The Role of the High Luminously Halls in JLab Science & How the JLab Theory Center can Help

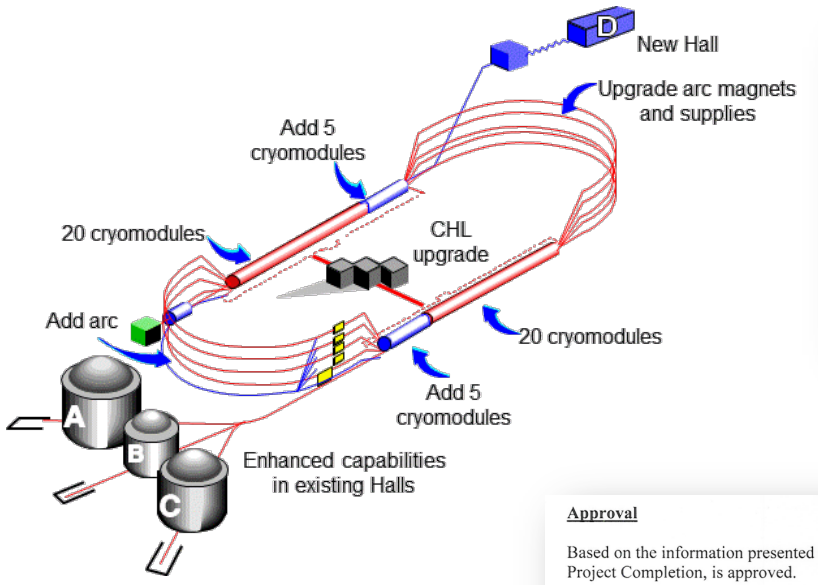
Jianwei Qiu
Theory Center, Jefferson Lab

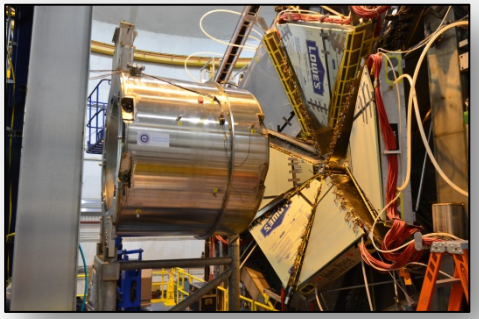
June 22, 2018

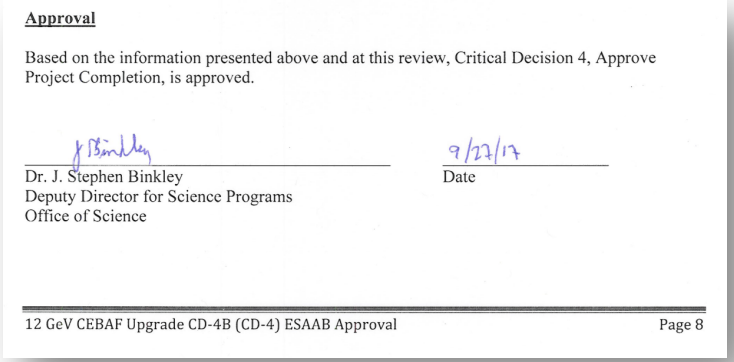
OUTLINE

- JLab 12 GeV science program and the role of all Halls
- How the JLab Theory Center can contribute
  - Spectroscopy
  - Hadron structure and properties
  - QCD and nuclei
  - Standard Model and beyond
- Summary

12 GeV CEBAF Upgrade Project is Complete, On-time and On-Budget!







Approval

Based on the information presented above and at this review, Critical Decision 4, Approve Project Completion, is approved.

J Binkley — 9/27/17

Dr. J. Stephen Binkley
Deputy Director for Science Programs
Office of Science

Date

12 GeV CEBAF Upgrade CD-4B (CD-4) ESAAB Approval — Page 8

Project Completion Approved September 27, 2017

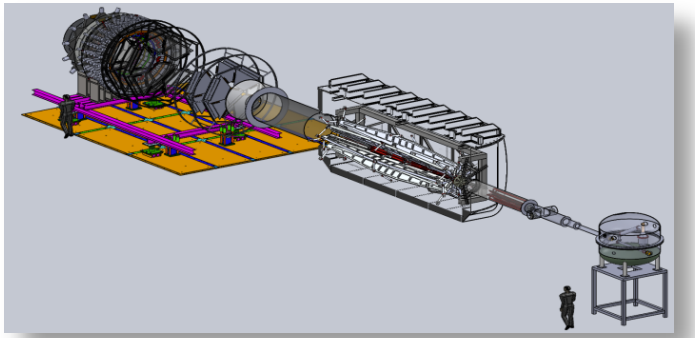
All four Halls are in physics operations

JLab 12 GeV Science Era is Here!

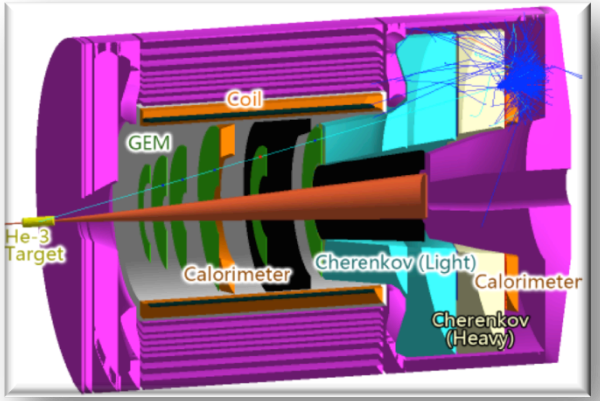
Jefferson Lab

Future Projects

- **MOLLER experiment:**
  (Possible MIE – FY19-23)
  - Precision Standard Model Test
  - DOE science review (Sept. 2014) – strong endorsement
  - Director's Cost, Schedule and Technical review held Dec. 2016
  - CD-0 approved, Dec. 2016
    (project paused due to budget)
  - Awaiting green light to proceed

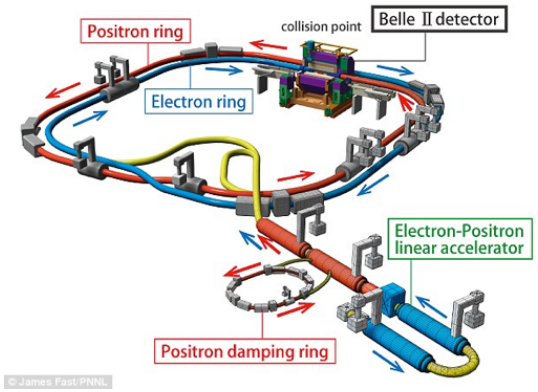


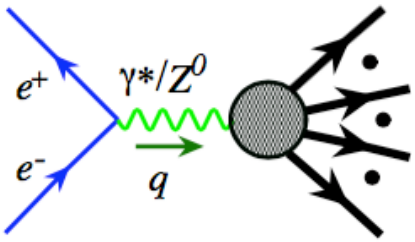
- **SoLID:**
  - Large acceptance, high lumi
  - SIDIS and PVDIS
  - CLEO Solenoid ✓
  - International collaboration
  - Director's review (Feb. 2015)
    → new pre-CDR complete
  - Awaiting science review from ONP



Advantage of Lepton-Hadron Facility

❑ Lepton-lepton collisions:

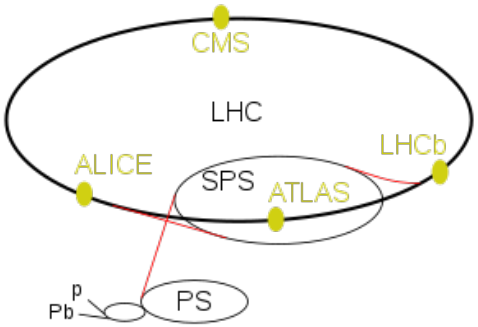


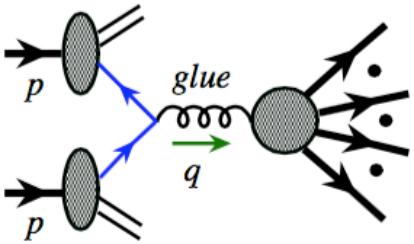


Hadrons

- ✧ No hadron in the initial-state
- ✧ Hadrons are emerged from energy
- ✧ Not ideal for studying hadron structure

❑ Hadron-hadron collisions:





Hadrons

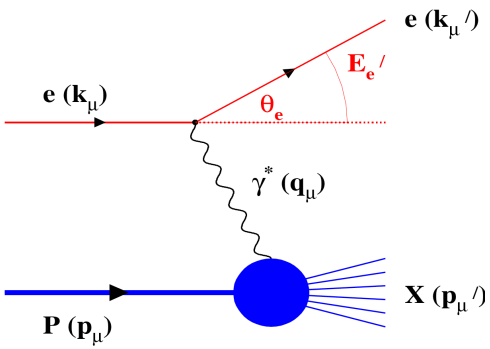
- ✧ Hadron structure – motion of quarks, …
- ✧ Emergence of hadrons, …
- ✧ Initial hadrons broken – collision effect, …

❑ Lepton-hadron collisions:

Hard collision without breaking the initial-state hadron – spatial imaging, …

Advantage of Lepton-Hadron Facility

❑ Lepton-hadron collisions:



Q^2 →Measure of resolution

y → Measure of inelasticity

x → Measure of momentum fraction of the struck quark in a proton

$Q^2 = S\,x\,y$

Inclusive events: e+p/A → e'+X

Detect only the scattered lepton in the detector

(Modern Rutherford experiment!)

Semi-Inclusive events: e+p/A → e'+h(π,K,p,jet)+X

Detect the scattered lepton in coincidence with identified hadrons/jets

(Initial hadron is broken – confined motion! – cleaner than h-h collisions)

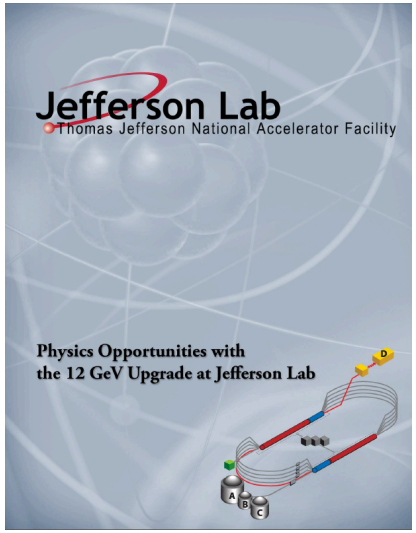
Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)

Detect every things including scattered proton/nucleus (or its fragments)

(Initial hadron is NOT broken – tomography! – almost impossible for h-h collisions)

JLab 12 GeV Science Program

- **Explore the origin of color confinement:**
  - ✧ What is the role of gluonic excitations in the spectroscopy of light mesons?
  - ✧ Can these excitations elucidate the origin of color confinement?
- **Probe the internal structure of hadrons:**
  - ✧ Can the 3D landscape of nucleon shed some lights on the confinement?
  - ✧ How quark/gluon and their 3D confined motion make up hadron's mass, spin, ..
  - ✧ How hadrons are emerged from quarks and gluons – Femtometer detector?
- **Understand the emergence of nuclei from QCD:**
  - ✧ What does a nucleus look like if we only see quark/gluon?
  - ✧ How nuclear force emerged from quark/gluon interaction?
  - ✧ What is the origin of short-range N-N correlations?
- **Test the Standard Model and beyond:**
  - ✧ Can the precision measurements at JLab help discover evidence for physics beyond the Standard Model of particle physics?



