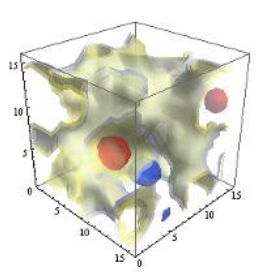
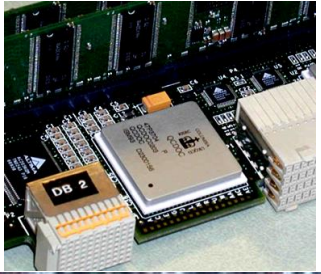
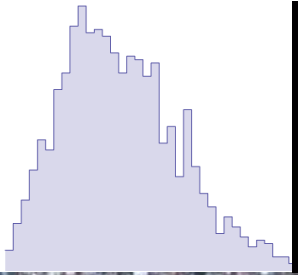
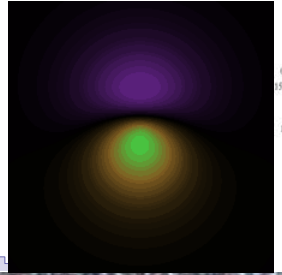
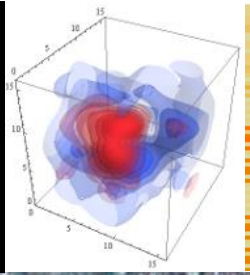
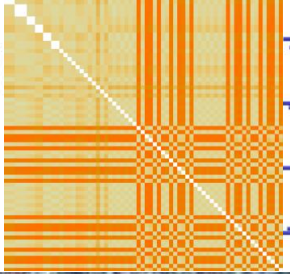
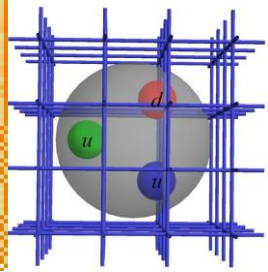



Spin and the 3D Structure of the Nucleon

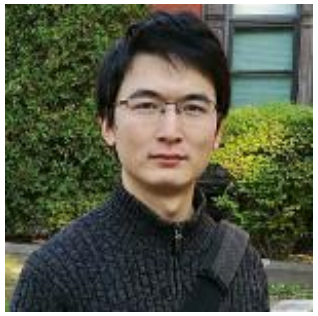
Huey-Wen Lin

Lattice Parton Physics Project (LP3)

https://www.pa.msu.edu/~hwlin/LP3/

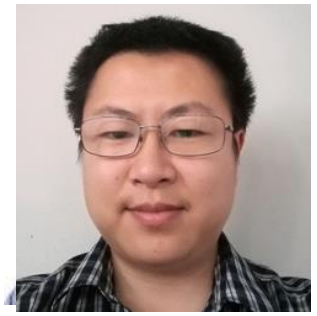
Huey-Wen Lin (PI)
(MSU)

Xiangdong Ji
(UMD)

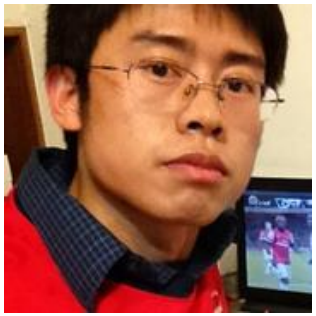


Luchang Jin
(BNL)

Peng Sun
(MSU)



Yi-Bo Yang
(MSU)



Yong Zhao
(MIT)

International collaborators

Jiunn-Wei Chen
(NTU)

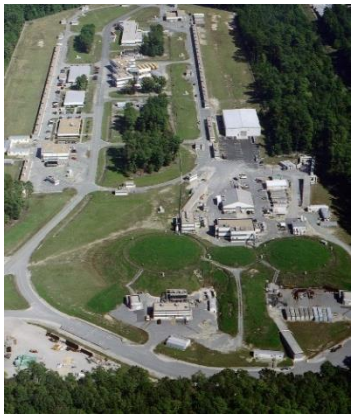
Tomomi Ishikawa
(SJTU)

Jian-Hui Zhang
(Regensburg)

