

Precision Nucleon Structure and Spectroscopy from Lattice QCD

Sungwoo Park

Sejong University

한국고에너지물리학회 (KSHEP) 2026년도 봄 학술대회
제주대학교 아라캠퍼스 자연과학대학 1호관

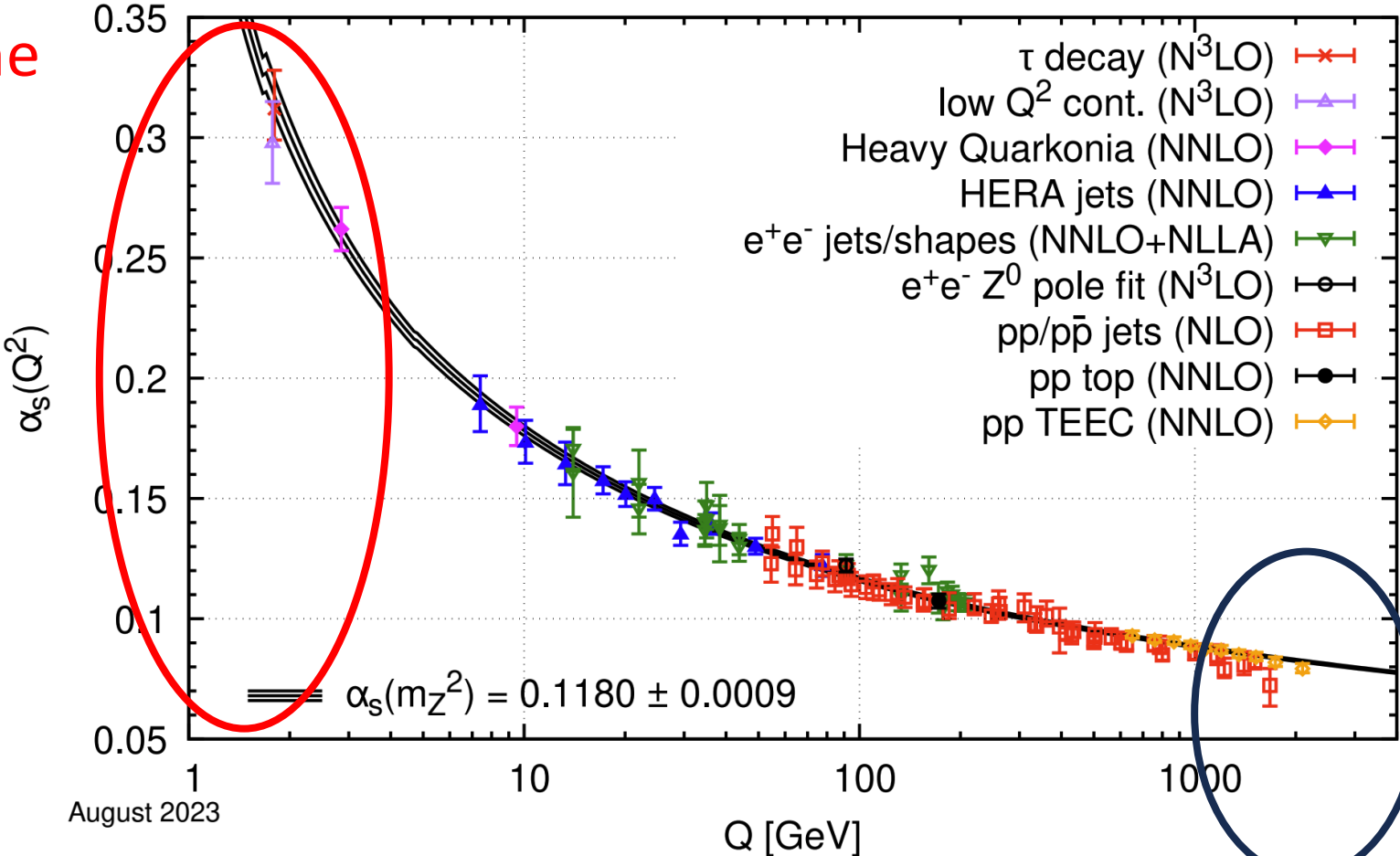
June 11, 2026



Nonperturbative nature of QCD at small Q

- QCD Coupling constant α_s of QCD varies with the energy scale Q

- $\alpha_s = O(1)$ at the nuclear physics scale $\sim 1\text{GeV}$
- Confinement
- Perturbation theory fails
- > **Need LATTICE QCD simulations**



Asymptotic Freedom (2004 Nobel Prize)

$\alpha_s \rightarrow 0$ in the high energy limit:

Perturbation theory works

Rich Landscape of LQCD calculations

Flavor Lattice Average Group (FLAG) reports 1902.08191, 2111.09849, 2411.04268

High Energy
Physics
(HEP)

ϵ, ϵ' in kaon CP
violation

s, c, b decay
form factors

$g-2$

α_s , quark
masses

Nuclear
Physics
(NP)

**Nucleon
structure**

**Hadron
Spectroscopy**

**Matrix
elements
within Nuclei**

Current Physics Objectives

Charges

$g_A, g_S, g_T, \sigma_{\pi N}, \sigma_S$

Neutron electric dipole moment
nEDM

Axial & EM
form factors

Moments,
and Distribution
functions PDFs,
TMD, GPD

Nucleon
mass

$N - \pi$
scattering

Hyperon
and multi-
strangeness
system

Lattice QCD:

What we compute,

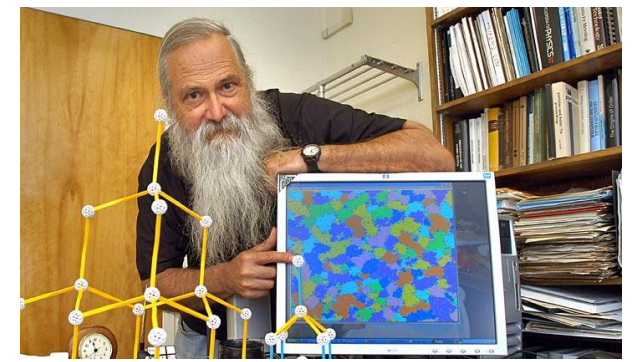
How we compute,

Using High Performance Supercomputing

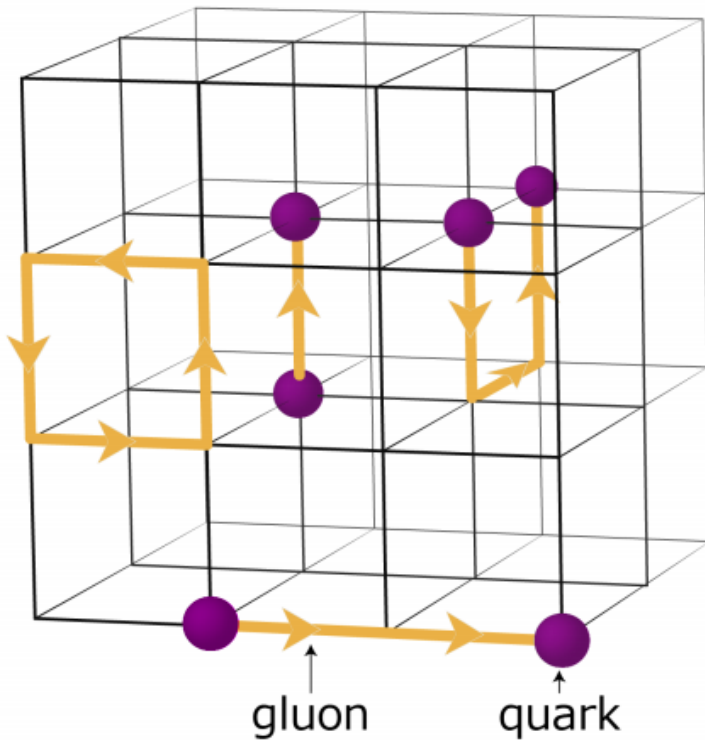
Lattice QCD



Formulated by K. Wilson (1974)



Numerical computation opened by M. Creutz (1979)



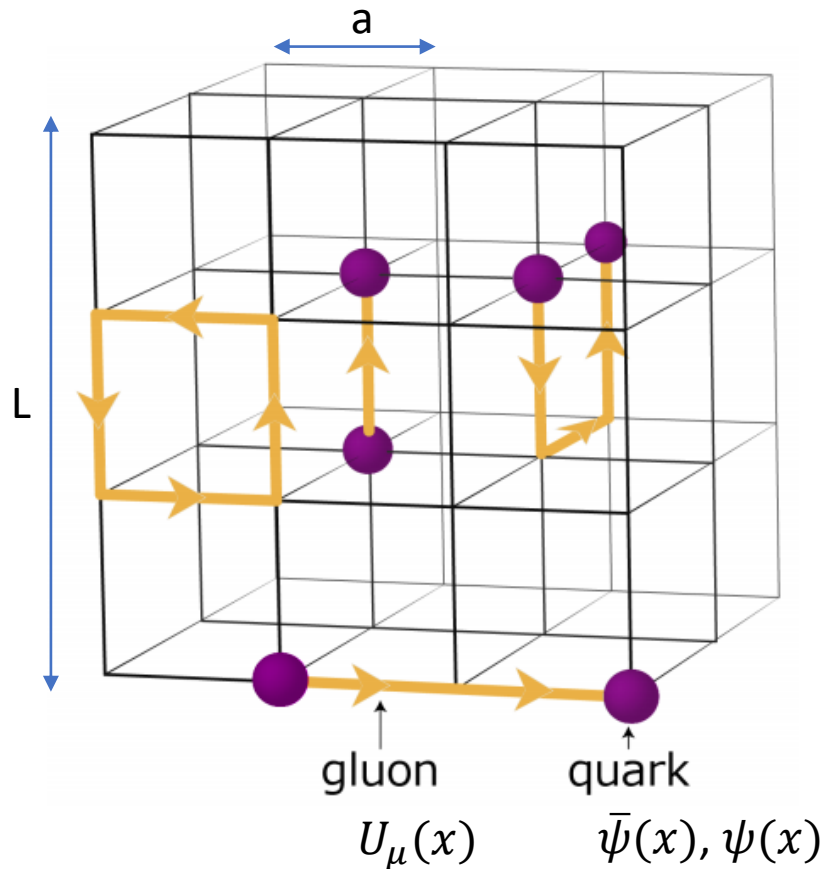
Lattice QCD is QCD defined on a 4-dimensional Euclidean space-time lattice

- Finite lattice spacing: (a)
- Quark fields (q, \bar{q}), Gauge fields (gluons): (U_μ)
- Perturbative & **Numerical (nonperturbative) calculations**

Major systematic errors coming from:

- Finite lattice spacing a (UV cut-off effect)
- Chiral fit to get value at physical pion mass
- Finite Volume
- Statistical errors
- Excited state contaminations
- Renormalization

Simulation of Lattice QCD using the path integral approach to QFT



- Allows **ab initio** calculations of nonperturbative **QCD** interactions of quarks and gluons using the **Feynman path integral** formulation of QFT.