JLab 12 GeV Science Program

- **Explore the origin of color confinement:** *Hall-B (CLAS12) & Hall D (GlueX)*
  - ✧ What is the role of gluonic excitations in the spectroscopy of light mesons?
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- **Probe the internal structure of hadrons:** *Halls: A, B, C, D*
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- **Test the Standard Model and beyond:** *Halls: A, B, C, D*
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All Halls could contribute to JLab 12 Science Program Complementarily

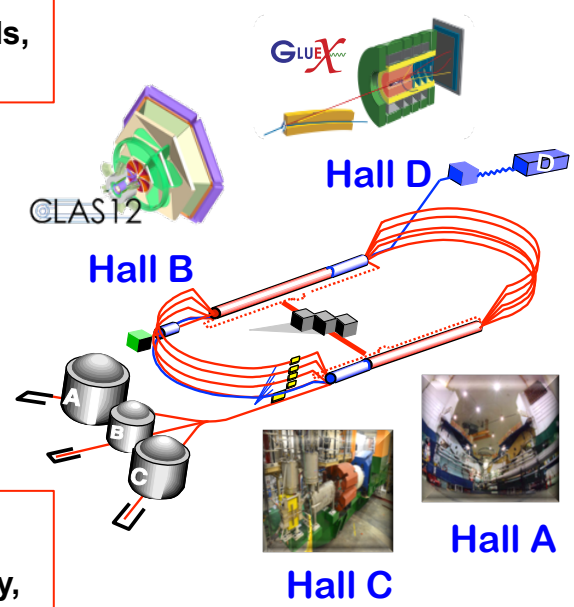
How the JLab Theory Center can Contribute

- **Organized in six thrust areas:**

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

Hadron spectroscopy – JPAC: Doring, Passimar, Szczepaniak

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



3D hadron & nuclear structure – LQCD: Briceno, Edwards, Orginos, Richards, Shanahan

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

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

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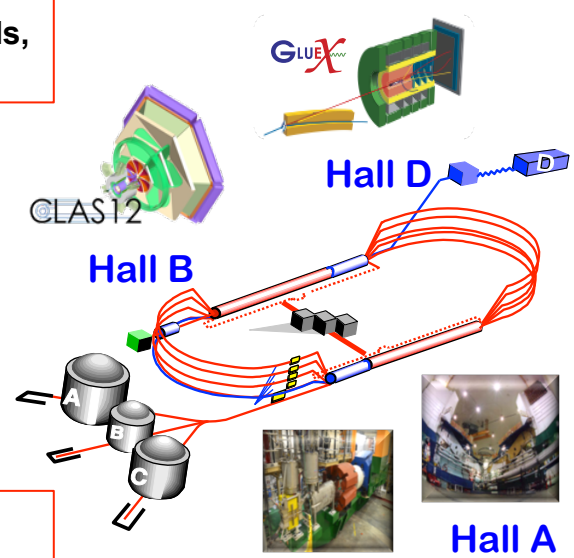

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- **Initiatives:**
  - ✧ JLab collaboration with PARTONS – Theory + Hall A/B/C – Data ⟶ 3D Images
  - ✧ Research with HPC: Exascale & Event generators with "no" theory biases, …

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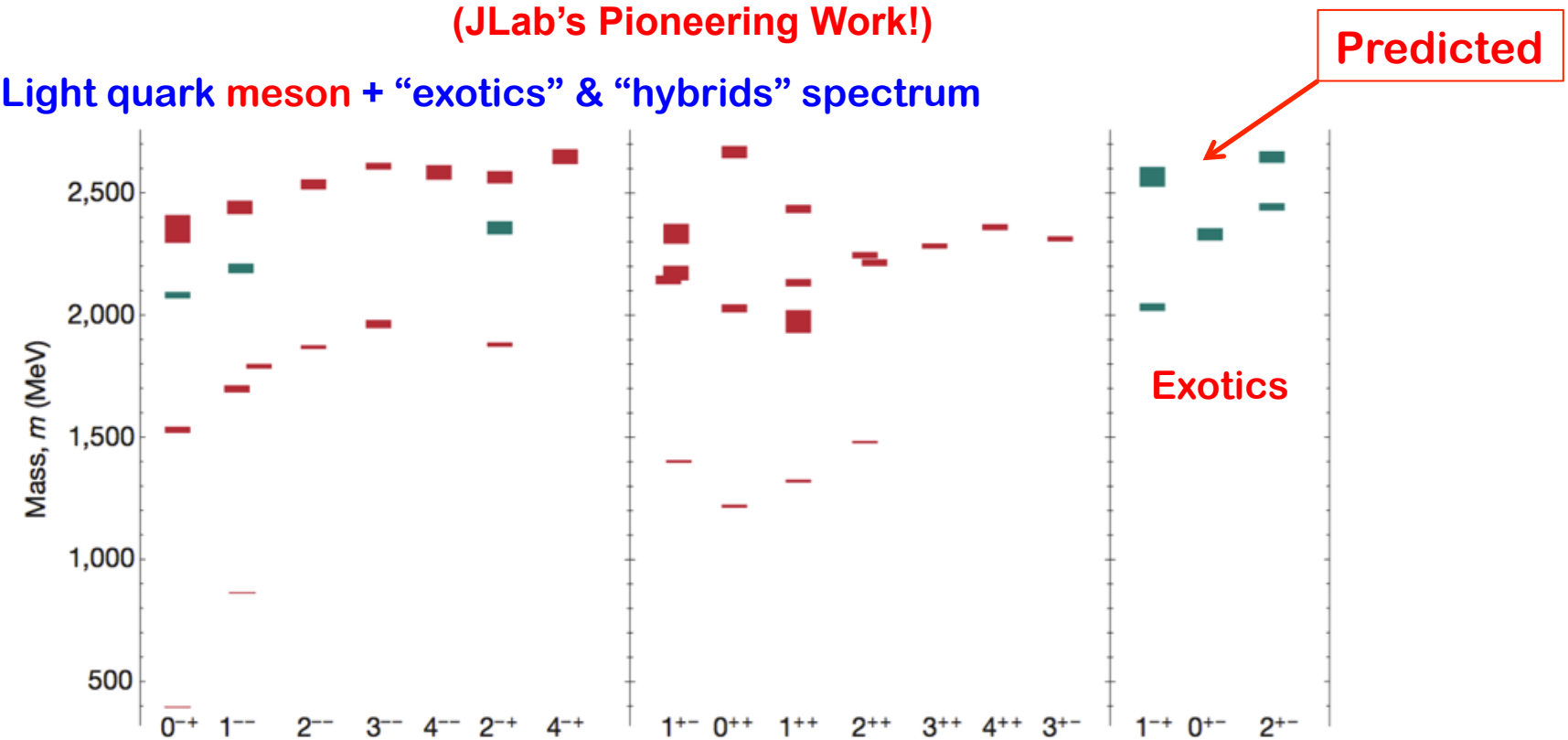
Hadron Spectroscopy – LQCD

- Focus on GlueX & CLAS12 @ JLab & COMPASS, BES, & LHCb

(JLab's Pioneering Work!)

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



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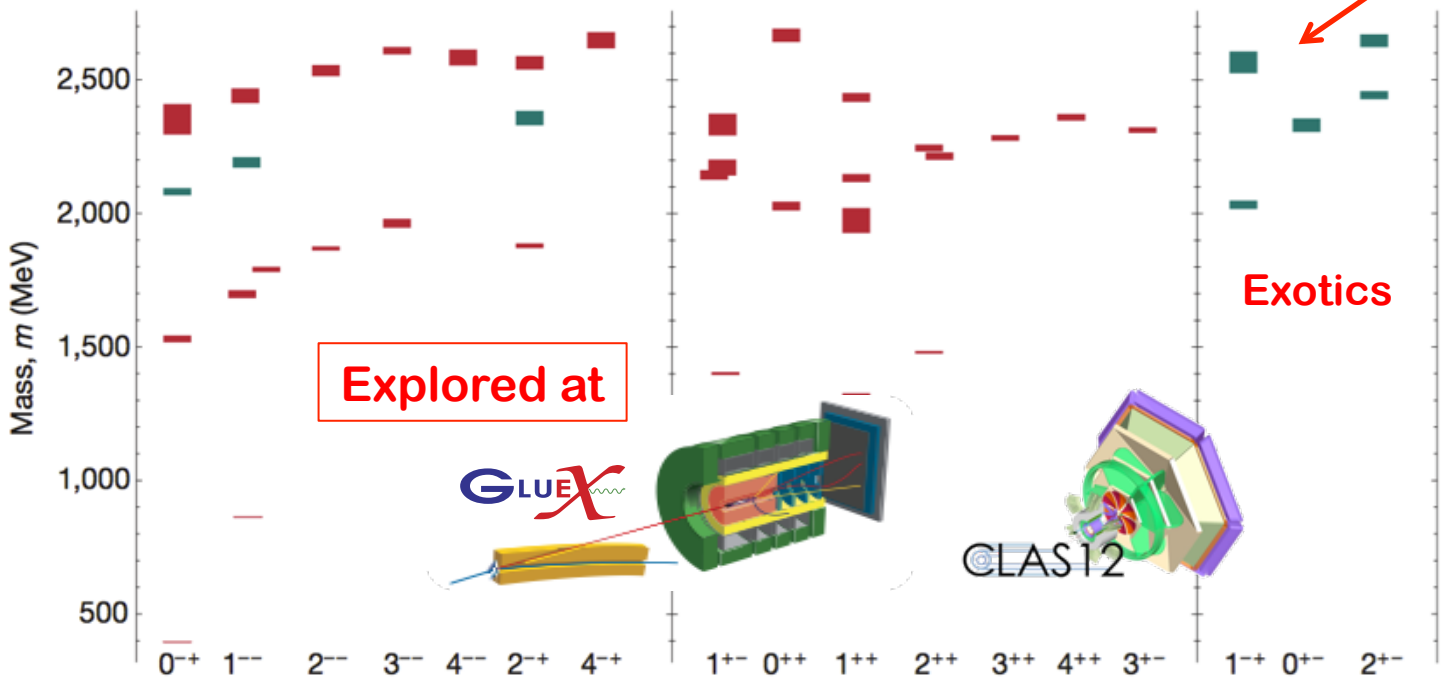


NATURE | REVIEW

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

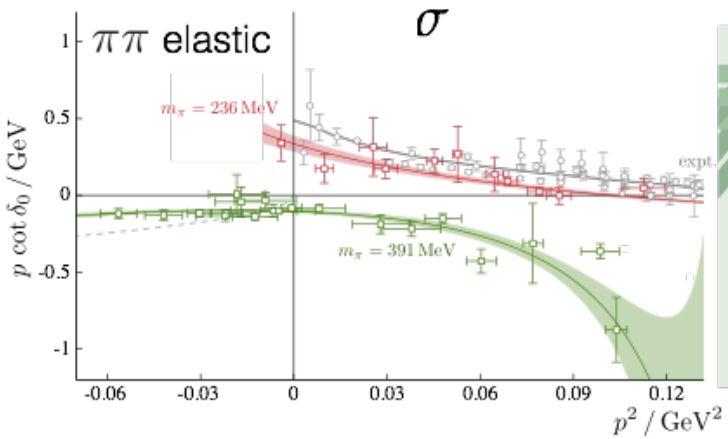
Recognized by Feature review

Jefferson Lab

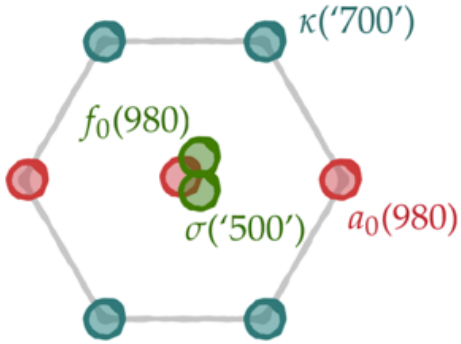
Hadron Spectroscopy – LQCD

- **New development:**

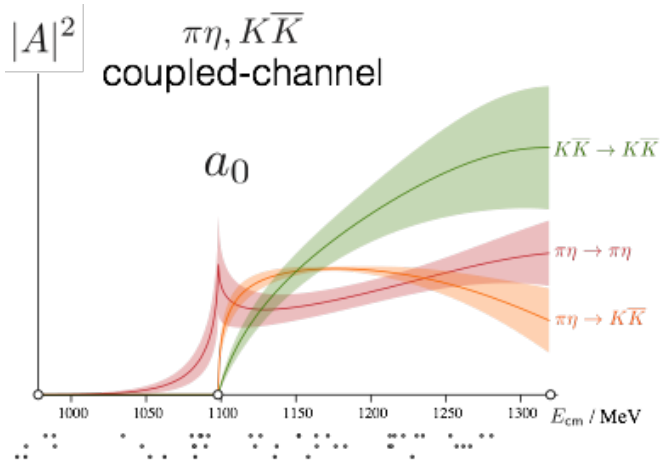
(Solving old mysteries – scalar sector)



PRL118 022002 (2017)



