Studies of GPDs and gravitational form factors at KEKB, J-PARC, and Fermilab-LBNF

Long-Baseline Neutrino Facility (LBNF)

From April 1, 2022

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Workshop on Origin of the Visible Universe: Unraveling the Proton Mass

INT, Seattle, Washington, USA, June 13-17, 2022

https://www.int.washington.edu/program/schedule/1042

June 16, 2022

Contents

- Introduction: Hadron tomography
  and generalized parton distributions (GPDs)
- Generalized distribution amplitudes (= timelike GPDs) and
  extraction of gravitational form factors from KEK-B data.
- GPDs at hadron accelerator facilities, *e.g.* at J-PARC
- GPDs at neutrino facilities
- GPDs for exotic-hadron candidates (if I have time)
- Prospects and summary

References on my GPD-related works

- Possible GPD studies at hadron accelerator facilities
  Novel two-to-three hard hadronic processes and possible studies of generalized parton distributions at hadron facilities,
  SK, M. Strikman, K. Sudoh, Phys. Rev. D 80 (2009) 074003.
- Possible GPD measurement by exclusive Drell-Yan at J-PARC
  Accessing proton generalized parton distributions and pion distribution amplitudes with the exclusive pion-induced Drell-Yan process at J-PARC,
  T. Sawada, Wen-Chen Chang, SK, Jen-Chieh Peng, S. Sawada, K. Tanaka, Phys. Rev. D 93 (2016) 114034.
- Letter of Intent for the 27th J-PARC PAC meeting, January 16 - 18 January, 2019
  Studying Generalized Parton Distributions with Exclusive Drell-Yan process at J-PARC,
  JungKeun Ahn *et al*. (SK 10th author),
  Contact persons: W. C. Chang, H. Noumi, S. Sawada

GPD studies at hadron facilities (J-PARC, NICA, GSI-FAIR, . . .)

- GPDs for exotic hadrons
  Tomography of exotic hadrons in high-energy exclusive processes,
  H. Kawamura, SK, Phys. Rev. D 89 (2014) 054007.
- Timelike GPDs (GDAs) and KEKB-data analysis for gravitational form factors
  Hadron tomography by generalized distribution amplitudes in pion-pair production process $\gamma^*\gamma\to\pi^0\pi^0$ and gravitational form factors for pion,
  SK, Qin-Tao Song, O. V. Teryaev, Phys. Rev.D 97 (2018) 014020.

GPD studies at e^+e^- facilities (KEKB, ILC, CEPC, . . .)

- High-energy neutrino interactions and GPDs
  High-energy neutrino-nucleus interactions,
  SK, EPJ Web Conf. 208 (2019) 07003; SK, R. Petti, PoS (NuFact2021) 092.
- Synergies between EIC (Electron-Ion Collider) project and neutrino reactions
  EIC yellow report, R. Abdul Khalek *et al*. (SK 150th author;
  Sec. 7.5.2, Neutrino physics by SK and R. Petti), arXiv:2103.05419.

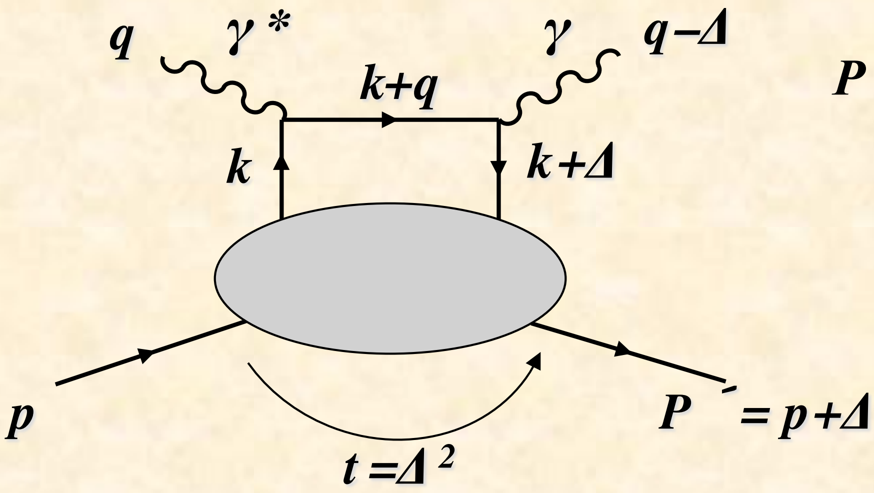
GPD studies at neutrino facilities (LBNF, . . .)

Introduction:

Origins of nucleon spin and mass

Generalized Parton Distributions (GPDs)

See B. Pasquini's talk at DIS2022 for updated information.



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

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:

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

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

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

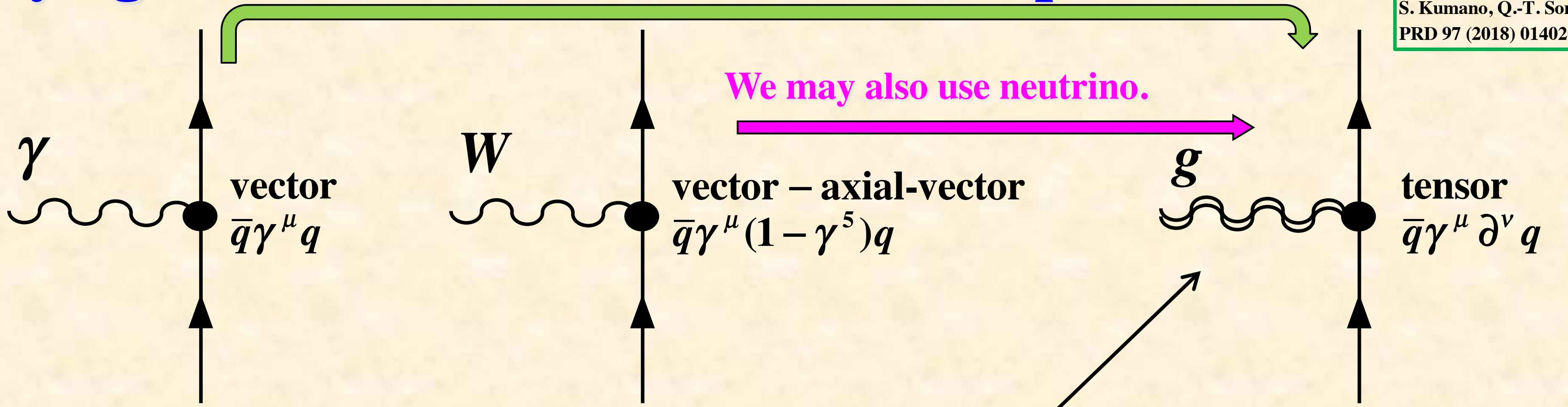
Sum rule: $J_q=\frac{1}{2}\int_{-1}^{1}dx\,x\left[H_q(x,\xi,t=0)+E_q(x,\xi,t=0)\right],\quad J_q=\frac{1}{2}\Delta q+L_q$

$\Rightarrow$ probe L_q, key quantity to solve the spin puzzle!

Why “gravitational” interactions with quarks

We studied in 2017-2018.

S. Kumano, Q.-T. Song, O. Teryaev, PRD 97 (2018) 014020.



It is possible to probe gravitational sources in the microscopic level without gravitons.

GPDs (Generalized Parton Distributions), GDAs (Generalized Distribution Amplitudes) = timelike GPDs

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

Non-local operator of GPDs/GDAs:

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

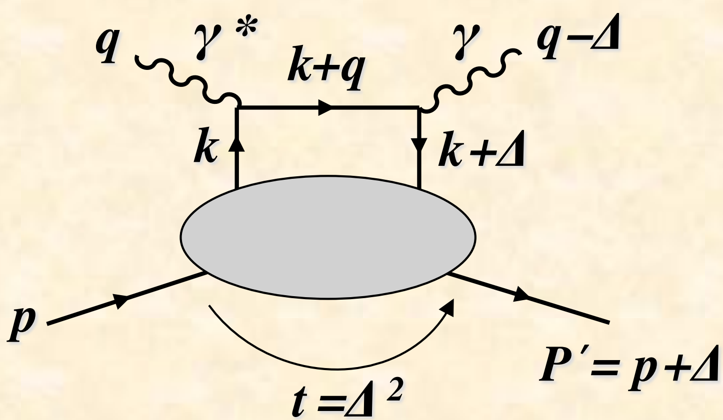
$$= \left(i\frac{\partial}{\partial z^-}\right)^{n-1} \left[\bar{q}(-z/2)\gamma^+ q(z/2)\right]_{z=0}$$

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

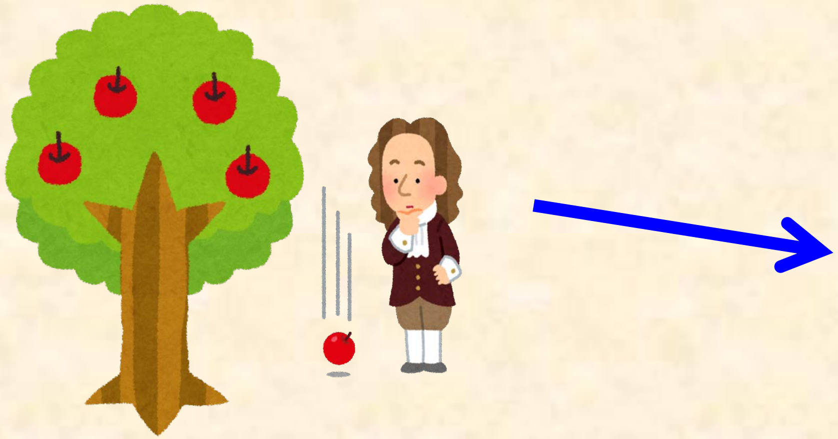
= energy-momentum tensor of a quark for $n=2$
(electromagnetic for $n=1$)

= source of gravitiy

Virtual Compton
or (timelike) two-photon process

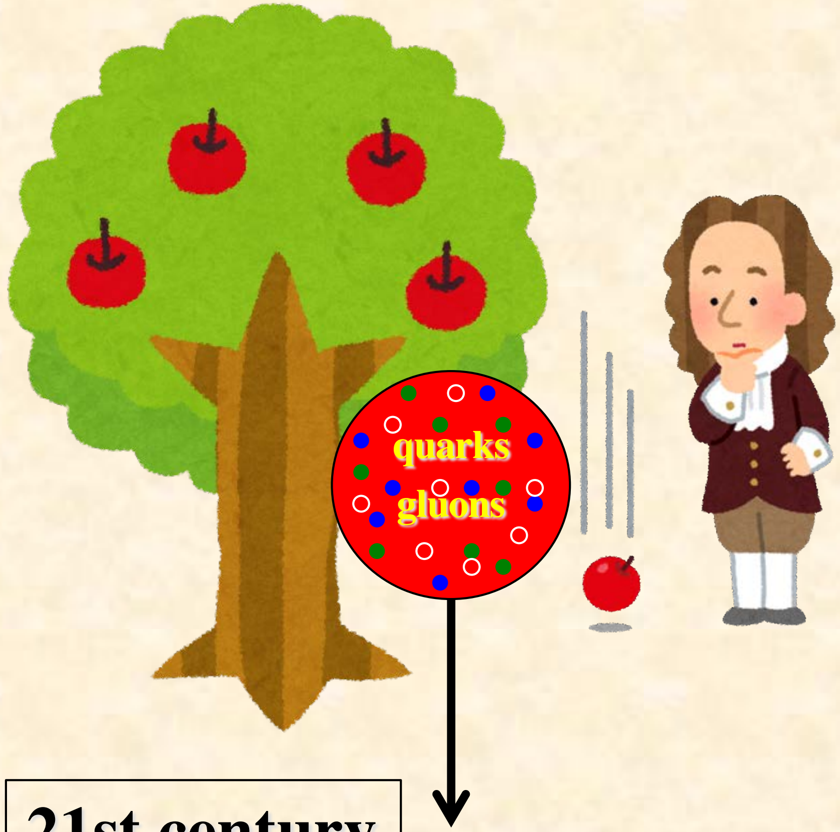


Time has come to understand the gravitational sources in microscopic (instead of usual macroscopic) world in terms of quark and gluon degrees of freedom.



17th century

@home due to plague pandemic



21st century

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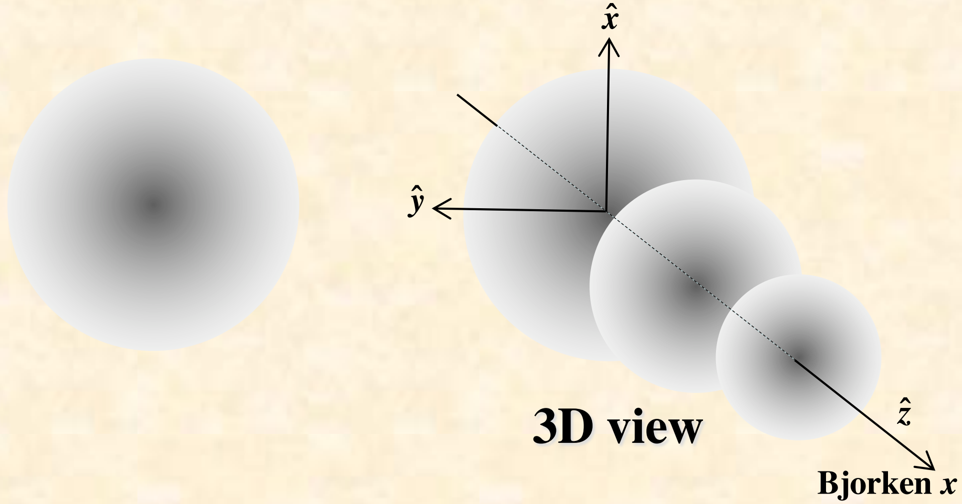
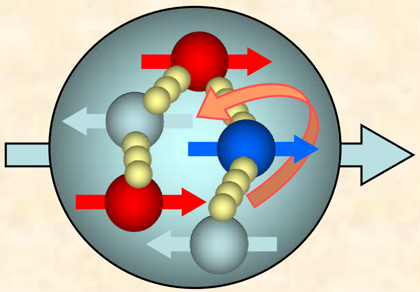
Proton (hadrons) puzzle studies by hadron tomography

Hadron tomography

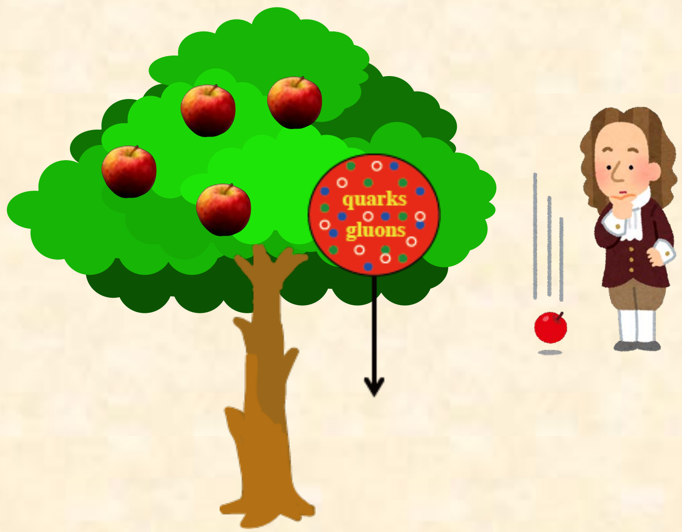
Proton radius puzzle



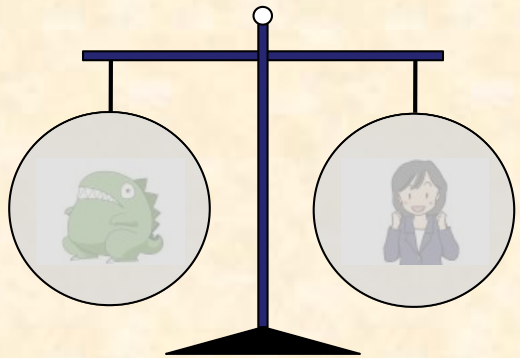
Origin of nucleon spin



Source of gravity (mass)

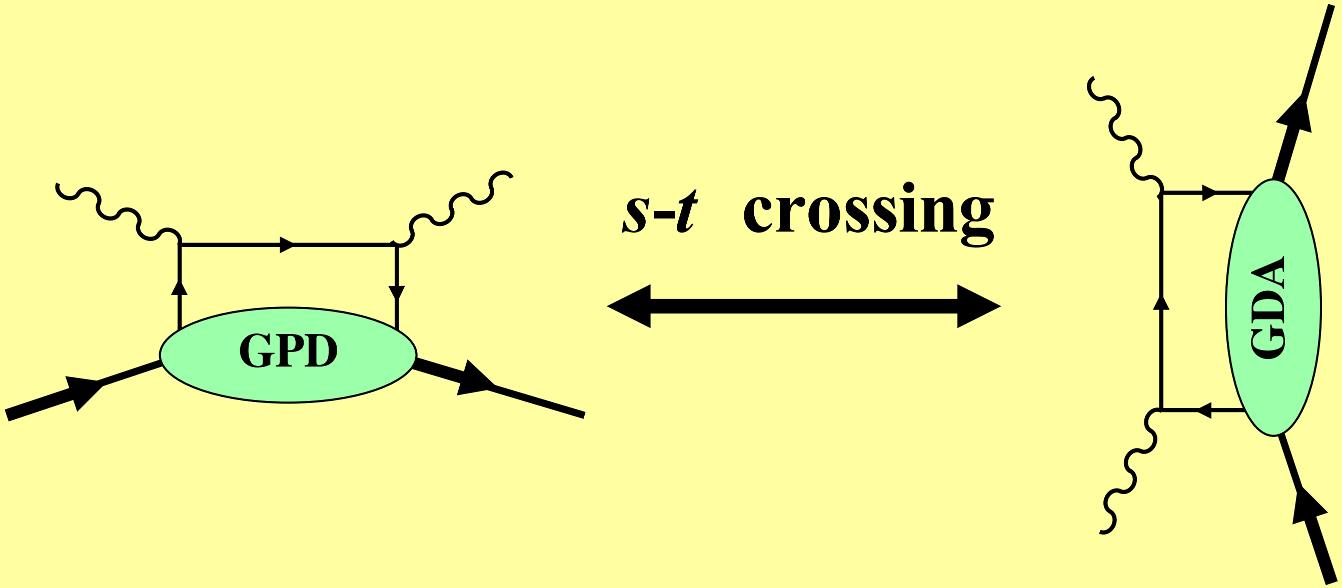


Exotic hadrons



Generalized Distribution Amplitudes (GDAs) and extraction of gravitational form factors from KEKB data

Spacelike GPDs **GDA = Timelike GPDs**



SK, Q.-T. Song, O. Teryaev,
Phys. Rev. D 97 (2018) 014020.

