Rising Researchers Seminar Series

The Rising Researchers Seminar Series is committed to creating an **environment which is welcoming and safe** for all speakers, attendees, organizers, and other affiliated persons, hereinafter ``participants". It is the responsibility of all participants to foster such an environment.

Participants shall **treat each other professionally and respectfully**. Participants shall refrain from any inappropriate behaviour, including discriminatory actions and comments based on individual characteristics such as age, race, ethnicity, sexual orientation, gender identity, gender expression, marital status, nationality, immigration status, political affiliation, ability status, or educational background. Disruptive or harassing behavior will not be tolerated including but not limited to inappropriate or intimidating language and unwelcome jokes or comments.

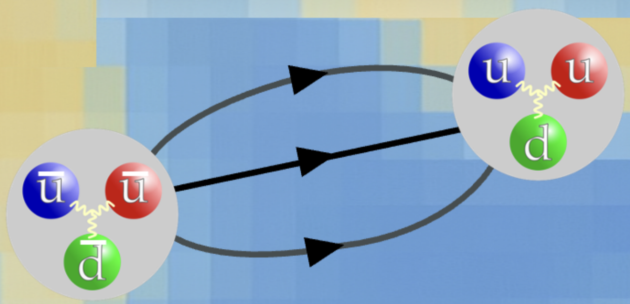
Violations of this code of conduct should be reported to any member of the executive committee (see About Us page on the website). The Executive committee may also act of their own accord should they notice violations. Sanctions may range from verbal warning, to ejection from the meeting or, in severe cases, partial or total bans from future meetings.

References: This code of conduct is based heavily on that of the INT and the APS. We are also grateful to Roxanne Springer for valuable discussion and guidance.

Hadron Structure Emerged from Topological Vacuum

Wei-Yang Liu
Stony Brook University

Rising Researchers Seminar Series 2025



Collaborators

Edward Shuryak	(SBU)
Ismail Zahed	(SBU)
Christian Weiss	(JLab)
Yong Zhao	(ANL)

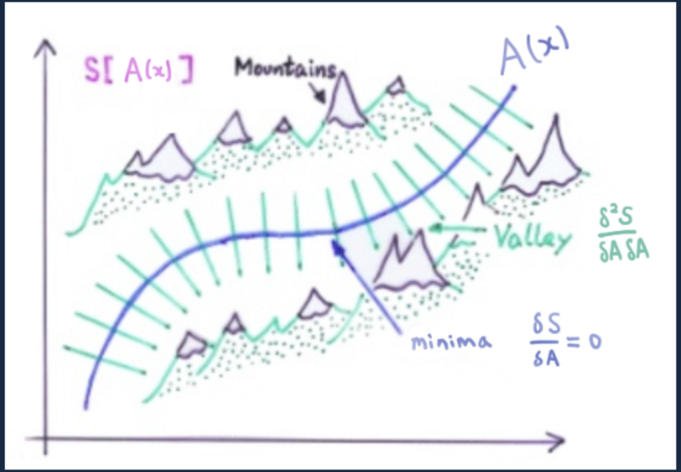
Outline

1. Overview: Vacuum-Based (Semiclassical) Effective Theories
2. Overview: Parton Structure in Hadrons
3. Hadronic Form Factor
4. Hadron Mass Decomposition
5. Nucleon Spin Decomposition

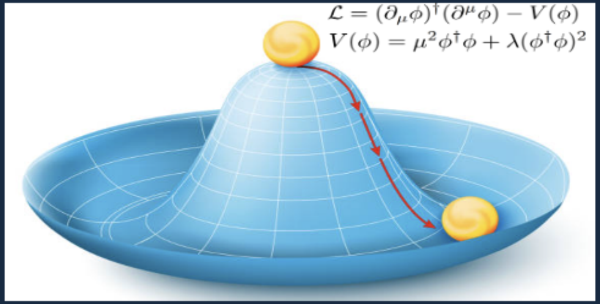
Vacuum in Quantum Field Theories

$$Z = \int \mathcal{D}A \, e^{-S[A]}$$

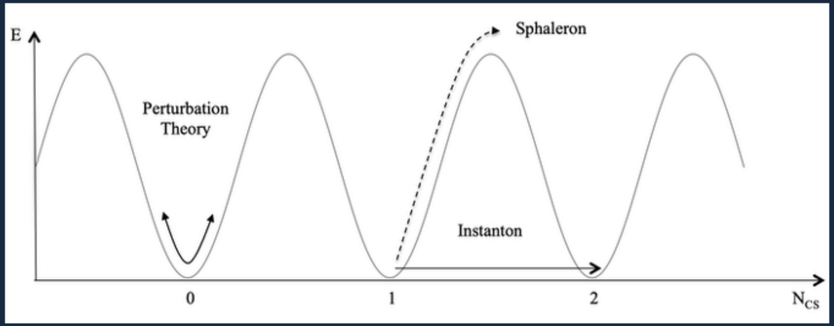
- Minima: EOM solution
- Valley: perturbation expansion



Higgs Vacuum (scalar)

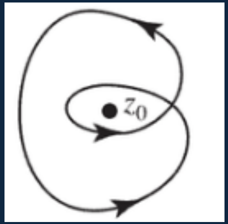


QCD Vacuum (non-Abelian gauge bosons)



QCD Vacuum

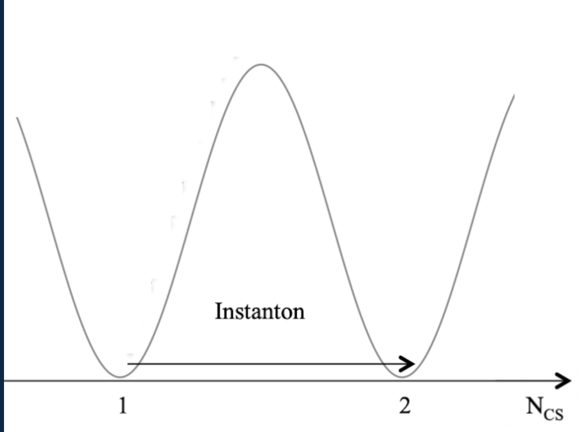
- QCD vacuum is degenerate: $\{|0_{N_{CS}}\rangle \cdots\}$
- Categorized by topology N_{CS}: Chern-Simon winding number



$$\mathcal{L}_{\mathrm{QCD}}[A] = \mathcal{L}_{\mathrm{QCD}}[\bar{A}] + \text{Feynman Diagrams } \mathcal{L}_{\mathrm{QCD}}[\delta \mathrm{A}]$$

Instanton (anti-instanton):

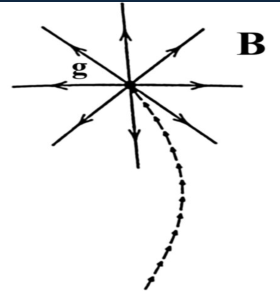
- Classical solutions in Euclidean
  → Quantum tunneling in Minkowski
- Nonzero topological charge
  → sources of strong CP
  → closely related to axial anomaly

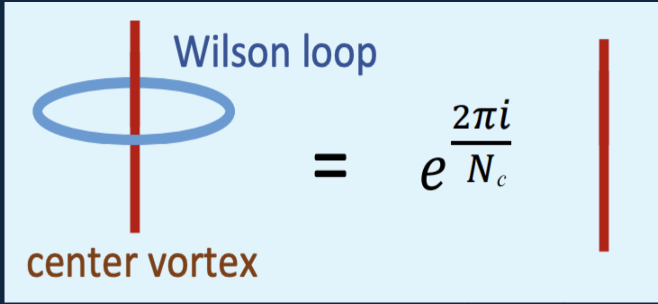


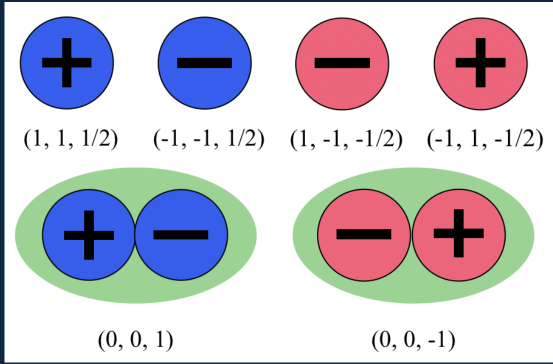
QCD vacuum

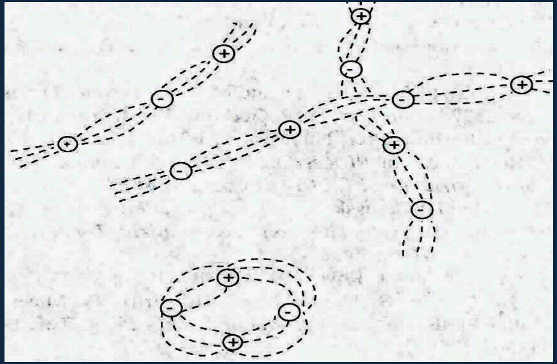
Are there other semi-classical gauge configurations?

- Monopoles 't Hooft '75, Shuryak-Zahed '15...
- Center Vortices 't Hooft '78, Greensite '15...









- Promising confinement candidates for YM
- "Monopole as junction of center vortices"
  Ambjørn-Giedt-Greensite '99, Engelhardt-Reinhard '99, Cornwall '99

QCD Important IR Features

Breaking of Scale Invariance

$$T^{\mu}{}_{\mu} = \underbrace{\frac{1}{4g^2}\beta(g^2)G^2}_{\text{trace anomaly}} + \underbrace{m\bar{q}q}_{\text{Higg mechanism}}$$

Breaking of Axial Symmetry

$$J_5^{\mu} = \underbrace{\frac{g^2 N_f}{32\pi^2}G\tilde{G}}_{\text{axial anomaly}} + \underbrace{m\bar{q}i\gamma^5 q}_{\text{Higg mechanism}}$$

Breaking of Chiral Symmetry

$$\langle \bar{q}q \rangle \neq 0 \Rightarrow \pi, K, \eta$$

Confinement

- QCD bound states $\Rightarrow$ color singlet
- $\langle P \rangle = 0 \Rightarrow$ unbroken Z_{N_c} symmetry
- $\langle W \rangle = e^{-\sigma A} \Rightarrow$ area law

Visualization of the gauge configurations?

