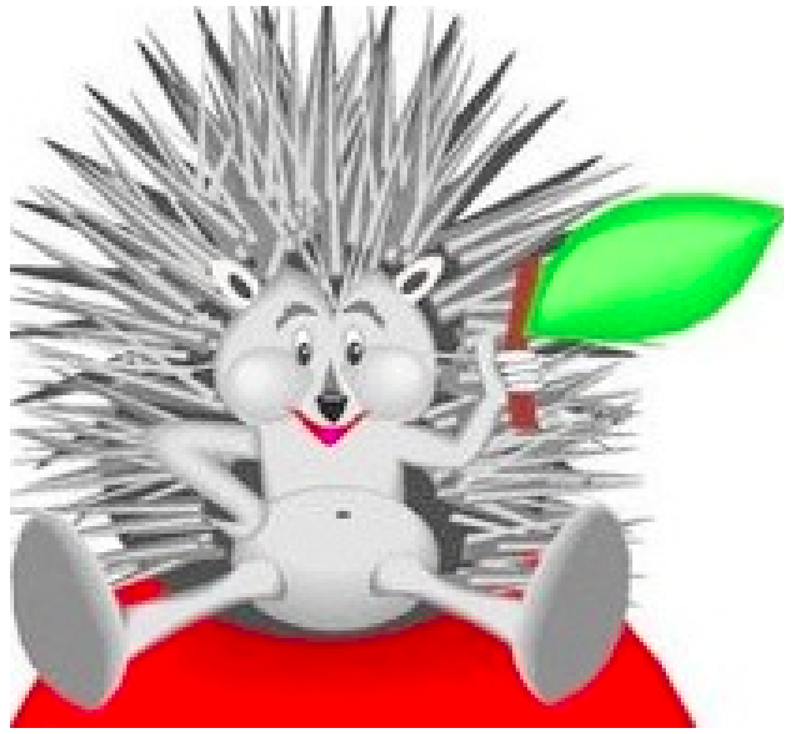
Gauge topology... ECT*, May 23 2022

Hadronic structure and spectroscopy on the light front

Edward Shuryak
Center for Nuclear Theory, Stony Brook

recent papers with Ismail Zahed



vacuum structure

Correlators in Euclidean time:

"instanton liquid models"

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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Traditional quark models

(too many to mention here):

(i) Mq (chiral symmetry breaking)

(ii) confining+Coulomb potentials

(iii) residual interactions (NJL,instantons)

(obviously done in the rest frame)

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Light-front quantization:

pro: light front DAs and PDFs
con: mostly pQCD-based
(except recently)

(nearly no) Hamiltonian and WFs
no account for nonperturbative phenomena
like chiral symmetry breaking
Little quantum mech.+wave functions so far

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Holographic QCD
hadrons are modeled by some fields
"in the bulk"
Veneziano limit in which both the number
of flavors and colors are large
Nf,Nc → ∞,Nf/Nc = fixed
Good spectra => Regge trajectories

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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
Edward Shuryak(SUNY, Stony Brook), Ismail Zahed(SUNY, Stony Brook) (Aug 14, 2020)
Phys.Rev.D 103 (2021) 5, 054028 • e-Print: 2008.06169 [hep-ph]

"dense instanton liquid" gives reasonable pion FF

Not a model but a program!

Hadronic structure on the light-front I. Instanton effects and quark-antiquark effective potentials
Edward Shuryak(Stony Brook U.), Ismail Zahed(Stony Brook U.) (Oct 29, 2021)
e-Print: 2110.15927 [hep-ph]

calibrating spin-dependent forces in mesons

Hadronic structure on the light-front II: QCD strings, Wilson lines and potentials
Edward Shuryak(Stony Brook U.), Ismail Zahed(Stony Brook U.) (Nov 2, 2021)
e-Print: 2111.01775 [hep-ph]

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
Edward Shuryak(Stony Brook U.), Ismail Zahed(Stony Brook U.) (Dec 31, 2021)
e-Print: 2112.15586 [hep-ph]

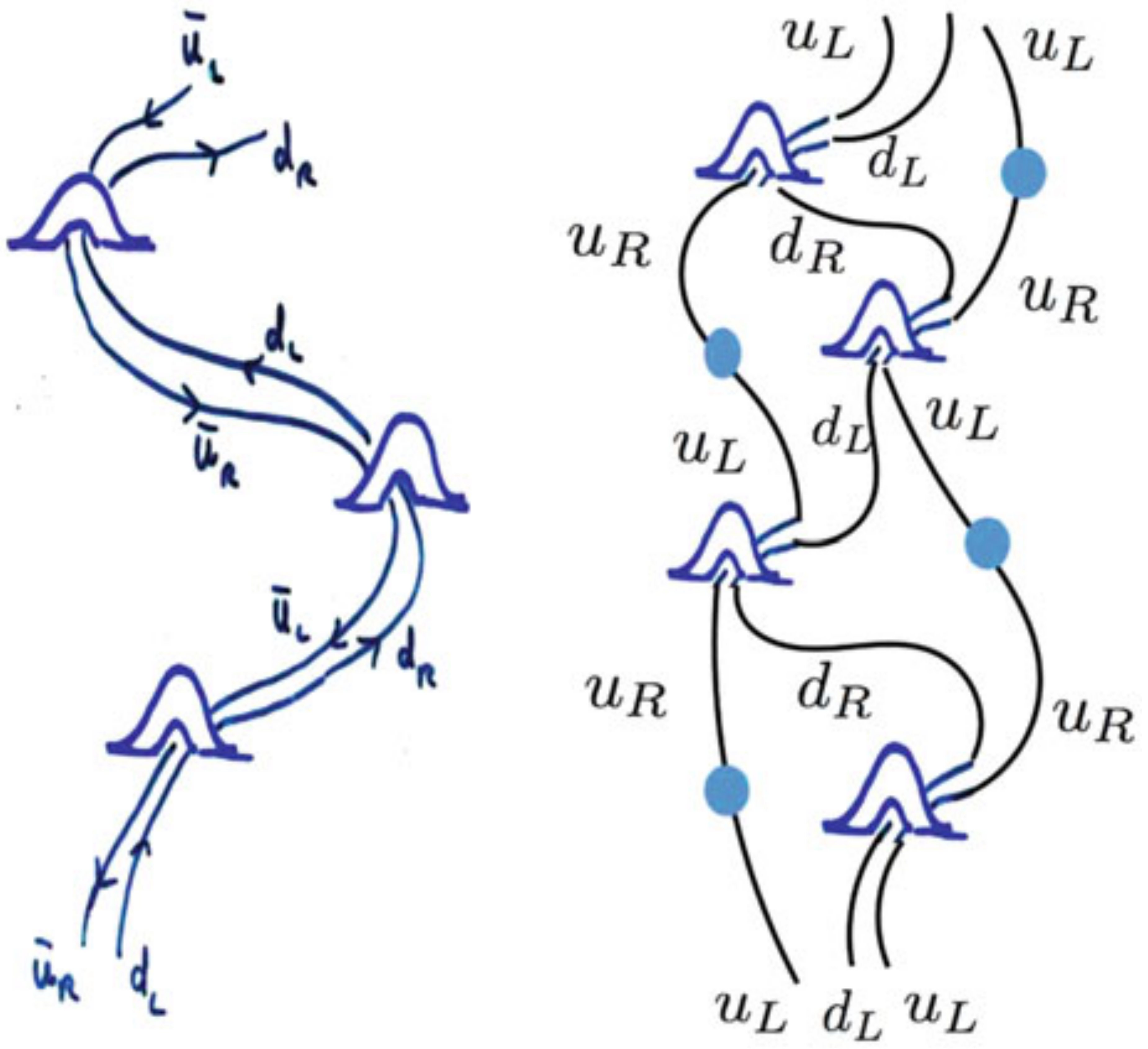
from heavy quarkonia to light mesons, spin effects, quadrupole moment of J/psi

Hadronic structure on the light-front IV: Heavy and light Baryons
Edward Shuryak(Stony Brook U.), Ismail Zahed (Jan 31, 2022)
e-Print: 2202.00167 [hep-ph]

flavor-symmetric baryons without "good diquarks"

paper 5: diquarks, Qud and QQ \bar u \bar d and other heavy-light systems

the pion and the nucleon functions in the instanton vacuum



.1 The pion (left) and the proton (right), depicted as a sequence of tunneling events.

mesons, heavy and light, on the light front

the simplest hadrons are heavy quarkonia for which one can use nonrelativistic Schreodinger eqn

red squares
are experimentally observed
Upsilons=bar b b

the idea here is to strip
down Coulomb and
spin forces,
keeping only confinement

we show that dependence
on n and L are then linear

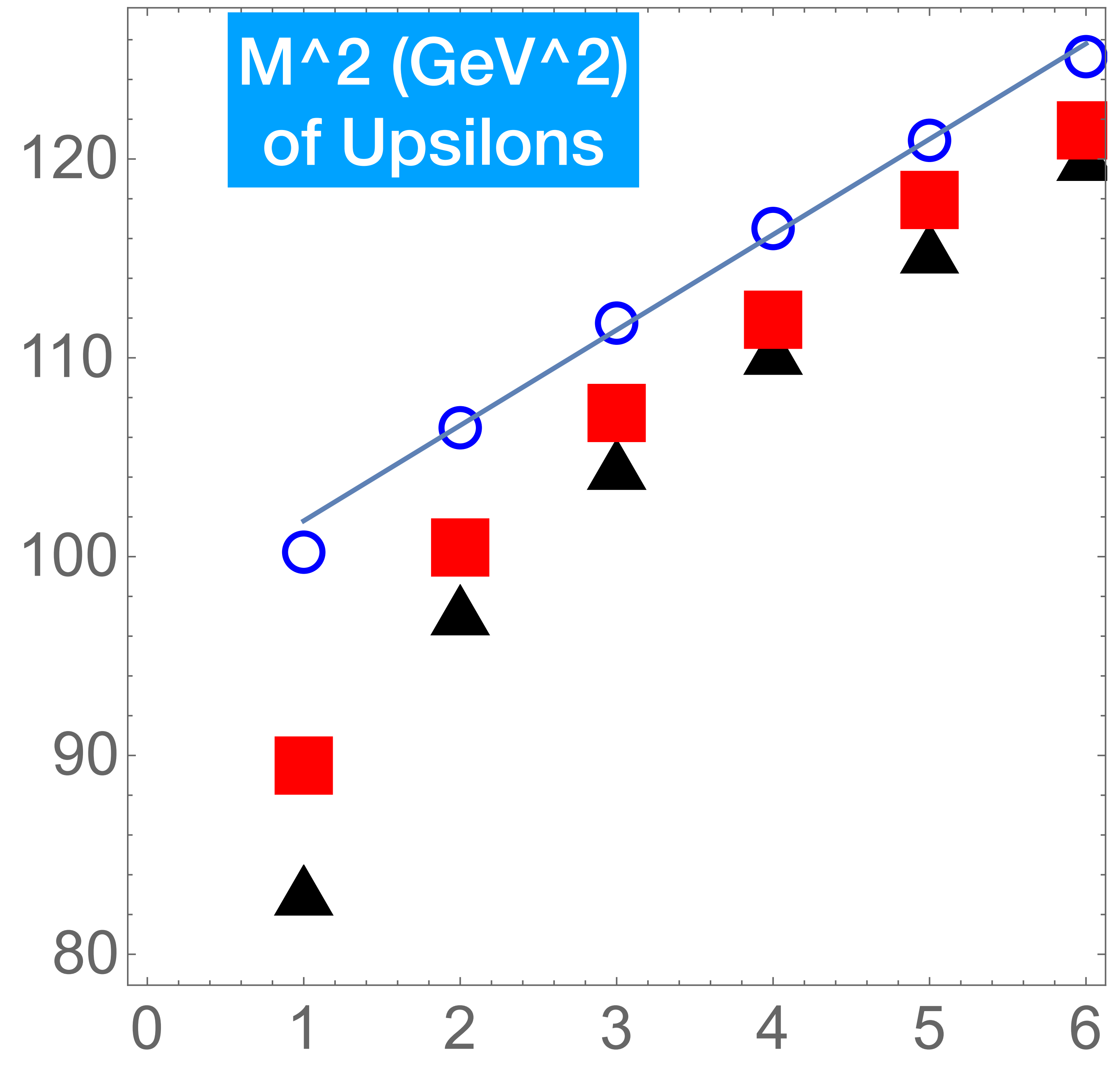


FIG. 2. $M^2_{n+1}\,(GeV)^2$ versus $n+1, n = 0, ..5$, for the six S zero orbital momentum (L=0) states of bottomonium. The red squares correspond to the experimentally observed Upsilons. The black triangles show the masses obtained from the Schroedinger equation, with the Cornell potential (linear and Coulomb potentials, no spin forces). The blue circles show the masses if the Coulomb potential is switched off, and only the linear potential is used. The straight line is shown for comparison.

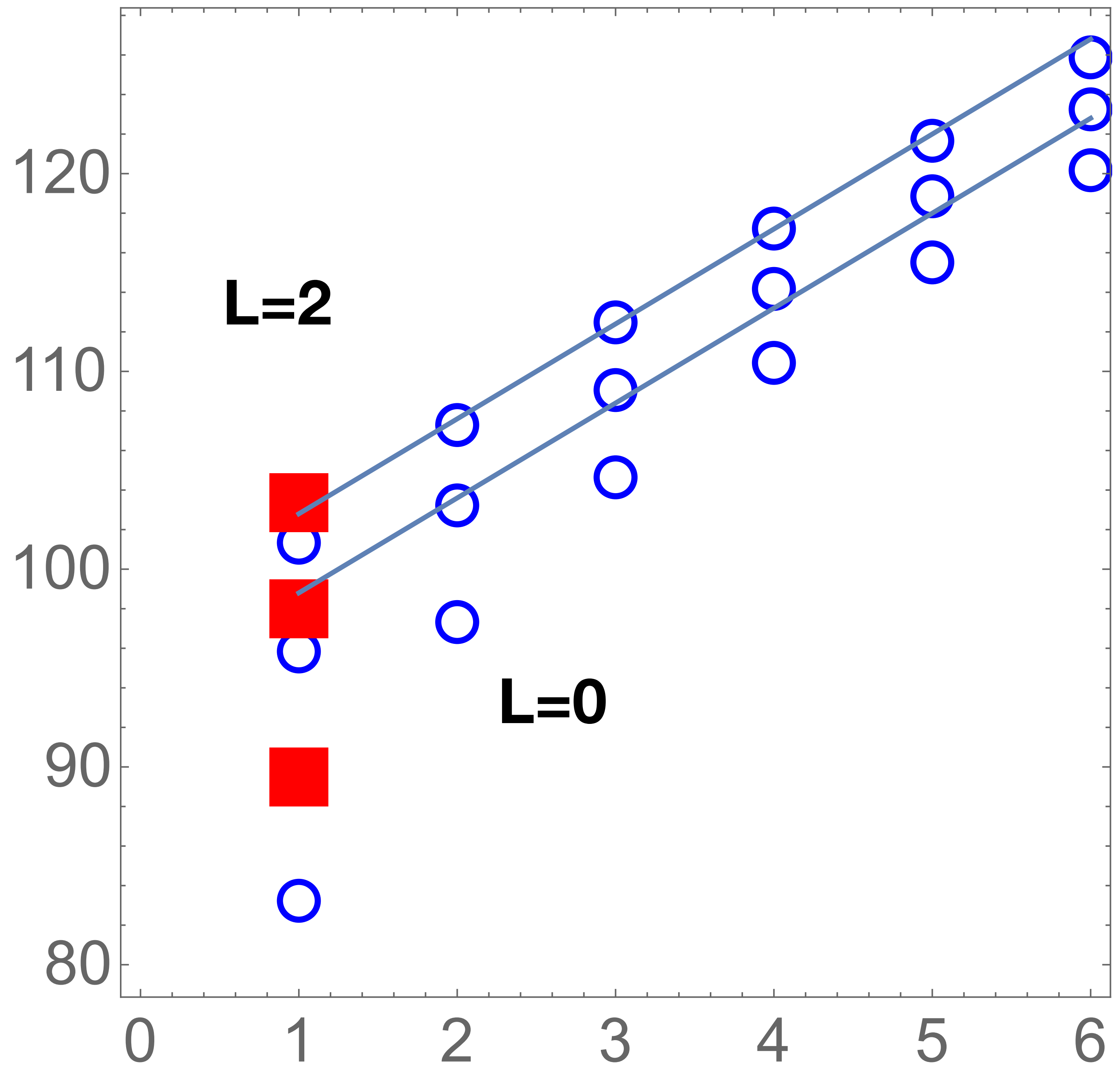


FIG. 3. $M^2_{n+1}\,(GeV)^2$ versus $n+1, n = 0, 1...$ for three families of bottomonium states, with orbital momentum $L = 0, 1, 2$ (from bottom up). The red squares correspond to the experimentally observed $\Upsilon, h_b, \Upsilon_2$ mesons (from bottom up). The blue circles show masses obtained from the Schroedinger equation, with the Cornell potential (linear and Coulomb potentials, still without spin forces). The straight lines are shown for comparison.

