Bridging the gap between spectroscopy and partonic observables: mesonic and baryonic wave functions on the light front.

Edward Shuryak

Center for Nuclear Theory, Stony Brook University

QCD spectrum, INT talk, March 23, 2023

vacuum structure

Correlators in Euclidean time:

"instanton liquid"

pro: chiral sim.breaking derived

numerical simulations in

lattice gauge theories:

pro: from first principles of QCD

confinement, spectra…

con: hard to get

PDF or light cone w.f.

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Light-front wave functions of mesons, baryons, and pentaquarks with topology-induced local four-quark interaction
ES (Aug 27, 2019): *Phys.Rev.D* 100 (2019) 11, 114018 • e-Print: 1908.10270 [hep-ph]

flavor asymmetry of “nuclear sea”

Nonperturbative quark-antiquark interactions in mesonic form factors
ES, Ismail Zahed (Aug 14, 2020)
Phys.Rev.D 103 (2021) 5, 054028 • e-Print: 2008.06169 [hep-ph]

“dense instanton liquid”
gives reasonable pion FF

Series with Ismail Zahed: Not a model but a program!

Hadronic structure on the light-front I. Instanton effects and quark-antiquark effective potentials
e-Print: 2110.15927 , PRD

calibrating
spin-dependent
forces in mesons

Hadronic structure on the light-front II: QCD strings, Wilson lines and potentials
e-Print: 2111.01775 PRD

derivation of confining H_LF
and solving it in various apprximations

Meson structure on the light-front III : The Hamiltonian, heavy quarkonia, spin and orbit mixing
e-Print: 2112.15586 PRD

from heavy quarkonia
to light mesons, spin
effects, quadrupole
moment of rho,J/psi

Hadronic structure on the light-front IV: Heavy and light Baryons
e-Print: 2202.00167 PRD

flavor-symmetric baryons
without “good diquarks”

Hadronic structure on the light-front V. Diquarks, Nucleons
and multiquark Fock component. e-Print: 2208.04428 PRD

baryons with diquarks
such as Qud and the nucleon,
bar-u/bar-d sea and chiral evotion

this talk

paper VI: nucleon and delta GPDs, e-Print: 2301.12238

why do QCD spectrum on light front?

connection to partonic observables, DA, PDFs,GPDs, formfactors

in the rest frame, nonrelativistic approximation only works
if masses are much larger than momenta,
on the LF p_t^2 appear as a sum with m^2
and it does not matter which one is larger
=> same setting from Upsilons to light quark hadrons

$$m^2 \gg \vec{p}^2$$

$$\frac{p_{1\perp}^2 + m_Q^2}{x_1} + \frac{p_{2\perp}^2 + m_Q^2}{x_2} + \frac{p_{3\perp}^2 + m_Q^2}{x_3} =$$

yet longitudinal momenta appear in a complicated manner,
how to do that I will tell

Philosophy: start with "bare bone" LF Hamiltonian and solve it as accurate as possible, with no arbitrary assumptions/approximations

such as "CM motion subtraction"

Jacobi coordinates

$$\vec{p}_{1\perp} = (\sqrt{6}\vec{p}_{\lambda\perp} + 3\sqrt{2}\vec{p}_{\rho\perp})/6,$$
$$\vec{p}_{2\perp} = (\sqrt{6}\vec{p}_{\lambda\perp} - 3\sqrt{2}\vec{p}_{\rho\perp})/6,$$
$$\vec{p}_{3\perp} = -\sqrt{6}\vec{p}_{\lambda\perp}/3$$

$$x_1 = (\sqrt{6}\lambda + 3\sqrt{2}\rho + 2X)/6$$
$$x_2 = (\sqrt{6}\lambda - 3\sqrt{2}\rho + 2X)/6$$
$$x_3 = (-\sqrt{6}\lambda + X)/3$$

$$X = x_1 + x_2 + x_3 \ =1$$

The kinetic part of the LF Hamiltonian

$$\frac{p_{1\perp}^2 + m_Q^2}{x_1} + \frac{p_{2\perp}^2 + m_Q^2}{x_2} + \frac{p_{3\perp}^2 + m_Q^2}{x_3} =$$
$$3\sum_i (p_{i\perp}^2 + m_i^2) + \sum_i (p_{i\perp}^2 + m_i^2)\left(\frac{1}{x_i} - 3\right)$$

transverse
two 2d oscillators

non-factoriwable
"cup potential"

which is mostly zero
except near the edges
forcing LFWFs to vanish

longitudinal variables
are defined on equilateral triangle

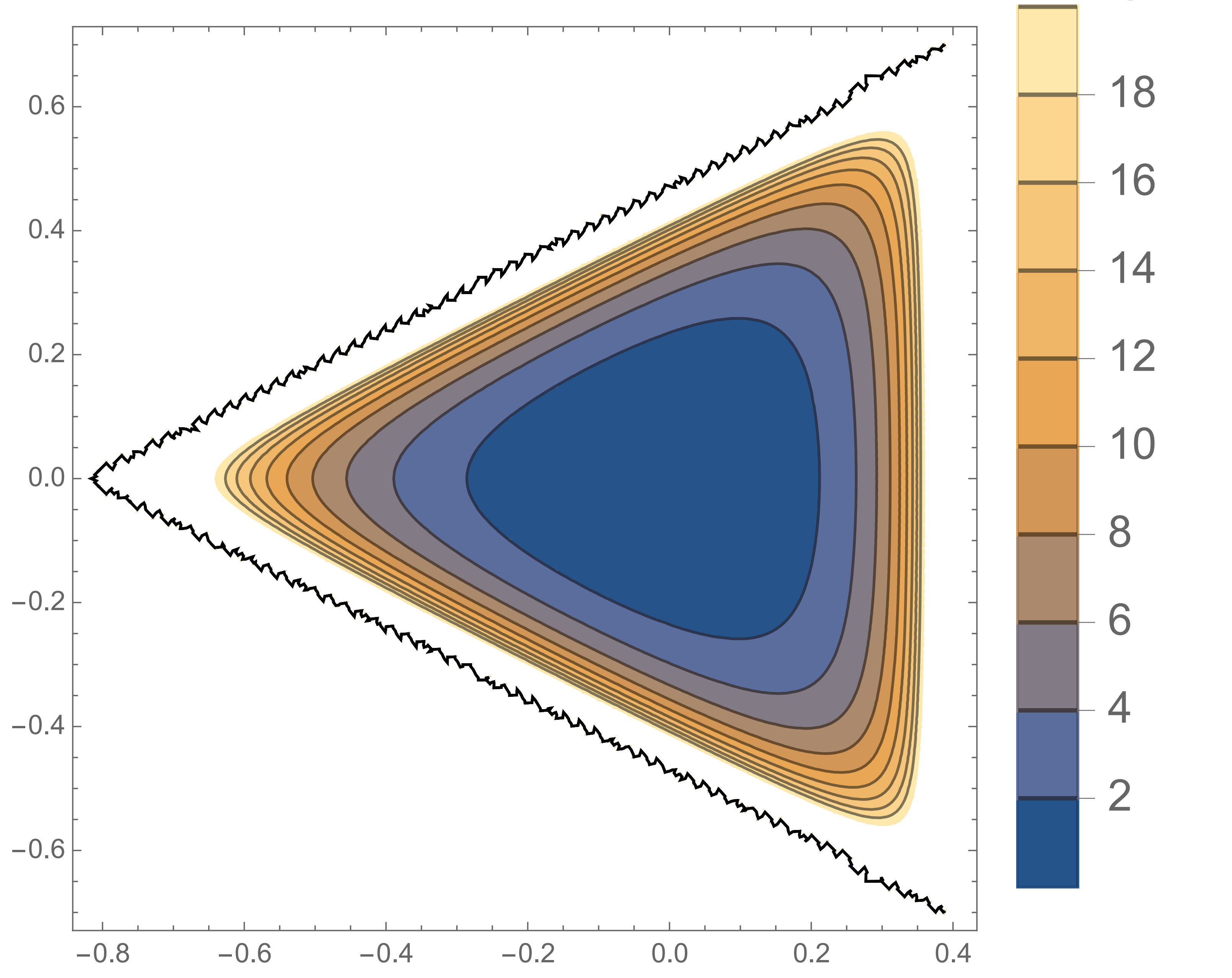

FIG. 4. The contour plot of the "triangular cup" poten-
tial $V(\lambda, \rho)$ on λ, ρ plot.

