



UNIVERSITY OF
MARYLAND

Evidence for Quark Confinement in the Proton

Extracting Quark Forces from Experimental Data

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Based on: X. Ji, G. A. Miller, C. Yang, *Research* 9 (2026) 1369

MENU 2026, Stony Brook University, Oct. 20, 2026

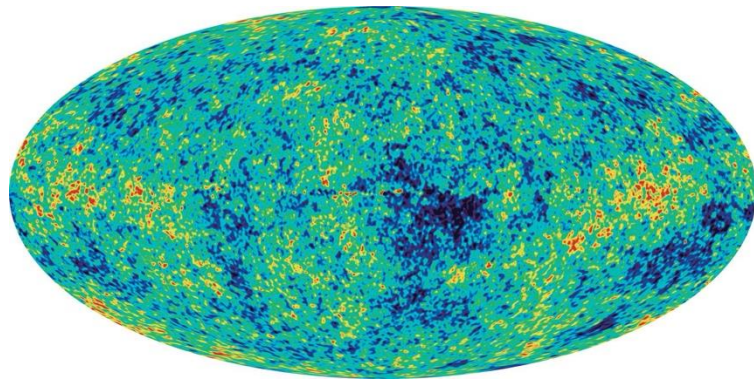
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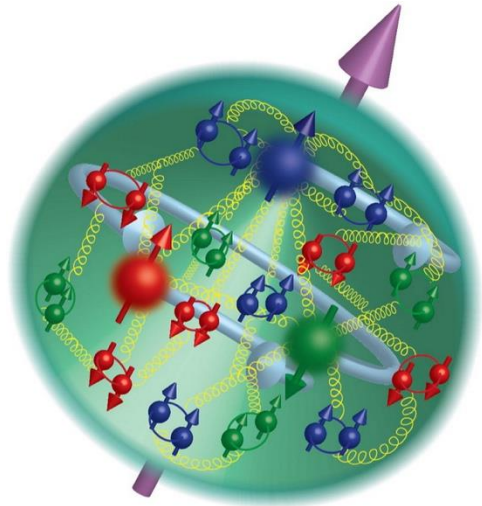
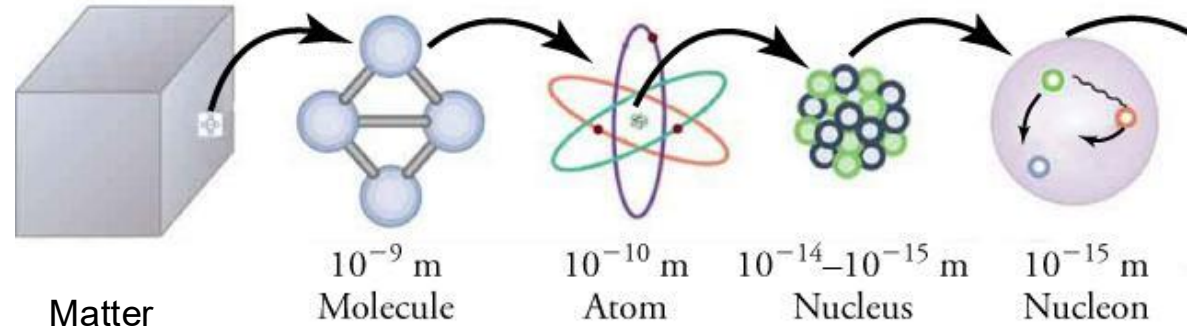
PART ONE

Introduction: Quark Confinement

What is Our Visible Universe Made of?



Universe



Nucleons are building blocks of visible universe.

Quarks and gluons form nucleons through strong forces.

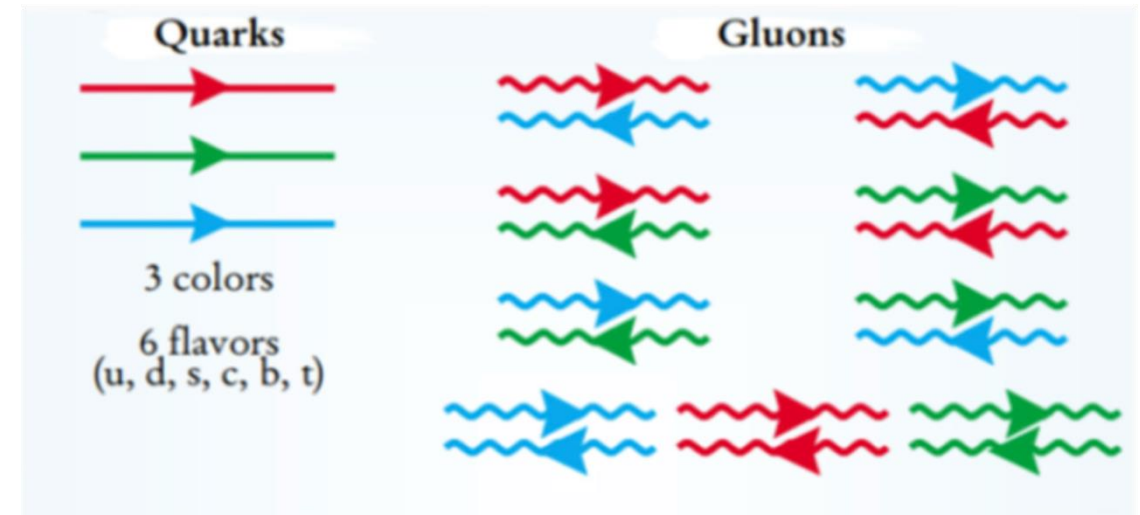
Theory of Strong Interactions

Quantum chromodynamics (QCD):

Color-charge SU(3) non-Abelian gauge theory

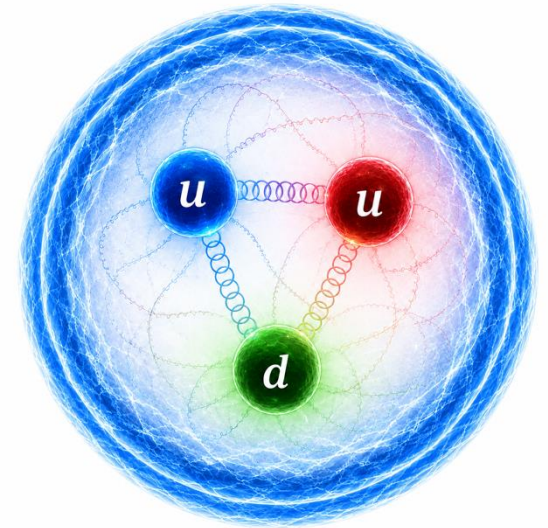
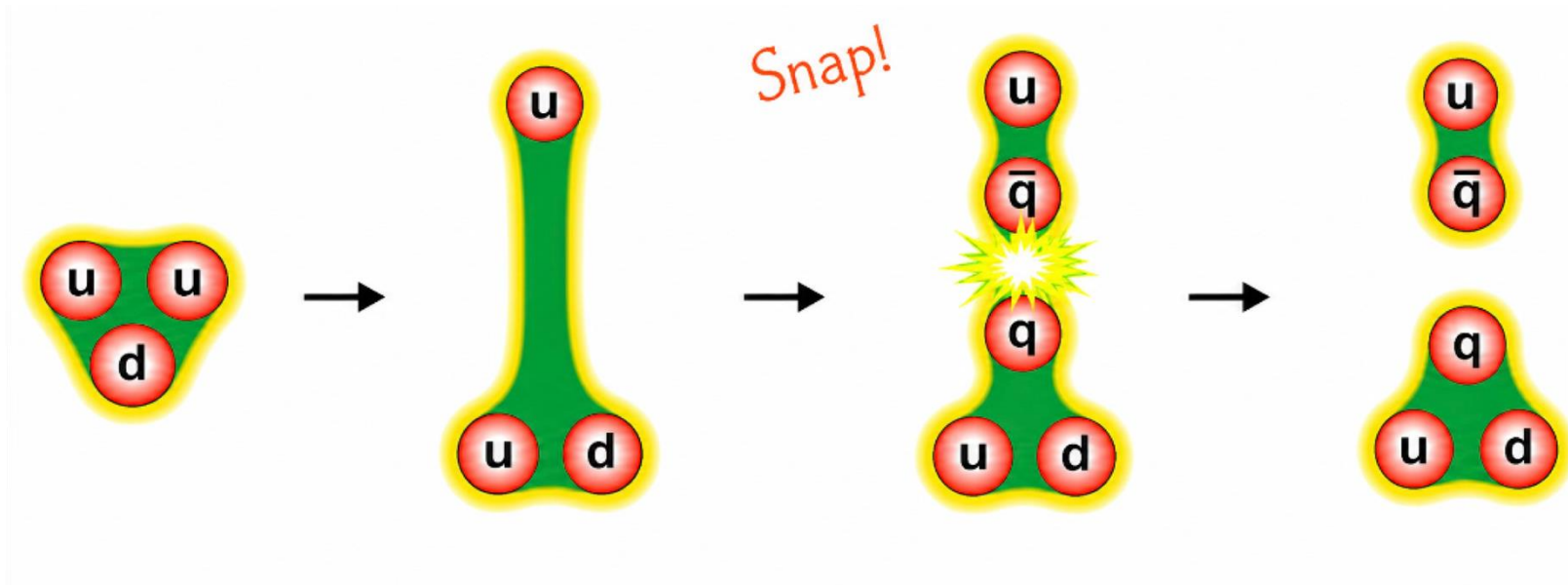
$$\text{QCD Lagrangian: } \mathcal{L}_{\text{QCD}} = \sum_f \bar{\psi}_f (i\gamma^\mu D_\mu - m_f) \psi_f - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$

	I	II	III	
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.273 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$	0
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
QUARKS	u up	c charm	t top	g gluon
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 93.5 \text{ MeV}/c^2$	$\approx 4.183 \text{ GeV}/c^2$	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	
	d down	s strange	b bottom	



Can We Isolate a Free Quark?

Free quarks have never been isolated in any detectors!



