Symmetry Constrains on Pion Valence Structure

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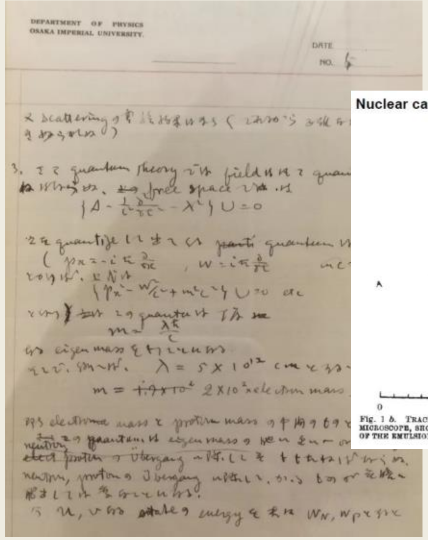
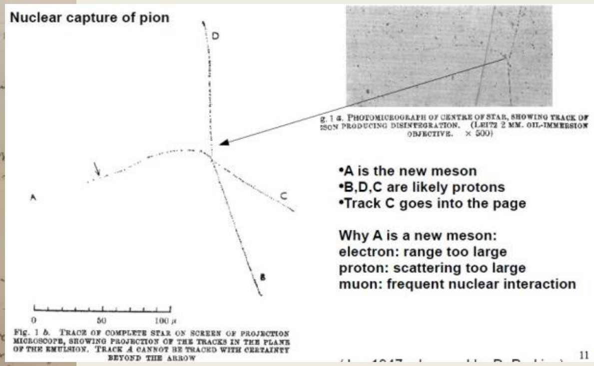
2026轻强子专题研讨会，2026/05/15，商丘

Messager of QCD

- 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.
- **Yoichiro Nambu** associated it with CSB in 1960.
- It was nicely accommodated in the Eight Fold way of **Murray Gell-Mann** in 1961.



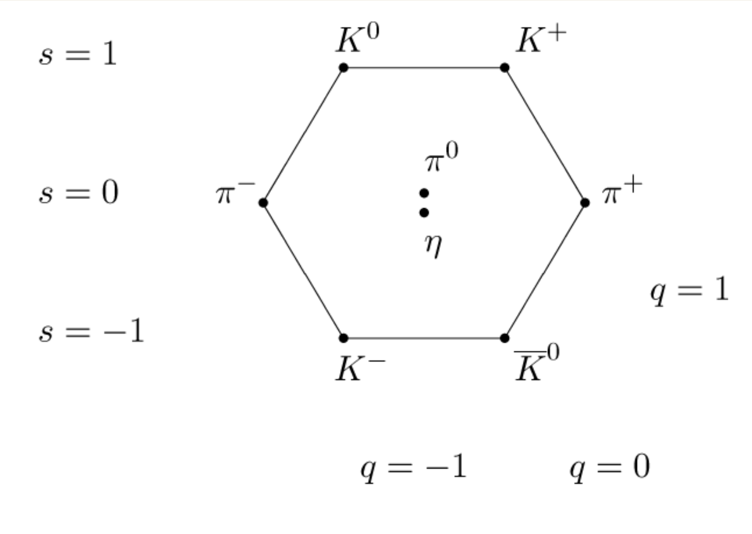


conveniently described by means of a coherent mixture of electrons and holes, which obeys the following

* Supported by the U. S. Atomic Energy Commission.
† Fulbright Fellow, on leave of absence from Instituto di Fisica dell' Universita, Roma, Italy and Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italy.
[1] A preliminary version of the work was presented at the Midwestern Conference on Theoretical Physics, April, 1960 (unpublished). See also Y. Nambu, Phys. Rev. Letters 4, 380 (1960);

$E\psi_2 = -\sigma \cdot p\psi_2 +$
$E_p = \pm(p^2+m^2)$

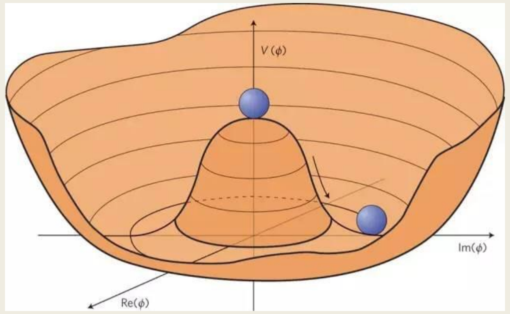
where ψ_1 and ψ_2 are the two eigen
operator $\gamma_5 = \gamma_1\gamma_2\gamma_3\gamma_4$.
According to Dirac's original
ground state (vacuum) of the worl
in the negative energy states, a
states (with zero particle number)



