"The proton mass: at the heart of most visible matter"

ECT*, Trento, Italy, April 3-7, 2017

Probing the origin of the proton mass with heavy quarkonium

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Outline

- Scale invariance and scale anomaly
- The proton mass
- Probing the origin of the proton mass with heavy quarkonium
- Pentaquarks as charmonium-nucleon bound states
- Charmonium photoproduction near the threshold

Scale invariance

Scale transformations (dilatations) are defined by

$$x \to e^{\lambda}\ x$$

Hermann Weyl
(1885-1955)

the corresponding dilatational current is

$$s^{\mu} = x_{\nu}\ \theta^{\mu\nu}$$

It is conserved
(a theory is scale-invariant)
if the energy-momentum is
traceless:

$$\partial_{\mu} s^{\mu} = \theta^{\mu}_{\mu}$$

Scale invariance

A scale-invariant theory cannot contain massive particles, all particles must be massless

For example, in Maxwell electrodynamics with action

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

the energy-momentum is traceless: $\theta^{\mu}_{\mu} = 0$
(massless photons)

Note: because of this, in scalar gravity (e.g. Einstein, 1913) there would be no light bending by massive bodies!

Scale invariance in QCD

The trace of the energy-momentum tensor in QCD (computed in classical field theory) is

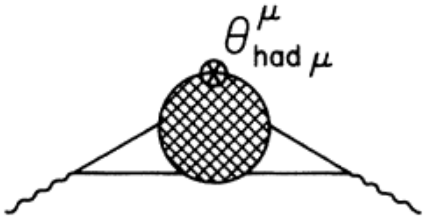
$$\Theta^{\alpha}_{\alpha} = \sum_{l=u,d,s} m_l \; \bar{q}_l q_l + \sum_{h=c,b,t} m_h \; \bar{q}_h q_h$$

Two problems:

1. Potentially large contribution from heavy quarks to the masses of light hadrons

2. If we forget about heavy quarks, all hadron masses must be equal to zero in the chiral limit

Scale anomaly in QCD



The quantum effects (loop diagrams) modify the expression for the trace of the energy-momentum tensor:

$$\Theta^\alpha_\alpha = \frac{\beta(g)}{2g} G^{\alpha\beta a} G^a_{\alpha\beta} + \sum_{l=u,d,s} m_l(1+\gamma_{m_l})\bar{q}_l q_l + \sum_{h=c,b,t} m_h(1+\gamma_{m_h})\bar{Q}_h Q_h,$$

Running coupling -> dimensional transmutation -> mass scale

Gross, Wilczek;
Politzer

$$\beta(g) = -b\frac{g^3}{16\pi^2} + \ldots, \quad b = 9 - \frac{2}{3}n_h,$$

Ellis, Chanowitz;
Crewther;
Collins, Duncan,
Joglecar; …

At small momentum transfer, heavy quarks decouple:

$$\sum_h m_h \bar{Q}_h Q_h \to -\frac{2}{3}\, n_h\, \frac{g^2}{32\pi^2} G^{\alpha\beta a} G^a_{\alpha\beta} + \ldots$$

SVZ ’78

so only light quarks enter the final expression

$$\Theta^\alpha_\alpha = \frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^a_{\alpha\beta} + \sum_{l=u,d,s} m_l \bar{q}_l q_l,$$

The proton mass

At zero momentum transfer, the matrix elements of the energy-momentum tensor are

$$\langle P|\theta^{\mu\nu}|P\rangle = 2P^{\mu}P^{\nu}$$

so that the trace of the energy-momentum tensor defines the masses of hadrons:

$$\langle P|\theta^{\mu}_{\mu}|P\rangle = 2M^{2}$$

$$\Theta^{\alpha}_{\alpha} = \frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \sum_{l=u,d,s} m_l \bar{q}_l q_l,$$

In the chiral limit, the entire mass is from gluons!