“a locked bag”

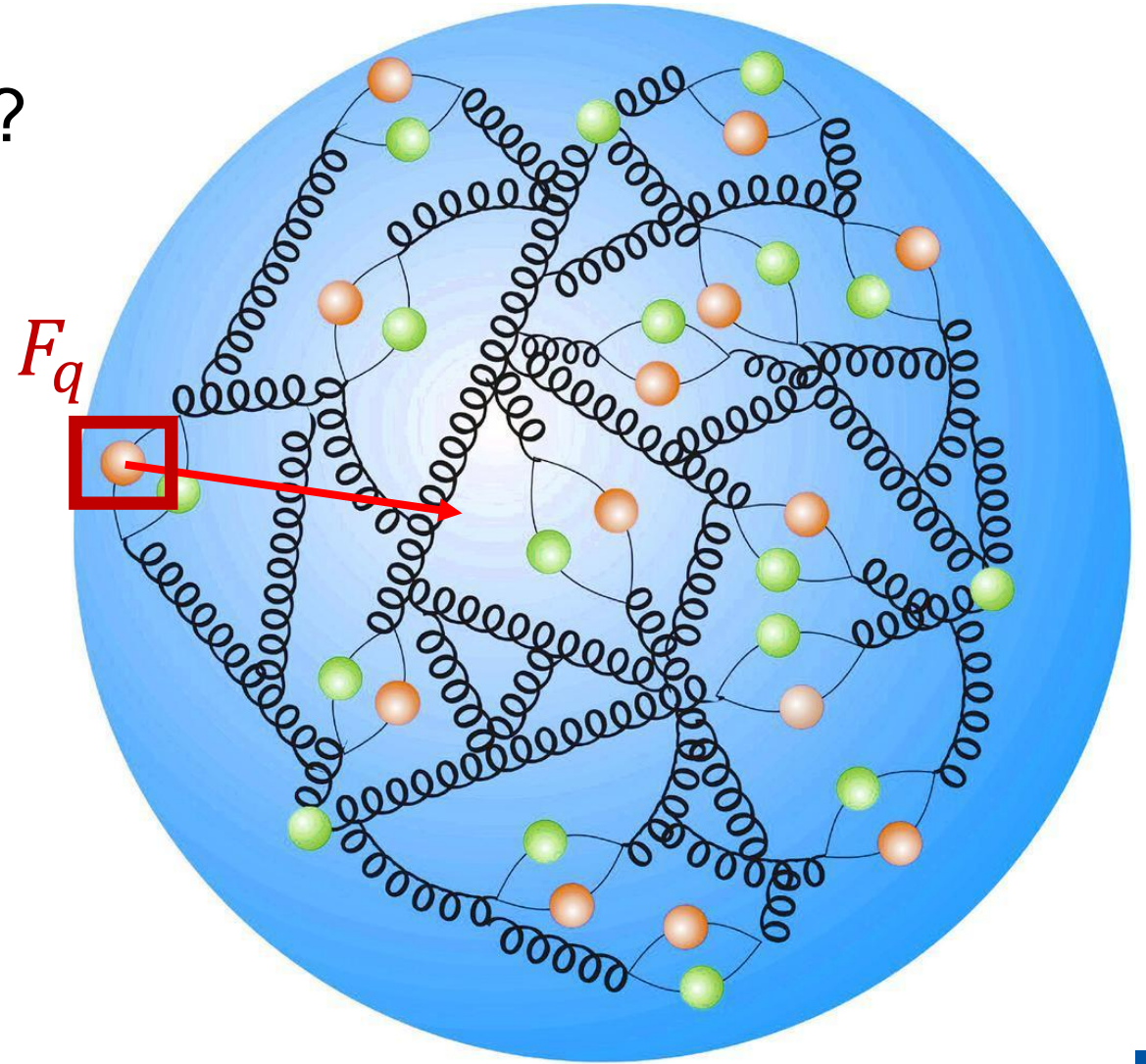
Quark Confinement

Find Forces on Quarks?

Internal force acting on quarks?

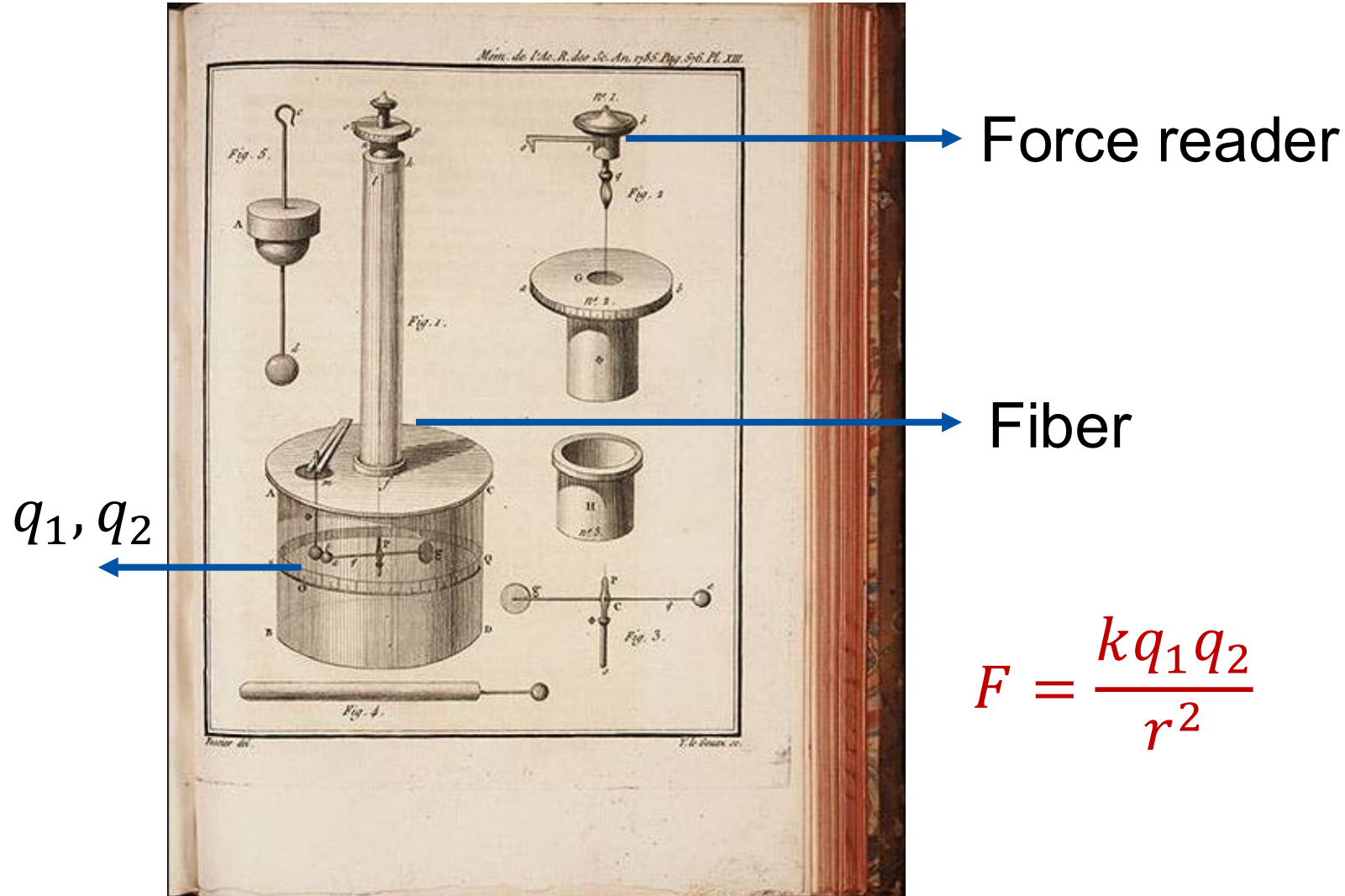
How to define?

How to measure?



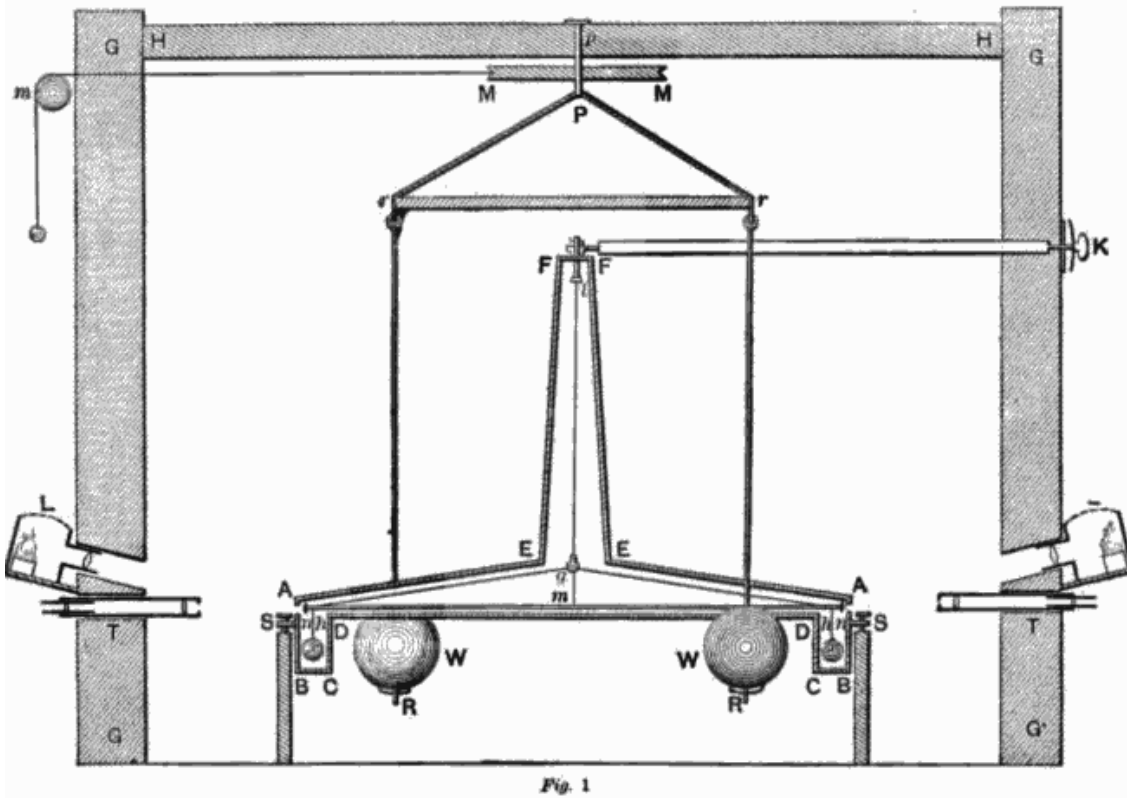
Measure Classical Electric Force

Torsion Balance by Charles-Augustin de Coulomb (1785)



$$F = \frac{kq_1q_2}{r^2}$$

Torsion Balance by Henry Cavendish (1798)