- Partition function:

$$Z = \int D[U] D[\bar{\psi}, \psi] e^{-S_{QCD}}$$

$$= \int D[U] e^{-S_{gluon}[U]} \det(M_{quark})$$

$$S_{QCD} = S_{gluon} + \bar{\psi} M_{quark} \psi$$

M_{quark} : Dirac operator

- Generate **gauge ensembles** $\{U_\mu(x)\}$ using Markov Chain Monte-Carlo with the probability distribution

$$P[\{U\}] = \frac{1}{Z} e^{-S_{gluon}[U]} \det(M_{quark}[U])$$

- Expectation value of the observable

$$\langle O \rangle = \frac{1}{N_{\text{sample}}} \sum_{\{U\}} O(\{U\})$$

Gauge Ensembles: Thirteen 2+1 flavor Wilson-clover

(Parameters of ensembles) → **Physical limit extrapolation**
 $a=0, M_\pi=135\text{MeV}$

Ensemble ID	a [fm]	M_π [MeV]	$M_\pi L$	N_{conf}	N_{LP}
a127m285	0.127	285	5.87	2002	256256
a094m270	0.094	269	4.09	2469	237024
a094m270L	0.094	269	6.15	4510	577280
a093m220	0.093	216	4.95	2000	256000
a093m220X	0.093	214	4.81	2005	256640
a091m170	0.091	169	3.35	4012	513536
a091m170L	0.091	170	5.01	3000	480000
a073m270	0.073	272	4.81	4720	604160
a072m220	0.072	223	5.10	2000	192000
a071m170	0.071	166	4.28	2500	240000
a070m130	0.070	127	4.37	980	94080
a056m280	0.056	281	5.10	2700	259200
a056m220	0.056	214	4.38	2049	196704

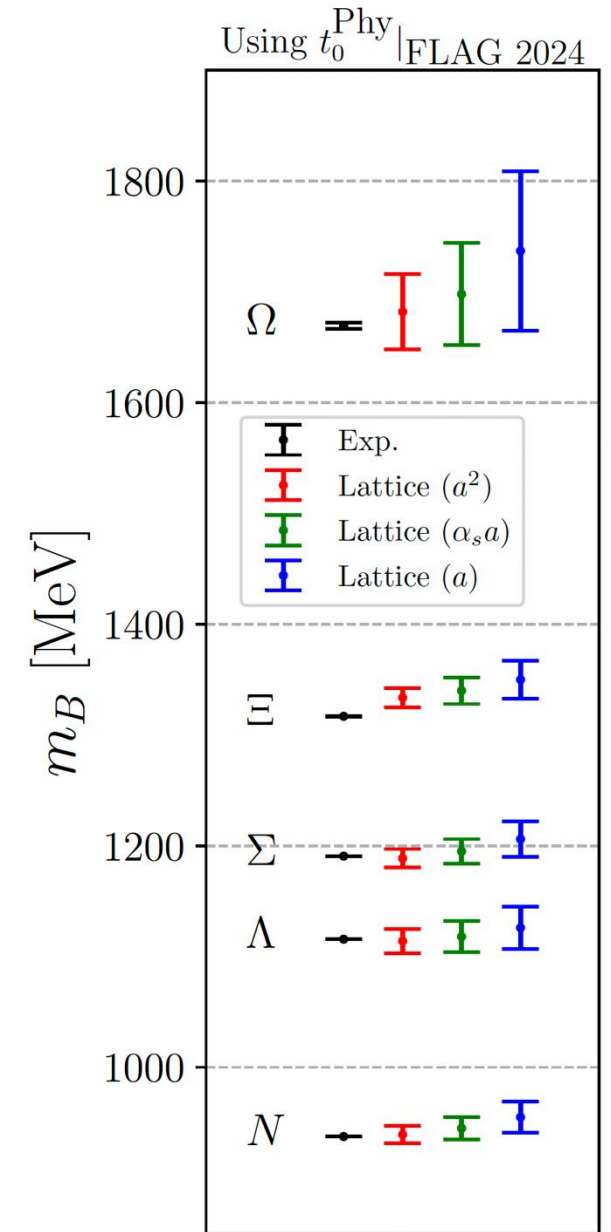
- Generated Jlab/W&M/LANL/MIT collaborations
- We have measured nucleon correlation functions over the past 7 years on supercomputers at LANL, NERSC, ORNL, JLab, FNAL.
- Managing O(PB) data and the analysis. (Stored and organized in Oak Ridge computing facility)
- Published first complete nucleon matrix element calculation using 7 ensembles in 2022 [Park et al., Phys.Rev.D 105,054505 (2022)] Complete scale setting and spectrum calculation [Yoo et al., 2601.10857, submitted to PRD]
- **Results highlighted in FLAG reports**

The Spectrum and Scale Setting on 2+1-flavor NME Lattices

NME Collab.
arXiv:2601.10857

	m_N	m_Λ	m_Σ
Pheno: Eq. (7)	937.54(6)	1115.68(1)	1190.66(12)
Fit with a^2	939.3(7.7)	1114(11)	1188.7(8.3)
Fit with $\alpha_s a$	945(10)	1118(14)	1195(11)
Fit with a	955(14)	1126(19)	1206(16)

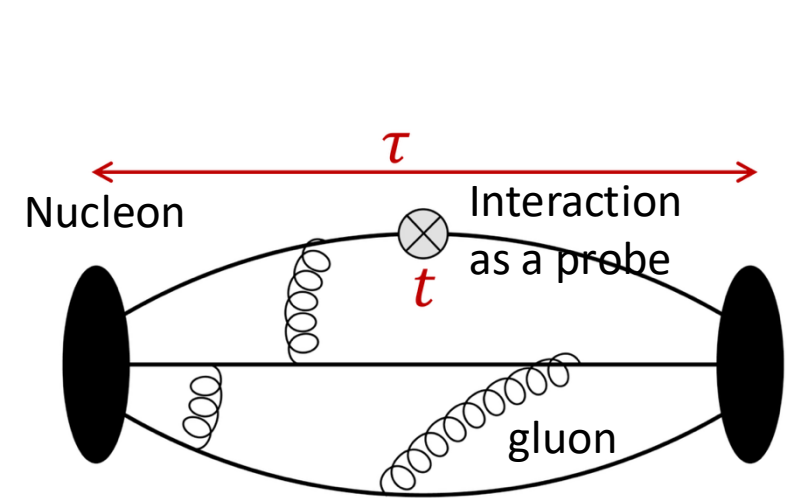
	m_Ξ	m_Ω	$f_{\pi K}$
Pheno: Eq. (7)	1316.9(3)	1669.5(3.0)	148.32(34)
Fit with a^2	1333.7(8.8)	1682(34)	146.3(1.5)
Fit with $\alpha_s a$	1340(12)	1698(46)	146.5(1.6)
Fit with a	1350(17)	1737(72)	147.0(1.9)



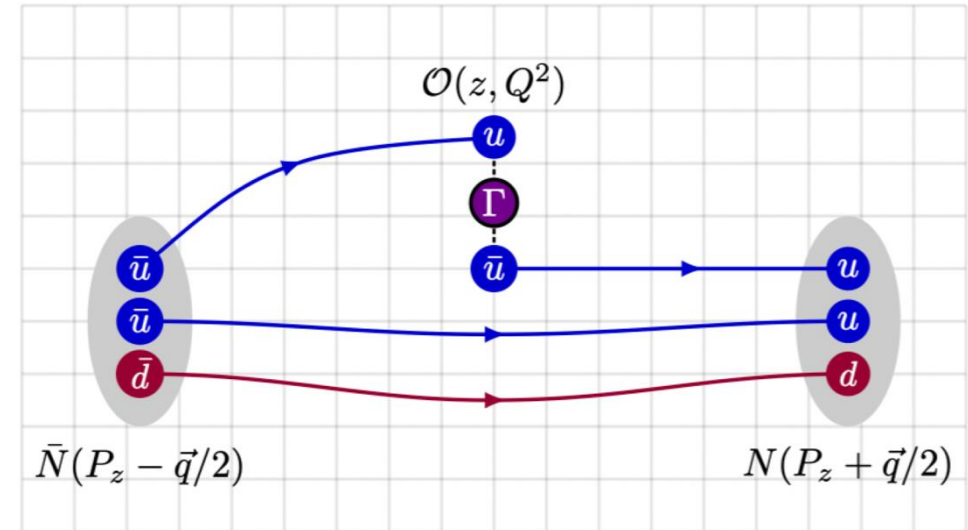
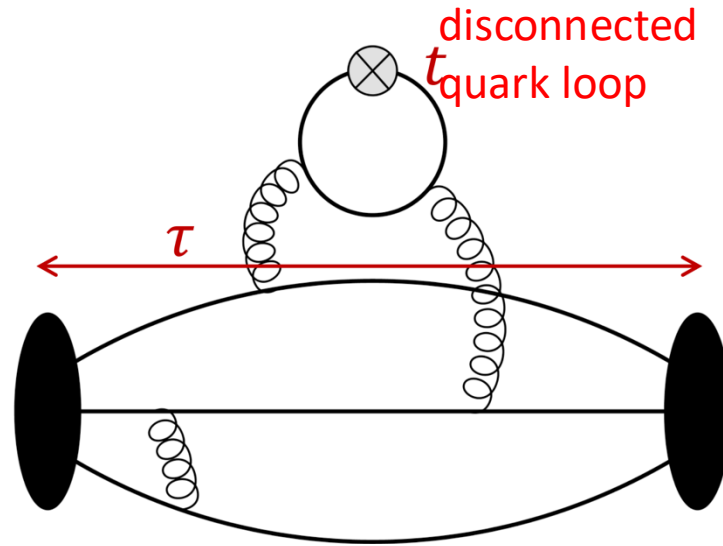
Exp values (corrected for the isospin breaking effects) from 2211.03744

