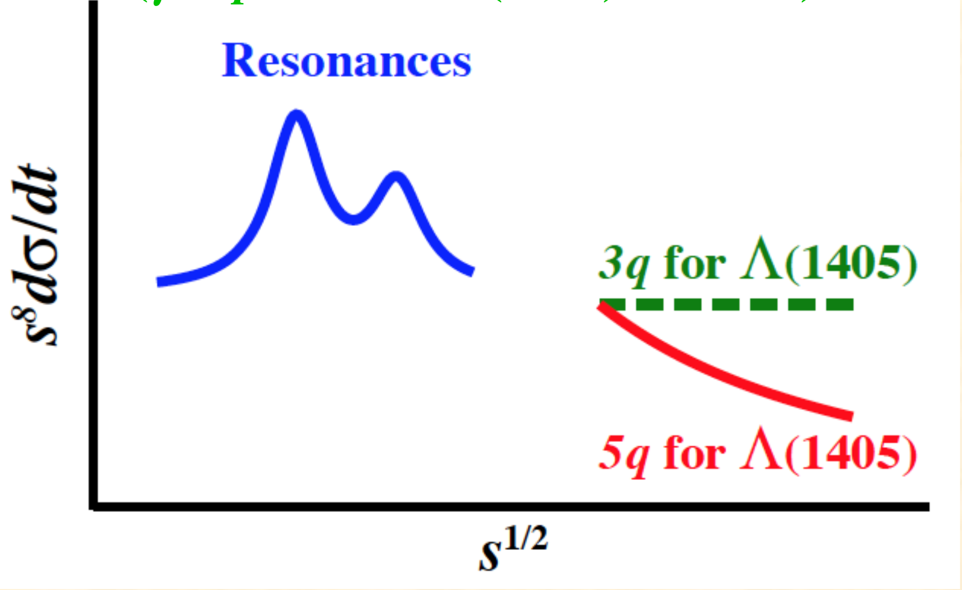
Our idea

- 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

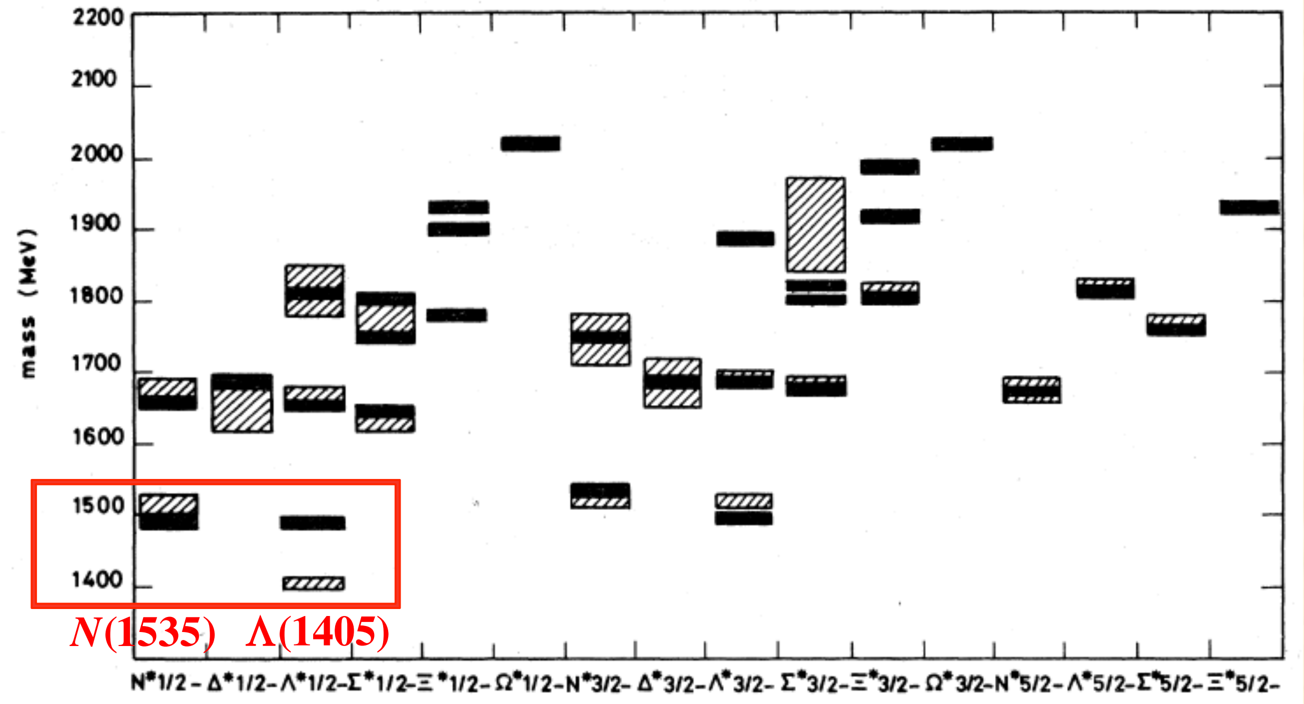
$$\pi^0 + p \rightarrow K^0 + \Lambda(1405)$$

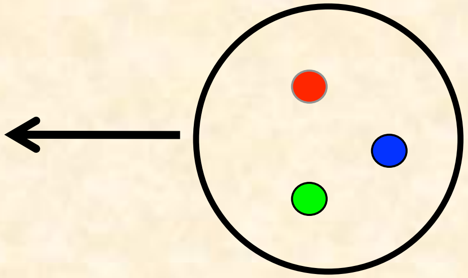
($\gamma + p \rightarrow K^+ + \Lambda(1405)$ at JLab)

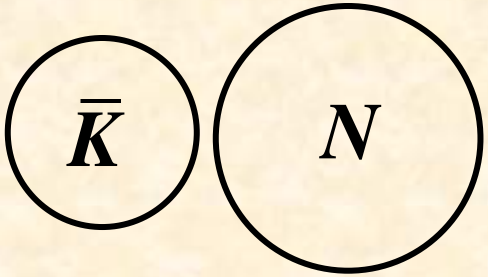


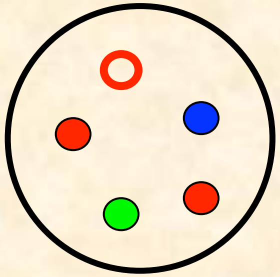
Λ(1405): exotic hadron?

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







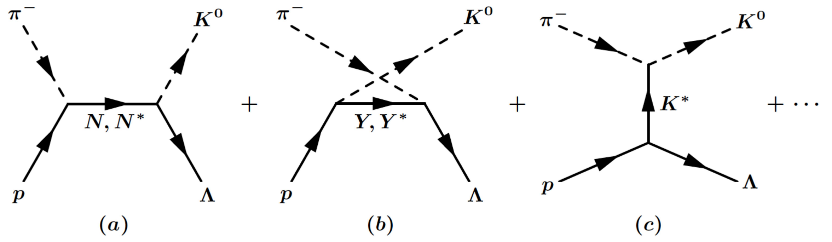


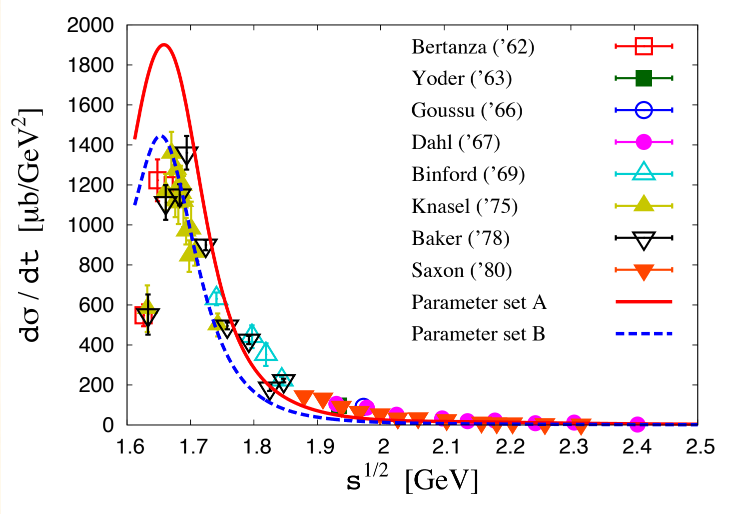
Most spectra agree with the ones by a 3q-picture