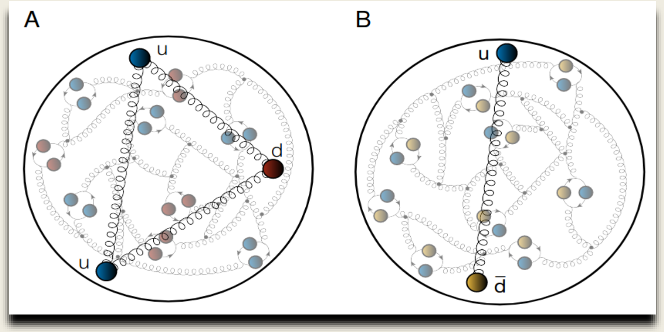
Messager of QCD

PION's dichotomy

Goldstone Boson

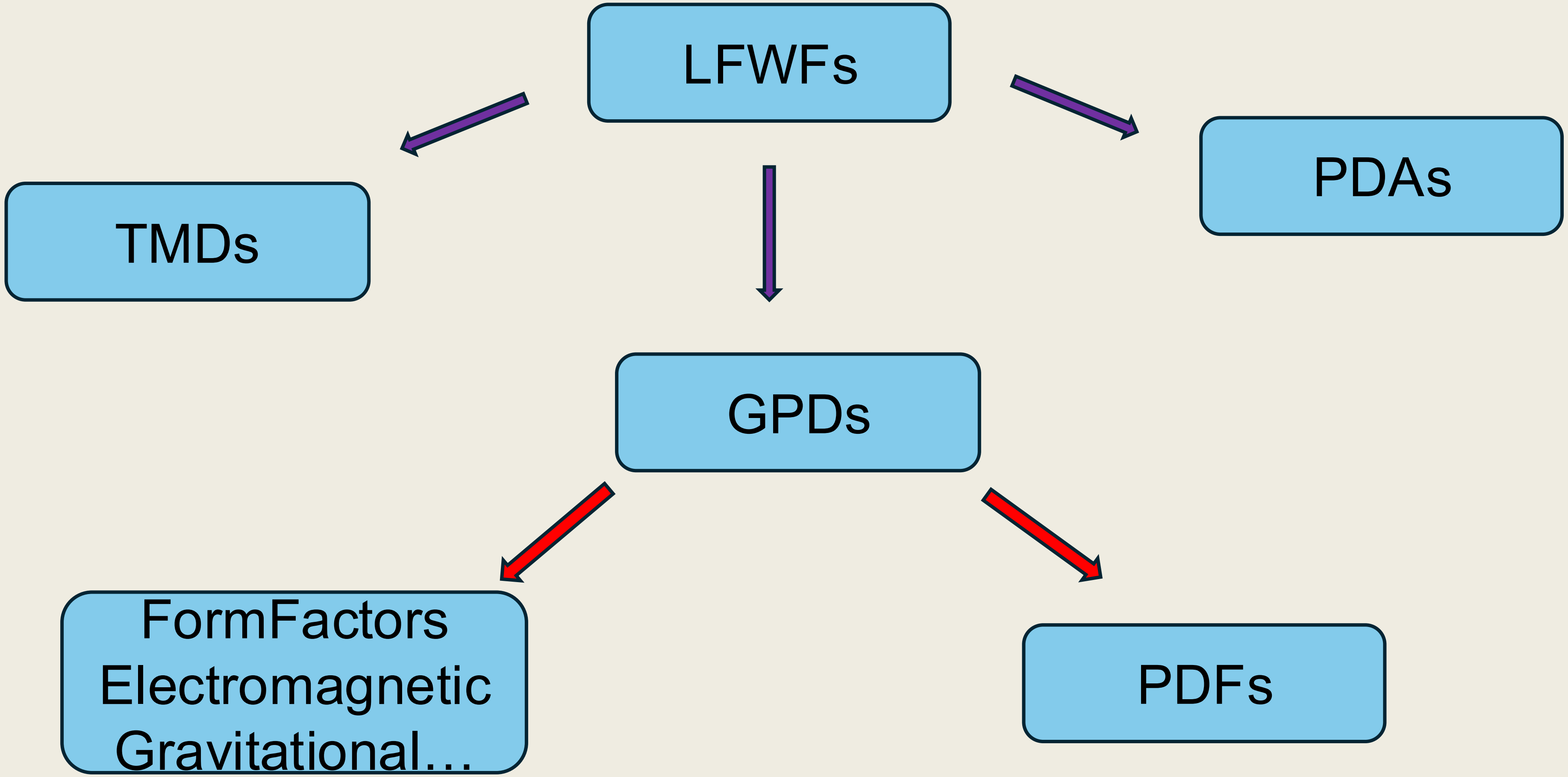


Bound State



[1] Yuan-Ben Dai, Chao-Shang Huang, and Dong-Sheng Liu. Calculation of chiral symmetry breaking and pion properties as a Goldstone boson. Phys. Rev. D, 43:1717–1725,1991.
[2] H. J. Munczek. Dynamical chiral symmetry breaking, Goldstone's theorem and the consistency of the Schwinger-Dyson and Bethe-Salpeter Equations. Phys. Rev. D, 52:4736–4740, 1995.
[3] Pieter Maris, Craig D. Roberts, and Peter C. Tandy. Pion mass and decay constant. Phys. Lett. B, 420:267–273, 1998.

Conventional way…if you like/can



Compute everything from LFWFs…

However…Emergent Phenomena

- 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 DCSB in terms of properties of the degrees-of-freedom used to formulate QCD?

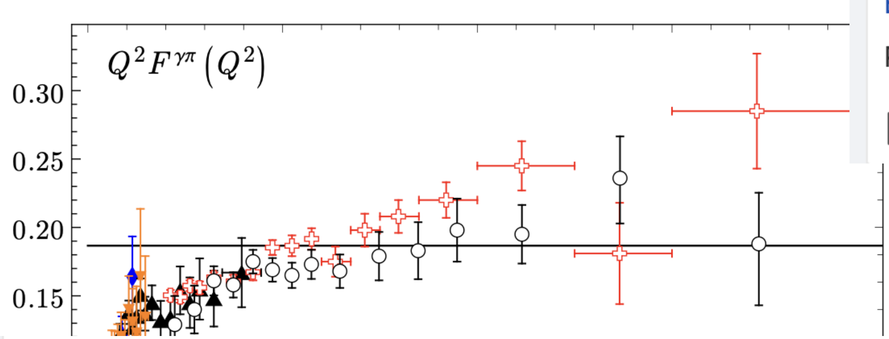
  E.g., is it pointless to attempt to predict the pion's DF/FF on a domain that is not yet accessible?

Must develop nonperturbative calculational methods to define and tackle QCD

1) Lattice-regularized QCD
2) Continuum methods in quantum filed theory

Lesson

- Transition Form Factor



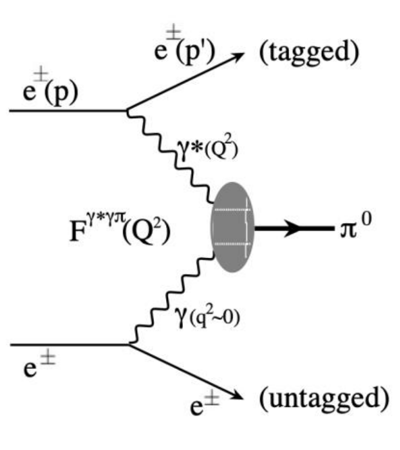
Measurement of the gamma gamma* ---> pi0 transition form factor

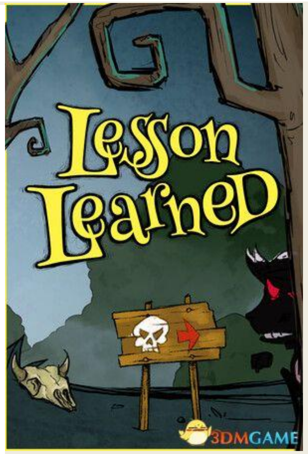
#1

BaBar Collaboration • Bernard Aubert (Annecy, LAPP) et al. (May, 2009)

Published in: *Phys.Rev.D* 80 (2009) 052002 • e-Print: 0905.4778 [hep-ex]

pdf links DOI cite claim reference search 462 citations





Shape of Pion Distribution Amplitude

#26

A.V. Radyushkin (Old Dominion U. and Jefferson Lab and Dubna, JINR) (Jun, 2009)

Published in: *Phys.Rev.D* 80 (2009) 094009 • e-Print: 0906.0323 [hep-ph]

pdf links DOI cite claim reference search 167 citations

On the Pion Distribution Amplitude Shape

M.V. Polyakov (Ruhr U., Bochum and St. Petersburg, INP) (Jun, 2009)

Published in: *JETP Lett.* 90 (2009) 228-231 • e-Print: 0906.0538 [hep

pdf DOI cite claim reference search 124 citations

Abstract: (arXiv)

We argue that the recent BaBar data on $\gamma \to \pi$ e.m. transition form factor at large photon virtuality supports the idea that pion distribution amplitude (DA) is close to unity with $\phi'_\pi(0)/6 \gg 1$ at a normalization point of $\mu = 0.6 \div 0.8$~GeV. Such pion DA can be obtained in the effective chiral quark model. The possible flat shape of the pion DA implies t the standard expansion of the DA in Gegenbauer polynomials can be divergent. On basis of chiral models we predict that the two-pion DA should be anomalously flat for pions in the S-wave and that such feature is absent for higher partial waves. The later implies that the ρ, f_2, etc. meson DAs have no anomalous endpoint behaviour. Possible implications such pion DA for other hard exclusive processes are shortly discussed.