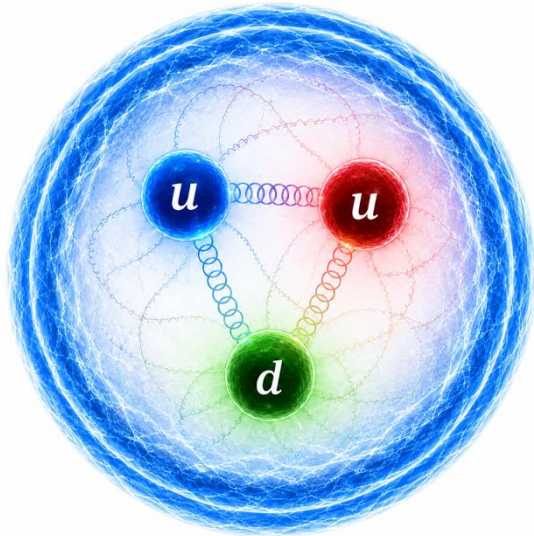
$$F = \frac{Gm_1m_2}{r^2}$$



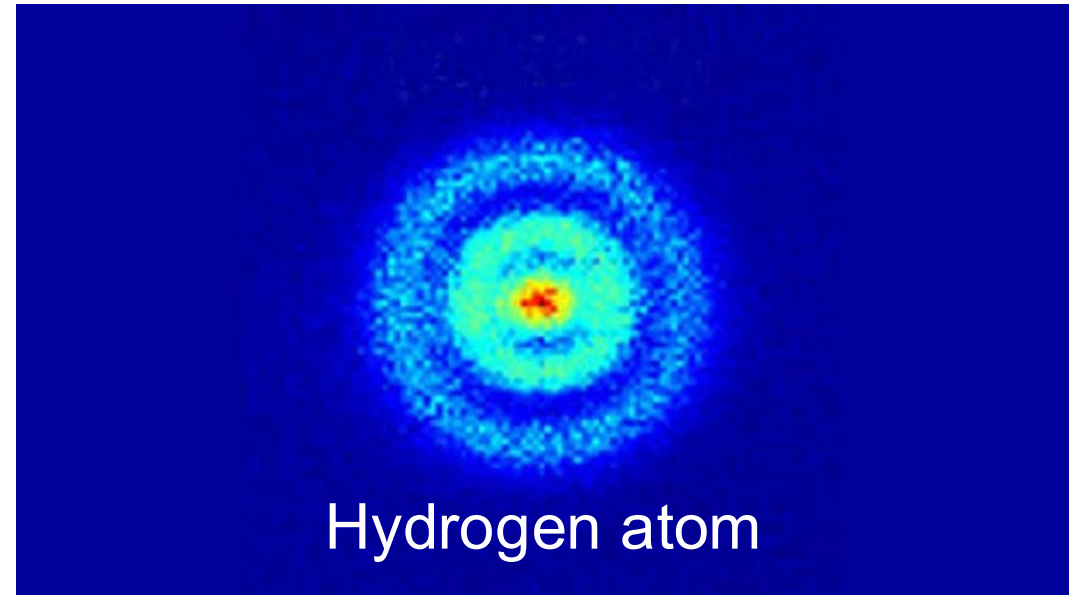
Obstacles in Quantum Domain

Smaller spatial scales $\rightarrow$ Quantum mechanics controls.

No free quarks as test particles.
No such small detector.



Quantum uncertainty principle.



Find other force observables within quantum theory.

PART TWO

Force Through Momentum-Current Density

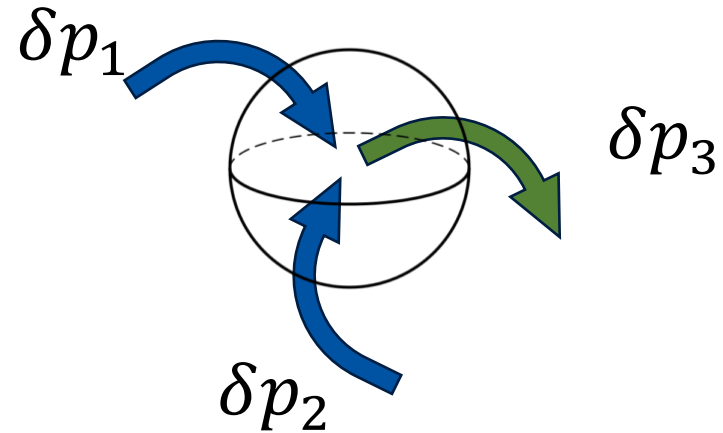
Force is Momentum Change

Newton's second law



$$F = \frac{dp}{dt}$$

Local force: momentum change
within some area

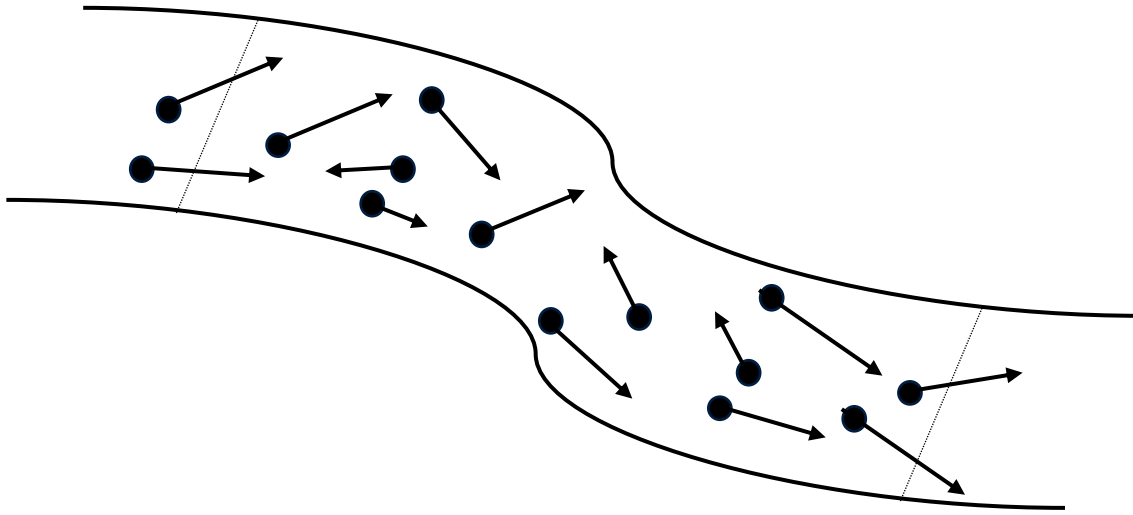


Momentum-current density

Momentum Current Density (MCD)

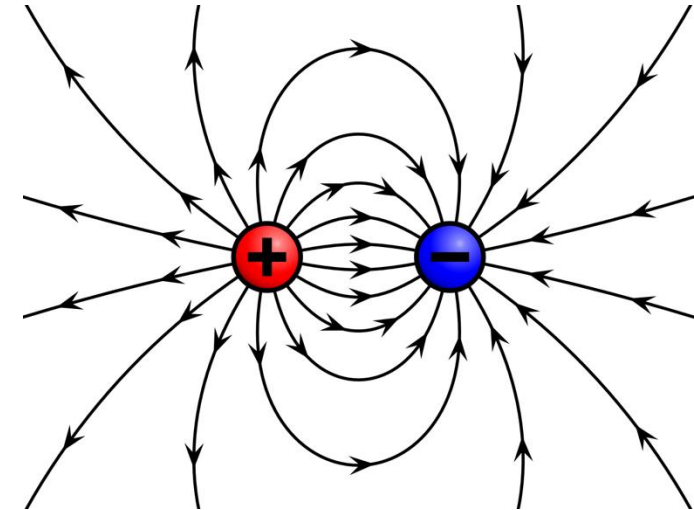
Particle kinetic MCD

$$T_K^{ij}(\vec{r}) = \sum_a v_a^i p_a^j \delta^{(3)}(\vec{r} - \vec{r}_a)$$



Interaction MCD

$$T_E^{ij}(\vec{r}) = \epsilon_0 \left[\frac{1}{2} \delta^{ij} \vec{E}^2 - E^i E^j \right]$$



X. Ji, C. Yang, *Nucl. Phys. B* 1024 (2026) 117342

Momentum Current Density Gives Force

Force on particles: local particle momentum change

$$\frac{\partial T_K^{0j}(\vec{r}, t)}{\partial t} + \nabla_i T_K^{ij}(\vec{r}, t) = \sum_a F_a^j(t) \delta^{(3)}(\vec{r} - \vec{r}_a(t))$$

Derivative of particle kinetic momentum density and MCD
gives force density.

X. Ji, C. Yang, *Nucl. Phys. B* 1024 (2026) 117342

Measure Coulomb Force in the Hydrogen Atom

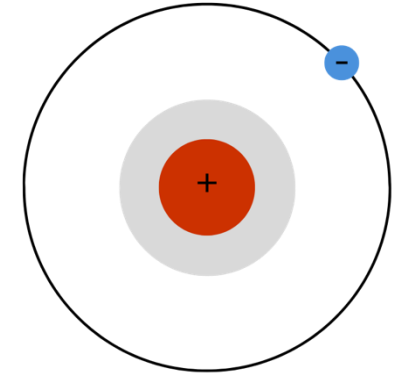
Electron kinetic MCD at ground state

$$\hat{T}_{e-K}^{ij} \sim \frac{\hat{p}^i \hat{p}^j}{m_e} \quad \left\langle \hat{T}_{e-K}^{ij} \right\rangle = \left\langle \psi_e | T_{e-K}^{ij} | \psi_e \right\rangle$$

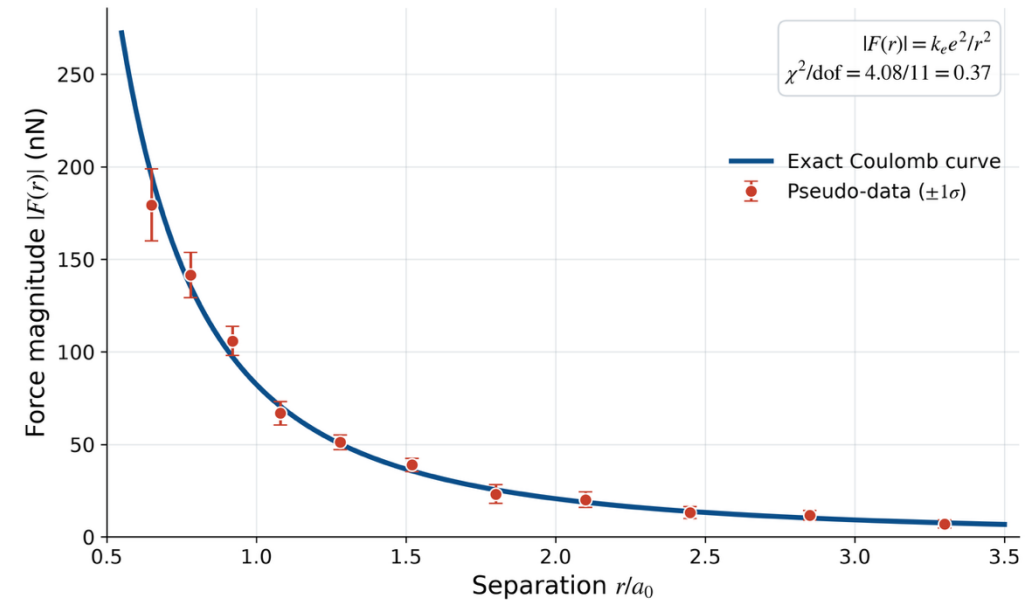
Coulomb force density on electron

$$\mathcal{F}^j(\vec{r}) = \partial_i \left\langle \hat{T}_{e-K}^{ij} \right\rangle = - \frac{\partial V(\vec{r})}{\partial r^j} |\psi_e(\vec{r})|^2$$

$$F^j = \frac{\mathcal{F}^j(\vec{r})}{|\psi_e(\vec{r})|^2} = - \frac{\partial V(\vec{r})}{\partial r^j}$$



Attractive proton-electron Coulomb force



Coulomb force: dividing electron force density by electron density!

