Proton without confinement

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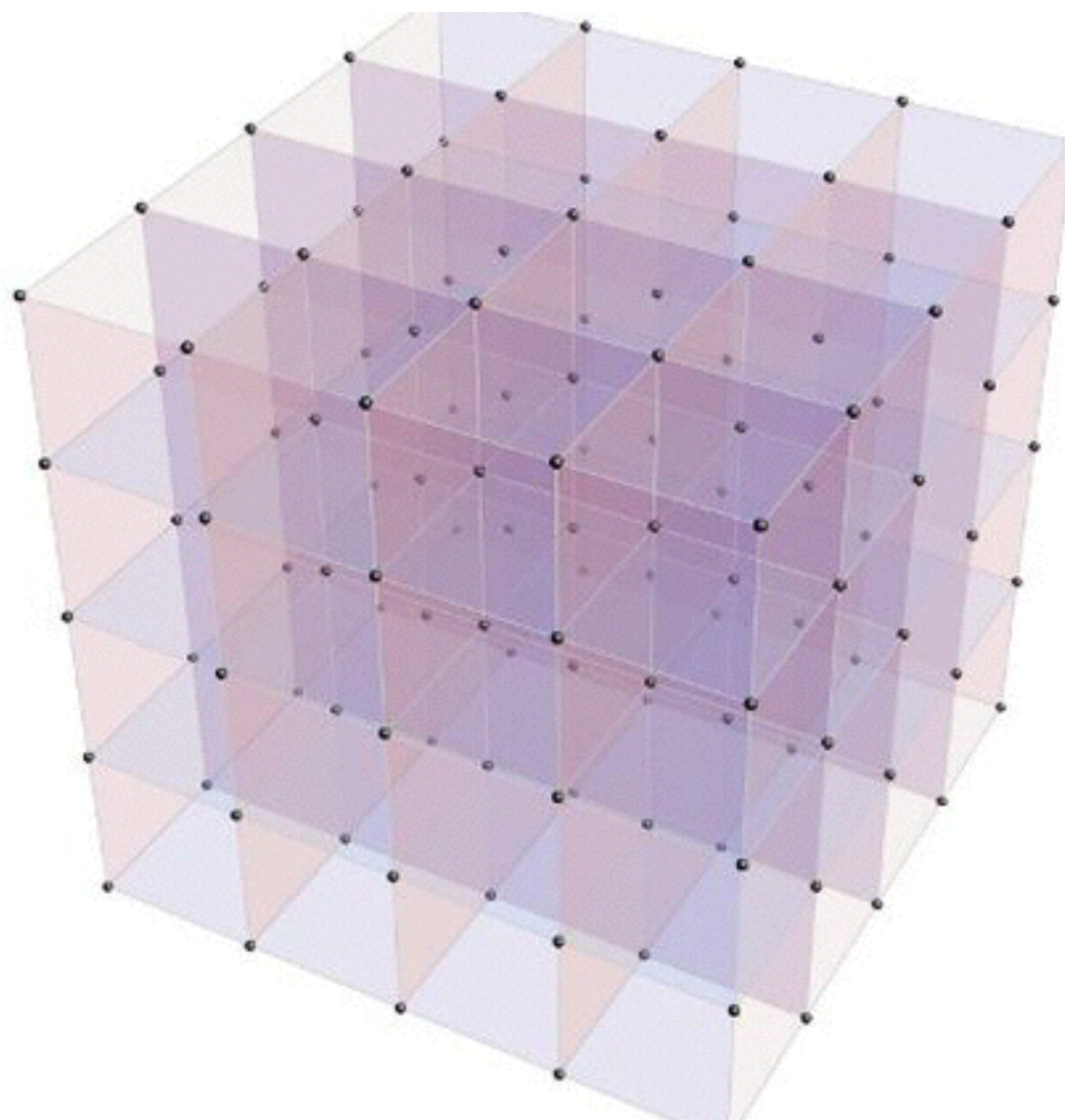
A few facts from lattice QCD



Fact 1: Proton and confinement

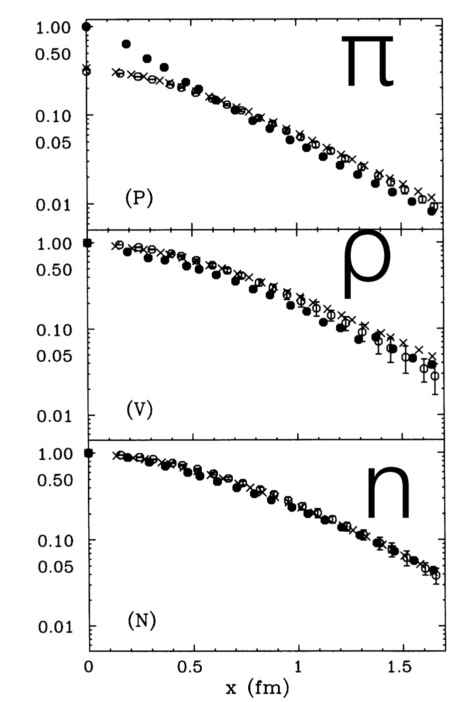
* In cooling numerical "experiments", the string tension disappears a few cooling steps:

Cooling steps	$\langle S\rangle/S_0$	σa^2
0	20,211	0.18
25	64	0.05
50	31	0.03

M-C Chu, J. Grandy, S Huang and J. Negele, PRD 49 (1994)

* However, more cooling steps are needed to kill the proton pole in the 2-point correlation function:

$$\Pi(x) = \langle 0|J(x)\bar{J}(0)|0\rangle$$



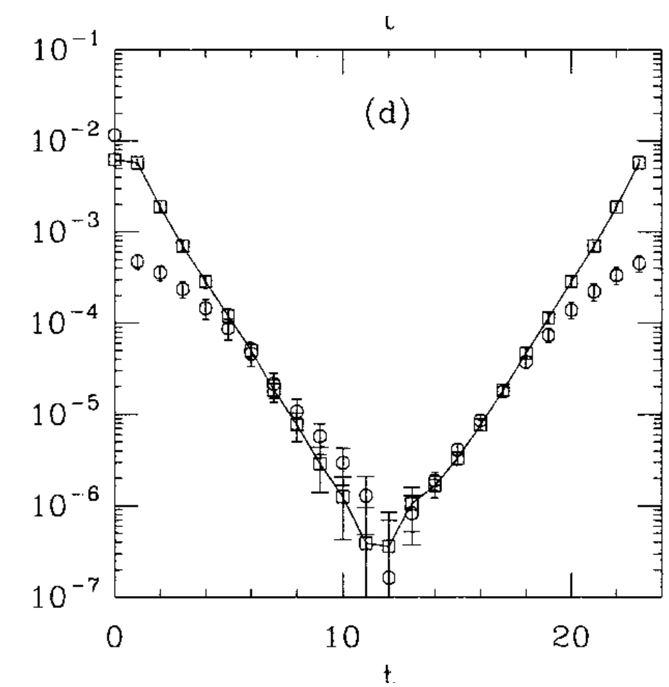
* After cooling, only smooth lumps of topological fields survive

Implication: protons (and pions) can be bound by QCD 'forces', without confinement. Quantitative statements are more delicate

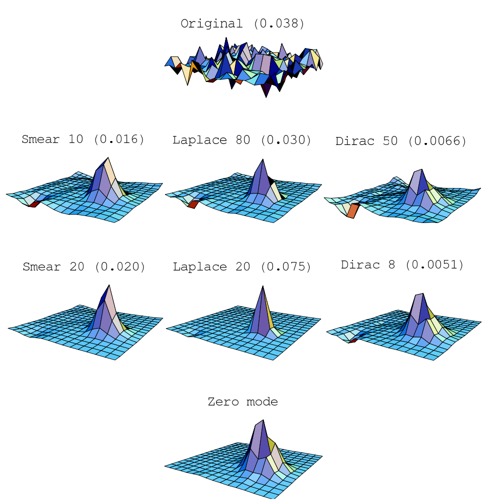
Fact 2: Topology and chiral symmetry breaking

* In eigenvalue filtering, chiral properties of QCD are well reproduced by lowest eigenmodes of Dirac operator and correlate with topological "lumps".

* The nucleon correlation function is "saturated" by the lowest modes



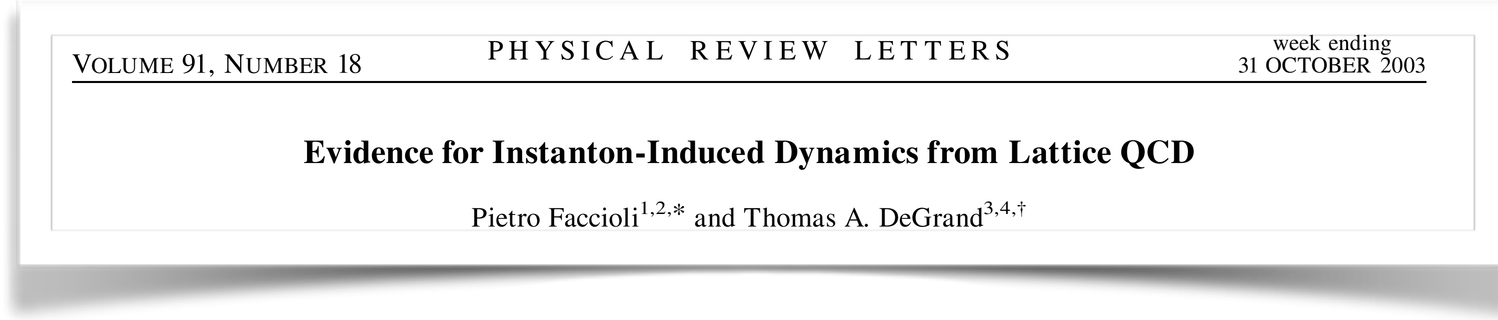
Bruckmann et a.
Eur. Phys. J. A 33, 333–338 (2007)



* If the same lattice configurations are cooled, then very similar **topological structures** are obtained

Implication: Topological lumps with low Euclidean action correlate with chiral properties of QCD. Chiral modes **bind** (not confine) the nucleon.