Confinement on LF can be desribed by:

Nambu-Goto string

instanton-induced
two and three-quark potentials

comparison
to lattice
potentials

not discussed in this talk

$$S[\theta] = \int_0^T d\tau \sum_{i=1}^{3} \left(e_i m_i^2 + \frac{1}{4e_i} \dot{x}_i^2 \right) + \sigma_T \sum_{i=1}^{3} \int_0^T d\tau \int_0^1 d\sigma_i \sqrt{\dot{X}_i^2 X_i'^2 - (\dot{X}_i \cdot X_i')^2} \quad (37)$$

$$\rightarrow \int_0^T d\tau \Big(3em_Q^2 + \frac{3}{4e} + \frac{1}{4e}(\dot{r_\lambda}^2 + \dot{r_\rho}^2) + \sigma_T \sum_{i=1}^{3} |\xi_i(\theta)| \Big)$$

the square root
on the next line

coord's
are derivative
over momenta

$$\sum_{i=1}^{3} \left(\frac{k_{i\perp}^2 + m_Q^2}{x_i} + 2\sigma_T \left(|i\partial/\partial x_i|^2 + M^2 r_{i\perp}^2 \right)^{\frac{1}{2}} \right)$$

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$$+ \sigma_T \sum_{i=1}^{3} \int_0^T d\tau \int_0^1 d\sigma_i \sqrt{\dot{X}_i^2 X_i'^2 - (\dot{X}_i \cdot X_i')^2} \qquad \left. + \frac{1}{4e} (\dot{r_\lambda}^2 + \dot{r_\rho}^2) + \sigma_T \sum_{i=1}^{3} |\xi_i(\theta)| \right)$$

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$$\boxed{\sum_{i=1}^{3} \left(\frac{k_{i\perp}^2 + m_Q^2}{x_i} + 2\sigma_T \left(|i\partial/\partial x_i|^2 + M^2 r_{i\perp}^2 \right)^{\frac{1}{2}} \right)}$$

$$\boxed{\approx \sum_{i=1}^{3} \left(\frac{k_{i\perp}^2 + m_Q^2}{x_i} + \sigma_T \left(3a + \frac{1}{a} \sum_{i=1}^{3} \left(|i\partial/\partial x_i|^2 + (3m_Q)^2 b_{i\perp}^2 \right) \right) \right)}$$

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coord's
are derivative
over momenta

minimization over auxiliary parameter a
can be done AFTER the Hamiltonian is diagonalized

Philosophy: in momentum representation confinement produces derivative terms leading to Schreodinger-like equation

The Laplacian (which we encounter in the confining term of the Hamiltonian) in the original coordinates also takes a simple form

$$\nabla^2 = \sum_i \frac{\partial^2}{\partial x_i^2} \to \frac{\partial^2}{\partial \lambda^2} + \frac{\partial^2}{\partial \rho^2} + 3\frac{\partial^2}{\partial X^2} \qquad (31)$$

$$\begin{aligned}\varphi^{Dc}_{m,n}(\lambda,\rho) = \frac{4}{L\,3^{\frac{3}{4}}}\Bigg[&\cos\left(\frac{2\pi(2m_L-n_L)\rho}{3L}\right)\sin\left(\frac{2\pi n_L\tilde\lambda}{\sqrt{3}L}\right)\\ -&\cos\left(\frac{2\pi(2n_L-m_L)\rho}{3L}\right)\sin\left(\frac{2\pi m_L\tilde\lambda}{\sqrt{3}L}\right)\\ +&\cos\left(\frac{2\pi(m_L+n_L)\rho}{3L}\right)\sin\left(\frac{2\pi (m_L-n_L)\tilde\lambda}{\sqrt{3}L}\right)\Bigg]\end{aligned}$$

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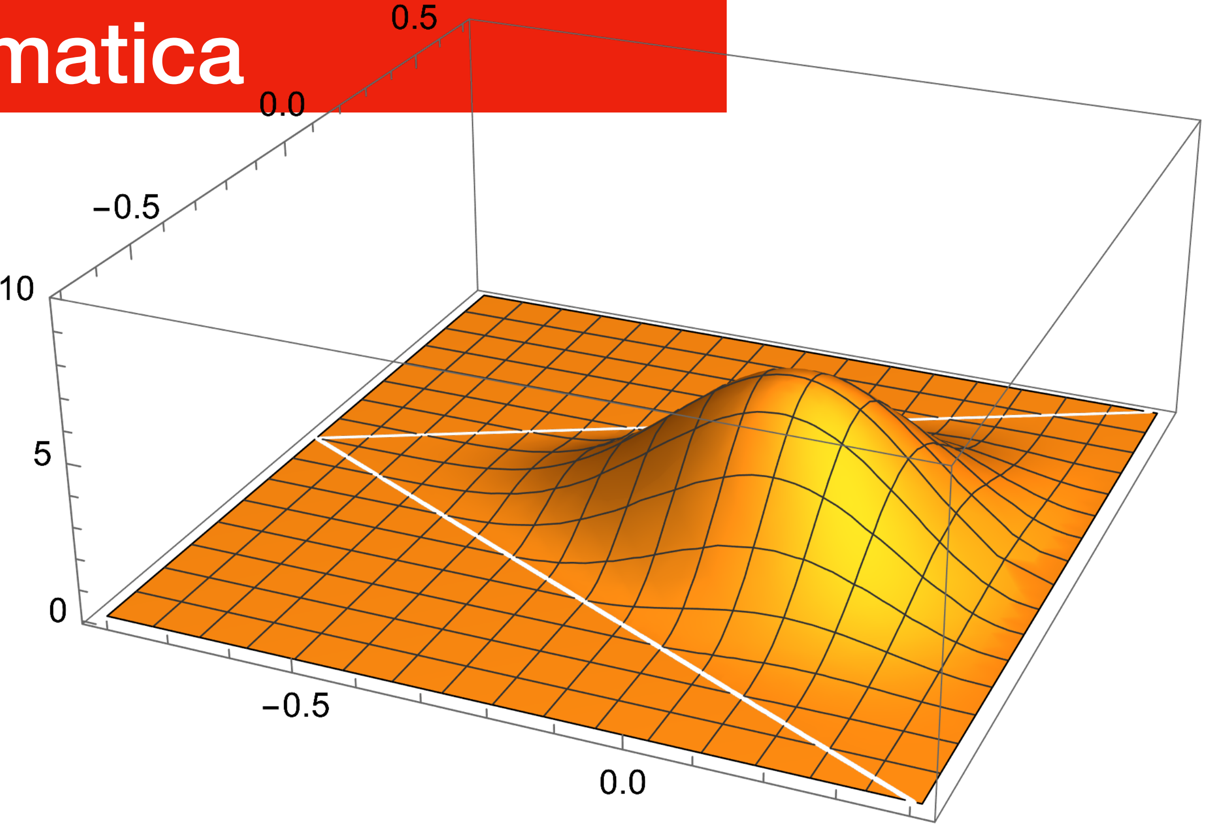
with $\tilde\lambda = \lambda + L/\sqrt{3}$. Their symmetry properties include e.g. ρ mirror symmetry

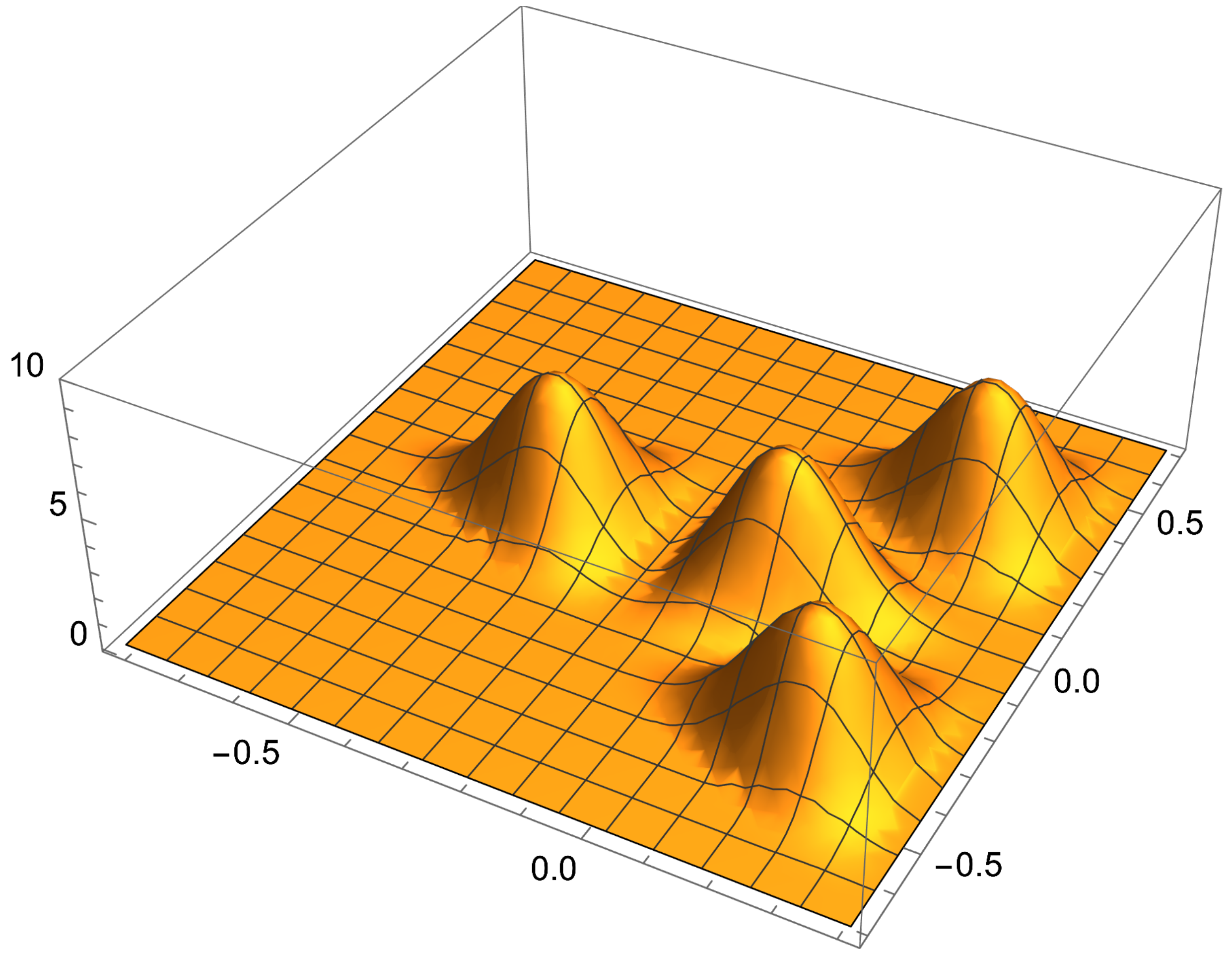
$$\varphi^{Dc,s}_{m_L,n_L}(\lambda,-\rho) = \pm\varphi^{Dc,s}_{m_L,n_L}(\lambda,\rho) \qquad (55)$$

