*March 6-9, 2018*
*Jefferson Lab, Newport News, VA*

# Highlights from Theory Group

**Jianwei Qiu**

*Theory Center, Jefferson Lab*

*March 7, 2018*

# JLab Theory Program

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

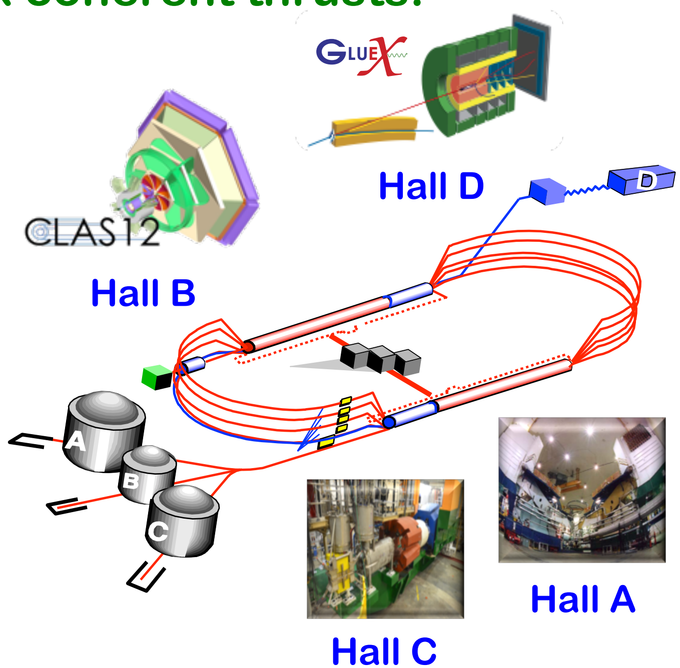
  *Area 1 – QCD and the structure of hadrons and nuclei*
  *Area 3 – Nuclear structure and reactions*
  *Area 5 – Fundamental symmetries and neutrinos*

- **Support JLab12 with six coherent thrusts:**

**Hadron spectroscopy – LQCD:** Edwards, Dudek, Orginos, Richards

**Hadron spectroscopy – JPAC:** Doring, Passimar, Szczepaniak

**Nuclear structure & Low energy EFTs:** Goity, Melnitchouk, Schiavilla, Van Orden, Weiss




**3D hadron structure – LQCD:** Edwards, Orginos, Richards, Shanahan

**3D hadron structure – Global analyses:** Accardi, Melnitchouk, Prokudin, Rogers

**3D hadron structure – QCD & EFTs:** Accardi, Balitsky, Melnitchouk, Prokudin, Qiu, Radyushkin, Rogers, Weiss

- **Research with high performance computing:**

  Lattice QCD, SciDAC4, Exascale computing, software supporting experiments, …

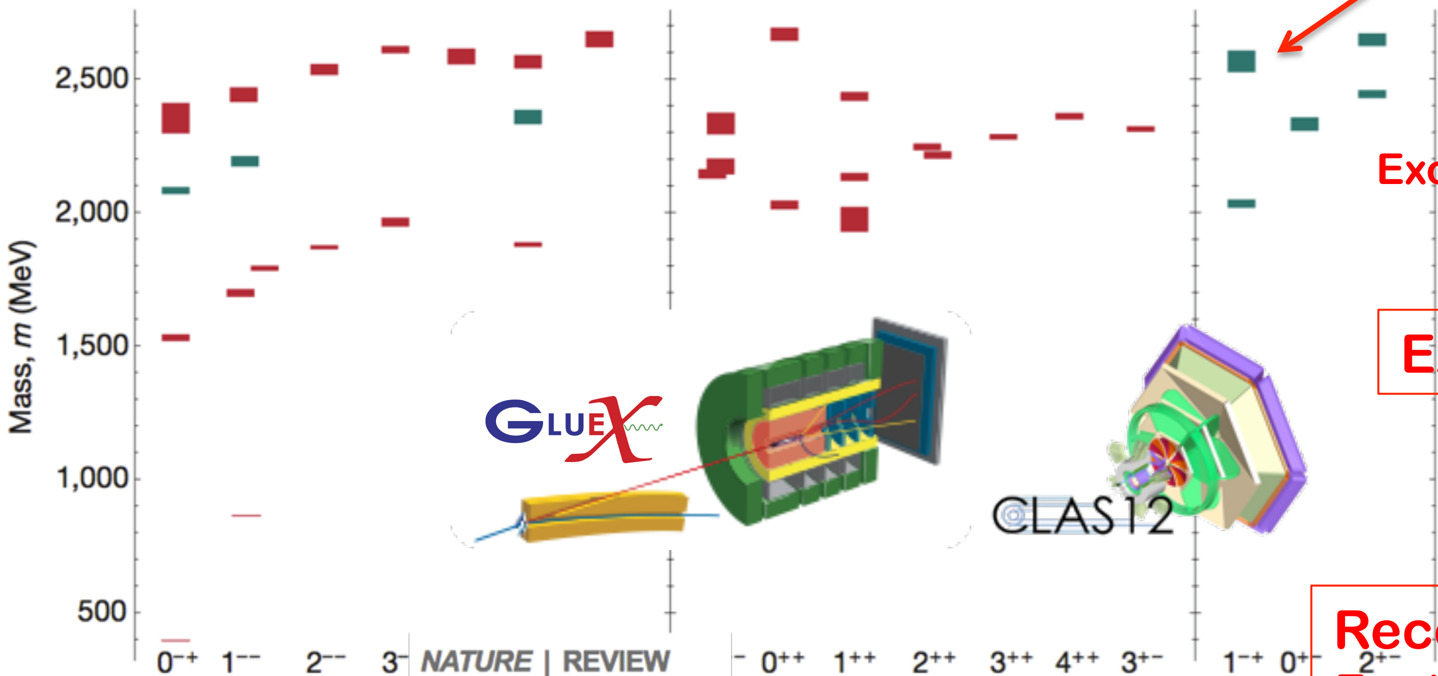
# Hadron spectroscopy – LQCD

❑ **Focus on GlueX & CLAS12 @ JLab & COMPASS, BES, & LHCb**

(JLab's Pioneering Work!)

Light quark meson + "exotics" & "hybrids" spectrum

Predicted




Exotics

Explored at

Recognized by Feature review

NATURE | REVIEW

Searching for the rules that govern hadron construction

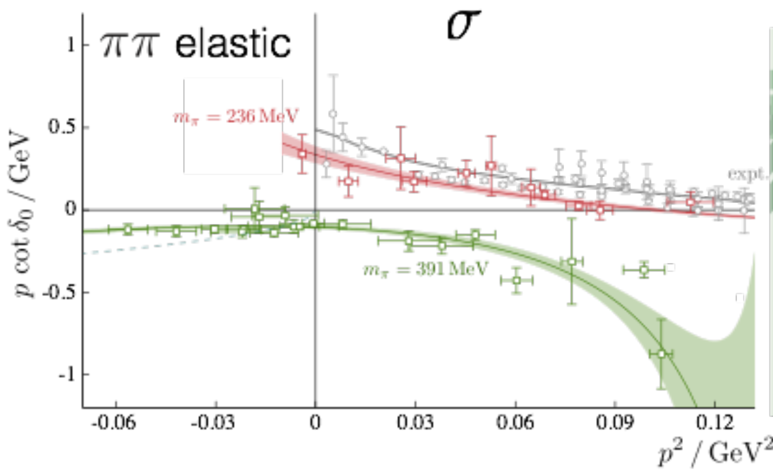
Matthew R. Shepherd, Jozef J. Dudek & Ryan E. Mitchell

*Nature* **534**, 487–493 (23 June 2016) | doi:10.1038/nature18011

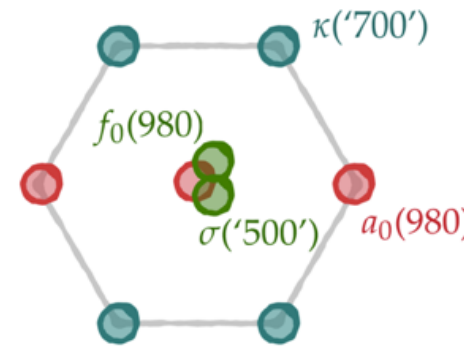
# Hadron spectroscopy – LQCD

- **New development:**

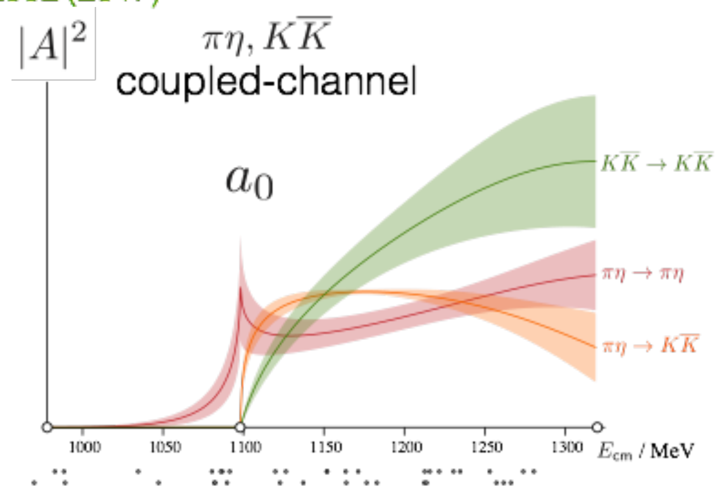
(Solving old mysteries – scalar sector)








PRL118 022002 (2017)




**First Lattice QCD calculation – "discovery" of "$a_0$", "σ", …**

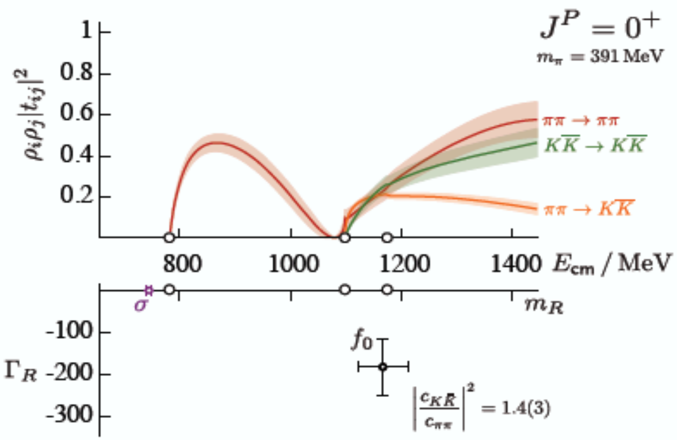
PRD93 094506 (2016)