Nucleon structures from LQCD correlation functions:

$$C_{\Gamma}^q(t, \tau) = C_{\Gamma}^{q,\text{conn}}(t, \tau) + C_{\Gamma}^{q,\text{disc}}(t, \tau) \rightarrow \text{Charges, form factors, moments, PDFs and GPDs}$$

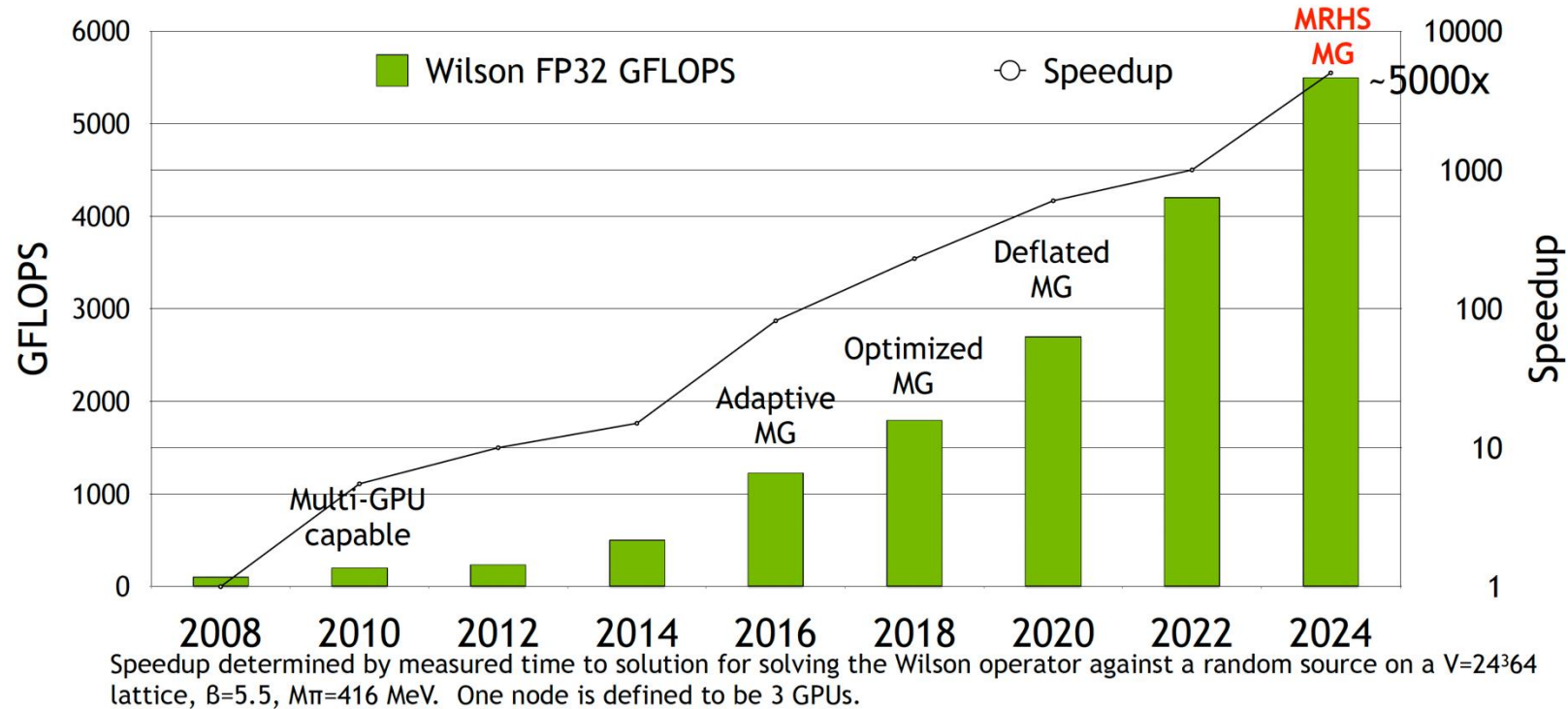


quark propagator
: inverse of large ($\mathcal{O}(10^9)$)
sparse Dirac matrix



QUDA node performance over time

- Multiplicative speedup through software and hardware



Kate Clark, NVIDIA, Lattice 2024 Conference

Study of Protons and Neutrons using Lattice QCD

Who Carries the Proton Spin? From the Naive Quark Model to the Proton Spin Puzzle

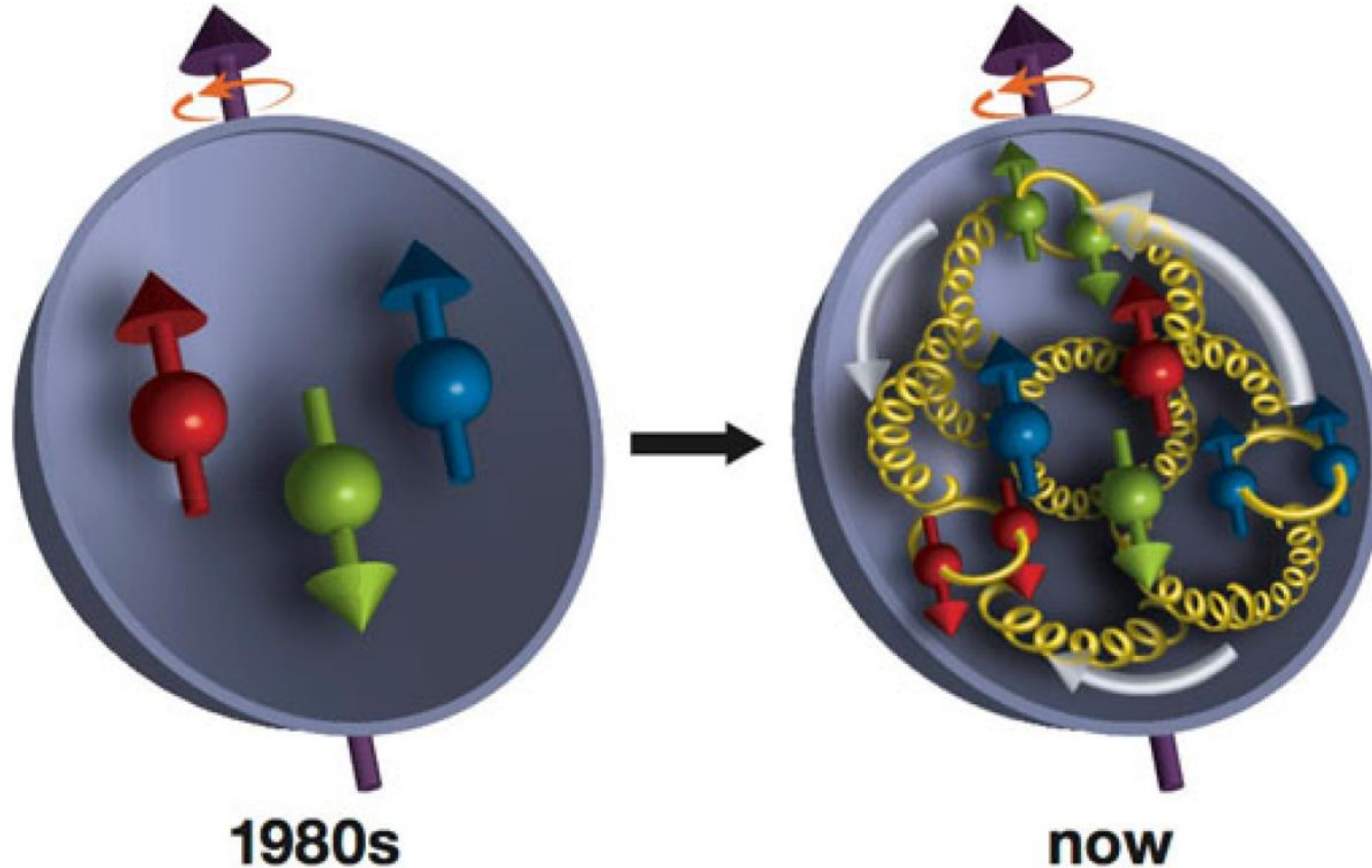


Photo courtesy of Brookhaven National Laboratory

Nucleon spin from quarks: Axial charge $g_A^q = \Delta q$

$g_A^q = \Delta q$: Quark contributions to the nucleon spin

$$\frac{1}{2} = \sum_{u,d,s,\dots} \left(\frac{1}{2} \Delta q + L_q \right) + J_g$$