Eigenfunctions of the Laplacian on the equilateral triangle can be found both analytically (6 standing waves) and numerically with Mathematica

The Dirichlet states with $m_L = 2n_L$ are non-degenerate, with normalized eigenstates [14]

$$\varphi^{D}_{2n_L,n_L}(\lambda,\rho) = \frac{2^{\frac{3}{2}}}{L\,3^{\frac{3}{4}}}\left[2\cos\left(\frac{2\pi n_L\rho}{L}\right)\sin\left(\frac{2\pi n_L\tilde\lambda}{\sqrt{3}L}\right) - \sin\left(\frac{4\pi n_L\tilde\lambda}{\sqrt{3}L}\right)\right]$$





Hadronic structure on the light-front IV. Heavy and light Baryons

$$H_{0LF} = 3(\vec{p}_\rho^2 + \vec{p}_\lambda^2 + 3m_Q^2)$$
$$+\frac{\sigma_T}{a}\left(|i\partial/\partial\lambda|^2 + |i\partial/\partial\rho|^2 + (3m_Q)^2(\vec{b}_\lambda^2 + \vec{b}_\rho^2)\right)$$

transverse oscillator
plus longitudinal Laplacian

$$qqq, sss, ccc, bbb$$

The non-factorizable part of the potential is

$$\tilde{V} = \frac{\vec{p}_1^2 + m_Q^2}{x_1} + \frac{\vec{p}_2^2 + m_Q^2}{x_2}$$
$$+\frac{\vec{p}_3^2 + m_Q^2}{x_3} - 3(\vec{p}_1^2 + \vec{p}_2^2 + \vec{p}_3^2) - 9m_Q^2$$

represented by a matrix
calculated in the eigenstates
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Single-flavor baryons

have **no ’t Hooft pairing**
interaction between quarks

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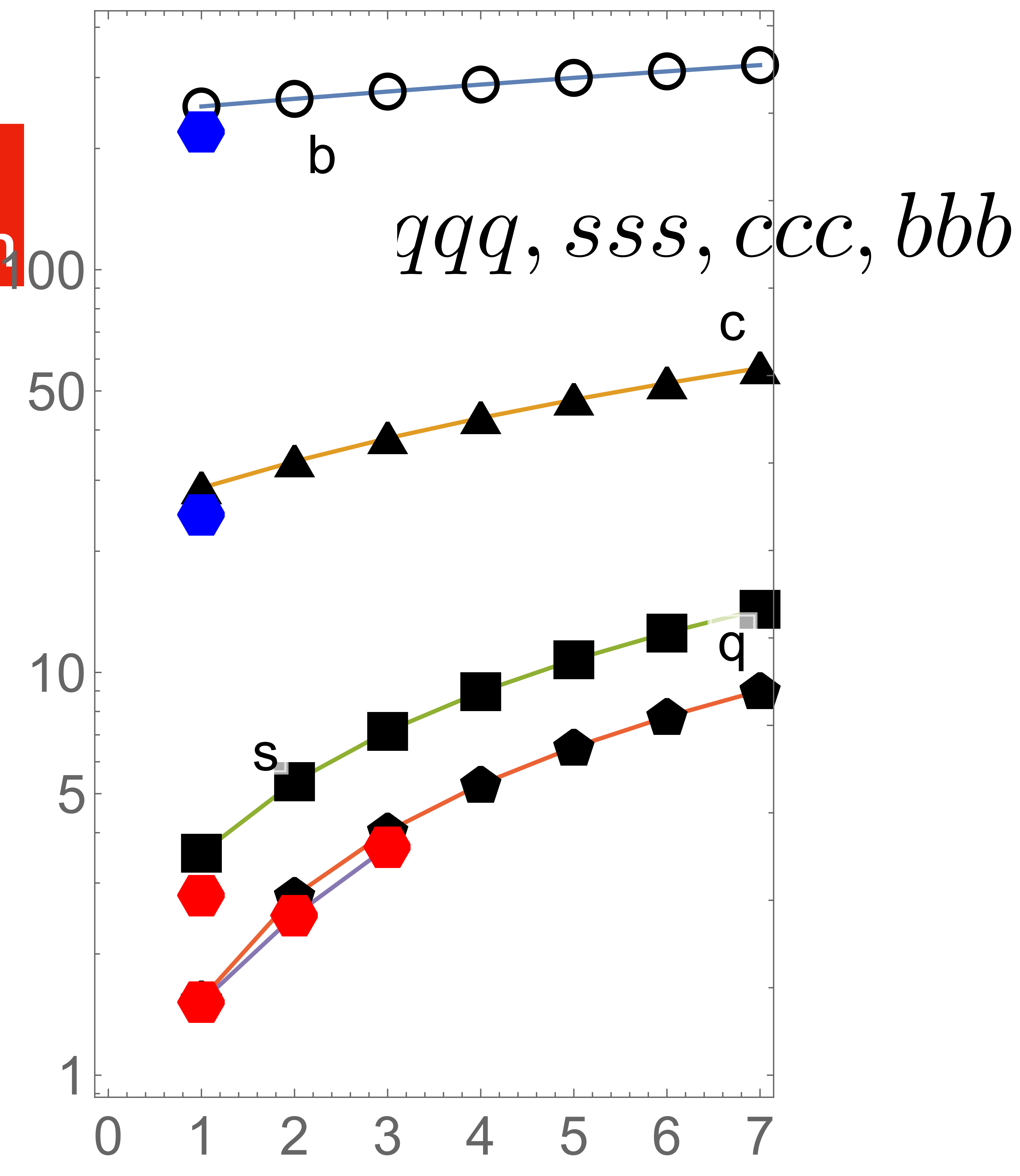

FIG. 9. Squared masses of baryons $M_{n+1}^2(Q, \frac{3}{2})$ in GeV^2, versus the principal quantum number $n+1 = 1..7$. The black circles, triangles, squared and pentagons are results of our calculations for the flavors b, c, s, q. The red hexagons are the experimental values of three Δ^{++} and one Ω^- masses, from PDG. The two blue hexagons are model predictions for masses of ccc and bbb baryons, from Table I.

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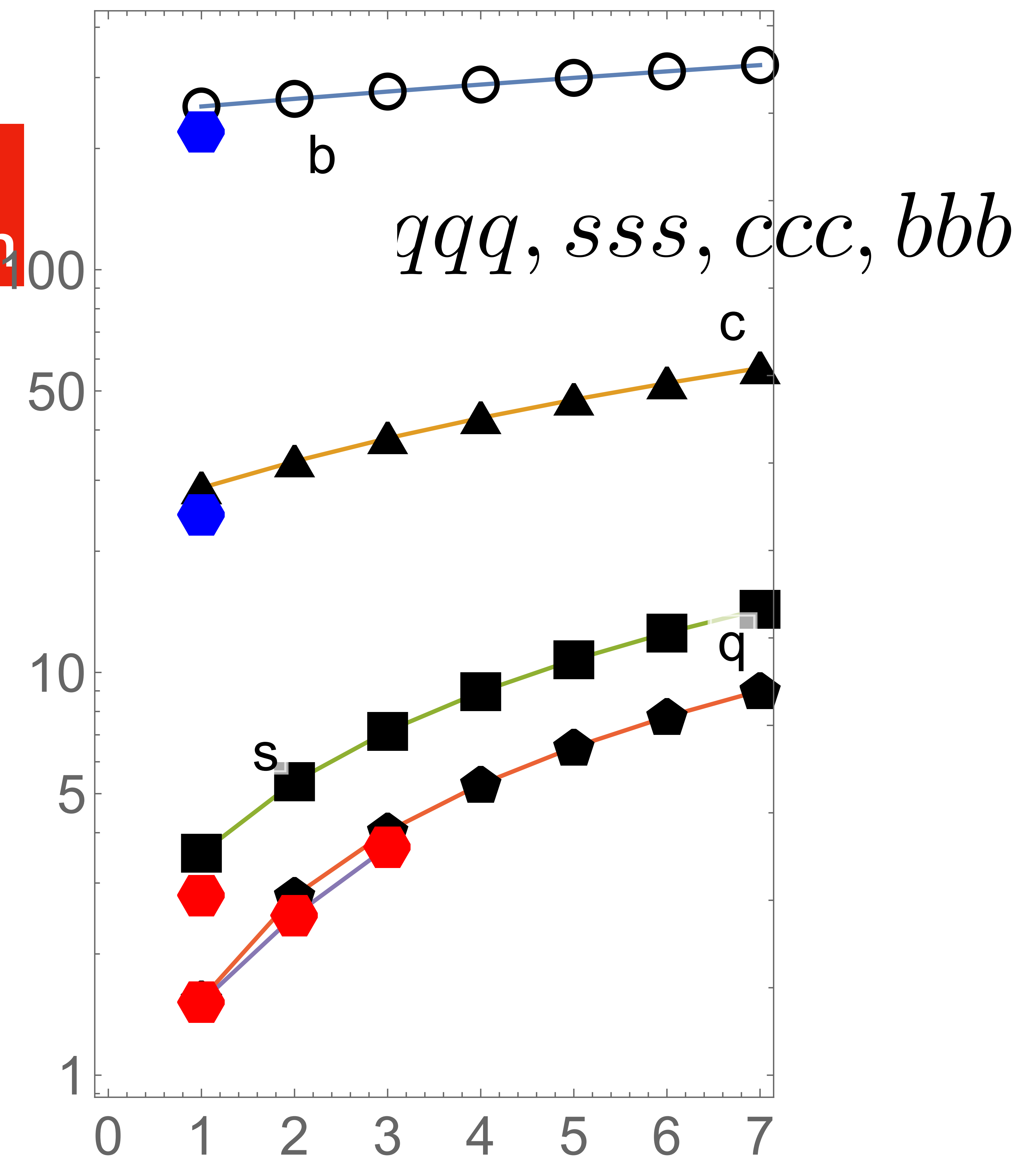
of course, we not just have all masses , but all light-front wave functions as well! Can be used to calculate PDFs,FFs,GPDs