Measure Quark Force in the Proton

Quark force: dividing quark force density by quark density

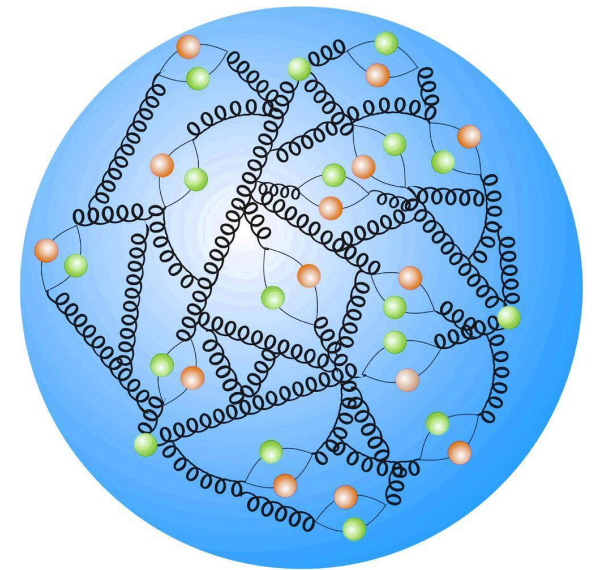
Quark kinetic EMT: momentum density and MCD

$$T_q^{\mu\nu} = \frac{1}{2} \bar{\psi} i \mathcal{D}^{(\mu} \gamma^{\nu)} \psi$$

Divergence gives quark force density

$$\mathcal{F}_q^i \equiv \partial_\mu T_q^{\mu i} = g \bar{\psi} \gamma_\mu F^{\mu i} \psi = g (\rho_c \vec{E}_c + \vec{j}_c \times \vec{B}_c)^i$$

color-Lorentz force density



Measure Quark Force in the Proton

Quark force: dividing quark force density by quark density

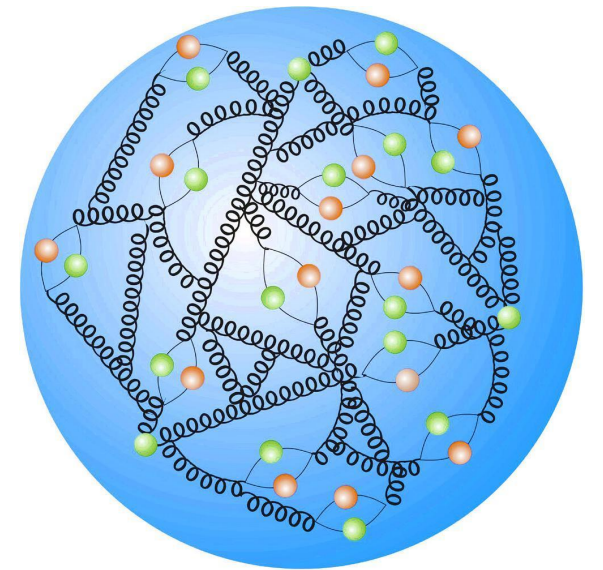
Quark density from proton and neutron charge density

$$\rho_p \approx \frac{2}{3}\rho_u - \frac{1}{3}\rho_d \quad \rightarrow \quad \rho_q \approx \rho_d + \rho_u \approx 3(\rho_p + \rho_n)$$

$$\rho_n \approx \frac{2}{3}\rho_d - \frac{1}{3}\rho_u$$

Quark force:

$$F_q^i \equiv \frac{\mathcal{F}_q^i}{\rho_q} = \frac{\partial_\mu T_q^{\mu i}}{3(\rho_p + \rho_n)}$$



Measure Quark Force in the Proton

$q = P' - P$: momentum transfer

Measure quark force density: EMT form factors $\{A_q(q^2), B_q(q^2), C_q(q^2)\}$

$$\mathcal{F}_q^j \sim -\frac{1}{4}q^j M G_{s,q}(q^2) = -\frac{1}{4}M \left[A_q(q^2) + B_q(q^2) \frac{q^2}{4M^2} - C_q(q^2) \frac{3q^2}{M^2} \right] q^j$$

Measure quark density: Dirac form factors $\rho_{p,n} = F_1^{p,n}(q^2)$

$$\langle P' | J^\mu | P \rangle = \bar{U}(P') \left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2M} F_2(q^2) \right] U(P)$$

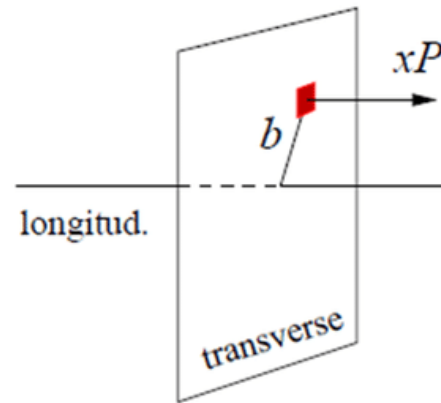
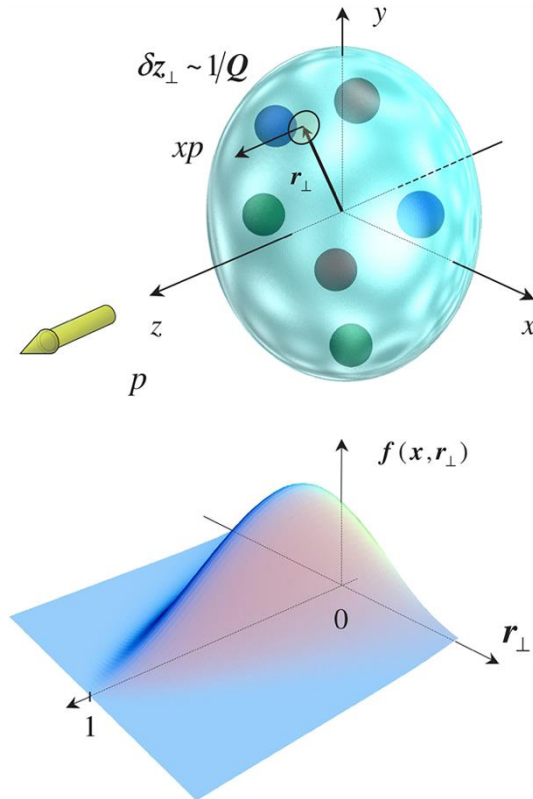
PART THREE

Experimental Extraction: Constant Force

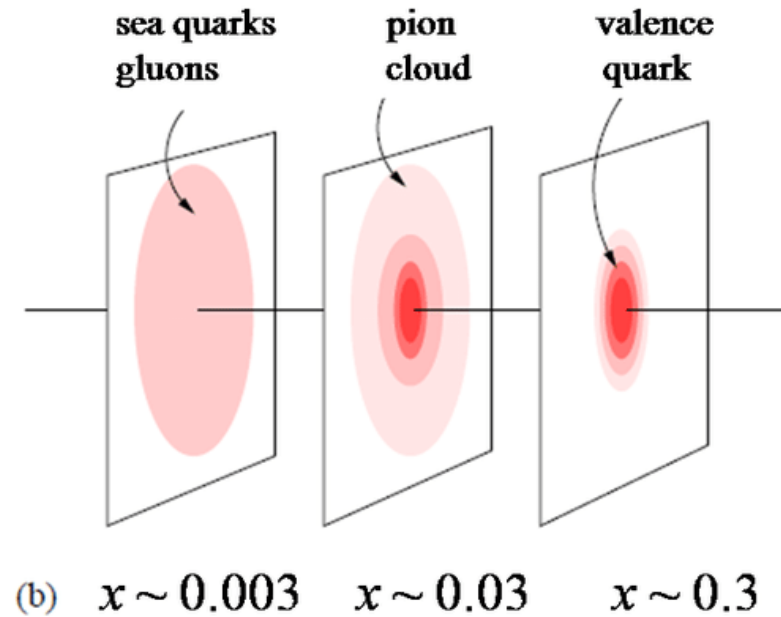
How to Measure Nucleon Form Factors?

GPDs: 3D imaging of hadrons (longitudinal $\times$ transverse)

Nucleon form factors: transverse picture of nucleons



(a)

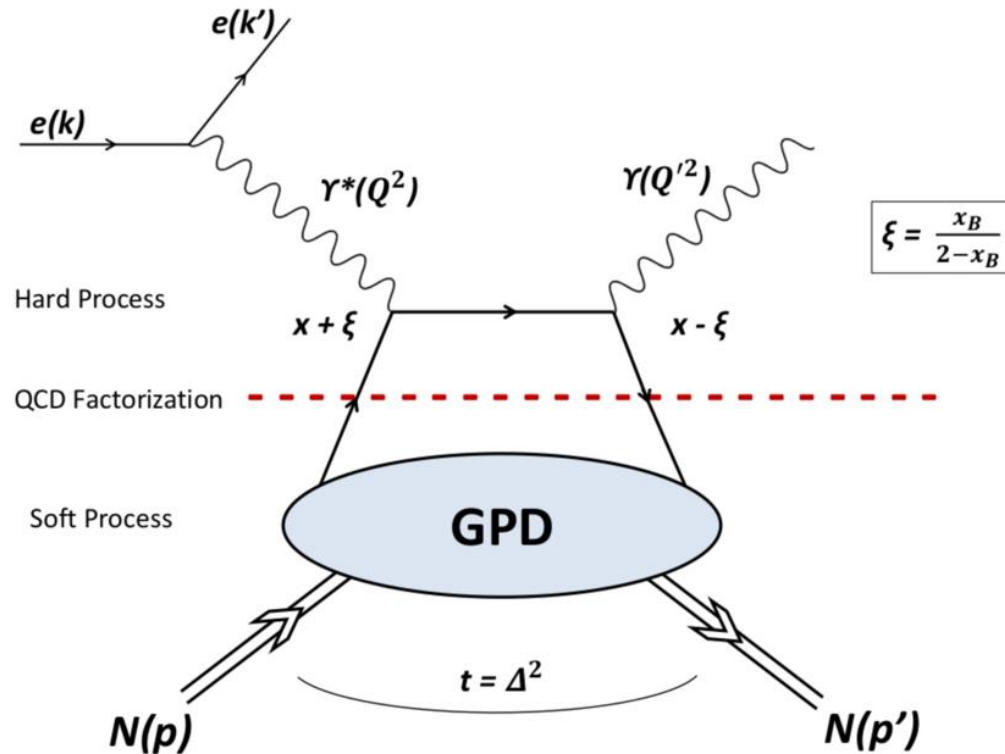


(b)