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

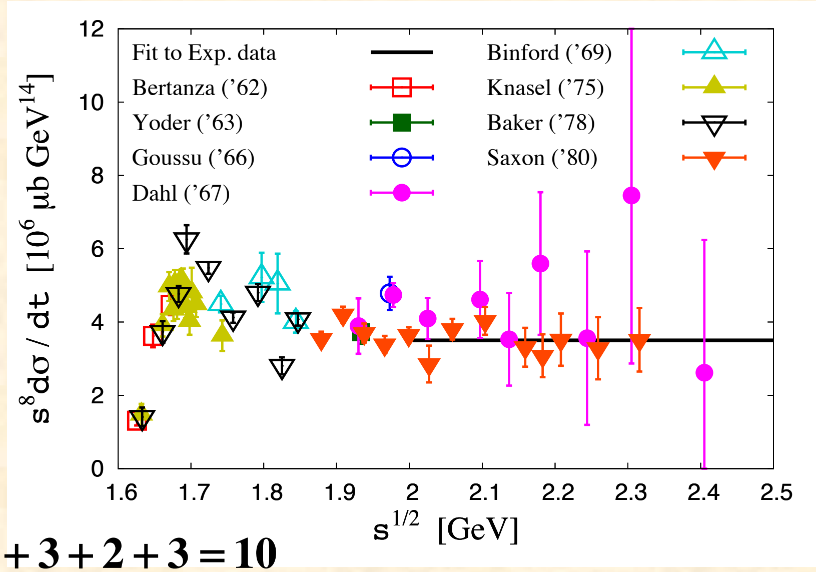
Ordinary-hadron production $\pi^- + p \to K^0 + \Lambda$ as a reference

At low energies





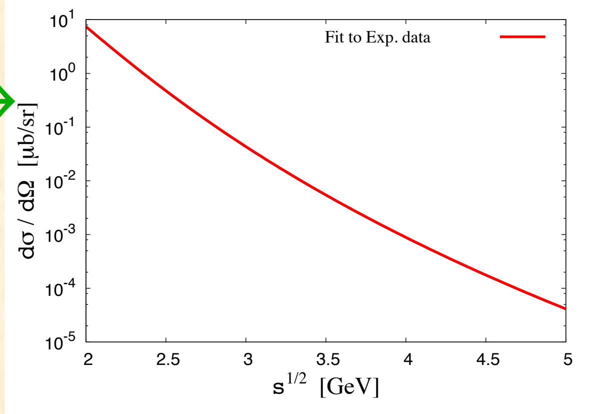
From low to higher energies



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

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

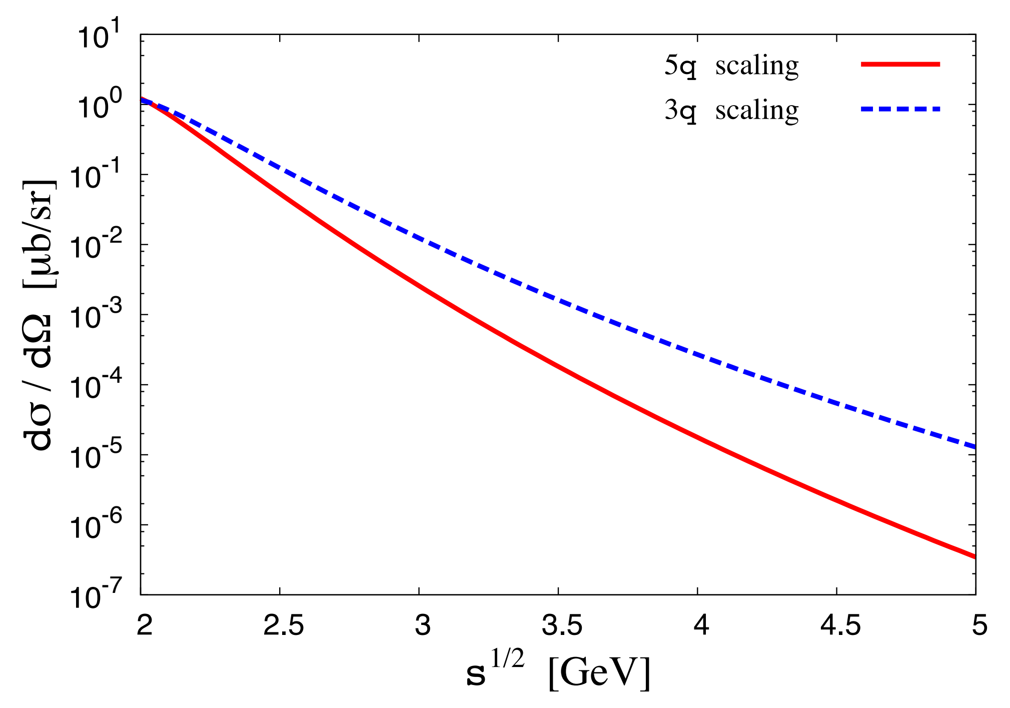
$$n = 2+3+2+3 = 10 \quad \text{if } \Lambda(1405) = \text{three-quark state}$$

$$= 2+3+2+5 = 12 \quad \text{if } \Lambda(1405) = \text{five-quark state}$$

(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



GPDs and GDAs for exotic hadrons

H. Kawamura and SK

arXiv:1312.1596 (Phys. Rev. D in press)

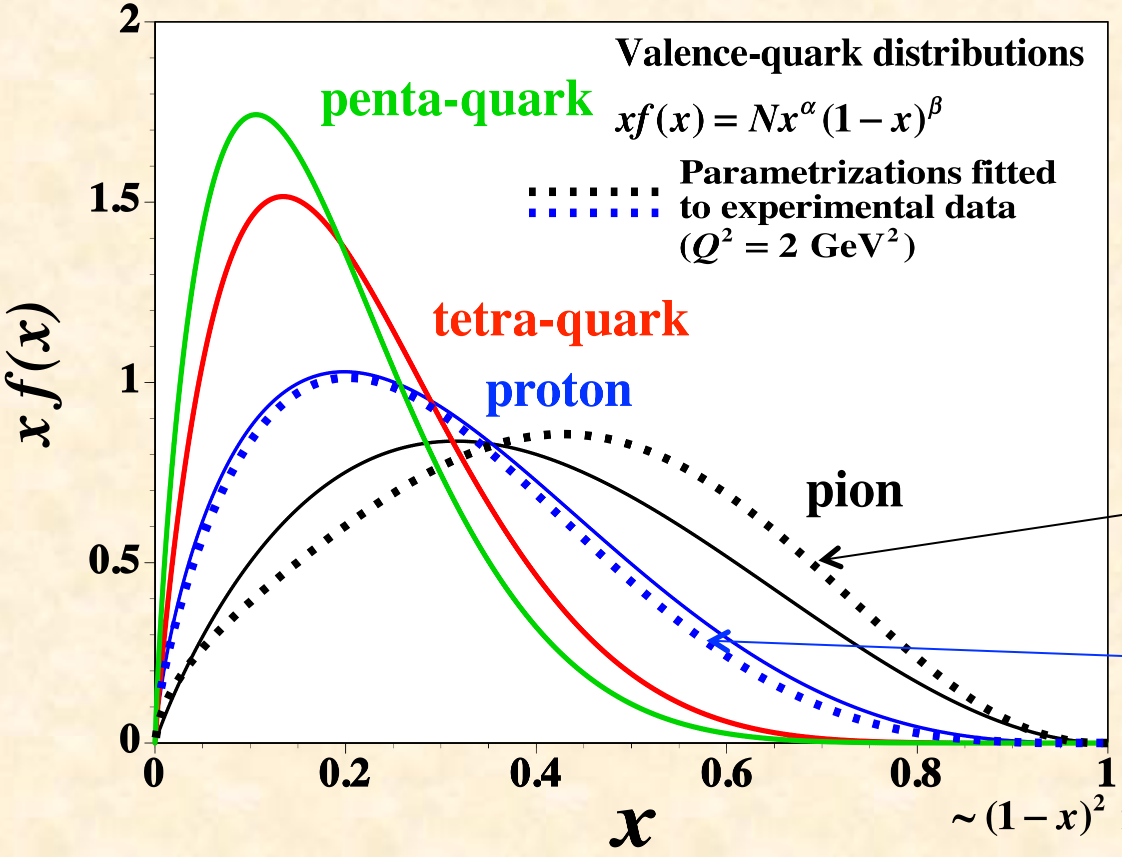
Simple function of GPDs

$\boxed{H_q^h(x,t) = f(x)F(t,x)}$

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** $\langle x \rangle_q \simeq \int_0^1 dx\, x f(x)$