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

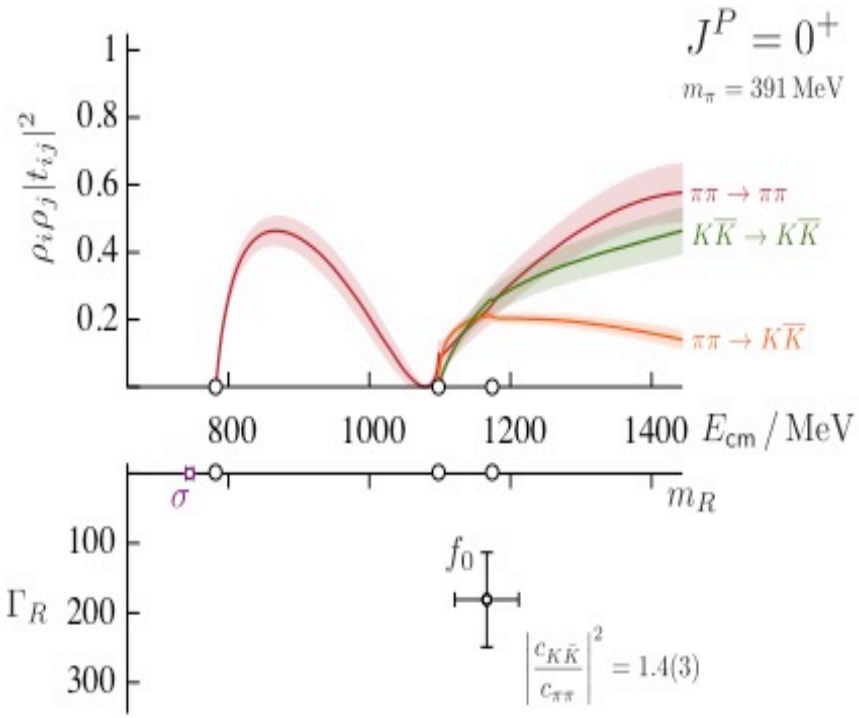


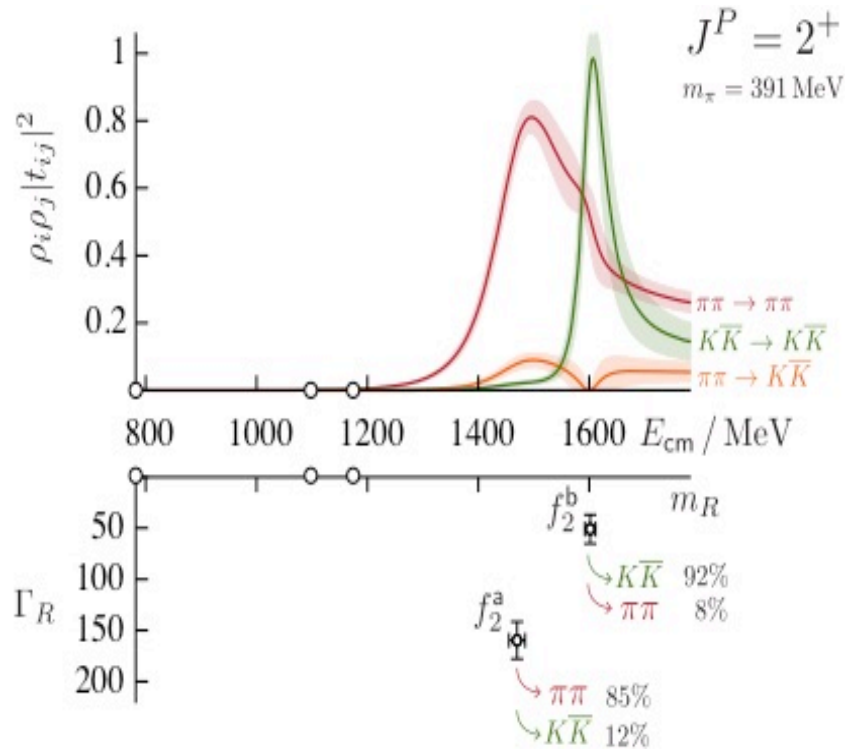
PRD93 094506 (2016)

Hadron Spectroscopy – LQCD

Motivation: GlueX looking for exotic hybrid mesons in photoproduction
(to theorists) Might appear as enhancement in ππππ ~ πρ, πσ, πf0(980)…

- **First LQCD resonance identification via flavor tagged decays:**





"Editors" Suggestion

HadSpec: Phys.Rev.D97, 054513 (2018)

In return:

Used as motivation in GlueX PID upgrade proposal
GlueX actively calibrating in this channel

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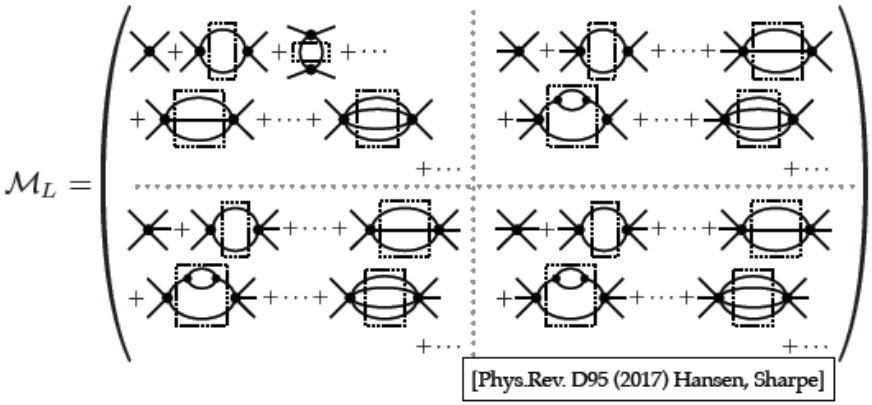
Hadron Spectroscopy – LQCD

- **Even newer development:**

Two/three body systems

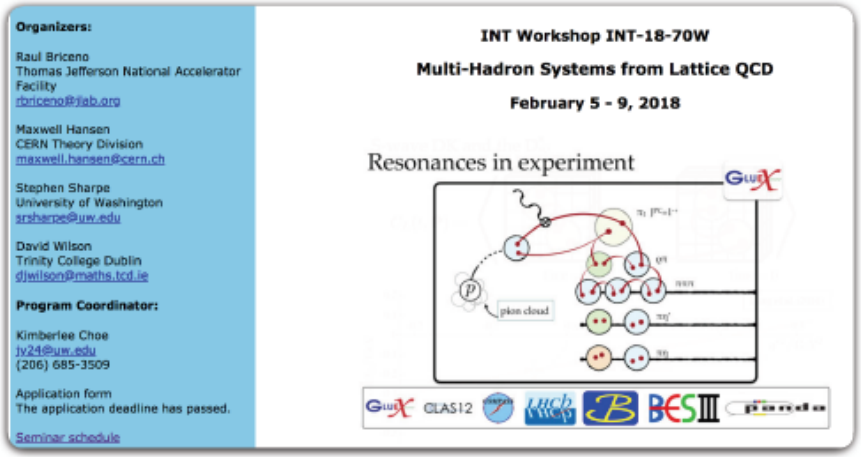
First development of formalism for coupled two/three-body scattering via lattice QCD



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

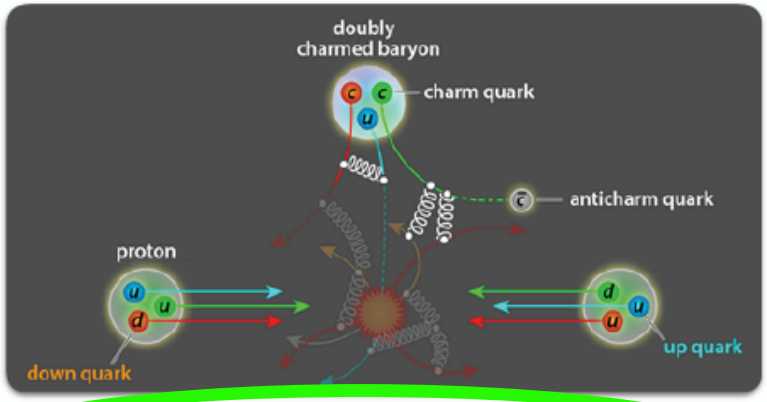
Multi-Hadron Systems from Lattice QCD

Organized workshop

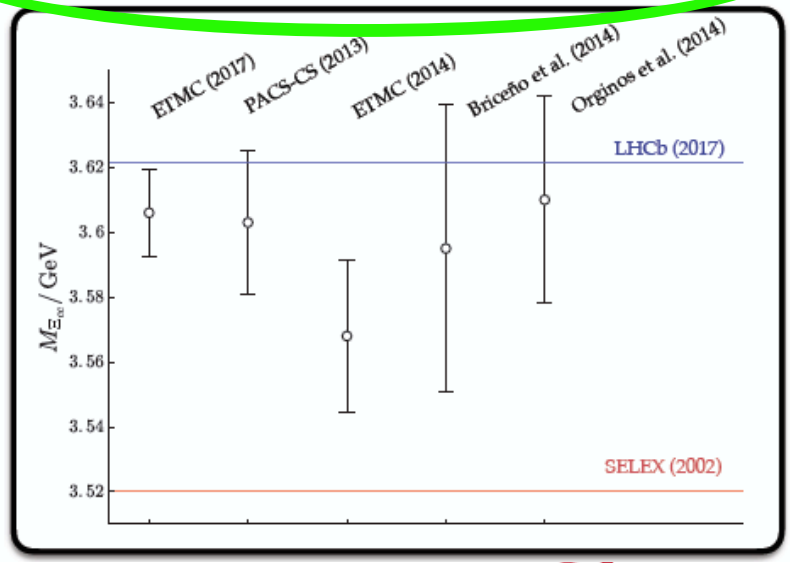


Viewpoint: A Doubly Charming Particle

Briceño, Physics 10 (2017) 100



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



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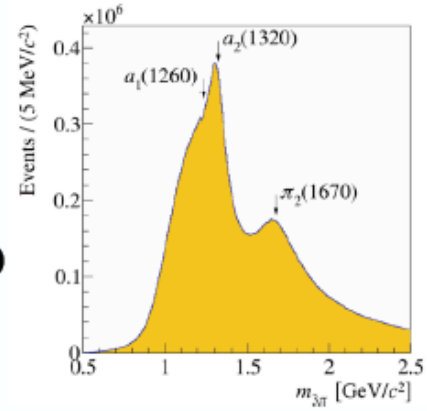
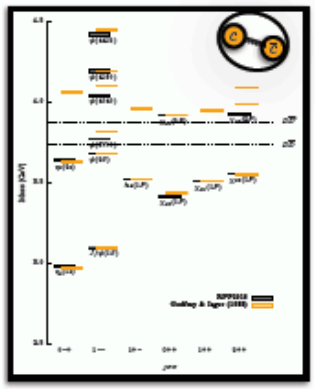
Hadron Spectroscopy – JPAC

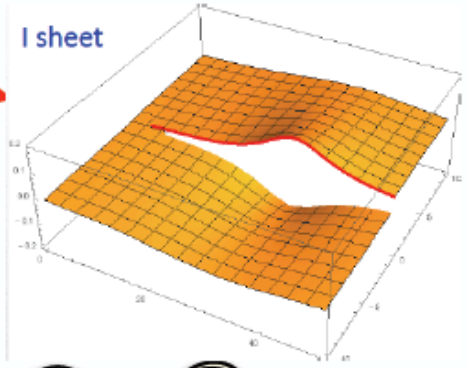
- **Joint Physics Analysis Center:**





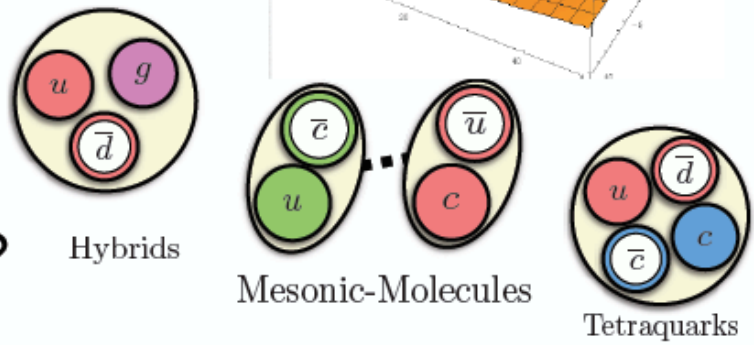
- Experimental or lattice signatures (real axis data: cross section bump and dips, energy levels)

Reaction amplitudes



- Theoretical signatures (complex plane singularities: poles, cusps)

Microscopic Models



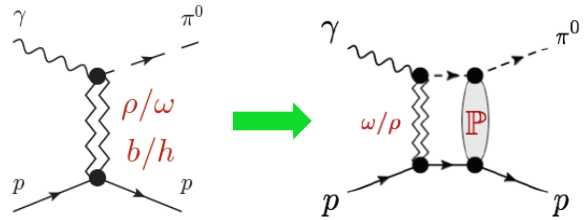
- What is the interpretation (constituent quarks, molecules, …) ?

Hadron Spectroscopy – JPAC

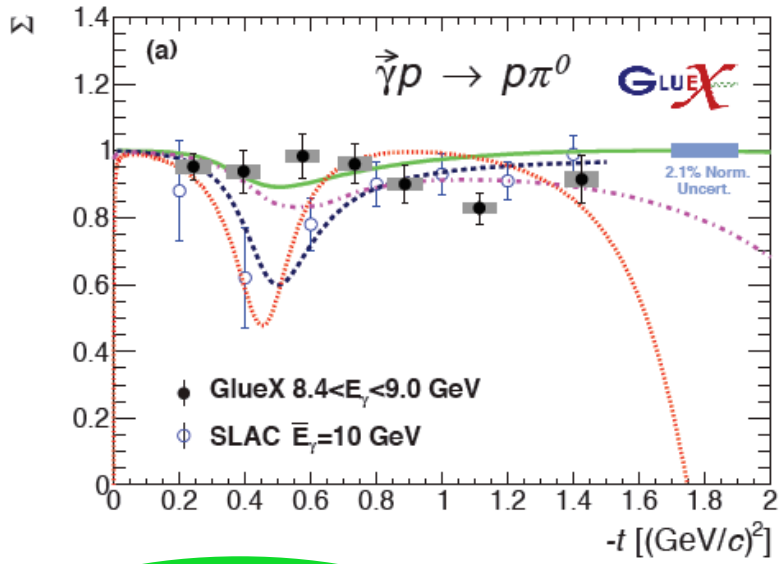
- **Beam asymmetry:**

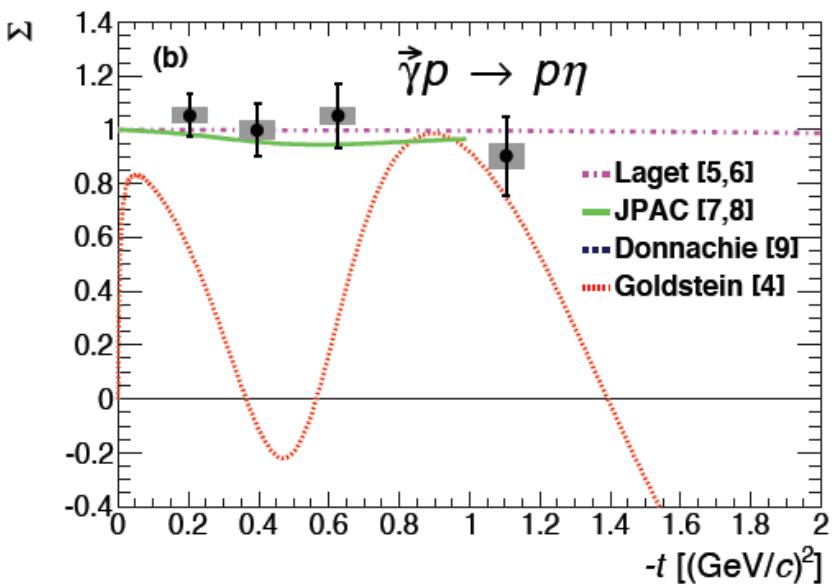
Successful predictions for GlueX!

