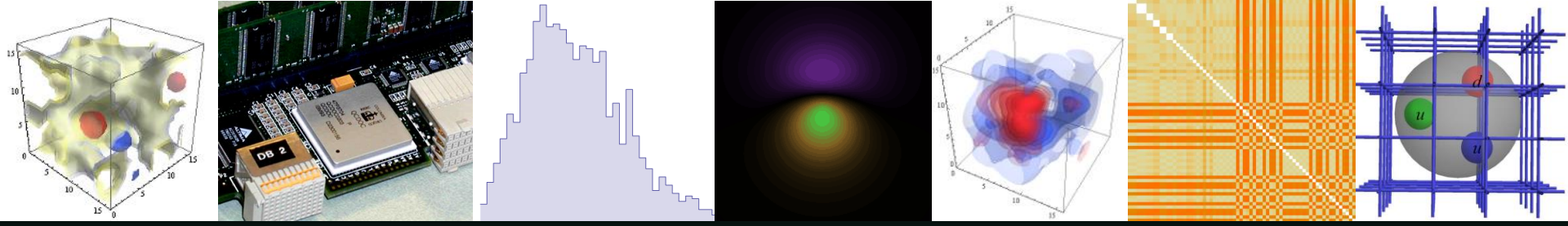


Hadron Structure & Spectroscopy

HUEY-WEN LIN

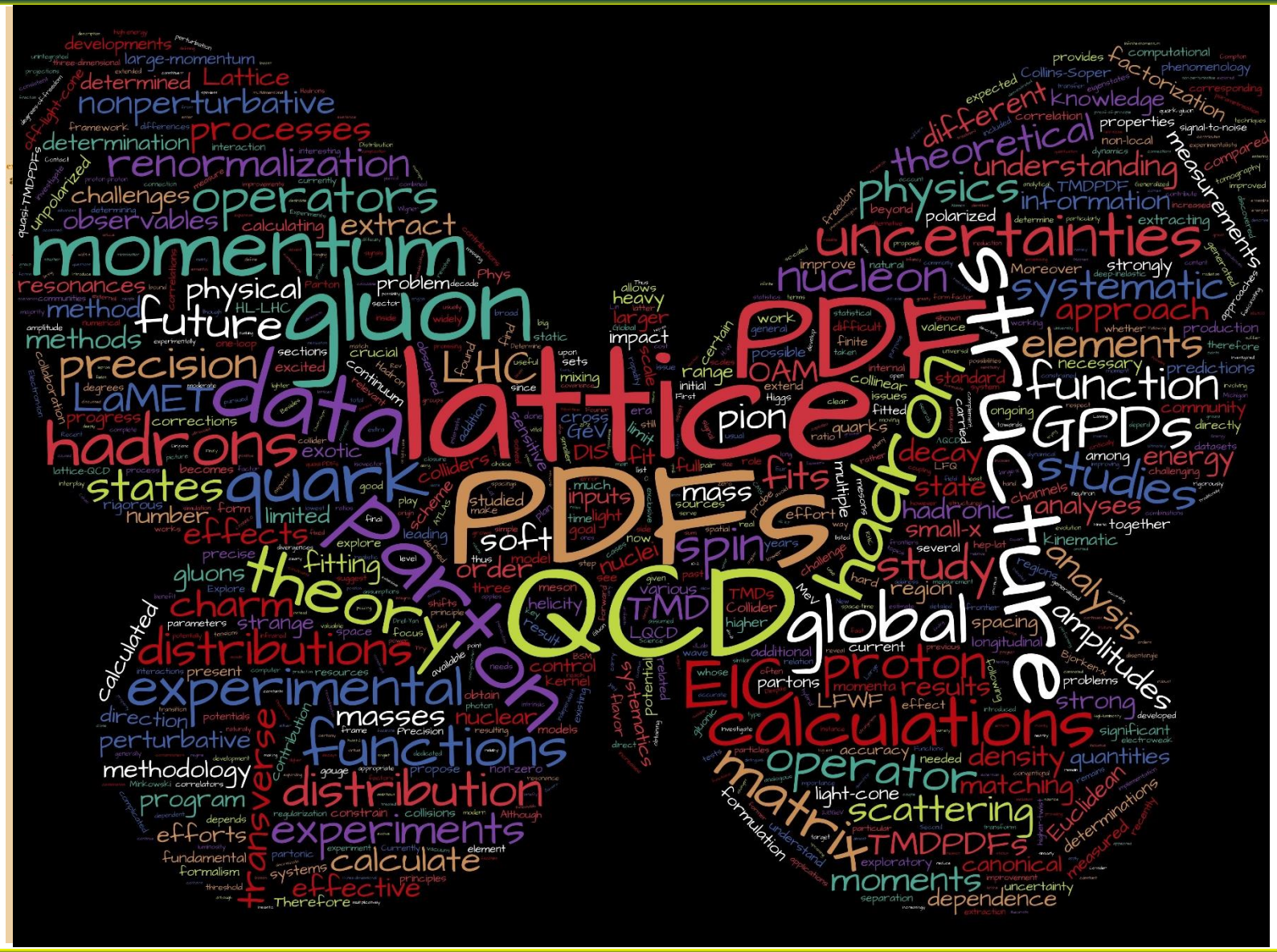
Many thanks to

Chris Monahan, Sasa Prelovsek, Jianhui Zhang,
Yong Zhao, Peter Pertreczky, Maria Ubiali, Tim Hobbs

