DSEs meet lQCD

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第十八届全国中高能核物理大会
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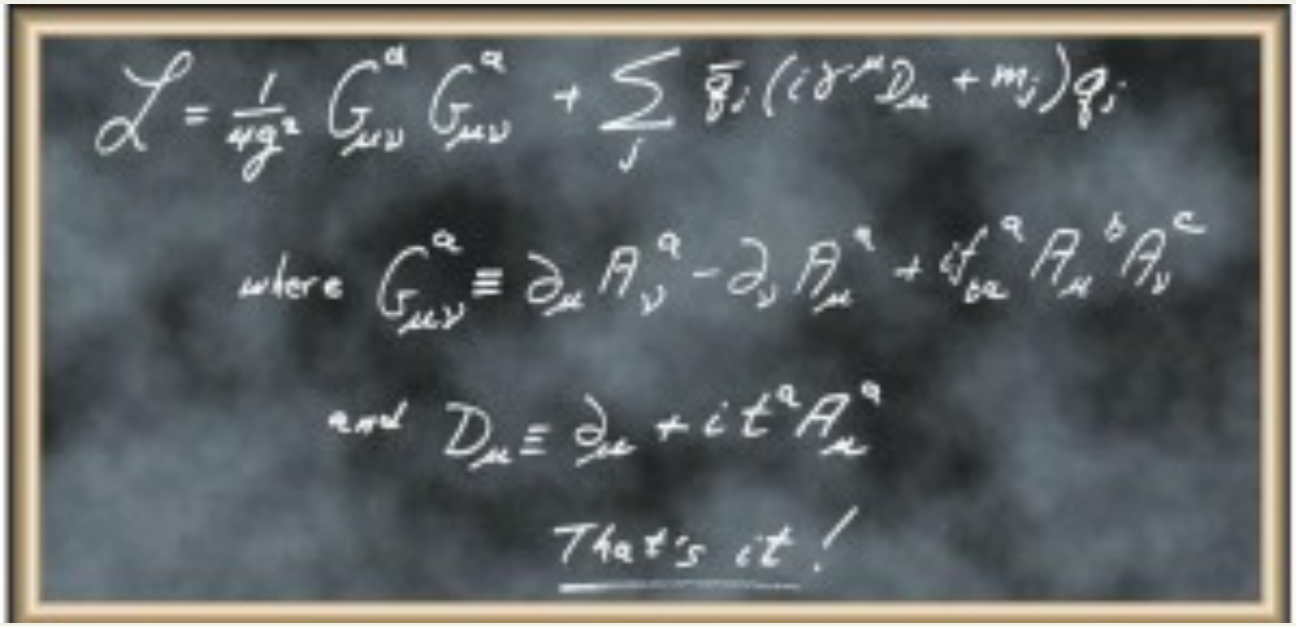
Emergent phenomena

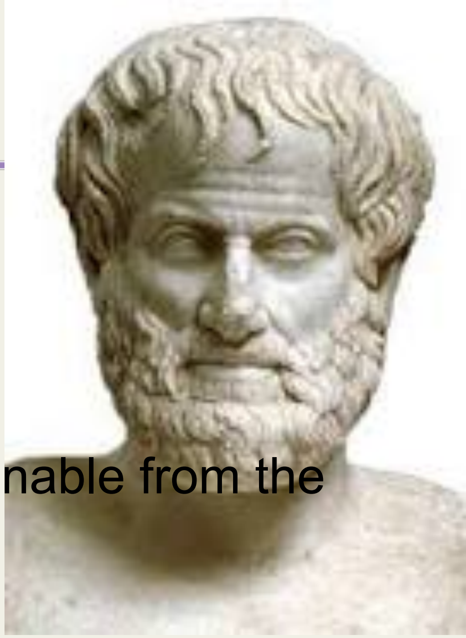


- Quark current mass…Higgs boson.
- Hadron physics mass-scale – 1 GeV

  – is an emergent feature of the Standard Model

  No amount of staring at L_{QCD} can reveal that scale

Holism=Emergentism

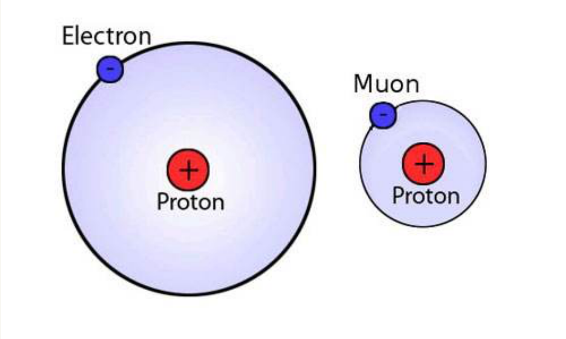


- Aristotle(亚里士多德): 383BC?-322 BC
- Holism:
  - the idea that items can have properties, (emergent properties), as a whole that are not explainable from the sum of their parts.
- Summarized concisely (Aristotle):
  - *The whole is more than the sum of its parts*

- Hegel(黑格尔) (Stuttgart 1770 – Berlin 1831):
  Das Wahre ist das Ganze (The true is the whole)

- Anderson (1972)
  More is different

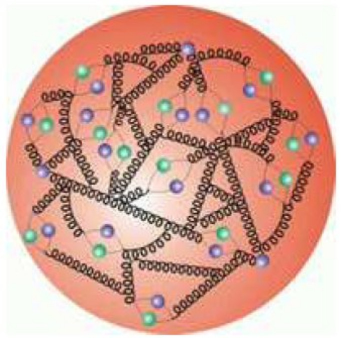
Bound state and quantum field theory



QED

Trace anomaly

- All renormalisable four-dimensional theories possess a trace anomaly;
- The size of the trace anomaly in QED must be great deal smaller than that in QCD.



QCD

Field theory Successful:

- Nonrelativistic quantum mechanics to handle bound state;
- Perturbation theory to handle relativistic effects

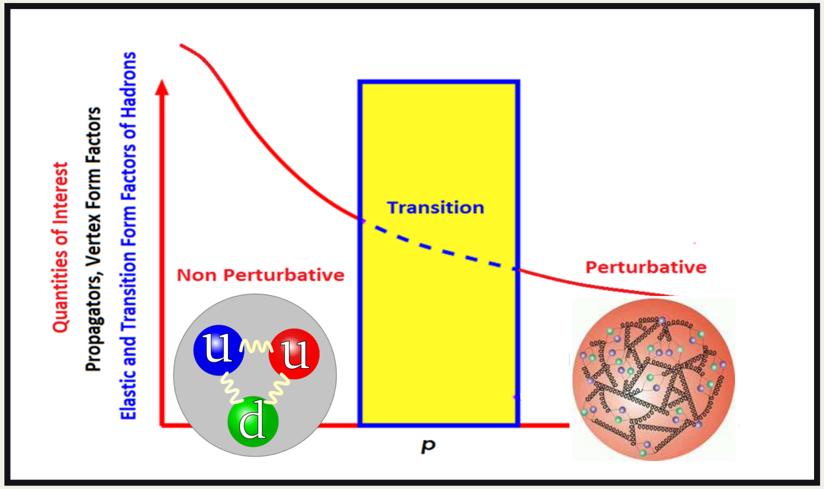
Field theory not Successful yet:

- Growth of the running coupling constant in the infrared region;
- Confinement;
- Dynamical Chiral Symmetry Breaking;
- Possible nontrivial vacuum structure in hadron

Hadron bound state problem

Constituent quark model-> intuitive understanding of many low energy observables.

Minimum number of constituents required



Feynman's parton model-> intuitive understanding of high-energy phenomena.

Constituent picture; Probabilistic interpretation of distribution functions

QCD vacuum in the hadron is very complicated medium
Individual quarks and gluons are lost in the sea

Both the constituent quark model and the parton model are put in peril by QCD with a possible complicated vacuum structure.

Emergent phenomena, 方法论

- Confinement and DCSB are emergent phenomena

  Not revealed by any amount of staring at Lagrangian for quantum chromodynamics;
  They determine the character of the QCD's spectrum, the structure and interactions of bound states

- Can one understand confinement and DCB in terms of properties of the degrees-of-freedom used to formulate QCD?

  E.g., is it pointless to attempt to predict the nucleon's form factor on a domain that is not yet accessible?

If YES:
Must rely on the vase array of effective field theories, developed for different systems, in order, to express and understand the consequences of confinement and DCSB, without identifying their source

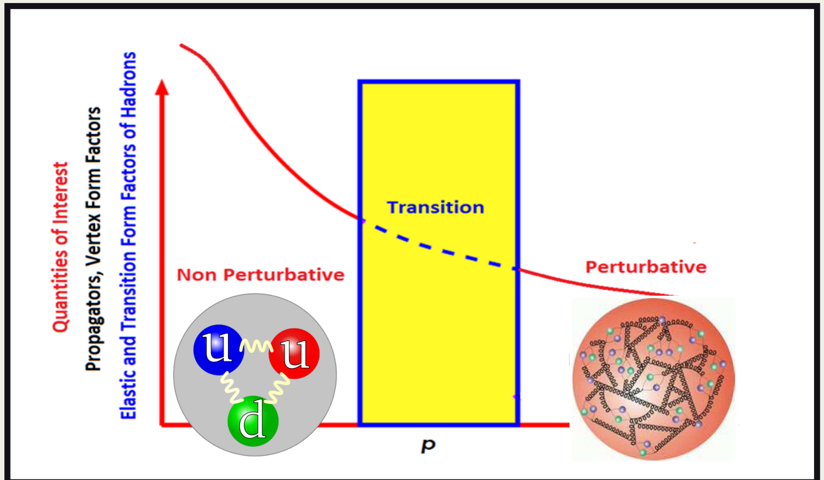
If NO:
Must develop nonperturbative calculational methods to define and tackle QCD

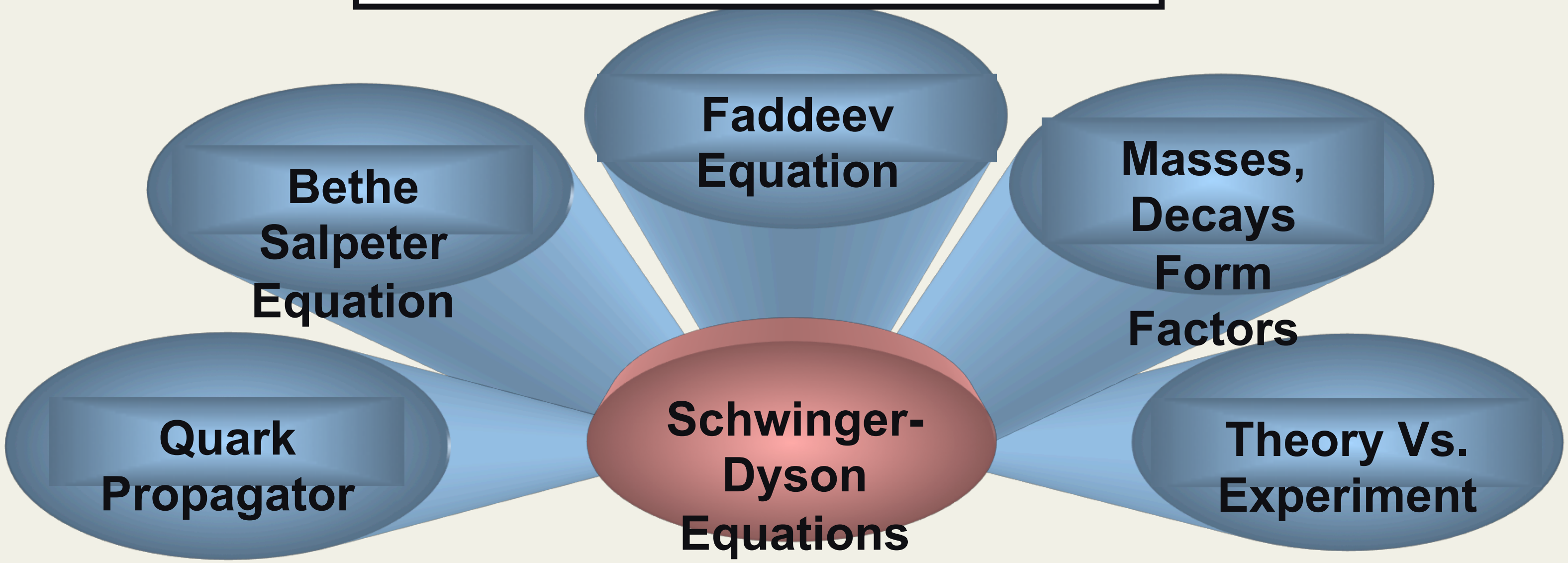
1) Lattice-regularized QCD
2) Continuum methods in quantum filed theory
3) Combination of all the above

Currently, each approach has strengths and weaknesses
So 3) is probably the best:
Combine all available methods to fullest extent reasonably possible.

