Emergent mass and the critical phenomena

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Nankai University

Emergent mass and its consequences in the Standard model,
2017/09/18, ECT*, Trento, Italy

Particle Data Group

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

g or gluon

$I(J^P) = 0(1^-)$

SU(3) color octet

Mass $m = 0$. Theoretical value. A mass as large as a few MeV may not be precluded, see YNDURAIN 95.

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	ABREU	92E	DLPH	Spin 1, not 0
	ALEXANDER	91H	OPAL	Spin 1, not 0
	BEHREND	82D	CELL	Spin 1, not 0
	BERGER	80D	PLUT	Spin 1, not 0
	BRANDELIK	80C	TASS	Spin 1, not 0

gluon REFERENCES

YNDURAIN	95	PL B345 524	F.J. Yndurain	(MADU)
ABREU	92E	PL B274 498	P. Abreu *et al.*	(DELPHI Collab.)
ALEXANDER	91H	ZPHY C52 543	G. Alexander *et al.*	(OPAL Collab.)
BEHREND	82D	PL B110 329	H.J. Behrend *et al.*	(CELLO Collab.)
BERGER	80D	PL B97 459	C. Berger *et al.*	(PLUTO Collab.)
BRANDELIK	80C	PL B97 453	R. Brandelik *et al.*	(TASSO Collab.)

In QCD: Gluons become massive!

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PHYSICAL REVIEW VOLUME 125, NUMBER 1 JANUARY 1, 1962

Gauge Invariance and Mass

JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts, and University of California, Los Angeles, California
(Received July 20, 1961)

It is argued that the gauge invariance of a vector field does not necessarily imply zero mass for an associated particle if the current vector coupling is sufficiently strong. This situation may permit a deeper understanding of nucleonic charge conservation as a manifestation of a gauge invariance, without the obvious conflict with experience that a massless particle entails.

- Schwinger 1962

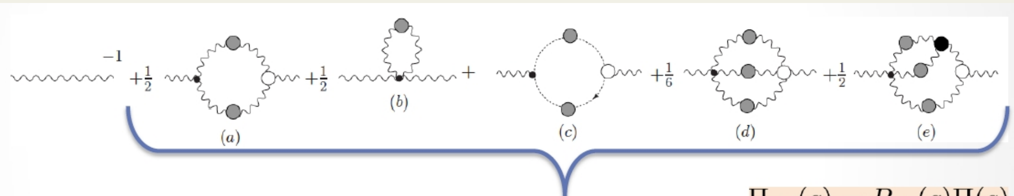
PHYSICAL REVIEW D VOLUME 26, NUMBER 6 15 SEPTEMBER 1982

Dynamical mass generation in continuum quantum chromodynamics

John M. Cornwall
Department of Physics, University of California, Los Angeles, California 90024
(Received 30 April 1982)

- Cornwall 1982

$$\Delta^{-1}_{\mu\nu}(q) =$$



$$\Pi_{\mu\nu}(q)$$

$$\Pi_{\mu\nu}(q) = P_{\mu\nu}(q)\Pi(q)$$

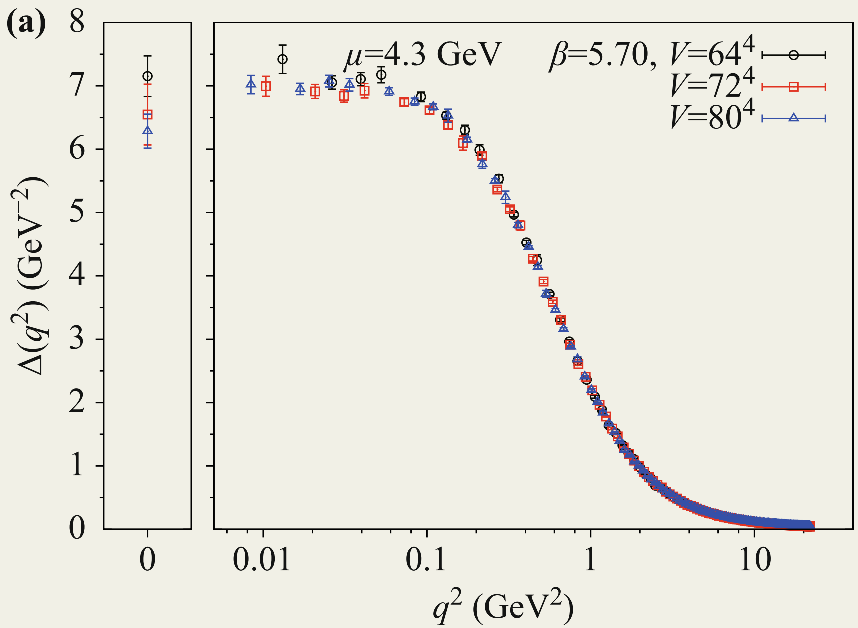
$$P_{\mu\nu}(q) = g_{\mu\nu} - q_\mu q_\nu / q^2$$

- Binosi & Papavassiliou

Phys. Rept. 479 (2009)1-152
Pinch Technique: Theory and Applications

On the Lattice

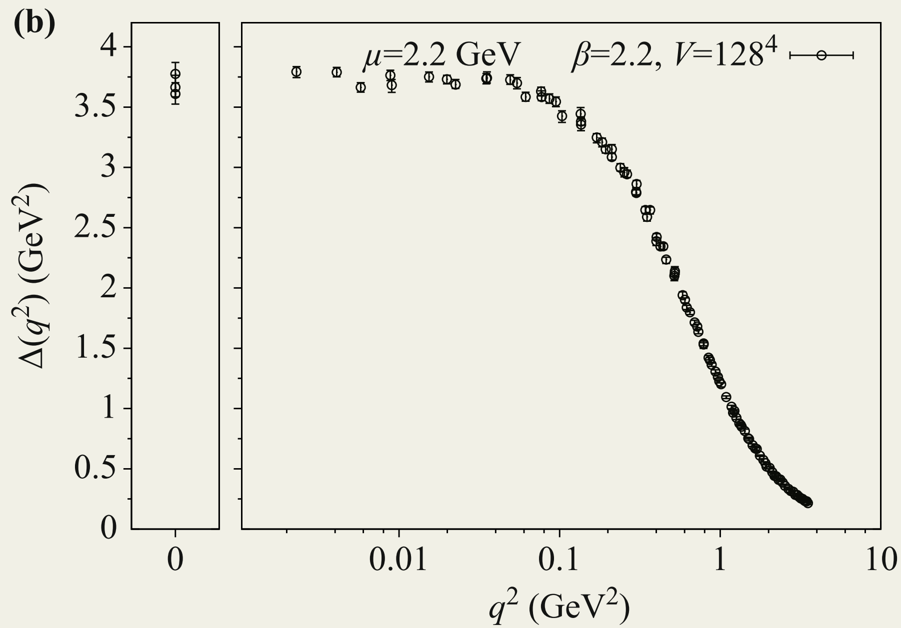
a) SU(3)



I. L. Bogolubsky, E. M. Ilgenfritz, M. Muller-Preussker, and A. Sternbeck, Lattice gluodynamics computation of Landau gauge Green's functions in the deep infrared, *Phys. Lett. B* 676, 69 (2009), arXiv: 0901.0736 [hep-lat]

I. L. Bogolubsky, E. M. Ilgenfritz, M. Muller-Preussker, and A. Sternbeck, The Landau gauge gluon and ghost propagators in 4D SU(3) gluodynamics in large lattice volumes, arXiv: 0710.1968 [hep-lat]

b)SU(2)



A. Cucchieri and T. Mendes, Numerical test of the Gribov–Zwanziger scenario in Landau gauge, *PoS QCD-TNT* 09, 026 (2009), arXiv: 1001.2584 [hep-lat]