To start, our "basic problem": two massive quarks connected by a string

$$M^2 = 2P^+P^- = \frac{m_Q^2 + k_\perp^2}{x\bar{x}} + 2\sigma_T\left(|id/dx|^2 + M^2 x_\perp^2\right)^{\frac{1}{2}}$$

$$\bar{x} = 1 - x$$

Eliminating the square root
by "einbine trick":

if minimize by a we go back,
but we can minimize in a
a posteriori, after diagonalization

$$M^2(a,b) = \frac{m_Q^2 + k_\perp^2}{x\bar{x}} + \sigma_T\left(\frac{|id/dx|^2 + bx_\perp^2}{a} + a\right)$$

transverse coordinate
oscillator, M^2 prop to n
longitudinally just harmonics

$$H_0 = \frac{\sigma_T}{a}\left(-\frac{\partial^2}{\partial x^2} - b\frac{\partial^2}{\partial k_\perp^2}\right) + \sigma_T a + 4(m_Q^2 + k_\perp^2)$$

$$V(x, \vec{k}_\perp) \equiv (m_Q^2 + k_\perp^2)\left(\frac{1}{x\bar{x}} - 4\right)$$

**a "cup"
potential
suppresses
LFWF at the edges**

the ``potential" depends
on all 3 momenta in non-factorizable way
it is a ``cup"
preventing x to be 0 or 1

red triangles are Upsilon masses
from light front Hamiltonian

same method, 12*12 matrix disgonalized
higher states affected by a cutoff

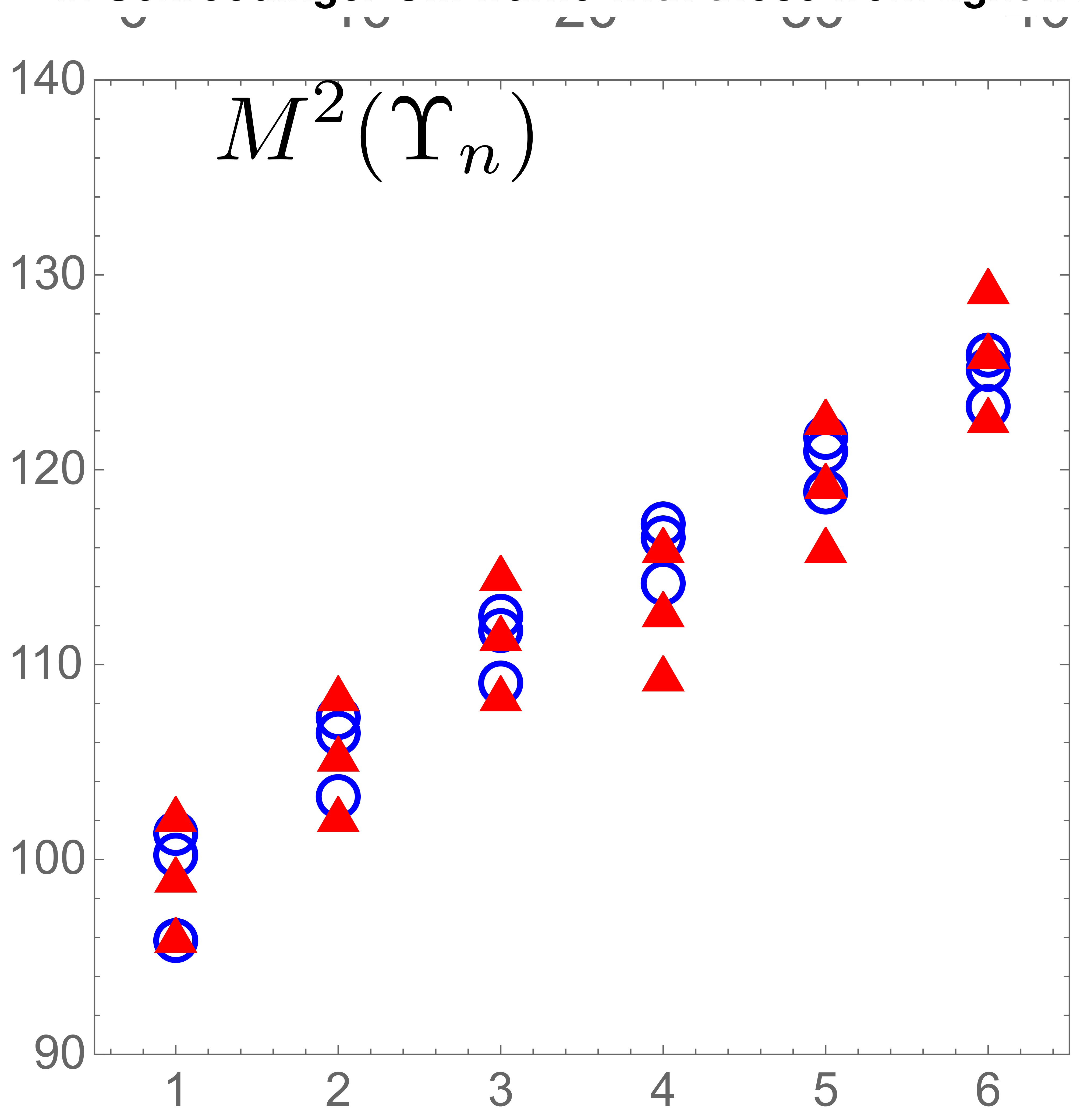
note: orbital is not L but 2d m

Squared masses for n = 0..5 (left to right)
and orbital momentum m = 0,1,2 (down to up),
calculated from the light front Hamiltonian H_{LF}

usi
u
usin

(red triangles), and shifted by a constant, $M^2 -$ n+1
5 GeV ^2
the blue-circles show the squared masses M^2
calculated from Schroedinger
n+1
equation in the CM frame, with only linear plus
centrifugal potentials.

**Comparison between Upsilon masses
in Schreodinger CM frame with those from light front**



now we move to light quarks, for which we have no nonrelativistic Schreodinger

Before we start, a useful hint: Regge trajectories again

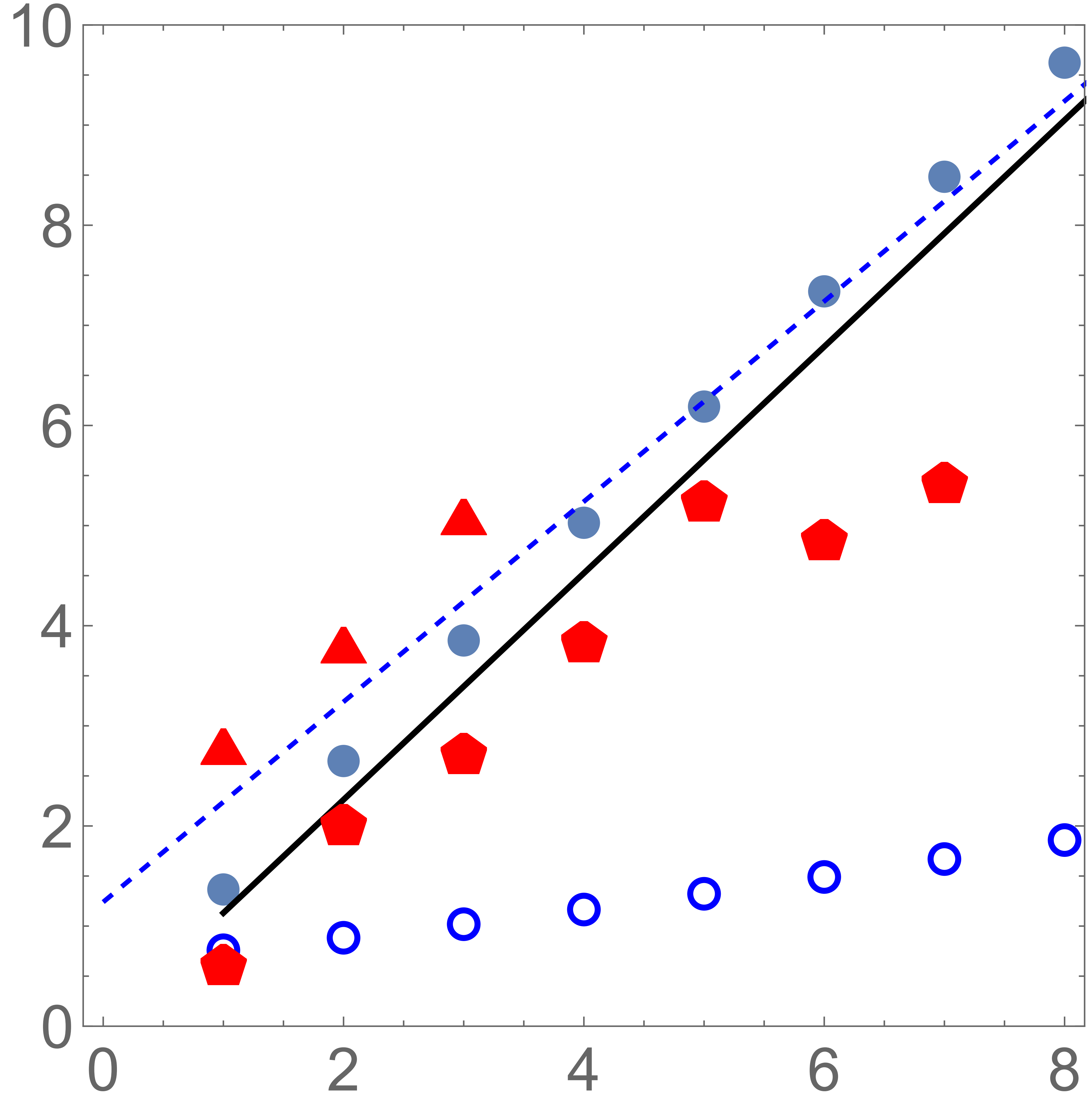


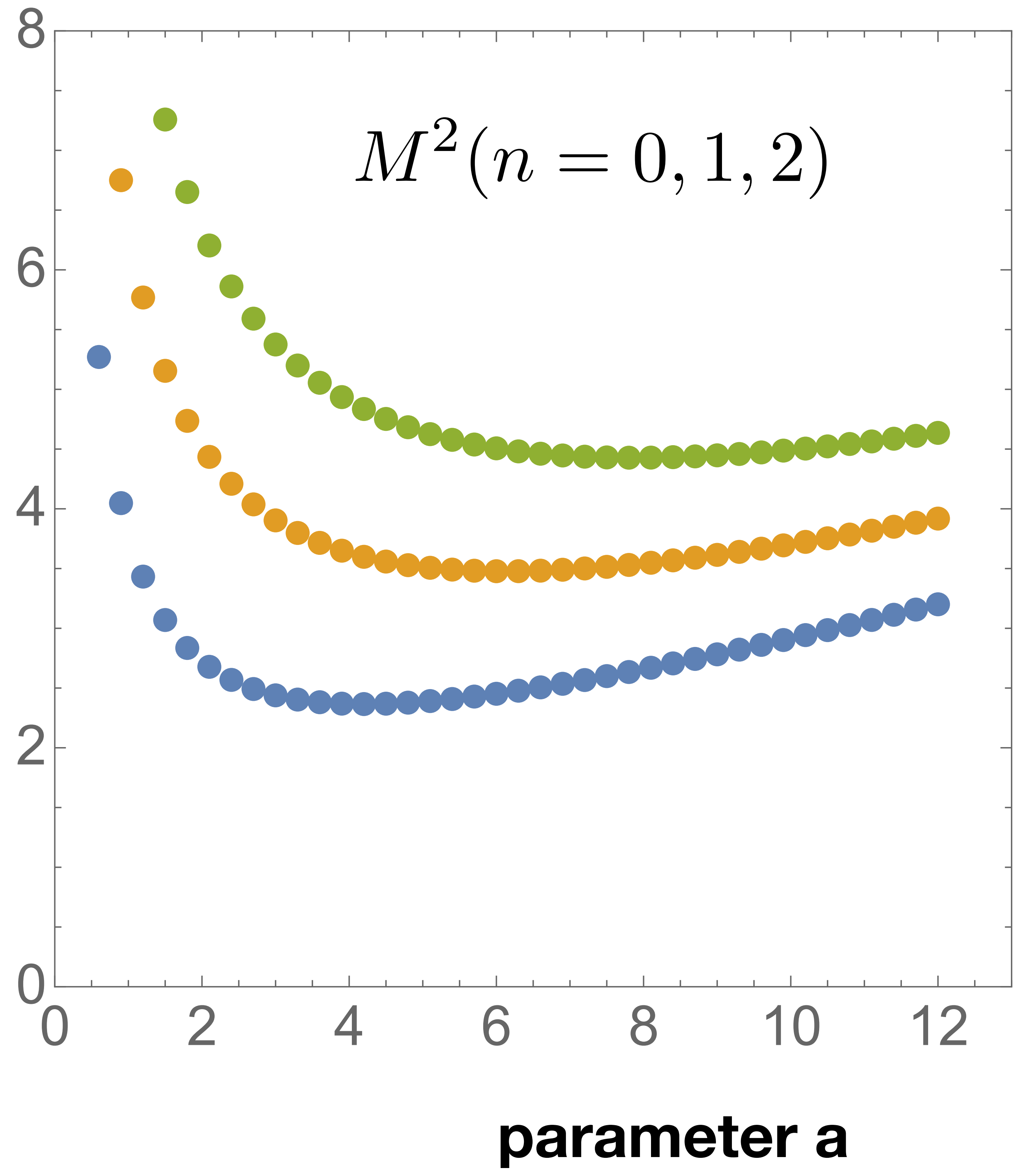
FIG. 2. The squared masses of the $n+1$-th states $E^2_{n+1}\,(GeV^2)$ versus the radial quantum number $n+1$. The closed points are for constituent quarks with mass $0.35\,GeV$. The solid line corresponds to the massless limit with $E^2_{n+1} = (n+1/2)/\alpha'$. The red five-polygons are the experimental data for the ω mesons, and the red triangles are for the ω_3 mesons listed in the PDG. The open points show the corresponding values from the Jia-Vary confining Hamiltonian (39), with their recommended value $\kappa = 0.227\,GeV$. The dashed line corresponds to the same expression with $\kappa = 0.5\,GeV$.

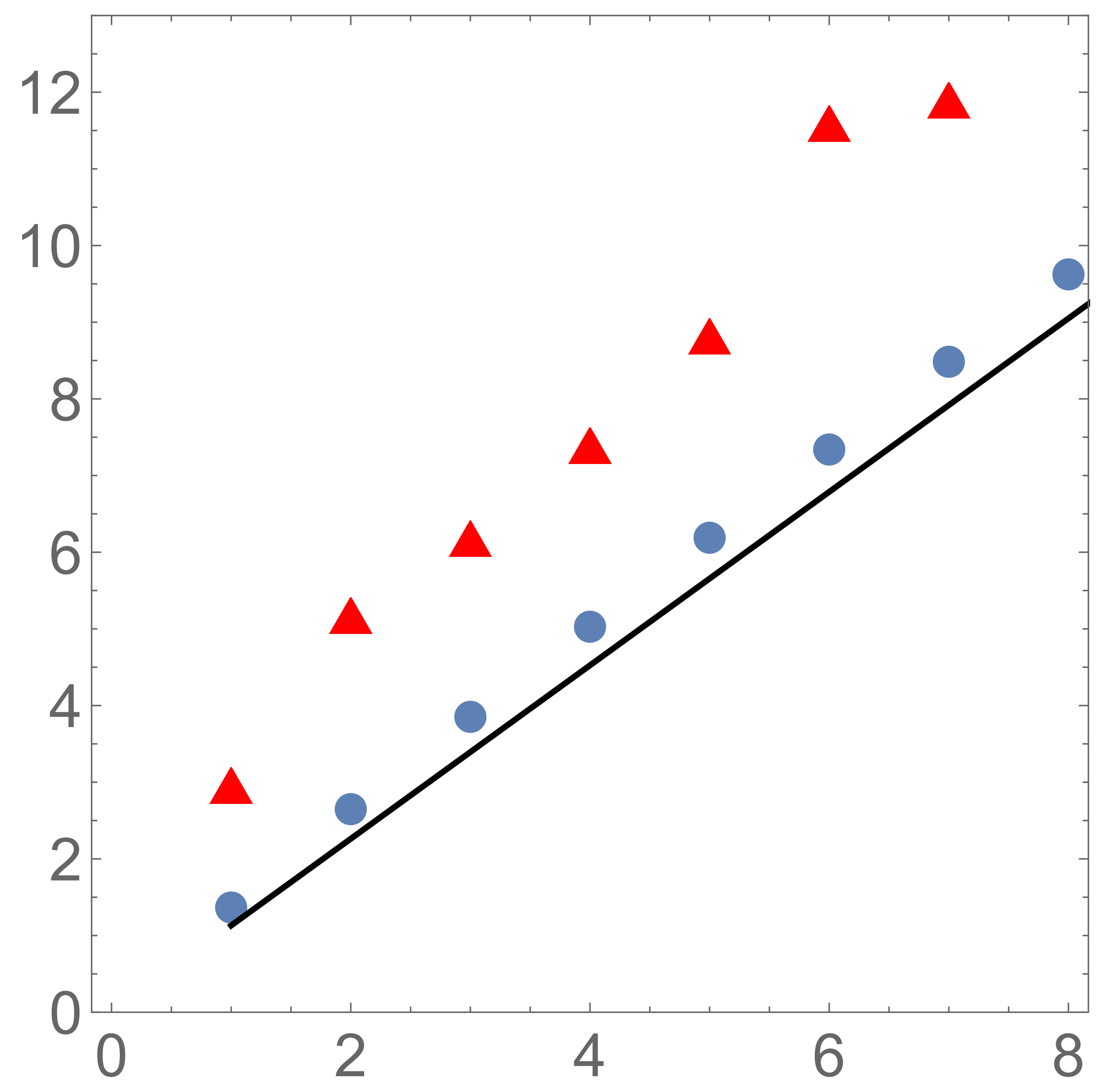
Two methods to solve this QM problem:

to define H as a matrix in certain basis and then diagonalize (part of) it

Directly solve numerically in 3d using tools from Mathematica

minimization in a





example of eigenvalues from 12*12 matrix for H
higher states affected by matrix cutoff

semiclassical relativistic string with two masses

Up to a constant, linear Regge trajectory is reproduced

Now let us have a look at the light front wave functions for those in more details