Dyson-Schwinger Equation scope

Study bound state problem within an continuum field theory





OPENING HIGHLIGHT

i) A Pattern for the Flavor Dependence of the Quark-Gluon Interaction, *arXiv: 1903.07808*, Muyang Chen and Lei Chang;

ii) Excited Bc States via Continuum QCD, *arXiv: 1904.00399*, Lei Chang, Muyang Chen and Yuxin Liu.

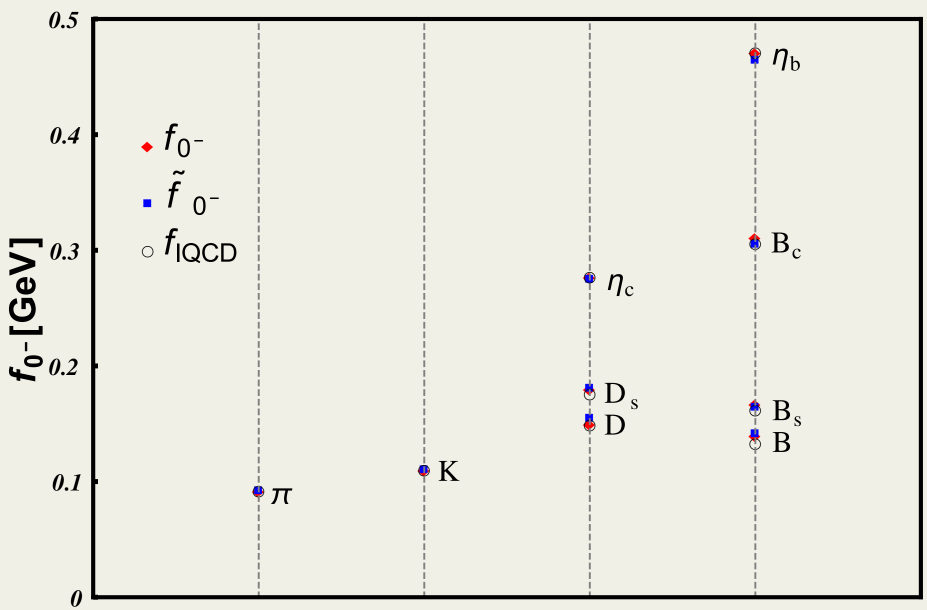


TABLE II. Masses of the first radial excited states of charm-beauty system (in GeV). The experimental data for $M_{\eta_c(2S)}$, $M_{\psi(2S)}$, $M_{\eta_b(2S)}$ and $M_{\Upsilon(2S)}$ are taken from Ref.[25], $M_{B_c^+(2S)}$ and $M_{B_c^+(2S)} - M^{\rm rec}_{B_c^{*+}(2S)}$ from Ref.[2]. The mass splitting, $M_{B_c^{*+}(1S)} - M_{B_c^+(1S)}$, is quoted from Ref.[22]. The uncertainties of our results correspond to the varying of the parameters in Table I.

	$M_{\eta_c(2S)}$	$M_{\psi(2S)}$	$M_{\psi(2S)} - M_{\eta_c(2S)}$
here	3.606(18)	3.645(18)	0.039
expt.	3.638(1)	3.686(1)	0.048
	$M_{B_c^+(2S)}$	$M_{B_c^{*+}(2S)}$	$M_{B_c^+(2S)} - M^{\rm rec}_{B_c^{*+}(2S)}$
here	6.813(16)	6.841(18)	0.039
expt.	6.872(2)	–	0.031
	$M_{\eta_b(2S)}$	$M_{\Upsilon(2S)}$	$M_{\Upsilon(2S)} - M_{\eta_b(2S)}$
here	9.915(15)	9.941(15)	0.026
expt.	9.999(4)	10.023(1)	0.024

- They deviate from each other by no more than 3% for all the pseudoscalar mesons;
- We conclude that the av-WTI is perfectly preserved in our approach.

QCDs Dyson-Schwinger Equations

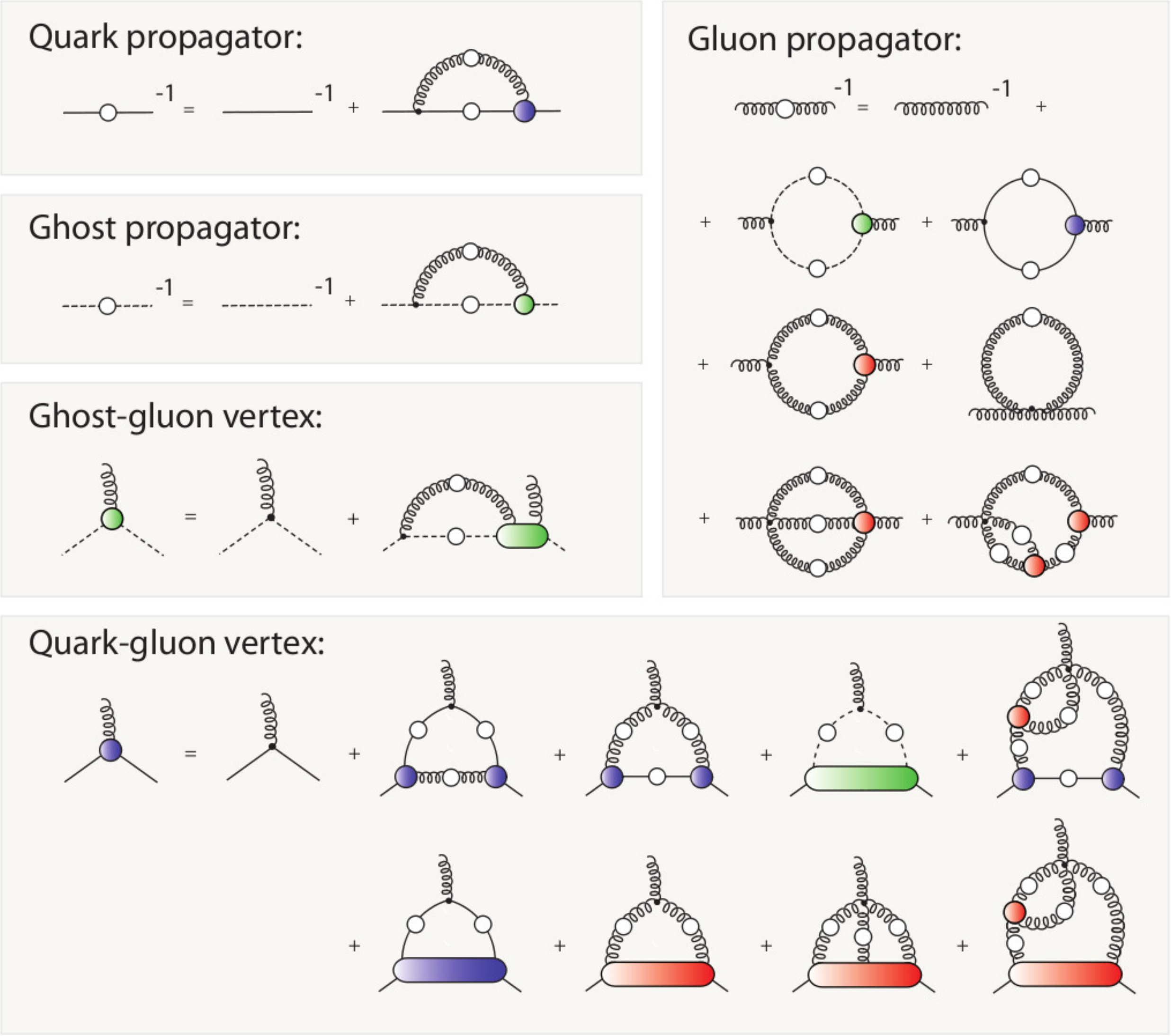


Image courtesy of Gernot Eichmann

Dyson-Schwinger Equation scope

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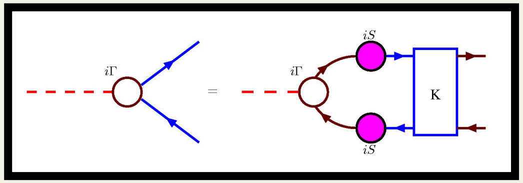
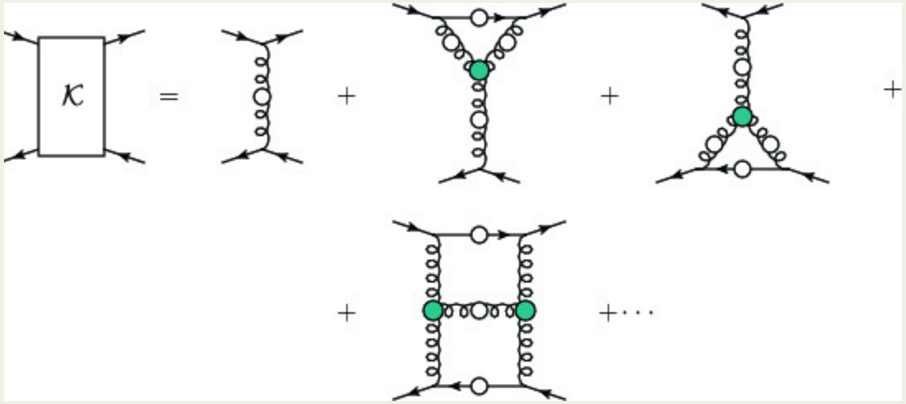
Bethe-Salpeter Equations