The proton mass

At finite quark mass, contribution from “sigma-terms”

$$\Sigma_{\pi N} = \hat{m}\langle p|\bar{u}u + \bar{d}d|p\rangle$$

can be extracted from pion-nucleon scattering or measured on the lattice

e.g. Y.-B.Yang et al arXiv:1511.09089

Sometimes interpreted as either

1. Contribution from quark masses

or

1. Contribution from chiral symmetry breaking

But the interpretation is more subtle

The proton mass

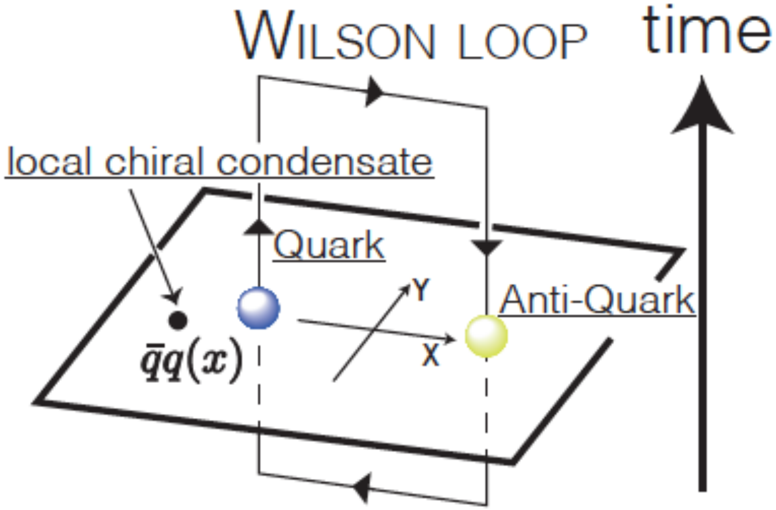
The matrix elements over a hadron state
have to be understood as the **difference** of the value of the measured quantity in the hadron and in the vacuum, e.g.

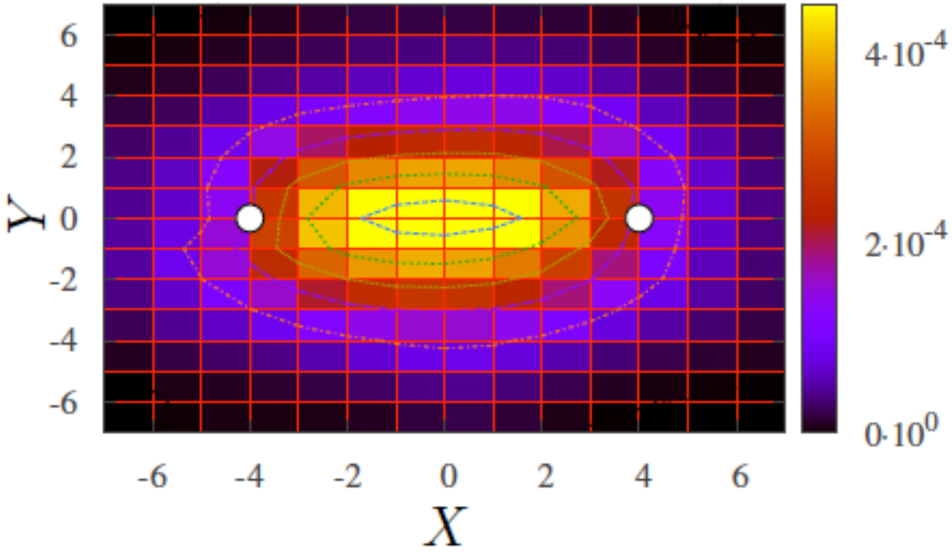
$$\langle P|\bar{q}q|P\rangle = \langle P|\int d^3x\ \bar{q}(x)q(x)|P\rangle - \langle 0|\bar{q}q|0\rangle V_P$$

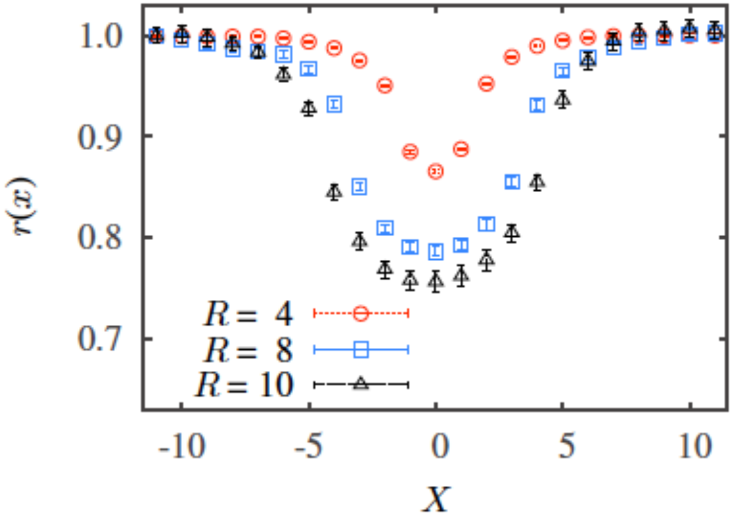
This difference results from the partial **restoration** of spontaneously broken chiral symmetry inside the hadron

