# Distribution of glue in the pion


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Perceiving the Emergence
of Hadron Mass through

**Regarding the distribution of glue in the pion**


Lei Chang (Nankai U.), Craig D Roberts (Nanjing U.) (Jun 15, 2021)

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Perceiving the EHM through AMBER@CERN-VI
2021/09/28, online

# Gluon !


Gluons are the most exotic gauge bosons in the Standard Model of particle physics (SM). Massless in perturbation theory; but, in the cleanest expression of the strong-interaction mass-scale anomaly, they are very massive when nonperturbative tools are used to solve the SM quantum field equations. The gluon mass dramatically changes the long-range behavior of Nature’s strong force

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.

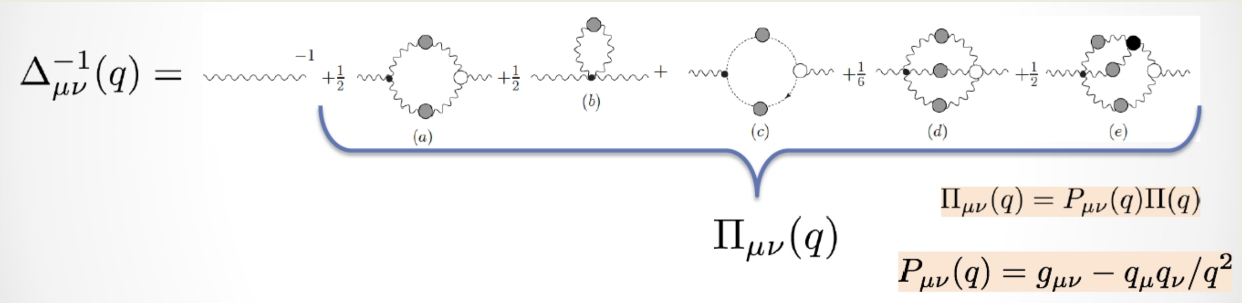
- Schwinger 1962

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

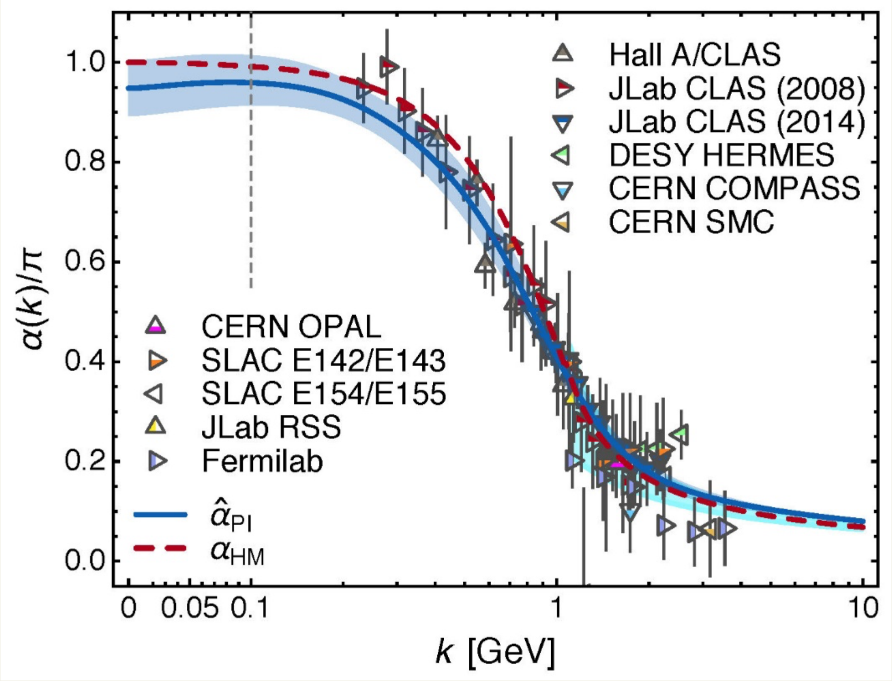



- Binosi & Papavassiliou

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

In QCD: Gluons become massive!

# PI running coupling of QCD

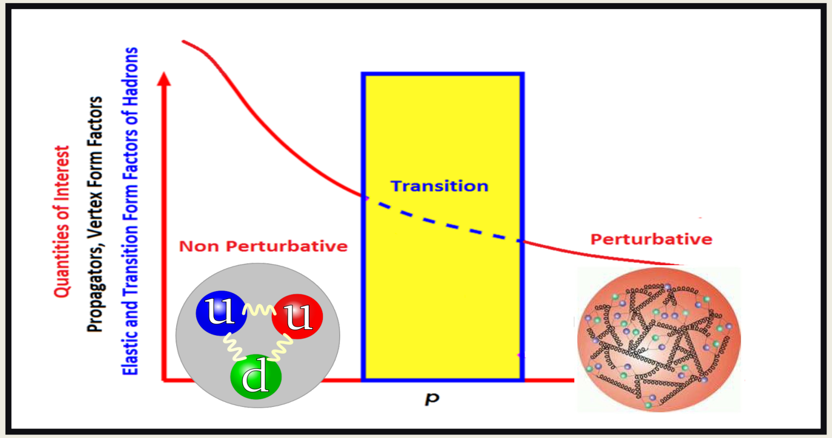



$$\hat{\alpha}(k^2) = \frac{\gamma_m \pi}{\ln\left[\frac{\mathcal{K}^2(k^2)}{\Lambda^2_{\rm QCD}}\right]}, \quad \mathcal{K}^2(y) = \frac{a_0^2 + a_1 y + y^2}{b_0 + y}$$

Define a screening mass:

$$m_G := \mathcal{K}(k^2 = \Lambda^2_{QCD}) = 0.331\text{GeV}$$

The running coupling alters at $m_G$ so that modes with $k^2<m^2$ are screened from interactions and theory enters a practically conformal domain.