Parton Distribution Functions

§ PDFs are universal quark/gluon distributions of nucleon

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

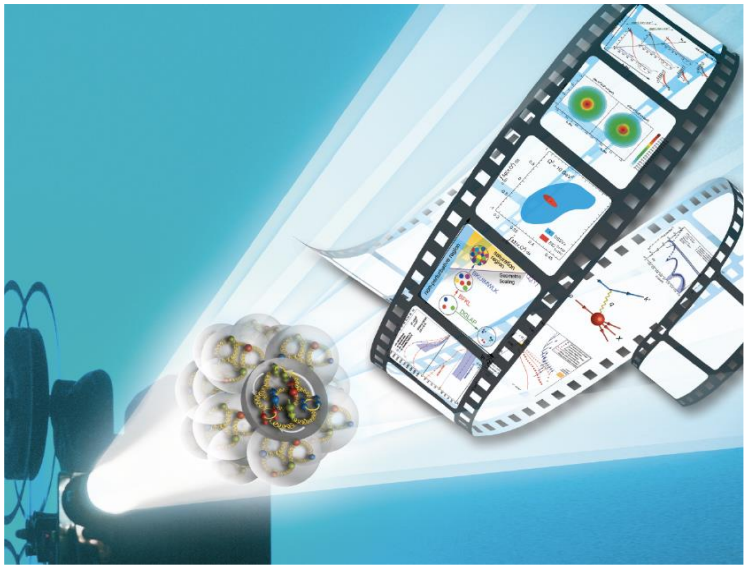


Electron Ion Collider:
The Next QCD Frontier

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 of nucleon

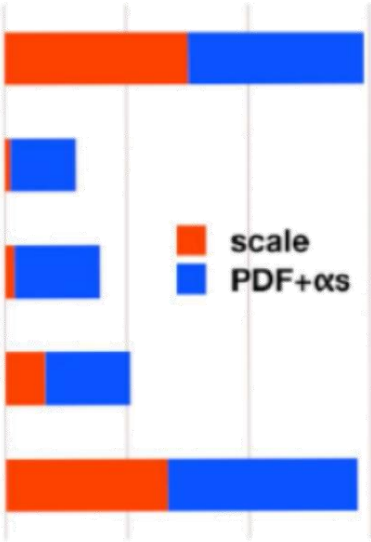
- Many ongoing/planned experiments (BNL, JLab, J-PARC, COMPASS, GSI, EIC, LHeC, …)

§ Important inputs to discern new physics at LHC

- Currently dominate errors in Higgs production

HIGGS PRODUCTION

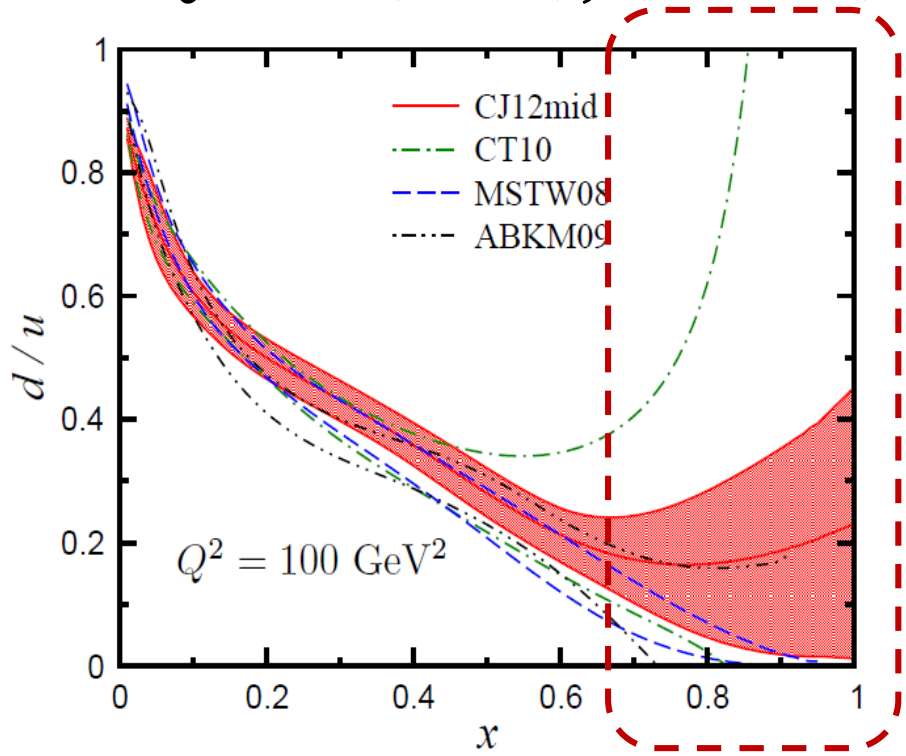
		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%

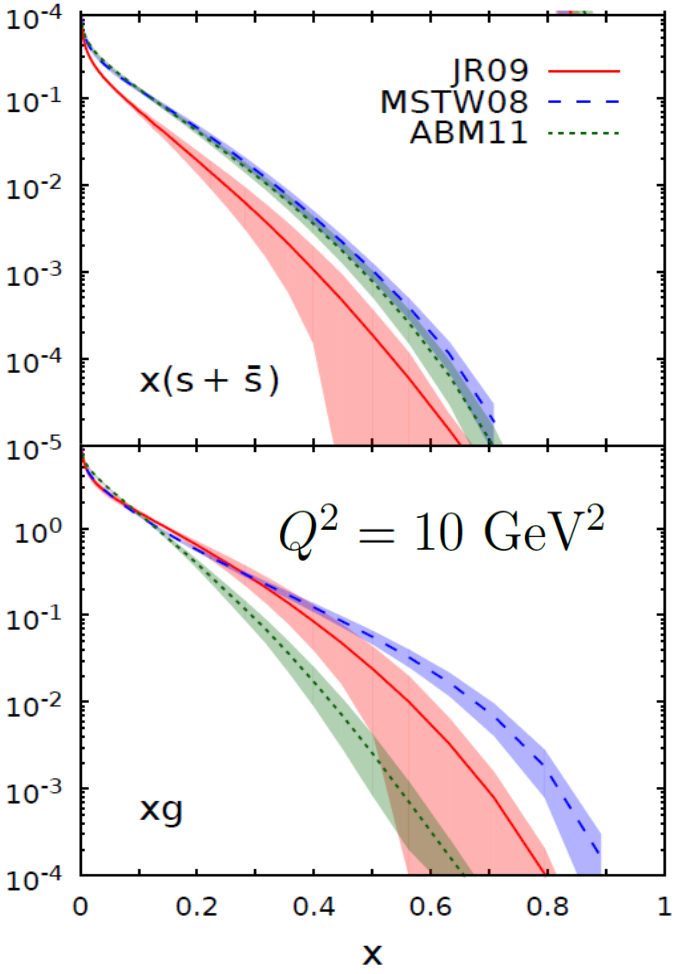


(J. Campbell, HCP2012)