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



Separation meson from baryon resonance





H. Al Ghoul et al. [GlueX]
Phys. Rev. C95 (2017) no.4, 042201

First paper from GlueX and JLab12 upgrades

JPAC prediction

V. Mathieu et al., PRD92 (2015) 074013
J. Nys et al., PRD95 (2017) 034014

Possible tension between GlueX and SLAC data?

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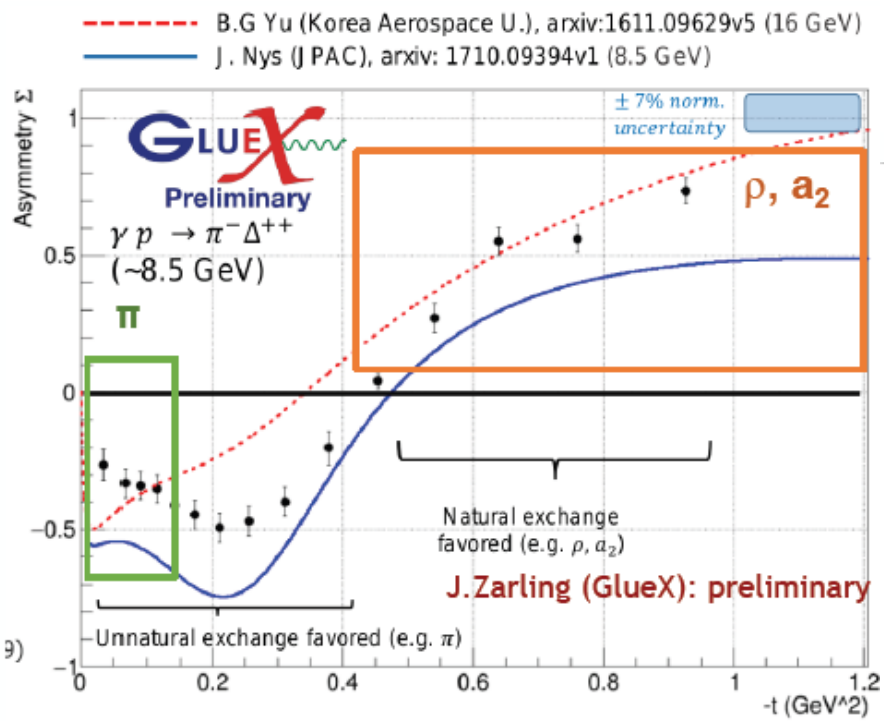
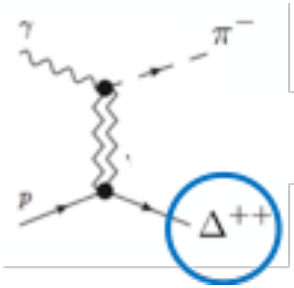
Hadron Spectroscopy – JPAC

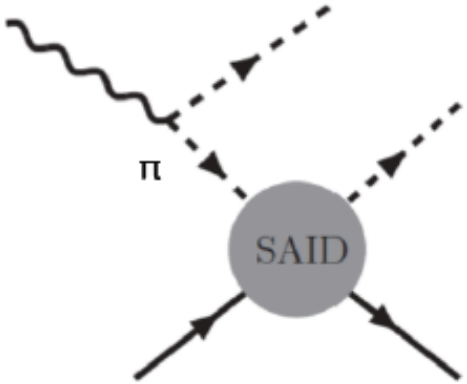
❑ πΔ-photoproduction:





- Stringent test of one-pion-exchnage production
- Possible to make parameter-free predictions

J.Nys et al. (JPAC) Phys.Lett. B779, 77 (2018)



$s_{\pi p} \leq 2$ GeV

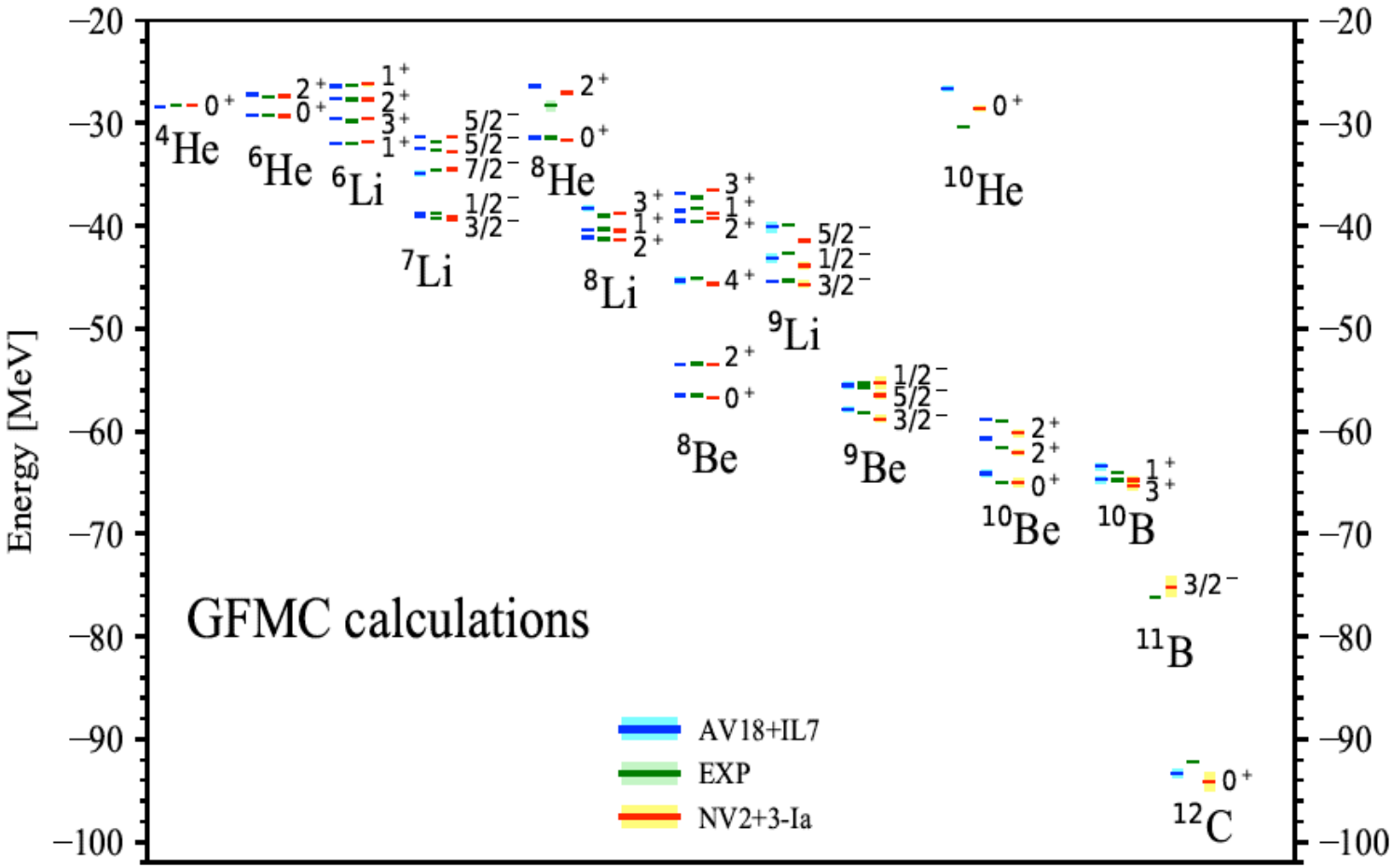
Łukasz Bibrzycki et al. (Cracow,JPAC)

Comparison with preliminary GlueX results

- ✧ Confirmation of interference pattern
- ✧ High –t: natural, Low –t: unnatural
- ✧ Mismatch: oddly behaved π exchange
  - on-going analysis – theory/experiment

Nuclear structure – EFT approach

- Light nuclei spectra from chiral dynamics:



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

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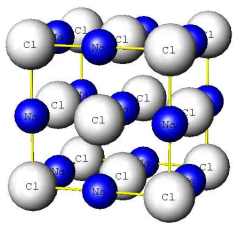
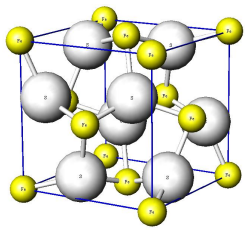
Internal Structure of Hadrons

- **Structure – "a still picture"**

Crystal Structure:

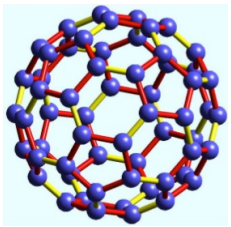


NaCl,
B1 type structure



FeS2,
C2, pyrite type structure

Nano-material:

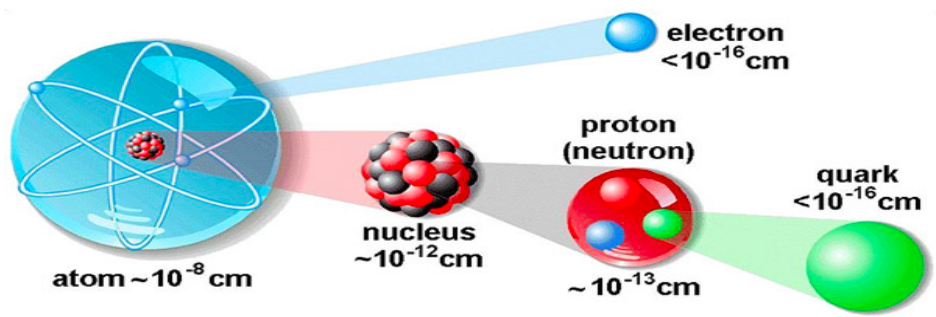


Fullerene, C60

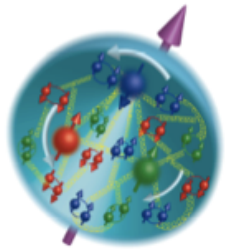
Motion of nuclei is much slower than the speed of light!

- **No "still picture" for hadron's partonic structure!**

Atomic world:



Gluon



Quantum Fluctuation

Motion of quarks/gluons inside hadrons is relativistic!

Partonic Structure: ***Quantum "probabilities"*** $\langle P,S|\mathcal{O}(\overline{\psi},\psi,A^{\mu})|P,S\rangle$

No still Picture!