- Compares well wiith world dat for Bjorken sumrule charge
- Saturates in the infrared region.

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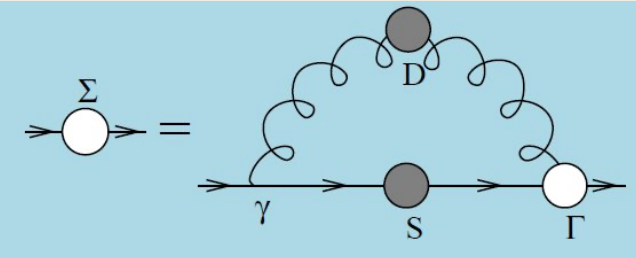
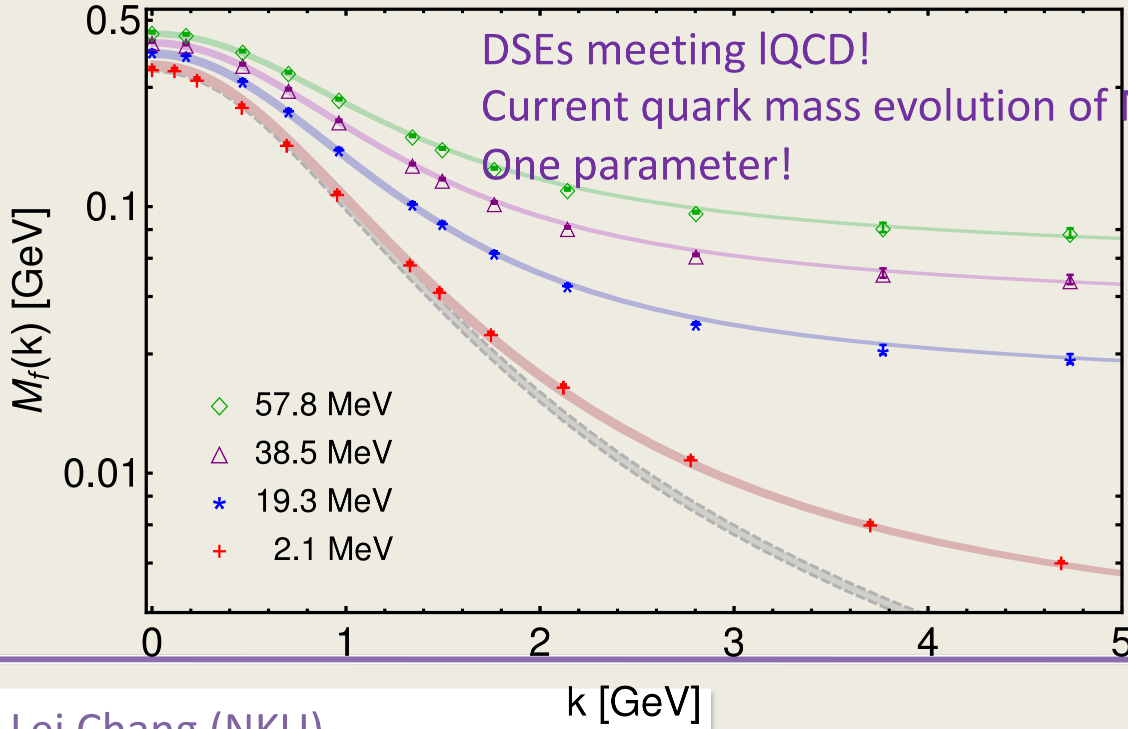



LC, and C.D.Roberts,PRL103(2009)081601, PRC85(2012)052201;
D. Binosi, et al., PLB742(20015) 183
Sixue Qin, C.D.Roberts, arXiv: 2009.13637




- Truncate quark-gluon vertex with DCSB-improvement ansatz;
- Performing the interaction from lattice QCD;
- Ward identity hold…guarantee proper current quark mass evolution;
- ACM generate quark mass and trigger DCSB.