X. Ji, PRL 78 (1997) 610

L_q : orbital angular momentum of the quark

J_g : total angular momentum of the gluons

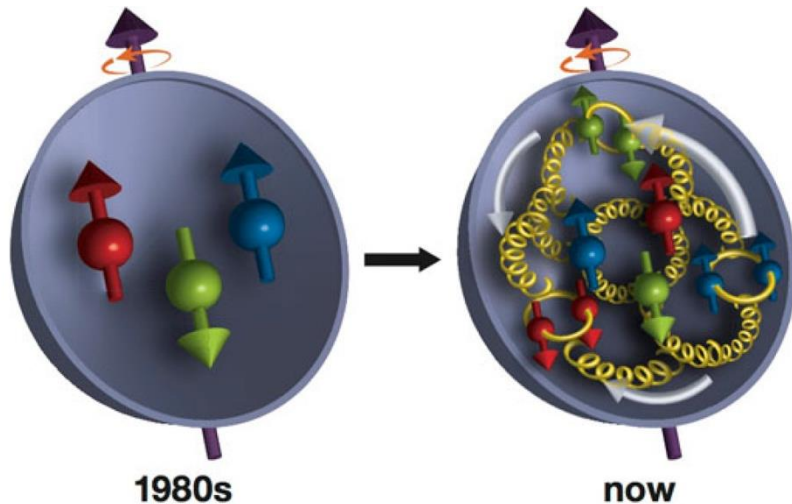
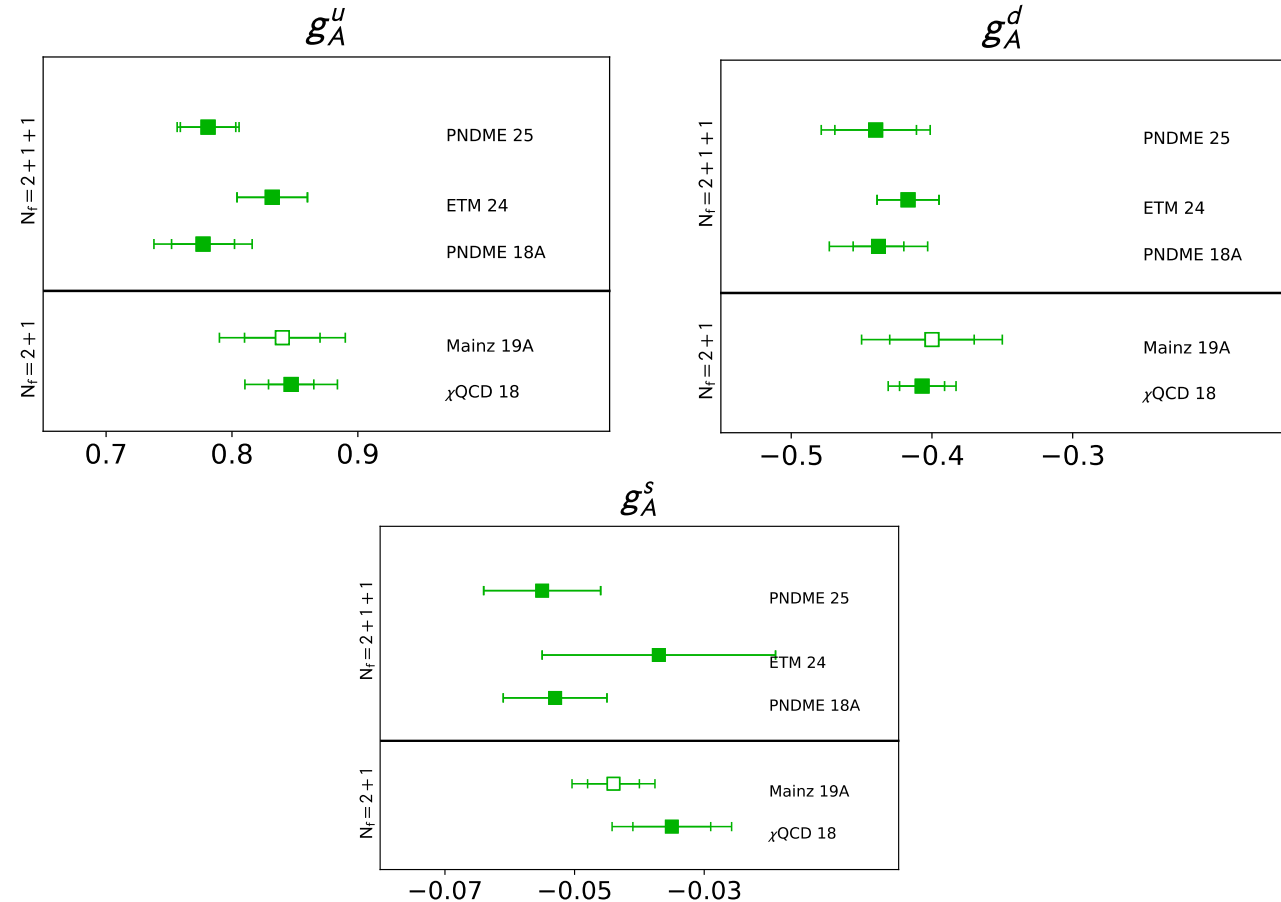


Photo courtesy of Brookhaven National Laboratory

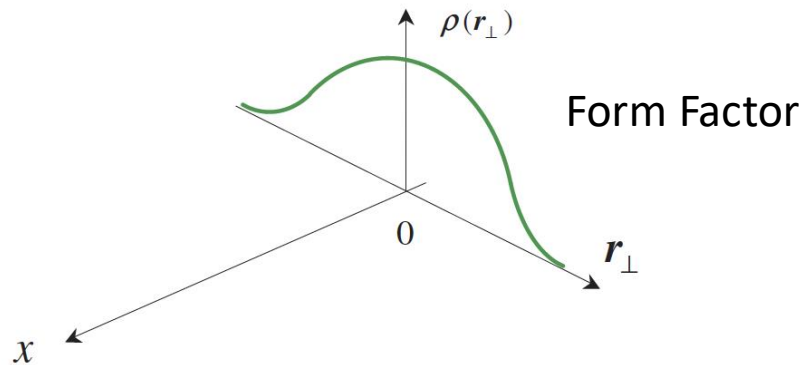
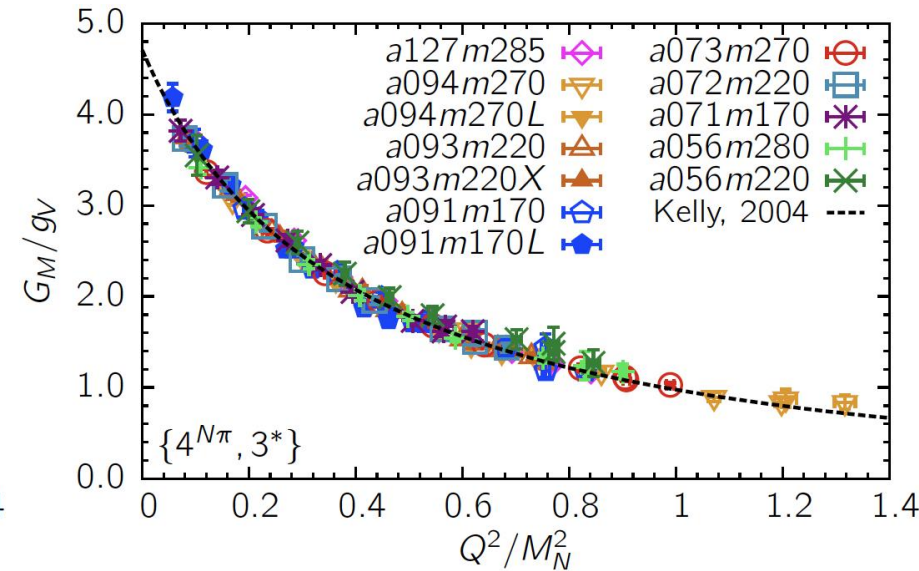
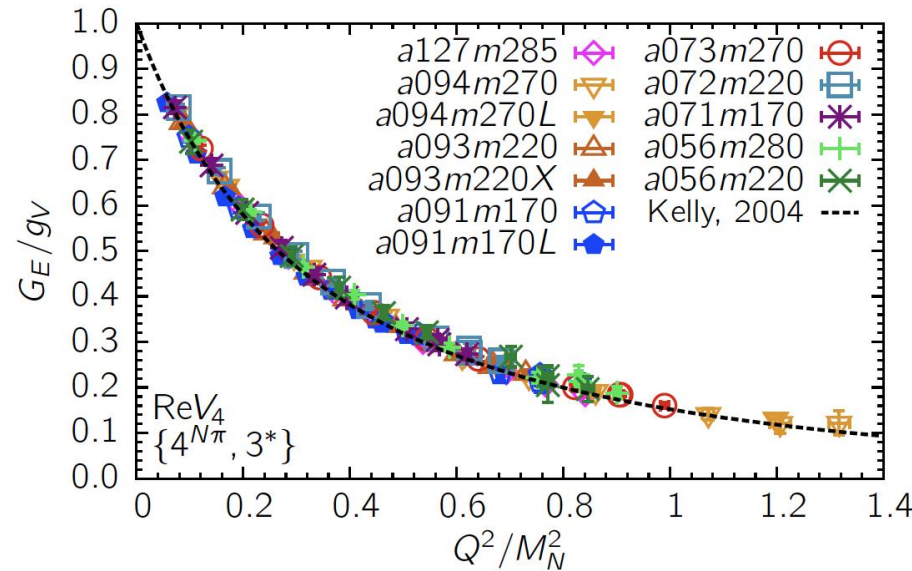
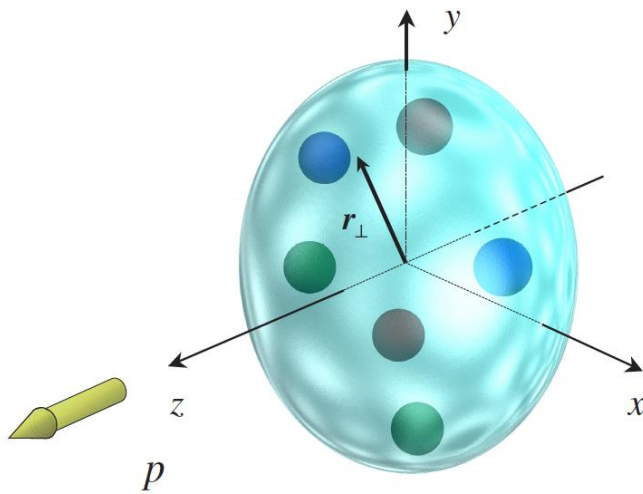


$$0.13 \leq \sum_q 0.5 \Delta q \leq 0.18 \quad \text{COMPASS, Phys. Lett. B753, 18 (2016)}$$

