Unveiling the inner structure of mesons

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XVIII International Conference on Hadron Spectroscopy and Structure

Guilin, China. Aug 16-21, 2019

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In Collaboration with...

L. Chang, M. Ding, C.D. Roberts...

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Motivation

- Decades after the formulation of the fundamental theory of quarks and gluons, **Quantum Chromodynamics (QCD)**, understanding the strong interactions is still being a challenge.

- QCD is characterized by two emergent phenomena: **confinement** and **dynamical chiral symmetry breaking.**

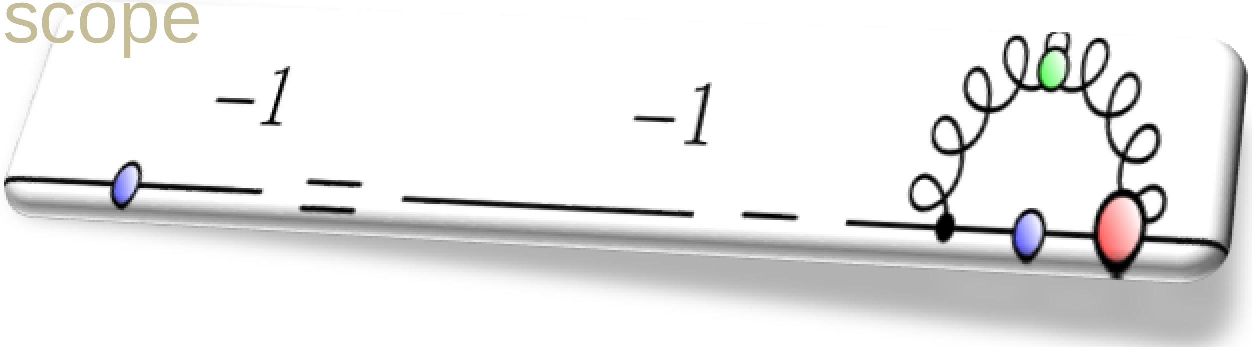
- Due to the non perturbative nature of QCD, studying the hadron structure, from first principles, is an outstanding problem.

- I shall present a unified treatment, based on **Dyson-Schwinger equations**, to compute a choice of parton distributions within the pion and neutral pseudoscalar mesons.

- Our treatment is suitable for other mesons and baryons as well.

Outline

1. Dyson-Schwinger equations (**DSEs**)
2. Parton Distribution Amplitudes (**PDAs**)
3. Electromagnetic Form Factors
   - Pion elastic form factor (**EFF**)
   - Pion transition form factor (**TFF**)
4. Parton Distribution Functions (**PDFs**)
5. Conclusions and scope

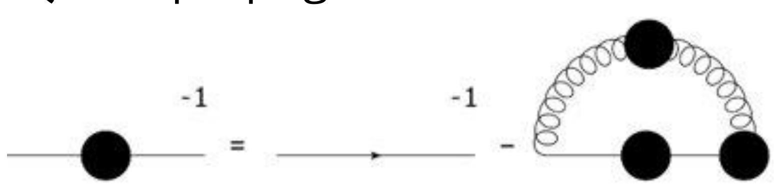


DSEs: Quark Propagator

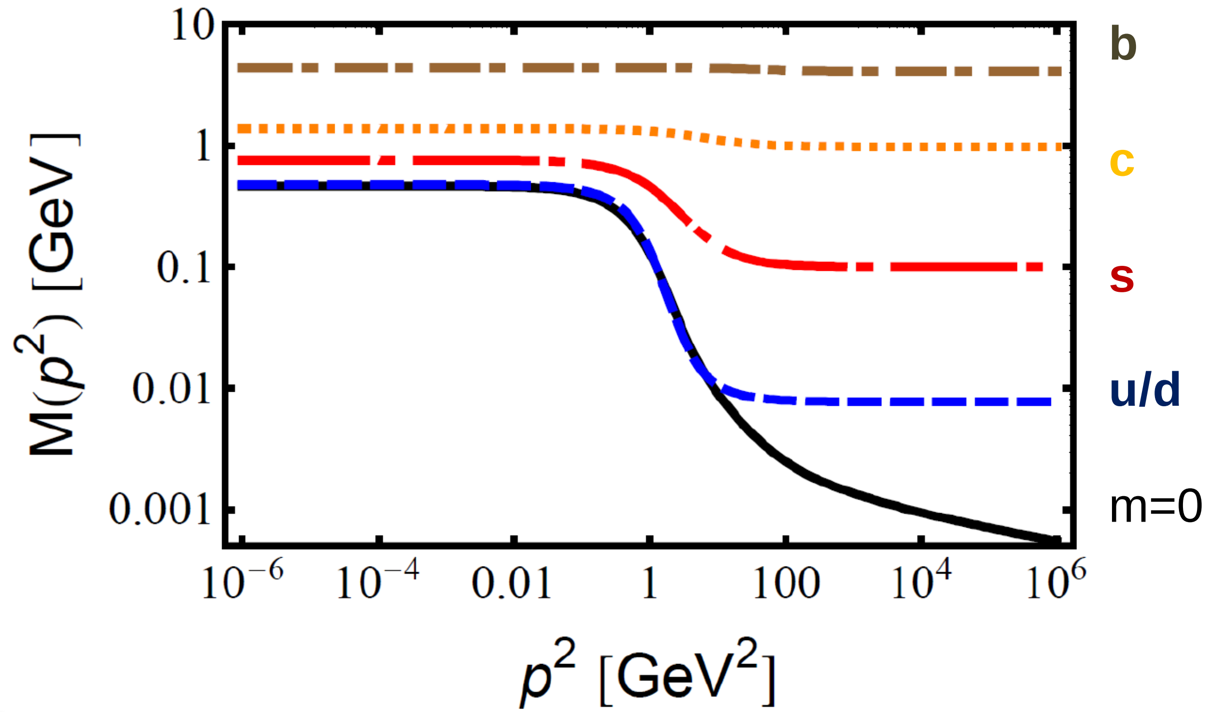
- **DCSB** is responsible for ***almost all*** of the mass of the visible universe. It is encoded in the quark propagator:

$$S(p;\zeta) = \frac{Z(p^2;\zeta)}{p^2 + M(p^2)}$$

- The lighter the quark is, the stronger the effect of DCSB.
- **Notably,** in the chiral limit, a dynamically generated mass appears.
- Quark propagator DSE:



Dynamically generated mass **Current-quark mass**

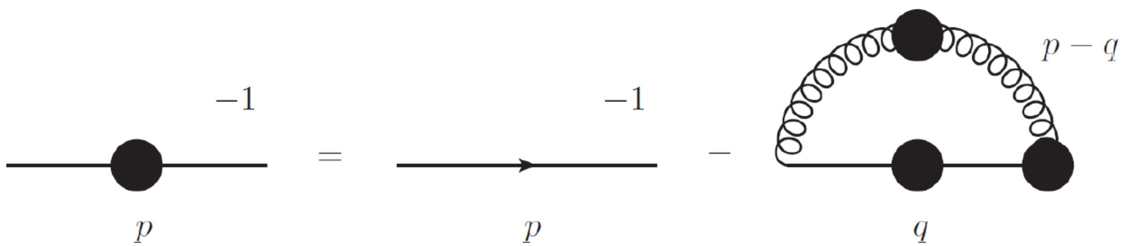


Few Body Syst. 58 (2017) no.1, 5

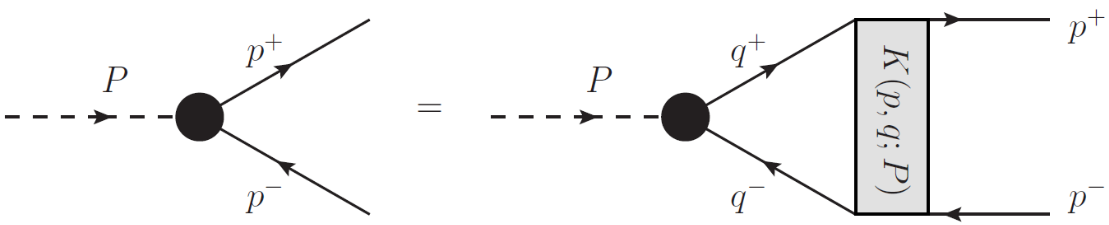
DSE-BSE approach

- **DSEs** are an infinite tower of coupled equations, which **must be systematically truncated** in order to extract the encoded physics.