# Hadron spectroscopy – LQCD

## ❑ Even newer development:

**$\pi\pi$,$K\bar{K}$,$\eta\eta$ scattering**

Wilson (TCD), Briceno, Dudek, Edwards



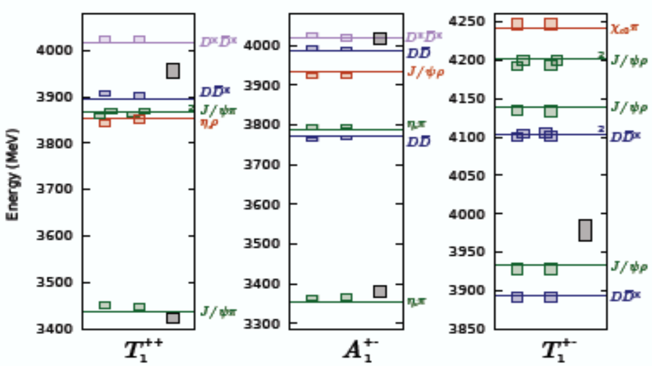

*arXiv:1708.06667*
*[ under review at PRD ]*

first calculation of coupled isospin=0 scattering

$\sigma$ as bound state, and $f_0$('980') resonance at $K\bar{K}$ threshold

**tetraquark operators**

Cheung, Thomas (Camb), Dudek, Edwards



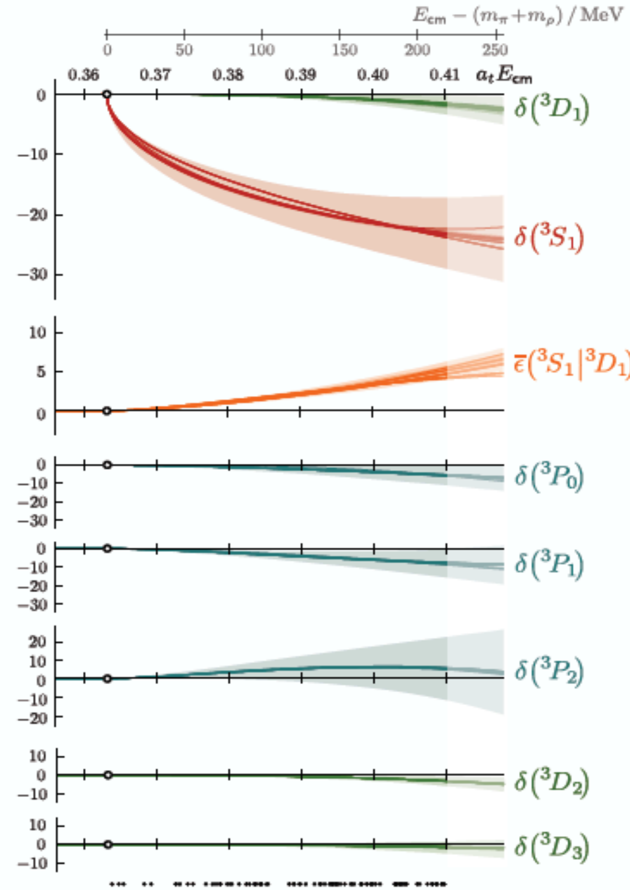

*JHEP 1711 (2017) 033*

first systematic exploration of tetraquark operators in lattice QCD

meson-meson operators found to be sufficient in exotic flavor channels

**$\pi\rho$ scattering**

Woss, Thomas (Camb), Wilson (TCD), Dudek, Edwards




*arXiv:1802.05580*

first explicit calculation using 'spinning-hadron' formalism

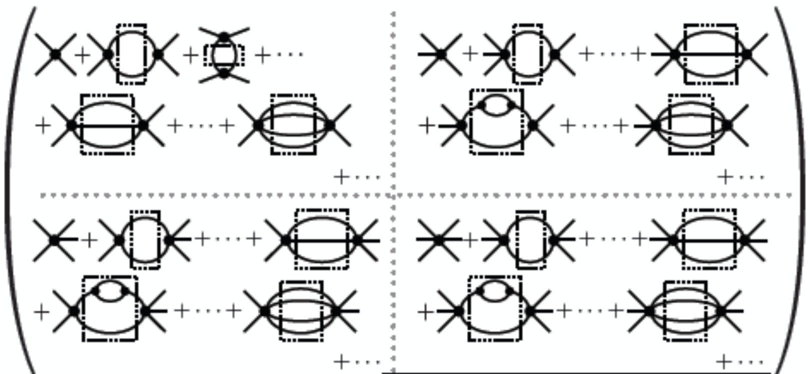
# Hadron spectroscopy – LQCD

## ❑ Even newer development:

Two/three body systems

First development of formalism for coupled two/three-body scattering via lattice QCD

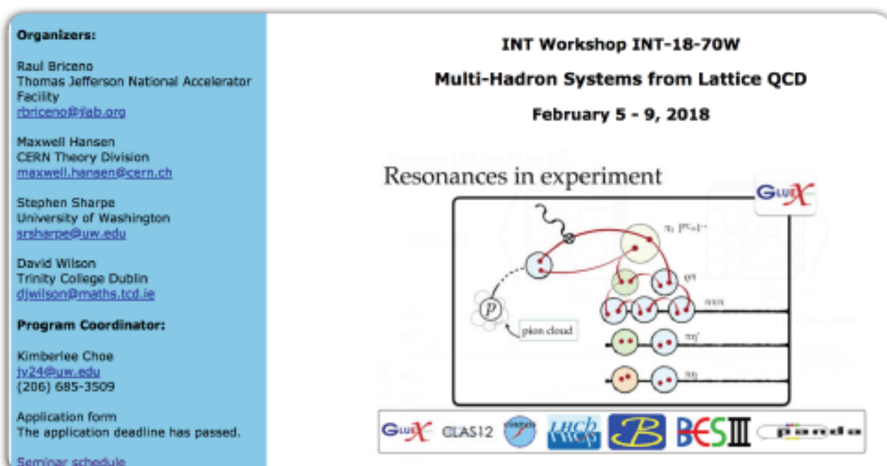
$\mathcal{M}_L =$



[Phys.Rev. D95 (2017) Hansen, Sharpe]

Multi-Hadron Systems from Lattice QCD

Organized workshop



# Hadron spectroscopy – LQCD

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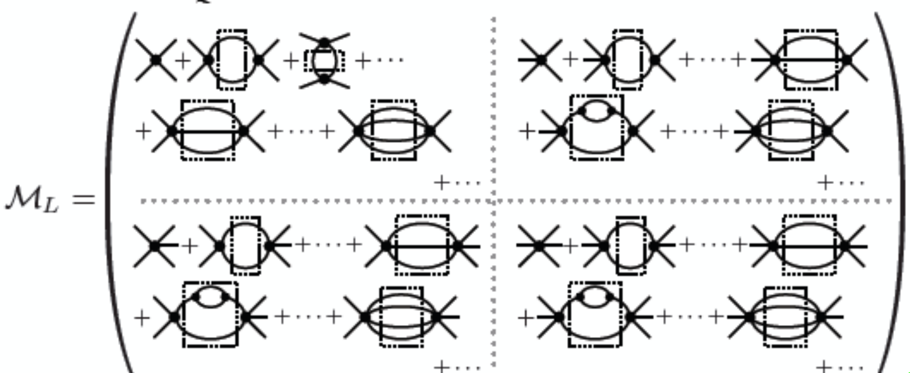
First development of formalism for coupled two/three-body scattering via lattice QCD




[Phys.Rev. D95 (2017) Hansen, Sharpe]

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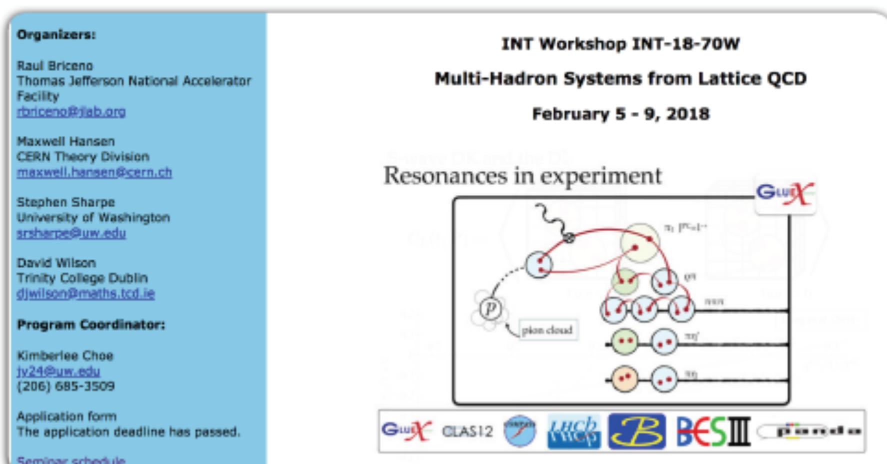
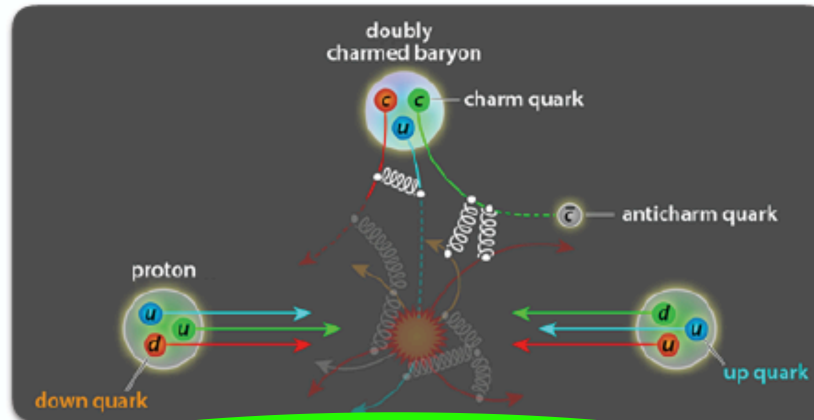
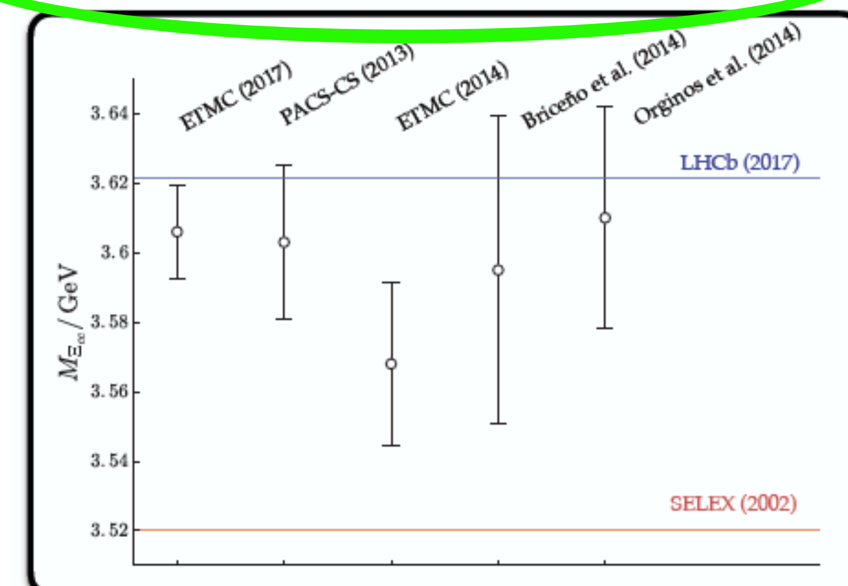



Viewpoint: A Doubly Charming Particle

Briceño, Physics 10 (2017) 100

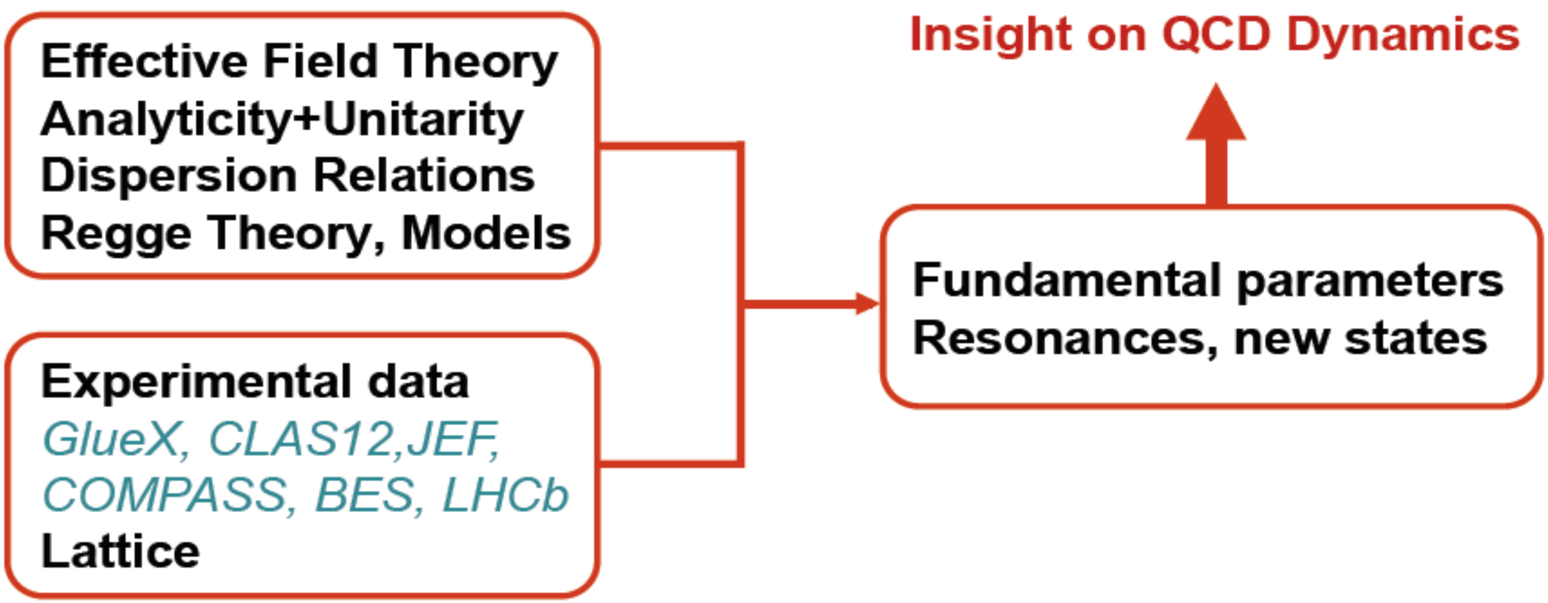



Lattice QCD prediction of the first doubly-charmed baryon is confirmed by LHCb



# Hadron spectroscopy – JPAC

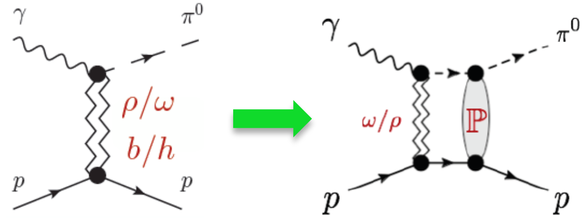
- **Joint Physics Analysis Center:**
  - ✧ Joint efforts between theorists and experimentalists to work together to make the best use of very precise data taken at JLab and in the world
  - ✧ Established in 2013 by JLab & Indiana University agreement
  - ✧ Providing strong support to *CLAS12, GlueX, …* JLab experiments