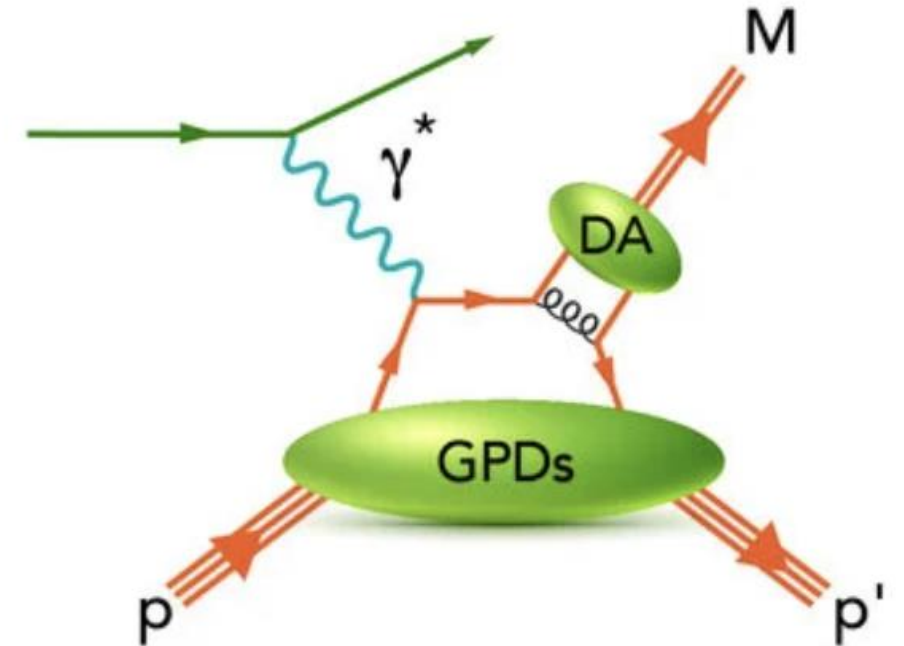
Deep-virtual Processes

X. Ji, *Phys. Rev. Lett.* 78 (1997) 610-613
X. Ji, *Phys. Rev. D* 55 (1997) 7114-7125

Deep-virtual Compton Scattering



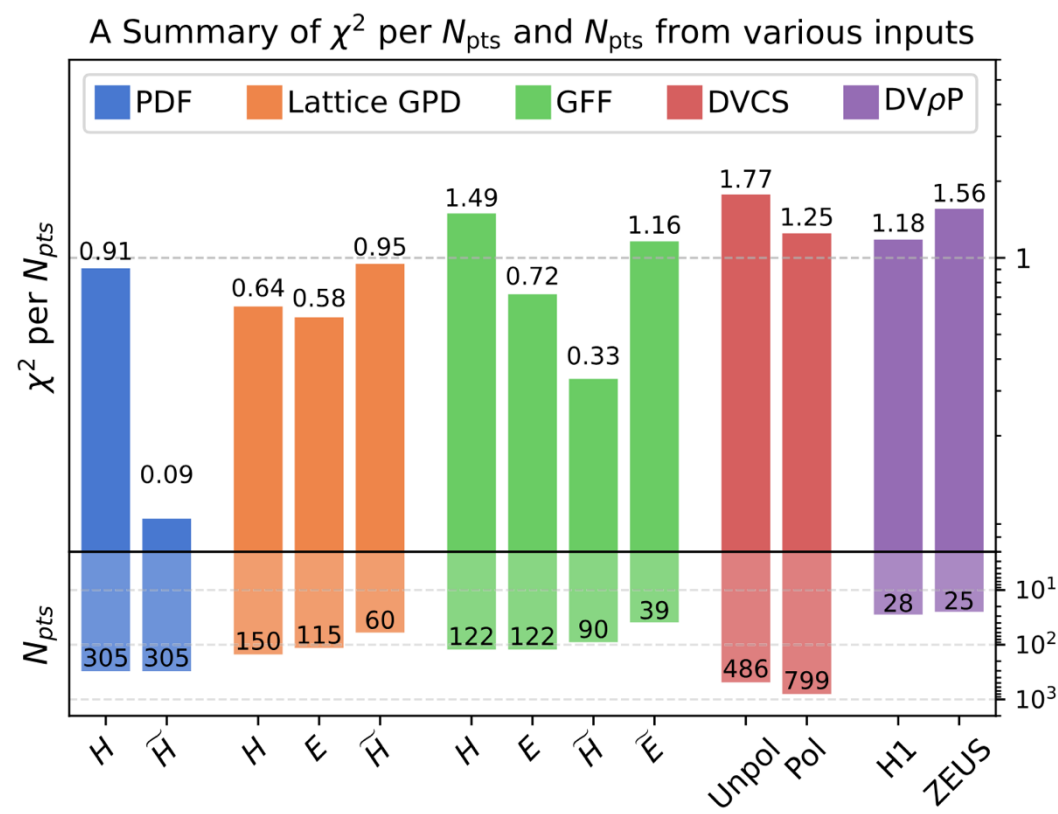
Deep-virtual Meson Production



Measure generalized parton distributions (GPDs)

A_q : Global Analysis of GPDs (GUMP)

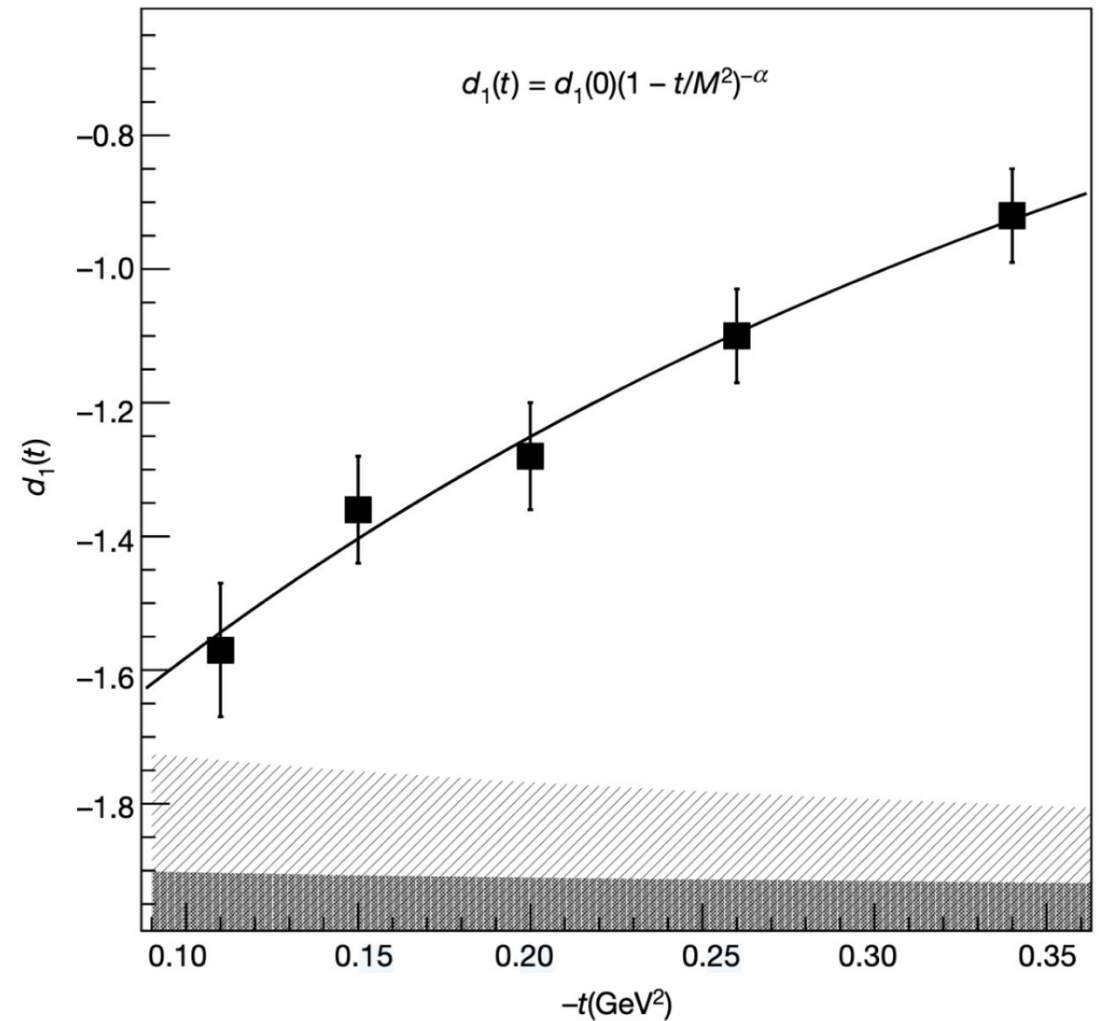
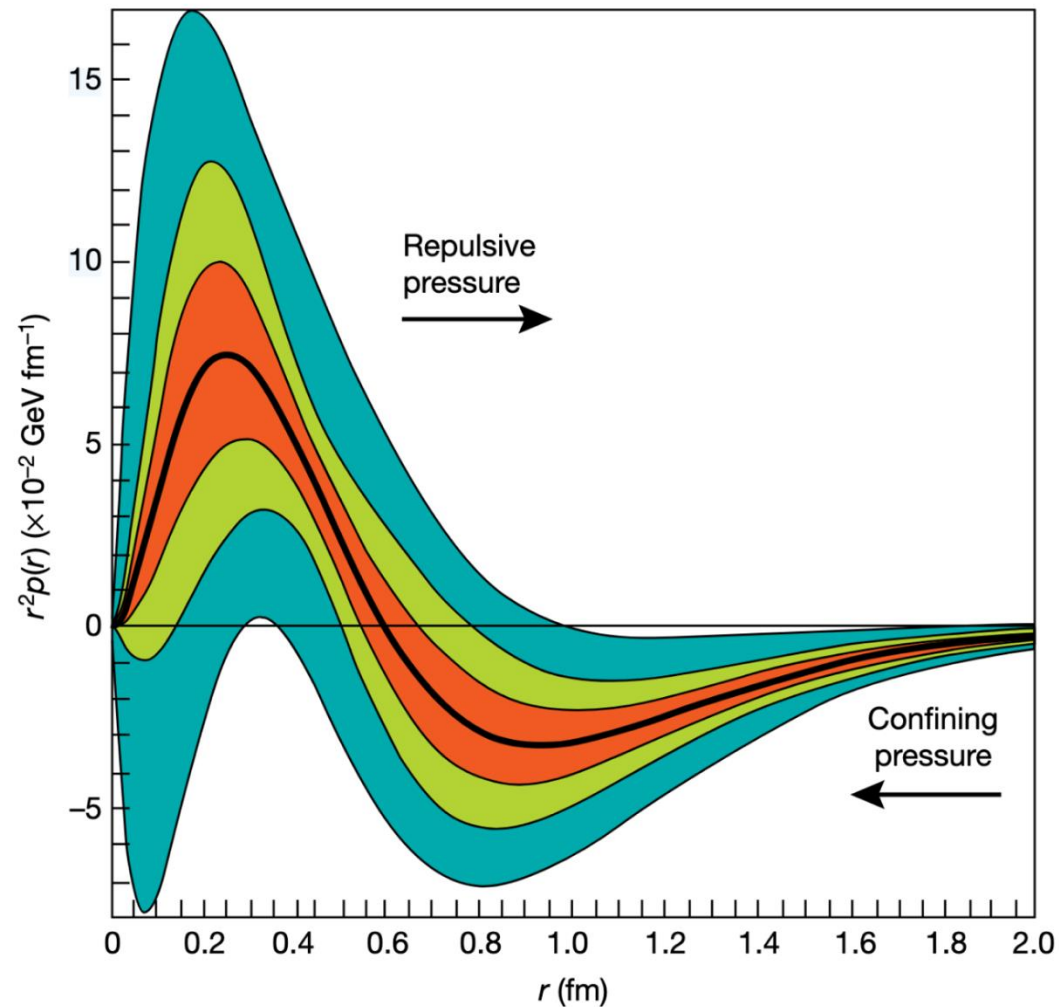
State-of-the-art global analysis of comprehensive experiments and lattice inputs



