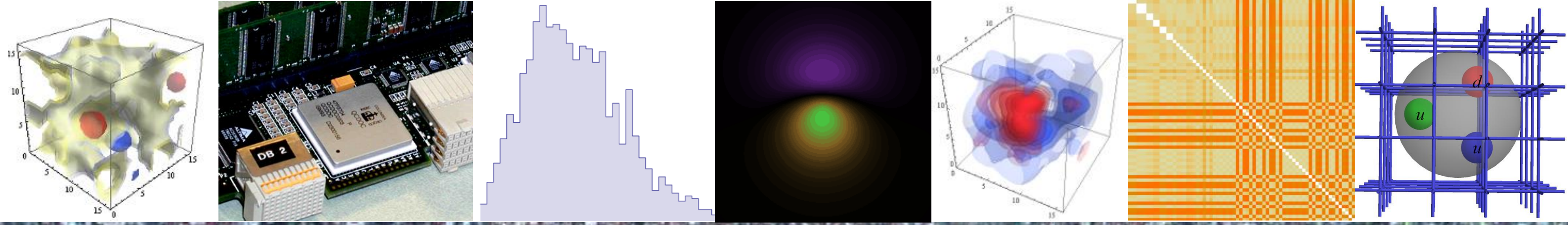


Latest hadron structure from Lattice QCD

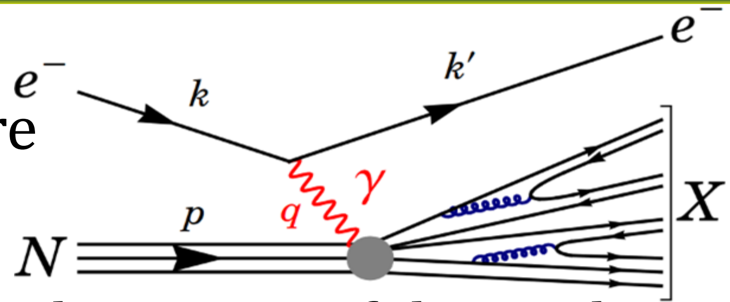
Huey-Wen Lin

Michigan State University

Nucleon Structure

§ Study nucleon structure since '60s

- Deep inelastic scattering @ SLAC, more



§ Fundamental QCD property

- Exploration of the valence and sea-quark content of the nucleon

§ Important for BSM searches

- Provides SM cross-section prediction for LHC new-physics search

§ Impressive results but still limited knowledge

- Many ongoing/planned experiments:
  (RHIC, JLab, J-PARC, COMPASS-II, GSI, EIC, LHeC, …)

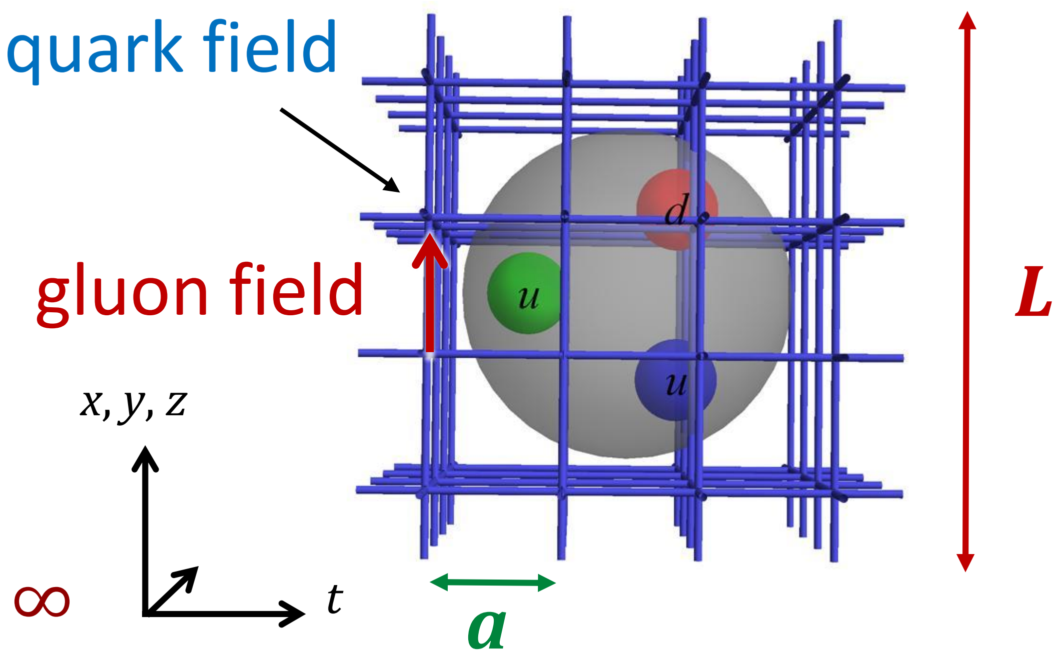
How Can LQCD Help?

- Lattice QCD is an ideal theoretical tool for investigating strong-coupling regime of quantum field theories
- Physical observables are calculated from the path integral

$$\langle 0|O(\bar{\psi},\psi,A)|0\rangle = \frac{1}{Z}\int \mathcal{D}A\,\mathcal{D}\bar{\psi}\,\mathcal{D}\psi\, e^{iS(\bar{\psi},\psi,A)}O\,(\bar{\psi},\psi,A)$$

in **Euclidian** space

- Quark mass parameter (described by m_π)
- Impose a UV cutoff
  discretize spacetime
- Impose an infrared cutoff
  finite volume



- Recover physical limit

$$m_\pi \to m_\pi^{\text{phys}},\ a \to 0,\ L \to \infty$$

How Can LQCD Help?

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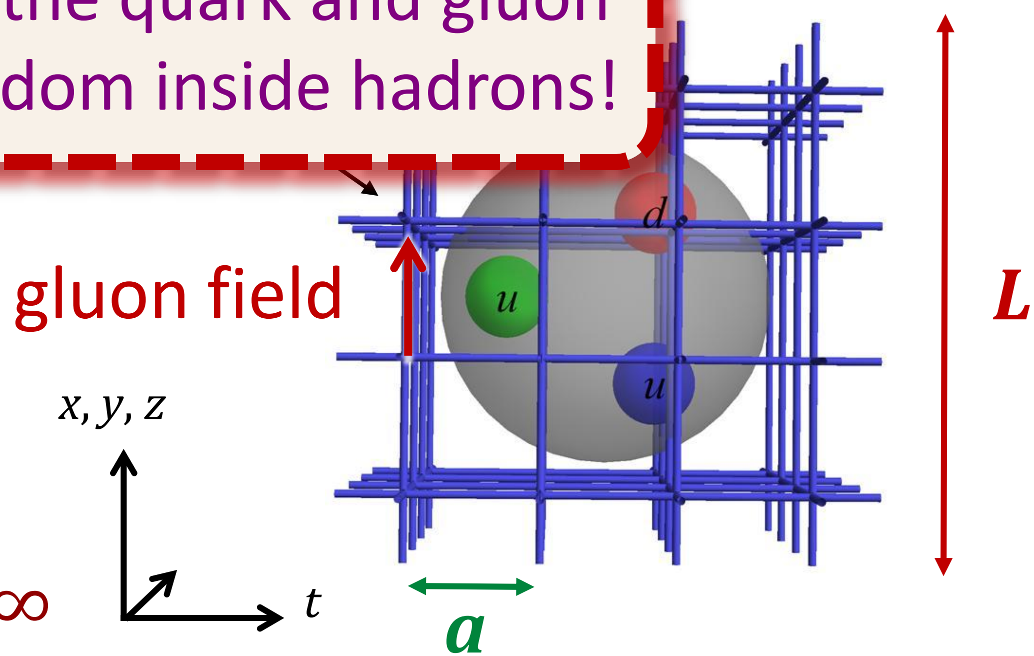
in **Euclidi**

Great to study the quark and gluon degrees of freedom inside hadrons!

- Quark m
  (describ
- Impose a UV cutoff
  discretize spacetime
- Impose an infrared cutoff
  finite volume



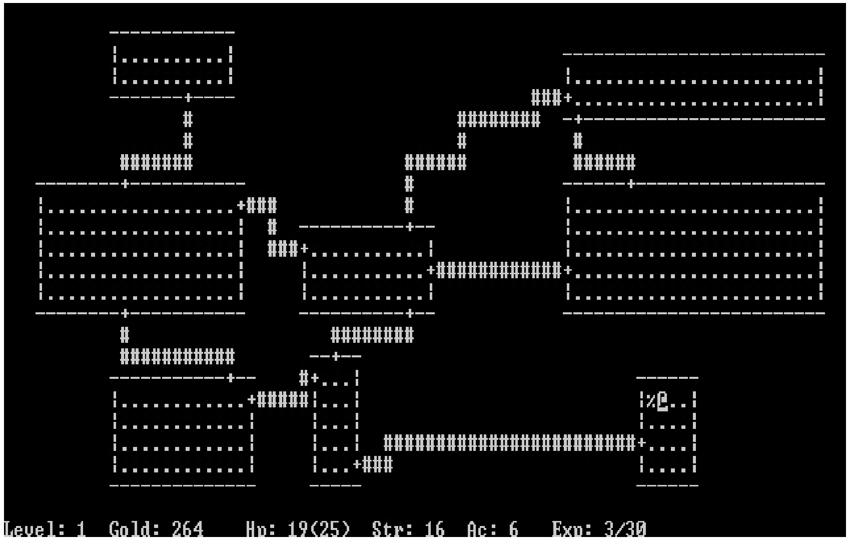
- § Recover physical limit

$$m_\pi \to m_\pi^{\text{phys}},\ a \to 0,\ L \to \infty$$

Are We There Yet?

- Lattice gauge theory was proposed in the 1970s by Wilson
  - Why haven't we solved QCD yet?
- Progress is limited by computational resources

1980s



Today

- Greatly assisted by advances in algorithms
  - Physical pion-mass ensembles are not uncommon!

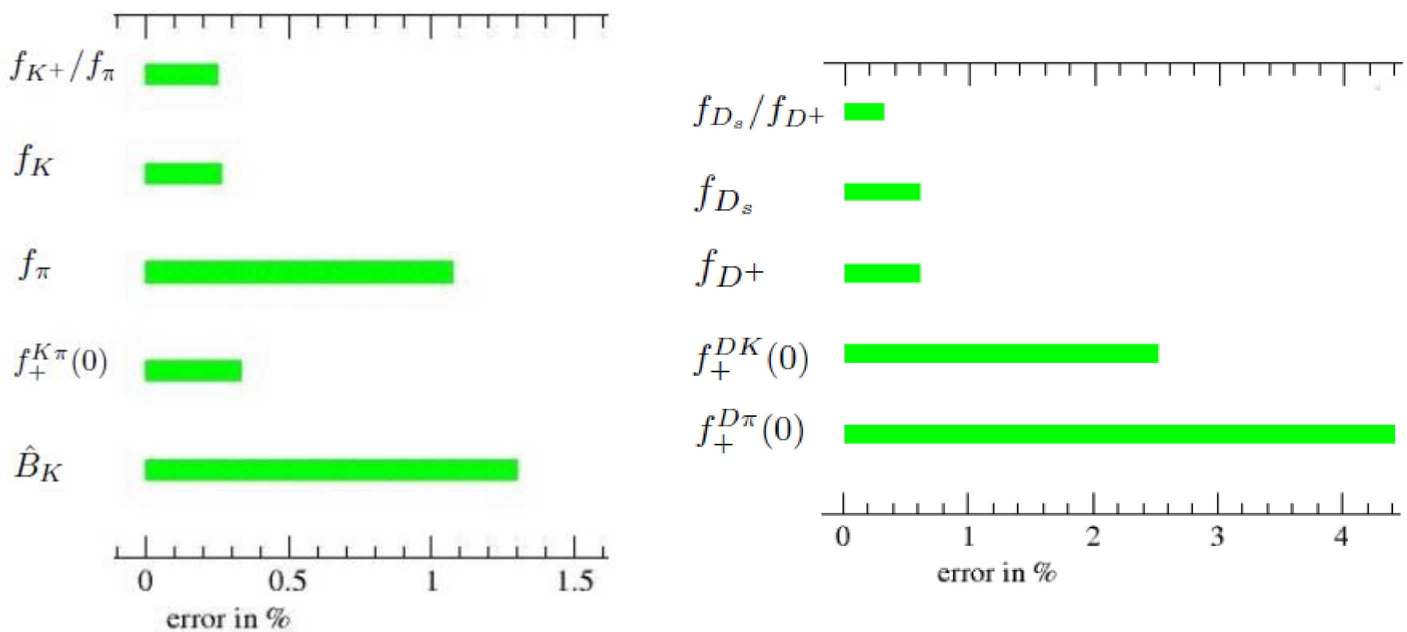
Successful Examples

§ Lattice flavor physics provides precise inputs from the SM

A. El-Khadra, Sep. 2015, INT workshop "QCD for New Physics at the Precision Frontier"

- Very precise results in many meson systems

errors (in %) **(preliminary) FLAG-3 averages**



§ We are beginning to do precision calculations in nucleons

Outline

§ Lattice Precision Frontier

- Nucleon structure with controlled systematics in physical limit ($m_\pi \to m_\pi^{\text{phys}}, a \to 0, L \to \infty$)
- New-physics implications

§ Lattice Pioneer Frontier

- Lattice parton distribution functions

Precision Nucleon Structure

- Much effort has been devoted to controlling systematics
- A state-of-the art calculation (PNDME)