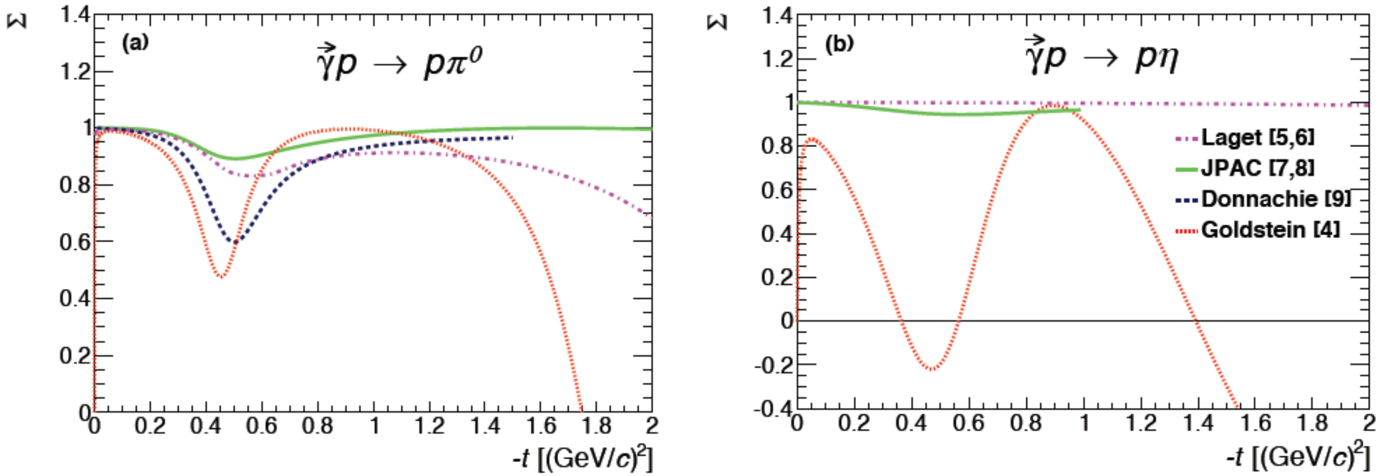
# Hadron spectroscopy – JPAC

## ❑ Making successful predictions for GlueX:

$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{|\rho+\omega|^2 - |b+h|^2}{|\rho+\omega|^2 + |b+h|^2}$$




**Separation meson from baryon resonance**




JPAC prediction

*V. Mathieu et al., PRD92 (2015) 074013*

*J. Nys et al., PRD95 (2017) 034014*

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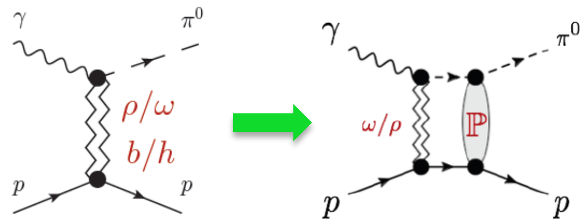


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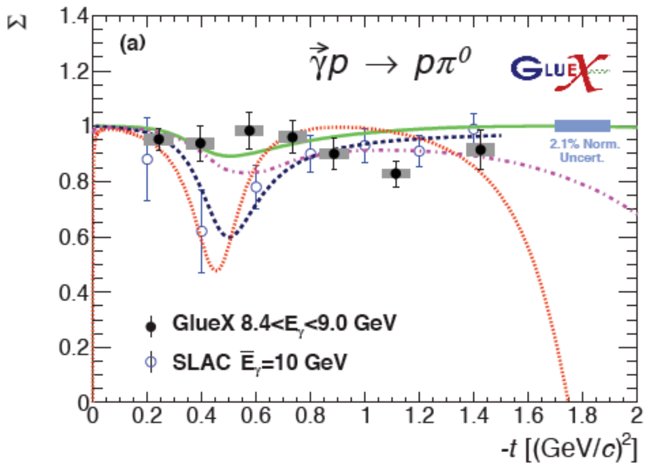


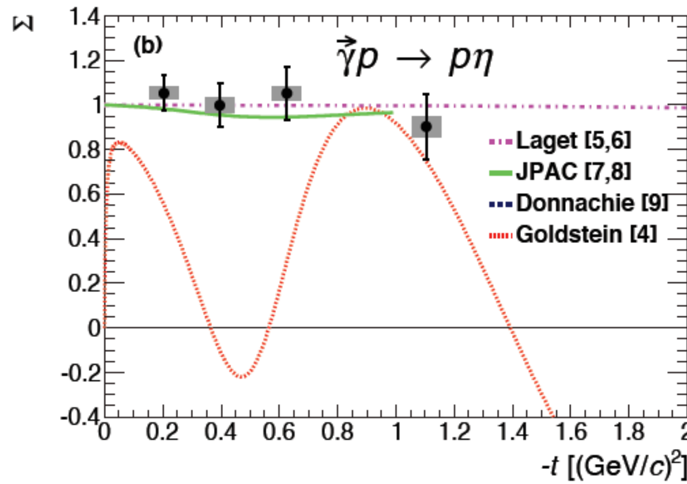


***First paper from GlueX and JLab12 upgrades***

JPAC prediction

*V. Mathieu et al., PRD92 (2015) 074013*

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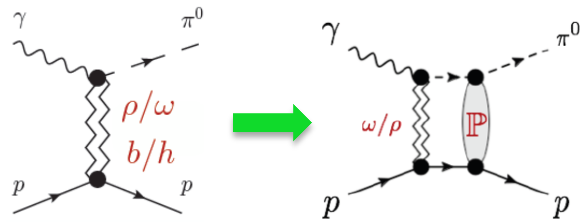


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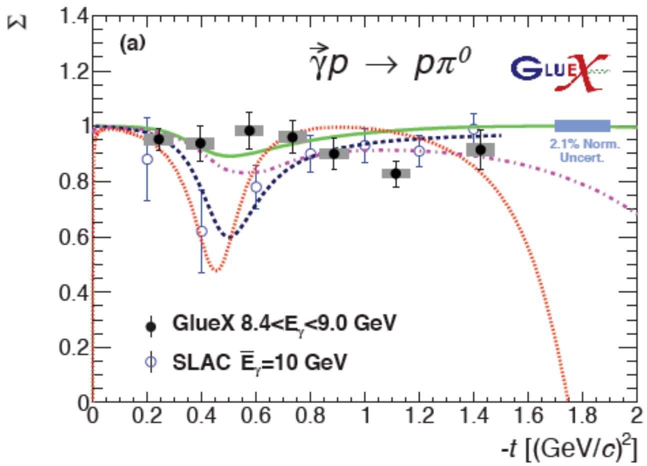


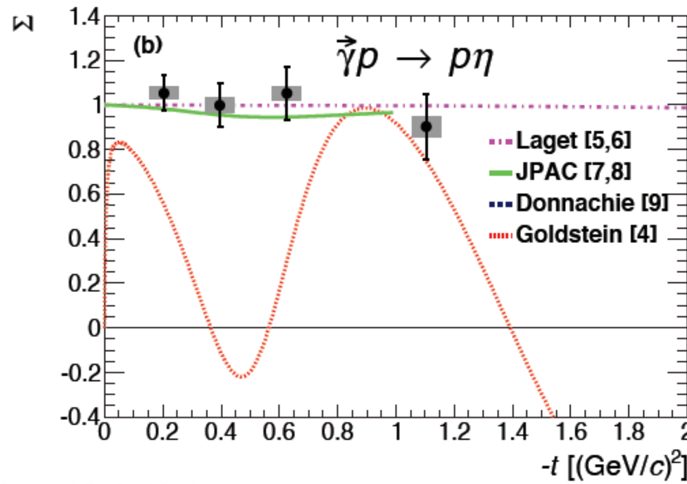


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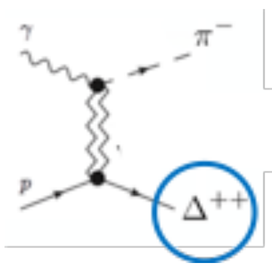
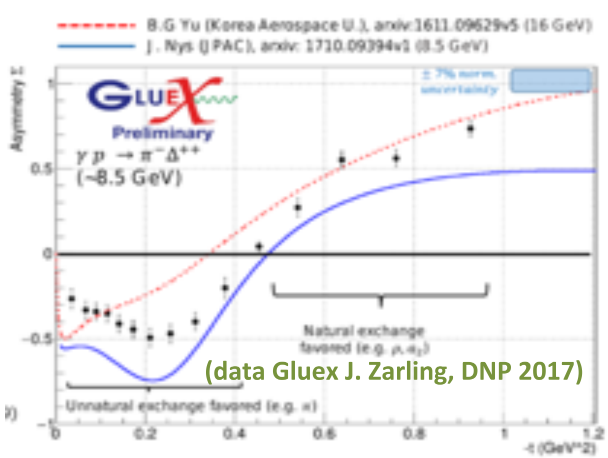



**Comparison with preliminary GlueX results**

- ✧ Natural exchanges at high–t
- ✧ Sensitive to details of p exchange (low-t)
- ✧ Same exchanges in production of exotic, hybrid mesons.

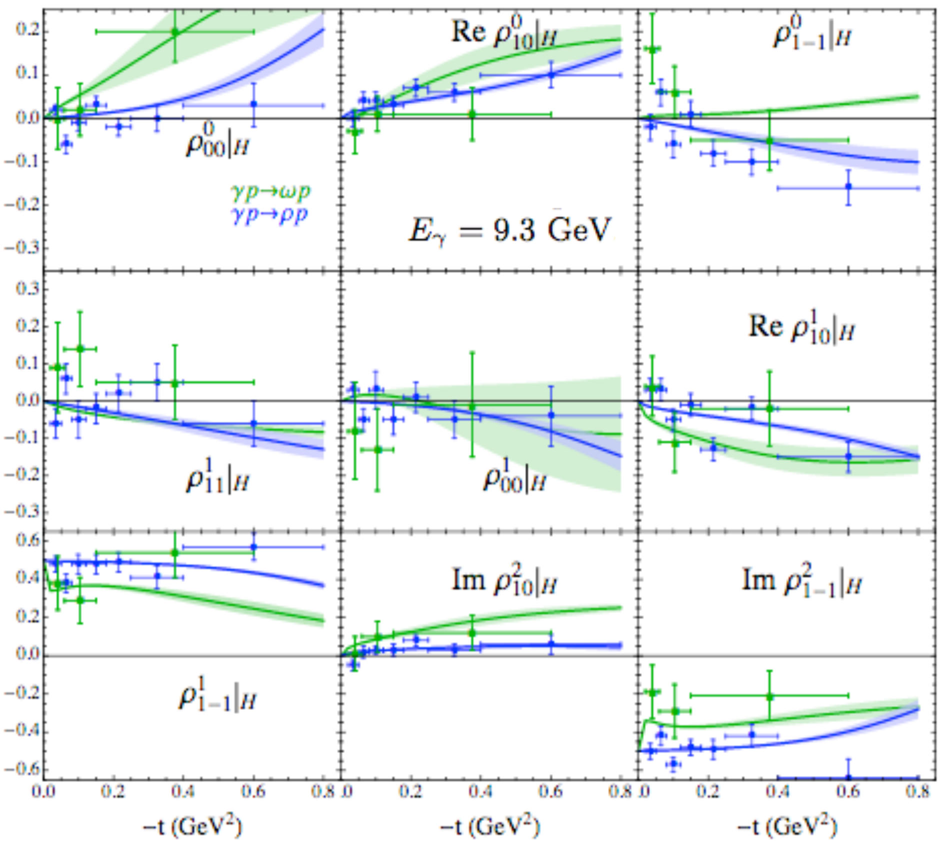
[JPAC: Phys. Lett. B779, 77, (2018)]