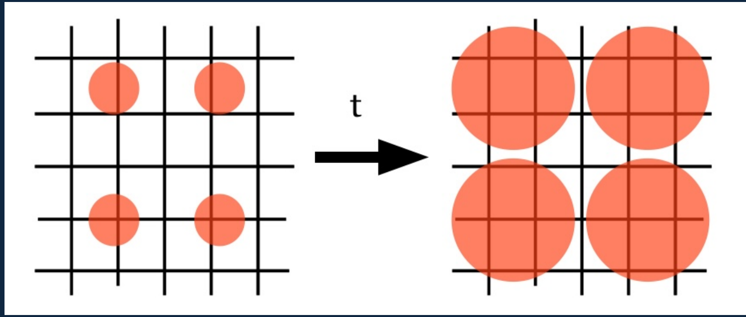
J. Biddle, W. Kamleh, D. Leinweber, PRD 102, 034504 (2020)

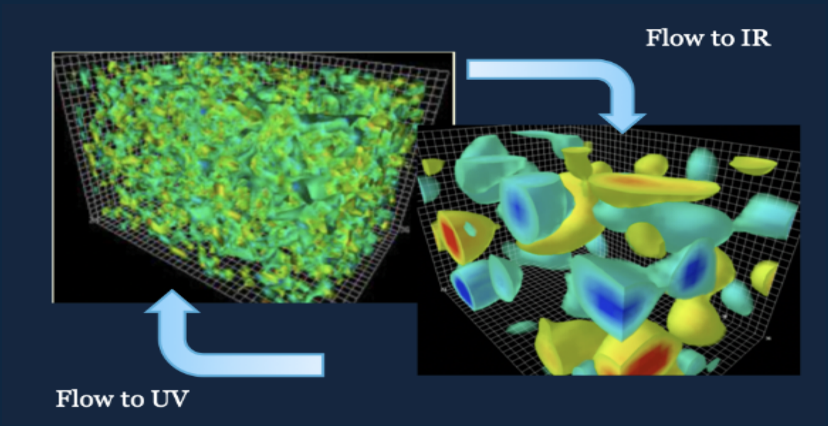
Gradient Flow RG

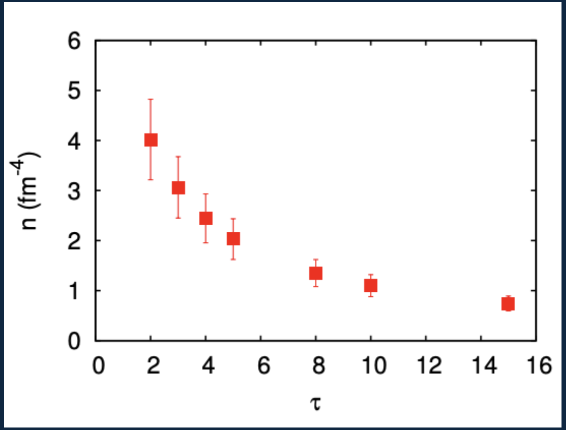
Gradient Flow

RG flow driven by EOM kernel (diffusive)

$$\partial_\tau B_\mu = \frac{\delta S_{QCD}}{\delta A}[B_\mu], \qquad B_\mu|_{\tau=0} = A_\mu$$

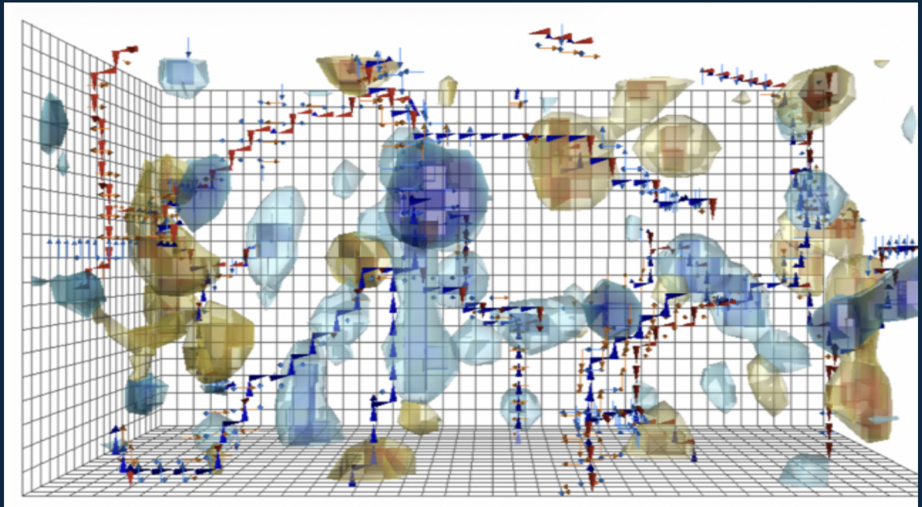






Athenodorou et. al, *JHEP 02 (2018) 140*

Visualization of QCD Vacuum



Biddle, Kamleh, Leinweber, PRD 102, 034504 (2020)

- LQCD gradient flow visualizes the IR
- Instantons, Anti-instantons
- Center vortices
- DBχS, anomalies, confinement
- Strong CP
- $\rho = 0.3$ fm and $R = 1$ fm

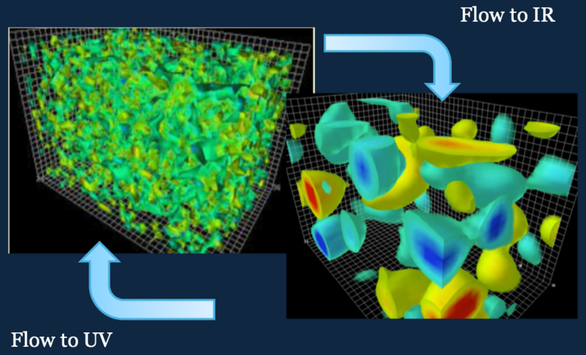
Effective field theories to describe them quantitatively?

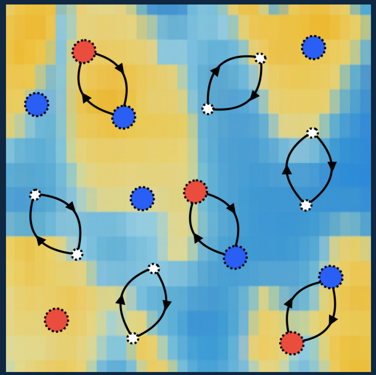
Instanton Liquid Model (ILM)

Wilsonian RG picture: UV modes integrated → effective QCD at scale 0.6 ~ 0.7 GeV

$$Z_{\rm QCD} = \int DU\, e^{-S_{\rm YM}[U]} \underbrace{\mathrm{Det}(\not{D} + m)}_{\rm sea\ quark}$$

$$Z_{\rm ILM} = \sum_{N_+,N_-} \left(Z_{N_\pm} = \overbrace{\frac{1}{N_+!N_-!} \prod_{I,A} \int d\Omega_I n(\rho_I) e^{-S_{\rm int}}}^{\rm glue} \overbrace{\int D\psi D\bar\psi e^{-\int d^4x \bar\psi \not{\partial} \psi} \prod_{I,A} \Theta_I \Theta_A}^{\rm quarks-instanton,\ Det(\not{D}+m)} \right)$$





UV Smeared QCD as Instanton Liquid

UV smeared lattice in *continuum limit* and *gradient flow renormalization scheme*

Pros:

- Clear physical picture of non-perturbative field configurations
  → (NJL, ChPT, CSM, QCD sum rule...)
- A few universal parameters: n_{I+A}, ρ, m_q, quark-instanton couplings
- Directly in continuum limit → well-defined ***chiral dynamics***
- Free of signal-to-noise ratio
  → easy to work on ***gluodynamics (gluon parton)***, ***physical*** m_q, and ***strong CPV***
- Analytical solutions → analytical continuation to Minkowski → ***real time dynamics***

UV Smeared QCD as Instanton Liquid

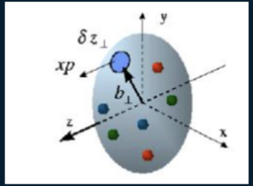
Cons:

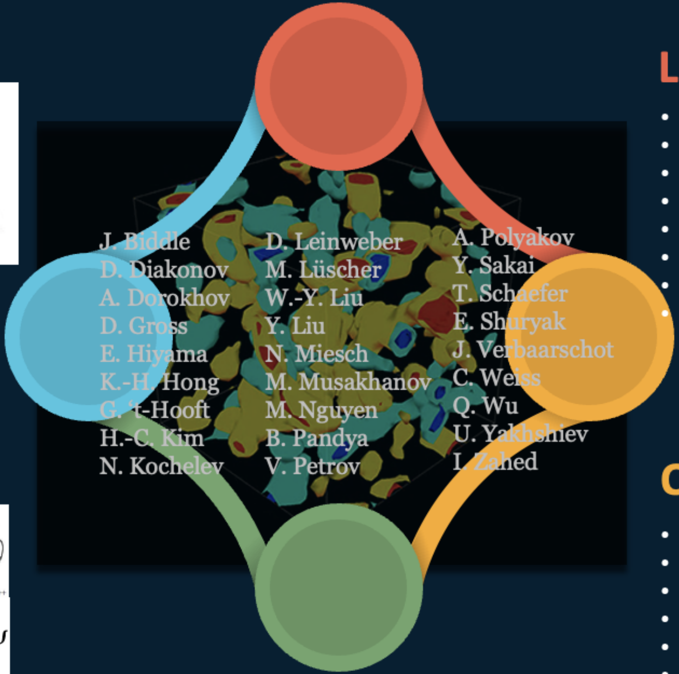
- UV removed → non-local interaction (natural UV cut-off $1/\rho \sim 600$ MeV)
- Detailed multi-instanton correlations
- Non-perturbative RG evolution
- Large flow time matching to $\overline{\mathrm{MS}}$
- No explicit confinement mechanism → incorporate with holographic QCD, center vortex effective models

Application of Vacuum Based Theories

Parton Structure

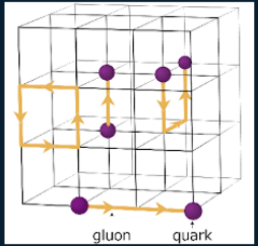
- CJP 52 (2002), C79
- EPJC 37 (2004), 105
- PRD 103 (2021) , 034012
- PRD 107 (2023), 034023
- PRD 107 (2023), 034024
- PRD 107 (2023), 034025
- PLB 848 (2024), 138387
- PRD 112 (2025), 034028
- PRD 111 (2025) , 074022





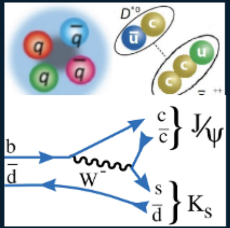
Lattice QCD

- PLB 125 (1983) 197
- arXiv: 9702006 (1997)
- PRL 91 (2003), 182001
- PRD 96 (2017), 095001
- JHEP 2018 (2018), 140
- EPJ 175 (2018) 12011
- PoS (LATTICE2018) 325
- PoS (LATTICE2023) 453



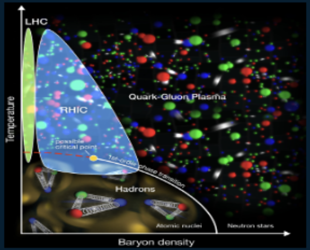
Heavy Flavors

- PRD 92 (2015) 054004
- EPJ 137 (2017) 03013
- CPC 41 (2017) 083102
- PTEP 2018 (2018) 123D01
- PRD 109, (2024) 014022
- PRD 110 (2024) 114044
- DAESNP 67 (2024) 901



QCD Phase

- RMP 53 (1981) 43
- NPB 364 (1991) 255
- PRD 50 (1994) 3323
- PRD 51 (1995) 4580
- PRD 53 (1996) 6522
- NPA 638 (1998) 511



Application of Vacuum Based Theories

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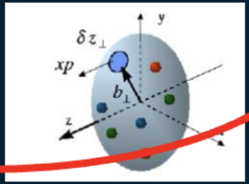