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Hadronic structure on the light-front V.
Diquarks, Nucleons and multiquark Fock components

phenomenology
scalar diquarks are deeply bound

that the standard spin-spin interactions are of the form $(\vec{\sigma}_1\vec{\sigma}_2)$, this spin interaction can be eliminated as follows

$$M(1^+ud) - M(0^+ud) \tag{1}$$
$$\approx \big((2M(\Sigma_Q^*) + M(\Sigma_Q)/3\big) - M(\Lambda_Q) \approx 0.21\,\mathrm{GeV}$$

the mass difference between heavy-light baryon and meson iof $m(Qud) - m(Qu) \approx 329\, MeV$, is close to a constituent quark mass, but does not seem to include any extra contribution to the kinetic energy of the extra quark. Apparently, it is cancelled by some attraction.

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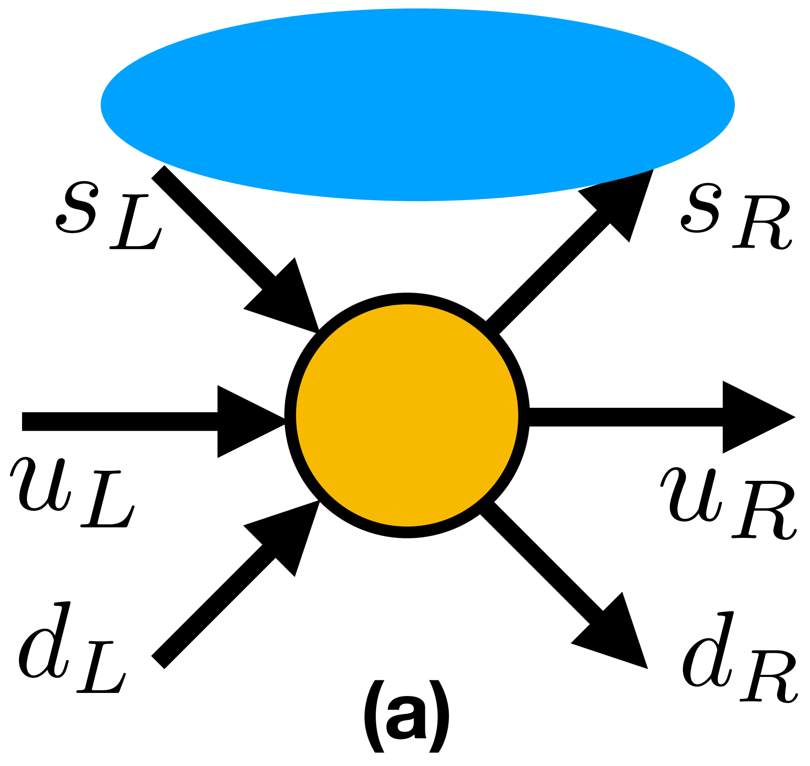
Diquark Bose condensates in high density matter and instantons
R.Rapp, Thomas Schäfer, Edward V. Shuryak, M. Velkovsky
Phys.Rev.Lett. 81 (1998) 53-56 • e-Print: hep-ph/9711396

Dynamical origins of those differences in light quark diquark correlations

instanton-induced 't Hooft interaction is antisymmetric in flavor, say ud not uu

Quasilocal + 4-quark approximation



$$G[\vec{\pi}^2 + \sigma^2 - \vec{\delta}^2 - \eta'^2]$$

$$\eta' = (\bar{q}\gamma_5 q)$$

$$\vec{\delta} = (\bar{q}\vec{\tau} q)$$

the original NJL model has only two first terms

repulsion explicit U(1)a breaking

when Firtz-transformed to qq channel it has a simple relation between q-q and anti-q q forces (like pQCD Coulomb forces)

$$\boxed{\frac{G_{qq}}{G_{\bar{q}q}} = \frac{1}{N_c - 1}}$$

$Nc = 2 \to 1$

$Nc = 3 \to 1/2$

$Nc = \infty \to 0$

Comparison between Sigma Quu and Lambda Qud baryons (plots for Q=charm) induced by ud pairing interaction (in quasiloca approximation done via matrices in funct.basis)

one diquark channel only already makes noticeable differences

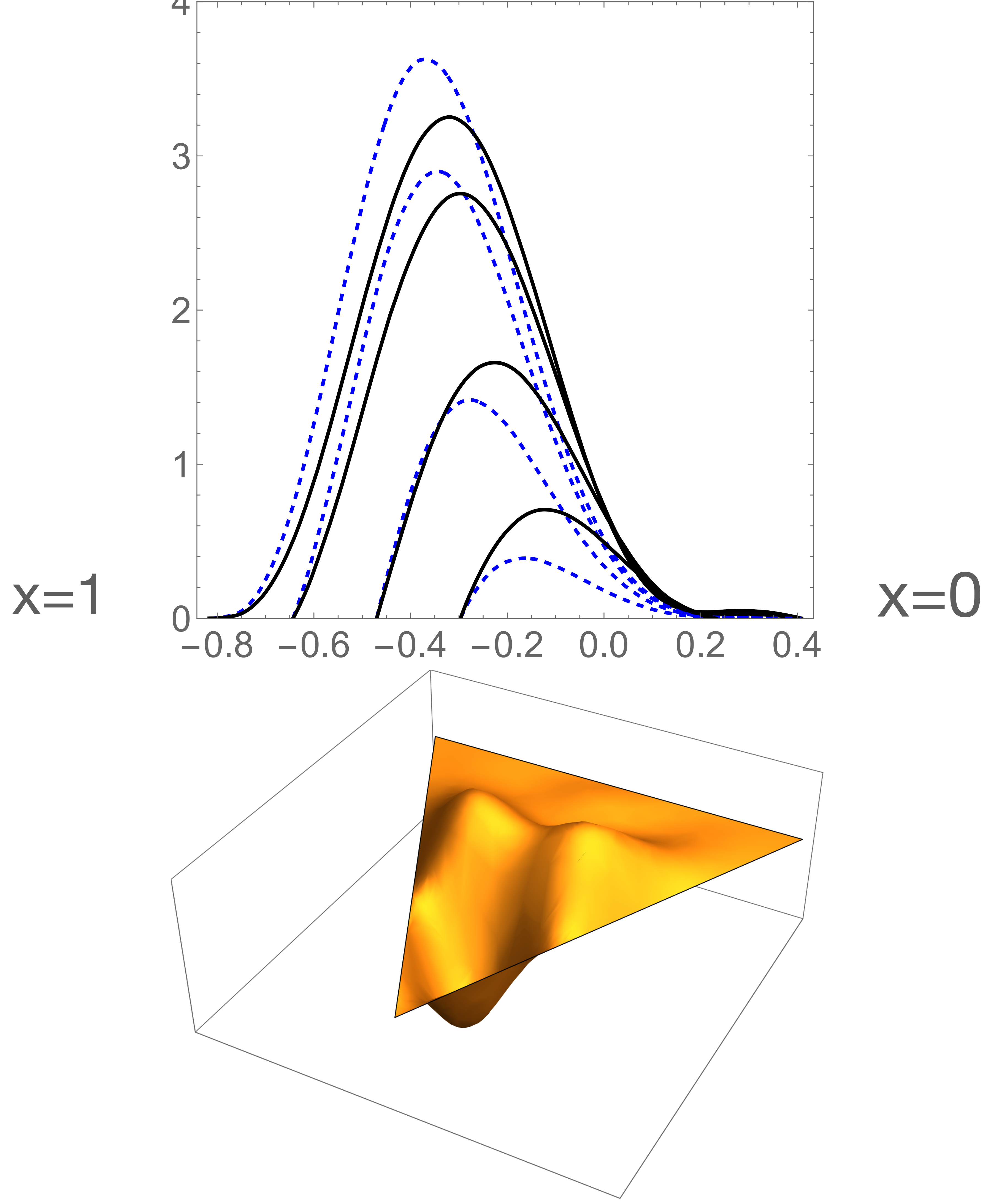


FIG. 5: Upper plot: the longitudinal wave functions $\Psi_\Sigma(\rho,\lambda)$ of Σ_c (blue dashed) and $\Psi_\Lambda(\rho,\lambda)$ of Λ_c (black solid), as a function of λ. Tl four pairs of curves are for $\rho = 0.0, 0.1, 0.2, 0.3$, to to bottom. The lower 3D plot shows their *difference*, $\Psi_\Lambda(\rho,\lambda) - \Psi_\Sigma(\rho,\lambda)$.