# Hadron spectroscopy – JPAC

## ❑ Making successful predictions for GlueX:

### Predictions for ($\rho$, $\omega$, $\Phi$) photoproduction

✧ **Spin Density Matrix Elements: detailed polarization information → isolation of exchanges** [JPAC: arXiv:1802.09403)]




[Data from J. Ballam *et al.* Phys. Rev. D7, 3150 (1973)]

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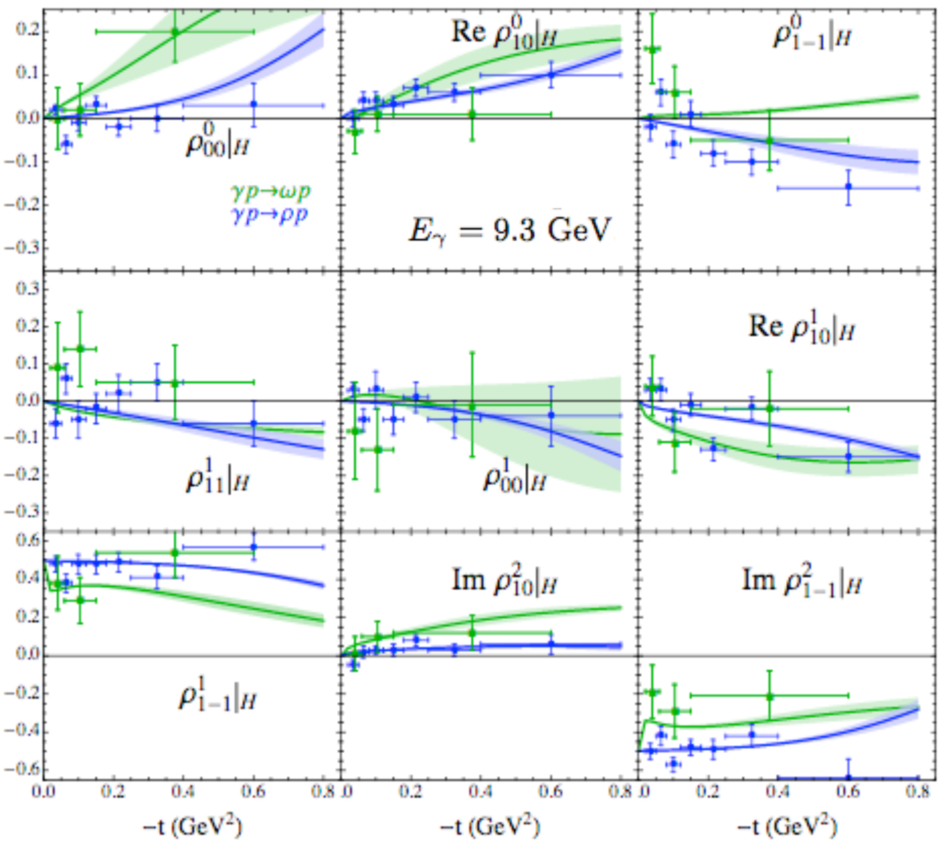
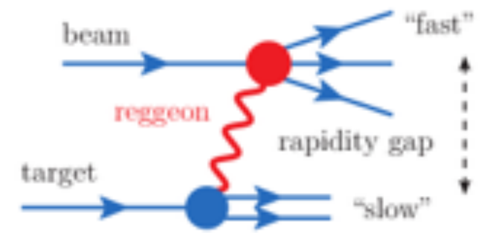


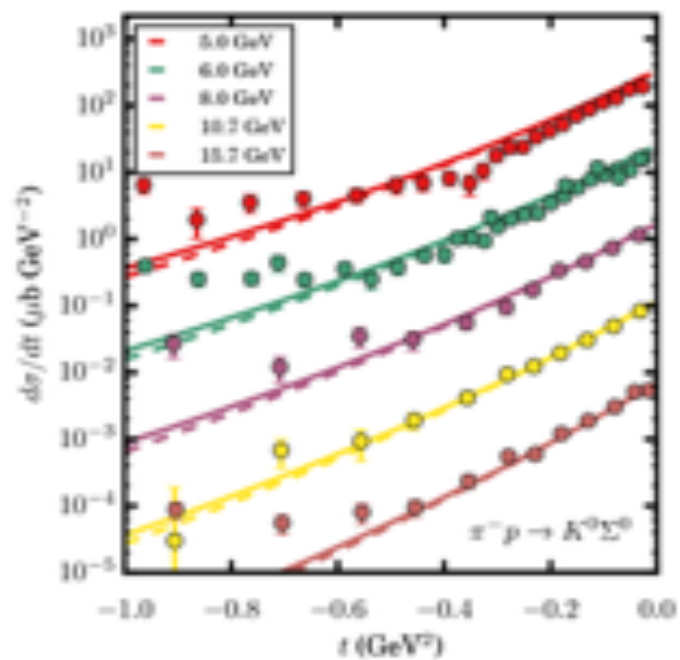

[Data from J. Ballam *et al.* Phys. Rev. D7, 3150 (1973)]

[JPAC: in preparation]

### Quasi two-body reactions

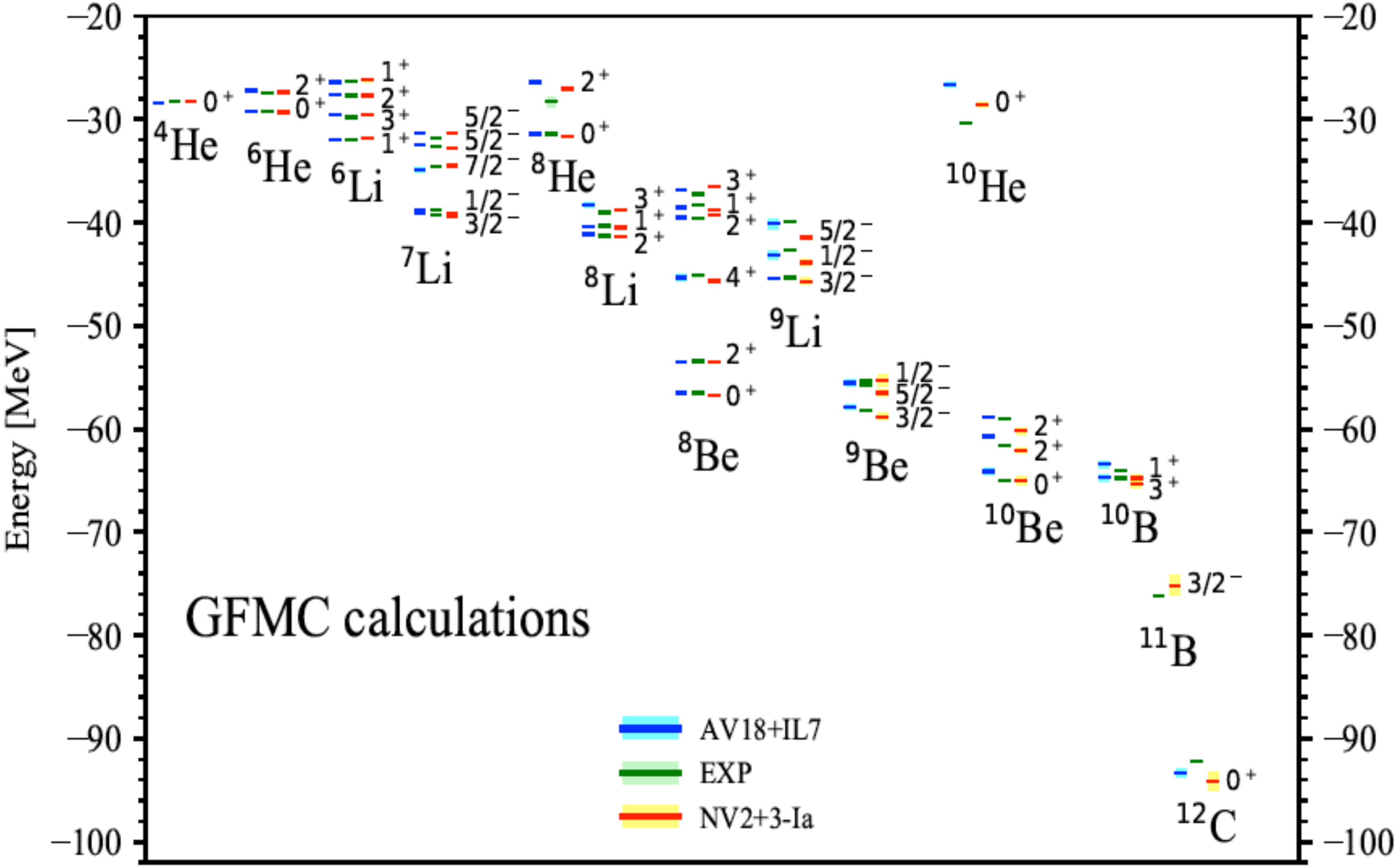



✧ Global analysis of world data
✧ Leading Regge pole theory
✧ Small number of parameters
✧ Compatible with data



# Nuclear structure

- **Light nuclei spectra from chiral dynamics:**




[Piarulli et al, Phys. Rev. Letts. 120, 052503 (2018)]

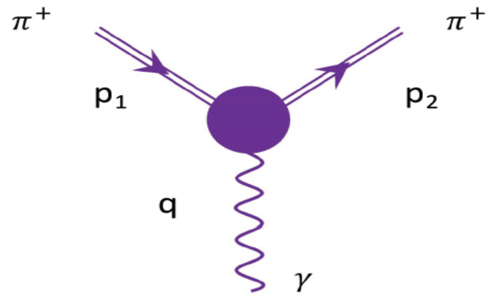
# Hadron structure – JLab12 to EIC

- ❑ **Form Factors:**

$$\langle \pi^+(\vec{p}\,')|j^\mu|\pi^+(\vec{p})\rangle = (p+p')^\mu \, F_\pi(Q^2)$$