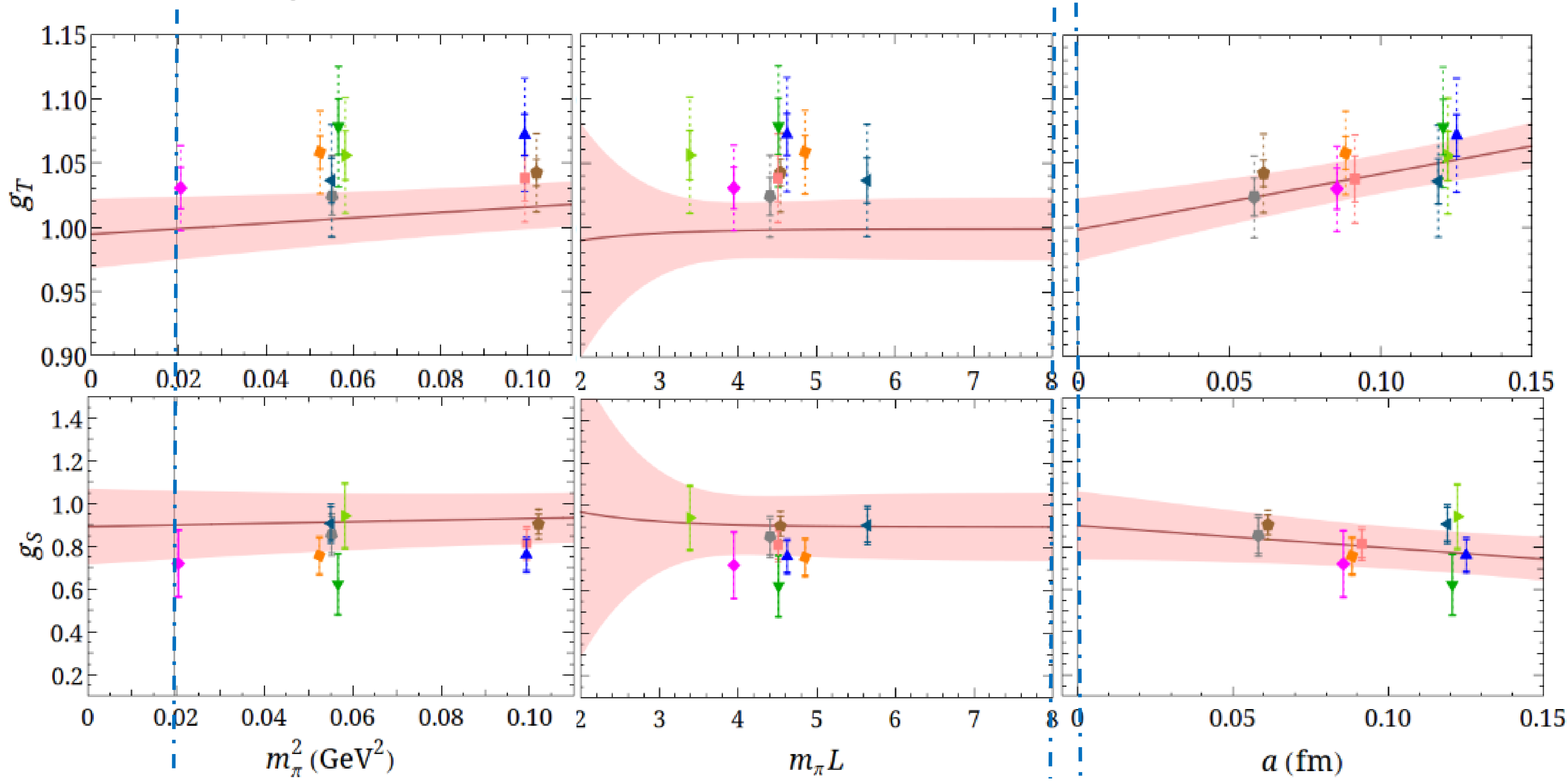
a (fm)	V	$M_\pi L$	M_π (MeV)	t_{sep}	# Meas.
0.12	$24^3 \times 64$	4.55	310	8,10,12	64.8k
0.12	$24^3 \times 64$	3.29	220	8,10,12	24k
0.12	$32^3 \times 64$	4.38	220	8,10,12	7.6k
0.12	$40^3 \times 64$	5.49	220	8,10,12,14	64.6k
0.09	$32^3 \times 96$	4.51	310	10,12,14	7.0k
0.09	$48^3 \times 96$	4.79	220	10,12,14	7.1k
0.09	$64^3 \times 96$	3.90	135	10,12,14	56.5k
0.06	$48^3 \times 144$	4.52	310	16,20,22,24	64.0k
0.06	$64^3 \times 144$	4.41	220	16,20,22,24	41.6k
0.06	$96^3 \times 192$	3.80	135	16,18,20,22	51.5 k

Tensor/Scalar Charge

§ PNDME's $g_{T,S}$ calculations PNDME, 1506.06411; 1506.04196; in preparation

- Extrapolate to the physical limit

$$g_T(a, m_\pi, L) = c_1 + c_2 m_\pi^2 + c_3 a + c_4 e^{-m_\pi L}$$



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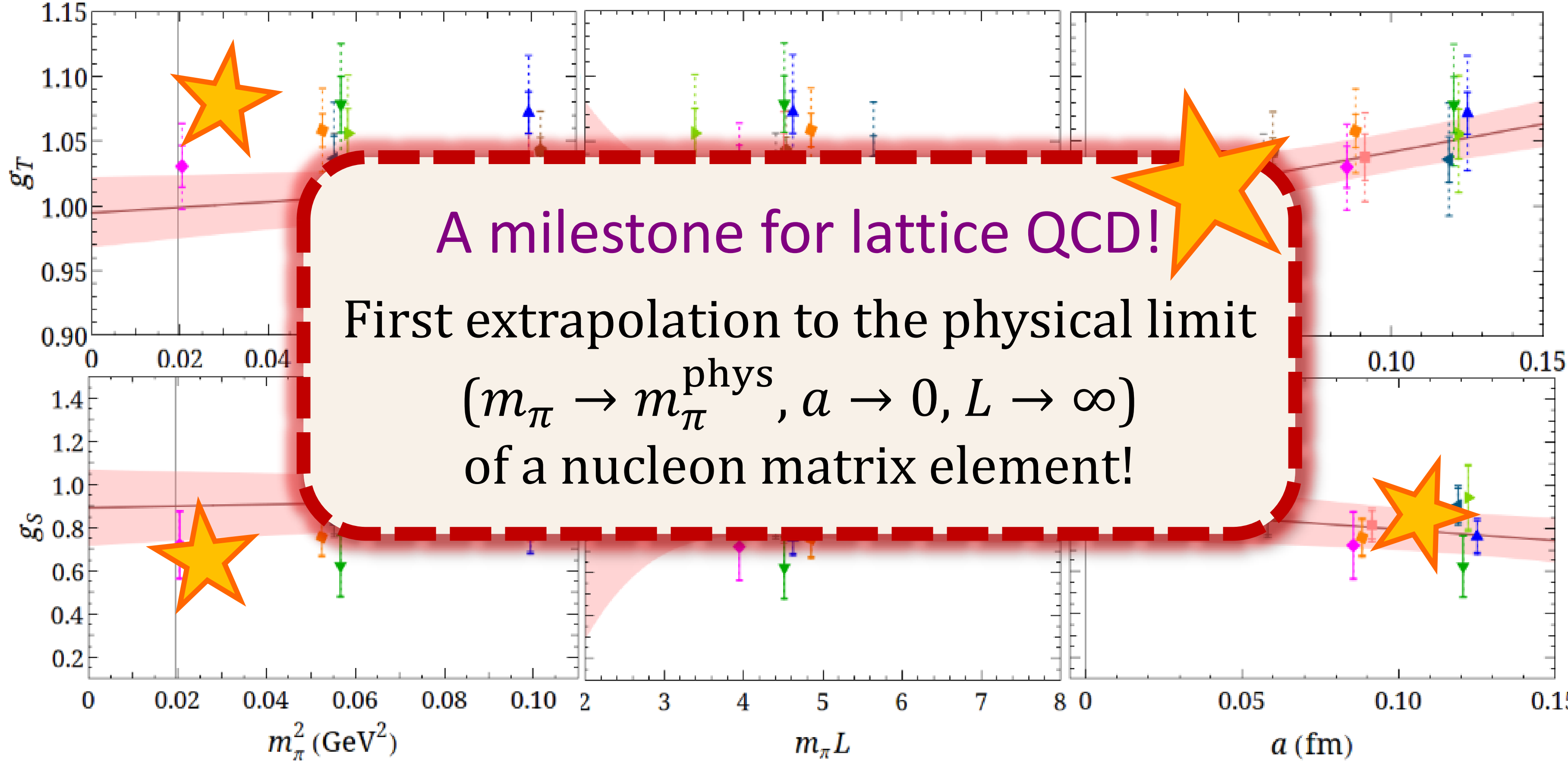


A milestone for lattice QCD!

First extrapolation to the physical limit $(m_\pi \to m_\pi^{\text{phys}}, a \to 0, L \to \infty)$ of a nucleon matrix element!

Precision Nucleon Couplings

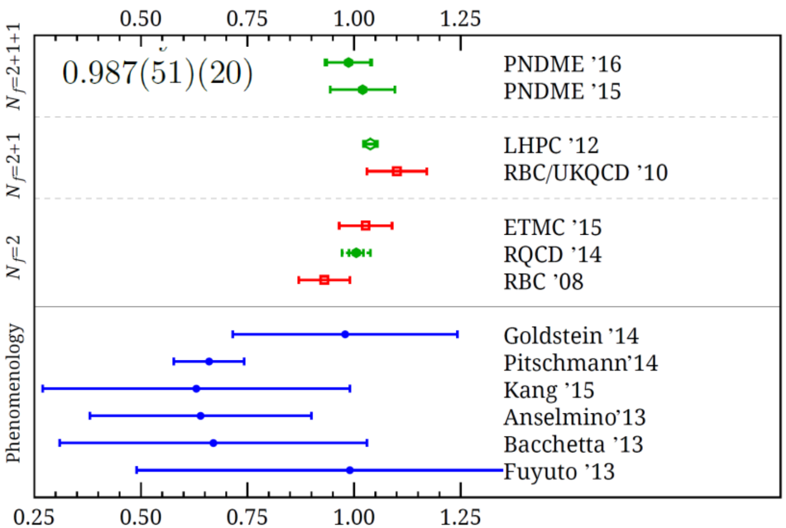
FLAG rating system

PNDME, 1506.06411; 1606.07049

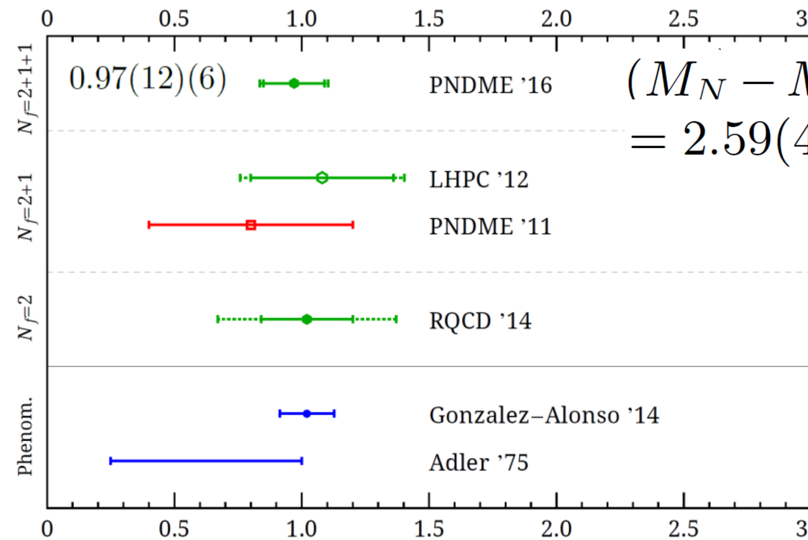
New: excited-state rating

Collaboration	Ref.	publication status	N_f	chiral extrapolation	continuum extrapolation	finite volume	excited state	renormalization	g_T
PNDME'15	This work	P	2+1+1	★	★	★	★	★	1.020(76)[a]
ETMC'13	[30]	C	2+1+1	■	○	○	■	★	1.11(3)[b]
LHPC'12	[28]	A	2+1	★	○	★	○	★	1.037(20)[c]
RBC/UKQCD'10	[29]	A	2+1	○	■	★	★	★	1.10(7)[d]
RQCD'14	[31]	P	2	★	★	★	○	★	1.005(17)(29))[e]
ETMC'13	[30]	C	2	★	■	○	■	○	1.114(46)[f]
RBC'08	[32]	P	2	■	■	★	■	★	0.93(6)[g]

g_T



g_S



$$(M_N - M_P)^{\text{QCD}} = 2.59(49)\ \text{MeV}$$

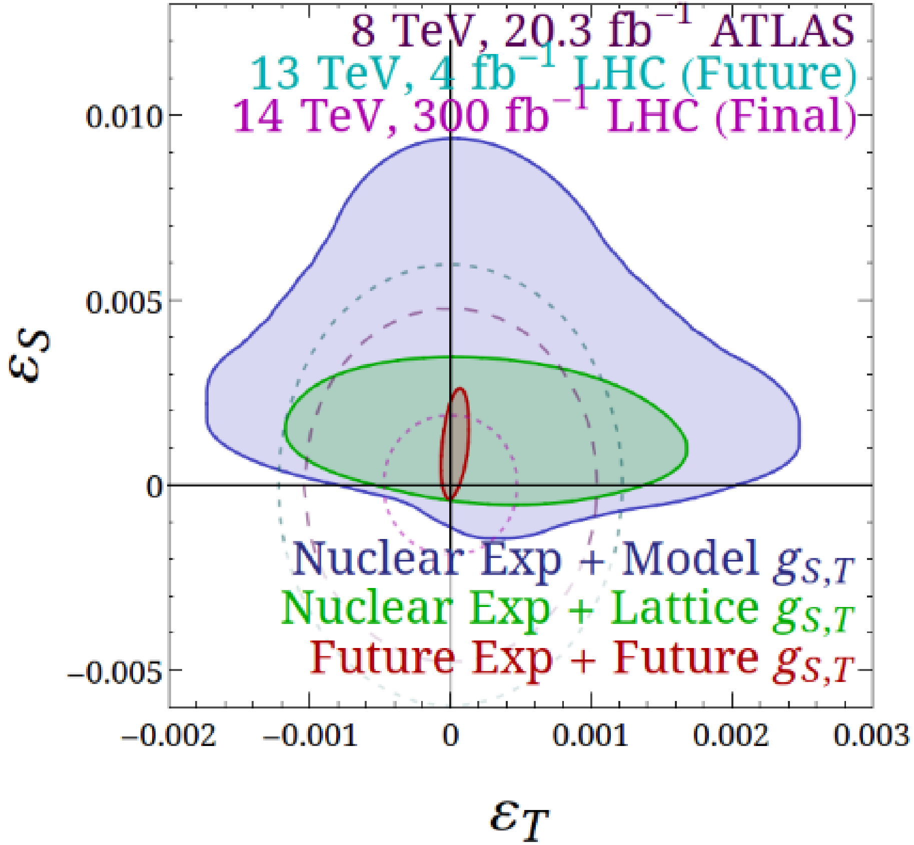
Beta Decays & BSM

§ Given precision $g_{S,T}$ and O_{BSM}, predict new-physics scales

Low-Energy Expt

$$O_{\mathrm{BSM}} = f_O(\varepsilon_{S,T}\, g_{S,T})$$

Precision LQCD input ($m_\pi \to 140$ MeV, $a \to 0$)



$$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$$

Upcoming precision low-energy experiments

LANL/ ORNL UCN neutron decay exp't

$|B_1 - b|_{\mathrm{BSM}} < 10^{-3}$

$|b|_{\mathrm{BSM}} < 10^{-3}$

CENPA: ^{6}He(b_{GT}) at 10^{-3}

PNDME, PRD85 054512 (2012); 1306.5435; 1606.07049

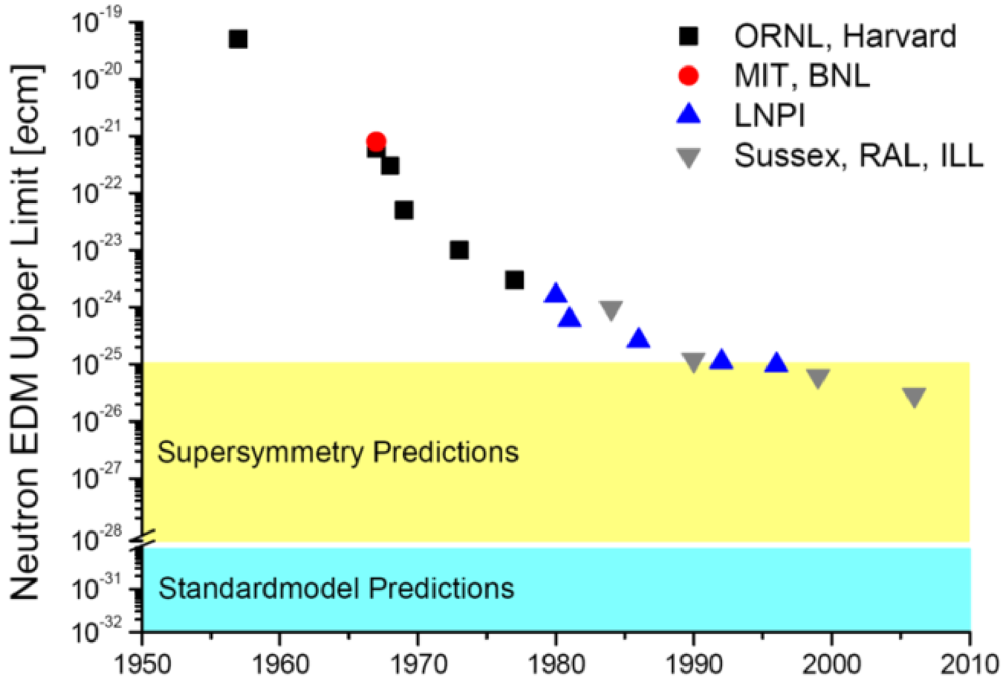
$\Lambda_S > 7$ TeV

$\Lambda_T > 13$ TeV

Electric Dipole Moment

§ Why do we care?