## Perspective of DCSB

Mass scale introduced by PI coupling

⇩

Trigger quark mass

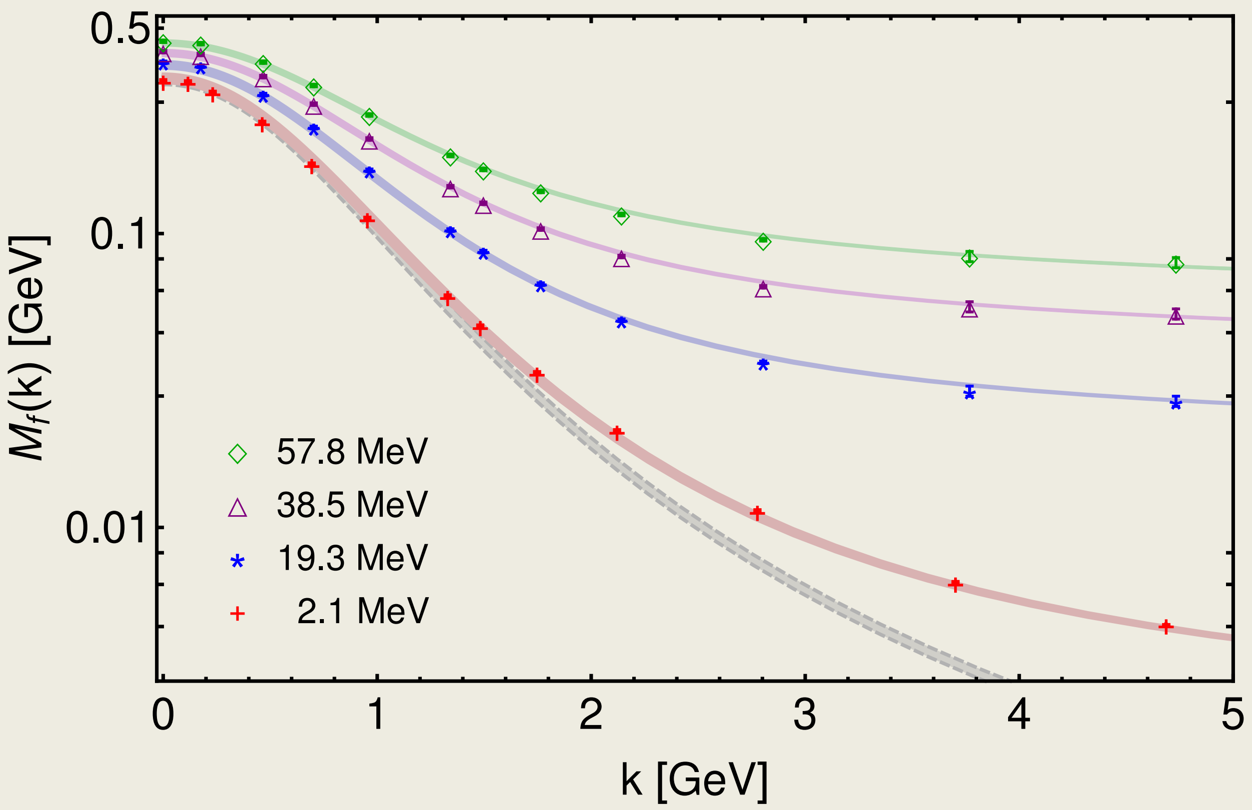
⇩

DCSB enhance quark-gluon coupling

Linking continuum and lattice quark mass functions via an effective charge
arXiv: 2105.06596, see Khepani's talk

# "Constituent" quarks






- In the chiral limit, the perturbative massless quark obtain a large infrared mass through the interactions of gluon;
- $M_0$ is about $m_p/3$ and runs as a logarithm-corrected $1/k^2$ power-law in the ultraviolet region;
- The strong interaction of a quark with its (gluon) surrounding gives rise to a "constituent" quark with effective mass $M_0$;
- This consistent quark has the finite size(B. Povh and J. Hufner, PLB245(1990)653);

Dressed-Quark Anomalous Magnetic Moments
Lei Chang, Yu-Xin Liu, and Craig D. Roberts
Phys. Rev. Lett. **106**, 072001 (2011) - Published 16 February 2011

# Measure Quark

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

$$S(p) = \frac{1}{i\gamma\cdot p\, A(p^2) + B(p^2)}$$

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

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

2M+U=0

$r_M \approx r_\pi$

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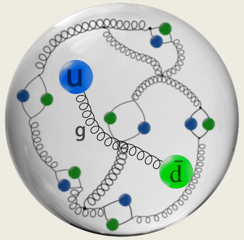
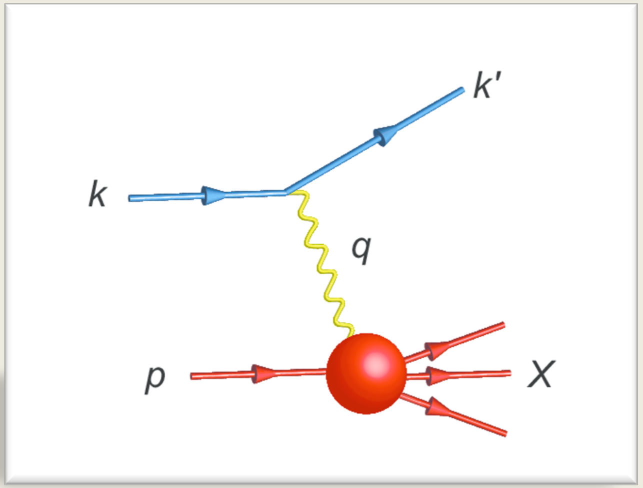
- The gluon has been hidden in the constituent quarks;
- At hadronic scale, the pion is constructed by two constituent quarks which are overlapped largely;
- Let gluon show up!

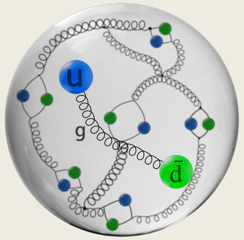



**GENESIS 1. The beginning**
In the beginning God created quarks,
And made them interact through the strong forces,
And it was dark ...
And God said, "I do not understand a damn thing",
And so he said "Let there be photons",
And there was light ...

# Probing glue

- The gluon has been hidden in the constituent quarks;
- At hadronic scale, the pion is constructed by two constituent quarks which are overlapped largely;
- Let gluon show up!




One-loop DGLAP with the effective charge

$$\frac{\partial q^{NS}}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} P_{qq} \otimes q^{NS} ,$$

$$\frac{\partial}{\partial \ln \mu^2} \begin{pmatrix} q^S \\ g \end{pmatrix} = \frac{\alpha_s(\mu^2)}{2\pi} \begin{pmatrix} P_{qq} & 2n_f\, P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} q^S \\ g \end{pmatrix} ,$$

$$\tilde{\alpha}(k^2) = \frac{\gamma_m \pi}{\ln\left[\frac{\mathcal{K}^2(k^2)}{\Lambda^2_{\rm QCD}}\right]} ,$$

$$\mathcal{K}^2(y) = \frac{a_0^2 + a_1 y + y^2}{b_0 + y}$$

with $\{a_0,\ a_1,\ b_0\} = \{0.104(1), 0.0975, 0.121(1)\}$

The sea quarks can arise from gluon splitting, xS(x) is expected to follow the trend of xg(x).