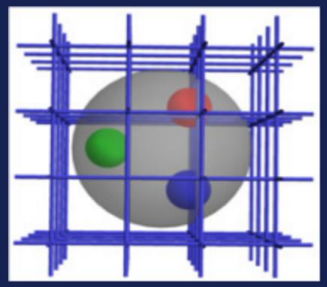
Global Analysis

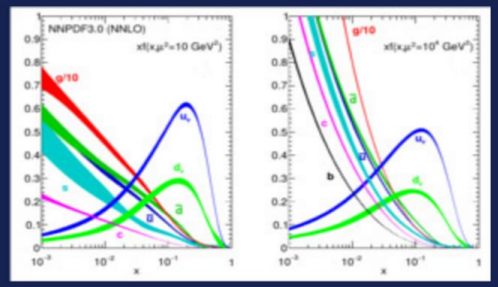
- Discrepancies appear when data is scarce
- Many groups have tackled the analysis
  - CTEQ, MSTW, ABM, JR, NNPDF, etc.





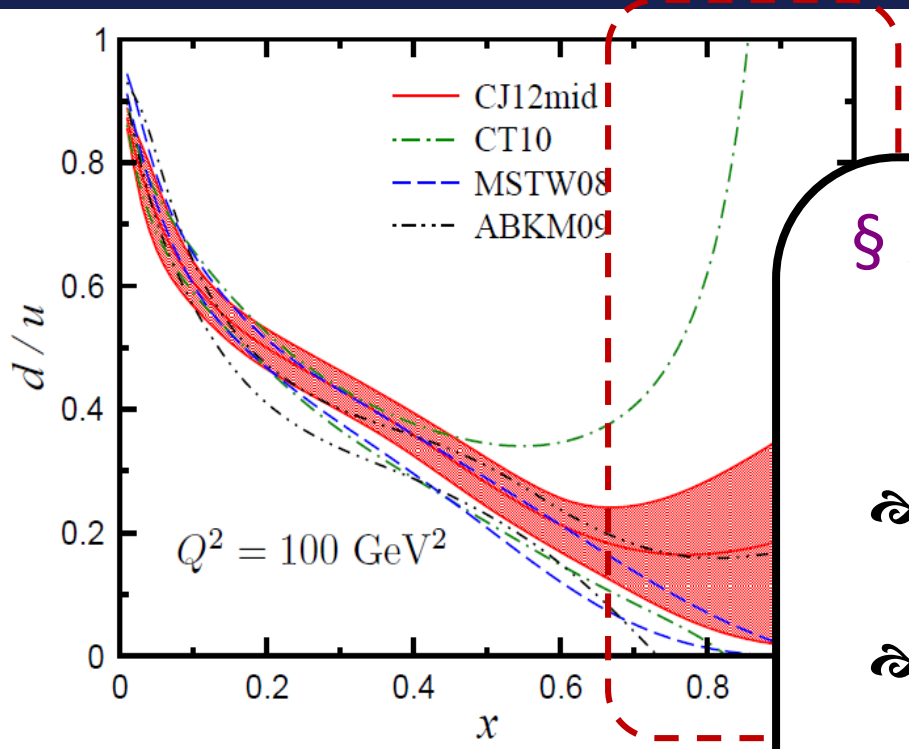
Jimenez-Delgado, Melnitchouk, Owens, J.Phys. G40 (2013) 09310



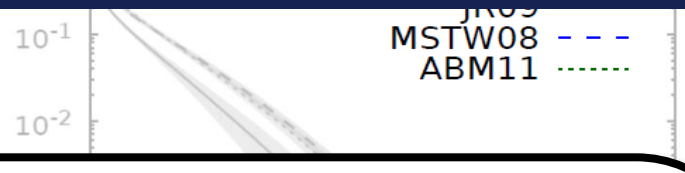


Parton Distributions and Lattice Calculations in the LHC era (PDFLattice 2017)

22-24 March 2017, Oxford, UK



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



§ A first joint workshop with global-fitting community to address key LQCD inputs

- http://www.physics.ox.ac.uk/confs/PDFlattice2017
- Whitepaper will study the needed precision of lattice PDFs in the large-x region

A Promising New Direction

PDFs on the Lattice

Long existing obstacles!

§ Lattice calculations rely on operator product expansion, only provide moments $\langle x^n \rangle$

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

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

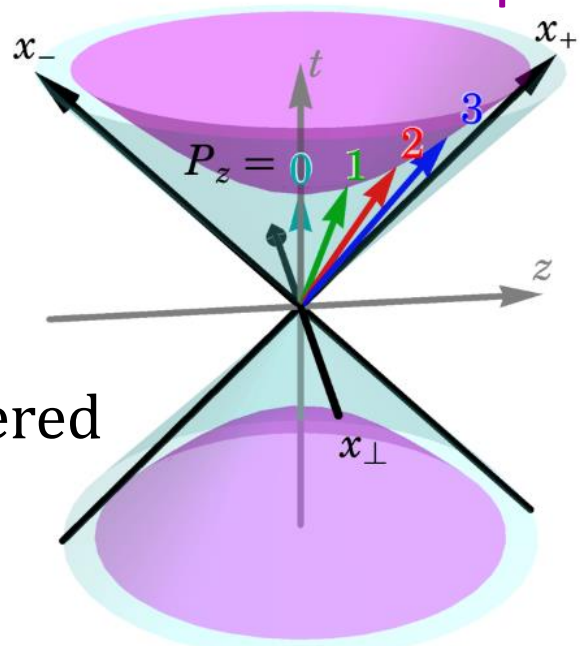
- No practical proposal to overcome this

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!