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Internal Structure of Hadrons

- **Landscape of hadrons:**

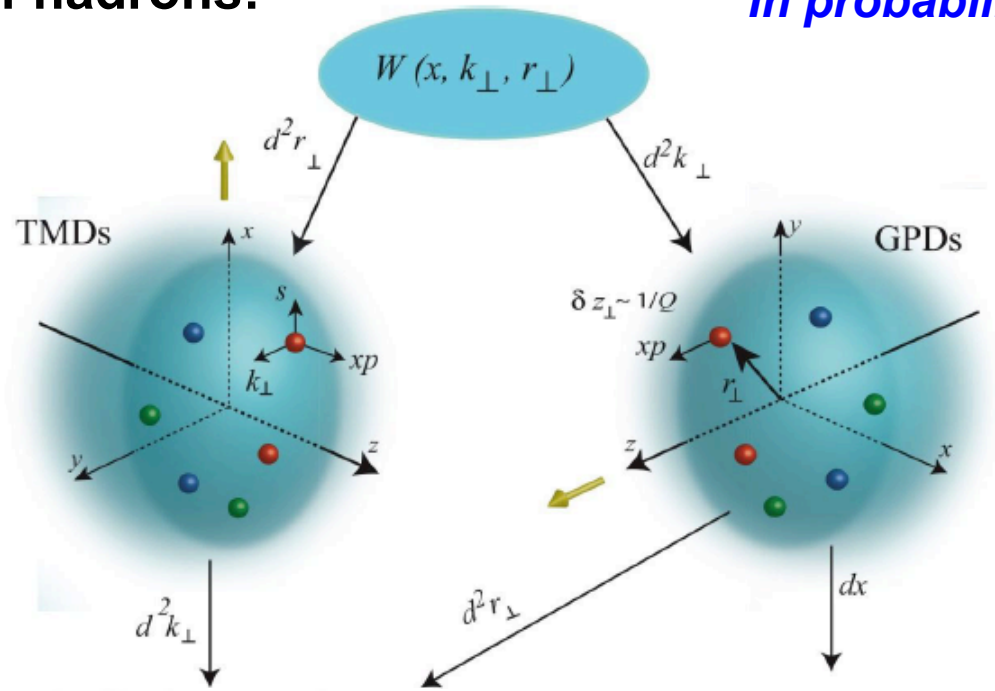
In probability distributions

Momentum Space

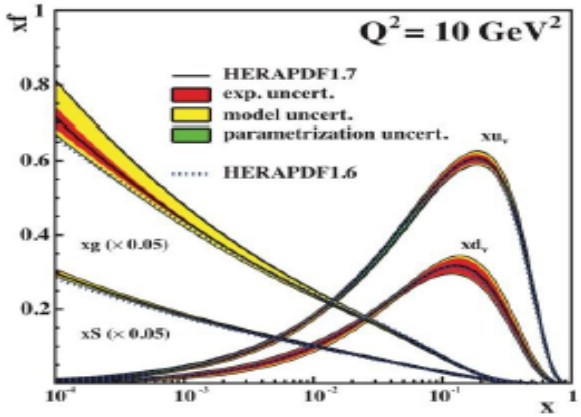
Coordinate Space

3D Confined motion

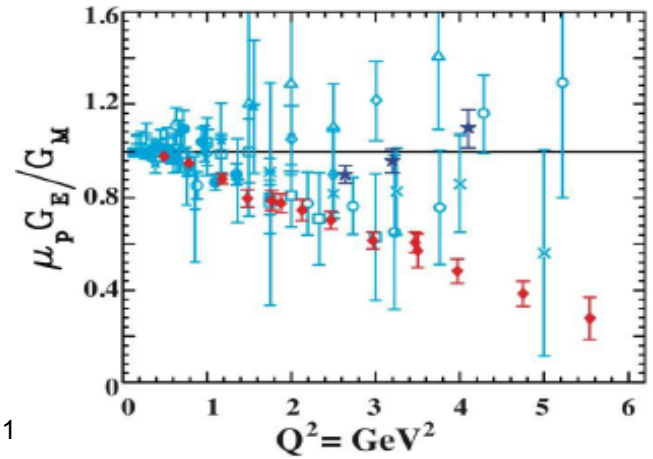
2D Spatial distribution



Parton Distribution Functions



Form Factors



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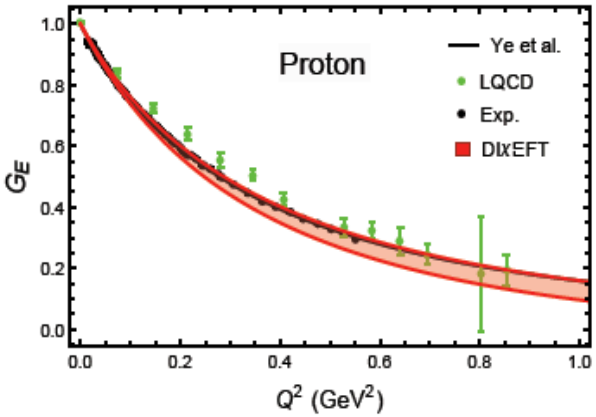
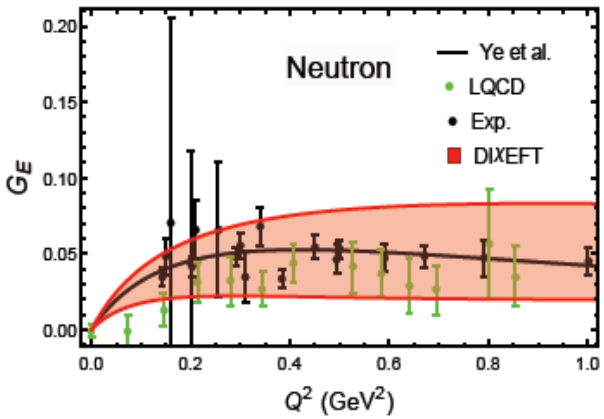
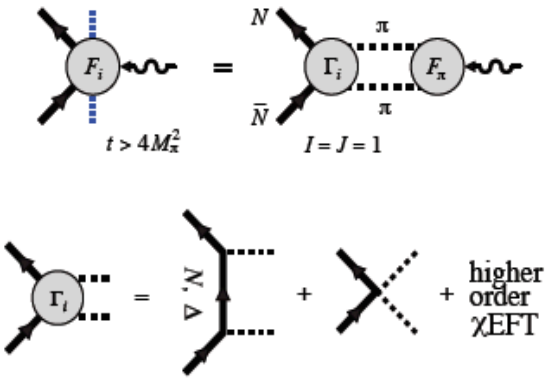
Form factors – Low energy EFTs

❑ Accurate form factors from chiral EFT:







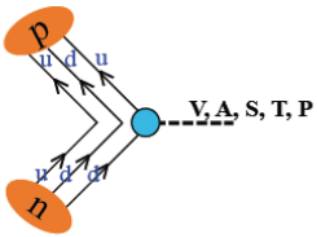
- Developed new first-principles method for calculating low-Q2 nucleon form factors combining chiral EFT and dispersion theory (DIχEFT). Includes ππ rescattering in t-channel through unitarity. **Alarcon, Hiller Blin, Vicente Vacas, Weiss, NPA 964, 18 (2017); Alarcon, Weiss PRC 96, 055206 (2017); Alarcon,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

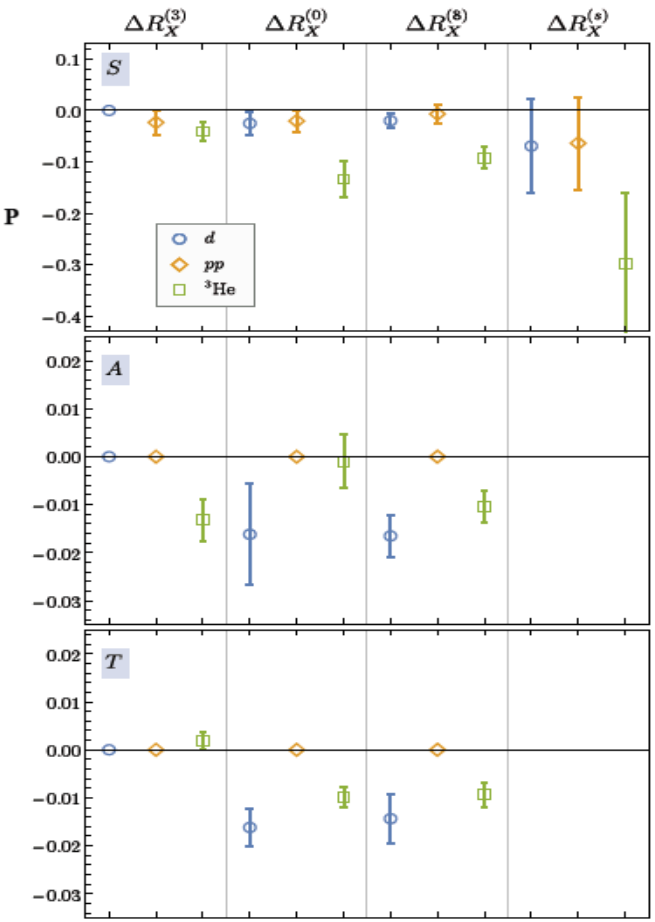
Form factors – LQCD

- **Scalar, axial and tensor currents of light nuclei (Halls A/B/C):**

  Chang, Orginos, Gambhir, Shanahan, Winter et al., Phys. Rev. Lett. 120, 152002 (2018)

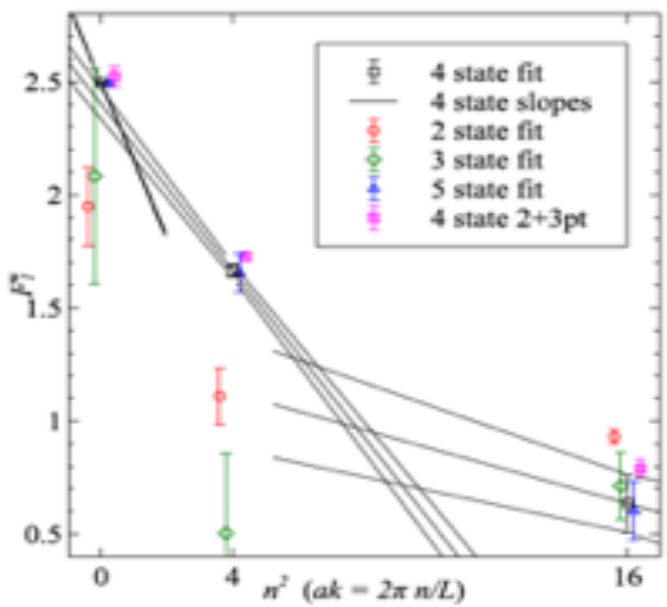
$$R_X^{(f)}(A) = g_X^{(\bar{f})}(A)/g_X^{(f)}(p)$$





- **Nucleon charge radius through coordinate-space moments (Hall B/Prad):**

  Bouchard, Chang, Orginos, Richards, PoS LATTICE2016 (2016)



- **Pion Form Factor at High Momenta and Pion Parton Distribution Function (Prad/Hall C):** Lattice/QCD Phenomenolog on-going joint effort

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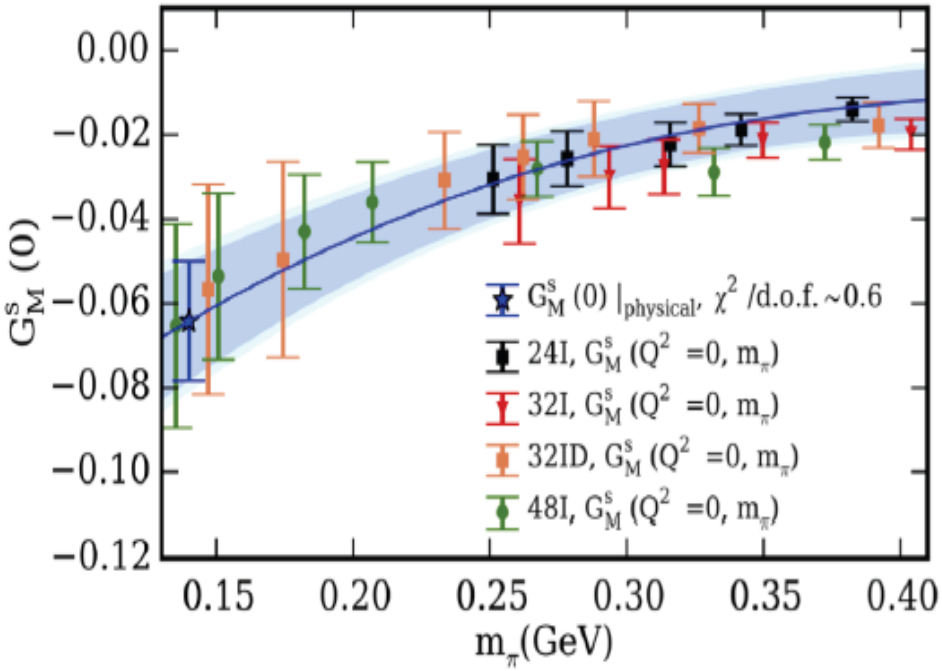
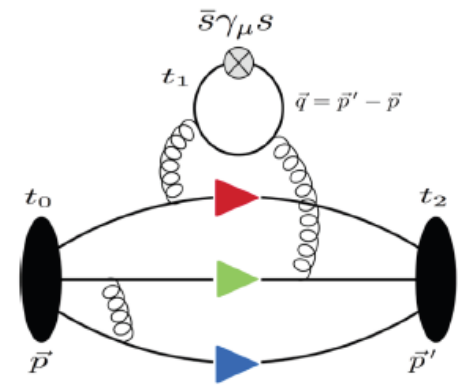
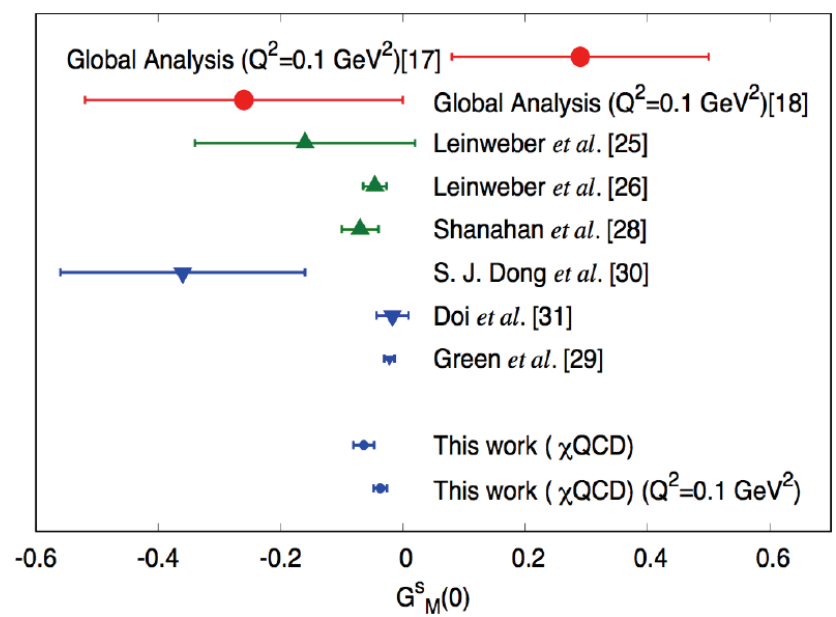
Form factors – LQCD