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

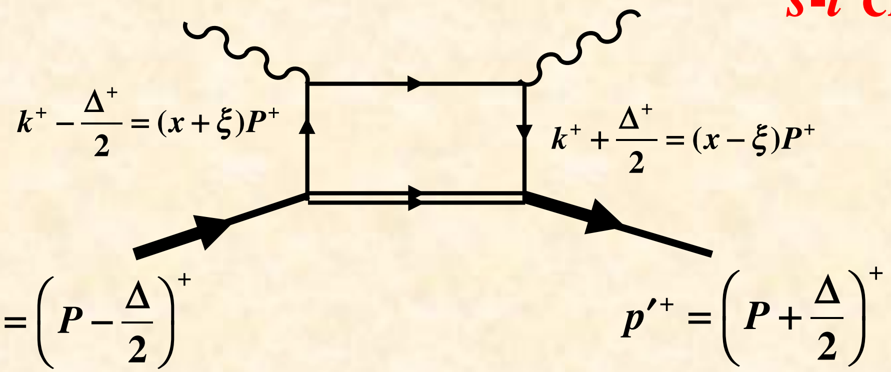
GPD: $H_q(x,\xi,t) = \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \langle h(p') | \bar{\psi}(-y/2)\gamma^+\psi(y/2) | h(p) \rangle \Big|_{y^+=0,\vec{y}_\perp=0}$, $\quad P^+ = \frac{(p+p')^+}{2}$

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

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

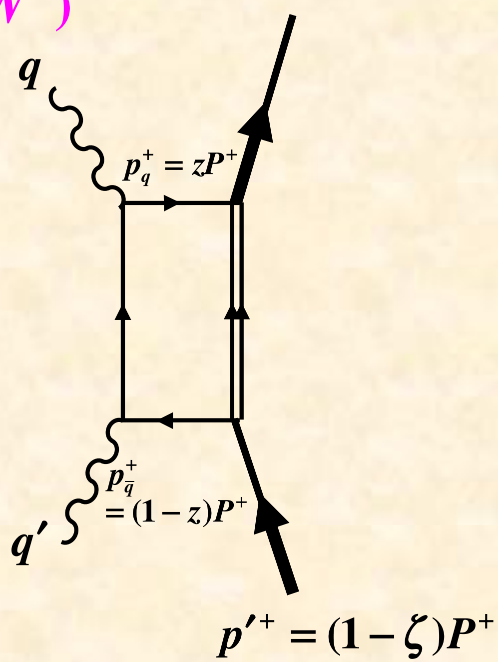
***s*-*t* crossing**



$z \Leftrightarrow \frac{1-x/\xi}{2}$

$\zeta \Leftrightarrow \frac{1-1/\xi}{2}$

$W^2 \Leftrightarrow t$



JLab / COMPASS

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

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

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

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

KEKB

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

Light-cone momentum ratio for a hadron 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 for $\gamma^* \gamma \to \pi^0 \pi^0$

$$\frac{d\sigma}{d(\cos\theta)} = \frac{1}{16\pi(s+Q^2)}\sqrt{1-\frac{4m_\pi^2}{s}}\sum_{\lambda,\lambda'}|\mathcal{M}|^2$$

$$\mathcal{M} = \varepsilon_\mu^\lambda(q)\varepsilon_\nu^{\lambda'}(q')T^{\mu\nu} = e^2 A_{\lambda\lambda'}, \quad T^{\mu\nu} = i\int d^4\xi\, e^{-i\xi\cdot q}\left\langle \pi(p)\pi(p')\left|T J_{em}^\mu(\xi) J_{em}^\nu(0)\right|0\right\rangle$$

$$A_{\lambda\lambda'} = \frac{1}{e^2}\varepsilon_\mu^\lambda(q)\varepsilon_\nu^{\lambda'}(q')T^{\mu\nu} = -\varepsilon_\mu^\lambda(q)\varepsilon_\nu^{\lambda'}(q')g_T^{\mu\nu}\sum_q \frac{e_q^2}{2}\int_0^1 dz\frac{2z-1}{z(1-z)}\Phi_q^{\pi\pi}(z,\zeta,W^2)$$

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

$$\frac{d\sigma}{d(\cos\theta)} \simeq \frac{\pi\alpha^2}{4(s+Q^2)}\sqrt{1-\frac{4m_\pi^2}{s}}|A_{++}|^2, \quad A_{++} = \sum_q \frac{e_q^2}{2}\int_0^1 dz\frac{2z-1}{z(1-z)}\Phi_q^{\pi\pi}(z,\zeta,W^2)$$

- Continuum: GDAs without intermediate-resonance contribution

$$\Phi_q^{\pi\pi}(z,\zeta,W^2) = N_\pi z^\alpha(1-z)^\alpha(2z-1)\zeta(1-\zeta)F_q^\pi(s)$$

$$F_q^\pi(s) = \frac{1}{\left[1+(s-4m_\pi^2)/\Lambda^2\right]^{n-1}},$$ $n=2$ according to constituent counting rule

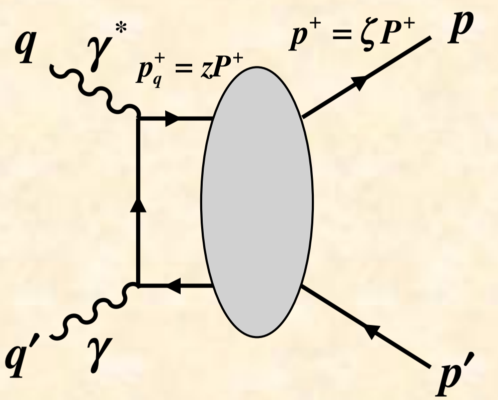
- Resonances: There exist resonance contributions to the cross section.

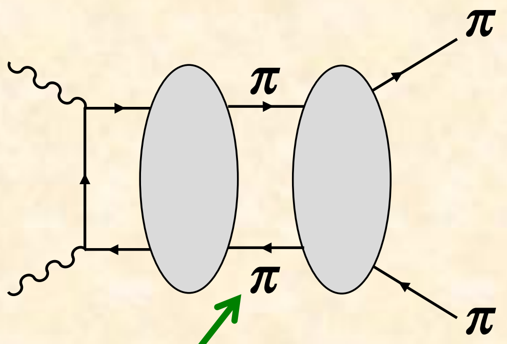
$$\sum_q \Phi_q^{\pi\pi}(z,\zeta,W^2) = 18N_f z^\alpha(1-z)^\alpha(2z-1)\left[\tilde{B}_{10}(W)+\tilde{B}_{12}(W)P_2(\cos\theta)\right]$$

$$P_2(x) = \frac{1}{2}(3x^2-1)$$

$\tilde{B}_{10}(W)$ = resonance $[f_0(500), f_0(980)]$ + continuum

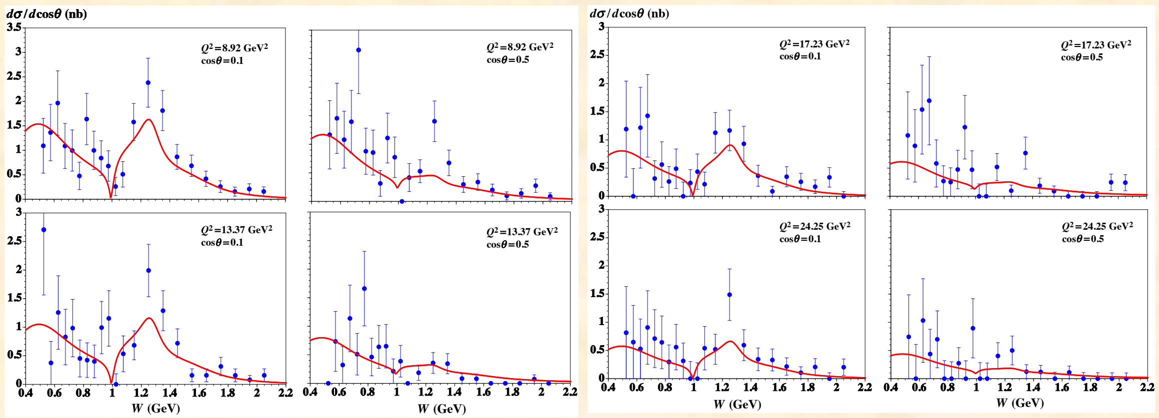
$\tilde{B}_{12}(W)$ = resonance$[f_2(1270)]$ + continuum





Including intermediate resonance contributions

$Q^2 = 8.92,\ 13.37\ \text{GeV}^2$ $\qquad$ $Q^2 = 17.23,\ 24.25\ \text{GeV}^2$



Belle measurements:
M. Masuda *et al.*,
PRD93 (2016) 032003.

Gravitational form factors and radii for pion

$$\int_0^1 dz(2z-1)\Phi_q^{\pi^0\pi^0}(z,\zeta,s) = \frac{2}{(P^+)^2}\left\langle \pi^0(p)\pi^0(p')\middle| T_q^{++}(0)\middle|0\right\rangle$$

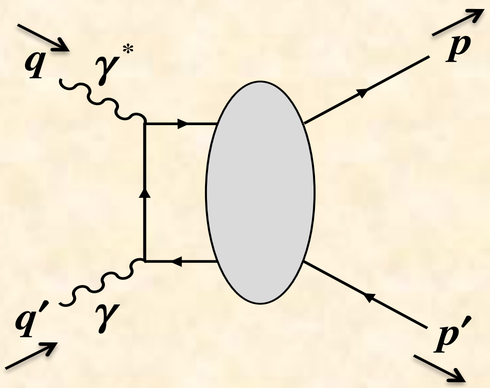
$$\left\langle \pi^0(p)\pi^0(p')\middle| T_q^{\mu\nu}(0)\middle|0\right\rangle = \frac{1}{2}\left[\left(sg^{\mu\nu} - P^\mu P^\nu\right)\Theta_{1,q}(s) + \Delta^\mu\Delta^\nu\Theta_{2,q}(s)\right]$$

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

See also Hyeon-Dong Son, Hyun-Chul Kim, PRD90 (2014) 111901.

$T_q^{\mu\nu}$: energy-momentum tensor for quark

$\Theta_{1,q}$, $\Theta_{2,q}$: gravitational form factos for pion



Analyiss of $\gamma^*\gamma \to \pi^0\pi^0$ cross section

$\Rightarrow$ Generalized distribution amplitudes $\Phi_q^{\pi^0\pi^0}(z,\zeta,s)$

$\Rightarrow$ Timelike gravitational form factors $\Theta_{1,q}(s)$, $\Theta_{2,q}(s)$

$\Rightarrow$ Spacelike gravitational form factors $\Theta_{1,q}(t)$, $\Theta_{2,q}(t)$

$\Rightarrow$ Gravitational radii of pion

Gravitational form factors:

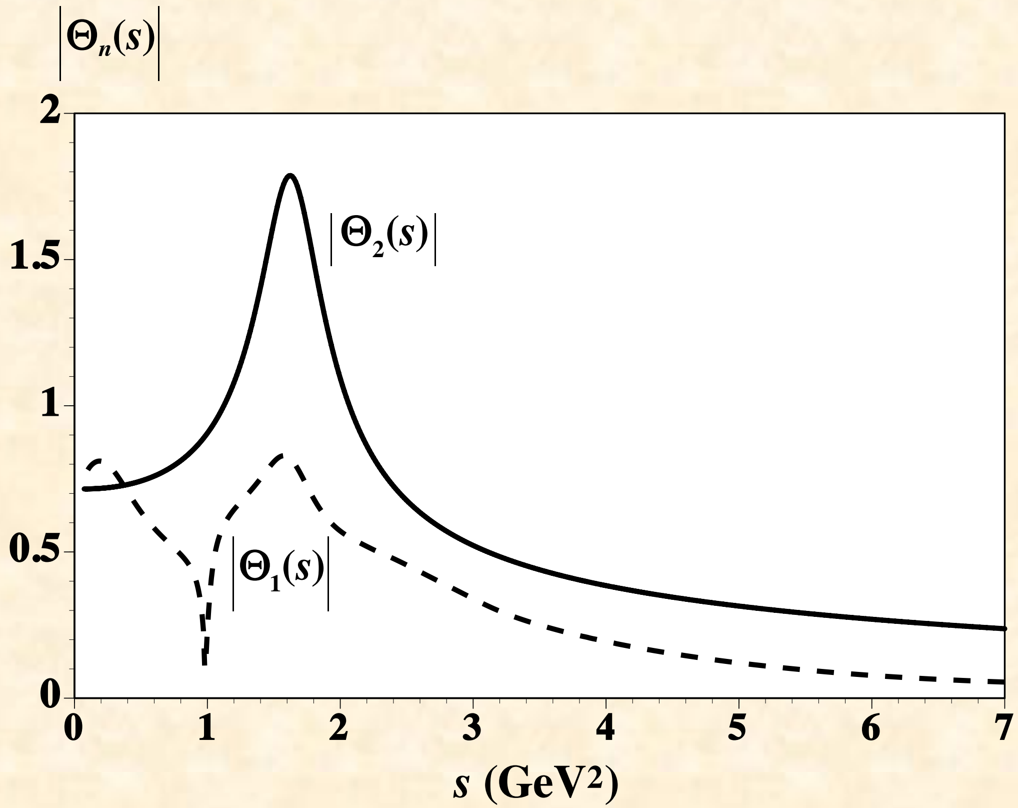
Original definition: H. Pagels, Phys. Rev. 144 (1966) 1250.

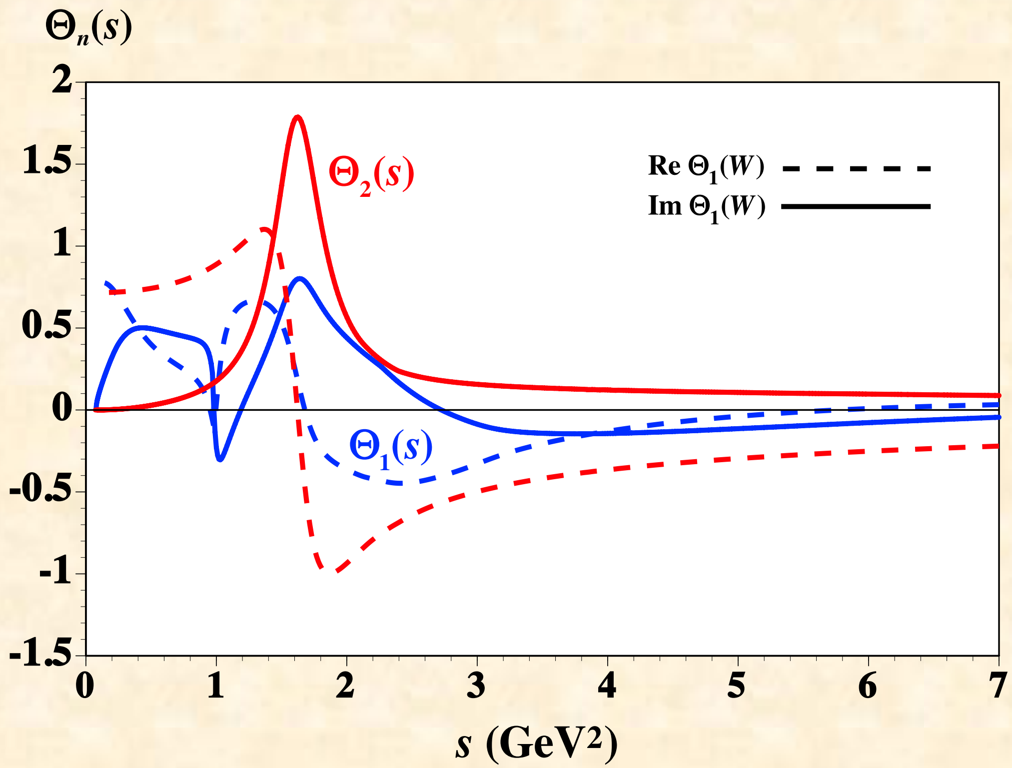
Operator relations: K. Tanaka, Phys. Rev. D 98 (2018) 034009;
Y. Hatta, A. Rajan, and K. Tanaka, JHEP 12 (2018) 008;
K. Tanaka, JHEP 01 (2019) 120.

