Possible studies on generalized parton distributions and gravitational form factors by high-energy LBNF neutrino beam

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with Roberto Petti (Univ of South Carolina)

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• Introduction
  Origin of nucleon spin and mass
  Hadron tomography and 3D structure functions

• Generalized distribution amplitudes
  [= timelike GPDs (generalized parton distributions)] and
  extraction of gravitational form factors from KEK-B data

• GPDs and gravitational form factors in neutrino reactions

• Prospects and summary

I may skip some slides.
References

• General introductory review on GPDs (Generalized Parton Distributions)
  Generalized parton distributions,

• Timelike GPDs (GDAs) and KEKB-data analysis
  Hadron tomography by generalized distribution amplitudes
  in pion-pair production process $\gamma^*\gamma \rightarrow \pi^0\pi^0$ and gravitational form factors for pion,

• Updated information on GPDs in neutrino reactions
  Hard exclusive neutrino production of a light meson,
  and references therein.

• High-energy neutrino interactions and GPDs
  High-energy neutrino-nucleus interactions,

• Synergies between EIC (Electron-Ion Collider) project and neutrino reactions
  EIC yellow report, A. Accardi et al., arXiv:2103.05419,
  see Sec. 7.5.2, Neutrino phyiscs by S. Kumano and R. Petti.

• Fermilab-LBNF neutrino-beam information
  Impact of high energy beam tunes on the sensitivities to the standard unknowns at DUNE,
Introduction

• Origins of nucleon spin and mass
• Hadron tomography and 3D structure functions
Origin of nucleon spin

“old” standard model

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

\[ \Delta q(x) \equiv q_\uparrow(x) - q_\downarrow(x) \]

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

Gluon spin

anglular momentum

\[ \frac{1}{2} = \frac{1}{2} \left( \Delta u_v + \Delta d_v + \Delta q_{\text{sea}} \right) + \Delta G + L_q + L_g \]

Possibly a large gluon-spin contribution (2014)

Scientific American (2014)
Origin of hadron masses

Mass and spin of the nucleon are two of fundamental quantities in physics.

Nucleon mass: \( M = \left\langle p \right| \int d^3 x \ T^{00} (x) \left| p \right\rangle \)

Energy-momentum tensor:
\[
T^{\mu \nu} (x) = \frac{1}{2} \bar{q} (x) i \tilde{D}^{(\mu \gamma)} q (x) \\
+ \frac{1}{4} g^{\mu \nu} F^2 (x) - F^{\mu \alpha} (x) F^\nu_{\alpha} (x)
\]

Nucleon spin: \( \frac{1}{2} = \left\langle p \right| J^3 \left| p \right\rangle \)

3rd component of total angular momentum: \( J^3 = \frac{1}{2} \varepsilon^{3jk} \int d^3 x \ M^{3jk} (x) \)

Angular-momentum density: \( M^{\alpha \nu} (x) = T^{\alpha \nu} (x) x^\mu - T^{\alpha \mu} (x) x^\nu \)
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

@home due to coronavirus pandemic
Hadron tomography: Wigner distribution and various structure functions

- Form factor: $\int dx\,d^2k_T$
- PDF (Parton Distribution Function): $\int d^2k_T$, $\Delta \to 0$
- GTMD $W(x, \vec{k}_T, \Delta) \xrightarrow{\Delta \to 0} W(x, \vec{k}_T, \vec{r}_T)$
- GPD (Generalized Parton Distribution): $s \leftrightarrow t \xrightarrow{s\leftrightarrow t} \text{GDA (Generalized Distribution Amplitude)}$
- TMD (Transverse Momentum Dependent) parton distribution
- Two-photon process $\gamma^*\gamma \to h\bar{h}$
- e.g. HERA studies
Generalized Parton Distributions (GPDs)

GPDs are defined as correlation of off-forward matrix:

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

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

Momentum transfer squared \( t = \Delta^2 \)