DIQUARK PAIRING IN THE NUCLEONS versus Delta

two diquark channels already makes noticeable differences especially near x->1

note that effect of pairing is smaller in excited states

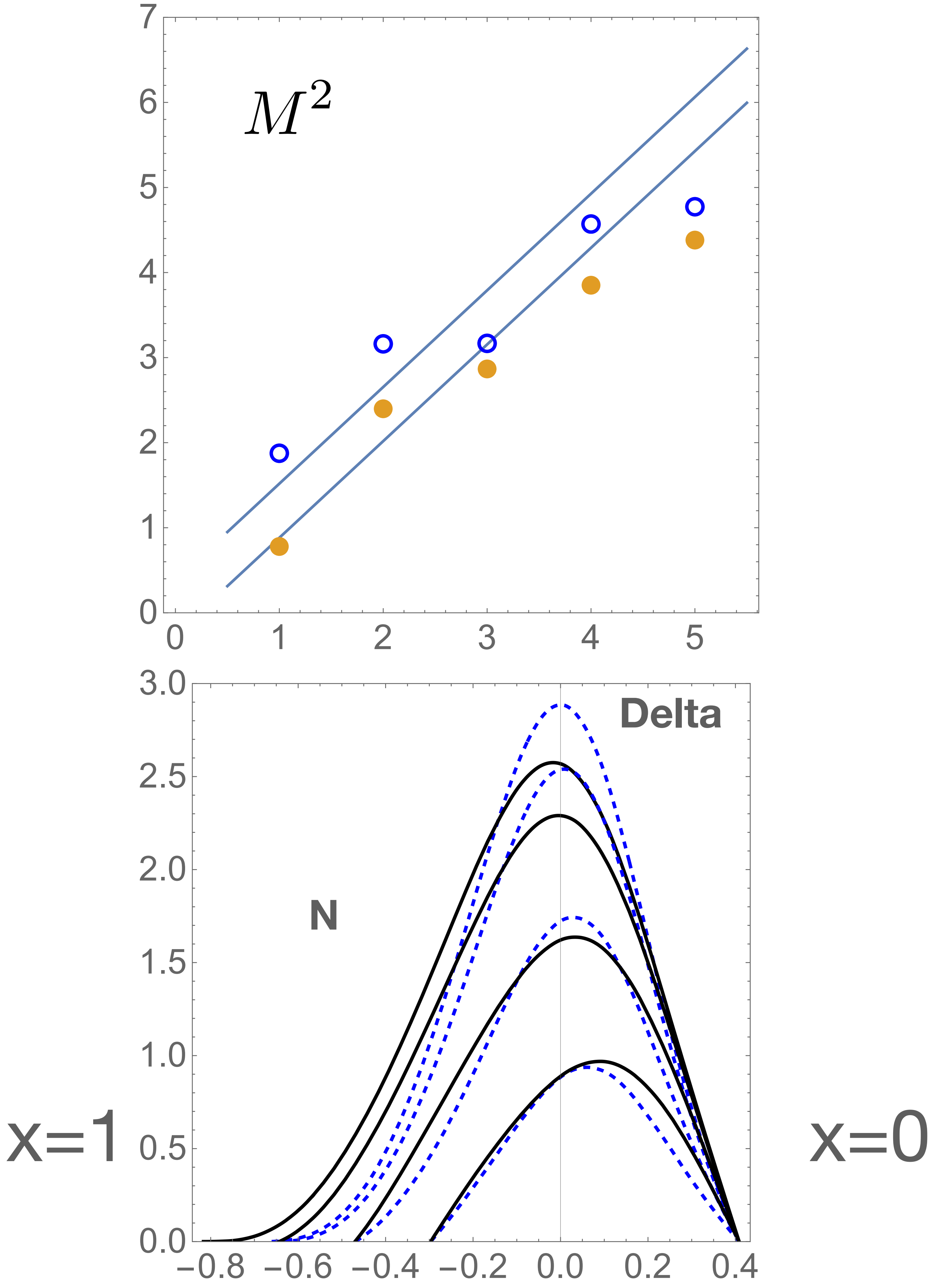
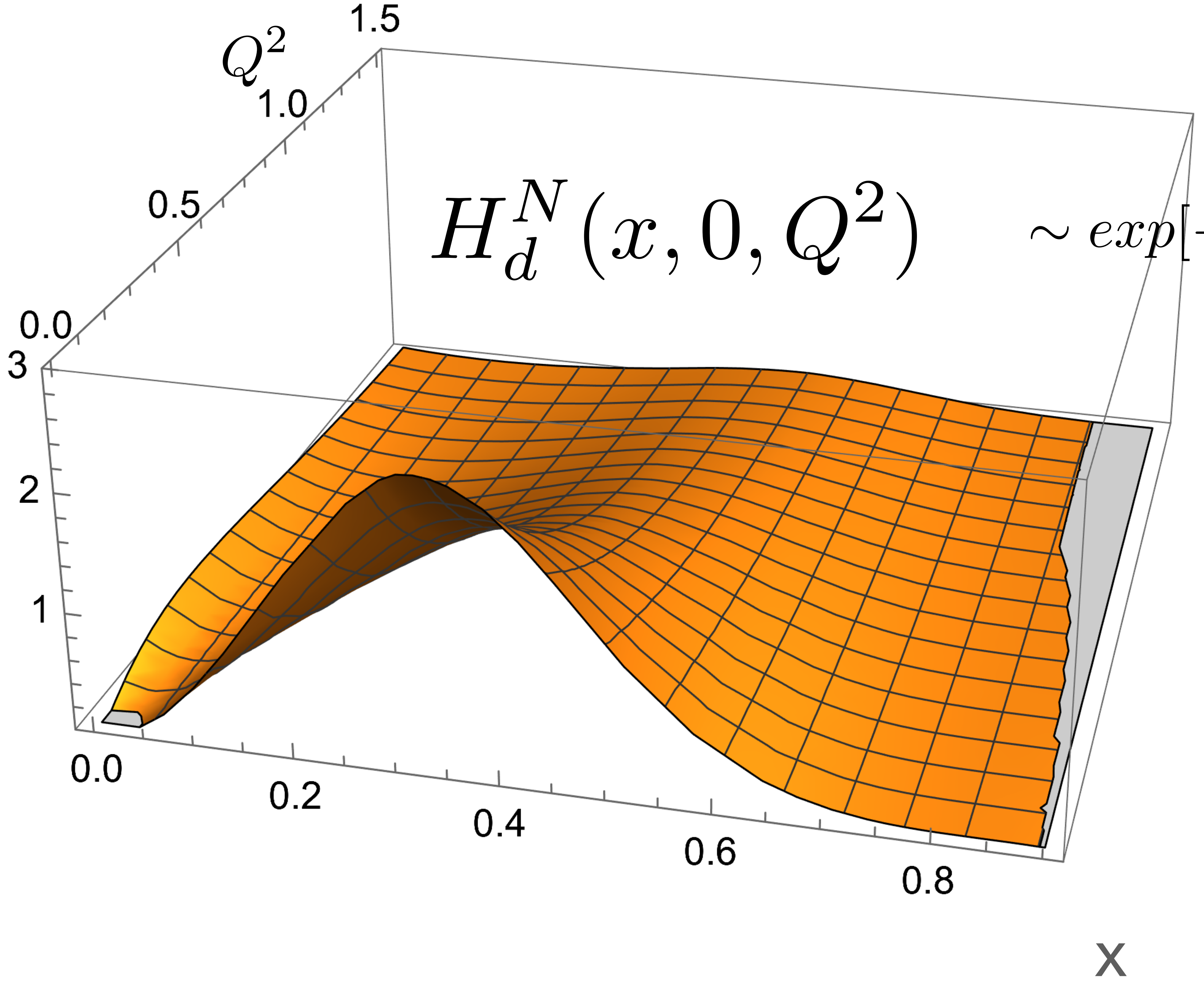


FIG. 6: Upper: Squared masses of the Delta (open points) and N (closed) resonances versus their successive quantum number n. The two straight lines shown for comparison, are the Regge trajectories fitted to the experimental values of $M^2(J)$, versus the total angular momentum J, with the slope $\alpha' = 0.88\,GeV^2$.
Lower: LFWFs for the lowest Delta (dashed lines) and N (solid lines). The plots are shown versus the Jacobi coordinate λ, for fixed $\rho = 0, 0.1, 0.2, 0.3$, top to bottom.

paper VI Nucleon and Delta GPDs

Zero skewness:

$$H(x,0,t) = \int_P \delta(x-x_1)\,\psi^{+*}([x'_i,k'_{i\perp},\lambda_i])\psi^{+}([x_i,k_{i\perp},\lambda_i])$$



$\sim exp[-Q^2R^2(x)/2]$

$-\partial log[H]/\partial Q^2$

N

Δ

paper VI **Nucleon and Delta GPDs**

it is a formfactor
but for particular
x of the struck quark,
and that turns out to be
Gaussians, with
x-dependent slopes