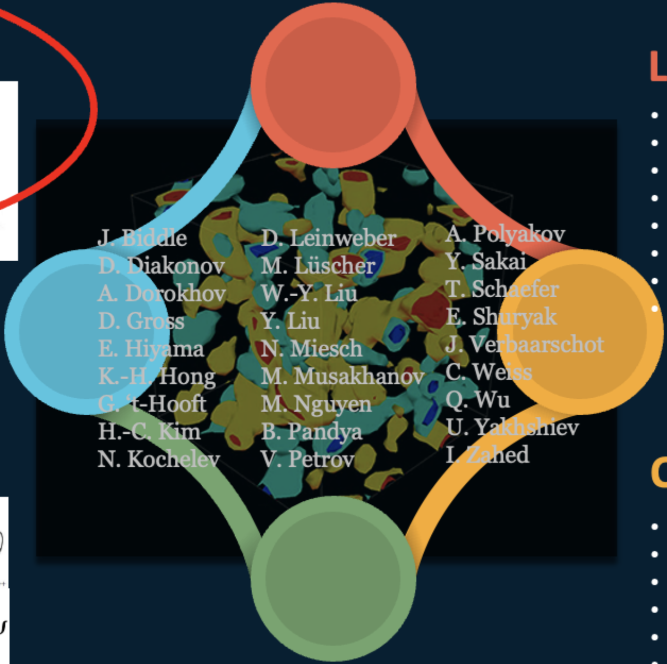

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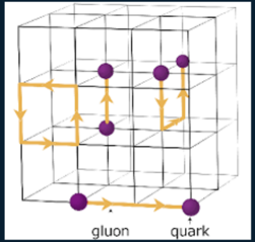

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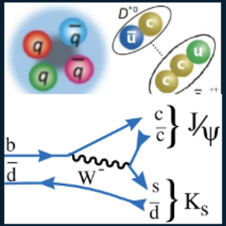
- DAESNP 67 (2024) 901



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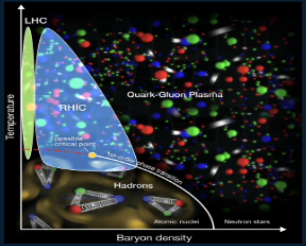
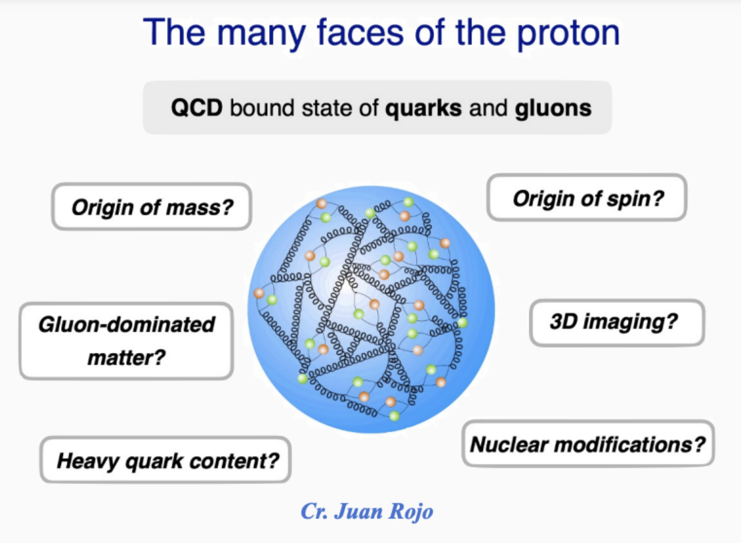


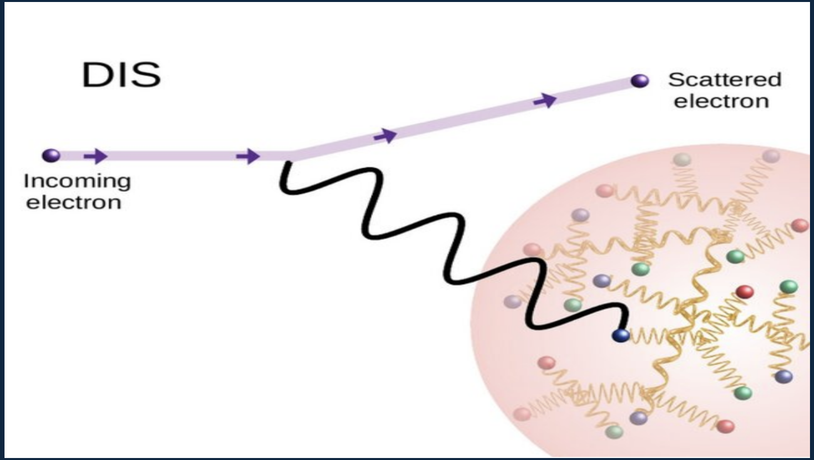
Outline

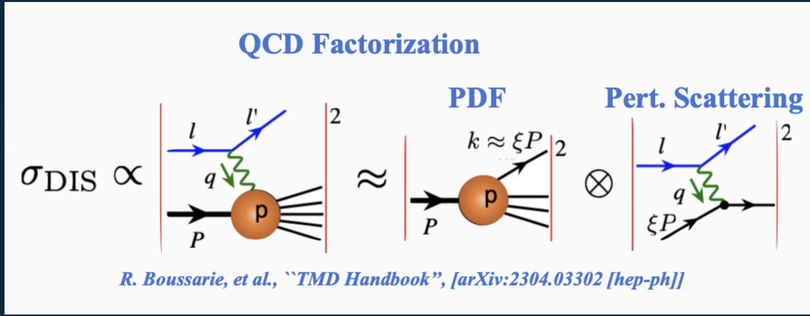
What is Parton?

Constituents of a hadron on light cone

The journey begins here:
How we describe a relativistic bound state



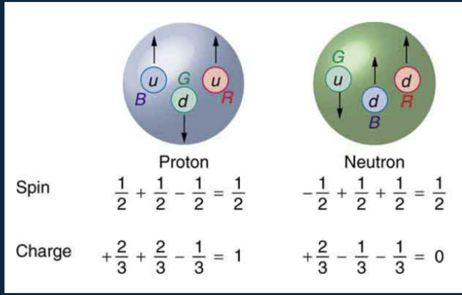


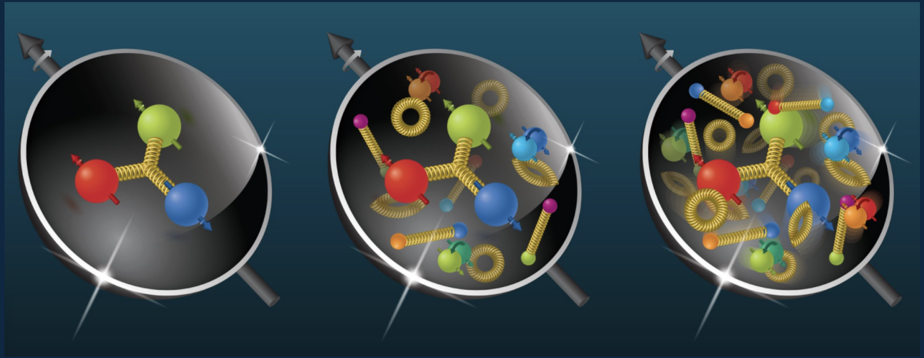


From Quark model to Parton model

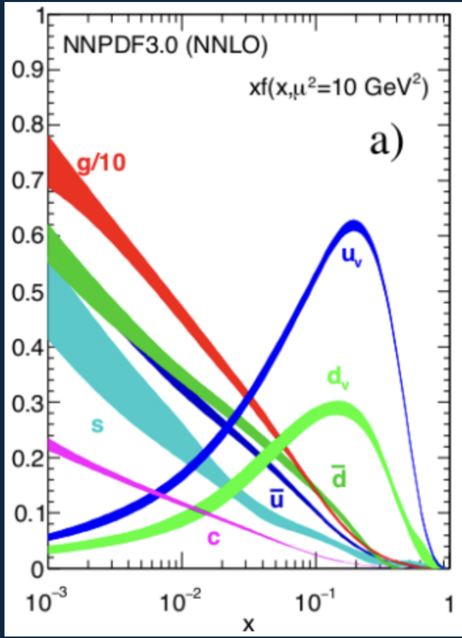
The description of constituent particles is scale dependent (varies with RG flow)

Quark Models



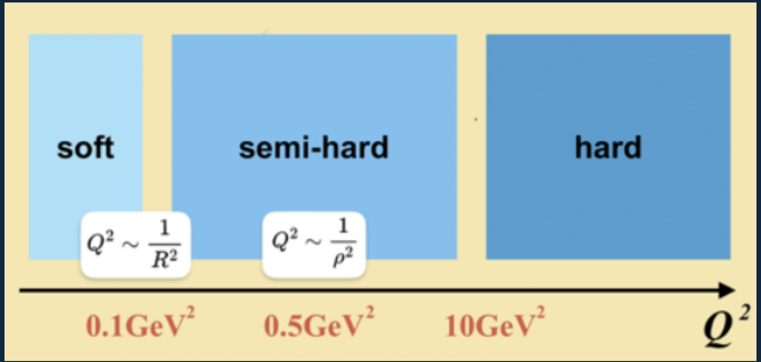


UV perturbative gluon regenerated

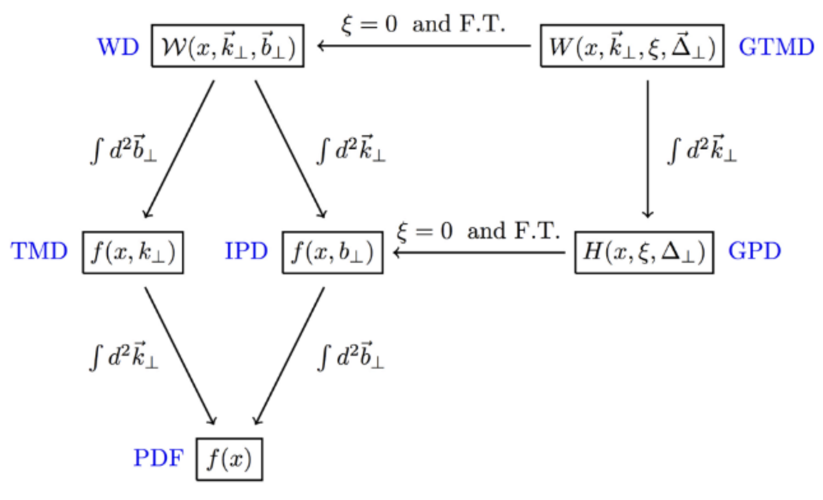


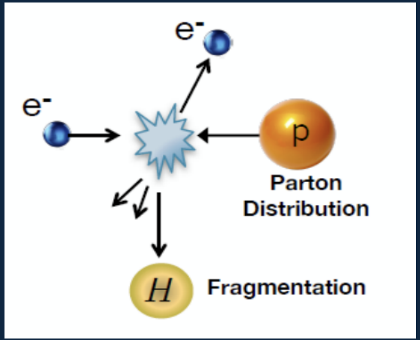
Mass $m_N \simeq 2M_u + M_d$

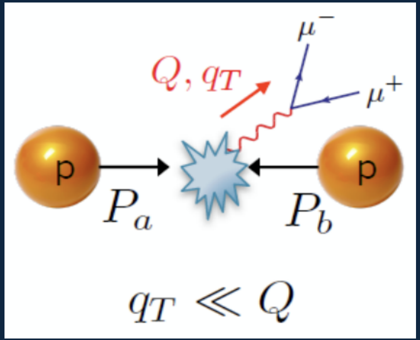
$$\mu_u = \frac{Q_u e}{2M_u}$$
$$\mu_d = \frac{Q_d e}{2M_u}$$