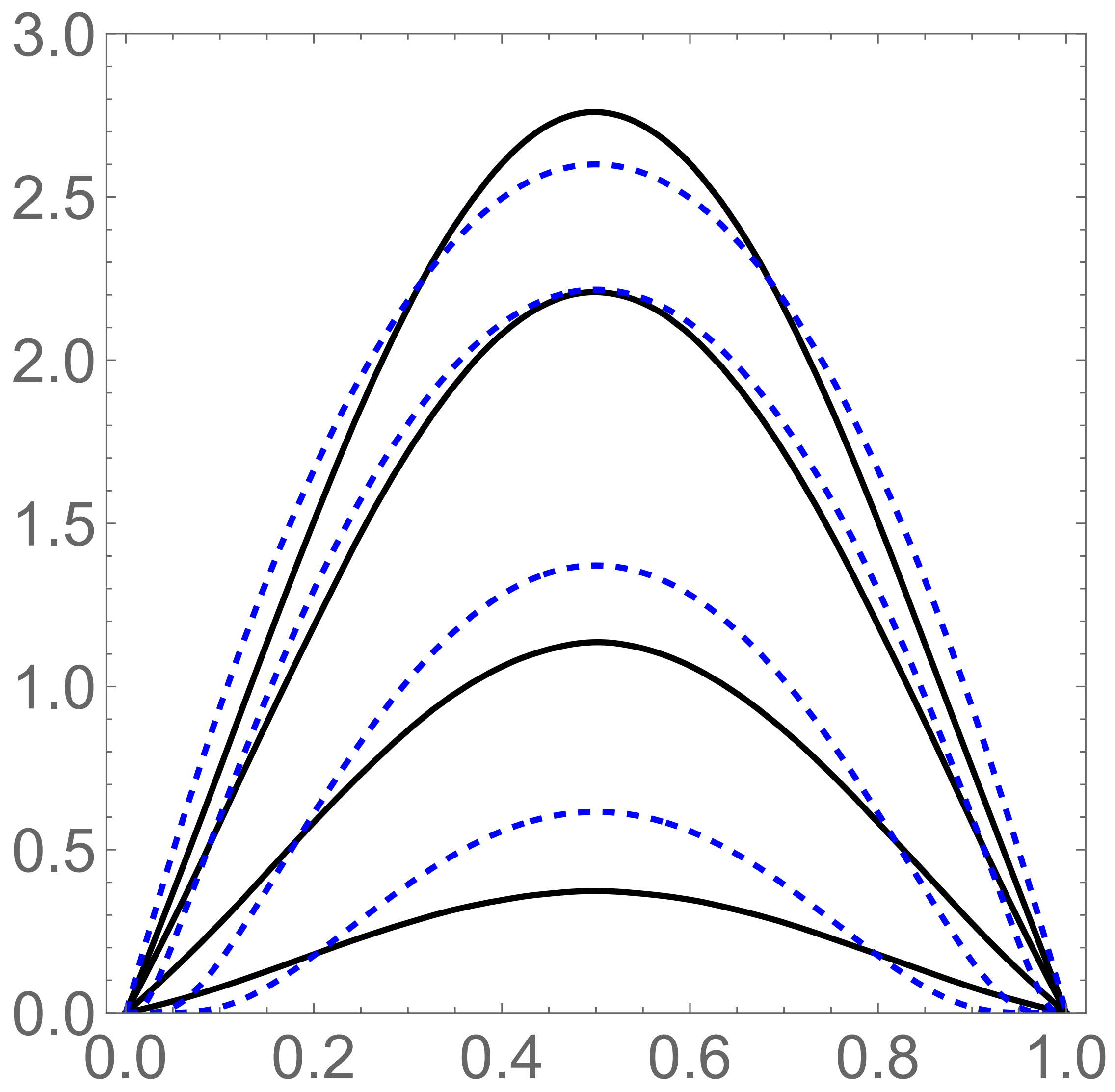
the ground state from 12*12 matrix diagonalization
rho=k_perp, beta parameter defined via a,sigma_T, mass

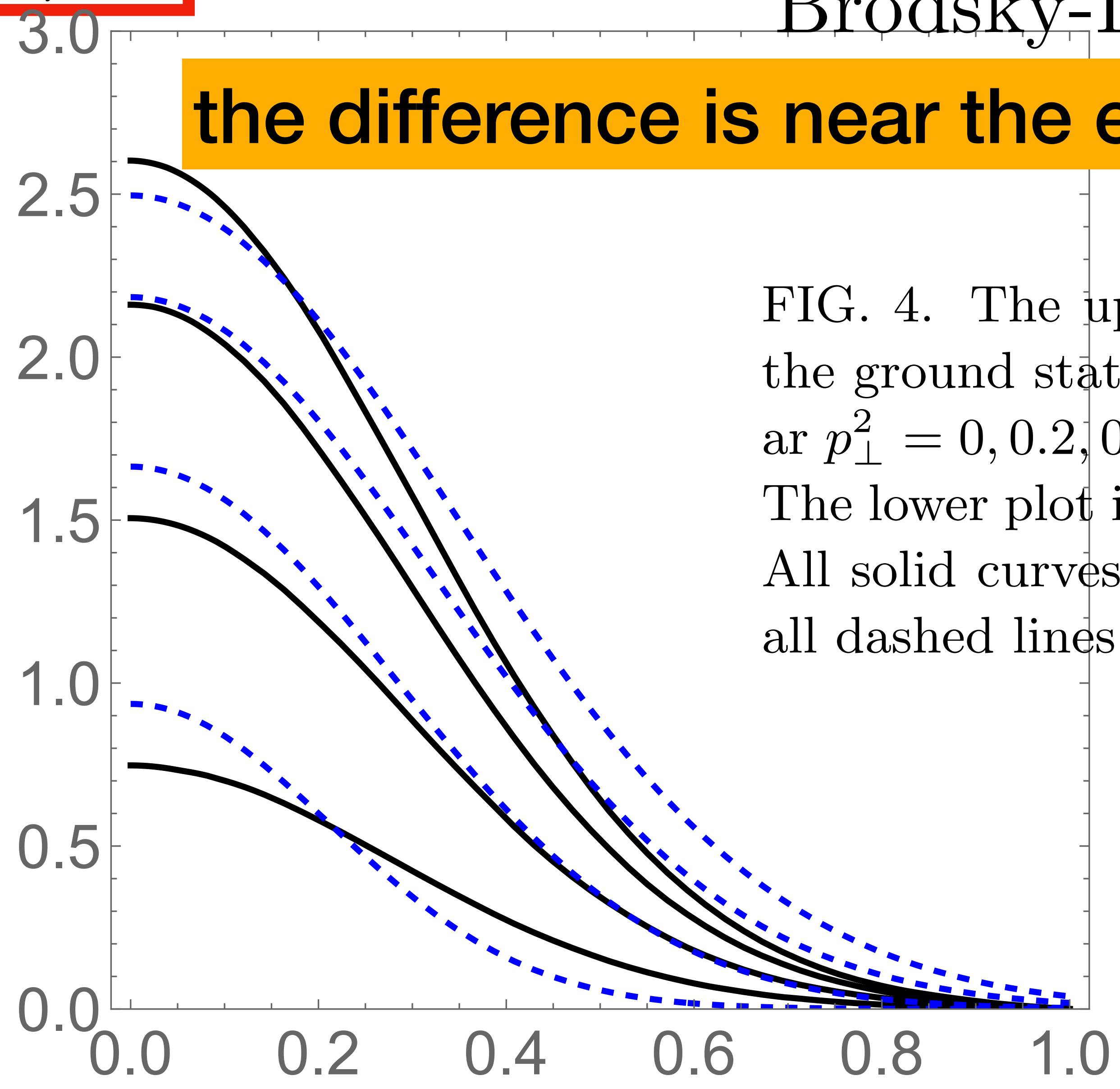
$$\psi_1(\rho,x) = \beta\, e^{-\beta^2\rho^2/2}\Big((0.831 - 0.0371\beta^2\rho^2 + 0.00100\beta^4\rho^4)\sin(\pi x)$$
$$+(-0.0252 - 0.0107\beta^2\rho^2 + 0.000566\beta^4\rho^4)\sin(3\pi x)$$
$$+(-0.00427 - 0.00207\beta^2\rho^2 + 0.000168\beta^4\rho^4)\sin(5\pi x)$$
$$+(-0.00145 - 0.000743\beta^2\rho^2 + 0.0000633\beta^4\rho^4)\sin(7\pi x)\Big)$$

$$\Psi_0(x,\xi) = 4C_2\, x\bar{x}\, e^{-C_1\xi^2}\,, \qquad \xi^2 = \frac{p_\perp^2}{x\bar{x}}$$

Brodsky-DeTeramond variable.

$$\langle p_\perp^2\rangle = \frac{1}{\beta^2} = \sqrt{\frac{\sigma_T b}{4a}}$$





the difference is near the edges, well seen after FT

FIG. 4. The upper plot shows the dependence of the ground state wave function $\Psi_0(x,p_\perp)$ versus x ar $p_\perp^2 = 0, 0.2, 0.4, 0.6\, GeV^2$, top to bottom curves. The lower plot is versus $p_\perp$ at $x = 0.1, 0, 2, 0.3, 0, 4$. All solid curves are from the exact solution, while all dashed lines are for the simplified form (??).

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several months after it was uploaded to arXiv
I learned how to solve it numerically
to my shock, all plots agree
withing the width
of the line!

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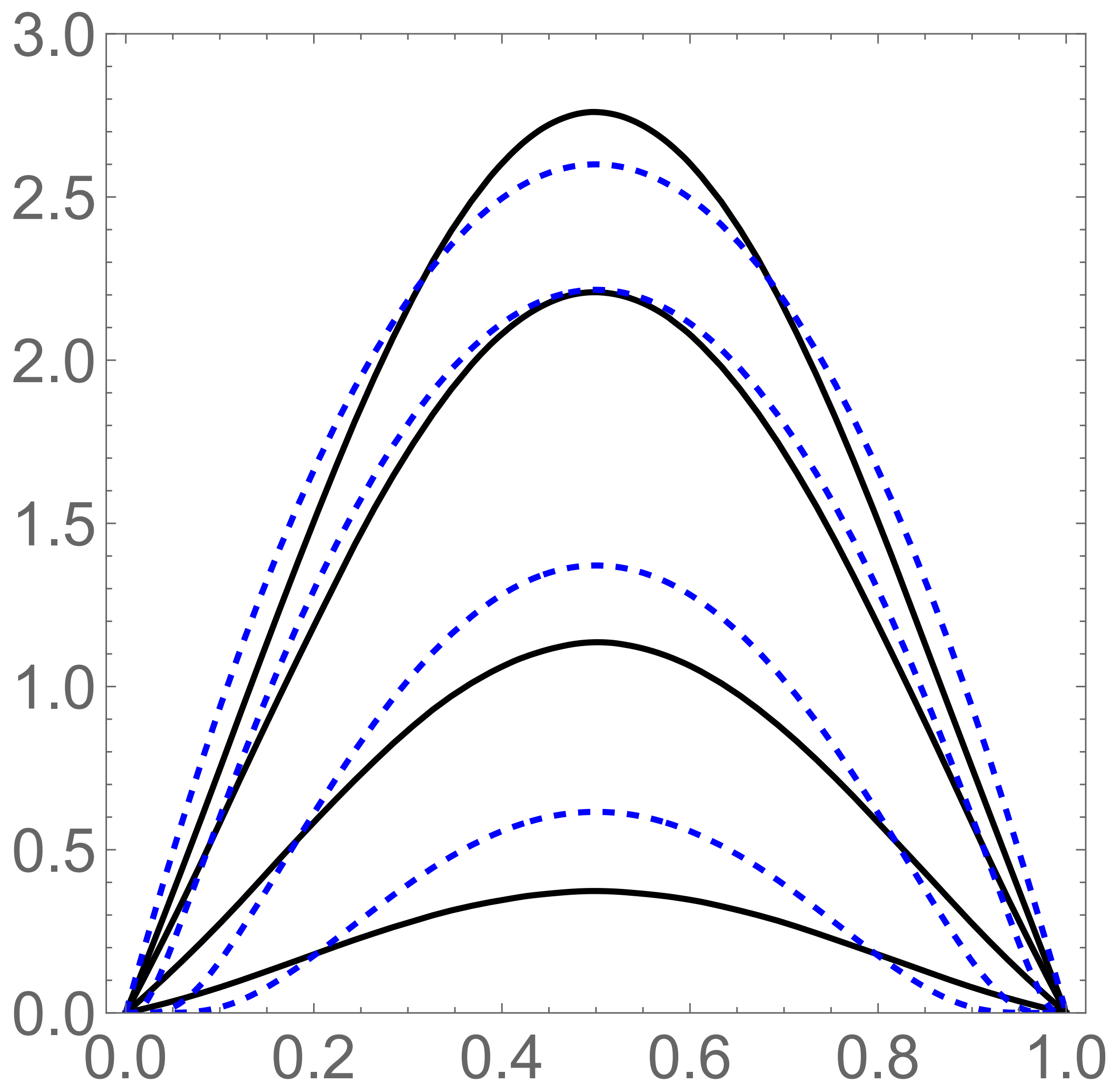

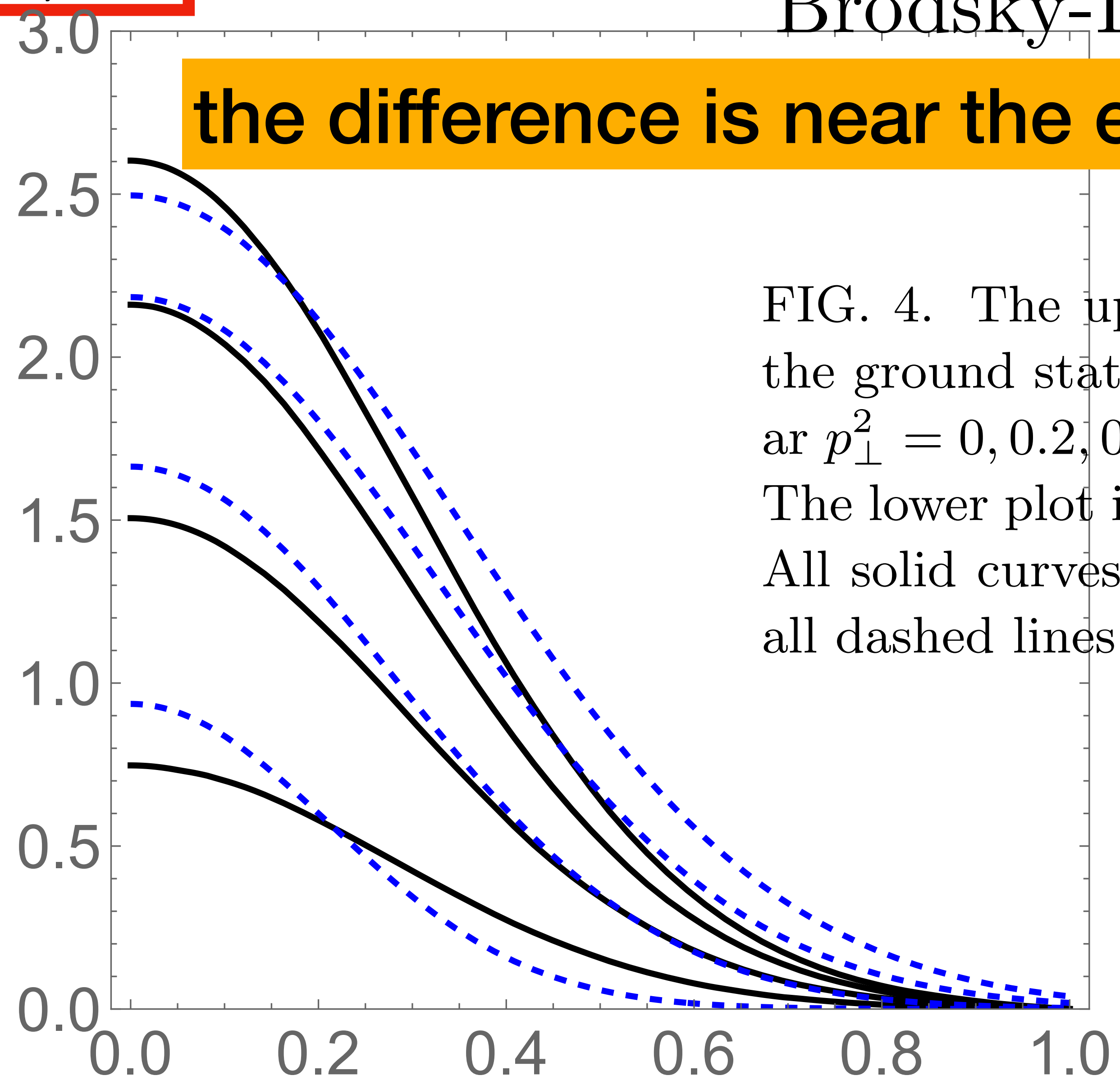

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Instantons and interquark potentials