$\sim (1-x)^2$ for π

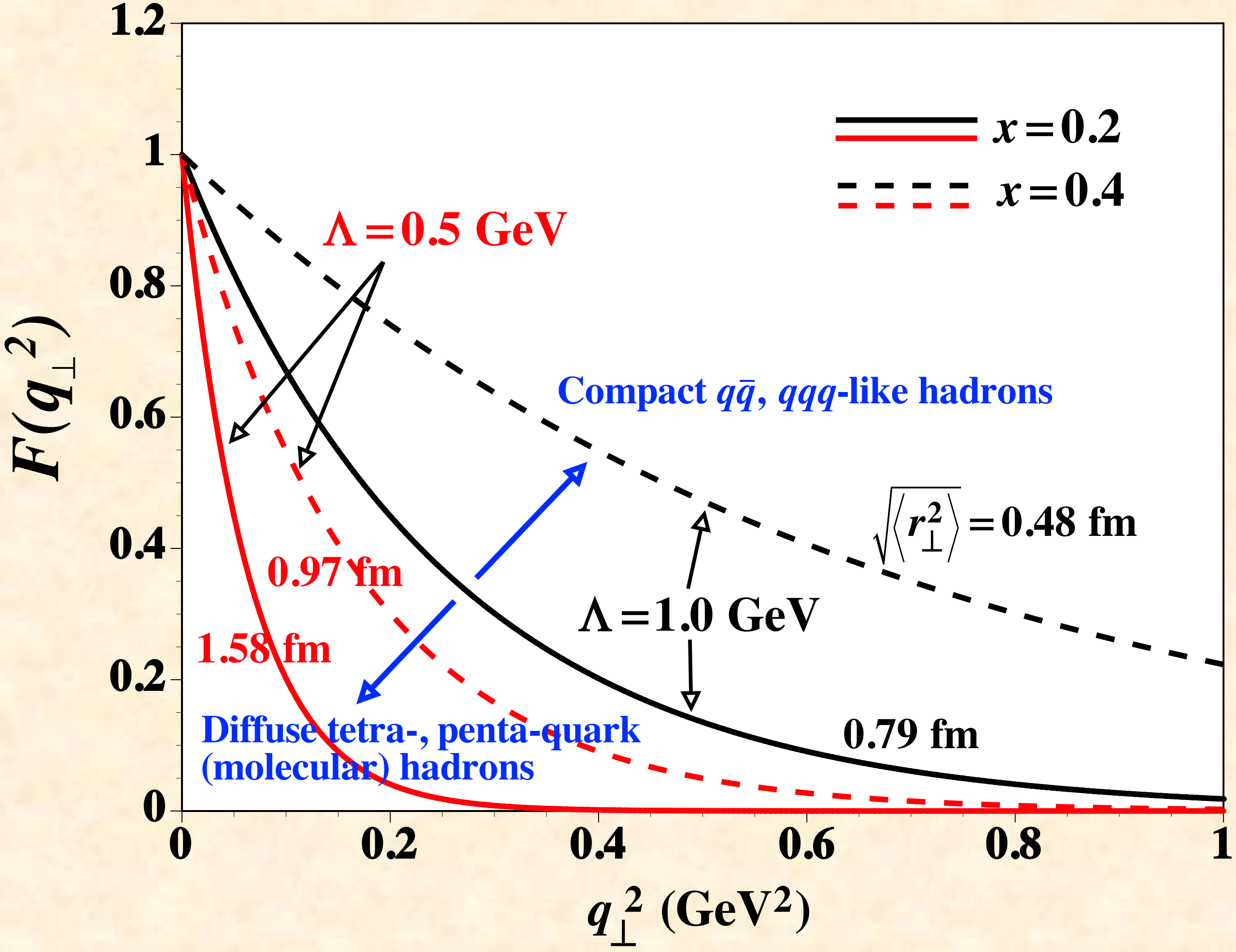
Gedankenexperiment, but …
read our paper for studying exotics in
high-energy processes at KEK-B,
Linear Collider, ….

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 !?

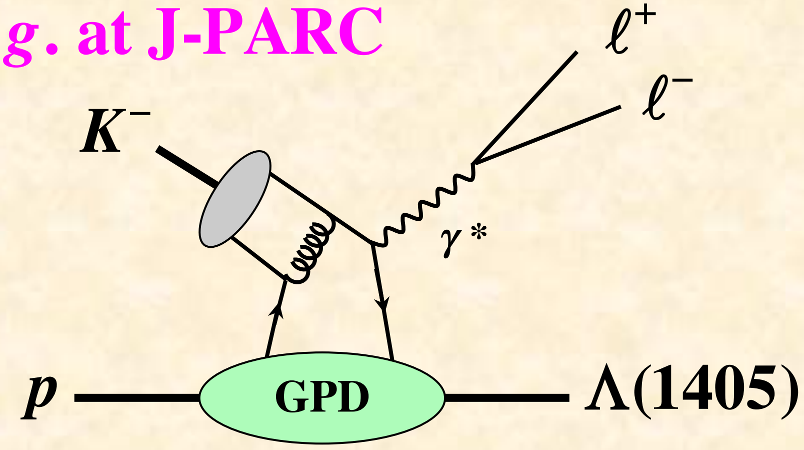
**Because stable targets do not exit for exotic hadrons,
it is not possible to measure their GPDs in a usual way.**

→ Transition GPDs

or

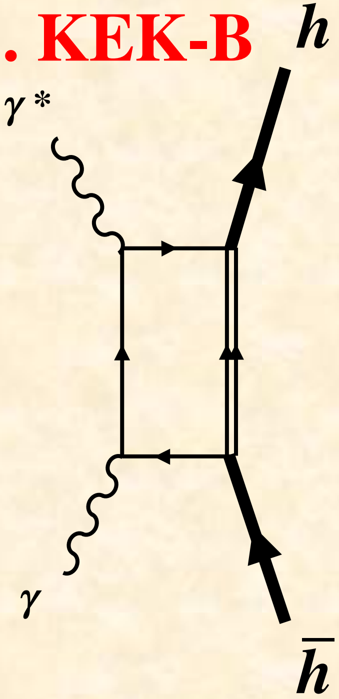
→ $s \leftrightarrow t$ crossed qunatity = GDAs at KEK-B, Linear Collider

***e.g.* at J-PARC**



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

***e.g.* KEK-B**



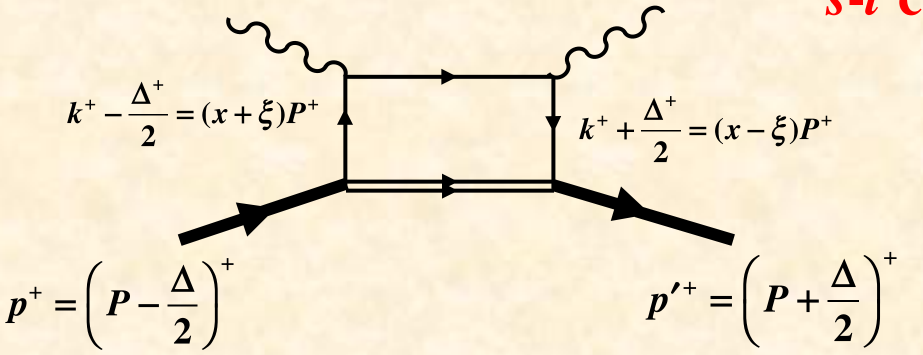
GPD $H_q^h(x,\xi,t)$ and GDA $\Phi_q^{h\bar{h}}(z,\zeta,W^2)$

