# (Challenges in) Precision Nucleon Structure and Lattice QCD

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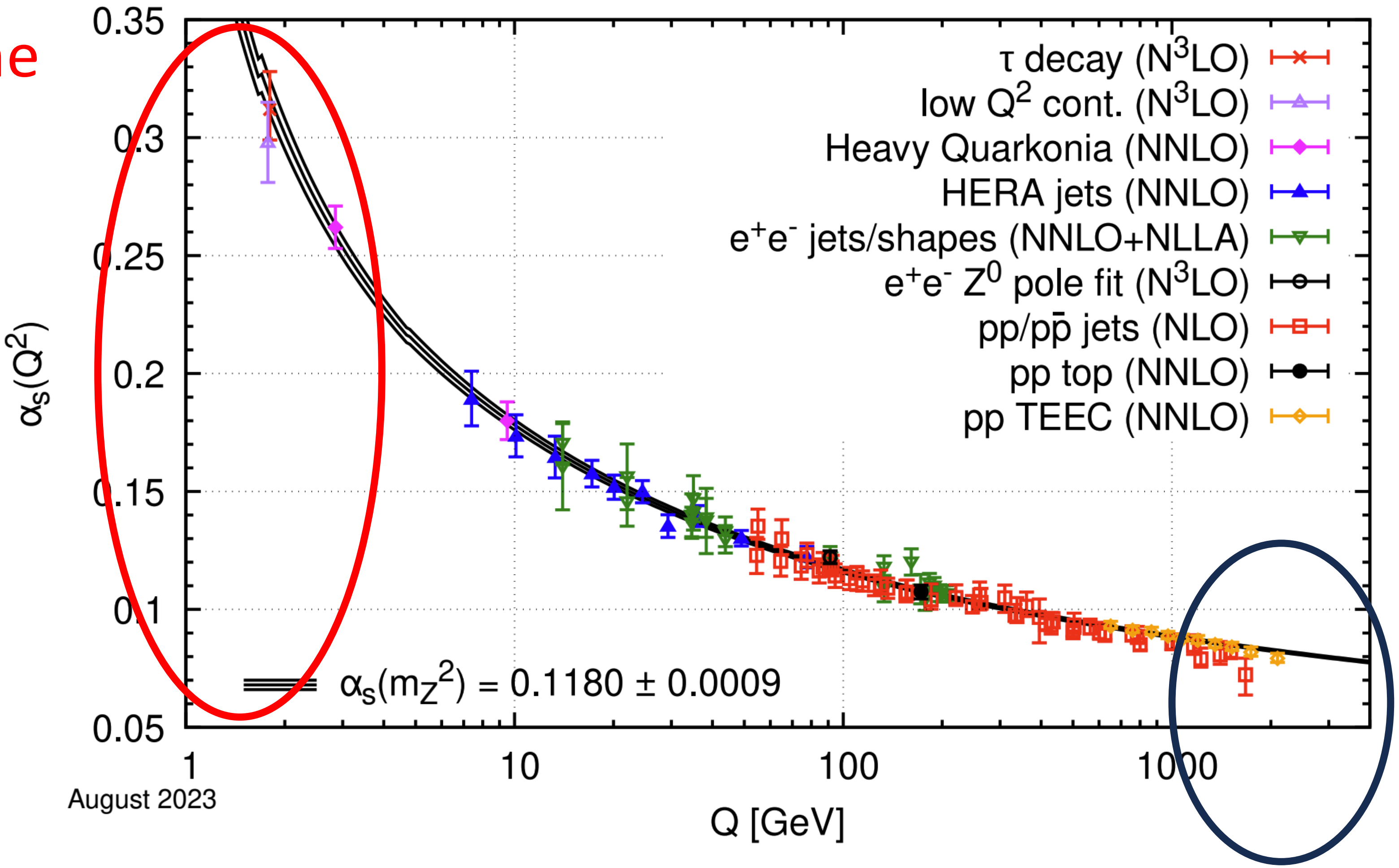
# Nonperturbative nature of QCD at small $Q$