Category	Inputs
(Polarized) PDFs	Unpolarized and polarized JAM22 PDFs [2]
Charge form factor	Global charge form factor [3]
Generalized form factors	Isovector and isoscalar quark $A_n^{u\pm d}(t)$ and $B_n^{u\pm d}(t)$ [4]
Generalized form factors ^a	Vector form factors $A_{2,0}^q(t)$ [5]
Generalized form factors	Isovector and isoscalar quark axial-vector $\tilde{A}_n^{u\pm d}(t)$ [6]
Generalized form factors	Axial-vector GFFs $\tilde{B}_{2,0}^q(t)$ [7]
Generalized form factors	Axial-vector GFFs $\tilde{B}_{1,0}^q(t)$ [8]
GPDs at zero skewness	Isovector quark GPD $H_{u-d}(x,t)$, $E_{u-d}(x,t)$, and $\tilde{H}_{u-d}(x,t)$ [9, 10]
GPDs at non-zero skewness	Isovector quark GPD $H_{u-d}(x,t)$ and $E_{u-d}(x,t)$ [11]
Exclusive Production cross sections	Differential DVCS cross sections from JLab [12–15]
Exclusive Production asymmetries	DVCS beam spin asymmetries from JLab, mostly in [16]
Exclusive Production cross sections	Differential DVCS cross sections from HERA [17]
Exclusive Production cross sections	Differential DVMP cross sections from HERA [18, 19]

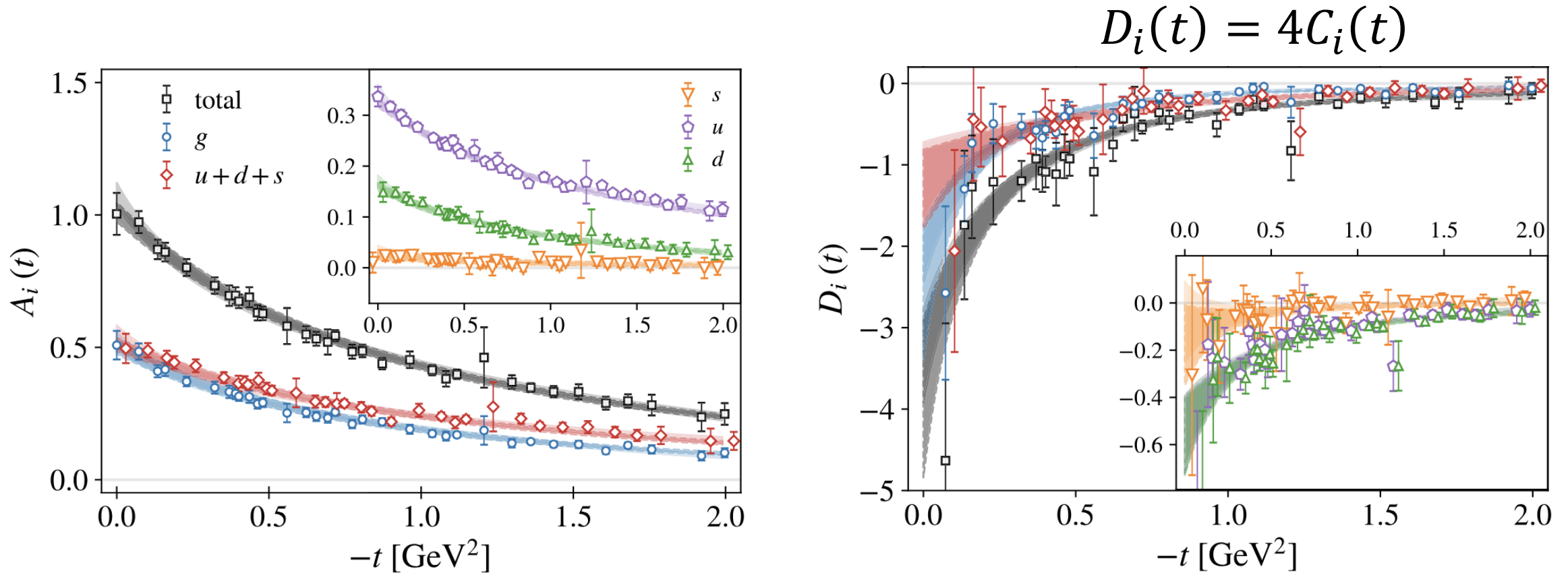
Y. Guo et al, *Phys. Rev. Lett.* 135 (2025) 26, 261903

C_q : Dispersive Analysis of DVCS



Lattice Calculations of EMT Form Factors

Latest Lattice Calculations ($\overline{\text{MS}}, \mu = 2\text{GeV}$)