$$G(Q^2) \to \frac{4\pi^2 f_\pi^2}{Q^2}\int_0^1 d\alpha\, \frac{\varphi(\alpha)}{3(1-\alpha)}\,,$$

Measurement of $\gamma\gamma^* \to \pi^0$ transition form factor at Belle

#1

Belle Collaboration • S. Uehara (KEK, Tsukuba) et al. (May, 2012)

Published in: *Phys.Rev.D* 86 (2012) 092007 • e-Print: 1205.3249 [hep-ex]

pdf DOI cite claim reference search 310 citations

Play games…Inverse Problem

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LFWFs

TMDs

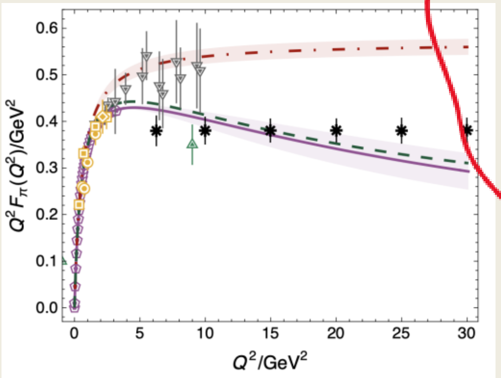
PDAs

GPDs

2GeV !

FormFactors
Electromagnetic
Gravitational…

PDFs



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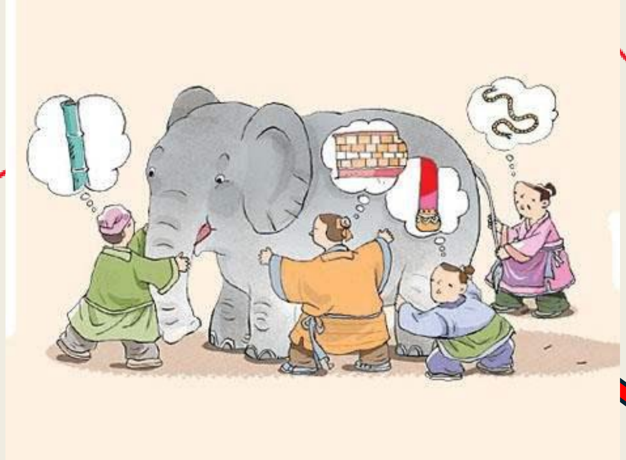
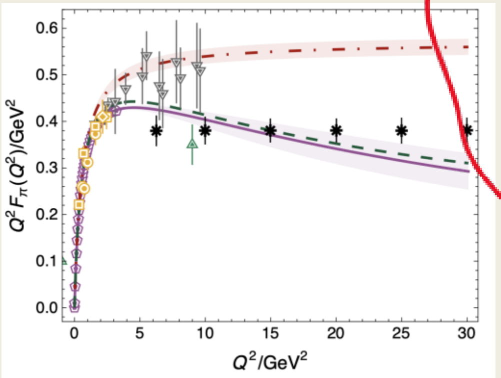
LFWFs

TMDs

PDAs



2GeV !



FormFactors
Electromagnetic
Gravitational…

PDFs

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TMDs

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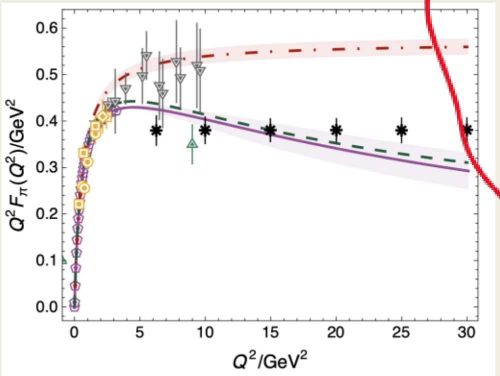
2GeV !

FormFactors
Electromagnetic
Gravita

PDFs



Determination of the pion generalized parton distributions at zero skewness #1

MMGPDs Collaboration • Muhammad Goharipour (IPM, Tehran) et al. (Aug 20, 2025)

e-Print: 2508.15073 [hep-ph]

pdf cite claim reference search 1 citation

Play games…Inverse Problem

FACT

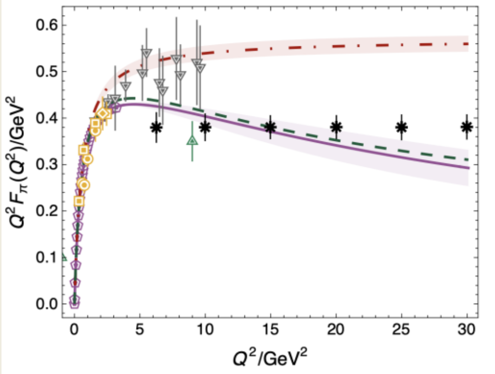
- VMD at low Q^2

$$\frac{m_v^2}{Q^2+m_v^2}$$

- QCD prediction at high Q^2

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

$$\sim \frac{m_v^2}{Q^2+m_v^2}\ \alpha(Q^2)\omega^2(Q^2)$$



FormFactors
Electromagnetic
Gravitational…

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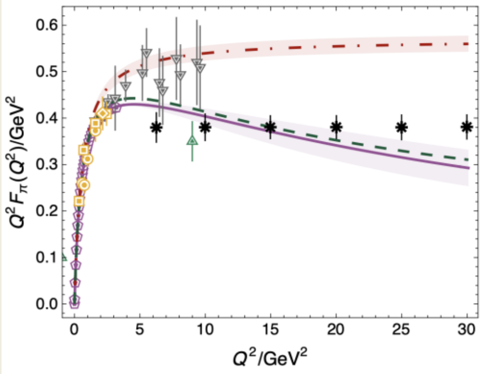
- Monople!

$$\frac{2\lambda}{Q^2 + 2\lambda}$$

- What we need?

$$F^q_\tau(t) = \int_0^1 dx\, H^q_v(x, \xi = 0, t)\,,$$



FormFactors
Electromagnetic
Gravitational…

An integral representation!

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$$F_\tau(Q^2) = \frac{1}{N_\tau} B\left(\tau - 1, \tau_0 + \frac{Q^2}{4\lambda}\right),$$

where $N_\tau = \Gamma(\tau_0)\Gamma(\tau-1)/\Gamma(\tau+\tau_0-1)$ and

$$B(\alpha,\beta) = \int_0^1 (1-y)^{\alpha-1} y^{\beta-1} dy\,.$$

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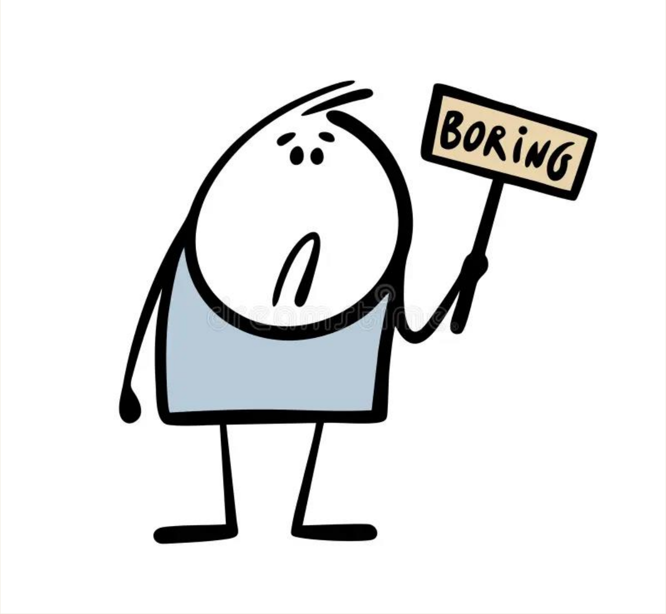
$$F_\tau^q(t) = \int_0^1 dx\, H_v^q(x, \xi = 0, t)\,,$$