for sending a one-slide summaries of LOIs

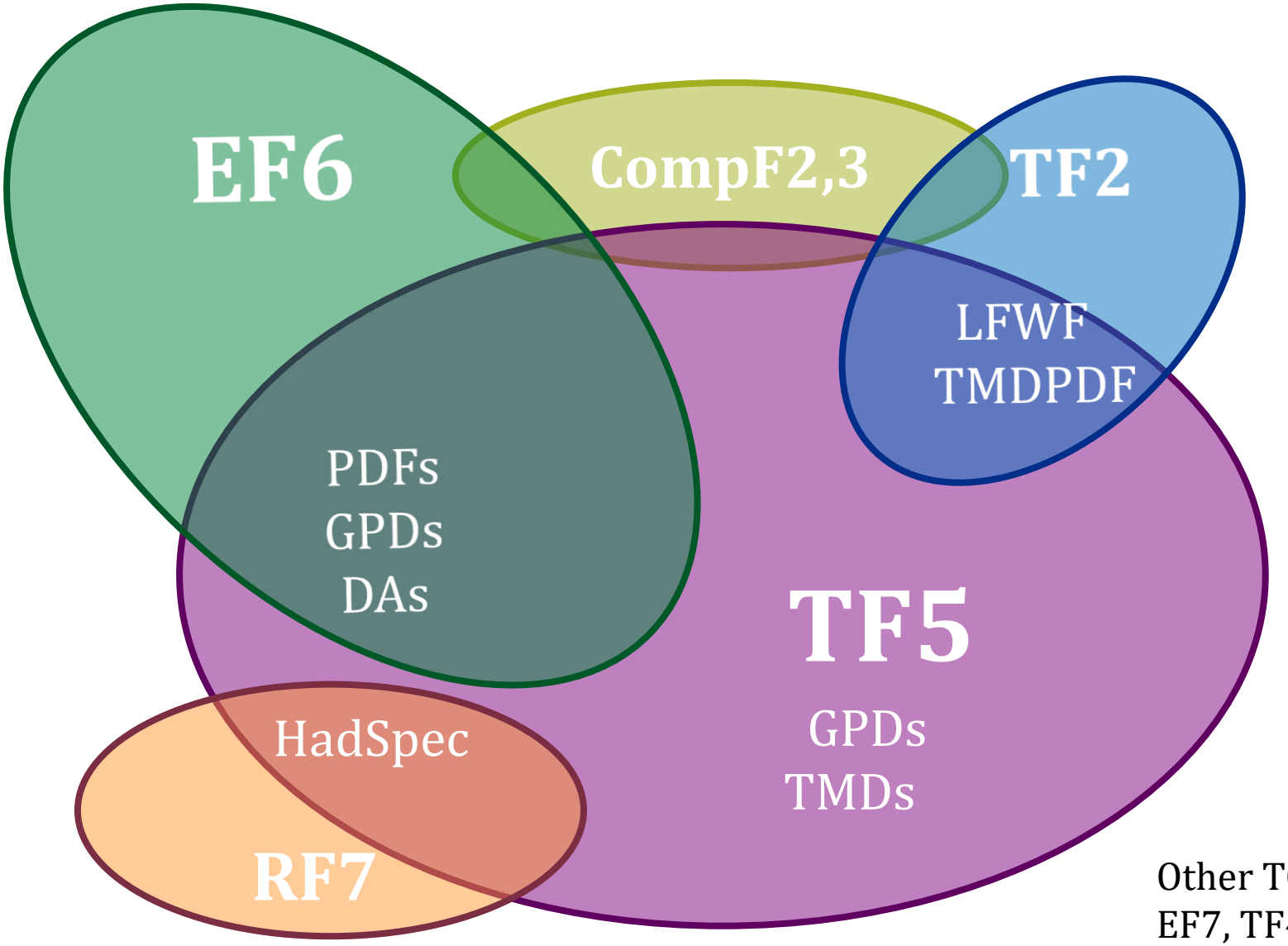
Apologies to those whose results I cannot cover due to time constraints

Hadron Structure & Spectroscopy



Hadron Structure & Spectroscopy

Topical Groups	Title
EF6-TF5	133: Gluon Parton Distribution Functions from Lattice QCD
EF6-TF5	143: Gluon helicity and parton orbital angular momentum contribution to the proton spin
EF6-TF5	247: Charm Parton Distribution Functions from Global Analysis and Lattice QCD
EF6-TF5	248: Precision Moments of Strange Parton Distribution Functions from Lattice QCD
EF6-TF5	151: Generalized Parton Distributions from Lattice QCD
EF6-TF5-TF2	165: Small-*x* parton physics on lattice
EF6-EF7-TF5	85: Parton distribution functions from lattice
EF6-EF7-TF5-TF7-CompF2-CompF3	205: Hadronic Tomography at the EIC and the Energy Frontier
TF2-TF5	43: 2020 TMD PDF in large-momentum effective theory
TF2-TF5-CompF2	44: Light-front wavefunction from lattice QCD through large-momentum effective theory
TF5-EF6-CompF2	21: Towards global fits of three-dimensional hadron structure from lattice QCD
TF5-TF2-EF6	63: Transverse-momentum-dependent parton distributions from lattice QCD
TF5-TF6	40: New frontiers in PDF analyses in the HL-LHC era
RF7-TF5-TF4	42: Hadron Spectroscopy with Lattice QCD



Other TGs:
EF7, TF4, TF6

Sorted by Topics

- Parton Distribution Functions (PDFs)
  - Global fits: 40: New frontiers in PDF analyses in the HL-LHC era (TF5)
  - Isovector PDFs with $a < 0.06$ fm: 85: PDFs from lattice (EF6)
  - Gluons: 133: Gluon PDFs from lattice QCD (EF6),
    143: Gluon helicity and parton OAM contribution to the proton spin (EF6)
  - Strange: 248: Precision moments of strange PDFs from lattice QCD (EF6)
  - Charm: 247: Charm PDFs from global analysis and lattice QCD (EF6)
  - Small-*x:* 165: Small-*x* parton physics on lattice (EF6)
- Generalized Parton Distributions (GPDs)
  - 21: Towards global fits of three-dimensional hadron structure from lattice QCD (TF5)
  - 151: Generalized parton distributions from lattice QCD (EF6)
- Transverse Momentum Distributions (TMDs)
  - 43: 2020 TMD PDF in large-momentum effective theory (TF2)
  - 63: Transverse-momentum-dependent parton distributions from lattice QCD (TF5)
- Wavefunctions (+DAs): 44: Light-front wavefunction from lattice QCD through large-momentum effective theory (TF2) + 85 (EF6)
- EIC connection to above topics: 205: Hadronic Tomography at the EIC and the Energy Frontier (EF6)
- Spectroscopy: 42: Hadron Spectroscopy with Lattice QCD (RF7)

Parton Distribution Functions

M. UBIALI – LOI "NEW FRONTIERS IN PDF ANALYSES IN THE HL-LHC ERA "

M.ubiali@damtp.cam.ac.uk

SNOWMASS21-TF5_TF6-040.pdf

- Precision physics frontier at HL-LHC opens up new fascinating challenges also in the field of PDF determination
- Precise and accurate understanding of the proton structure is key to achieve accurate theoretical predictions
- HL-LHC projection: reduction of PDF uncertainties by factor 2-3, but to achieve this goal benchmark among PDF sets and thorough scrutiny of each PDF analysis is a must.

Global PDF point of view…

- Need: robust methodology (e.g. closure tests) and increased precision in theoretical predictions in PDF fits (N3LO, estimate of missing higher order uncertainties, EW corrections, photon and lepton PDFs)
- News: estimate of theoretical uncertainties associated with missing higher order and nuclear models in PDF fits, fit of the methodology, new tools to quantify the effects of new data.
- Longer-term aim is to build up technologies that allow to perform global fits of all parameters that enter LHC analyses (PDFs + α_s, PDFs + EW parameters) and also of PDFs + BSM EFT parametrisation, to prevent PDFs from absorbing signs of new physics
- Broad effort and cross-talk essential to advance and face these challenges

Slide by M. Ubiali

Parton Distribution Functions (PDFs)