Gluon Propagator

Spectral representation

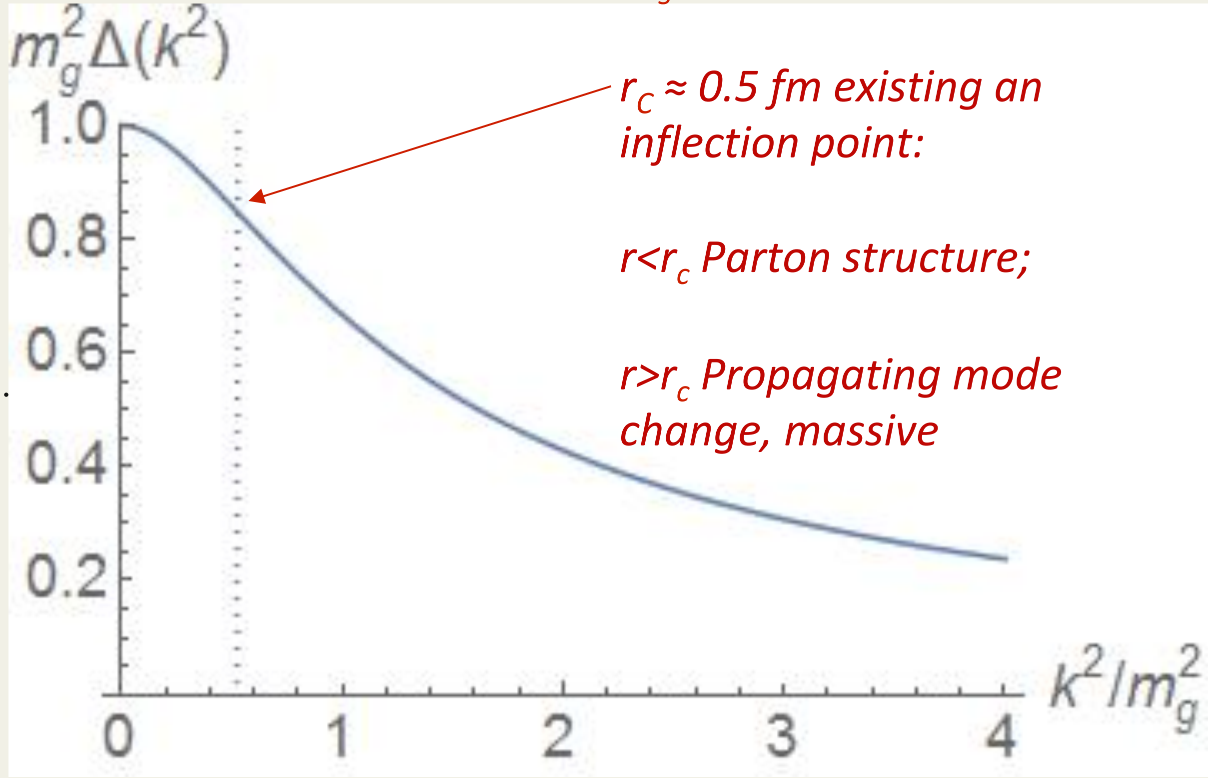
$$\Delta(q^2) = \int_0^\infty \mathrm{d}\sigma \frac{\rho(\sigma)}{q^2+\sigma},$$

if

$$\Delta''(q_\star^2) = 2\int_0^\infty \mathrm{d}\sigma \frac{\rho(\sigma)}{(q_\star^2+\sigma)^3} = 0.$$

Non positive definite

$m_g \approx 0.5$ GeV

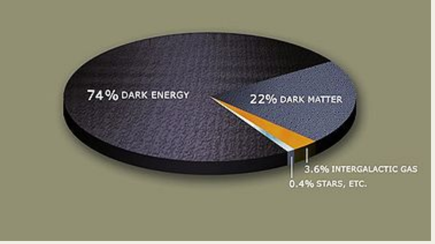


$r_C \approx 0.5$ fm existing an inflection point:

$r<r_c$ Parton structure;

$r>r_c$ Propagating mode change, massive

胶子=汉尼拔



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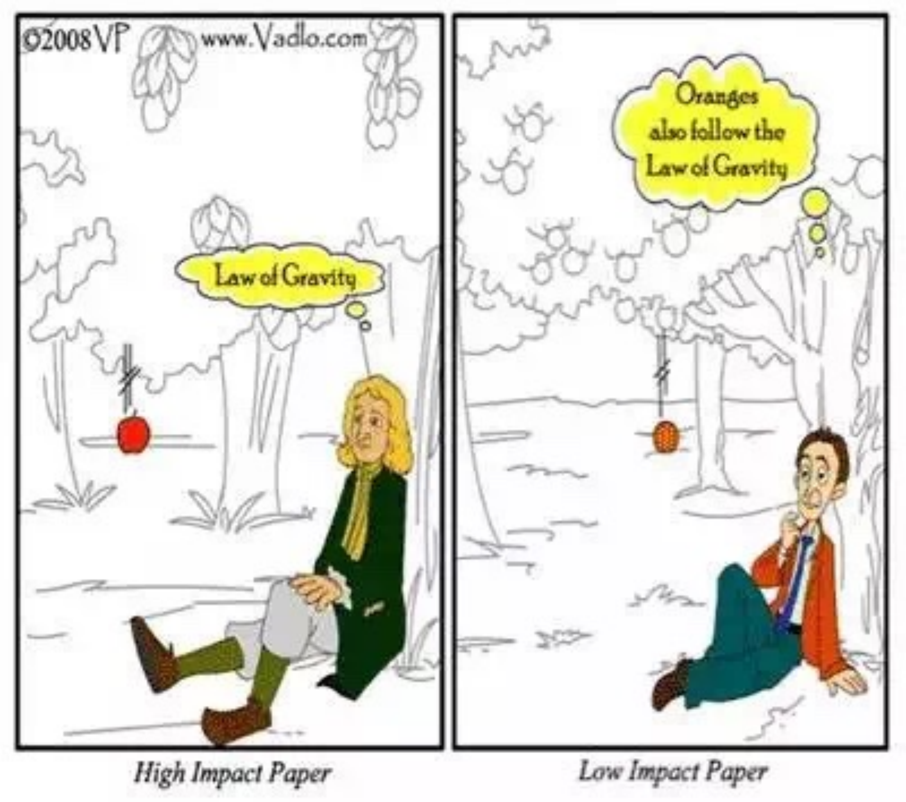
- ……
- Can we quantitatively understand quark and gluon confinement in quantum chromodynamics and the existence of a mass gap?

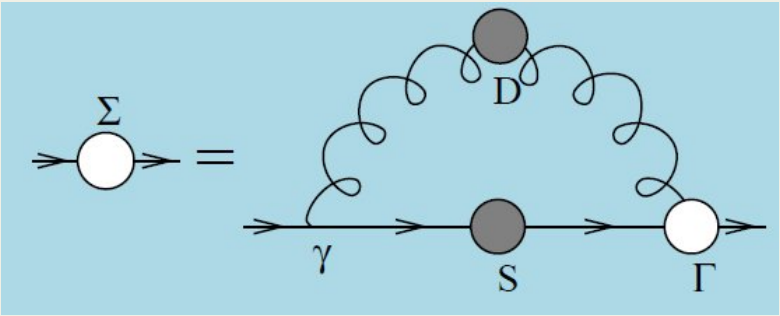
Quantum chromodynamics, or QCD, is the theory describing the strong nuclear force. Carried by gluons, it binds quarks into particles like protons and neutrons. Apparently, the tiny subparticles are permanently confined: one can't pull a quark or a gluon from a proton because the strong force gets stronger with distance and snaps them right back inside.