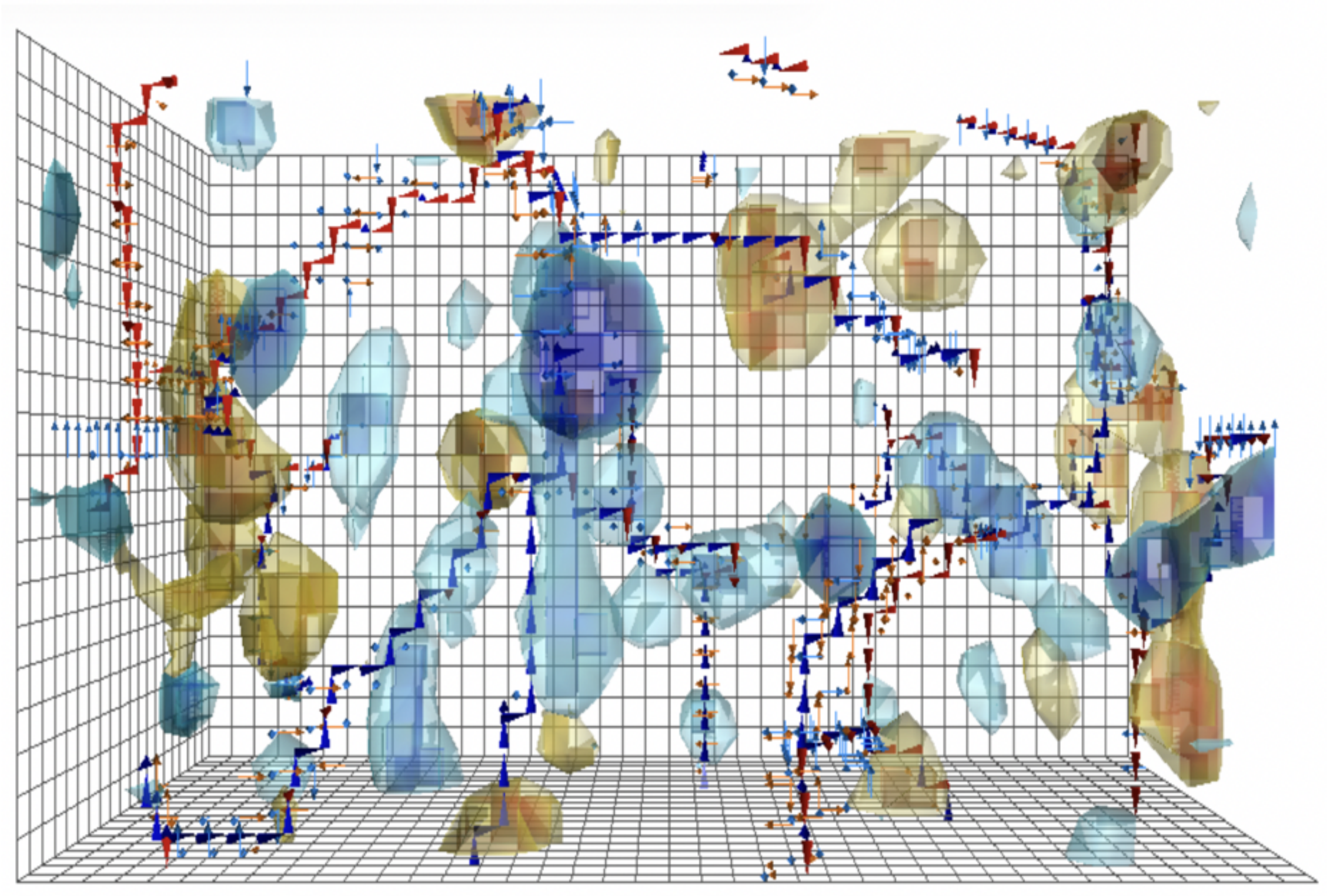
“dense instanton liquid model” has two components

$$\kappa = \pi^2 (\frac{\rho}{R})^4 \approx 0.12$$

ES, 1982

dilute:
consists of well-separated instantons
their collectivised zero modes = quark condensate

inputs <Q^2> and <qbar q>



“molecular component”
which is denser
because overlapping
I and bar-I
has smaller action
but it do not lead
to near-zero
Dirac eigenvalues!

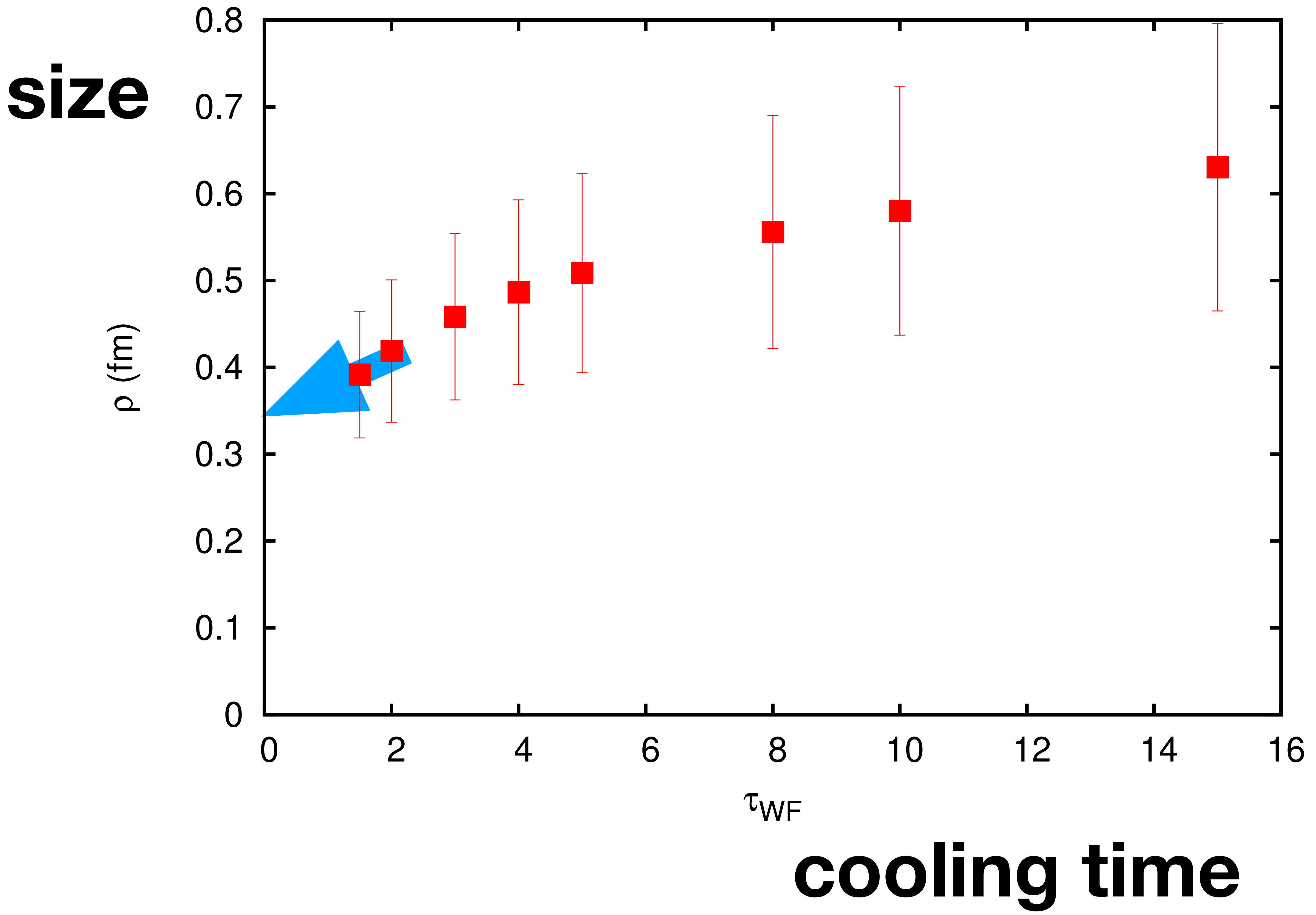
Ilgenfritz,ES 1988,1993

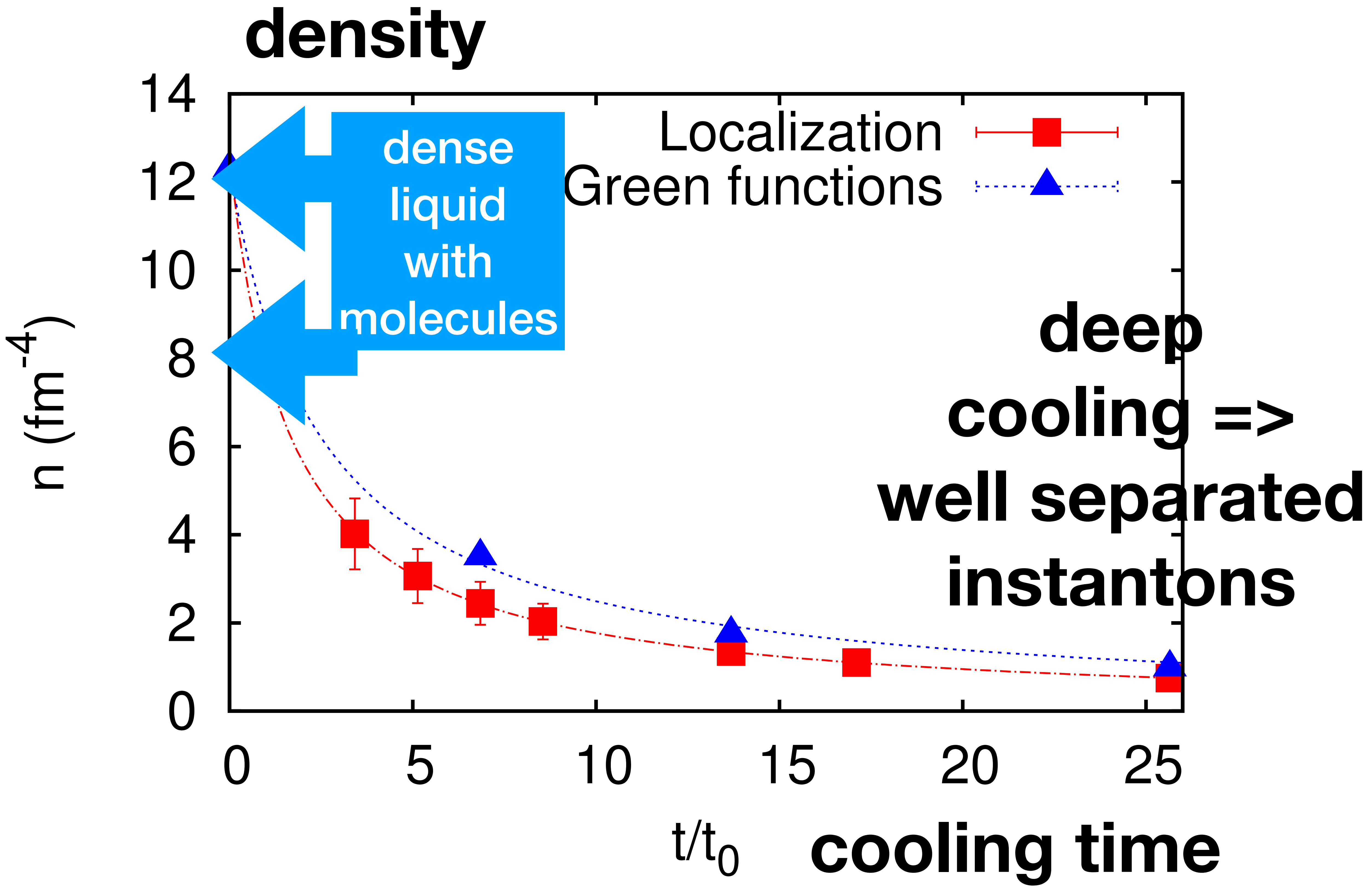
current lattice studies with G^2,G^3 observables and gradient flow cooling (extrapolated to zero time) suggest kappa=O(1)

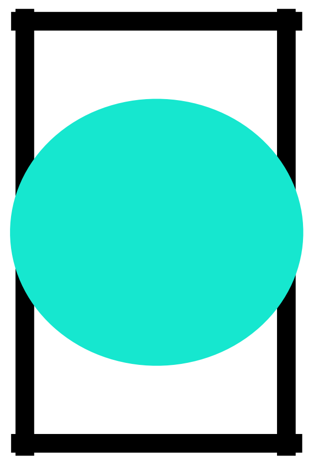
in the ff plots we used kappa=1
and this gets the data!

- A. Athenodorou, P. Boucaud, F. De Soto, J. Rodr´ıguez-Quintero, and S. Zafeiropoulos, JHEP 02, 140 (2018), arXiv:1801.10155 [hep-lat].

- **Careful studyof “cooling” by gradient flow**







Instanton effects in central potentials

$$e^{-V_c(r)T} = \langle W(\vec{x}_1) W^+(\vec{x}_2) \rangle$$

$$W = Pexp[ig \int dx^\mu A^a_\mu \hat{t}^a]$$

$$V_{instanton}(r) = \frac{4\pi n_{\bar{I}+I}\rho^3}{N_c \rho} I(\frac{r}{\rho})$$

spin forces are related to WGWG nonlocals

**Callan et al 1978,
Eichten, Feinberg 1981**

angle of color rotationalong a straight line
is easy to calculatefor instanton fields

$$I(x) = \int_0^\infty dy y^2 \int_{-1}^{1} dc [1 - cos(\alpha_1)cos(\alpha_2) - \frac{y + xc}{\sqrt{y^2 + x^2 + 2xyc}} sin(\alpha_1) sin(\alpha_2)]$$

in which $c = cos(\phi)$, and two color rotation angles are

$$\alpha_1 = \pi \frac{y}{\sqrt{y^2+1}}, \quad \alpha_2 = \pi \sqrt{\frac{y^2 + x^2 + 2xyc}{y^2 + x^2 + 2xyc + 1}}$$

if "dense ensemble"
its magnitude
is similar to Cornell

$$n_{mol} + n_I + n_{\bar{I}} = 7.\,\mathrm{fm}^{-4} \quad R_{dense} \equiv n^{-1/4} = 0.61\, fm \approx 2\rho$$

Nonperturbative central potential

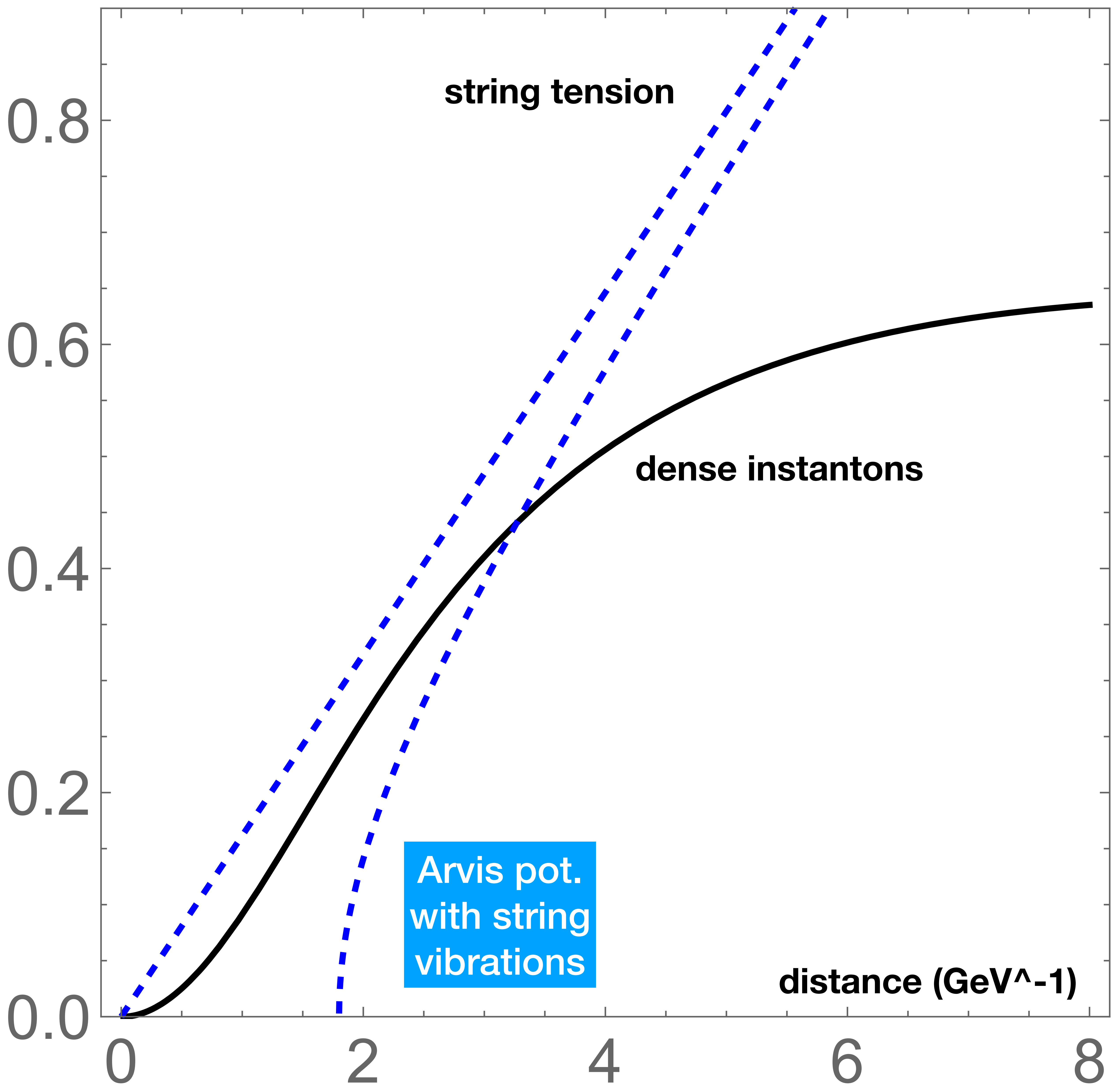
flux tube is electric
spins interact with
magnetic field

instantons on the other hand
are selfdual E=B

instanton-induced is
as good as Cornell potential for
many mesons, e.g.

$$\Upsilon[1S], \eta_b[1S], \Upsilon[2S], \Upsilon[3S], \Upsilon[4S],$$

but for bb states with N>4 or
ligher quark states, still one has to use linear
for r> 1 fm