e.g., Donoghue, Nappi '86

Partial restoration of chiral symmetry inside the nucleon



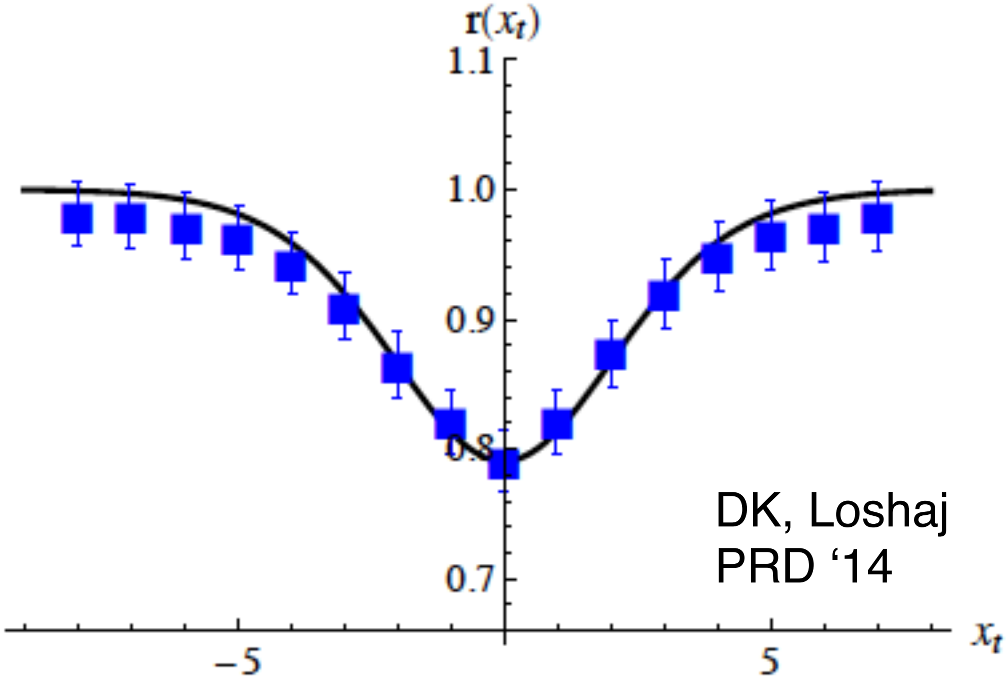




Significant suppression of the local quark condensate by the confining flux tube!