$y = x$

$$\sim \frac{1}{\sqrt{x}} x^{\frac{Q^2}{4\lambda}}$$



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$$F_\tau^q(t) = \int_0^1 dx\, H_v^q(x, \xi = 0, t)\,,$$

$y = w(x)$

a transformation $y = w_\tau(x, Q^2)$, provided the following conditions [33, 36–38]:

$$w_\tau(0, Q^2) = 0,\ w_\tau(1, Q^2) = 1,\ \frac{\partial w_\tau(x, Q^2)}{\partial x} \geq 0\,. \quad (5)$$

According to Ref. [33], we can assume that $w_\tau(x, Q^2)$ is independent of Q^2, working hereafter with $w_\tau(x)$. Thus, the EBF representation of the EFF can be cast as:

$$F_\tau(Q^2) = \frac{1}{N_\tau} \int_0^1 dx\, (1 - w_\tau(x))^{\tau-2} w_\tau(x)^{\frac{Q^2}{4\lambda} - \frac{1}{2}} \frac{\partial w_\tau(x)}{\partial x}\,.$$

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假设：w和Q无关！

Let us now consider the valence-quark GPD, expressed in terms of its corresponding LFWF via the overlap representation [21, 22]:

$$H_\tau^q(x, Q^2) = \int d^2\mathbf{b}_\perp\, e^{i(1-x)\mathbf{b}_\perp\cdot\mathbf{Q}} |\psi_\tau^q(x, \mathbf{b}_\perp)|^2. \quad (10)$$

Here $\mathbf{b}_\perp$ denotes the distance between the struck parton, relative to the hadron's transversse center of momentum. Inverting the Fourier transform, one gets:

$$|\psi_\tau^q(x, \mathbf{b}_\perp)|^2 = \frac{(1-x)^2}{(2\pi)^2} \int d^2Q\, e^{-i(1-x)\mathbf{b}_\perp\cdot\mathbf{Q}} H_\tau^q(x, Q^2).$$

Play games…Inverse Problem

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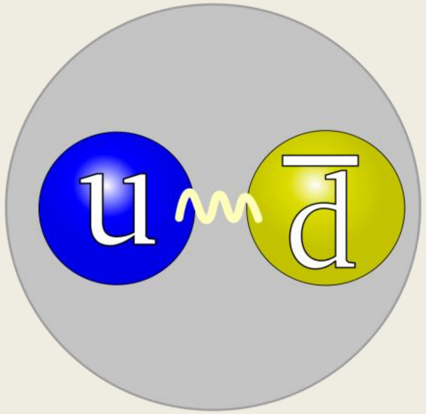
Imagine the Hadron at the Hadronic Scale



Physics Letters B
Volume 93, Issue 3, 16 June 1980, Pages 313-317

Normalizing the renormalization group analysis of deep inelastic leptoproduction

R.L. Jaffe[1], G.G. Ross[2]

Regarding the Distribution of Glue in the Pion #34

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

Published in: *Chin.Phys.Lett.* 38 (2021) 8, 081101 • e-Print: 2106.08451 [hep-ph]

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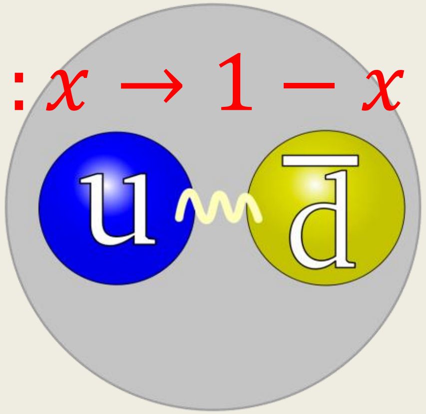
Imagine the Hadron at the Hadronic Scale

$M_u = M_d: x \to 1 - x$ symmetry



ζ_H

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Master equation

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$x \to 1-x$ symmetry

$$\psi(x,\mathbf{b}_\perp) = \psi(1-x,\mathbf{b}_\perp)$$

$$\Leftrightarrow H(x,Q^2) = H\left(1-x, \frac{(1-x)^2}{x^2}Q^2\right) .$$

$$H(x,Q^2) \sim q(x)\mathcal{M}(x)^{\frac{Q^2}{2\lambda}}$$

$$q(x) = \left[\frac{1}{2}w'(x)w(x)^{-\frac{1}{2}}\right] = \mathcal{M}'(x)\,,\ \mathcal{M}(x) := \sqrt{w(x)}\,.$$

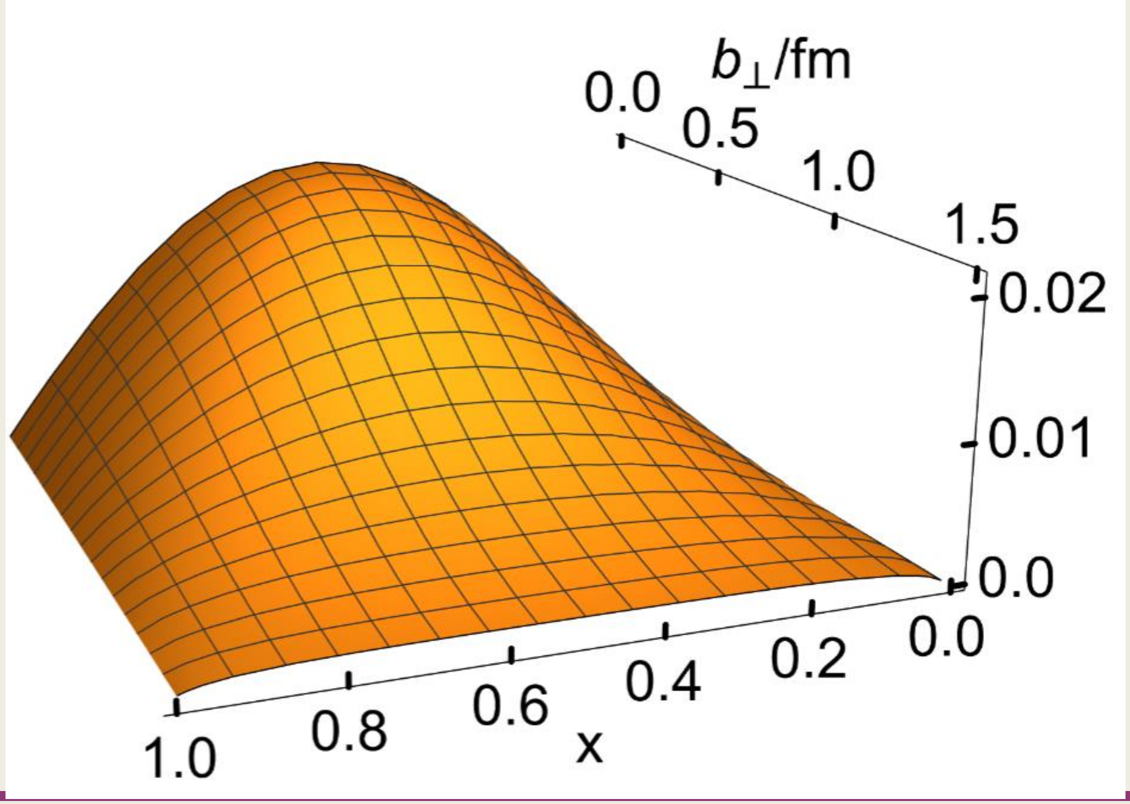
$$\mathcal{M}(x) + \mathcal{M}(1-x) = 1\,,$$