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

GPDs are defined as correlation of off-forward matrix:

\[
\int \frac{dz^-}{4\pi} e^{i z^- p^-} \langle (p') \bar{\psi}(-z/2) \gamma^+ \gamma_5 \psi(z/2) \rangle_{z^+ = 0, z^- = 0} = \frac{1}{2P^+} \left[ H(x, \xi, t) \bar{u}(p') \gamma^+ u(p) + E(x, \xi, t) \bar{u}(p') \frac{i\sigma^+ \Delta \cdot u(p)}{2M} \right]
\]

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

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

First moments: Form factors

Dirac and Pauli form factors \( F_1, F_2 \)

Axial and Pseudoscalar form factors \( G_A, G_P \)

Second moments: Angular momenta

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

\( \Rightarrow \) probe \( L_q \), key quantity to solve the spin puzzle!
Why “gravitational” interactions with quarks

\[ \gamma q \gamma^\mu q \]
\[ W \quad \text{vector} \quad \bar{q} \gamma^\mu q \]
\[ g \quad \text{vector} - \text{axial-vector} \quad \bar{q} \gamma^\mu (1 - \gamma^5) q \]
\[ \text{tensor} \quad \bar{q} \gamma^\mu \partial^\nu q \]

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

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

Non-local operator of GPDs/GDAs:

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

\[ \bar{q}(0)\gamma^+ (i\sigma^+)^{n-1} q(0) \]

= energy-momentum tensor of a quark for \( n = 2 \)

(electromagnetic for \( n = 1 \))

= source of gravity

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

Virtual Compton or (timelike) two-photon process

We studied in 2017-2018.


We are considering to use neutrino.
Generalized Distribution Amplitudes (GDAs) and extraction of gravitational form factors from KEKB data

\[ \text{GDA} = \text{Timelike GPDs} \]

Cross section for $\gamma^* \gamma \rightarrow \pi^0 \pi^0$

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

\[
\mathcal{M} = e^2_\mu (q) e^\dagger_\nu (q') T^{\mu \nu} = e^2 A_{\lambda\lambda'}, \quad T^{\mu \nu} = i \int d^4 \xi e^{-i \xi \cdot q} \langle \pi(p) \pi(p') | TJ_{\text{em}}(\xi) J_{\text{em}}^\dagger (0)|0\rangle
\]

\[
A_{\lambda\lambda'} = \frac{1}{e^2} e^\dagger_\mu (q) e^\dagger_\nu (q') T^{\mu \nu} = -e^2_\mu (q) e^\dagger_\nu (q') g^{\mu \nu} \sum_q e^2_q \int_0^1 dz \frac{2z - 1}{z(1 - z)} \Phi_q^{\text{res}}(z, \zeta, W^2)
\]

GDA: \( \Phi_q^{\text{res}}(z, \zeta, s) = \int \frac{dz'}{2\pi} e^{izp' \cdot y} \langle \pi(p) \pi(p') | \bar{\psi}(-y/2) \gamma^\mu \gamma^\nu y/2 |0\rangle \); \( y^+ = 0, y_z = 0 \)

\[
\frac{d\sigma}{d(\cos \theta)} = \frac{\pi \alpha^2}{4(s + Q^2)} \sqrt{1 - \frac{4m^2}{s}} \sum_{\lambda \lambda'} |A_{++}|^2, \quad A_{++} = \sum_q e^2_q \int_0^1 dz \frac{2z - 1}{z(1 - z)} \Phi_q^{\text{res}}(z, \zeta, W^2)
\]

- Continuum: GDAs without intermediate-resonance contribution
  \( \Phi_q^{\text{res}}(z, \zeta, W^2) = N_q z^\alpha (1 - z)^\alpha (2z - 1) \zeta (1 - \zeta) F_q^\alpha (s) \)

\[
F_q^\alpha (s) = \frac{1}{\left[ 1 + (s - 4m^2_q) / A^2 \right]^{n+1}}, \quad n = 2 \text{ according to constituent counting rule}
\]

