New Horizons for Strong QCD Theory in the 12 GeV era at Jefferson Lab

Strong QCD from Hadron Structure Experiments

Jefferson Lab, Newport News, VA
6-9 November 2019

- QCD at Fermi scale
- "See" hadron structure
- CEBAF 12 GeV upgrade
- Science & Capabilities
- Initial excitements
- Future opportunities
- JLab12 to EIC
- Summary

Jianwei Qiu
Theory Center

Jefferson Lab   TMD Collaboration   U.S. DEPARTMENT OF ENERGY | Office of Science   JSA

QCD at Fermi Scale

- ❑ **QCD landscape of nucleon and nuclei – Strong QCD!**

Color Confinement **Asymptotic freedom**

Q (GeV)

200 MeV (1 fm) **2 GeV (1/10 fm)**

Probing scale

New Horizon: Femto-science (0.1-10 fm)

Asymptotic regime PQCD works beautifully!

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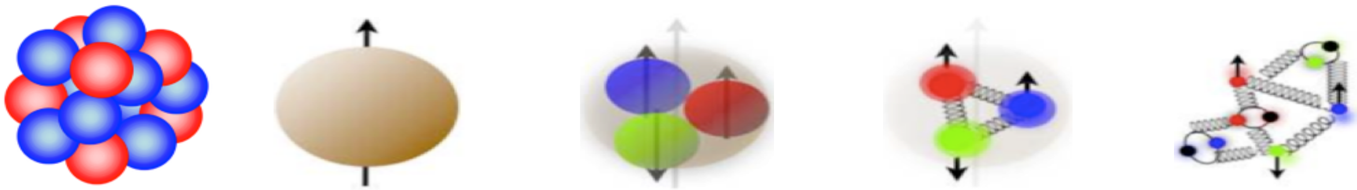

New Horizon: Femto-science (0.1-10 fm)

Asymptotic regime PQCD works beautifully!

Strong QCD – QCD at the Fermi scale
is the most interesting, rich, and complex,
but mysterious and challenging regime of the theory!

We do not see quarks and gluons in isolation!

All emergent phenomena depend on the probes
and the scale at which we probe them!

QCD at Fermi Scale

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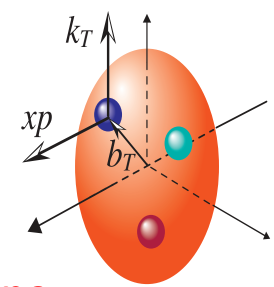


- **My talk:**

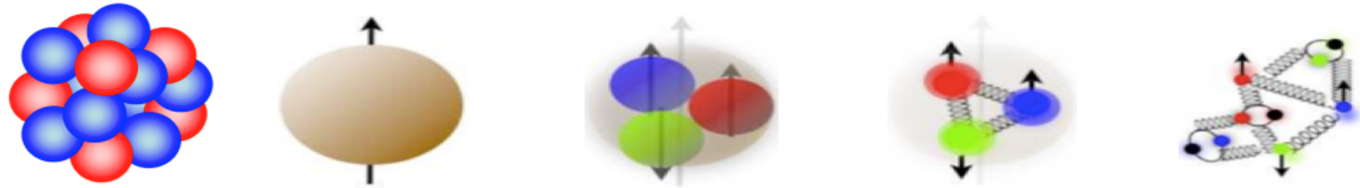
Explore the QCD landscape of nucleon and nuclei by using <u>controllable</u>, <u>shape</u>, <u>local</u> probes, but, "moving or scanning" them throughout the regime!

QCD at Fermi Scale

- **QCD landscape of nucleon and nuclei – Strong QCD!**

Color Confinement | **Asymptotic freedom** — Q (GeV)

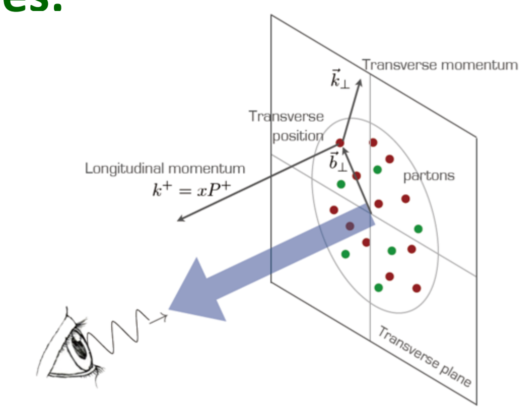
200 MeV (1 fm) | **2 GeV (1/10 fm)** — ***Probing scale***