- Isovector PDFs with $a < 0.06$ fm: 85: PDFs from lattice (EF6)
  - Unpolarized and polarized parton distribution functions (PDF) using large-momentum effective theory (LaMET) and lattice calculations on fine lattices
- Gluon contribution
  - 133: Gluon parton distribution functions from lattice QCD (EF6)
    - Improved operator and renormalization strategy, reduces higher-twist contamination
  - 143: Gluon helicity and parton OAM contribution to the proton spin (EF6)
    - LQCD to study total gluon helicity contribution to proton spin and orbital angular momentum
    - Goal: Systematic calculation with precision (5–10%) comparable to the EIC
- Strange: 248: Precision moments of strange PDFs from LQCD (EF6)
  - Continuum-extrapolated with full systematics (with 3–4 lattice spacings) to improve the current strange moment calculations. Impact study done in PDFLattice 2017 whitepaper
- Charm: 247: Charm PDFs from global analysis and lattice QCD (EF6)
  - Use lattice-calculated charm quantities to shed light into long-debated intrinsic charm in combination with global analysis
- Small-x: 165: Small-x parton physics on lattice (EF6)
  - Difficulties in reliably extracting small-x in current x-dependent methods
  - Bring together small-x and LQCD communities to explore ways in resolve this in near future

Generalized Parton Distributions (GPDs)

- 21: Towards global fits of three-dimensional hadron structure from lattice QCD (TF5)
  - Goal: systematic study of GPDs from lattice QCD, based on large-momentum effective theory
  - Flavor-nonsinglet GPDs in the pion and the nucleon: renormalization and matching, extend to non-zero skewness, flavor-depedent GPDs
- 151: Generalized parton distributions from lattice QCD (EF6)
  - Motivation: Global GPD fit is limited experimental data, challenging interpretation and theoretical framework
  - Multiple lattice-QCD calculations with different method, fermion setup
  - Multi-disciplinary collaboration required
    - Experimental, phenomenological, theoretical and computational

Transverse Momentum Distributions (TMDs)

- 43: 2020 TMD PDF in large-momentum effective theory (TF2)
  - Investigate possible Euclidean formulation for general soft functions
  - High-twist effect on quasi-TMDs, study renormalization property,
  - Carry out high-loop calculations for quasi-TMDs
- 63: TMD parton distributions from lattice QCD (TF5)
  - Precision calculation of the nonperturbative Collins-Soper kernel for the energy evolution of TMDs
  - Lattice calculation of the soft function in TMD factorization theorems
  - Lattice calculation of the TMDs at small transverse parton momentum
    - Constrain models used in global fits
    - 3D imaging of the proton in momentum space
- 44: Light-front wavefunction from lattice QCD through large-momentum effective theory (TF2)
  - LFWF amplitudes play important role in exclusive and hadronic form-factors
  - Study renormalization properties, develop matching, theoretical problems in the lightcone limit

Connection with EIC

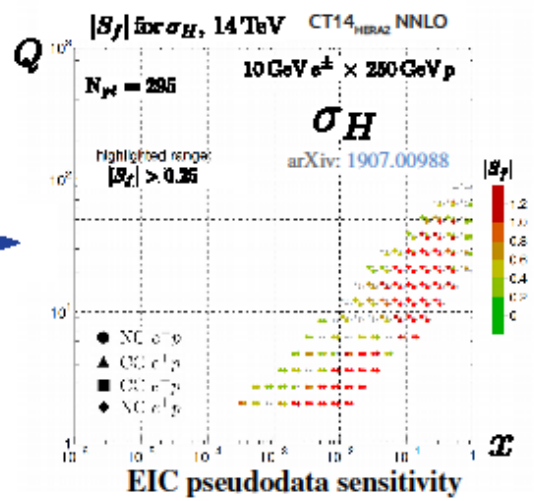
EIC@Snowmass21 LOI: Hadronic Tomography at the EIC and the Energy Frontier

October 2020 **Editors: Salvatore Fazio, Tim Hobbs, Alexei Prokudin, Alessandro Vicini** **160+ coauthors/signers**

- tomography encompasses a wide range of EIC ↔ HEP topics
- EIC determinations of partonic distributions (PDFs, TMDs, GPDs)

- high-energy QCD (DIS measurements; heavy quarks/masses, jets, α_s)
- gluonic structure/Higgs (gluon PDF/GPD; improvements to gg→ h production)
- QED effects (photon PDF; improved EW corrections)
- TMD measurements, precision EW physics (TMDs and M_W extractions)
- nuclear structure (nuclear PDFs; connections to heavy-ion UPCs)

select topics



EIC pseudodata sensitivity

- progress will depend on various methods
  - → phenomenological studies; global analyses
  - → continuum QCD approaches
  - → lattice QCD input
  - → AI/machine-learning and MCEGs

Slide by Tim Hobbs; check more details for his talks at #92

- completed LoI available here

Spectroscopy

Letter of interest for Hadron Spectroscopy with Lattice QCD

J. Bulava[(1)], R. Briceño[(2)], M. Döring[(3)] A. Francis[(4)], F. Knechtli[(5)], R. Lewis[(6)], S. Prelovsek[(7)1]
S. Ryan[(8)], A. Rusetsky[(9)], A. Szczepaniak[(10)], S. Sharpe[(11)], C.E. Thomas[(12)], M.Wagner[(13)]

Solved problems:

- Masses of hadrons that cannot decay strongly
- Masses and widths of resonances with one (two-particle) decay channel: lattice study of scattering

Challenges:

- Resonances with more than two decay channels: lattice study of coupled-channel scattering
  - try rigorous lattice study, look for simplifications whether some channels can be omitted
  - most of experimentally discovered exotic hadrons have more than two decay channels
- Resonances that have two-particle as well as three-particle decay channels
  - try rigorous lattice study, look for simplifications
- Analytically or numerically determine the effect of omitted $Q\bar{Q}$ annihilation for quarkonium(like) states
- Find a reliable criterion on the importance of molecular and diquark configurations
- Vary the quark masses in order to explore the position of the resonances with respect to the position of thresholds
- Determine the yet unknown Born-Oppenheimer potentials for systems with two heavy particles
- Establish exotic candidated that can be reliably studied on the lattice and in experiment

Slide by Sasa Prelovsek

Backup Slides:
One-slide LOI Summary

Towards global fits of three-dimensional hadron structure from lattice QCD

TF/SNOWMASS21-TF5_TF0-EF6_EF0-CompF2_CompF0_Chris_Monahan-021.pdf

C. Monahan[1], L. Del Debbio, H.-W. Lin, K. Orginos

Natural to try to extend successful PDF global fitting framework to GPDs**, but**

- limited experimental data, challenging interpretation and theoretical framework

Conceptually straightforward to extend promising lattice PDF methods to GPDs, **but**

- particularly challenging signal-to-noise issue for boosted baryons
- coordinated and systematic approach to data analysis required
- global fitting framework yet to be established

State of the field

- established calculations of GPD moments (generalized form factors)
- first results for isovector nucleon and pion GPDs this year

Multi-disciplinary collaboration required

- experimental, phenomenological, theoretical and computational communities
- many open questions and many opportunities

[1]*cjmonahan@wm.edu*

LOI Hadron Spectroscopy with lattice QCD

Solved problems:

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- Masses and widths of resonances with one (two-particle) decay channel: lattice study of scattering

Challenges:

- Resonances with more than two decay channels: lattice study of coupled-channel scattering
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- Establish exotic candidated that can be reliably studied on the lattice and in experiment