$$\sum_q 0.5 \Delta q = 0.143(24) \quad \text{Park et al., PNDME (2025)}$$

Nucleon electromagnetic form factor: charge distribution inside the nucleon

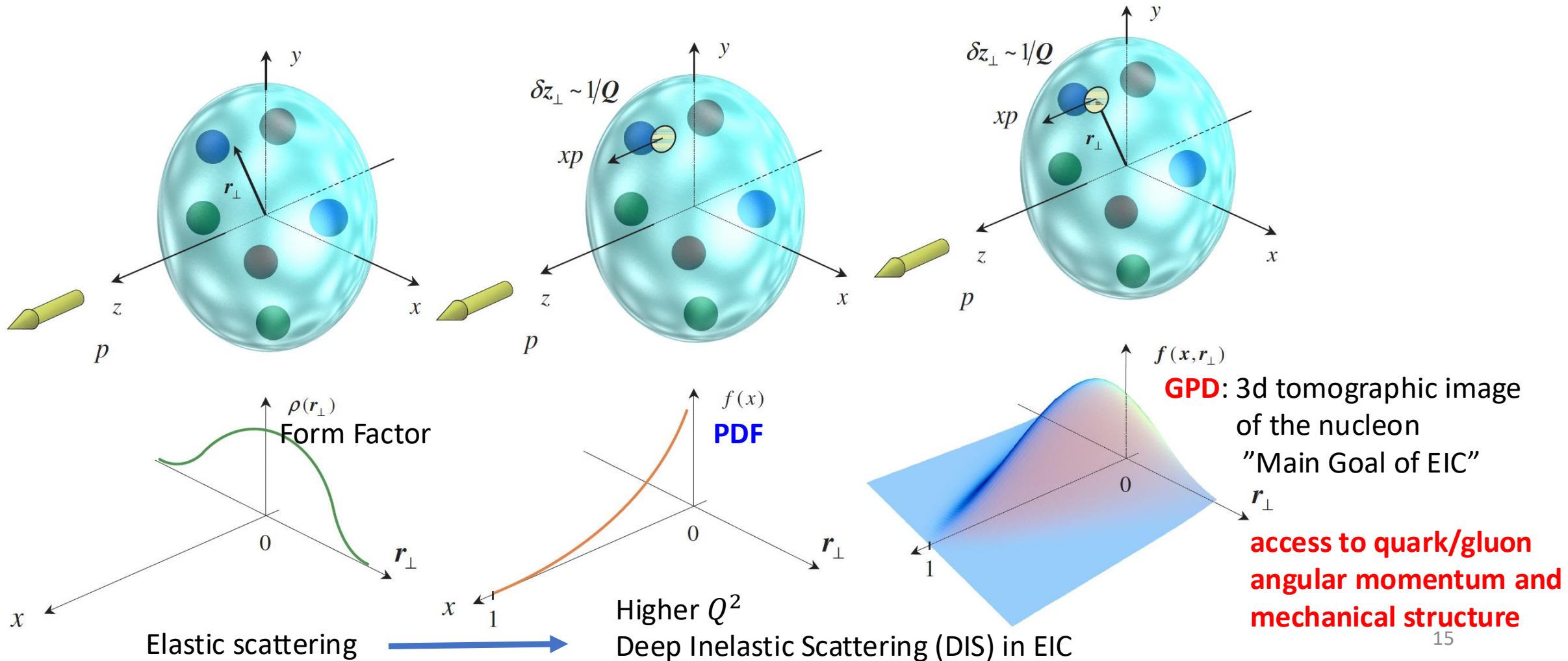
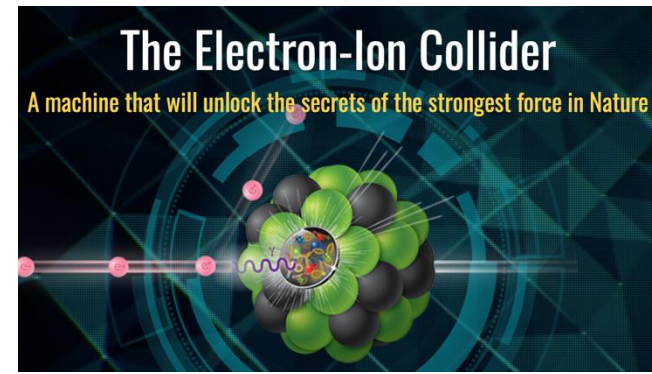
[S.Park, J.Yoo et al., in preparation]



Preliminary results on the nucleon electric (G_E) and magnetic (G_M) form factors from 12 $N_f=2+1$ clover ensembles.

With highly improved statistics, these results show excellent agreement with experimental data (Kelly, 2004) representing significant advancement over all previous lattice calculations

Beyond the nucleon form factor: Parton Distribution Function (PDF) Generalized Parton Distribution (GPD)



Remove Excited State (ES) effects from Nucleon Matrix Element

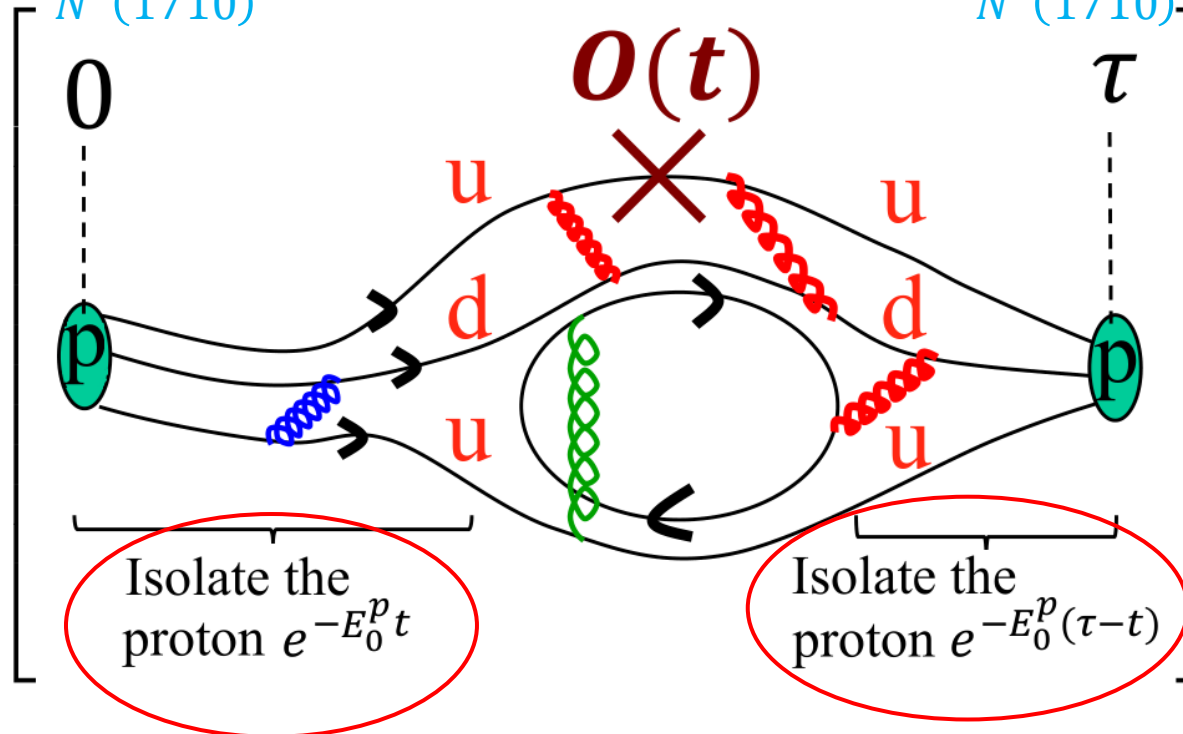
- Nucleon signal/noise decays $\propto e^{-(E-1.5M_\pi)\tau}$ with Euclidean time τ . Cannot go to large τ

Created **Excited states**
must be removed!
But can we identify them?

$N\pi, N\pi\pi,$
 $N\rho,$
 $N^*(1440),$
 $N^*(1710)$

$N\pi, N\pi\pi,$
 $N\rho,$
 $N^*(1440),$
 $N^*(1710)$

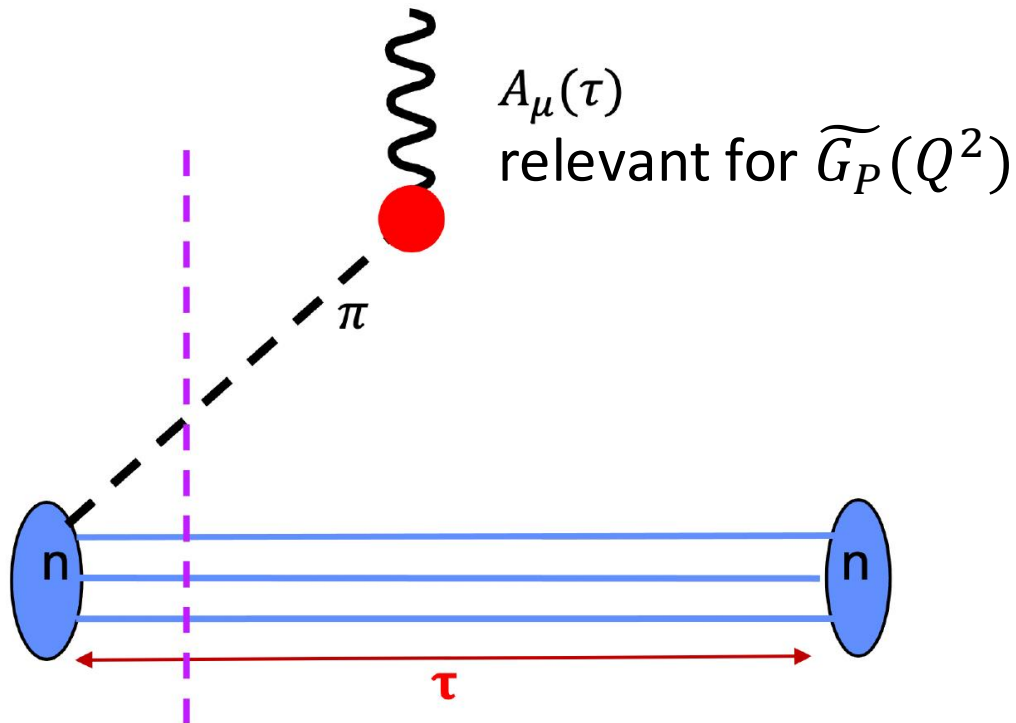
$$C(t, \tau) = \frac{1}{N_{\text{samp}}} \sum_{\{U\}}$$