New Horizon: Femto-science (0.1-10 fm)

- **Need to identify observables with two-momentum scales:**

$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$



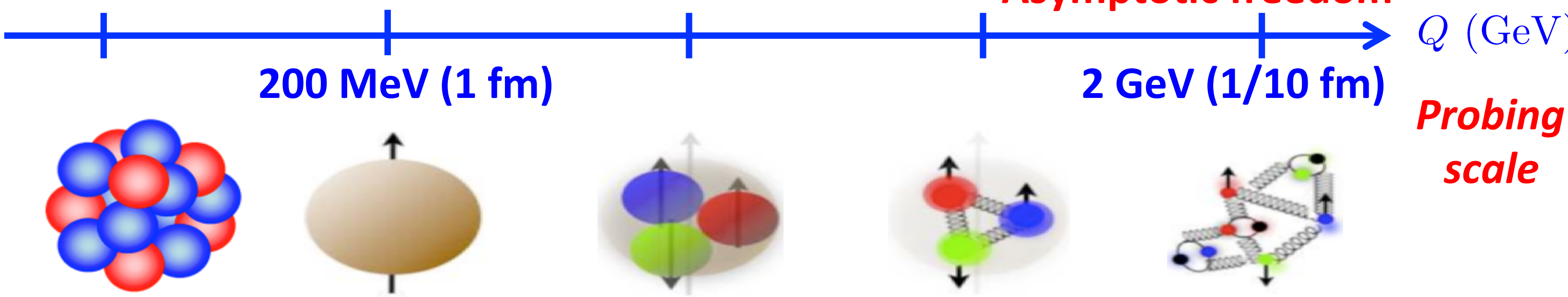
✧ **Hard scale:** localizes the probe
particle nature of quarks/gluons

✧ **"Soft" scale:** could be more sensitive to the
hadron structure ~ 1/fm

✧ **Hit the hadron "very hard" without breaking it, clean information on the structure!**