Gluon parton distributions from lattice QCD

- Goal: systematic study of the x-dependence of gluon PDFs from lattice QCD, based on large momentum effective theory
- Participants: W. Wang (SJTU), Y.-B. Yang (ITP, CAS), J.-H. Zhang (BNU), S. Zhao (ODU&JLab), R. Zhu (NJNU)

- Issues to investigate:
  - Appropriate operator choice for the calculation
    - Simple renormalization without higher-twist contamination
  - Renormalization strategy
    - Avoid gauge invariance issue etc. in RI/MOM
  - Control of lattice systematics

Link to LOI

Contact: zhangjianhui@bnu.edu.cn

Generalized parton distributions from lattice QCD

- Goal: systematic study of GPDs from lattice QCD, based on large momentum effective theory
- Participants: C. Alexandrou (UCY), J.-W. Chen (NTU), M. Constantinou (TU), K. Jansen (DESY), X. Ji (UMD), H.-W. Lin (MSU), A. Schaefer (UR), J.-H. Zhang (BNU)

- Issues to investigate:
  - Flavor-nonsinglet GPDs in the pion and the nucleon
    - Extend to more lattice ensembles for zero/non-zero skewness
  - Renormalization and matching: Theory inputs to high accuracy
  - Theory/lattice studies of flavor-singlet and gluon GPDs

Link to LOI

Contact: zhangjianhui@bnu.edu.cn

Transverse-Momentum-Dependent Parton Distributions from Lattice QCD

Collaboration: Markus Ebert (MIT), Jian Liang (U. Kentucky), Yizhuang Liu (T.-D. Lee Institute), Phiala Shanahan (MIT), Iain Stewart (MIT), Michael Wagman (FNAL), Wei Wang (SJTU), Yong Zhao (BNL)

LOI Webpage

Contact: yzhao@bnl.gov

Within the framework of large-momentum effective theory (LaMET):

- Precision calculation of the nonperturbative Collins-Soper kernel for the energy evolution of transverse-momentum-dependent parton distribution functions (TMDPDFs);

  Providing input for the global fitting of TMDPDFs.

- Lattice calculation of the soft function in TMD factorization theorems;

- Lattice calculation of the TMDPDFs at small transverse parton momentum.

  - **Constraining models used in global fits;**
  - **3D imaging of the proton in momentum space.**

Gluon Helicity and Parton Orbital Angular Momentum Contribution to the Proton Spin

Collaboration: Yoshitaka Hatta (BNL), Xiangdong Ji (UMD), Luchang Jin (U. Conn), Jian Liang (U. Kentucky), Keh-Fei Liu (U. Kentucky), Swagato Mukherjee (BNL), Peter Petreczky (BNL), Sergey Syritsyn (SBU), Gen Wang (U. Kentucky), Yi-Bo Yang (ITP, CAS), Feng Yuan (LBNL), Jian-Hui Zhang (BNU), Yong Zhao (BNL)

LOI Webpage

Contact: yzhao@bnl.gov

- Lattice calculation of the total gluon helicity contribution ΔG to proton spin;
  - **Methodology: Large-momentum effective theory (LaMET)**
  - **Goal: Systematic calculation with precision (5~10%) comparable to the EIC**

- Parton orbital angular momentum from lattice QCD;
  - **Completion of the naive sum rule for the proton spin**
- Extraction of the canonical parton orbital angular momentum from hard exclusive processes.

Parton distribution functions from lattice QCD

Collaboration: Peter Boyle(BNL, U. Edinburgh) Taku Izubuchi (BNL, RIKEN-BNL), Luchang Jin (U. Connecticut, RIKEN-BNL) , Peter Petreczky (BNL), Swagato Mukherjee (BNL), and Sergey Syritsyn (U. Stony Brook, RIKEN-BNL)

- Lattice calculations of unpolarized and polarized parton distribution functions (PDF)

Goal: aid an improved determination of PDF through lattice calculations

Methodology: Large Momentum Effective Theory (LaMET) and lattice calculations on fine lattices a<0.06 fm

- Determination of meson distribution amplitudes (DA) which are important for some high energy processes involving meons

Goal: provide reliable first principle calculations of meson DAs

Methodology: Large Momentum Effective Theory (LaMET) and lattice calculations on fine lattices a<0.06 fm

Contact: Luchang Jin (luchang.jin@uconn.edu)

https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF6_EF7-TF5_TF0_RBC-085.pdf

M. UBIALI – LOI "NEW FRONTIERS IN PDF ANALYSES IN THE HL-LHC ERA "

M.ubiali@damtp.cam.ac.uk

SNOWMASS21-TF5_TF6-040.pdf

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- Precise and accurate understanding of the proton structure is key to achieve accurate theoretical predictions

- HL-LHC projection: reduction of PDF uncertainties by factor 2-3, but to achieve this goal benchmark among PDF sets and thorough scrutiny of each PDF analysis is a must.

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- News: estimate of theoretical uncertainties associated with missing higher order and nuclear models in PDF fits, fit of the methodology, new tools to quantify the effects of new data.

- Longer-term aim is to build up technologies that allow to perform global fits of all parameters that enter LHC analyses (PDFs + α_S, PDFs + EW parameters) and also of PDFs + BSM EFT parametrisation, to prevent PDFs from absorbing signs of new physics

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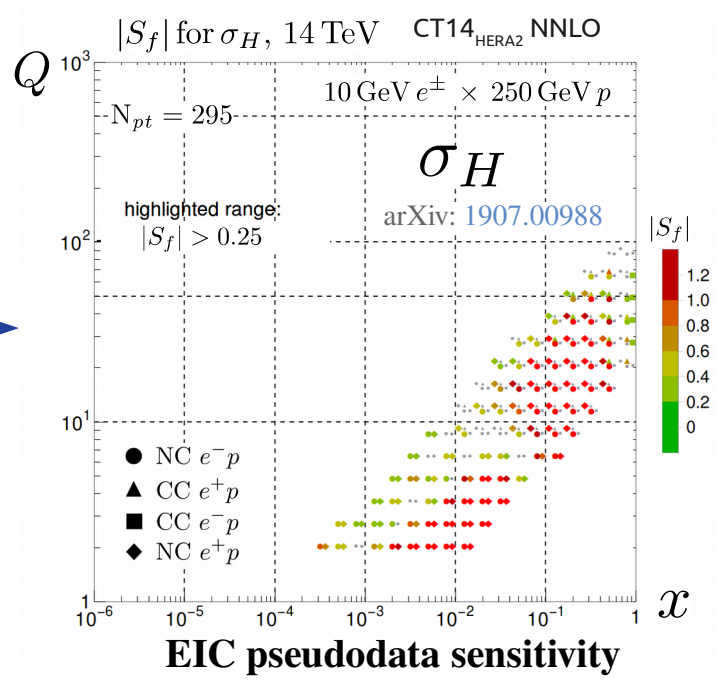
select topics