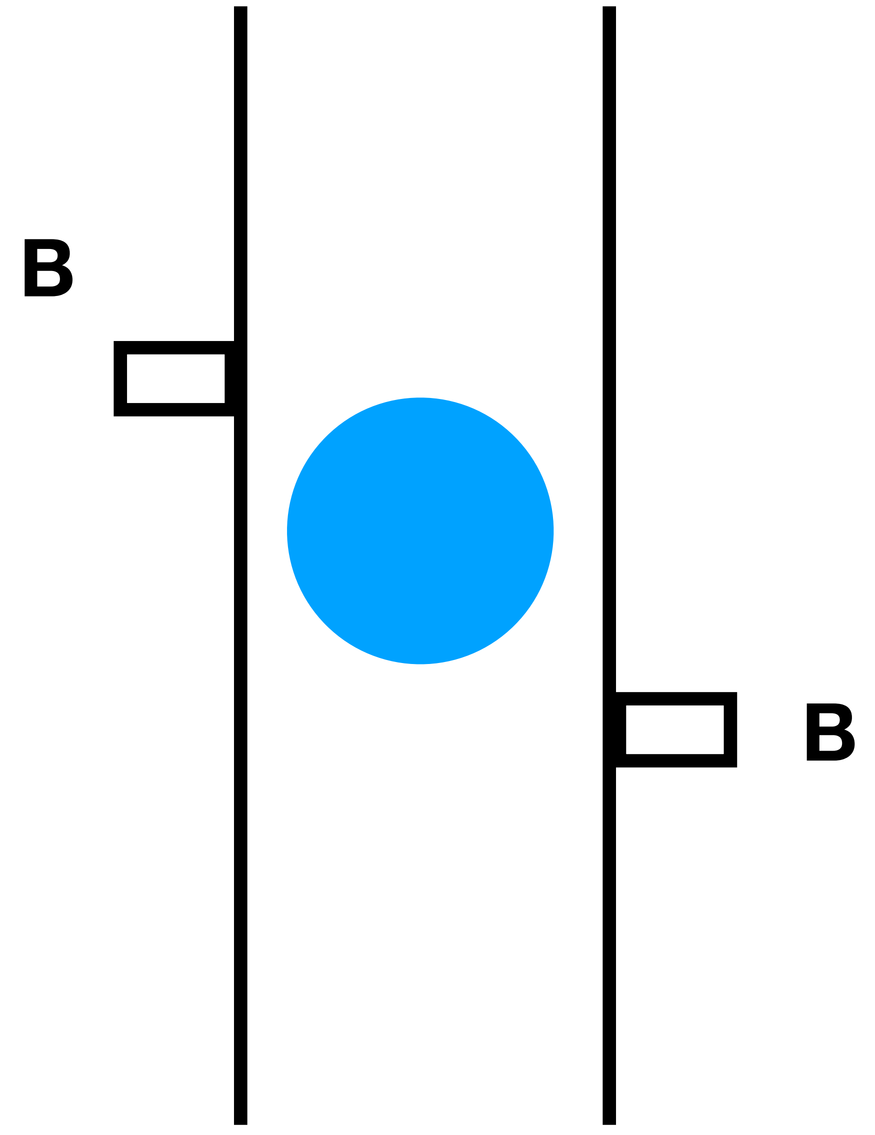


relativistic corrections to order 1/M^2 have in genral 5 potentials
3 spin-dependent potentials
spin-spin, spin-orbit and tensor

E. Eichten and F. Feinberg, "Spin Dependent Forces in QCD," Phys. Rev. D **23**, 2724 (1981

the corresponding potentials
are given by Wilson lines
decorated by field strength
insertions

Here is the main point:
electric flux tubes
models do not give
predictions
for magnetic fields



instantons, on the other hand,
are selfdual B=E
and have strong B field

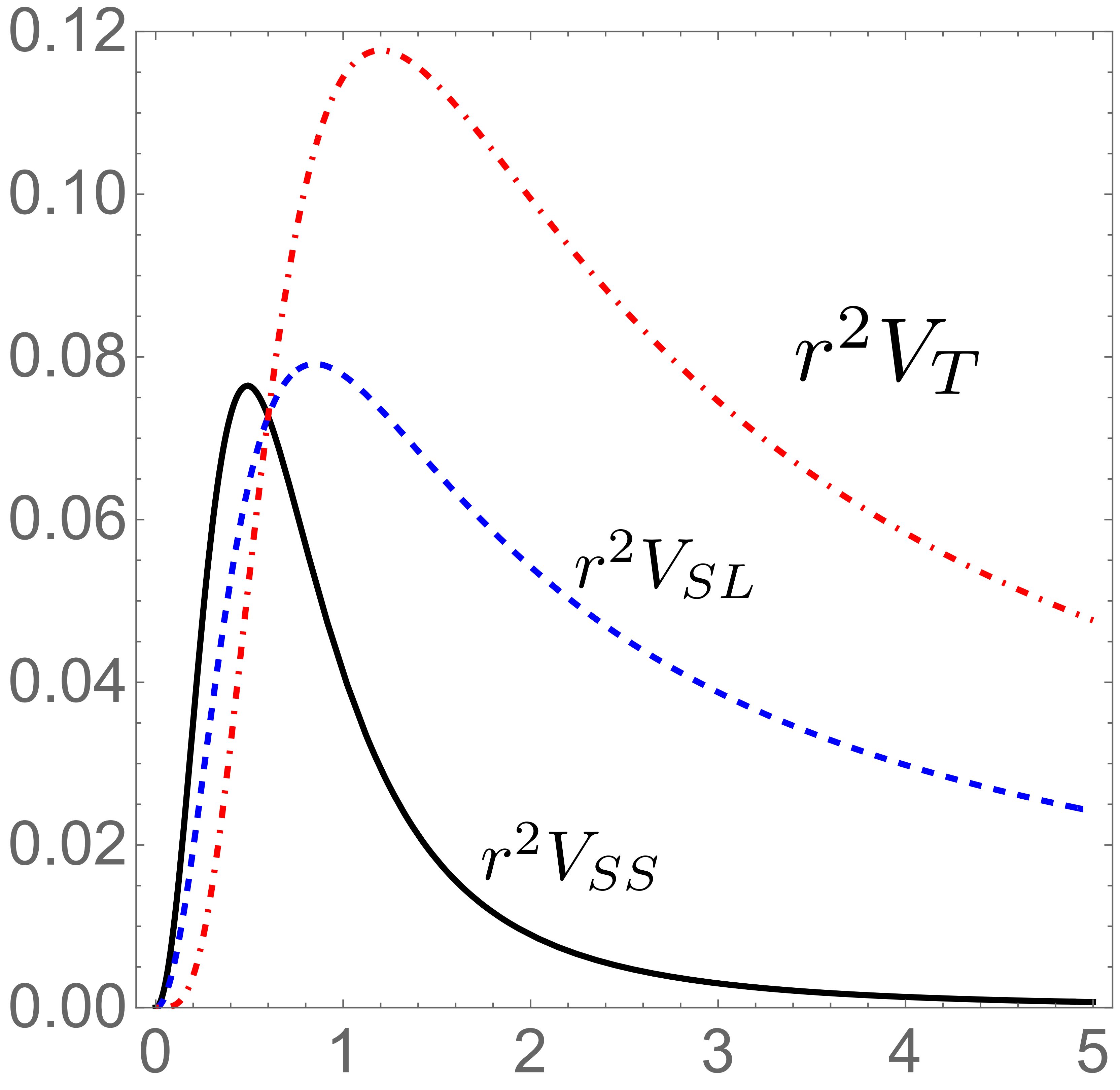
Instanton effects in spin-related potentials

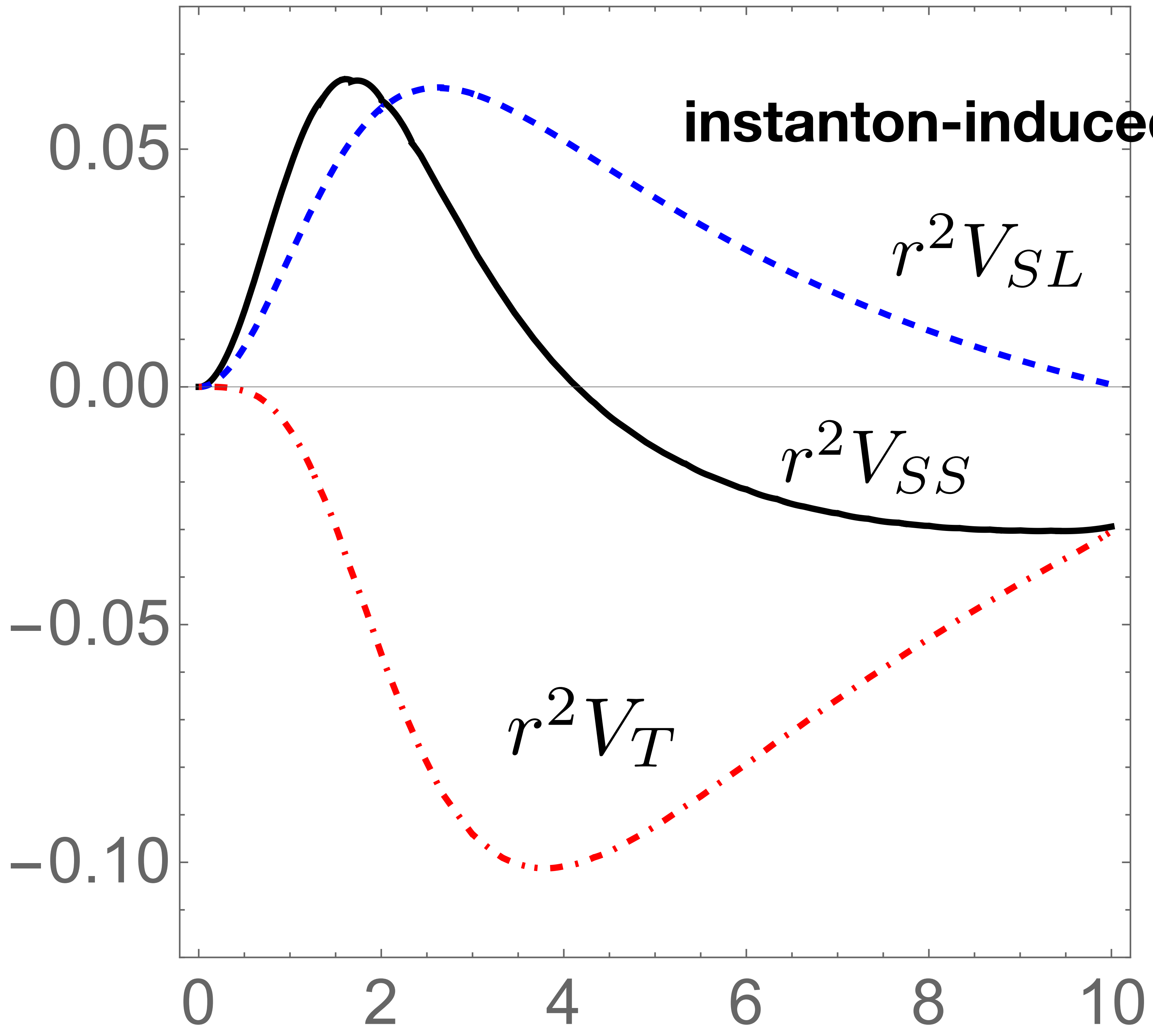
Wilson lines complemented by two field strengths => in general, 5 potentials for instantons related to Vc

E. Eichten and F. Feinberg, "Spin Dependent Forces in QCD," Phys. Rev. D **23**, 2724 (1981

$$V_{SD} = \left(\frac{S_Q \cdot L_Q}{2m_Q^2} - \frac{S_{\bar{Q}} \cdot L_{\bar{Q}}}{2m_{\bar{Q}}^2}\right)\left(\frac{1}{r}\frac{d}{dr}(V(r) + 2V_1(r))\right) + \left(\frac{S_{\bar{Q}} \cdot L_Q}{m_Q m_{\bar{Q}}} - \frac{S_Q \cdot L_{\bar{Q}}}{m_{\bar{Q}} m_{\bar{Q}}}\right)\left(\frac{1}{r}\frac{d}{dr}V_2(r)\right) + \frac{(3S_Q \cdot \hat{r} S_{\bar{Q}} \cdot \hat{r} - S_Q \cdot S_{\bar{Q}})}{3m_Q m_{\bar{Q}}}V_3(r) + \frac{1}{3}\frac{S_Q \cdot S_{\bar{Q}}}{m_Q m_{\bar{Q}}}V_4(r)$$

perturbative





Their sum explains lattice data for Vss and explains spin splittings rather well, except in light-light mesons

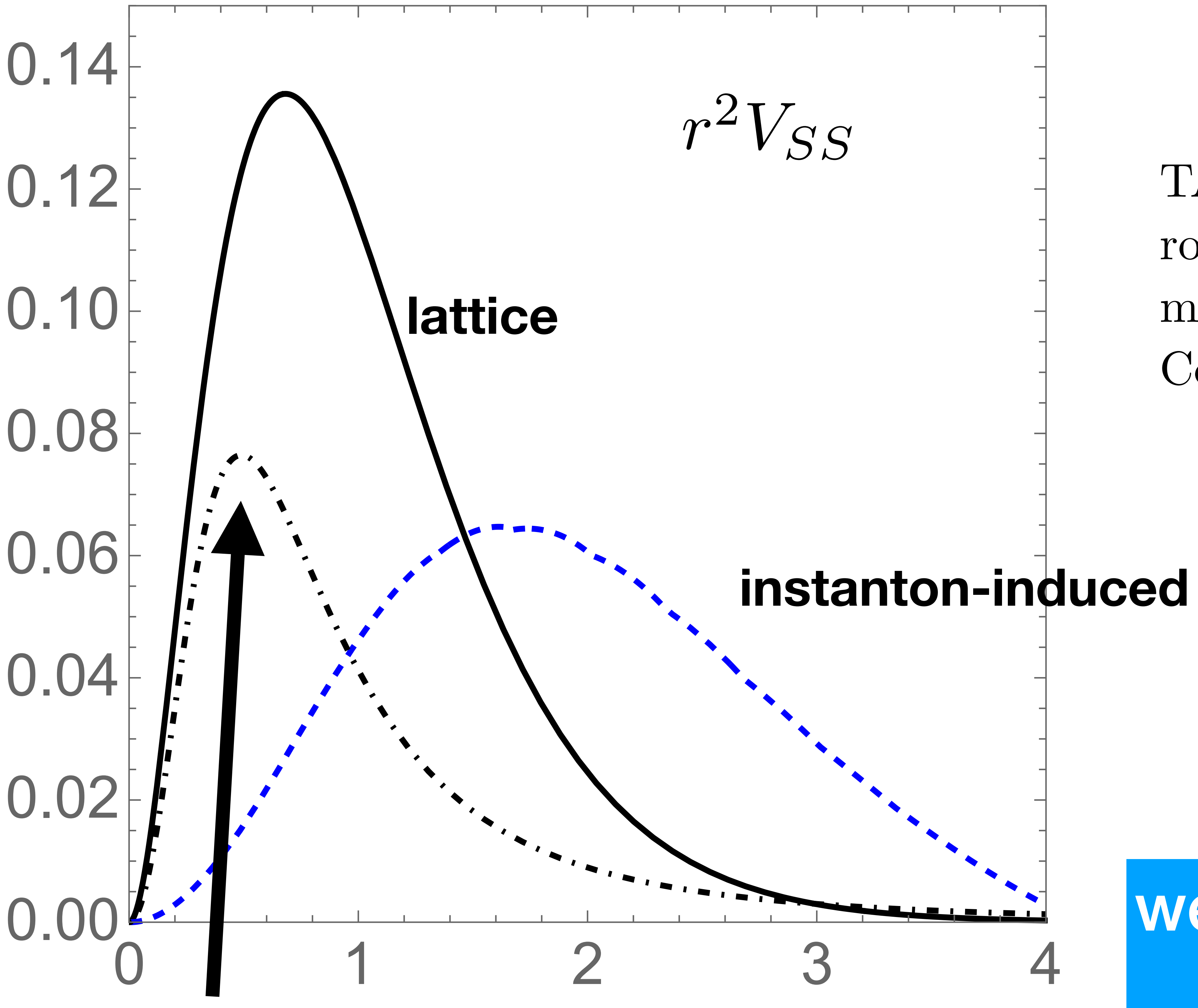


TABLE II. "Hyperfine" splittings of certain $L = 0$ mesons with $J = 1$ and $J = 0$. The first row of numbers shows the experimental values (MeV) (rounded to 1 MeV). The second gives matrix elements of the lattice-based spin-spin potential (19), the next two are those for (regulated) Coulomb and instanton-induced spin-spin forces.

flavors	$M_\Upsilon - M_{\eta_b}$	$M_{J/\psi} - M_{\eta_c}$	$M(D^*) - M(D)$	$M(K^*) - M(K)$	$M(\rho) - M(\pi)$
Exp	61.	116.	137.	398.	636.
$\langle V^{lat}_{SS}/3M_1M_2\rangle$	46.	108.	98.	170.	
$\langle \vec{\nabla}^2 V_C/3M_1M_2\rangle$	28.	58.	48.	82.	
$\langle \vec{\nabla}^2 V_{inst}/3M_1M_2\rangle$	7.	30.	48.	90.	