- The quantum field theory (QFT) equation that describes quark-antiquark boundstates is the Bethe-Salpeter equation (BSE). Together with the DSE for the quark propagator, those are depicted as:



Quark DSE



Meson BSE

- In which the **DSEs** and the quark-antiquark **scattering kernel are related through the axial-vector Ward-Takahashi identity.**

Phys.Lett. B733 (2014) 202-208

DSE-BSE approach

- A symmetry-preserving truncation, sufficient for many needs, is the **rainbow-ladder truncation** (**RL**).

arXiv:1905.05208, Phys.Rev. C85 (2012) 052201

- Besides accurately describing pseudoscalar* and light vector mesons, it guarantees the preservation of the Goldstone's Theorem:

$$f_\pi E_\pi(k; P=0) = B(k^2)$$

"Goldstone's theorem"

$$\Gamma_\pi(k;P) = \gamma_5[iE_\pi(k;P) + \gamma\cdot P F_\pi(k;P) + \gamma\cdot k k\cdot P G_\pi(k;P) + k_\alpha \sigma_{\alpha\beta} P_\beta H_\pi(k;P)]$$

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

Phys.Lett. B420(1998) 267-273

* Non-Abelian anomaly is required for eta-eta' mesons
See M. Ding's talk

DSE-BSE approach

- The most fundamental expression of Goldstone's Theorem and DCSB:

$$f_\pi E_\pi(k; P=0) = B(k^2)$$

“Goldstone’s theorem”

$E_\pi(p^2)$: Leading Bethe-Salpeter amplitude $\quad B_\pi(p^2) \sim M(p^2)$: quark mass function

- The above relationship is **exact in** the **chiral limit**.

- It implies that the **two body** problem is **solved**, almost completely, **once** the solution of **one body** problem **is known**.

- **Remark**: **Pions** exist if, and only if, **DCSB** is realized.

Phys.Lett. B420(1998) 267-273

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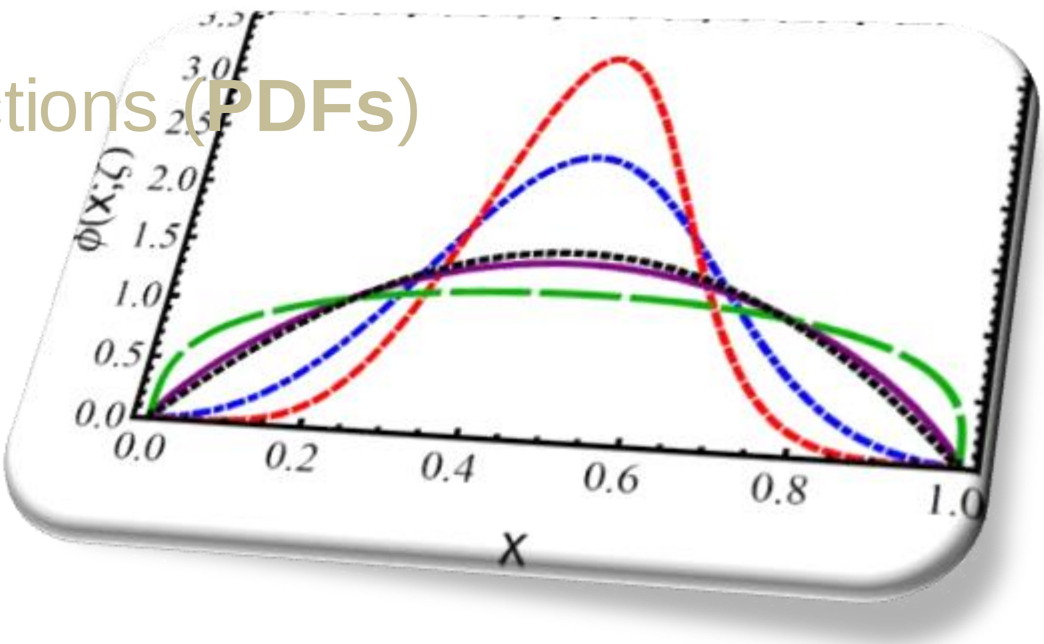


Parton Distribution Amplitudes

- The PDA is the projection of the meson BS wavefunction onto the light-front. It is process independent and **plays a crucial role** in the **understanding** meson's properties.

- Given a **pseudoscalar** meson, the **PDA** reads as:

$$f_H \phi_H(x;\zeta) = Z_2 \int_q \delta(n\cdot q + x\, n\cdot P)\gamma_5 \gamma\cdot n[S(q^+)\Gamma_H(q;P)S(q^-)] \,.$$

- The **moments** of the distribution:

$$<x^m>_\zeta = \int_0^1 dx x^m \phi(x;\zeta) = \mathrm{tr} Z_2 \int_q \frac{(n\cdot q^+)^m}{(n\cdot P)^{m+1}} \gamma_5 \gamma\cdot n \,\chi_H(q;P) \,.$$

Light-cone four-vector *n*:

$$n^2 = 0 \,, n\cdot P = -m_M \,, P^2 = -m_M^2$$

Phys.Rev.Lett. 110 (2013) no.13, 132001
Phys.Rev. D22 (1980) 2157

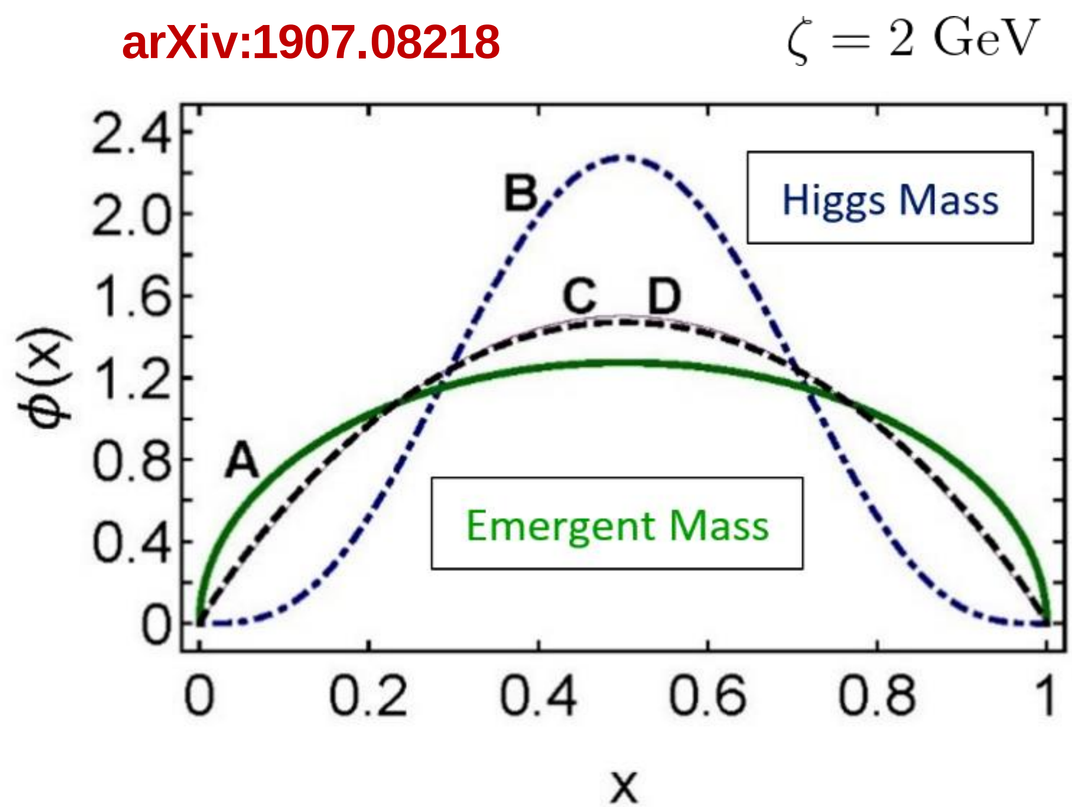
Parton Distribution Amplitudes

- **Light sector**:
  Broad and concave PDAs. Largely influenced by **DCSB**.

- **Heavy sector**:
  Narrow PDAs. Largely influenced by **Higgs** mass generation.