- **Strange quark magnetic moment of the nucleon:**

(at physical pion mass with domain wall fermions)







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

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

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Hadron structure – JLab webfitter

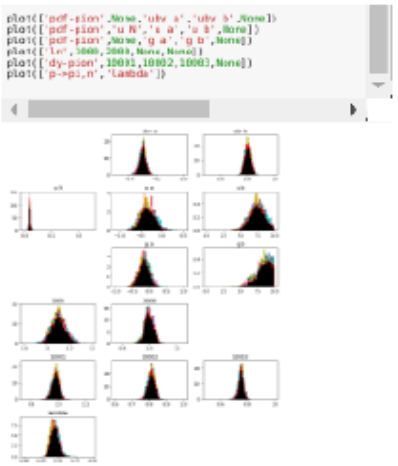
JLab webfitter

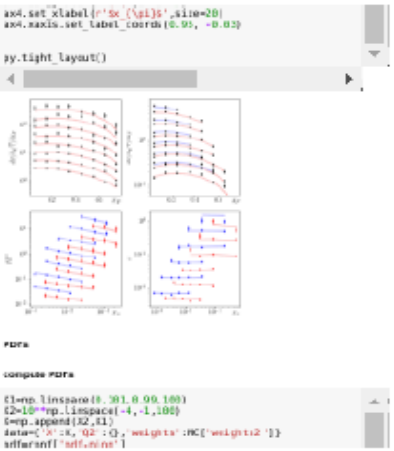
User friendly setups

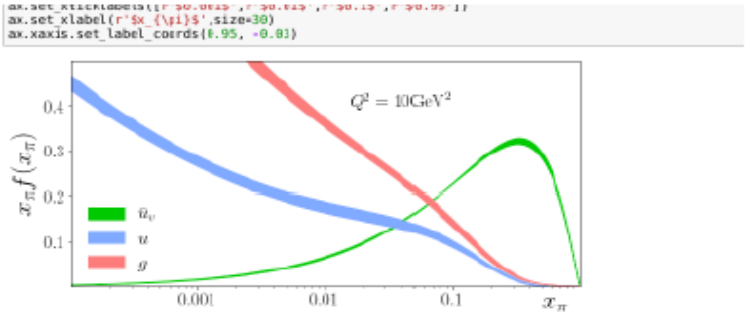
JupyterHub

With JupyterHub you can create a multi-user Hub which spawns, manages, and proxies multiple instances of the single-user Jupyter notebook server.

Project Jupyter created JupyterHub to support many users. The Hub can offer notebook servers to a class of students, a corporate data science workgroup, a scientific research project, or a high performance computing group.







Easy data visualization tools

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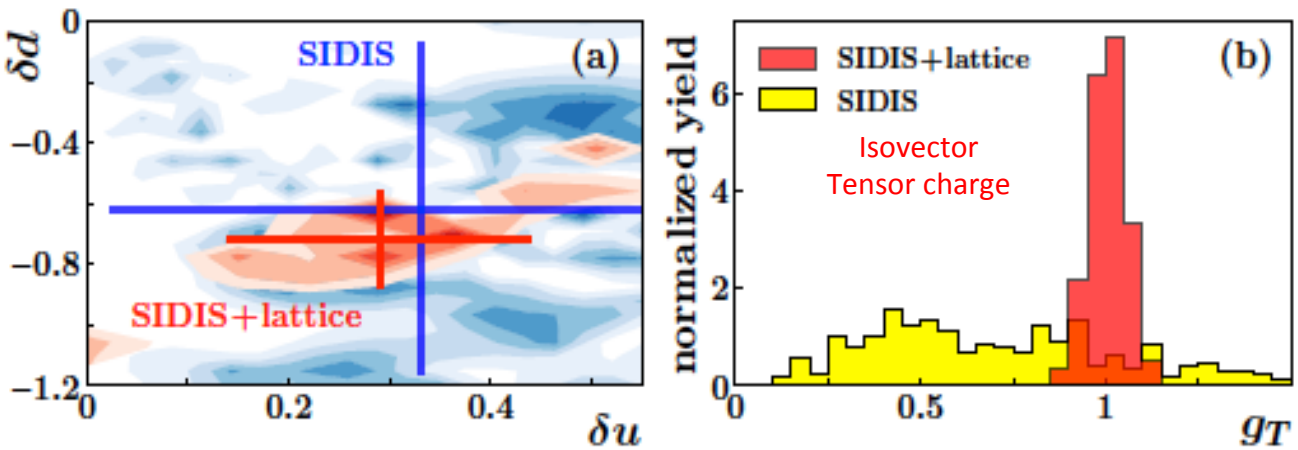
Hadron structure – JAM – Global analysis

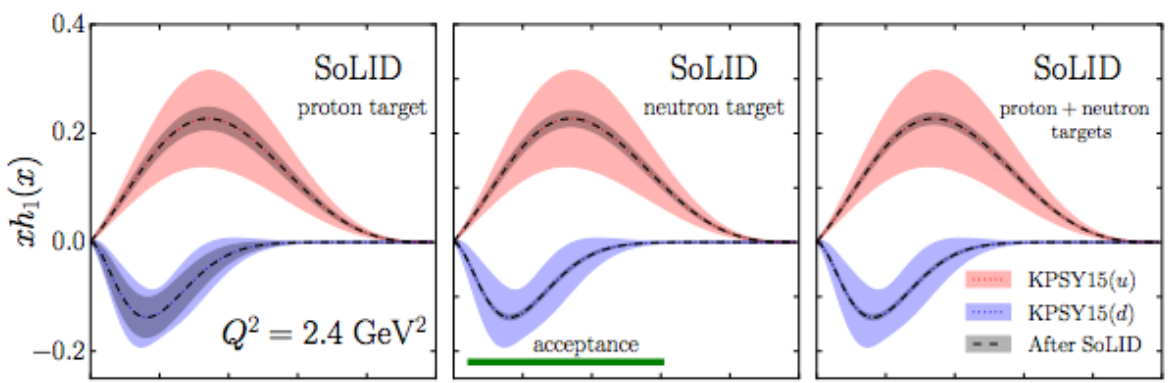
- **First global QCD analysis of transversity distribution**
  – using Monte Carlo methodology with lattice QCD constraints

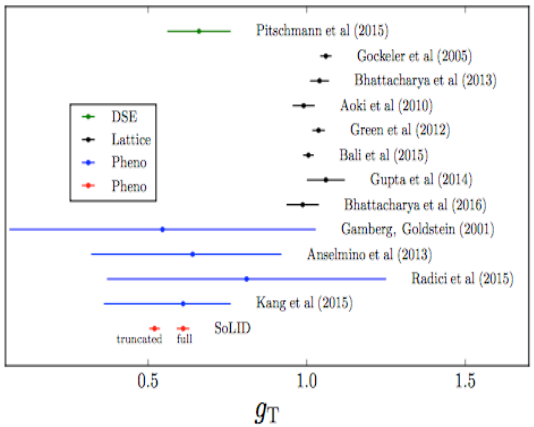


isovector
tensor charge

H.W. Lin et al, PRL 120, 152502 (2018)

- **Impact of a future SoLID, …**





Hall A + Theory, Phys. Lett. B767, 91 (2017)

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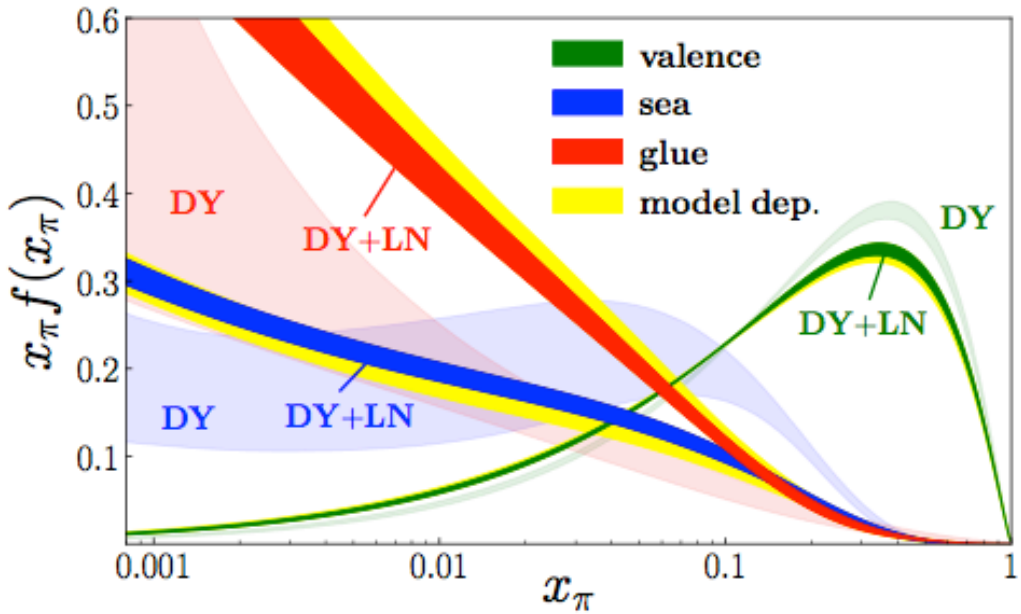
Hadron structure – JAM – Global analysis

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



DY = πN 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

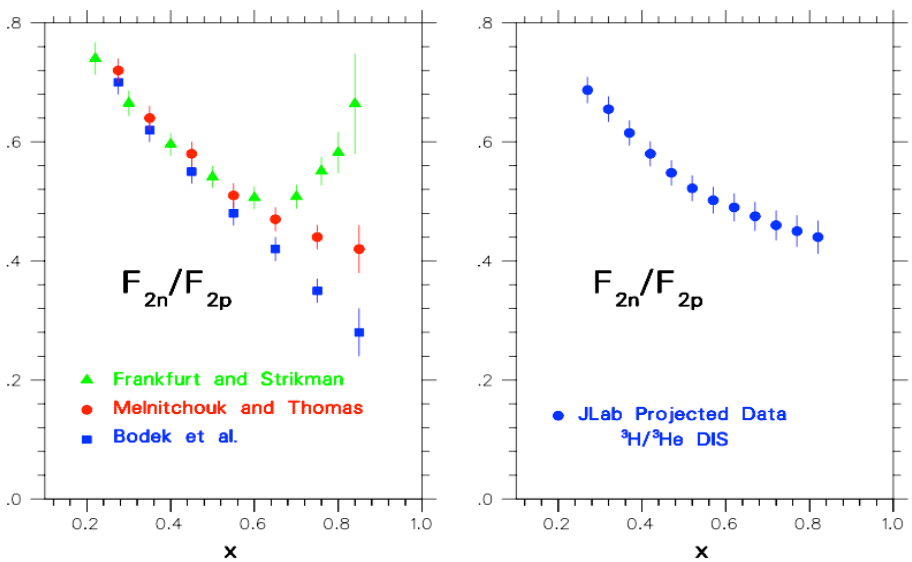
Valence Quark Structure – Global Analysis

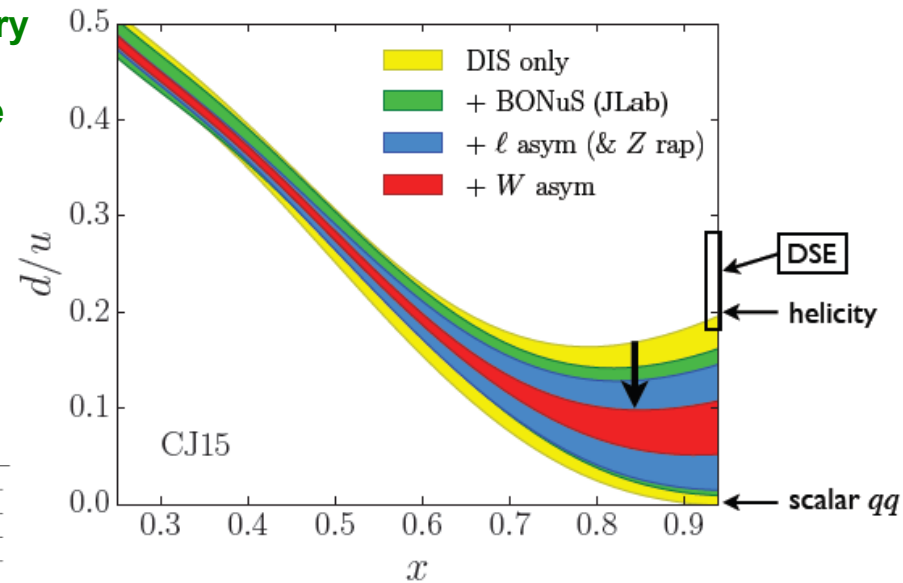
- **Inclusive DIS at large x:**

Unique JLab strength!

