March 28-31, 2017
Jefferson Lab, Newport News, VA

The Role of JLab Theory Center in Supporting the JLab/CLAS12 Science Program

Jianwei Qiu
Theory Center, Jefferson Lab

March 29, 2017

Key roles of Theory at JLab

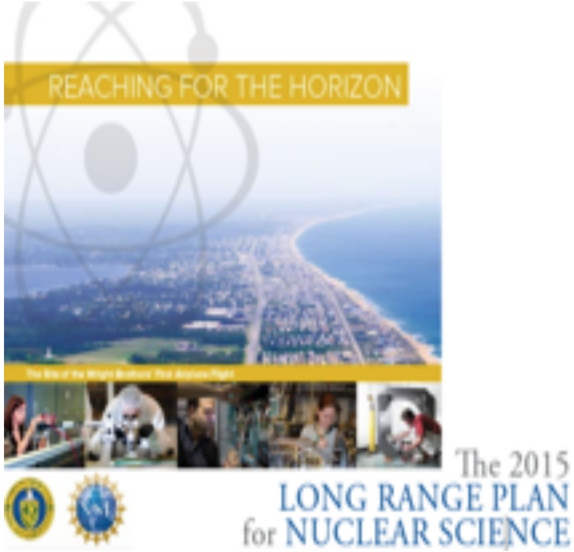
As presented at the recent Comparative Review of DOE Labs' NP theory groups
September, 2016

- Lead scientific campaigns
  - Compute spectrum, structure & dynamics of hadrons in QCD
  - Determine structure and binding forces within nuclei
  - Tests of fundamental symmetries
- Guide & support JLab 12GeV program
  - Contribute to PAC
  - members Involvement in expt. proposals and analysis efforts
- Contribute to intellectual leadership of NP program
  - Visitor program, conferences/workshops
  - Foundational documents for NSAC/DOE/NSF
- National & Global Initiatives:
  - Next generation expts. with JLab 12, Electron Ion Collider (EIC), and other facilities
  - LQCD scientific campaigns including software & hardware
  - International efforts for data-analysis, including JPAC, JAM, CTEQ & PARTONS
  - Topical collaborations
- Support workforce development, education and outreach

Science Campaigns – the JLab Theory Program

- *Focus on 3 of the 5 Research Areas identified in 2015 NSAC LRP Document*

  Area 1 – QCD and the structure of hadrons and nuclei
  Area 3 – Nuclear structure and reactions
  Area 5 – Fundamental symmetries and neutrinos



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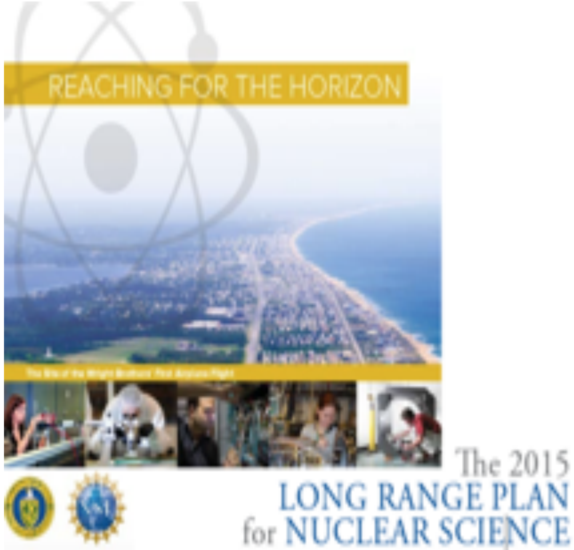

- ❑ ***QCD and the structure of hadrons and nuclei***
  - ✧ **Quark structure of Hadrons**

    Accardi, Balitsky, Melnitchouk, Orginos, Prokudin, Radyushkin, Qiu, Richards, Rogers, Shanahan, Weiss
  - ✧ **Hadron spectroscopy**

    Doring, Dudek, Edwards, Goity, Richards, Passemar, Szczepaniak
  - ✧ **QCD & Nuclei**

    Accardi, Melnitchouk, Orginos, Qiu, Weiss
  - ✧ **Electron-Ion Collider**
- ❑ ***Nuclear structure and reactions***

  Goity, Schiavilla, Van Orden
- ❑ ***Fundamental symmetries and neutrinos***

  Melnitchouk, Schiavilla, Van Orden

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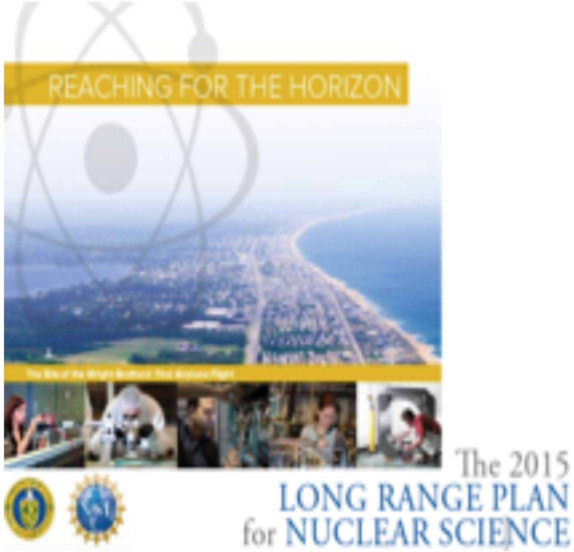

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  Melnitchouk, Schiavilla, Van Orden

These are effectively the same focuses of JLab/CLAS12 science program!

Science Campaigns – the JLab Theory Program

- ***Focus on 3 of the 5 Research Areas identified in 2015 NSAC LRP Document***

  Area 1 – QCD and the structure of hadrons and nuclei
  Area 3 – Nuclear structure and reactions
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- ***Major Research programs in Hall B:***
  - **to measure the spectrum of excited states of the nucleon**
  - **to perform three dimensional imaging of the quark structure of the nucleon**
  - **to characterize nucleon-nucleon correlations in nuclei**
  - **to search for the existence of heavy photons**

(http://www.jlab.org/Hall-B/)

These are effectively the same focuses of JLab/CLAS12 science program!

QCD and the structure of hadrons and nuclei

- **Challenge:**

  No modern detector can see quarks and gluons in isolation!

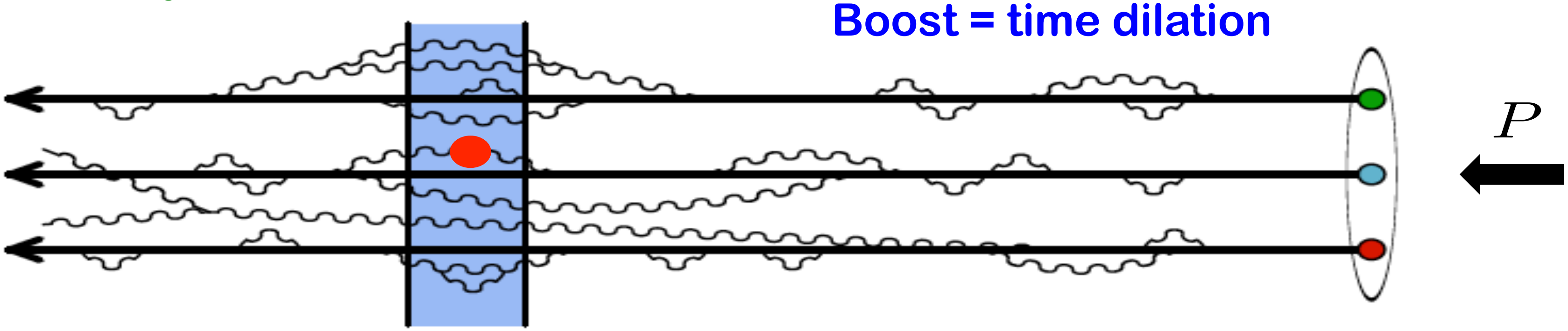
QCD and the structure of hadrons and nuclei

- **Challenge:**

  No modern detector can see quarks and gluons in isolation!

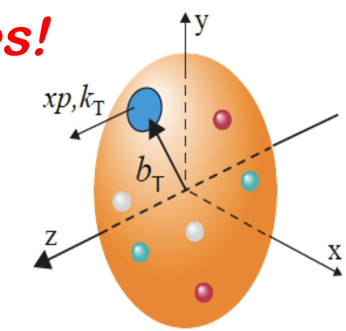
- **How to probe the structure?**

  Boost = time dilation



Hard probe ($t \sim 1/Q$ < fm): Catches the particle features!

- ✧ Longitudinal momentum fraction – x : $xP \sim Q$
- ✧ Transverse momentum – k_T: $1/R \sim \Lambda_{\rm QCD} \ll Q$
- ✧ Transverse position – b_T : $R \sim 1/\Lambda_{\rm QCD} \gg 1/Q$



- **Question:**

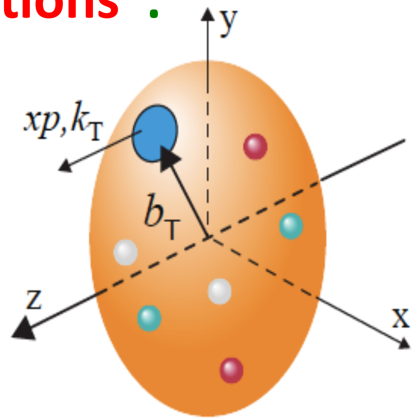
  How to quantify the hadron structure if we cannot see quarks and gluons?

- **Answer:** QCD factorization (*controllable approximation*)!

  Matching hadrons to quarks/gluons – experiment/theory collaboration!