- QCD Coupling constant $\alpha_s$ of QCD varies with the energy scale Q

- $\alpha_s = O(1)$ at the nuclear physics scale ~1GeV
- Confinement
- Perturbation theory fails

**-> Need LATTICE QCD simulations**




*Asymptotic Freedom (2004 Nobel Prize)*

$\alpha_s \to 0$ 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)**

- $\epsilon, \epsilon'$ in kaon CP violation
- $s$, $c$, $b$ decay form factors
- $g$-2
- $\alpha_s$, quark masses

**Nuclear Physics (NP)**

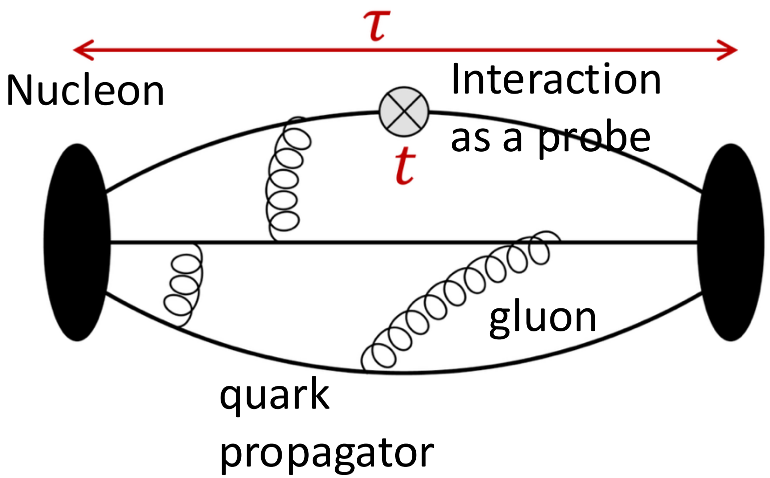
- Nucleon structure
- Hadron Spectroscopy
- Matrix elements within Nuclei