EIC pseudodata sensitivity

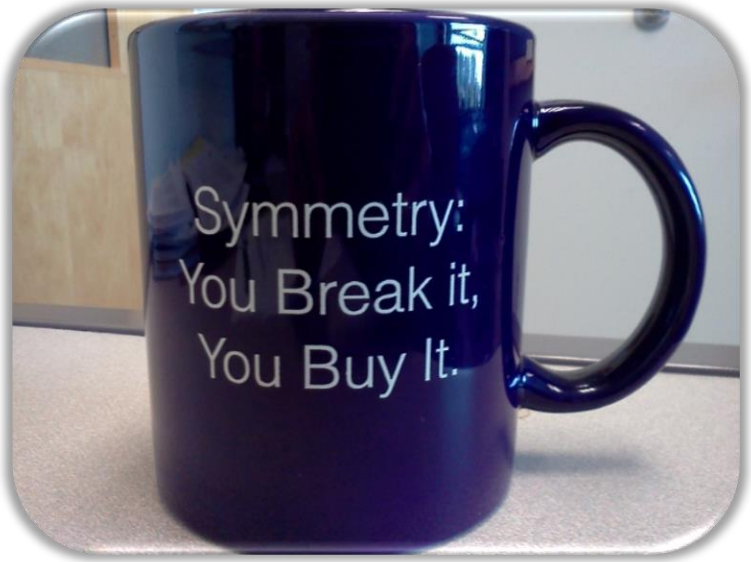
- progress will depend on various methods
  - → phenomenological studies; global analyses
  - → continuum QCD approaches
  - → lattice QCD input
  - → AI/machine-learning and MCEGs

- completed LoI available here

Backup Slides
More about Lattice PDFs

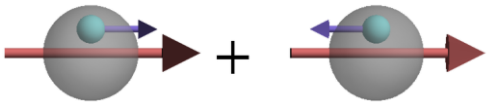
PDFs on the Lattice

- § Limited to the lowest few moments
  - For higher moments, all ops mix with lower-dimension ops
  - No practical proposal yet to overcome this problem
- § Relative error grows in higher moments
  - Calculation would be costly
  - Cannot separate valence contrib. from sea



PDFs on the Lattice

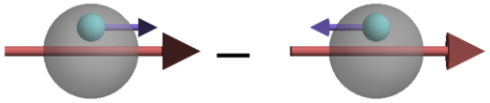
§ Lattice calculations rely on operator product expansion, only provide moments



spin-averaged/unpolarized

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

most well known



spin-dependent longitudinally polarized

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

spin-dependent transversely polarized

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

very poorly known

§ True distribution can only be recovered with all moments

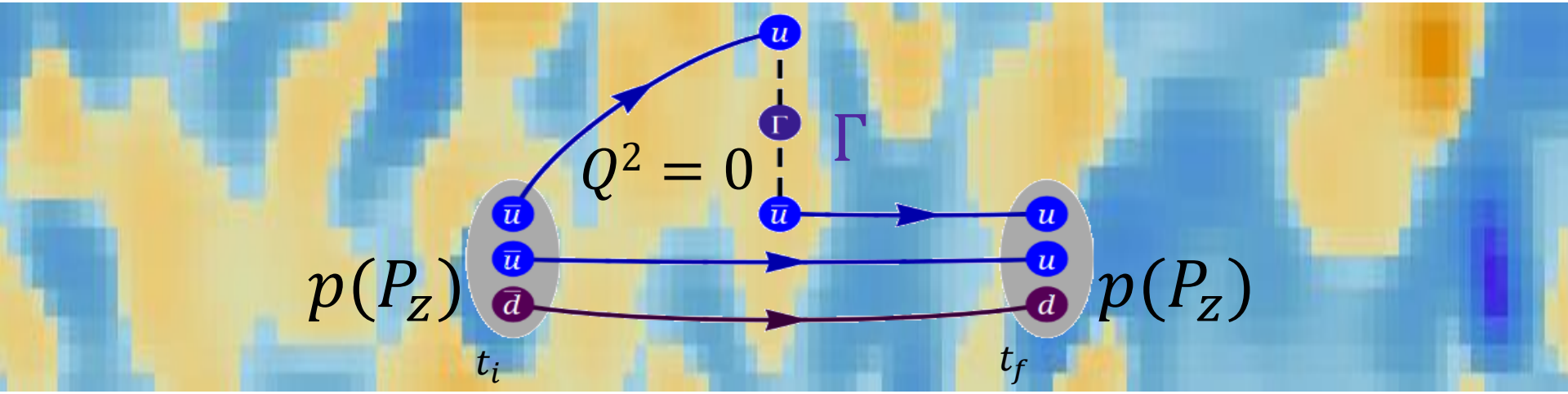
Direct x-Dependent Structure

§ Direct *x*-dependent structure:
Longstanding obstacle to lattice calculations!

- **Quasi-PDF**/large-momentum effective theory (LaMET) (X. Ji, 2013; See 2004.03543 for review)
- **Pseudo-PDF** method: differs in FT (A. Radyushkin, 2017)
- Lattice cross-section method (**LCS**) (Y Ma and J. Qiu, 2014, 2017)
- Hadronic tensor currents (Liu et al., hep-ph/9806491, … 1603.07352)
- Euclidean correlation functions (RQCD, 1709.04325)
- …

Quasi-PDF vs Pseudo-PDF

§ They both calculate the matrix element $h(z, P_z)$



§ Pseudo-PDF

- No renormalization

$$\mathcal{M}\left(zP_z, z^2\right) = \frac{h(z,P_z)}{h(z,0)}$$

- FT zP_z-space to x-space at fixed z^2

pseudo-PDF $\quad \tilde{\mathcal{M}}\left(x, z^2\right)$

§ Quasi-PDF

- Renormalization and ratios

$$h^R\left(z, P_z, P^R\right) \text{ or } \frac{h\left(z,P_z,P^R\right)}{h\left(z=0,P_z,P^R\right)}$$

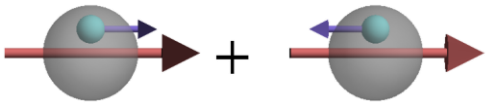
- FT z-space to x-space at fixed P_z

quasi-PDF $\quad \tilde{q}\left(x, P_z, P^R\right)$

- **Inverse problem to extract the wanted distribution**

Moments of PDFs

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



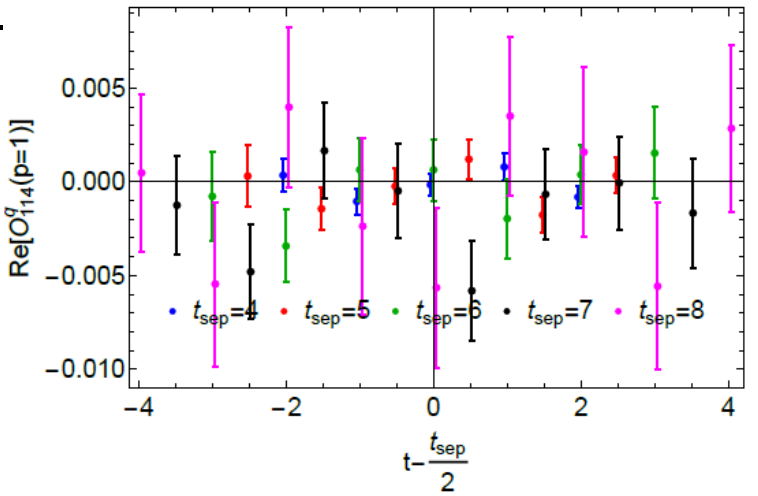
§ Strange-antistrange asymmetry

- There is no local operator for $\langle x \rangle_{s_-} = \int dx\, x\big(s(x) - \bar{s}\,(x)\big)$
- Global fit does not even constrain sign: $-0.001 < \langle x \rangle_{s_-} < 0.005$
- Second moment is measurable in lattice QCD:

$$\langle x^2 \rangle_{s_-} = \int dx\, x^2 \big(s(x) \cdot$$

- Challenge is to get the signal

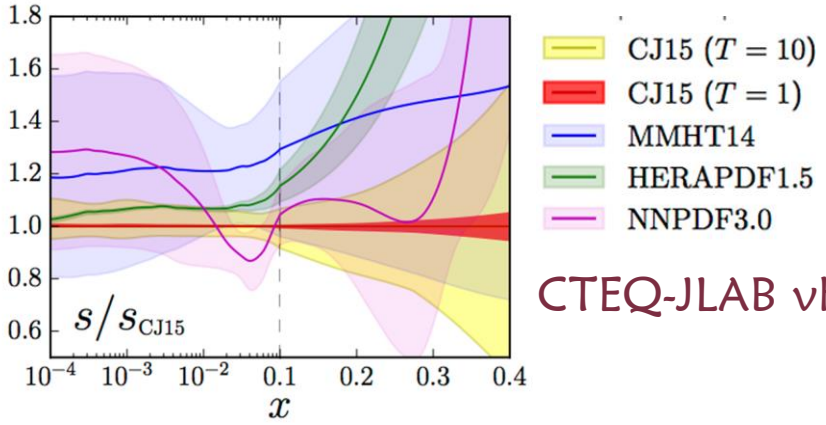
USQCD allocations support this effort



Preliminary result

First Lattice Strange PDF

§ Large uncertainties in global PDFs



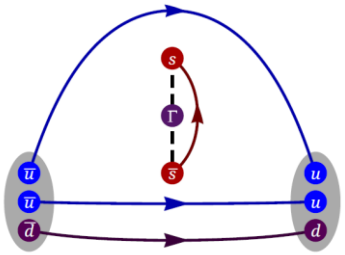
- Assumptions imposed due to lack of precision data

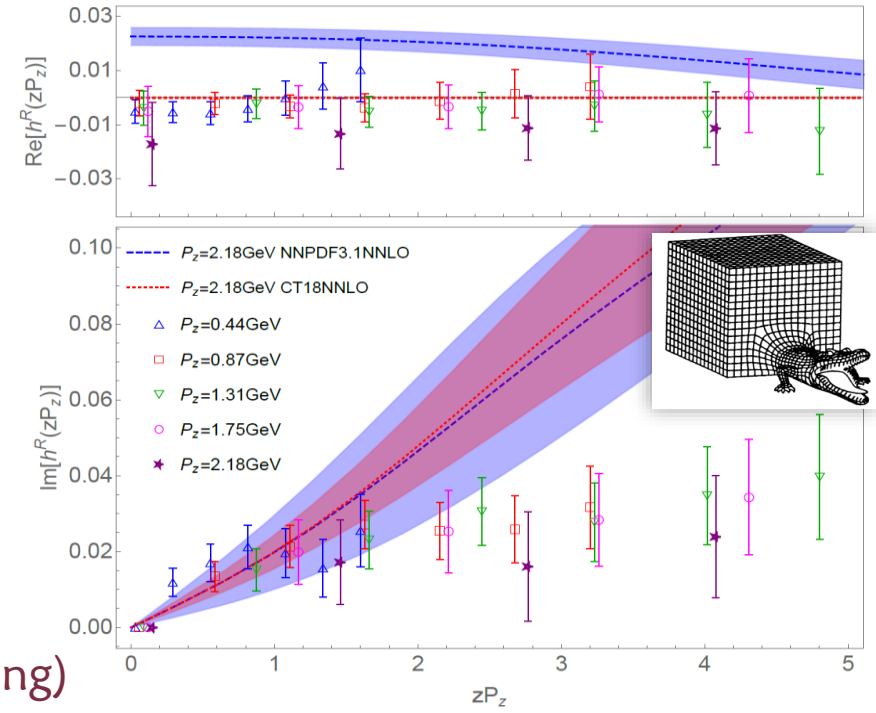
$$s = \bar{s} = \kappa(\bar{u} + \bar{d})$$

CTEQ-JLAB vhttps://www.jlab.org/theory/cj/

§ Results by MSULat/quasi-PDF method 2005.12015, Zhang, Lin, Yoon

- Clover on 2+1+1 HISQ,
  $a \approx 0.12$ fm
  extrapolated
  to $M_\pi \approx 140$ MeV