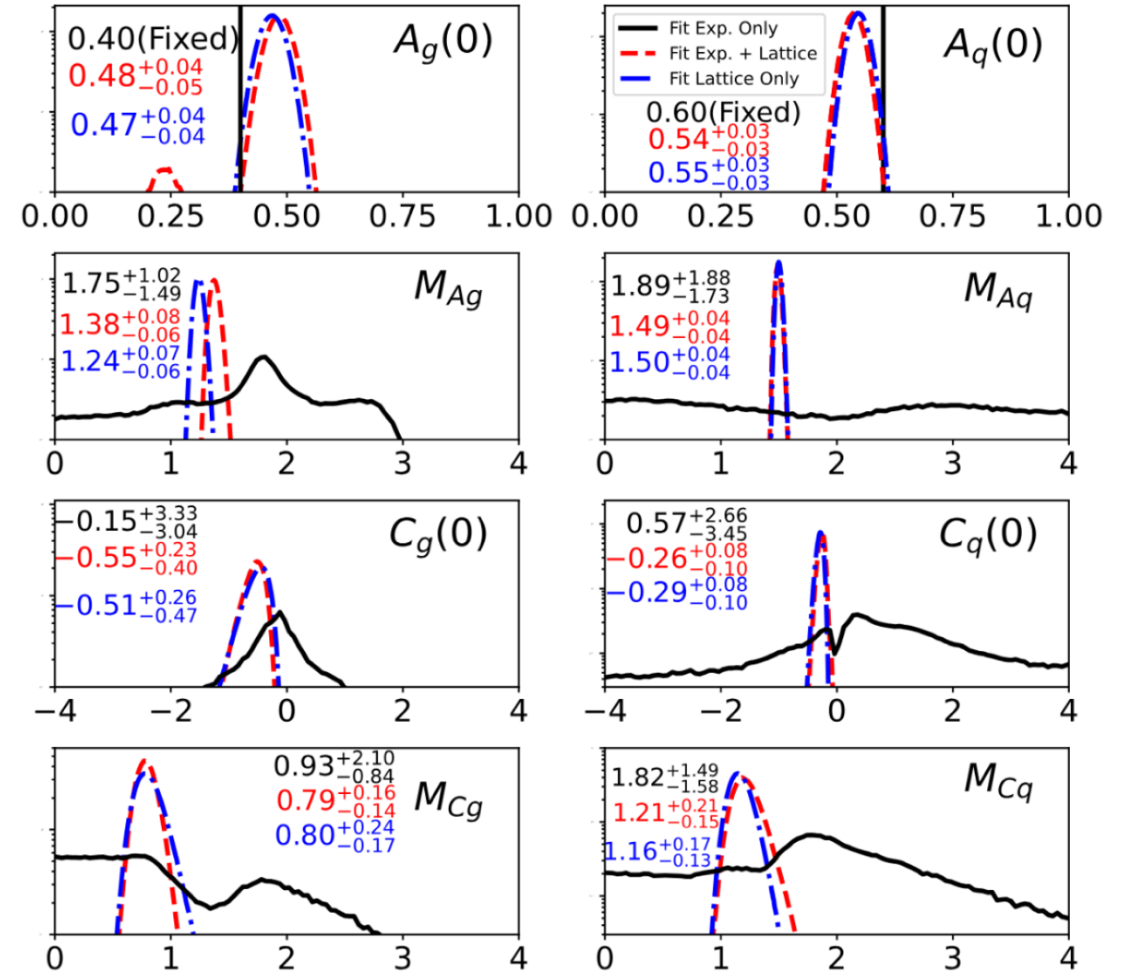


Bayesian Analysis of Lattice EMT Form Factors

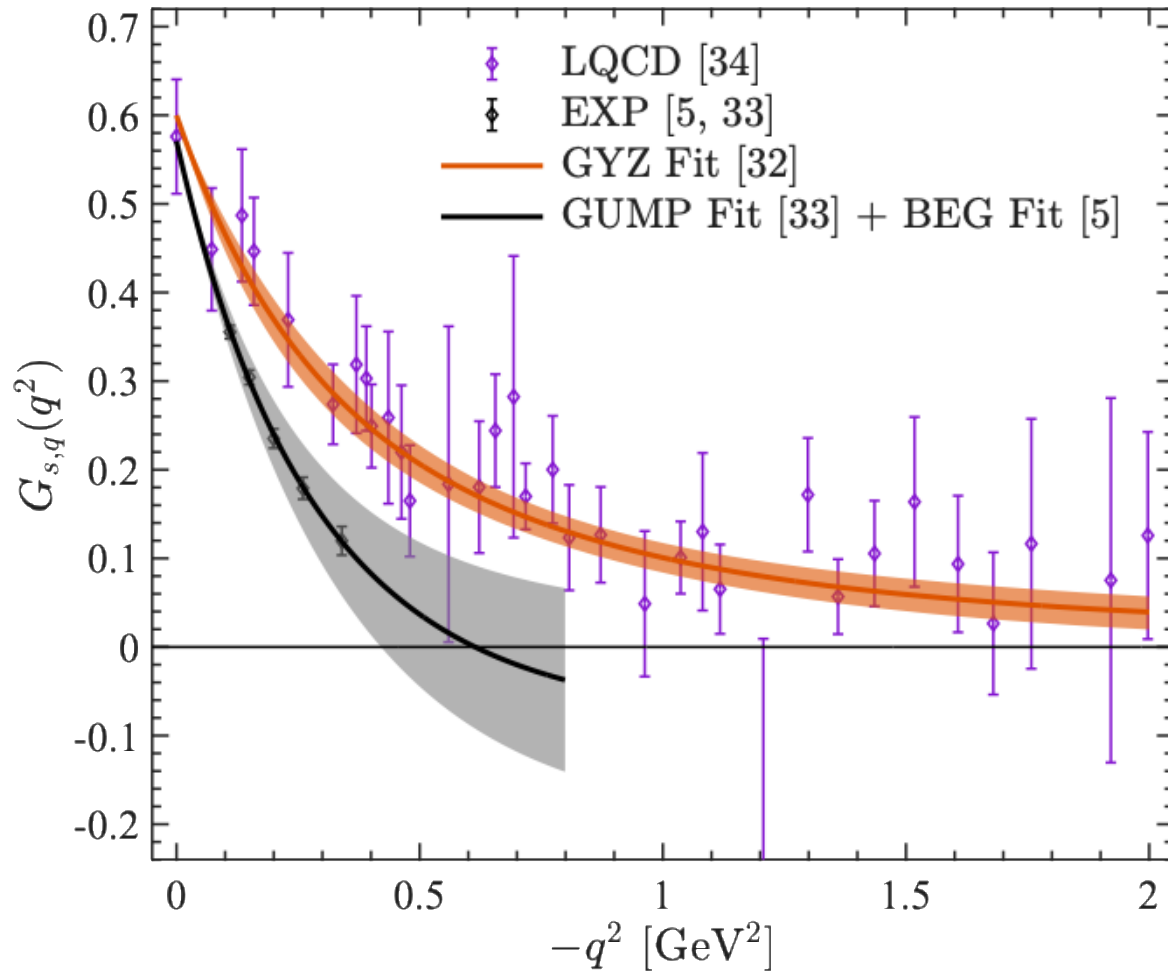
TABLE I. Summary of parameters, their prior ranges, and the highest likelihood parameters fitting to experiment data with NLO accuracy, lattice GFFs, and their combination with $\mu = m_c$ and masses in GeV.

Parameters	Prior	Experiment Only	Lattice + Experiment	Lattice Only
$A_g(0)$	[0, 1]	0.40 (Fixed)	0.47	0.48
M_{Ag}	[0, 4]	1.95	1.27	1.23
$C_g(0)$	[-4, 4]	-0.12	-0.51	-0.46
M_{Cg}	[0, 4]	2.59	0.80	0.83
$A_q(0)$	[0, 1]	0.60 (Fixed)	0.53	0.53
M_{Aq}	[0, 4]	0.1	1.48	1.50
$C_q(0)$	[-4, 4]	0.14	-0.23	-0.27
M_{Cq}	[0, 4]	2.59	1.29	1.18

$$F_i(t) = F_i(0)(1 - t/M_{F_i}^2)^{-p}$$



Force Density Form Factor



Black: experimental inputs

Purple: direct lattice calculations

Orange: Bayesian analysis of lattice

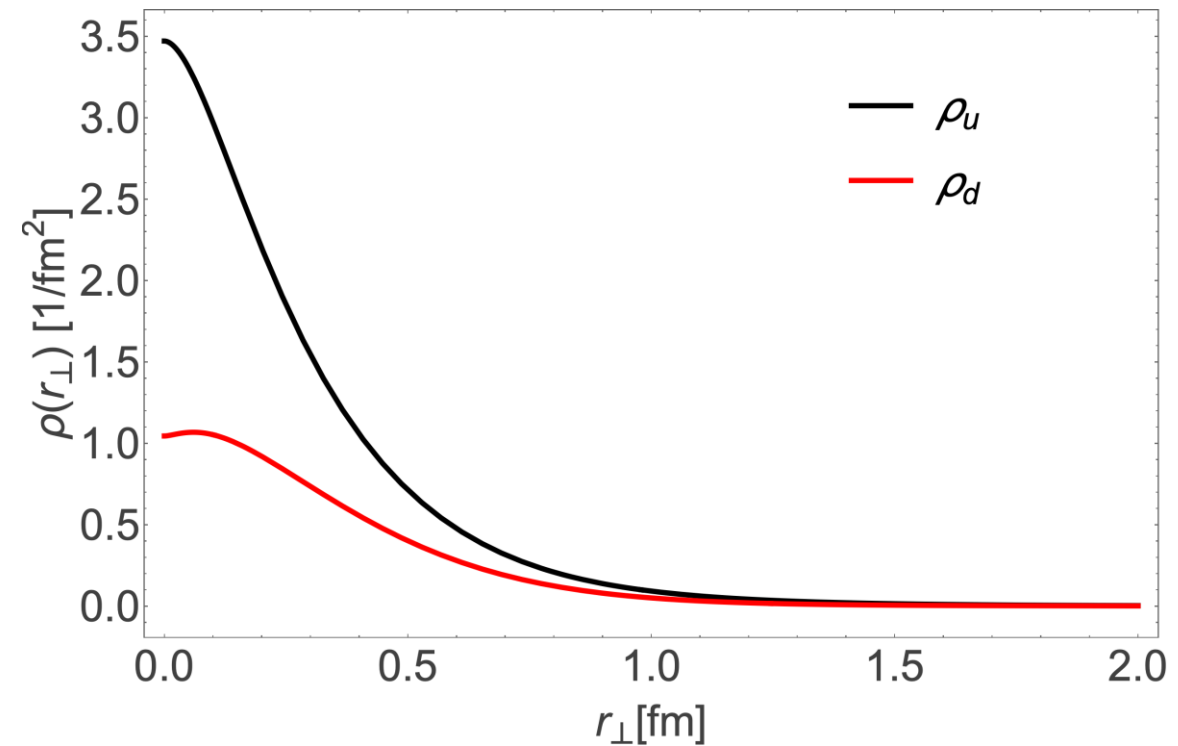
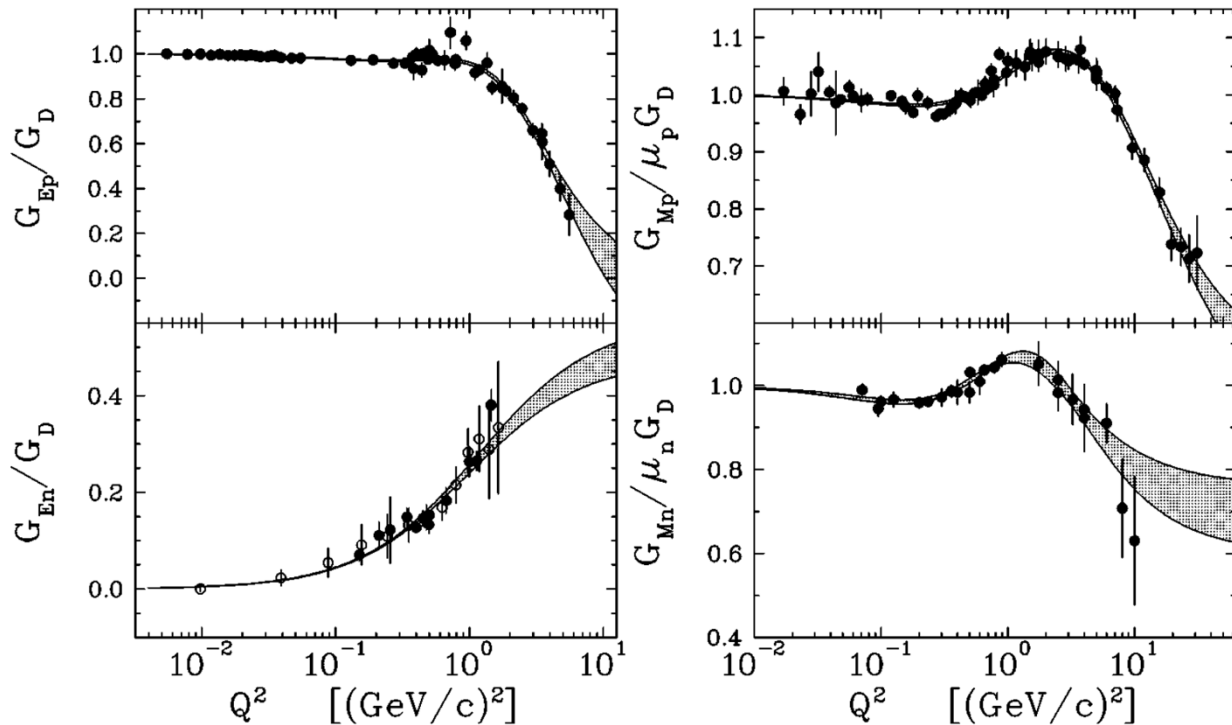
$$\mathcal{F}^j = \partial_\mu \langle T_q^{\mu j} \rangle = \frac{1}{4} \nabla^j M G_{s,q}(r_\perp)$$