- **s-quark** mass is the **boundary** between dominance of strong and Higgs mass-generation.

arXiv:1907.08218



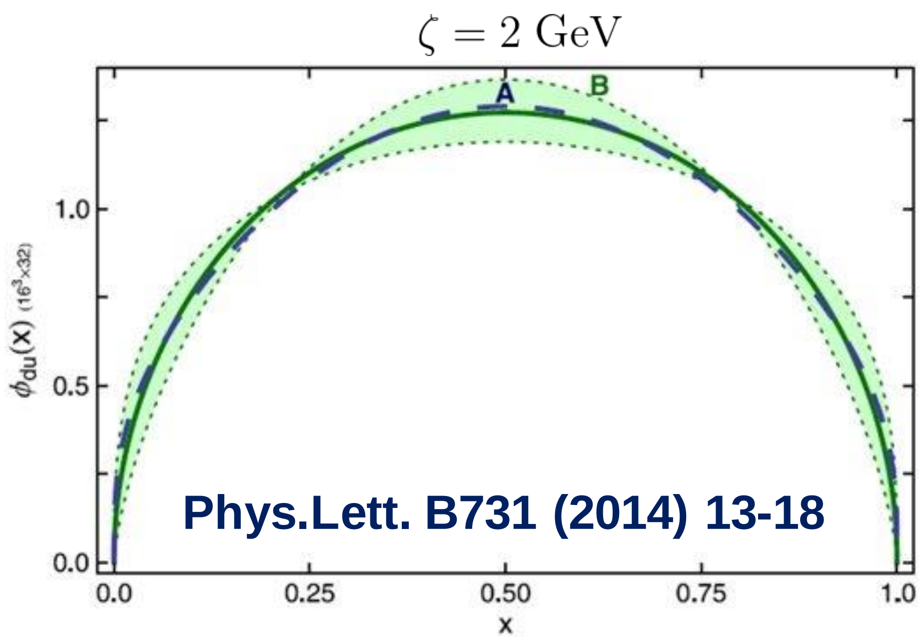
- [Green]: $\phi_{\pi}(x)$.
- [Blue]: $\phi_{\eta_c}(x)$.
- [Black]: $\phi_{\eta_s}(x)$.
- [Purple]: $\phi_{CL}(x) = 6x(1-x)$.

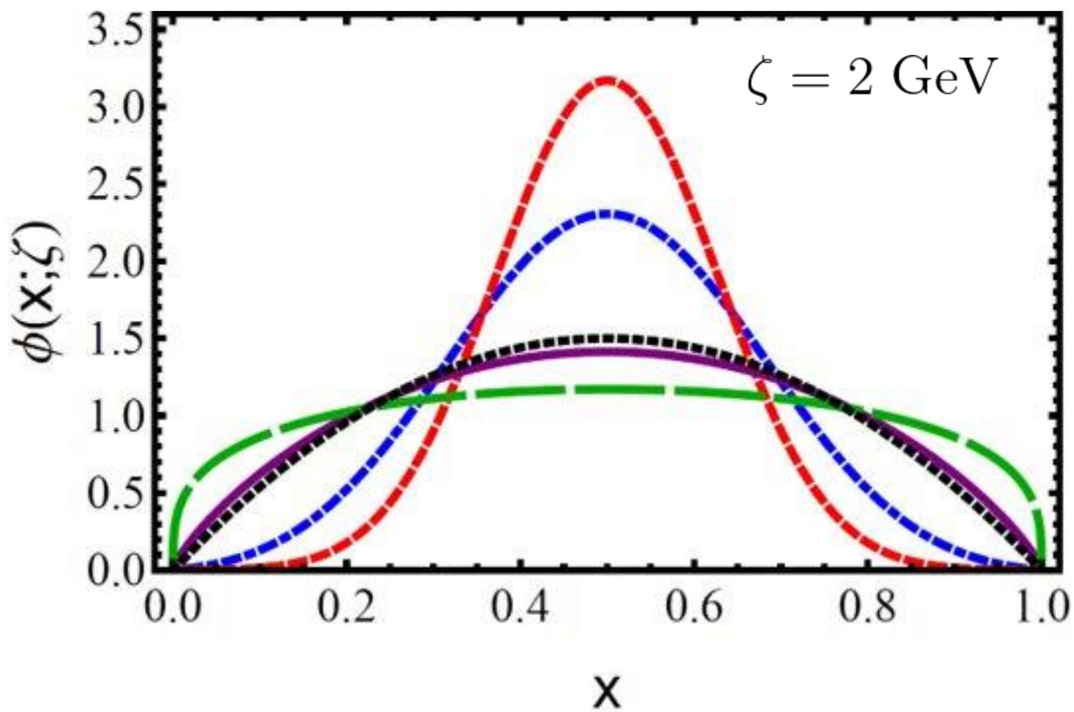
Phys.Rev. D22 (1980) 2157

Parton Distribution Amplitudes

➢ **Light sector**:
Dilation of the light meson PDAs is supported by lattice:

- **Phys.Rev. D83 (2011) 074505**
- **Phys.Rev. D95 (2017) no.9, 094514**
- **arXiv:1903.08038**



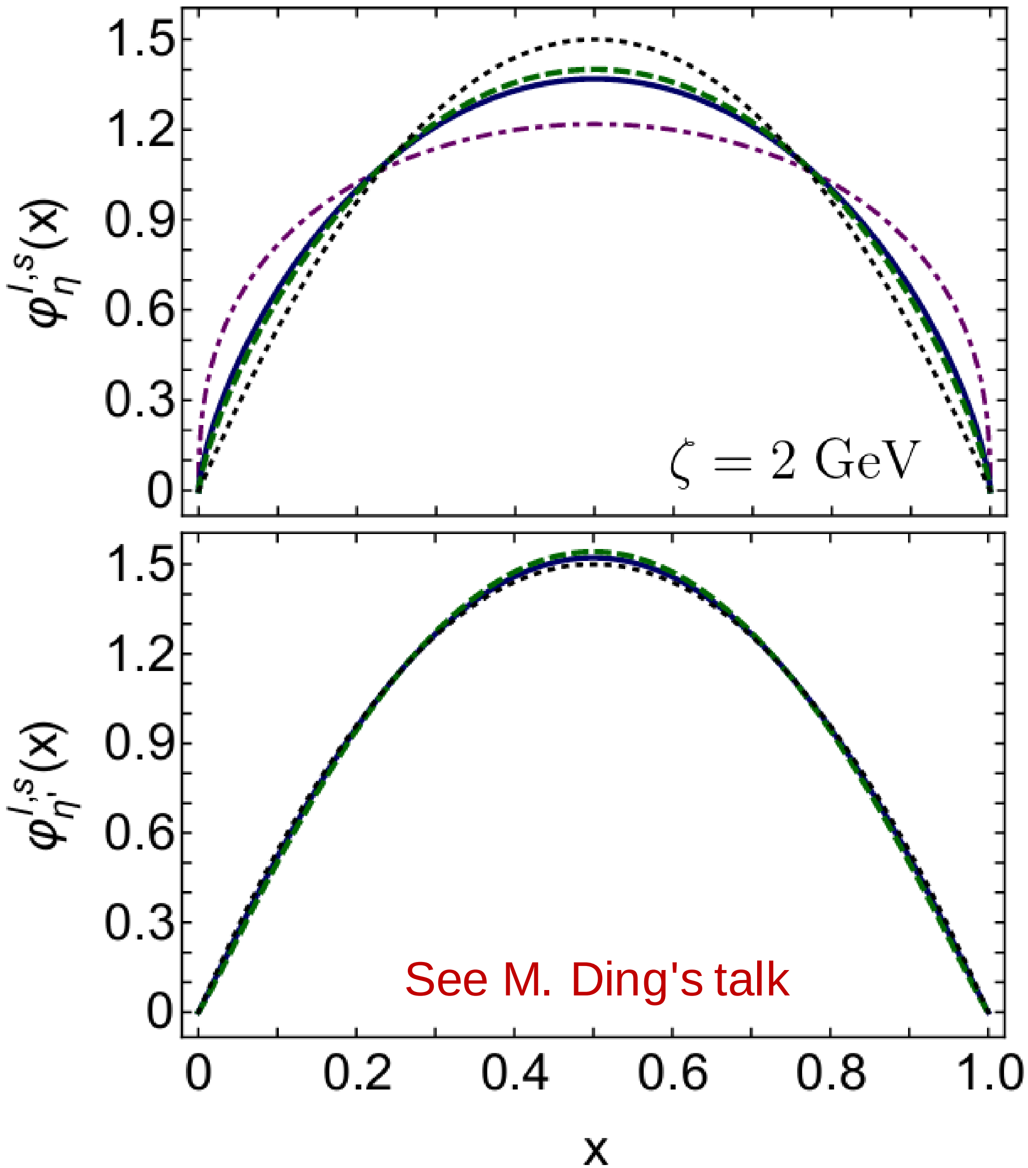


- [Green]: $\phi_\pi(x)$.
- [Red]: $\phi_{\eta_b}(x)$.
- [Purple]: $\phi_{\eta_s}(x)$.
- [Blue]: $\phi_{\eta_c}(x)$.
- [Black]: $\phi_{CL}(x) = 6x(1-x)$.