Fact 3: Chirality flipping interactions


VOLUME 91, NUMBER 18 PHYSICAL REVIEW LETTERS week ending 31 OCTOBER 2003

Evidence for Instanton-Induced Dynamics from Lattice QCD

Pietro Faccioli[1,2,*] and Thomas A. DeGrand[3,4,†]

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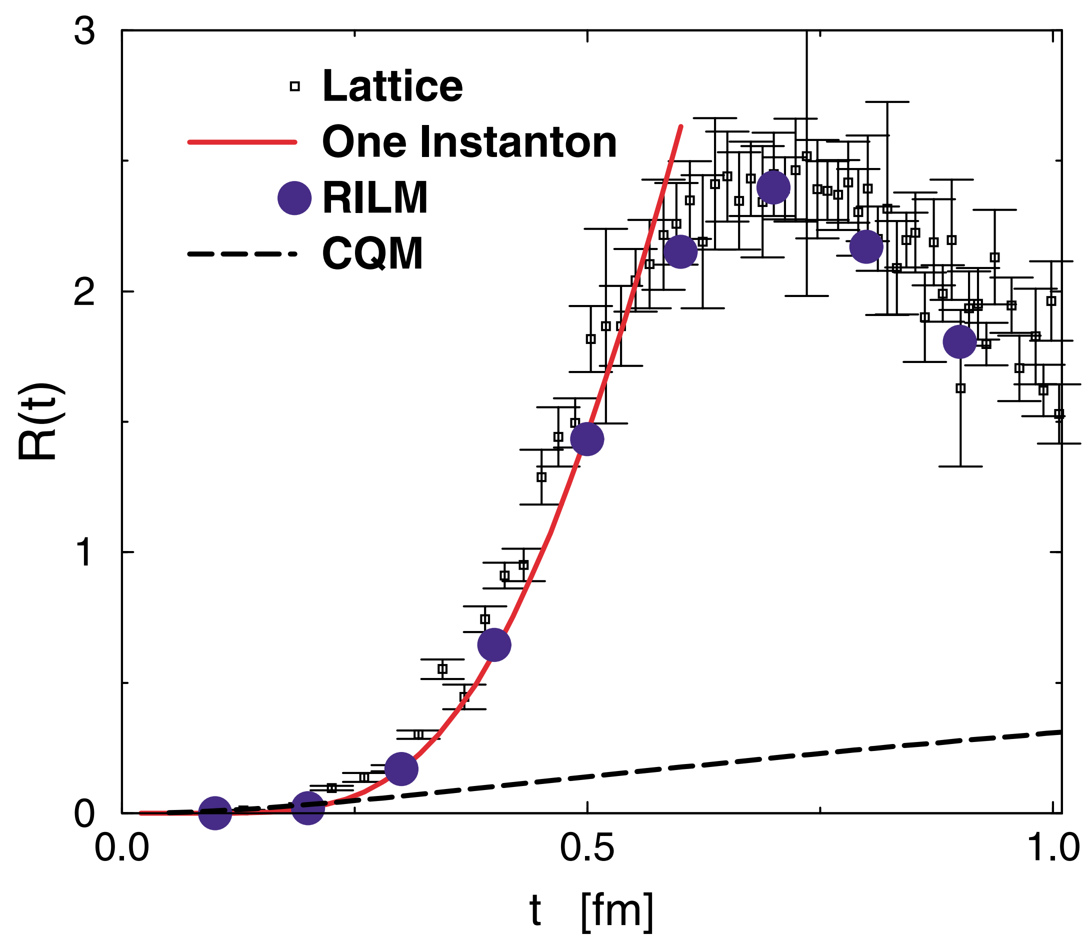
* Chiral asymmetry in lattice:

$$R(|x|) = \frac{\mathcal{P}(LR \stackrel{|x|}{\rightarrow} RL)}{\mathcal{P}(LR \stackrel{|x|}{\rightarrow} LR)}$$



Explanation: Quasi-local non perturbative chirality-flipping interactions large non-vector components to the quark-gluon vertex.

Summarizing…

- Light hadrons are bound also at zero string tension
- Their quark wave-function is saturated by near zero-modes correlated with isolated topological gauge field lumps with low action (chiral dynamics)
- Non-perturbative q$\underline{q}$ interactions flip chirality.

Can we embody this information in a qualitative picture leading to a calculable model?

Why bother about a model if we have LQCD?

Compute observables which are hard/impossible to get from LQCD

E.g. time-like, hadronic resonances, neutron EDM, …

Build qualitative insight:
E.g. what is the structure of the nucleon wave function?
-i.e. why E/M form factors are what they are?

…also learn from failures

QCD Instantons

(Belavin, Polyakov, Schwartz, Tyupkin, ’t Hooft)

Instanton solution: $\delta S_{YM}[A^I_\mu] = 0$

One can build *multi-instanton* fields $\bar{A}^\Lambda_\mu(x)$ such that: $\delta S[\bar{A}^\Lambda_\mu] \simeq 0$

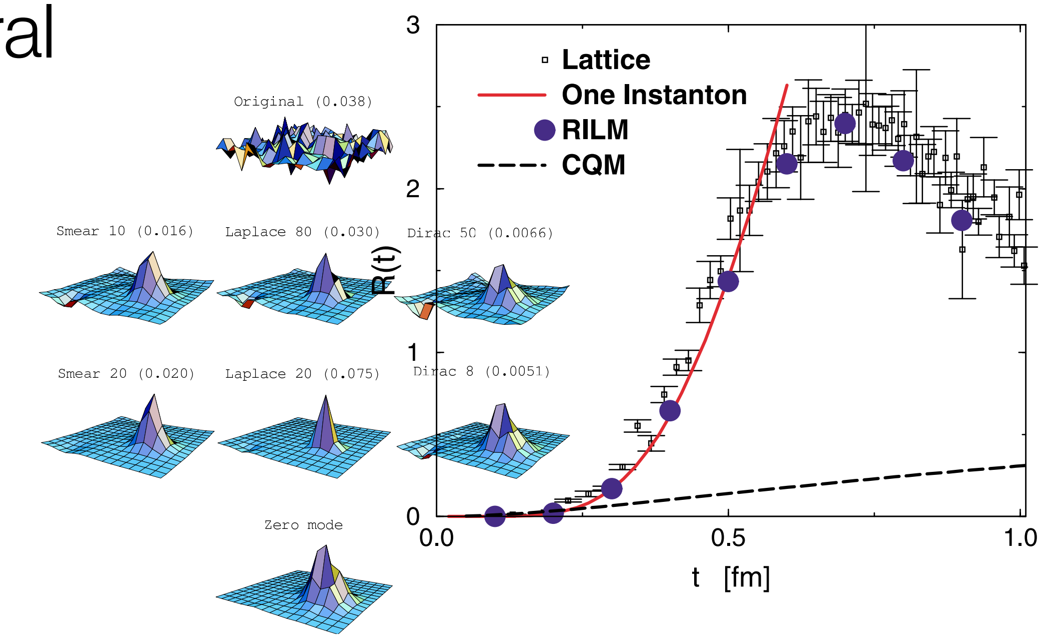
They are attractive because

* topological lumps with low action

* naturally generate near zero-mode zone (chiral symmetry breaking)

* they induce chirality flipping interactions

* Do not provide confinement



Instanton liquid model

(Shuryak, Diakonov et al. 1982-200X)

$$A_\mu(x) = \bar{A}_\mu^\Lambda(x) + \delta A_\mu \qquad \Lambda = (\lambda_1, \lambda_2, \ldots) \qquad \text{(collective coordinates)}$$

Then the QCD partition function is written as

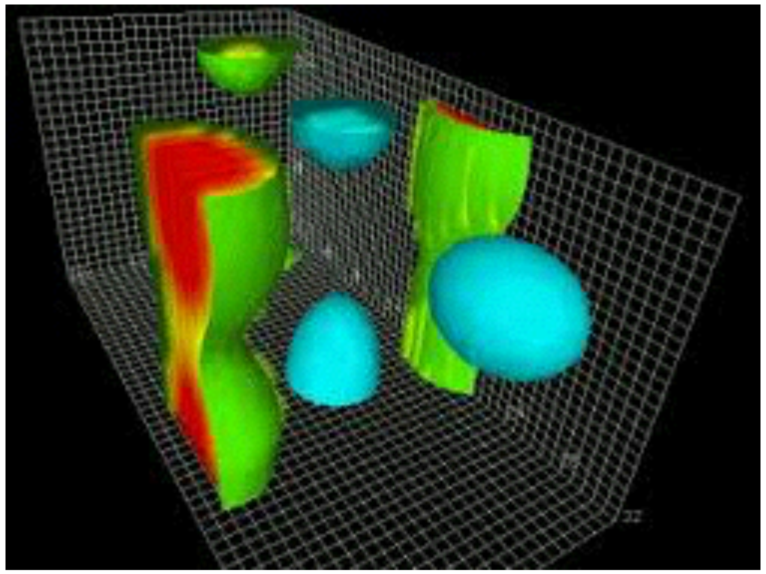
$$Z_{YM} = \int d\Lambda e^{-S_{YM}[\bar{A}_\mu(\Lambda)]} \int d\delta A_\mu e^{-(S_{YM}(\bar{A}^\Lambda + \delta A) - S_{YM}[\bar{A}^\Lambda])}$$

NB: expand this to o(δA^2_μ) -semiclassical approx- wouldn't work (IR divergent)

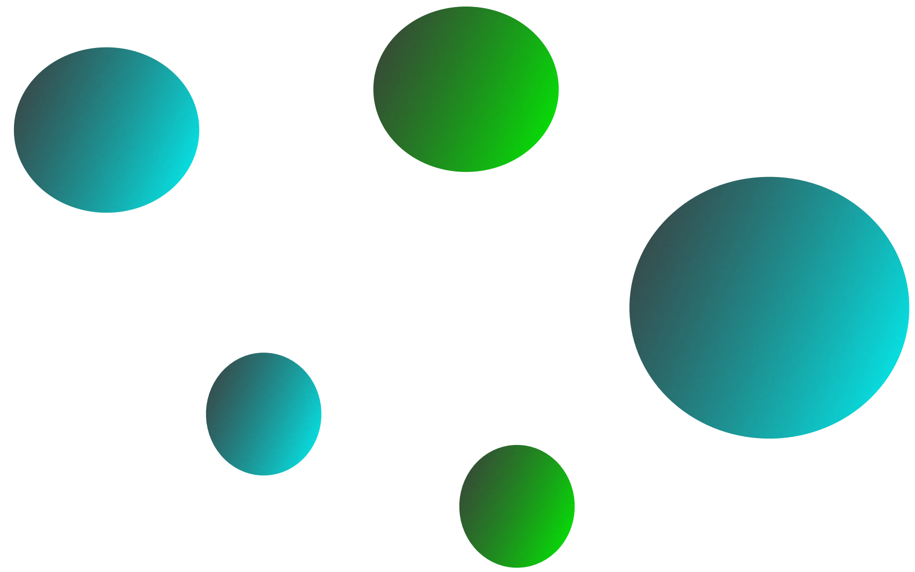
$$\simeq \int d\Lambda e^{-S_{YM}[\bar{A}_\mu(\Lambda)]} \times n(\Lambda) \equiv Z_{ILM}$$

Variational estimate of the QCD path integral

Instanton Models



Lattice



ILM

$$\bar{n} \sim 1 \text{ fm}^{-4} \qquad \bar{\rho} \sim \frac{1}{3}\text{fm}$$

phenomenology or self-consistent variational principle

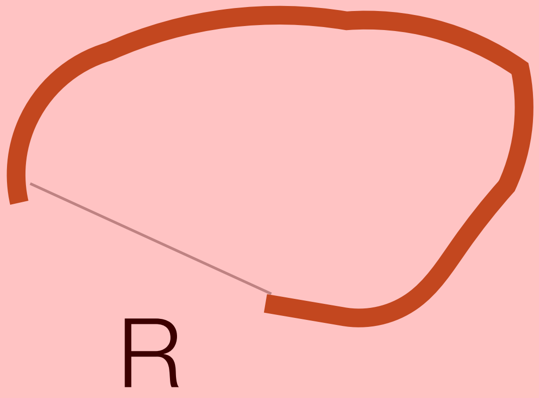
NB: (near) zero-mode wave function is analytically known
(light-quark propagator in a given background)

Can we compute these parameters from LQCD?

Cooling computing n(ρ) by cooling or filtering is tricky: when should we stop?

Can we compute it without “touching” the lattice configurations?