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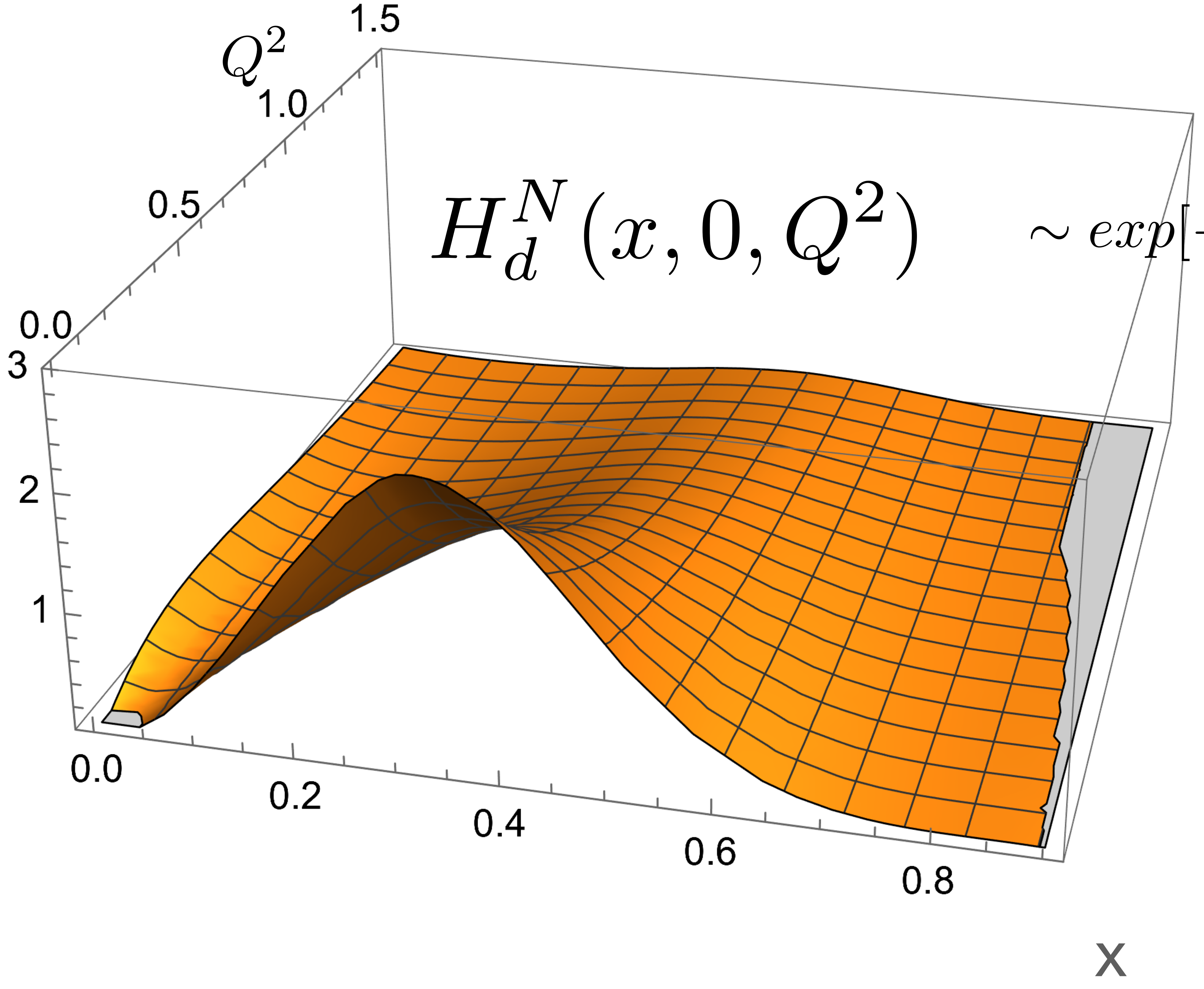

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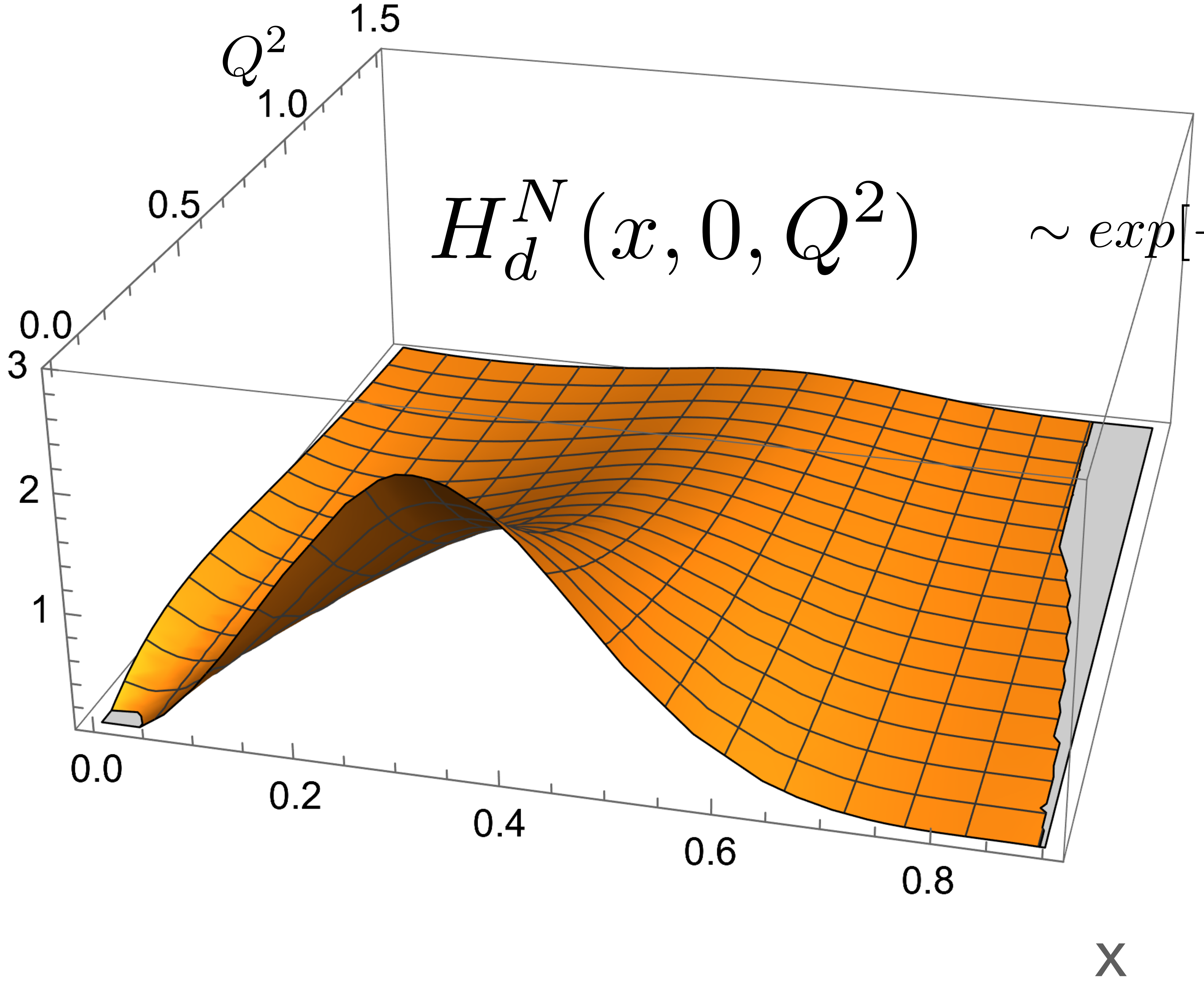
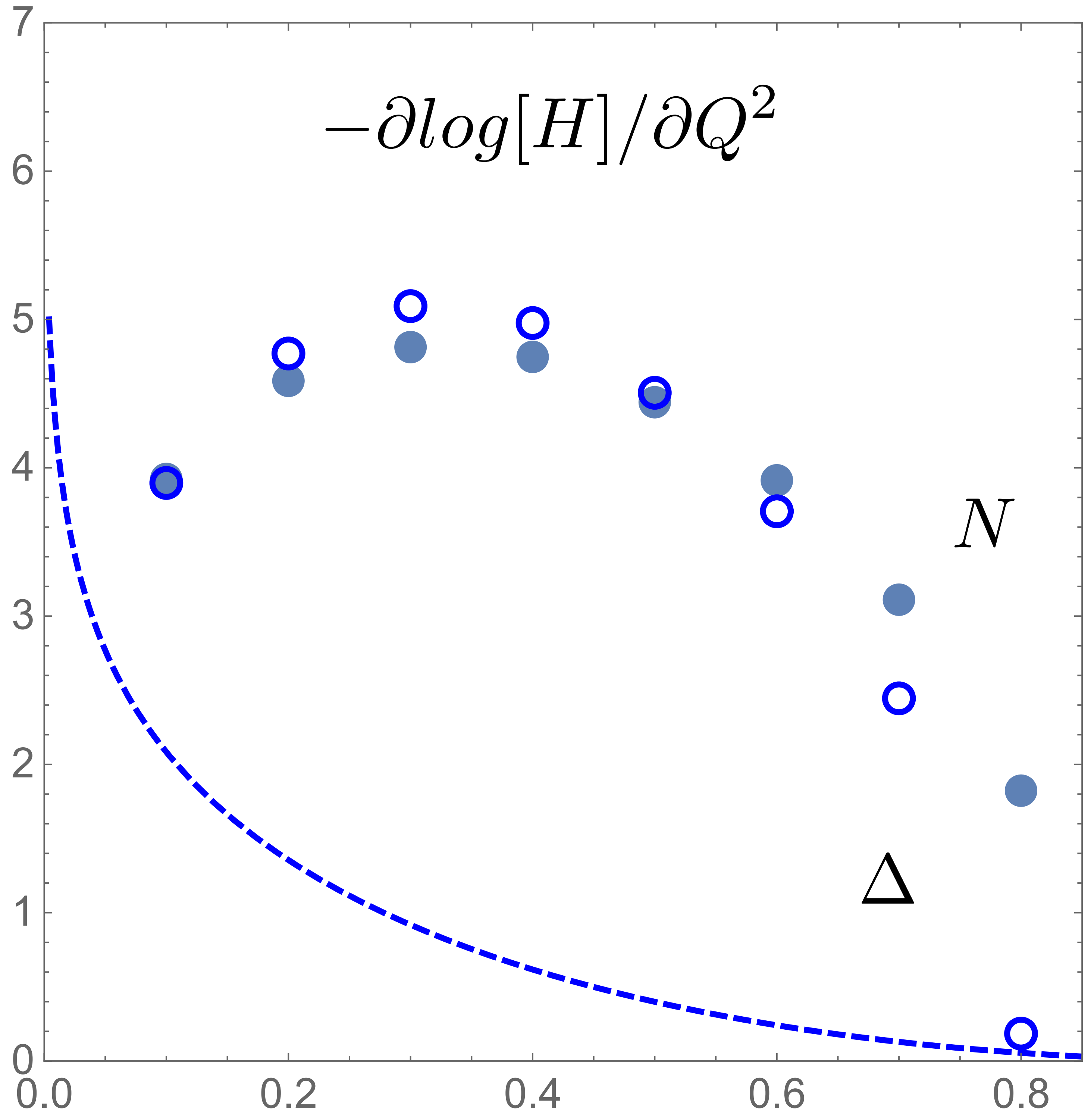
Zero skewness:

$$H(x,0,t) = \int_P \delta(x - x_1)\,\psi^{+*}([x'_i, k'_{i\perp}, \lambda_i])\psi^{+}([x_i, k_{i\perp}, \lambda_i])$$