QCD and the structure of hadrons and nuclei

❑ **The structure of a colliding hadron – encoded in "distributions":**



✧ ***Parton Distribution Functions (PDFs)***

Probability density to find a parton of a given flavor carrying the hadron's fractional momentum, *xP* (1-D): $q(x,Q^2)$

– Catches the quantum fluctuations, resolution – 1/Q …

✧ ***Polarized Parton Distribution Functions (pPDFs)***

Probability density to find a polarized parton of a given flavor carrying the hadron's fractional momentum, *xP* (1-D): $\Delta q(x,Q^2)$

– Correlations of hadron & parton spin states, resolution – 1/Q …

✧ ***Generalized Parton Distribution Functions (GPDs)***

Probability density to find a parton carrying the 1-D momentum fraction, *x*, at the impact parameter, b_T, of the colliding hadron: $H_q(x,\xi,t,Q^2)$, … t ➔ b_T *(FT)*

– Spatial Imaging, color confining radius (moments of b_T-distribution, …), …

✧ ***Transverse Momentum Dependent Parton Distribution Functions (TMDs)***

Probability density to find a parton carrying the 3-D momentum (1-D longitudinal momentum fraction, x, plus 2-D transverse motion, k_T): $q(x,k_T,Q^2)$, …

– Confined motion, spin-orbital correlations, …

PDFs at large x

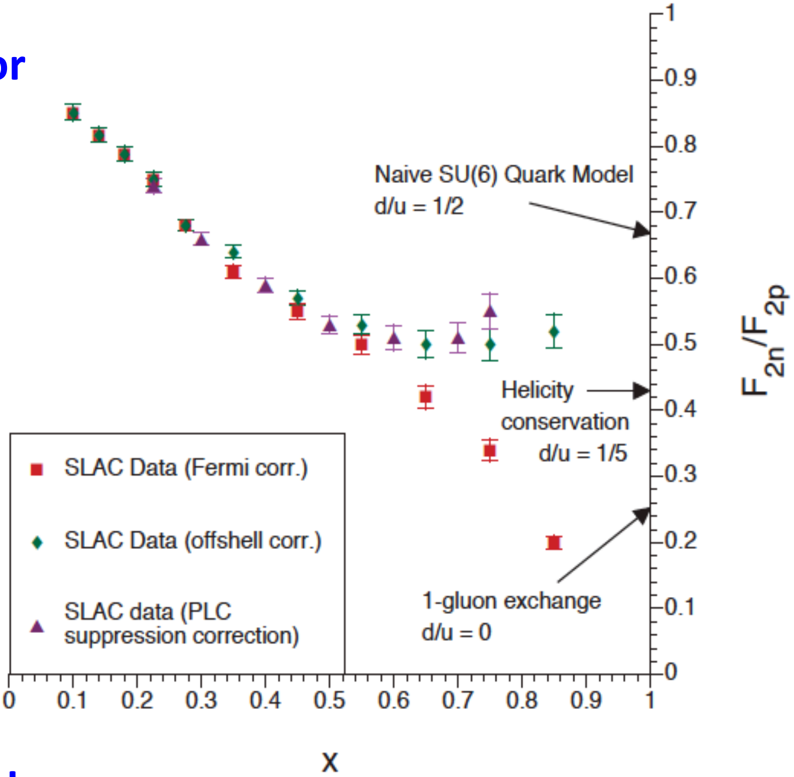
❑ **Testing ground for hadron structure at x → 1:**

✧ $d/u \to 1/2$ — **SU(6) Spin-flavor symmetry**

✧ $d/u \to 0$ — **Scalar diquark dominance**

✧ $d/u \to 1/5$ — **pQCD power counting**

✧ $$d/u \to \frac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \approx 0.42$$ — **Local quark-hadron duality**



Hall B: E12-06-113
The structure of the free neutron at large-x_B
+ …

PDFs at large x

❑ **Testing ground for hadron structure at x → 1:**

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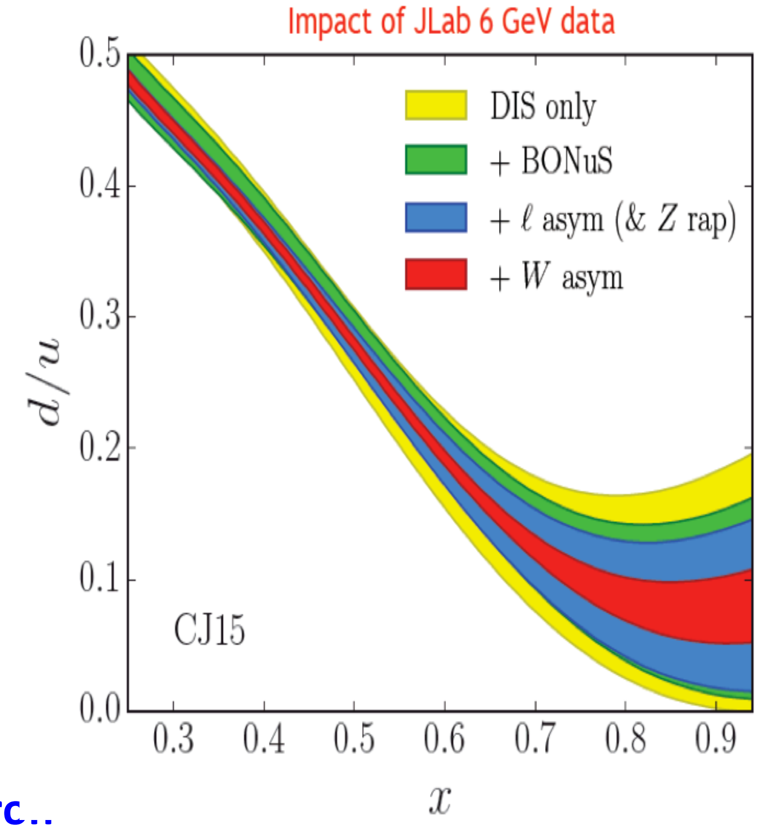


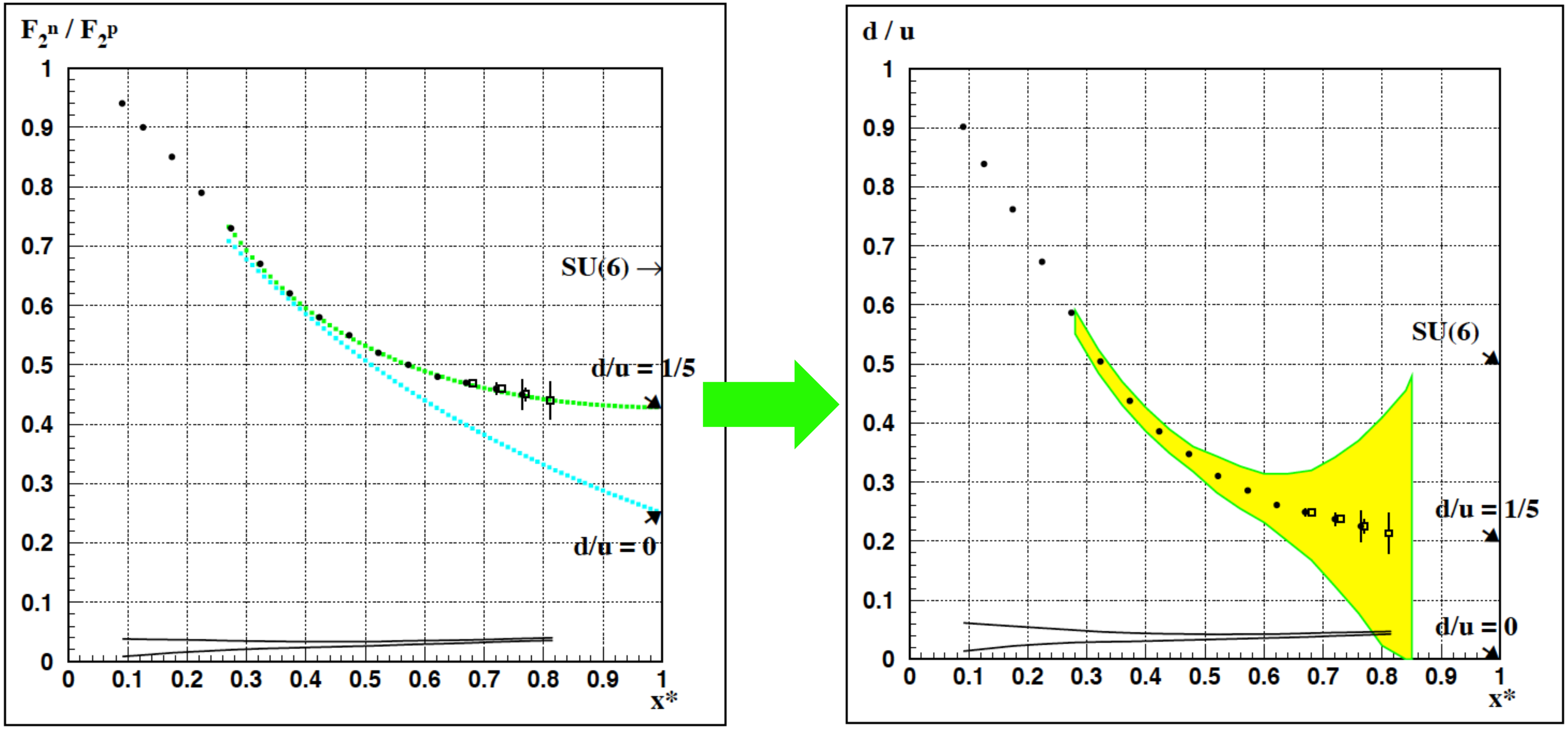
Accardi, Brady, Melnitchouk, Owens, Sato

PRD 93 (2016) 074005 & 114017

Jefferson Lab Angular Momentum Collaboration

Hall B Experiments

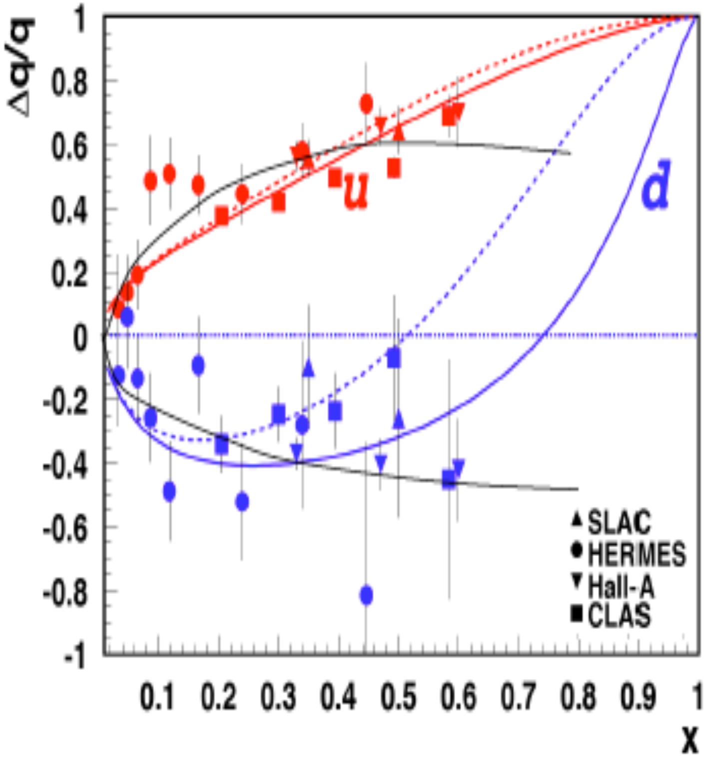
- E12-06-113:



Plus other JLab experiments and Fermilab E906, …

PDFs at large x

- **Polarized PDFs at x → 1:**



SU(6) Spin-flavor symmetry

✧ $\Delta u/u \to\ 2/3$

$\Delta d/d \to -1/3$

Scalar diquark dominance

✧ $\Delta u/u \to\ 1$

$\Delta d/d \to -1/3$

pQCD power counting

✧ $\Delta u/u \to 1$

$\Delta d/d \to 1$

Local quark-hadron duality

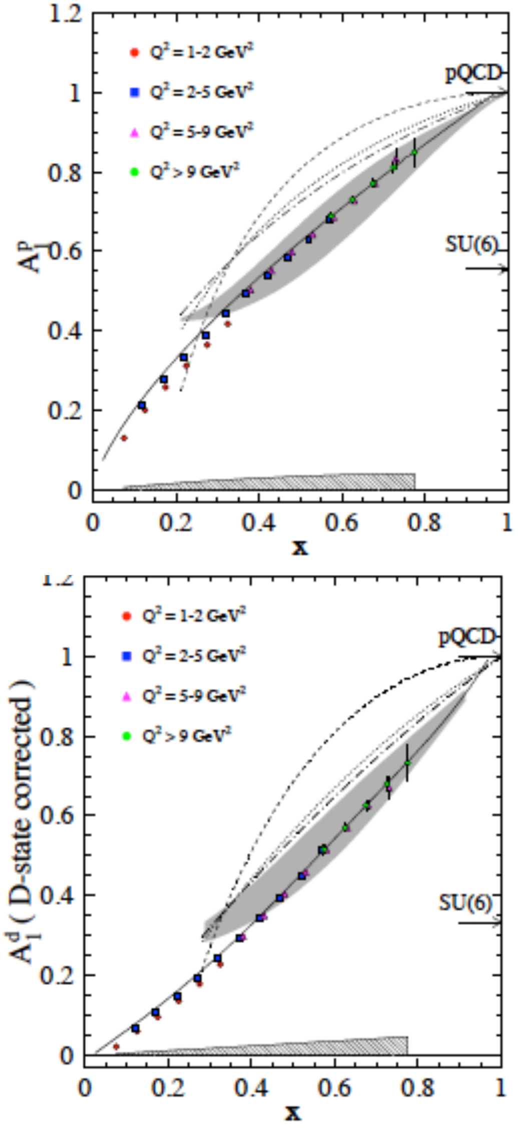
✧ $\Delta u/u \to 1$

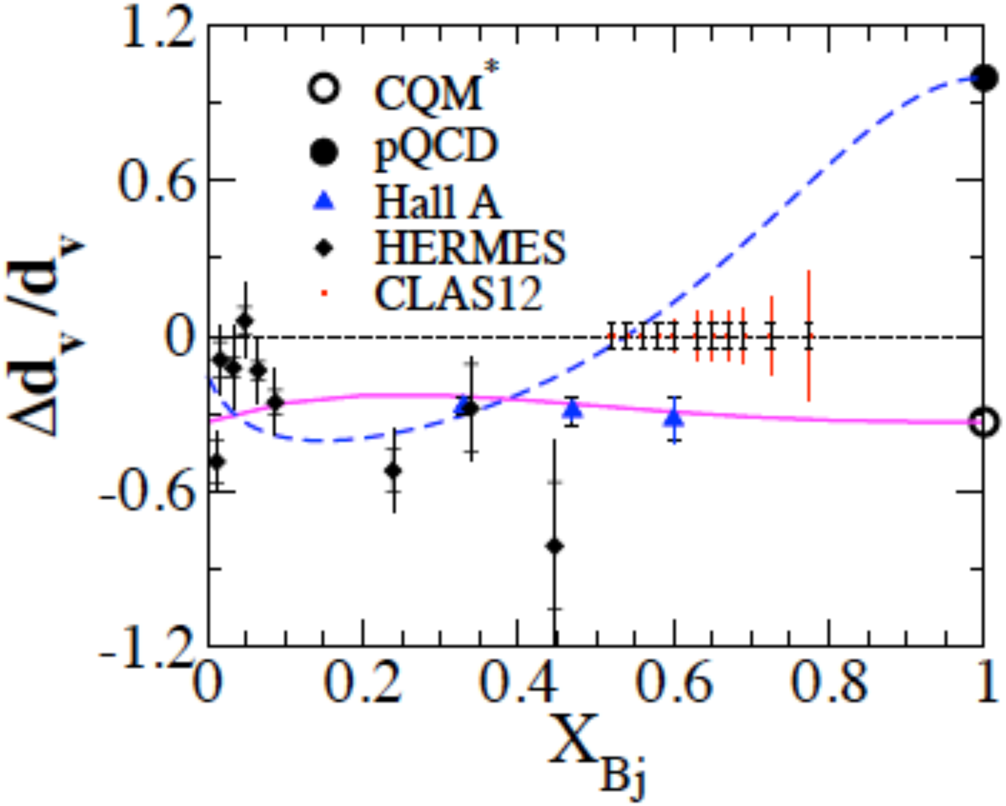
$\Delta d/d \to 1$

Hall B Expt: E12-06-109
+ …

Hall B Experiments

- E12-06-109:





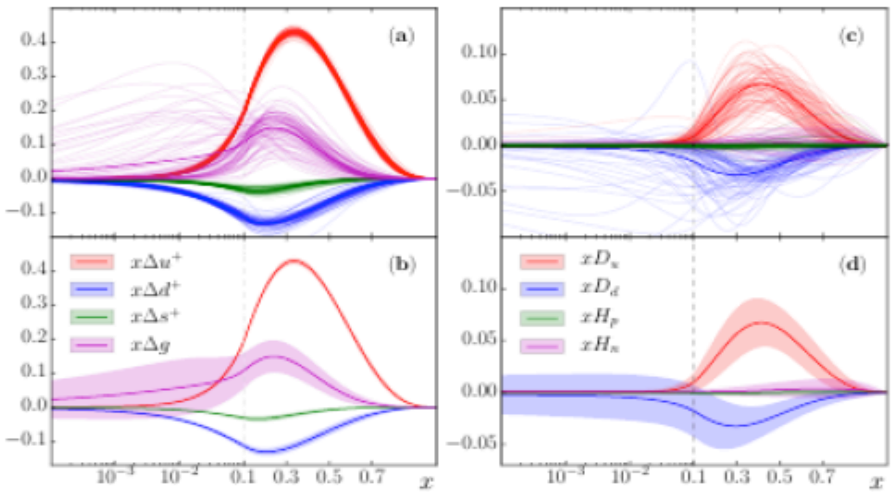
Plus JLab experiments from other Hall's

Plus complementary Lattice QCD effort

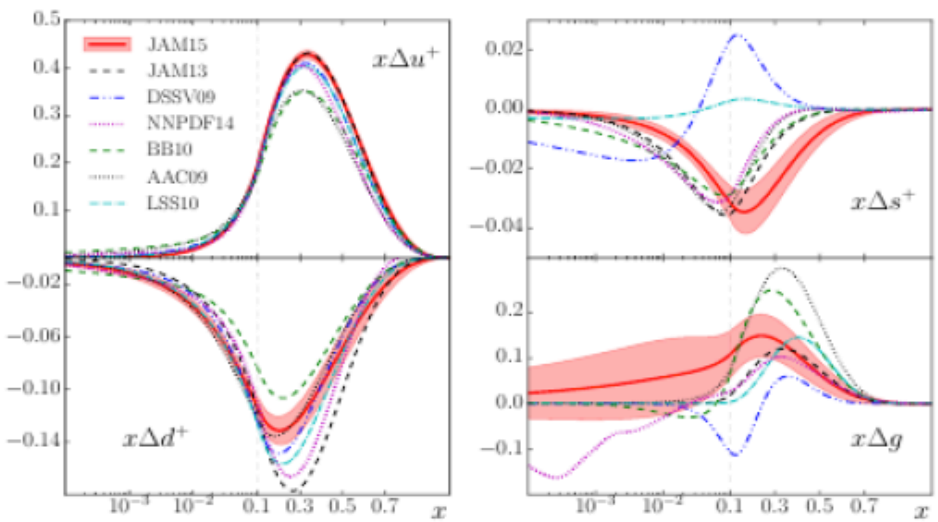
JLab Theory Effort

The JAM15 polarized PDFs

Accardi @ PDFLattice2017
23 March 2017



moment	truncated	full
Δu^+	0.82 ± 0.01	0.83 ± 0.01
Δd^+	-0.42 ± 0.01	-0.44 ± 0.01
Δs^+	-0.10 ± 0.01	-0.10 ± 0.01
$\Delta\Sigma$	0.31 ± 0.03	0.28 ± 0.04
ΔG	0.5 ± 0.4	1 ± 15
d_2^p	0.005 ± 0.002	0.005 ± 0.002
d_2^n	-0.001 ± 0.001	-0.001 ± 0.001
h_p	-0.000 ± 0.001	0.000 ± 0.001
h_n	0.001 ± 0.002	0.001 ± 0.003

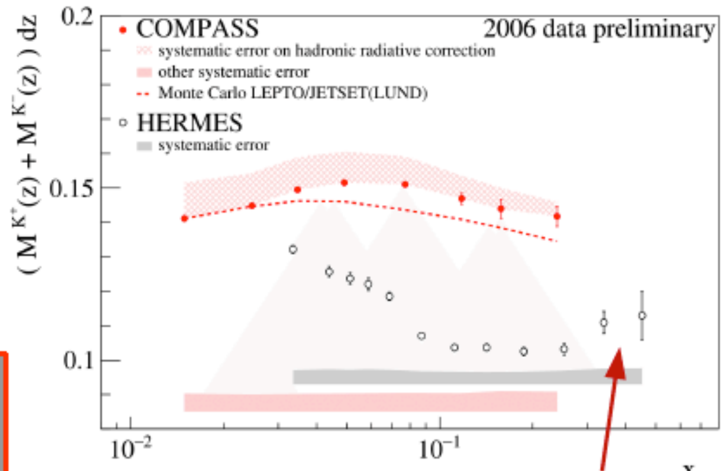


- Significant constraints on Δs^+ and Δg
- Non zero T3 quark distributions
- T4 contribution to g_1 consistent with zero
- **Negative Δs^+**
- JAM15 Δg compatible with recent DSSV fits.