$$G_{s,q}(r_\perp) = A_q(r_\perp) - \frac{3\nabla^2}{M^2} C_q(r_\perp).$$

Scalar form factor

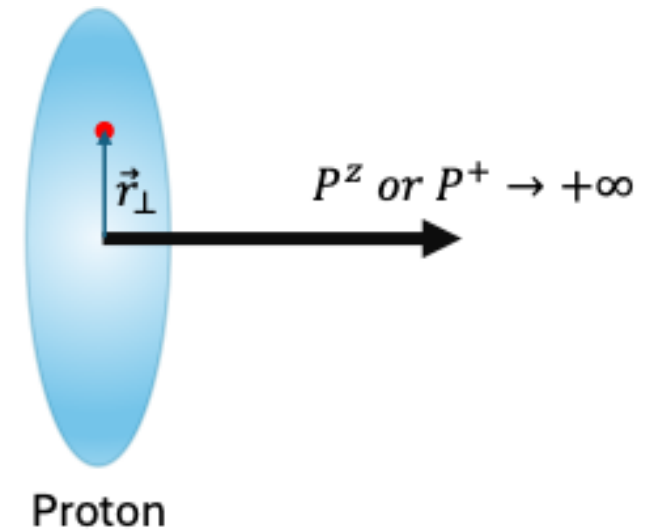
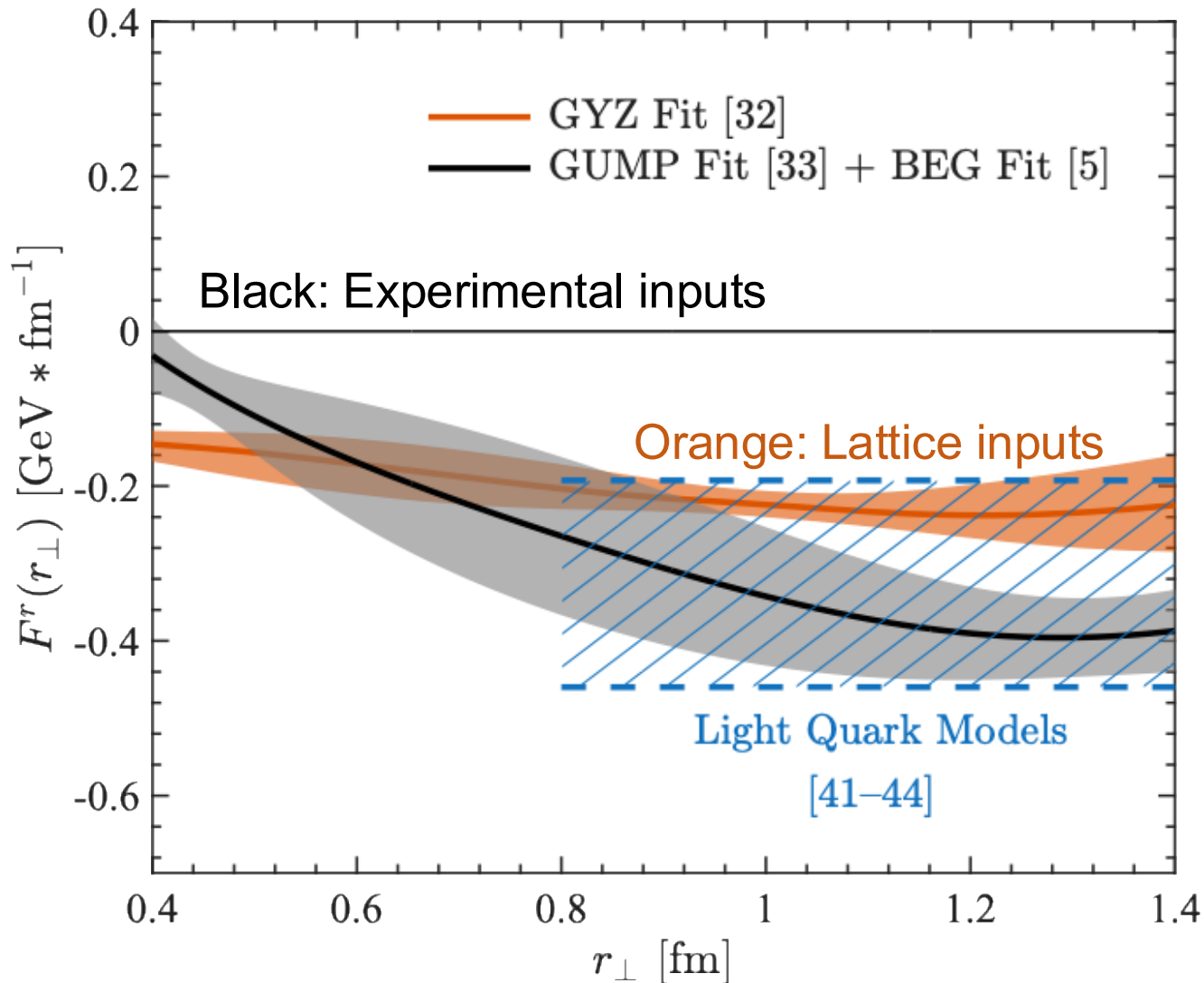
Quark Density Form Factors

Proton and neutron E&M form factors u, d -quark densities in the proton



$$\rho_q(\vec{r}_\perp) = 3[F_1^p(\vec{r}_\perp) + F_1^n(\vec{r}_\perp)]$$

Quark Confinement Force



$$\vec{F}_q(\vec{r}_\perp) \equiv \frac{\vec{\mathcal{F}}_q(\vec{r}_\perp)}{\rho_q(\vec{r}_\perp)} = \frac{(M/4)\vec{\nabla}_\perp G_{s,q}(\vec{r}_\perp)}{3[F_1^p(\vec{r}_\perp) + F_1^n(\vec{r}_\perp)]}$$

Constant at intermediate distance

Linear potential

Compatible with quark models

PART FOUR

Summary and Outlook

Summary

We define and measure forces on quarks in the proton:

$$\overrightarrow{F}_q(\overrightarrow{r}_\perp) \equiv \frac{\overrightarrow{\mathcal{F}}_q(\overrightarrow{r}_\perp)}{\rho_q(\overrightarrow{r}_\perp)} = \frac{(M/4)\overrightarrow{\nabla}_\perp G_{s,q}(\overrightarrow{r}_\perp)}{3[F_1^p(\overrightarrow{r}_\perp) + F_1^n(\overrightarrow{r}_\perp)]}$$

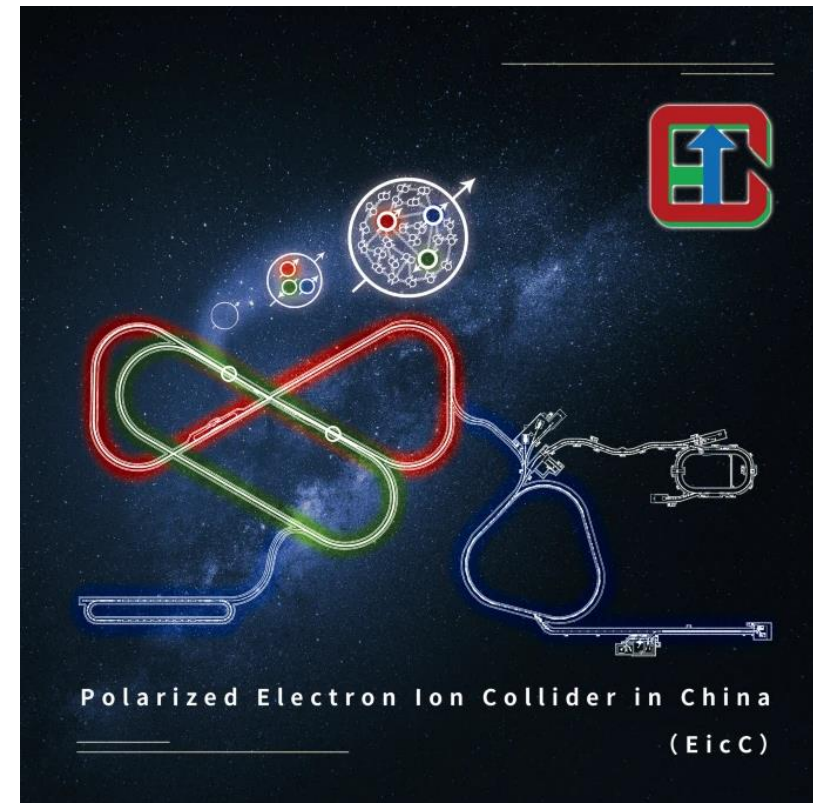
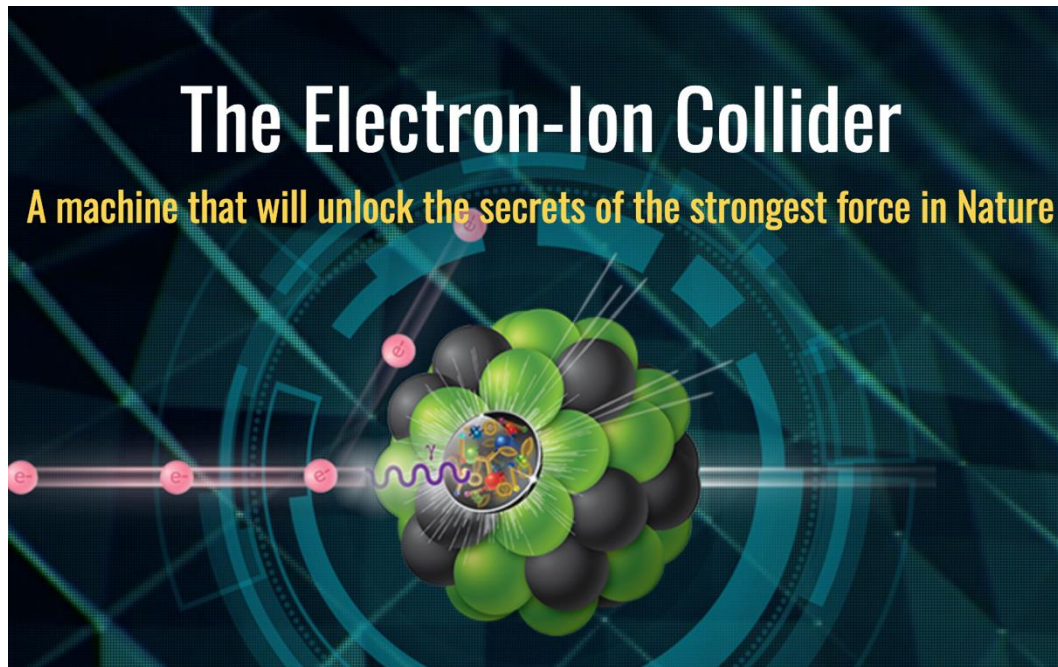
We find first experimental evidence for quark confinement in the proton:

Constant attractive force over intermediate distance

■ Outlook

Current data exhibits relatively large uncertainties at large distances.

We expect improved precision with measurements at future EICs.



THANKS