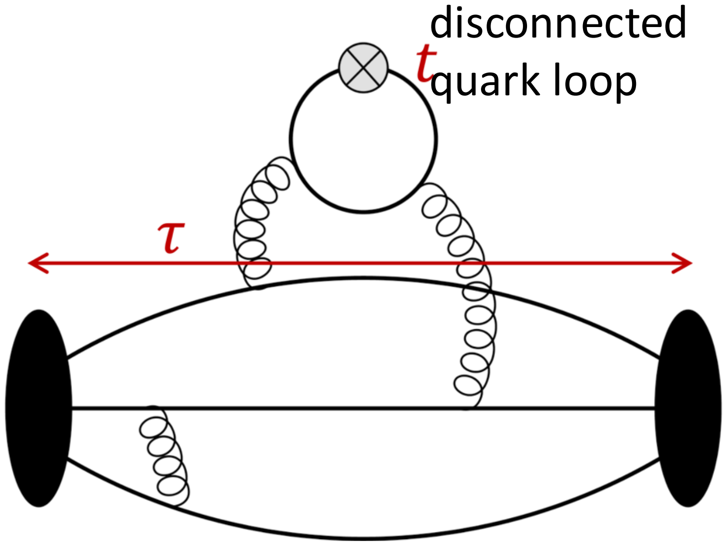
**Current Physics Objectives**

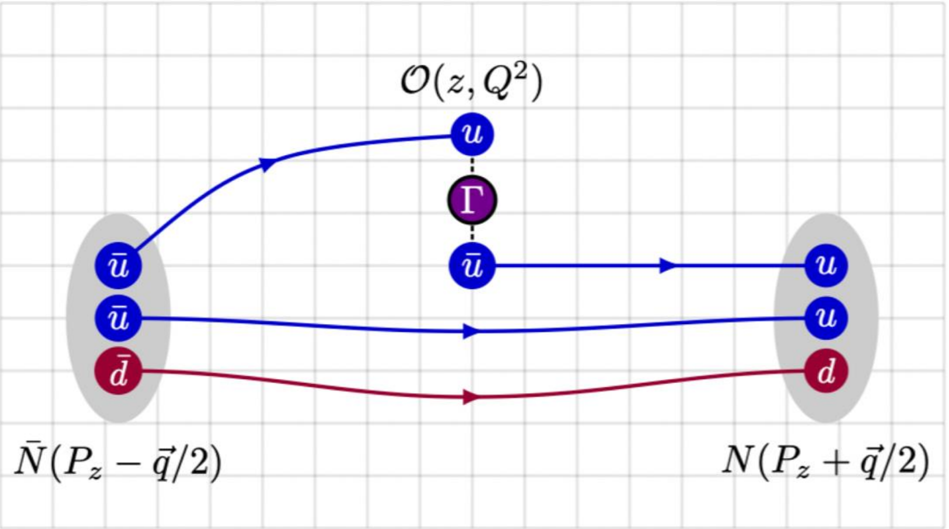
- Charges $g_A, g_S, g_T, \sigma_{\pi N}, \sigma_s$
- Axial & EM form factors
- Neutron electric dipole moment nEDM
- Moments, and Distribution functions PDFs, TMD, GPD