Phys.Rev.Lett. 110 (2013) no.13, 132001
Phys.Lett. B753 (2016) 330-335
Phys.Rev. D99 (2019) no.1, 014014

Parton Distribution Amplitudes

- **Interplay** between **emergent** and **explicit** mass generation in the Standard Model:
  - *'light'* and *'s'* quark **PDAs**, whithin the **eta-eta'** mesons, exhibit **similar profiles**.
  - But, in contrast to the eta meson, **eta' PDAs** are **narrower** than the **CL**.
  - Nonetheless, all PDAs are fairly **approximated** by the **conformal distribution**.



[Pion] [l = *u/d* quarks] [s quark]

Phys.Rev. D99 (2019) no.1, 014014

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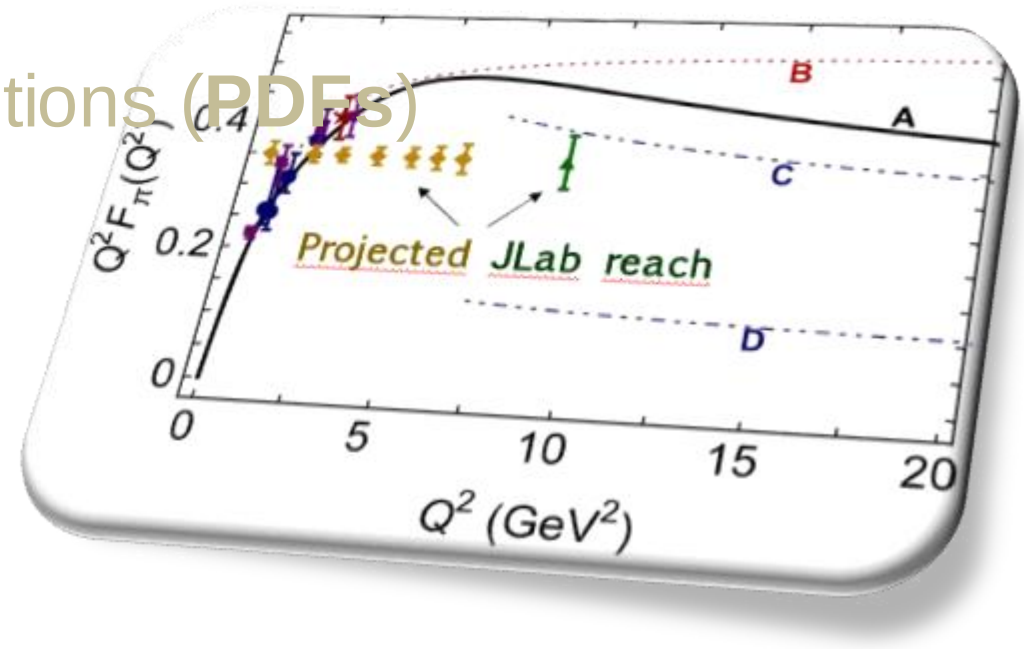
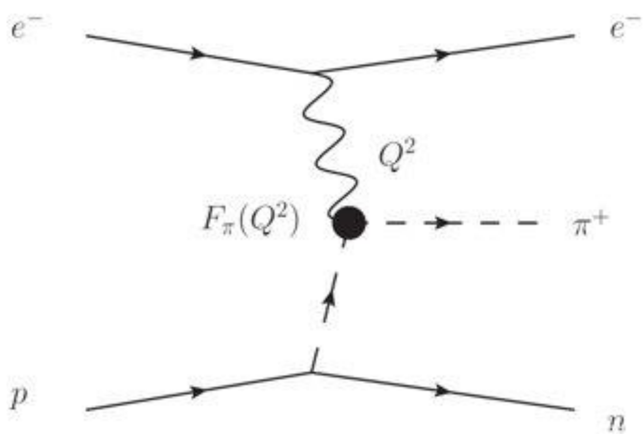
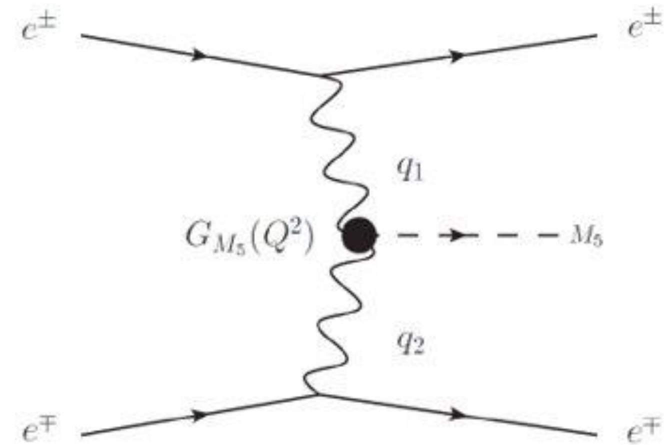


Pion elastic and transition FFs

- Electromagnetic structure of mesons is revealed via form factors:



Elastic form factor (EFF)



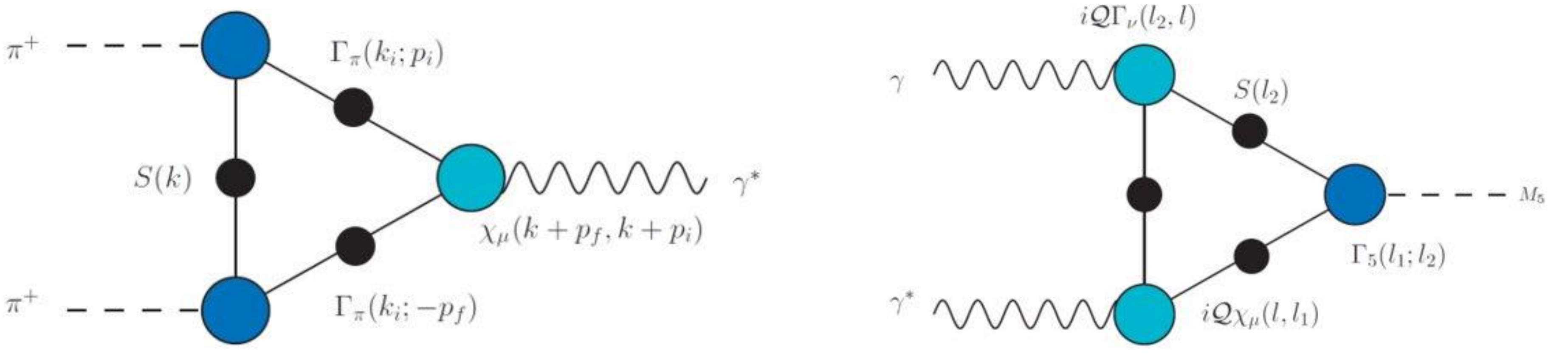
γ- Transition form factors (TFFs)

- **EFF**: **Studied** at JLab. **Important** for its 12 GeV Program.

- **TFFs**: **Studied** at Babar, Belle, etc. **Important** for Belle II and BES III experiments. **Crucial input** for muon's anomalous magnetic moment measurements at J-Parc and Fermilab.

Pion elastic and transition FFs

- In the impulse approximation, those form factors are depicted as:



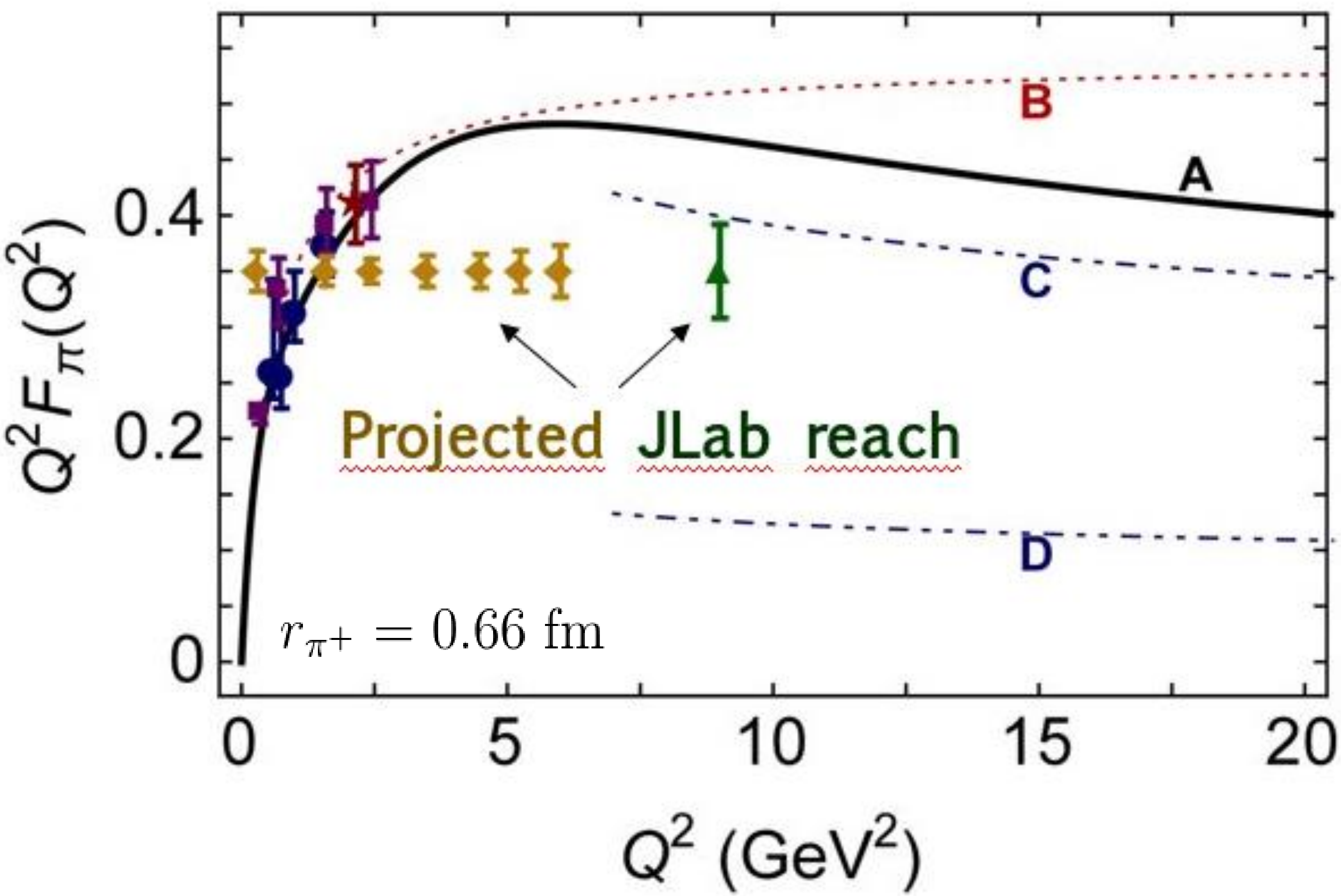
- **Quark propagator** and **meson BSA** are obtained from **solutions** of the corresponding **DS-BS equations** (quark-photon vertex can be written in terms of quark propagator dressing functions).

- **Perturbation theory integral representations** of those elements allow to compute the form factors for **arbitrarily large** space-like **momenta**.

Phys.Rev. D93 (2016) no.7, 074017
Phys.Rev.Lett. 111 (2013) no.14, 141802
Phys.Rev. D99 (2019) no.1, 014014
Phys.Rev. D95 (2017) no.7, 074014

Pion elastic form factor

Phys.Rev.Lett. 111 (2013) no.14, 141802. Chang *et al.*



DSE Prediction

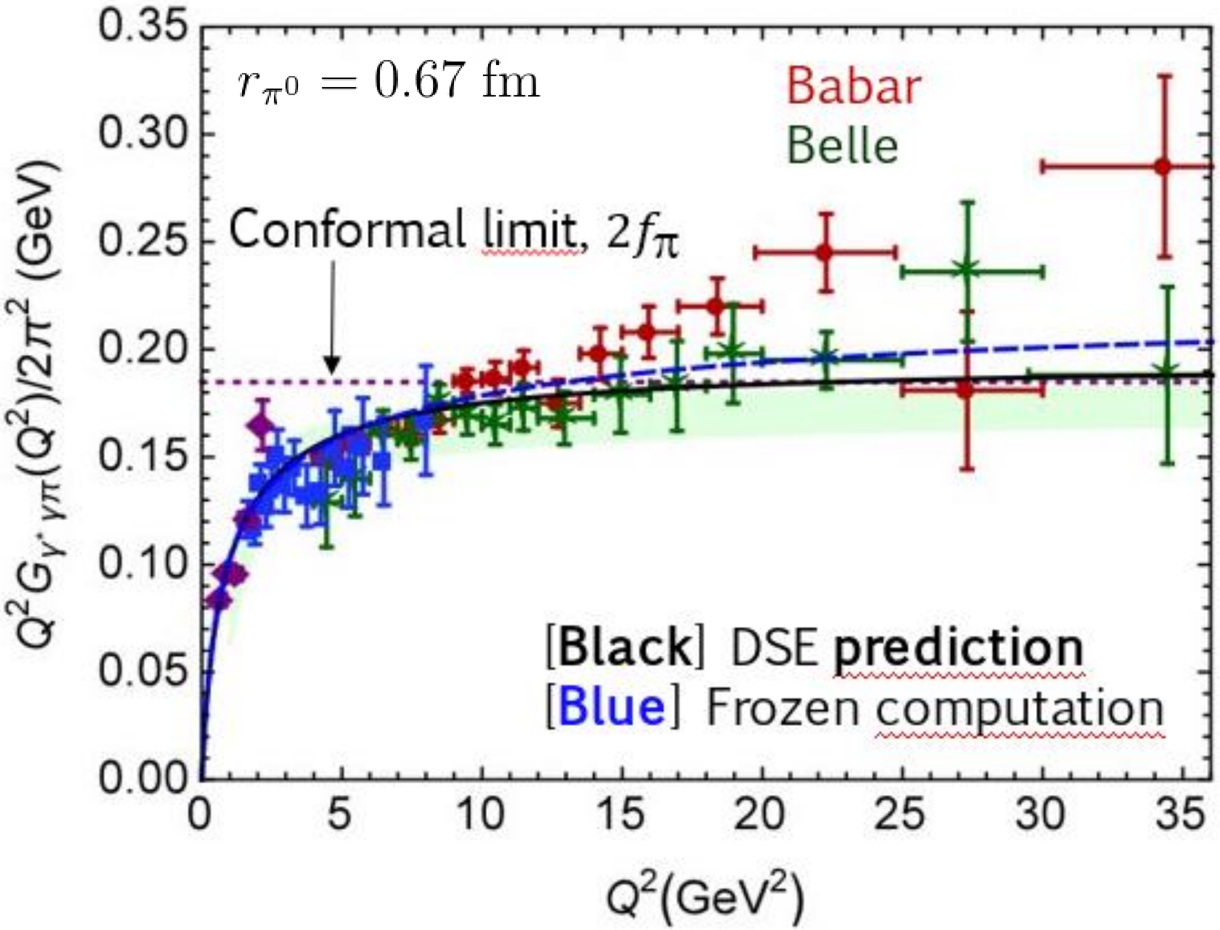
HS formula with:
$$\phi_\pi(x;\zeta = 2\ \mathrm{GeV})$$

HS formula with:
$$\phi_\pi(x) = 6x(1-x)$$

DSE prediction of charged pion form factor motivated a re-evaluation of the reach of JLab12 program, with the aim of testing such prediction (so that green point was added).

Pion transition form factor

Phys.Rev. D93 (2016) no.7, 074017. K. Raya *et al.*

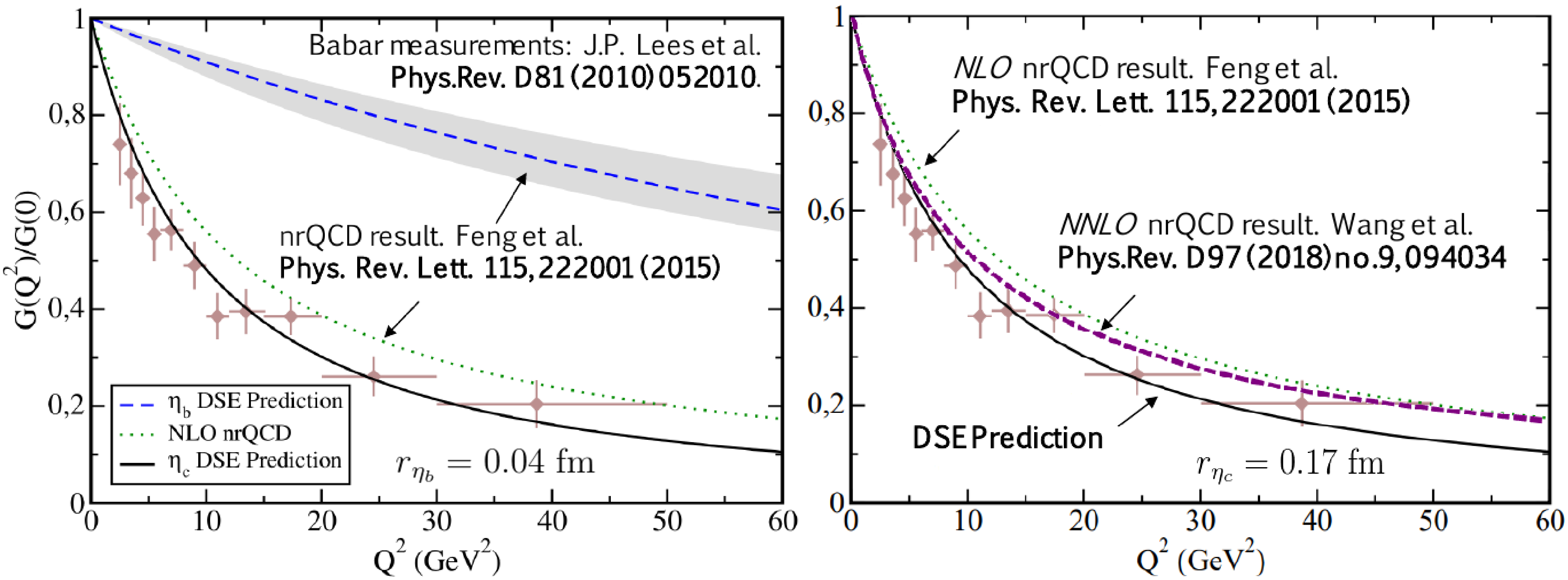


A **new measurement** is **needed!**
... Belle II, BES III?