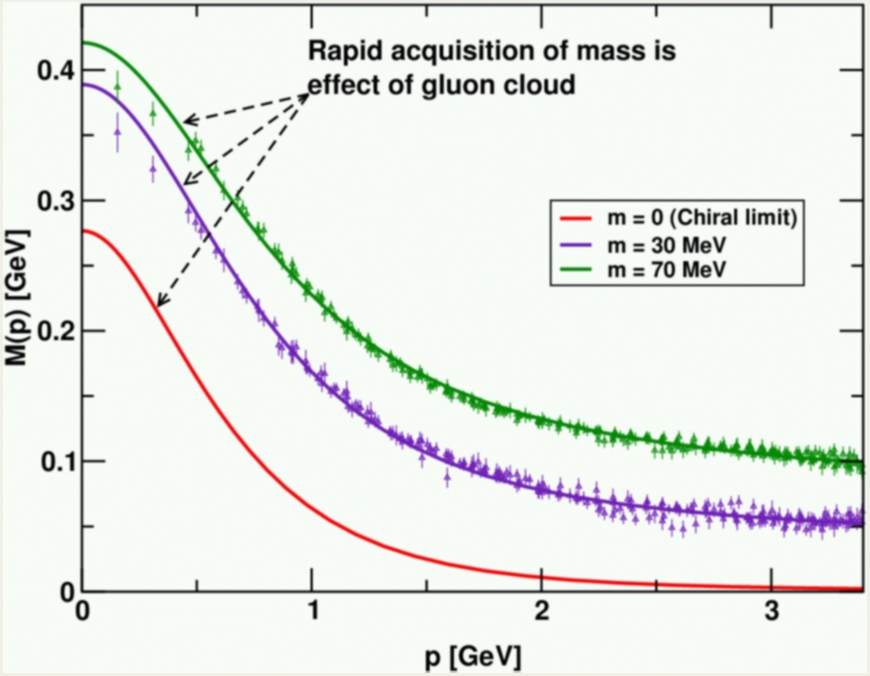


Dynamical Chiral Symmetry Breaking

南開大學 Nankai University

- Is a crucial emergent phenomenon in QCD
- Expressed in hadron wave functions not in vacuum condensates
- Contemporary theory indicates that it is responsible for more than 98% of the visible mass in the Universe; namely, given that classical massless-QCD is a conformally invariant theory, then DCSB is the origin of *mass from nothing*.





- ***Dynamical***, not spontaneous
  - Add nothing to QCD ,
    No Higgs field, nothing!
    Effect achieved purely through quark+gluon dynamics.

Quark, das ist alles Quark！（夸克［胡扯］，全是夸克［胡扯］！）

Nankai University 南開大學

Maris, Roberts and Tandy, Phys. Lett. **B420**(1998) 267-273

- Pion's Bethe-Salpeter amplitude

  Solution of the Bethe-Salpeter equation

$$\Gamma_{\pi^j}(k;P) = \tau^{\pi^j}\gamma_5\Big[iE_\pi(k;P)+\gamma\cdot P F_\pi(k;P) + \gamma\cdot k\, k\cdot P\, G_\pi(k;P)+\sigma_{\mu\nu}\,k_\mu P_\nu\, H_\pi(k;P)\Big]$$

- Dressed-quark propagator $S(p)=\dfrac{1}{i\gamma\cdot p\,A(p^2)+B(p^2)}$

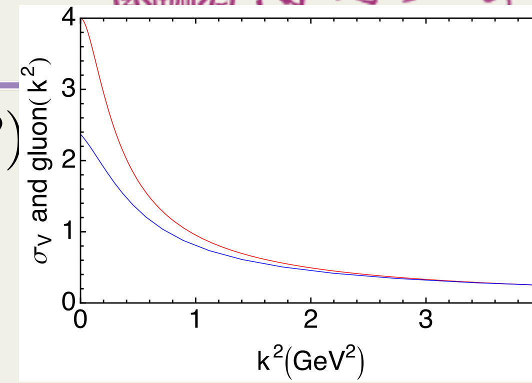
- Axial-vector Ward-Takahashi identity entails(chiral limit)

$$f_\pi E(k;P|P^2=0) = B(k^2)+(k\cdot P)^2\frac{d^2B(k^2)}{d^2k^2}+\dots$$

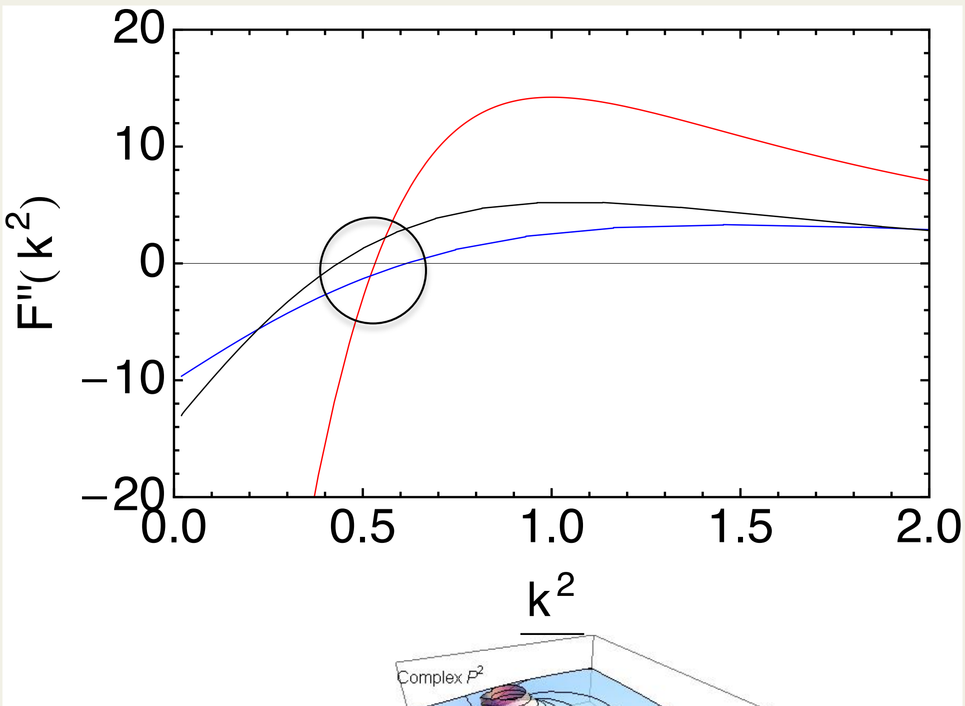
- Given the dichotomy of pion the fine-tuning should not play any role in an explanation of pion properties;
- Descriptions of pion within frameworks that cannot faithfully express symmetries and their breaking patterns(such as constituent-quark models) are unreliable;
- Hence, pion properties are an almost direct measure of the dressed-quark mass function.

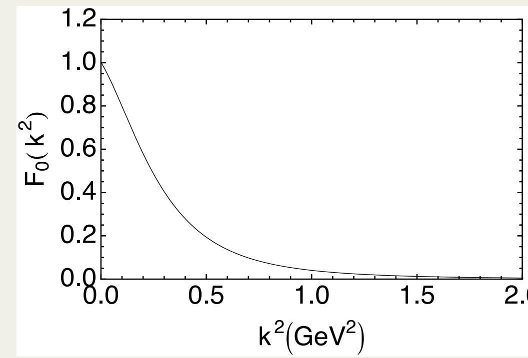
Properties of Pion BS Wave Function

$$\chi_\pi(k;P) = \gamma_5\left(iE(k;P) + \gamma\cdot PF(k;P) + \gamma\cdot kG(k;P)\right)$$