$$Q^2 = -q^2$$

$$q^2 = (p_2 - p_1)^2 \leq 0$$

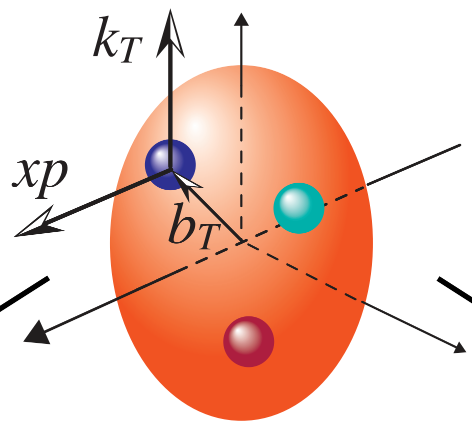



**Also for nucleons, and other hadrons**

- ❑ **Landscape of hadrons:**

*Momentum Space*

*Coordinate Space*




*TMDs (3D)* $\int d^2b_T$ $\int d^2k_T$ *GPDs (3D)*

Confined motion $f(x,k_T)$ $f(x,b_T)$ Spatial distribution

*PDFs (1D)*

$\int d^2k_T$ $f(x,\mu^2)$ $\int d^2b_T$

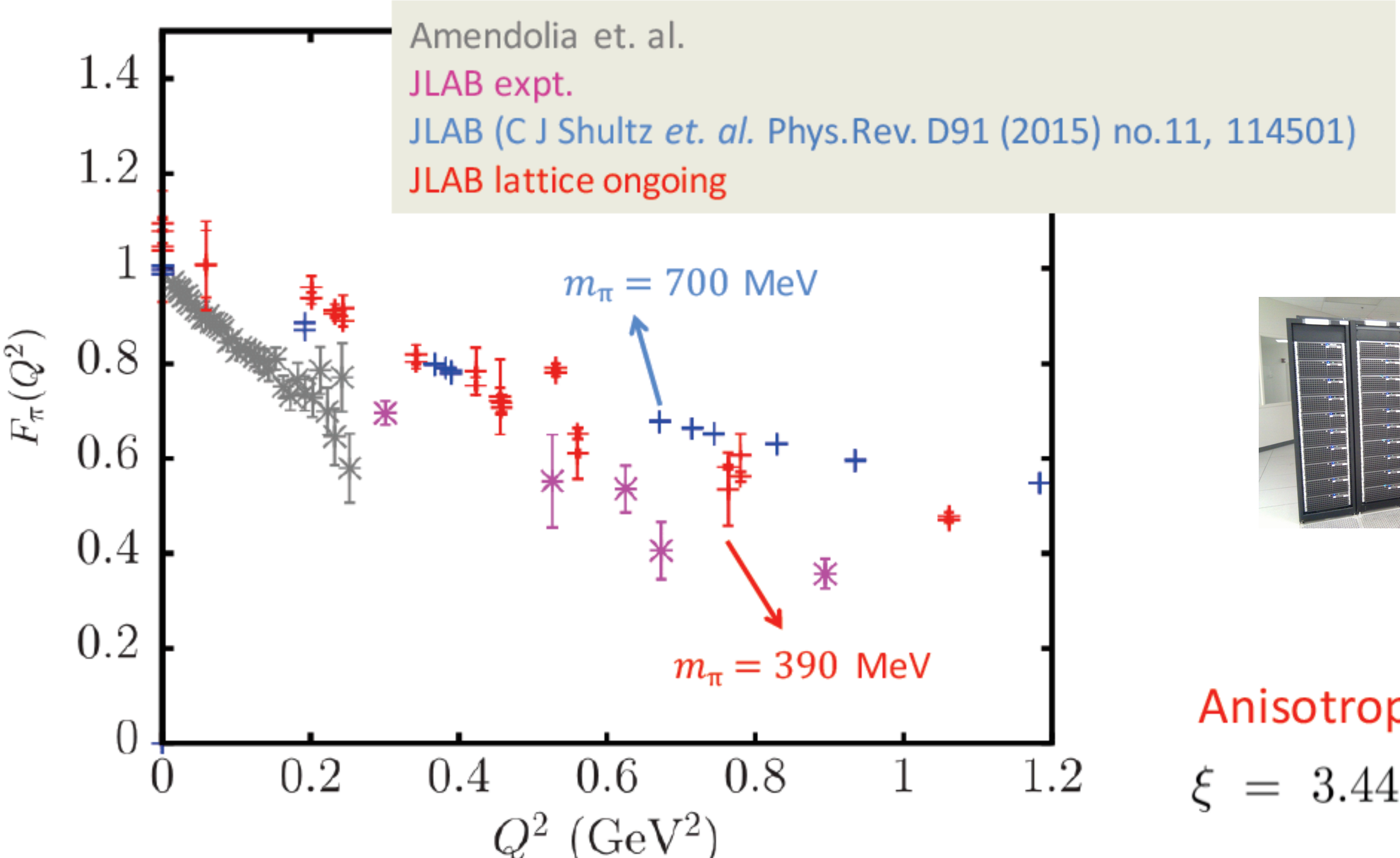
**Probability distributions**

- ❑ **Coherent three-pronged approaches:**

**Theory, Phenomenology and Lattice QCD – unique strength of JLab**

# Form factors – LQCD

- **Pion EM form factors:**




Anisotropy

$$\xi = 3.44$$

$$(L/a_s)^3 \times (T/a_t) = 20^3 \times 128$$

$$a_s = 0.12 \text{ fm}, \quad \frac{a_s}{a_t} = 3.44$$

In progress, …

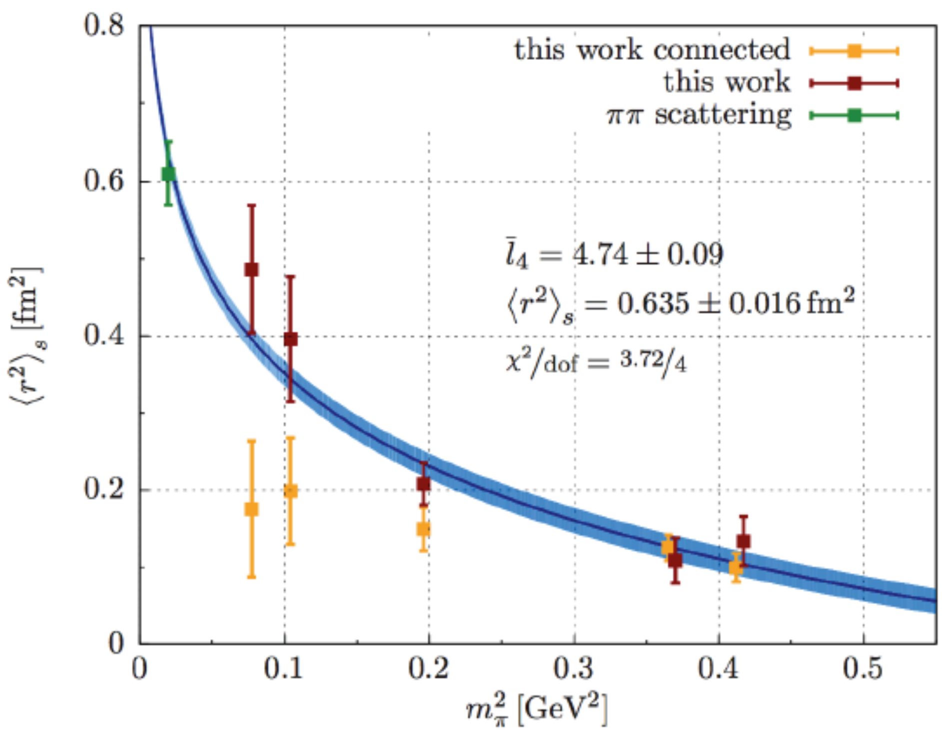
Chakraborty, Richards, …

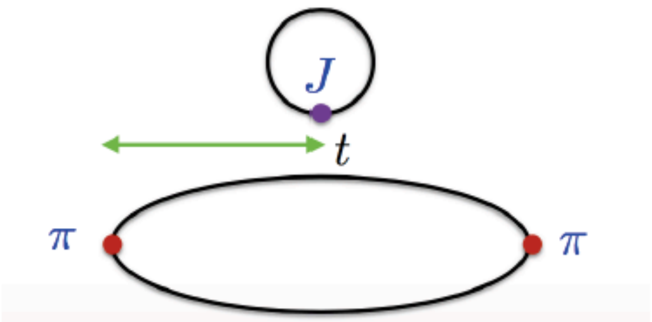
# Form factors – LQCD

- **Pion scalar radius:**

$$F_S^\pi(Q^2) \equiv \langle \pi^+(p_f) | m_d \bar{d}d + m_u \bar{u}u | \pi^+(p_i) \rangle, \qquad Q^2 = -q^2 = -(p_f - p_i)^2$$

Scalar charge radius: $$\langle r^2 \rangle_S^\pi = -\frac{6}{F_S^\pi(0)} \frac{\partial F_S^\pi(Q^2)}{\partial Q^2}\Big|_{Q^2=0}$$



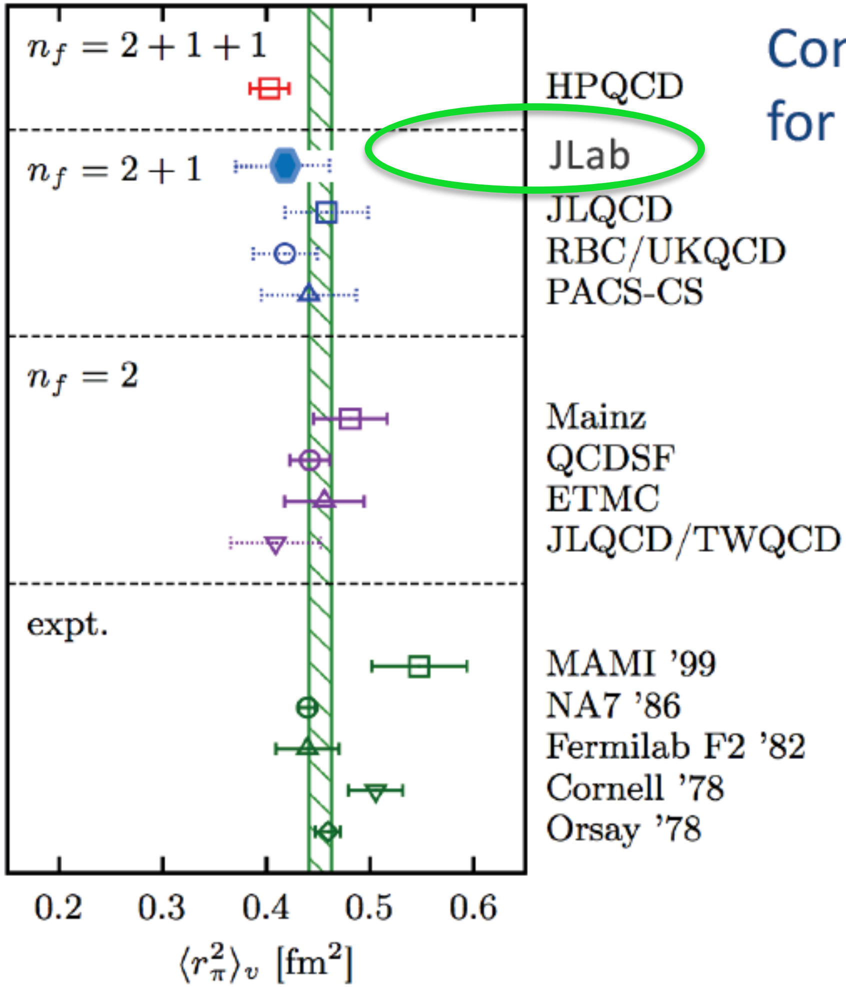




$$\langle r^2 \rangle_S^\pi = 0.635 \pm 0.016\ \mathrm{fm}^2$$

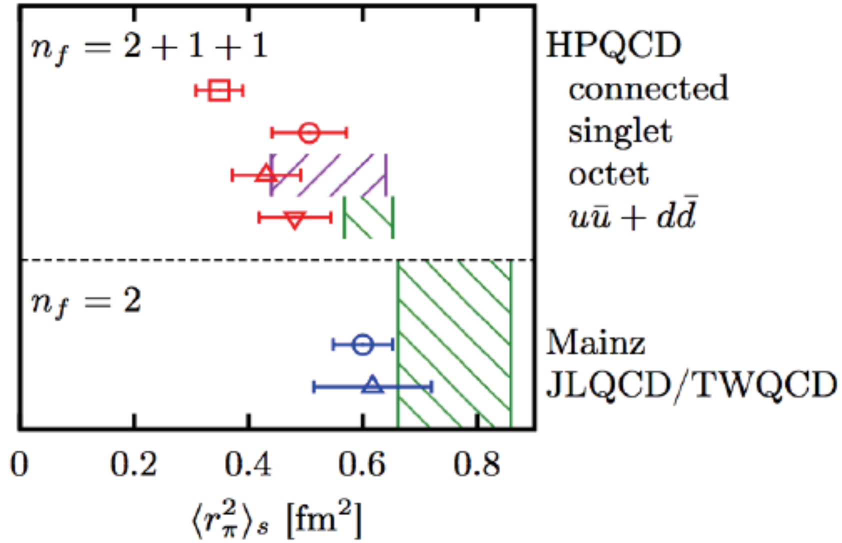
V. Gulpers et. al.
Phys.Rev. D89 (2014) no.9, 094503