$\Leftarrow$ $q(x) = q(1-x)$

$$\mathcal{M}(x)^{x^2/(1-x)^2} = 1 - \mathcal{M}(x)\,.$$

Symmetry-Driven Outcomes

- Monople
- *w(x):Q independent*
- *symmetry*



Light-Front Wavefunctions

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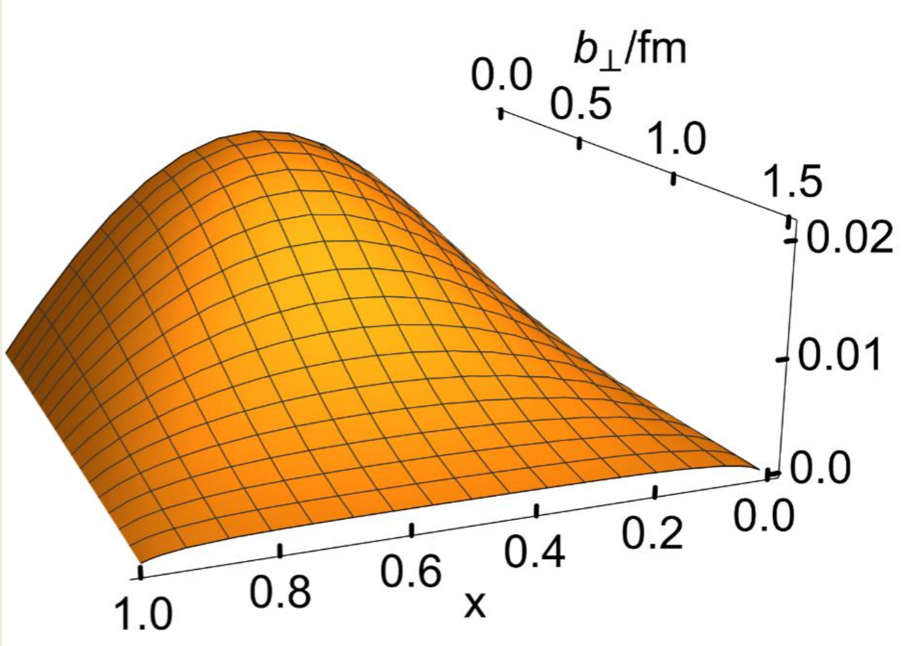
- The **overlap** representation raises a bridge with the **LFWFs**:

$$H^{u_\pi}(x, Q^2; \zeta_{\mathcal{H}}) = \int d^2 b_\perp \, \mathrm{e}^{i(1-x)b_\perp \cdot Q} |\psi^{u_\pi}(x, b_\perp; \zeta_{\mathcal{H}})|^2$$

$|\psi(x, b_\perp; \zeta_{\mathcal{H}})|^2$



Leading-twist LFWF

A **broad, symmetric** function with **Gaussian** profile.

- **Broadness** → **EHM** manifestation

- The **distribution amplitude** thus reads:

$$\varphi_\pi(x; \zeta_{\mathcal{H}}) = 2\pi |\psi(x, b_\perp = 0; \zeta_{\mathcal{H}})| / m_M$$
$$= (1-x)(\pi u_\pi(x; \zeta_{\mathcal{H}}) / \ln[1/a(x)])^{\frac{1}{2}}$$

Distribution Amplitude

- The **pion DA** reads:

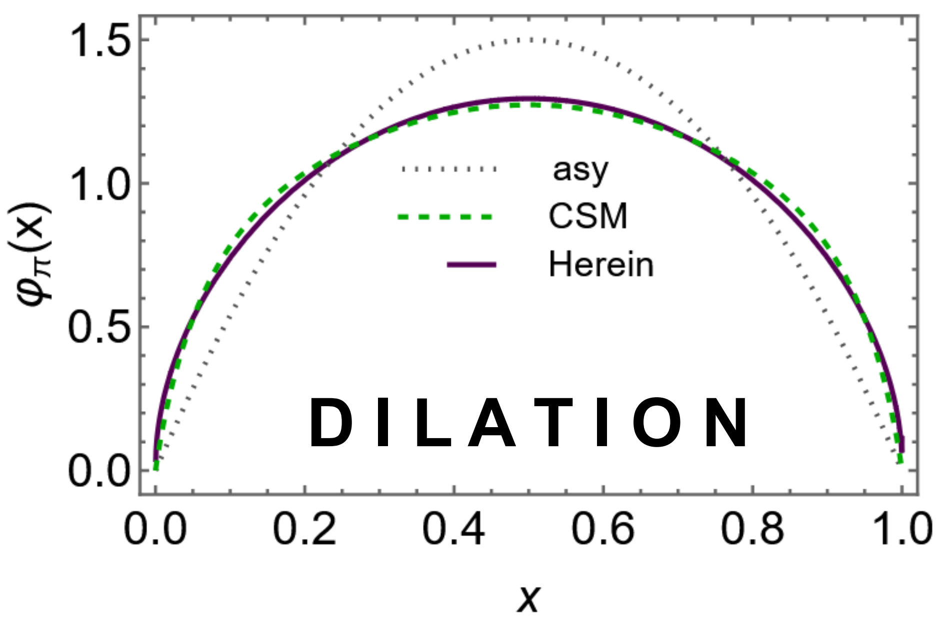
$$\varphi_\pi(x;\zeta_{\mathcal{H}}) = (1-x)(\pi u_\pi(x;\zeta_{\mathcal{H}})/\ln[1/a(x)])^{\frac{1}{2}}$$

- The produced profile captures the **EHM induced dilation**.
  - Which can be quantified via:

$$\int_0^1 dx(2x-1)^2\varphi_\pi(x) = 0.246 =: \langle\xi^2\rangle_{\varphi_\pi}$$