Inspiration: potential of mean-force in stat. mech.



$$e^{-\beta G(R)} \equiv \int dPdQ\ \delta(R - |\mathbf{r}_1 - \mathbf{r}_N|)\ e^{-\beta H[P,Q]}$$

Project onto the plane of reaction coordinate and count…

How can we extent this simple idea to lattice QCD?

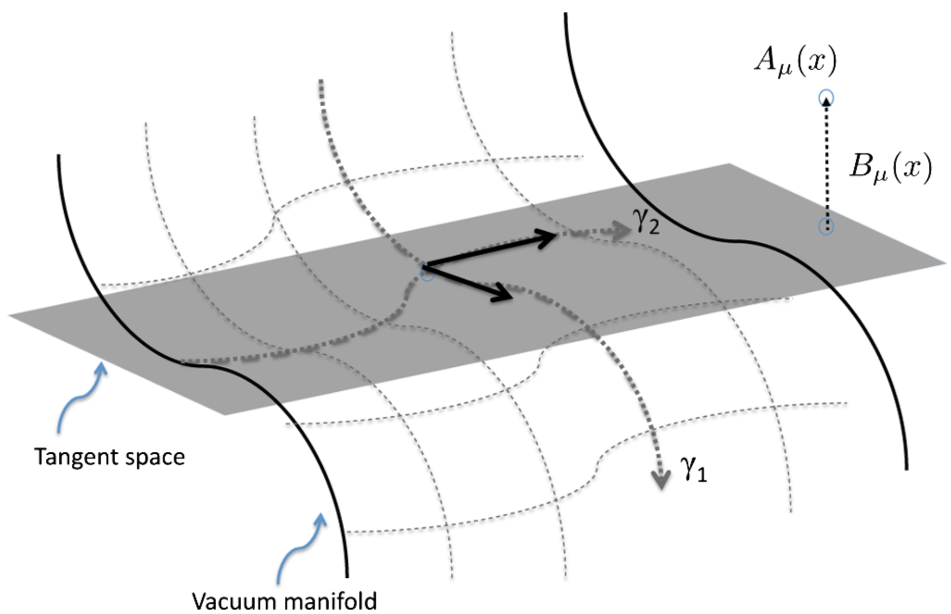
PHYSICAL REVIEW D **84**, 034504 (2011)

Computing the effective Hamiltonian of low-energy vacuum gauge fields

R. Millo[1,2,*] and P. Faccioli[1,2]

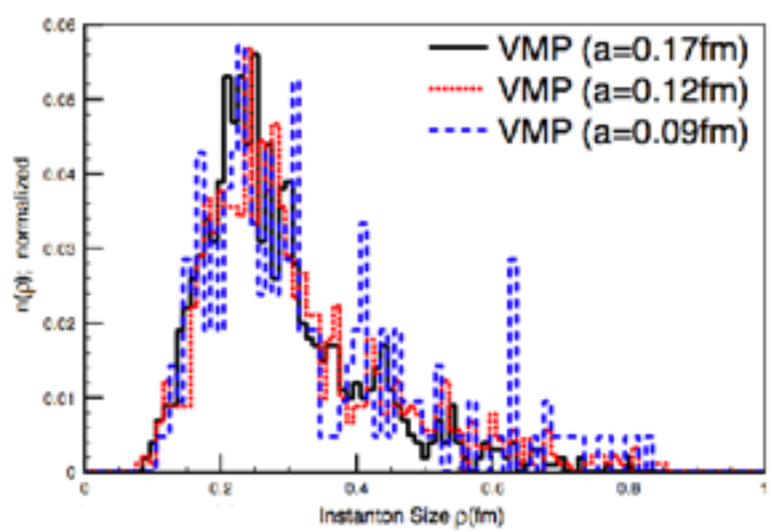
Computing n(ρ) from LQCD

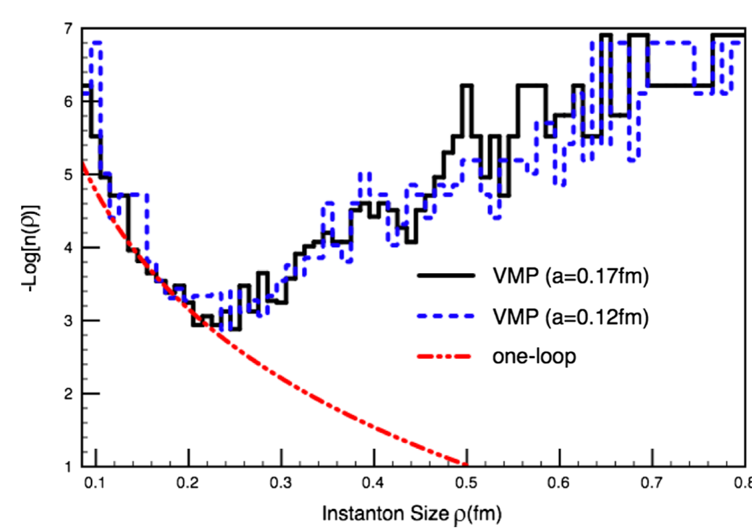
Step 1: define a local system of coordinates in the back-ground field manyfold

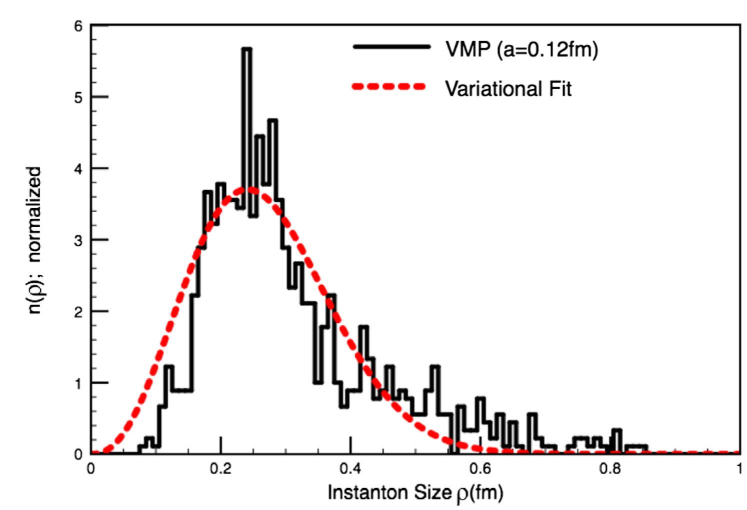


$$g^i_\mu(x) \equiv \frac{\partial}{\partial \lambda_i} \bar{A}^\Lambda_\mu(x)|$$

$$(g^i_\mu(x), A_\mu(x)) = \mathrm{Tr}_c \left[\int d^4x A_\mu(x) g^i_\mu(x) \right]$$







NB some observables depend only on ρ!

Applications to light hadron phenomenology:

Strategies to compute in the ILM

Monte Carlo Simulations (Shuryak, Schäfer)

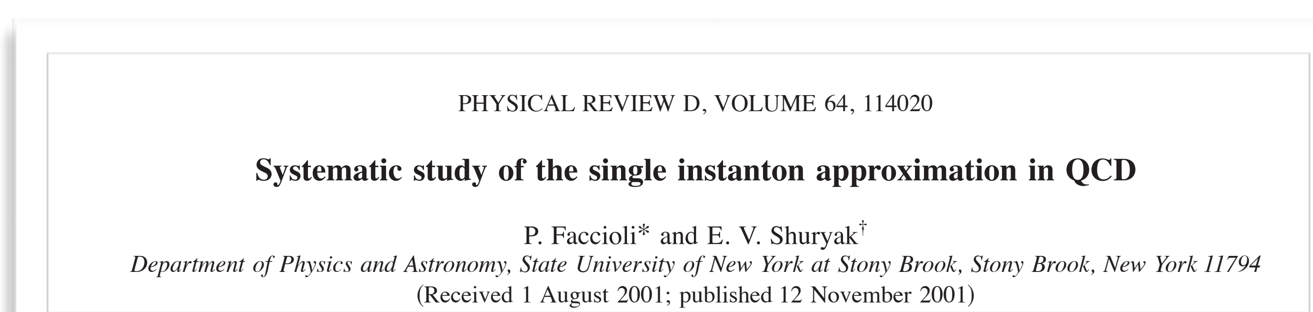
\+ no further approx.
\- numeric (limited insight)

Mean Field (chiral soliton) (Dyakonov, Petrov …)

\+ Analytic
\- Mean field for hadrons….

Single Instanton Approximation (Shifman, Shuryak, Forkel,PF)

\+ Anaytic, one parameter ρ=*0.3*
\- Valid only for Q^2>1 GeV


PHYSICAL REVIEW D, VOLUME 64, 114020

Systematic study of the single instanton approximation in QCD

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(Received 1 August 2001; published 12 November 2001)

Spectroscopy: Proton and pion mass

PHYSICAL REVIEW D **75,** 034008 (2007)

Exploring the chiral regime of QCD in the interacting instanton liquid model

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Dipartimento di Fisica and I.N.F.N., Università degli Studi di Trento, Via Sommarive 15, Povo (Trento) 38050 Italy.
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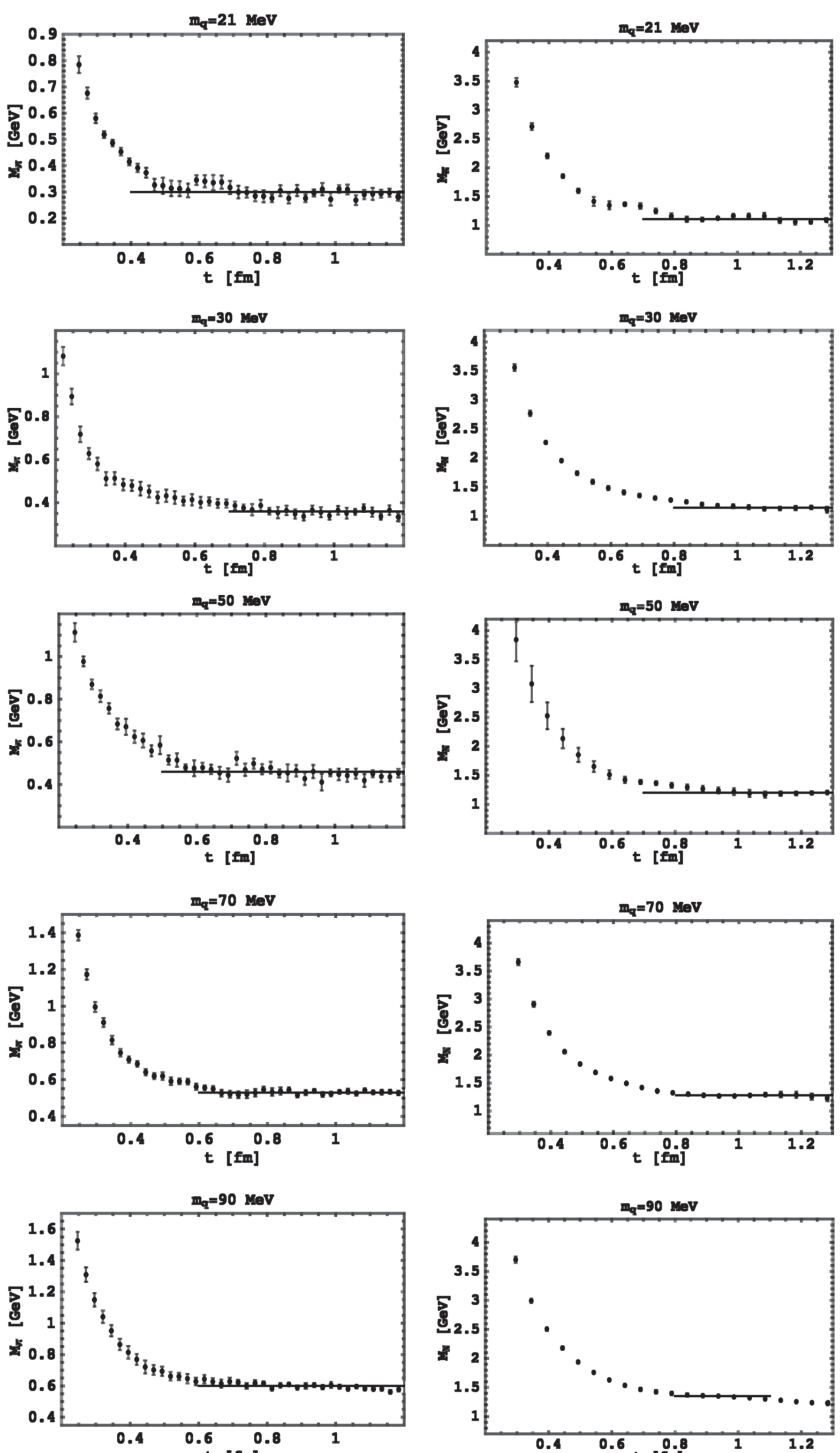