Charges,
form factors,
PDFs,
GPDs

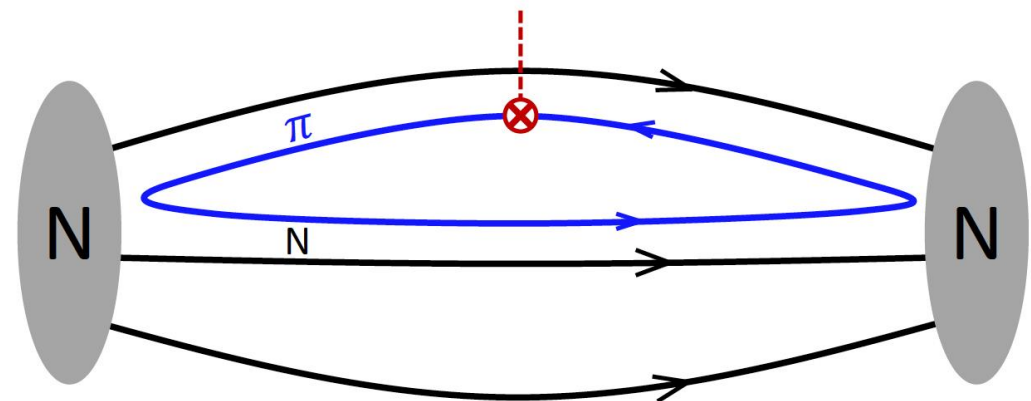
$N\pi$ -Excited state contribution can be enhanced

- To control ESC, we need to first determine the spectrum
- In nucleon 2pt functions, $1/L^3$ -suppressed coupling to $N\pi$ -state makes it challenging to extract its spectrum
- In certain 3pt functions (matrix elements), ChPT suggests $N\pi$ -state contributions are enhanced and compensate for the $1/L^3$ -suppression



Jang et al., [PNDME 2020]
Park et al., [NME 2022]

Scalar operator
relevant for $g_S^{u,d}$ and $\sigma_{\pi N} = m_{ud}g_S^{u+d}$



Gupta, Park et al., [PNDME 2021]

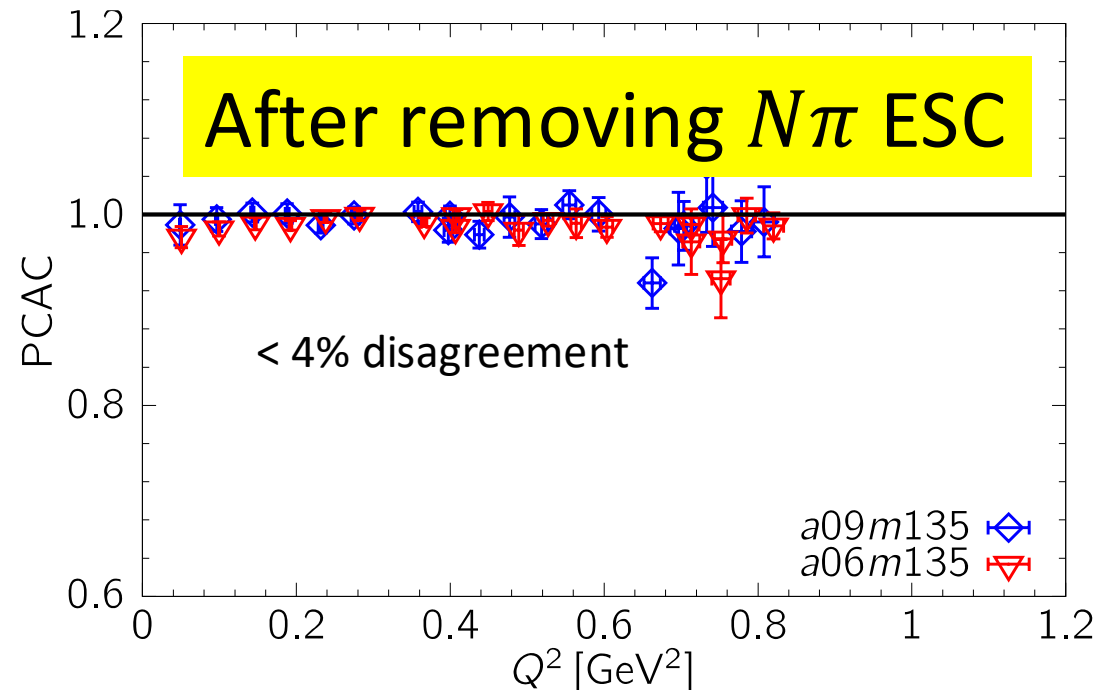
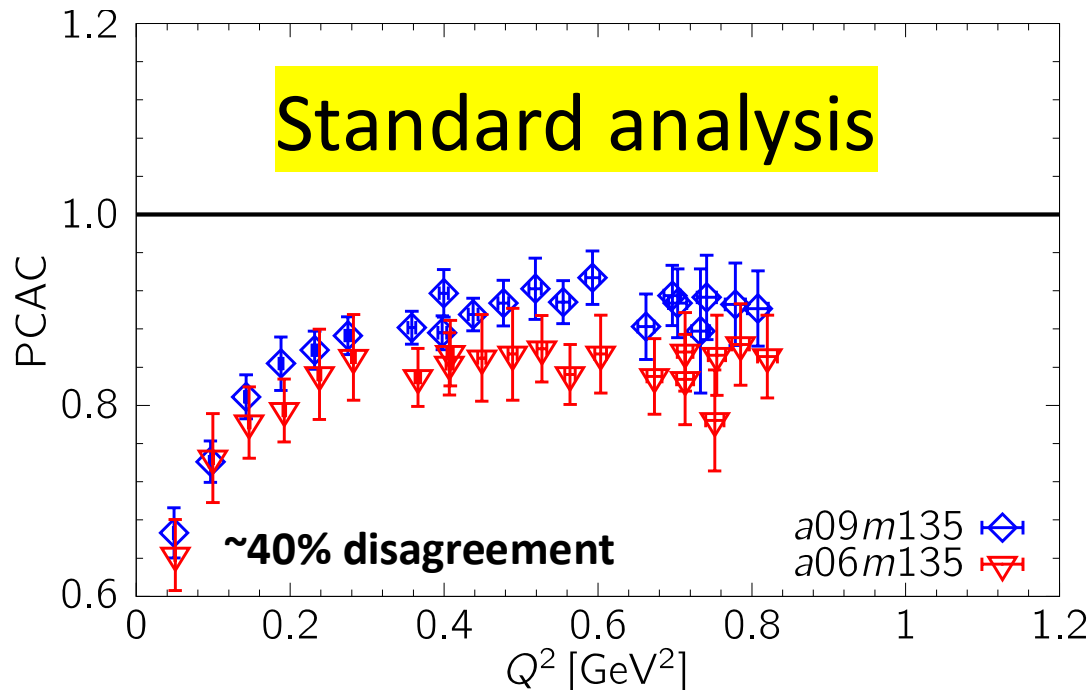
Axial Channel: large $N\pi$ excited-state effects

There are 3 axial form factors $G_A, \widetilde{G}_P, G_P$

Must satisfy the **PCAC relation**: $\partial_\mu A_\mu(x) = 2\hat{m}P(x)$ where $\hat{m} = Z_m m_{ud} Z_P Z_A^{-1}$

Applied to nucleon ground state, it relates the 3 nucleon form factors

$$\frac{\widetilde{G}_P(Q^2)}{G_A(Q^2)} \frac{Q^2}{4M^2} + \frac{G_P(Q^2)}{G_A(Q^2)} \frac{2\hat{m}}{2M} = 1$$