# The scale dependence of momentum fractions

Pure valence(no gluon no sea) at hadronic scale picture

u $\bar{d}$

1, Valence quarks carry all the momentum
2, the scale dependence of momentum fractions does not depend on the details of valence distribution at hadronic scale
3, a closed equation can be derived

$$\langle 2x(\zeta_{\rm ex})\rangle_q = \exp\left(-\frac{8}{9\pi}S\left(\zeta_H,\zeta_{\rm ex}\right)\right),$$

$$\langle x(\zeta_{\rm ex})\rangle_{\rm sea} = \frac{3}{7}+\frac{4}{7}\langle 2x(\zeta_{\rm ex})\rangle_q^{7/4} - \langle 2x(\zeta_{\rm ex})\rangle_q,$$

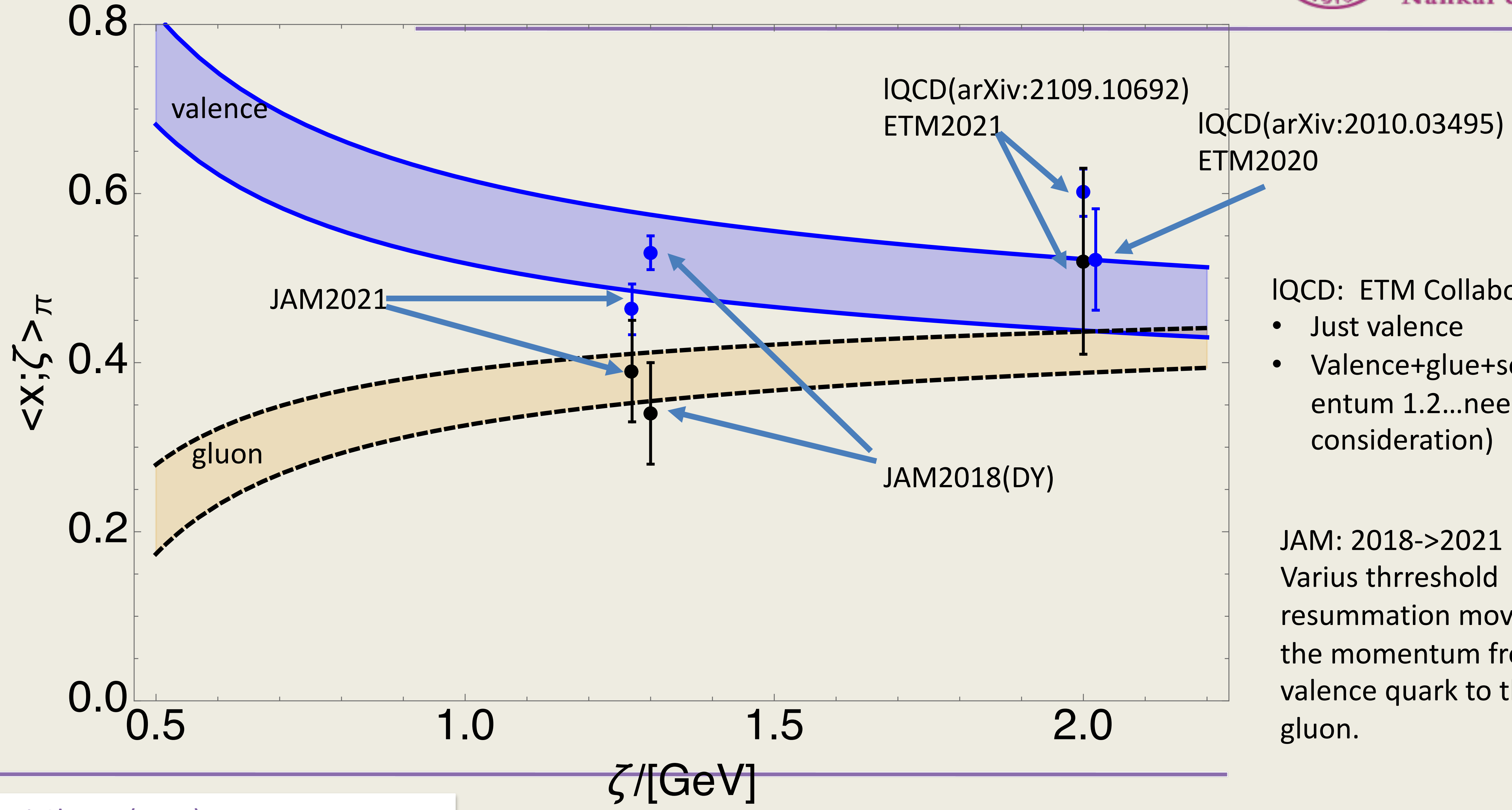
$$\langle x(\zeta_{\rm ex})\rangle_{\rm glue} = \frac{4}{7}\left(1-\langle 2x(\zeta_{\rm ex})\rangle_q^{7/4}\right),$$

with

$$S\left(\zeta_H,\zeta_{\rm ex}\right) = \int_{t(\zeta_H)}^{t(\zeta_{\rm ex})} dt(\zeta)\,\widetilde{\alpha}(t(\zeta))$$

and $t(\zeta)=\ln\left(\zeta^2/\Lambda^2_{\rm QCD}\right)$.