- Our prediction satisfies the Abelian anomaly, while also being in **accordance with** the **conformal limit**.
- **Precise agreement with experiment** from low to intermediate momenta.
- A **PDA** that is **broad-concave** at the hadronic scale, **connects** both the **EFF** and the **TFF**.
- **Cannot concilliate with Babar** large Q^2 data, which favors a *flat-top* PDA.

Transition form factors...

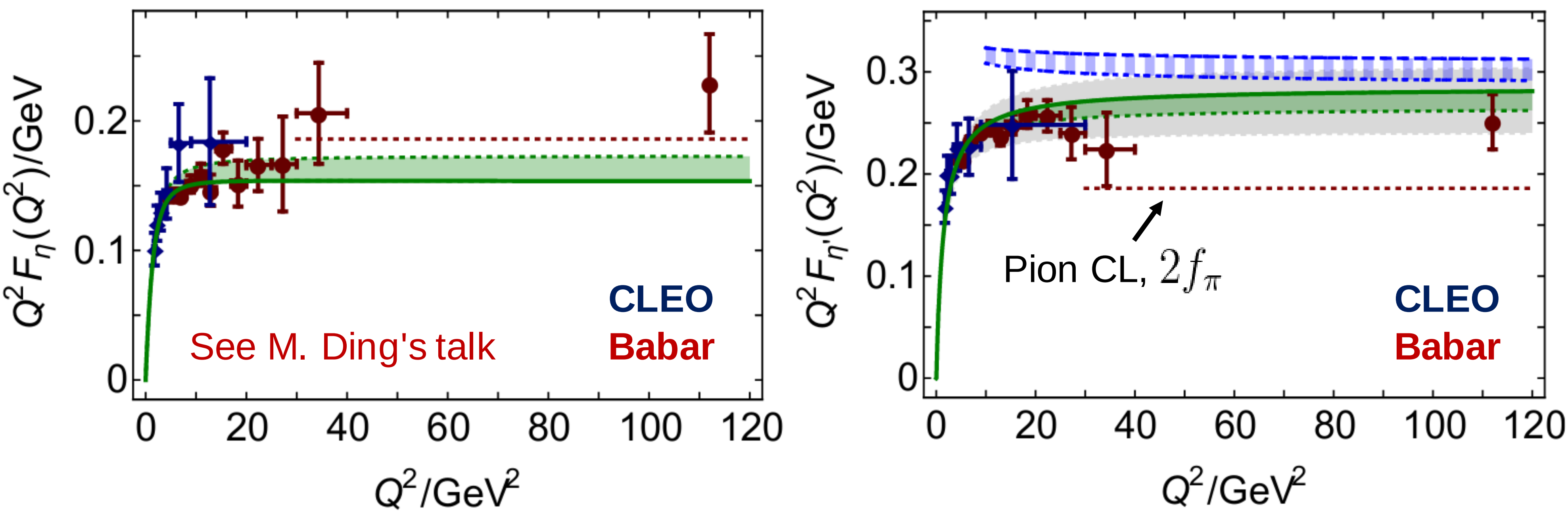
Phys.Rev. D95 (2017) no.7, 074014. K. Raya, M Ding *et al.*



- The corresponding **TFFs** for the analogous heavy systems, **eta-c** and **eta-b**, were computed within the same framework.
- Eta-c **prediction** shows keen agreement with the only available data.
  Eta-b **prediction** lies within the band of the NRQCD result.

Transition form factors...

Phys.Rev. D99 (2019) no.1, 014014. M. Ding, K. Raya *et al.*



- The **good agreement** with the experiment **is encouraging**.
- There are **many** extra **subtleties**: *evolution of decay constants, gluon DAs, quark-photon vertex improvement*.
- Within the **same framework**, we unified **ALL** gamma-gamma to neutral pseudoscal **TFFs, pion EFF**, their corresponding **valence-quark DAs**, etc.

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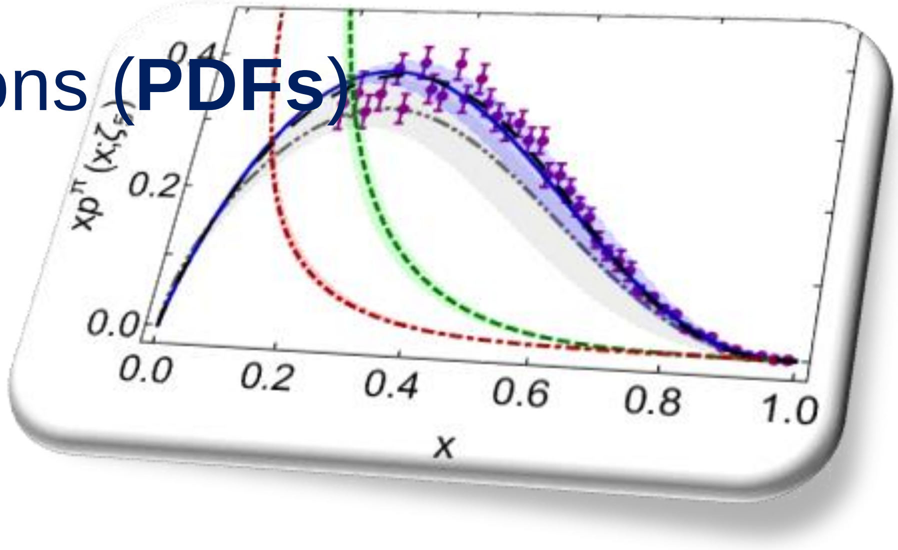
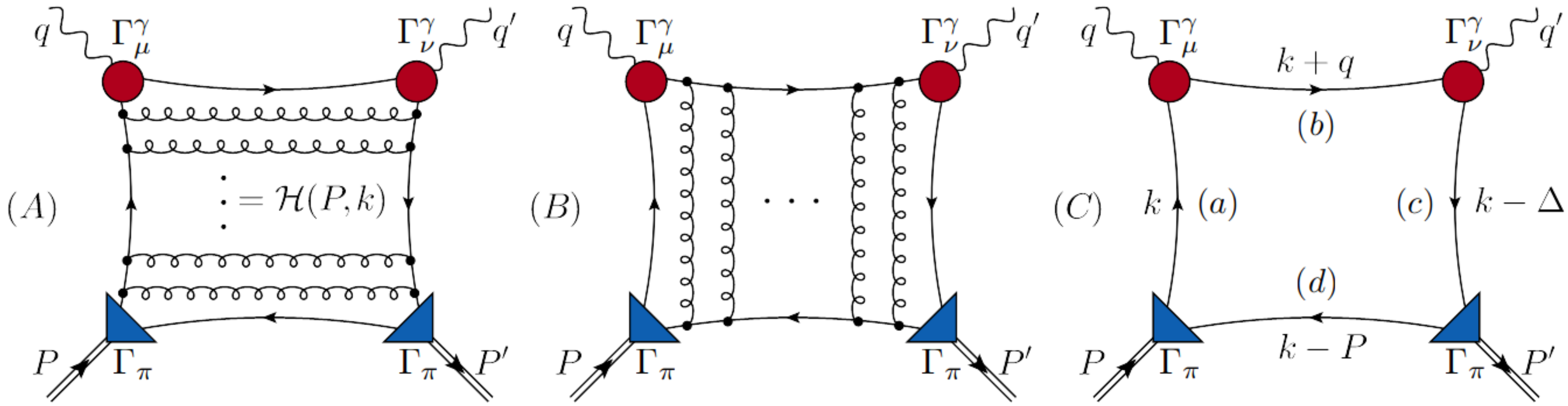


5. Conclusions and scope

Pion parton distributions

- Pion structure function is infered from the process: $\gamma^*\pi \to \gamma^*\pi$
- In the RL truncation, the collection of **symmetry preserving diagrams** is:

Phys.Lett. B737 (2014) 23-29, arXiv:1905.05208



- We compute, at **hadronic scale** (where *fully-dressed quasiparticles* are the correct degrees of freedom), the valence-quark distribution functions.