$\sim exp[-Q^2 R^2(x)/2]$

it is a formfactor
but for particular
x of the struck quark,
and that turns out to be
Gaussians, with
x-dependent slopes



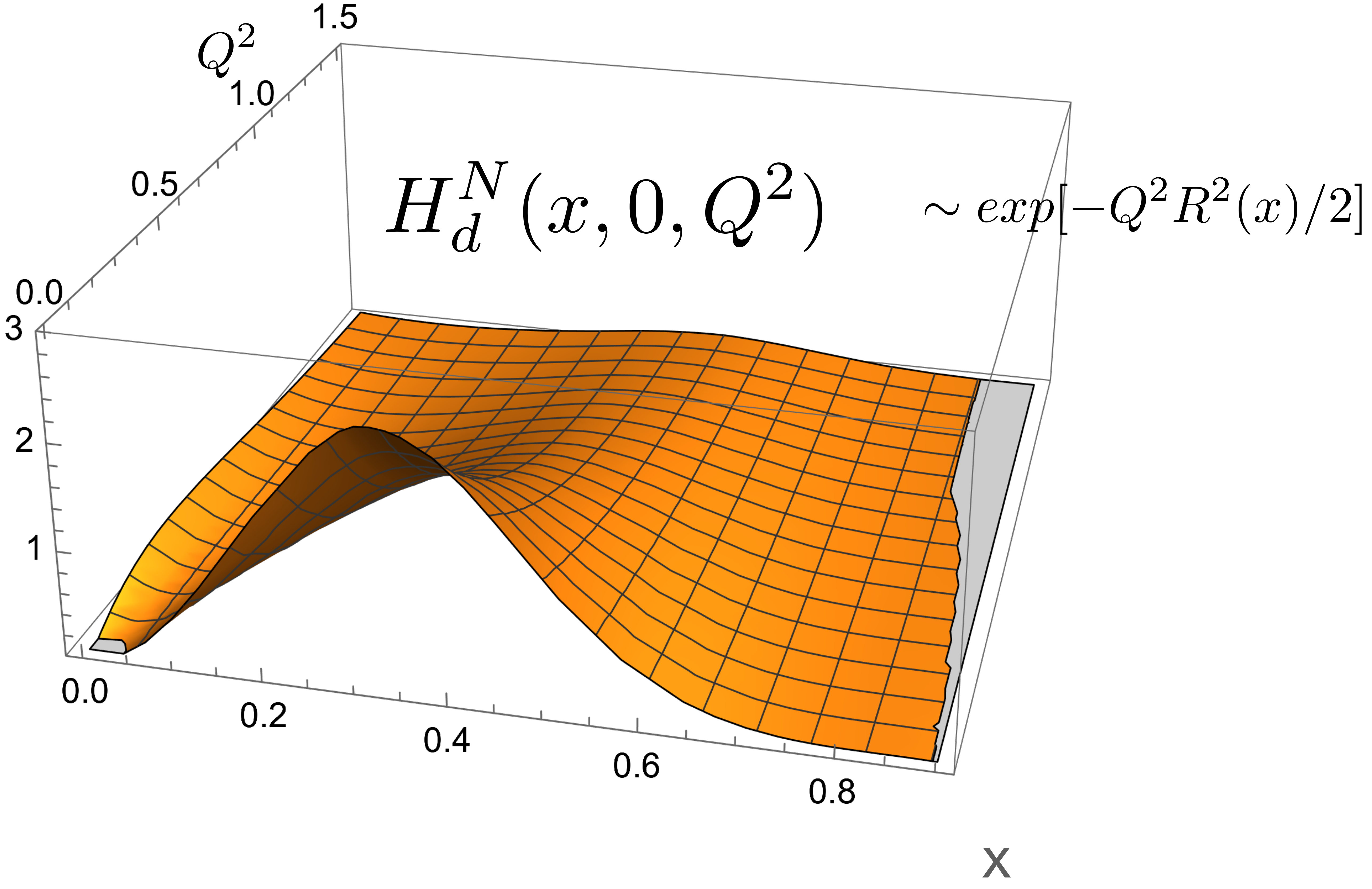
paper VI Nucleon and Delta GPDs

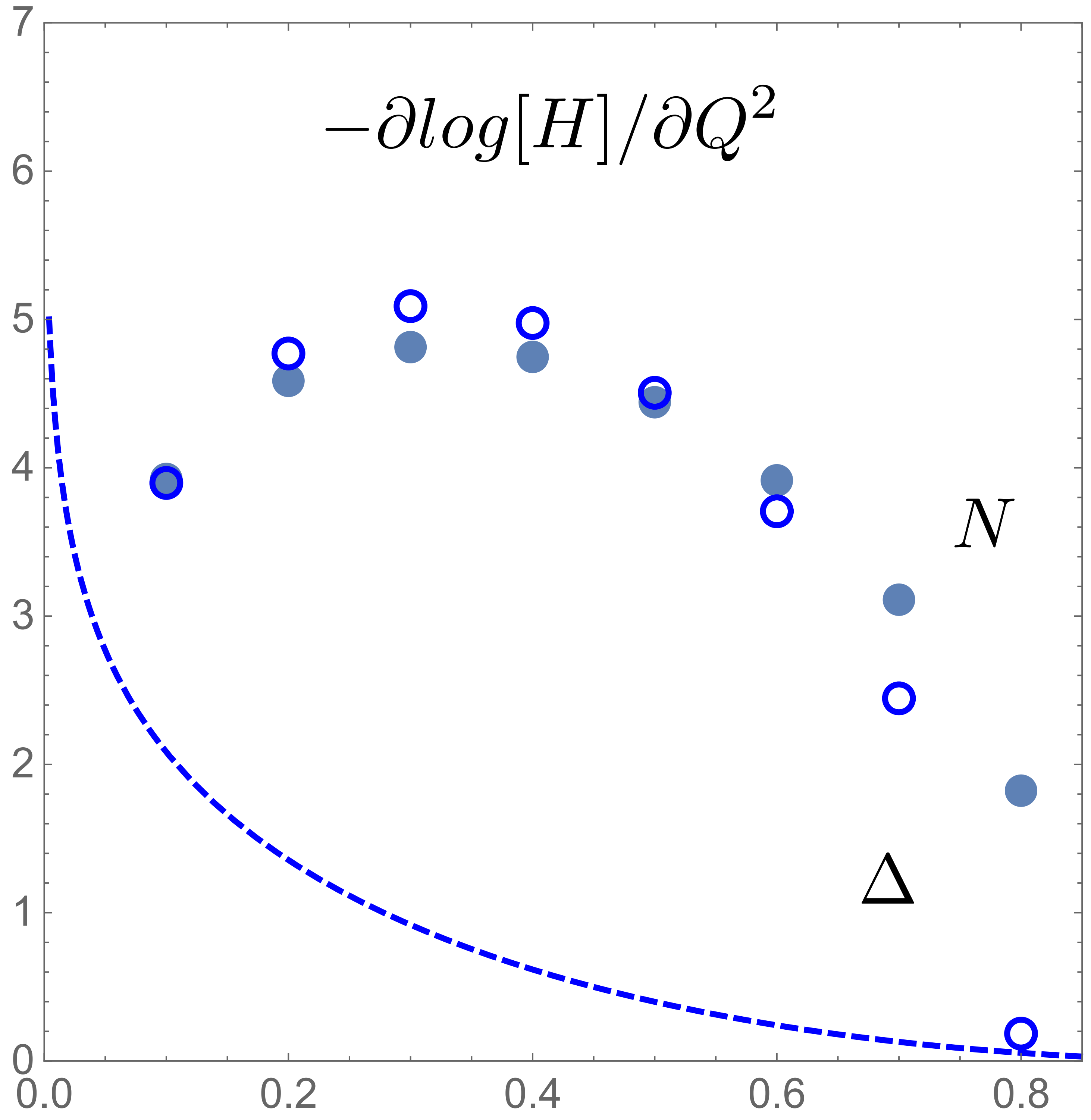
Zero skewness:

$$H(x,0,t) = \int_P \delta(x-x_1)\,\psi^{+*}([x_i', k_{i\perp}', \lambda_i])\psi^{+}([x_i, k_{i\perp}, \lambda_i])$$

it is a formfactor
but for particular
x of the struck quark,
and that turns out to be
Gaussians, with
x-dependent slopes

so ff\sim 1/Q^4
appears only
after x integration





Nucleon and Delta Formfactors are approximately 1/Q^4

but show differences at large enough Q, Delta is softer which means its size is about 2^(1/4) times larger