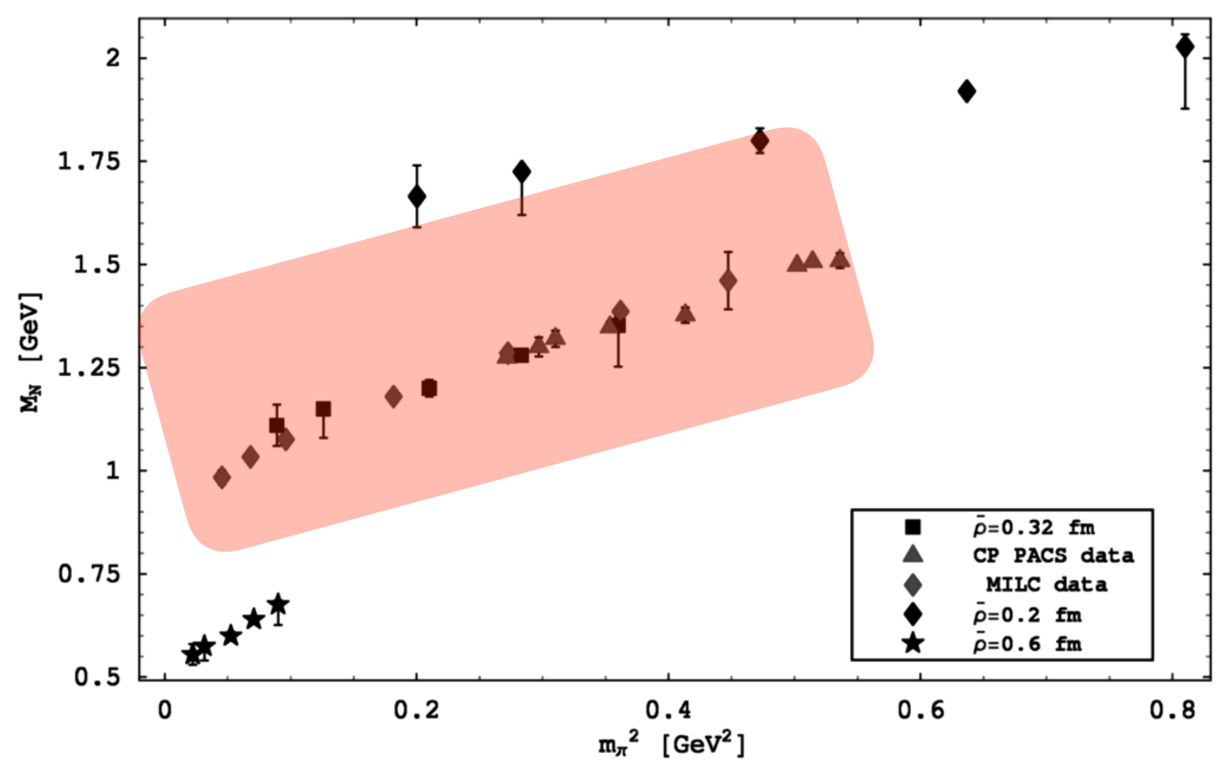

$$G_2(\tau) = \int d^3\mathbf{x} \langle 0 | J_N(\mathbf{x}, \tau) J^\dagger(\mathbf{0}, 0) | 0 \rangle$$

$$M_{eff}(\tau) = -\frac{d}{d\tau} \log G_2(\tau)$$

Spectroscopy:
Lowest-lying resonances

PHYSICAL REVIEW D **75,** 034008 (2007)

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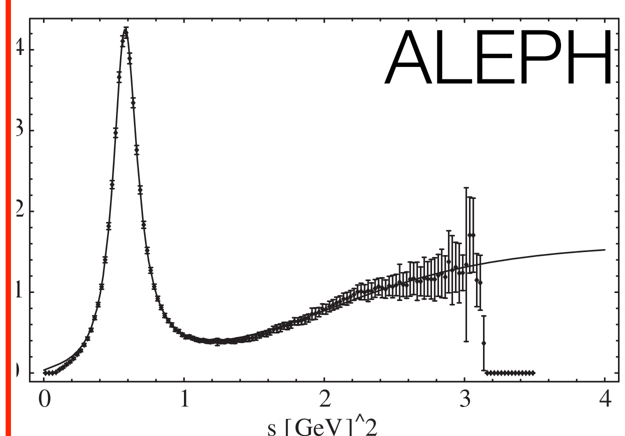
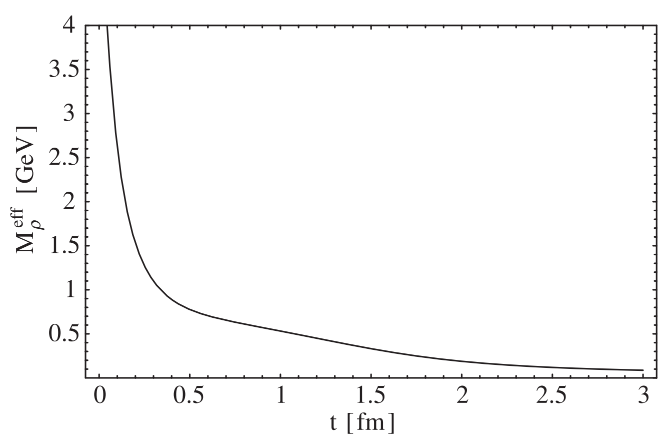
Hadron effective mass form phenomenology:

$$G_H(\tau) = \int d^3\mathbf{x}\langle 0|J_H(\mathbf{x},\tau)J_H^\dagger(\mathbf{0},0)|0\rangle \qquad G_H(\tau) = \int \frac{ds}{2\sqrt{s}}\rho_H(s)e^{-\sqrt{s}\tau},$$

ρ meson:



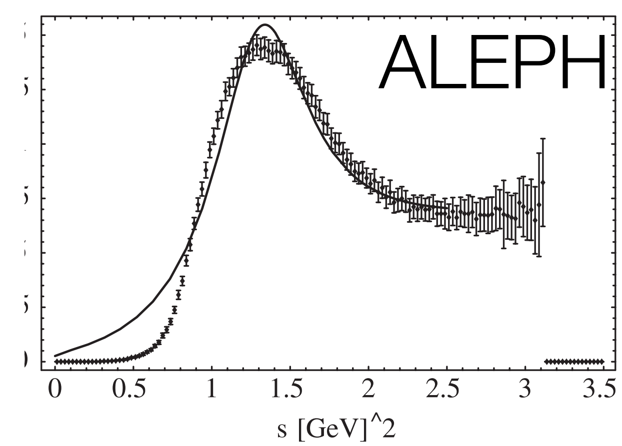


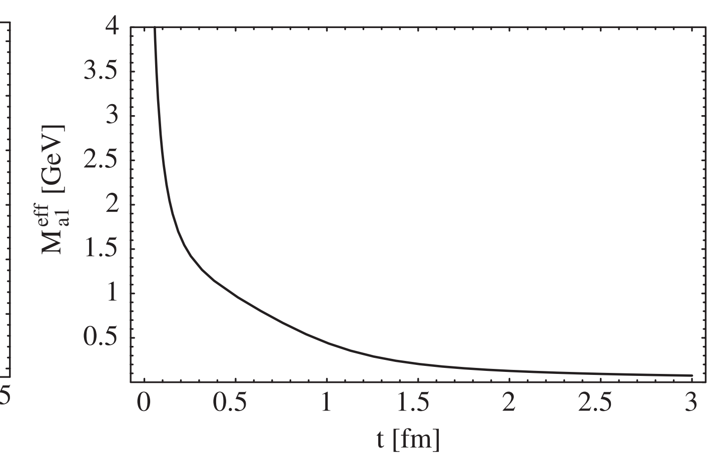
$$\rho_\rho(s) = C_1^\rho \frac{(\Gamma_\rho/2)^2}{(\Gamma_\rho/2)^2 + (\sqrt{s}-m_\rho)^2} + \frac{C_2^\rho}{1+\exp[(E_0-\sqrt{s})/0.2]}.$$

$$M_{eff}(\tau) = -\frac{d}{d\tau}\log G_H(\tau)$$

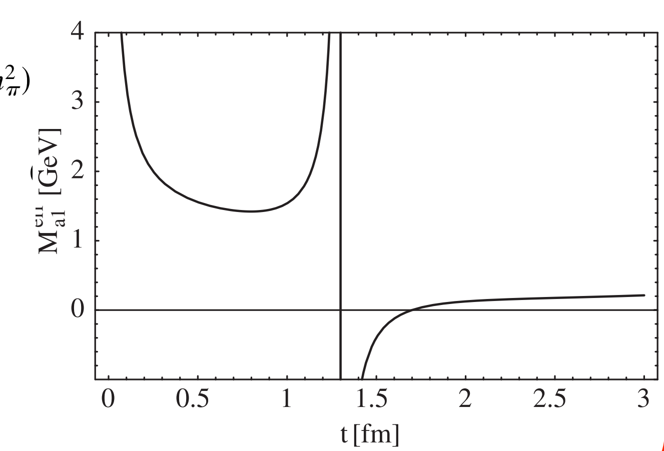
$$G_H(\tau) = \int \frac{ds}{2\sqrt{s}}\rho_H(s)e^{-\sqrt{s}\tau},$$

a_1 meson:



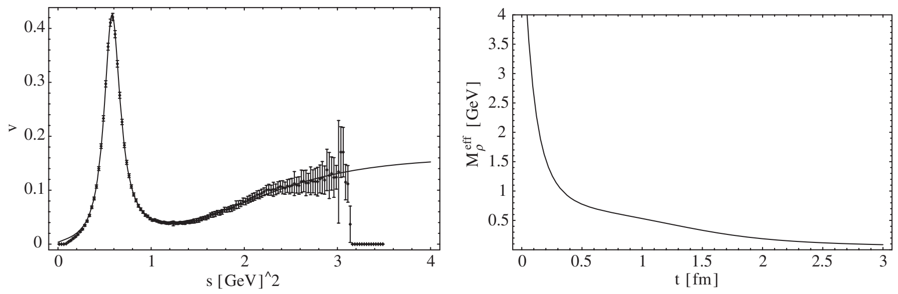


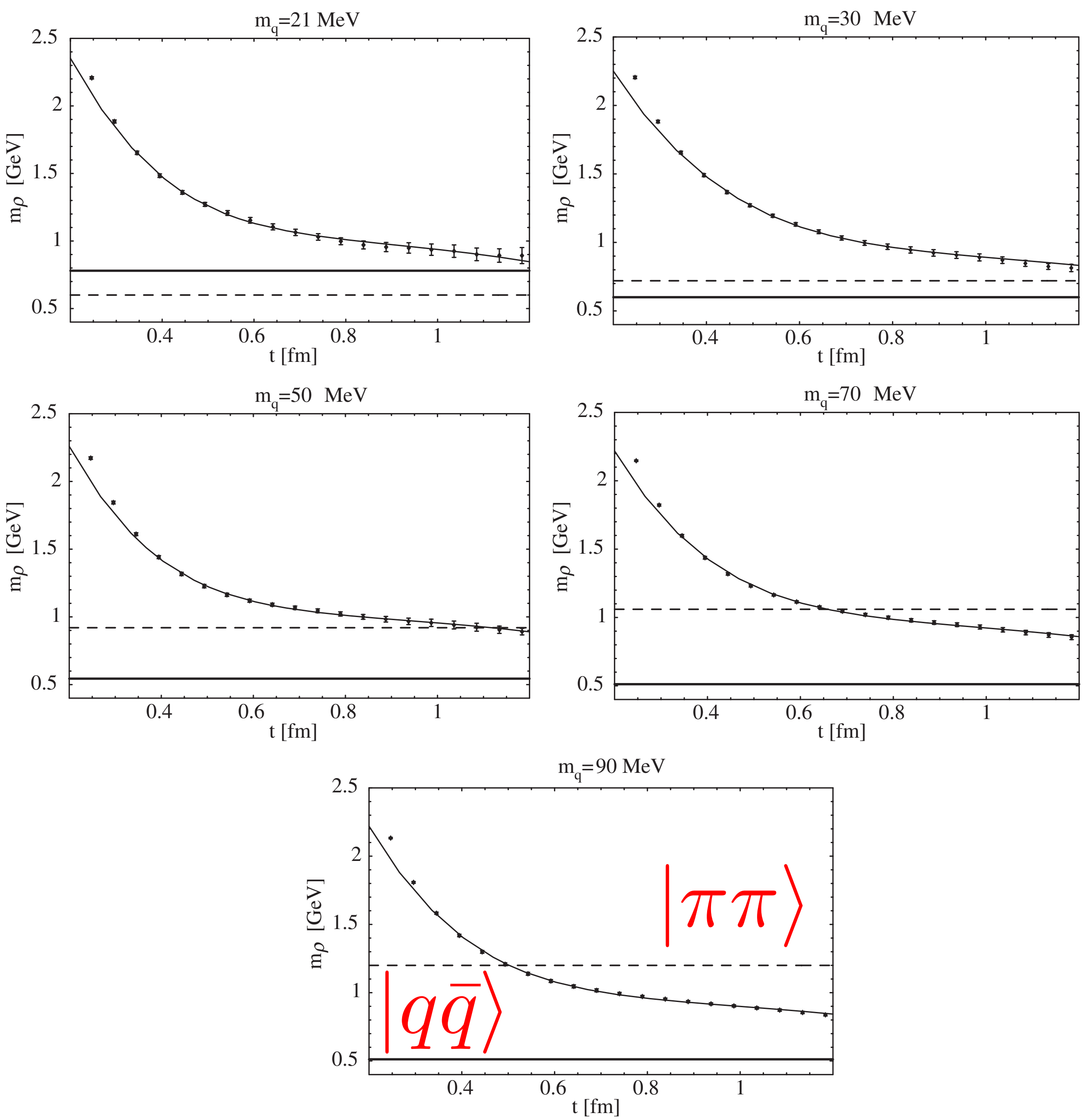
$$\rho(s) = C_1^{a_1}\frac{(\Gamma_{a_1}/2)^2}{(\Gamma_{a_1}/2)^2 + (\sqrt{s}-m_{a_1})^2} - f_\pi^2 m_\pi^2 \delta(s-m_\pi^2) + \frac{C_2^{a_1}}{1+\exp[(E_0-\sqrt{s})/0.2]},$$



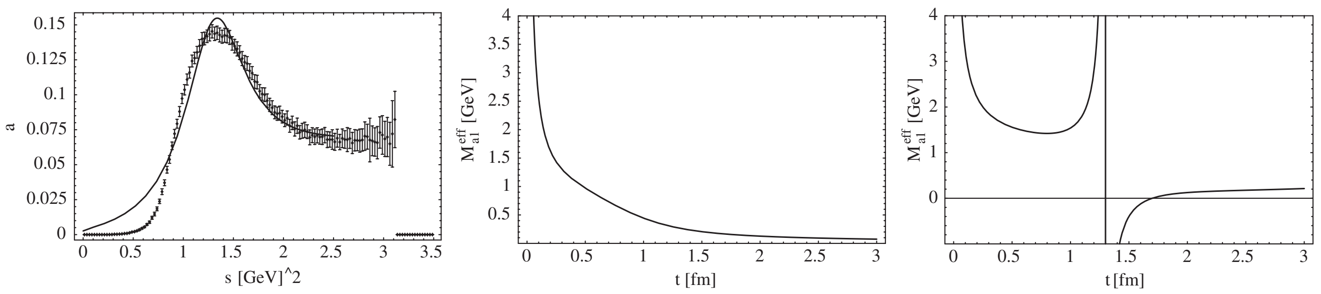
ILM analysis

ρ meson:





a_1 meson:



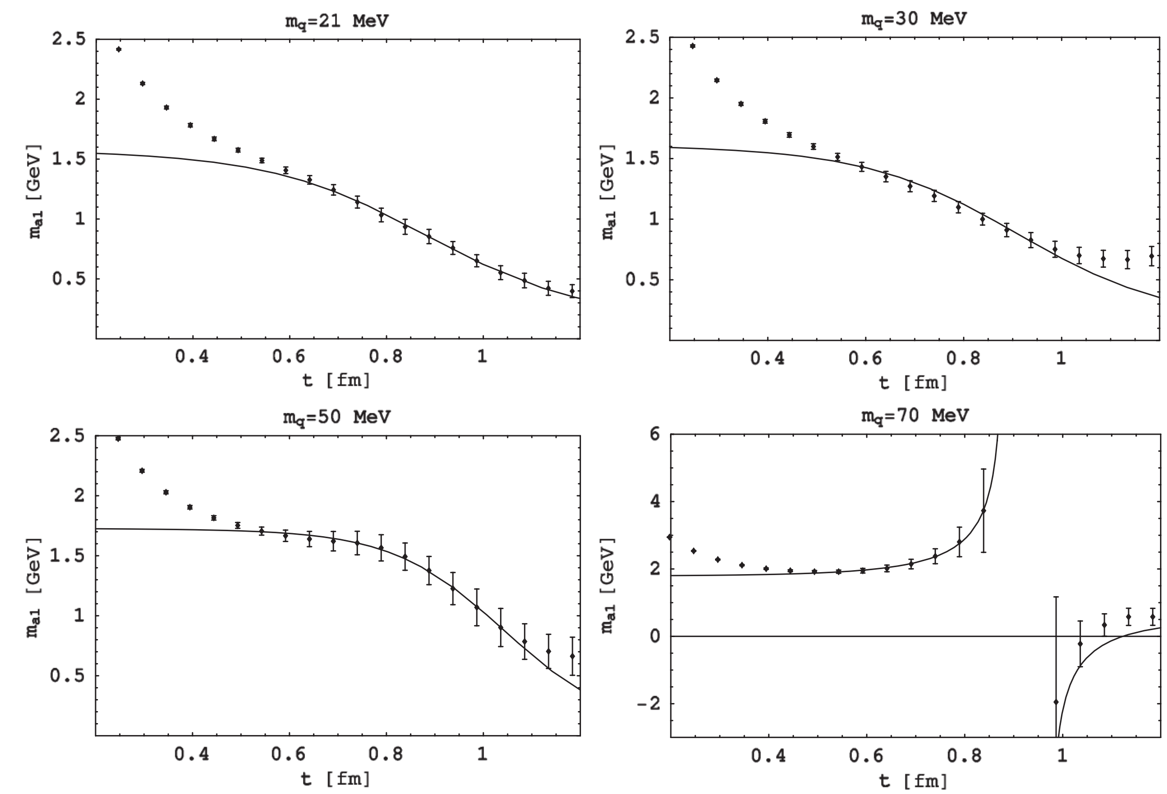


TABLE I. π, ρ, a_1 masses (in GeV units) calculated in the IILM for different quark masses.

m_q	M_π	M_ρ	M_{a_1}	Γ_ρ	Γ_{a_1}
0.02	0.30 ± 0.04	1.0 ± 0.1	1.6 ± 0.1	≃ 0.01	<0.02
0.03	0.36 ± 0.04	0.9 ± 0.1	1.6 ± 0.1	≲ 0.01	<0.03
0.05	0.46 ± 0.04	1.0 ± 0.1	1.7 ± 0.1	≃ 0.05	<0.01
0.07	0.53 ± 0.04	1.0 ± 0.1	1.7 ± 0.1	≃ 0.05	<0.01
0.09	0.60 ± 0.04	0.9 ± 0.1	1.8 ± 0.2	≃ 0.05	<0.01

Learn from failure: No confinement!

Glueballs

- V.A. Novikov, M.A. Shifman, A.I. Vainsthein, V.I. Zakharov, Nucl. Phys. B 191, 301 (1981)
- E.V. Shuryak, Nucl. Phys. B 203, 116 (1982)
- H. Forkel, Phys. Rev. D 64, 034015 (2001)
- H. Forkel, Phys. Rev. D 71, 054008 (2005)
- T. Schafer, E.V. Shuryak, Phys. Rev. Lett. 75, 1707 (1995)
- M. Tichy and P. Faccioli, Eur. Phys. J. C 63: 423–433 (2009)

Electro-weak structure of light hadrons

E/M form factors of pion, neutrons and proton

Instanton contribution to the proton and neutron electric form factors

P. Faccioli, A. Schwenk, E.V. Shuryak

Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794-3800, USA

PHYSICAL REVIEW D **67**, 113009 (2003)

Instanton contribution to the pion electromagnetic form factor at $Q^2 > 1$ GeV^2

P. Faccioli, A. Schwenk, and E. V. Shuryak

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(Received 1 March 2002; published 26 June 2003)

Instanton contribution to the electromagnetic form factors of the nucleon

P. Faccioli

Phys. Rev. C **69**, 065211 – Published 30 June 2004

Non-leptonic decays of kaons & hyperons (ΔI = 1/2 rule)

Instantons, diquarks, and nonleptonic weak decays of hyperons

M. Cristoforetti, P. Faccioli, E. V. Shuryak, and M. Traini

Phys. Rev. D **70**, 054016 – Published 16 September 2004

Instantons and the $\Delta I = 1/2$ Rule

N. I. Kochelev and V. Vento

Phys. Rev. Lett. **87**, 111601 – Published 24 August 2001

Are there diquarks in the nucleon?