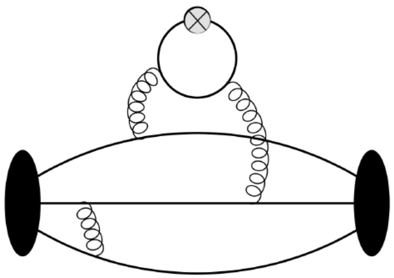
- CP-violating effect ⇒ Key ingredient for baryogenesis
  ⇒ Why matter exists
- Extremely small in SM: ≈ 10^{-31} e-cm (expect to probe 10^{-28} soon)
- Good candidate to constrain BSM models



Electric Dipole Moment

§ Quark EDM (d_q) in nucleon comes from

$$d_N = d_u g_T^{(n,u)} + d_d g_T^{(n,d)} + d_s g_T^{(n,s)}$$



- Hadronic contribution: $\langle N|\bar{q}\sigma_{\mu\nu}q|N\rangle$, $q \in \{u, d, s\}$
- Need "disconnected" diagram contributions

§ Extrapolate to the continuum limit PNDME, 1506.04196; 1506.06411

$$g_T^u = 0.774(66),\ g_T^d = -0.233(28),\ g_T^s = 0.008(9)$$

§ Implications for new physics?

Wells, 2003;
Arkani-Hamed and Dimopoulos, 2004;
Giudice and Romanino, 2004

- Take split SUSY for example
- Using our lattice inputs, we can derive an upper limit for the neutron EDM in split SUSY

$$|d_n| < 4 \times 10^{-28} e\cdot\mathrm{cm}$$

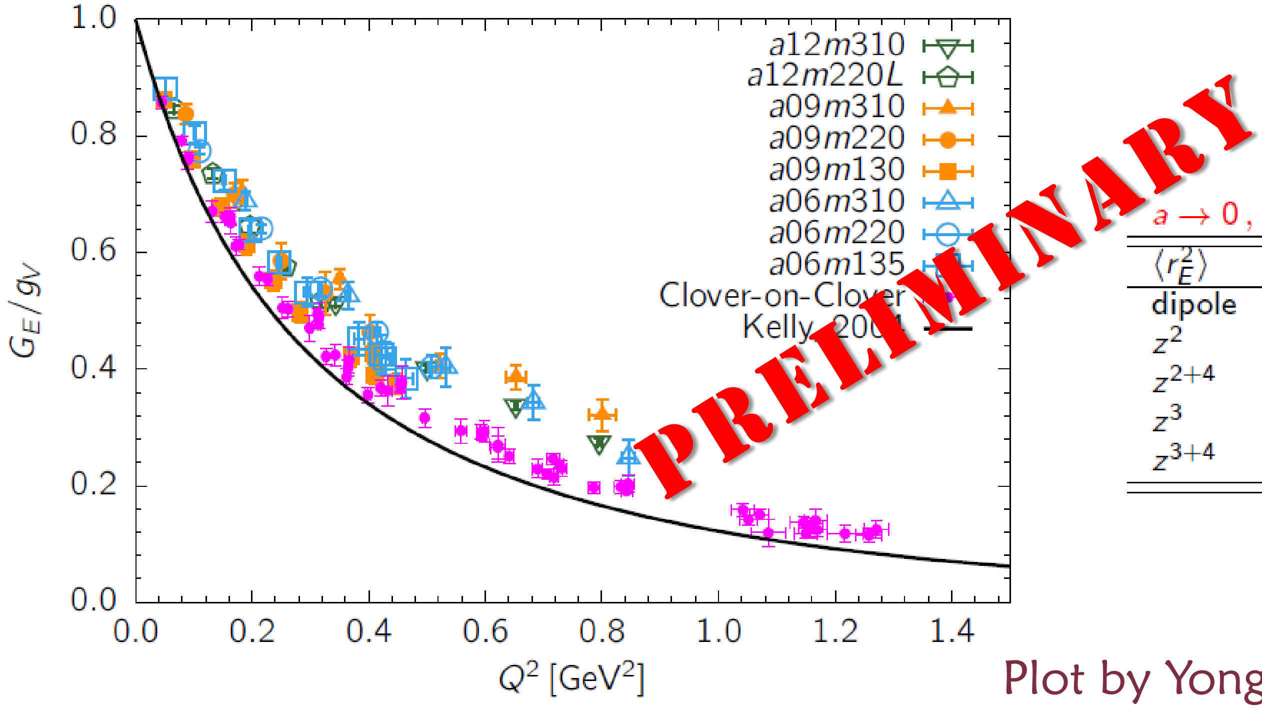
using $|d_e| < 8.7 \times 10^{-29} e\cdot\mathrm{cm}$ with 90% confidence

ACME Coll., Science Vol. 343 no. 6168 pp. 269-272 (2014)

EM Form Factors

§ Electromagnetic form factor and nucleon isovector radius

- $\langle N(\vec{p}_f)|V_\mu(\vec{q})|N(\vec{p}_i)\rangle = \bar{u}(\vec{p}_f)\left[F_1(Q^2)\gamma_\mu + \sigma_{\mu\nu}q_\nu \frac{F_2(Q^2)}{2M}\right]u(\vec{p}_i)$
  - $G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4M^2}F_2(Q^2)$
  - $G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$



$a \to 0$, $M_\pi \to 135$ MeV extrapolation

$\langle r_E^2 \rangle$	with FV	without FV
dipole	0.53(03)	0.55(02)
z^2	0.61(05)	0.63(04)
z^{2+4}	0.60(07)	0.61(06)
z^3	0.72(09)	0.71(07)
z^{3+4}	0.88(13)	0.89(11)

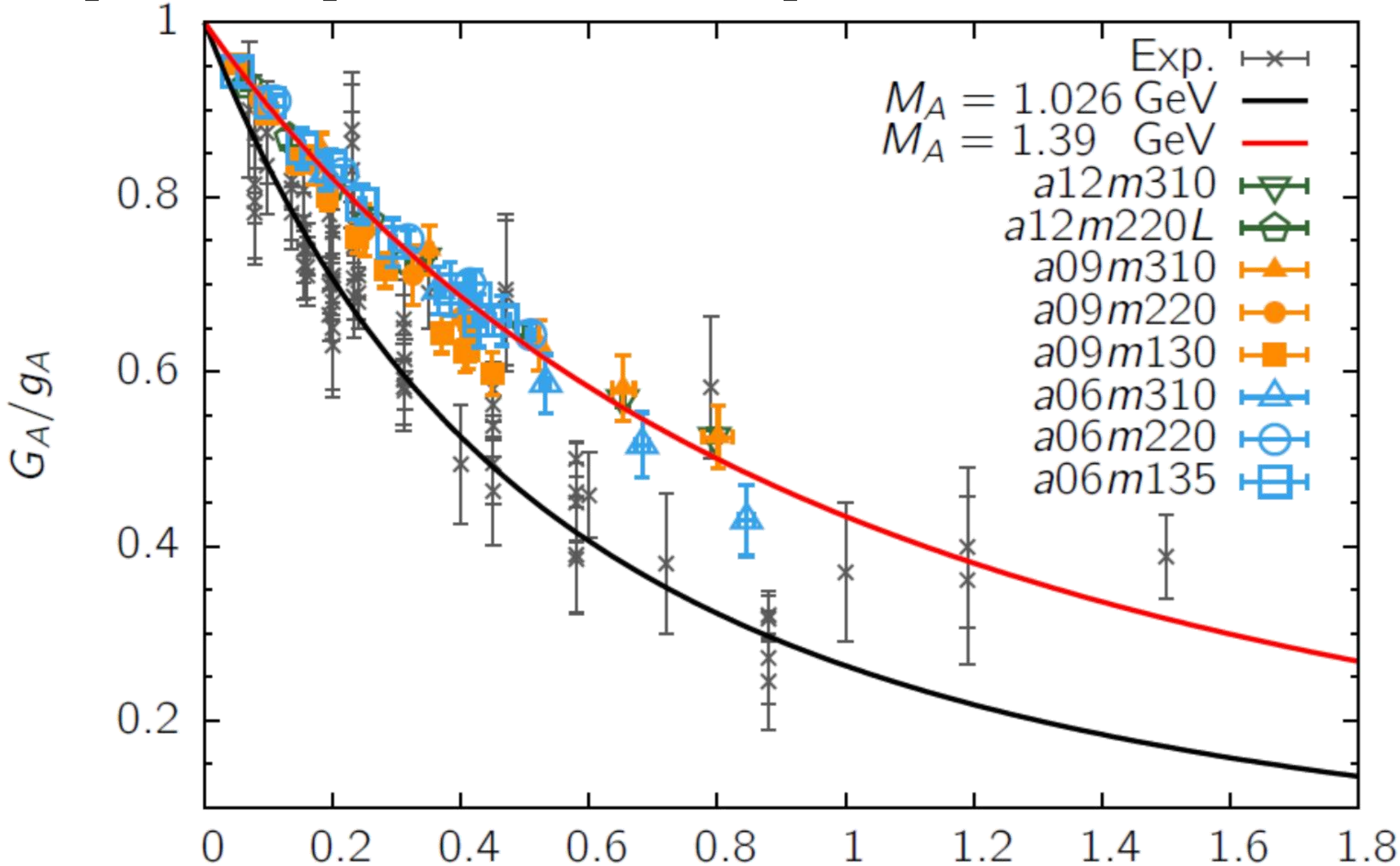
Plot by Yong-Chull Jang (PNDME)

Axial Form Factors

§ Axial form factor

PNDME, 1705.06834

- $\langle N(\vec{p}_f)|A_\mu(\vec{Q})|N(\vec{p}_i)\rangle = \bar{u}(\vec{p}_f)\left[G_A(Q^2)\gamma_\mu + q_\mu \frac{\tilde{G}_P(Q^2)}{2M_N}\right]\gamma_5 u(\vec{p}_i)$
- Important input for neutrino experiments, such as DUNE



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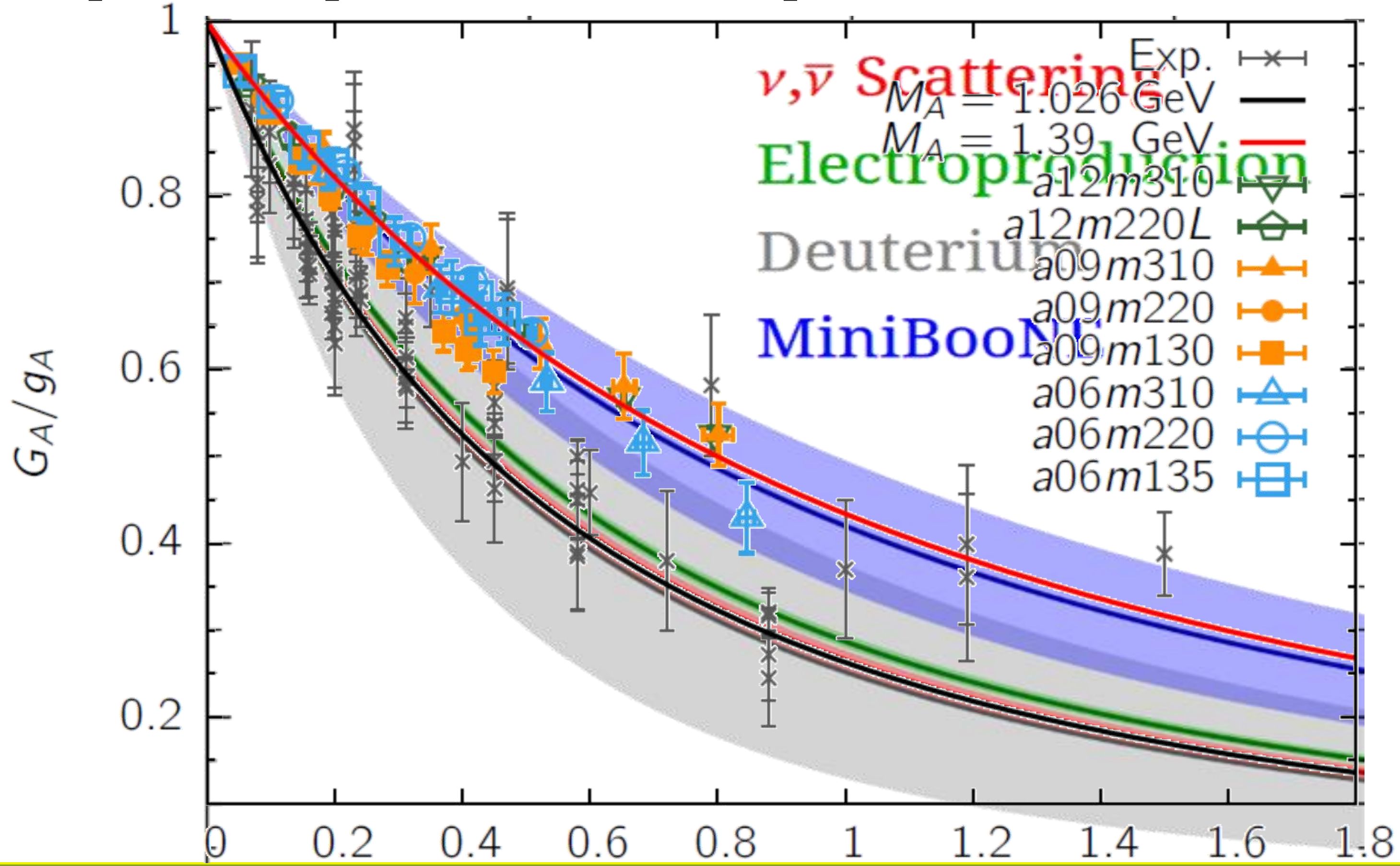


Lattice Pioneer Frontier

Xiangdong Ji, Phys. Rev. Lett. 111, 039103 (2013)

"Flavor Structure of the Nucleon Sea from Lattice QCD",
PRD 91, 054510 [arXiv:1402.1462]

"Nucleon Helicity and Transversity Parton Distributions from Lattice QCD",
to be appeared in Frontier Article in Nuclear Physics B,
[arXiv:1603.06664]

PDFs on the Lattice

Long existing obstacles!