Timelike gravitational form factors for pion

$$\langle \pi^a(p)\pi^b(p')|T_q^{\mu\nu}(0)|0\rangle = \frac{\delta^{ab}}{2}\left[(sg^{\mu\nu} - P^\mu P^\nu)\Theta_{1(q)}(s) + \Delta^\mu\Delta^\nu\Theta_{2(q)}(s)\right], \quad P = p + p', \quad \Delta = p' - p$$

- $\Theta_{1(q)}(s) = -\frac{3}{10}\tilde{B}_{10}(W^2) + \frac{3}{20}\tilde{B}_{12}(W^2) = -4B_{(q)}(s)$ **Mechanical (pressure and shear force) distribution**
- $\Theta_{2(q)}(s) = \frac{9}{20\beta^2}\tilde{B}_{12}(W^2) = A_{(q)}(s)$ **Mass (energy) distribution**





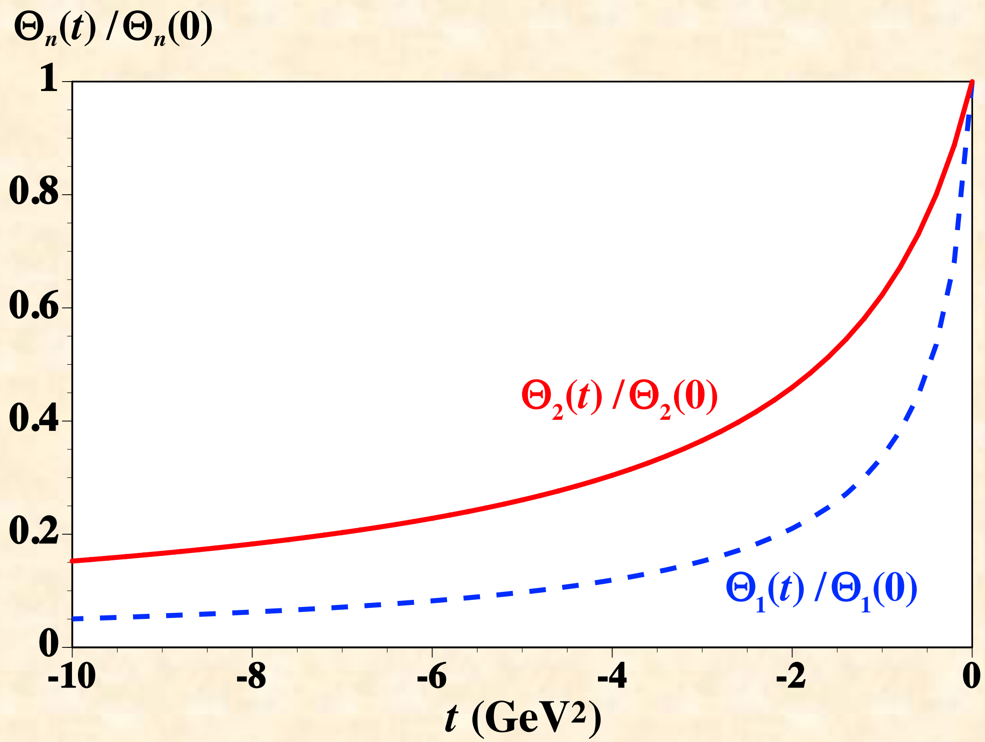
Spacelike gravitational form factors and radii for pion

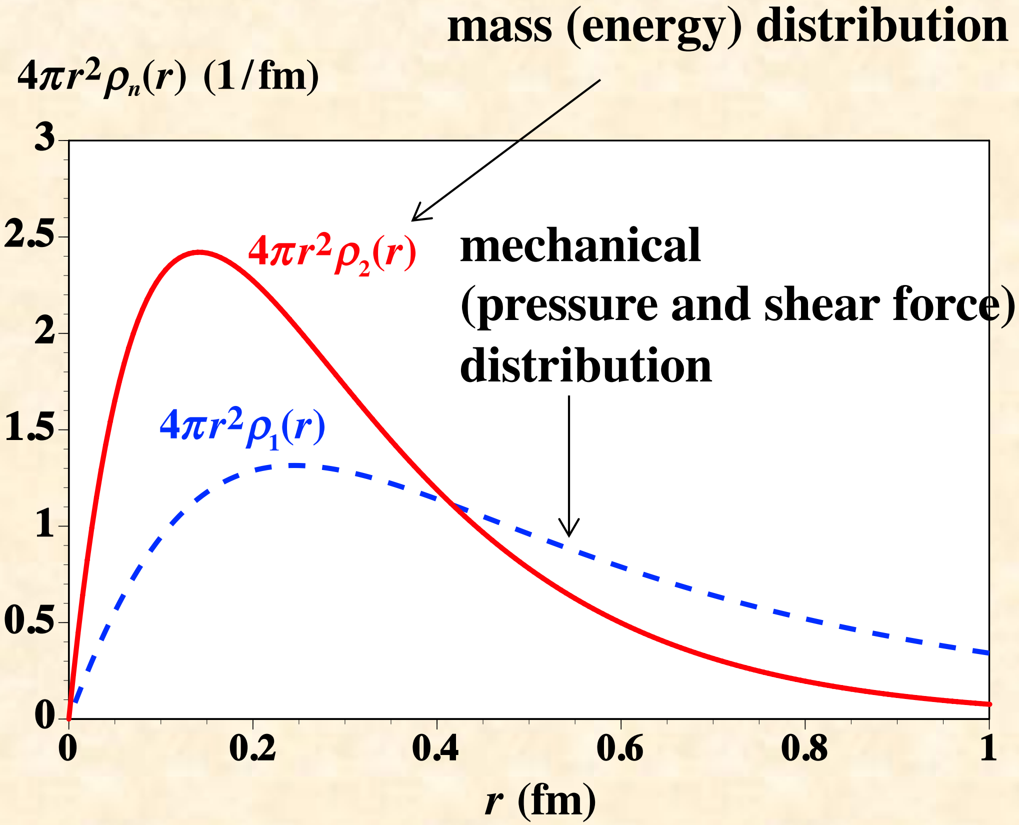
$$F(s)=\Theta_1(s),\ \Theta_1(s),\quad F(t)=\int_{4m_\pi^2}^{\infty} ds\,\frac{\mathrm{Im}\,F(s)}{\pi(s-t-i\varepsilon)},\quad \rho(r)=\frac{1}{(2\pi)^3}\int d^3q\,e^{-i\vec{q}\cdot\vec{r}}F(q)=\frac{1}{4\pi^2}\frac{1}{r}\int_{4m_\pi^2}^{\infty} ds\,e^{-\sqrt{s}r}\,\mathrm{Im}\,F(s)$$

This is the first report on gravitational radii of hadrons from actual experimental measurements.

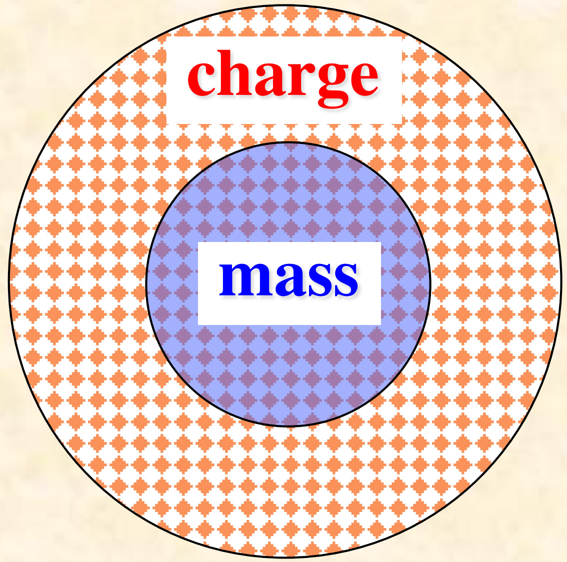
$\sqrt{\langle r^2\rangle_{\text{mass}}}=0.32\sim0.39$ fm, $\sqrt{\langle r^2\rangle_{\text{mech}}}=0.82\sim0.88$ fm ← First finding on gravitational radius from actual experimental measurements

$\Leftrightarrow\ \sqrt{\langle r^2\rangle_{\text{charge}}}=0.672\pm0.008$ fm





Hadron mass radius puzzle?



For pion

$$\sqrt{\langle r^2 \rangle_{\text{mass}}} = 0.32 \sim 0.39 \text{ fm} \;\Leftrightarrow\; \sqrt{\langle r^2 \rangle_{\text{charge}}} = 0.672 \pm 0.008 \text{ fm}$$

S. Kumano, Q.-T. Song, O. Teryaev, PRD 97 (2018) 014020;
Erratum in v3 of arXiv:1711.08088.

Mass radius seems to be much smaller than the charge radius for pion.

This is the first result on the mass radius from actual measurement, so further studies are needed to find whether there is acutally a significant difference

Quarks contribute to both charge and mass distributions, but gluons contribute to only the mass distribution.

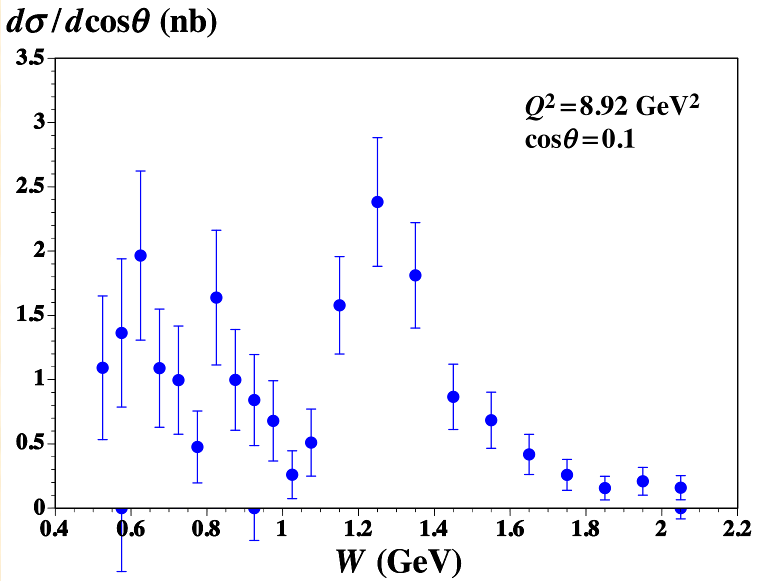
Electric interactions are repulsive (or could be attractive) and gravitational interactions are always attractive, so there would be some differences in both radii.
However, the difference of the factor of 2 may not be expected.

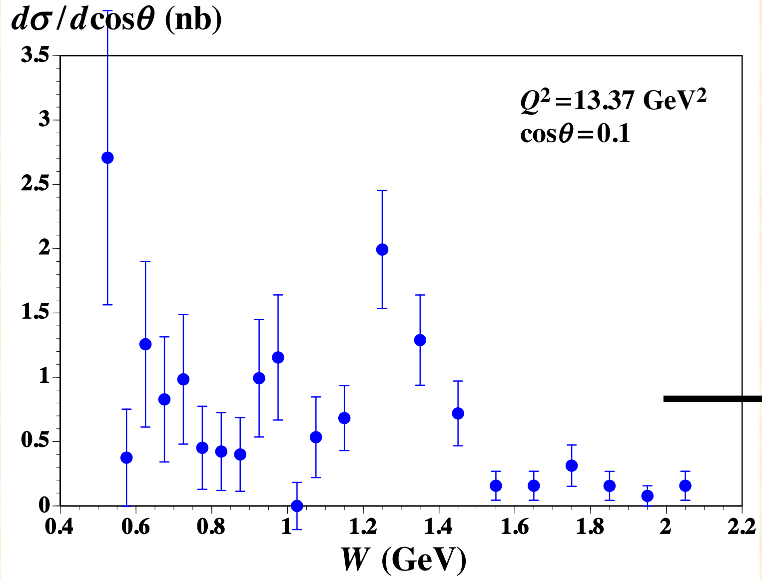
For example, related theoretical studies:
- **A. Freeseand I. C. Cloet, Phys. Rev. C 100 (2019) 015201;**
- **P. E. Shanahan and W. Detmold, Phys. Rev. D 99 (2019) 014511;**
- **C. D. Roberts, D. G. Richards, T. Horn, and L. Chang, Prog. Part. Nucl. Phys.120 (2021) 103883.**

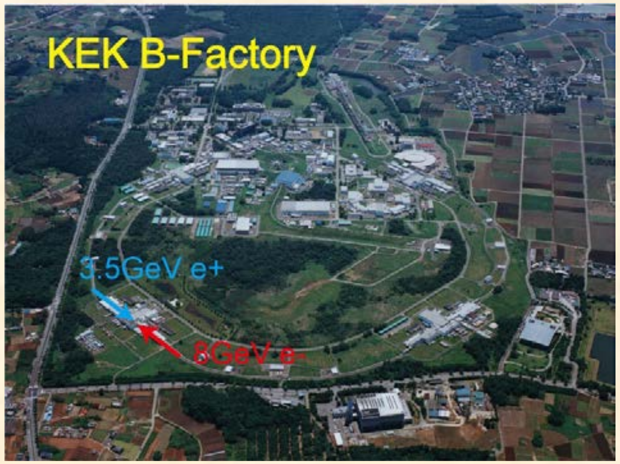
I may miss some of your papers.

Super KEKB

The errors are dominated by statistical errors, and they will be significantly reduced by super-KEKB.





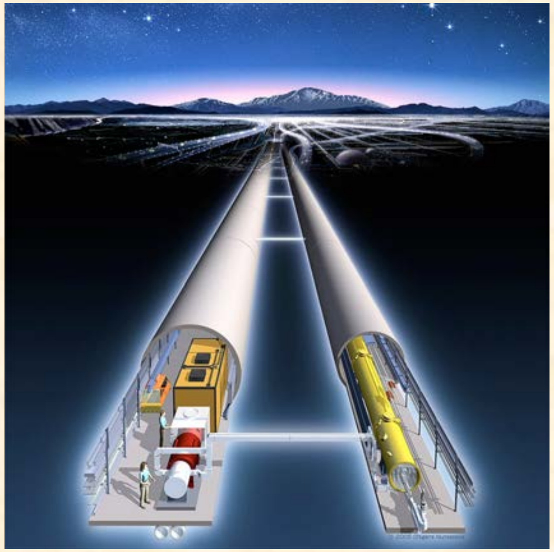


From KEKB to ILC

- **Very Large Q^2**
- **Large W^2**

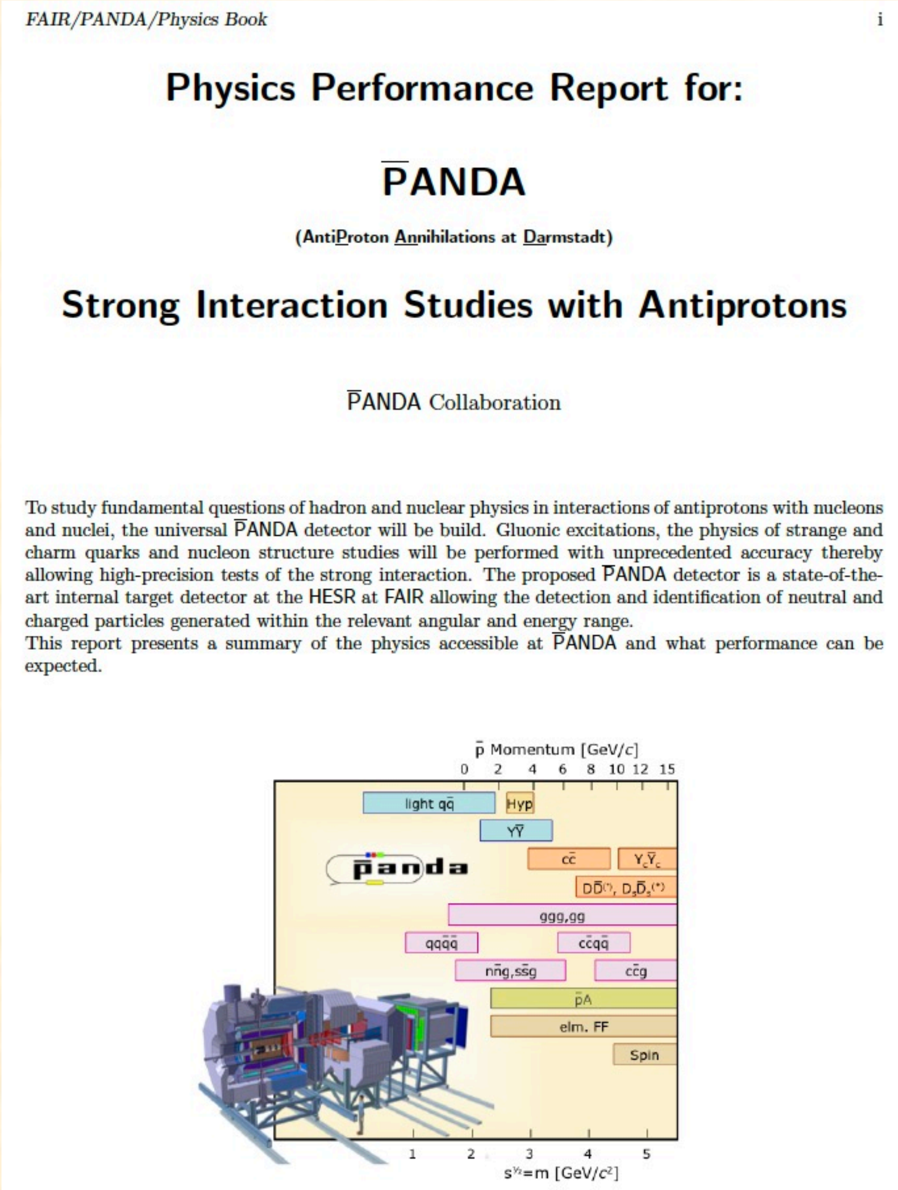
for extracting GDAs

→ **ILC**



GSI-FAIR (PANDA)

arXiv:0903.3905 [hep-ex]



FAIR/PANDA/Physics Book i

Physics Performance Report for:

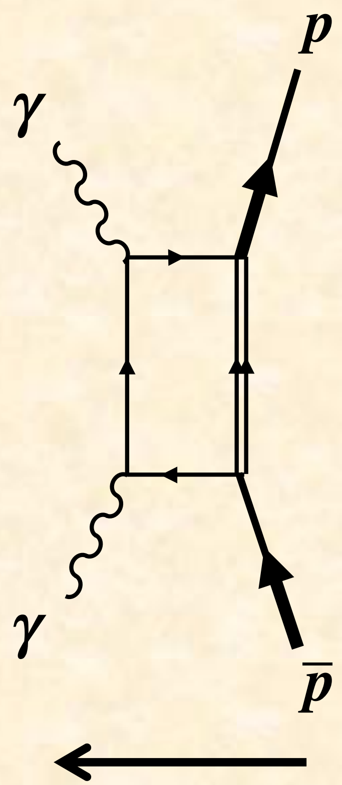
$\overline{\text{P}}$ANDA

($\overline{\text{A}}$nti**P**roton **An**nihilations at **Da**rmstadt)

Strong Interaction Studies with Antiprotons

$\overline{\text{P}}$ANDA Collaboration

To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal $\overline{\text{P}}$ANDA detector will be build. Gluonic excitations, the physics of strange and charm quarks and nucleon structure studies will be performed with unprecedented accuracy thereby allowing high-precision tests of the strong interaction. The proposed $\overline{\text{P}}$ANDA detector is a state-of-the-art internal target detector at the HESR at FAIR allowing the detection and identification of neutral and charged particles generated within the relevant angular and energy range.
This report presents a summary of the physics accessible at $\overline{\text{P}}$ANDA and what performance can be expected.