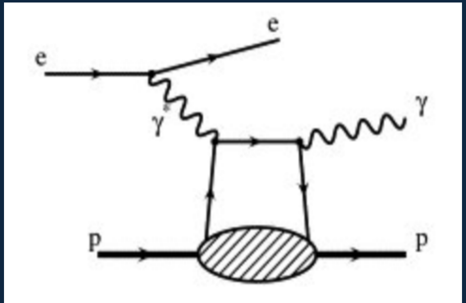
Parton 3D Imaging Road Map

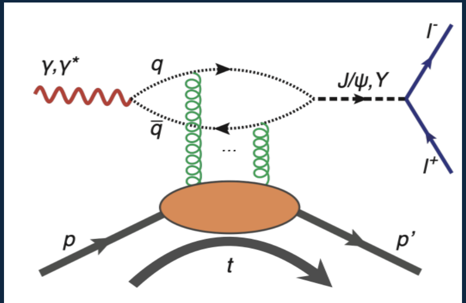




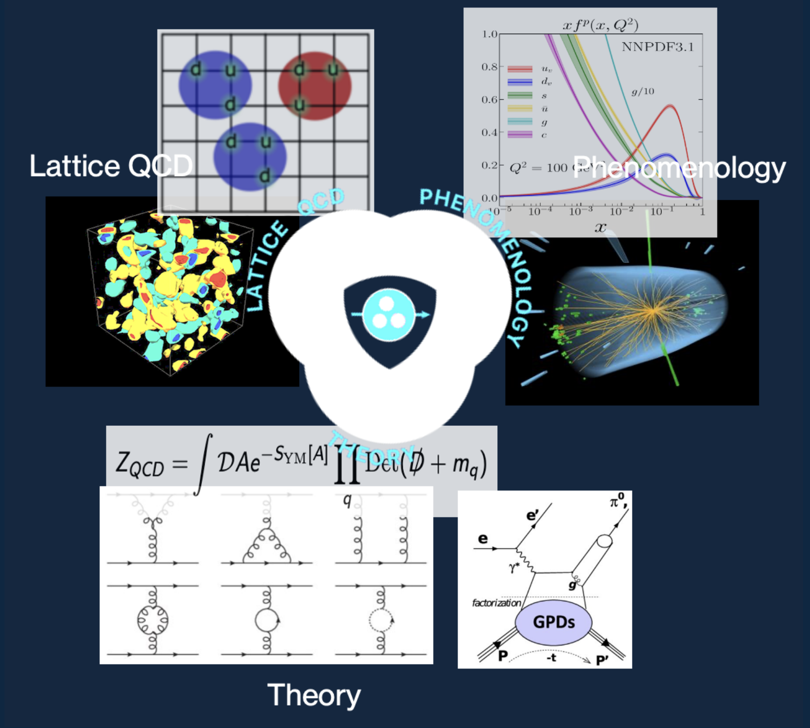


- $f(x, k_\perp)$ TMDs
- $H(x, \xi, t)$ GPDs $\leftrightarrow$ IPDs
- $\mathcal{W}(x, \vec{k}_\perp, \vec{b}_\perp)$ Wigner distributions

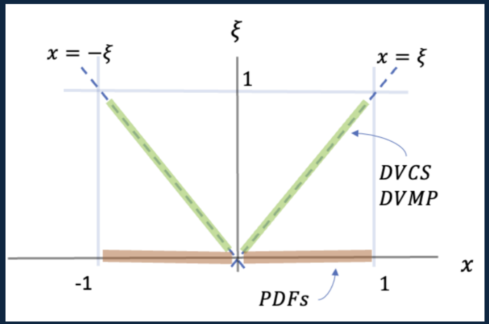




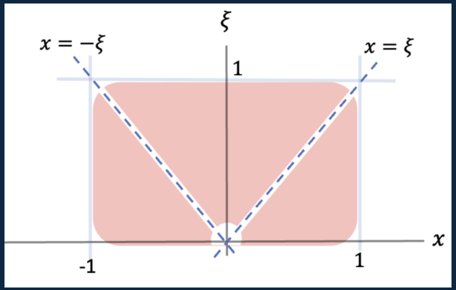
Synergy in Hadron 3D Imaging



experimental data

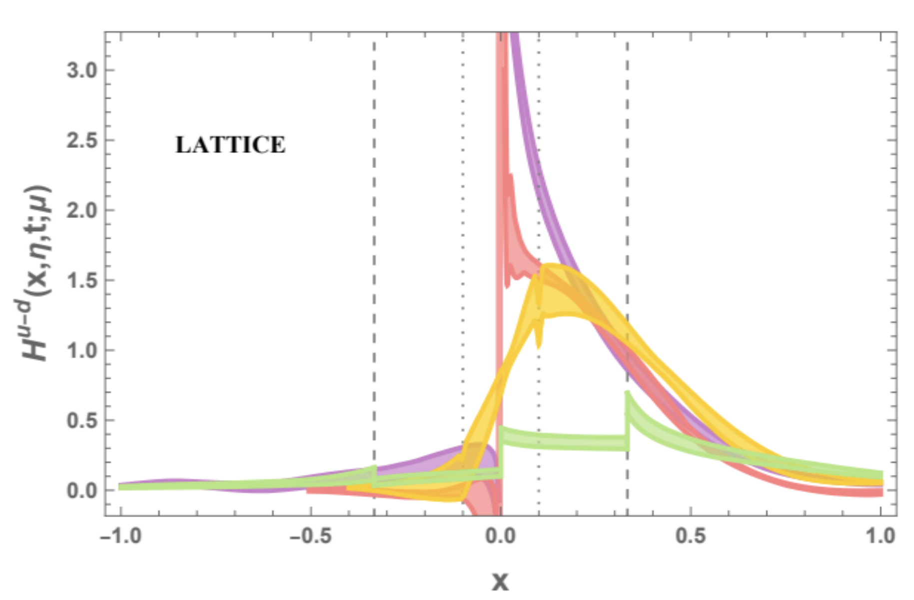


lattice QCD

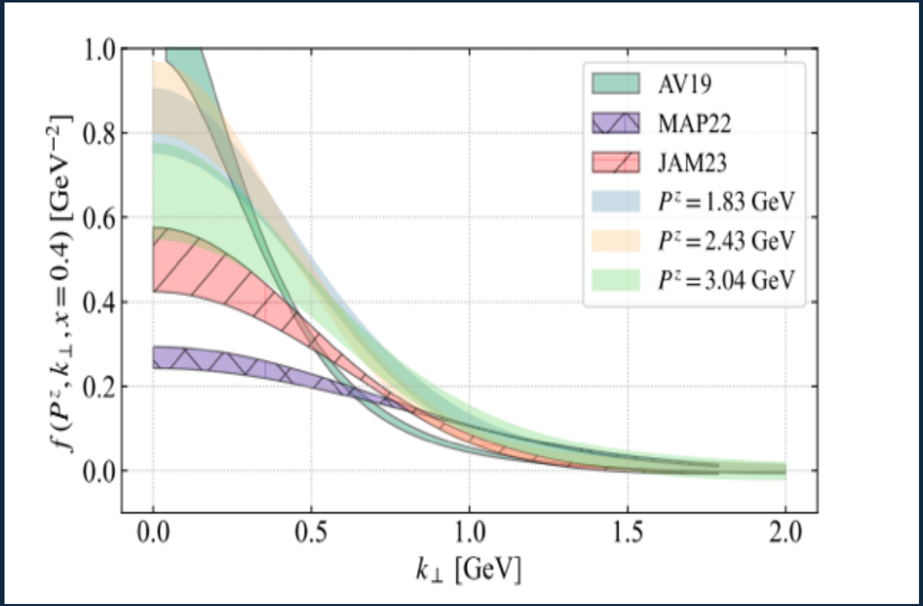


Nonperturbative Physics in Needs

GPD



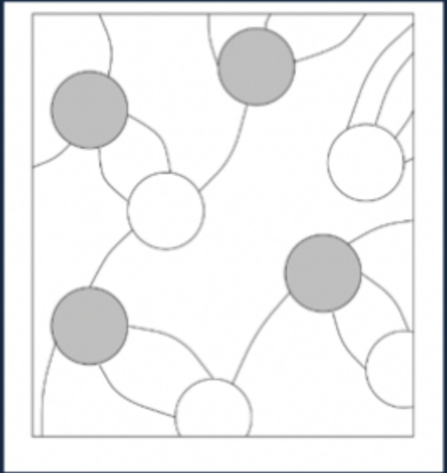
TMD



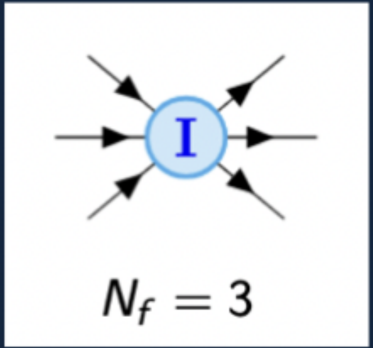
Outline

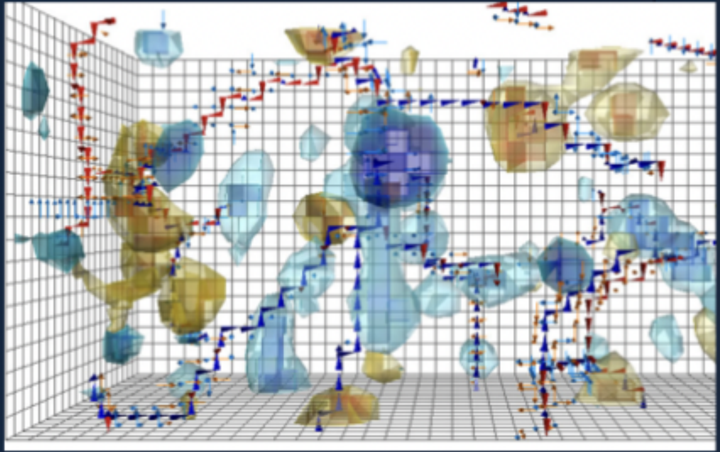
QCD Vacuum Phenomenology

- Stabilized at $\rho = \frac{1}{3}$ fm with density $n_{I+A} = 1$ fm^{-4}
- Perturbative gluons depleted, regenerated by RG evolution