# Form factors – LQCD

- ❑ **Pion scalar radius:**




Comparison of different lattice results for pion vector and scalar charge radius

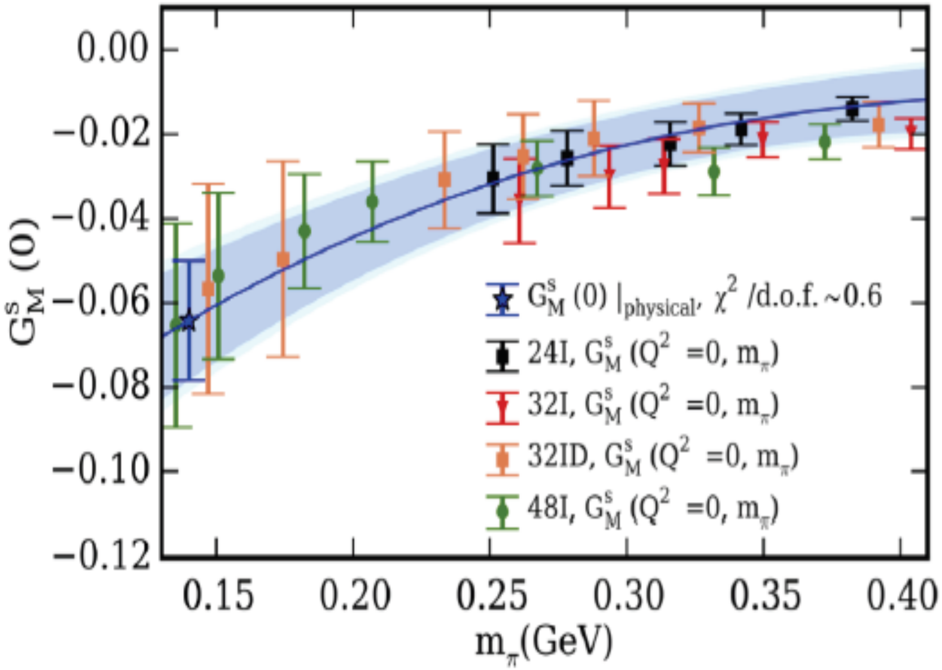


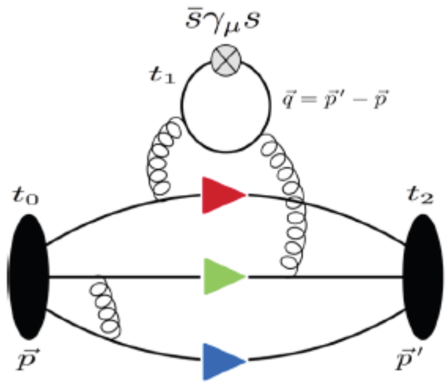

HPQCD, J. Koponen *et. al.*
Phys.Rev. D93, 054503

# Form factors – LQCD

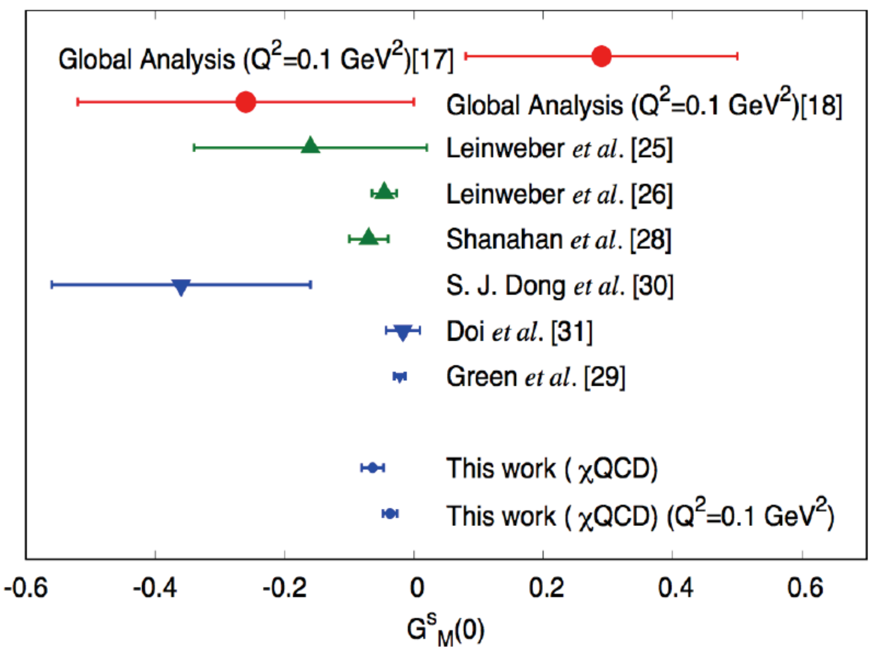
## ❑ Strange quark magnetic moment of the nucleon:

**(at physical pion mass with domain wall fermions)**



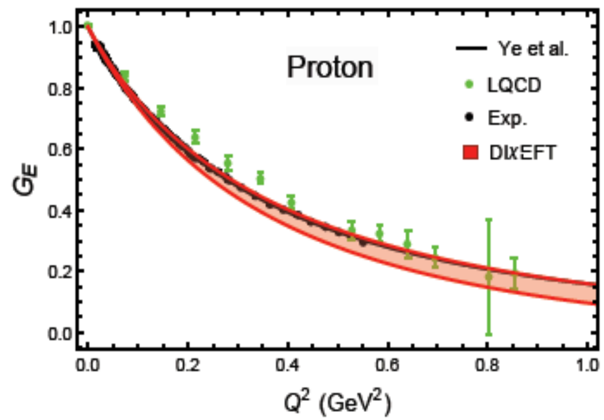

- Ratio 3pt/2pt method
- Z-expansion

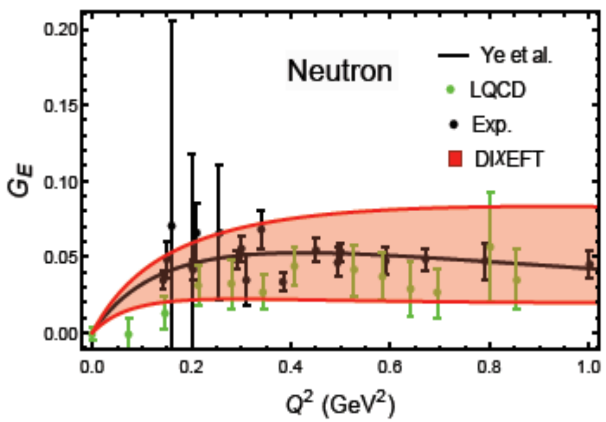


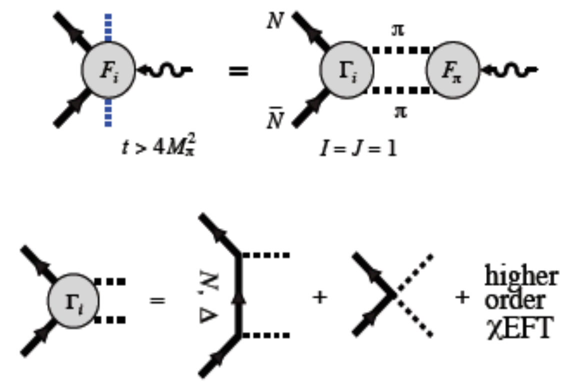

Raza Sufian, Phys. Rev. Letts. 118, 042001

# Form factors – Low energy EFTs

## ❑ Accurate form factors from chiral EFT:




- Developed new first-principles method for calculating low-Q2 nucleon form factors combining chiral EFT and dispersion theory (DIχEFT). Includes ππ rescattering in t-channel through unitarity. **Alarcon, Hiller Blin, Vicente Vacas, Weiss, NPA 964, 18 (2017); Alarcon, Weiss PRC 96, 055206 (2017); Alarcon, Weiss arXiv:1710.06430**

- Controlled accuracy, systematic improvements

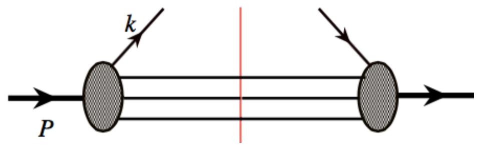
- Calculated nucleon electromagnetic FFs and transverse densities, scalar FF. Extending approach to GPDs

- Results used in experimental analysis: Low-Q2 electron scattering, proton radius extraction. **Higinbotham et al. 18, Horbatsch et al. 18. JLab12 PRAD experiment**

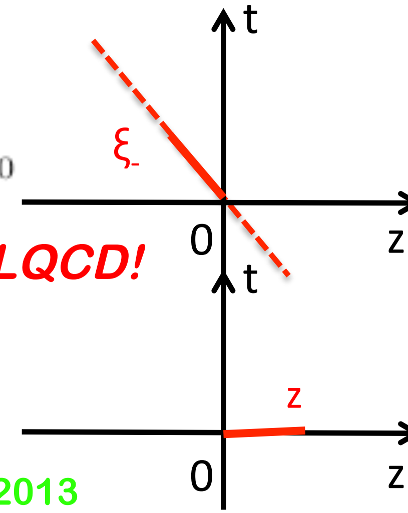
# 3D hadron structure – LQCD

## ❑ PDFs, TMDs, GPDs, … from Lattice QCD:

**PDFs:**




$\propto \langle P|\overline{\psi}(0)U(0,\xi)\psi(\xi)|P\rangle_{\xi^+=0,\vec{\xi}_T=0}$




***Cannot be calculated directly in LQCD!***

**New Idea and great potential:**

***Calculate quasi-PDFs → Normal PDFs when $P_z \to \infty$***

X. Ji, 2013

**Major challenges:**

- ✧ Ability to calculate in LQCD
- ✧ Renormalization of quasi-DPFs
- ✧ Factorization to PDFs

TMD collaboration

Ma, Qiu 2014,
Phys. Rev. Lett.
120, 022003 (2018)

## ❑ Renormalization:

**Complete proof for the renormalization of quasi-DPFs**

$$\tilde{F}^{R}_{i/p}(\xi_z,\tilde{\mu}^2,p_z) = e^{-C_i|\xi_z|} Z_{wi}^{-1} Z_{vi}^{-1} \tilde{F}^{b}_{i/p}(\xi_z,\tilde{\mu}^2,p_z)$$

**Completely multiplicative - No mix with other flavors or gluon!**

Ishikawa, Ma,
Qiu, Yoshida
Phys. Rev. D96,
094019 (2017)

# 3D hadron structure – LQCD

Radyushkin, 2017

- **Pseudo-PDFs = generalization of PDFs:**
  - **Definition:** $\xi^2 < 0$

$$\mathcal{M}^\alpha(\nu = p\cdot\xi, \xi^2) \equiv \langle p|\overline{\psi}(0)\gamma^\alpha\Phi_v(0,\xi,v\cdot A)\psi(\xi)|p\rangle$$
$$\equiv 2p^\alpha\mathcal{M}_p(\nu,\xi^2) + \xi^\alpha(p^2/\nu)\mathcal{M}_\xi(\nu,\xi^2) \approx 2p^\alpha\mathcal{M}_p(\nu,\xi^2)$$
$$\mathcal{P}(x,\xi^2) \equiv \int \frac{d\nu}{2\pi}\, e^{ix\,\nu}\, \frac{1}{2p^+}\mathcal{M}^+(\nu,\xi^2)$$

  - **Interpretation:** with $\xi^\mu = (0^+, \xi^-, 0_\perp)$

**Off-light-cone extension of PDFs:** $f(x) = \mathcal{P}(x, \xi^2 = 0)$

- **Quasi-PDFs:**

$$\xi^\mu = (0, 0_\perp, \xi_z)$$

No longer Lorentz invariant

$$\tilde{q}(x,\mu^2,p_z) = \int \frac{d\nu}{2\pi}\, e^{ix\nu}\, \frac{1}{2p_z}\mathcal{M}^z(\nu = p_z\xi_z, -\xi_z^2)$$

- **TMDs:**

at $Q = 2.15$ GeV

$$\xi^\mu = (0^+, \xi^-, \xi_\perp)$$
$$\mathcal{P}(x, -\xi_\perp^2) \equiv \int d^2k_\perp\, e^{i\vec{k}_\perp\cdot\vec{\xi}_\perp}\mathcal{F}(x, k_\perp^2)$$

← **TMDs with a straight gauge link**

# 3D hadron structure – LQCD

Radyushkin, 2017

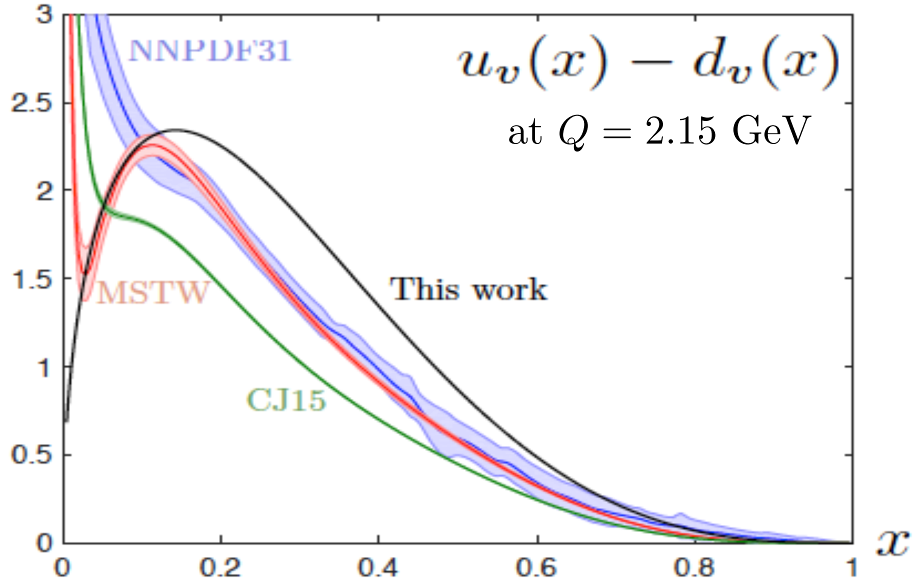
- **Pseudo-PDFs:**
  - Lattice calculation with $\alpha = 0$:

$$\mathcal{M}^\alpha(\nu = p\cdot\xi, \xi^2) \equiv \langle p|\overline{\psi}(0)\gamma^\alpha\Phi_v(0,\xi,v\cdot A)\psi(\xi)|p\rangle$$
$$\equiv 2p^\alpha\mathcal{M}_p(\nu,\xi^2) + \xi^\alpha(p^2/\nu)\mathcal{M}_\xi(\nu,\xi^2) \approx 2p^\alpha\mathcal{M}_p(\nu,\xi^2)$$
$$\mathcal{P}(x,\xi^2) \equiv \int \frac{d\nu}{2\pi}\, e^{ix\,\nu}\mathcal{M}_{p=p^0}(\nu,\xi^2)/\mathcal{M}_{p=p^0}(0,\xi^2)$$

Remove UV!