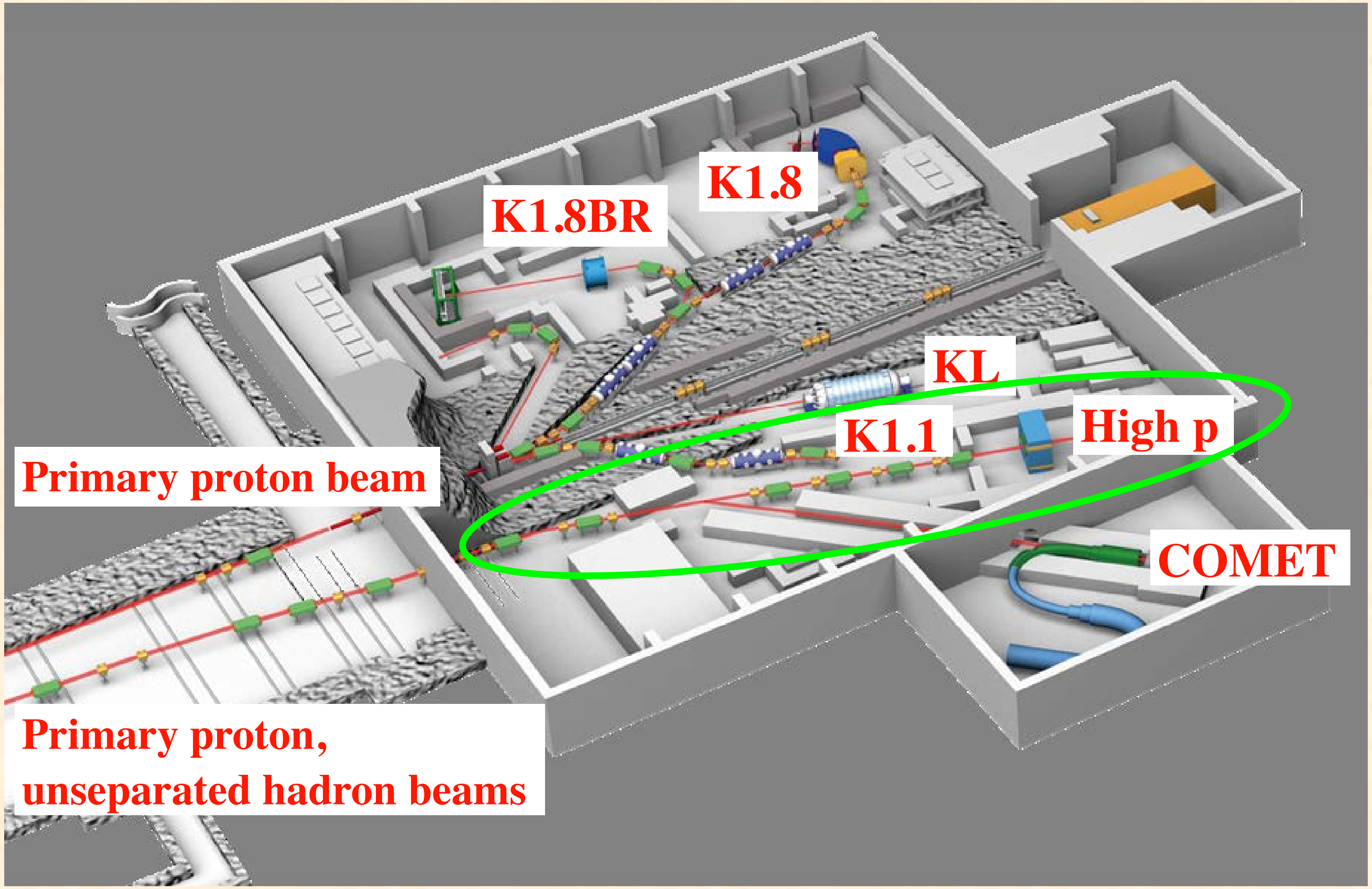
GDAs for the proton!
(also @super-KEKB)

Possible studies on GPDs at hadron accelerator facilities

SK, M. Strikman, K. Sudoh,
PRD 80 (2009) 074003;
T. Sawada, W.-C. Chang, SK, J.-C. Peng, S. Sawada, and K. Tanaka,
PRD 93 (2016) 114034.
J-PARC LoI 2019-07, J.-K. Ahn *et al*. (2019).
J-PARC proposal under preparation (2022),
Please get in touch with W.-C. Chang if you are interested in this project.

Hadron facility

Workshops on high-momentum beamline physics,
http://www-conf.kek.jp/hadron1/j-parc-hm-2013/
http://research.kek.jp/group/hadron10/j-parc-hm-2015/.

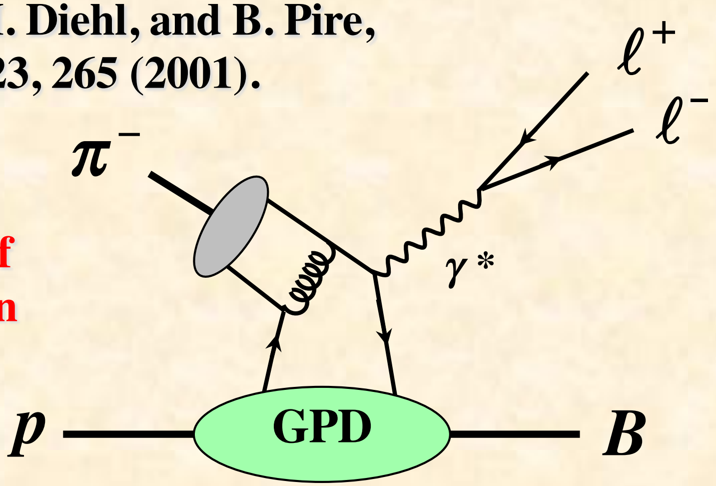


- Proton beam up to 30 GeV
- Unseparated hadron (pion, …) beam up to 15~20 GeV

Toward J-PARC experiments

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

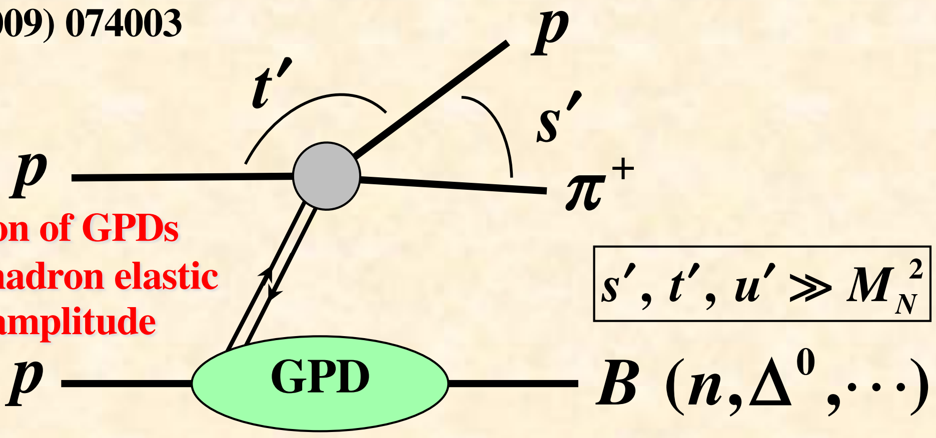
Investigation of
GPDs with pion
distribution
amplitude



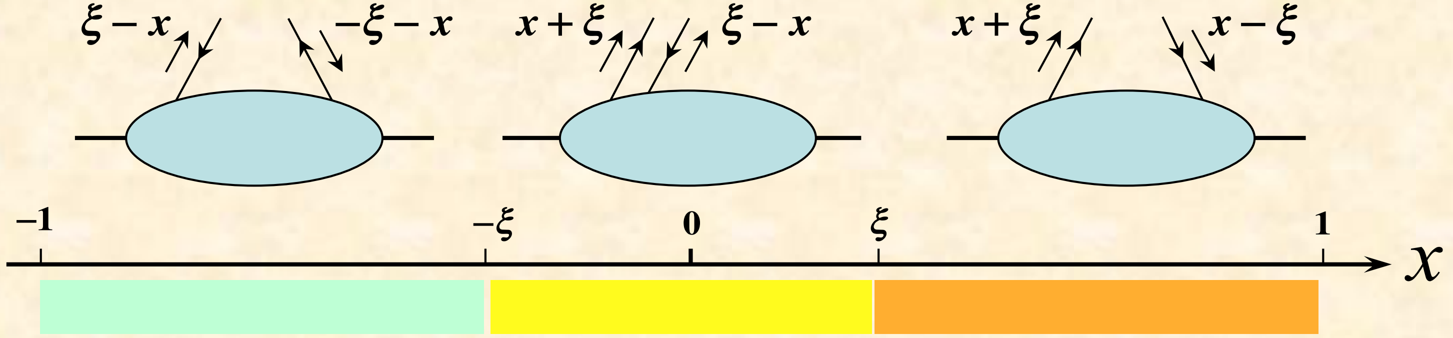
$$\pi^-(\bar{u}d) + p(uud) \rightarrow B(udd) + \gamma^*(\rightarrow \ell^+\ell^-)$$

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

Investigation of GPDs
with 2→2 hadron elastic
scattering amplitude



GPDs in different x regions and GPDs at hadron facilities



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

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

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

Quark distribution

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

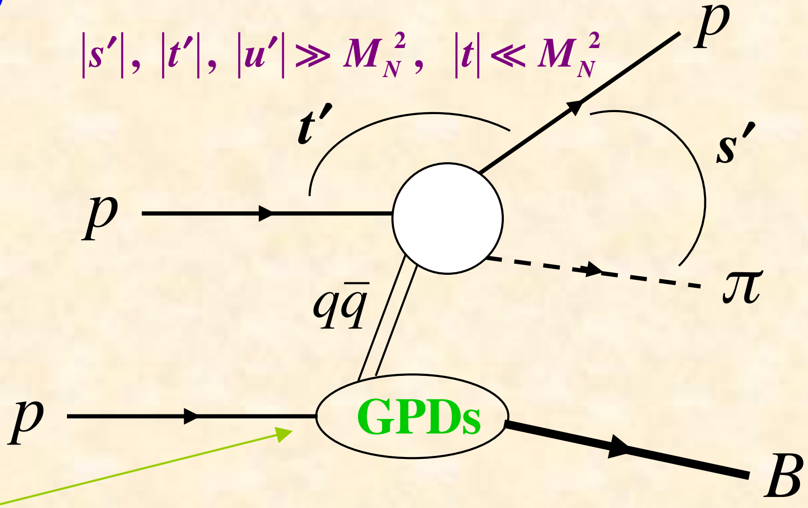
$q\bar{q}$(meson)-like distribution amplitude

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

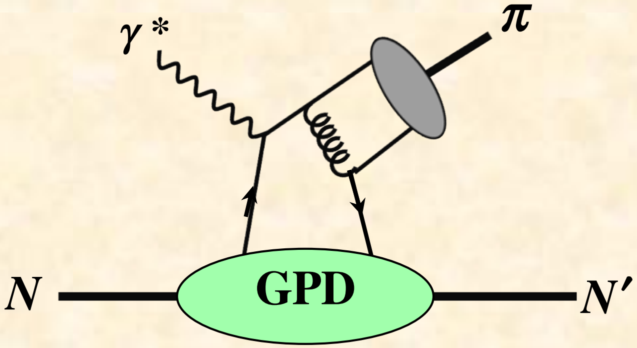


GPDs at J-PARC: SK, M. Strikman, and K. Sudoh, PRD 80 (2009) 074003.

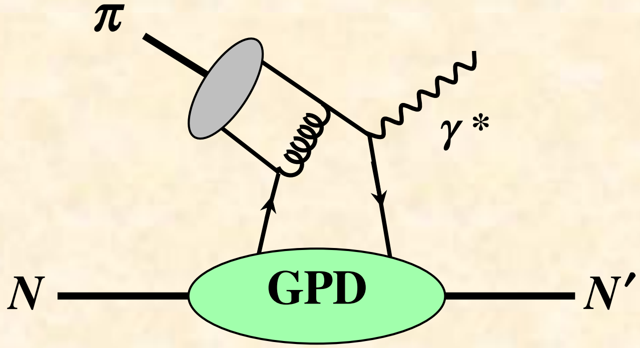
Efremov-Radyushkin -Brodsky-Lepage (ERBL) region

GPD projects at JLab /EIC and J-PARC

JLab / EIC



J-PARC



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

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

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

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

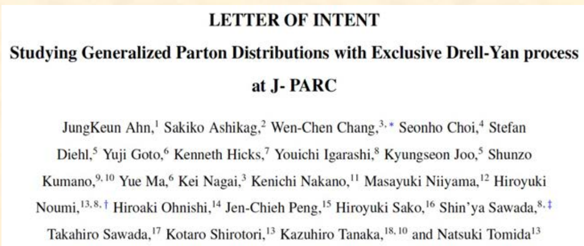
$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \left\langle p(p')\right| \bar{q}(-z/2)\gamma^+\gamma_5 q(z/2) \left| p(p)\right\rangle\Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[\tilde{H}_p^q(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}_p^q(x,\xi,t)\bar{u}(p')\frac{\gamma_5\Delta^+}{2M}u(p)\right]$$

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

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

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

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

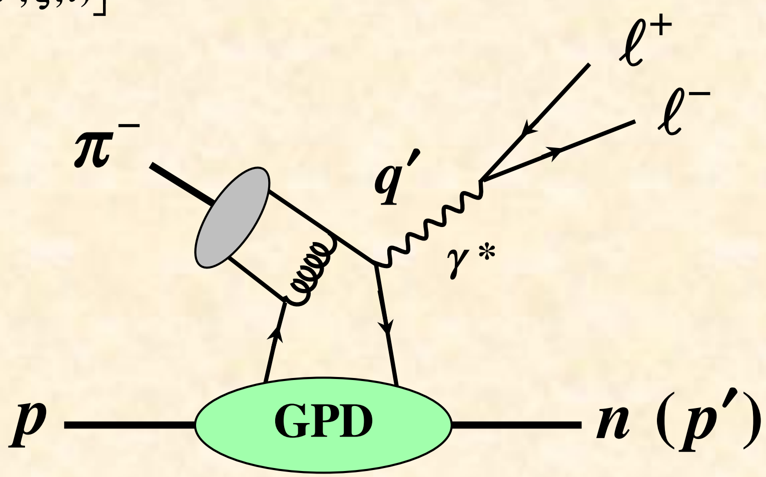


LETTER OF INTENT

Studying Generalized Parton Distributions with Exclusive Drell-Yan process at J-PARC

JungKeun Ahn,[1] Sakiko Ashikag,[2] Wen-Chen Chang,[3,*] Seonho Choi,[4] Stefan Diehl,[5] Yuji Goto,[6] Kenneth Hicks,[7] Youichi Igarashi,[8] Kyungseon Joo,[5] Shunzo Kumano,[9,10] Yue Ma,[6] Kei Nagai,[3] Kenichi Nakano,[11] Masayuki Niiyama,[12] Hiroyuki Noumi,[13,8,†] Hiroaki Ohnishi,[14] Jen-Chieh Peng,[15] Hiroyuki Sako,[16] Shin'ya Sawada,[8,‡] Takahiro Sawada,[17] Kotaro Shirotori,[13] Kazuhiro Tanaka,[18,10] and Natsuki Tomida[13]

LoI for a J-PARC experiment

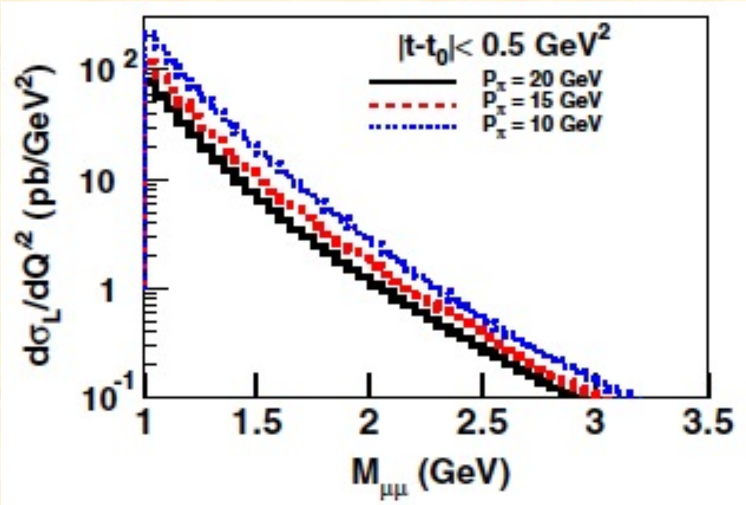


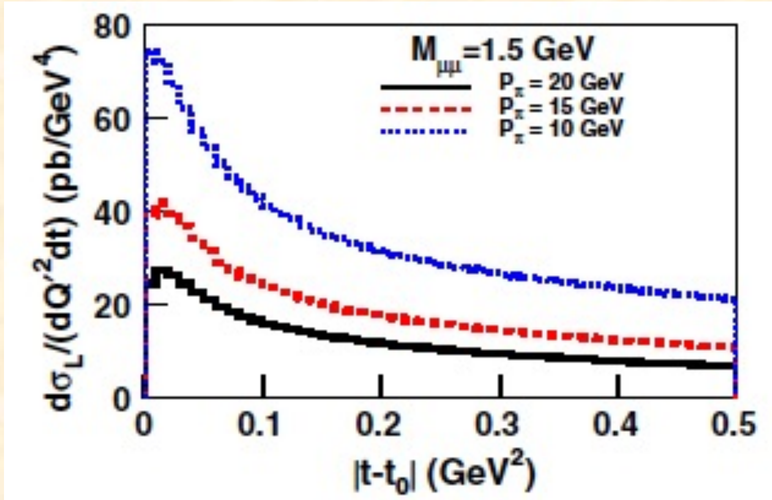
$$\pi^-(\bar{u}d) + p(uud) \to n(udd) + \gamma^*(\to \ell^+\ell^-)$$