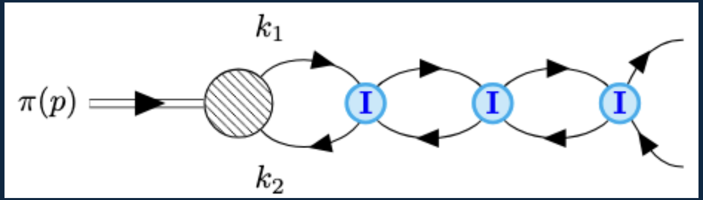


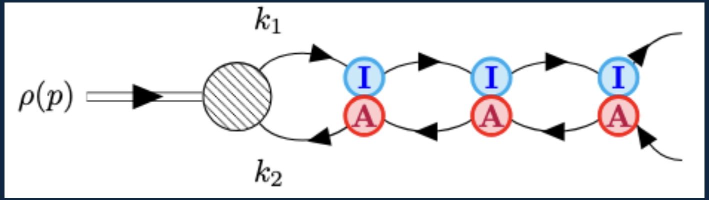
L to R handed quark





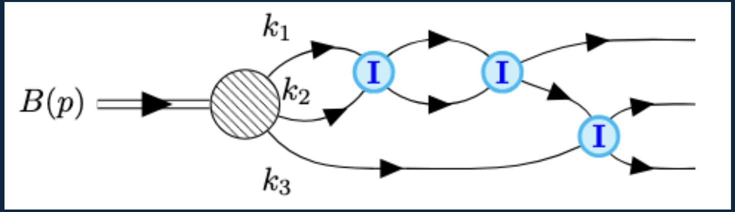
Hadron Spectrum and Wave Function

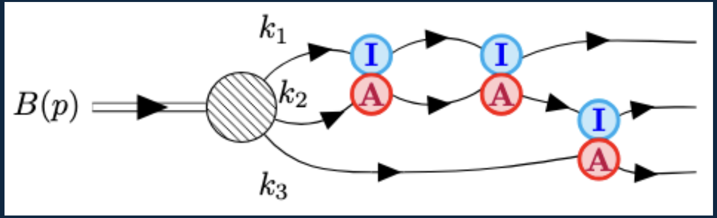




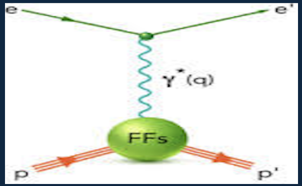
Model	m_{π^0} (MeV)	$m_{\pi^\pm}$ (MeV)	m_ω (MeV)	m_ρ (MeV)
ILM ($N_f = 2$)	139.4	139.4	790.0	790.0
ILM ($N_f = 3$)	142.00	142.00	787.23	787.23
PDG	134.9766(6)	139.57018(35)	782.65(12)	775.26(25)

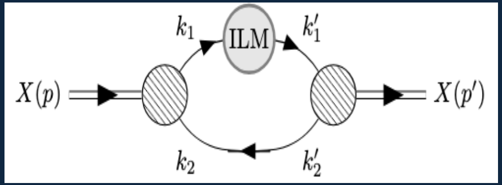
Nucleon: to be continued

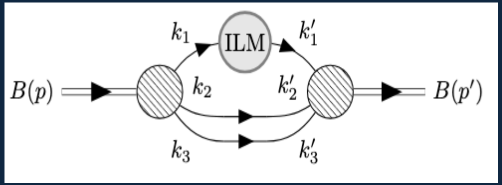


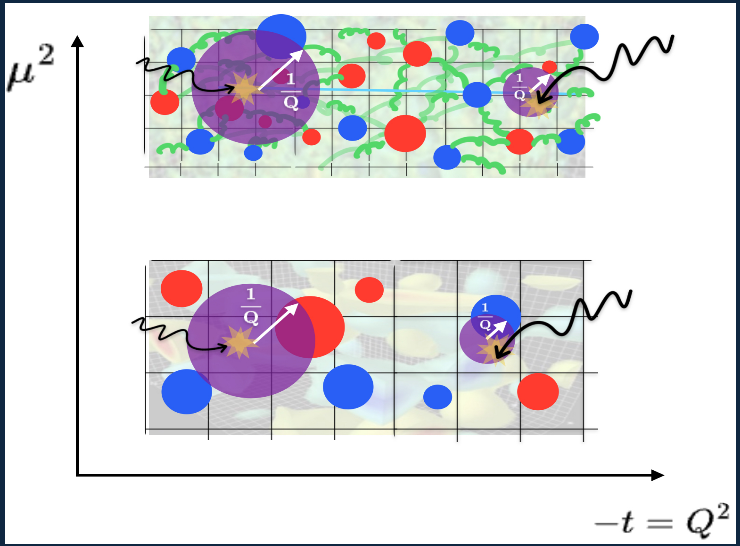


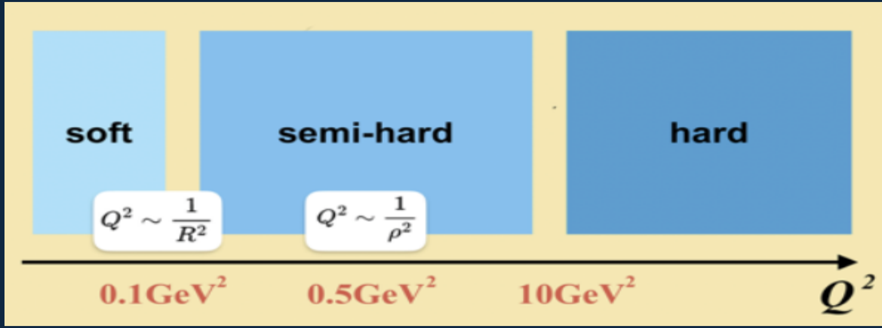
Hadronic Form Factors

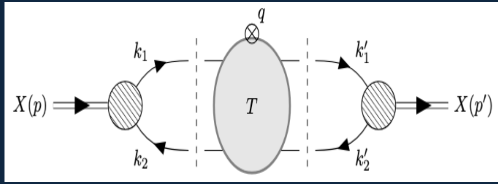


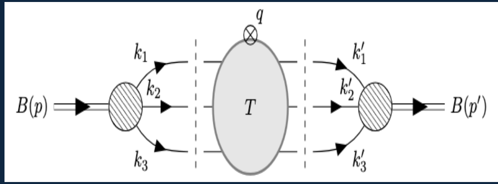






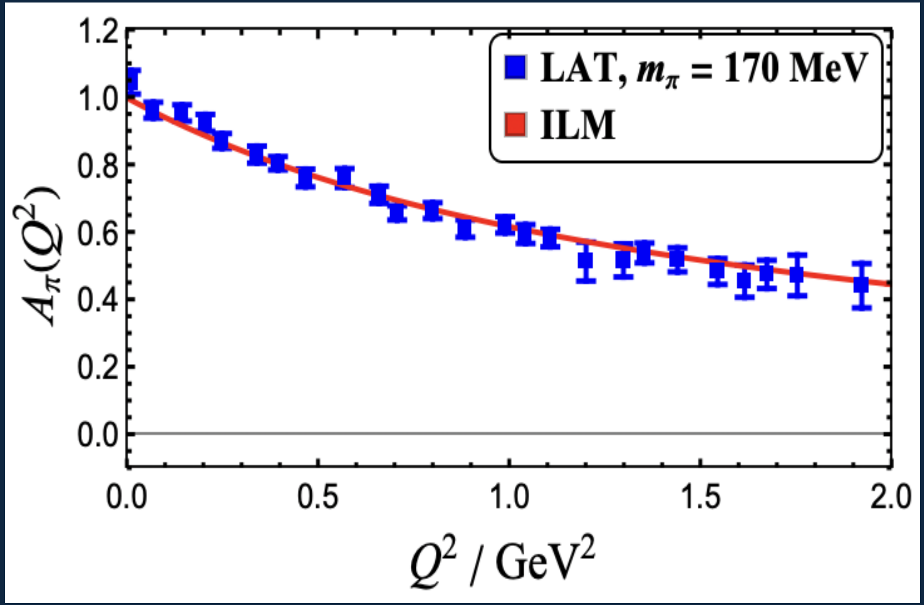


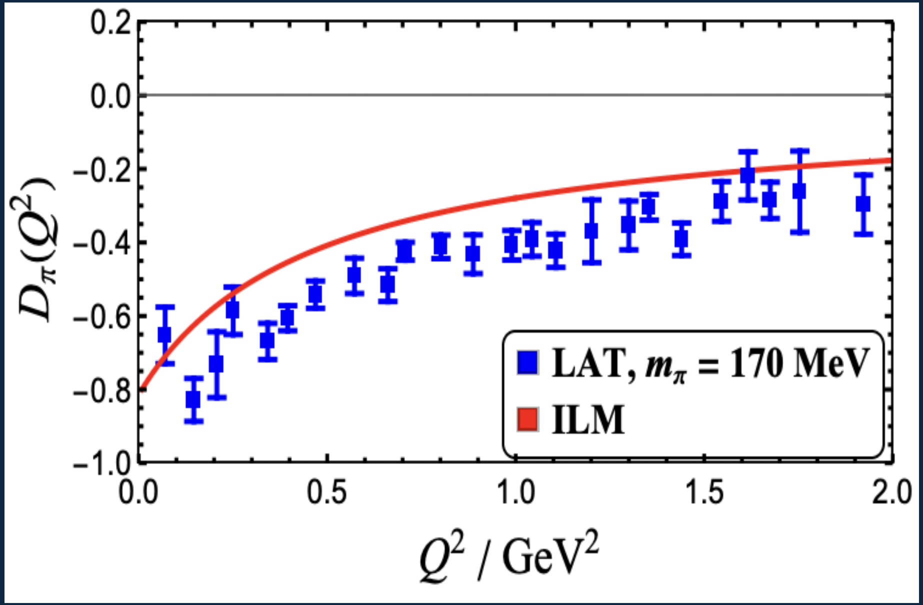




Pion Gravitational Form Factor

$$\langle \pi' \,|\, T^{\mu\nu} \,|\, \pi \rangle = 2\bar{p}^{\mu}\bar{p}^{\nu} A_{\pi} + \frac{1}{2}(q^{\mu}q^{\nu} - g^{\mu\nu}q^{2})\, D_{\pi}$$