Iritani, Cossu, Hashimoto
arXiv:1502.04845 PRD

Partial restoration of chiral symmetry inside the nucleon

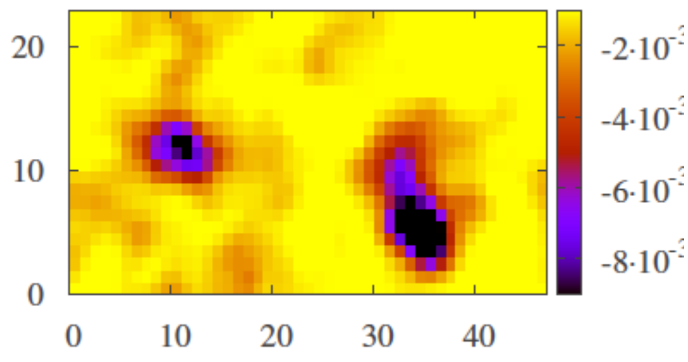


DK, Loshaj
PRD ‘14

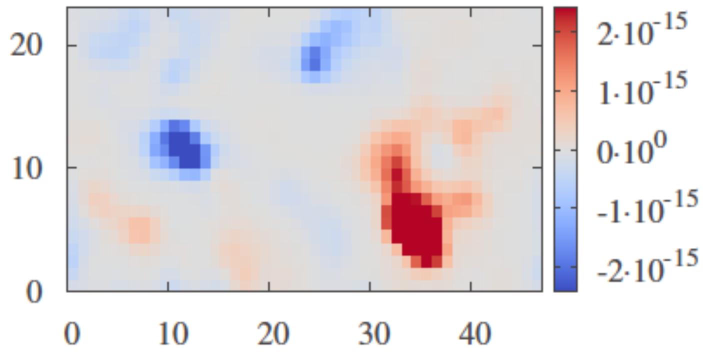
A possible mechanism
of chiral condensate
suppression involves
the chiral anomaly –

so the entire mass of
the proton might originate
from anomalies –
scale and chiral !

(a) local chiral condensate



(c) topological charge density

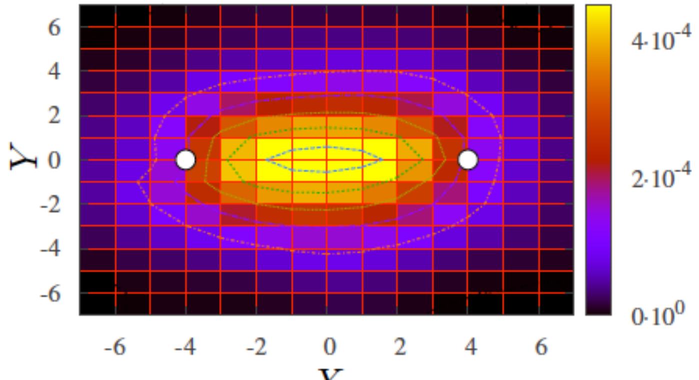


The proton mass as a result of the vacuum polarization induced by the presence of the proton

$$\Theta^{\alpha}_{\alpha} = \frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \sum_{l=u,d,s} m_l \bar{q}_l q_l ,$$

Polarization of the gluon field;

~ 90% of the proton's mass ?



Polarization of the quark condensate;

numerically, ~ 80 MeV using

Y.-B.Yang et al
arXiv:1511.09089

Probing the proton mass

How do we probe the distribution of mass inside the proton?

Need a dilaton source… closest approximation: the heavy quarkonium

The scattering amplitude

$$F_{\Phi h} = r_0^3 \epsilon_0^2 \sum_{n=2}^{\infty} \underset{\substack{\Uparrow \\ \text{Wilson coefficients}}}{d_n} \langle h | \frac{1}{2} G^a_{0i} (D^0)^{n-2} G^a_{0i} | h \rangle$$

The Wilson coefficients

$$d_n^{(1S)} = \left(\frac{32}{N}\right)^2 \sqrt{\pi}\, \frac{\Gamma(n+\frac{5}{2})}{\Gamma(n+5)}$$

M.Peskin ‘78

$$d_n^{(2S)} = \left(\frac{32}{N}\right)^2 4^n \sqrt{\pi}\, \frac{\Gamma(n+\frac{5}{2})}{\Gamma(n+7)} (16n^2 + 56n + 75)$$

$$d_n^{(2P)} = \left(\frac{15}{N}\right)^2 4^n 2\sqrt{\pi}\, \frac{\Gamma(n+\frac{7}{2})}{\Gamma(n+6)}$$

DK, nucl-th/9601029

Quarkonium-proton interaction

$$F_{\Phi h} = r_0^3 \epsilon_0^2 \sum_{n=2}^{\infty} d_n \langle h | \frac{1}{2} G_{0i}^a (D^0)^{n-2} G_{0i}^a | h \rangle$$

1. Interaction is attractive (VdW force of QCD)

S.Brodsky, I.Schmidt, G. de Teramond ‘90

2. For n=2 (low energy) the amplitude is proportional to the trace of the energy-momentum tensor

M.Luke, A.Manohar, M.Savage ‘92

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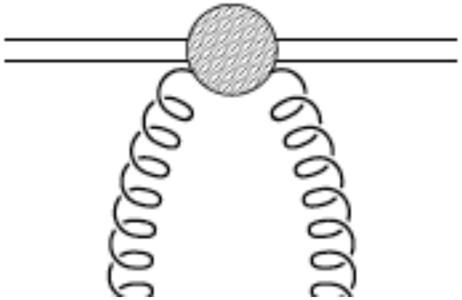
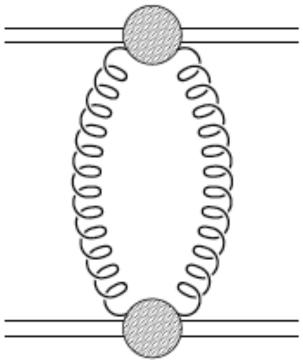
What is the distribution of proton mass?