Expected Drell-Yan events at J-PARC

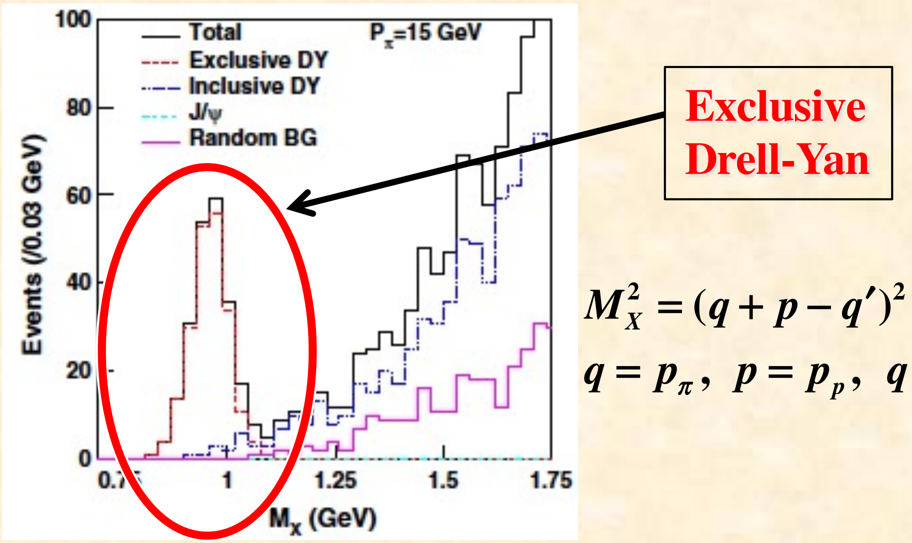
$$Q'^2 = q'^2,\; t = (p - p')^2,\; \tau = \frac{Q'^2}{2p\cdot q_\pi} \simeq \frac{Q'^2}{s - m_N^2}$$

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



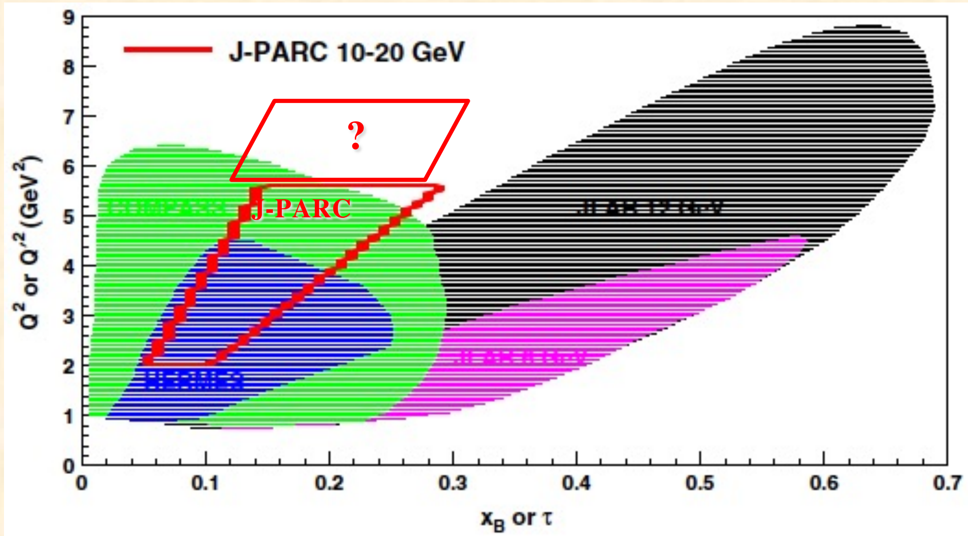


Missing mass



$$M_X^2 = (q + p - q')^2$$

$$q = p_\pi,\; p = p_p,\; q = p_{\mu^+\mu^-}$$

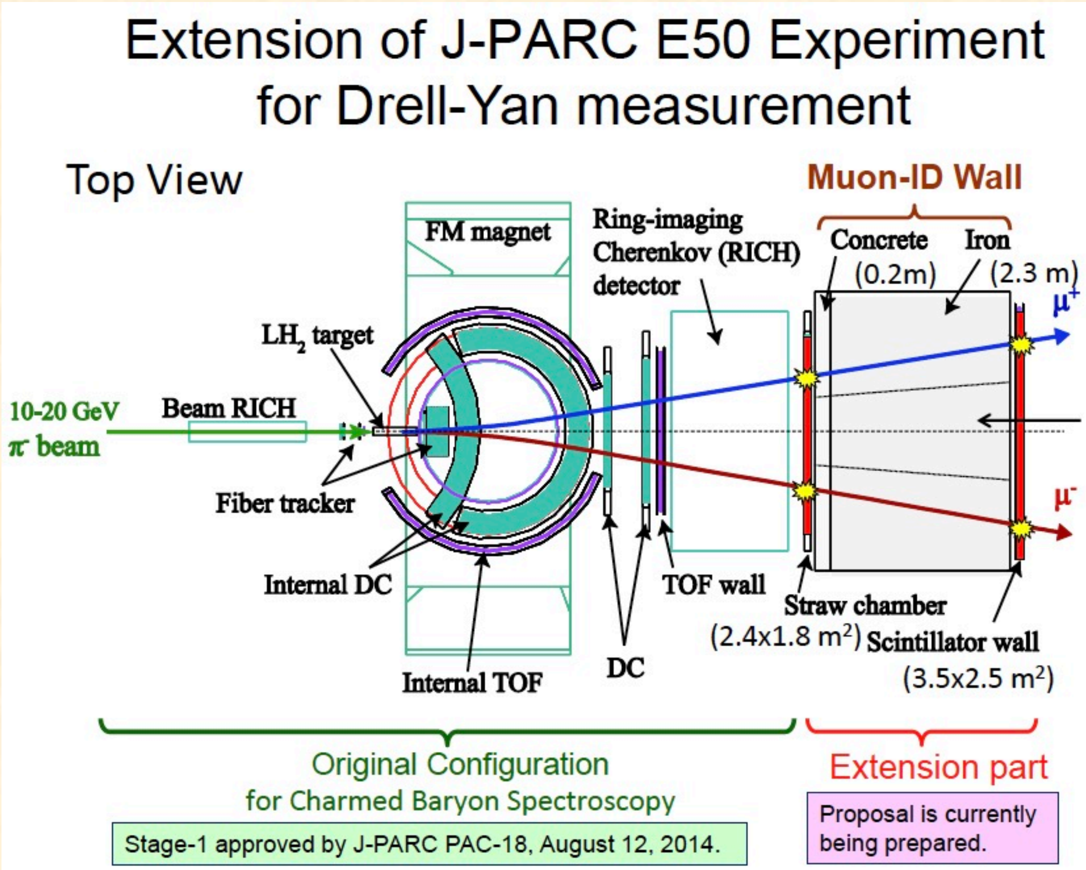


Letter of Intent to join J-PARC-E50 collaboration (Jan. 2019)

LETTER OF INTENT

Studying Generalized Parton Distributions with Exclusive Drell-Yan process at J- PARC

JungKeun Ahn,[1] Sakiko Ashikag,[2] Wen-Chen Chang,[3,*] Seonho Choi,[4] Stefan Diehl,[5] Yuji Goto,[6] Kenneth Hicks,[7] Youichi Igarashi,[8] Kyungseon Joo,[5] Shunzo Kumano,[9,10] Yue Ma,[6] Kei Nagai,[3] Kenichi Nakano,[11] Masayuki Niiyama,[12] Hiroyuki Noumi,[13,8,†] Hiroaki Ohnishi,[14] Jen-Chieh Peng,[15] Hiroyuki Sako,[16] Shin'ya Sawada,[8,‡] Takahiro Sawada,[17] Kotaro Shirotori,[13] Kazuhiro Tanaka,[18,10] and Natsuki Tomida[13]



U.S.-Japan Hadronic Physics Exchange Program for Studies of Hadron Structure and QCD

Travel support to Japan on joint projects,
https://www.jlab.org/usjhpe

Covid-19 is clearing in Japan. Good for this program!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for Studies of Hadron Structure and QCD

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ABOUT USJHPE

USJHPE is a US-Japan exchange program supporting collaborative scientific research in hadronic physics. It focuses on subject areas related to the programs at current and future experimental facilities in the US and Japan and supports both experimental and theoretical studies.

USJHPE particularly aims to realize synergies between the hadronic physics programs at Jefferson Lab 12 GeV and J-PARC resulting from the complementarity of electromagnetic and hadronic probes in the multi-GeV energy range. Subject areas of common interest include the quark-gluon structure of hadrons and nuclei, meson and baryon spectroscopy, strangeness and hypernuclear physics, and other related topics.

USJHPE also supports research in hadronic physics and nuclear-physics-enabled tests of fundamental symmetries related to the programs at Brookhaven National Lab, Fermilab, KEK, Spring-8, and university-based facilities in the US and Japan. USJHPE especially promotes collaboration between the US and Japanese nuclear physics communities in the development of the physics program for the future Electron-Ion Collider.

USJHPE is intended to provide travel grants to US-based scientists (primary institutional affiliation with a US university, national laboratory, or other research center) to visit Japanese institutions and conduct collaborative research there. The program can support senior researchers, postdoctoral fellows, and students.

Researchers interested in participating in the program should submit an application following the guidelines given in Application. Applications will be reviewed by a Coordinating Committee, and awards will be made competitively, subject to the availability of funds.

For questions about the program, please contact usjhpe@jlab.org

USJHPE is supported by the US Department of Energy under grant DE-SC0021359 "U.S.-Japan Hadronic Physics Exchange Program for Studies of Hadron Structure and QCD." The program governance is described in Governance.

Possible studies on GPDs at neutrino facilities

- SK, EPJ Web Conf. 208 (2019) 07003.
- EIC yellow report, R. Abdul Khalek *et al*., arXiv:2103.05419, Sec. 7.5.2, Neutrino physics by SK and R. Petti.
- SK and R. Petti, PoS (NuFact2021) 092.

References on GPDs in ν reactions

- B. Lehmann-Dronke and A. Schafer, Phys. Lett. B 521, 55 (2001).
  D_s production
- P. Amore, C. Coriano, and M. Guzzi, J. High Energy Phys. 02 (2005) 038.
  DVNS (Deeply Virtual Neutrino Scattering): Neutral current
- C. Coriano and M. Guzzi, Phys. Rev. D 71, 053002 (2005).
  DVNS (Deeply Virtual Neutrino Scattering): Charged current
- A. Psaker, W. Melnitchouk, and A. V. Radyushkin, Phys. Rev. D 75, 054001 (2007).
  Detailed GPD formalism and numerical analysis on DVNS
- G. R. Goldstein, O. G. Hernandez, S. Liuti, and T. McAskill, AIP Conf. Proc. 1222, 248 (2010).
  π^0 production formalism and nuclear target
- B. Z. Kopeliovich, I. Schmidt, and M. Siddikov, Phys. Rev. D 86, 113018 (2012).
  Meson (π, K, η) productions and GPDs
- B. Z. Kopeliovich, I. Schmidt, and M. Siddikov, Phys. Rev. D 89, 053001 (2014).
  Higher-twist effects in π production
- B. Pire and L. Szymanowski, Phys. Rev. Lett. 115, 092001 (2015).
  $D^{+/-}$ production and chiral-odd GPDs
- M. Siddikov and I. Schmidt, Phys. Rev. D 95, 013004 (2017).
  NLO corrections in π and K productions
- B. Pire, L. Szymanowski, and J. Wagner, Phys. Rev. D 95, 094001 (2017).
  D production with gluon (in addition to quark) contributions
- B. Pire, L. Szymanowski, and J. Wagner, Phys. Rev. D 95, 114029 (2017).
  π and ρ production with gluon (in addition to quark) contributions

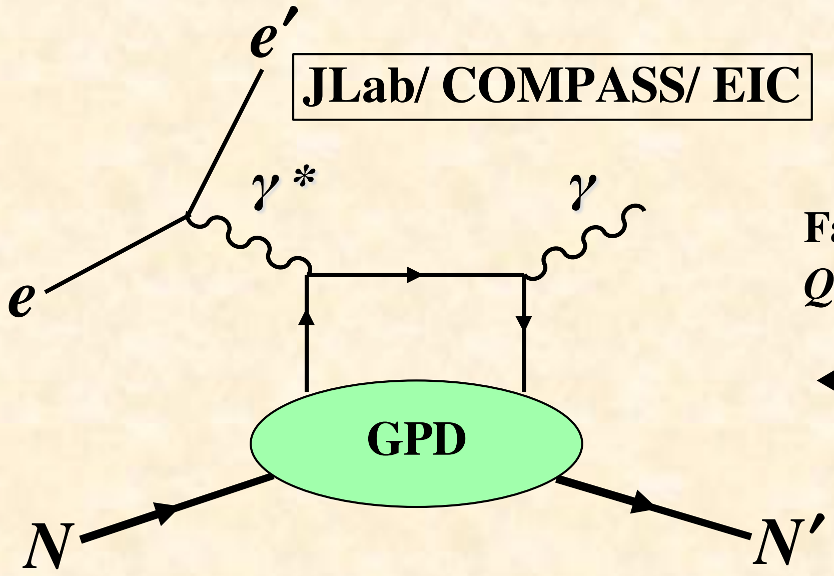
↑ * The most updated information is obtained in this 2017 publication for the pion production.

Our studies

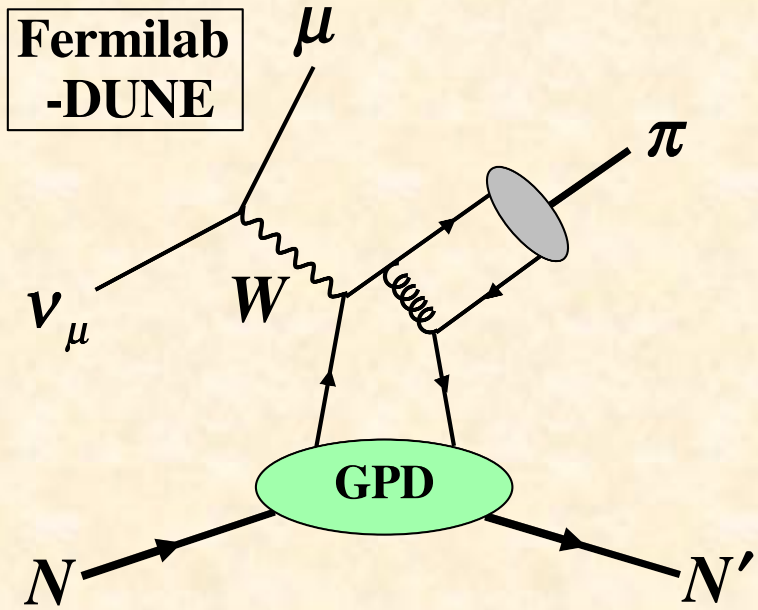
- **High-energy neutrino interactions and GPDs**
  High-energy neutrino-nucleus interactions,
  SK, EPJ Web Conf. 208 (2019) 07003.
- **Synergies between EIC project and neutrino reactions**
  EIC yellow report, A. Accardi *et al*., arXiv:2103.05419,
  see Sec. 7.5.2, Neutrino phyiscs by SKand R. Petti.
- **Fermilab-LBNF neutrino-beam information**
  Impact of high energy beam tunes on the sensitivities
  to the standard unknowns at DUNE,
  J. Rout, S. Roy, M. Masud, M. Bishai, P. Mehta,
  Phys. Rev. D 102 (2020) 116018.

  Deep Underground
  Neutrino Experiment (DUNE)
- **Possible studies on generalized parton distributions and gravitational form factors in neutrino reactions,**
  Neutrino-factory 2021 workshop, proceedings
  SK and R. Petti, PoS (NuFact2021) 092.