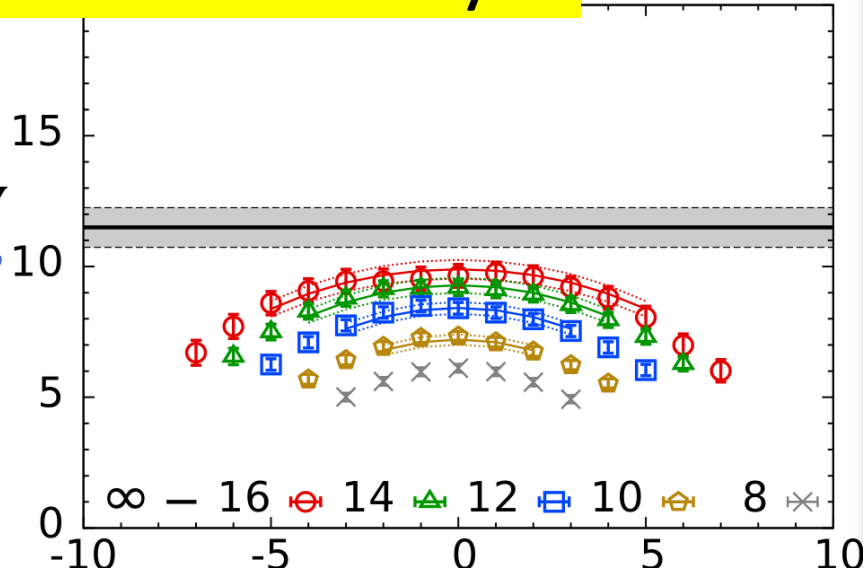


g_S^{u+d} : Excited state effect

[PNDME] Gupta, Park et al., PRL 127 (2021) 242002

Standard analysis

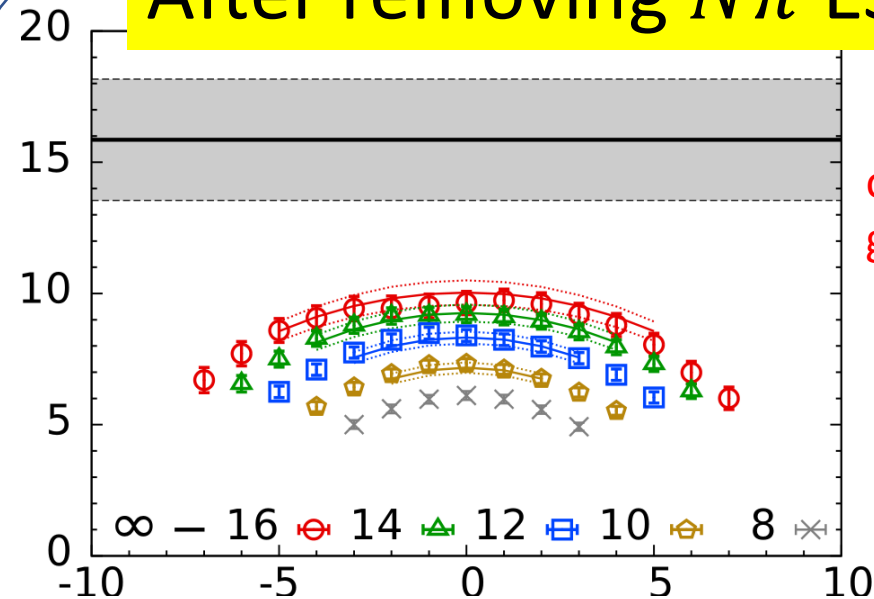
$M_1 \approx 1.6 GeV$
 "Standard"



$$\sigma_{\pi N} = m_l g_S^{u+d} \sim 40 \text{ MeV}, \quad \frac{\chi^2}{dof} = 1.1$$

After removing $N\pi$ ESC

$N(1)\pi(-1)$
 or, $N(0)\pi(0)\pi(0)$
 gives $M_1 \approx 1.2 GeV$
 "N π "

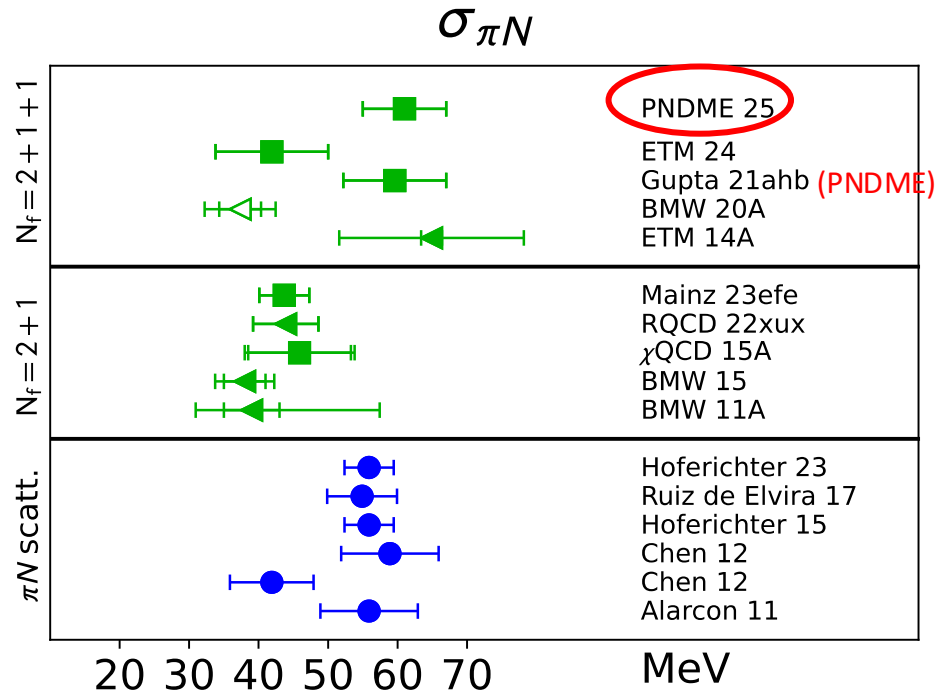


$$\sigma_{\pi N} = m_l g_S^{u+d} \sim 60 \text{ MeV}, \quad \frac{\chi^2}{dof} = 1.2$$

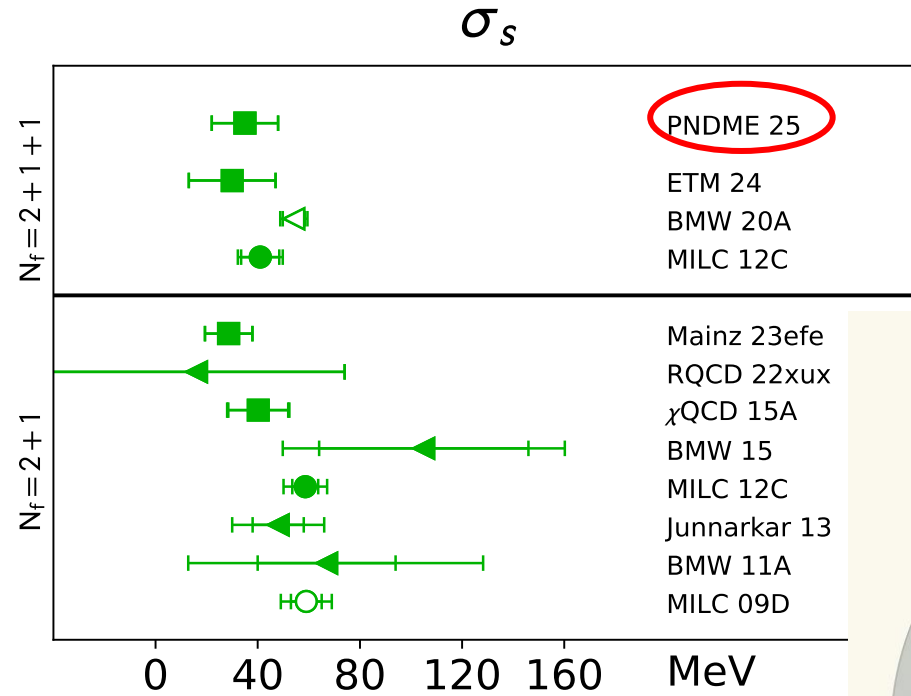
- Scalar is sensitive to $N\pi$ state
- Output is close to the phenomenological determination

Sigma terms: Quark contributions to the nucleon mass

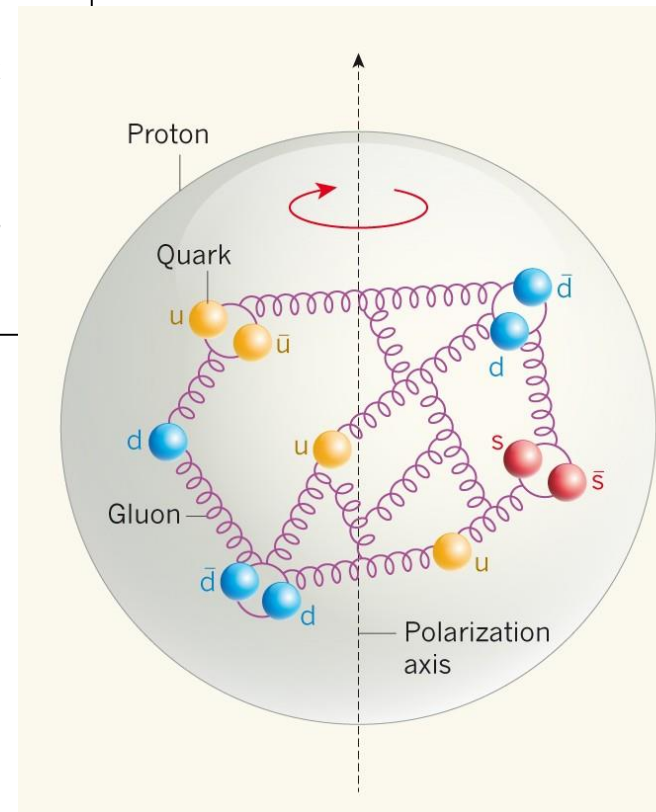
Fundamental parameter of QCD that quantifies the amount of the nucleon mass generated by quarks.



A value around 60 MeV means this contribution is only about 6% of the nucleon mass; the rest mainly comes from nonperturbative QCD dynamics.



Strange quark effect inside the nucleon mass!



Precision Nucleon Structure using Lattice QCD

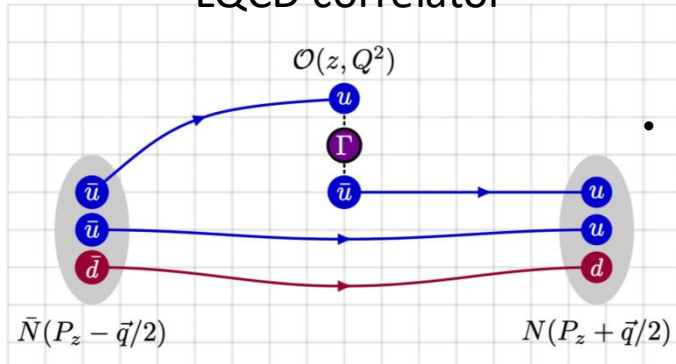


While Euclidean LQCD cannot directly access light-cone observables, our project bridges this gap using the LaMET framework.