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

$H_q^h(x,\xi,t)$



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

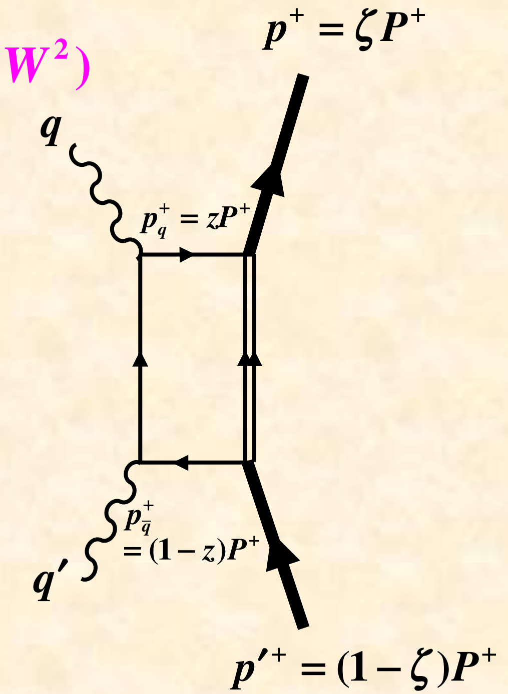
Bjorken variable: $x=\frac{Q^2}{2p\cdot q}$

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

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

s-t crossing

$\Phi_q^{hh}(z,\zeta,W^2)$



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

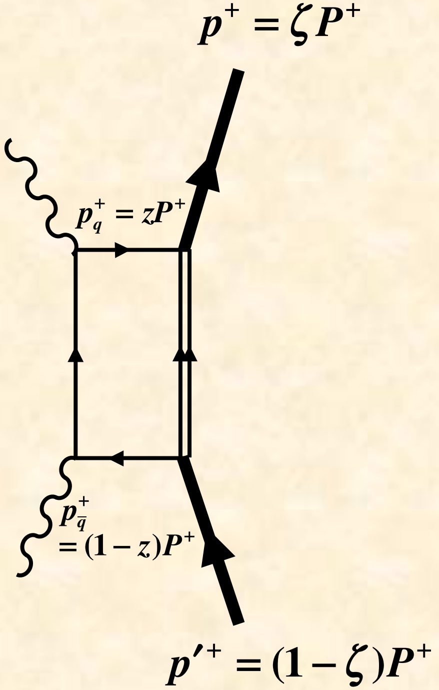
Light-cone momentum ratio for h in $h\bar{h}$: $\zeta=\frac{p^+}{P^+}=\frac{1+\beta\cos\theta}{2}$

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

Functional form of GDAs $\Phi_q^{h\bar{h}}(z,\zeta,W^2)$

Kinematical variables

$$z=\frac{k^+}{P^+},\quad \zeta=\frac{1}{2}(1+\beta\cos\theta),\quad \beta=\sqrt{1-\frac{4m_\pi^2}{W^2}},\quad W^2=(p+p')^2$$



Sum rule

$$\int_0^1 dz(2z-1)\Phi_q^{h\bar{h}(I=0)}(z,\zeta,W^2)=-2M_{2(q)}^h\zeta(1-\zeta)F_{h(q)}(W^2)$$

Exotic signatures should appear in the functional form ($e.g.$ form factor).

GDA could be expressed by

$$\Phi_q^{h\bar{h}(I=0)}(z,\zeta,W^2)=N_h z^\alpha(1-z)^\beta(2z-1)\zeta(1-\zeta)F_{h(q)}(s)$$

$$N_h=-\frac{2M_{2(q)}^h}{B(\alpha+1,\beta+1)}\frac{(\alpha+\beta+3)(\alpha+\beta+2)}{(\alpha+2)(\alpha+1)+(\beta+2)(\beta+1)-2(\alpha+1)(\beta+1)}$$

Cross section: form factor dependence

$$\Phi_q^{h\bar{h}(I=0)}(z,\zeta,W^2) = N_h z^\alpha (1-z)^\beta (2z-1)\zeta(1-\zeta) F_h(W^2)$$