Strange strange kaons

Accardi @ PDFLattice2017
23 March 2017

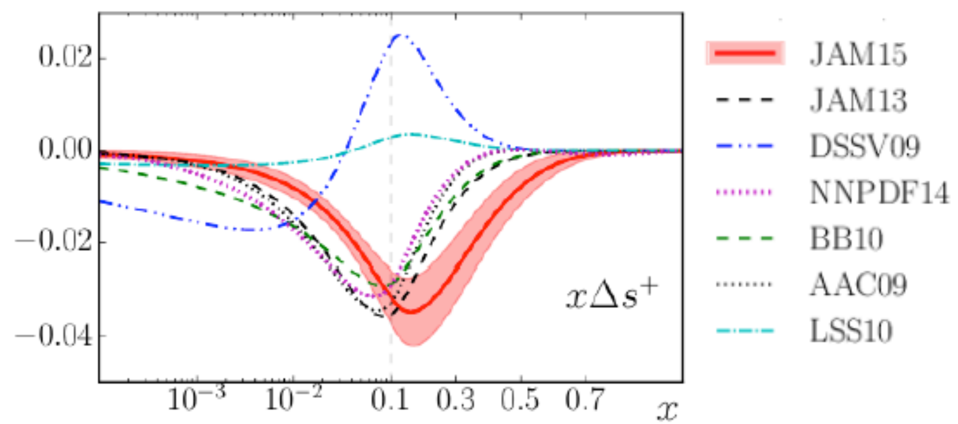
- s : large or small?
  - Possibly, large Hadron Mass effects
    Guerrero, Accardi, in preparation
  - Extraction of s(x) strongly affected by **kaon FF systematic uncertainty**



Non-perturbative strange ???

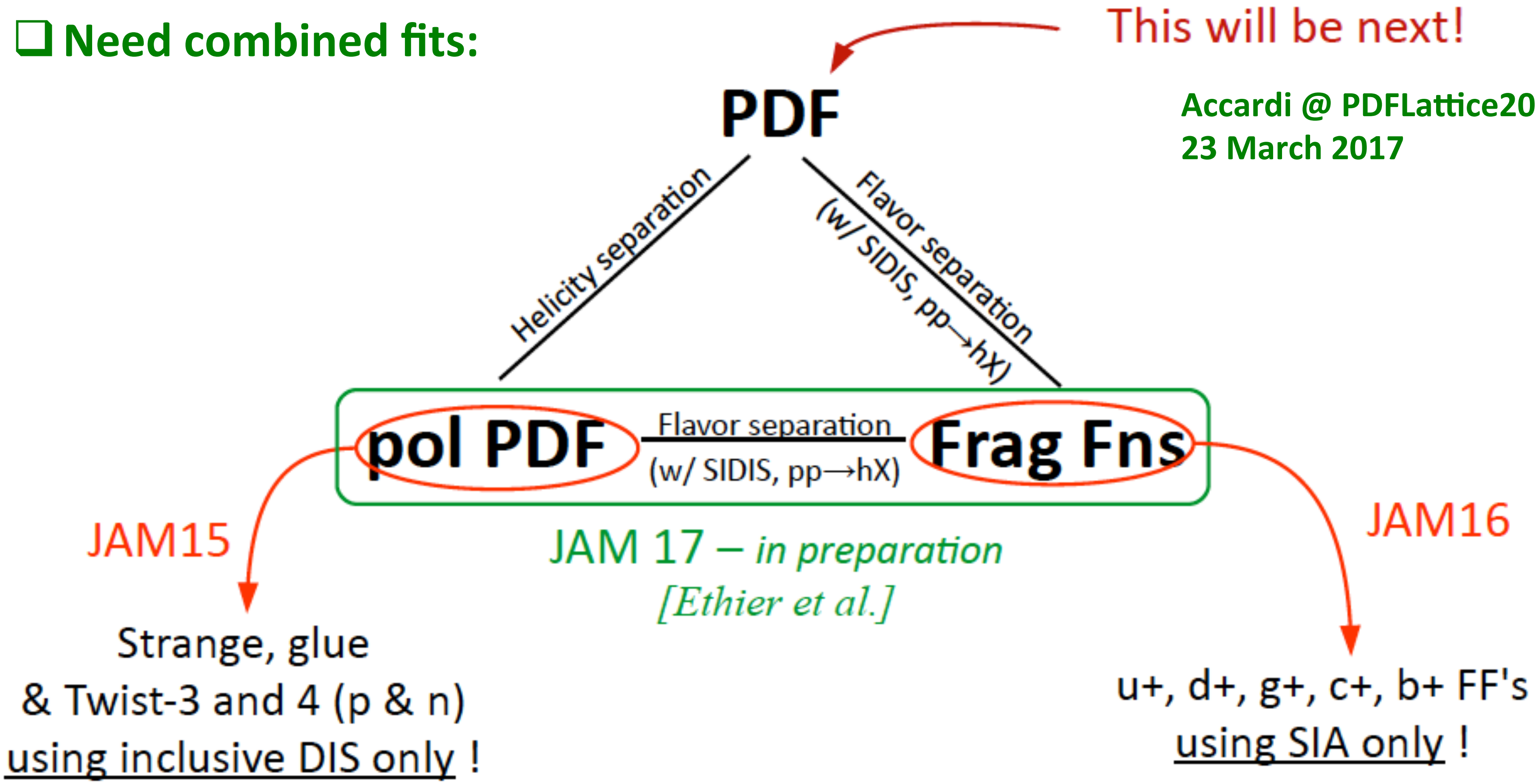
Lattice guidance?
(does not need precision)

- Δs : positive or negative?
  - Depends on **kaon FF used in SIDIS calculations!**
  - What about the unpol s ?



JLab Theory Effort

❑ **Need combined fits:**



Accardi @ PDFLattice2017
23 March 2017

Iterative Monte Carlo:
the JAM approach

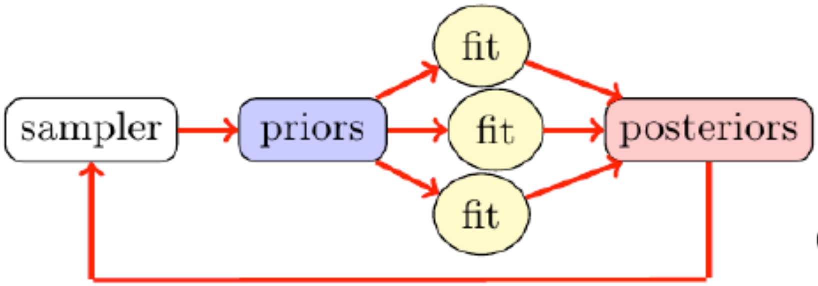
Sato, Ethier, Melnitchouk, Kuhn, Accardi, Hirai, Kumano

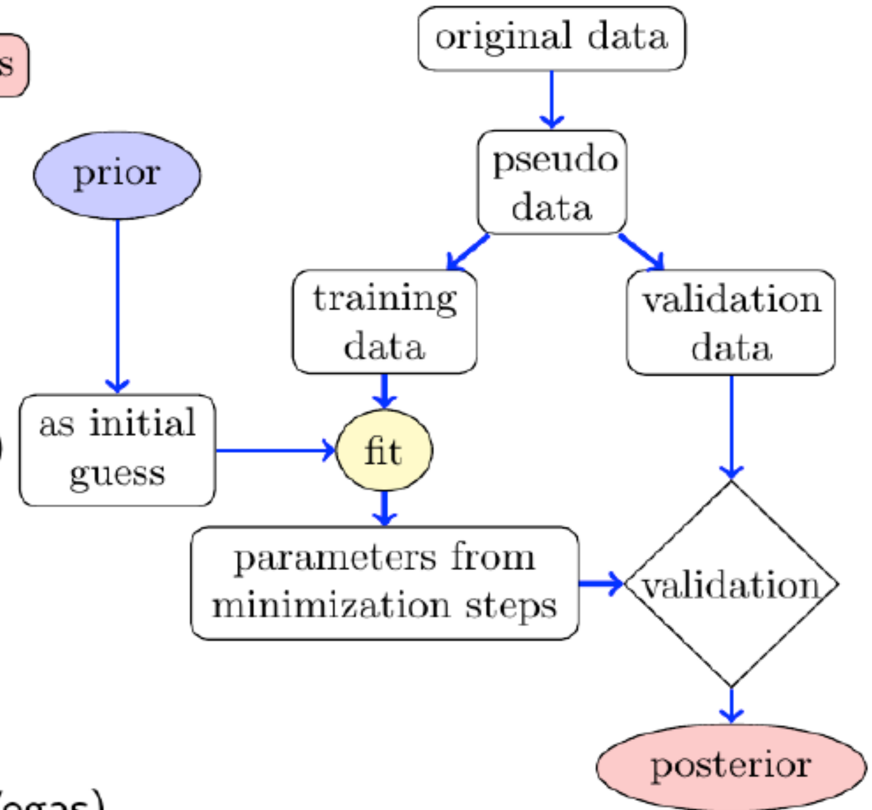
PRD93 (2016) 074005 and PRD94 (2016) 114004