Need to study the scalar gluon formfactor of the proton – quarkonium scattering



theoretically, we can do onium-onium scattering at low energy

Quarkonium interactions at low energy and the scale anomaly



Perturbation theory:

at large distances,
the Casimir-Polder
interaction (retardation)

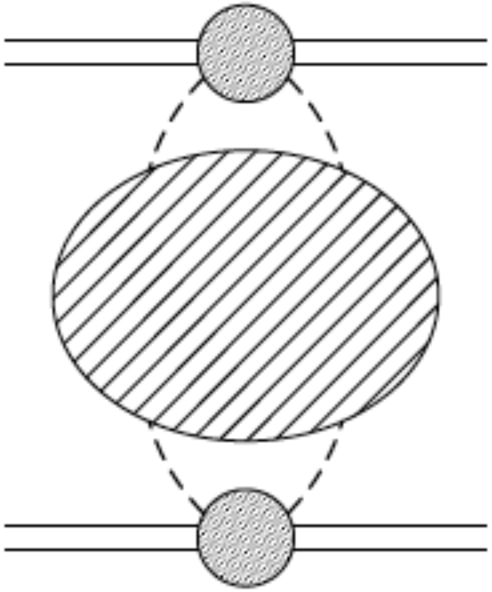
$$V^{\mathrm{pt}}(R) = -g^4 \left(\bar{d}_2 \frac{a_0^2}{\epsilon_0} \right)^2 \frac{23}{8\pi^3} \frac{1}{R^7}$$

Bhanot, Peskin ‘78

Fujii, DK, PRD’99

Quarkonium interactions at low energy and the scale anomaly

But, at very large distances, the interaction must be dominated by the lightest physical states - pions



conversion of gluons to pions is a (hopeless?) non-perturbative problem

…but, can use scale anomaly matching!

Voloshin, Zakharov ‘80

Quarkonium interactions at low energy and the scale anomaly

Use RG invariance to match the TEM computed in QCD and in the chiral theory:

$$\theta^\mu_\mu = -2\,\frac{f_\pi^2}{4}\,\mathrm{tr}\,\partial_\mu U \partial^\mu U^\dagger \;-\; m_\pi^2 f_\pi^2\,\mathrm{tr}\left(U + U^\dagger\right)$$

to lowest order in the pion field

$$\theta^\mu_\mu = -\partial_\mu \pi^a \partial^\mu \pi^a + 2 m_\pi^2 \pi^a \pi^a + \cdots$$

In the chiral limit scale anomaly yields:

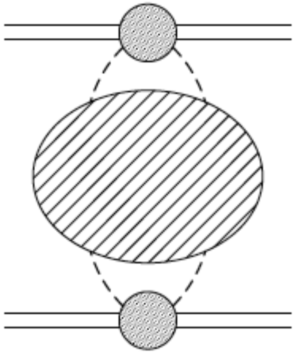
$$\langle \pi^+ \pi^- | \theta^\mu_\mu | 0 \rangle = q^2$$

Quarkonium interactions at low energy and the scale anomaly

The result:

$$V^{\pi\pi}(R) \to -\left(\bar{d}_2 \frac{a_0^2}{\epsilon_0}\right)^2 \left(\frac{4\pi^2}{b}\right)^2 \frac{3}{2}(2m_\pi)^4 \; \frac{m_\pi^{1/2}}{(4\pi R)^{5/2}} \; e^{-2m_\pi R}.$$