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

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

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

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

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

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

\[ Q^2 = 8.92, 13.37 \text{ GeV}^2 \]

\[ Q^2 = 17.23, 24.25 \text{ GeV}^2 \]
Gravitational form factors and radii for pion

\[
\int_0^1 dz (2z - 1) \Phi_q^{\pi^0\pi^0}(z, \zeta, s) = \frac{2}{(P^+)^2} \left< \pi^0(p)\pi^0(p') | T_q^{++}(0) | 0 \right>
\]

\[
\left< \pi^0(p)\pi^0(p') | T_q^{\mu\nu}(0) | 0 \right> = \frac{1}{2} \left[ (s g^{\mu\nu} - P^\mu P^\nu) \Theta_1,q(s) + \Delta^\mu \Delta^\nu \Theta_2,q(s) \right]
\]

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

\(T_q^{\mu\nu}\) : energy-momentum tensor for quark
\(\Theta_1,q, \Theta_2,q\) : gravitational form factors for pion

Analyis of \(\gamma^*\gamma \rightarrow \pi^0\pi^0\) cross section
⇒ Generalized distribution amplitudes \(\Phi_q^{\pi^0\pi^0}(z, \zeta, s)\)
⇒ Timelike gravitational form factors \(\Theta_1,q(s), \Theta_2,q(s)\)
⇒ Spacelike gravitational form factors \(\Theta_1,q(t), \Theta_2,q(t)\)
⇒ Gravitational radii of pion

Gravitational form factors:
Spacelike gravitational form factors and radii for pion

\[ F(s) = \Theta_1(s), \quad \Theta_1(s), \quad F(t) = \int_{4m^2}^{\infty} ds \frac{1}{\pi(s-t-i\varepsilon)} \text{Im} F(s), \quad \rho(r) = \frac{1}{(2\pi)^3} \int d^3q e^{-iqr} F(q) = \frac{1}{4\pi^2} \int_{4m^2}^{\infty} ds e^{-\sqrt{s}r} \text{Im} F(s) \]

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

\[ \sqrt{\langle r^2 \rangle_{\text{mass}}} = 0.32 \sim 0.39 \text{ fm}, \quad \sqrt{\langle r^2 \rangle_{\text{mech}}} = 0.82 \sim 0.88 \text{ fm} \]

⇔ \[ \sqrt{\langle r^2 \rangle_{\text{charge}}} = 0.672 \pm 0.008 \text{ fm} \]

First finding on gravitational radius from actual experimental measurements

Hadron mass radius puzzle?

\[ \Theta_n(t) \sim \Theta_n(0) \]

\[ 4\pi r^2 \rho_n(r) \quad (1/\text{fm}) \]

mass (energy) distribution

mass (energy) distribution

pressure and shear force distribution

\[ 4\pi r^2 \rho_n(r) \]

\[ 4\pi r^2 \rho_2(r) \]

\[ 4\pi r^2 \rho_1(r) \]
Possible studies on GPDs and gravitational form factors in neutrino reactions
References on GPDs in ν reactions

  D_s production
  DVNS (Deeply Virtual Neutrino Scattering): Neutral current
  DVNS (Deeply Virtual Neutrino Scattering): Charged current
  Detailed GPD formalism and numerical analysis on DVNS
  π^0 production formalism and nuclear target
  Meson (π, K, η) productions and GPDs
  Higher-twist effects in π production
  D^{+/−} production and chiral-odd GPDs
  NLO corrections in π and K productions
  D production with gluon (in addition to quark) contributions
  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.
Neutrino reactions for gravitational form factors @Fermilab-DUNE (Origins of hadron masses and pressures)