渐进两夸克
说几个夸克态构成束缚态是难以定义的

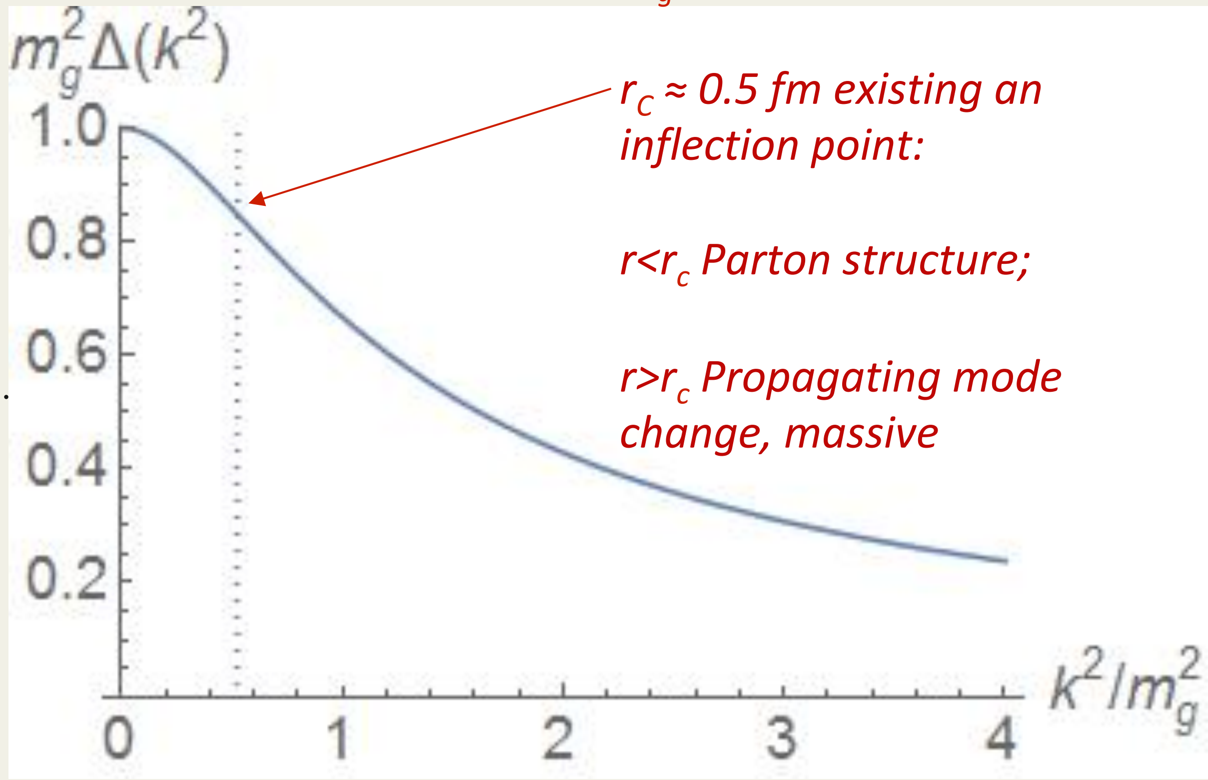
Spectral representation

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

if

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

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

Quark Propagator $S(k) = -i\gamma \cdot k\sigma_V(k^2) + \sigma_S(k^2)$

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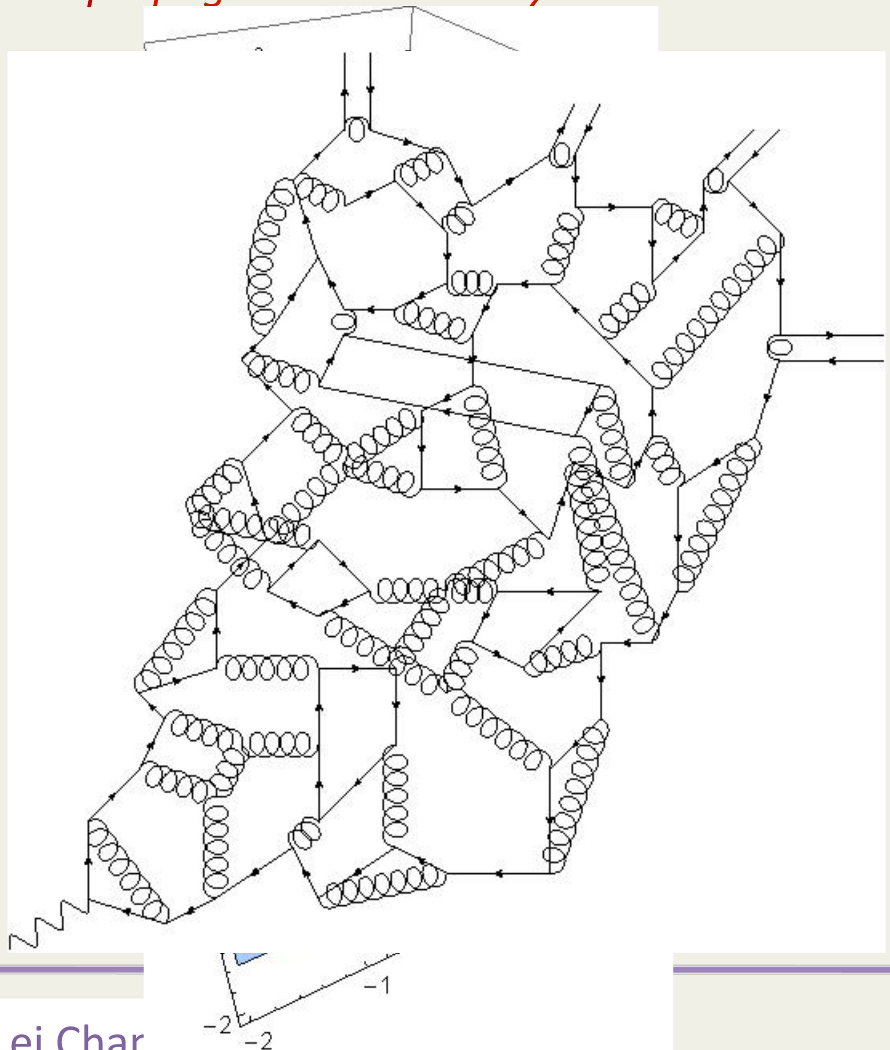
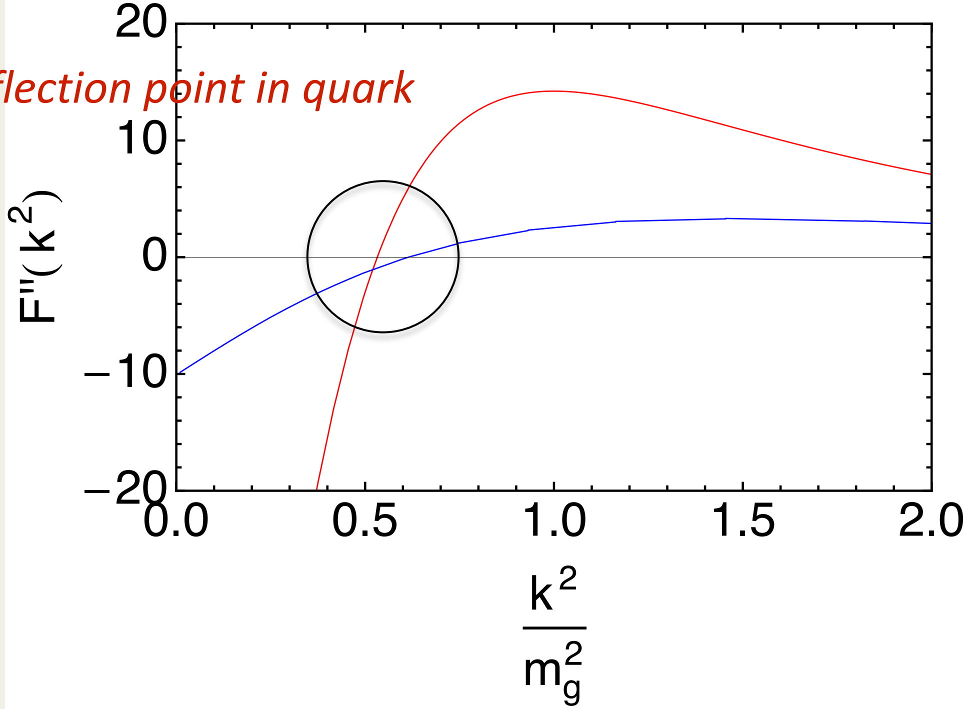
- *at around $k^2 \approx 0.5\ m_g^2$ there exists an inflection point in quark propagator consistently*

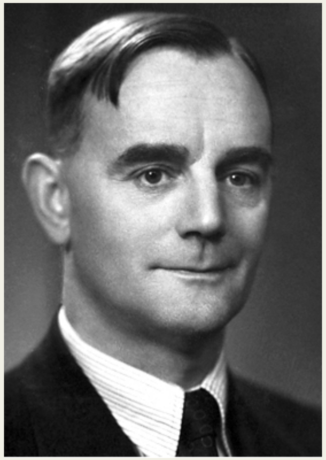




- Inflection points
- Red line: running gluon propagator
- Blue line: vector part of propagator

Why Pion-----Messager of QCD

- Pion is Massless...

- In October 1934**, Hideki Yukawa** predicated the existence of a "heavy quantum" meson, exchanging nuclear force between neutrons and protons.
- It was discovered by **Cecil Powel** in 1949 in cosmic ray tracks in a photographic emulsion.
- Pion was nicely accommodated in the Eight Fold way of **Murray Gell-Mann** in 1961.
- **Yoichiro Nambu** associated it with CSB in 1960.

Pion's dichotomy
Goldstone boson and Bound State

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

- Pion's Bethe-Salpeter amplitude

  Solution of the Bethe-Salpeter equation

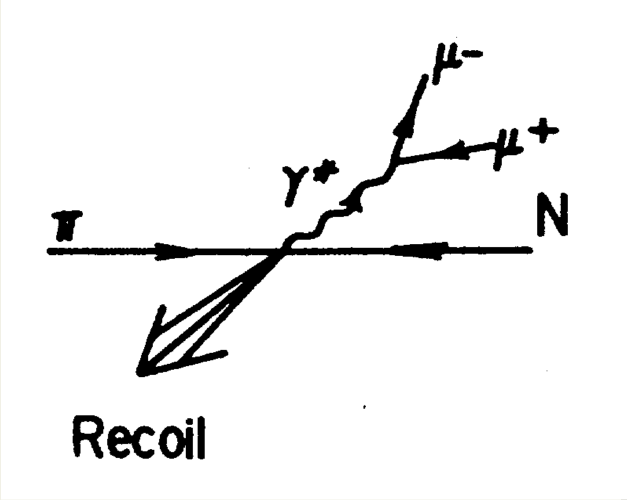
$$\Gamma_{\pi^j}(k;P) = \tau^{\pi^j}\gamma_5\left[iE_\pi(k;P) + \gamma\cdot P F_\pi(k;P) + \gamma\cdot k\, k\cdot P\, G_\pi(k;P) + \sigma_{\mu\nu}\, k_\mu P_\nu\, H_\pi(k;P)\right]$$

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

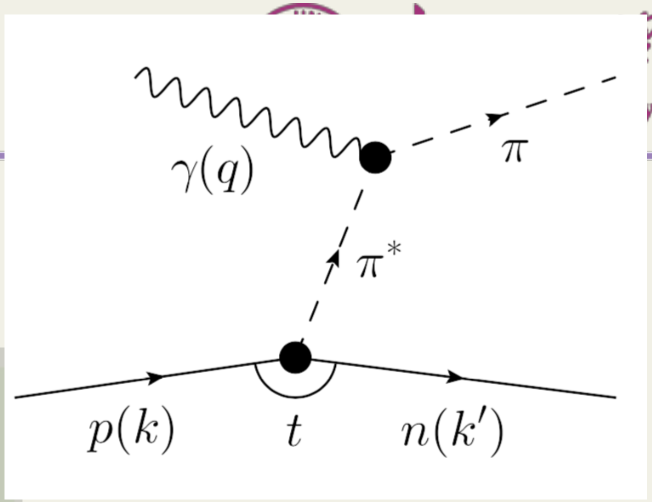
- Axial-vector Ward-Takahashi identity entails(chiral limit)

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

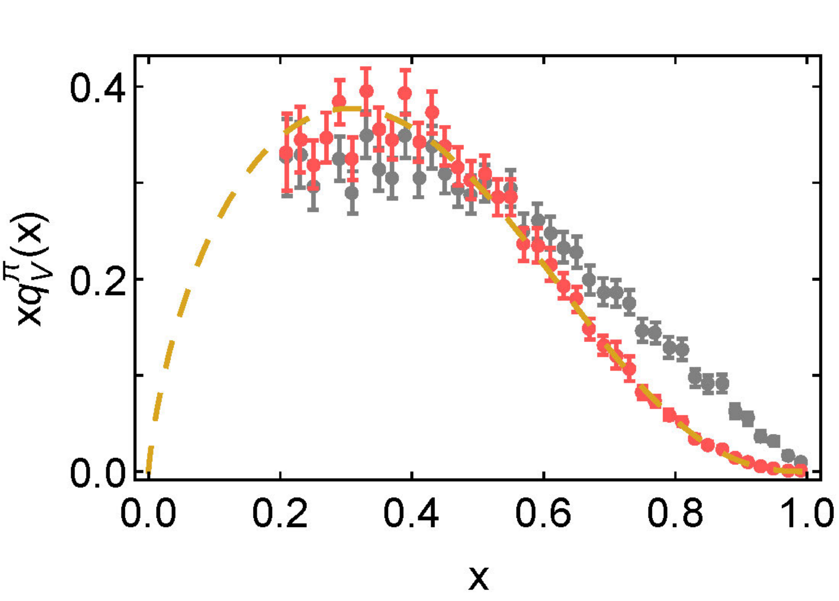
- Given the dichotomy of pion the fine-tuning should not play any role in an explanation of pion properties;
- Descriptions of pion within frameworks that cannot faithfully express symmetries and their breaking patterns(such as constituent-quark models) are unreliable;
- Hence, pion properties are an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