JLab Theory Effort

Iterative Monte Carlo (IMC) analysis

Accardi @ PDFLattice2017
23 March 2017



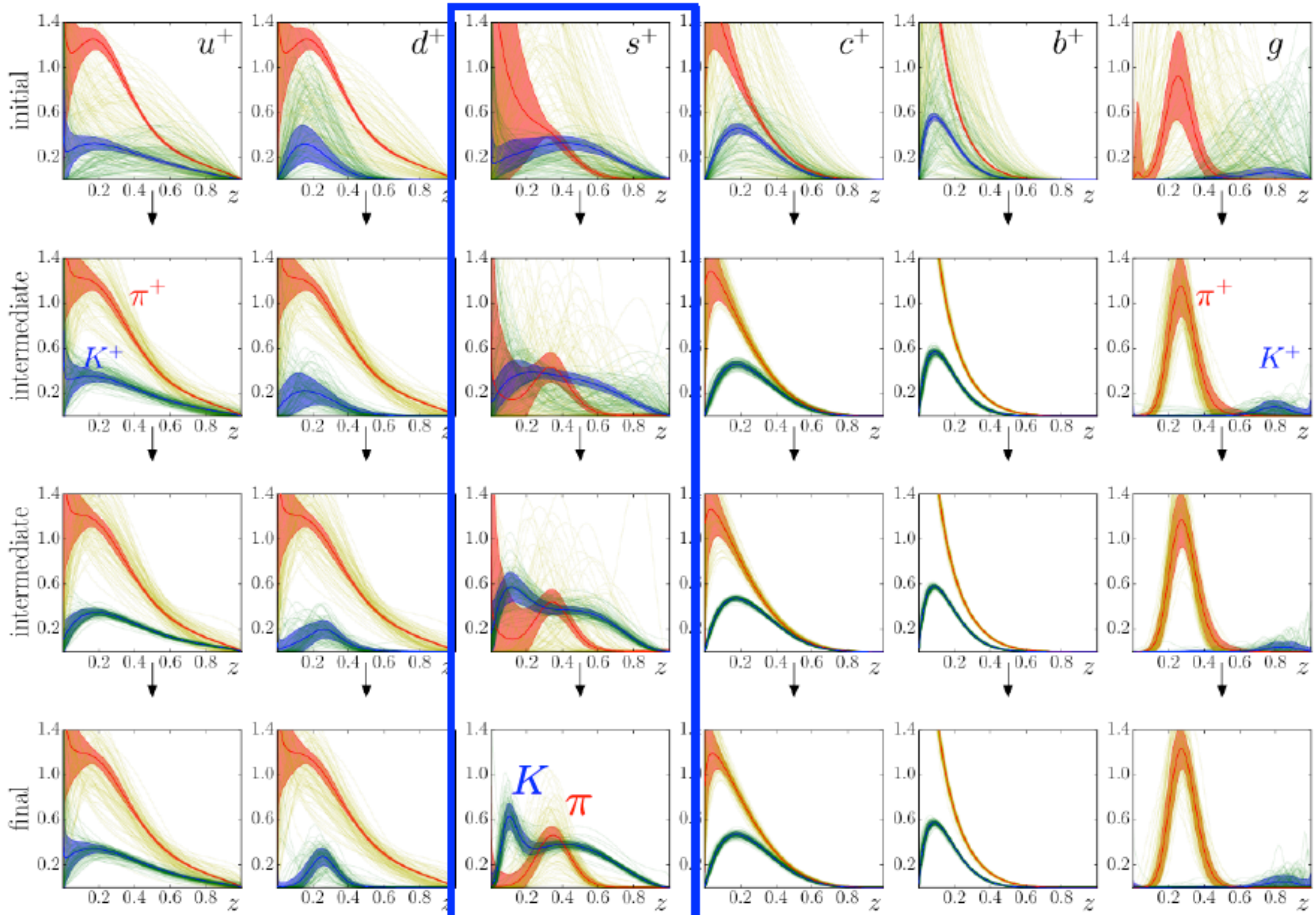


- Use traditional ansatz
  $xf(x) = Nx^a(1-x)^b(1+c\sqrt{x}+dx)$
- Keep all the parameters free.
  No assumptions on the exponents
- Avoid over-fitting by Cross-Validation
- **Iterative procedure**
  $\rightarrow$ Adaptive MC integration (like in Vegas)
- Robust estimation of uncertainties

JLab Theory Effort

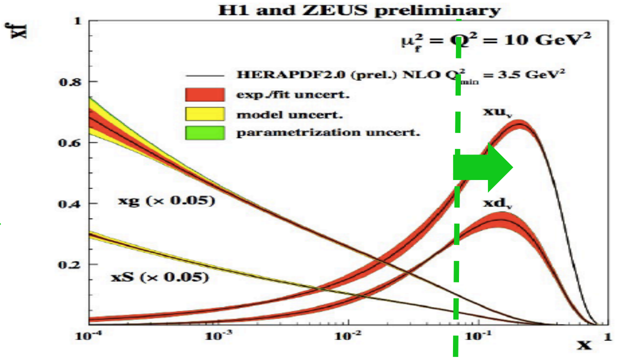
Accardi @ PDFLattice2017
23 March 2017

IMC method in action



Lattice calculations of hadron structure

Lattice QCD



X-dep distributions

- New ideas – from quasi-PDFs (lattice calculable) to PDFs:
  - High P_z effective field theory approach:

$$\tilde{q}(x,\mu^2,P_z) = \int_x^1 \frac{dy}{y} Z\left(\frac{x}{y},\frac{\mu}{P_z}\right) q(y,\mu^2) + \mathcal{O}\left(\frac{\Lambda^2}{P_z^2},\frac{M^2}{P_z^2}\right)$$

Ji, et al., arXiv:1305.1539 1404.6680

  - QCD collinear factorization approach:

$$\tilde{q}(x,\mu^2,P_z) = \sum_f \int_0^1 \frac{dy}{y} \mathcal{C}_f\left(\frac{x}{y},\frac{\mu^2}{\bar{\mu}^2},P_z\right) f(y,\bar{\mu}^2) + \mathcal{O}\left(\frac{1}{\mu^2}\right)$$

Ma and Qiu, arXiv:1404.6860 1412.2688
Ishikawa, Ma, Qiu, Yoshida, 1609.02018
Monohan, Orginos, 1612.01584
…

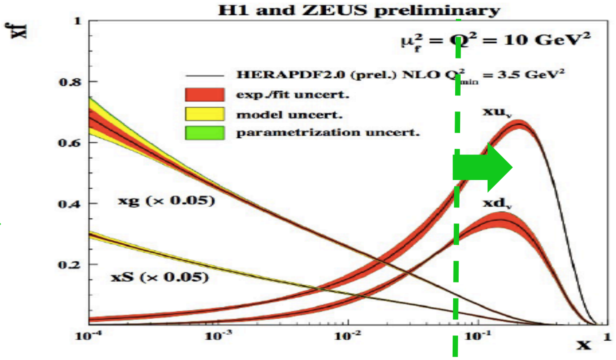
Non-perturbative lattice UV renormalization:
Effective mass renormalization, Gradient flow, …

- The TMD Collaboration + on-going effort around the world!

Plus the intense local JLab theory effort!

Lattice calculations of hadron structure

Lattice QCD



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Ji, et al., arXiv:1305.1539, 1404.6680

✧ **QCD collinear factorization approach:**

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Non-perturbative lattice UV renormalization:

Effective mass renormalization, Gradient flow, …

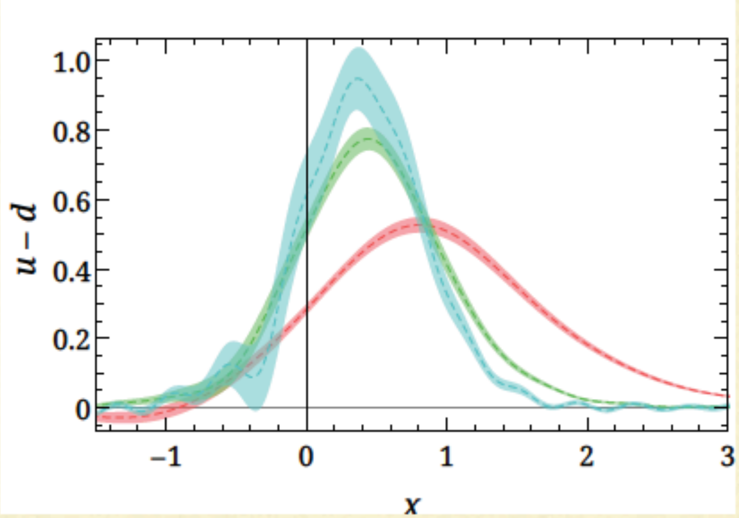
❑ Tremendous potentials!

PDFs of proton, neutron, pion, …; TMDs, GPDs, …; JLab12 expts

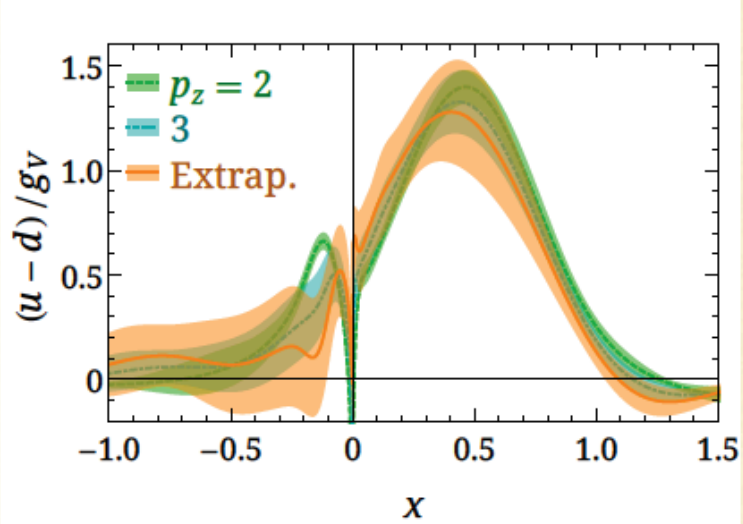
Lattice calculations of hadron structure

First Lattice results (Chen et. al)

Kostas Orginos, JLab 3D Workshop



Convergence with momentum extrapolation



Including the 1-loop matching kernel

Plots taken from: Chen et al. arXiv:1603.06664

Similar results have been achieved by Alexandrou et. al (ETMC)

3D Nucleon Tomography – GPDs

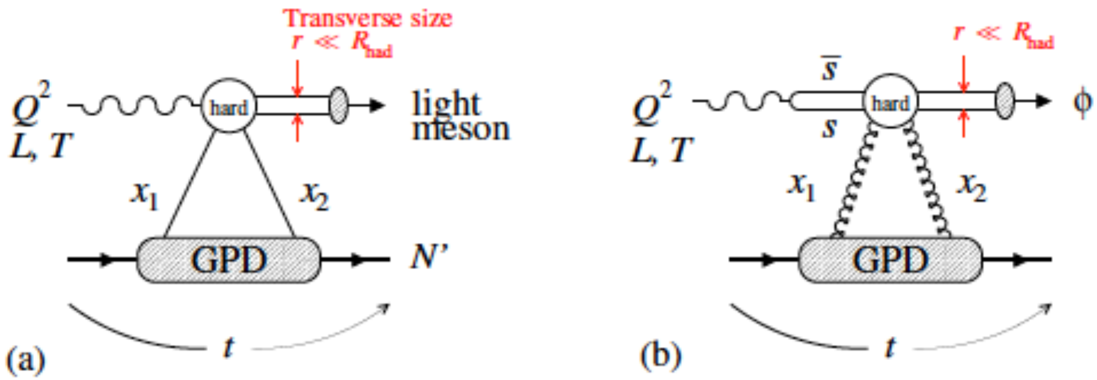
❑ Theory member involved in experimental proposal:

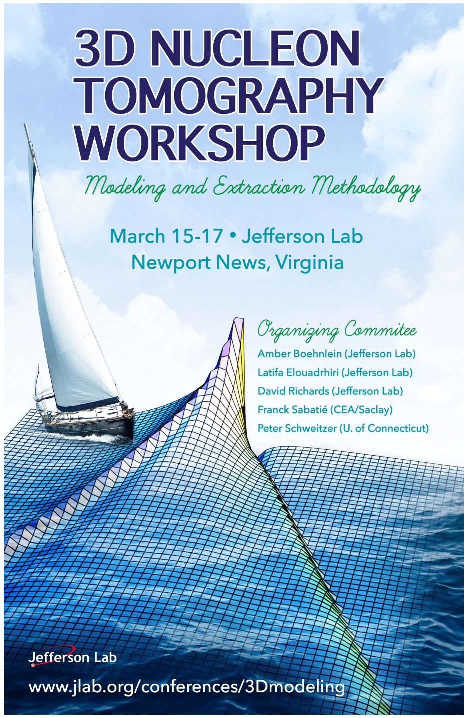
Proposal to Jefferson Lab PAC39

Exclusive Phi Meson Electroproduction with CLAS12

H. Avakian,[1] J. Ball,[2] A. Biselli,[3] V. Burkert,[1] R. Dupr,[2] L. Elouadrhiri,[1]
R. Ent,[1] F.–X. Girod,[1,*] S. Goloskokov,[4] B. Guegan,[5,6] M. Guidal,[5,*]
H.–S. Jo,[5] K. Joo,[7] P. Kroll,[8] A Marti,[5] H. Moutarde,[2] A. Kubarovsky,[6,*]
V. Kubarovsky,[1,*] C. Munoz Camacho,[5] S. Niccolai,[5] K. Park,[1] R. Paremuzyan,[5]
S. Procureur,[2] F. Sabatié,[2] N. Saylor,[6,5] D. Sokhan,[5] S. Stepanyan,[1] P. Stoler,[6,†]
M. Ungaro,[7] E. Voutier, C. Weiss,[1,*] D. Weygand,[1] and the CLAS Collaboration

[1]*Jefferson Lab, Newport News, VA 23606, USA*
[2]*IRFU/SPhN, Saclay, France*
[3]*Fairfield University*
[4]*Joint Institute for Nuclear Research, Dubna, Russia*
[5]*Institut de Physique Nucleaire Orsay, France*
[6]*Rensselaer Polytechnic Institute*
[7]*Department of Physics, University of Connecticut, Storrs, CT 06269, USA*
[8]*Wuppertal University, Wuppertal, Germany*
[9]*LPSC Grenoble, France*

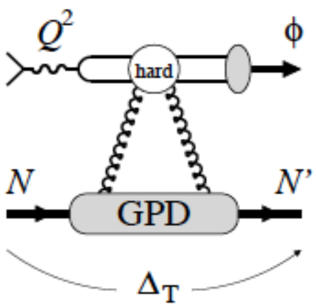


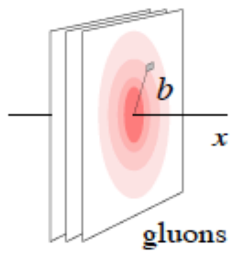


3D Nucleon Tomography – GPDs

JLab12: Exclusive ϕ and gluonic radius

C. Weiss, JLab 3D Workshop
3



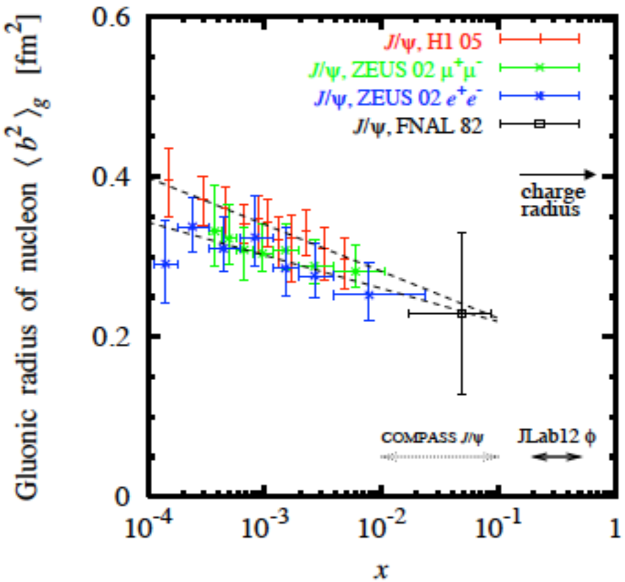


- Exclusive ϕ probes gluon GPD

  Small–size regime established at HERA
  ϕ–J/ψ comparison, universal t–slope $Q^2 \sim 10\ \text{GeV}^2$

  GPD calculation describes absolute cross secn from HERA to JLab energies Goloskokov, Kroll 08+

  L/T from ϕ decay + SCHC



- Transverse spatial distribution of gluons

  Fundamental gluonic radius, cf. charge radii

  Leading-twist characteristic: LQCD, models

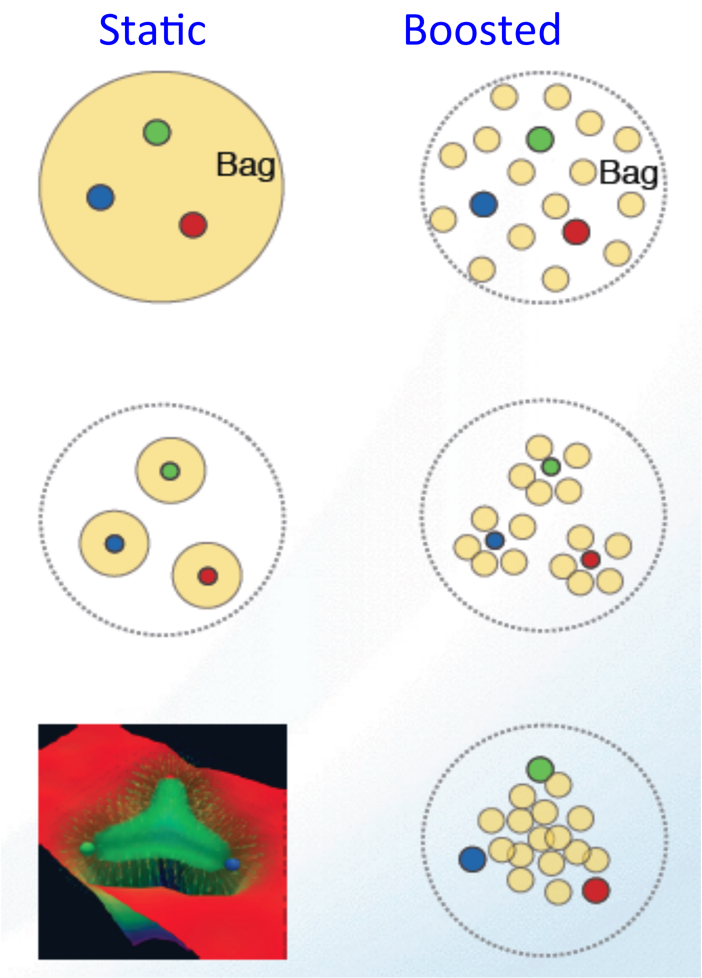
  $x < 0.01$ measured at HERA, FNAL,
  $x > 0.1$ practically unknown

  Changes with x: Chiral dynamics, diffusion

  DIS: Large gluon density above $x > 0.1$

Why 3D nucleon structure?

❑ **Spatial distributions of quarks and gluons:**



Bag Model:

Gluon field distribution is wider than the fast moving quarks.

Gluon radius > Charge Radius

Constituent Quark Model:

Gluons and sea quarks hide inside massive quarks.

Gluon radius ~ Charge Radius

Lattice Gauge theory (with slow moving quarks):

Gluons more concentrated inside the quarks

Gluon radius < Charge Radius

3D Confined Motion (TMDs) + Spatial Distribution (GPDs)

Relation between charge radius, quark radius (x), and gluon radius (x)?