Pion parton distributions

- Evolution enables the **dressed-quarks** degrees of freedom to **become less well-dressed**, in the manner that QCD prescribes.

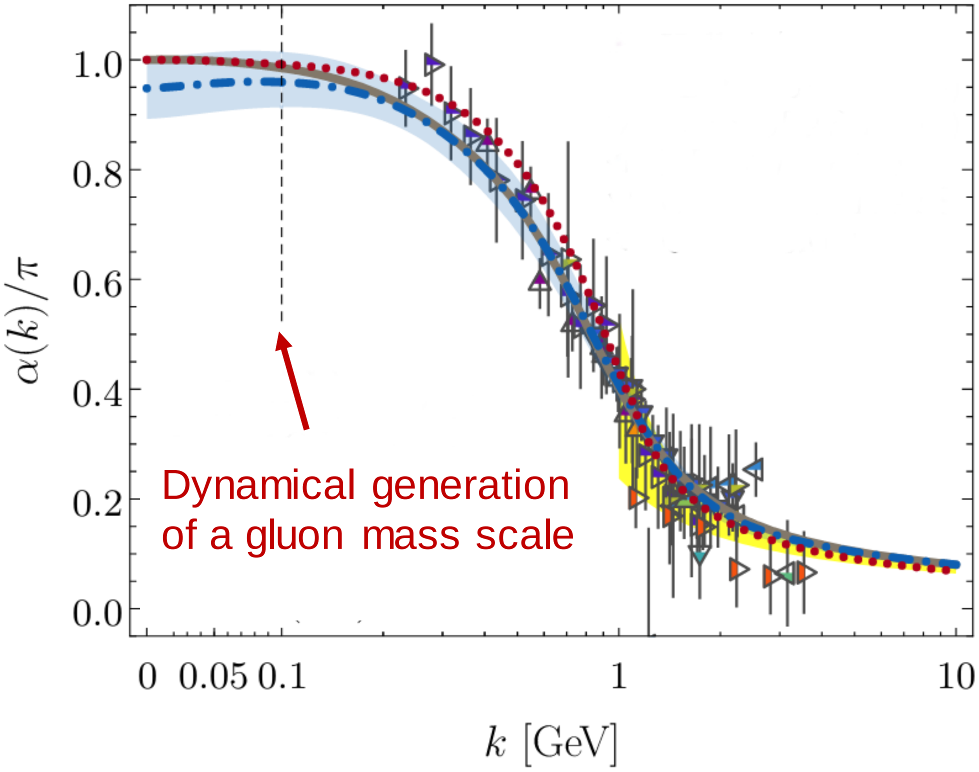
- The natural **hadronic scale** arises from the PI effective charge*, which saturates in the infrared.

- These features and the connection to pQCD are **captured** by:

$$\alpha_{PI}(k^2) = \frac{4\pi}{\beta_0 \ln[(m_\alpha^2 + k^2)/\Lambda_{QCD}^2]}$$

- We identify the hadronic scale:

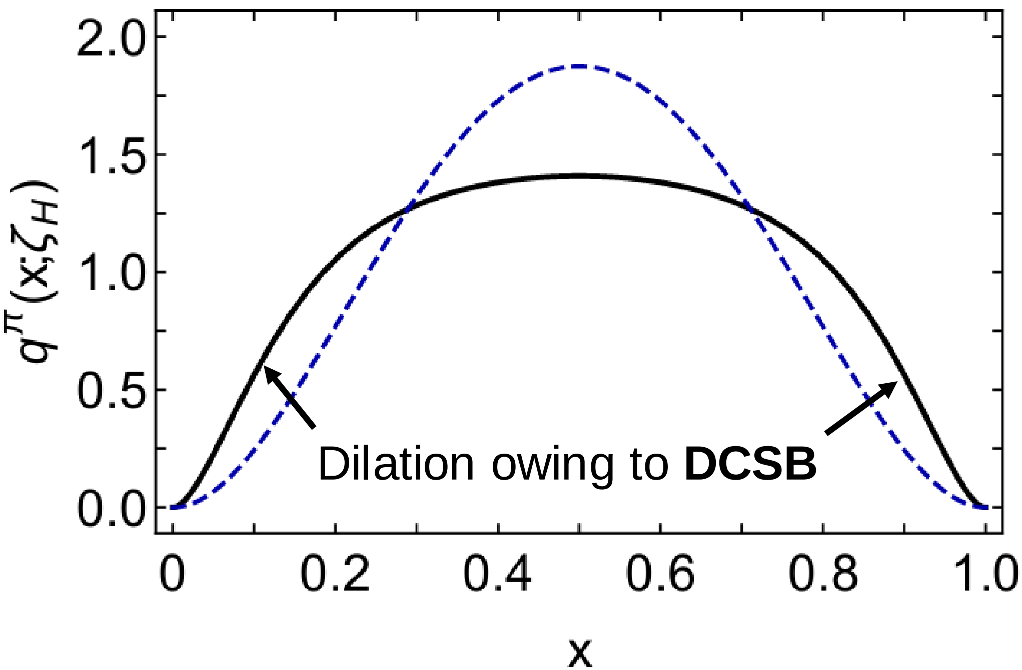
$$\zeta_H = m_\alpha \approx 300 \text{ MeV}$$



* Few Body Syst. 59 (2018) no.6, 121, Phys.Rev. D96 (2017) no.5, 054026

Pion parton distributions

- Valence quark PDF reconstructed from Mellin moments:



$[\text{Blue}]:\ q_\pi(x) = 30x^2(1-x)^2$

Scale-free parton-like *model**

$[\textbf{Black}]:\ \text{DSE}\ \textbf{Prediction}$

$$q_\pi(x;\zeta_H) = 213.32\, x^2(1-x)^2$$
$$\times[1 - 2.9342\sqrt{x(1-x)} + 2.2911x(1-x)]$$

Fully non-perturbative **computation**

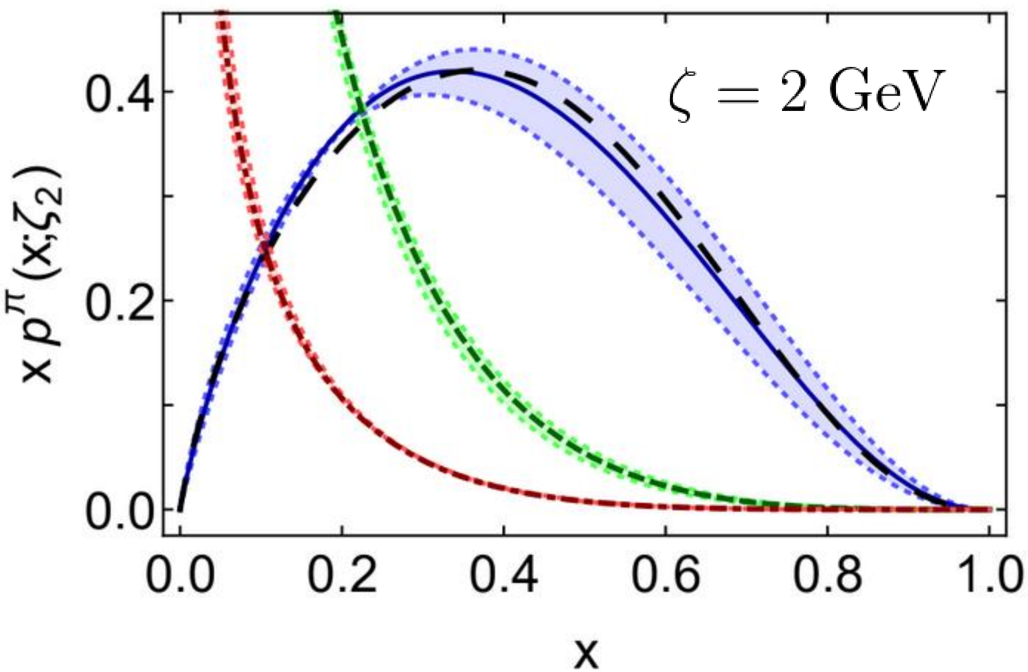
- Induced **hardening owing** to **DCSB**. Same effect is observed in the pion valence-quark DA.
  - DCSB manifests in wave functions, form factors, distribution amplitudes and parton distribution functions.