# Momentum evolution(valence quarks and gluon)



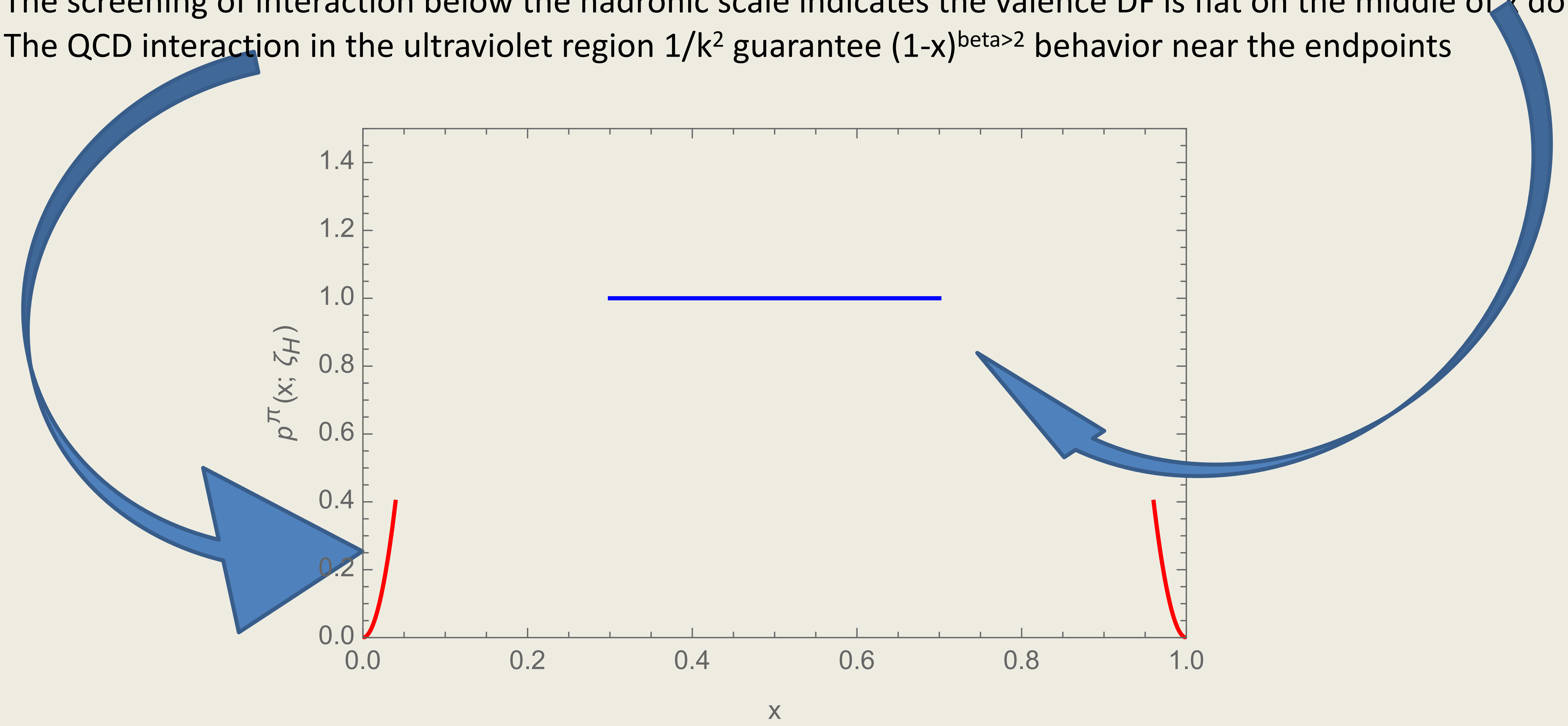

lQCD: ETM Collaboration

- Just valence
- Valence+glue+sea(momentum 1.2…need more consideration)

JAM: 2018->2021
Varius thrreshold resummation move 5% of the momentum from the valence quark to the gluon.

# Valence parton distribution of pion at the hadronic scale

- Valence DF(x) is symmetric function under $x \to 1 - x$(isospin symmetry)
- The screening of interaction below the hadronic scale indicates the valence DF is flat on the middle of x domain
- The QCD interaction in the ultraviolet region $1/k^2$ guarantee $(1\text{-}x)^{beta>2}$ behavior near the endpoints