Fundamental, most sensitive to confining structure, beyond SM search, …

- $d/u \to 1/2$ — **SU(6) Spin-flavor symmetry**
- $d/u \to 0$ — **Scalar diquark dominance**
- $d/u \to 1/5$ — **pQCD power counting**
- $d/u \to \dfrac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \approx 0.42$ — **Local quark -hadron duality**





Newly extracted ratio at x=1:

$$d/u \to 0.09 \pm 0.03$$

Does not match any models!

CTEQ-Jefferson Lab collaboration
http://www.jlab.org/CJ

Jefferson Lab

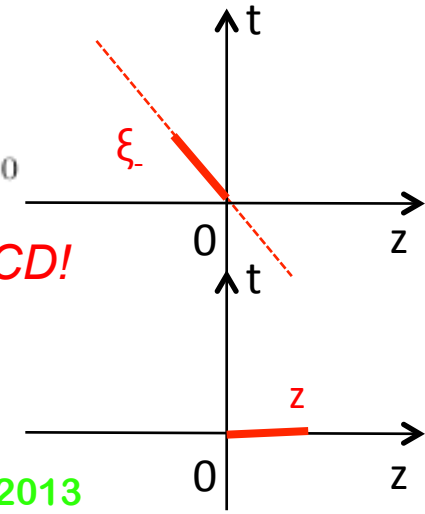
Hadron structure – LQCD

❑ 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 ➔∞

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

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

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

Completely multiplicative - No mix with other flavors or gluon!

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Hadron structure – LQCD

Radyushkin, 2017

❑ Pseudo-PDFs:

✧ **Lattice calculation with** $\alpha = 0$:

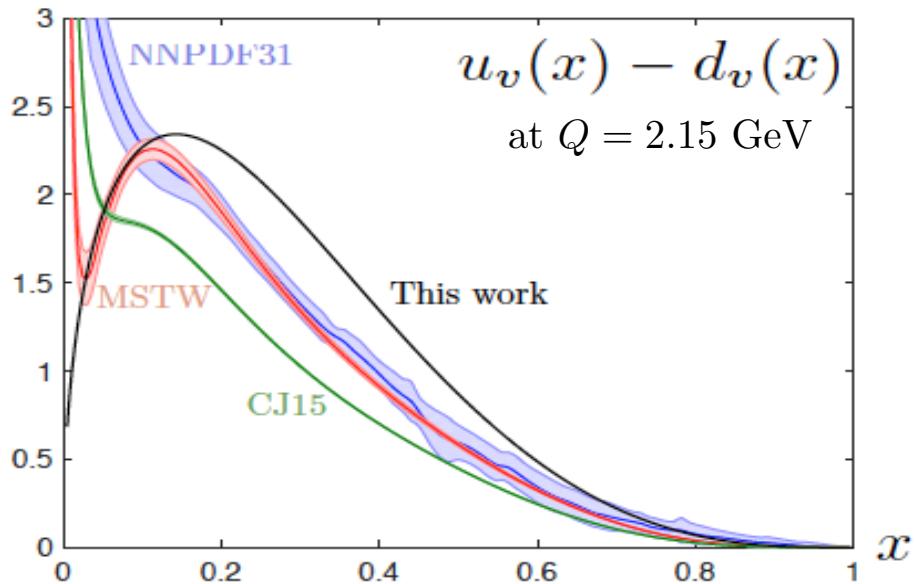
$$\mathcal{M}^\alpha(\nu = p\cdot\xi, \xi^2) \equiv \langle p|\overline{\psi}(0)\gamma^\alpha \Phi_v(0,\xi,v\cdot A)\psi(\xi)|p\rangle$$
$$\equiv 2p^\alpha \mathcal{M}_p(\nu,\xi^2) + \xi^\alpha (p^2/\nu)\mathcal{M}_\xi(\nu,\xi^2) \approx 2p^\alpha \mathcal{M}_p(\nu,\xi^2)$$

$$\mathcal{P}(x,\xi^2) \equiv \int \frac{d\nu}{2\pi}\, e^{ix\,\nu}\mathcal{M}_{p=p^0}(\nu,\xi^2)/\mathcal{M}_{p=p^0}(0,\xi^2)$$

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

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Hadron structure – LQCD

- **Lattice "cross sections":**

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

  - 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

PDFs

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

Key: controllable hard scale!

DGLAP-Evolution

- **Many choices for the operator:**

  - **Doing experiments on the lattice!**

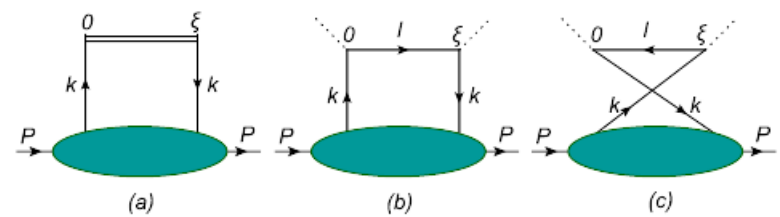
$$\mathcal{O}_{j_1 j_2}(\xi) \equiv \xi^{d_{j_1}+d_{j_2}-2} Z_{j_1}^{-1} Z_{j_2}^{-1} j_1(\xi)\, j_2(0)$$

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

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

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

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



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

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

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

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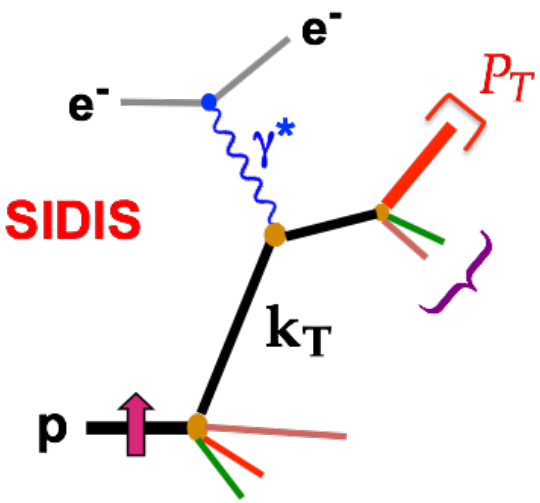
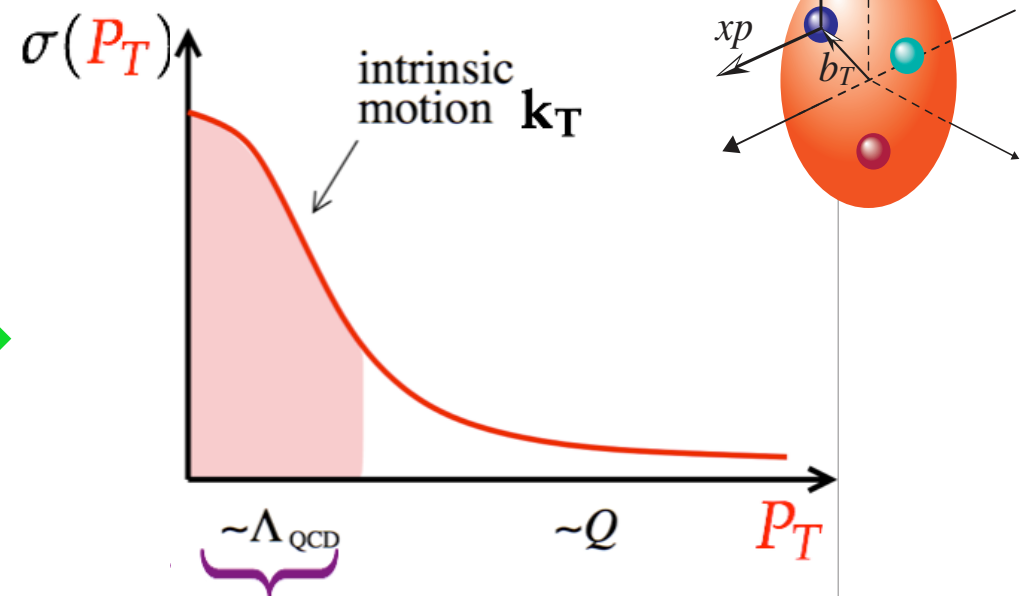
3D hadron structure – TMDs

- **Confined motion:**



Halls A/B/C

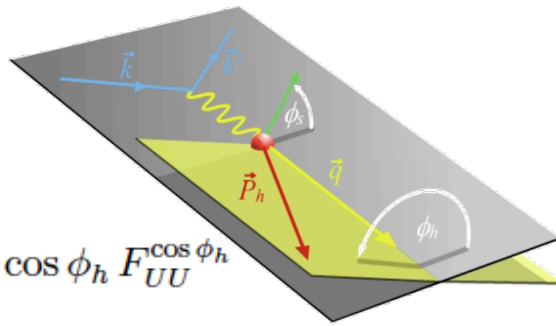


Non-perturbative confined motion!

- **JLab strength & efforts:**
  - ✧ **Theory:** Match the measured hadron to QCD quarks/gluons
  - ✧ **Phenomenology:** Extract the physics of "confined motion" from data
  - ✧ **Lattice QCD:** Calculate the role of the non-perturbatives