§ Lattice calculations rely on operator product expansion,

only pr… $\int_{-1}^{1} dx\, x^{n-1} q(x)$

§ For highe… …imension ops

- No practi…

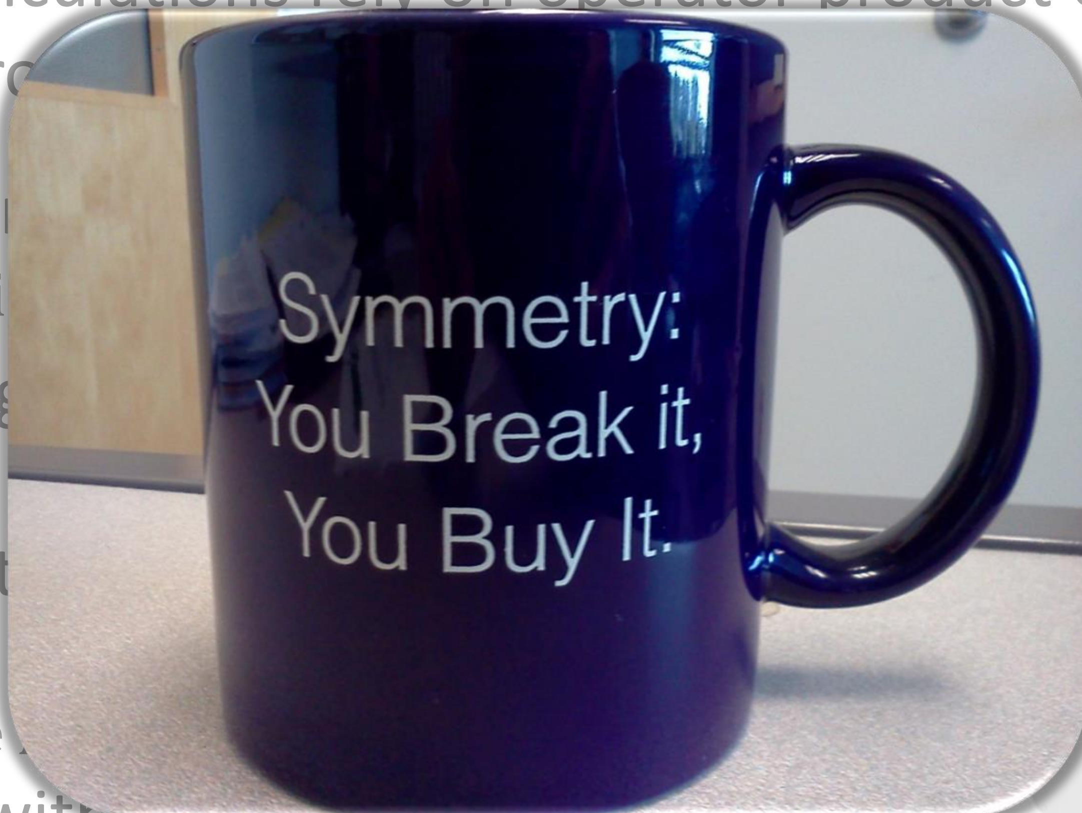
New Strate…

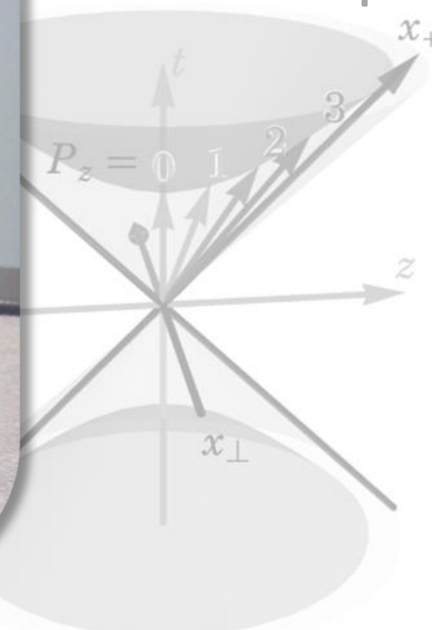
§ Calculate …

quark dist…

- In $P_z \to \infty$ …
- For finite …

§ Feasible with today's resources!





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$$\langle x^n \rangle_q = \int_{-1}^{1} dx\, x^n q(x)$$

§ For higher moments, all ops mix with lower-dimension ops

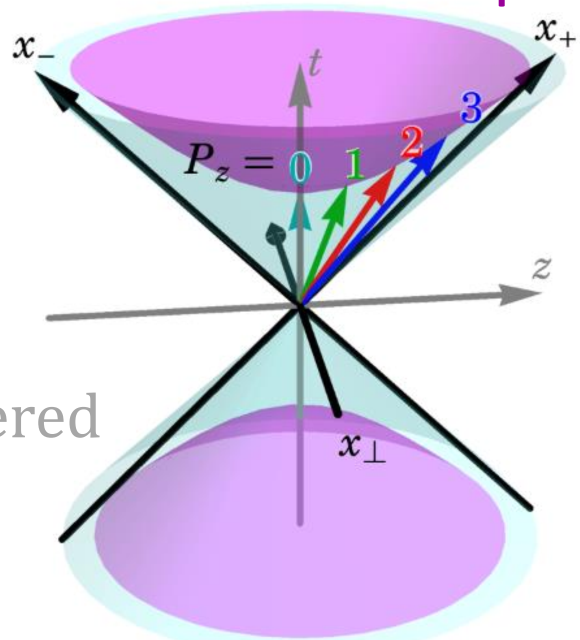
- No practical proposal to overcome this

New Strategy (LaMET):

§ Calculate finite-momentum boosted quark distribution

- In $P_z \to \infty$ limit, parton distribution is recovered
- For finite P_z, corrections are needed

§ Feasible with today's resources!



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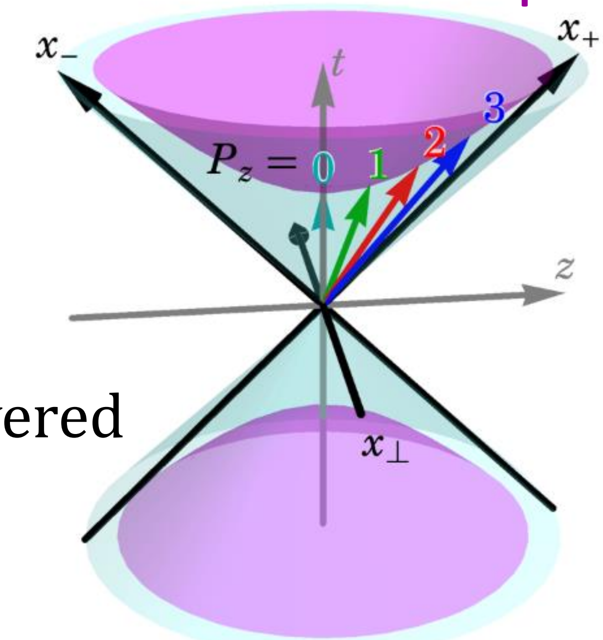

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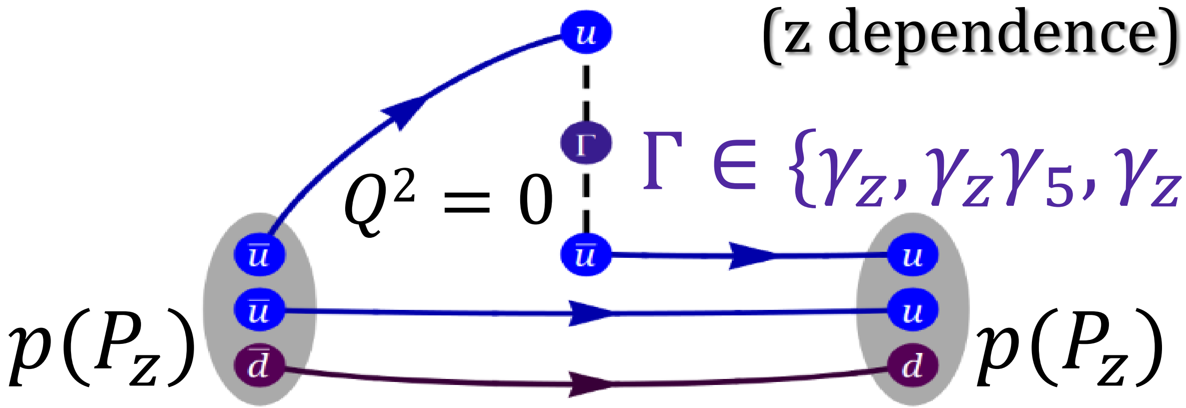
Xiangdong Ji, Phys. Rev. Lett. 111, 039103 (2013)

A New Direction

Large-Momentum Effective Theory for PDFs

1) Calculate nucleon matrix elements on the lattice

(z dependence)



$\Gamma \in \{\gamma_z, \gamma_z\gamma_5, \gamma_z\gamma_\perp\gamma_5\}$

2) Compute quasi-distribution via

$$\tilde{q}(x,\mu,P_z) = \int \frac{dz}{4\pi} e^{-izk_z} \left\langle P \middle| \bar{\psi}(z)\, \Gamma \exp\left(-ig\int_0^z dz'\, A_z(z')\right) \psi(0) \middle| P \right\rangle$$

3) Recover true distribution (take $P_z \to \infty$ limit)

$$q(x,\mu) = \tilde{q}(x,\mu,P_z) + \mathcal{O}(\alpha_s) + \mathcal{O}(M_N^2/P_z^2) + \mathcal{O}\left(\Lambda_{\mathrm{QCD}}^2/P_z^2\right)$$

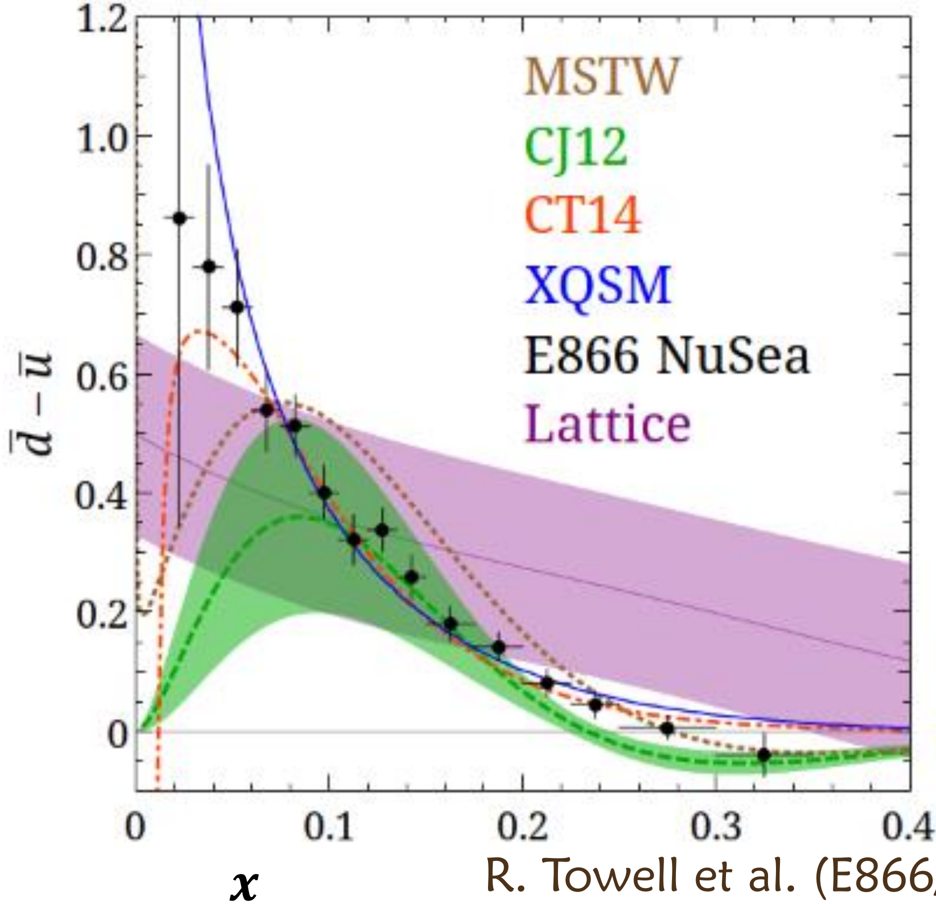
X. Xiong et al., 1310.7471; J.-W. Chen et al, 1603.06664

Sea Flavor Asymmetry

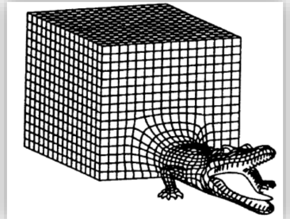
§ First time in LQCD history to study antiquark distribution!