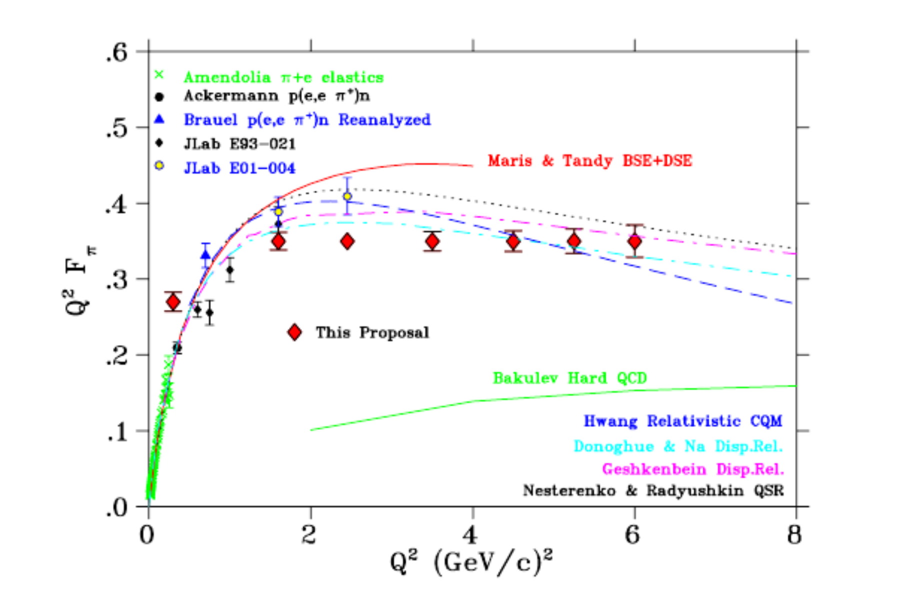


$\pi N \to \mu^+ \mu^- X$



p(e, e′ π^+)n





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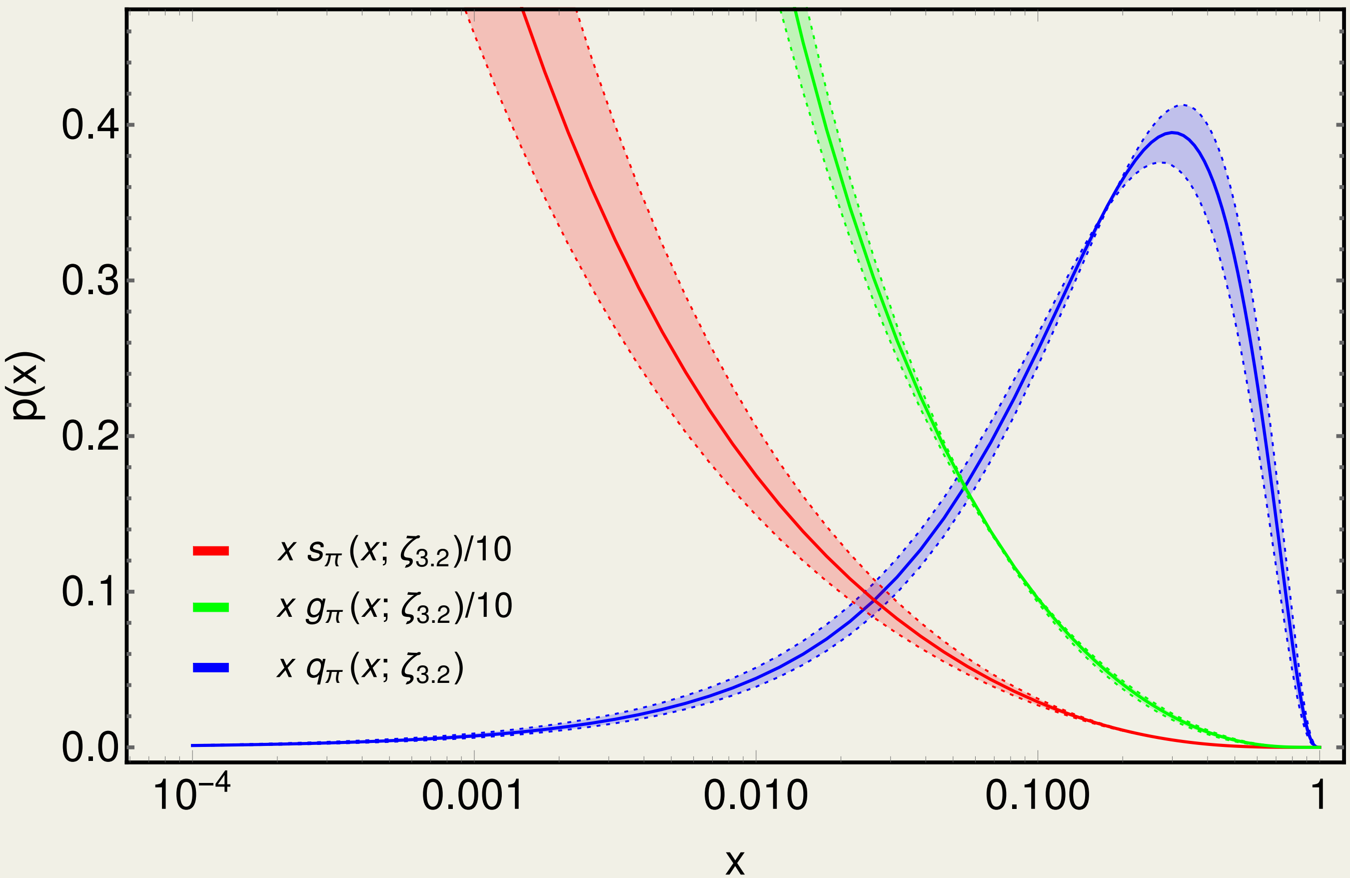
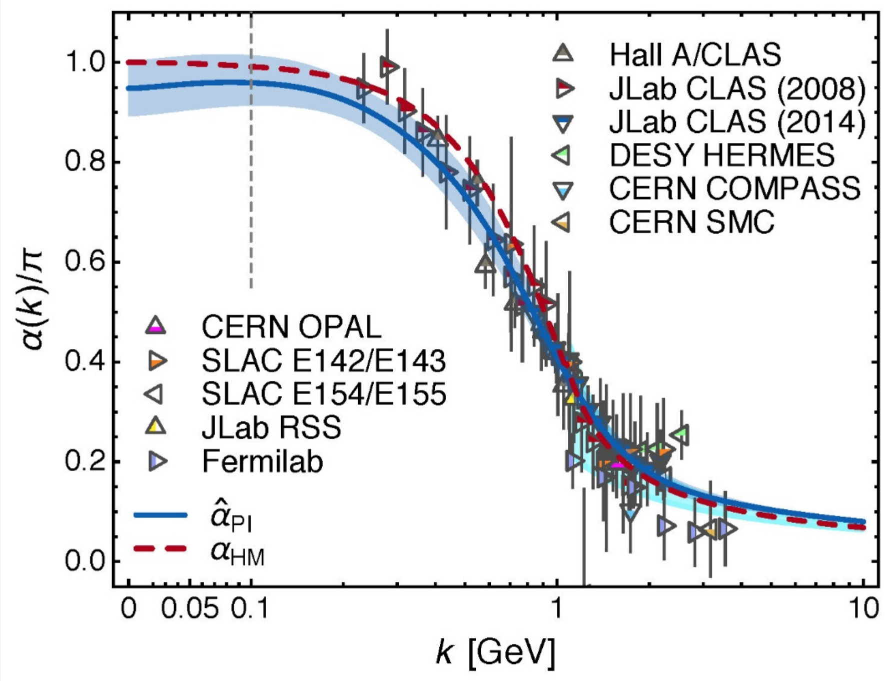
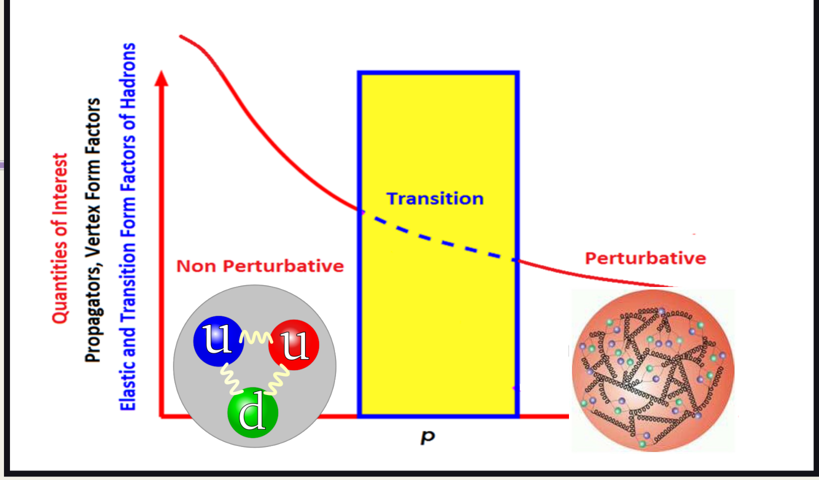
PDF



Hadronic Scale



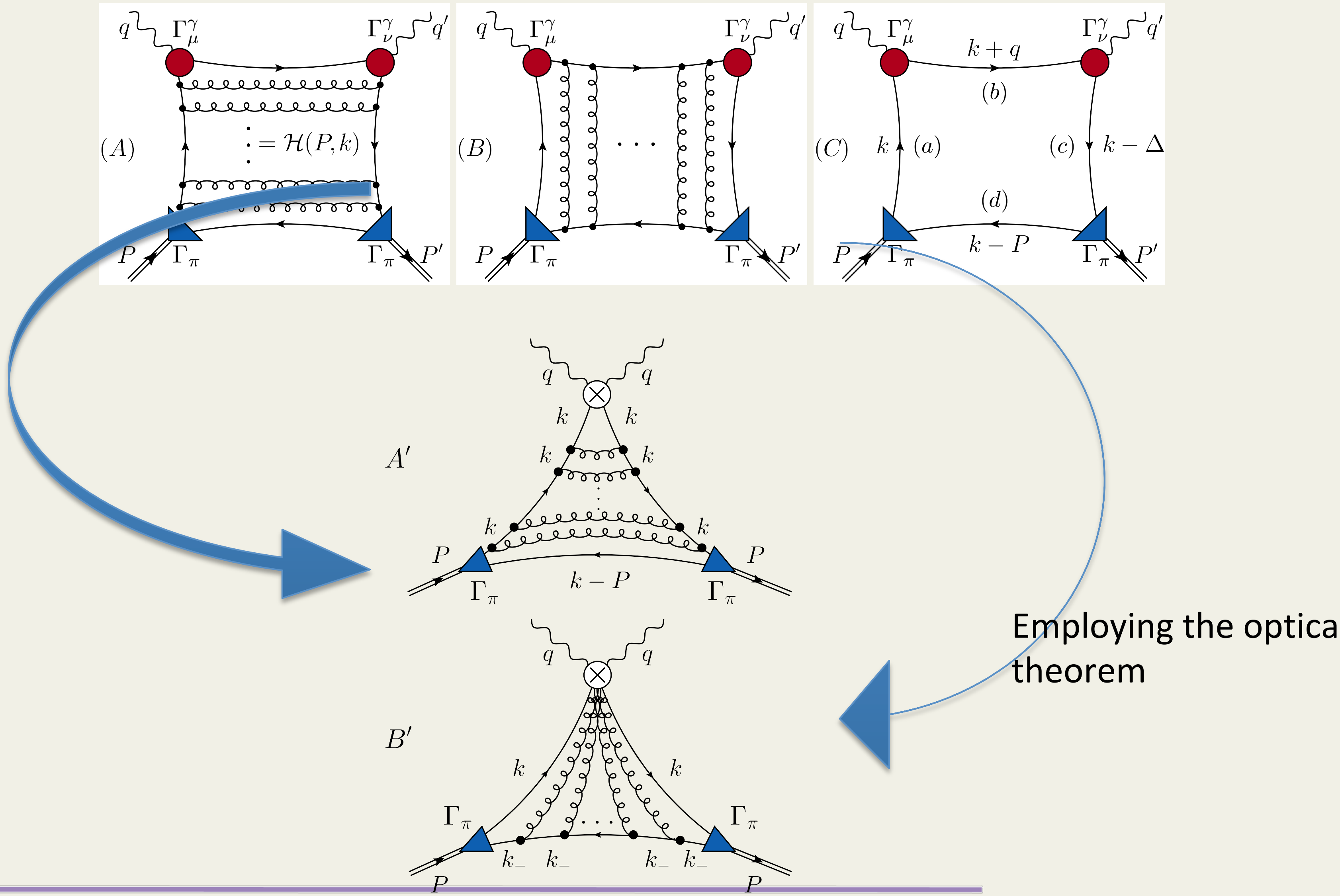


$$\alpha_{\rm PI}(k^2) = \frac{\pi \gamma_m}{\ln[(m_\alpha^2 + k^2)/\Lambda_{\rm QCD}^2]},$$

$$m_\alpha = 0.30\,{\rm GeV} \gtrsim \Lambda_{\rm QCD}.$$

- Rainbow-Ladder truncation
- Renormalize our DSEs at the hadronic scale $\zeta = m_\alpha$
- Pure valences