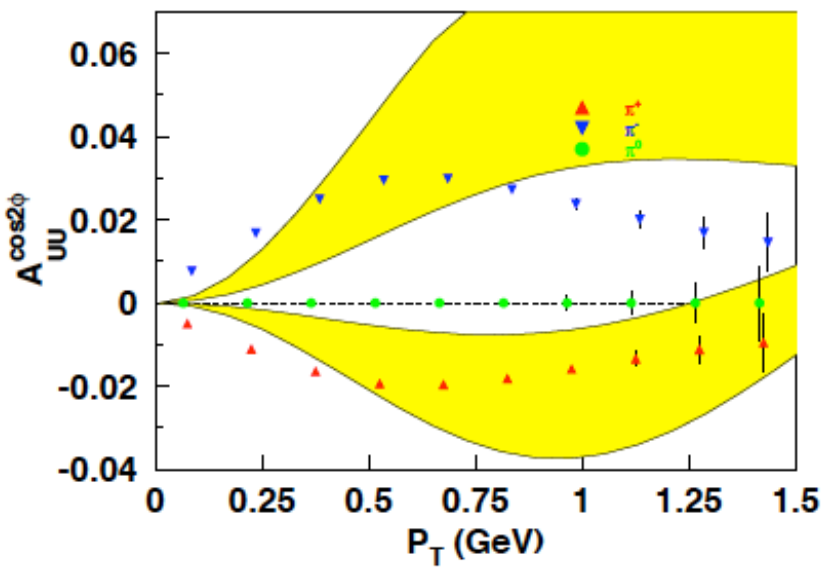
3D hadron structure – TMDs

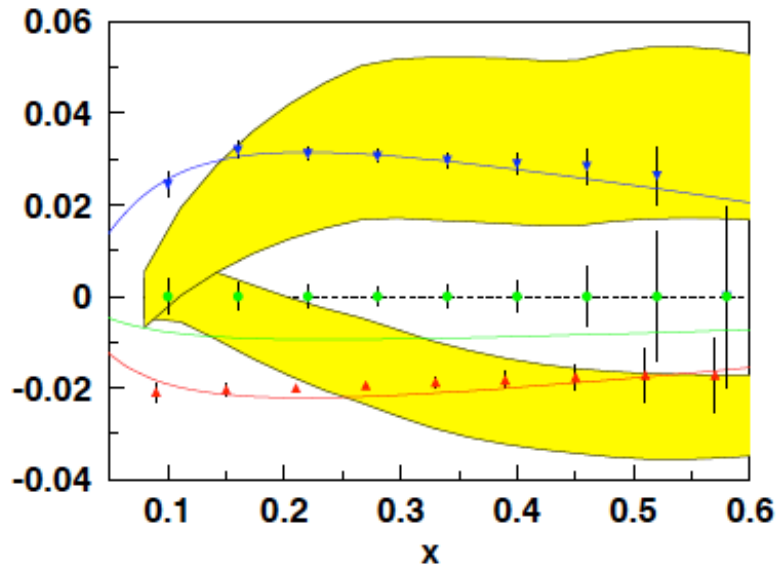
- **SIDIS at JLab:**



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

- **Hall B (E12-06-112):**





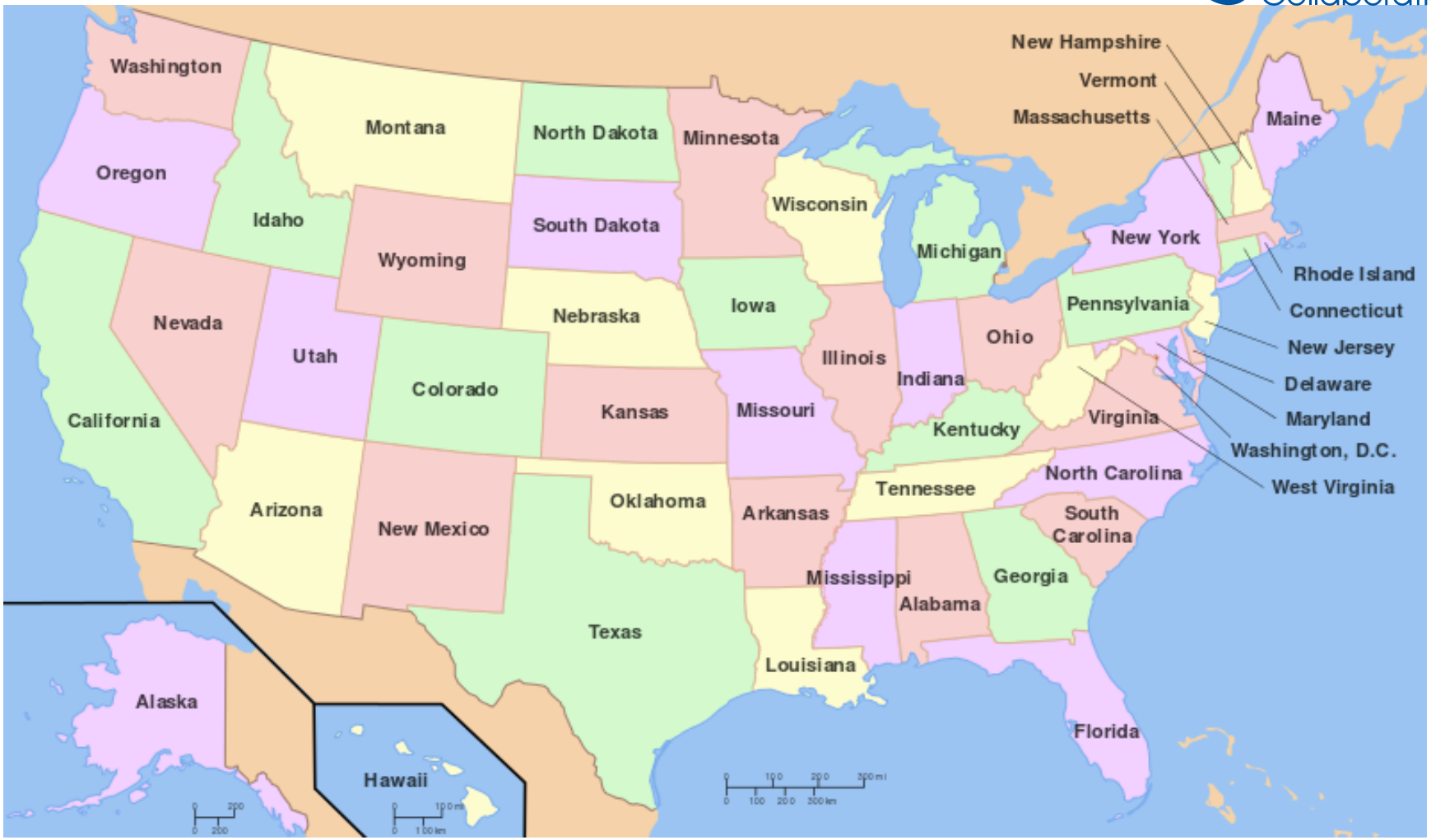
Boer-Mulders functions & Collins FFs – how does spin influence hadronization?

Global Effort on TMDs – TMD Collaboration

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

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

TMD Collaboration



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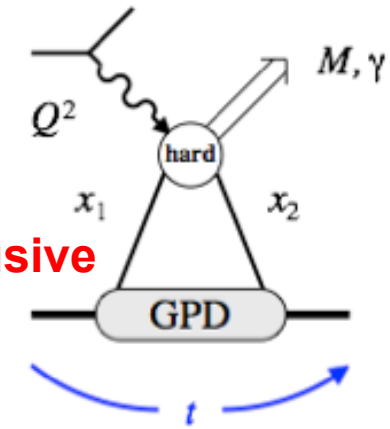
3D hadron structure – GPDs

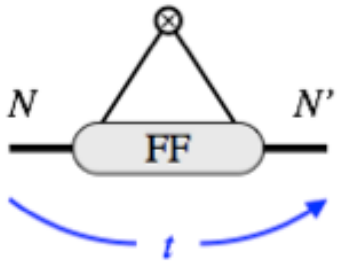
- **Confined spatial imaging:**

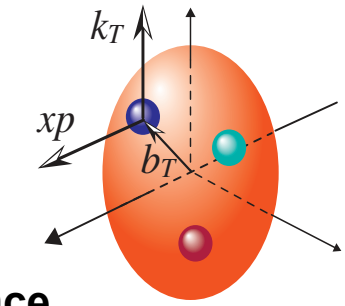


Exclusive

Halls A/B/C

✧ **Generalized version of Form Factor**





F.T. of t-dependence

➡ **Hadron EM charge radius**

✧ F.T. of t-dependence ➡ Spatial imaging!
Hadron radius of quark/gluon distribution

- **Theoretical progress:**

✧ GPD parametrizations, evolution, power corrections in hard processes (virtuality distributions)

✧ Peripheral 3D nucleon structure from chiral EFT: Charge/current densities, GPDs

✧ $1/N_c$ expansion of GPDs: Spin-flavor structure

Radyushkin PRD93 (2016) 056002, …
Granados, Weiss, JHEP 1606 (2016) 075, JHEP 1507, 170 (2015), PRC92 (2015) 025026
Alarcón, Hiller Blin, Vicente Vacas, Weiss, NPA 964, 18 (2017). Schweitzer, Weiss, PRC94, 045202 (2016)

3D hadron structure – GPDs

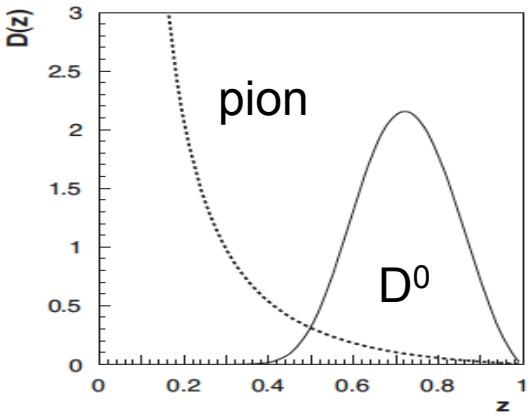
- **Initiative: JLab – PARTONS collaboration – 3D imaging:**
  - DOE approved the ICRADA for JLab – PARTONS collaboration
  - Theory – C. Weiss – is the point-of-contact between JLab and PARTONS
  - He also coordinates JLab effort with all experimental Halls
- **First video meeting – took place today (8:30-12:30):**

DVCS	p, n	CLAS12	GPDs $H, E, \tilde{H}, \tilde{E}$
	p, n(L pol)		
	p, var. E	Hall A	
	p	Hall C	
DVMP	π^0, η	CLAS12	transversity GPDs
	π^0 var. E	Hall A	
	π^0	Hall C	
	π^+, var. E	Hall C	Pion FF/L-T
	K^+, var. E	Hall C	L-T
	ϕ	CLAS12	Gluonic radius
TCS	p	CLAS12	Re(Amp)

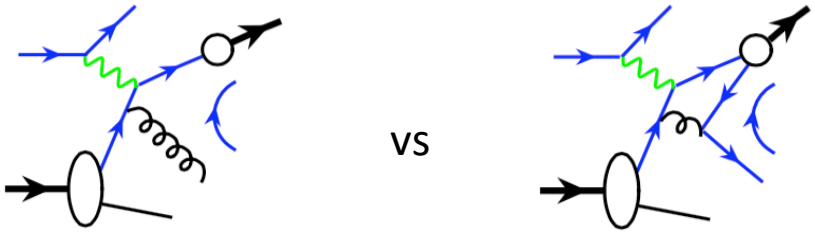
  - What JLab experimental halls need, and what PARTONS can deliver?
  - How to extract physics results from JLab12 data quicker and less theory biased?

Emergence of hadrons

- **Production of light hadrons (All Halls):**
  – high p_T photoproduction of mesons

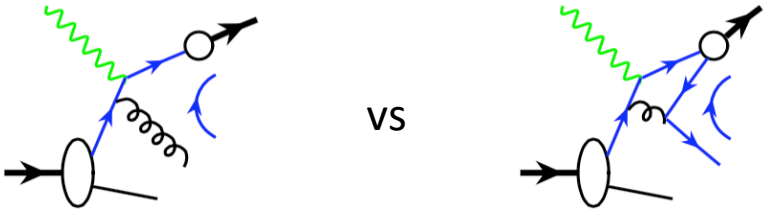


  - ✧ **SIDIS (Halls A/B/C):**



Impact TMD extraction!

  - ✧ **Photo-production (Hall D):**



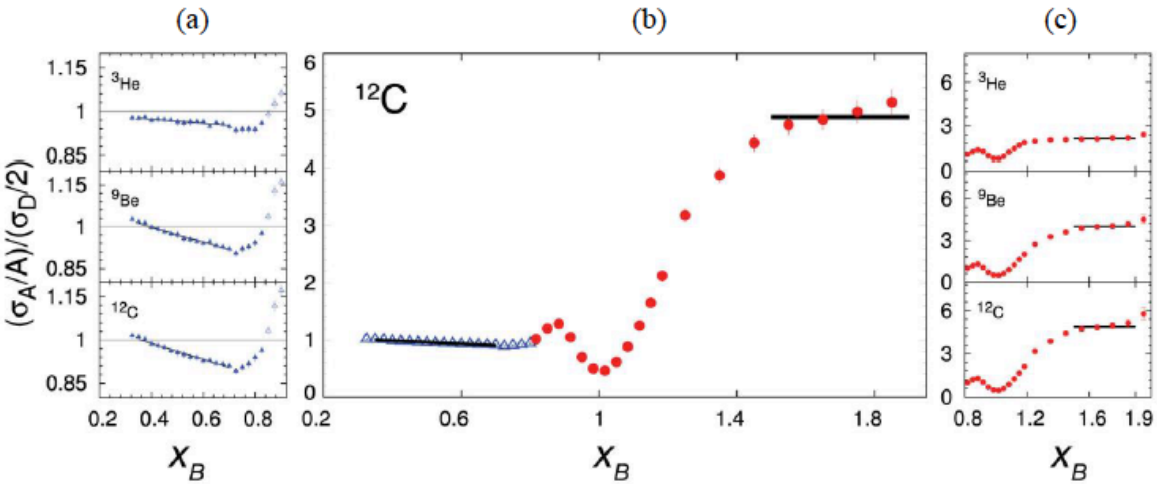
Similar phenomena appeared in heavy quarkonium production

- **Heavy flavor physics (All Halls):**
  – production of charm mesons, J/Ψ, P^c, … near the threshold

Challenge to Theory for developing a reliable prediction near the threshold!

Emergence of Nuclear Phenomena

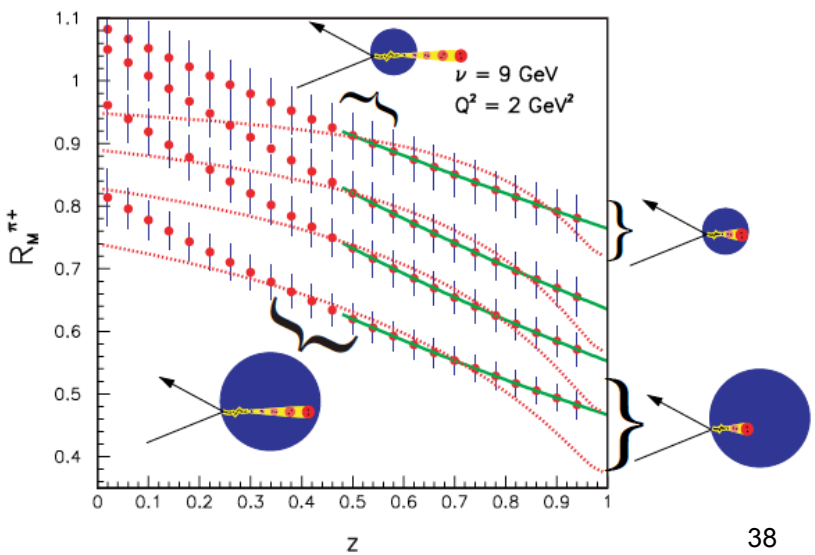
- **Short-range structure of nuclei (Halls A/B/C):**



No one is actively investigating this phenomenon in Theory Center now (man power)

Reaching out experts to get support (visits)

- **Femtometer size detectors (Halls A/B/C):**



- ✧ Probing color neutralization by medium effect of color propagation
- ✧ Color transparency, …

Theory Center does have expertise on nuclear medium effects, …
(Andres, Accardi, Qiu, …)

Similar situation for physics BSM effort!

Summary and outlook

- All four Halls are in operation, and have had the successful data taking runs
- JLeb 12 GeV Science era is started, and will be exciting for many years to come
- Theory Center is fully engaged with JLab12 GeV program,

  having the sense of the urgency and working with experimental colleagues

  to help analyze and interpret the data to publish physics results, …
- Theory Center is lack of man power for some science goals of JLab12 program,

  reaching out expertise in the field to establish a strong network to provide

  the necessary support to for reaching these goals
- Theory Center is a part of the JLab12 science program, and will continue
  - Help motivate, promote, stimulate, justify, and support the JLab12 *experimental program*
  - Help analyze, interpret, and model JLab12 *experimental data*

Thank you!