- Nucleon mass
- $N - \pi$ scattering

# Nucleon properties from LQCD correlation functions:

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



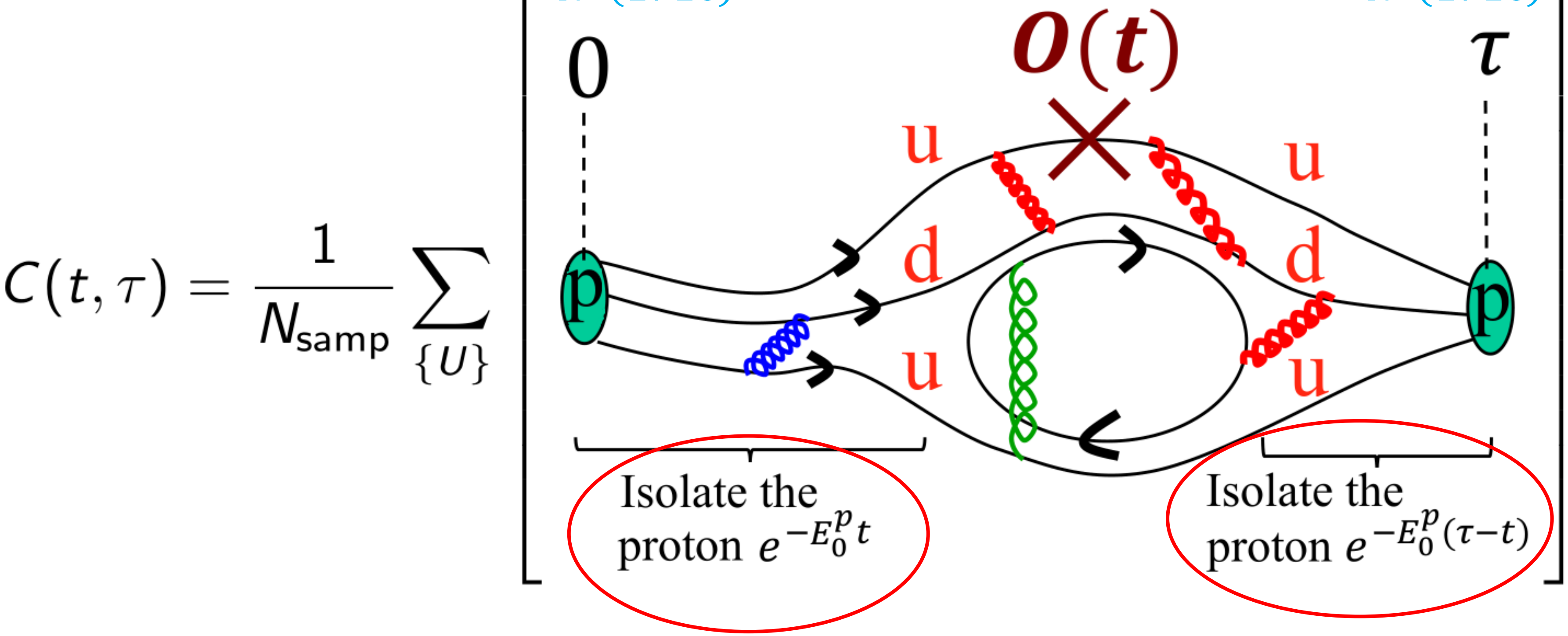
# Remove Excited State (ES) effects from Nucleon Matrix Element