  - Model quasi-PDFs: with $\xi^\mu = (0, 0_\perp, \xi_z)$

- **First numerical results:**




Orginos, et al,
PRD96, 094503 (2017)

One-loop matching recently Completed!

A. Radyushkin, arXiv:1801.02427

# 3D hadron structure – LQCD

Ma, Qiu 2014,
Phys. Rev. Lett.
120, 022003 (2018)

- **Lattice "cross sections":**
  - ✧ Go beyond quasi- or pseudo-PDFs
  - ✧ Any single-hadron matrix elements satisfies: $\sigma_n(\xi^2,\omega,P^2)=\langle P|T\{\mathcal{O}_n(\xi)\}|P\rangle$

*Lattice calculable, reliable continuum limit, pQCD factorizable*

$$\widetilde{\sigma}_{\rm Lattice}(\tilde{x},Q,P\sim\sqrt{s})\approx\sum_f\int\frac{dx}{x}\mathcal{C}_f\left(\frac{x}{\tilde{x}},\frac{\mu^2}{Q^2},\alpha_s(\mu);P\right)f(x,\mu^2)+\mathcal{O}\left[\frac{1}{Q^2}\right]$$

PDFs

Key: controllable hard scale!

DGLAP-Evolution

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PDFs

Key: controllable hard scale!

DGLAP-Evolution

- **Many choices for the operator:**
  - ✧ Doing experiments on the lattice!

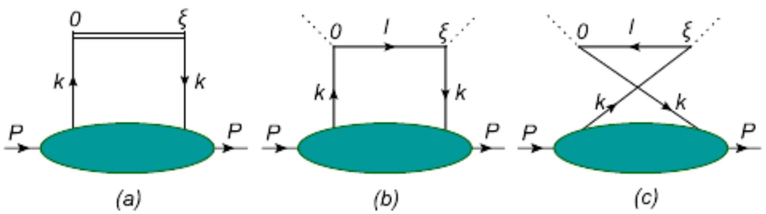
$$\mathcal{O}_{j_1 j_2}(\xi) \equiv \xi^{d_{j_1}+d_{j_2}-2}\, Z_{j_1}^{-1}\, Z_{j_2}^{-1} j_1(\xi)\, j_2(0)$$

$$j_{V'}(\xi) = \xi Z_{V'}^{-1}[\overline{\psi}_q \gamma\cdot\xi\psi_{q'}](\xi),$$

$$j_G(\xi) = \xi^3 Z_G^{-1}[-\frac{1}{4}F^c_{\mu\nu}F^c_{\mu\nu}](\xi)$$

$$\mathcal{O}_q(\xi) = Z_q^{-1}(\xi^2)\overline{\psi}_q(\xi)\,\gamma\cdot\xi\Phi(\xi,0)\,\psi_q(0)$$

$$\Phi(\xi,0) = \mathcal{P}e^{-ig\int_0^1 \xi\cdot A(\lambda\xi)\,d\lambda}$$



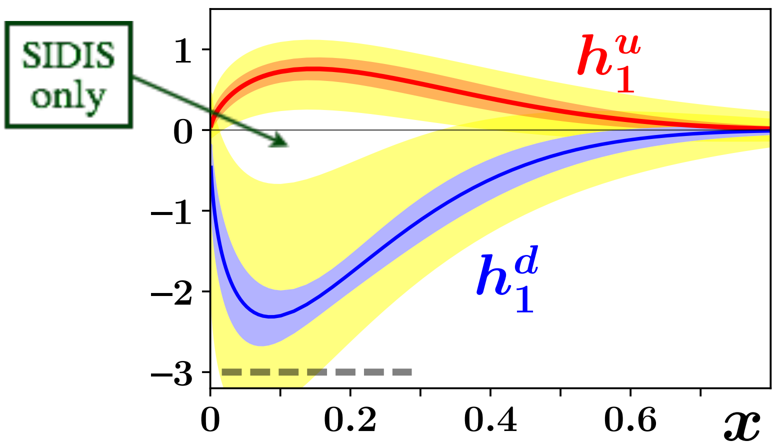

$$\int \frac{d\omega}{\omega}\frac{e^{-ix\omega}}{4\pi}\sigma_q(\omega,\xi^2,P^2) \approx f_q(x,\mu)$$

Module O( $\alpha_s$) corrections
And HT corrections

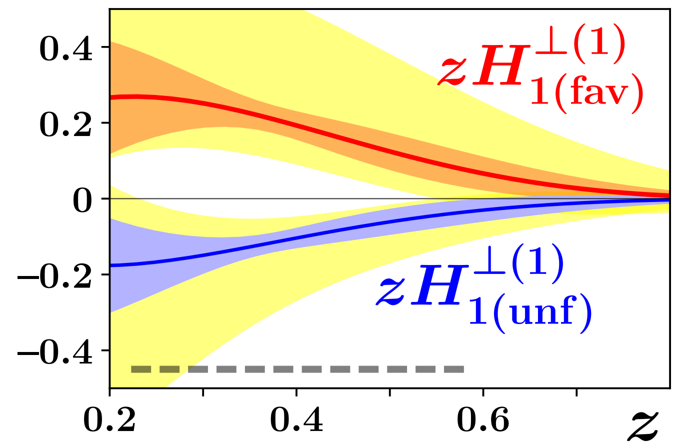
$$\omega = -|\vec{\xi}||\vec{P}|\cos(\theta)$$

# 3D Hadron structure – Global analyses

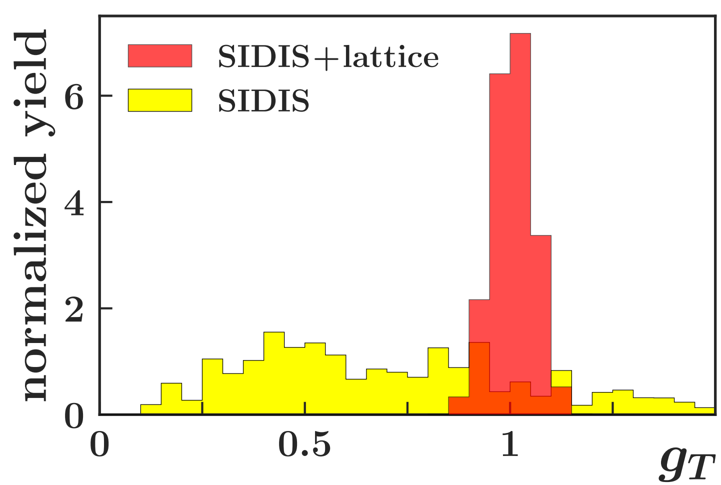
- **First global QCD analysis of transversity distribution**
  **– using Monte Carlo methodology with lattice QCD constraints**




Transversity PDF




Collins fragmentation function

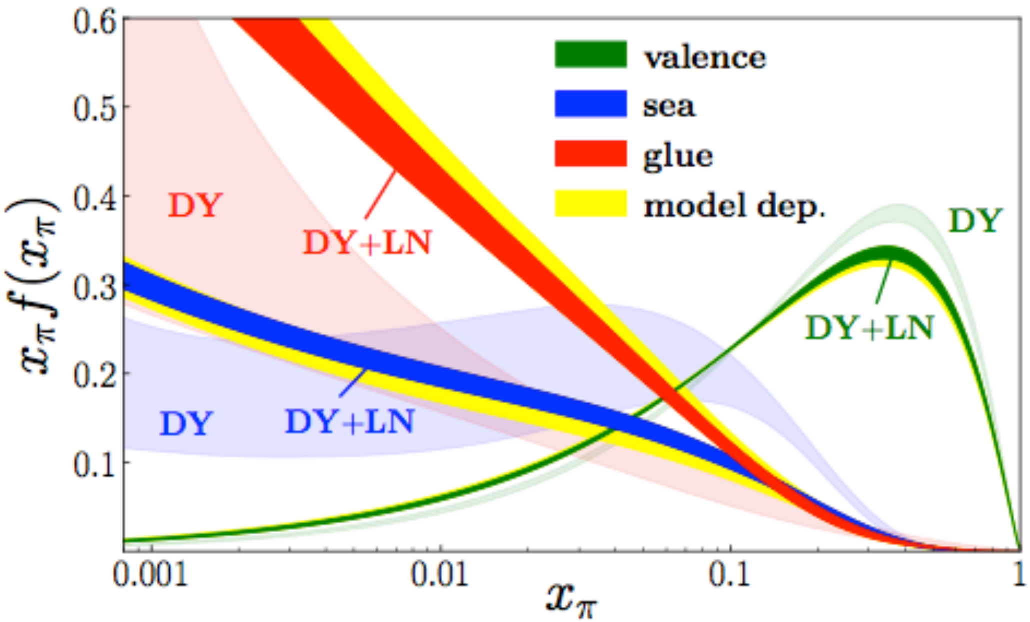



isovector
tensor charge

*Lin, Melnitchouk, Prokudin, Sato, Shows*
*PRL (2018, to appear)*

# 3D Hadron structure – Global analyses

- **First MC global QCD analysis of pion PDFs:**




DY = $\pi N$ Drell-Yan

LN = leading neutron

*Barry, Sato, Melnitchouk, Ji (2018, to appear)*

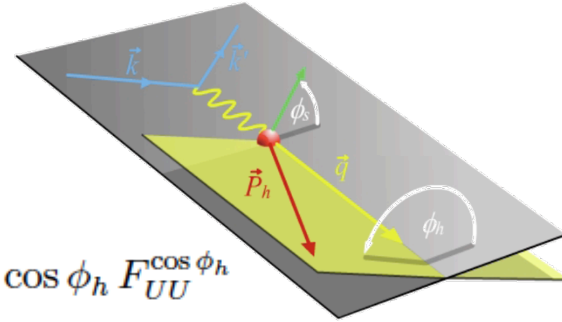
→ significant reduction of uncertainties on sea quark and gluon distributions in the pion with inclusion of HERA leading neutron data