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

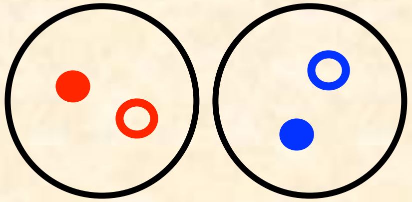
Constituent-counting rule

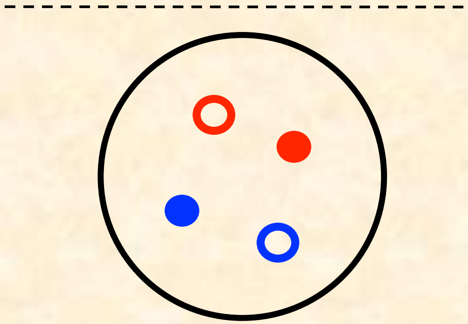
$n = 2:$ **ordinary meson**

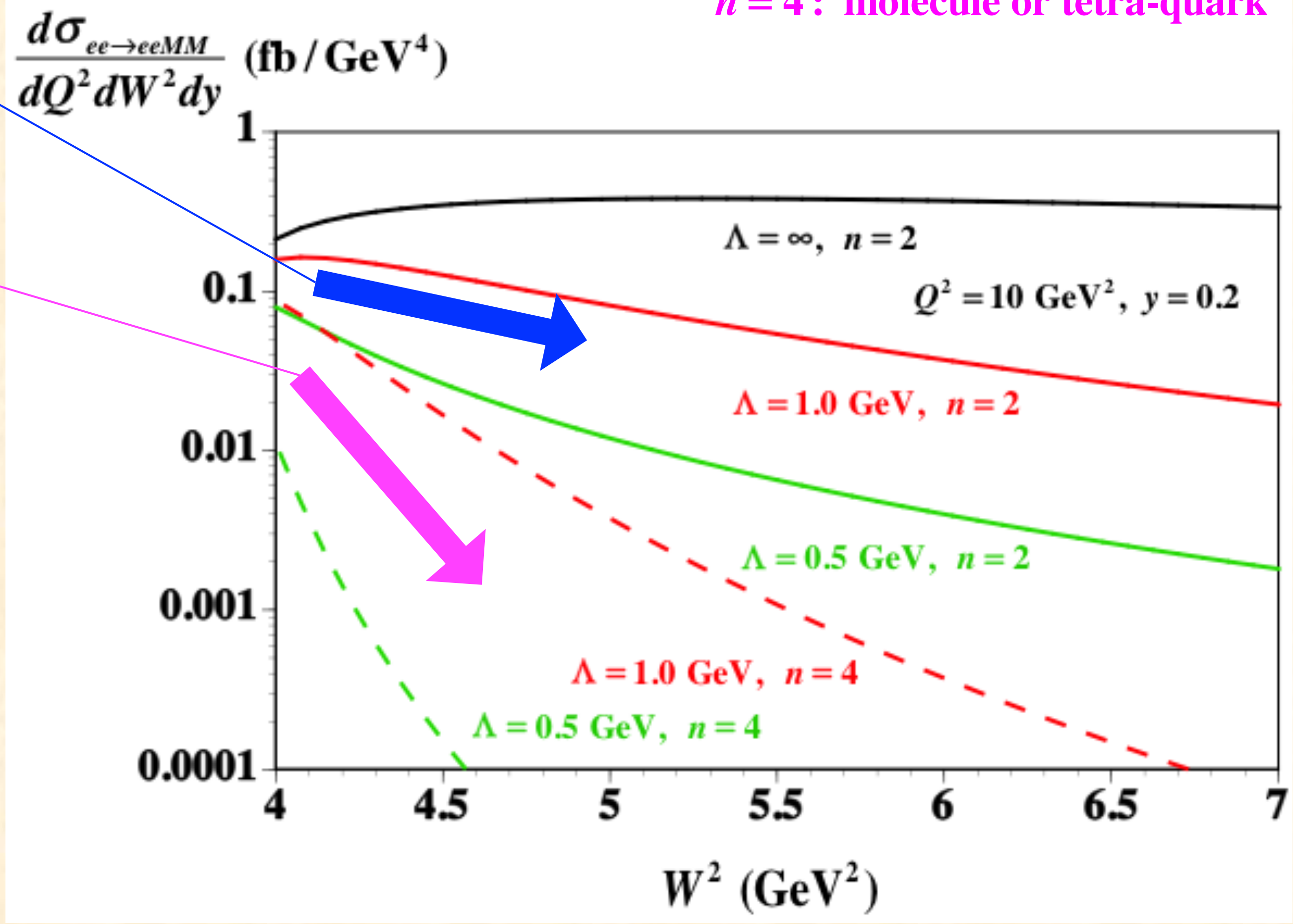
$n = 4:$ **molecule or tetra-quark**

Ordinal $q\bar{q}$

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



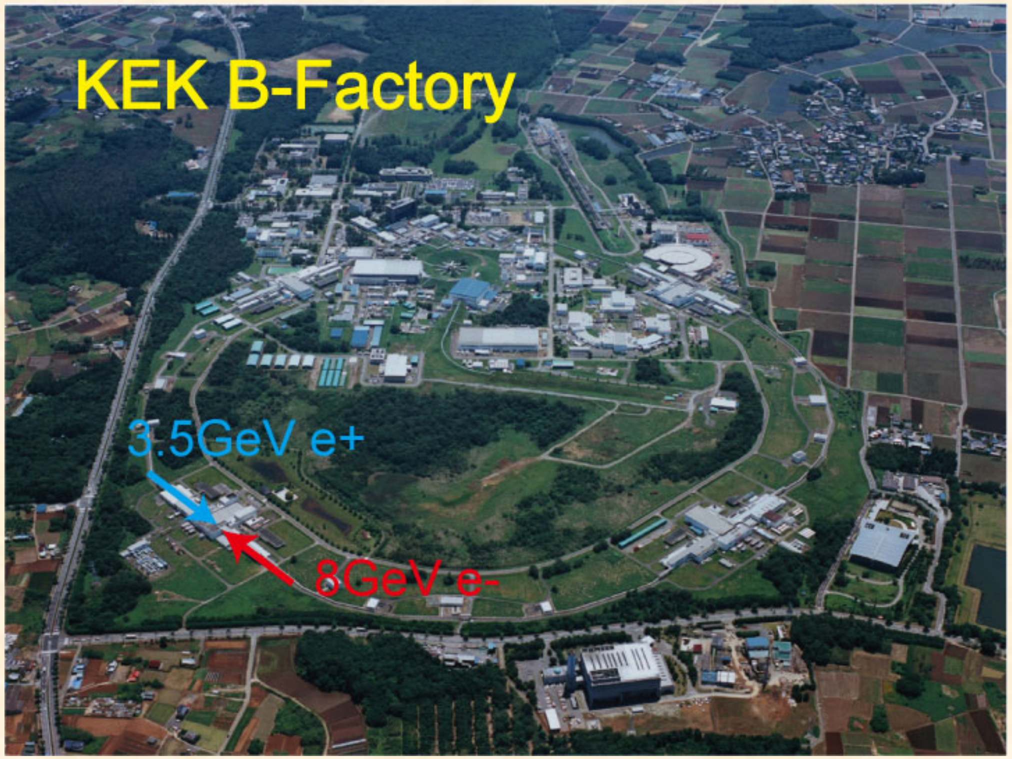




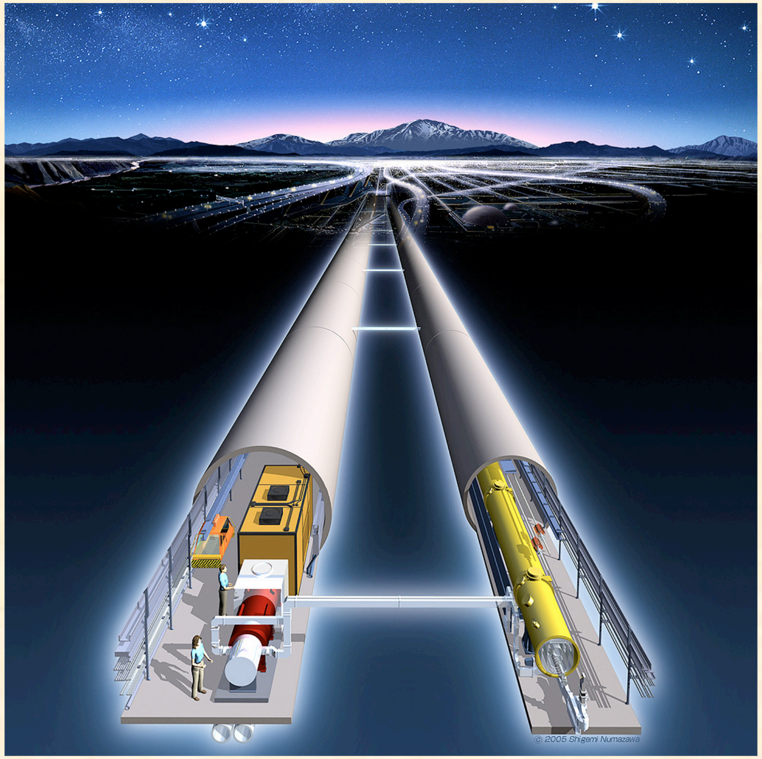
Experimental studies of GDAs in future

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

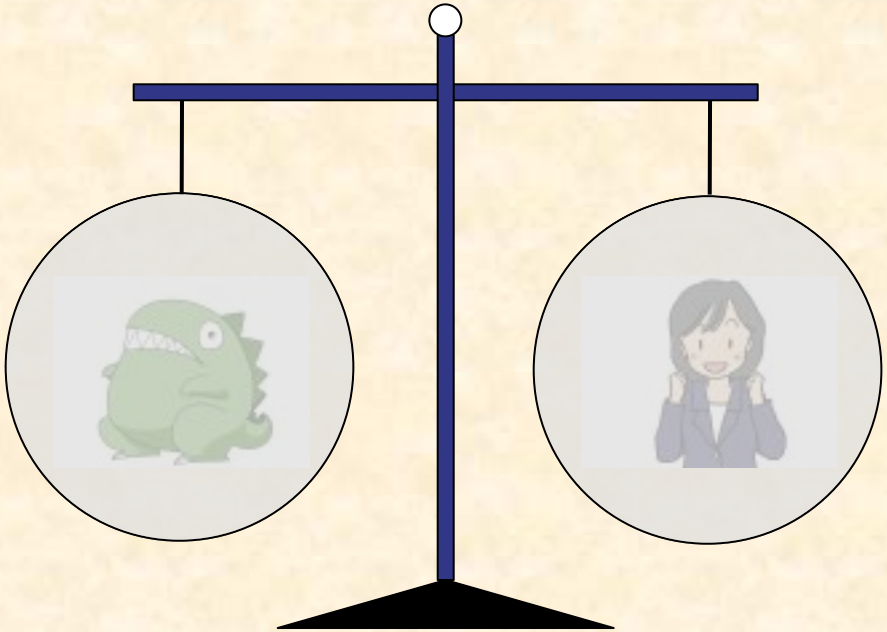
KEK B-factory



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

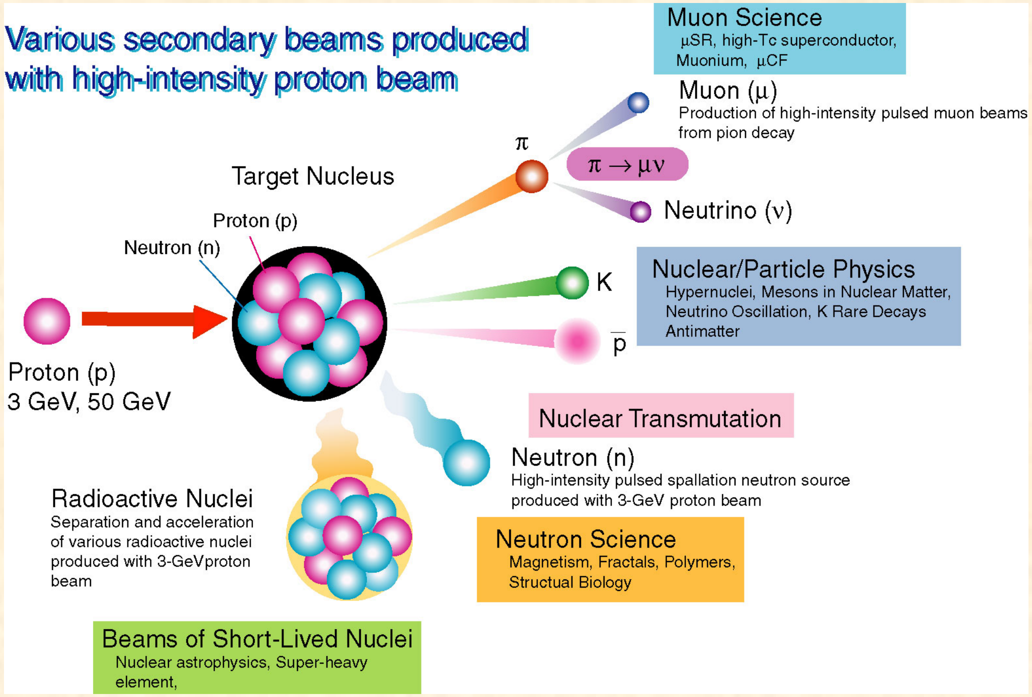
or

.

Comments on J-PARC project

High-Intensity Frontier of Proton Accelerator

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