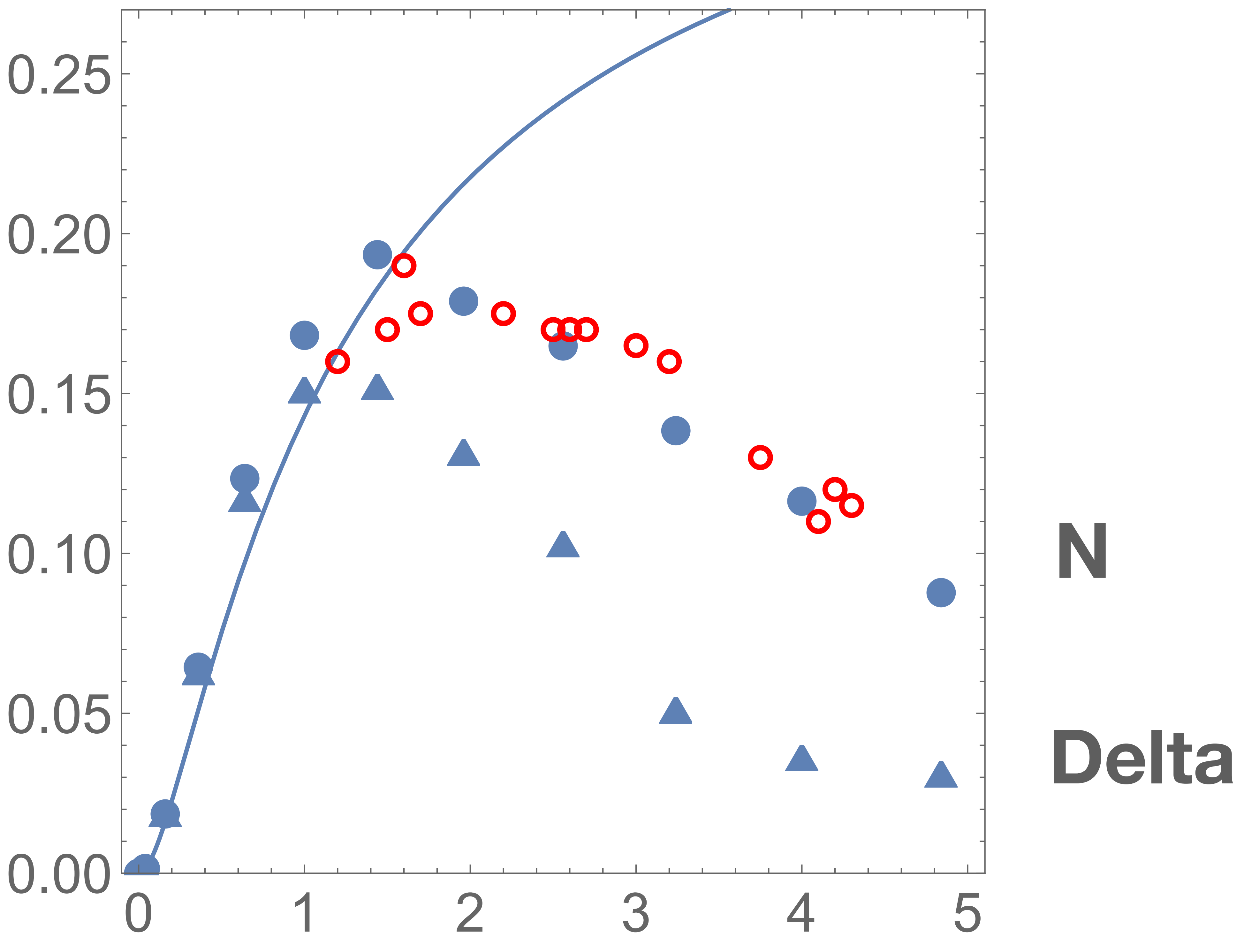


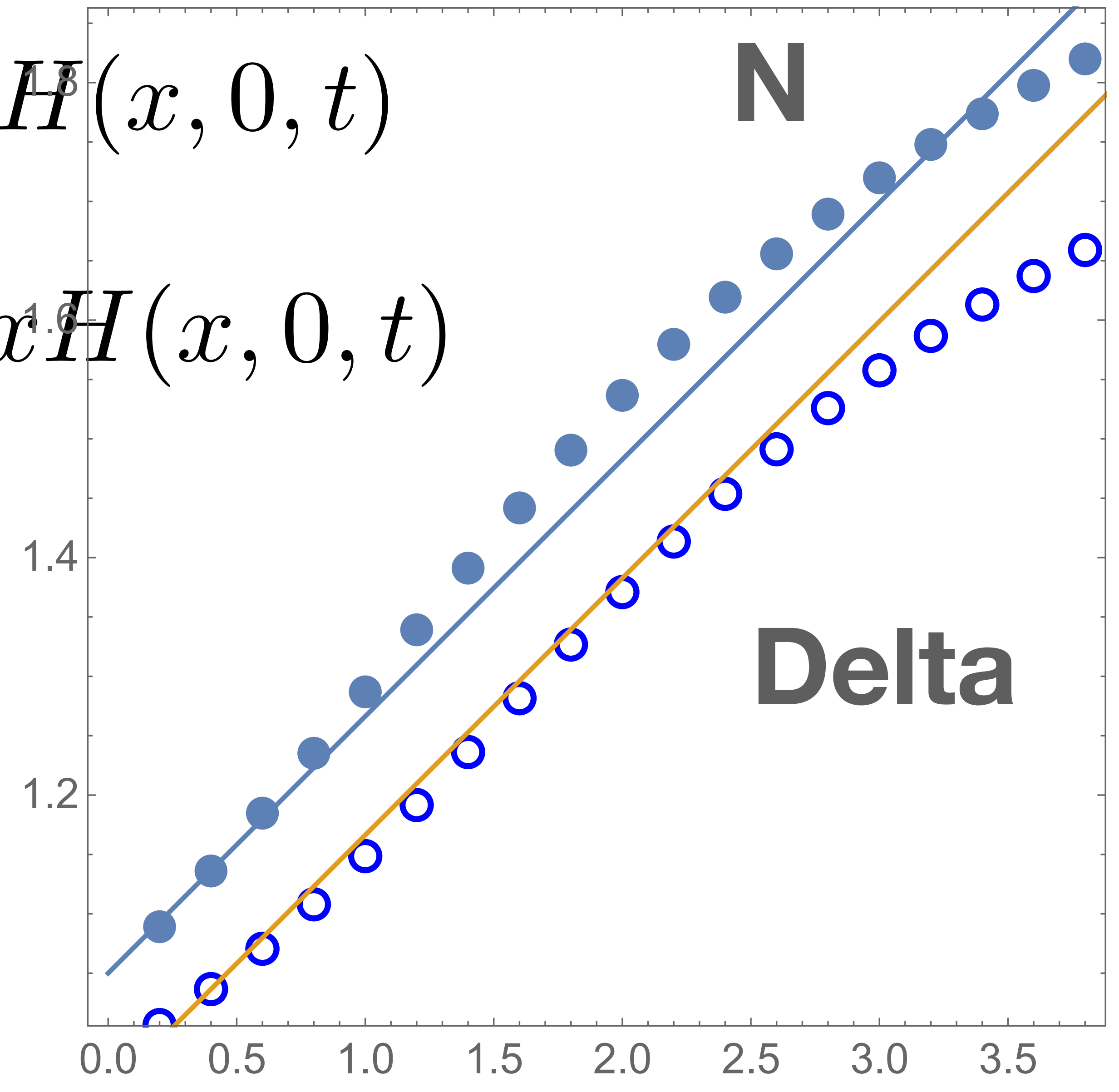
FIG. 8: $Q^4 F_1^d(Q^2)$, (GeV^4) versus the momentum transfer Q^2 (GeV^2). The triangles and closed points correspond to the Delta and Proton LFWFs, respectively. The red circles are extraction from the experimental data on the p and n formfactors mentioned in the text. The solid line shown for comparison, corresponds to the dipole form factor $Q^4/(1+Q^2/m_\rho^2)^2$.

gravitational formfactors from GPDs

$$F_1(t) = \int dx H(x,0,t)$$

$$A(t) = \int dx\, x H(x,0,t)$$

$A(Q^2)/F_1(Q^2)$



Bridging the gap between hadronic spectroscopy and partonic physics

The *first ark of the bridge* (described in detail in these series of works) is to transfer such quark models from the CM frame to the light front. For some simplest cases – like heavy quarkonia – it amounts to a transition from spherical to cylindrical coordinates, with subsequent transformation of longitudinal momenta into Bjorken-Feynman variable x. But in general, it is easier to start with light-front Hamiltonians H_{LF} and perform its quantization. One of the benefit is that no nonrelativistic approximation is needed, therefore heavy and light quarks are treated in the same way.

The *second ark of the bridge* is built via *chiral dynamics* , which seeds the quark sea by producing extra quark-antiquark pair. In section VIII we discuss how it can be done, in the first order in 't Hooft effective action as well as via intermediate pions.

$$\boxed{\mu^2 \approx 1\, GeV^2}$$

We will then argue that as the *third ark of the bridge* one should use the well known DGLAP evolution of the PDFs (perhaps modified), down to the scale at which there are no gluons. There the $q\bar{q}$ sea should be reduced to only the part generated by chiral dynamics (step two). The antiquark flavor asymmetry $\bar{d}-\bar{u}$ is the tool allowing us to tell gluon and chiral contributions, as it cannot be generated by "flavor blind" gluons.