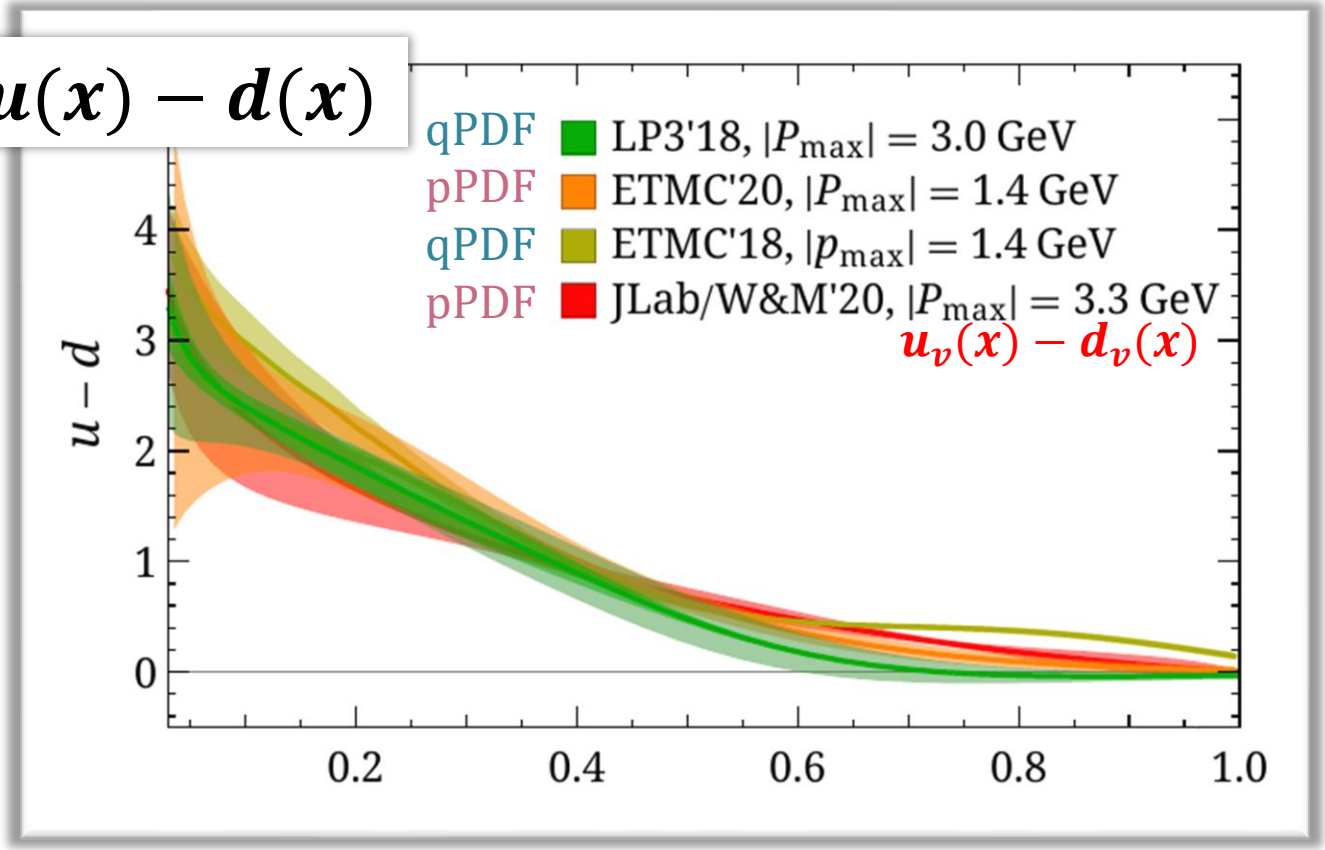


(plot by Rui Zhang)

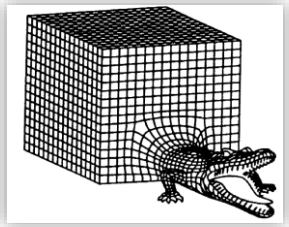
Physical Pion Mass Results

§ Summary of physical pion mass results

- Recent study increase boost momenta $P_z > 3$ GeV



2006.08636, PDFLattice2019 report



Finite volume,
Discretization,
…

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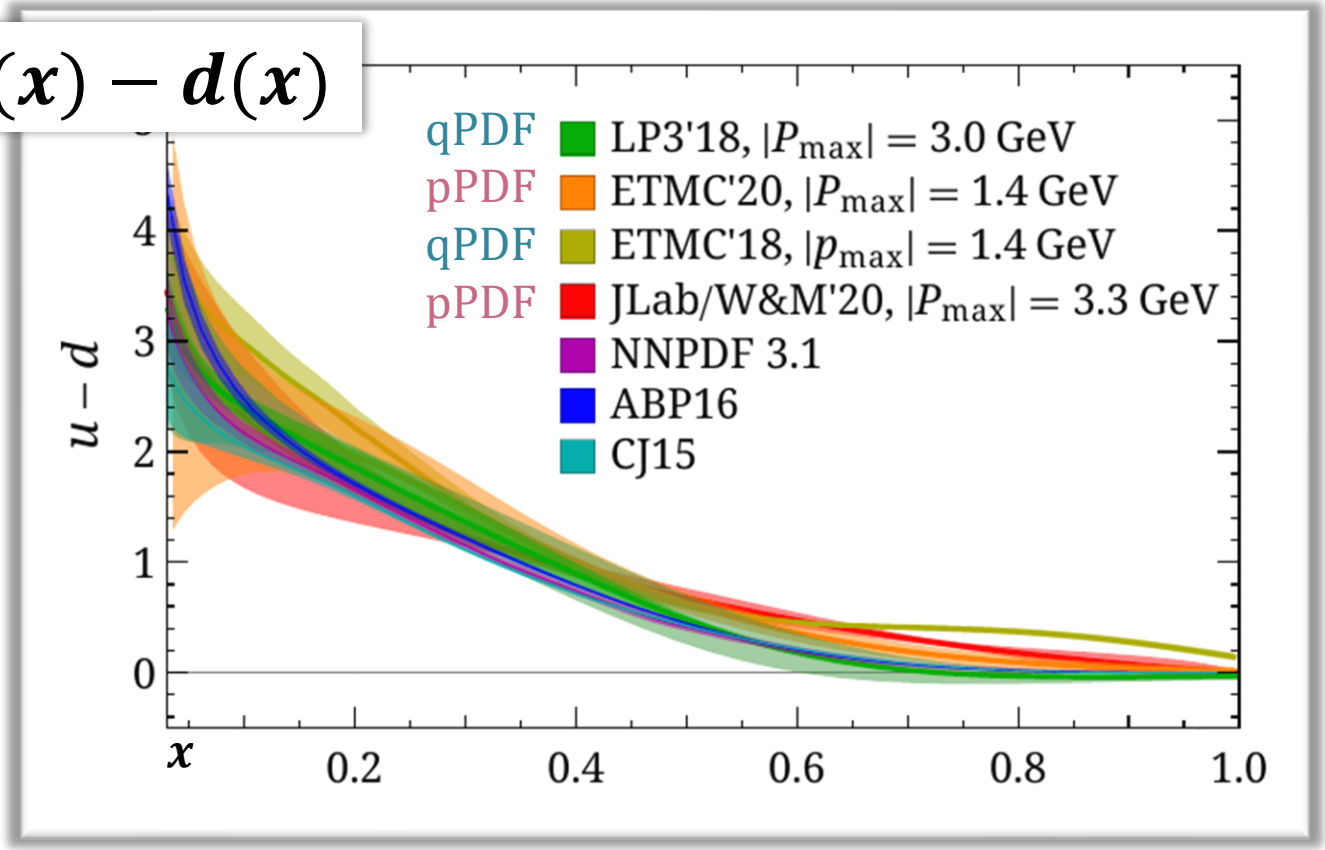
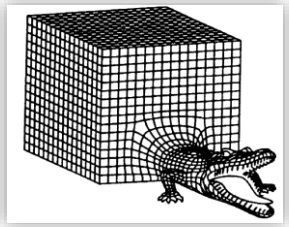
- Recent study increase boost momenta $P_z > 3$ GeV