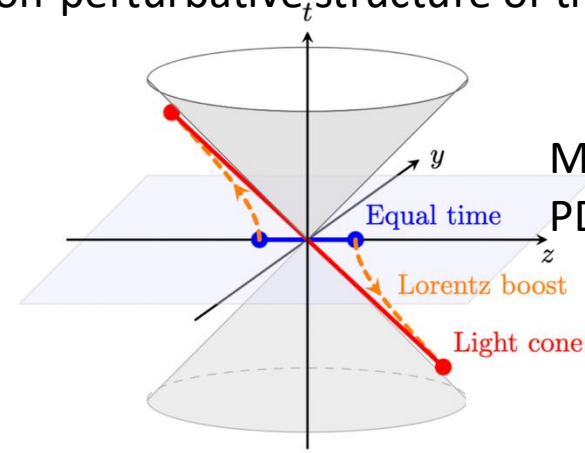
We aim to establish the **Korea-PDF (K-PDF) and K-GPD** as the definitive first-principles benchmark, providing unprecedented precision in decoding the non-perturbative structure of the nucleon

First Principles (LQCD)

LQCD correlator



- Unprecedented precision through advanced operator constructions.
- Systematically controlled excited-state contaminations for reliable benchmarks



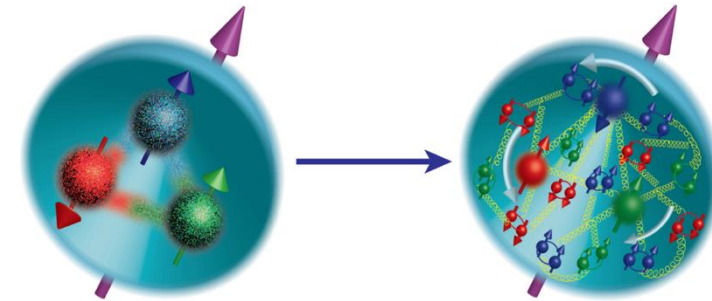
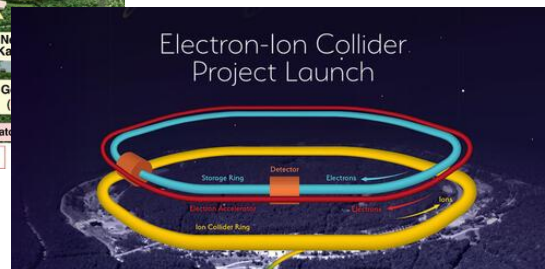
Matching to light-cone PDF/GPD via LaMET

Synergy with Experiments by providing crucial constraints



J-PARC

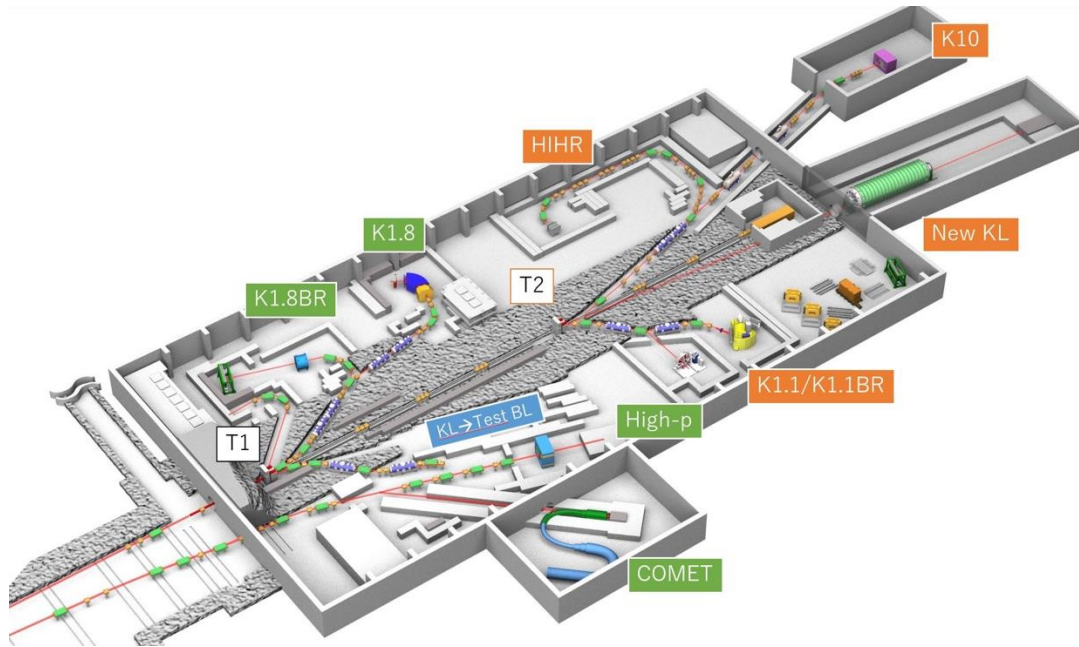
EIC



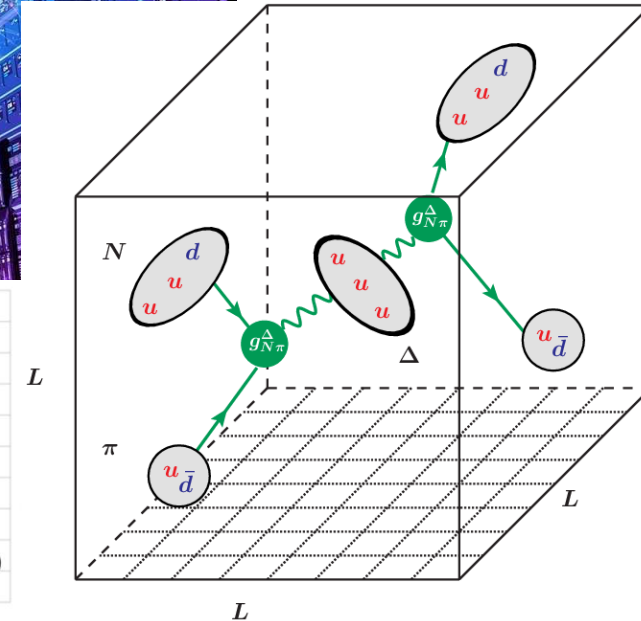
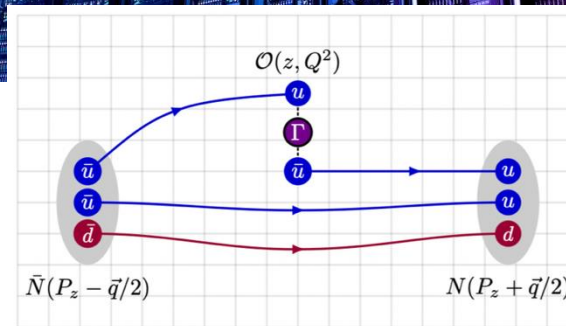
K-PDFs and K-GPDs

KLASIQ Collaboration
EICphi Collaboration

LQCD Synergy with J-PARC K10 physics



K10 world best high-intensity separated K and \bar{p} beams, opening new measurements of strange hadrons, hadron interactions, and structure measurements of cross-sections and mass spectra



LQCD & computational methods as toolkits provides **first-principles** QCD inputs: masses, finite-volume spectra, form factors, moments, and matrix elements.

(Since 2024)

KLASIQ Collaboration

- Alexander Rothkopf (Korea U.)
- Seyong Kim (Sejong U.)
- Yongsun Kim (Sejong U.)
- Jangho Kim (Seoul Natl. U.)
- Seung-il Nam (Pukyong U.)
- **Sungwoo Park (Sejong U.)**
- Young-Ho Song (IBS)
- Saehanseul Oh (Sejong U.)
- Weonjong Lee (Seoul Natl. U.)
- Jongwan Lee (IBS)
- Junsik Yoo (Korea U.)

Korean lattice community has seen a significant expansion in recent years!

1ST LATTICE QCD WORKSHOP

**04 - 06 Jan. 2024, Youngsil gwan 601,
Sejong University, Seoul, Korea**

TOPICS

Lattice-kit tutorials
Structure functions in LQCD
QCD medium via LQCD
Effective models with LQCD
Nuclear physics in Monte Carlo computation
High-energy experiments

INVITED SPEAKERS

Seyong Kim (Sejong U., Korea)
Yongsun Kim (Sejong U., Korea)
Jong-Wan Lee (IBS, Korea)
C.-J. David Lin (NYCU, Taiwan)
Huey-Wen Lin (MSU, USA)
Seung-il Nam (PKNU, Korea)
Sungwoo Park (LLNL, USA)
Young-Ho Song (IBS, Korea)

ORGANIZERS

Seyong Kim (Sejong U.)
Yongsun Kim (Sejong U.)
Jong-Wan Lee (IBS)
Seung-il Nam (PKNU)



KoALICE

Summary

- Lattice QCD can provides complementary first-principles QCD inputs for hadron study: form factors, moments, spectra and interaction constraints.
- Controlled systematics especially the excited state for nucleon system are essential
 - Demonstrated in recent studies on nucleon sigma terms, and form factors, and spectra.
 - Crucial for the study of exotic and strange hadrons, and eventually requires large-scale computational resources to resolve
- J-PARC K10 and EIC will open new strange-hadron and hadron-structure measurements, and lattice can provide complementary constraints and interpretation.

Thank you.

Nucleon Matrix Elements

PNDME and NME Collaborations

T. Bhattacharya, R. Gupta, E. Mereghetti (LANL)
V. Cirigliano (INT), B. Yoon, B. Joo (NVIDIA)
J. Yoo (Korea U.), H.-W. Lin (MSU), F. Winter (JLab)

Beyond the Standard Model Physics

Lattice Strong Dynamics Collaboration

R.C. Brower, C. Rebbi, N. Matsumoto (Boston U.)
G.T. Fleming (FNAL), A. Hasenfratz (U. of Colorado)
J. Ingoldby (Durham U.), X.Y.Jin, J.C. Osborn (ANL)
E. Rinaldi (Quantinuum), D. Schaich (U. of Liverpool)
O. Witzel (U. of Siegen), A. Meyer, P.M. Vranas (LLNL)

Nucleon Scattering from spectrum in a finite box

Hadron Spectrum Collaboration

R. Edwards (JLab), A. Jackura (W&M),
C. Thomas (Cambridge U.)

CoSMoN Collaboration

M.A. Clark, B. Joo (NVIDIA), A. Meyer, P.M. Vranas (LLNL)
S. Krieg (Julich), D. McDougall (AMD)
H. Monge-Camacho (ORNL), C. Morningstar (CMU)
F. Romero-Lopez (U. of Bern), A. Walker-Loud (LBL)