- $M_\pi \approx 310$ MeV

HWL et al. 1402.1462



$$\bar{q}(x) = -q(-x)$$



Lost resolution in small-x region

Future improvement:
 larger lattice volume

$$\int dx\,\left(\bar{u}(x) - \bar{d}(x)\right) \approx -0.16(7)$$

Experiment	x range	$\int_0^1[\overline{d}(x)-\overline{u}(x)]dx$
E866	$0.015<x<0.35$	0.118 ± 0.012
NMC	$0.004<x<0.80$	0.148 ± 0.039
HERMES	$0.020<x<0.30$	0.16 ± 0.03

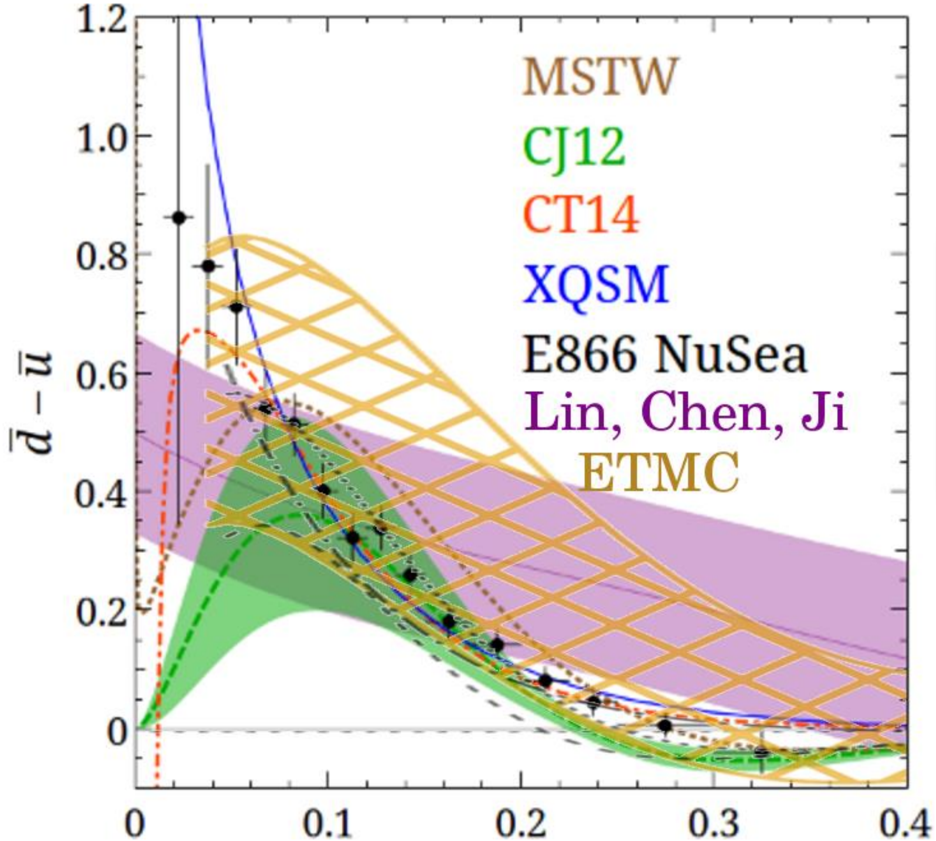
R. Towell et al. (E866/NuSea), Phys.Rev. D64, 052002 (2001)

Sea Flavor Asymmetry

§ Lattice exploratory study

- $M_\pi \approx 310$ MeV

HWL et al 1402.1462



Compared with E866

Too good to be true?

Lost resolution in small-x region

Similar results repeated by ETMC, at $M_\pi \approx 373$ MeV

ETMC, 1504.07455

(7)

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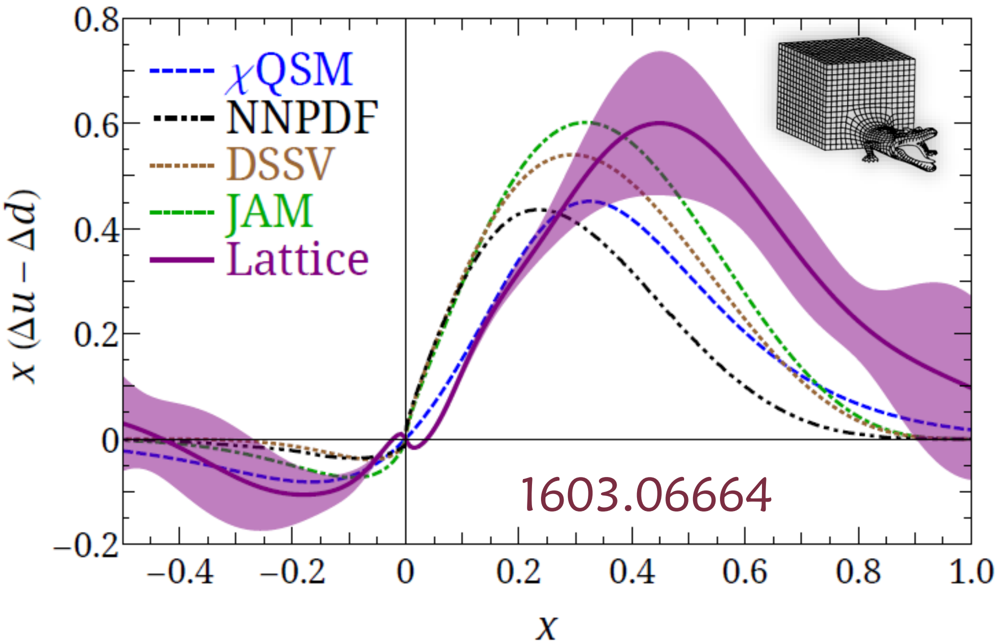
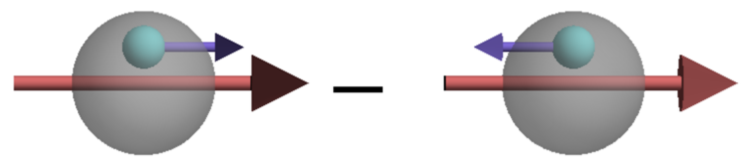
Helicity Distribution

§ Exploratory study ☙ $M_\pi \approx 310$ MeV





Removing
$O(M_N^n/P_z^n)$ errors + $O(\alpha_s)$
+ $O(\Lambda_{\mathrm{QCD}}^2/P_z^2)$

☙ We see polarized "sea asymmetry" $\int dx\left(\Delta\bar{u}(x) - \Delta\bar{d}(x)\right) \approx 0.14(9)$

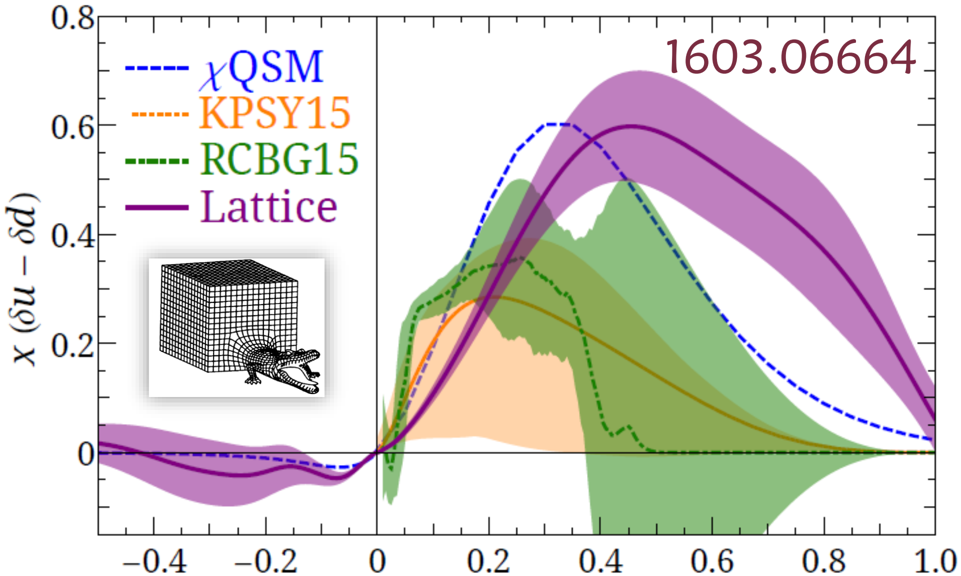
☙ Both STAR and PHENIX at RHIC see $\Delta\bar{u} > \Delta\bar{d}$

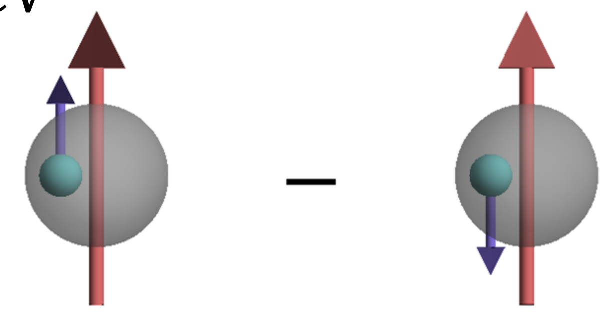
1404.6880 and 1504.07451

☙ Other experiments, Fermilab DY exp'ts (E1027/E1039), future EIC

Transversity Distribution

§ Exploratory study ☙ $M_\pi \approx 310$ MeV





Removing $O(M_N^n/P_z^n)$ errors + $O(\alpha_s)$ + $O(\Lambda_{\mathrm{QCD}}^2/P_z^2)$

$\delta\bar{q}(x) = -\delta q(-x)$ 1505.05589; 1503.03495

☙ We found sea asymmetry of $\int dx\,(\delta\bar{u}(x) - \delta\bar{d}(x)) \approx -0.10(8)$

☙ Chiral quark-soliton model $\int dx\,(\delta\bar{u}(x) - \delta\bar{d}(x)) \approx -0.082$

P. Schweitzer et al., PRD 64, 034013 (2001)

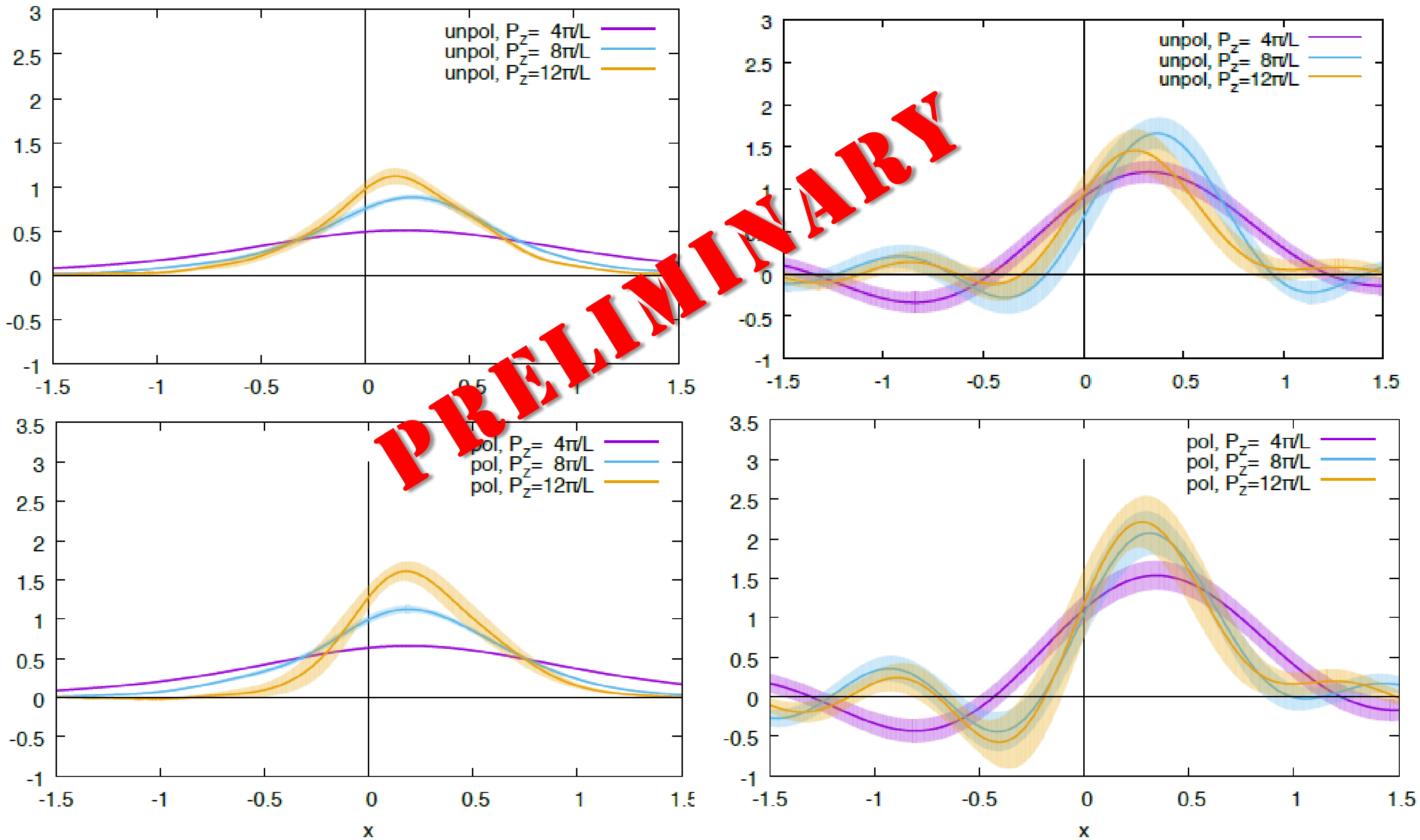
☙ SoLID at JLab, Drell-Yan exp't at FNAL (E1027+E1039), EIC, ...

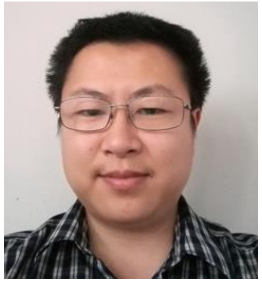
Physical Pion Mass

§ Preliminary results

$M_\pi \approx$ **135 MeV**, $a \approx$ **0.09 fm**

Bare | RI/MOM renormalized





Yi-Bo Yang (MSU)

A NEW HOPE

It is a period of war and economic uncertainty.

Turmoil has engulfed the galactic republics.

Basic truths at foundation of the human civilization are disputed by the dark forces of the evil empire.

A small group of QCD Knights from United Federation of Physicists has gathered in a remote location on the third planet of a star called Sol on the inner edge of the Orion–Cygnus arm of the galaxy.

The QCD Knights are the only ones who can tame the power of the Strong Force, responsible for holding atomic nuclei together, for giving mass and shape to matter in the Universe.