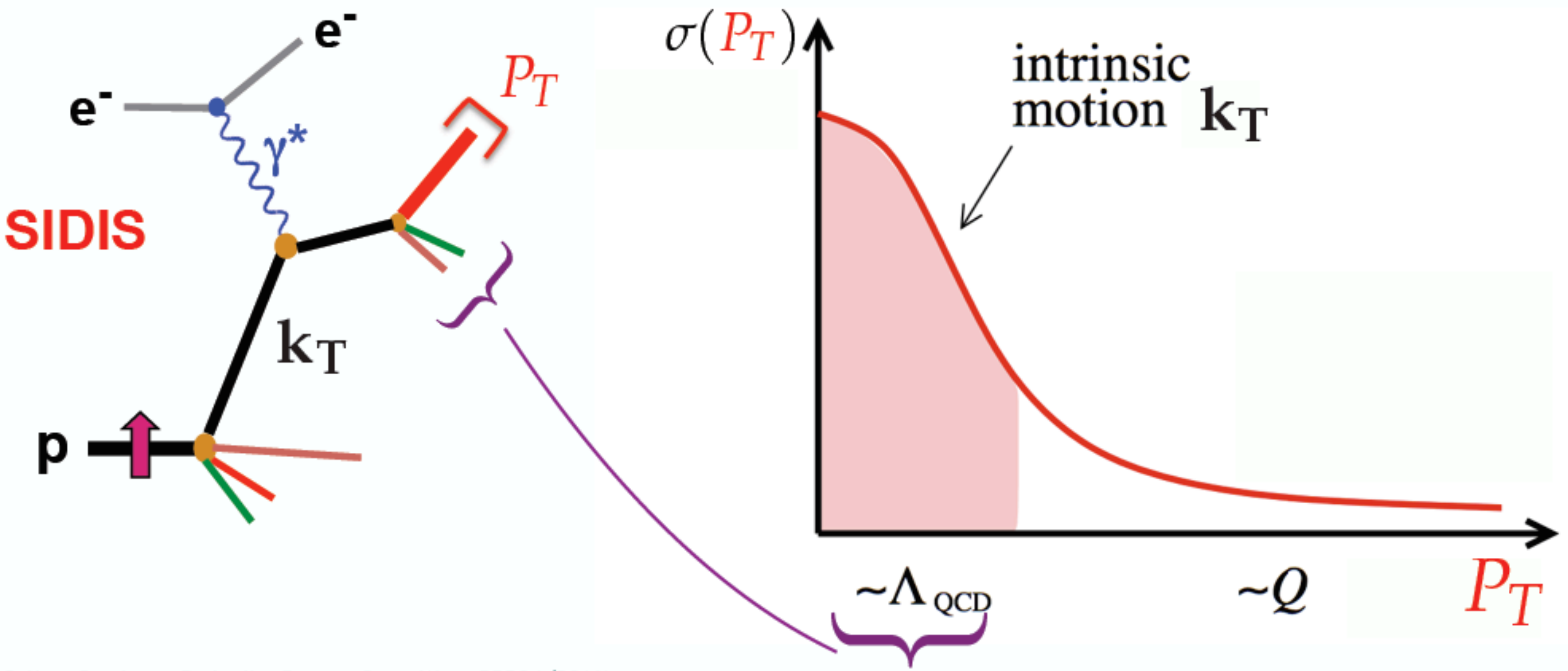
3D Confined motion – TMDs

A. Prokudin
T. Rogers

Major programs for JLab12 & EIC

- Non-perturbative, but universal evolution
- Relate SIDIS, Drell-Yan, e+e-

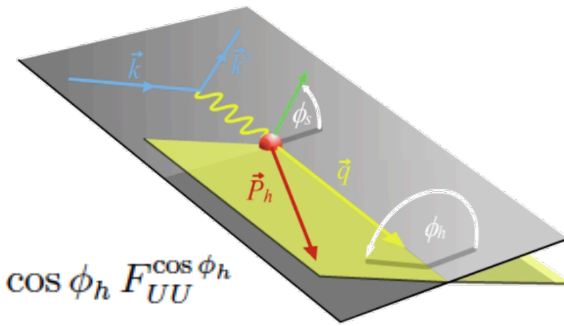
- JLab members of DOE TMD Topical Collab



Colins, Gamberg, Prokudin, Rogers, Sato, Wang PRD94 (2016)

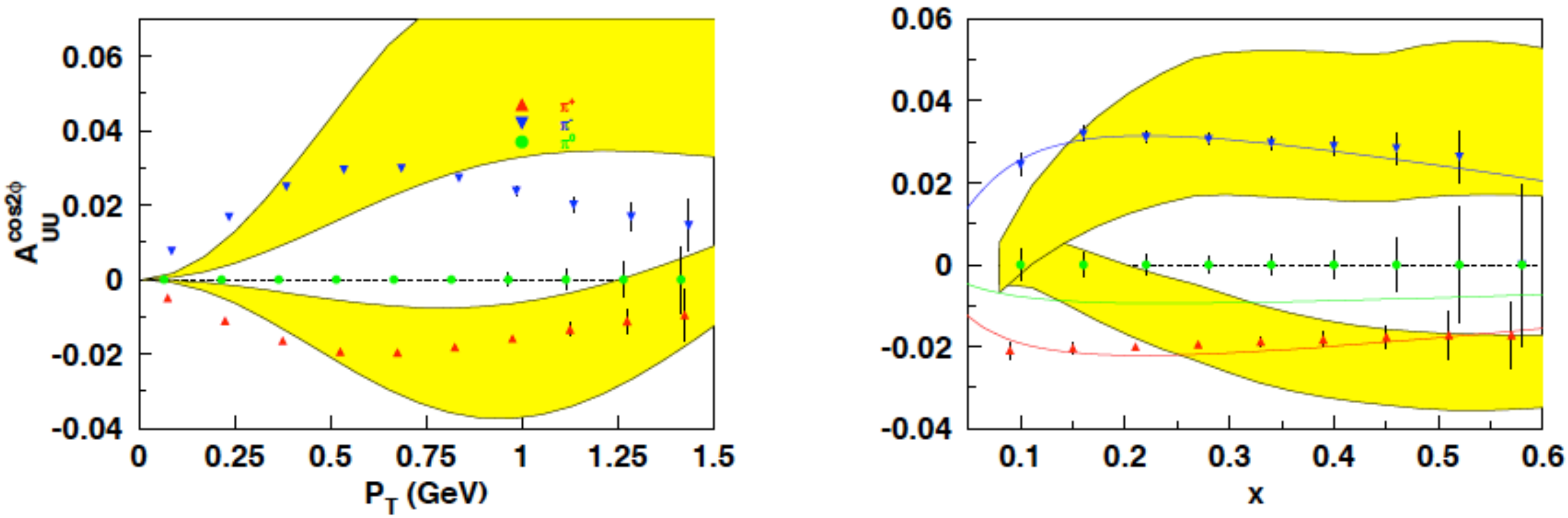
3D Confined motion – TMDs

❑ SIDIS at JLab:



$$\frac{d\sigma}{dx_B\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x_B}\right) \Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h\, F_{LU}^{\sin\phi_h} \Big\}$$

❑ Hall B (E12-06-112):



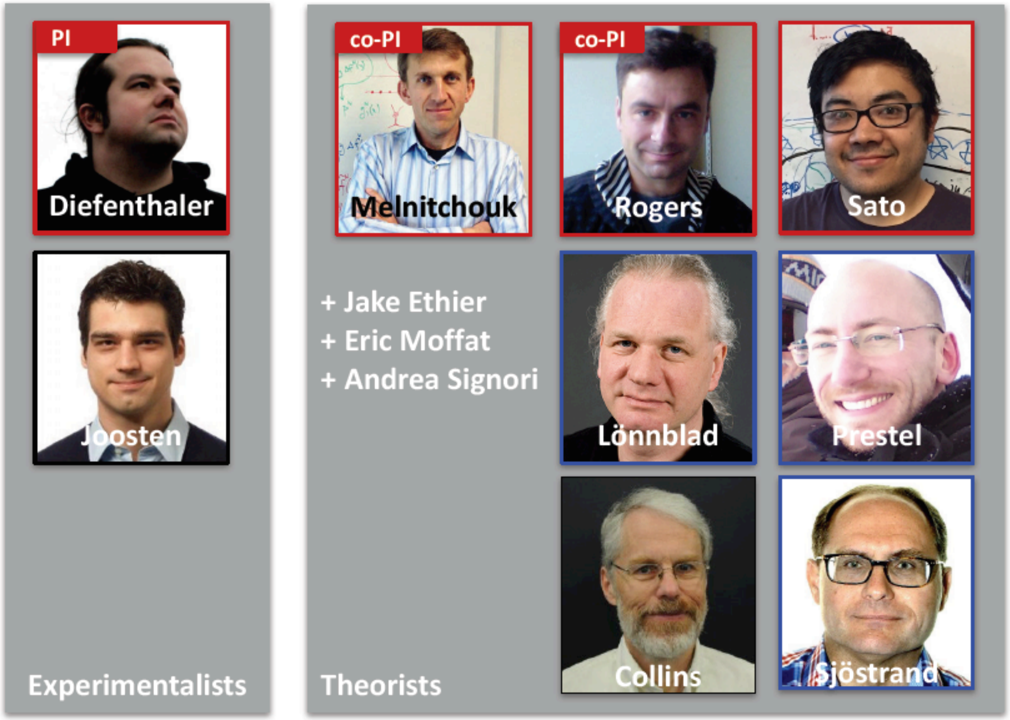
Sensitive to Boer-Mulders functions & Collins FFs – how does spin influence hadronization?

3D Confined motion – TMDs

- **LDRD project at JLab:**

  Mapping the hadronization description in the Pythia MCEG to the correlation functions of TMD factorization

- **Joint Exp/Thy collaborative effort:**

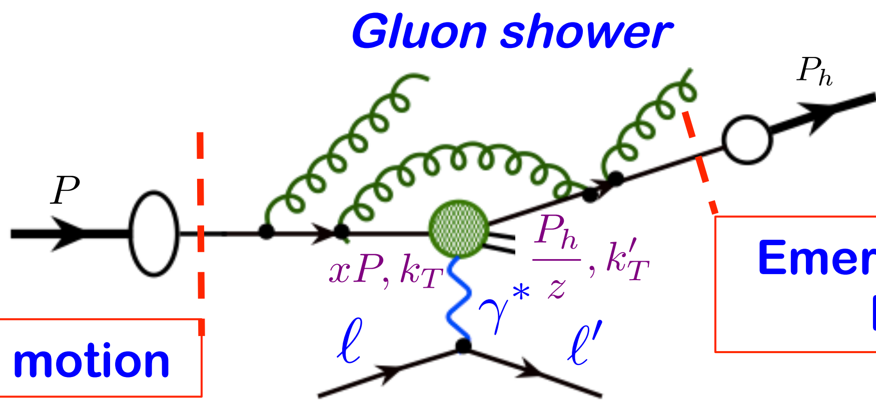


Markus Diefenthaler
JLab 3D workshop

Physics intuition for the TMDs, "Live Picture" for the emergence of hadrons from the colored quarks and gluons, …

3D Confined motion – TMDs

❑ **Sources of parton k_T at the hard collision:**



Confined motion

Emergence of a hadron
hadronization

❑ **Large k_T generated by the shower (caused by the collision):**

✧ Q^2-dependence – linear evolution equation of TMDs in b-space

✧ The evolution kernels are perturbative at small b, but, not large b

➡ The nonperturbative inputs at large b could impact TMDs at all Q^2

❑ **Challenge: to extract the "true" parton's confined motion:**

✧ Separation of perturbative shower contribution from nonperturbative hadron structure – QCD evolution - not as simple as PDFs

✧ Role of lattice QCD?