For **comparison**: $\langle\xi^2\rangle_{\varphi_\pi^{\rm CSM}} = 0.247$ $\langle\xi^2\rangle_{\varphi_{\rm asy}} = 0.2$

$$\varphi_{asy}(x) = 6x(1-x)$$



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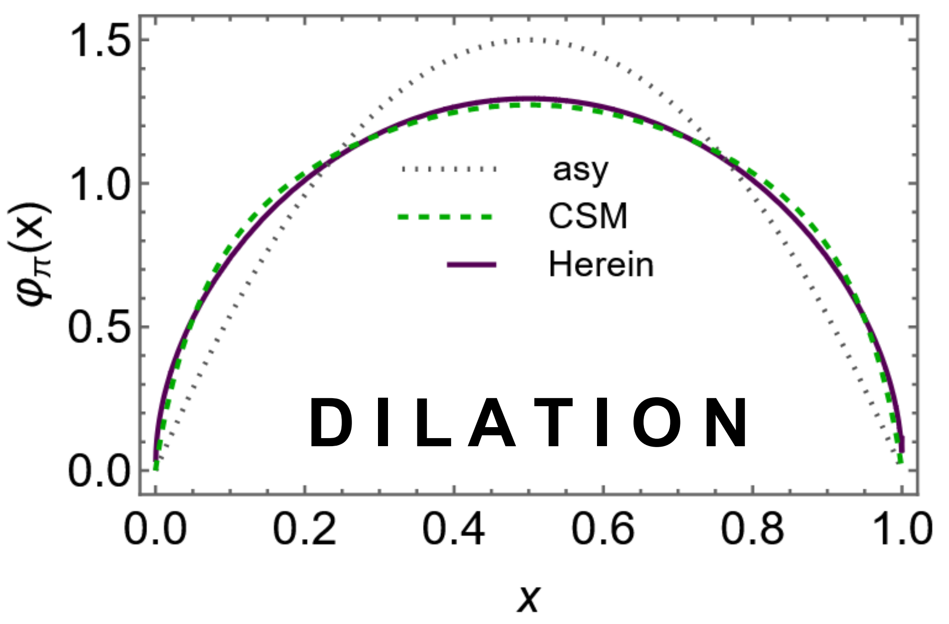

- The **large-x** behavior:

$$\varphi_\pi(x) \overset{x\simeq 1}{=} 2.507\sqrt{1-x} + \ldots$$

Distribution Amplitude

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Pion Distribution Amplitudes from Functional QCD

Lei Chang,[1] Wei-jie Fu,[2] Chuang Huang,[3,*] Jan M. Pawlowski,[3,4] and Yang-yang Tan[5,6]

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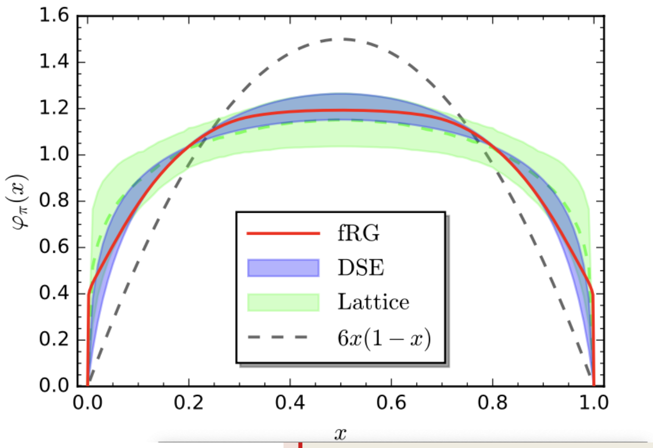
[2]*School of Physics, Dalian University of Technology, Dalian, 116024, P.R. China*
[3]*Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany*
[4]*ExtreMe Matter Institute EMMI, GSI, Planckstr. 1, D-64291 Darmstadt, Germany*
[5]*Institute for Physics of Intelligence, Graduate School of Science, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan*
[6]*RIKEN Center for Interdisciplinary Theoretical and Mathematical Sciences (iTHEMS), Wako, Saitama 351-0198, Japan*

We present the first functional QCD calculation of the pion distribution amplitude (DA) using the large-momentum effective theory within the functional renormalization group (fRG) approach. With only the strong coupling and current quark masses as inputs, we compute the quasi-DA from first-principles QCD correlation functions. By pushing the pion momentum up to $P_z = 4.5$ GeV, the quasi-DA becomes fully saturated, rendering the extrapolation errors to the light-cone limit negligible. The resulting second-order moment $\langle \xi^2 \rangle_\pi = 0.267$ is significantly smaller than existing lattice-LaMET determinations and lies in a range consistent with other nonperturbative approaches.

Introduction.– The pion light-front parton distribution amplitude (PDA) describes how the pion's longitudinal momentum is shared between its valence quark and antiquark. As the pseudo-Goldstone boson of dynamical chiral symmetry breaking (DCSB)—the mechanism responsible for most of the visible mass in the universe—the pion's PDA provides a direct image of DCSB in a light-front wave function. Despite decades of study, the shape of the pion PDA remains controversial: different nonperturbative approaches yield conflicting results, with the second-order moment $\langle \xi^2 \rangle_\pi$ ranging from 0.23 to 0.30. Resolving this tension is essential for understanding how DCSB manifests in hadron structure.

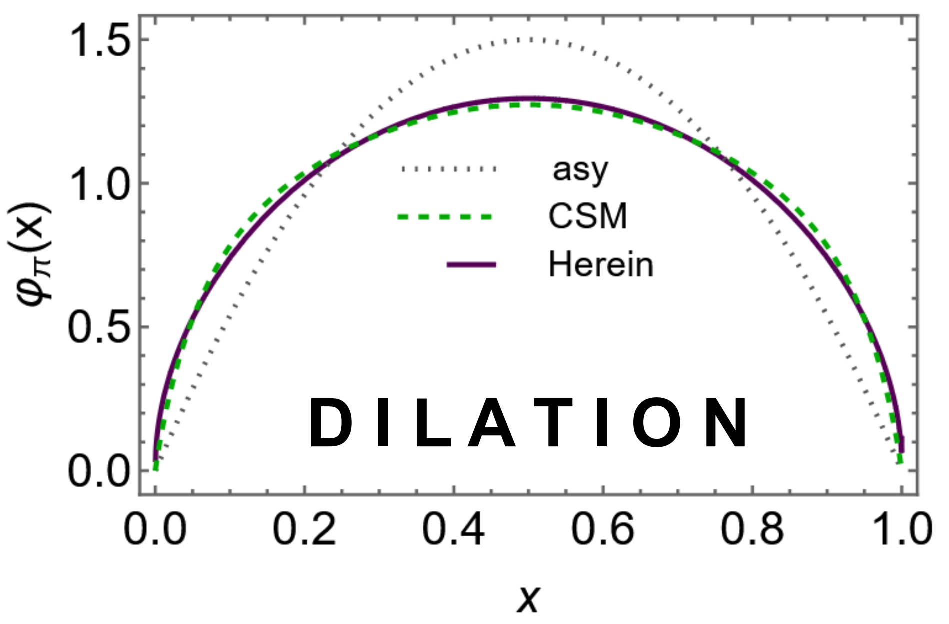
In this work, we present the first computation of the pion PDA within the functional QCD framework



$$\ldots_{\mathcal{H}})/\ln[1/a(x)])^{\frac{1}{2}}$$

ation.