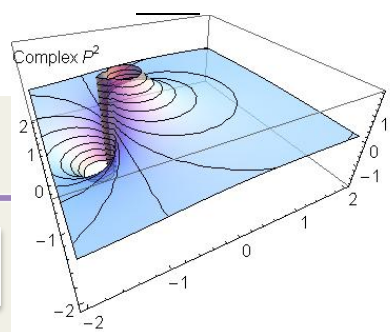


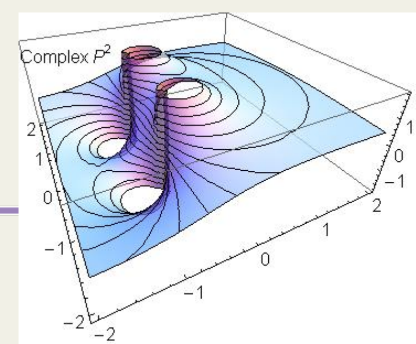
- Infrared Behaviors





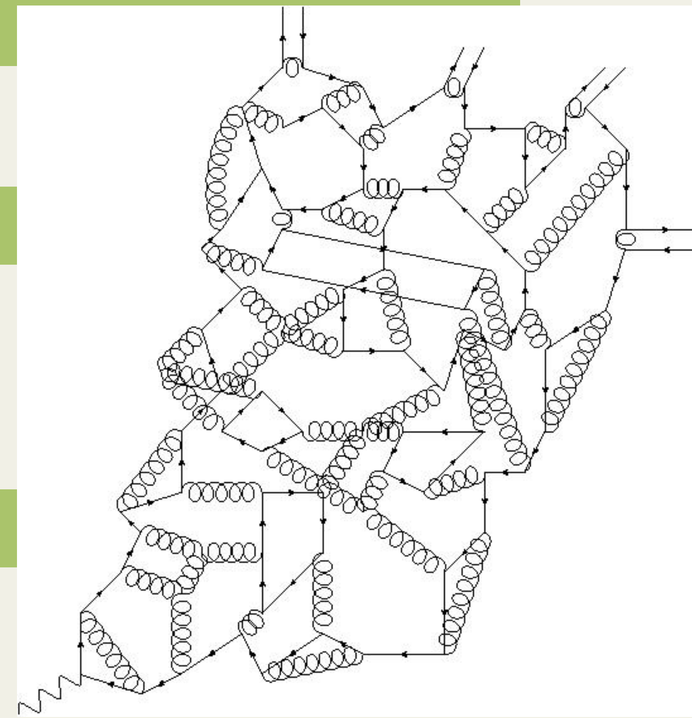
- Inflection points
- Black line: F function
- Red line: running gluon propagagor
- Blue line: vector part of propagator



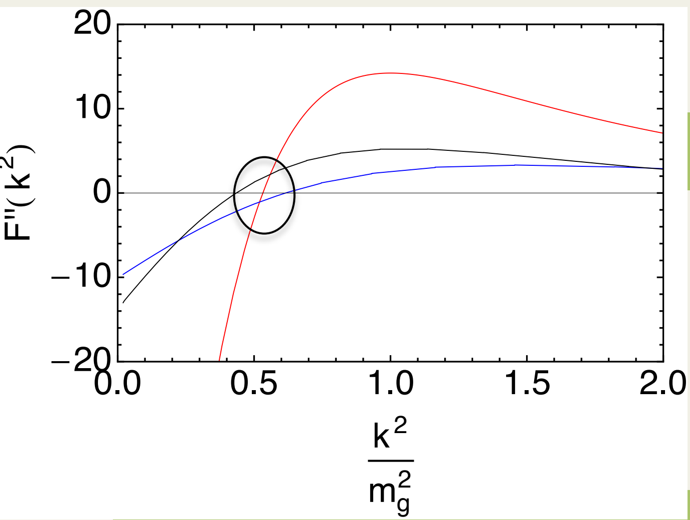


Gluon mass scale--->Quark--->LFWFs

$m_g \approx 0.5\ GeV$: A dynamical mass scale generation

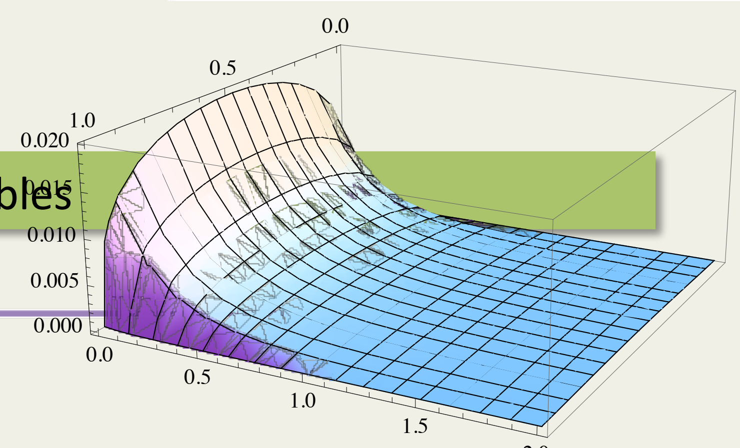


$l_C \approx 0.5$: *maxium wavelength*



Quark and Hadron

LFWFs and obervables



Transition from Dynamical Chiral Symmetry Breaking to Explicit Chiral Symmetry Breaking

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

- Current quark mass, Higgs boson coupling;
- m=0, chiral limit, physics controlled by the emergent phenomena: confinement and DCSB;
- The chiral symmetry is broken explicitly if the coupling of Higgs boson increasing;

- Question: could we describe the transition erea and does it has the any relation with gluon mass m_g?

Transition from Dynamical Chiral Symmetry Breaking to Explicit Chiral Symmetry Breaking

Nankai University 南開大學

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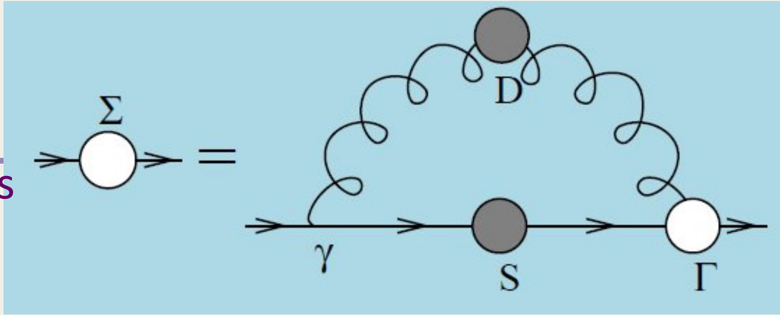
Three examples:

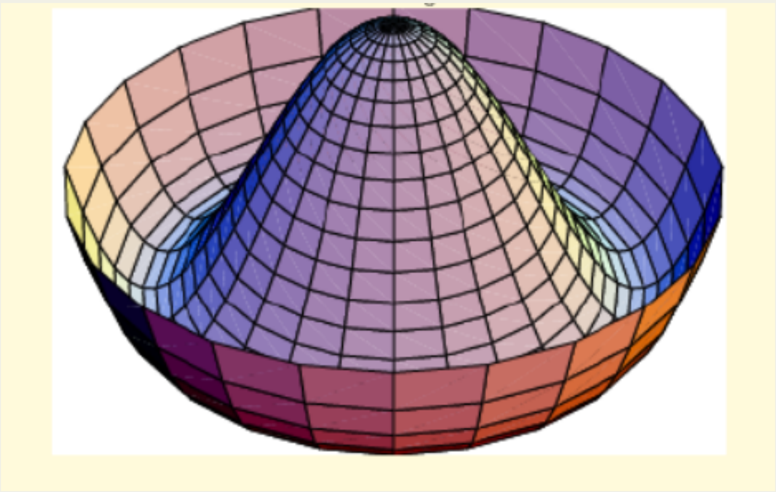
- Multisolution of gap equation and the critical mass;
- The mass dependence of parton distribution amplitudes of pseudoscalar mesons
- Observables