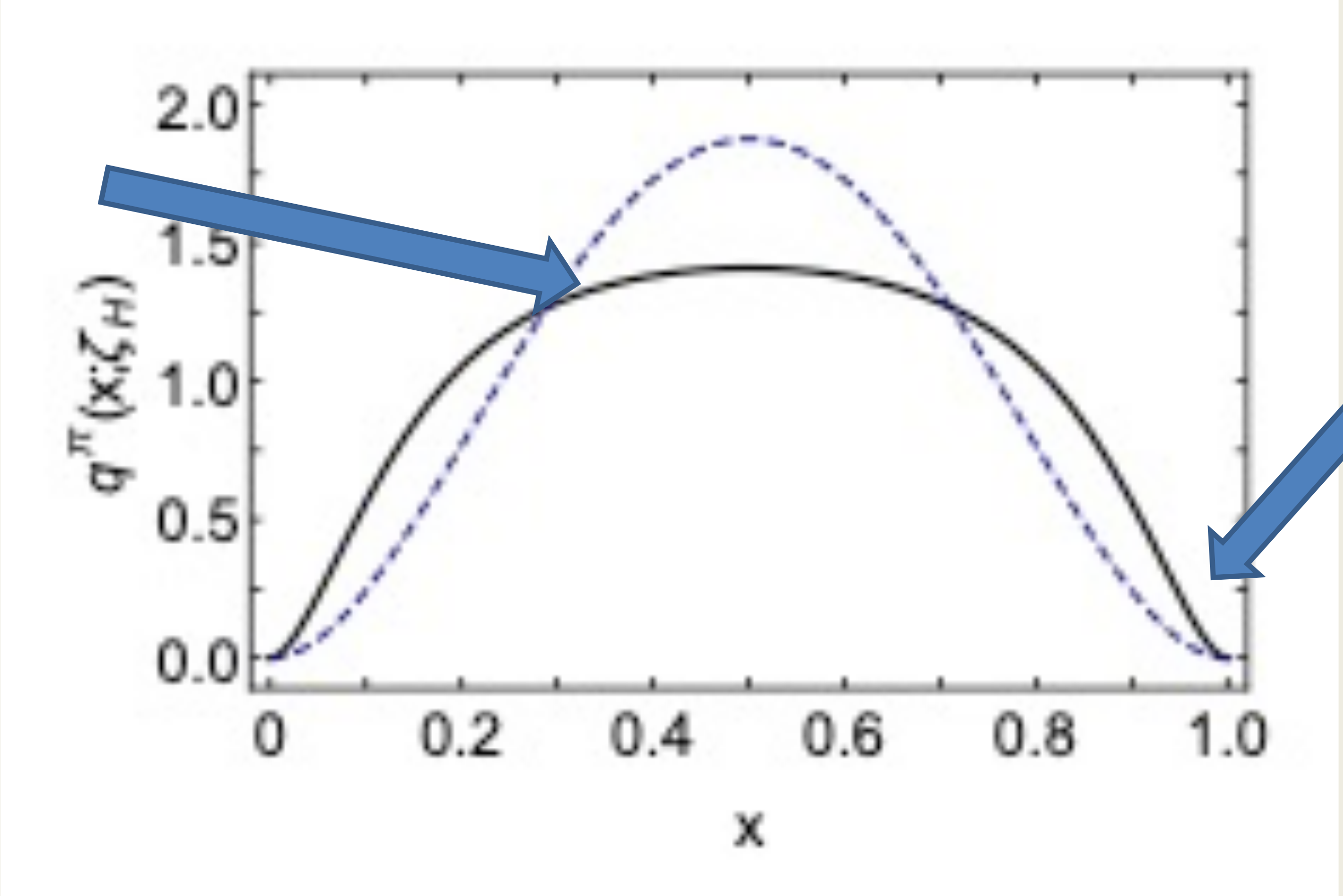


# Valence parton distribution of pion at the hadronic scale

We evaluated the BSE at the hadronic scale with DB improved kernel
Project the wave function on the light front

Minghui Ding, *et al.*, arXiv:1912.07529
Zhu-Fang Cui, *et al.*, arXiv:2006.14075

- DF of valence parton is broad…
  the infrared interaction behavior, constituent quark picture
- At hadronic scale, DF(x) sim DA(x)$^2$

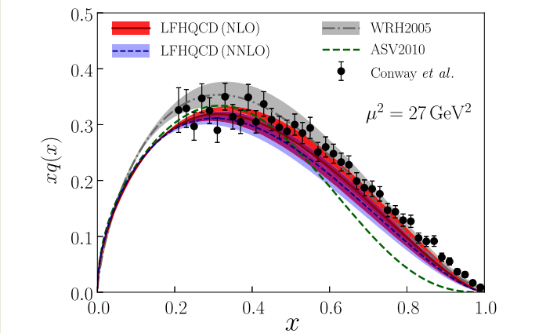



- (1-x)$^2$ near the endpoints which is the natural output of interacion 1/k$^2$
- The exponent would increase with increasing of scale

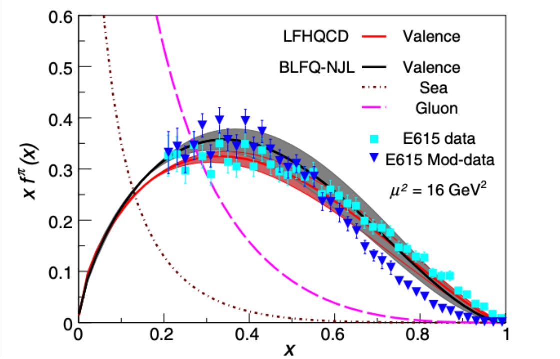
# Large x

CSM community insists $(1-x)^{\beta}$; $\beta \geq 2$ !

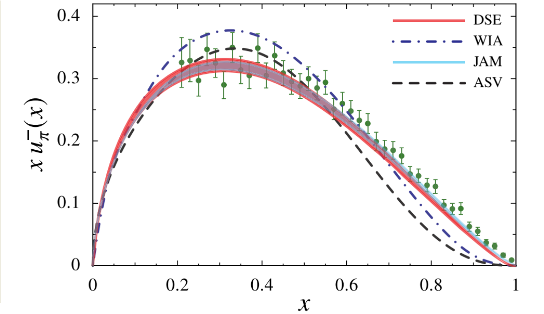





PHYSICAL REVIEW LETTERS **120,** 182001 (2018)