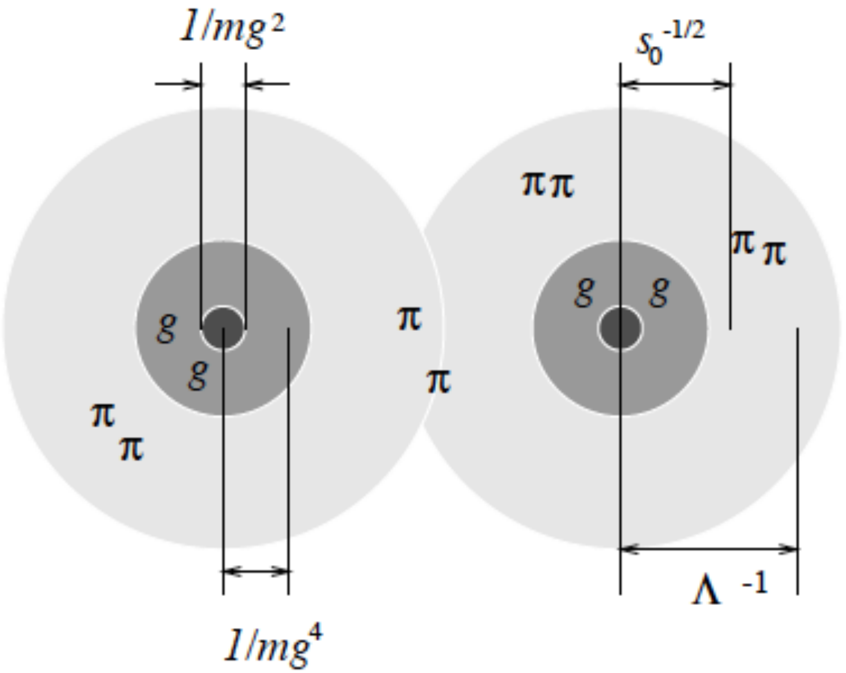
Fujii, DK, PRD’99



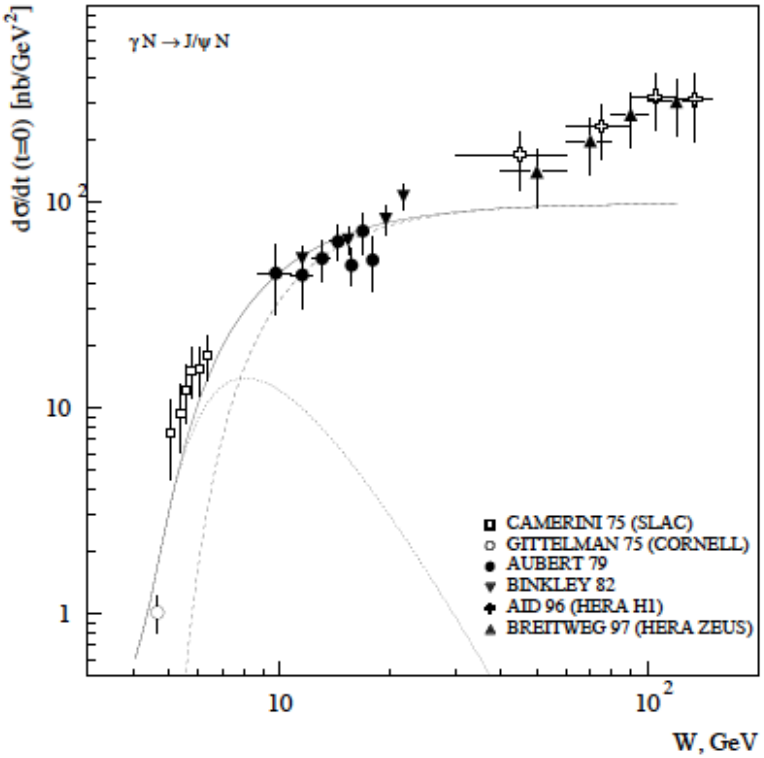
1. Not a Yukawa potential (retardation)
2. The QCD coupling has disappeared at large distance (but note b from the beta-function)

Onium-onium interaction:

quarkonia are surrounded by the pion clouds, and polarize the quark condensate



Quarkonium-proton interaction at low energy probes the distribution of mass inside the proton



The real part of the amplitude is crucially important

DK, Satz, Syamtomov, Zinovjev EPJ ‘99

Figure 1: Forward J/ψ photoproduction data compared to our results with (solid line) and without (dashed line) the real part of the amplitude. The curves were obtained using a scaling PDF [4]