Pion Gravitational Form Factor

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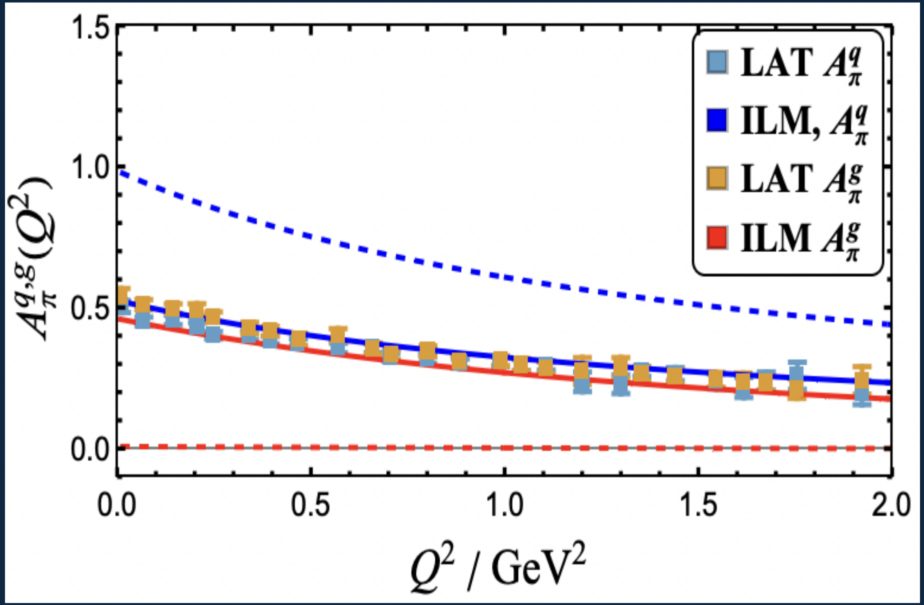
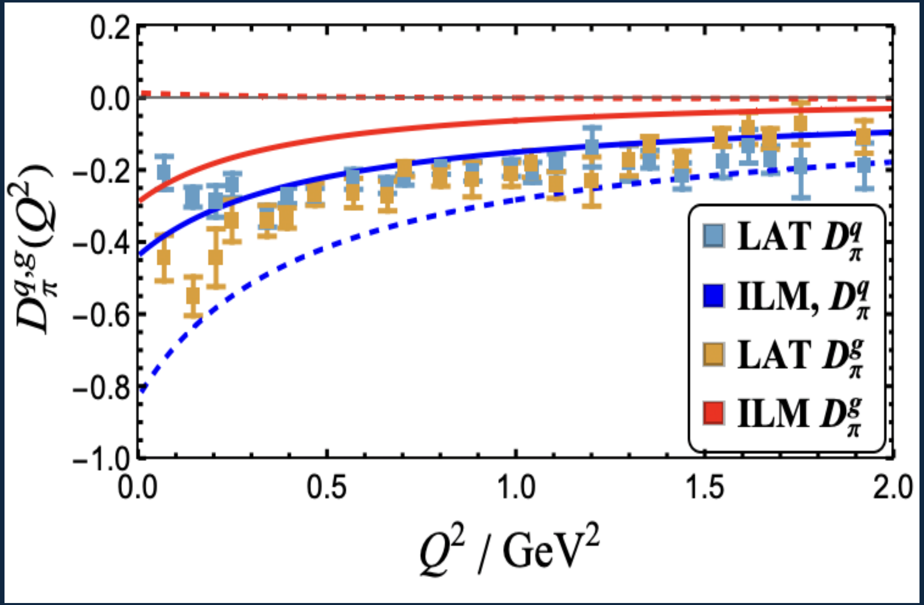
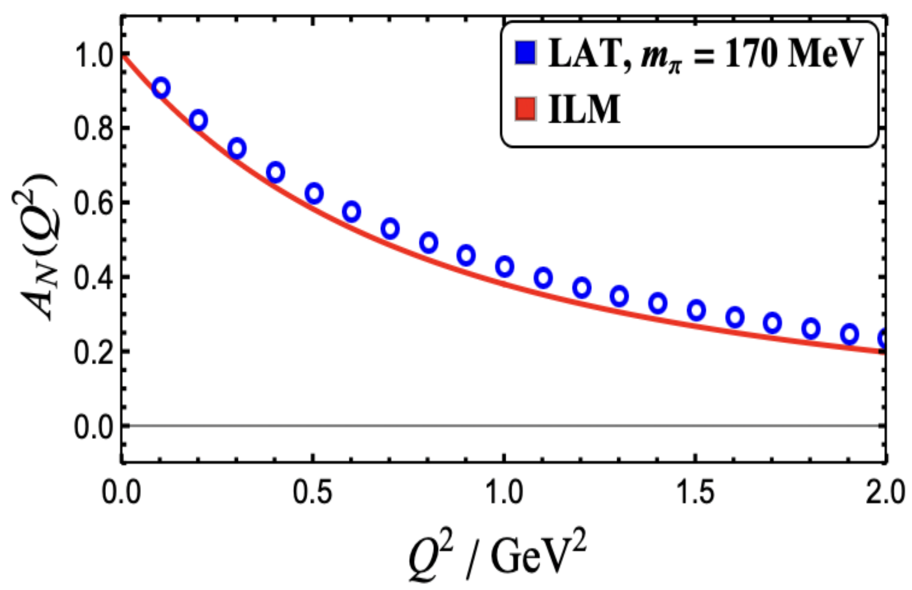
D. Hackett, P. Oare, D. Pefkou, P. Shanahan, PRD 108, 114504 (2024)

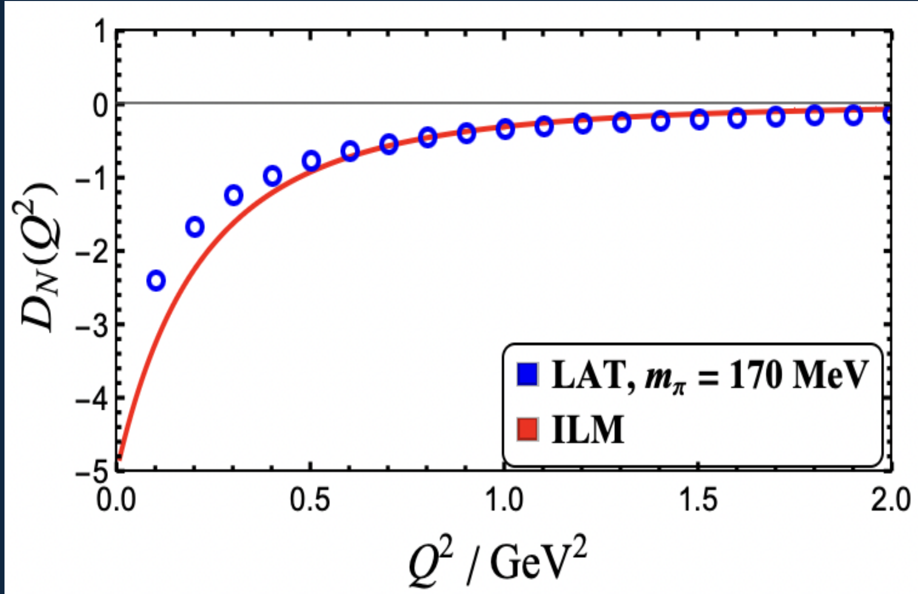




Nucleon Gravitational Form Factor

$$\langle N' \,|\, T^{\mu\nu} \,|\, N \rangle = \bar{u}' \left(A_N \, \gamma^{\{\mu} \bar{p}^{\nu\}} + B_N \frac{iP^{\{\mu} \sigma^{\nu\}\rho} q_\rho}{2M_N} + D_N \frac{q^\mu q^\nu - g^{\mu\nu} q^2}{4M_N} \right) u$$

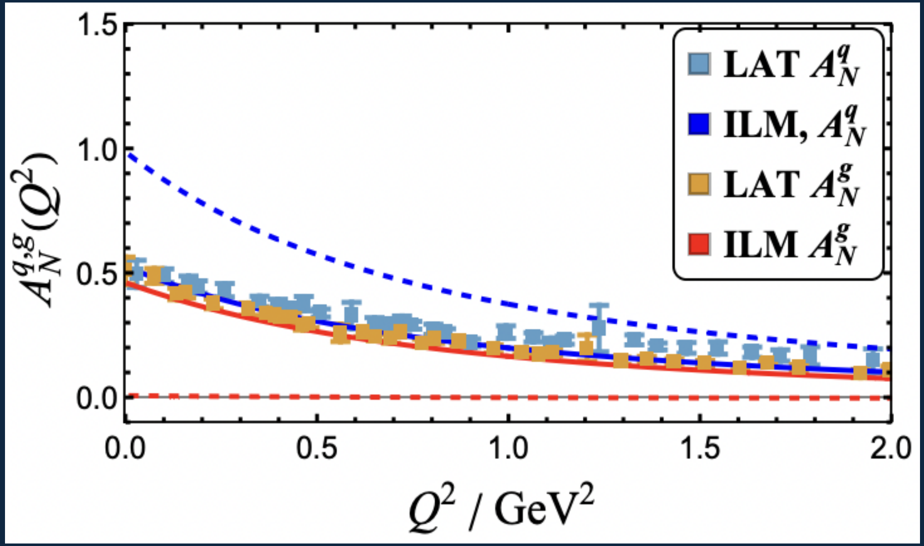


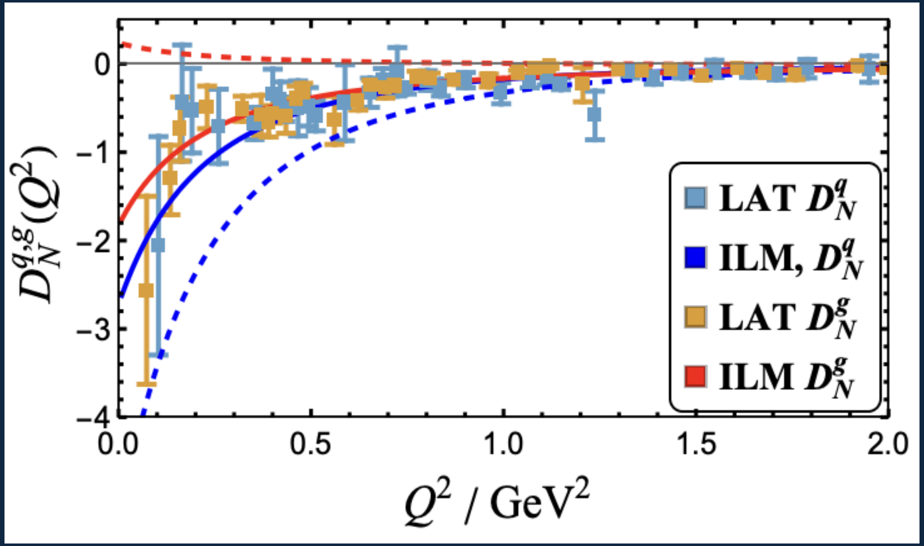


Nucleon Gravitational Form Factor

$$\langle N' \,|\, T^{\mu\nu} \,|\, N \rangle = \bar{u}' \left(A_N \, \gamma^{\{\mu} \bar{p}^{\nu\}} + B_N \, \frac{i P^{\{\mu} \sigma^{\nu\}\rho} q_\rho}{2 M_N} + D_N \, \frac{q^\mu q^\nu - g^{\mu\nu} q^2}{4 M_N} \right) u$$

D. Hackett, D. Pefkou, P. Shanahan, PRL, 132, 25 (2024)





Momentum fraction and D charge

	$A^q_N(0)$	$A^g_N(0)$
ILM (0.6 GeV)	0.9877	0.0123
ILM (2 GeV)	0.530	0.470
χQCD (2 GeV)	0.530(72)	0.460(50)
Global Analysis	0.58(1)	0.414(8)

χQCD, PRD 106 (2022) 1, 014512

	$A^q_\pi(0)$	$A^g_\pi(0)$
ILM (0.6 GeV)	0.9877	0.0123
ILM (2 GeV)	0.530	0.470
ETMC (2 GeV)	0.532(56)	0.388(49)

ETMC, PRL 134 (2025) 13, 131902

	D^q_N	D^g_N
ILM (0.6 GeV)	-5.223	0.308
ILM (2 GeV)	-2.697	-2.220
MIT (2 GeV)	-1.300(48)	-2.572(84)
Exp. (6 GeV)	$-1.632(112)(132)$	-