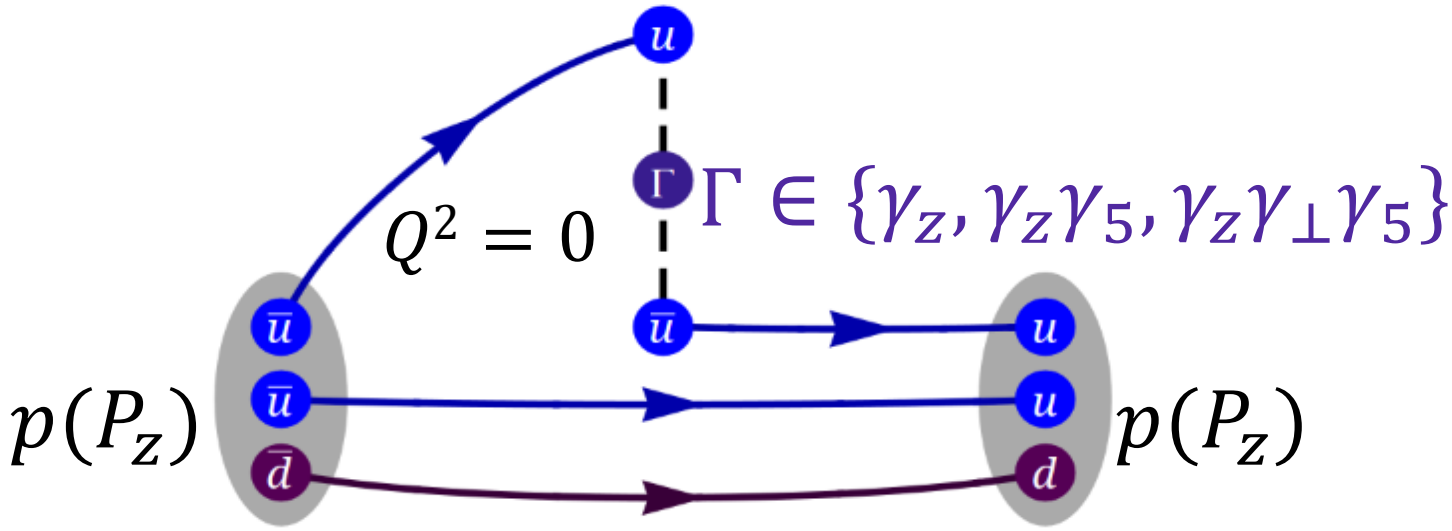


Xiangdong Ji, Phys. Rev. Lett. 111, 039103 (2013)

Parton Distribution Functions

Large-Momentum Effective Theory for PDFs

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



$P_z \to \infty$ limit

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

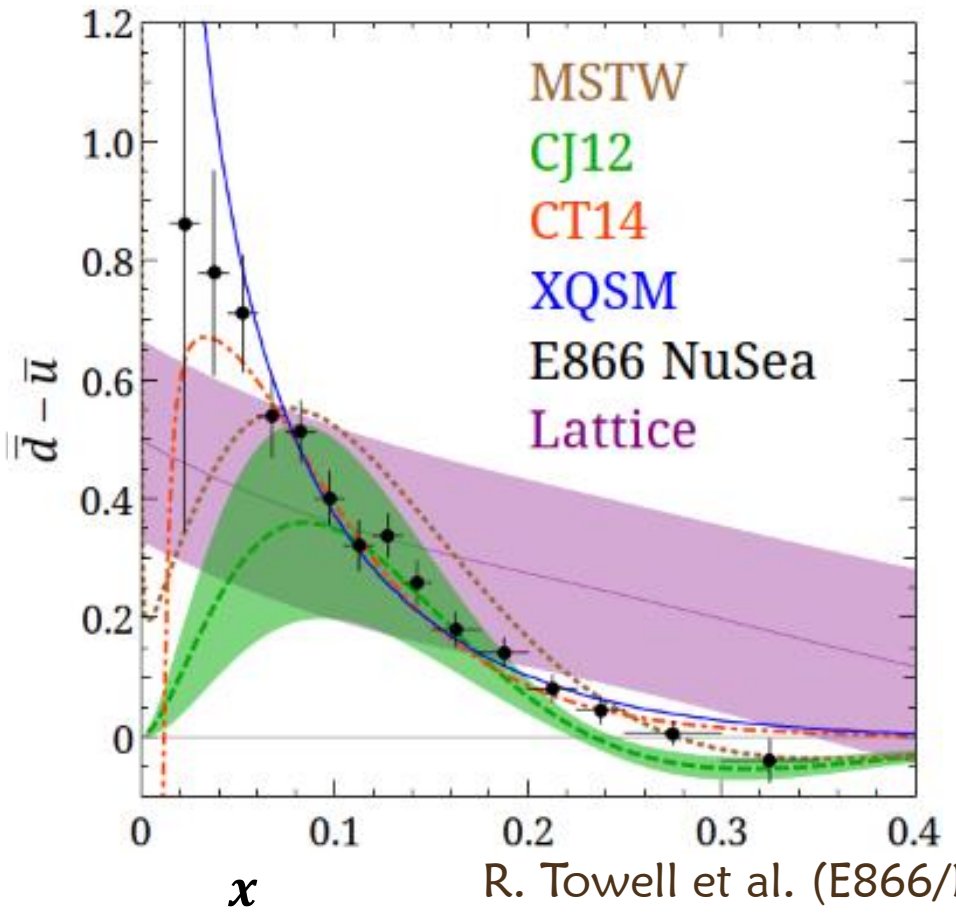
X. Xiong et al., 1310.7471; J.-W. Chen et al, 1603.06664