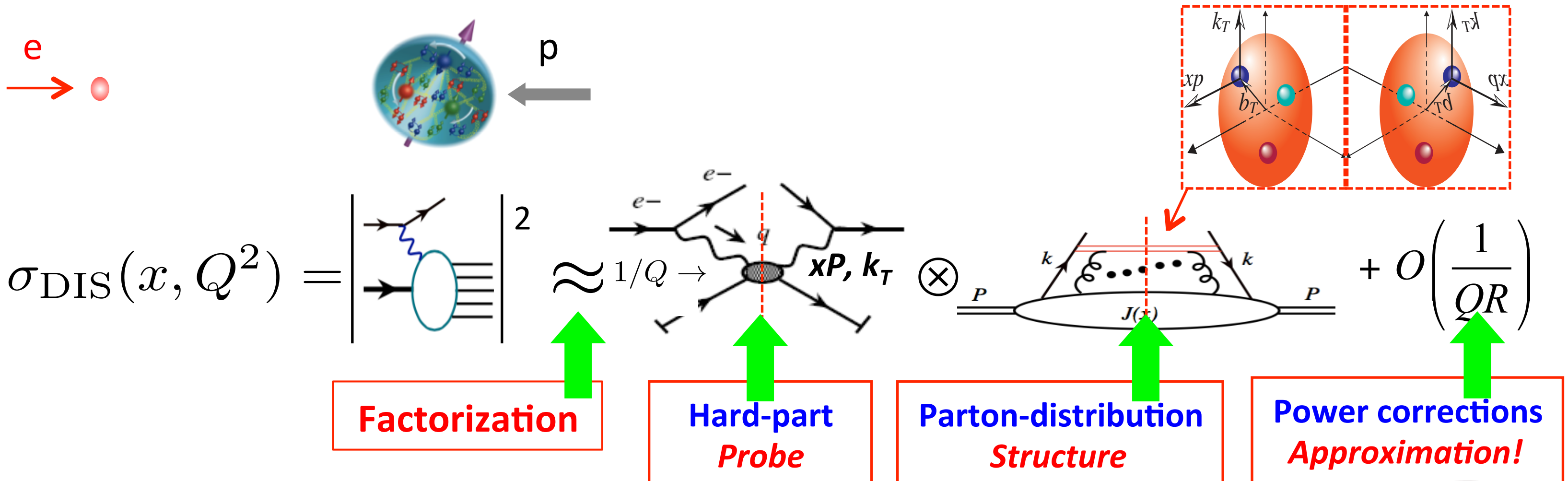
QCD at Fermi Scale

- QCD landscape of nucleon and nuclei – Strong QCD!



New Horizon: Femto-science (0.1-10 fm)

- **Any cross section with identified hadron(s) is NOT perturbatively calculable!**



Structure: in terms of quantum matrix elements/probabilities, …

Jefferson Lab

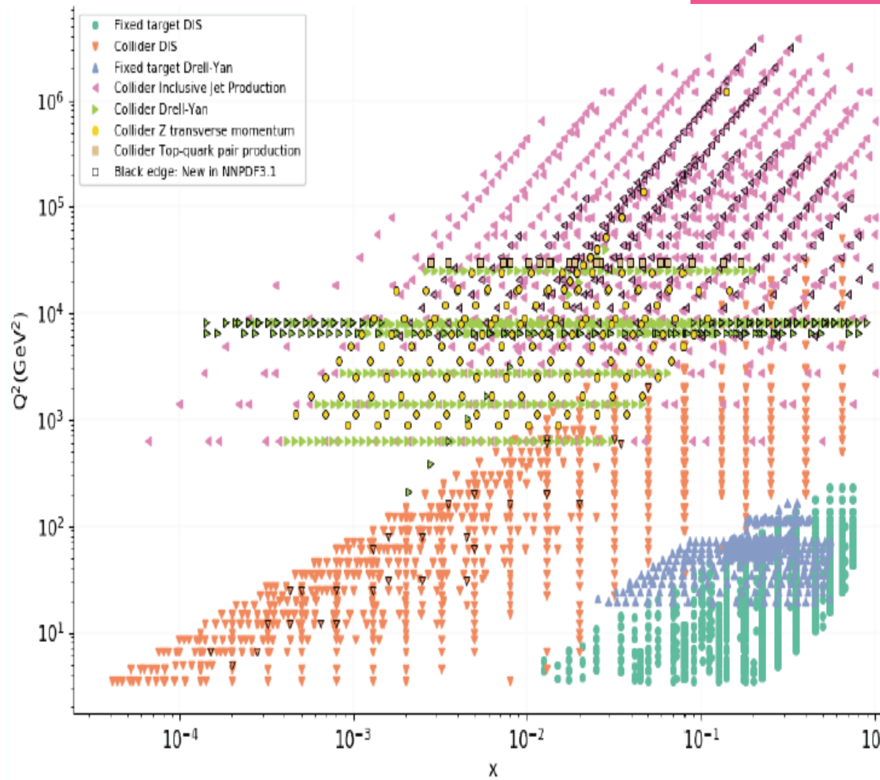
QCD factorization works to the precision

❑ Data sets for Global fits:

	Process	Subprocess	Partons	x range
Fixed Target	$\ell^\pm\{p,n\}\to\ell^\pm+X$	$\gamma^* q\to q$	$q,\bar q,g$	$x\gtrsim 0.01$
	$\ell^\pm n/p\to\ell^\pm+X$	$\gamma^* d/u\to d/u$	d/u	$x\gtrsim 0.01$
	$pp\to\mu^+\mu^-+X$	$u\bar u, d\bar d\to\gamma^*$	$\bar q$	$0.015\lesssim x\lesssim 0.35$
	$pn/pp\to\mu^+\mu^-+X$	$(u\bar d)/(u\bar u)\to\gamma^*$	$\bar d/\bar u$	$0.015\lesssim x\lesssim 0.35$
	$\nu(\bar\nu)N\to\mu^-(\mu^+)+X$	$W^* q\to q'$	$q,\bar q$	$0.01\lesssim x\lesssim 0.5$
	$\nu N\to\mu^-\mu^+ +X$	$W^* s\to c$	s	$0.01\lesssim x\lesssim 0.2$
	$\bar\nu N\to\mu^+\mu^-+X$	$W^*\bar s\to\bar c$	$\bar s$	$0.01\lesssim x\lesssim 0.2$
Collider DIS	$e^\pm p\to e^\pm+X$	$\gamma^* q\to q$	$g,q,\bar q$	$0.0001\lesssim x\lesssim 0.1$
	$e^+ p\to\bar\nu+X$	$W^+\{d,s\}\to\{u,c\}$	d,s	$x\gtrsim 0.01$
	$e^\pm p\to e^\pm c\bar c+X$	$\gamma^* c\to c, \gamma^* g\to c\bar c$	c,g	$10^{-4}\lesssim x\lesssim 0.01$
	$e^\pm p\to e^\pm b\bar b+X$	$\gamma^* b\to b, \gamma^* g\to b\bar b$	b,g	$10^{-4}\lesssim x\lesssim 0.01$
	$e^\pm p\to \text{jet}+X$	$\gamma^* g\to q\bar q$	g	$0.01\lesssim x\lesssim 0.1$
Tevatron	$p\bar p\to\text{jet}+X$	$gg,qg,q\bar q\to 2j$	g,q	$0.01\lesssim x\lesssim 0.5$
	$p\bar p\to(W^\pm\to\ell^\pm\nu)+X$	$ud\to W^+, \bar u\bar d\to W^-$	$u,d,\bar u,\bar d$	$x\gtrsim 0.05$
	$p\bar p\to(Z\to\ell^+\ell^-)+X$	$uu,dd\to Z$	u,d	$x\gtrsim 0.05$
	$p\bar p\to t\bar t+X$	$qq\to t\bar t$	q	$x\gtrsim 0.1$
LHC	$pp\to\text{jet}+X$	$gg,qg,q\bar q\to 2j$	g,q	$0.001\lesssim x\lesssim 0.5$
	$pp\to(W^\pm\to\ell^\pm\nu)+X$	$u\bar d\to W^+, d\bar u\to W^-$	$u,d,\bar u,\bar d,g$	$x\gtrsim 10^{-3}$
	$pp\to(Z\to\ell^+\ell^-)+X$	$q\bar q\to Z$	$q,\bar q,g$	$x\gtrsim 10^{-3}$
	$pp\to(Z\to\ell^+\ell^-)+X, p_\perp$	$gq(\bar q)\to Zq(\bar q)$	$g,q,\bar q$	$x\gtrsim 0.01$
	$pp\to(\gamma^*\to\ell^+\ell^-)+X$, Low mass	$q\bar q\to\gamma^*$	$q,\bar q,g$	$x\gtrsim 10^{-4}$
	$pp\to(\gamma^*\to\ell^+\ell^-)+X$, High mass	$q\bar q\to\gamma^*$	$\bar q$	$x\gtrsim 0.1$
	$pp\to W^+\bar c, W^- c$	$sg\to W^+ c, \bar s g\to W^-\bar c$	$s,\bar s$	$x\sim 0.01$
	$pp\to t\bar t+X$	$gg\to t\bar t$	g	$x\gtrsim 0.01$
	$pp\to D,B+X$	$gg\to c\bar c, b\bar b$	g	$x\gtrsim 10^{-6}, 10^{-5}$
	$pp\to J/\psi,\Upsilon+pp$	$\gamma^*(gg)\to c\bar c, b\bar b$	g	$x\gtrsim 10^{-6}, 10^{-5}$
	$pp\to\gamma+X$	$gq(\bar q)\to\gamma q(\bar q)$	g	$x\gtrsim 0.005$

❑ Kinematic coverage:

NNPDF3.1



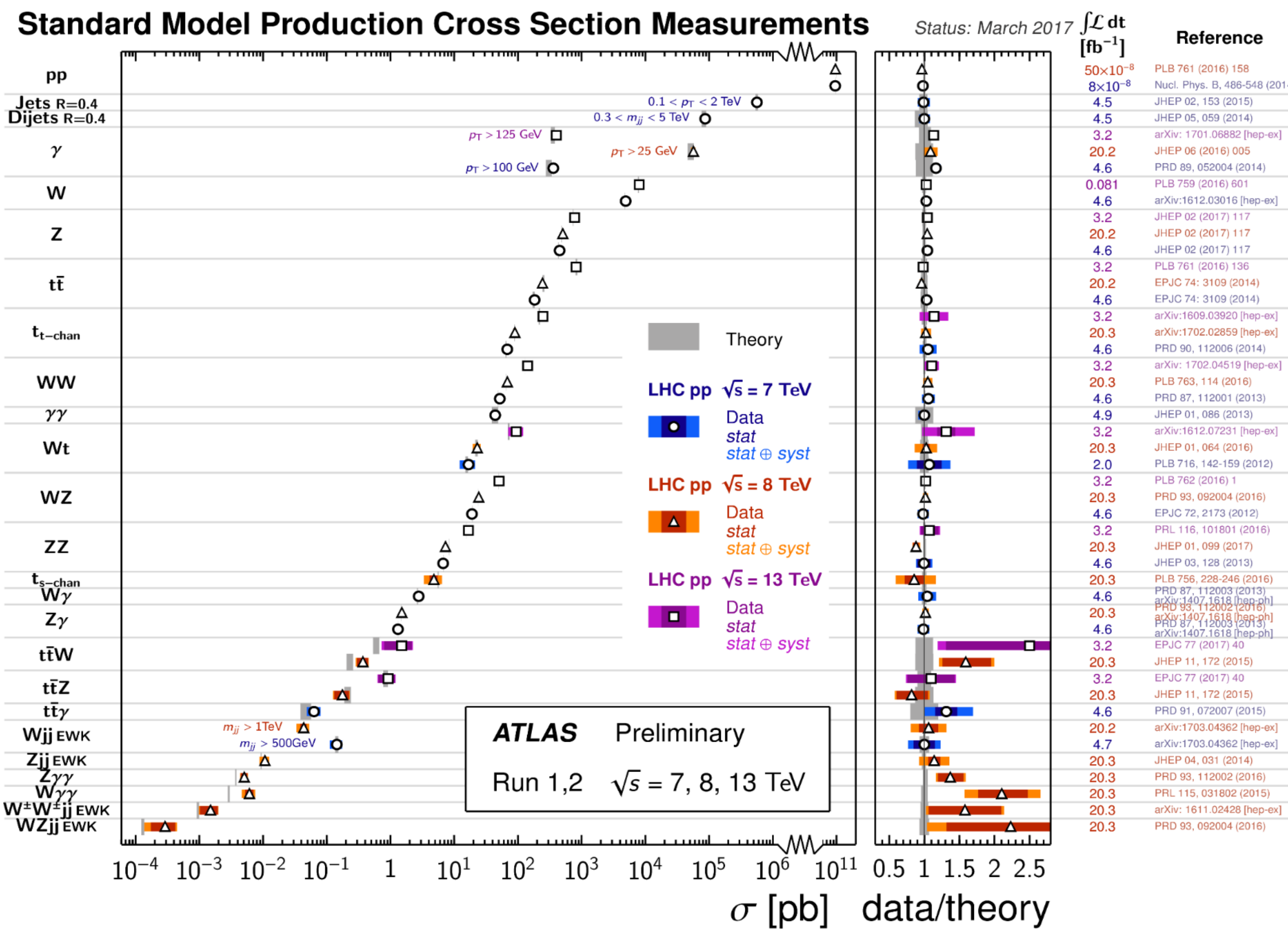
❑ Fit quality:

$\chi^2/\text{dof}\sim 1 \;\Rightarrow$ Non-trivial check of QCD

	LO	NLO	NNLO
All data sets	3706 / 2763	3267 / 2996	2717 / 2663

Jefferson Lab

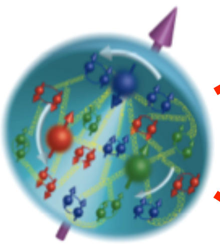
QCD factorization works to the precision