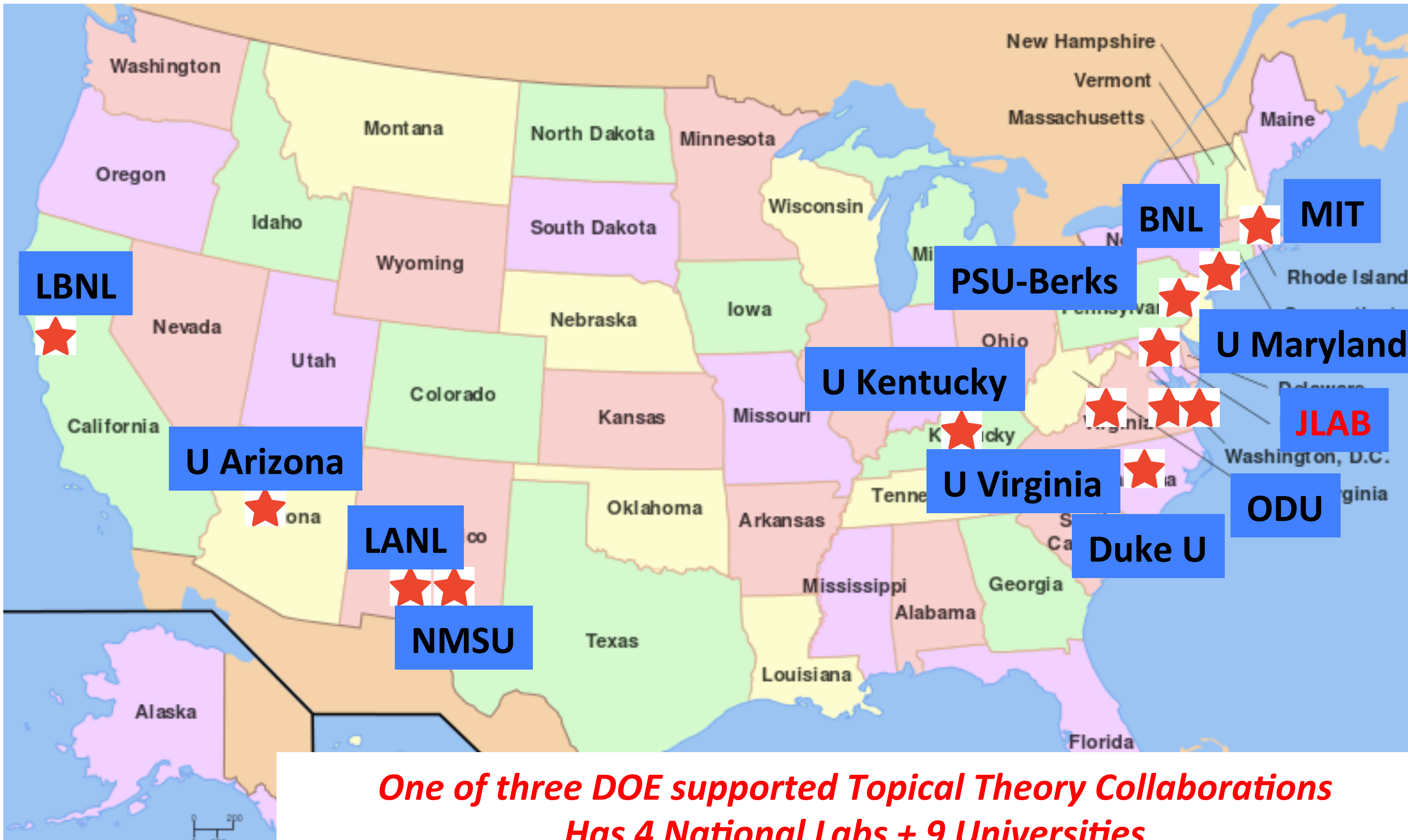
Task of the DOE supported TMD collaboration

TMD Topical Theory Collaboration

Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD (TMD Collaboration)

Co-spokespersons: W. Detmold, J.W. Qiu

TMD Collaboration



One of three DOE supported Topical Theory Collaborations
Has 4 National Labs + 9 Universities

TMD Summer School @ Temple University

Travel

Program

Email Us

TMD Collaboration Summer School 2017

June 22 - 28, 2017
Temple University
Philadelphia, USA

Organizing Committee:

Matthias Burkardt (New Mexico State University)
Martha Constantinou (Temple University)
Sean Fleming, Co-Chair (University of Arizona)
Leonard Gamberg (Penn State University-Berks)
Keh-Fei Liu (University of Kentucky)
Andreas Metz, Co-Chair (Temple University)
Alexei Prokudin (Penn State University-Berks)

http://www.physics.arizona.edu/~fleming/Main.html

Topics and Speakers:

- QCD and Parton Model: Pavel Nadolsky (SMU)
- TMD Phenomenology: Alessandro Bacchetta (U. di Pavia) & Andrea Signori (JLAB)
- TMD Factorization and Evolution: Ted Rogers (ODU)
- TMDs in Experiement: Matthias Grosse-Perdekamp (UIUC)
- Lattice QCD: Will Detmold (MIT)
- SCET: Iain Stewart (MIT)
- Quasi-PDFs: Martha Constantinou (Temple U.)
- GPDs and Generalized TMDs: Cedric Lorce (Ecole Polytechnique)
- TMDs in Lattice QCD: Michael Engelhardt (NMSU)
- TMDs at small x: Feng Yuan (LBNL)

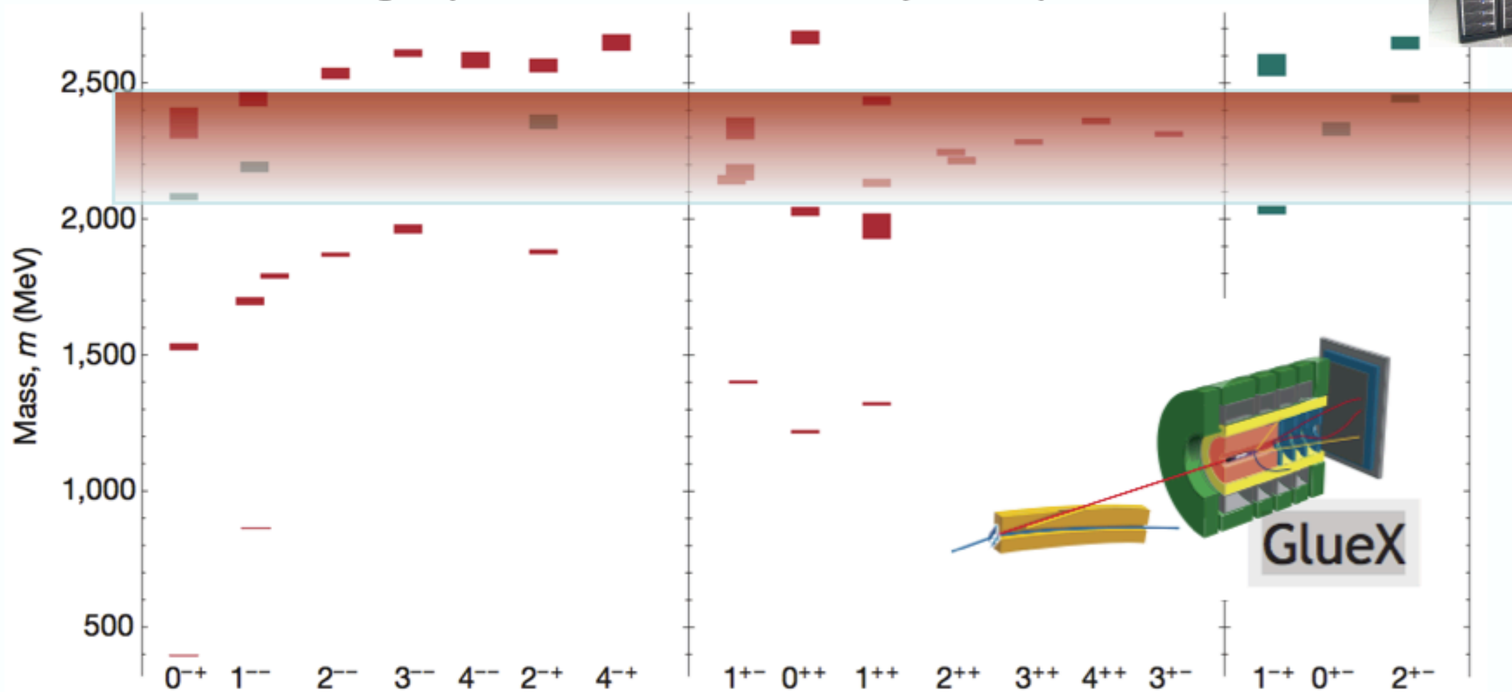
Hadron spectroscopy

❑ The role of the glue:

Focus of GlueX & CLAS12 @ JLab & COMPASS, BES, & LHCb

Light quark meson + “exotics” & “hybrids” spectrum

Exotics



Pattern of states suggest gluonic excitations

➡ Need to know decay modes and rates to compare to expt.

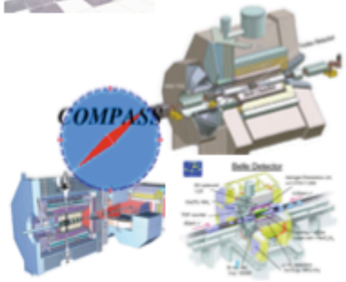
HADRON SPECTRUM: PRD83 (2011); PRD88 (2013)

Hadron spectroscopy

❑ JPAC – Joint Physics Analysis Center:

- Started Fall 2013 - support analyses of expt. data from JLab12 & other accel. labs
- Theoretical/phenomenological/data-analysis tools
- Successful 3-year by external membership panel (May 2016)
- Avg. 1 paper/month, 100 invited talks, ~10 ongoing expt. analyses
- Supports data curation, workshops, summer schools

- Applications:
  - Light meson spectroscopy & structure (η,ω,φ)
  - Heavy meson spectroscopy, XYZ's, & implications for JLab
  - Light meson exotics
  - Baryon spectroscopy (global analyes, hyperons, novel states)



- Future:
  - Structure studies (form factors, transverse densities)
  - BSM searches (precision amplitude analysis of hadron final states in EW processes)

Summary and outlook

- **The Theory Program at Jlab is a strong and diversified group:**

  As stated in the recent DOE's Review Report:

  - **The scientific contributions of the Group to the national nuclear theory research effort are very strong, and**
  - **the research of the Group is well integrated into the national effort**

- **The Theory Center has been working closely with experimental collaborations in supporting the JLab/CLAS12 science program**

- **Theory center has one of the best lattice QCD groups in the world, and more actions are on the way to develop the tools to study the hadron structure directly on the lattice, complementary to the JLab experimental program**

Thank you!