Neutrino reactions for gravitational form factors @Fermilab-DUNE (Origins of hadron masses and pressures)

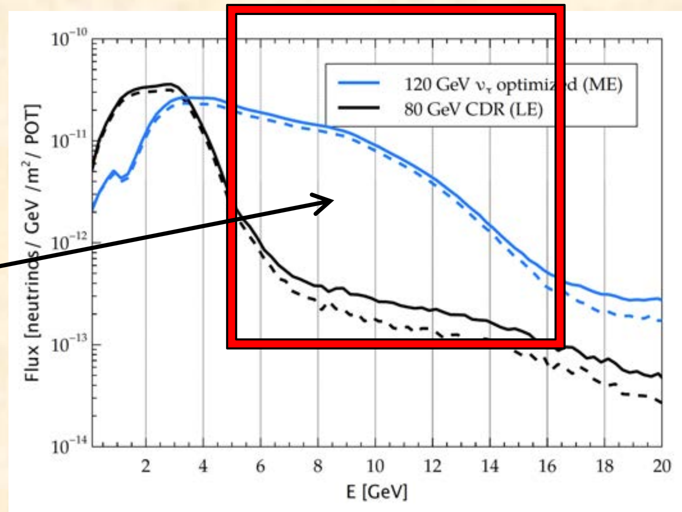


Factorization condition:
$Q^2 \gg |t|, \Lambda^2_{QCD}$



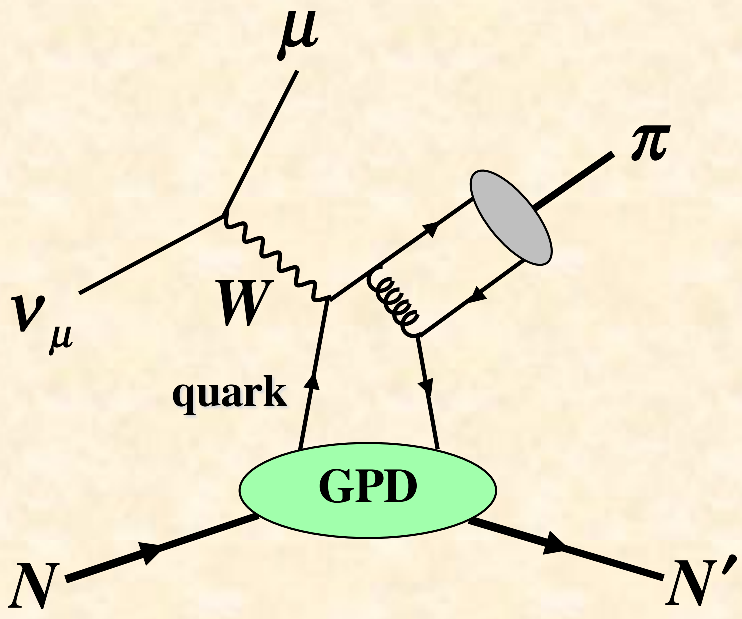
Deep Underground Neutrino Experiment (DUNE) at Long-Baseline Neutrino Facility (LBNF)

High-energy part of the LBNF ν beam can be used for the GPD studies.



J. Rout *et al.*, PRD 102 (2020) 116018

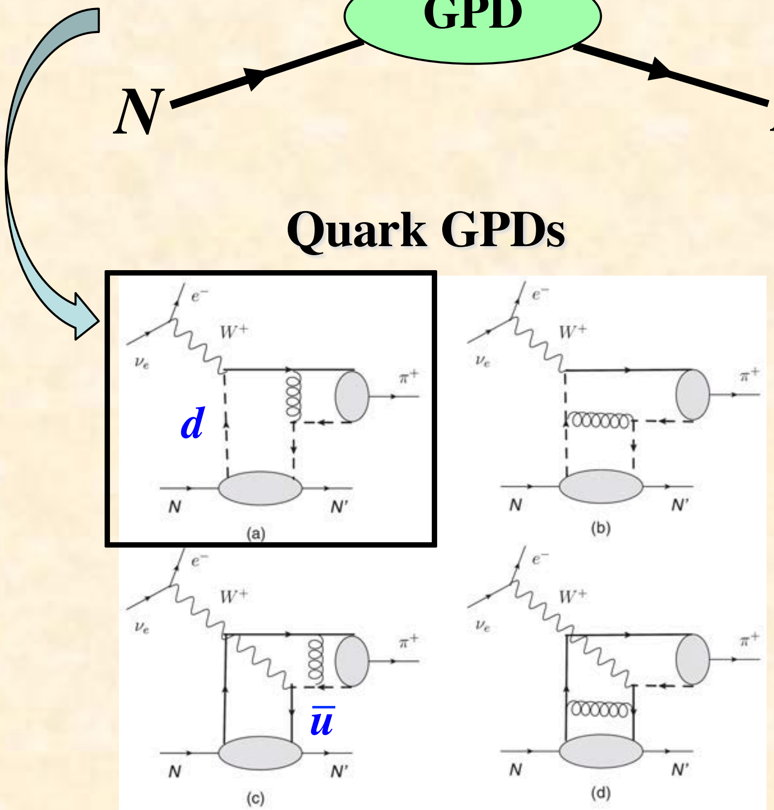
Recent work on pion production in neutrino reaction for GPD studies



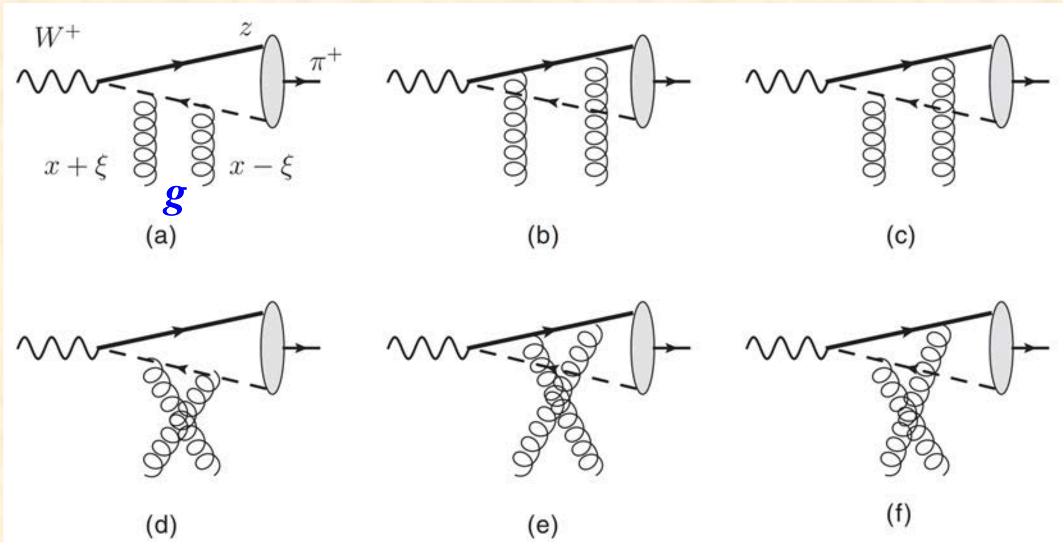
B. Pire, L. Szymanowski, and J. Wagner,
Phys. Rev. D 95, 114029 (2017).

There are several processes to contribute to the pion-production cross section, including the gluon GPD terms.

Quark GPDs



Gluon GPDs



Cross section formalism

B. Pire, L. Szymanowski, J. Wagner, Phys. Rev. D 95, 114029 (2017).

Cross section

$$\frac{d\sigma(\nu_\ell N \to \ell^- N'\pi)}{dy\,dQ^2\,dt\,d\phi} = \Gamma\,\varepsilon\,\sigma_L,\quad \varepsilon \simeq \frac{1-y}{1-y+y^2/2},\quad \Gamma = \frac{G_F^2 Q^2}{32\,(2\pi)^4 (s-m_N^2)^2\, y\,(1-\varepsilon)\sqrt{1+4x^2 m_N^2/Q^2}}$$

$$\sigma_L = \varepsilon_L^{*\mu} W_{\mu\nu}\varepsilon_L^{\nu} = \frac{1}{Q^2}\Big[(1-\xi^2)\Big\{\left|C_q\mathcal{H}_q + C_g\mathcal{H}_g\right|^2 + \left|C_q\widetilde{\mathcal{H}}_q\right|^2\Big\} + \frac{\xi^4}{1-\xi^2}\Big\{\left|C_q\mathcal{E}_q + C_g\mathcal{E}_g\right|^2 + \left|C_q\widetilde{\mathcal{E}}_q\right|^2\Big\}$$
$$-2\xi^2\,\mathrm{Re}\Big\{(C_q\mathcal{H}_q + C_g\mathcal{H}_g)(C_q\mathcal{E}_q + C_g\mathcal{E}_g)^*\Big\} - 2\xi^2\,\mathrm{Re}\Big\{C_q\widetilde{\mathcal{H}}_q(C_q\widetilde{\mathcal{E}}_q)^*\Big\}\Big]$$

Quark contributions

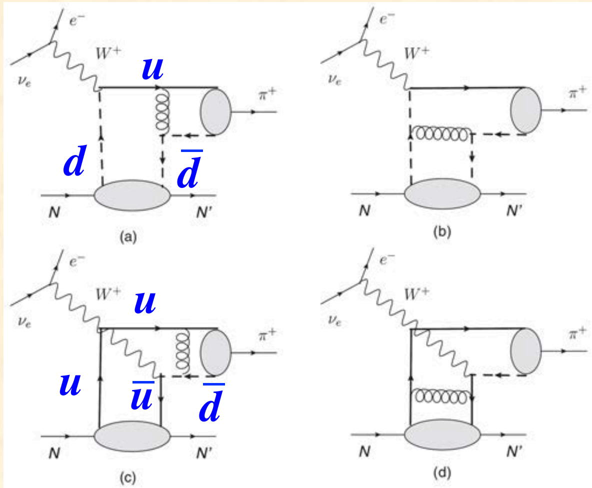
$$T_q = -i\frac{C_q}{2Q}N(p')\left[\mathcal{H}_q\hat{n} + \mathcal{E}_q\frac{i\sigma^{\mu\nu}n_\mu\Delta_\nu}{2m_N} - \widetilde{\mathcal{H}}_q\hat{n}\gamma_5 - \widetilde{\mathcal{E}}_q\frac{\gamma_5 n\cdot\Delta}{2m_N}\right]N(p)$$

$$\mathcal{F}_q = 2f_\pi\int\frac{dz\,\phi_\pi(z)}{1-z}\int dx\frac{F_q(x,\xi,t)}{x-\xi+i\varepsilon}$$

= (pion distribution amplitude) · (quark GPD)

$$F_q(x,\xi,t) \equiv F_d(x,\xi,t) - F_u(-x,\xi,t)$$

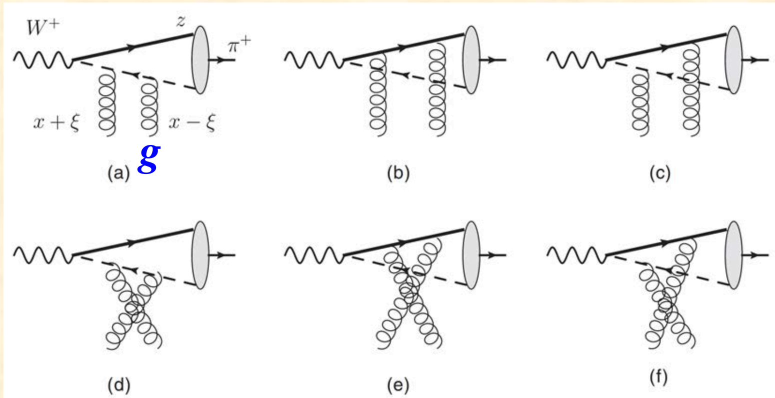
$$F = H,\ E,\ \tilde{H},\ \tilde{E}$$



Gluon contributions

$$T_g = -i\frac{C_g}{2Q}N(p')\left[\mathcal{H}^g\hat{n} + \mathcal{E}^g\frac{i\sigma^{\mu\nu}n_\mu\Delta_\nu}{2m_N}\right]N(p)$$

$$\mathcal{F}_g = \frac{8f_\pi}{\xi}\int\frac{dz\,\phi_\pi(z)}{z(1-z)}\int dx\frac{F_g(x,\xi,t)}{x-\xi+i\varepsilon}$$



Cross section estimates

proton: $\nu p \to \ell^- \pi^+ p$ **neutron: $\nu n \to \ell^- \pi^+ n$**

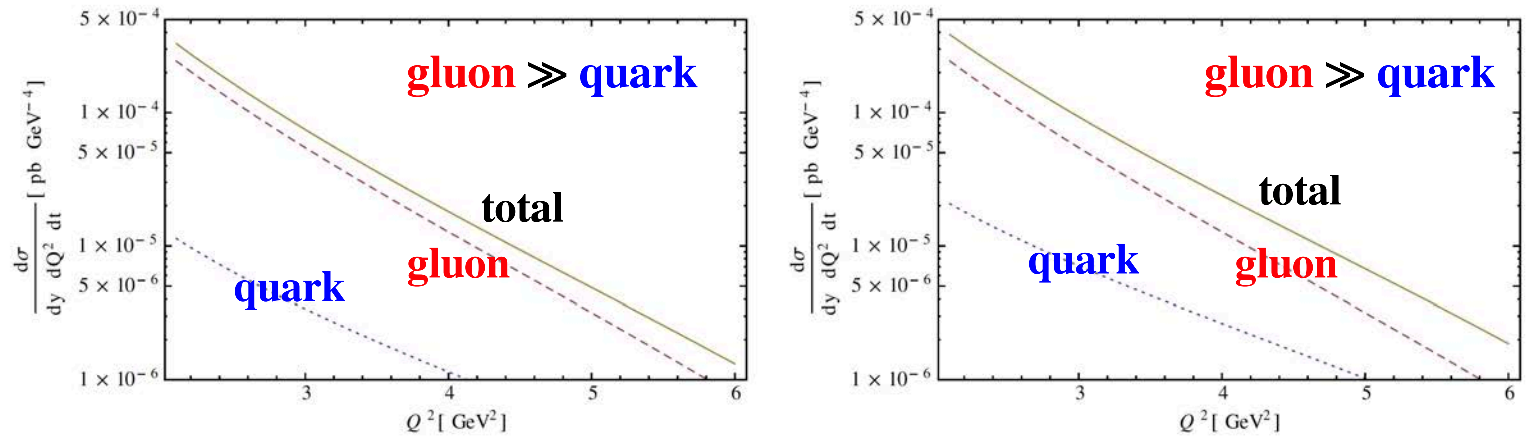


FIG. 3. The Q^2 dependence of the cross section $\frac{d^3\sigma(\nu N \to l^- N \pi^+)}{dy dQ^2 dt}$ (in pb GeV^{-4}) for $y = 0.7$, $\Delta_T = 0$ and $s = 20$ GeV^2, on a proton (left panel) and on a neutron (right panel). The quark contribution (dotted curves) is significantly smaller than the gluon contribution (dashed curves). The solid curves are the sum of the (quark + gluon + interference) contributions.

neutron → proton: $\nu n \to \ell^- \pi^0 p$

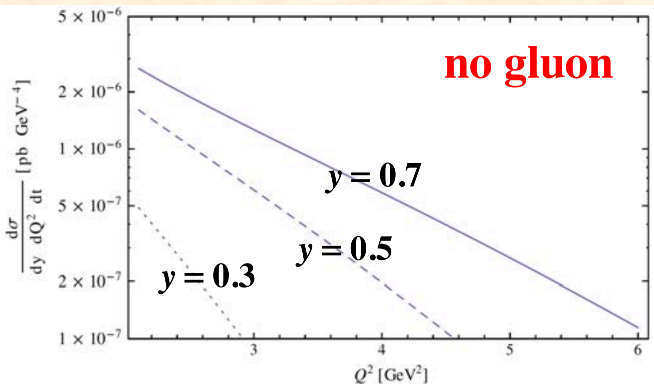
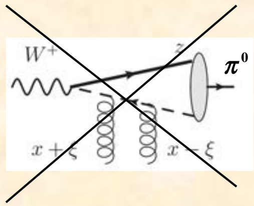


FIG. 6. The Q^2 dependence of the cross section $\frac{d^3\sigma(\nu n \to l^- p \pi^0)}{dy dQ^2 dt}$ (in pb GeV^{-4}) for $\Delta_T = 0$ and $s = 20$ GeV^2. The solid, dashed, and dotted lines correspond to $y = 0.7$, 0.5, and 0.3, respectively. There is no gluon contribution to this amplitude.

Neutrino GPD studies are complementary to the charged-lepton projects.

- **Gluon GPDs could be probed in charged-pion production.**
- **Flavor dependece of quark GPDs could be investigated.**

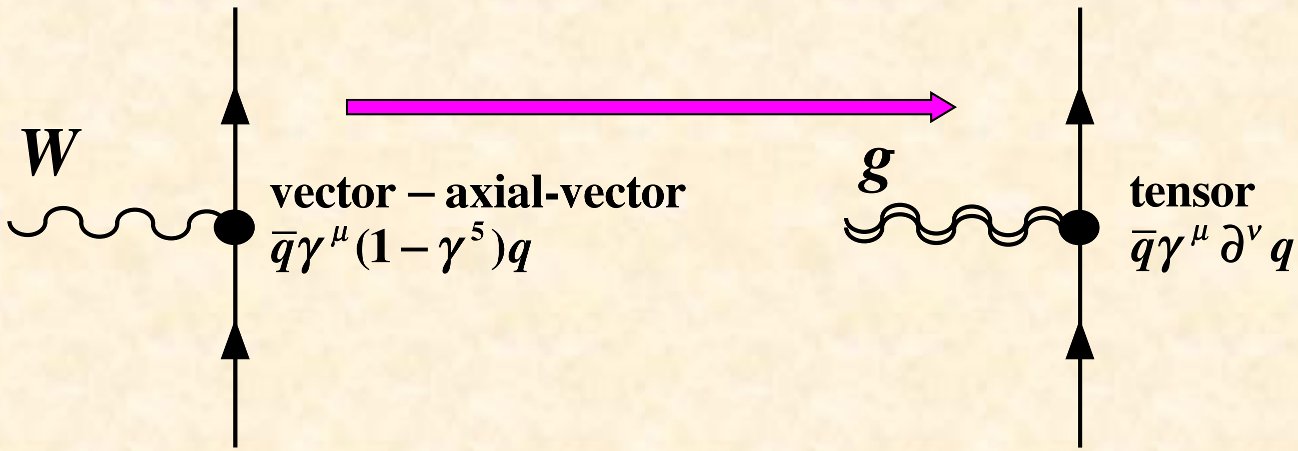


no gluon for π^0

Prospects on neutrino GPD project

- Neutrino-scattering experiments (LBNF) are valuable and complementary to JLab, COPMASS, KEK-B, and the other facility projects in the sense that the cross sections are sensitive to quark flavor.
- This project is already in progress.

  The new detector, which was the basis of various GPD measurements, was selected by the DUNE collaboration to be part of the near detector complex. (September, 2021, R. Petti)



GPDs for exotic hadrons

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

Constituent counting rule for exotic hadrons:
H. Kawamura, SK, T. Sekihara, PRD 88 (2013) 034010;
W.-C. Chang, SK, and T. Sekihara, PRD 93 (2016) 034006.