Various secondary beams produced with high-intensity proton beam

Muon Science
μSR, high-Tc superconductor, Muonium, μCF

Muon (μ)
Production of high-intensity pulsed muon beams from pion decay

Neutrino (ν)

Nuclear/Particle Physics
Hypernuclei, Mesons in Nuclear Matter, Neutrino Oscillation, K Rare Decays
Antimatter

Nuclear Transmutation

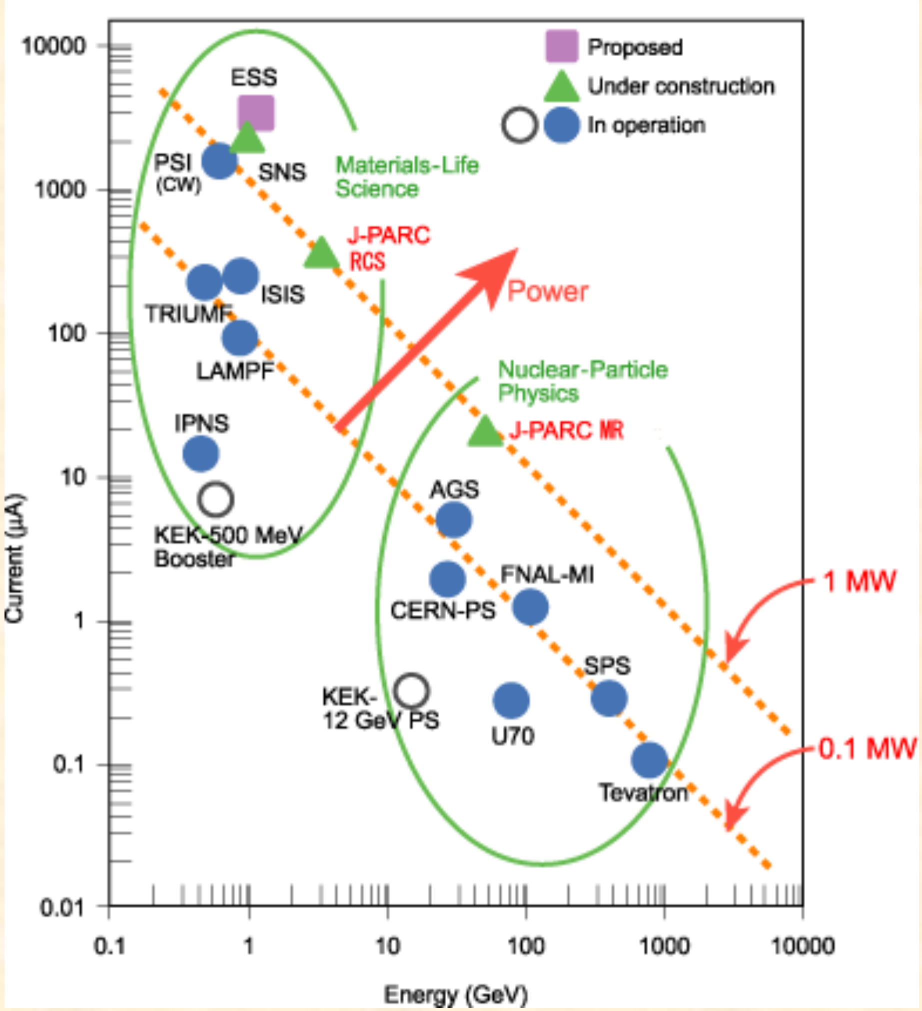
Neutron (n)
High-intensity pulsed spallation neutron source produced with 3-GeV proton beam

Neutron Science
Magnetism, Fractals, Polymers, Structural Biology

Radioactive Nuclei
Separation and acceleration of various radioactive nuclei produced with 3-GeVproton beam

Beams of Short-Lived Nuclei
Nuclear astrophysics, Super-heavy element,

Power map of worldwide proton accelerators



Aerial photograph

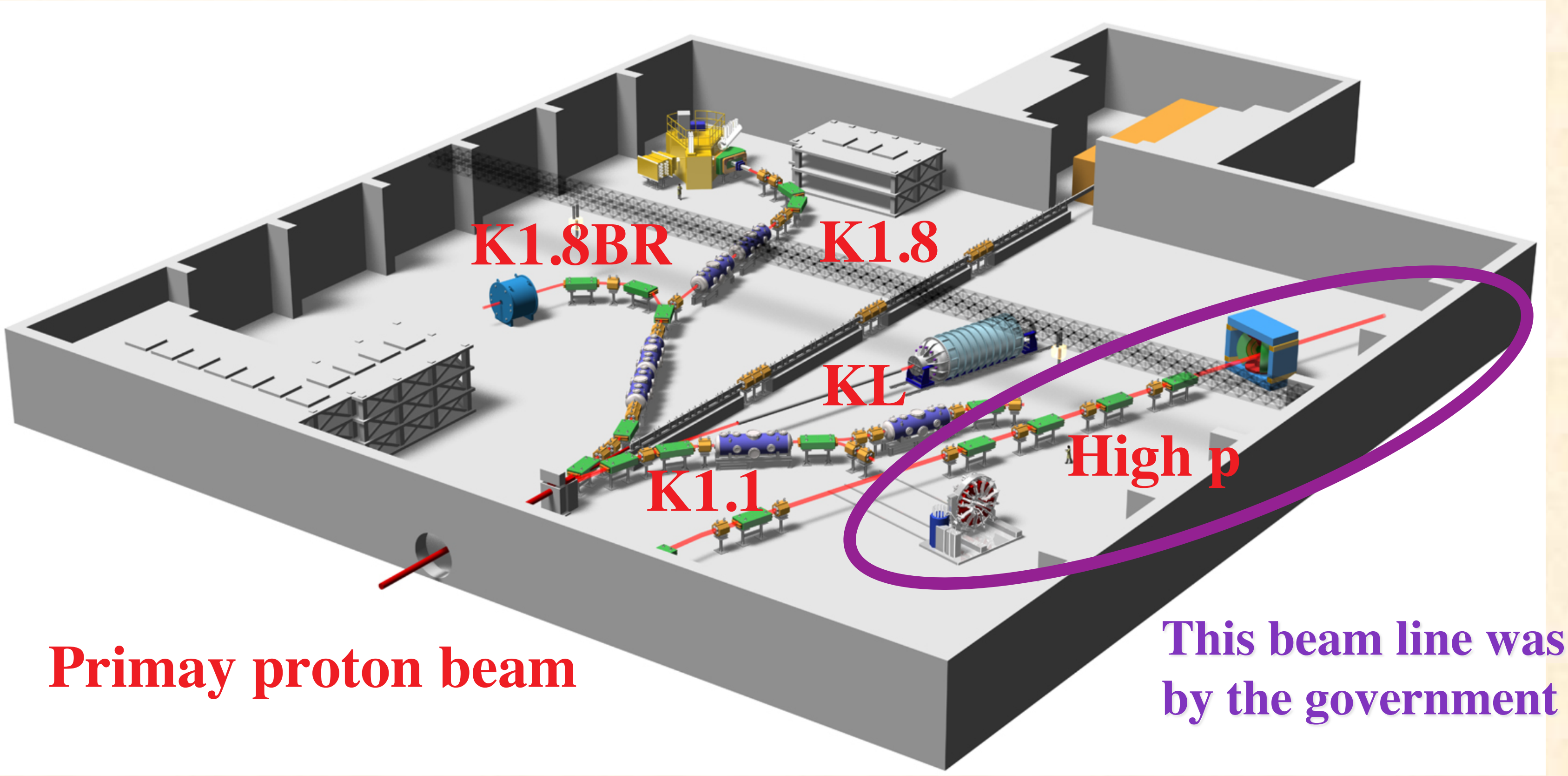
KEK Tokai campus,
J-PARC branch
KEK theory center