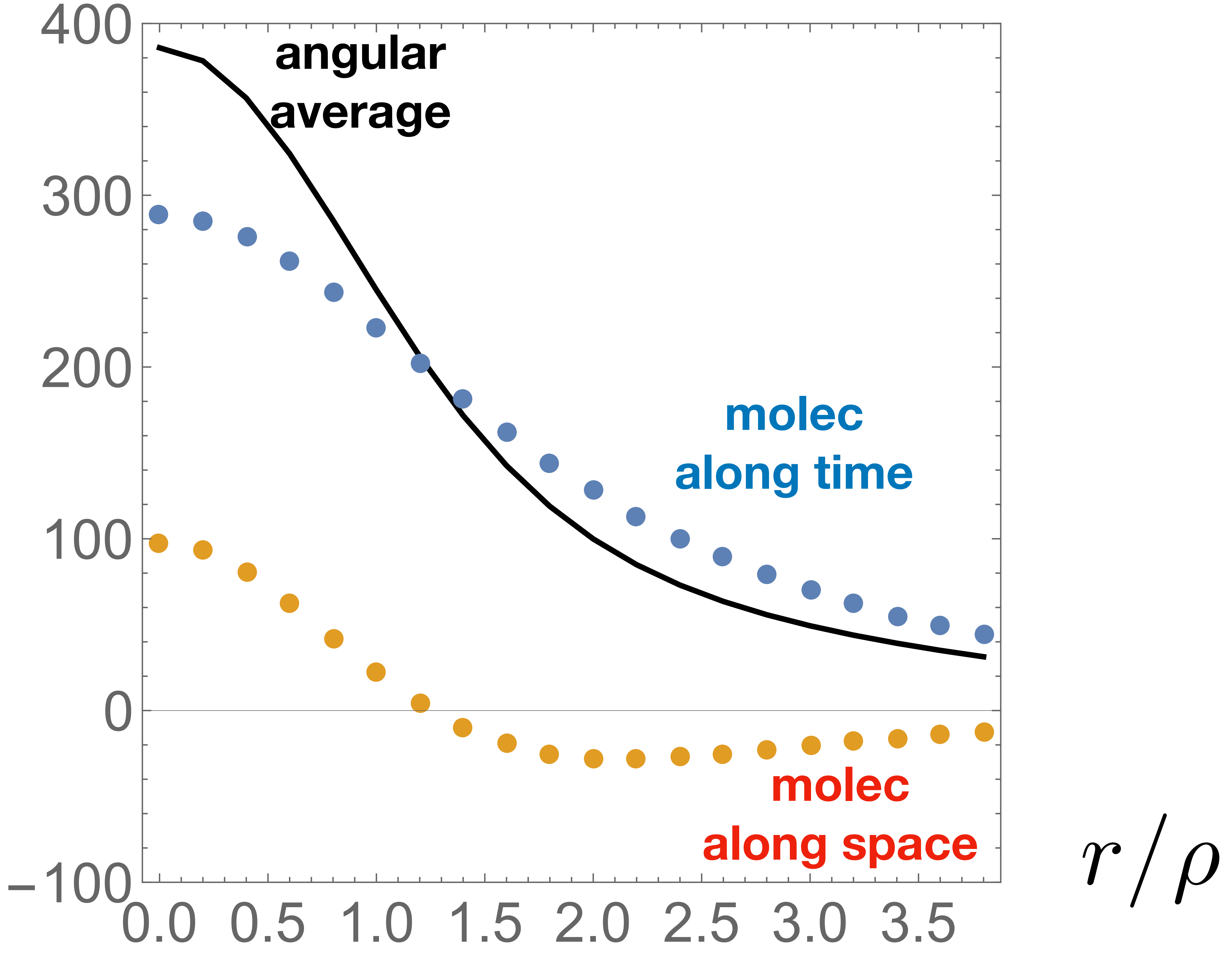
we also studied splittings of 1P states h,chi_0,chi_1,chi_2
and calculated matrix elements of VSS,VSL,VT also

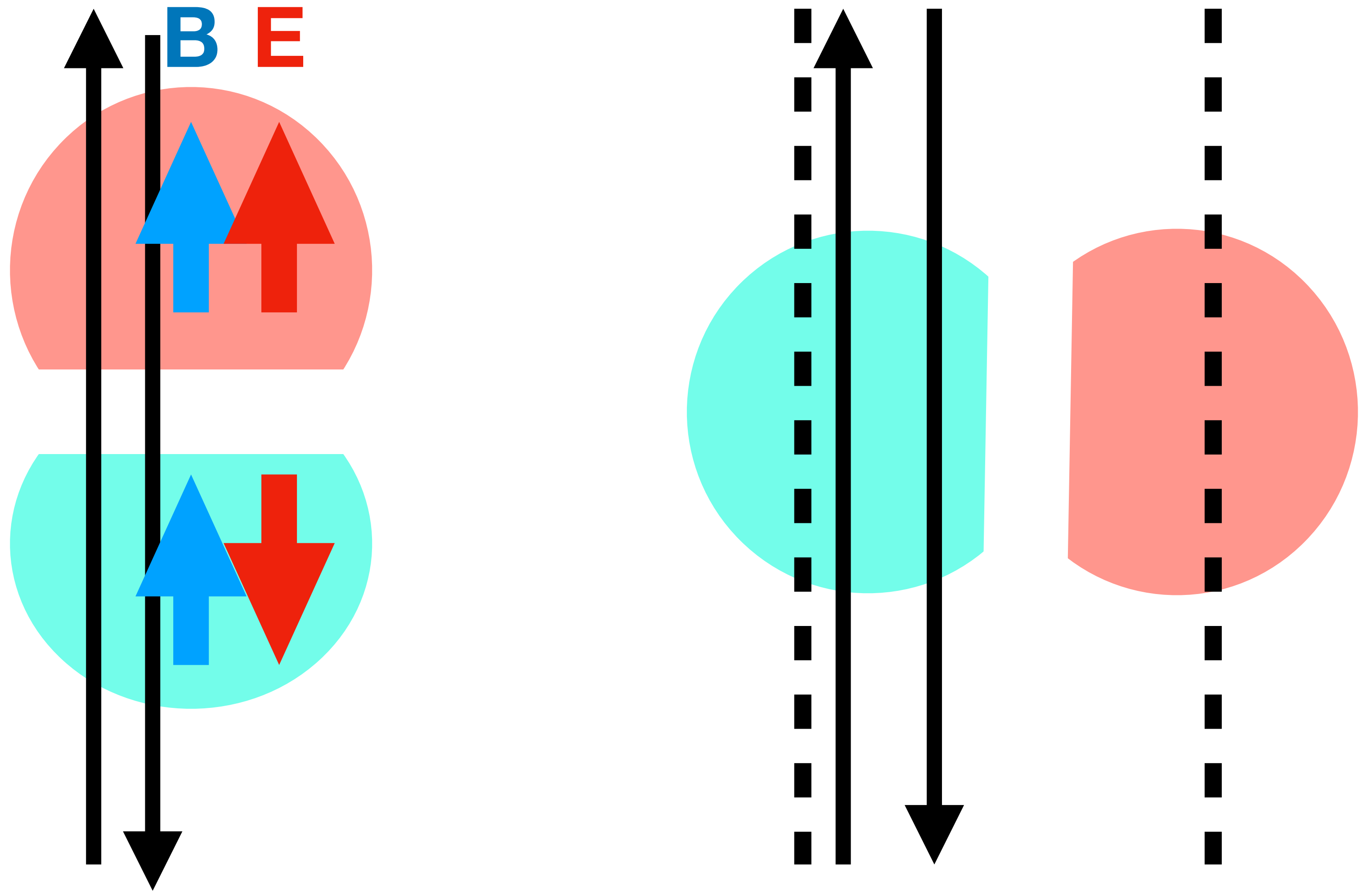
massless pion is due to zero modes (t' Hooft Lagrangian)

correct mass of rho meson needs "molecular forces" to be included

Instanton-antiinstanton molecules are not (anti) selfdual and therefore there is no relation between Vc and Vss

yet their electric and magnetic fields are correlated in a particular way



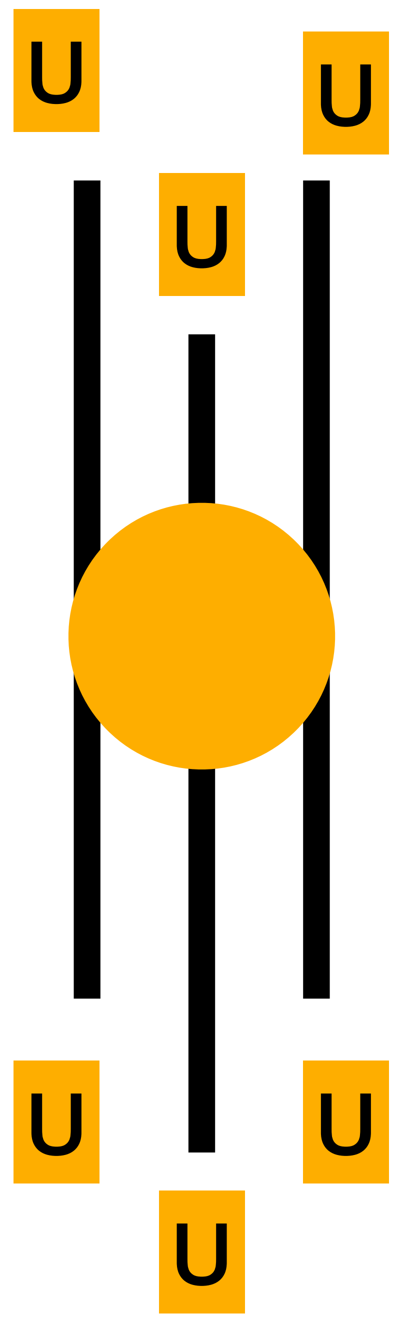


W=1, Vc=0

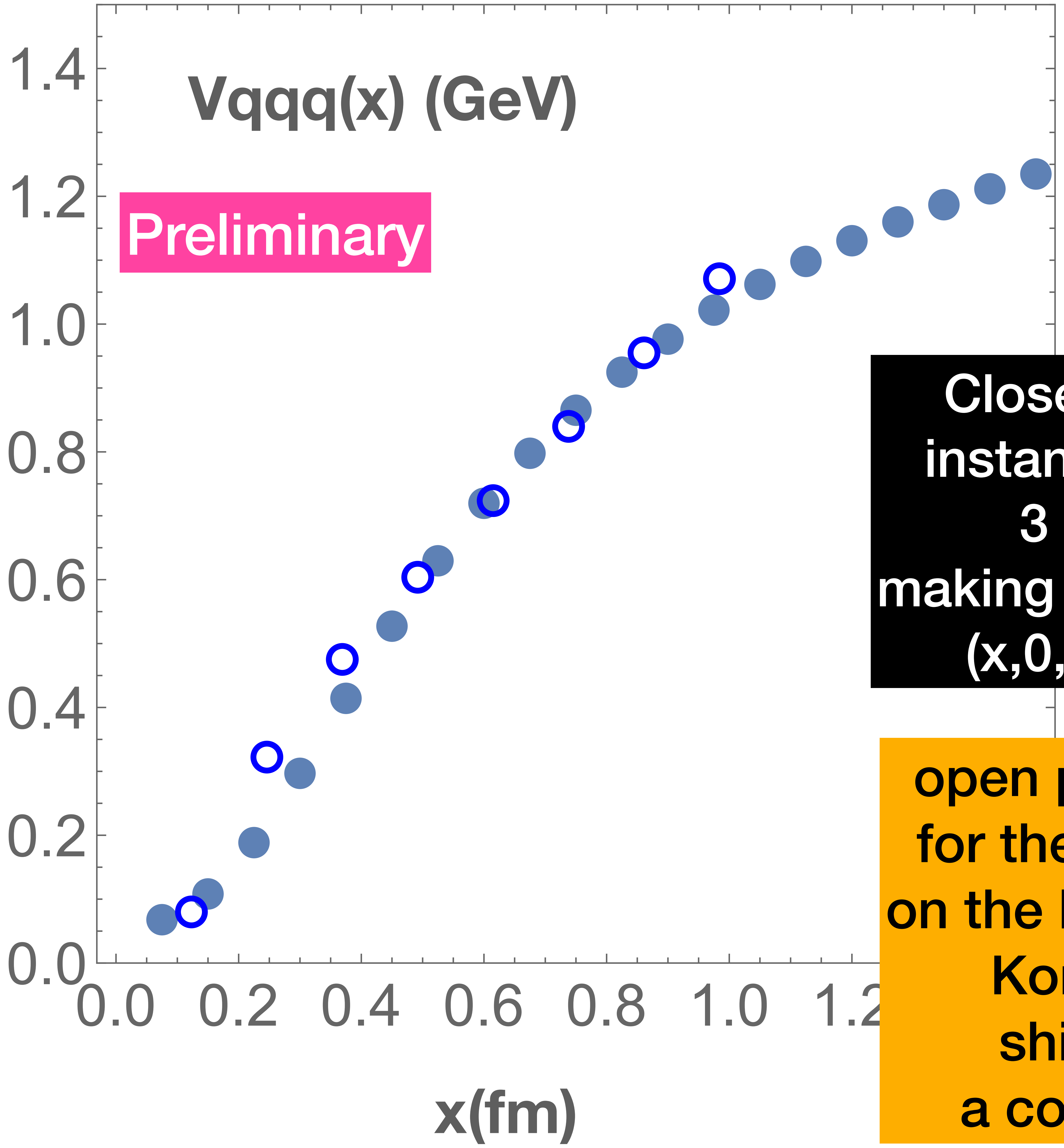
$$\int d\Delta t \vec{B}(0)\vec{B}(\Delta t) \neq 0$$

Conclusion: angular average correlator has a range smaller than even single instanton!
Spin forces may tell us about field structure of vacuum fluctuations

<WWW> $\sim e^{-V\tau}$



Instanton is in 12-SU(2) plane,
so it needs to be rotated by a random SU(3) unitary matrix U and then averaged over Haar measure
formulae for <UUUUUU>
are known as Weingarten formulae,
too long to put it here
the operator is color singlet then



instanton go to 3 Meff
Meff=0.46 GeV

Closed points are for instanton-induced V(x)
3 static quarks
making equilateral triangle
(x,0,0), (0,x,0),(0,0,x)

open points calculated for the same geometry on the lattice 1703.06247 Koma and Koma
shifted down by
a const=- 0.85 GeV

Baryons (and pentaquarks) on the light front

Now baryons: 3 quarks with motion of CM excluded:
modified Jacobi coordinates 9-3=6 dof
4d of transverse oscillator and 2 Bjorken fractions

we started with flavor symmetric ones
so that no ``good” diquarks possible

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

$$x_1 + x_2 + x_3 = 1$$

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

cut the cube [0,1]^3 and makes the physical domain to be a triangle

step 1: standing waves solutions can be found
(only for equilateral triangles, btw)
step 2: include the ``cup” potential on the right

$$-\left(\frac{\partial^2}{\partial \lambda^2} + \frac{\partial}{\partial \rho^2}\right)\varphi_{m_L,n_L}(\lambda,\rho) = e_{m_L n_L}\varphi_{m_L,n_L}(\lambda,\rho)$$