Sea Flavor Asymmetry

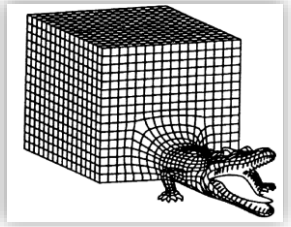
§ First time in LQCD history to study antiquark distribution!

$M_\pi \approx 310$ 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	$\int_0^1[\bar{d}(x)-\bar{u}(x)]dx$
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)

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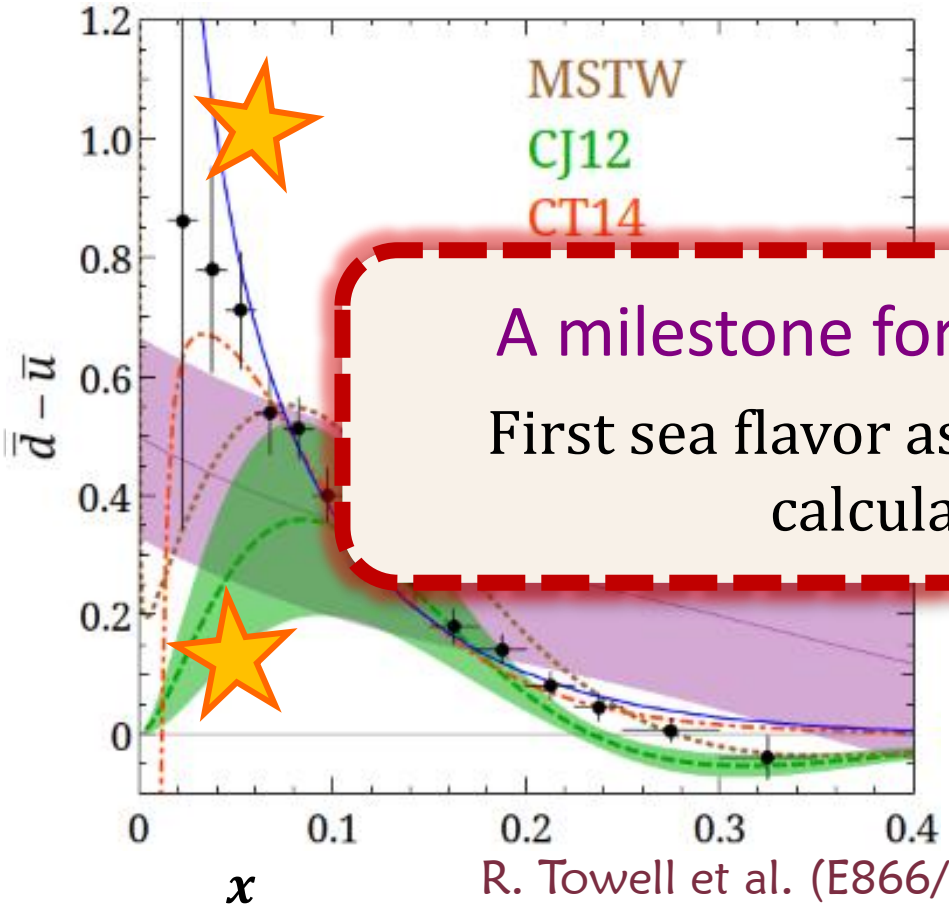
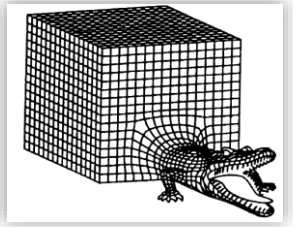


$\bar{q}(x) = -q(-x)$



Lost resolution in small-x regi

A milestone for lattice QCD!

First sea flavor asymmetry ever calculated!

ent:

ume

$\approx -0.16(7)$

Experiment	x range	$\int_0^1[\bar{d}(x)-\bar{u}(x)]dx$
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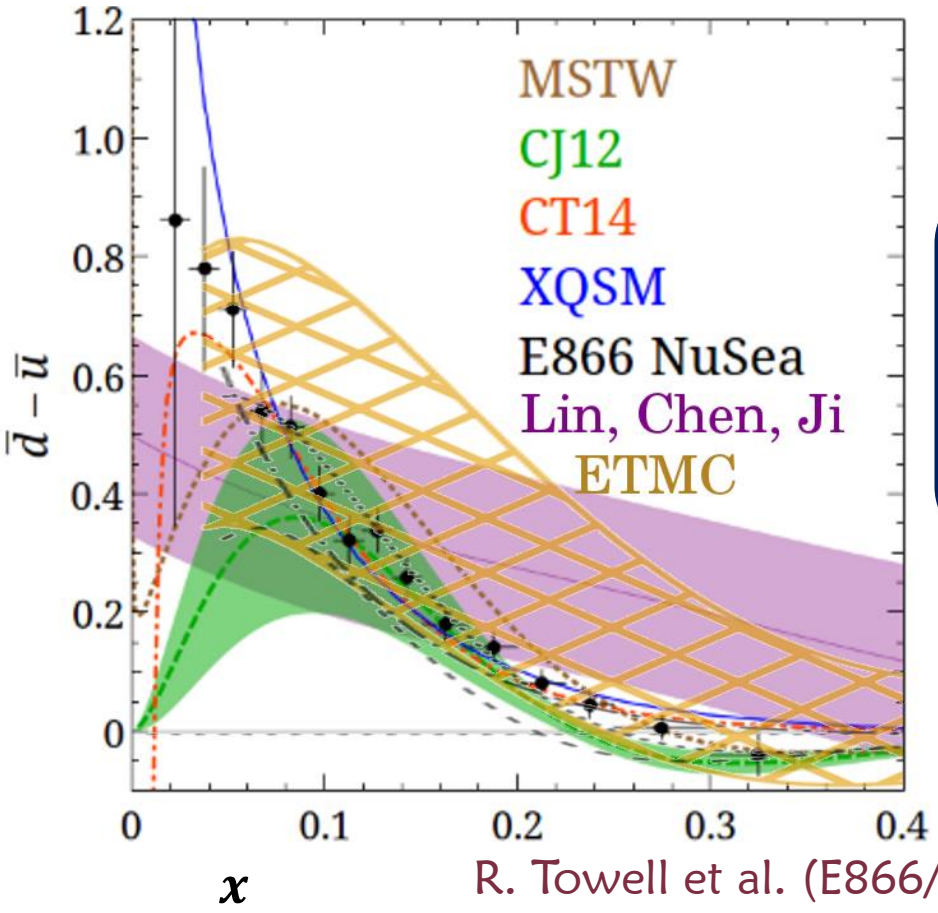
R. Towell et al. (E866/NuSea), Phys.Rev. D64, 052002 (2001)

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)

Experiment	x range	$\int_0^1[\bar{d}(x)-\bar{u}(x)]dx$
E866	$0.015<x<0.35$	0.118 ± 0.012
NMC	$0.004<x<0.80$	0.148 ± 0.039
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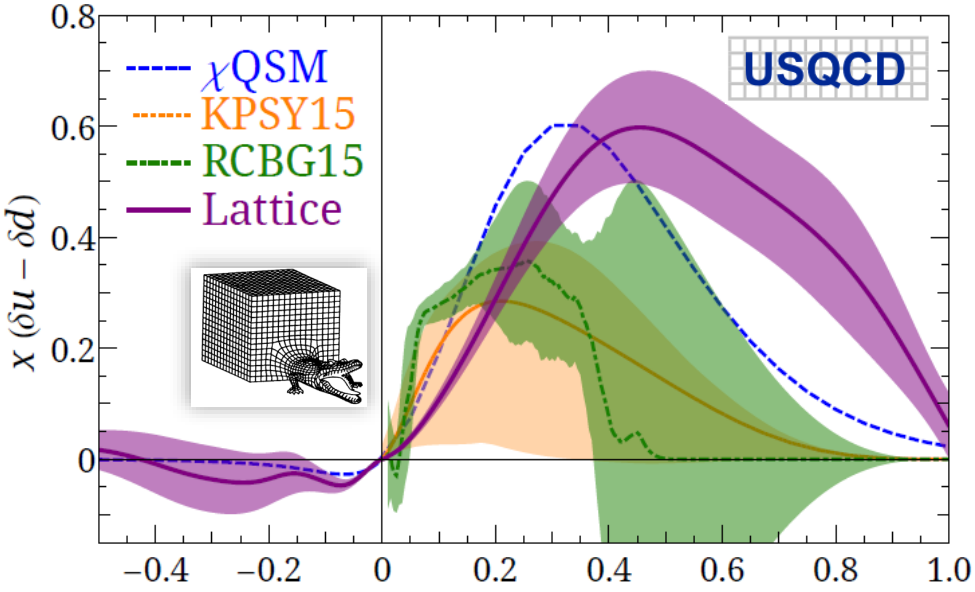
R. Towell et al. (E866/NuSea), Phys.Rev. D64, 052002 (2001)

Transversity Distribution

§ Exploratory study

$M_\pi \approx 310$ MeV

Pos(LATTICE 2013), 1603.06664



$$\int dx \left(\delta\bar{u}(x) - \delta\bar{d}(x)\right) \approx -0.10(8)$$

The calculation was also repeated by ETMC, at $M_\pi \approx 373$ MeV

ETMC, 1610.03689

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

1505.05589; 1503.03495

- We found sea asymmetry of $\int dx \left(\delta\bar{u}(x) - \delta\bar{d}(x)\right) \approx -0.10(8)$
- Chiral quark-soliton model $\int dx \left(\delta\bar{u}(x) - \delta\bar{d}(x)\right) \approx -0.082$