Example-I

Multi-solutions of quark Gap equation and a critical mass



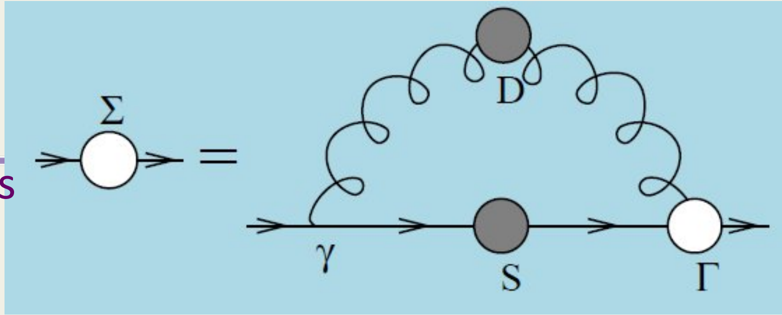
CJT effective potential



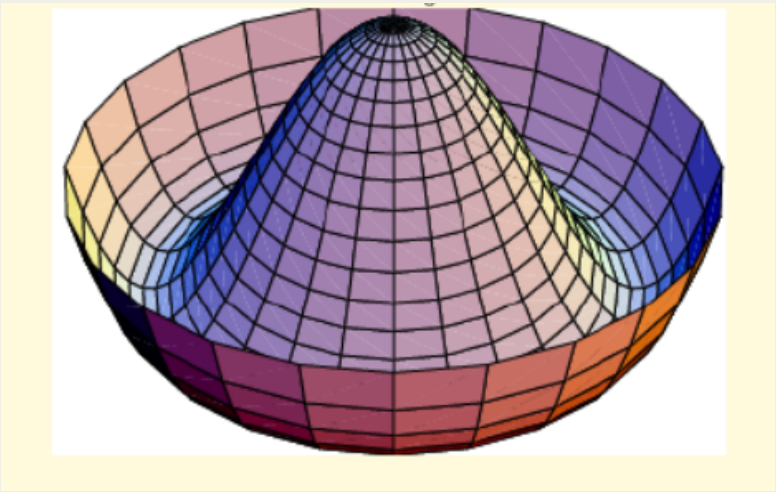
In chiral limit

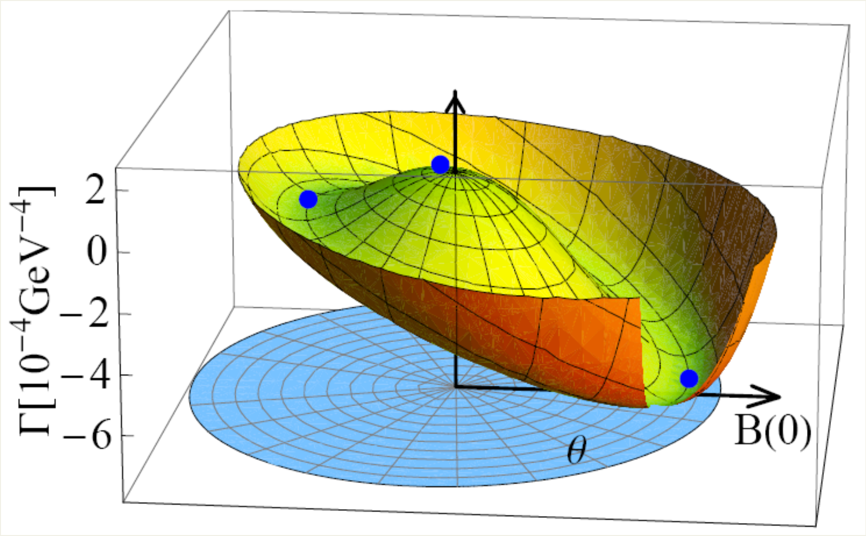
Example-I

Multi-solutions of quark Gap equation and a critical mass



CJT effective potential



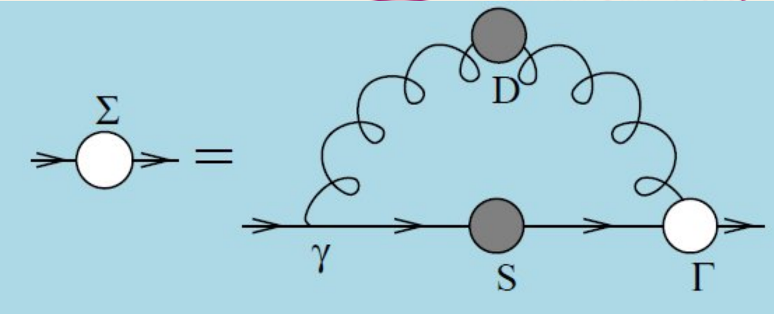


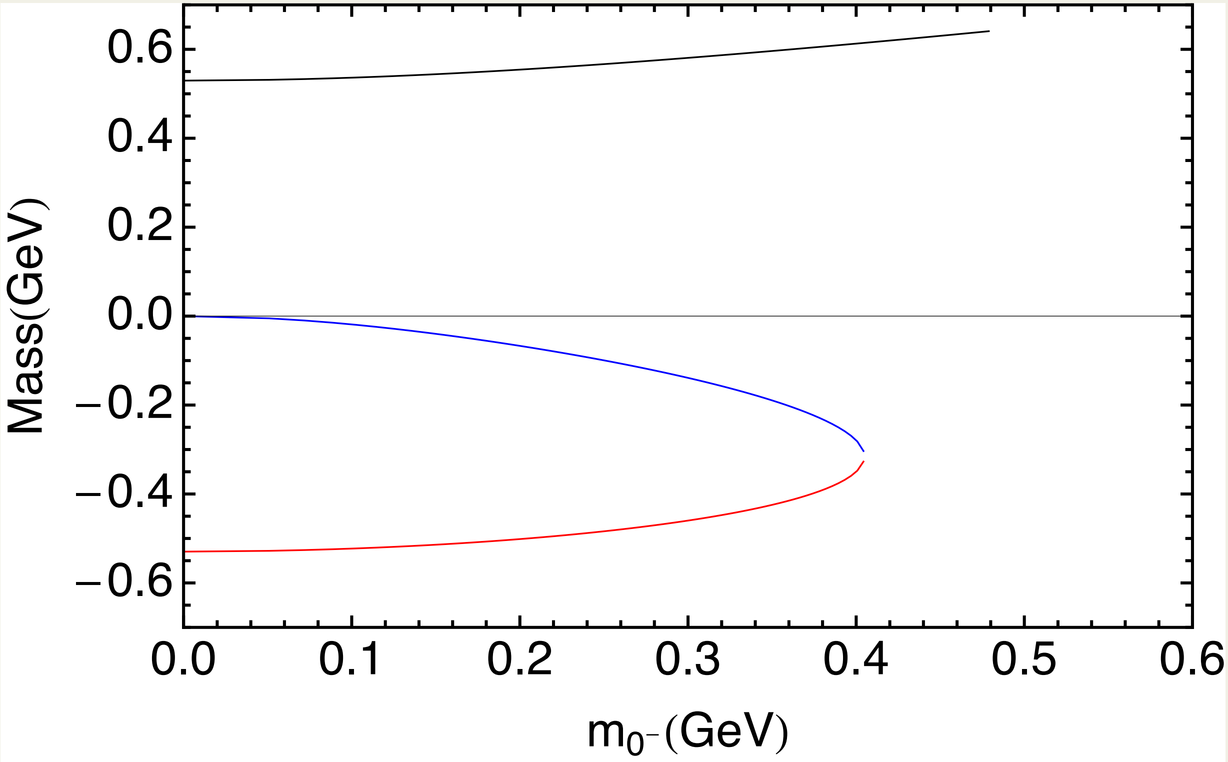
In chiral limit

Beyond chiral limit

Critical mass

Dynamical chiral symmetry breaking and a critical mass
Lei Chang, *et.al*, PRC 75 (2007) 015201





- Critical current quark mass, the related pseudoscalar meson mass is around~0.4GeV;
- Belowed the critical mass there are three diffferent quark propagators
- Analytical convergence radius, without considerring log or fraction power

Example-II

Mass dependence of pseudoscalar meson's parton distribution amplitudes

Consider(without gauge link…)

$$\langle 0|\psi(-x)\gamma_5\gamma_\mu\psi(x)|\pi(q)\rangle$$
$$= f_\pi \int_0^1 du\, \mathrm{e}^{-i(2u-1)x\cdot q}\left(\check{q}_\mu\left[\phi_\pi^{(2)}(u) + \frac{1}{4}x^2\phi_\pi^{(4)}(u) + \mathrm{O}(x^4)\right] + \frac{1}{2}\frac{x_\mu}{x\cdot q}\psi_\pi^{(4)}(u)\right),$$

Equally

$$\langle 0|\psi(-x)\gamma_5\gamma_\mu\psi(x)|\pi(q)\rangle = Z_2\mathrm{tr}_{\mathrm{CD}}\int_{dk}^{\Lambda}\mathrm{e}^{-ix\cdot k - ix\cdot(k-q)}\gamma_5\gamma_\mu S(k)\Gamma_\pi(k;q)S(k-q)\,,$$