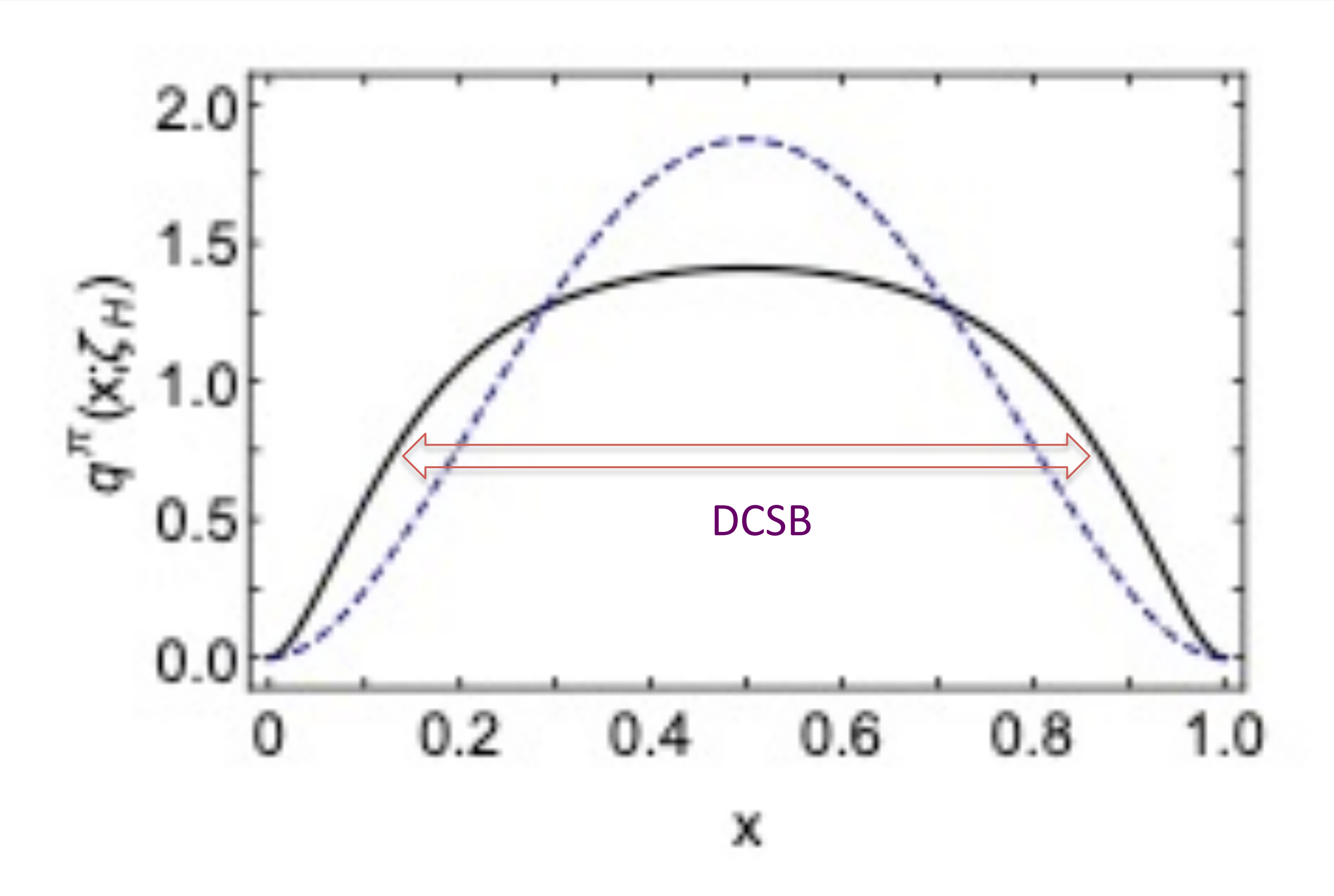
Pion Compton Scattering(RL symmetry)



$$q^\pi(x;\zeta_H) = q^\pi(1-x;\zeta_H)\,;$$

- Numerical m=0,1,2,3,4,5
- SPM extrapolation to m=11
- PDF extraction

$$q^\pi(x;\zeta_H) = N_c \mathrm{tr} \int_{dk} \delta_n^x(k_\eta)$$
$$\times\, n \cdot \partial_{k_\eta} \left[\Gamma_\pi(k_\eta, -P) S(k_\eta)\right] \Gamma_\pi(k_{\bar\eta}, P)\, S(k_{\bar\eta})\,,$$



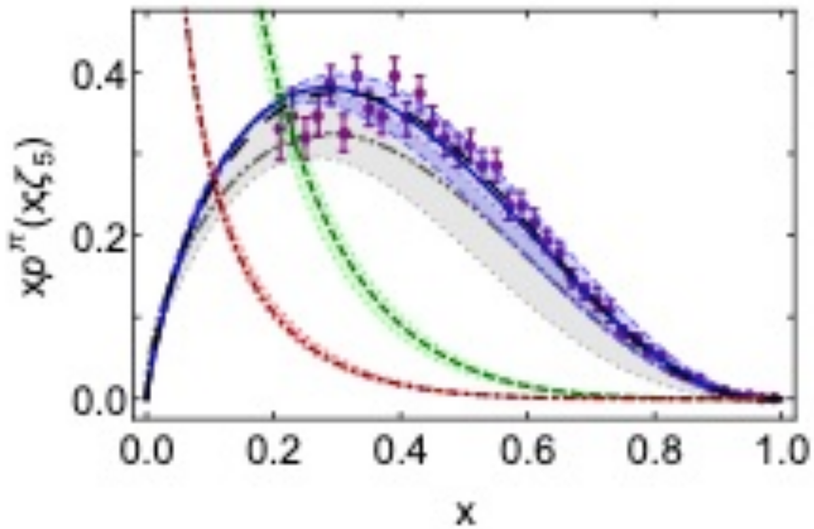


FIG. 7. Pion valence-quark momentum distribution function, $xq^\pi(x;\zeta)$, evolved $\zeta_H \to \zeta_5 = 5.2\,\mathrm{GeV}$ – solid (blue) curve embedded in shaded band; and long-dashed (black) curve – ζ_5 result from Ref. [12]. Gluon momentum distribution in pion, $xg^\pi(x;\zeta_2)$ – dashed (green) curve within shaded band; and sea-quark momentum distribution, $xS^\pi(x;\zeta_2)$ – dot-dashed (red) curve within shaded band. See Eqs. (39), (40). In all the above cases, the shaded band indicates the effect of $\zeta_H \to \zeta_H(1 \pm 0.1)$. Dot-dot-dashed (grey) curve within shaded band – lQCD result [31]. Data (purple) from Ref. [9], rescaled according to the analysis in Ref. [14].

- Solid Blue=nonsinglet evolution for valence-quark

$$\langle x_{\text{valence}} \rangle = 0.48(3)\,,$$

- glue& sea quarks distribution are generated by singlet evolution

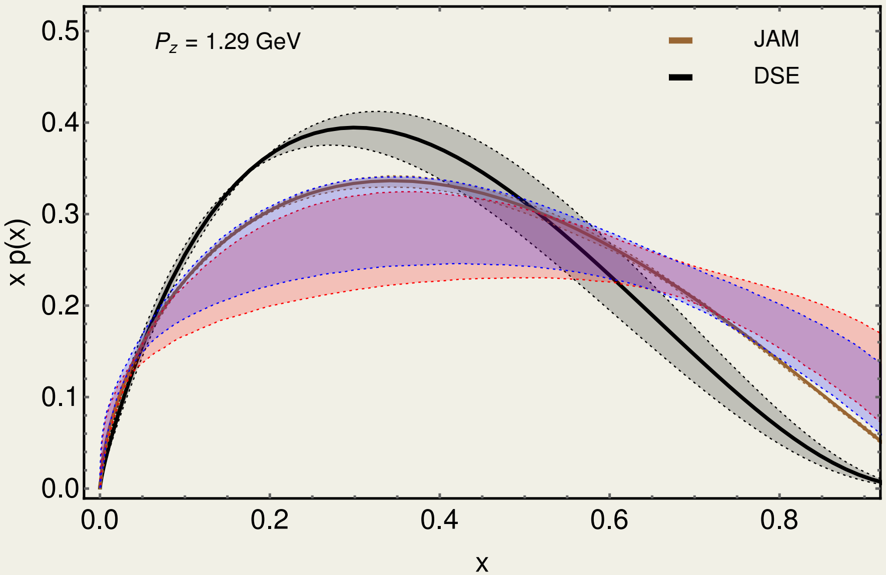
$$\langle x_{\text{glue}} \rangle = 0.41(2)\,,$$
$$\langle x_{\text{sea}} \rangle = 0.11(2)\,,$$

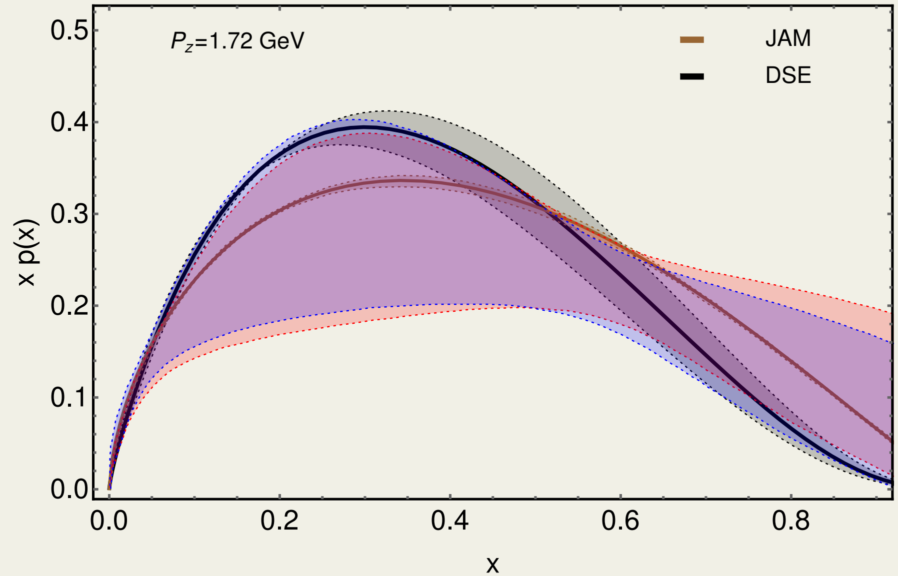
- dot-dot-dashed(grey)=lQCD result for the pion valence-quark distribution
- Pointwise form of the lQCD prediction agrees with our result(with errors).
- Significant: two disparate treatments of the pion have arrived at the same prediction.

lQCD result, R. S. Sufian *et al*, PRD99(2019)074507

Pion valence quark distribution from matrix element calculated in Lattice QCD.