- Calculate nucleon **3-point correlation function** $\boldsymbol{C(t,\tau) \equiv \langle N^p(\tau) O(t) \bar{N}^p(0) \rangle}$ → then decompose into ***Form Factors***
- Nucleon signal/noise decays $\propto e^{-(E-1.5M_\pi)\tau}$ with Euclidean time $\tau$. Cannot go to large $\boldsymbol{\tau}$

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

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

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



# Ensembles: Thirteen 2+1 flavor Wilson-clover

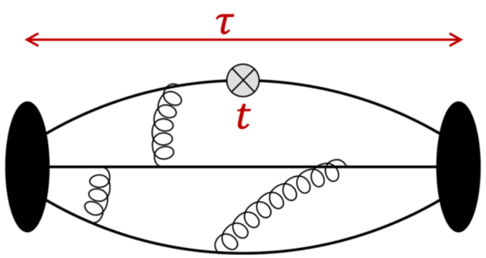
(Parameters of ensembles)

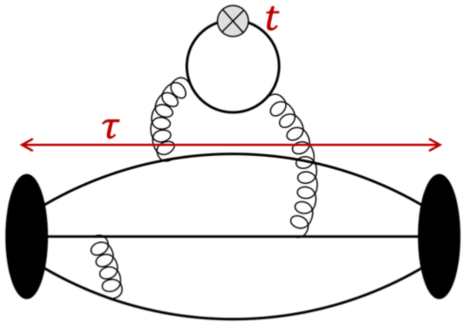
| Ensemble ID | a [fm] | $M_\pi$ [MeV] | $M_\pi L$ | $N_{conf}$ | $N_{LP}$ |
|---|---|---|---|---|---|
| a127m285 | 0.127 | 285 | 5.87 | 2002 | 256256 |
| a094m270 | 0.094 | 269 | 4.09 | 2469 | 237024 |
| a094m270L | 0.094 | 269 | 6.15 | 4510 | 577280 |
| a093m220 | 0.093 | 216 | 4.95 | 2000 | 256000 |
| 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 |

- Ensembles generated by the Jlab/W&M/LANL/MIT collaborations
- Measured nucleon correlation functions over the past 7+ years on supercomputers at LANL, NERSC, ORNL, JLab, FNAL
- O(PB) data stored and organized in Oak Ridge computing facility