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


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

Cross section

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

\[
\sigma_L = \varepsilon_L^\nu W_{\mu \nu} \sigma_L^\nu = \frac{1}{Q^2} \left[ (1 - \xi^2) \left( |C_q H_q + C_g H_g|^2 + |C_q \overline{H}_q|^2 \right) + \frac{\xi^4}{1 - \xi^2} \left( |C_q E_q + C_g E_g|^2 + |C_q \overline{E}_q|^2 \right) \right]
\]

\[
-2\xi^2 \text{Re} \left( (C_q H_q + C_g H_g)(C_q E_q + C_g E_g)^* \right) - 2\xi^2 \text{Re} \left( C_q \overline{H}_q (C_q \overline{E}_q)^* \right)
\]

Quark contributions

\[
T_q = -i \frac{C_q}{2Q} N(p') \left[ \mathcal{H}_q \gamma_\mu + \mathcal{E}_q \frac{i\sigma_{\mu\nu} n_\nu \Delta_\nu}{2m_N} - \mathcal{H}_q n_\gamma - \mathcal{E}_q \gamma_5 n_\cdot \Delta \right] N(p)
\]

\[
\mathcal{F}_q = 2f_\pi \int \frac{dz \phi_\pi(z)}{1 - z} \int dx \frac{F_q(x, \xi, t)}{x - \xi + i\varepsilon} = (\text{pion distribution amplitude}) \cdot (\text{quark GPD})
\]

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

\[
F = H, E, \overline{H}, \overline{E}
\]

Gluon contributions

\[
T_g = -i \frac{C_g}{2Q} N(p') \left[ \mathcal{H}_g \gamma_\mu + \mathcal{E}_g \frac{i\sigma_{\mu\nu} n_\nu \Delta_\nu}{2m_N} \right] N(p)
\]

\[
\mathcal{F}_g = \frac{8f_\pi}{\xi} \int \frac{dz \phi_\pi(z)}{z(1 - z)} \int dx \frac{F_g(x, \xi, t)}{x - \xi + i\varepsilon} = 2(\text{pion distribution amplitude}) \cdot (\text{gluon GPD})
\]

\[
F_g(x, \xi, t) \equiv 2F_d(x, \xi, t) - 2F_u(-x, \xi, t)
\]

\[
F = H, E, \overline{H}, \overline{E}
\]
Cross section estimates

**proton:** $\nu p \rightarrow \ell^- \pi^+ p$

**neutron:** $\nu n \rightarrow \ell^- \pi^+ n$

![Graphs showing cross section dependence on $Q^2$](image)

FIG. 3. The $Q^2$ dependence of the cross section $\frac{d^2\sigma(\nu N \rightarrow \ell^- N \pi^+)}{dy dQ^2 dt}$ (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:** $\nu n \rightarrow \ell^- \pi^0 p$

### Neutrino GPD studies are complementary to the charged-lepton projects.
- Gluon GPDs could be probed in charged-pion production.
- Flavor dependence of quark GPDs could be investigated.
Prospects & Summary
By hadron tomography

3D view of hadrons

Origin of nucleon spin
By the tomography, we determine

Origin of gravitational source (mass)
By tomography, we determine gravitational sources in terms of quarks and gluons.

Exotic hadrons
By tomography, we determine gravitational sources in terms of quarks and gluons.
Origin of nucleon spin: decomposition

\[
\frac{1}{2} = \langle p | J^3 | p \rangle, \quad J^3 = \frac{1}{2} \varepsilon^{ijk} \int d^3 x \, M^{3jk}(x), \quad M^{\alpha\nu}(x) = T^{\alpha\nu}(x)x^\mu - T^{\alpha\mu}(x)x^\nu
\]


\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta g + L_q + L_g, \quad \Delta \Sigma = \text{quark spin contribution}, \quad \Delta g = \text{gluon spin contribution},
\]

\( L_q = \text{quark orbital-angular-momentum (OAM) contribution}, \quad L_g = \text{gluon orbital-angular-momentum (OAM) contribution} \)