Large Momentum Effective Theory





lQCD result, T. Izubuchi *et al*, arXiv:1905.06349.
Valence parton distribution function of pion from fine lattice

还不是时候

Pion PDF 20年

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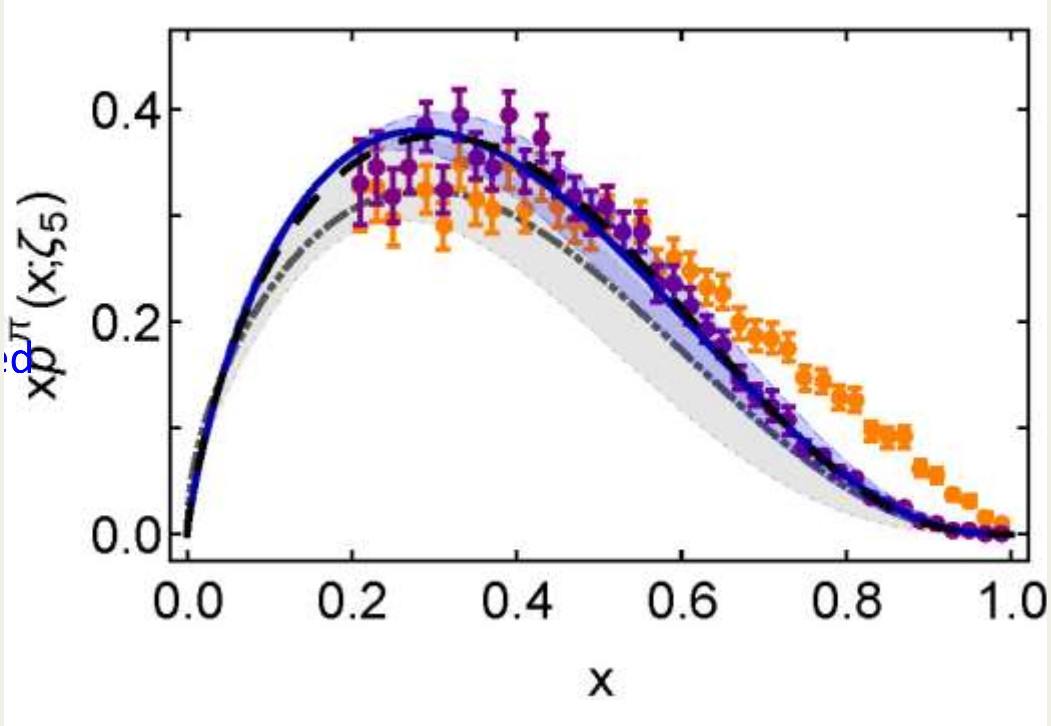
- 1989…Conway et al. Phys. Rev.D 39 (1989) 92
  Leading-order analysis of Drell-Yan data
- 2000…Hecht et al. Phys. Rev.C 63 (2001)025213
  QCD connected model calculation
- 2010...Aicher et al. Phys. Rev. Lett. 105 (2010) 252003
  Consistent next-to-leading order anaylsis
- 2019/04...Ding, et al.
  Continuum QCD prediction
- 2019/01...Sufian, et al.
  1st exploratory lattice-QCD calculation
  Using lattice-calculated matrix element obtained through spatially separated current-current correlations in coordinate space



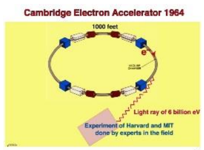
Sufian…extending lattice calculation on three other ensembles and the preliminary result gives an indication MORE COINCIDE.

Meson Form Factor Data Evolution

Experiment

Capability to reliably access large Q^2 regime

From T.Horn



DESY

Jefferson Lab

JLab 6 GeV

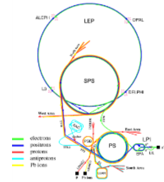
JLab 12 GeV

EIC

1959 1971 1976 1979 1981 1984 1986 1997 2003 2004 2017+ 2025+

Cornell University

Fermilab



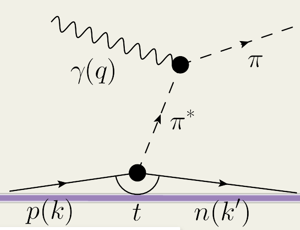
*[L. Chang, et al., PRL **111** (2013) 141802; PRL **110** (**2013**) 1322001]*

Theory

- Accessing the form factor through electroproduction
- Extraction of meson form factor from data
- Electroproduction formalism

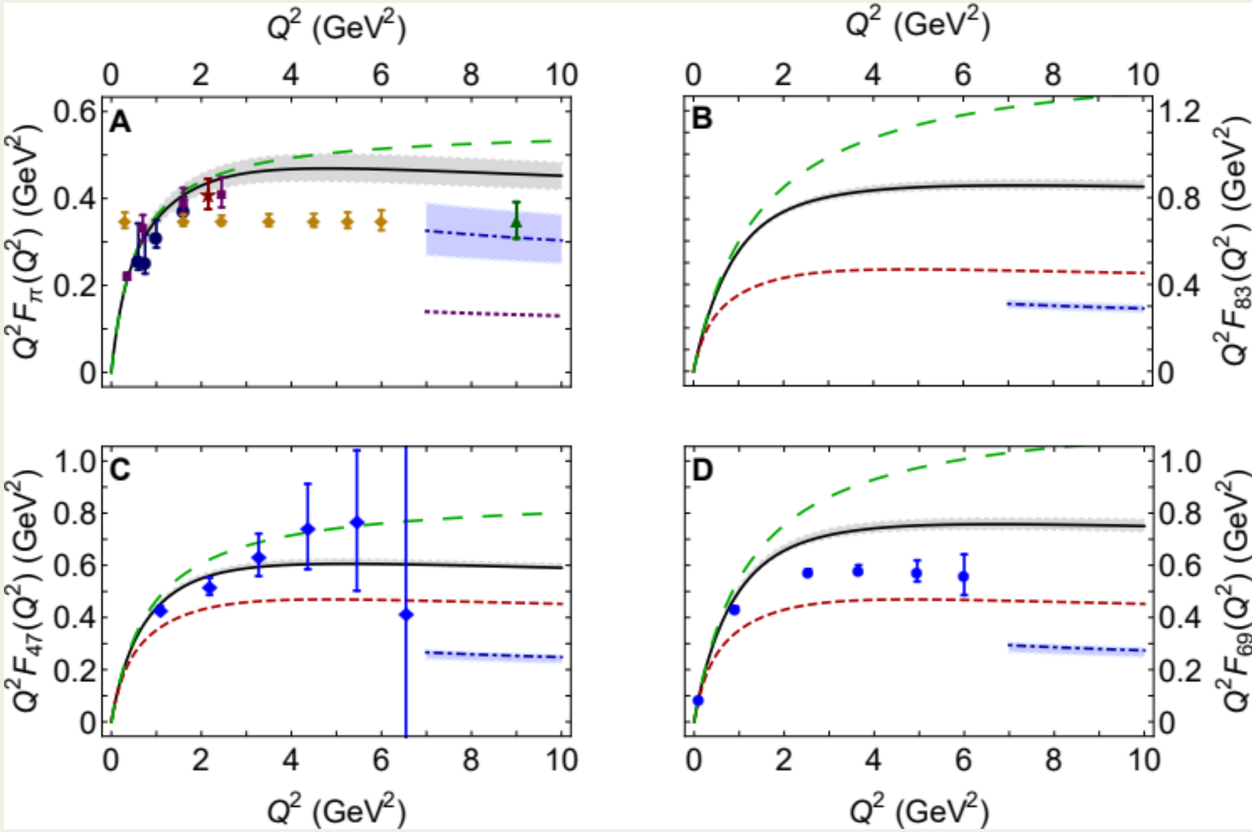
Theory

Major progress on large Q^2 behavior of meson form factor



- 如何理解不在壳的pion？
- 如何理解基于第一性原理计算的格点QCD结果

- ✓ 彩虹梯子近似
- ✓ 赝标介子质量分别 m_{0-}/GeV=0.14, 0.47, 0.69, 0.83
- ✓ 电磁形状因子 $Q^2 \lesssim 10$ GeV^2.
- ✓ 与格点结果比较



- lQCD(QCDSF/UKQCD/CSSM Collaborations) in panel C: PRD96(2017)114509
- lQCD(HPQCD Collaboration) in panel D: PRD96(2017)054501

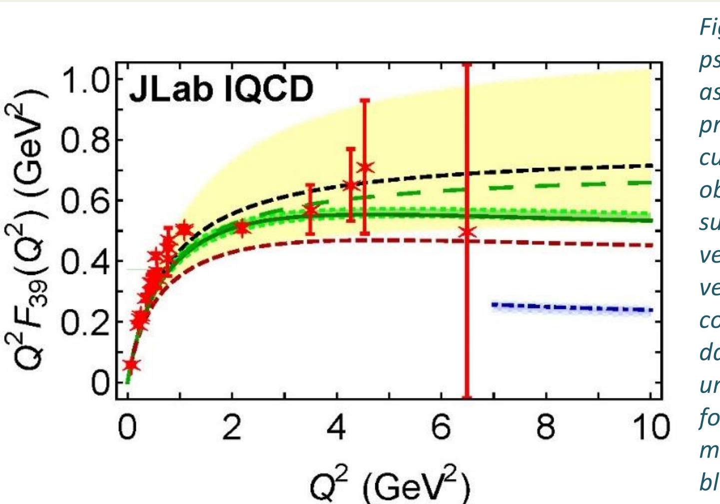


Figure 2. Elastic form factor of a pion-like pseudoscalar meson with mass m_{0^-} = 0.39 GeV. Red asterisks -- JLab lattice results drawn from the ECT presentation by D.G. Richards. Curves: Solid green curve within green bands -- our prediction, obtained using the methods described in our submission; long-dashed green curve -- single-pole vector meson dominance result obtained with vector meson mass, m_{1^-}=0.86 GeV, computed consistent with the form factor prediction; short-dashed black curve within yellow bands -- range of uncertainty in single-monopole fit to lQCD results following from the JLab-quoted error on the meson's radius; and dot-dashed blue curve within blue bands -- result from QCD hard-scattering formula, Eq. (1) in our submission, computed with the consistent meson decay constant and PDA, as predicted by the our analysis. For comparison, the dashed red curve is the DSE prediction for the physical-pion, taken from Fig. 1A in our submission.*

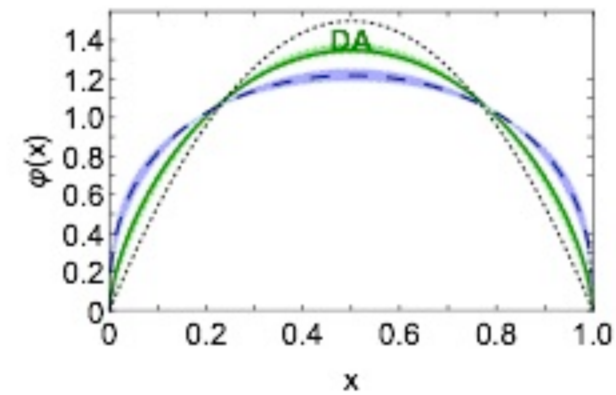


FIG. 2. Dressed-valence-quark distribution amplitude of pion-like pseudoscalar mesons. Solid green curve within green bands – prediction for m_{0^-} = 0.39 GeV; long-dashed blue curve within blue bands – prediction from Ref. [1] for the physical pion; and dotted black curve – asymptotic profile, $\varphi_\infty(x) = 6x(1-x)$.

The lattice results in Figure 2 were drawn from a presentation by D. G. Richards at the ECT* Workshop on Mapping Parton Distribution Amplitudes and Functions. That presentation is available here

https://indico.ectstar.eu/event/22/contributions/503/attachments/387/532/pion_pdf_richards.pdf

	r_{0^-}/fm	m_{1^-}/GeV	f_{0^-}/GeV
DSE	0.58(1)	$0.86^{+0.04}_{-0.02}$	0.109(1)
lQCD	0.55(10)	$0.88^{+0.19}_{-0.13}$	?

Notably, in common with the Adelaide lattice-QCD results (Fig. 1C in our submission), the JLab results are consistent with our predictions. The Glasgow results (Fig. 1D in our submission) alone appear to be inconsistent with physics expectations.