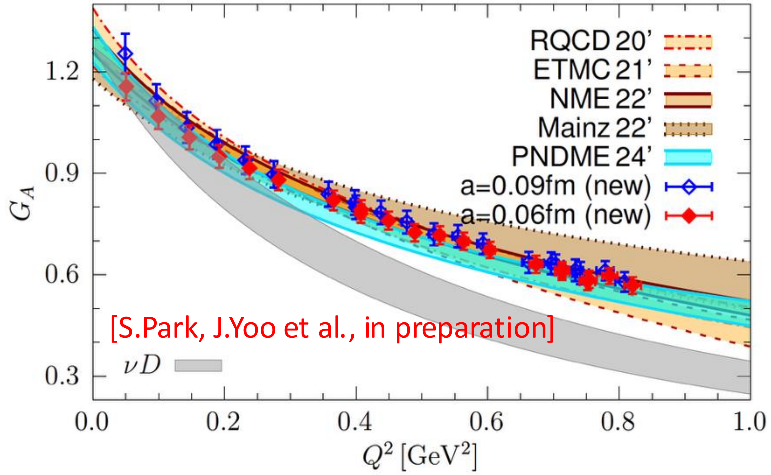
*[NME Collab., J.Yoo, J.Ee, S.Park et al., 2601.10857]*

# Recent Highlights on Nucleon Matrix Element Calculations

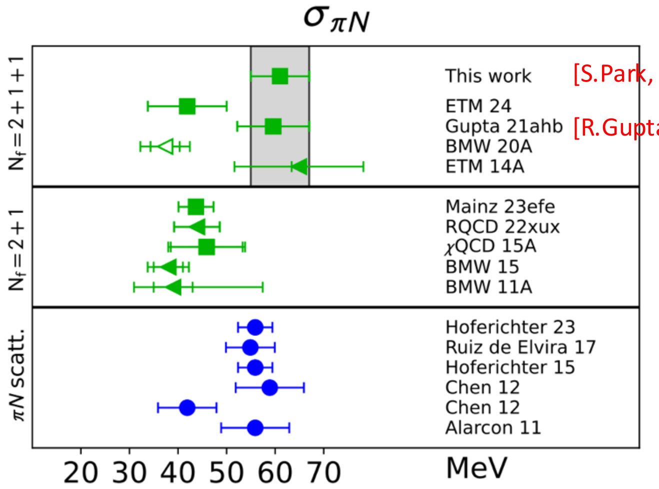



Ongoing 13-ensemble (Nf=2+1 clover [J.Yoo, J.-H.Ee, S.Park et al., arXiv:2601.10857]) and 9-ensemble (Nf=2+1+1, HISQ) calculation involves nucleon three-point lattice correlation functions as shown above



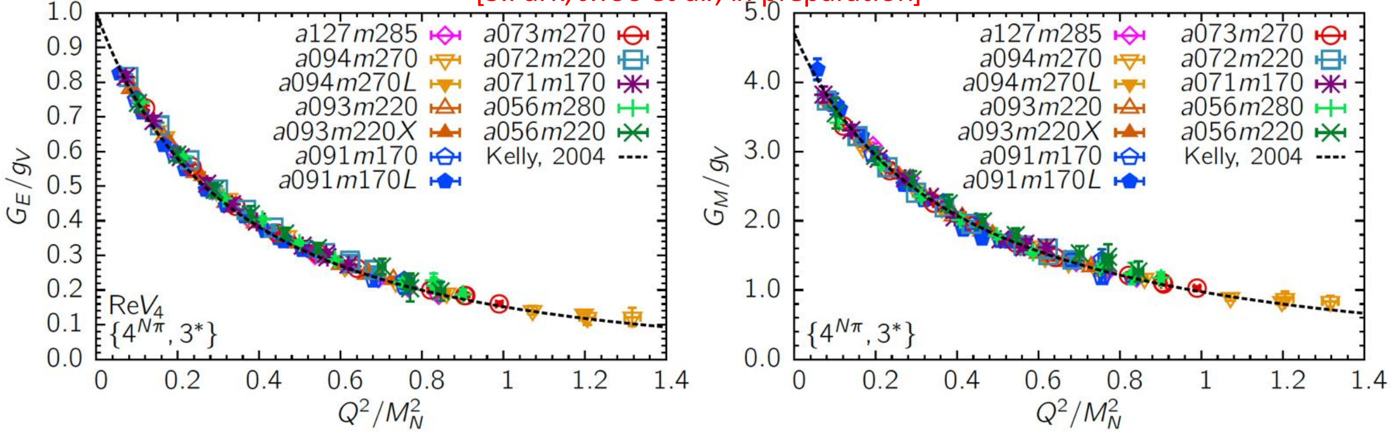

Preliminary results (new) on nucleon axial form factor (G_A) from two physical pion HISQ ensembles with highly improved statistics and reach larger Q^2~0.8. Comparison with other lattice determinations included.