2006.08636, PDFLattice2019 report



Finite volume,
Discretization,
…

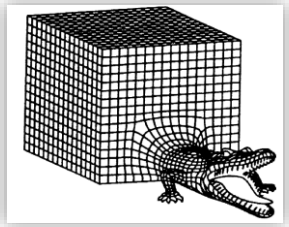
Polarized PDFs

§ Summary of physical pion mass results

- Quasi-PDF method only

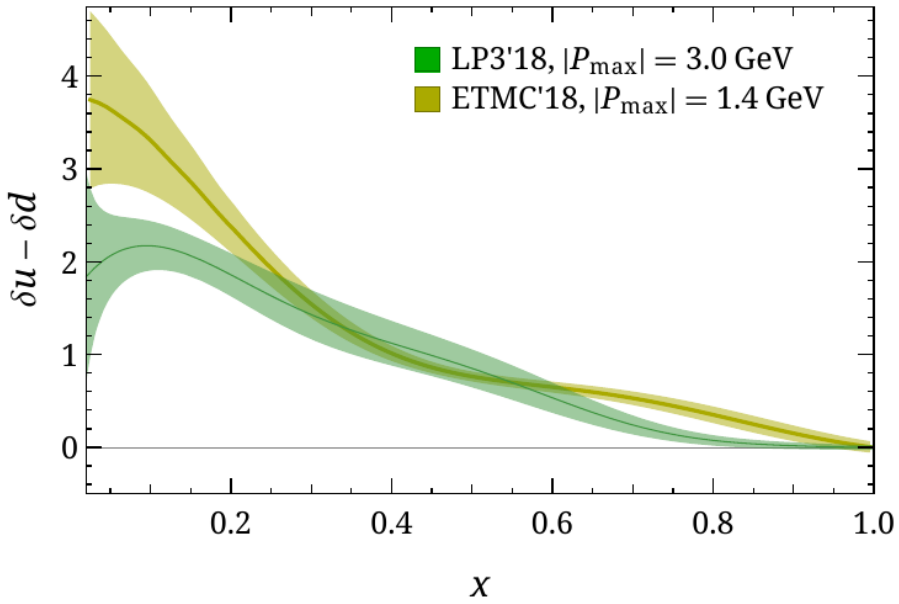
$$\delta u(x) - \delta d(x)$$

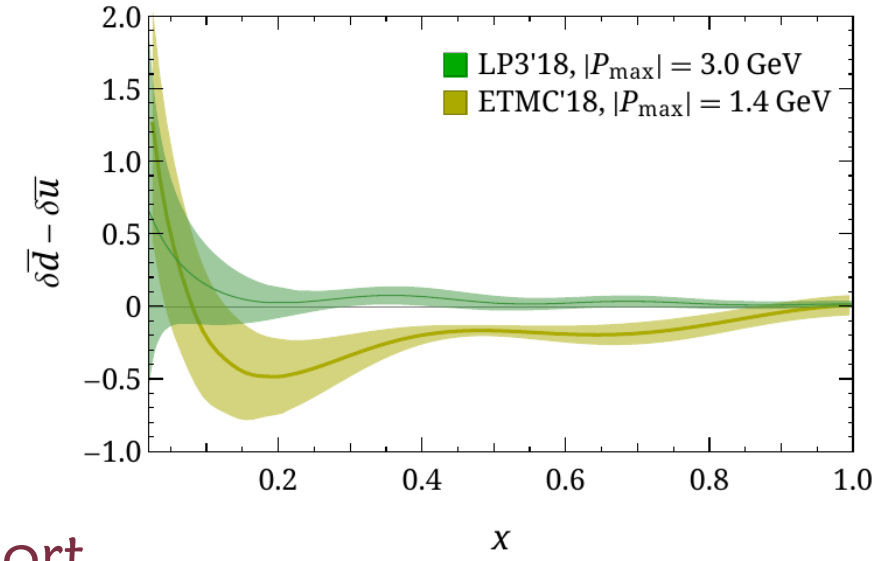
spin-dependent
transversely polarized



Finite volume,
Discretization,
…

$$\delta \bar{d}(x) - \delta \bar{u}(x)$$





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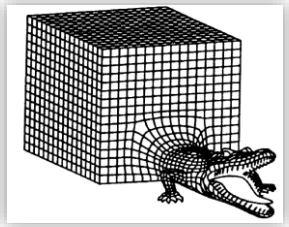

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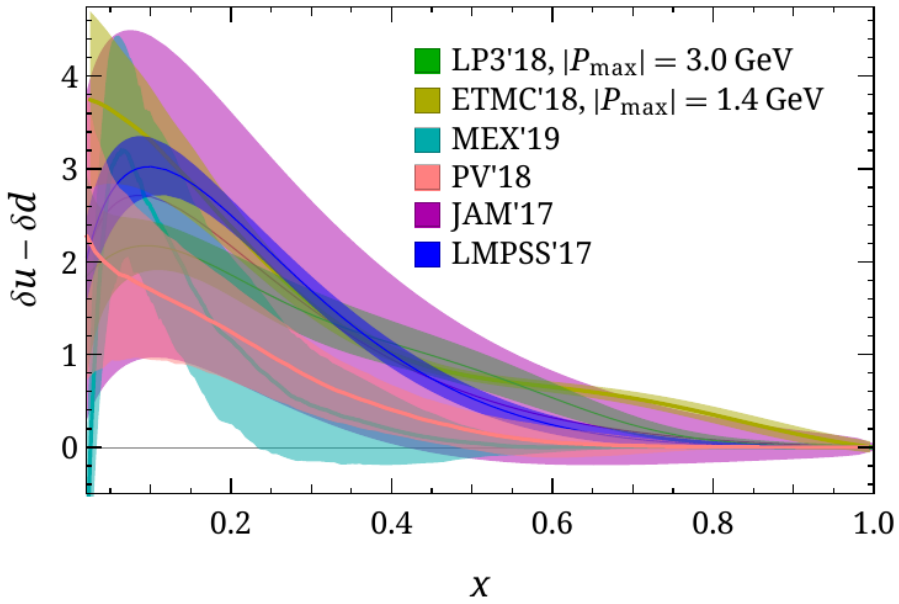

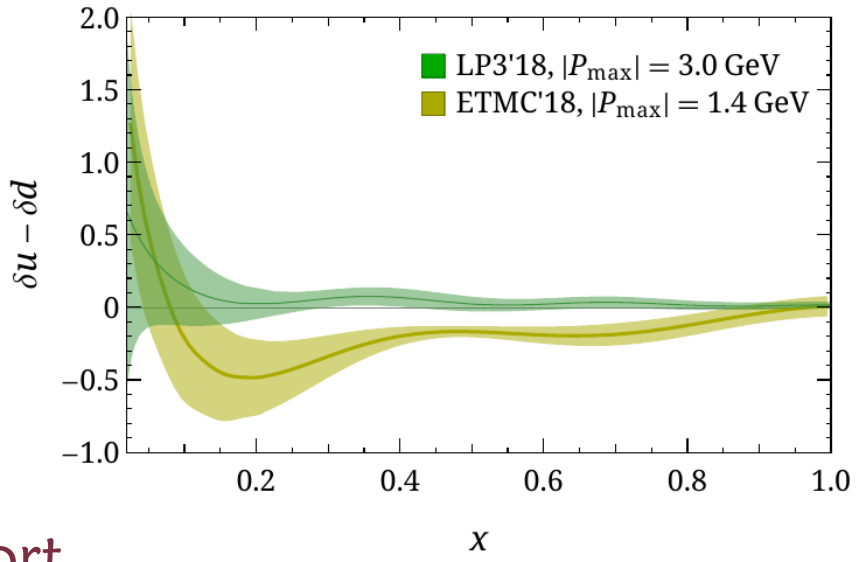

2006.08636, PDFLattice2019 report