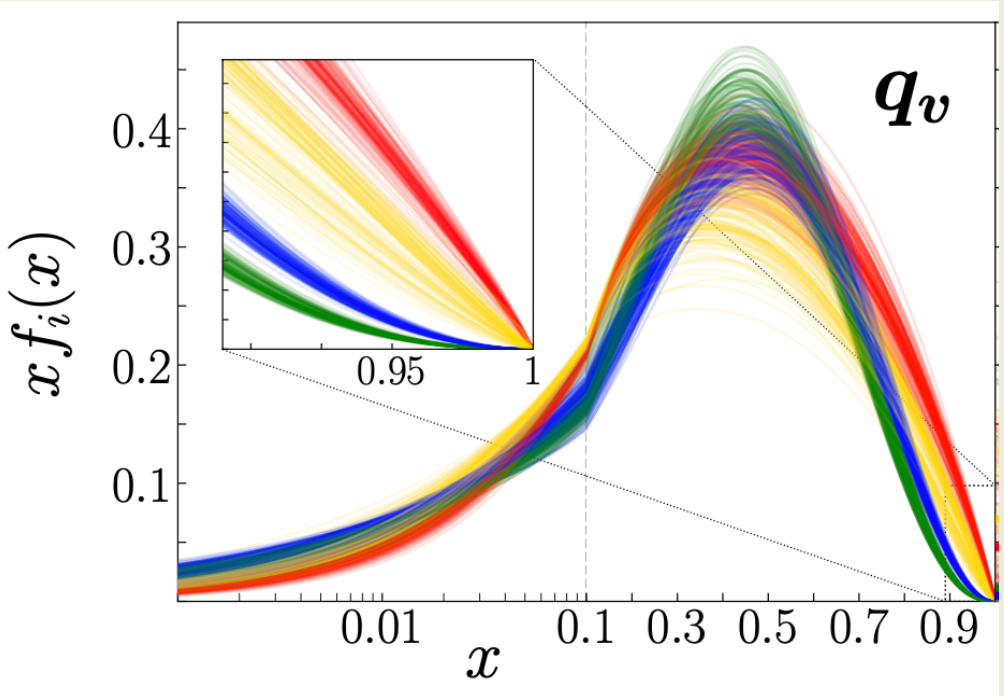



PHYSICAL REVIEW LETTERS **122,** 172001 (2019)



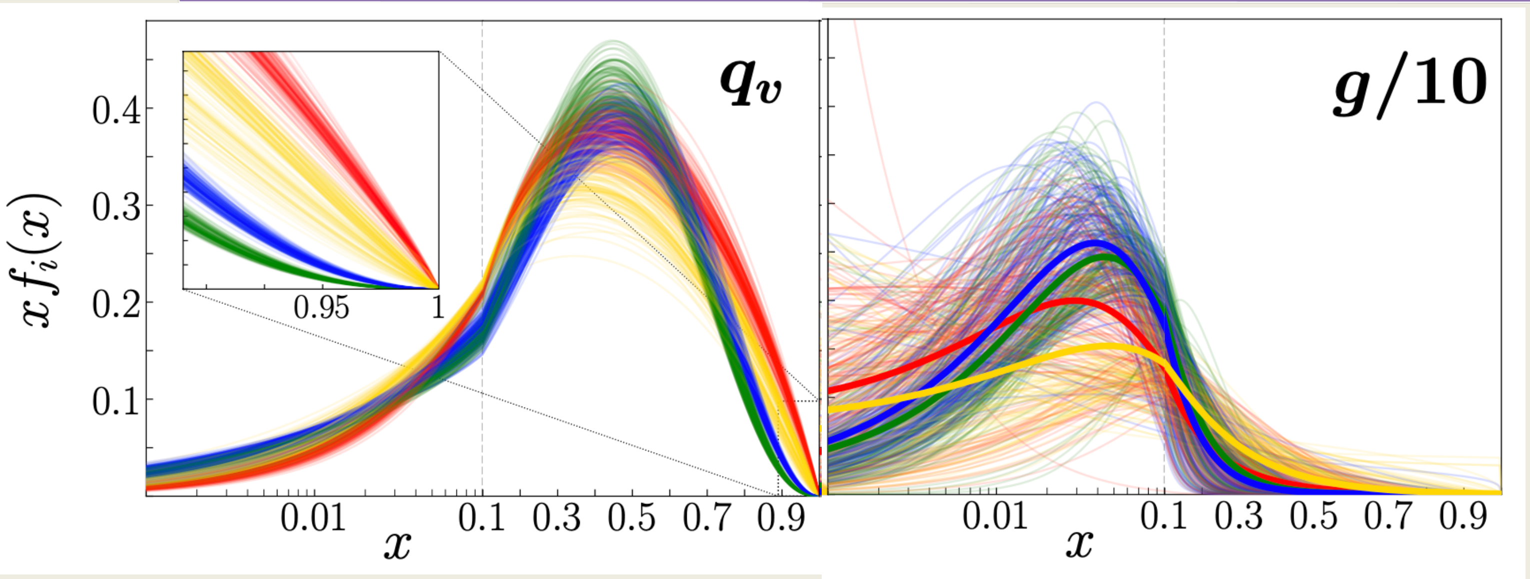

PHYSICAL REVIEW LETTERS **124,** 042002 (2020)