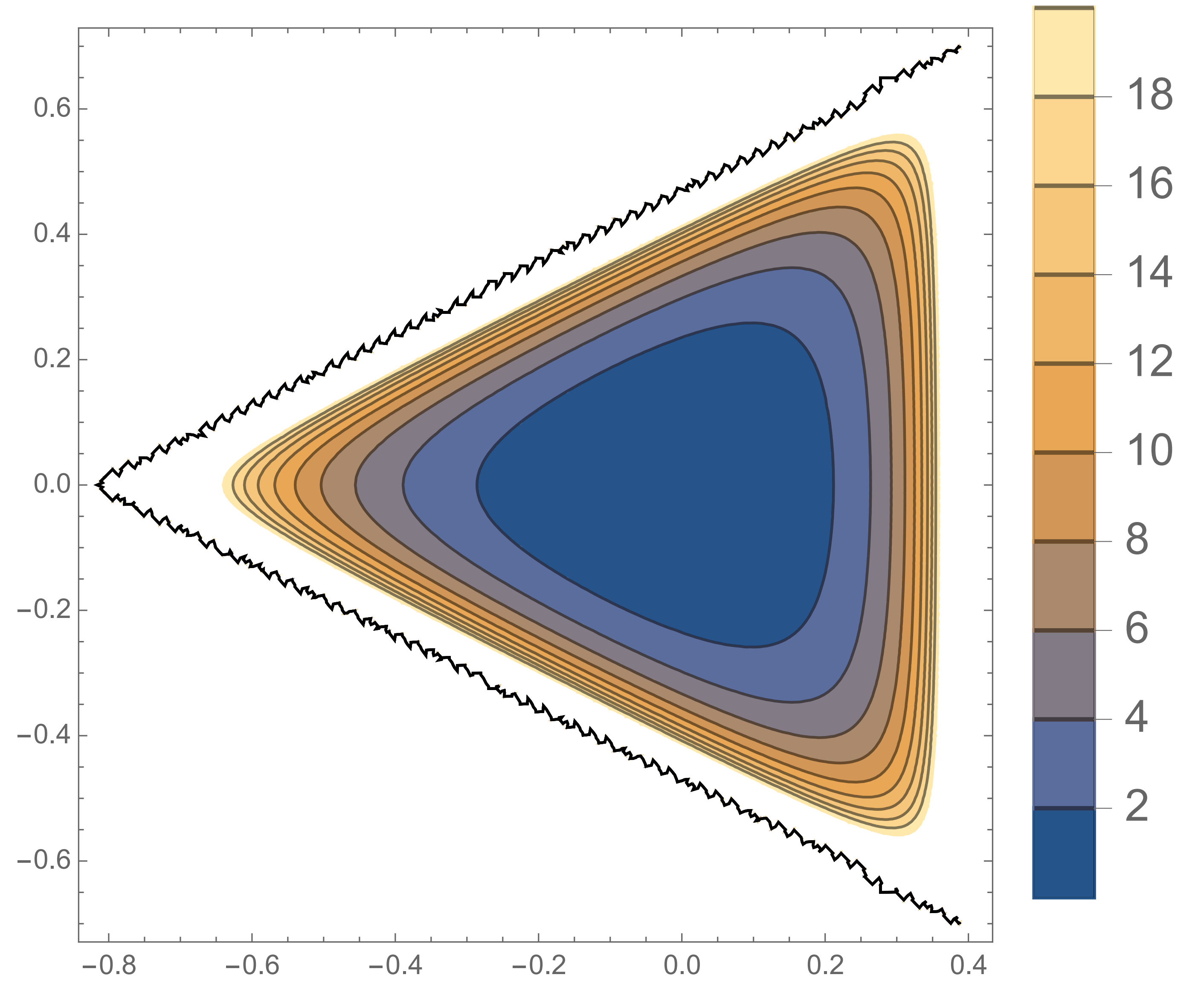
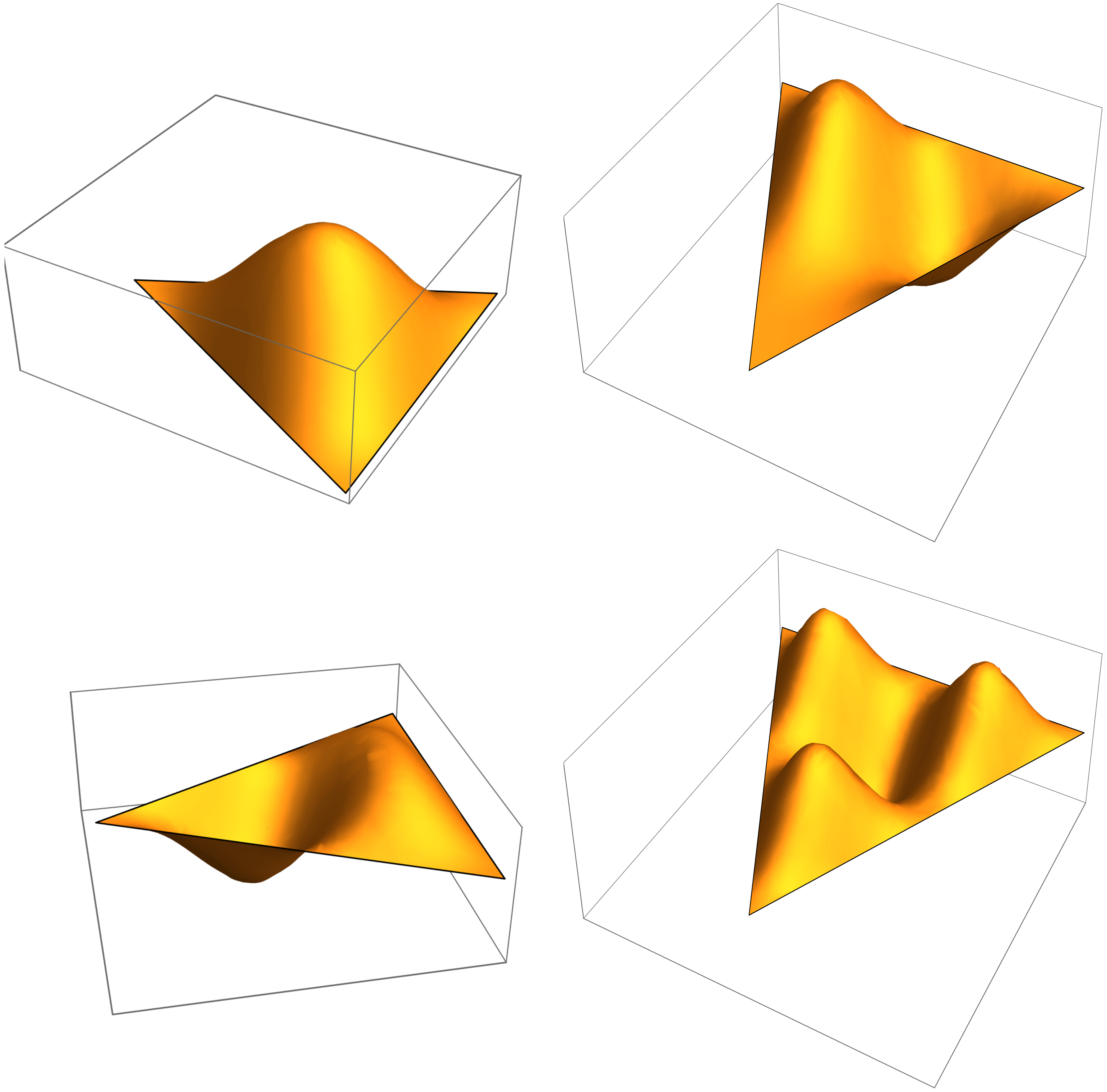
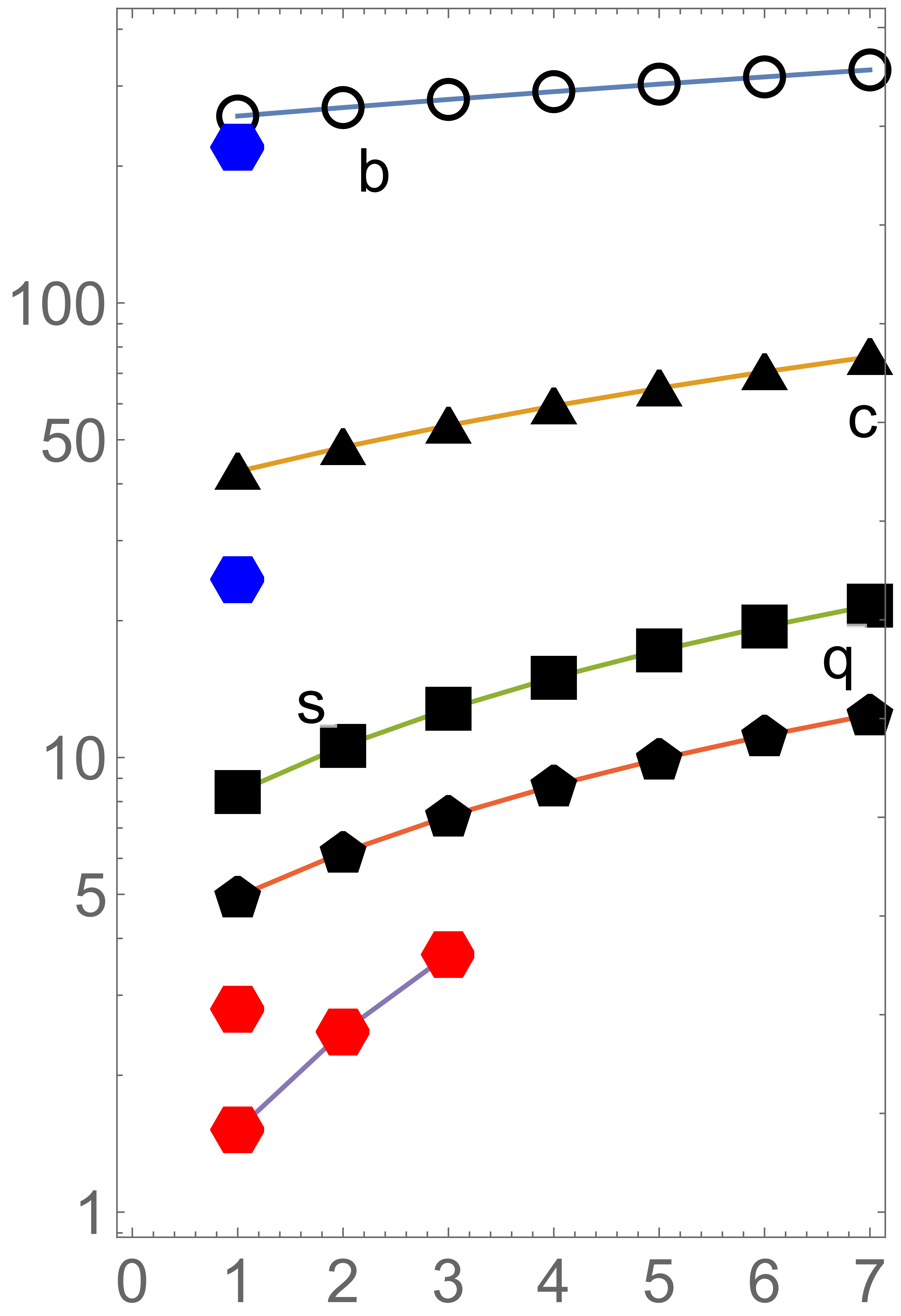


FIG. 2. The contour plot of the “triangular cup" potential $V(\lambda,\rho)$ on λ,ρ plot.

recently we also obtained numerical solutions on the physical triangle (in Mathematica, with and without (shown) any potentials)

this allows to calculate masses and LFWFs for unequal masses





Flavor-symmetric baryons in which "good" diquarks are not present

FIG. 7. Squared masses of baryons $M^2_{n+1}(Q,\frac{3}{2})$ 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.

CCC baryon is expected to be experimentally observed in the next run of LHC (Alice)

masses can be shifter by a constant and agree for ground states

but the Regge slope remains a problem

THE 5-QUARK SECTOR OF THE BARYONS

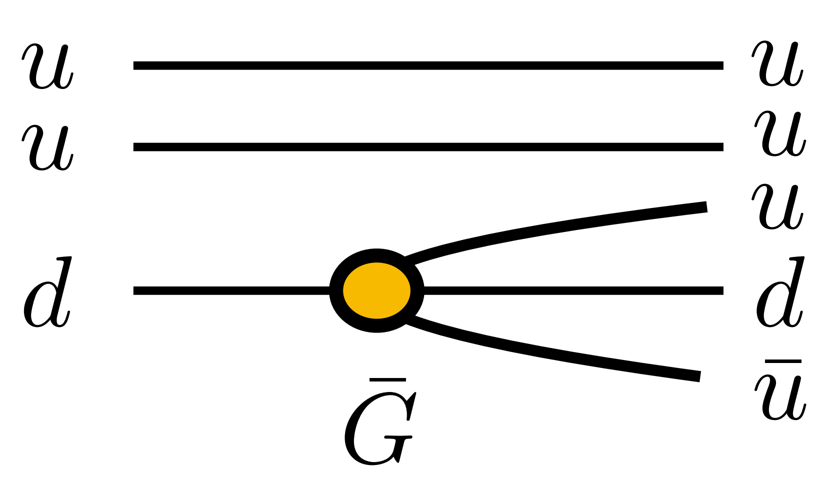


FIG. 9: The only diagram in which 4-quark interaction connects the 3 and 5 quark sectors, generating the $\bar{u}$ sea.

As originally emphasized by Dorokhov and Kochelev [23], The 't Hooft topology-induced 4-quark interaction leads to processes

$$u \to u(\bar{d}d), \quad d \to d(\bar{u}u)$$

but not

$$u \to u(\bar{u}u), \quad d \to d(\bar{d}d)$$

which creates strong flavor asymmetry of the sea up to \bar d/\bar u =2

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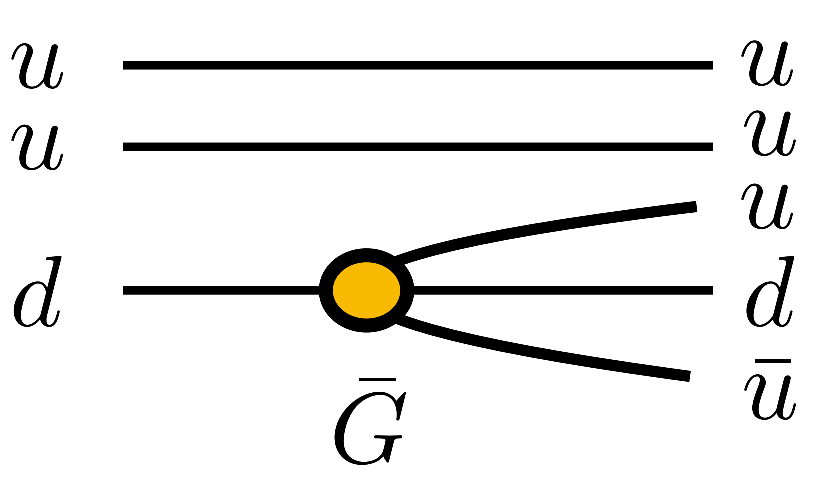

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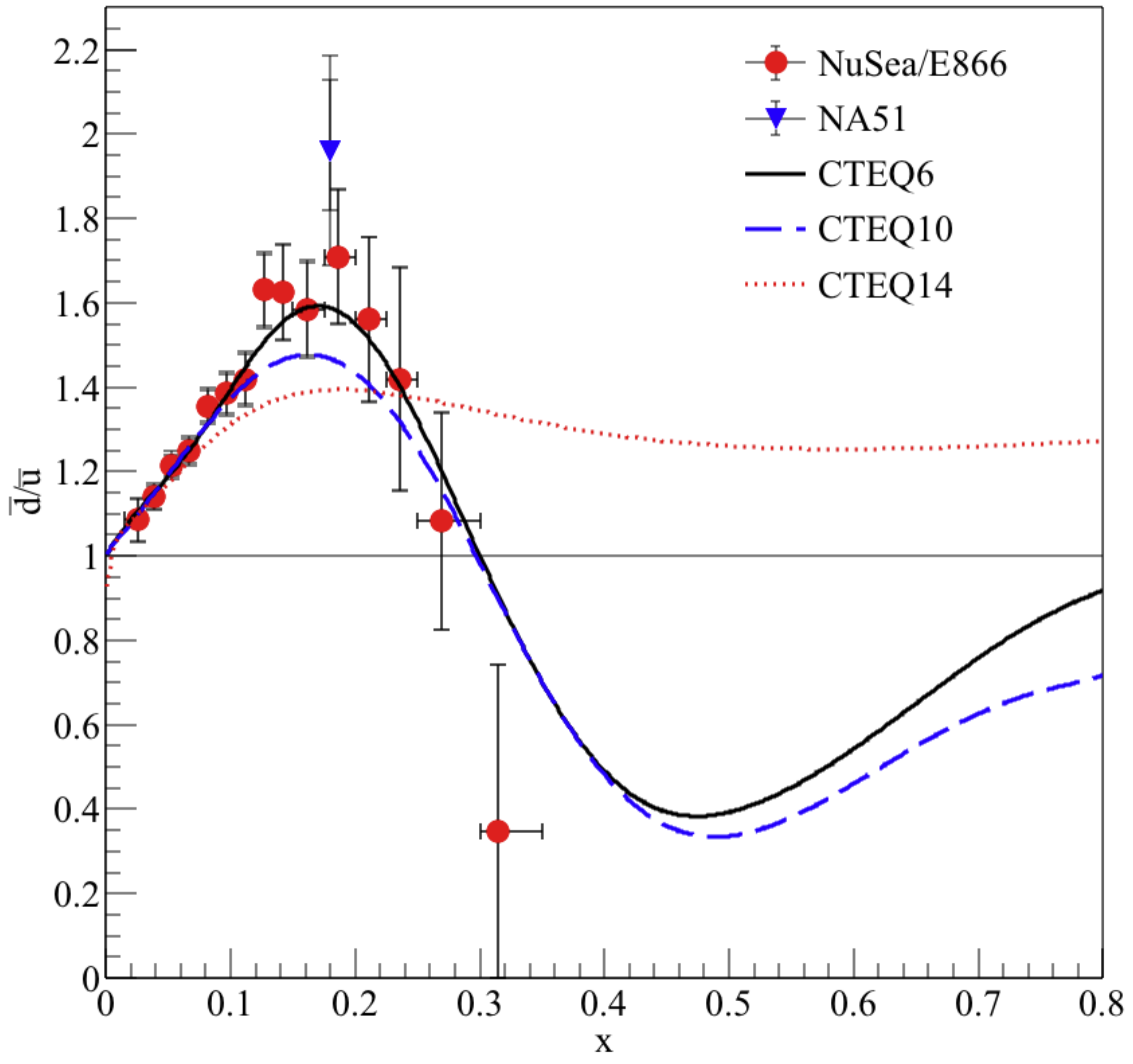

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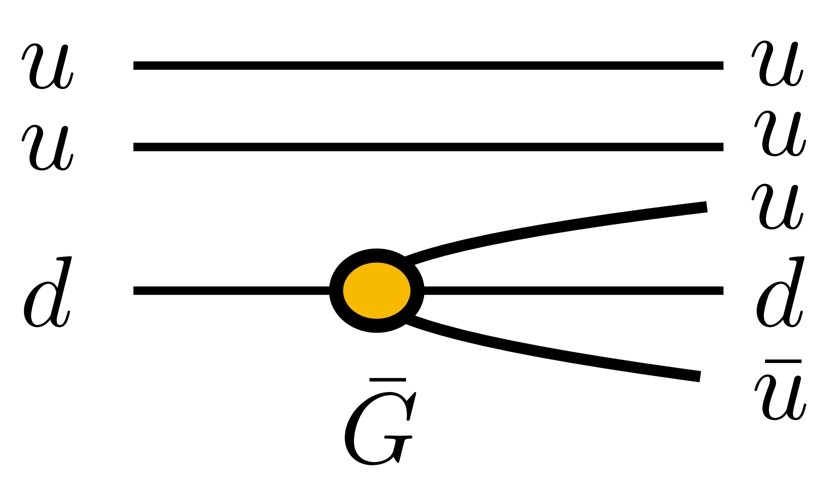

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$$\psi_{tail}(s',t',u',w') = -\sum_i \frac{\langle N|H|5q,i\rangle}{M_i^2 - M_N^2}\psi_i(s',t',u',w')$$