Neutrino
facility

Hadron
facility

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.

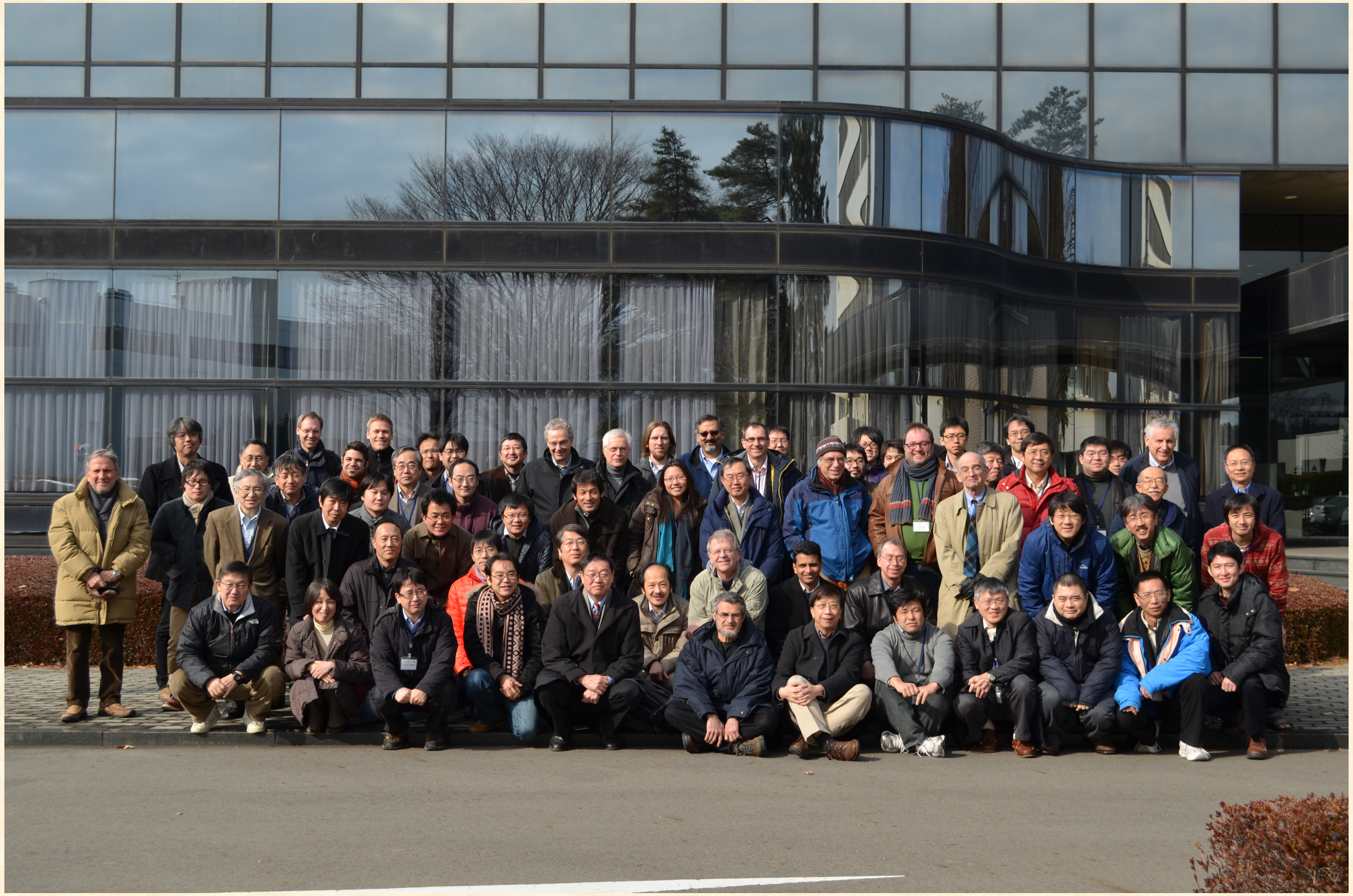
You may propose your experiments!

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

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

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

88 participants (~100 including non-registered ones)

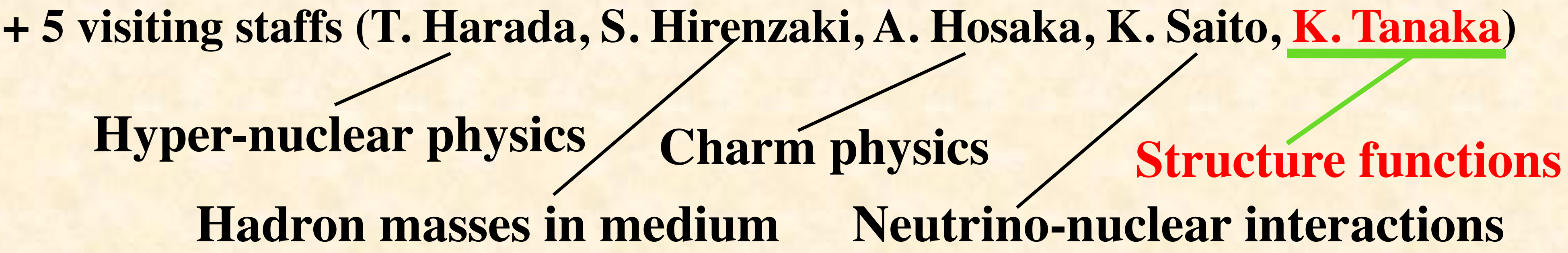


Theory activities at J-PARC

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)

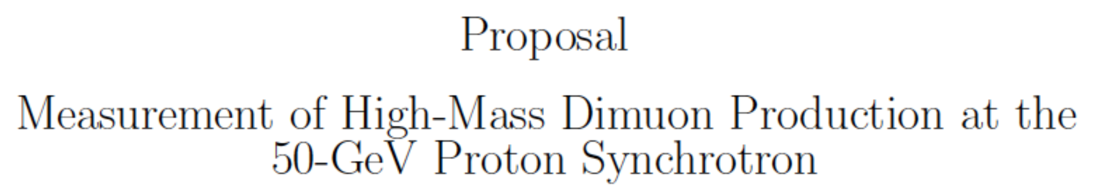
Hyper-nuclear physics
Charm physics
Structure functions
Hadron masses in medium
Neutrino-nuclear interactions