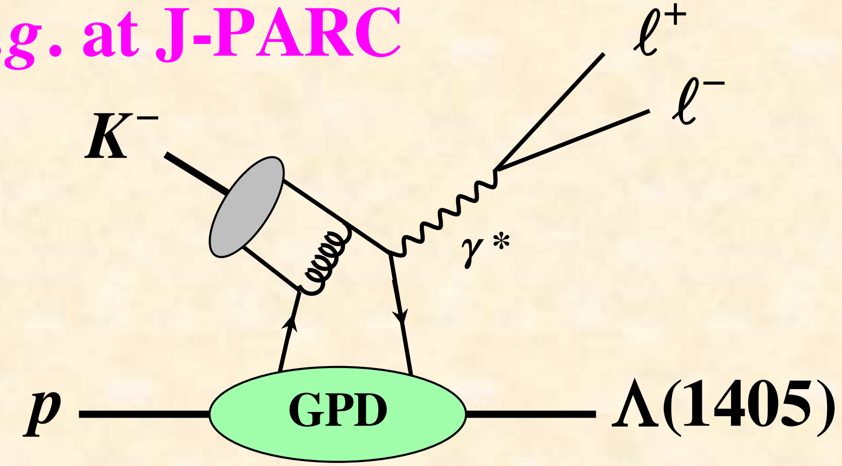
GPDs for exotic hadrons !?

Because stable targets do not exist 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 KEKB, Linear Collider

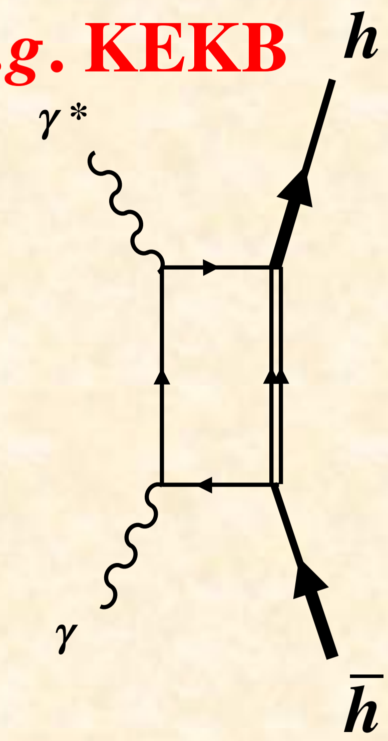
e.g. at J-PARC



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

Λ_{1405} = pentaquark ($\bar{K}N$ molecule) candidate

e.g. KEKB



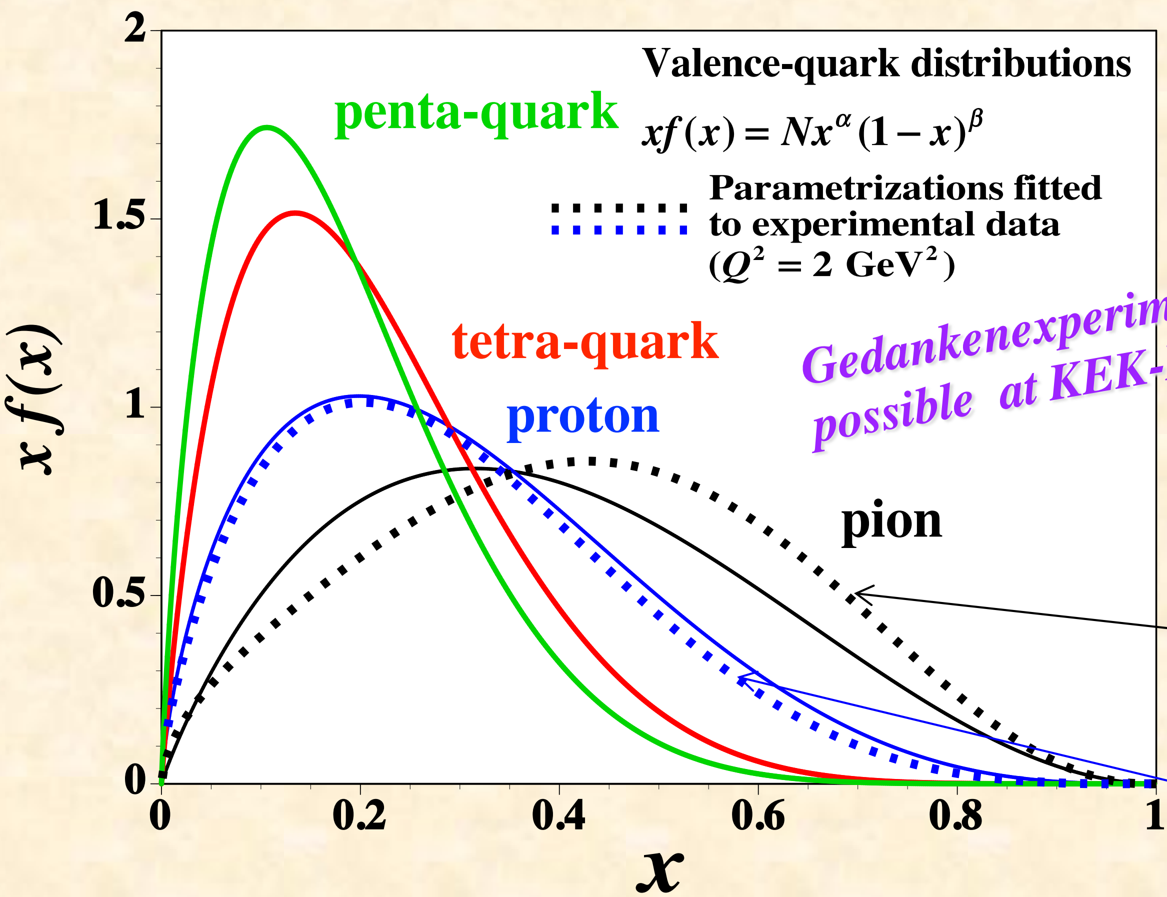
Simple function of GPDs

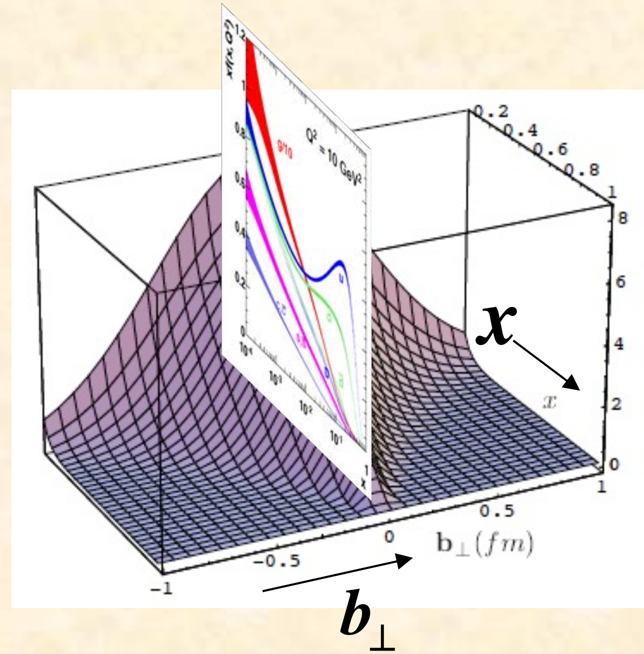
$H_q^h(x,t) = f(x)F(t,x)$

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



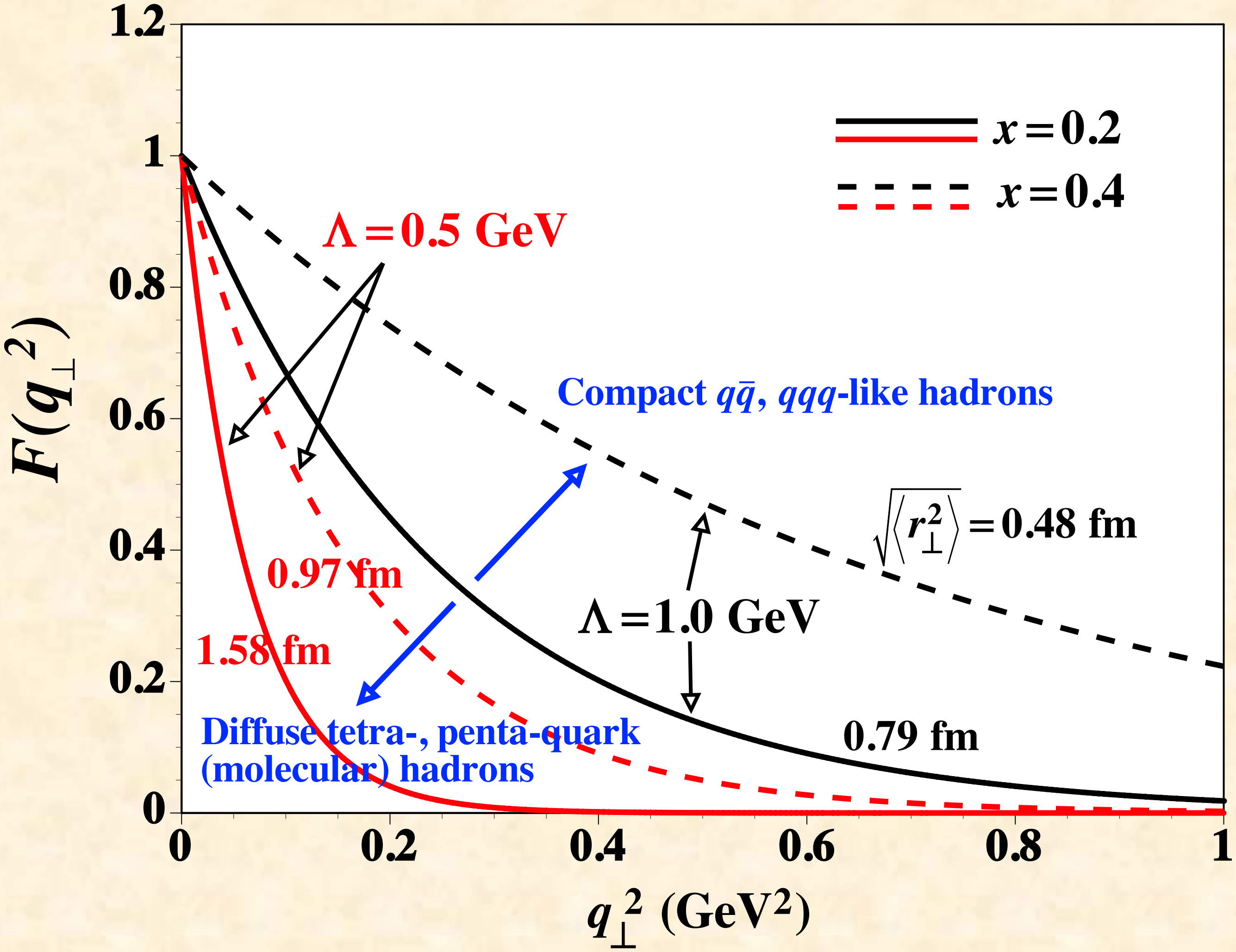


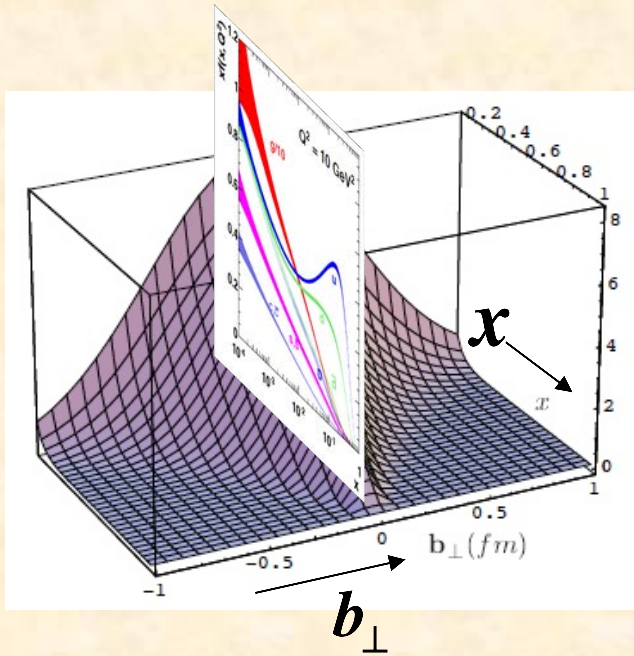
π: M. Aicher, A. Schafer, W. Vogelsang, PRL 105 (2010) 252003.

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

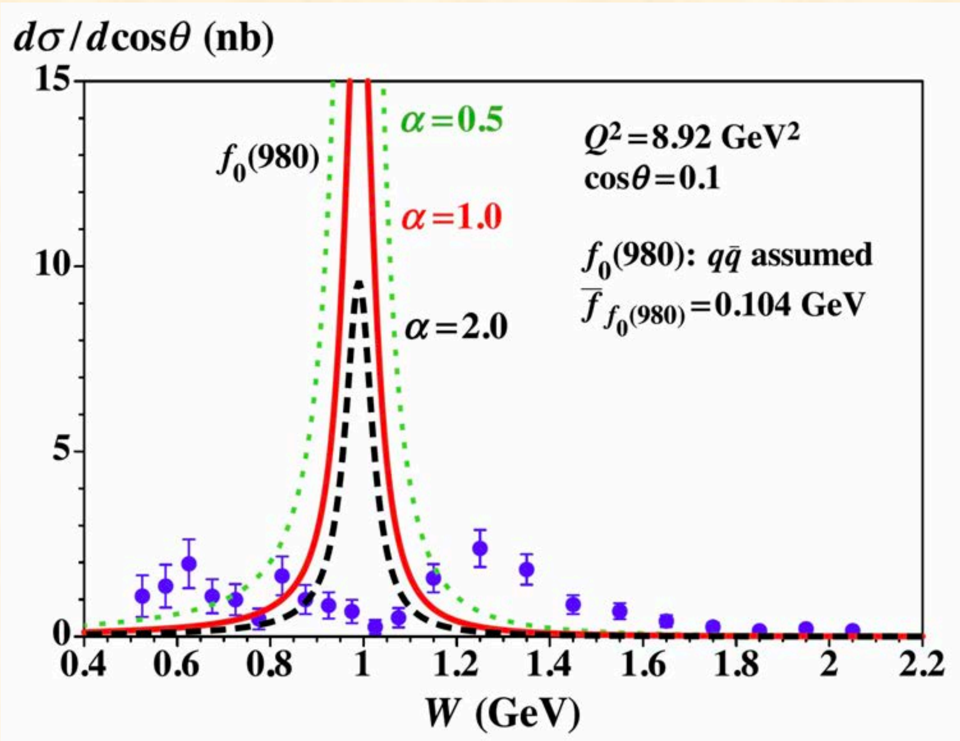
Two-dimensional form factor

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





$f_0(980)$ contribution to $\gamma^*\gamma \to \pi^0\pi^0$



- $f_0(980)$ decay constant is calculated so far by assuming $q\bar{q}$ configuration.

$\to$ not consistent with data

$\to$ $f_0(980)$ is not a $q\bar{q}$ state but likely to be tetra quark or $K\bar{K}$ molecule.

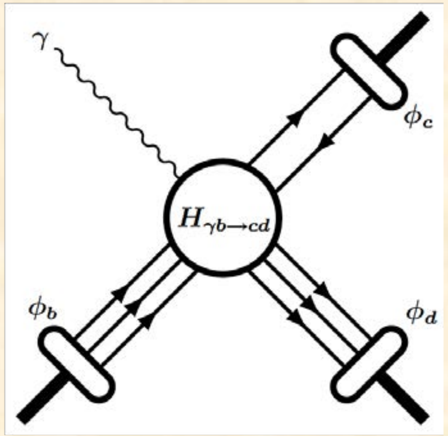
$\to$ $f_0(980)$ is not included in our analysis.

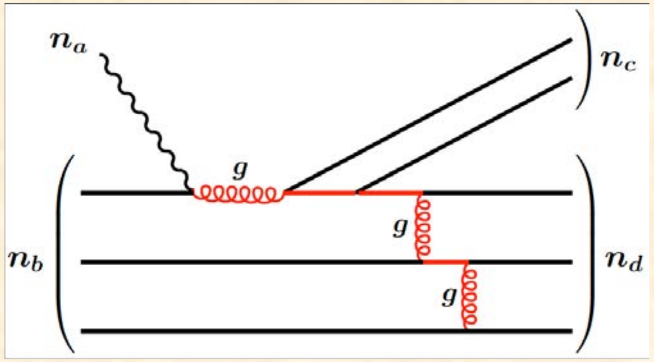
- Resonances: There exist resonance contributions to the cross section.

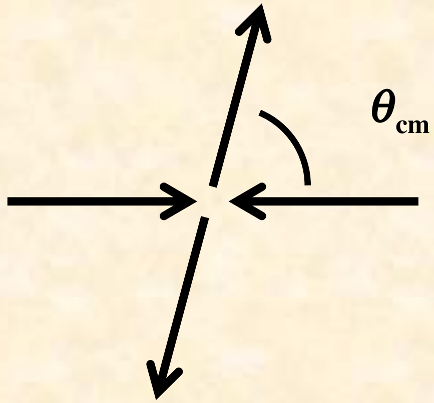
$$\sum_q \Phi_q^{\pi\pi}(z,\zeta,W^2) = 18 N_f z^\alpha (1-z)^\alpha (2z-1)\left[\tilde{B}_{10}(W) + \tilde{B}_{12}(W) P_2(\cos\theta)\right]$$

$\gamma^*\gamma \to \pi^0\pi^0$ analysis:
SK, Q.-T. Song, O. Teryaev,
Phys. Rev. D 97 (2018) 014020.