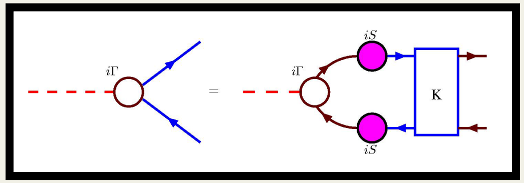
Definition for the twist-2

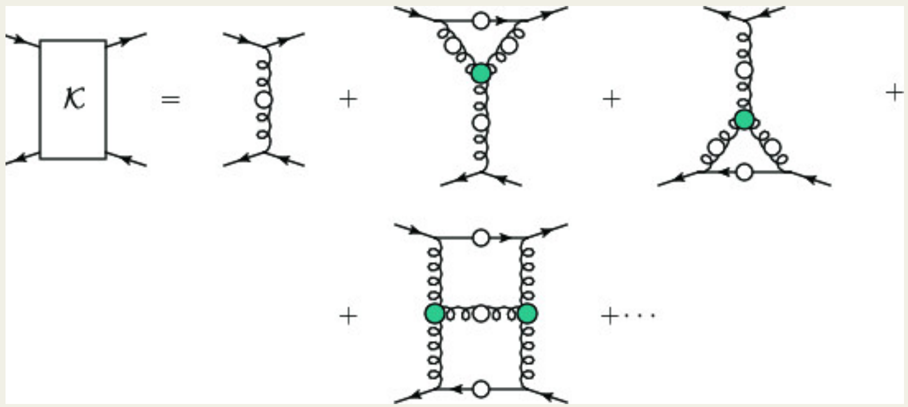
$$f_\pi\phi_\pi^{(2)}(u) = Z_2\mathrm{tr}_{\mathrm{CD}}\int_{dk}^{\Lambda}\delta(u\,n\cdot q - n\cdot k)\gamma_5\gamma\cdot n\,S(k)\Gamma_\pi(k;q)S(k-q)\,,$$

- PDAs depends on the BS wave function…model calculation.
- Fix renormalization scale μ=2GeV
- Moments calculation
- Current quark mass dependence of PDA can be read from the corresponding BS wave function

Dyson-Schwinger Equation scope

Bethe-Salpeter Equations

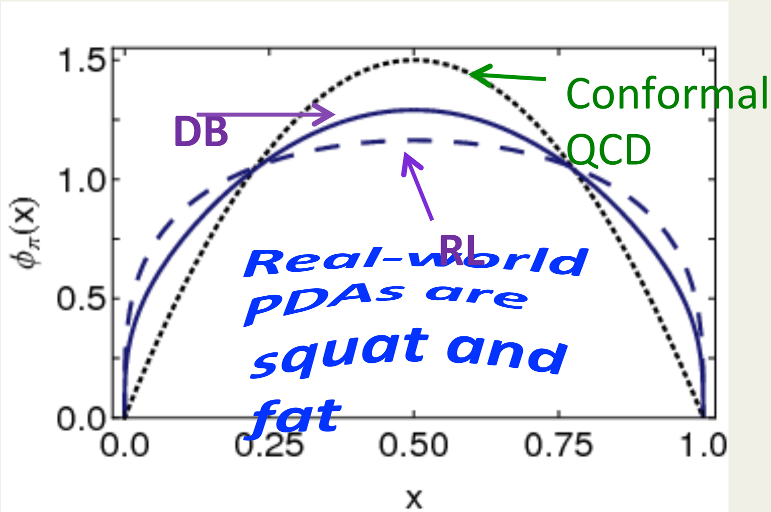


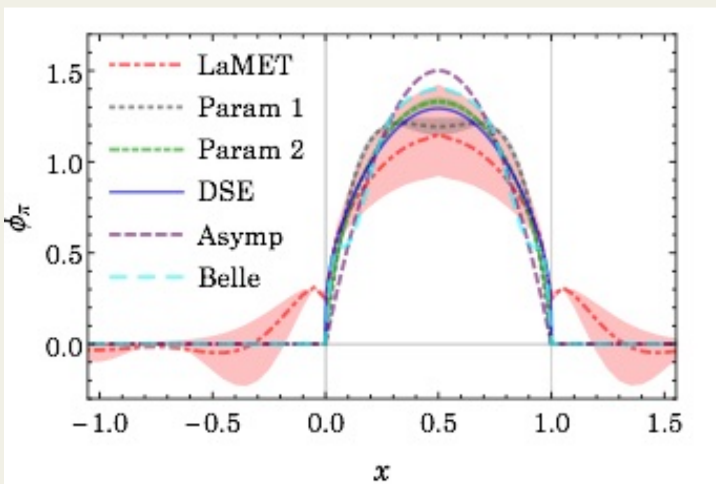


- Landau gauge
- Truncate kernel
- Fix renormalization point
- Modeling Interaction

GaoFei's talk

Pion PDA——dynamical chiral symmetry breaking





Pion Distribution Amplitude from Lattice QCD

Jian-Hui Zhang,[1,*] Jiunn-Wei Chen,[2,3,†] Xiangdong Ji,[4,5,‡] Luchang Jin,[6,§] and Huey-Wen Lin[7,8,¶]

- Continuum-QCD prediction: marked broadening of φ_π(x), which owes to DCSB
- Scale evolution quite slow

Imaging dynamical chiral symmetry breaking: pion wave function on the light front, Lei Chang, *et al.*, Phys. Rev. Lett. 110 (2013) 132001

- Lattice simulation: arxiv: 1702.00008(林慧雯)
- X-d Ji, large momentum effective theory

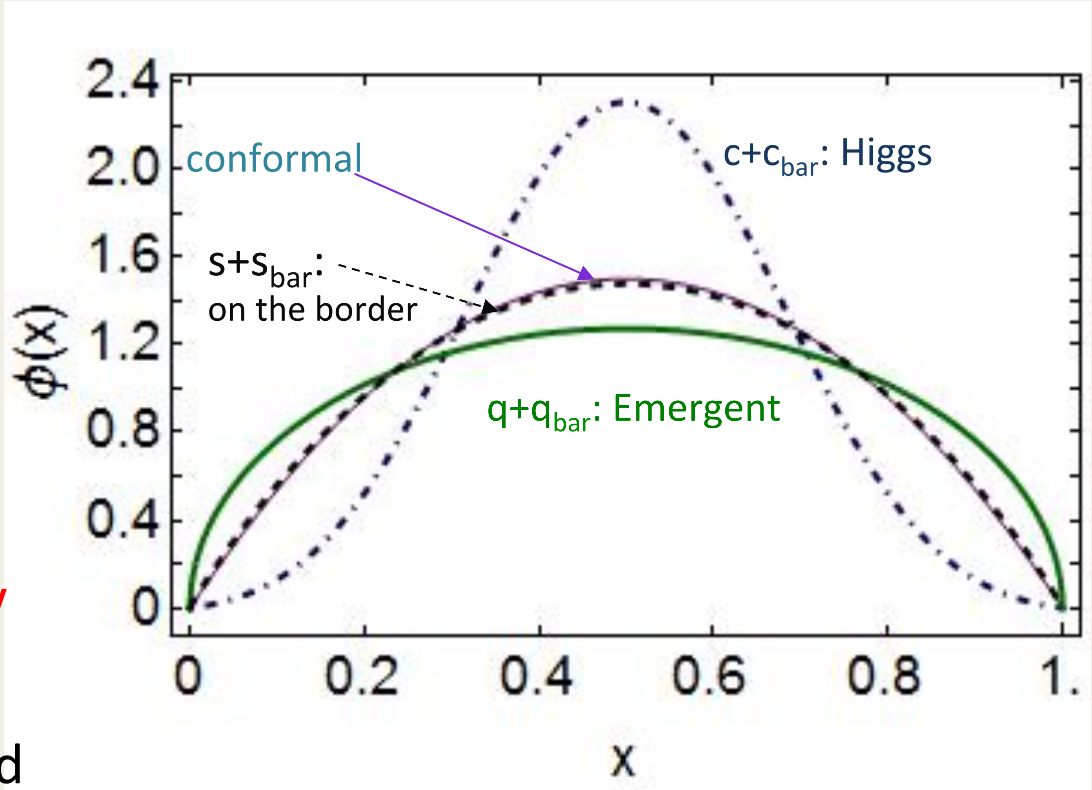
DSE & lQCD predictions are practically indistinguishable; Favor no-humped behavior