*** Phys.Lett. B737 (2014) 23-29**

arXiv:1905.05208. M. Ding, K. Raya *et al.*

Pion parton distributions

- Excellent agreement with **lattice** and **phenomenological** results.



ζ_2	$\langle x \rangle_u^\pi$	$\langle x^2 \rangle_u^\pi$	$\langle x^3 \rangle_u^\pi$
Ref. [34]	0.24(2)	0.09(3)	0.053(15)
Ref. [35]	0.27(1)	0.13(1)	0.074(10)
Ref. [36]	0.21(1)	0.16(3)	
Herein	0.24(2)	0.098(10)	0.049(07)

Lattice moments:
Detmold et al., Brommel et al., Oehm *et al.*

- **Valence** content is **roughly 50%**.
- Gluon and sea contributions:

$$<x_{\text{gluon}}> = 0.41(2)\ ,\ <x_{\text{sea}}> = 0.11(2)$$

- It **confirms** the large gluon momentum fraction:

  Phys.Rev. D93 (2016) no.7, 074021
  Phys.Rev. C63, 025213 (2001).

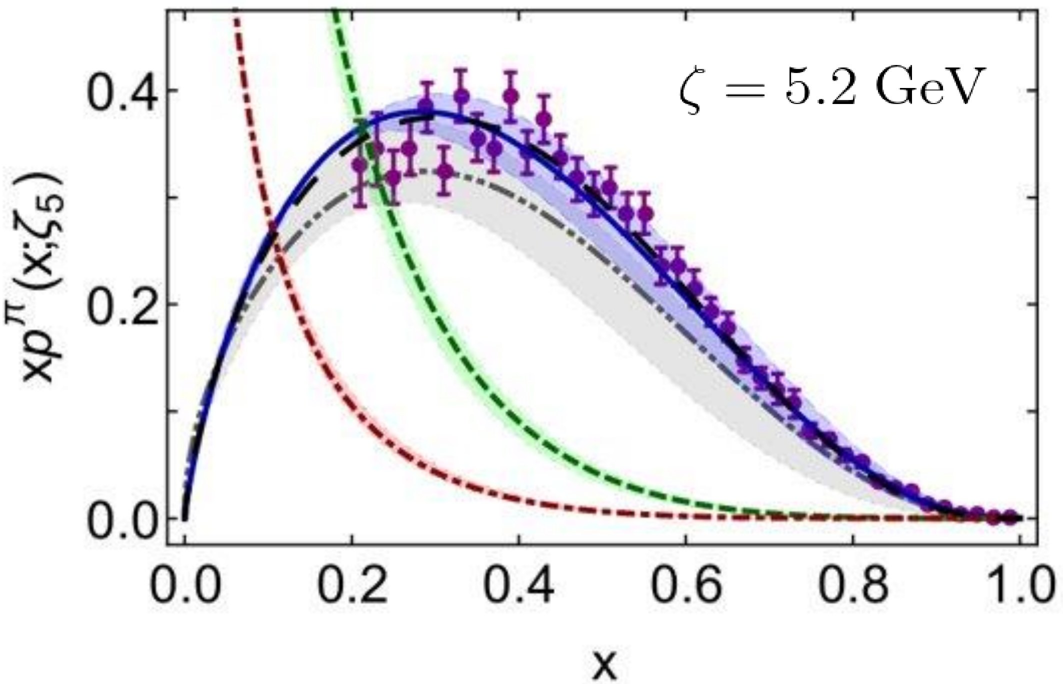
- A **similar trend** has been seen in a recent analysis:

  Phys. Rev. Lett.121, 152001 (2018)

arXiv:1905.05208. M. Ding, K. Raya *et al.*

Pion parton distributions

- Excellent agreement with **experimental** and **lattice** results.



ζ_5	$\langle x\rangle_u^\pi$	$\langle x^2\rangle_u^\pi$	$\langle x^3\rangle_u^\pi$
Ref. [31]	0.17(1)	0.060(9)	0.028(7)
Herein	0.21(2)	0.076(9)	0.036(5)

$$<x_{\rm val}> = 0.42(3)$$

arXiv:1905.05208. M. Ding, K. Raya *et al.*

- Gluon and sea contributions:

$$<x_{\rm gluon}> = 0.45(1)\ ,\ <x_{\rm sea}> = 0.14(2)$$

- Pointwise form of the **lattice** result **agrees** with **DSE** prediction (*within errors*).
- Two **disparate** treatments have arrived at the *same* prediction.
- It **encourages** to get **more data**.

Experimental data:

J. S. Conway *et al*. Phys. Rev. D39, 92 (1989)
M. Aicher *et al*. Phys. Rev.Lett.105, 252003 (2010)

Lattice results:

Sufian *et al*., Phys. Rev. D99, 074507 (2019)

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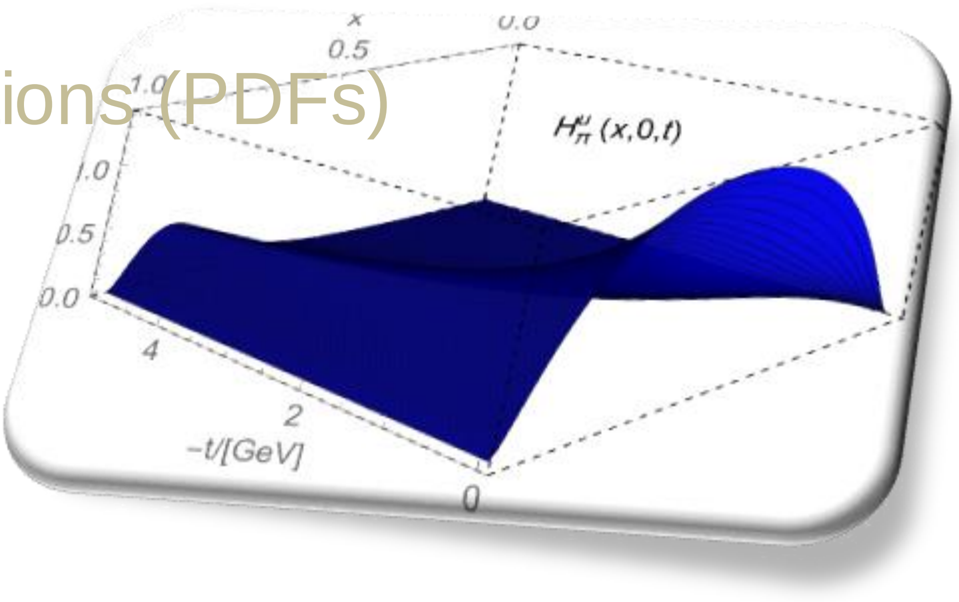


Conclusions and scope

- Within a single, fully consistent treatment of QCD, a **variety** of linked predictions have been discussed:

1. Pion electromagnetic **form factor**
2. $\gamma\gamma^*$ TFFs of ALL neutral **pseudoscalars**
3. Valence-quark **distribution amplitudes**
4. Pion parton **distribution functions**

Computed, for the first time, for arbitrarily large Q^2.

Real progress towards understanding the pion structure

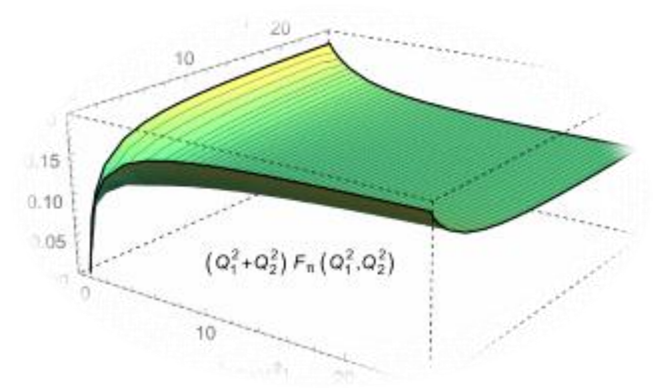
- All predictions are **connected** within the same picture: a picture that connects the pion EFF and TFF with the corresponding broad valence-quark DA and PDF.

- The good agreement with experimental and sophisticated lattice QCD results (*when available*), is **encouraging**.

Urgent need for new data!

Conclusions and scope

- Following the same trail, there are many recent and ongoing predictions, *e.g.*:



- **Generalized parton distributions**
- **Kaon PDF**
- **Nucleon TFFs**
- **Doubly off-shell TFFs**

- Continuum QCD has evolved to the point where realistic predictions for elastic and transition form factors and parton distributions of **all types are within reach**.

- Nowadays, there is an array of **exciting opportunities** at existing and planned facilities.

Good times to be interested in hadron physics!