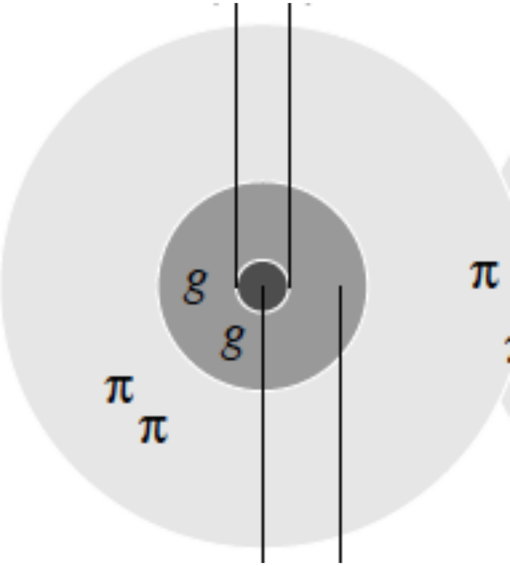
What if a quarkonium is put inside a nucleon?

Attractive interaction, possibly a bound state –
e.g. it exists in the Skyrme model

Gobbi, Boffi, DK '94

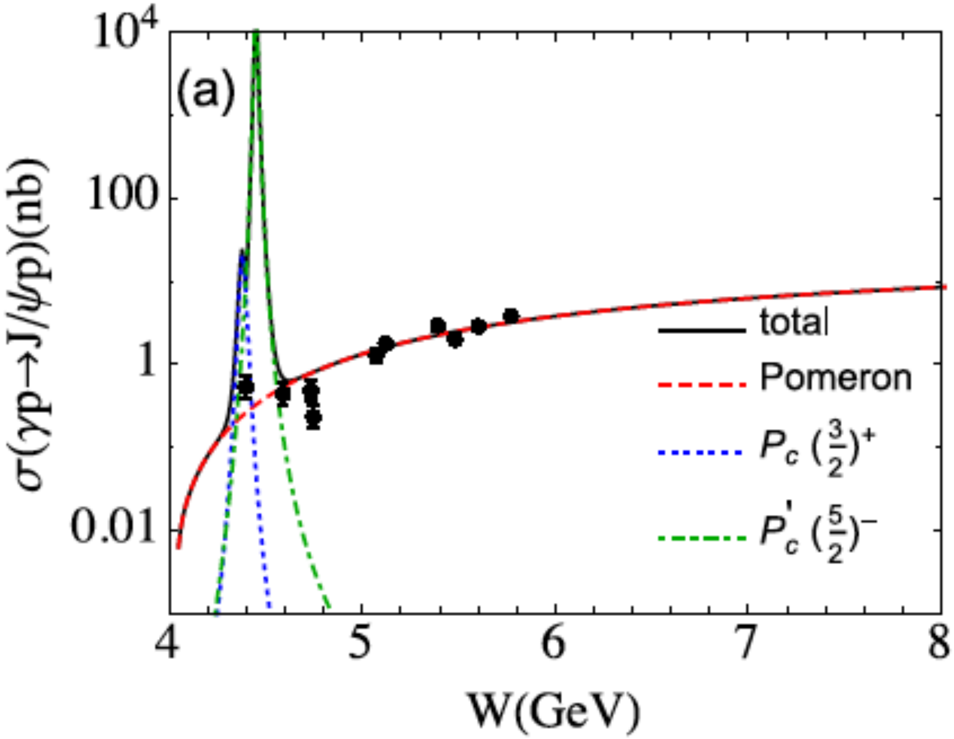
quarkonium surrounded by
the light hadron –
"hadro-quarkonium"

Dubynskyi, Voloshin '08



Possible description of $P_c(4380)$ and $P_c(4450)$ pentaquarks discovered by LHCb?

Charmonium photoproduction close to the threshold



Wang, Liu, Zhang
arxiv:1508.00339

Kubarovsky,
Voloshin
arxiv:1508.00888

But, the cross section may be much smaller – O(pb)
Gobbi, Boffi, DK ‘94

Summary

- The proton mass to large extent originates from quantum anomalies

- The threshold photoproduction of charmonium can probe the mass distribution inside the proton

- It can also clarify the origin of hidden charm Pentaquarks, and perhaps lead to new discoveries