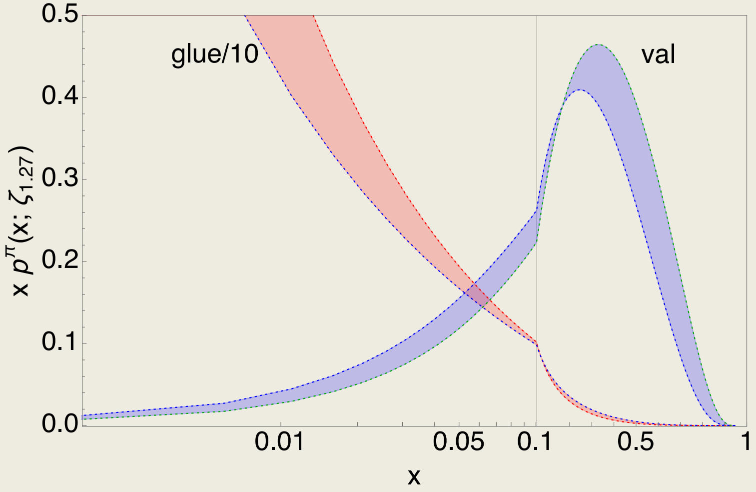
**Global Fit(JAM2021, arXiv:2108.05822, $\mu_0 = 1.27GeV$)**




- JAM2018: For the valence PDF in the large-x region, our analysis find a behavior (1-x) at the input scale.
- JAM2021(resummation): This suggests that with currently available data and theoretical methods, we cannot distinguish between 1 and 2 asymptotic behavior.

# DFs in the pion: JAM and CSM

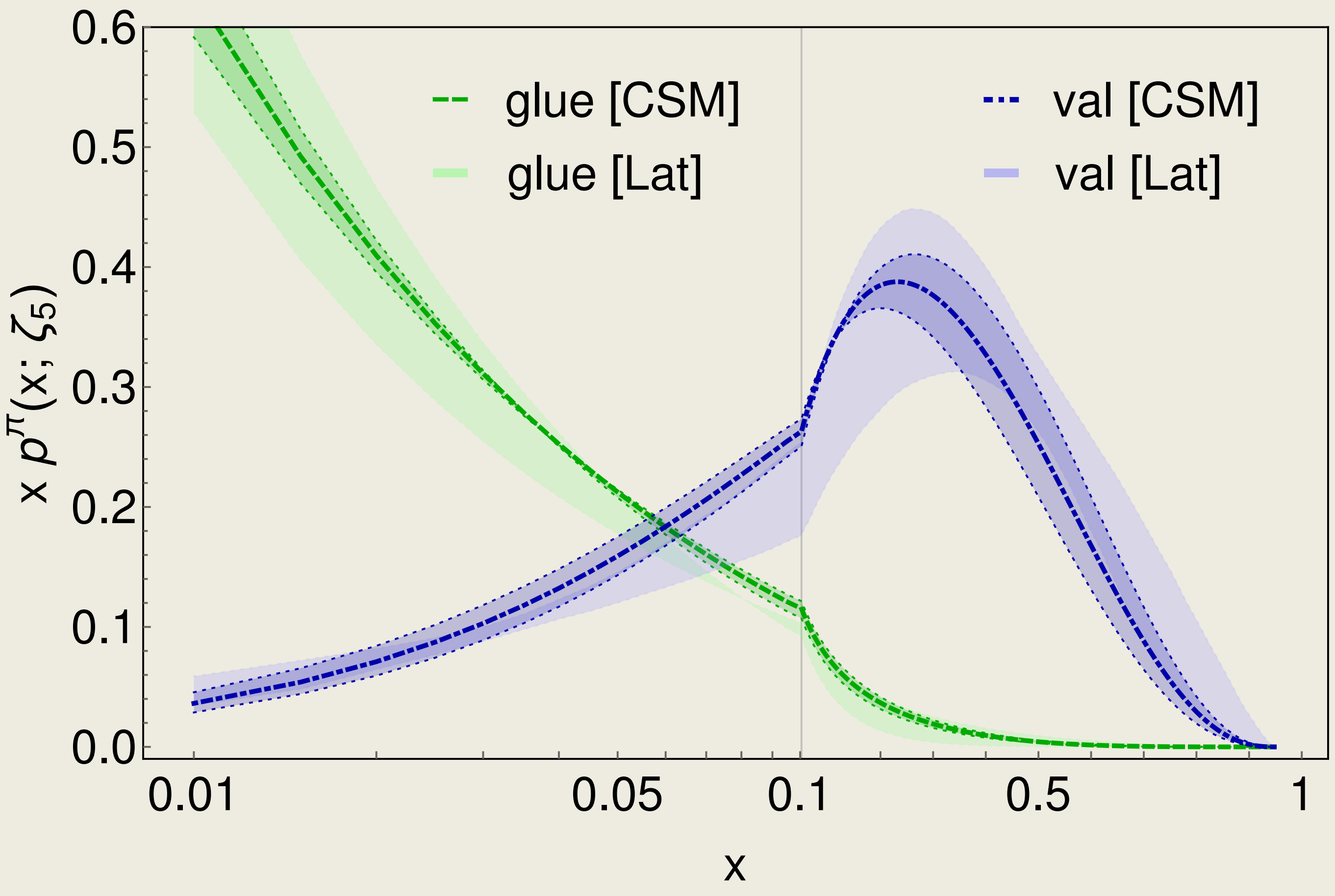



- Evolute DF from my hadronic scale to $\mu_0$=1.27GeV
- The valence distributionis comparable on the entire x region for some resummation methods.
- Regarding the glue DF, our predition agrees on $x \geq 0.05$; but they are markedly different on the complementary domain.
- These observations highlight the need for new experiments that are directly sensitive to the pion's gluon content.

# DFs in the pion: lQCD and CSM






- Val[Lat] Sufian et al., arXiv: 1901.03921

(Using lattice-calculated matrix element obtained through spatially separated current-current correlations in coordinate space)

- Glue[Lat] Fan et al., arXiv: 2104.06372

(Using pseudo-PDF approach)

➢ Within uncertainties, there is pointwise agreement between the two results on the entire depicted domains

# Thanks for your attention