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

Proposals on high-energy hadron physics

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

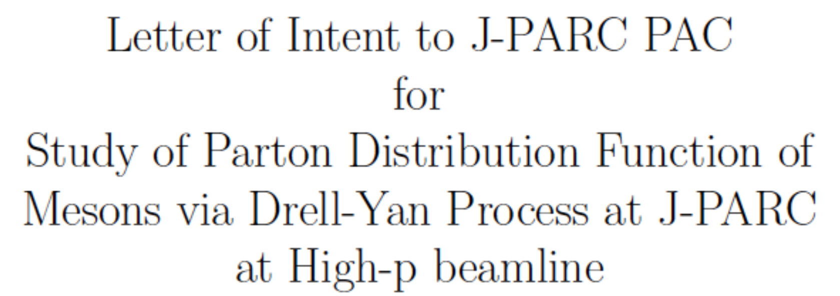
J. C. Peng, S. Sawada *et al.*



Proposal

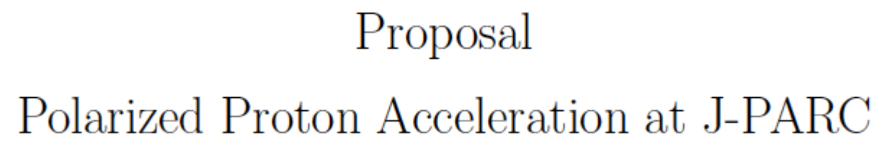
Measurement of High-Mass Dimuon Production at the 50-GeV Proton Synchrotron

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

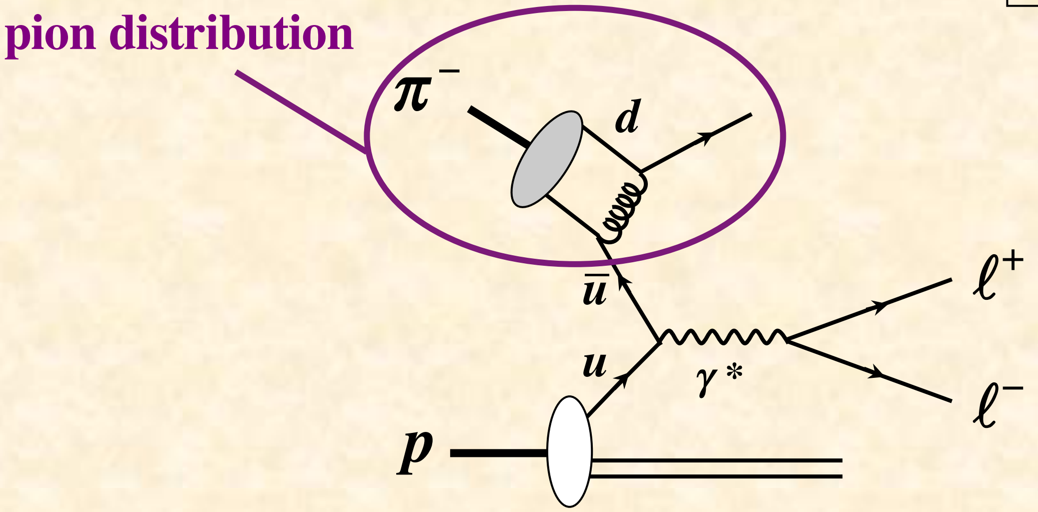
The high-momentum had not been approved financially until 2013, so these proposals were deferred.

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

New LoI / proposal under consideration!

Toward a new proposal

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



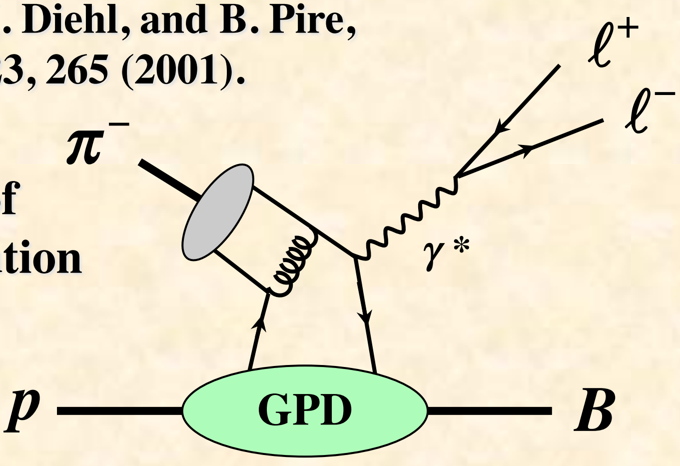
A. Brandenburg, S. J. Brodsky, V. V. Khoze, and D. Müller, Phys. Rev. Lett. 73 (1994) 939.

Investigation of
- Pion distribution amplitude

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

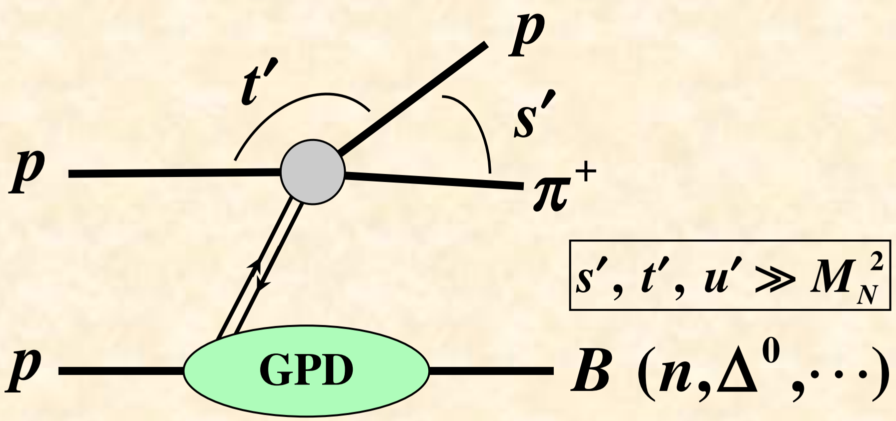
E. R. Berger, M. Diehl, and B. Pire, Phys. Lett. B 523, 265 (2001).

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

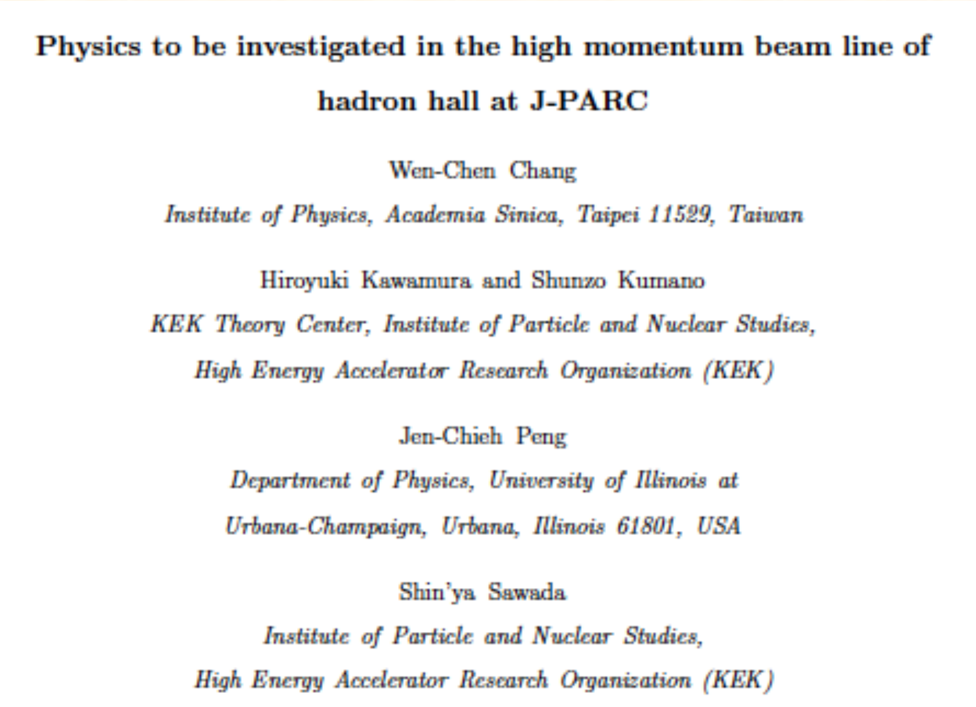


In progress for LoI / proposal

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

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)

Summary

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

It is appropriate to use high-energy processes for determination of internal configurations for exotic-hadron candidates.

GPDs and GDAs for exotic hadrons

3D structure of hadrons can be investigated by GDAs ($s \Leftrightarrow t$).

Related experimental projects

J-PARC, COMPASS, JLab, KEK-B, Liner Collider, …

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

The End

The End