Emergent Mass *vs*. Higgs Mechanism

Parton distribution amplitudes of S-wave heavy-quarkonia
Minghui Ding, et al, Phys. Lett. B **753** (2016) pp. 330-335

- When does Higgs mechanism begin to influence mass generation?
- limit $m_{quark} \to \infty$
  $\varphi(x) \to \delta(x-½)$
- limit $m_{quark} \to 0$
  $\varphi(x) \sim (8/\pi)\,[x(1-x)]^{½}$
- Transition boundary lies just above $m_{strange}$, the related ps meson mass is around 700MeV
- Comparison between distributions of light-quarks and those involving strange-quarks is obvious place to find signals for strong-mass generation

μ=2GeV

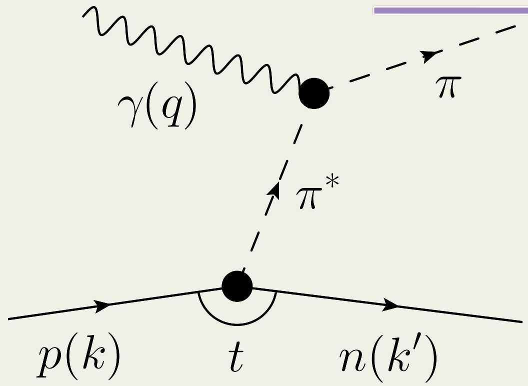


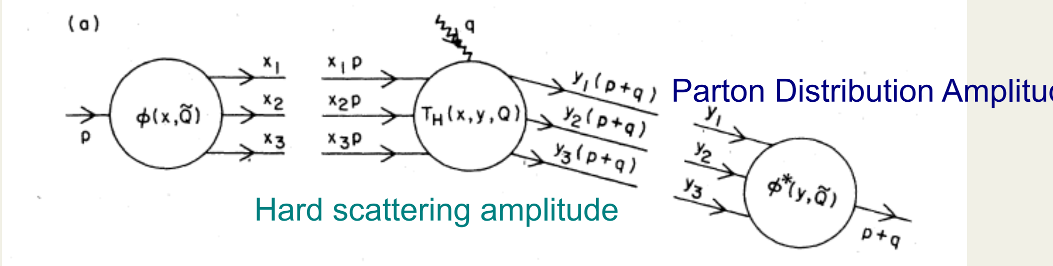
Example-III

Mass dependence of electromagnetic form factors

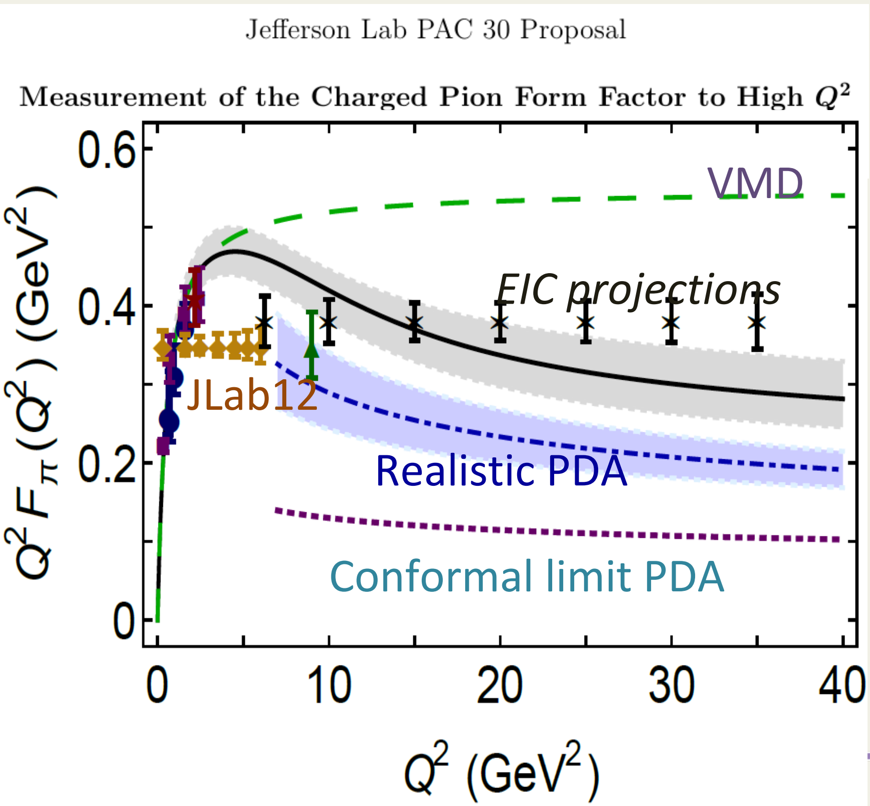
Muyang Chen's talk, Friday

Measure pion elastic form factor in space-like region





(G.R. Farrar and D.R.Jackson, PRL43 (1979) 246;
P. Lepage and S. Brodsky, PLB 87 (1979) 359)



$$Q^2 F_\pi(Q^2) \overset{Q^2 \gg \Lambda^2_{QCD}}{\sim} 16\,\pi\, f_\pi^2\, \alpha_s(Q^2)\, w_\pi^2; \qquad w_\pi = \frac{1}{3}\int_0^1 dx\, \frac{1}{x}\, \varphi_\pi(x)$$

Performing asymptotic valence-quark distribution amplitude 6x(1-x)

$Q^2F=0.15$ at $Q^2=4GeV^2$

A factor 2.7 smaller than the empirical value $0.41GeV^2$ quoted at $Q^2=2.45GeV^2$

A factor 3 smaller than the case of BSE

From C. Roberts

Messure π_0-γ transition form factor in space like region

☆ Ultraviolet scale---pion gamma transition form factor at lowest-order pQCD and leading twist 2

$$Q^2F(Q^2) = 2f_\pi \frac{1}{3}\int_0^1 \frac{\varphi_\pi^{(2)}(x)}{1-x}$$

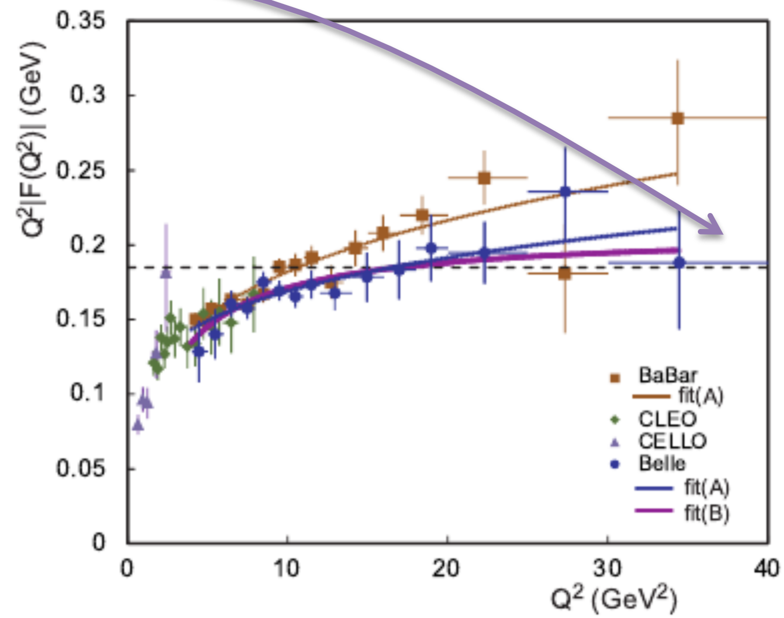


FIG. 24: Comparison of the results for the product $Q^2|F(Q^2)|$ for the π^0 from different experiments. The error bars are a quadratic sum of statistical and systematic uncertainties. For the Belle and BaBar results, only a Q^2-dependent systematic-error component is included. The two curves denoted fit(A) use the BaBar parameterization while the curve denoted fit(B) uses Eq.(23) (see the text). The dashed line shows the asymptotic prediction from pQCD ($\sim$ 0.185 GeV).