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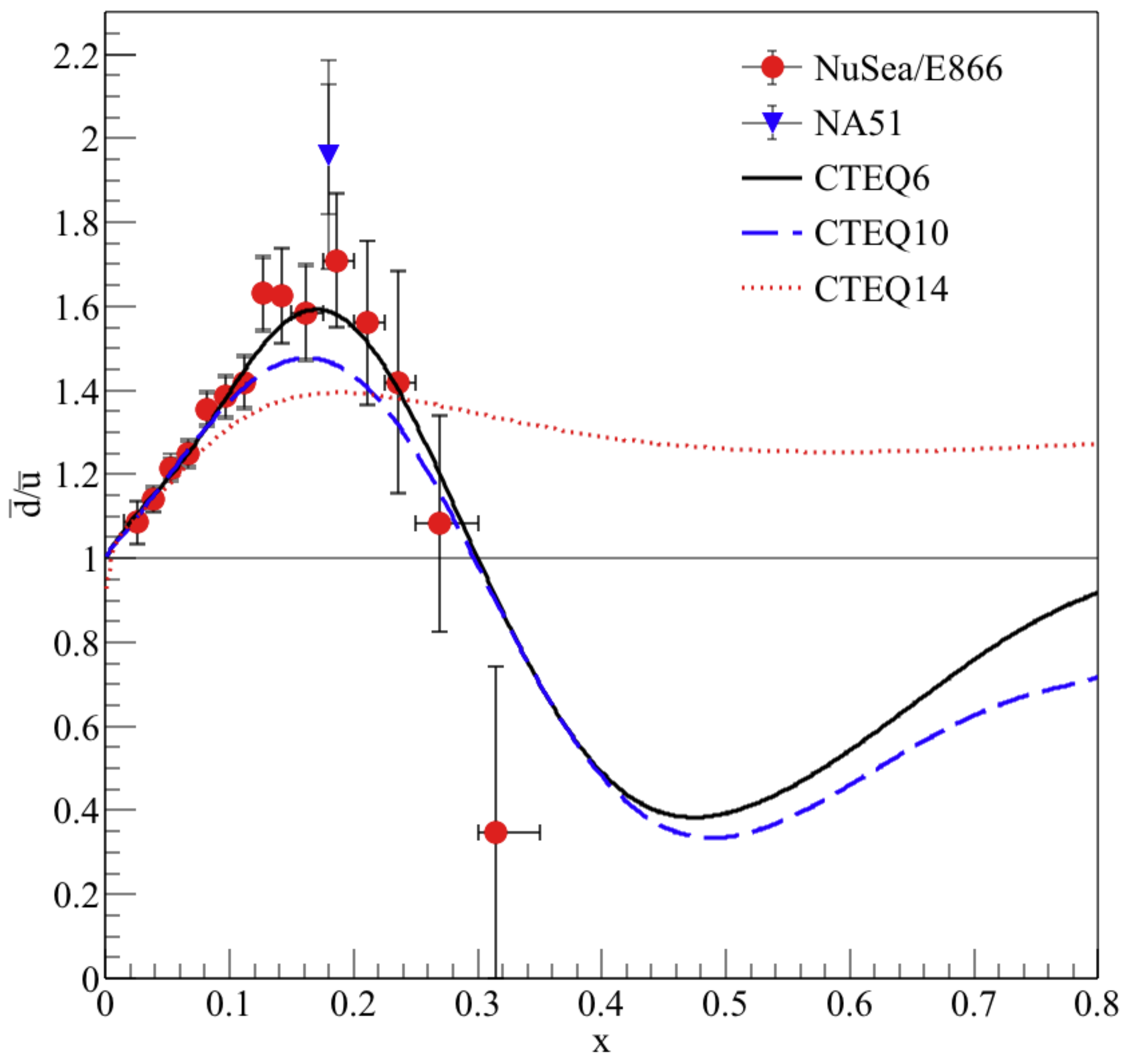

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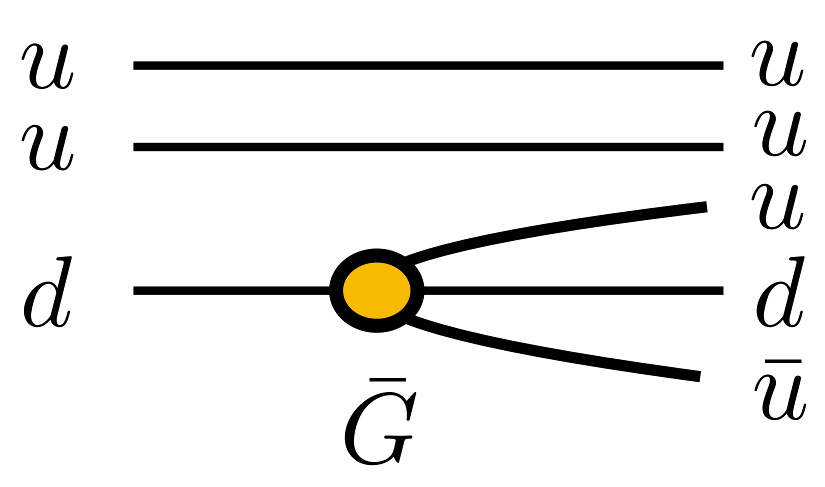

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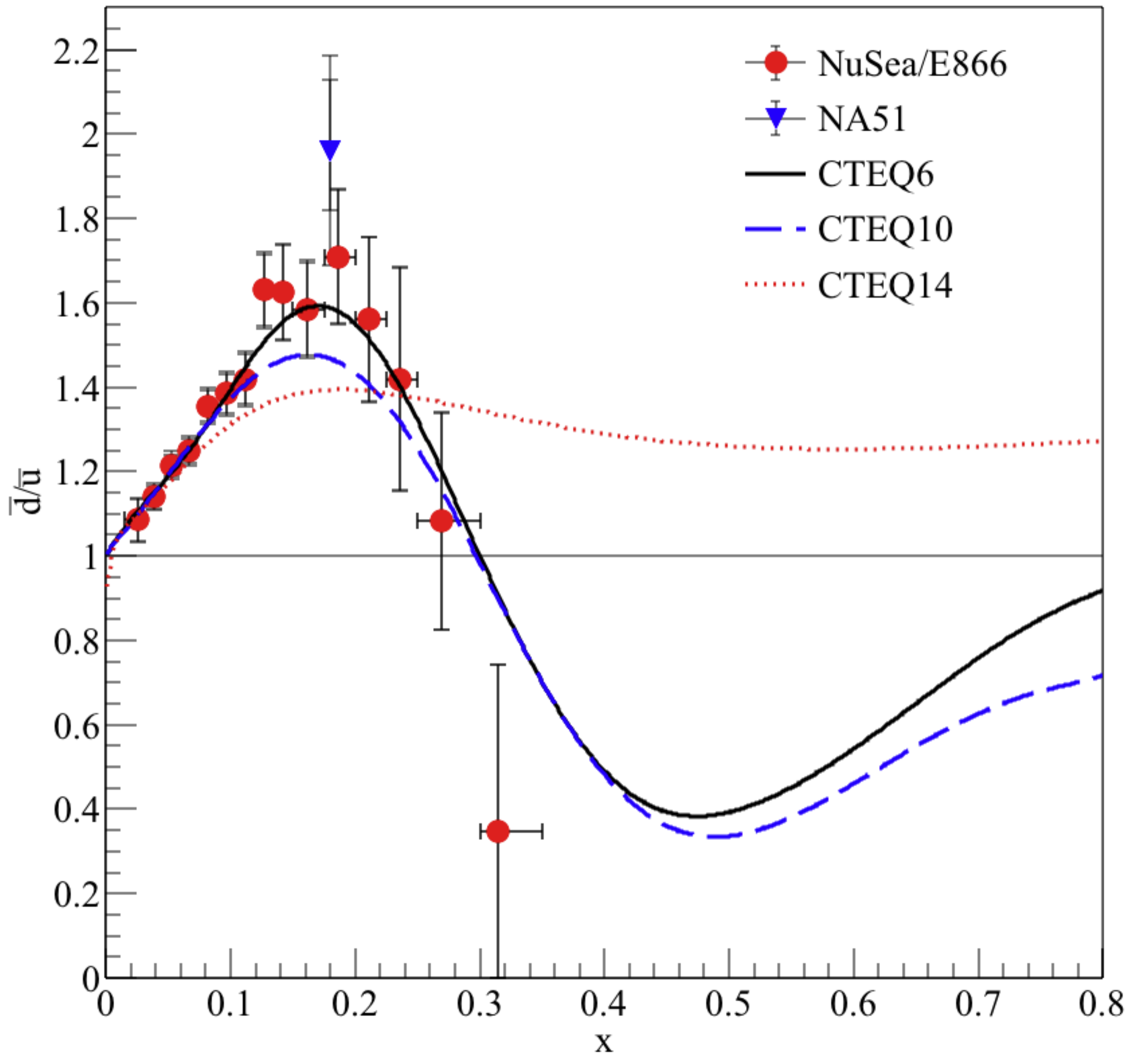
mixing between 3q and 5q calculated with absolute normalization for the first time!
It is hard to plot function of 4 variables…



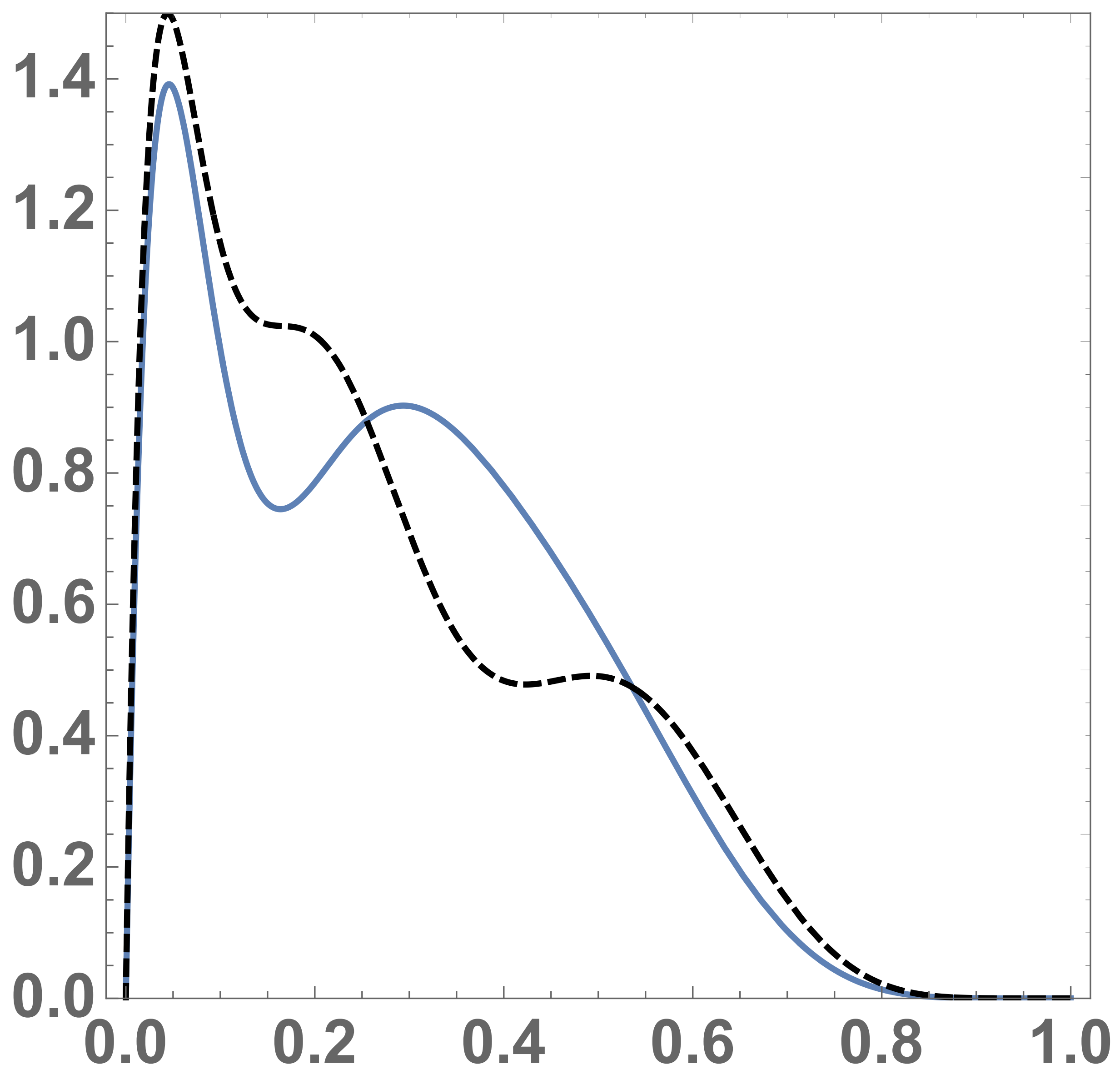
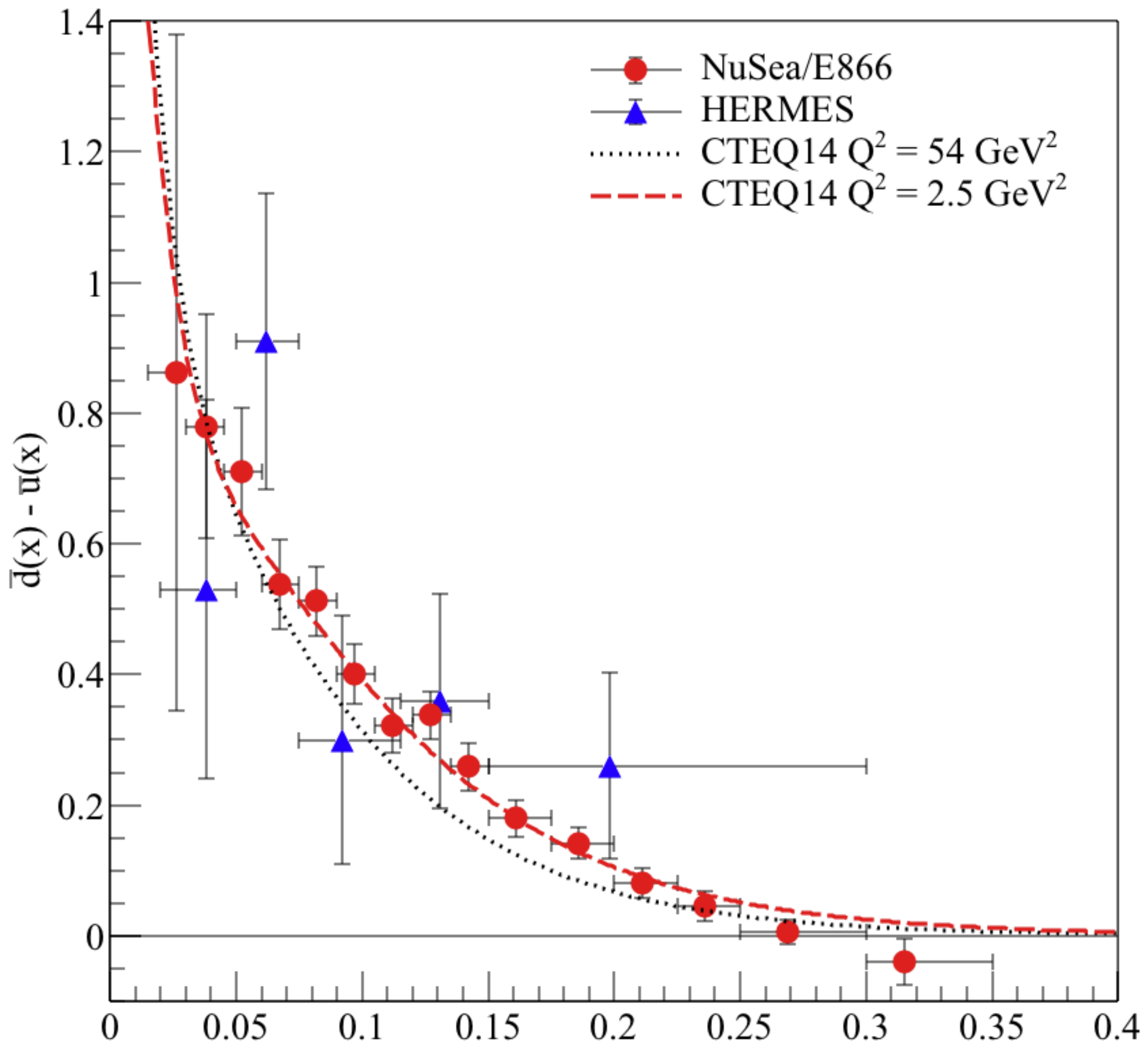


FIG. 10: The distribution over that $\bar{u}$ in its momentum fraction, for the Nucleon and Delta 5-quark "tails" (solid and dashed, respectively).

The "Kochelev mechanism" works semi-quantitatively: The magnitude and shape are basically correct

The isospin sea problem is thus declared solved

(sea spin problem is in work now)



The available experimental data, for the *difference* of the sea antiquarks distributions $\bar{d}-\bar{u}$ (from [18]) is shown in Fig.11. In this difference the symmetric gluon production should be cancelled out, and therefore it is sensitive only to a non-perturbative contributions.

Few comments: (i) First of all, the sign of the difference is indeed as predicted by the topological interaction, there are more anti-d than anti-u quarks;

(ii) Second, since 2-1=1, this representation of the data directly give us the nonperturbative antiquark production per valence quark, e.g. that of $\bar{u}$. This means it can be directly compared to the distribution we calculated from the 5-quark tail of the nucleon and Delta baryons, Fig.10.

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now we are working on diquark effects
(known by their support to color superconductivity)
but in LFWFs of N and exotica T(cc\bar u bard)