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

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

Progress Last Year: Systematics

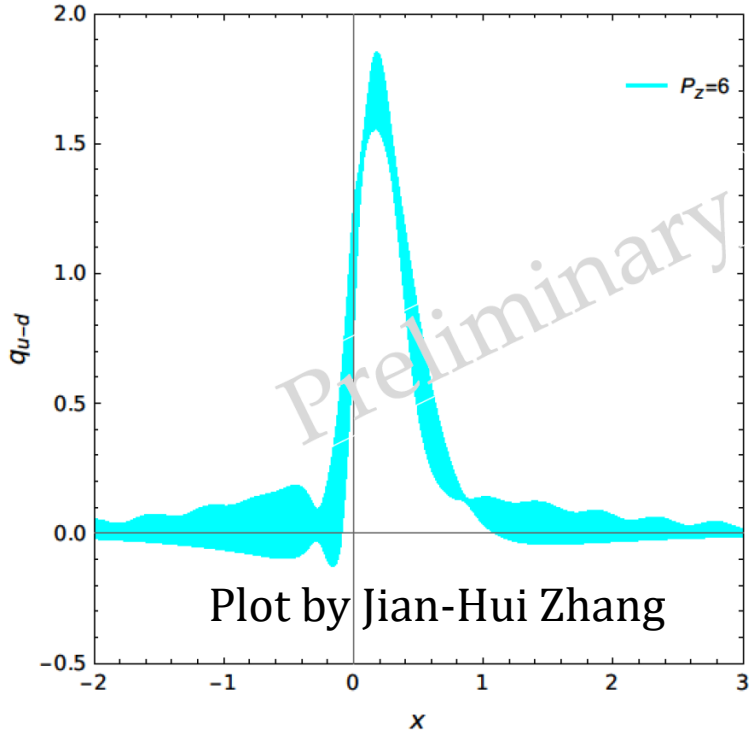
Power Divergence

§ Improved quasi-quark distribution

$$\tilde{q}_{\text{imp}}(x,\Lambda,p_z) = \int_{-\infty}^{\infty} \frac{dz}{4\pi} e^{izk_z - \delta m|z|} \langle p|\bar{\psi}(0,0_\perp,z)\gamma_z L(z,0)\psi(0)|p\rangle$$

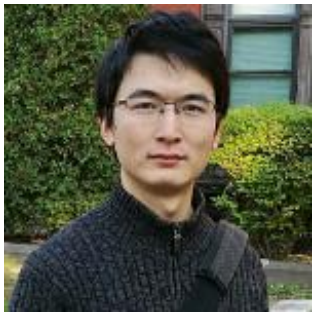
§ Wilson-line renormalization to remove power divergence

$a \approx 0.09$ fm, $L \approx 6$ fm, $M_\pi \approx 130$ MeV, clover/HISQ



Plot by Jian-Hui Zhang

Jian-Hui Zhang



Luchang Jin

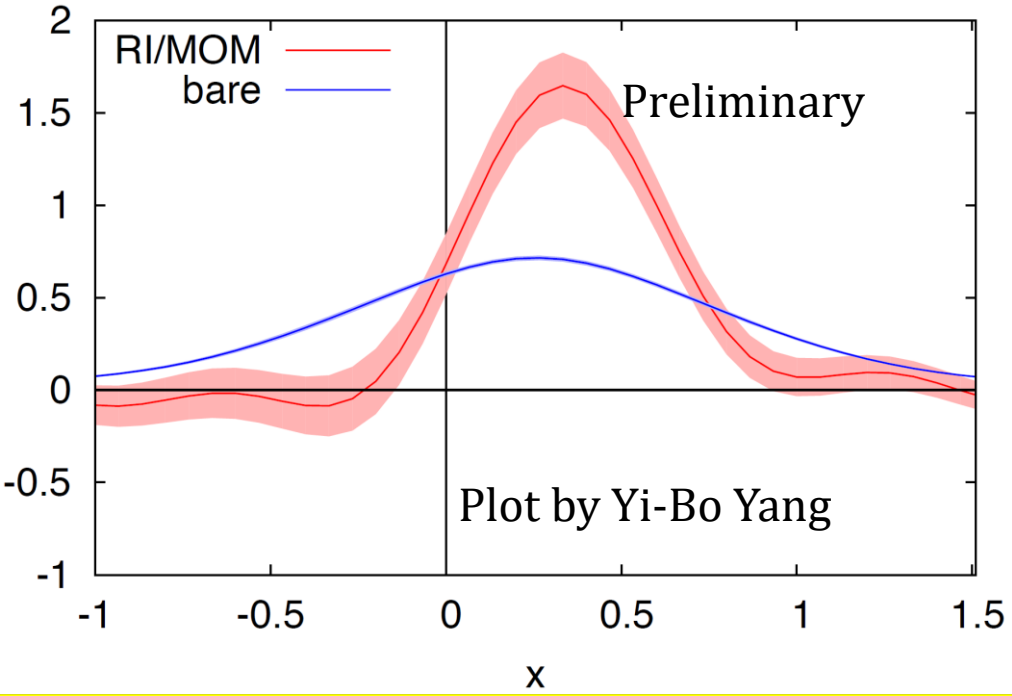
Renormalization

§ Ongoing investigation of renormalization

- Investigating RI'MOM scheme renormalization (Yang)
- RI'MOM to $\overline{\text{MS}}$ matching (Zhao)