Comparison of lattice (green) and phenomenological determinations (blue)

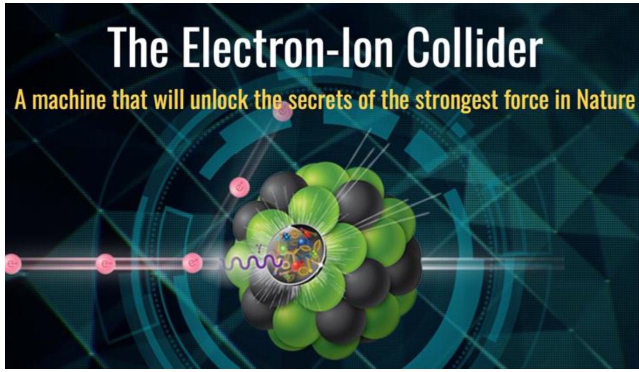
Lattice determination of nucleon sigma term (sigma_piN) has resolved the tension with phenomenological determinations (blue circles) by revealing large excited state contamination from nucleon-pion states. Highlighted in FLAG Review 2024.

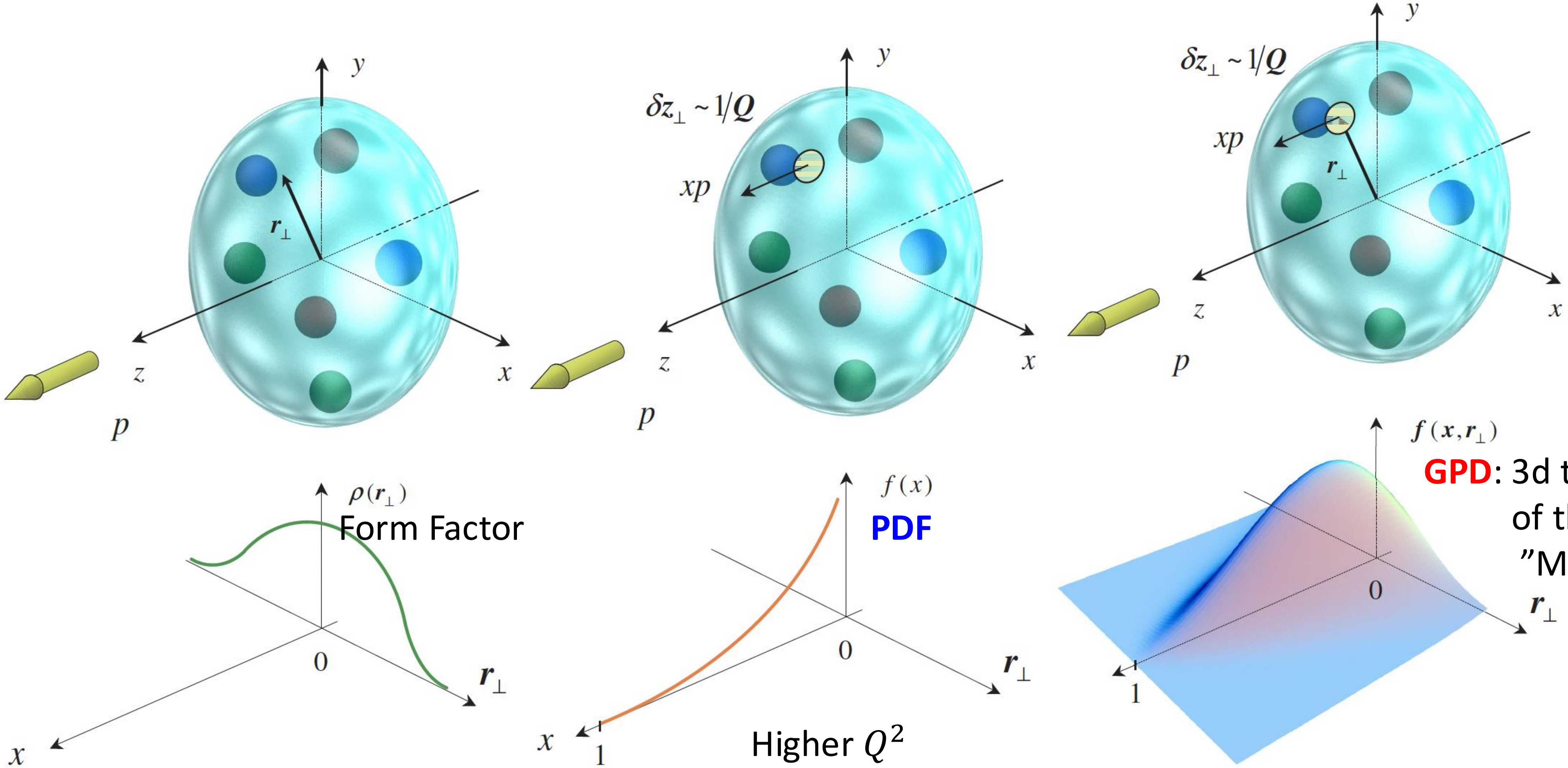
[S.Park, J.Yoo et al., in preparation]