Lattice QCD estimate in M. Deke et al., Phys. Rev. D 91 (2015) 0145505

<table>
<thead>
<tr>
<th>Spin decomposition</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>quark spin</td>
<td>25%</td>
</tr>
<tr>
<td>quark OAM</td>
<td>45%</td>
</tr>
<tr>
<td>gluon spin + OAM</td>
<td>30%</td>
</tr>
</tbody>
</table>
Origin of nucleon mass

Nucleon mass: \( M = \langle p \vert H \vert p \rangle \), \( H = \int d^3x \, T^{00}(x) \)

Energy-momentum tensor:

\[
T^{\mu\nu}(x) = \frac{1}{2} \bar{q}(x)i\tilde{D}^{(\mu} \gamma^{\nu)}q(x) + \frac{1}{4} g^{\mu\nu} F^2(x) - F^{\mu\alpha}(x)F_{\alpha}^{\nu}(x)
\]

We need theoretical and experimental efforts to decompose nucleon mass for finding its origin.

\[
T^{\mu\nu} = \hat{T}^{\mu\nu} + \bar{T}^{\mu\nu} = \left( T^{\mu\nu} - \frac{1}{4} g^{\mu\nu} T^{\alpha}_\alpha \right)_{\text{traceless}} + \left( -\frac{1}{4} g^{\mu\nu} T^{\alpha}_\alpha \right)_{\text{trace}}, \quad T^{\alpha}_\alpha = \bar{q} \, m \, q + \frac{\beta(g)}{2g} F^2
\]

\[ H = H_q (\text{quark energy}) + H_g (\text{gluon energy}) + H_m (\text{quark mass}) + H_a (\text{trace anomaly}) \]

\[
H_q = \int d^3x \, \bar{q}(x) \left( -i\tilde{D} \cdot \tilde{\alpha} \right) q(x), \quad H_g = \int d^3x \, \frac{1}{2} \left( \tilde{E}^2 + \tilde{B}^2 \right)
\]

\[
H_m = \int d^3x \, \bar{q}(x) \, m \, q(x), \quad H_s = \int d^3x \, \frac{9 \alpha_s}{16\pi} \left( \tilde{E}^2 + \tilde{B}^2 \right)
\]

Recent progress on trace-anomaly, gravitational form factor, scale dependence in perturbative QCD:


Nucleon pressure

\[
\langle N(p')|T_{\mu\nu}^{(0)}|N(p)\rangle = \bar{u}(p') \left[ A\gamma^{(\mu}\bar{P}^{\nu)} + B\frac{\bar{P}^{(\mu}i\sigma^{\nu)}\Delta_{\alpha}}{2M} + D\frac{\Delta^{\mu}\Delta^{\nu} - g^{\mu\nu}\Delta^2}{M} + \bar{C}Mg^{\mu\nu} \right] u(p)
\]

Recent progress

Highest pressure in nature 1 Pa (Pascal) = 1 N/m²

Earth atmosphere 10⁵ Pa = 1000 hPa
Center of earth 10¹¹ Pa = 100 GPa
Center of Sun 10¹⁶ Pa = 10 PPa
Neutron star 10³⁴ Pa
Hadron 10³⁵ Pa
GPD studies in neutrino reactions at LBNF is unique!

Fermilab (SeaQuest, DUNE)

BNL (RHIC, EIC)

JLab

CERN (LHC, COMPASS/AMBER, LHCspin, LHeC, FCC, CLIC)

GSI (FAIR)

KM3NeT

JINR (NICA)

Baikal GVD

IHEP (BEPC, CEPC)

IMP (HIAF, EicC)

ILC

KEK (KEKB, J-PARC)

IceCube

Facilities on hadron structure functions.
DUNE could be used for structure function studies (e.g. gravitational form factors).
Summary

Hadron-tomography project at neutrino facilities

• Puzzle to find the origin of nucleon spin

• Puzzle to find the origin of hadron masses
  in terms of quark and gluon degrees of freedom

• 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.

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