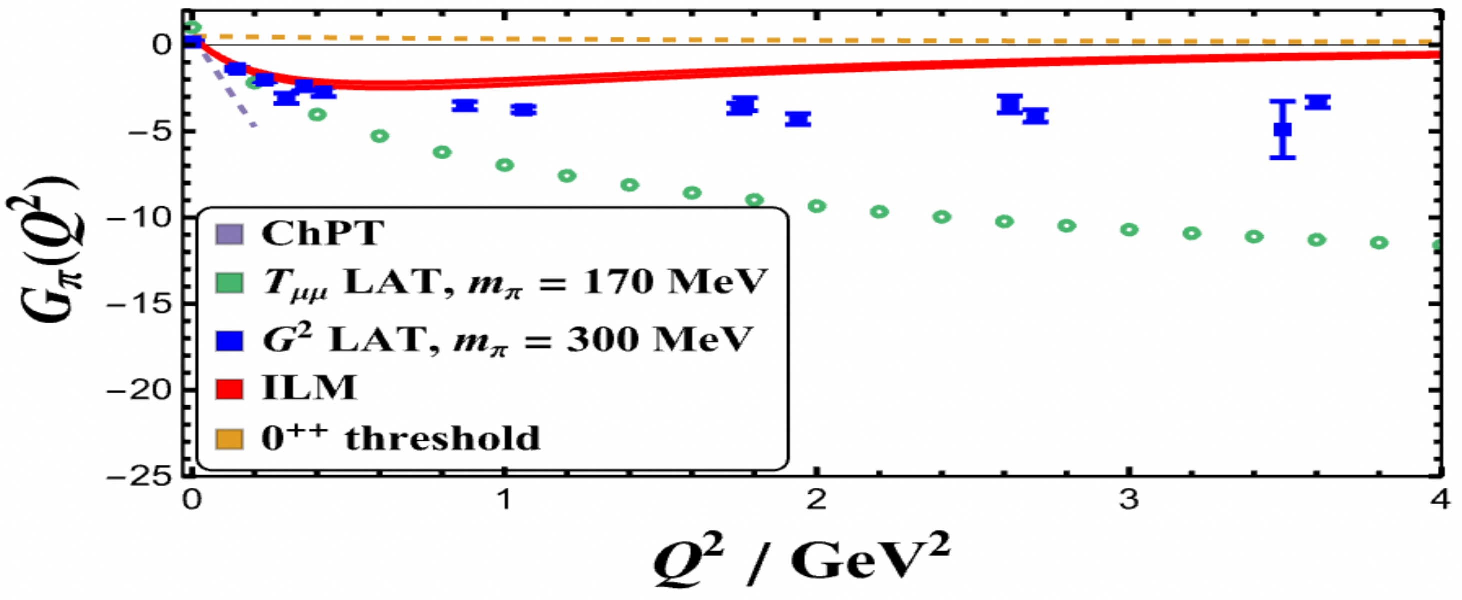
Shanahan et. al, PRL 132, 251904; Burkert, Nature 557 (2018) 7705

	$D^q_\pi(0)$	$D^g_\pi(0)$
ILM (0.6 GeV)	-0.827	0.0228
ILM (2 GeV)	-0.434	-0.370

0^{++} C-even Glueball Form Factor of Pion

$$\frac{\beta(g^2)}{4g^2}\langle\pi'|G^2_{\mu\nu}|\pi\rangle = 2m_\pi^2 G_\pi(Q^2)$$

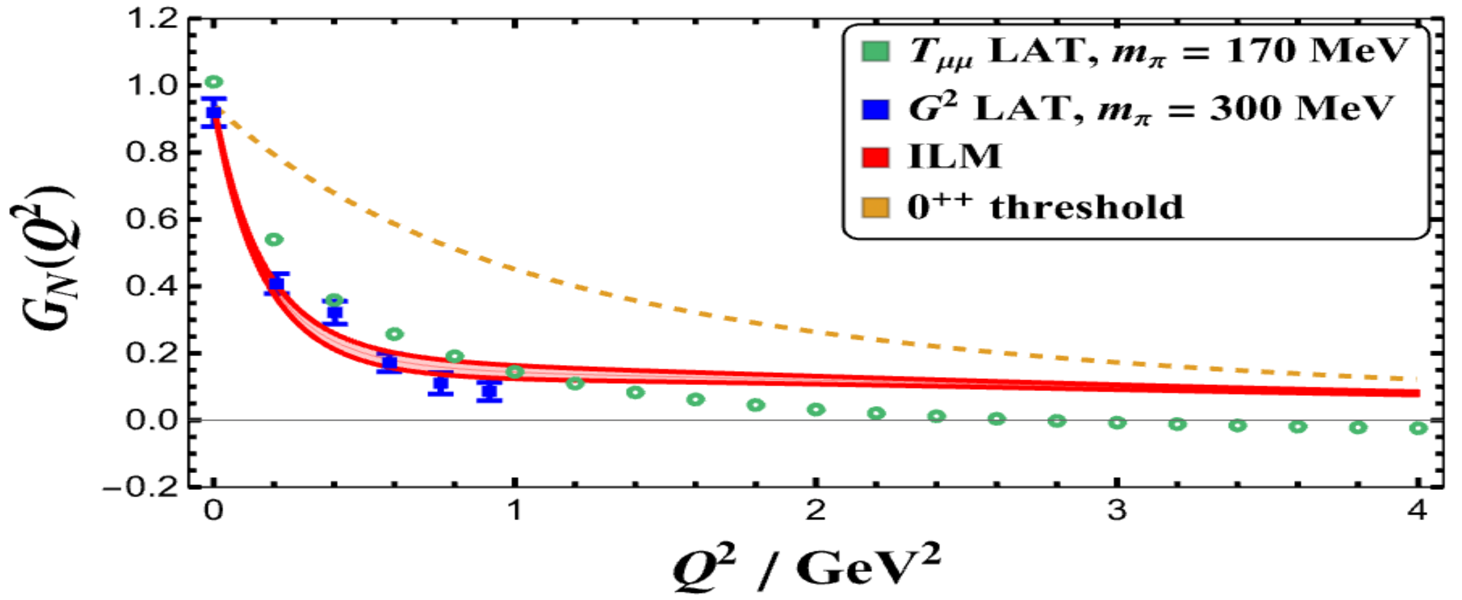
Lattice: χ QCD (Yi-Bo Yang)



0^{++} C-even Glueball Form Factor

$$\frac{\beta(g^2)}{4g^2}\langle N'|G^2_{\mu\nu}|N\rangle = m_N G_N(Q^2)\bar{u}'u$$

Lattice: χ QCD (Yi-Bo Yang)



Outline

Mass Decomposition

Decomposition from EMT → energy perspective

$$T^{00} = \underbrace{\overline{T}_q^{00} + \overline{T}_g^{00}}_{\text{traceless } 2^{++}} + \underbrace{\frac{1}{4} T^{\mu}{}_{\mu}}_{\text{trace spin } 0^{++}}$$

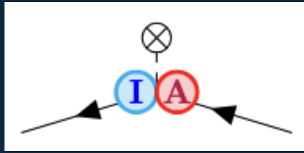
scale dependent → partonic picture

$$M_h^Q / M_h = \frac{3}{4}\left(A_h^q(0) - \frac{\sigma_{\pi h}}{M_h}\right) \qquad M_h^a / M_h = \frac{1}{4}\left(1 - \frac{\sigma_{\pi h}}{M_h}\right)$$

$$M_h^G / M_h = \frac{3}{4} A_h^g(0) \qquad M_h^m / M_h = \frac{\sigma_{\pi h}}{M_h}$$

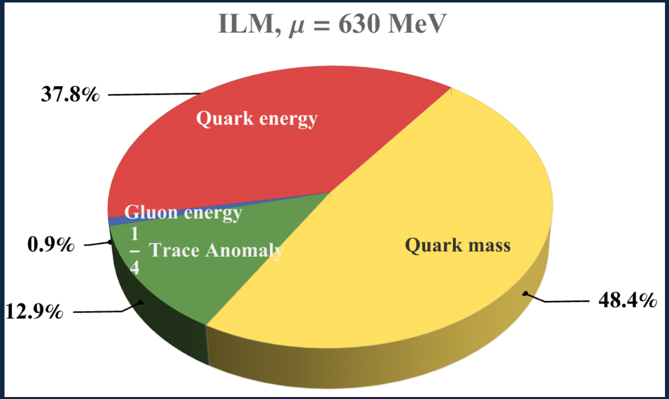
ILM prediction

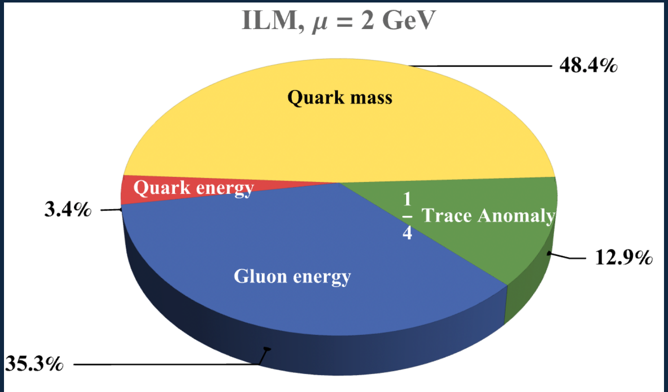
$$A_h^g(0) = \frac{n_{IA}}{2N_c(N_c^2 - 1)} \gamma_{IA} \beta_{T_g,1}^{(+-)}(0) A_h^q(0)$$



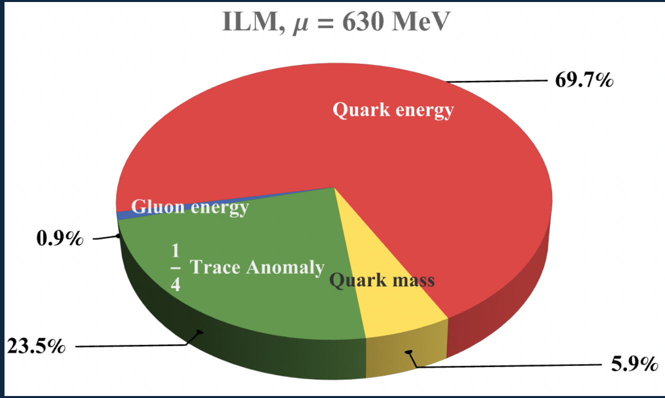
Mass Sum Rule

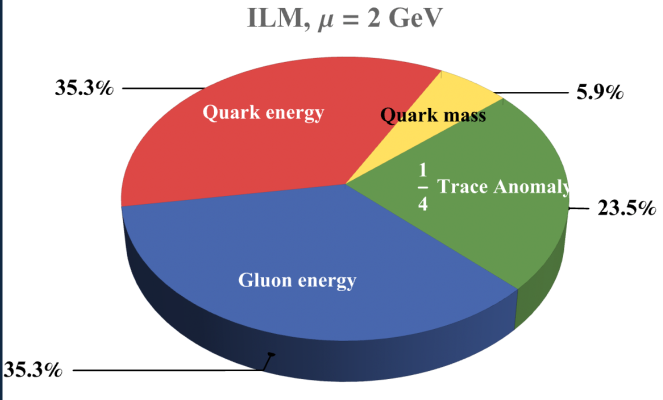
Pion:



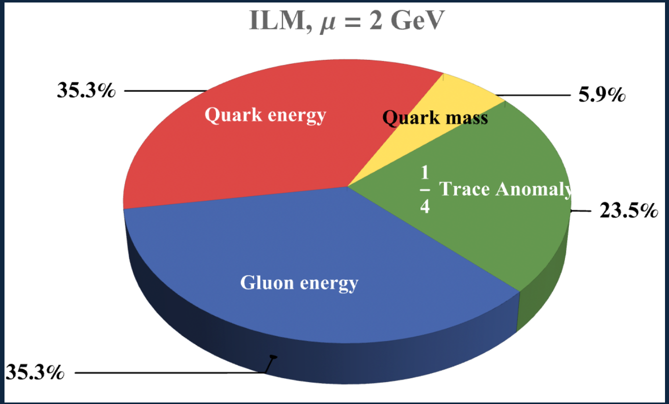


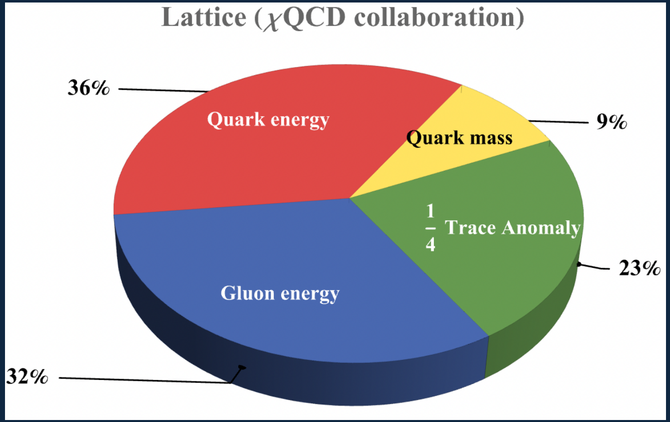
Nucleon:





Nucleon Mass Sum Rule





Yi-Bo Yang, Jian Liang, Yu-Jiang Bi, Ying Chen, Terrence Draper, Keh-Fei Liu, and Zhaofeng Liu, Phys. Rev. Lett. 121, 212001 (2018)

Outline

1. Overview: Vacuum-Based (Semiclassical) Effective Theories
2. Overview: Parton Structure in Hadrons
3. Hadronic Form Factor
4. Hadron Mass Decomposition
5. Nucleon Spin Decomposition

Spin Decomposition

- Proton spin

$$\frac{1}{2} = \frac{1}{2}\Sigma_q + L_q + J_g$$

- Intrinsic quark spin: ABJ anomaly (RG-invariant)

$$\partial_\mu J_5^\mu = \frac{N_f}{32\pi^2} G\tilde{G} + m\bar{q}i\gamma^5 q$$

- Quark OAM L_q and gluon angular momentum J_g are scale-dependent

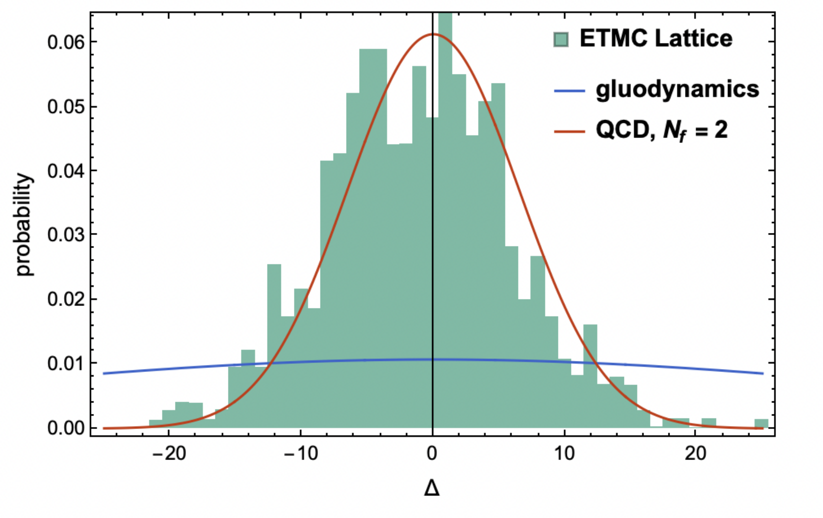
Intrinsic Quark Spin

Intrinsic quark spin is an emergent RG invariant property from Axial $U(1)$ symmetry breaking.

$$\partial_\mu J_5^\mu = \frac{N_f g^2}{32\pi^2} G\tilde{G} + m\bar{q}i\gamma^5 q \;\rightarrow\; \Sigma_q = N_f \Delta\tilde{g} + \Delta\tilde{q}$$

$$\Delta\tilde{g} \simeq -\frac{2M_q}{M_N}\left(\frac{\chi_T}{\bar{N}}\right)$$

	Σ_q	$\Delta\tilde{g}$	$\Delta\tilde{q}$
ILM ($N_f = 2$)	0.362	0.156	0.049



Intrinsic Quark Spin

- Lattice

Σ_q	MSU	χQCD	ETMC
$N_f = 2$	0.339(30)(42)	0.440(24)(40)	0.438(23)

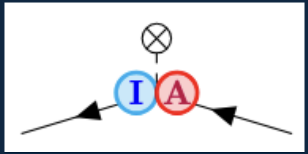
- Global analysis

Σ_q	NNPDF	DSSV	ILM
$N_f = 2$	0.35 ± 0.06	0.38 ± 0.04	0.362

Quark & Gluon AM

From energy momentum tensor

$$J_g = \frac{n_{IA}}{2N_c(N_c^2-1)}\gamma_{IA}\beta^{(+-)}_{T_g,1}(0)J_q$$



Large N_c: $B_q \to 0$. Thus $J = (A+B)/2 \to A/2$

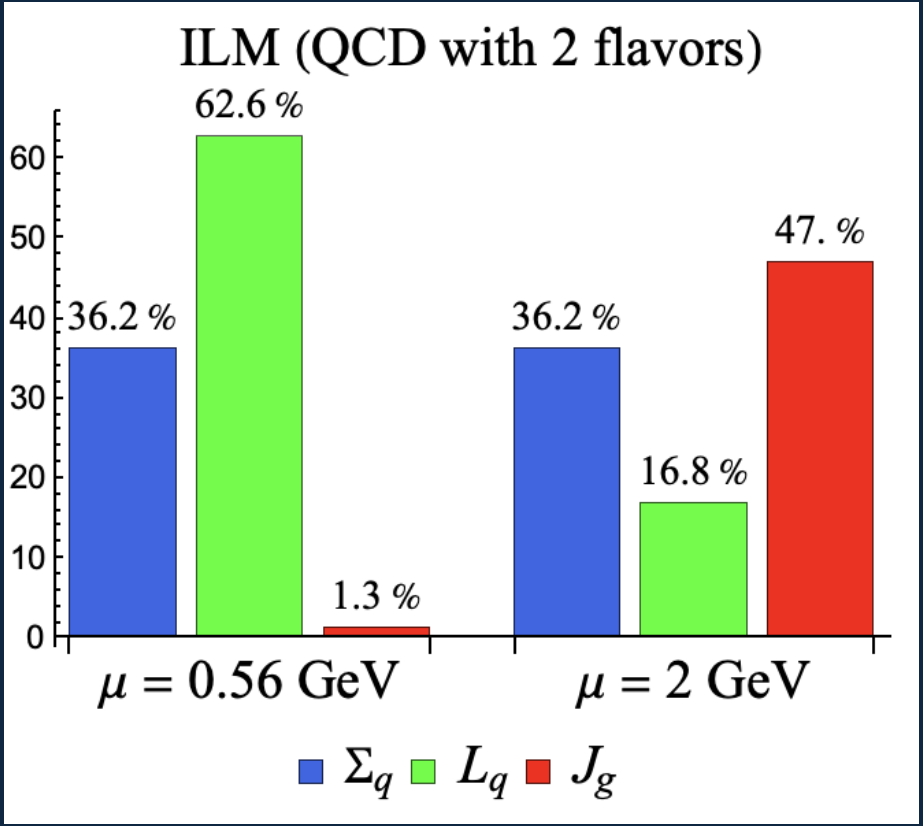
	J_q	J_g
ILM (this work, 0.6 GeV)	0.4938	0.0062
ILM (this work, 2 GeV)	0.265	0.235
Lattice (ETMC)	0.285(45)	0.187(46)
Lattice (χQCD)	0.265(32)	0.230(25)

$$J_q = \frac{1}{2}\Sigma_q + L_q$$

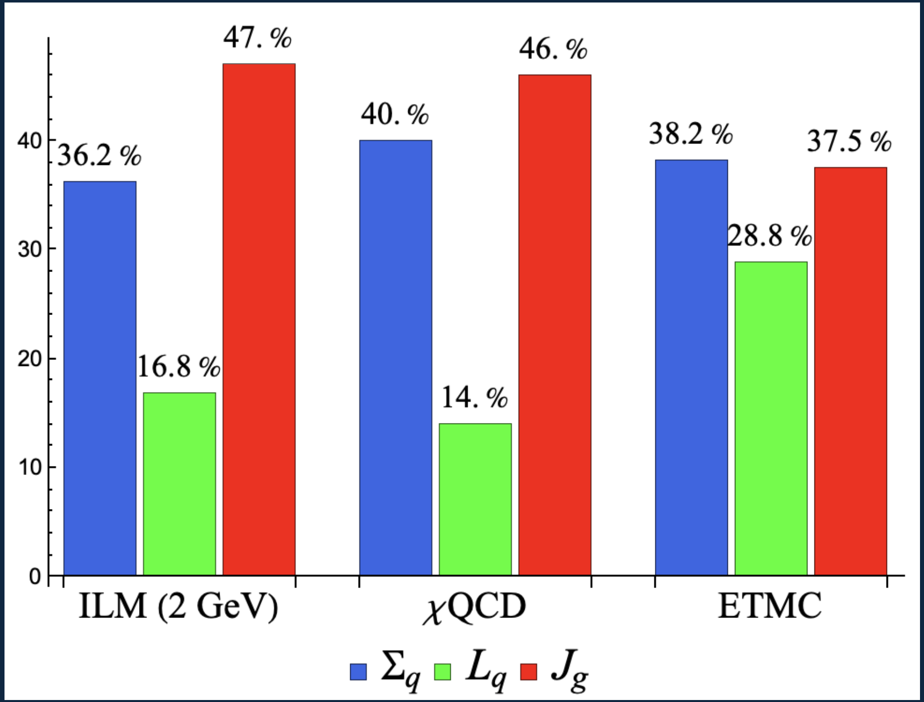
ETMC, PRD 101, 094513 (2020)

χQCD, PRD 98, 074505 (2018)

Spin Sum Rule in ILM



Spin Sum Rule



Remarks for Instanton Model

I. Zahed

C. Weiss

E. Shuryak

- Analytically quantitative nonperturbative QCD
  → UV smeared QCD vacuum
- Form Factors (EM, Grav., etc.) $Q^2 \lesssim 4$ GeV^2
- PDF, TMD, GPD with a few parameters $\rho, n_{I+A}, m, \cdots$
  → provide new pheno insight for global / lattice fitting

Thank You