They carry secret plans to build the most powerful

Summary & Outlook

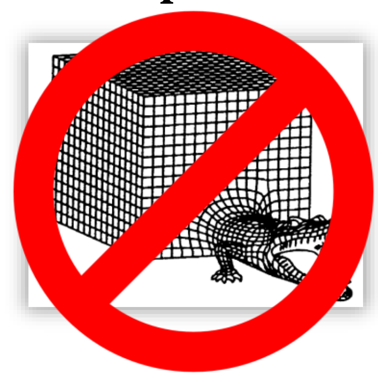
Exciting era for studying structure on the lattice

§ We are entering the precision era for charges

- More nucleon matrix elements with physical pion masses
- Well-studied systematics → precision inputs

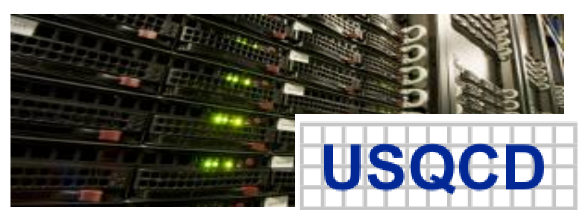
§ Overcoming longstanding obstacle to full x-distribution

- Most importantly, this can be done with today's computer
- First lattice approach to study sea asymmetry



§ Systematics, systematics, systematics…

- Working on **renormalization**,
  statistics, physical pion mass,
  finer lattice-spacing ensembles, …



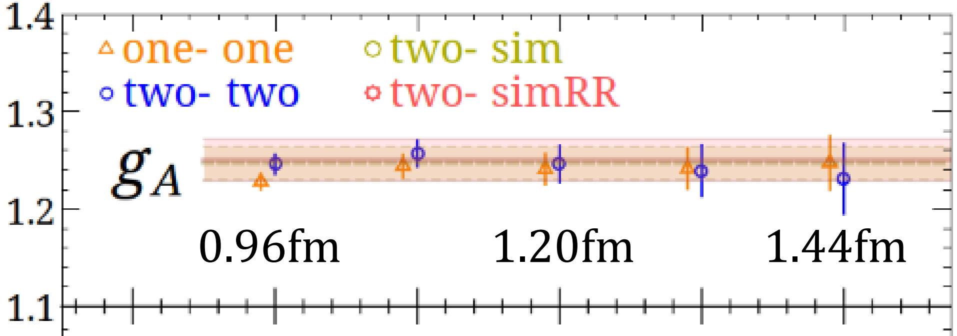
Backup Slides

Approaching the Continuum

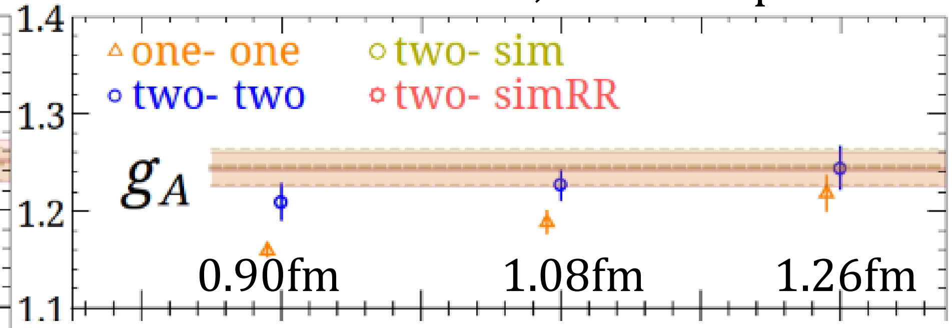
§ Worse excited-state contamination

PNDME, 1606.07049

a = 0.12 fm, 310-MeV pion

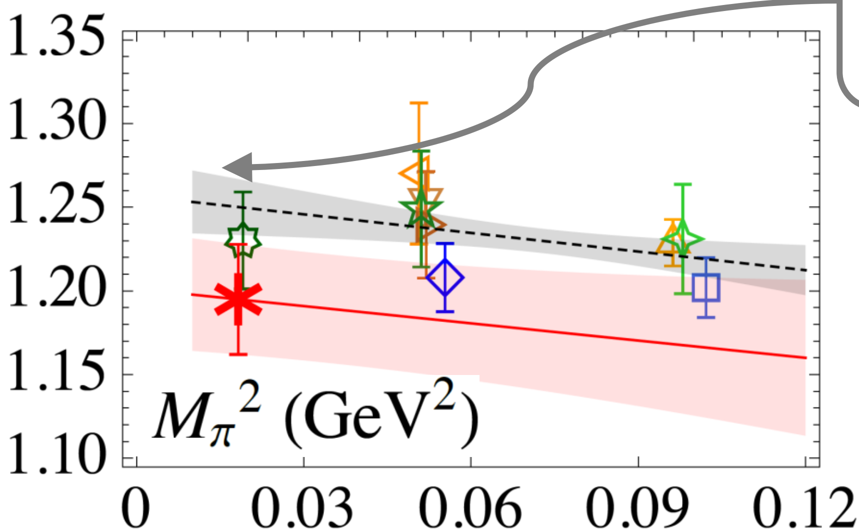


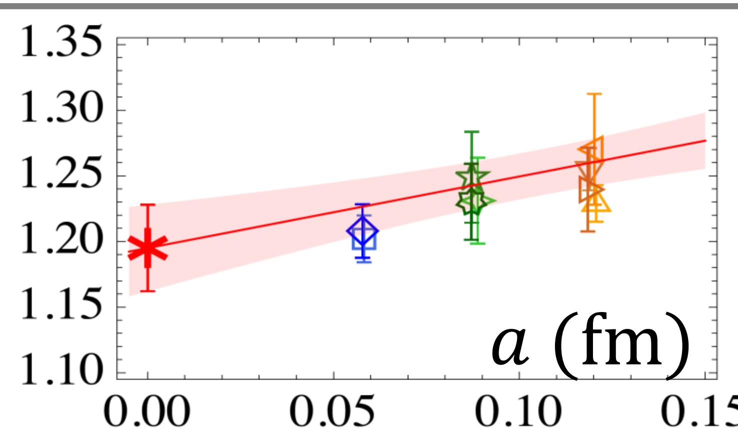
a = 0.09 fm, 310-MeV pion



§ Smaller g_A extrapolation

Higher extrapolation of g_A assumes no lattice-spacing dependence
(how people get consistency with exp. g_A)





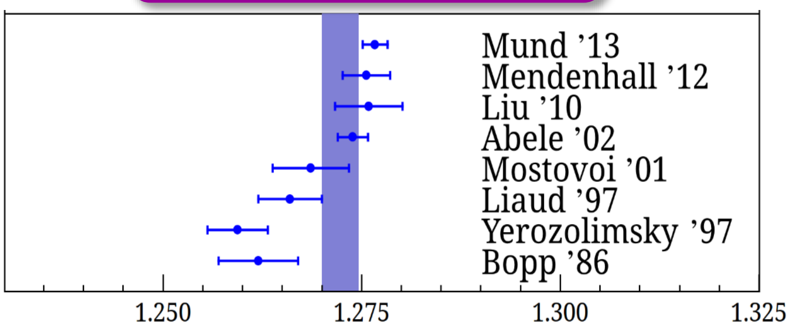
Nucleon Axial Charge

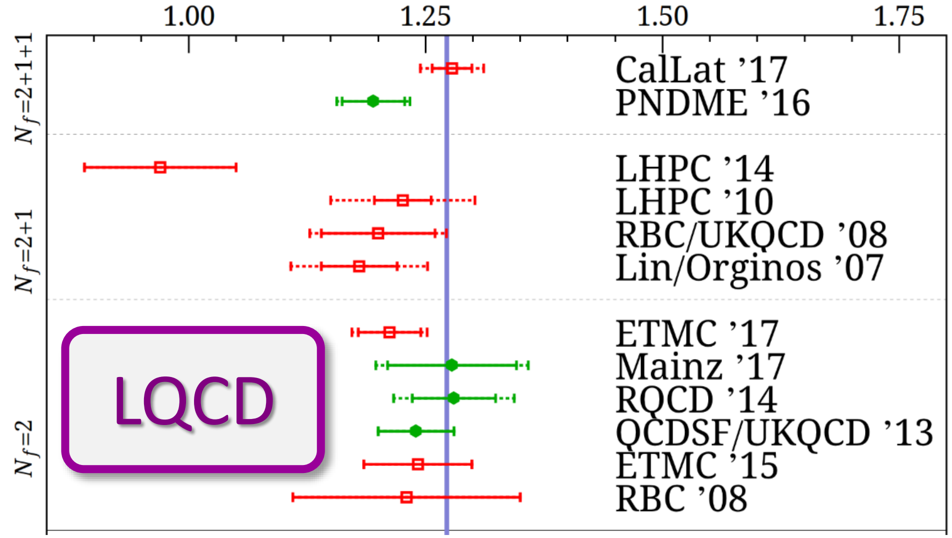
FLAG-like rating system
New: excited-state rating

White paper in progress with representatives from each collaboration

Ref.	N_f	P.S.	Lattice sp.	Quark mass	Finite Vol.	Renorm.	Excited St.
CalLat '17 [2]	2+1+1	PreP	■	★	★	★	★
PNDME '16 [3]	2+1+1	P	○	★	★	★	★
LHPC '14 [4]	2+1	P	■	★	★	★	★
Mainz '17 [5]	2	PreP	★	○	★	★	★
ETMC '17 [6]	2	PreP	■	★	○	★	★
RQCD '15 [7]	2	P	○				

Neutrino Exp't



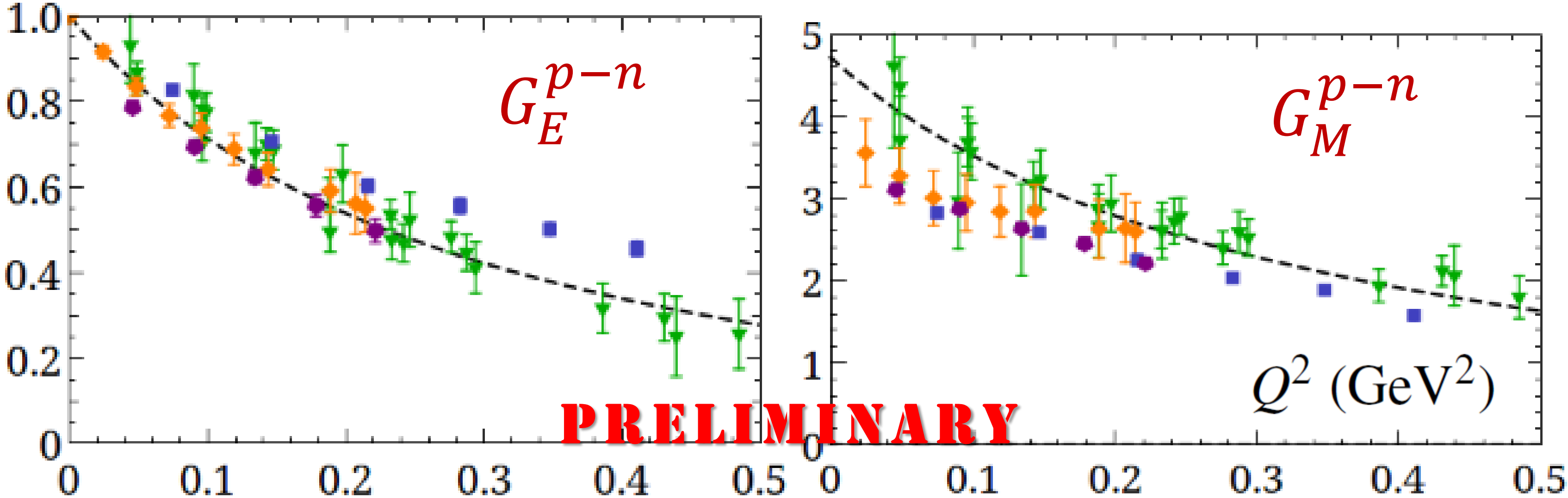


§ New physics?

- Crucial to have independent/unbiased g_A from LQCD, $\lambda_{\text{exp}} = g_A/g_V\, f_{\text{New Physics}}$

Form Factors

- EM form factors very close to physical pion mass
  - PNDME (2+1+1f): $M_\pi = 130$ MeV, $a = 0.09$fm, $M_\pi L = 3.9$, 2-state, 56K
  - ETMC (2f): $M_\pi = 131$ MeV, $a = 0.09$fm, $M_\pi L = 3$, $t_{sep} = 1.3$fm, O(10K)?
  - LHPC (2+1f): $M_\pi = 149$ MeV, a = 0.12 fm, $M_\pi L = 4.2$, sum., O(7K)
  - PACS (2+1f): $M_\pi = 145$ MeV, $a = 0.085$ fm, $M_\pi L = 6$, $t_{sep} = 1.3$fm, O(9K)



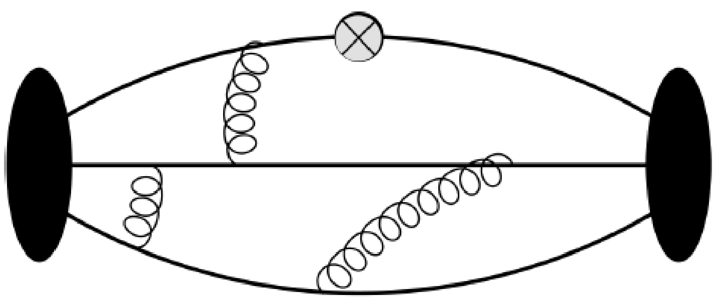
- Expecting more precise results in the next couple years
- New way of calculating form factors

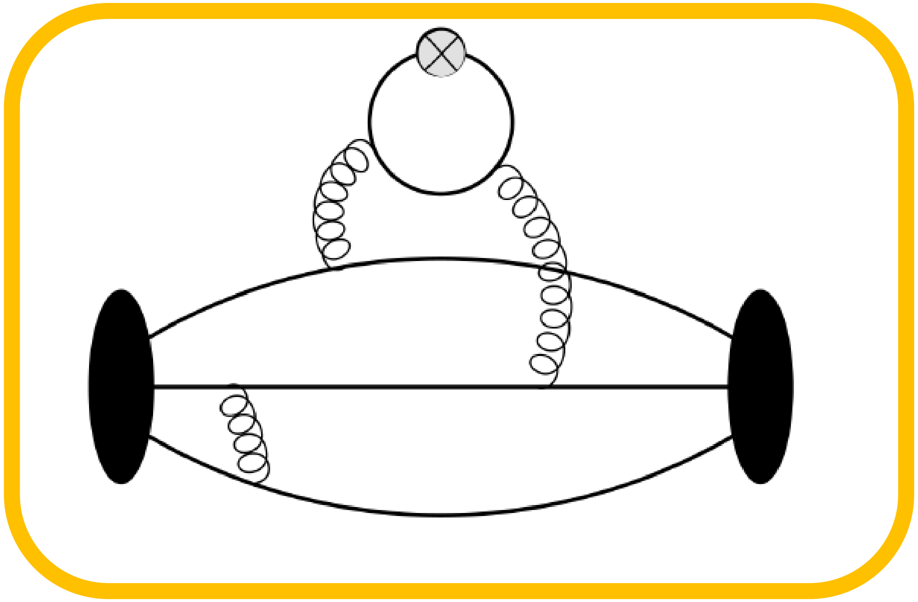
C. Chang, Tue. Lattice, "Form factors from moments of correlation functions"

Disconnected Diagrams

§ Disconnected diagram

- Multiple ways to calculate this notorious contribution…
- Truncated solver, hopping-parameter expansion, hierarchical probing, …





Strangeness

§ Importance of g_A^s

- Strange-quark intrinsic-spin contribution to proton
- Astrophysics application: the CCSN "problem"

  3D explosions require $g_A^s \approx -0.2$ Janka, Melson, & Summa (2016)

§ Global fit: $g_A^s \approx -0.1$

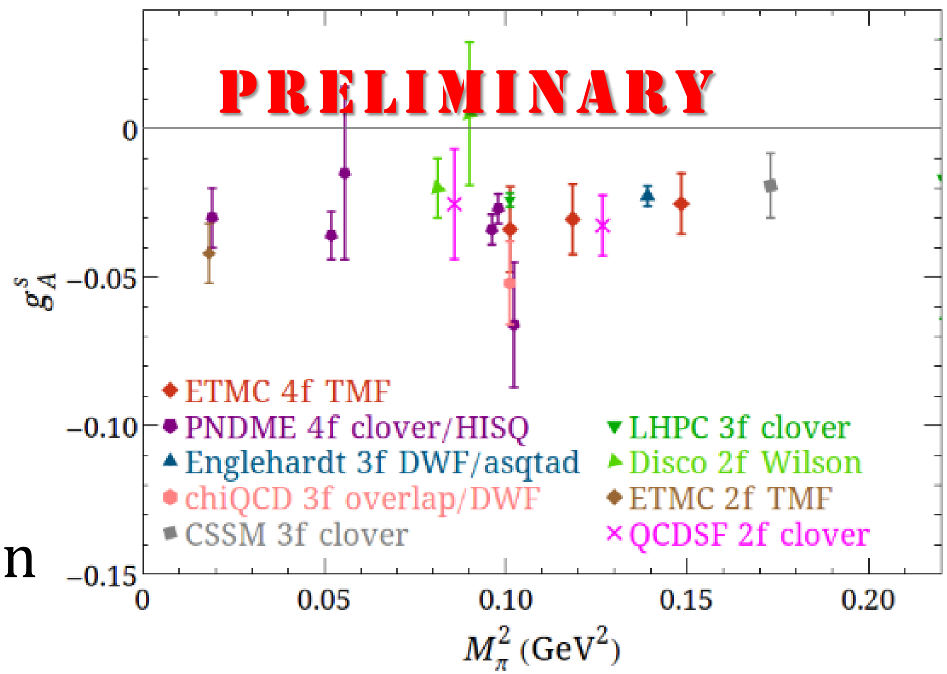
assumptions often used:

$$\Delta\bar{s}(x,Q^2) = \Delta\bar{u}(x,Q^2) = \Delta\bar{d}(x,Q^2) = \frac{1}{2}\Delta s^+(x,Q^2)$$