电磁半径

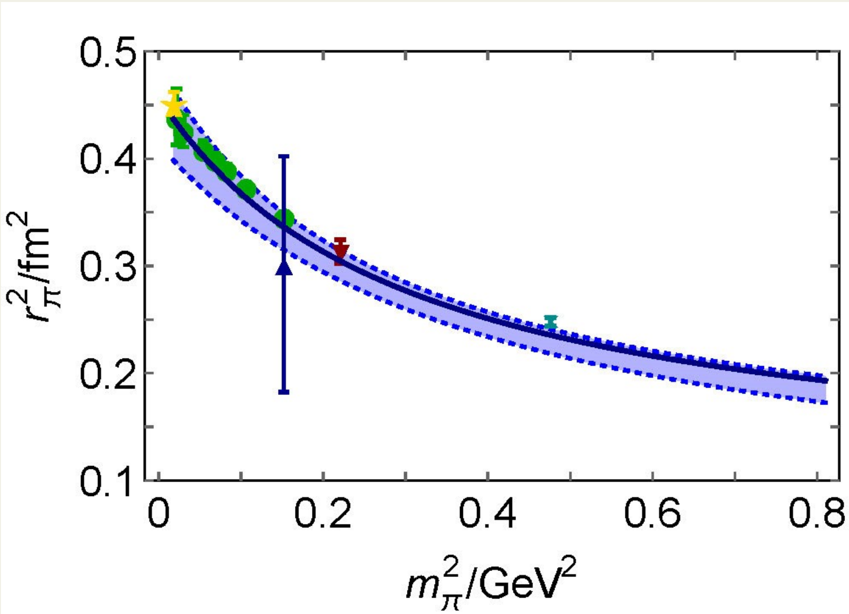
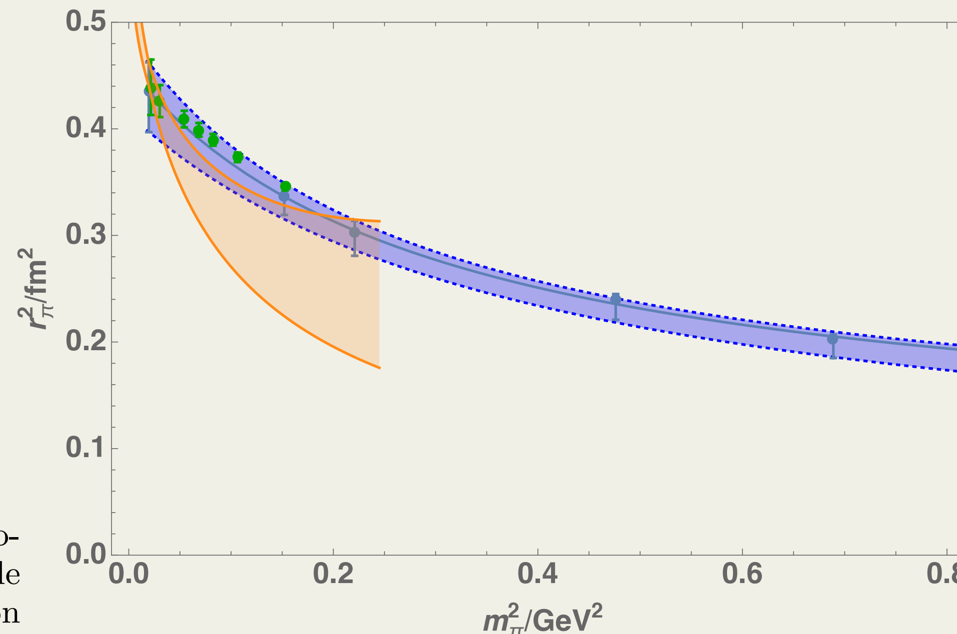


FIG. 2: Lattice-QCD computations of the pion's electromagnetic charge radius (green circles [34], blue up-triangle [35], red down-triangle [36], cyan cross [37]) as a function of m_π^2, compared with a continuum theory prediction [38] (blue curve within bands, which indicate response to reasonable parameter variation). The continuum analysis establishes $f_\pi r_\pi \approx$ constant, from which it follows that the size of a Nambu-Goldstone mode decreases in inverse proportion to the active strength of the dominant mass generating mechanism. The empirical value of r_π is marked by the gold star.

Feng-kun Guo

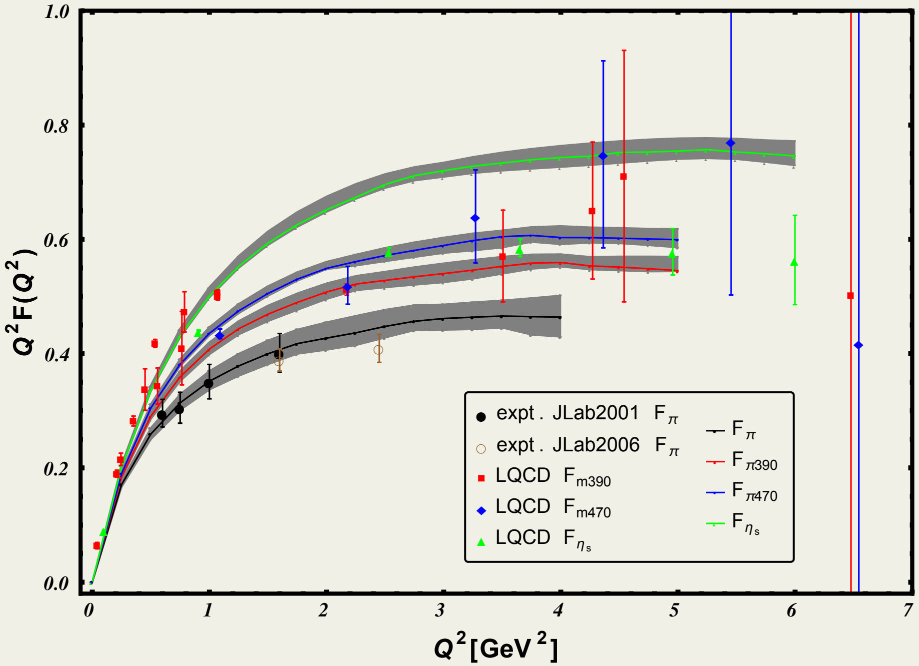


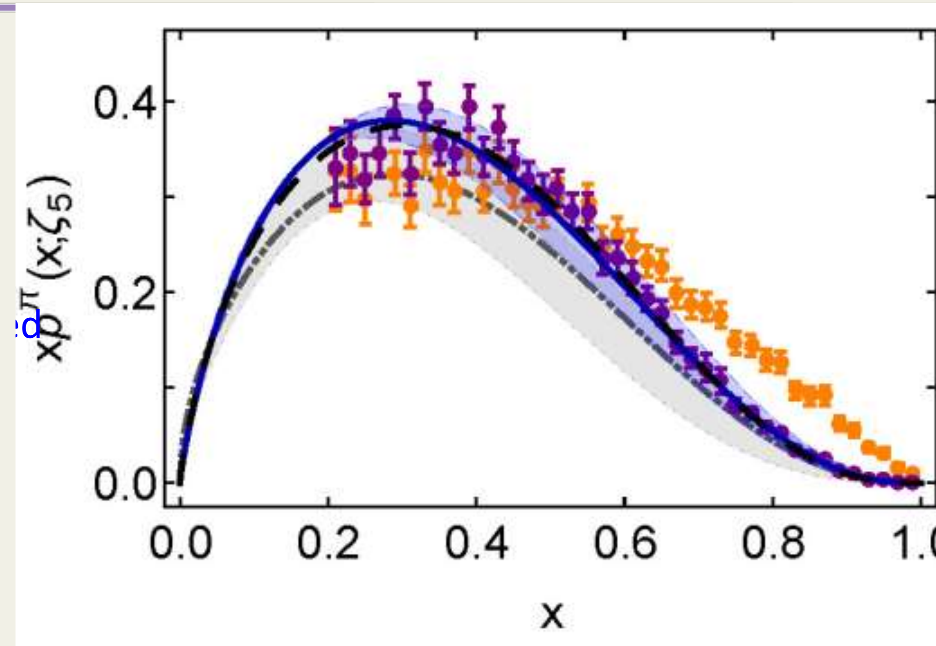
[34] G. Wang, J. Liang, T. Draper, K.-F. Liu and Y.-B. Yang, PoS **LATTICE2018**, 127 (2018).

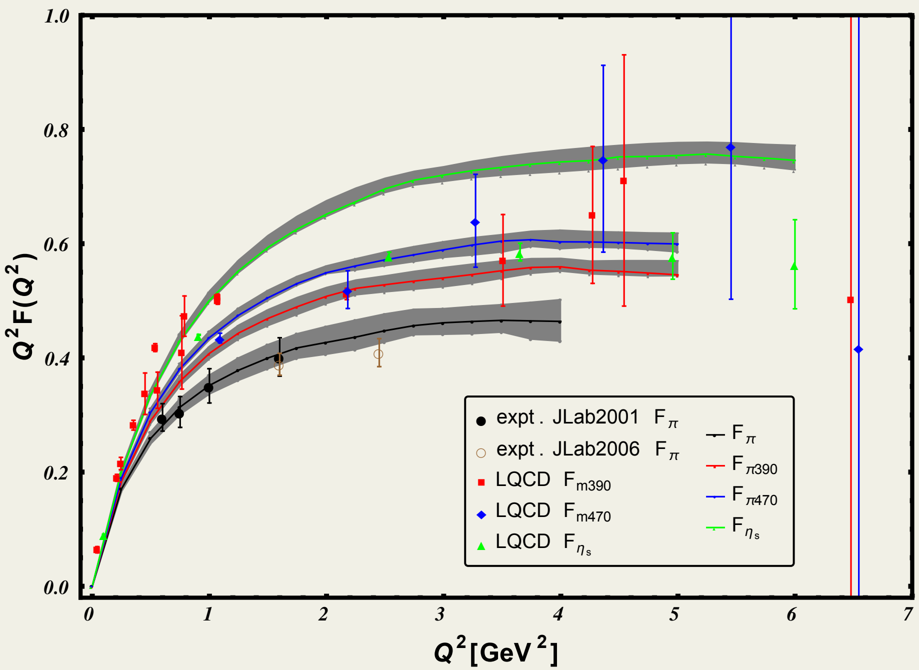
[35] B. Chakraborty and D. G. Richards, (2018), *private communication*.

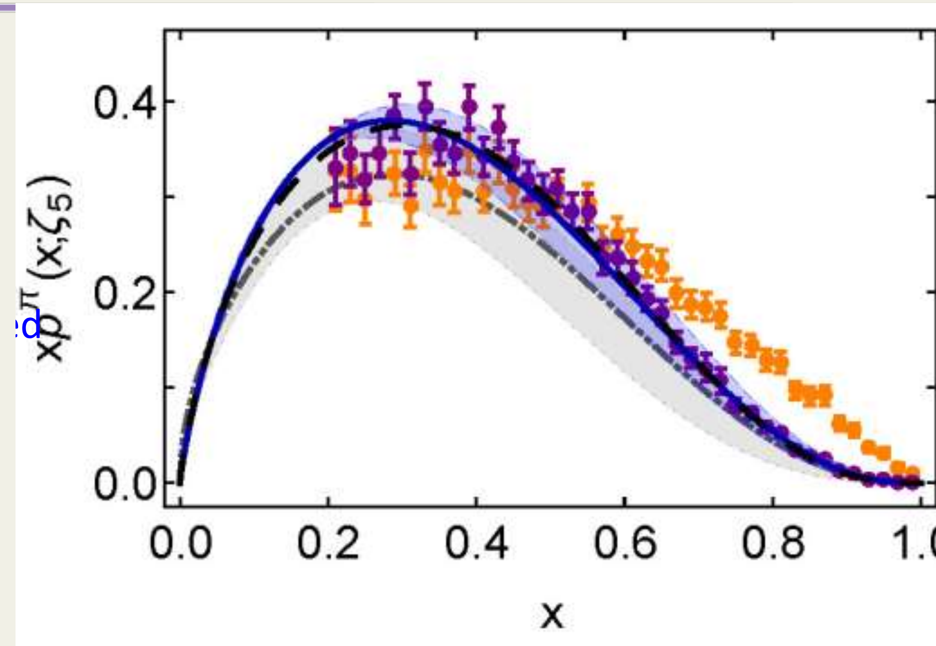
[36] A. J. Chambers *et al.*, Phys. Rev. D **96**, 114509 (2017).