$$\varphi_{asy}(x) = 6x(1-x)$$



Distribution Function

- As the **DA**, the **DF's** **large-x** behavior is influence by that of ***a**(x)*, which reads:

$$a(x) \overset{x\simeq 1}{\cong} 1 - 1.581(1-x)^2 \ln 1/(1-x) \quad - 5.458(1-x)^4[\ln 1/(1-x)]^2 + \ldots$$

- The **pion DF** thus adopts the following **large-x** profile:

$$u_\pi(x;\zeta_{\mathcal{H}}) = a'(x)$$

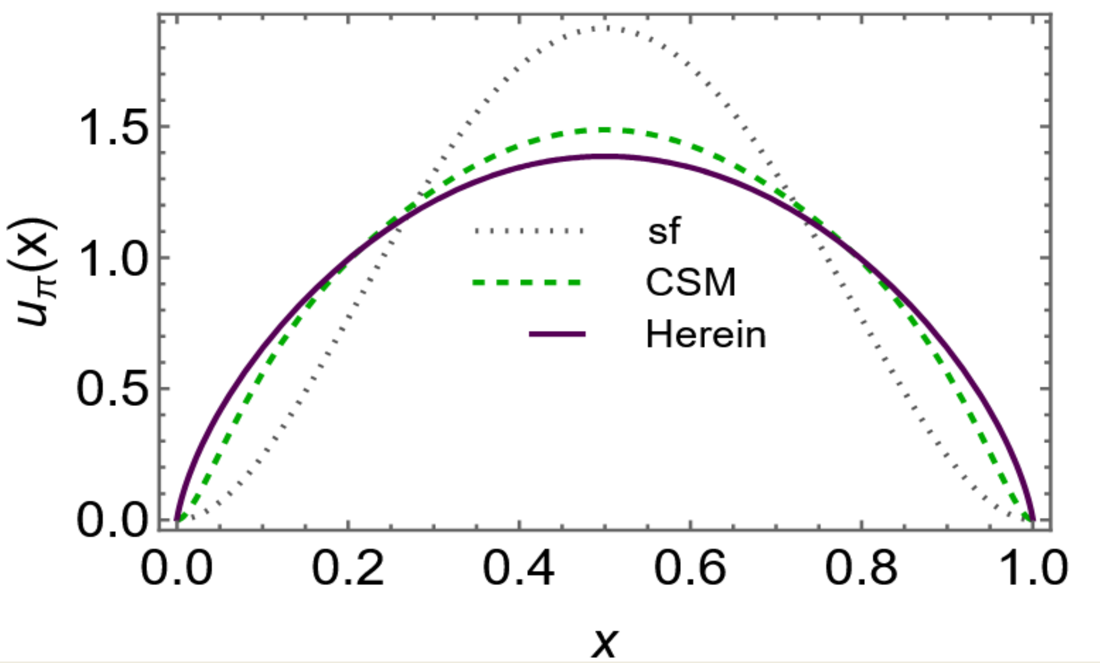
$$u_\pi(x) \overset{x\simeq 1}{\cong} 3.163(1-x)\ln 1/(1-x) + \ldots$$

- The **symmetry-based** approach *misses* exact counting rules but captures **QCD-like** qualitative DF **features**.

- For comparison:

$$u_\pi^{\rm CSM}(x) \approx 375.3(1-x)^2 \ \text{ on } x \simeq 1$$

$$q_{\rm sf} = 30x^2(1-x)^2$$

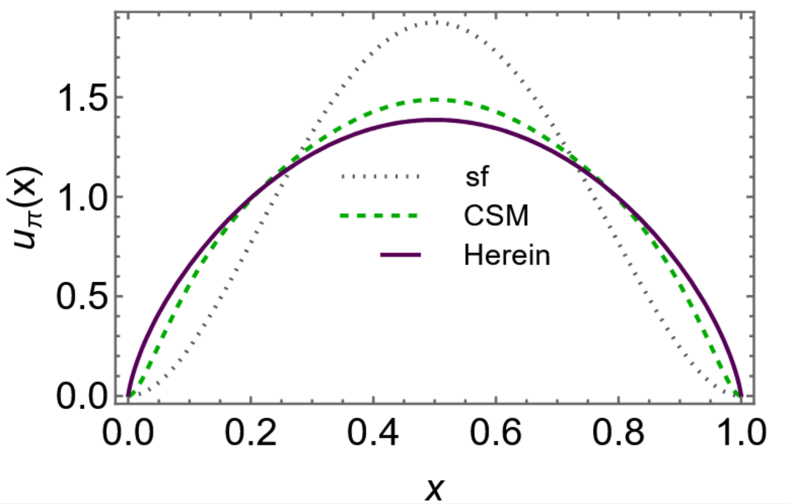


Empirical Validation

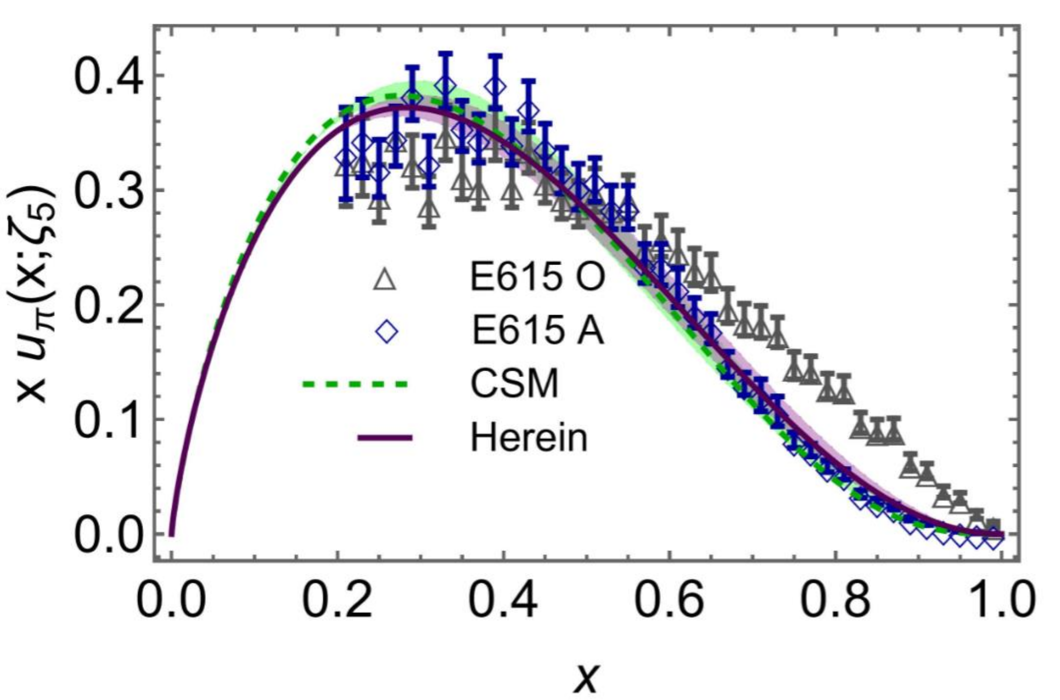
- The **pion DF** adopts the following **large-x** behavior:

$$u_\pi(x) \overset{x\simeq 1}{=} 3.163(1-x)\ln 1/(1-x) + \ldots$$

- The symmetry-based approach *misses* exact counting rules but captures **QCD-like** qualitative DF **features**.