§ Lattice status

More players since the last Spin

Lighter pion masses

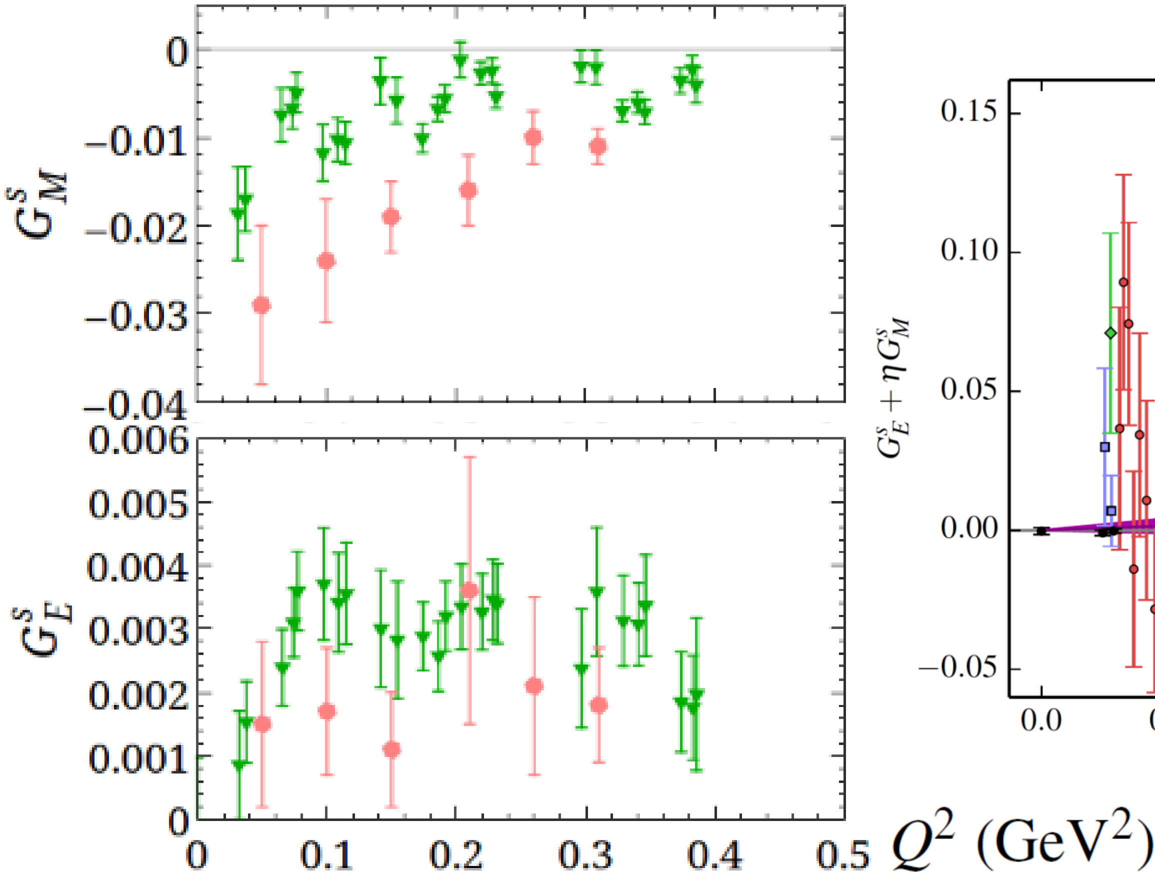


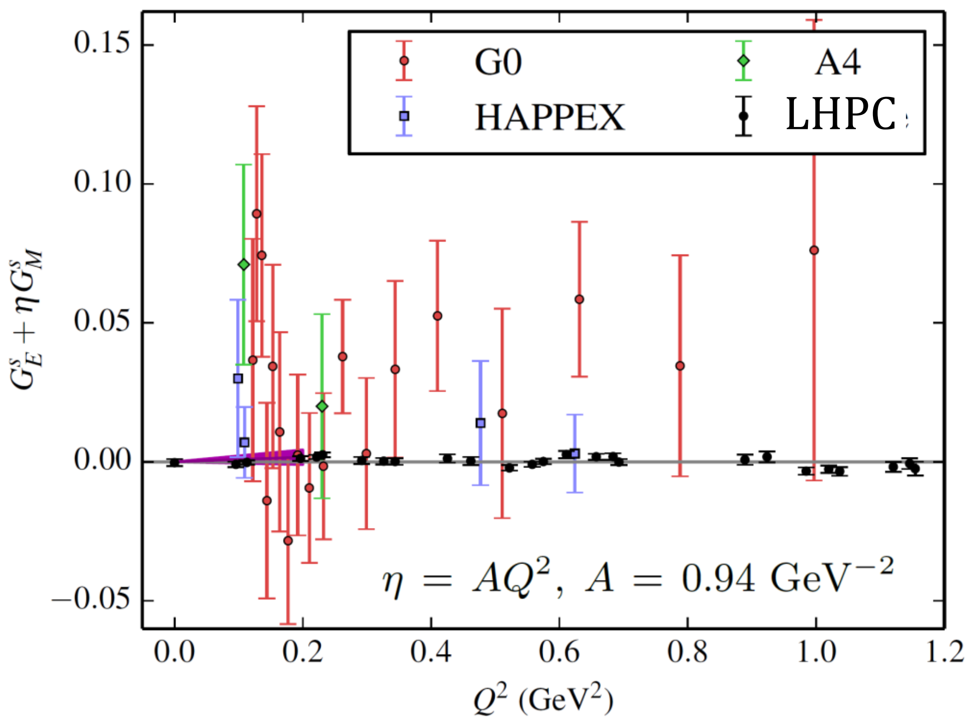
Strange Form Factors

K. Orginos/R. Sufian, Tue. Lattice

§ Better determined strange form factors

- LHPC (2+1f): clover $M_\pi = 317$ MeV, $a = 0.11$ fm
- χQCD (2+1f): ov/DWF $M_\pi = 207{,}140$ MeV, $a = 0.11$ fm



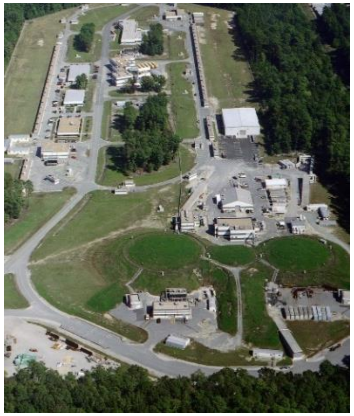


Parton Distribution Functions

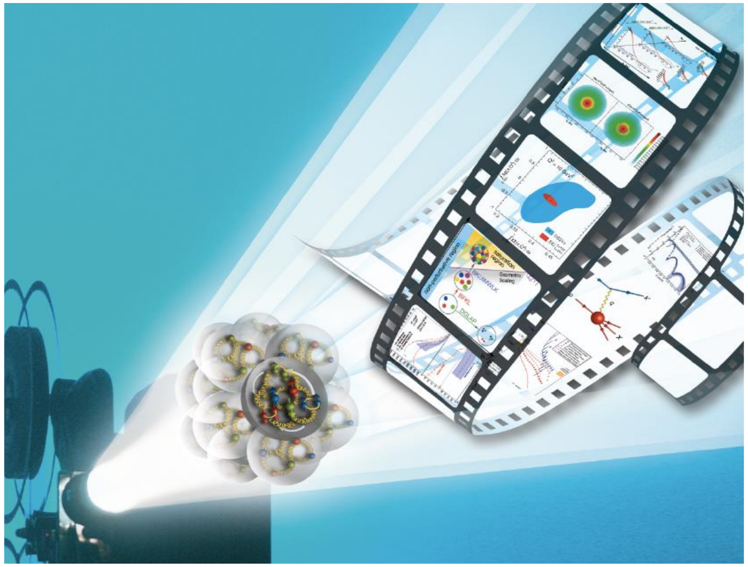
§ PDFs are universal quark/gluon distributions inside nucleon

- Many ongoing/planned experiments (BNL, JLab, J-PARC, COMPASS, GSI, EIC, LHeC, …)





Electron Ion Collider: The Next QCD Frontier



Imaging of the proton

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

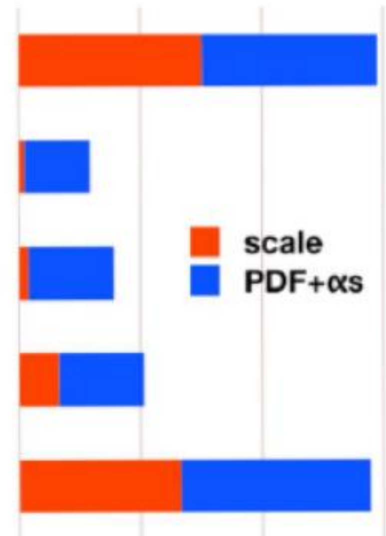
EIC White Paper, 1212.1701

Parton Distribution Functions

- PDFs are universal quark/gluon distributions inside nucleon
  - Many ongoing/planned experiments (BNL, JLab, J-PARC, COMPASS, GSI, EIC, LHeC, …)
- Important inputs to discern new physics at LHC
  - Currently dominate errors in Higgs production

HIGGS PRODUCTION

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
NNLO QCD +NLO EW	VBF	1.56 pb	2.9%
	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



(J. Campbell, HCP2012)

Global Analysis

§ Experiments cover diverse kinematics of parton variables

- Global analysis takes advantage of all data sets

Theory Input

Exp't Input

Global Analysis of PDFs

§ Some choices made for the analysis

- Choice of data sets and kinematic cuts
- Strong coupling constant $\alpha_s(M_Z)$
- How to parametrize the distribution

$$xf(x,\mu_0) = a_0 x^{a_1}(1-x)^{a_2}P(x)$$

- Assumptions imposed

  SU(3) flavor symmetry, charge symmetry, strange and sea distributions

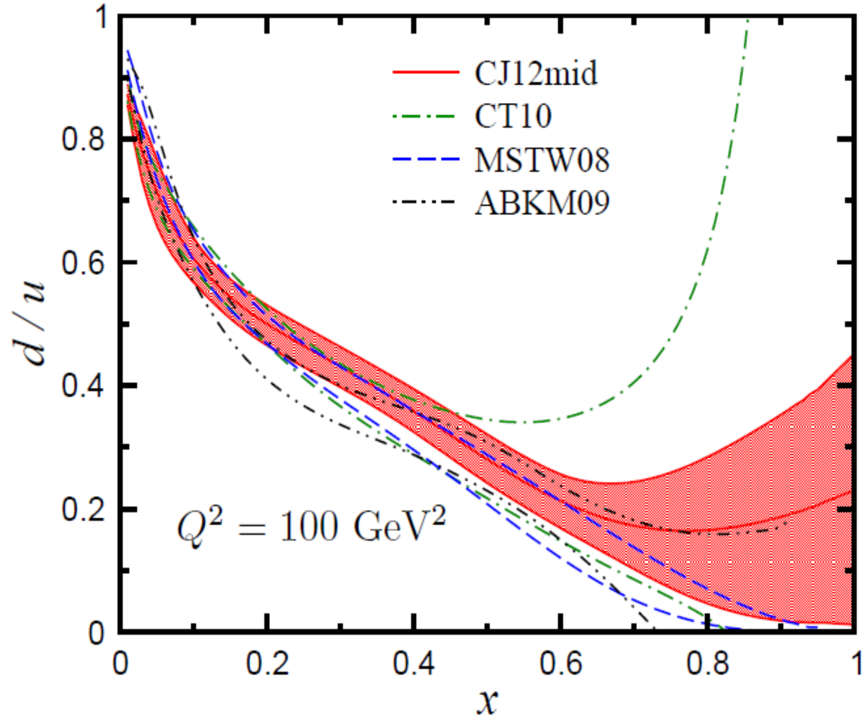
$$s = \bar{s} = \kappa(\bar{u} + \bar{d})$$

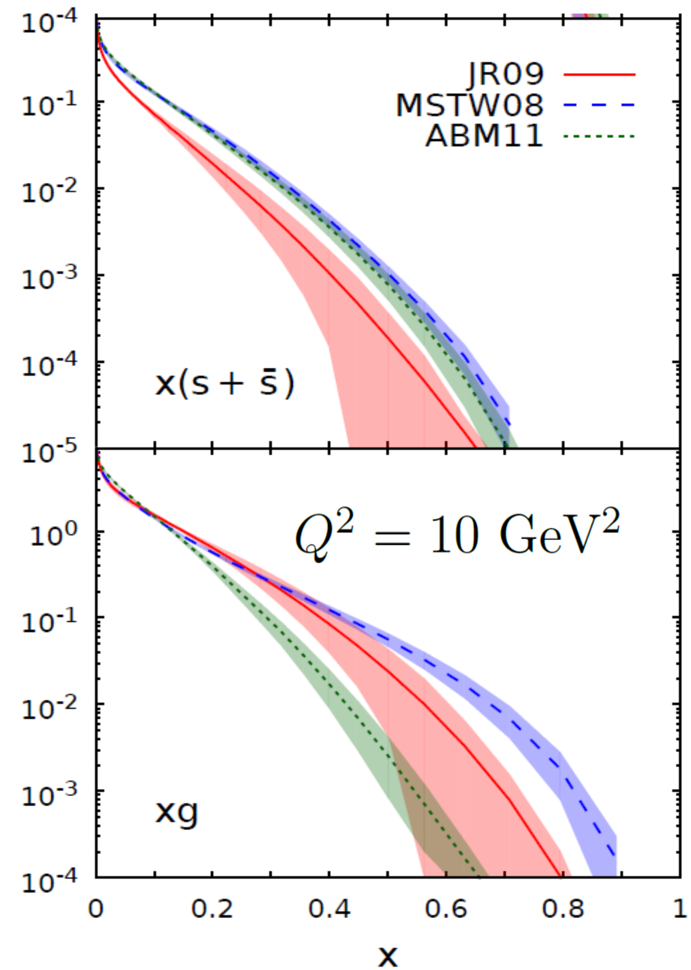
Global Analysis

§ Discrepancies appear when data is scarce

§ Many groups have tackled the analysis

- CTEQ, MSTW, ABM, JR, NNPDF, etc.