JLab hyperon productions







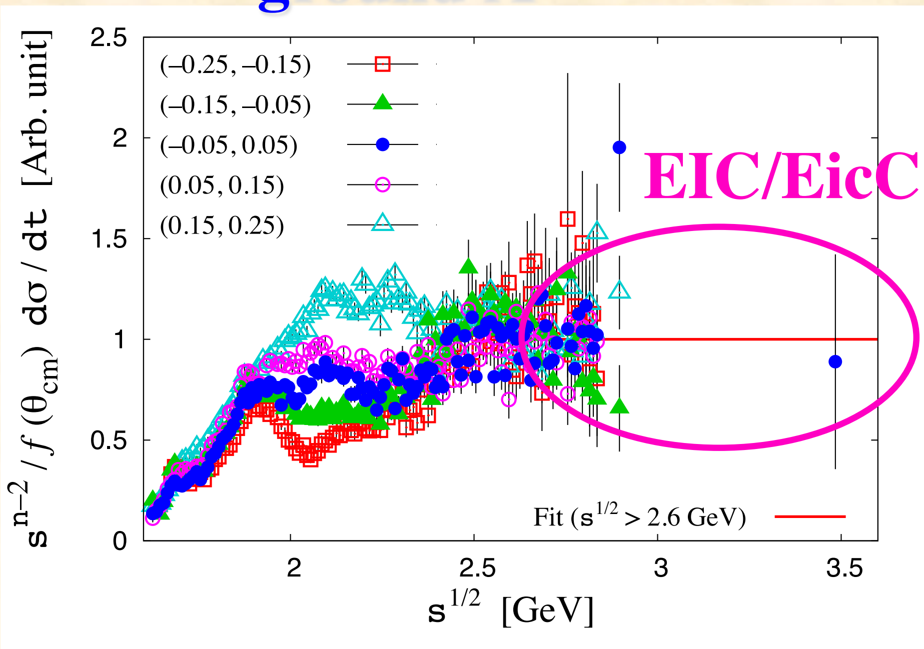
5 bins: $-0.25 < \cos\theta_{cm} < -0.15, \ \cdots, \ 0.15 < \cos\theta_{cm} < 0.25$

4 bins: $-0.20 < \cos\theta_{cm} < -0.10, \ \cdots, \ 0.10 < \cos\theta_{cm} < 0.20$

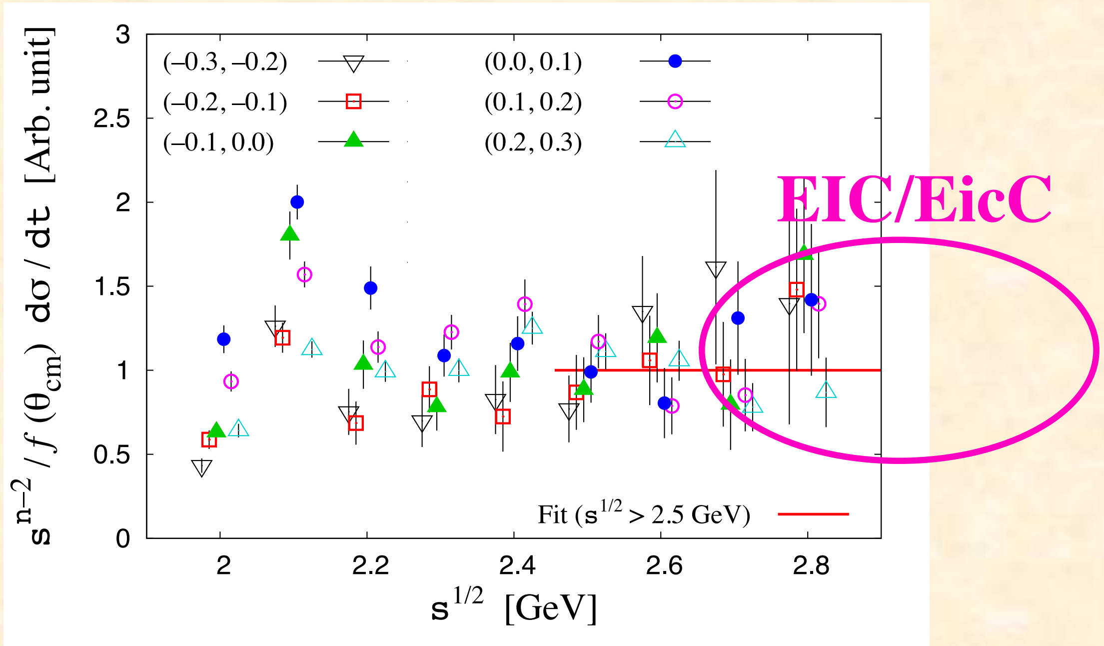
...

1 bin: $-0.05 < \cos\theta_{cm} < +0.05$

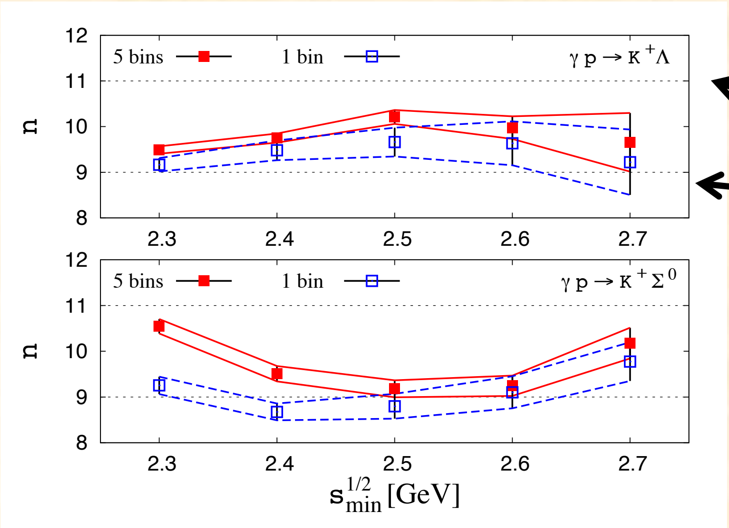
ground Λ



Λ(1405)

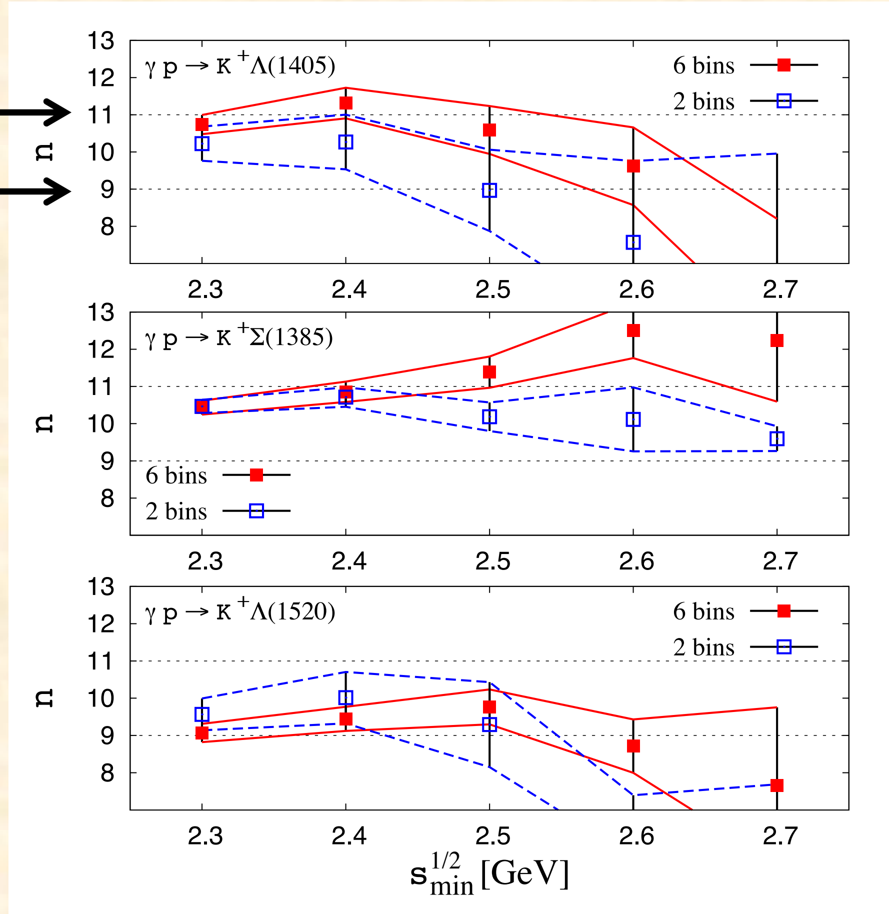


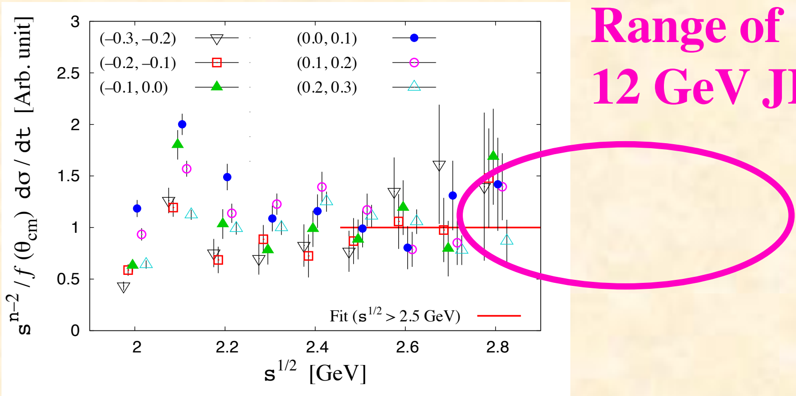
JLab hyperon productions including Λ(1405)



$n_\Lambda = 5$ →

$n_\Lambda = 3$ →





Range of 12 GeV JLab!

- Λ. Λ(1520) and Σ seem to be consistent with ordinary baryons with $n = 3$.
- Λ(1405) looks penta-quark at low energies but $n \sim 3$ at high energies???
- Σ(1385) : $n = 5$???

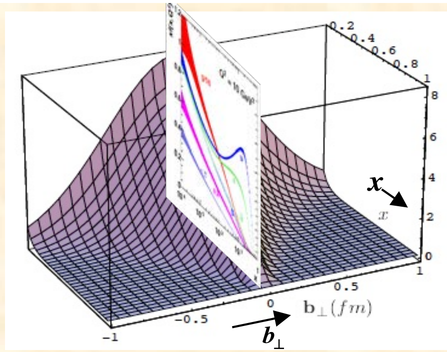
→ In order to clarify the nature of Λ(1405) $\left[qqq,\ \bar{K}N,\ qqqq\bar{q}\right]$, the JLab 12-GeV experiment plays an important role!

W.-C. Chang, SK, T. Sekihara, PRD 93 (2016) 034006.

Prospects & Summary

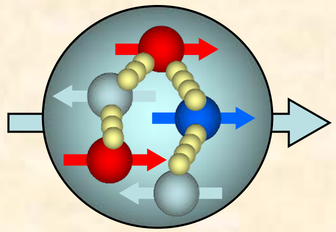
By hadron tomography

3D view of hadrons

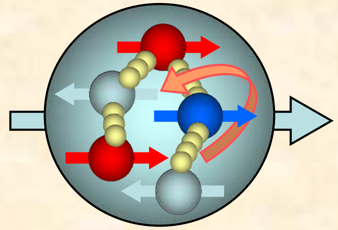


Origin of nucleon spin

By the tomography, we determine



or



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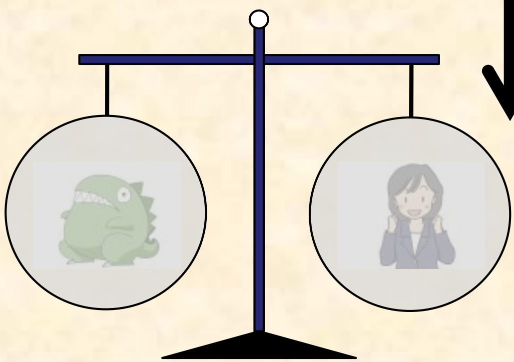
Exotic hadrons



By tomography, we determine

or

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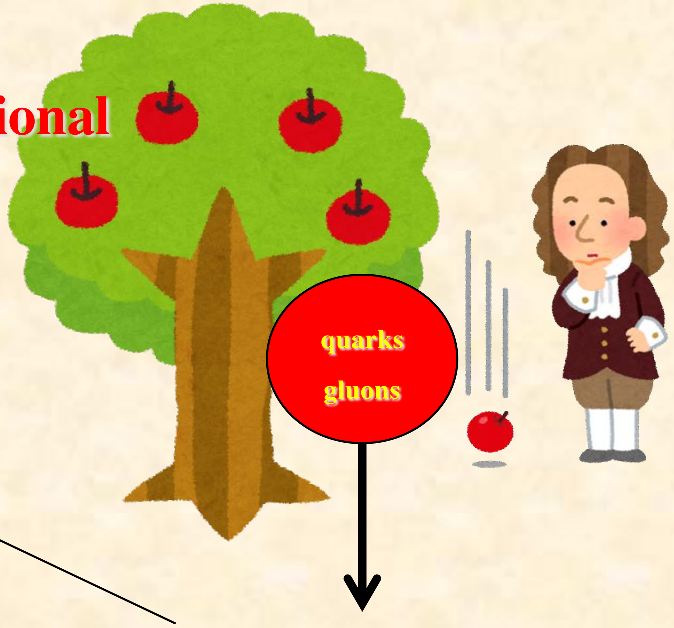
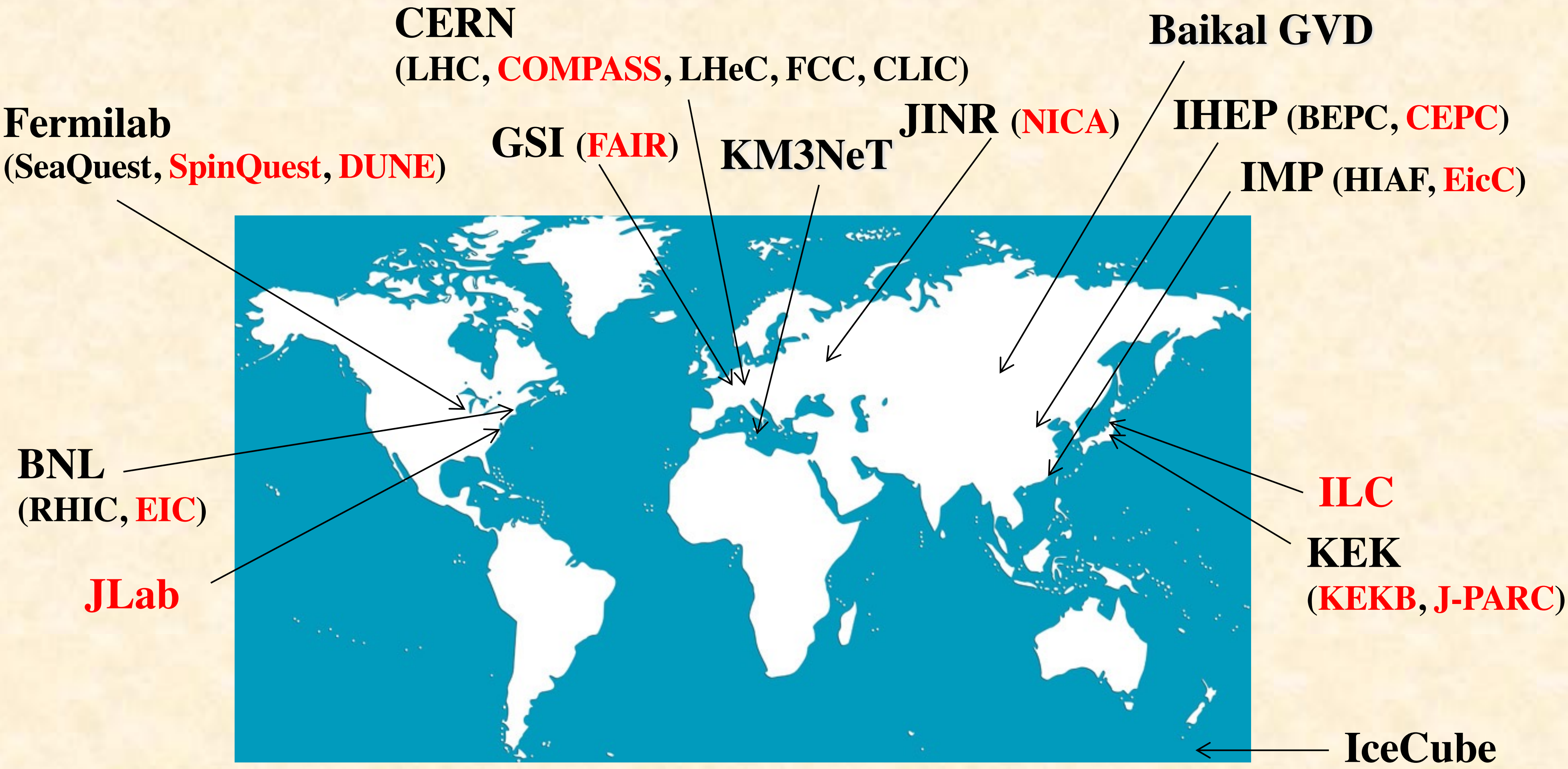
Origin of gravitational source (mass)

By tomography, we determine gravitational sources in terms of quarks and gluons.



High-energy hadron physics experiments



Facilities on hadron structure functions on GPDs including future possibilities.

Summary

Hadron-tomography and gravitational form factors

- **Puzzle to find the origin of hadron masses and pressures in terms of quark and gluon degrees of freedom**

- **Puzzle to find the origin of nucleon spin**

- **Exotic hadron candidates could be studied in the same tomography method.**

- **There are world-wide lepton and hadron accelerator facilities which has been used and could be used in future for our studies.**

Time has come to understand the gravitational sources in microscopic (instead of usual macroscopic/cosmic) world in terms of quark and gluon degrees of freedom.

The End

The End