[37] J. Koponen, A. C. Zimermmane-Santos, C. T. H. Davies, G. P. Lepage and A. T. Lytle, Phys. Rev. D **96**, 054501 (2017).


Q²F(Q²)
Q²[GeV²]
expt. JLab2001 F_π
expt. JLab2006 F_π
LQCD F_m390
LQCD F_m470
LQCD F_η_s
F_π
F_π390
F_π470
F_η_s


xp^π(x;ζ_5)
x





Thanks for your attention

Particle Data Group

Nankai University

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!

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

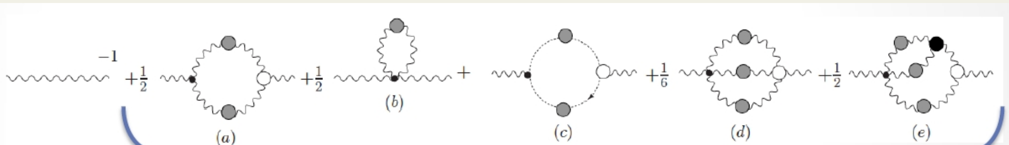
PHYSICAL REVIEW D VOLUME 26, NUMBER 6 15 SEPTEMBER 1982

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

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



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

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

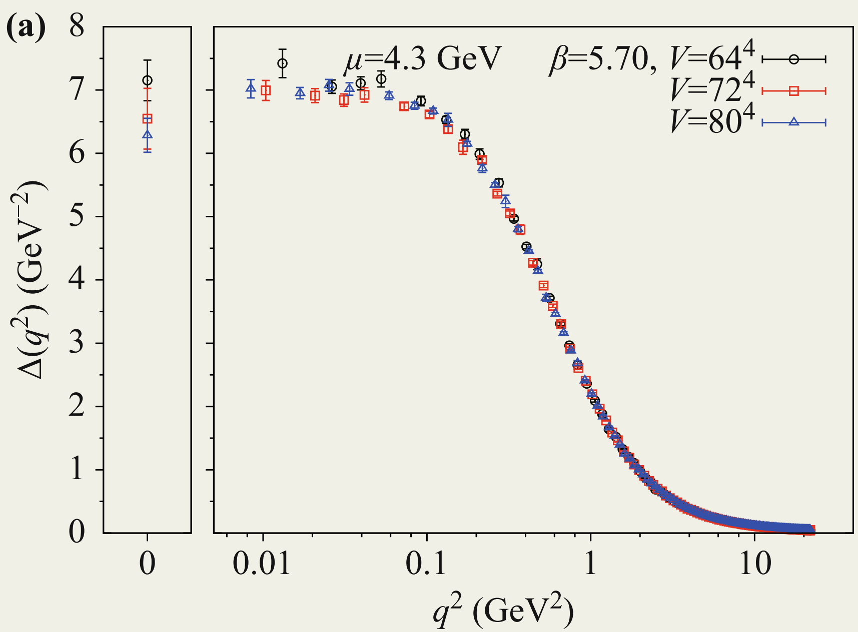
$$P_{\mu\nu}(q) = g_{\mu\nu} - q_\mu q_\nu / q^2$$

- Binosi & Papavassiliou

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

On the Lattice

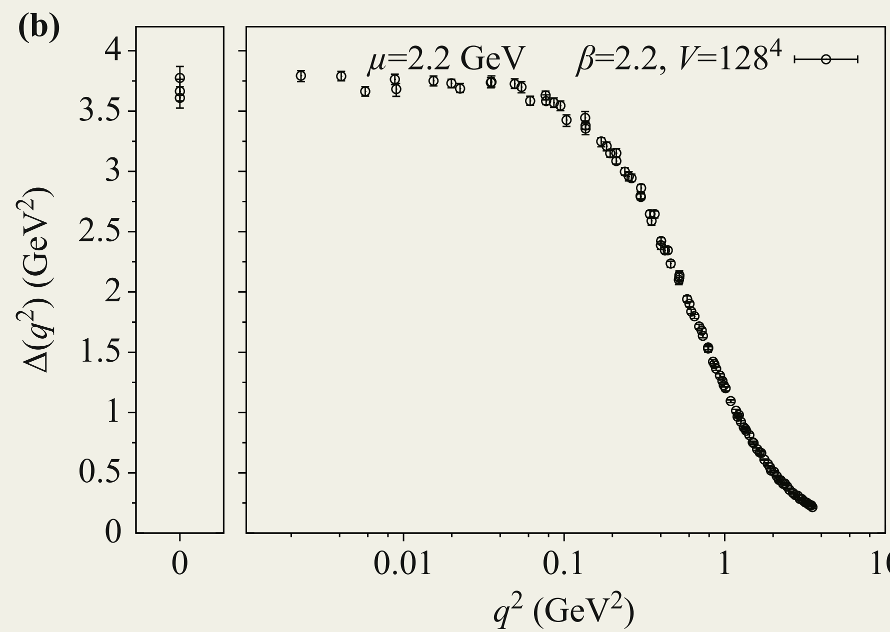
a) SU(3)



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]

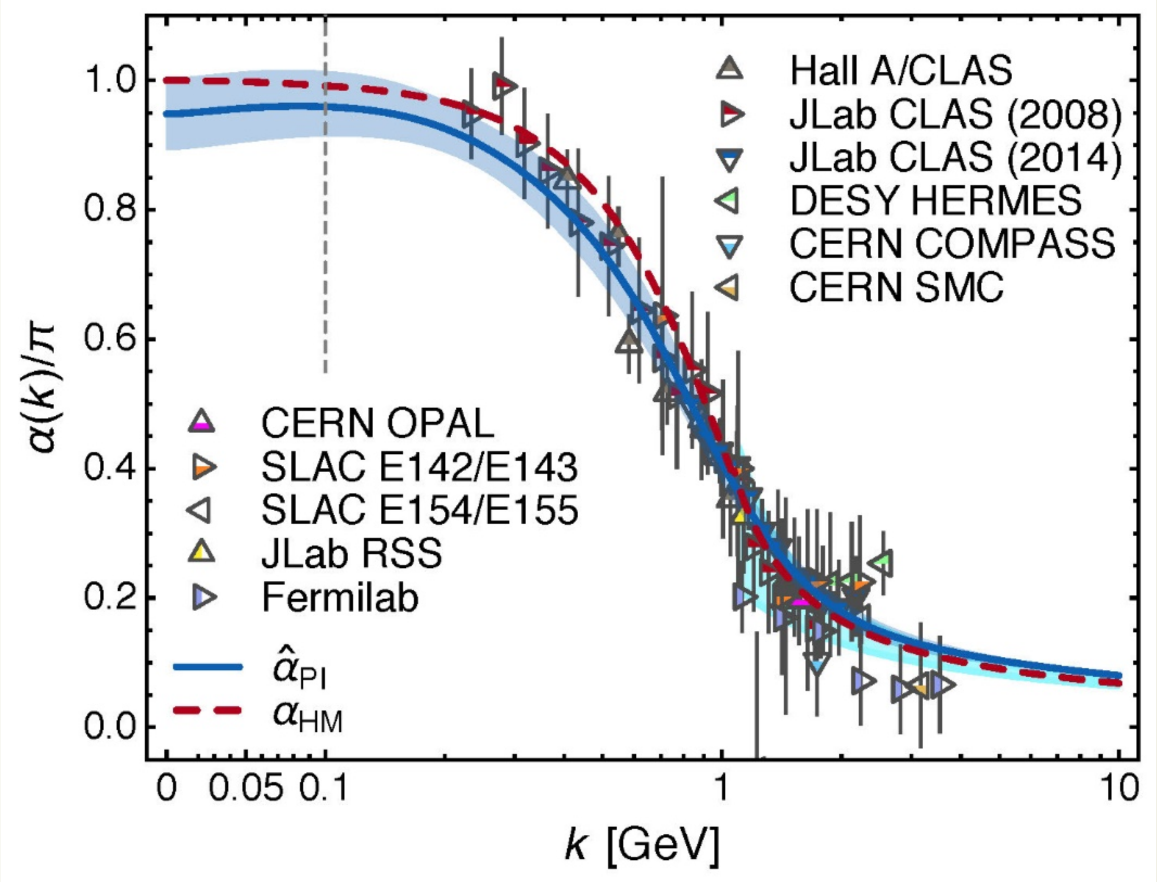
I. L. Bogolubsky, E. M. Ilgenfritz, M. Muller-Preussker, and A. Sternbeck, The Landau gauge gluon and ghost propagators in 4D SU(3) gluodynamics in large lattice volumes, arXiv: 0710.1968 [hep-lat]

b)SU(2)



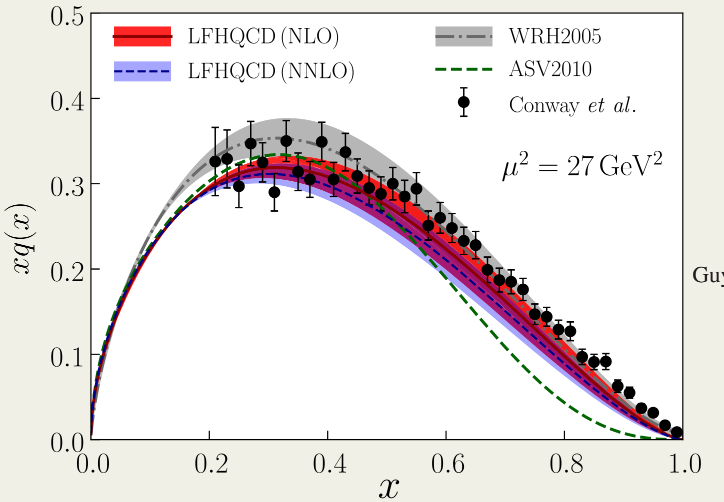
A. Cucchieri and T. Mendes, Numerical test of the Gribov–Zwanziger scenario in Landau gauge, *PoS QCD-TNT* 09, 026 (2009), arXiv: 1001.2584 [hep-lat]

Process-independent effective-charge in QCD



Modellers still insist on...

Nankai University 南開大學

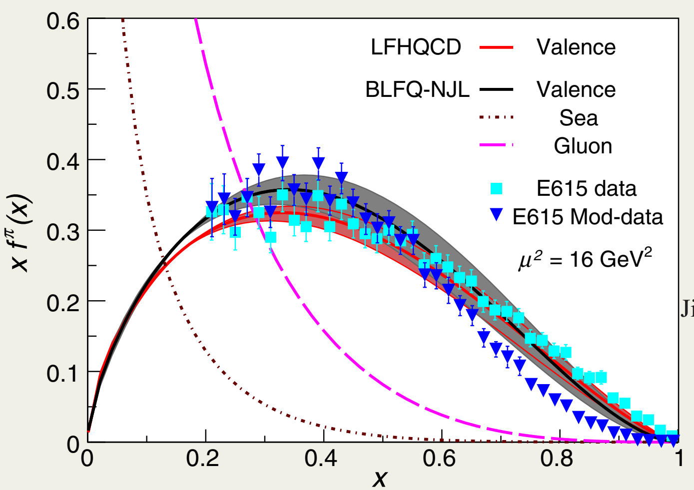


PHYSICAL REVIEW LETTERS **120,** 182001 (2018)

Universality of Generalized Parton Distributions in Light-Front Holographic QCD

Guy F. de Téramond,[1] Tianbo Liu,[2,3] Raza Sabbir Sufian,[2] Hans Günter Dosch,[4] Stanley J. Brodsky,[5] and Alexandre Deur[2]

(HLFHS Collaboration)



PHYSICAL REVIEW LETTERS **122,** 172001 (2019)

Parton Distribution Functions from a Light Front Hamiltonian and QCD Evolution for Light Mesons

Jiangshan Lan,[1,2,†] Chandan Mondal,[1,*] Shaoyang Jia,[3,‡] Xingbo Zhao,[1,2,§] and James P. Vary[3,‖]

(BLFQ Collaboration)