Jimenez-Delgado, Melnitchouk, Owens, J.Phys. G40 (2013) 09310

New Direction

Large-Momentum Effective Theory (LaMET)

X. Ji, PRL. 111, 262002 (2013)

Finite-P_z corrections needed

- Neglect typical lattice corrections for now:

$$\tilde{q}(x,\mu,P_z) = \int_{-\infty}^{\infty} \frac{dy}{|y|} Z\left(\frac{x}{y}, \frac{\mu}{P_z}\right) q(y,\mu) + \mathcal{O}(M_N^2/P_z^2) + \mathcal{O}\left(\Lambda_{\text{QCD}}^2/P_z^2\right)$$

Finite $P_z \leftrightarrow \infty$ perturbative matching

$$Z(x,\mu/P_z) = C\delta(x-1) - \frac{\alpha_s}{2\pi} Z^{(1)}(x,\mu/P_z)$$

Non-singlet case only

X. Xiong, X. Ji, J. Zhang, Y. Zhao, 1310.7471;

Ma and Qiu, 1404.6860

Dominant correction (for nucleon); known scaling form

HWL et al. 1402.1462

J.-W. Chen et al, 1603.06664

§ Benefit from our pQCD colleagues

New Direction

Large-Momentum Effective Theory (LaMET)

X. Ji, PRL. 111, 262002 (2013)

Finite-P_z corrections needed

- Neglect typical lattice corrections for now:

$$\tilde{q}(x,\mu,P_z) = \int_{-\infty}^{\infty} \frac{dy}{|y|} Z\left(\frac{x}{y}, \frac{\mu}{P_z}\right) q(y,\mu) + \mathcal{O}(M_N^2/P_z^2) + \mathcal{O}\left(\Lambda_{\mathrm{QCD}}^2/P_z^2\right)$$

complicated higher-twist operator;
smaller P_z correction for nucleon
J.-W. Chen et al, 1603.06664 and reference within
(extrapolate it away)

§ Some similarity to more broadly studied HQET…

$$O\left(\frac{m_b}{\Lambda}\right) = Z\left(\frac{m_b}{\Lambda}, \frac{\Lambda}{\mu}\right) o(\mu) + \mathcal{O}\left(\frac{1}{m_b}\right) + \cdots$$

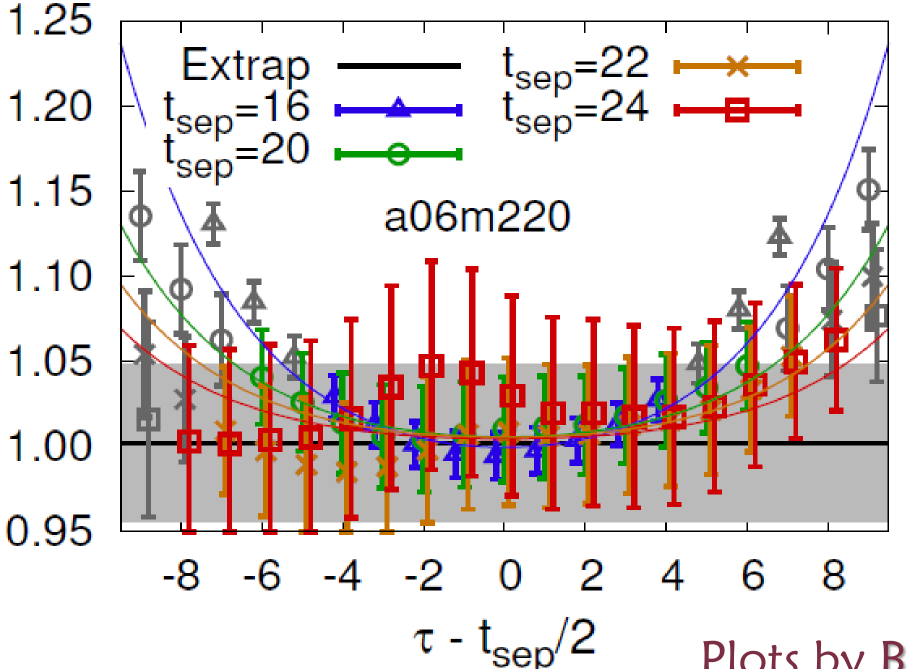
Systematic Control

- § Much effort has been devoted to controlling systematics
- § A state-of-the art calculation (PNDME)

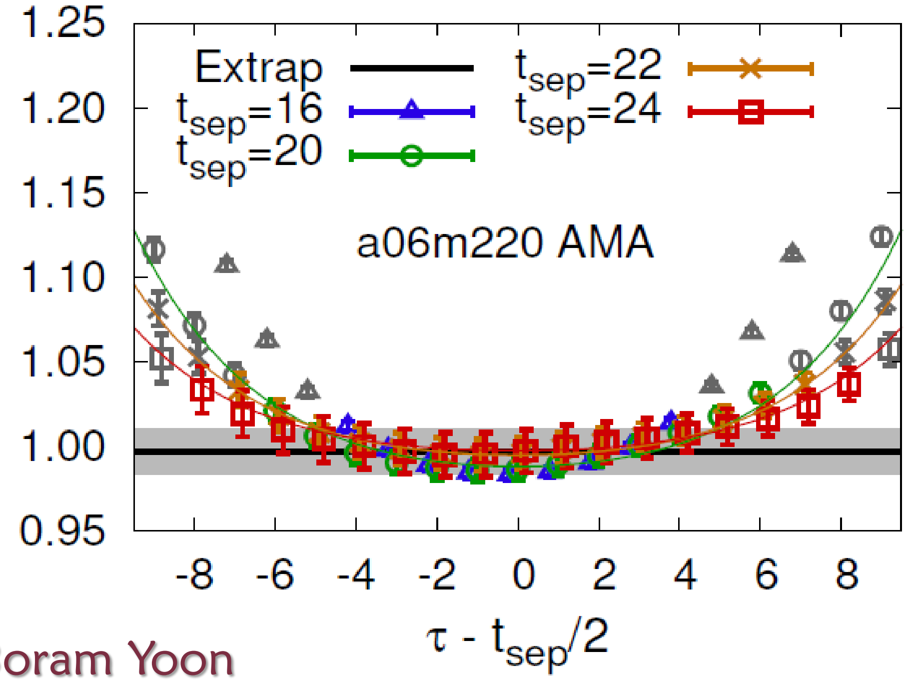
☙ Statistical effect $a = \mathbf{0.06\ fm}$, 220-MeV pion

g_T

2.6k



41.6k



Plots by Boram Yoon

Systematic Control

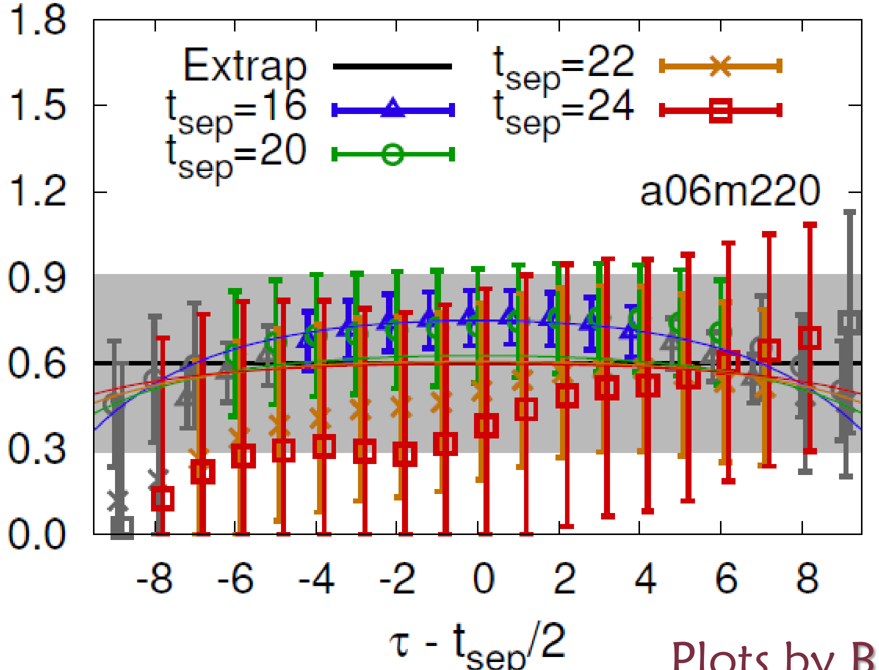
§ Much effort has been devoted to controlling systematics

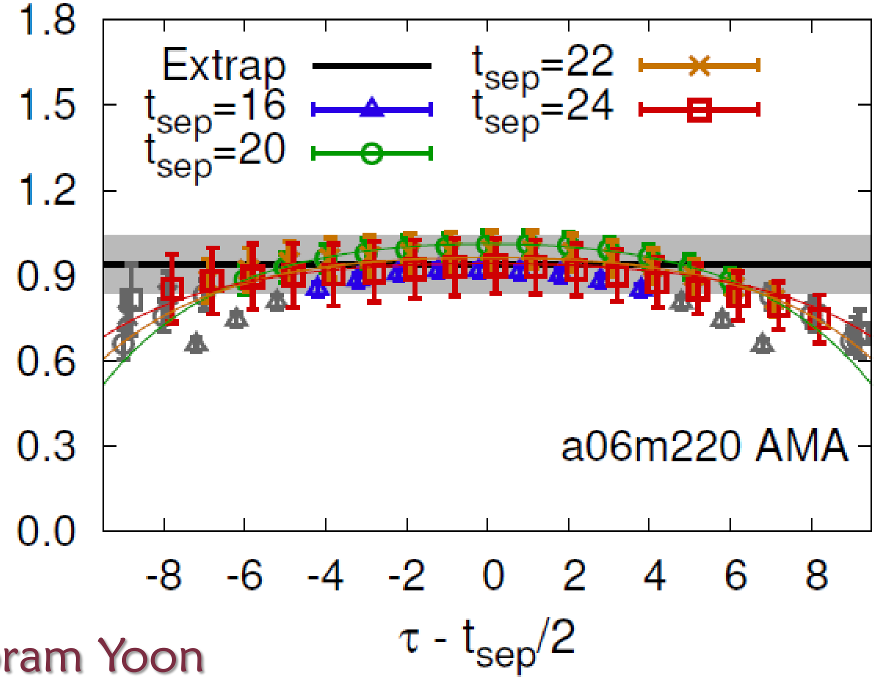
§ A state-of-the art calculation (PNDME)

- Statistical effect $\qquad$ $a = 0.06$ fm, 220-MeV pion

g_S

2.6k $\qquad$ 41.6k



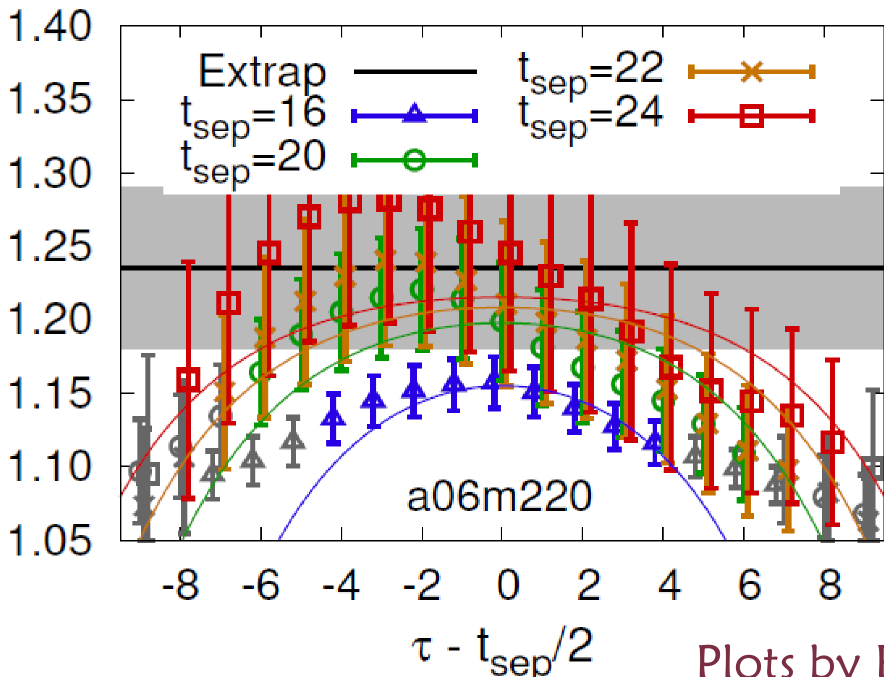


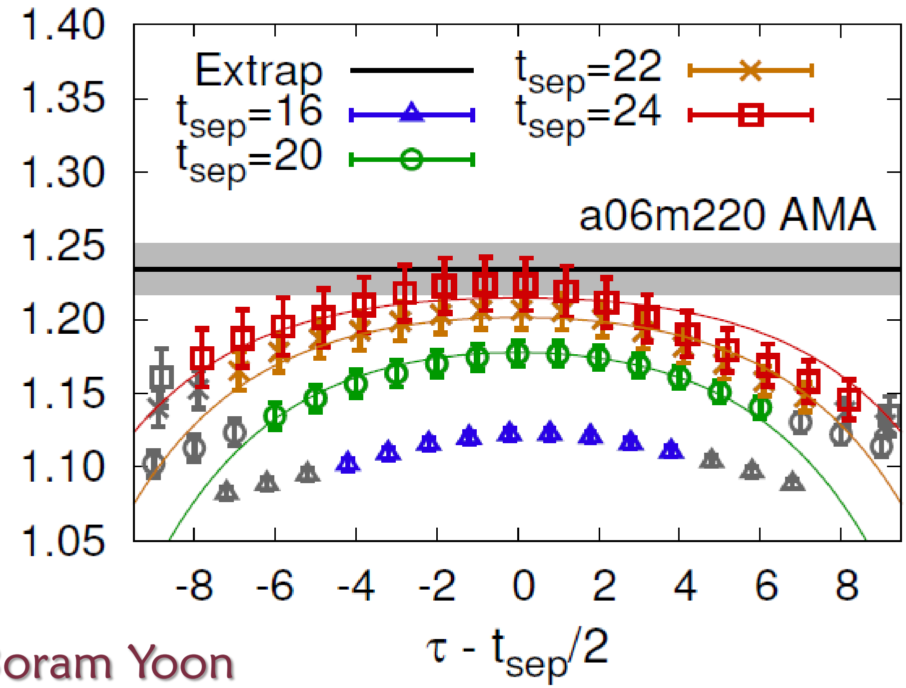
Plots by Boram Yoon

Systematic Control

- § Much effort has been devoted to controlling systematics
- § A state-of-the art calculation (PNDME)
  - Statistical effect (worst case) $a = \mathbf{0.06\ fm}$, 220-MeV pion

2.6k g_A 41.6k





Plots by Boram Yoon