M. Cristoforetti, P. Faccioli, G. Ripka, and M. Traini

Phys. Rev. D **71**, 114010 – Published 27 June 2005

So what?

Why bother about a model ?

Build qualitative insight:
E.g. what is the structure of the nucleon wave function?
-i.e. why E/M form factors are what they are?

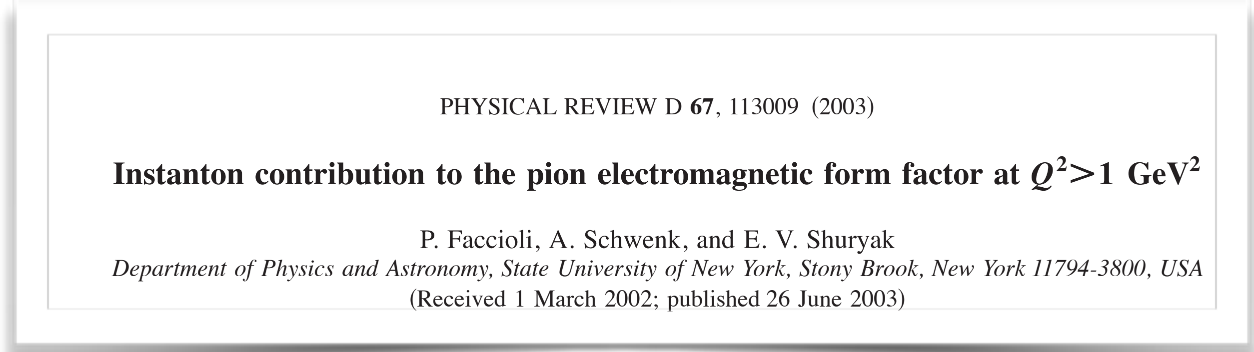
Compute observables which are hard/impossible to get from LQCD

E.g. time-like, hadronic resonances, neutron EDM, …

Learn from failures

The purpose of this exercise is not that of trying to prove the model “is right” (what does it mean?)
But rather to learn from success and failures

CASE 1: Pion FF


PHYSICAL REVIEW D **67**, 113009 (2003)

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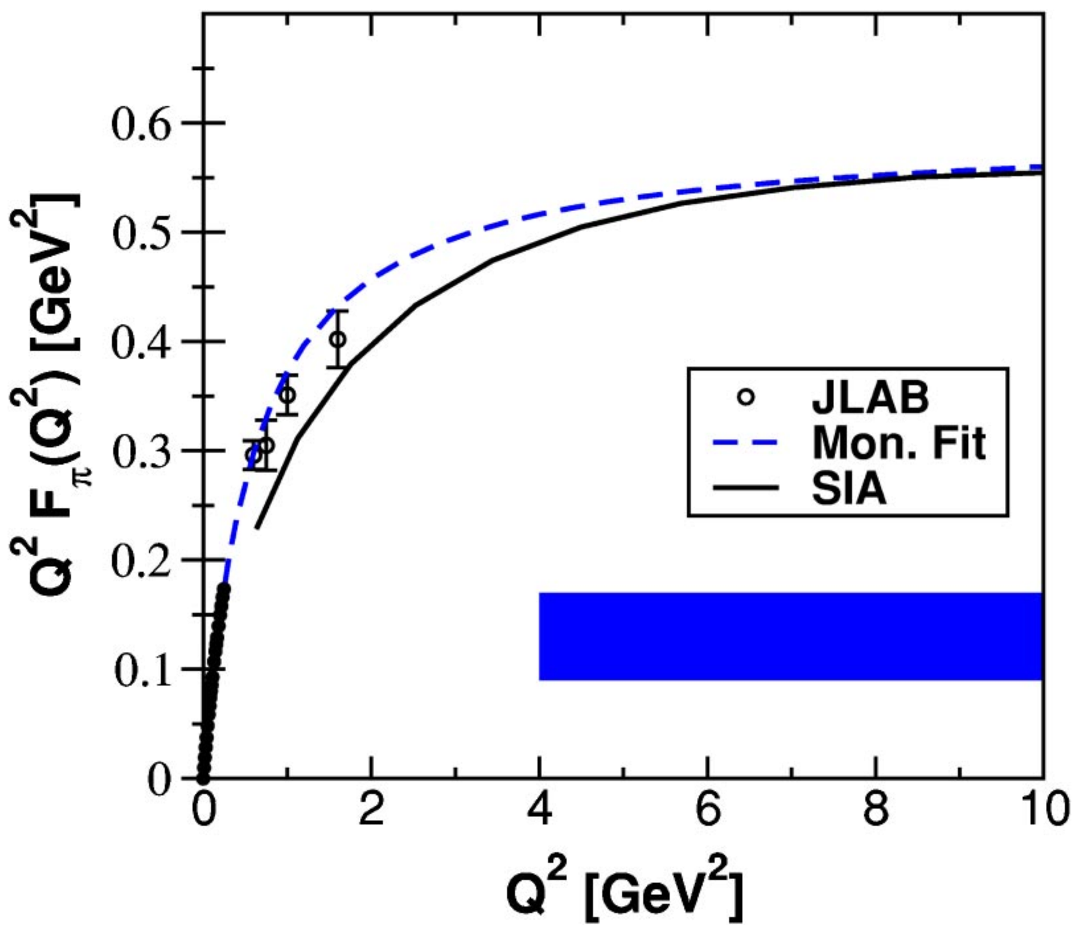
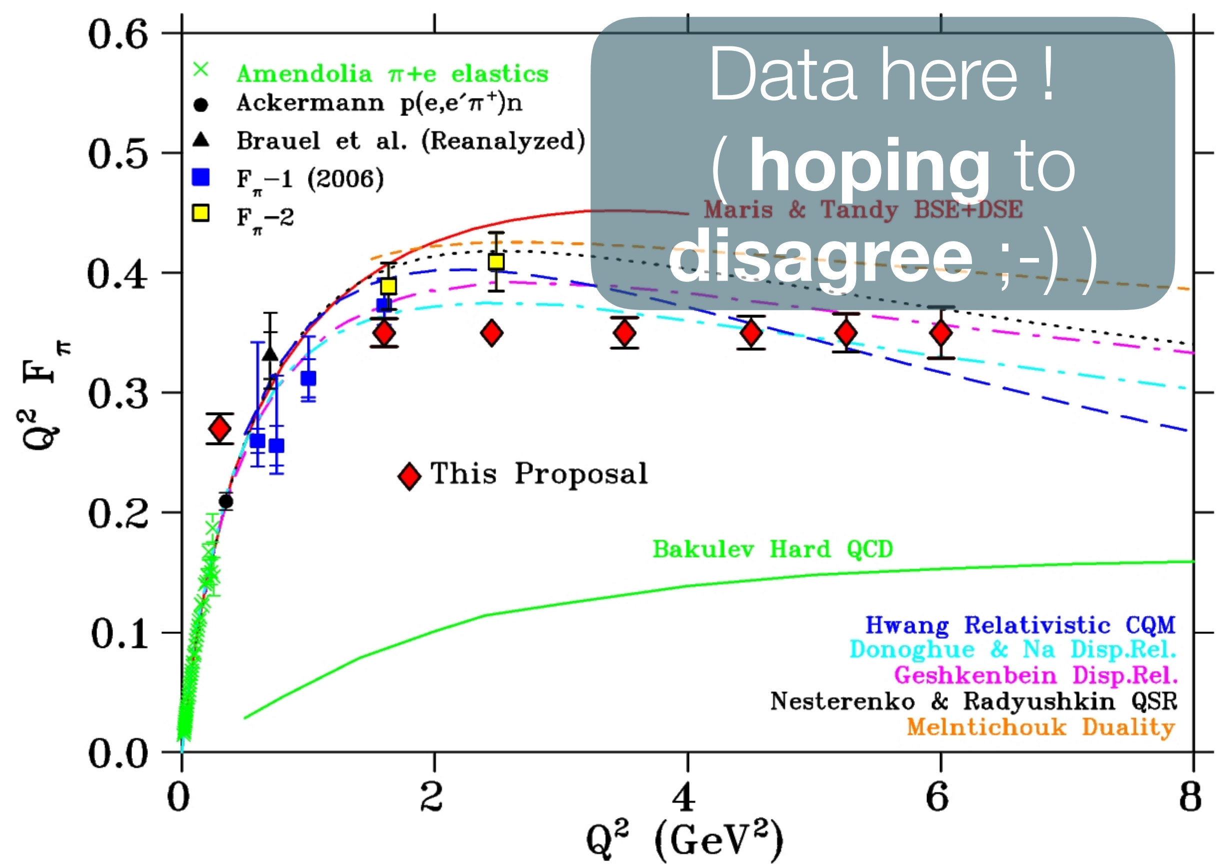
(Received 1 March 2002; published 26 June 2003)

* Picture: localized fluctuations of size 0.3 fm explain short range non perturbative forces at the ~1 GeV scale -> Delay of the onset of pert. theory

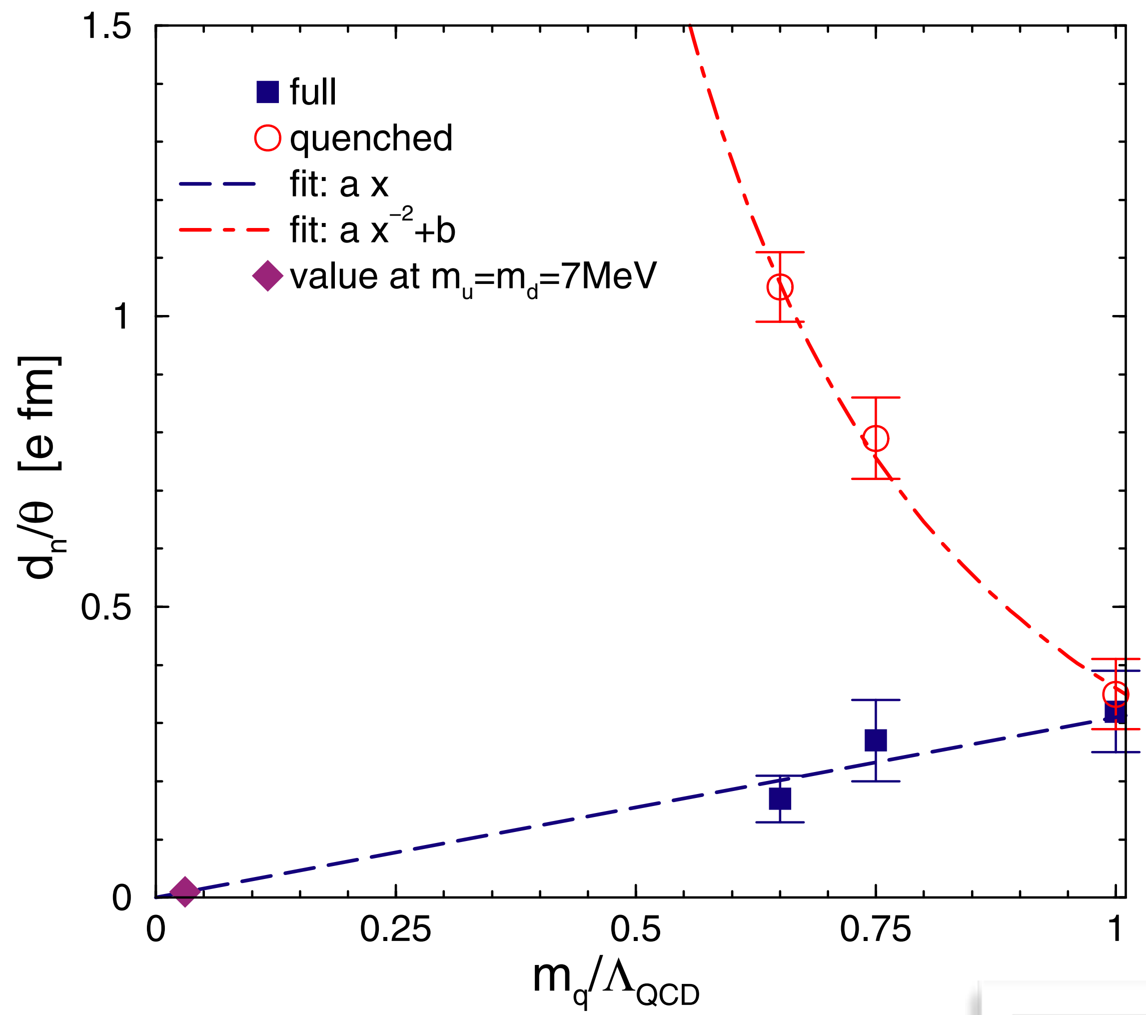




It also qualitatively explains the earlier on-set of pert. regime in $\gamma\gamma^* \to \pi_0$ form factror.