Preliminary results on the nucleon electric (G_E) and magnetic (G_M) form factors from 12 Nf=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)




**GPD**: 3d tomographic image of the nucleon "Main Goal of EIC"

Elastic scattering → Higher $Q^2$ Deep Inelastic Scattering (DIS) in EIC underway and showing successful progress

# Moments and Beyond

Will contribute to the global fits of GPD and PDF

**GPD**

$f(x, \vec{r}_{\perp})$

- $1^{st}$ moments = Form Factors ✓
- $2^{nd}$ moments = Generalized Form Factors ✓

**PDF**

$f(x)$

- $1^{st}$ moments = charges ✓
- $2^{nd}$ moments = momentum fraction, helicity & transversity moments ✓

**Direct calculation using LQCD is challenging** → LaMET method

**However, the observable is essentially a nucleon matrix element of a bi-local operator, and our expertise and techniques can be naturally applied!**

# Precision Nucleon Structure using Lattice QCD and Large Momentum Effective Theory (LaMET)

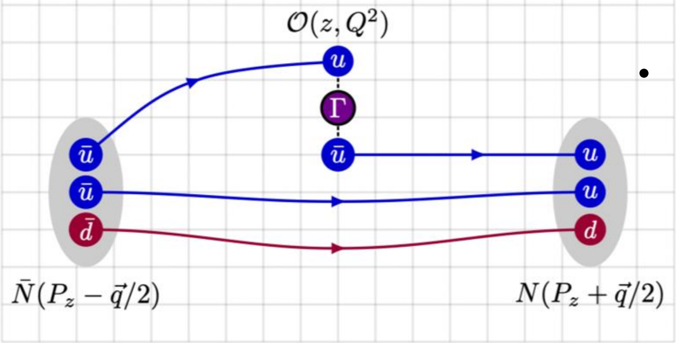
**KLASIQ Collaboration**

**EICphi Collaboration**

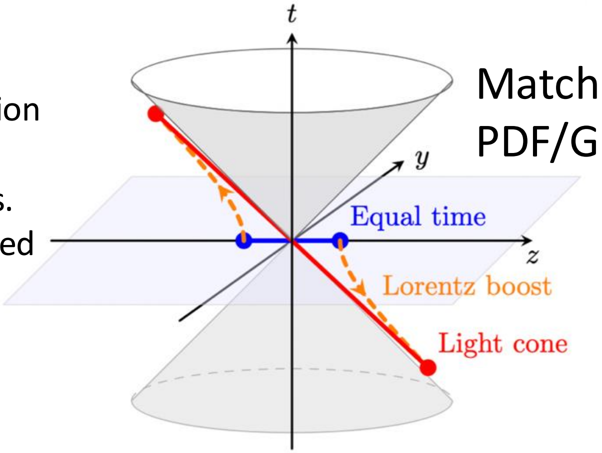
While Euclidean LQCD cannot directly access light-cone observables, our project bridges this gap using the LaMET framework.
We aim to establish the **Korea-PDF (K-PDF) and K-GPD** as the definitive first-principles benchmark, providing unprecedented precision in decoding the non-perturbative structure of the nucleon

First Principles (LQCD)

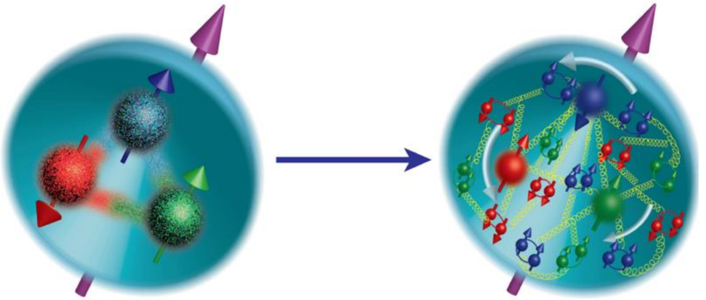
Equal-time LQCD quasi-PDF/GPD




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

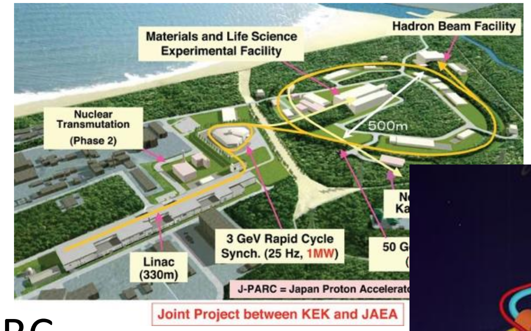



Matching to light-cone PDF/GPD via LaMET



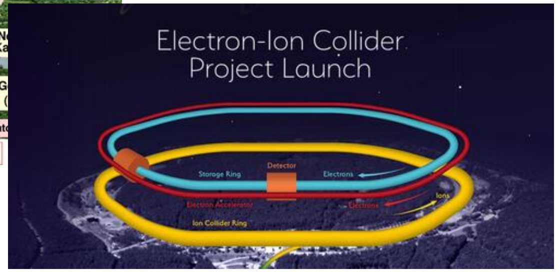
**K-PDFs and K-GPDs**

Synergy with Experiments by providing crucial constraints




J-PARC

EIC



# KLASIQ Collaboration

- Alexander Rothkopf (고려대)
- 김세용 (세종대)
- 김용선 (세종대)
- 김장호 (서울대)
- 남승일 (부경대)
- 박성우 (세종대)
- 송영호 (IBS)
- 오새한슬 (세종대)
- 이원종 (서울대)
- 이종완 (IBS)
- 유준식 (고려대)

# Problems with data

- Continuum extrapolation with several lattice spacings
- Pion mass must be physical
- Excited state contamination (becomes a serious problem for large momentum hadrons)
  - Excited suppression goes like

$$\exp\left(-\frac{\delta M_n T}{\gamma}\right) \qquad \delta M_n = M_n - M_0$$

- All these effects conspire to make the first moment $\langle x_{u-d} \rangle$ too large.

# Thank you.