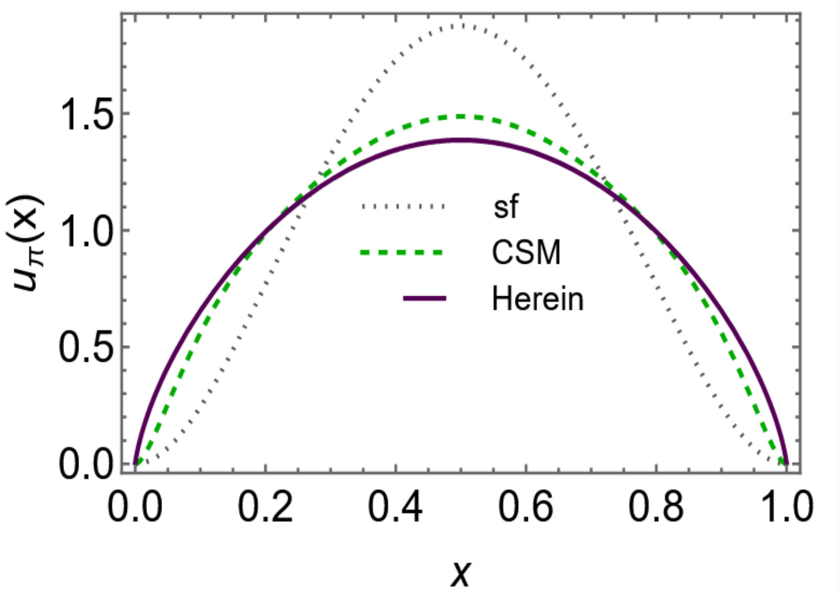


- Its soundness is nevertheless **validated empirically**, after scale evolution to ζ = 5.2 GeV



Final Highlights

- The **emergent** phenomena in **QCD** produces unique outcomes:
  - **Confinement**, dynamical **mass** generation, and a peculiar effective **coupling**.
  - These orchestrate the formation of **hadrons** and their properties, and are responsible for almost all of the **mass** of the **VM**.
- The **pion** must take **center** stage in elucidating these aspects.
  - **Key** pion features emerge from **symmetry principles** alone.
- With **minimal assumptions**, and no parameters, **essential** DF **features** are well-reproduced:
  - **M_u = M_d** symmetry + pion **EFF** as a **monopole**
- Differences with **QCD-based** results appear only in **fine details** (e.g. anomalous dimensions)
  - In an age captivated by computational power, we **shouldn't lose** sight of **symmetry principles**



Measurements-I

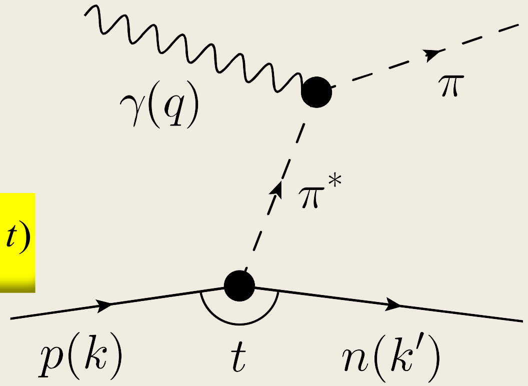
- At low Q^2, F_π can be measured directly via high energy elastic π^+ scattering from the atomic electrons
  - ➢ CERN SPS used 300 GeV pions to measure form factor up to Q^2=0.25GeV^2
    (Amedolia et al, NPB277, 168 (1986))
  - ➢ These data used to constrain the pion charge radius: r_π=0.657±0.012 fm

pion electroproduction and elastic pion scattering

Experiment	Process	$-t$ range (GeV^2)	N_{pts}
Brown 1973 [97]	$ep \to e'\pi^+ n$	0.176 – 1.188	5
Ackermann 1978 [98]	$ep \to e'\pi^+ n$	0.35	1
Bebek 1978 [99]	$ep \to e'\pi^+ n$	0.18 – 9.77	21
Brauel 1979 [100]	$ep \to e'\pi^+ n$	0.7	1
Volmer 2001 [101]	$ep \to e'\pi^+ n$	0.6 – 1.6	4
Huber 2008 [102]	$ep \to e'\pi^+ n$	0.6 – 2.45	8
Adylov 1977 [103]	e-π scattering	0.0138 – 0.0353	22
Dally 1981 [104]	e-π scattering	0.0317 – 0.0705	20
Dally 1982 [105]	e-π scattering	0.039 – 0.092	14
Amendolia 1986 [106]	e-π scattering	0.015 – 0.253	45
Total	–	0.0138 – 9.77	141

arxiv:2508.15073

- At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton in exclusive pion electroproduction: p(e, e' π^+)n
  - ➢ at small –t, the pion pole process dominates the longitudinal cross section, σ_L
    (L. Favart, et al, Eur. Phys. J. A 52 (2016) 158)
  - ➢ In the Born term model, F_π appears as $\frac{d\sigma_L}{dt} \propto \frac{-t}{(t-m_\pi^2)} g_{\pi NN}^2(t) Q^2 F_\pi^2(Q^2,t)$



Sullivan process, in which a nucleon's pion cloud is used to provide access to the pion's elastic form factor

Measurements-I

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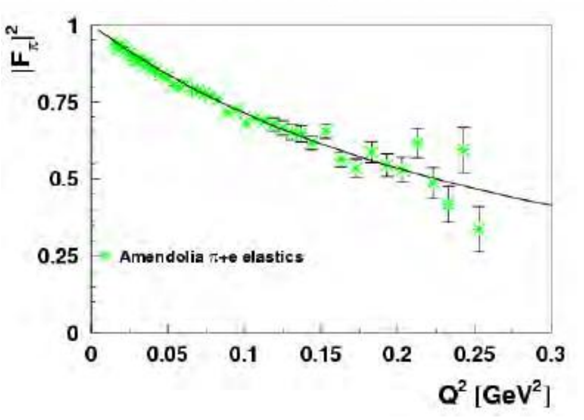

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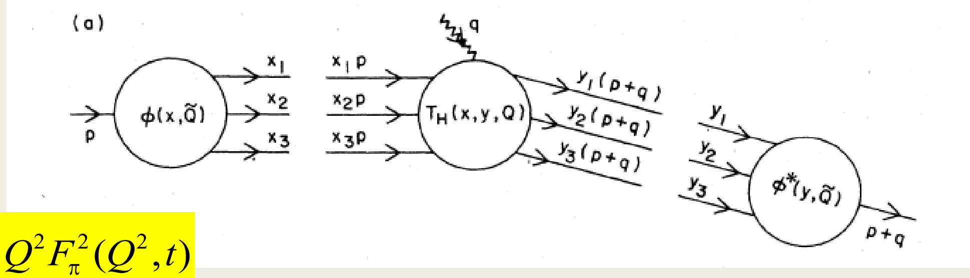

(G.R. Farrar and D.R.Jackson, PRL43 (1979) 246;
P. Lepage and S. Brodsky, PLB 87 (1979) 359)

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

Experimental studies over the last decade have given confidence in the electroproduction method yielding the physical pion form factor----Tanja Horn