CASE 2: Compute observables which are not accessible to exact calculations

* Electric dipole momento of the neutron.



PHYSICAL REVIEW D, VOLUME 70, 074017

Neutron electric dipole moment in the instanton vacuum: Quenched versus unquenched simulations

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[2]Dipartimento di Fisica, Università di Roma "La Sapienza", and INFN, Sezione di Roma, P.le A. Moro 2, I-00185 Rome, Italy
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(Received 7 July 2004; published 14 October 2004)

CASE 3: Learn from failures

Chiral physics and confinement

These results would seem to imply that the chiral properties of the QCD vacuum are at most *weakly entangled* with color confinement

Puzzle: however, the de-confinement and chiral restoration phase transition occur at (almost?) the same temperature. Some *strong entanglement* must there!

Discovery of instanton monopoles (Kraan-van-Baal-Lee-Lu calorons)

PHYSICAL REVIEW D **87,** 074009 (2013)

QCD topology at finite temperature: Statistical mechanics of self-dual dyons

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(Received 27 January 2013; published 9 April 2013)

PHYSICAL REVIEW D **92,** 094022 (2015)

Interacting ensemble of the instanton-dyons and the deconfinement phase transition in the SU(2) gauge theory

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(Received 4 September 2015; published 19 November 2015)

Conclusions and models

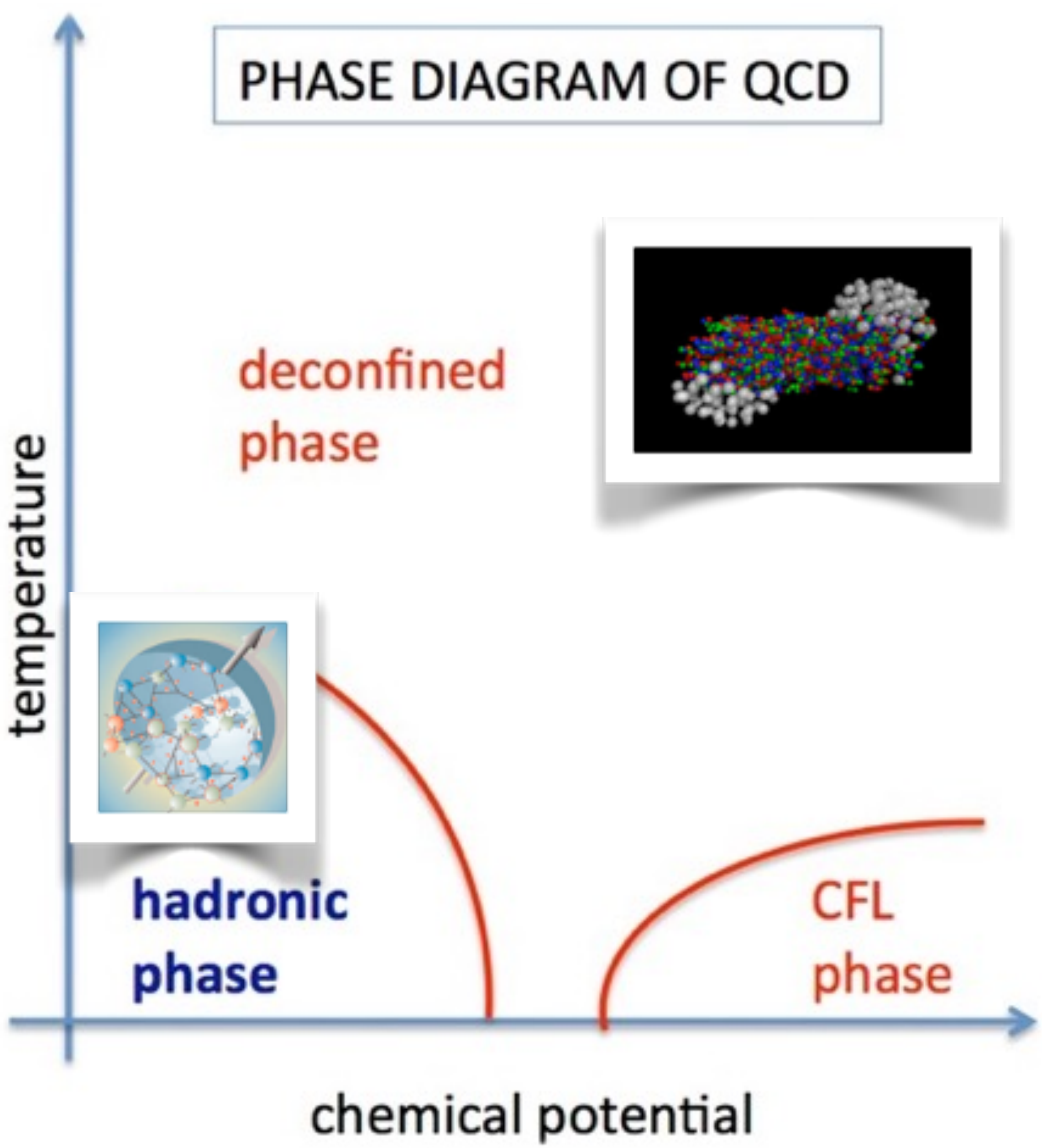
The wave function of light hadrons is strongly influenced by topology and chiral symmetry breaking

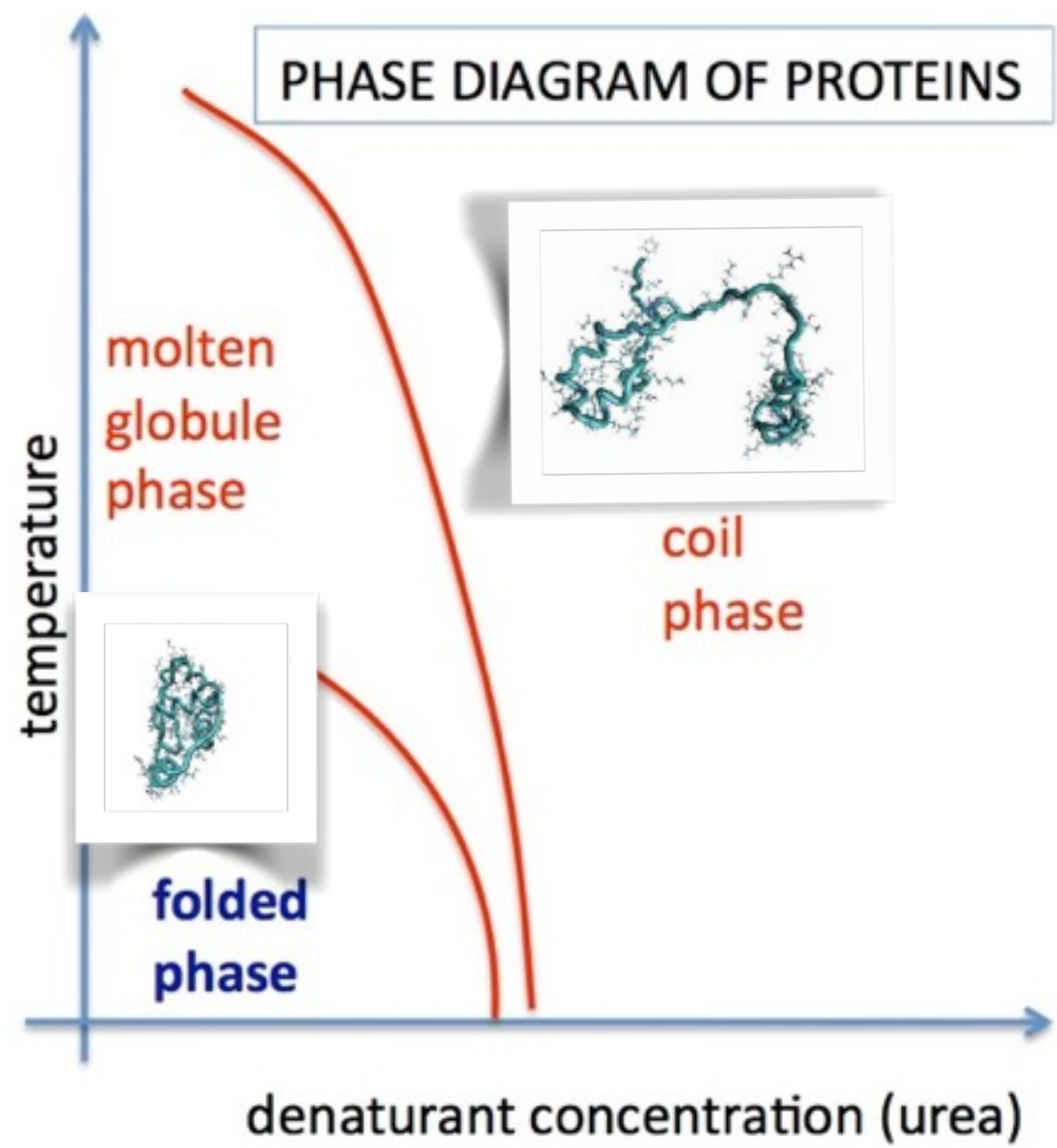
To a point that global phenomenology of pions and nucleon is well reproduced even in a theory which ignores confinement

…but we know confinement is there…Fundamental ingredients are missing and are needed to understand the QCD phase transition and the heavy hadron sector.