§ Preliminary result

- Test case: $a \approx 0.12$ fm, $M_\pi \approx 310$ MeV, clover/HISQ



Yi-Bo Yang

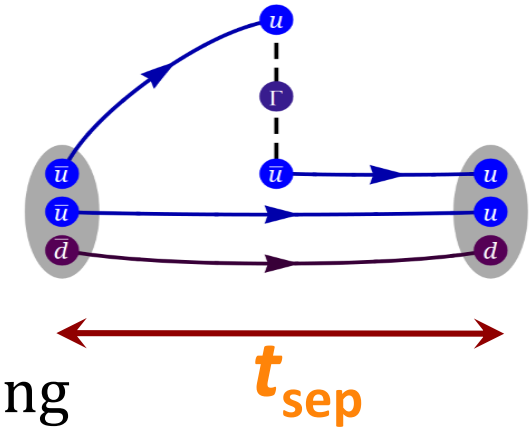
Yong Zhao

2017/18 Allocation

Proposed Calculation

§ Proposed ensemble

- N_f= 2+1+1 clover/HISQ lattices (MILC)
  $M_\pi \approx$ **130 MeV**, $a \approx 0.09$ fm ($L \approx 6$ fm)



§ Proposed physics case

- At least 3 $t_{\rm sep}$, multiple mom. source smearing
- Extended unpol. PDFs to larger p_z (w/mom. source) and polarized structure (helicity + transversity)
- First LQCD study of x-dep't GPDs (*3D Spatial Maps of the Nucleon*)

$$F_q(x,\xi,t) = \int \frac{dz^-}{4\pi} e^{ixp^+z^-} \langle p''|\bar\psi(-\frac{z}{2})\gamma^+ L(-\frac{z}{2},\frac{z}{2})\psi(\frac{z}{2})|p'\rangle_{z^+=0,\vec z_\perp=0}$$

$$= \frac{1}{2p^+}\left[H(x,\xi,t)\bar u(p'')\gamma^+ u(p') + E(x,\xi,t)\bar u(p'')\frac{i\sigma^{+\nu}\Delta_\nu}{2m}u(p')\right]$$

$$p^\mu = \frac{p''^\mu + p'^\mu}{2}, \qquad \Delta^\mu = p''^\mu - p'^\mu, \qquad t = \Delta^2, \qquad \xi = \frac{p''^+ - p'^+}{p''^+ + p'^+}$$

"The Tomography of the Nucleon — Spatial Imaging of Gluons and Sea Quarks"

Proposed Calculation

§ Proposed ensemble

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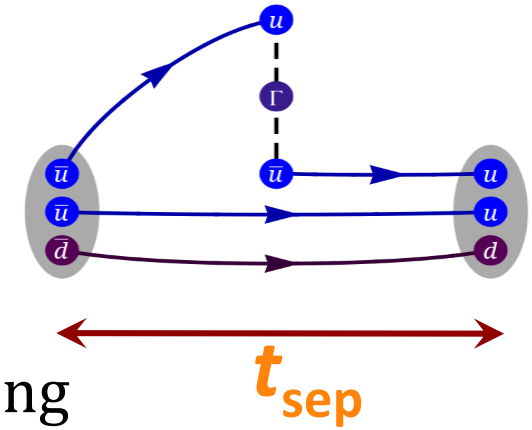
  $M_\pi \approx$ **130 MeV**, $a \approx 0.09$ fm ($L \approx 6$ fm)



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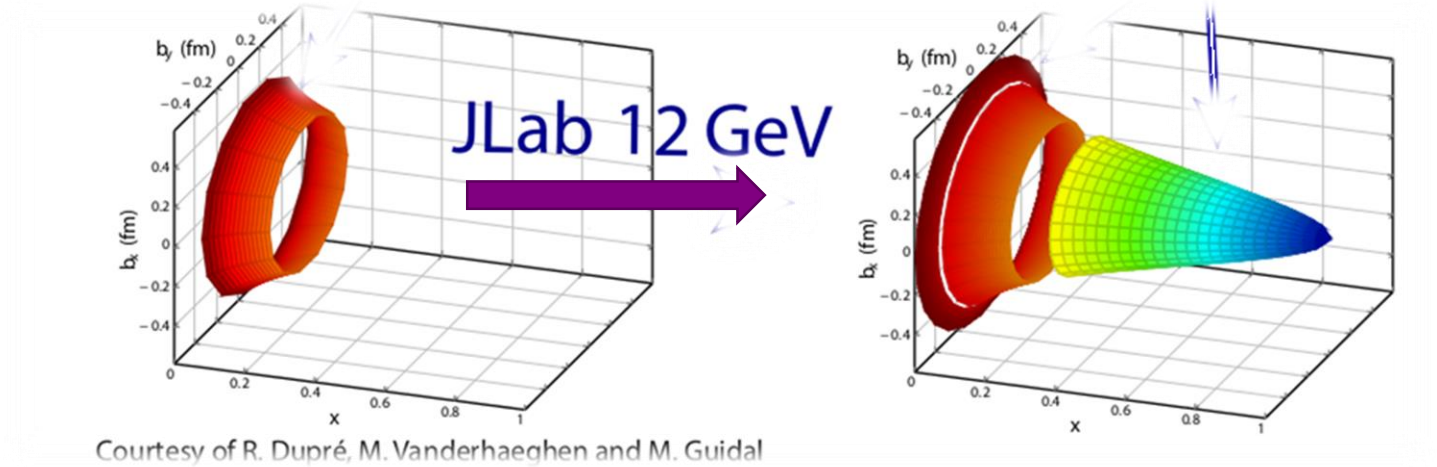

Courtesy of R. Dupré, M. Vanderhaeghen and M. Guidal