→ implications for "TDIS" (Tagged DIS) experiment at JLab

Using Fermilab DY data and HERA leading neutron production data

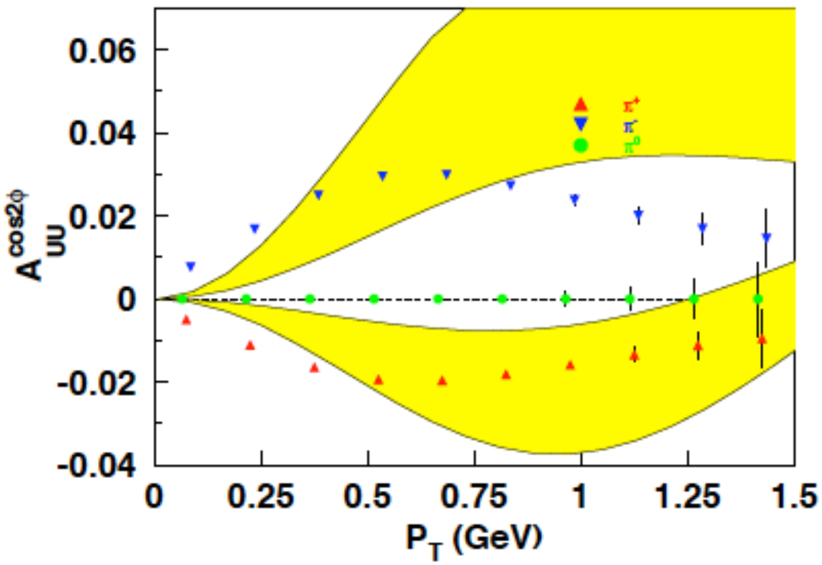
# 3D Hadron structure – NNLO

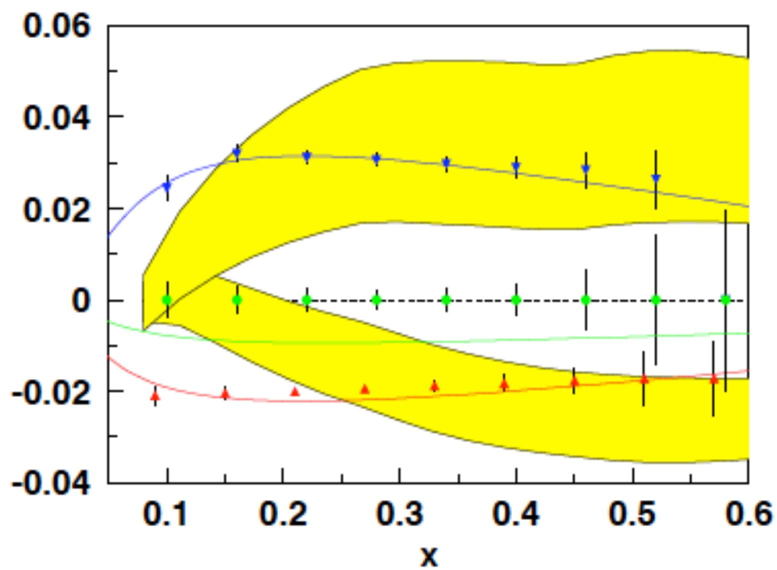
- ❑ **SIDIS at JLab:**



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

- ❑ **Hall B (E12-06-112):**

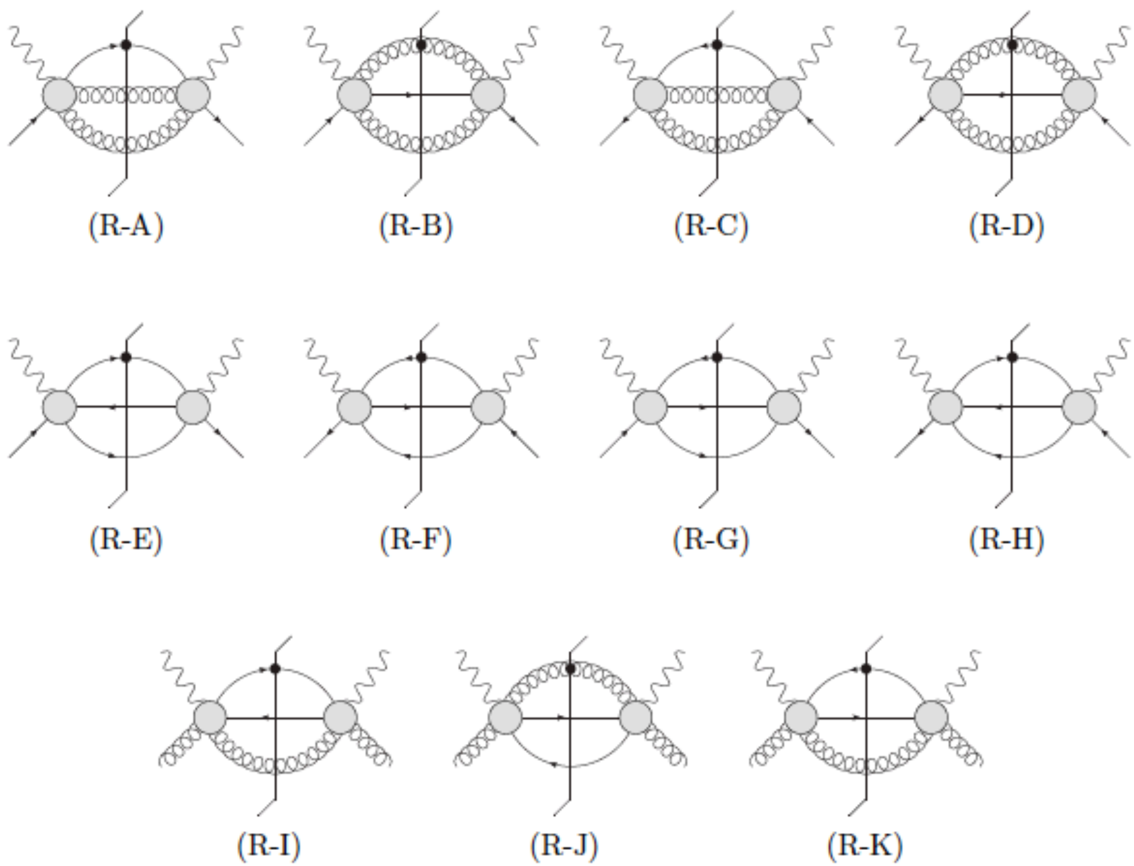



**Sensitive to Boer-Mulders functions & Collins FFs – how does spin influence hadronization?**

# 3D Hadron structure – NNLO

## QCD graphs needed for a good phenomenological description of SIDIS




Stay tuned …

Rogers, et al.

# 3D Hadron structure – NNLO

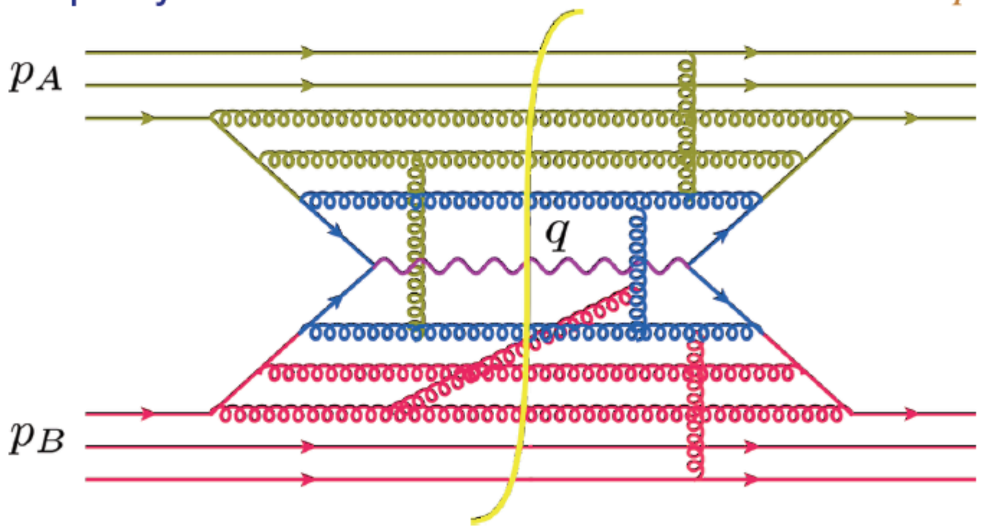
## ❑ TMD factorization at 1st power correction level:

$$\frac{d\sigma}{d\eta d^2 q_\perp} = \sum_f \int d^2 b_\perp e^{i(q,b)_\perp} \mathcal{D}_{f/A}(x_A, b_\perp, \eta) \mathcal{D}_{f/B}(x_B, b_\perp, \eta) \sigma(f\!f \to H)$$

$$+ \text{ power corrections } + \text{ Y} - \text{terms}$$

Rapidity factorization:

$p = \alpha p_A + \beta P_B + p_\perp$



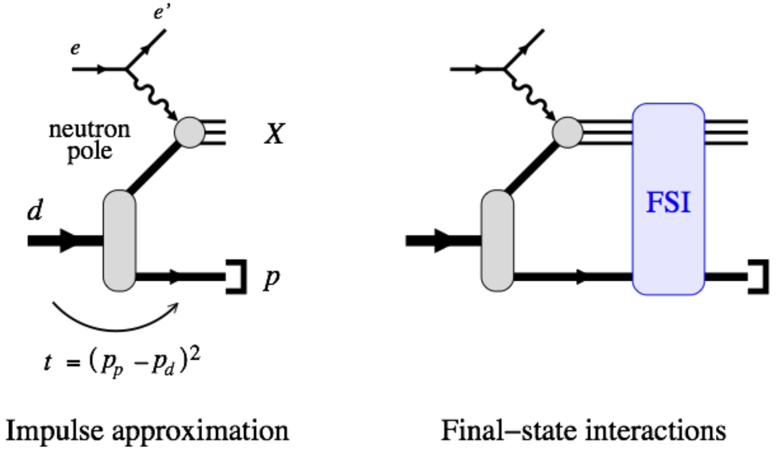

We integrate over "central" fields in the background of projectile and target fields.

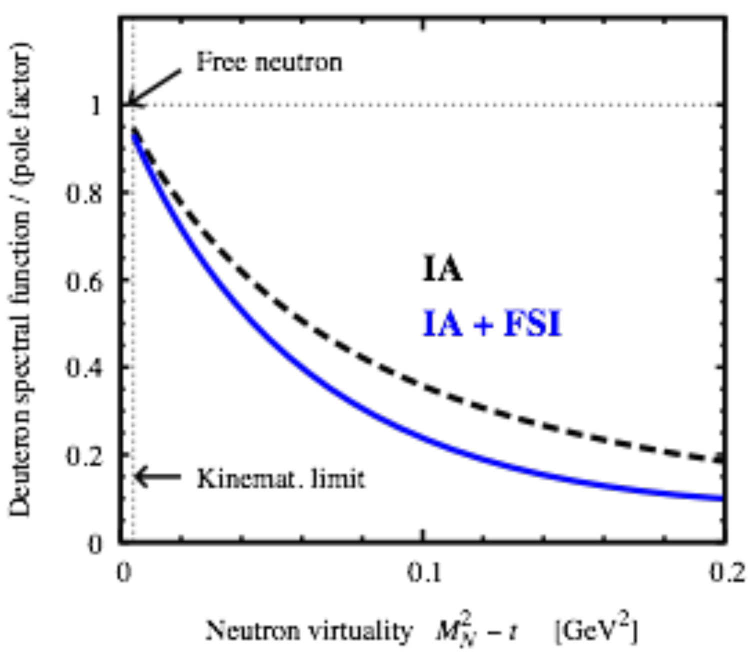
Kinematical region is $s = (p_A + p_B)^2 \gg m_Z^2 \gg q_\perp^2$

**Stay tuned …**

**Balitsky, et al.**

# Hadron structure – EIC




- Developed theoretical framework for DIS on deuteron with spectator nucleon tagging at EIC, e + d -> e' + p + X.
  **Strikman, Weiss arXiv:1706.02244**

- Calculated final-state interactions in new approach based on space-time picture of hadron formation in DIS. Appropriate for EIC kinematics.

- Extension to polarized deuteron DIS and small-x diffractive scattering in progress
  **Strikman, Weiss, Cosyn, Sargsian**

- Enables precise measurements of neutron structure with EIC: On-shell extrapolation
  **EIC simulations performed in 2014/15 LDRD project, PI Weiss, https://www.jlab.org/theory/tag/**

**Weiss et al**

# Nuclear and hadron structure + machine learning

## Nuclear physics

- Exploratory studies with unphysical quark masses
- Constrain nuclear inputs for BSM searches

- Proton-proton fusion and tritium β-decay
  [PRL **119**, 062002 (2017)]
- Double β-decay
  [PRL **119**, 062003 (2017), PRD **96**, 054505 (2017)]
- Baryon-baryon interactions
  [PRD **96**, 114510 (2017)]
- Gluon structure of light nuclei
  [PRD **96**, 094512 (2017)]
- Nuclear modification of scalar, axial tensor charges
  [arXiv:1712.03221]


Physics ABOUT BROWSE PRESS COLLECTIONS

Synopsis: Strong Force Calculations for Weak Force Reactions

August 10, 2017

Theorists have used lattice-QCD calculations to predict two weak-force-driven reactions—proton fusion and tritium decay.

## Hadron Structure

- Gluon structure of hadrons and nuclei and predictions for EIC

- Gluon generalised form factors
  [PRD **95**, 114515 (2017)]

## Machine Learning

- First application of machine learning to accelerate numerical studies of SM

- Machine learning action parameters in lattice quantum chromodynamics
  [arXiv:1801.05784 ]

P. Shanahan et al.

# Summary and outlook

**Theory Center Mission:**

- ❑ Help motivate, promote, stimulate, support and contribute to the JLab12 program
- ❑ Support with leadership to the national nuclear theory research effort

**Thank you!**