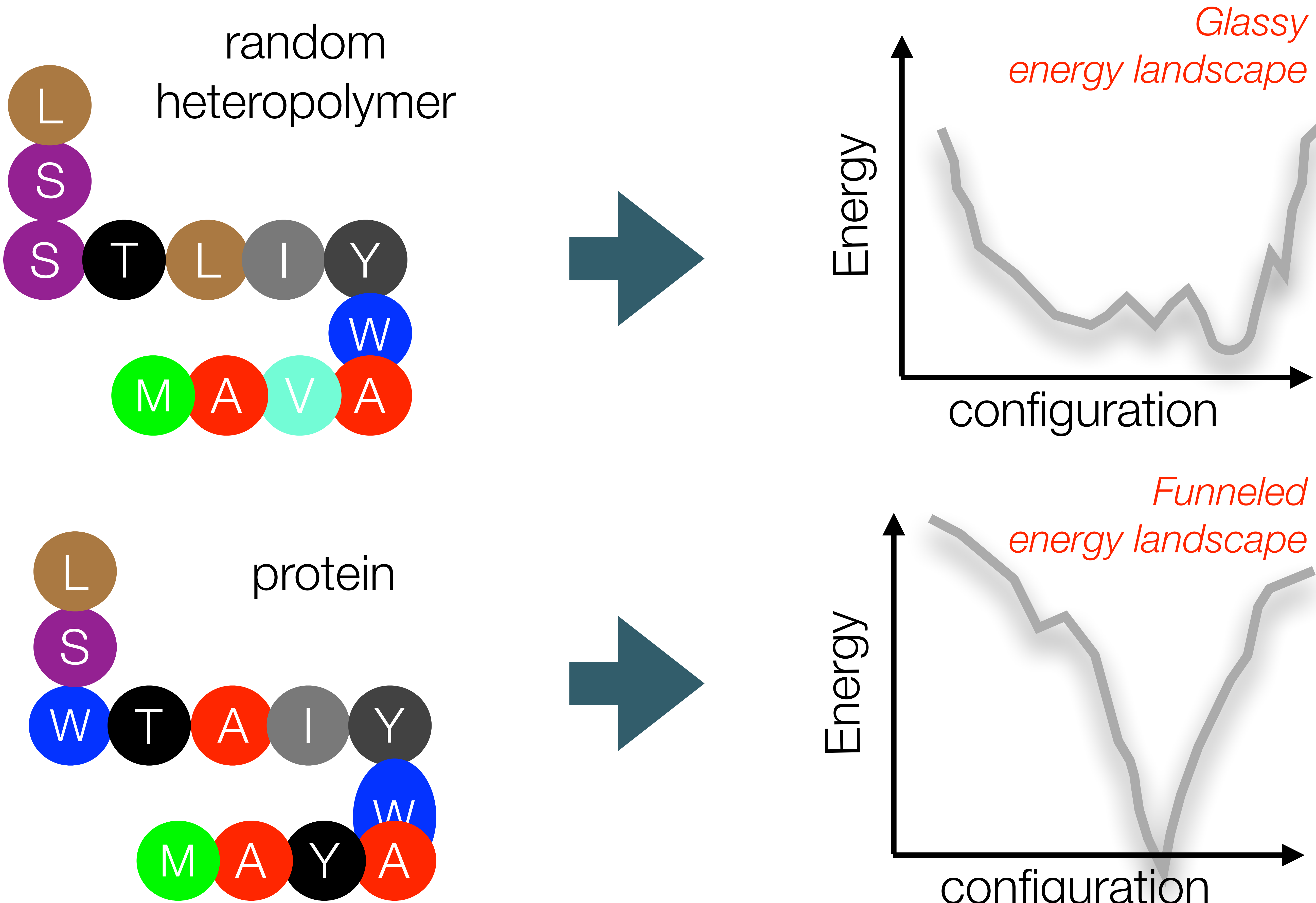
The discovery of instanton dyons open an interesting perspective to unify the monopole picture with the instanton picture.

Prologue: a suggestive analogy

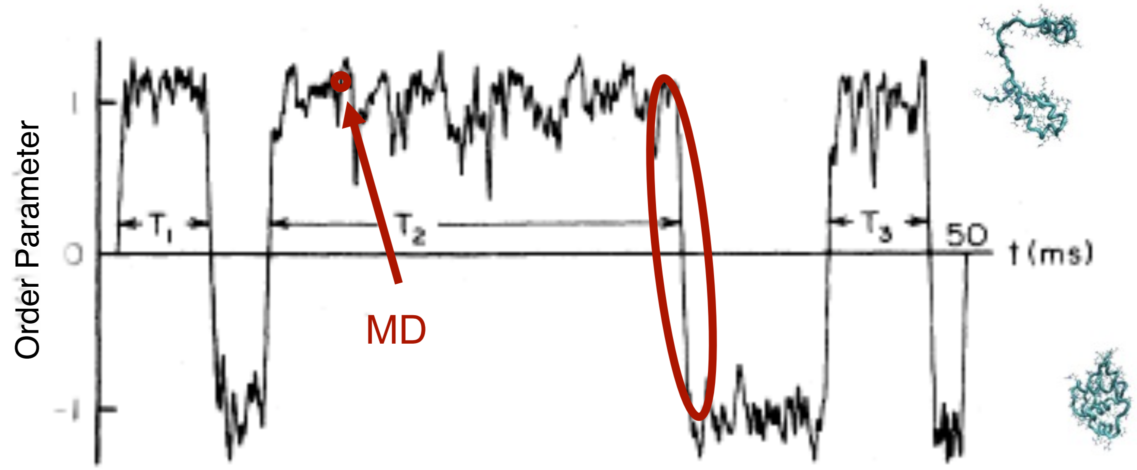




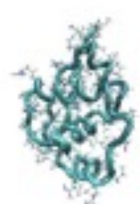
ONLY EXTREMELY SPECIFIC COMBINATION OF AMINOACID LEAD TO A UNIQUE NATIVE STATE:

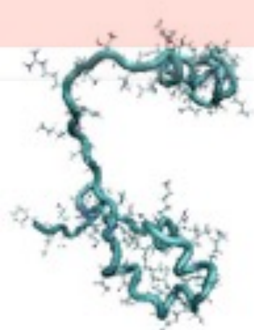


Instanton Theory of Protein folding



$$P(Q_f, t|Q_i) \quad = \quad \int_{Q_i}^{Q_f} \mathcal{D}R \; e^{-\frac{\beta}{4M\gamma}\int_0^t d\tau \left(M\ddot{R} - M\gamma\dot{R} + \nabla U(R)\right)^2}$$

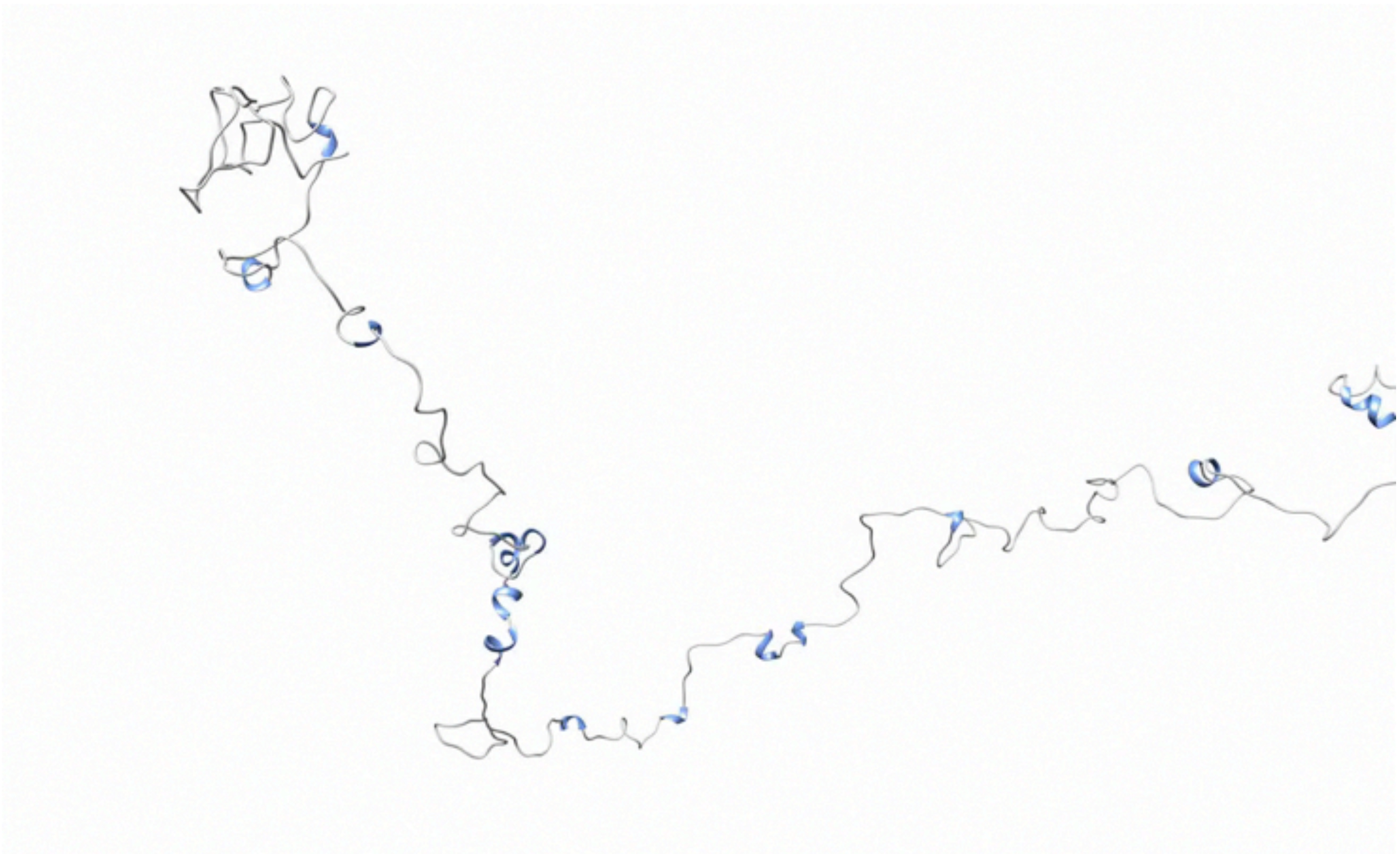




$$\rho_{Q_0,Q_0}(0) = |Q_0\rangle\langle Q_0|$$

Develop variational approximations for this path integral

Protein folding instanton



With electronic excitations:
MOLECULAR QUANTUM FIELD THEORY:

$$\rho \propto \int_{Q_i}^{Q_f} \mathcal{D}R \int \mathcal{D}\bar{\psi}\mathcal{D}\psi \; e^{iS_0[\bar{\psi},\psi]} \times e^{-S_{OM}[R]} \times e^{iI[R,\bar{\psi},\psi]}$$

$\langle k_i|\hat{\rho}(t)|k_i\rangle$ $\hat{\rho}(0) = |k_0\rangle\langle k_0|$

$$\times \bar{\psi}_i(t)\gamma_-\gamma_5\psi_i(t) \times \bar{\psi}_{k_0}(0)\gamma_+\gamma_5\psi_{k_0}(0)$$

real time

irreversible dynamics

Electronic-vibronic coupling

Molecular Dynamics

$$S_{OM} = -\frac{\beta}{4M\gamma}\int_0^t d\tau \left[M\ddot{R} + M\gamma\dot{R} + \nabla_R V(R)\right]^2$$

$$I[R,\bar{\psi},\psi] = \text{"coupling of elect. excitations to molecular dynamics"}$$

analog to $(F_{\mu\nu})^2$

Tackling nuclear physics fundamental questions
(such as the origin on proton mass)
is useful beyond nuclear physics…