See Khepani's talk(DSE approach)

f_{0^-} w_{0^-}

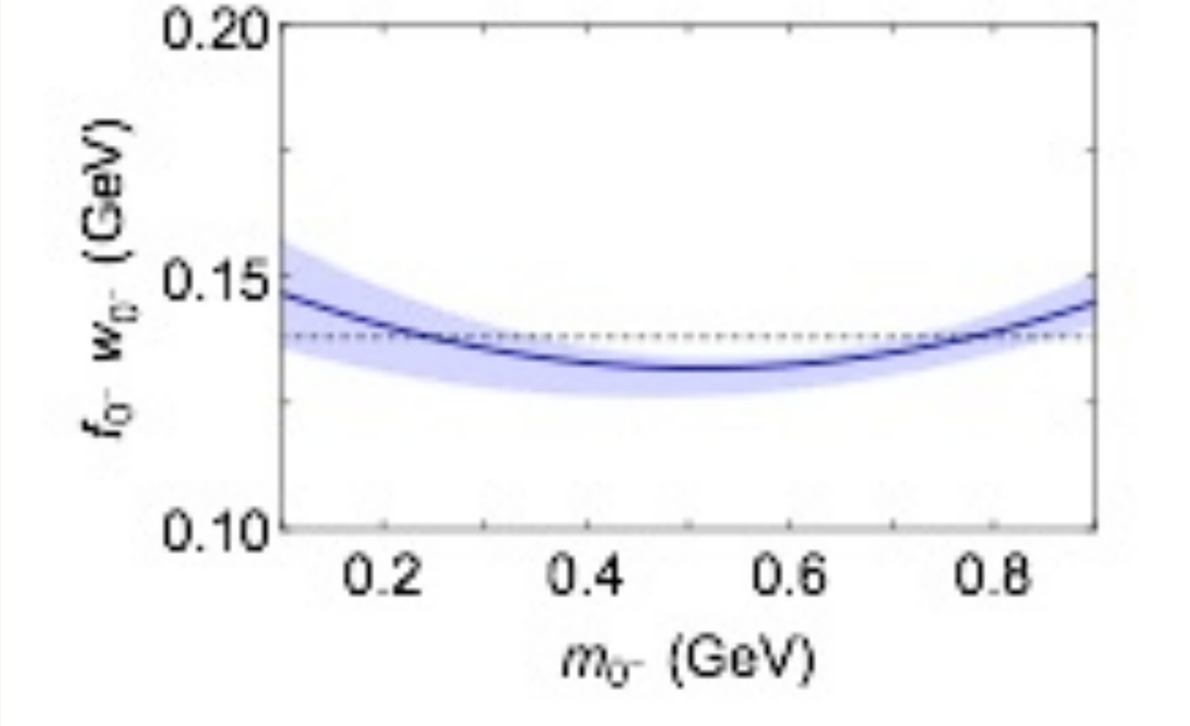
$$f_{0^-}\varphi(x) = Z_2 \mathrm{tr}_{CD} \int_{dk} \delta(n\cdot k - x n\cdot P)\gamma_5\gamma\cdot n S(k)\Gamma_{0^-}(k, k-P)S(k-P)$$

$$w_{0^-} = \int_0^1 dx \frac{\varphi(x)}{3(1-x)}$$

μ=2GeV
without evolution

Mass-dependence of pseudoscalar meson elastic form factors

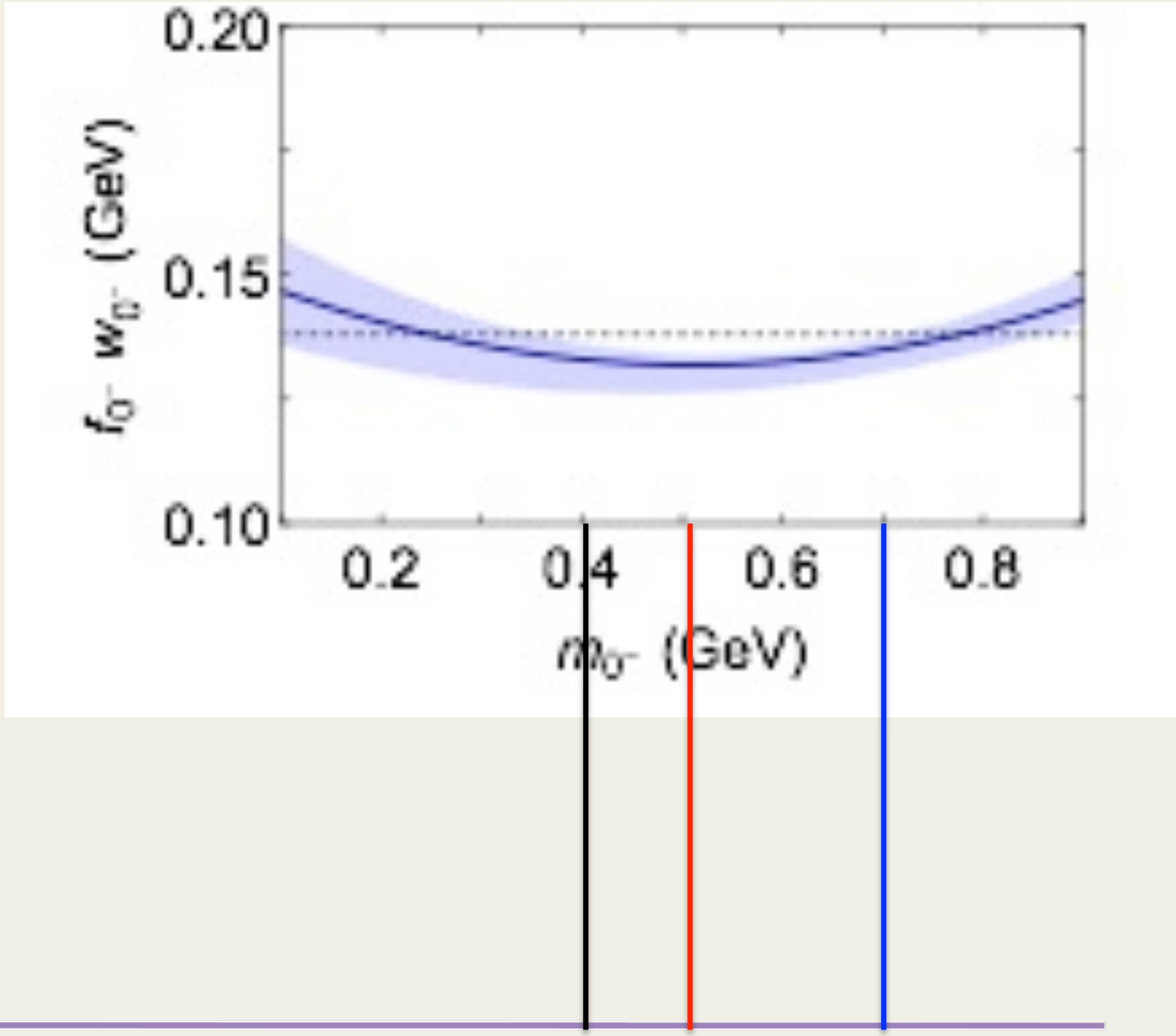
Muyang Chen, et.al, arXiv:1808.09461



- A consistent rainbow-ladder truncation
- Minimum exist around 0.5GeV, the gluon mass

Mass-dependence of pseudoscalar meson elastic form factors

Muyang Chen, et.al, arXiv:1808.09461



- Gluon mass generation…
- QCD is well-defined at UV momenta owing to asymptotic freedom; QCD is IR finite, owing to dynamical generation of gluon mass-scale;
- Maximum wavelength for gluon/quark;
- Critical behavior for the wave function…
- Transition from dynmaical breaking to explicit prekaing.

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THANKS FOR YOUR ATTENTION