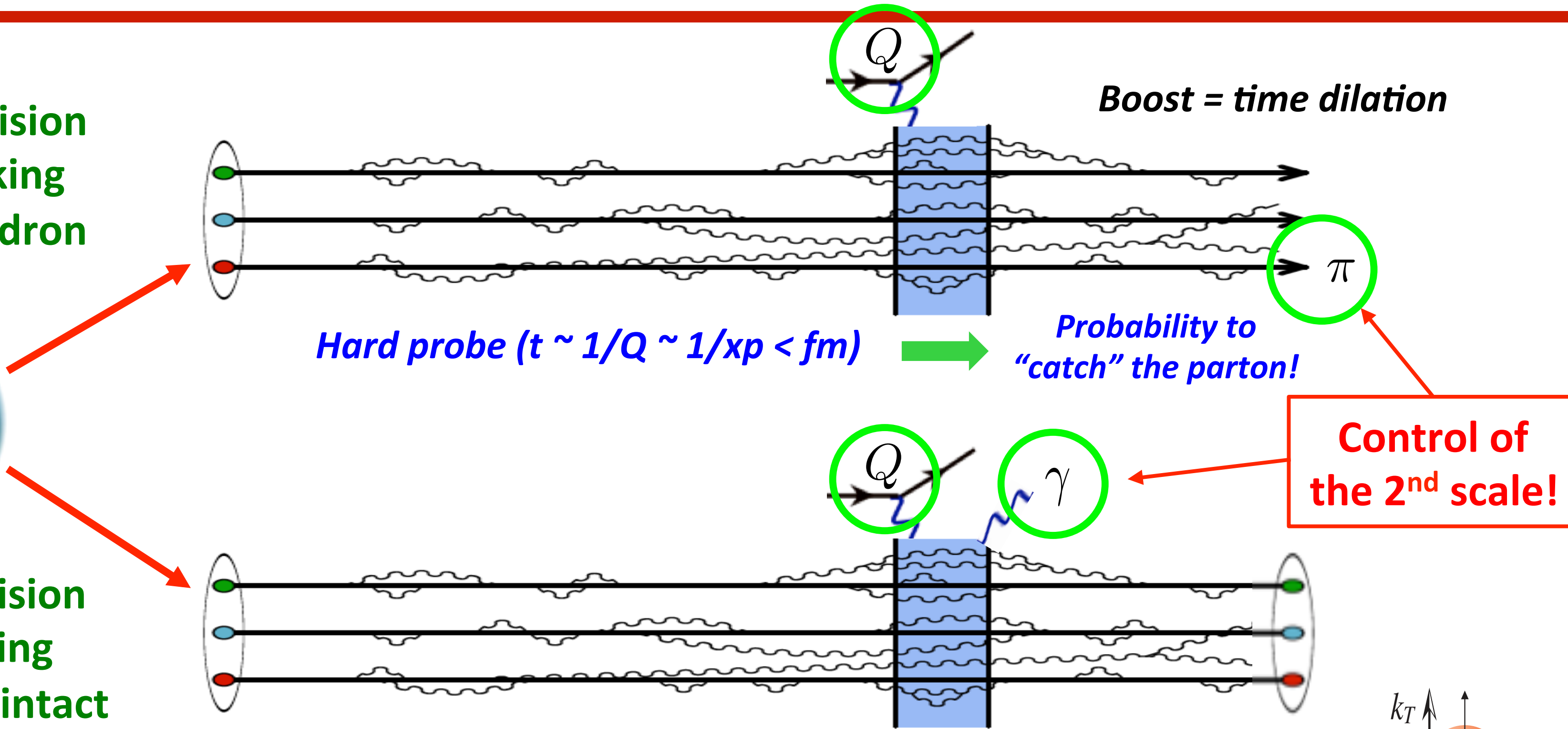


SM: Electroweak processes + QCD perturbation theory + PDFs works!

“See” the hadron structure

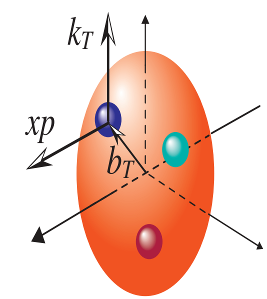
By collision breaking the hadron



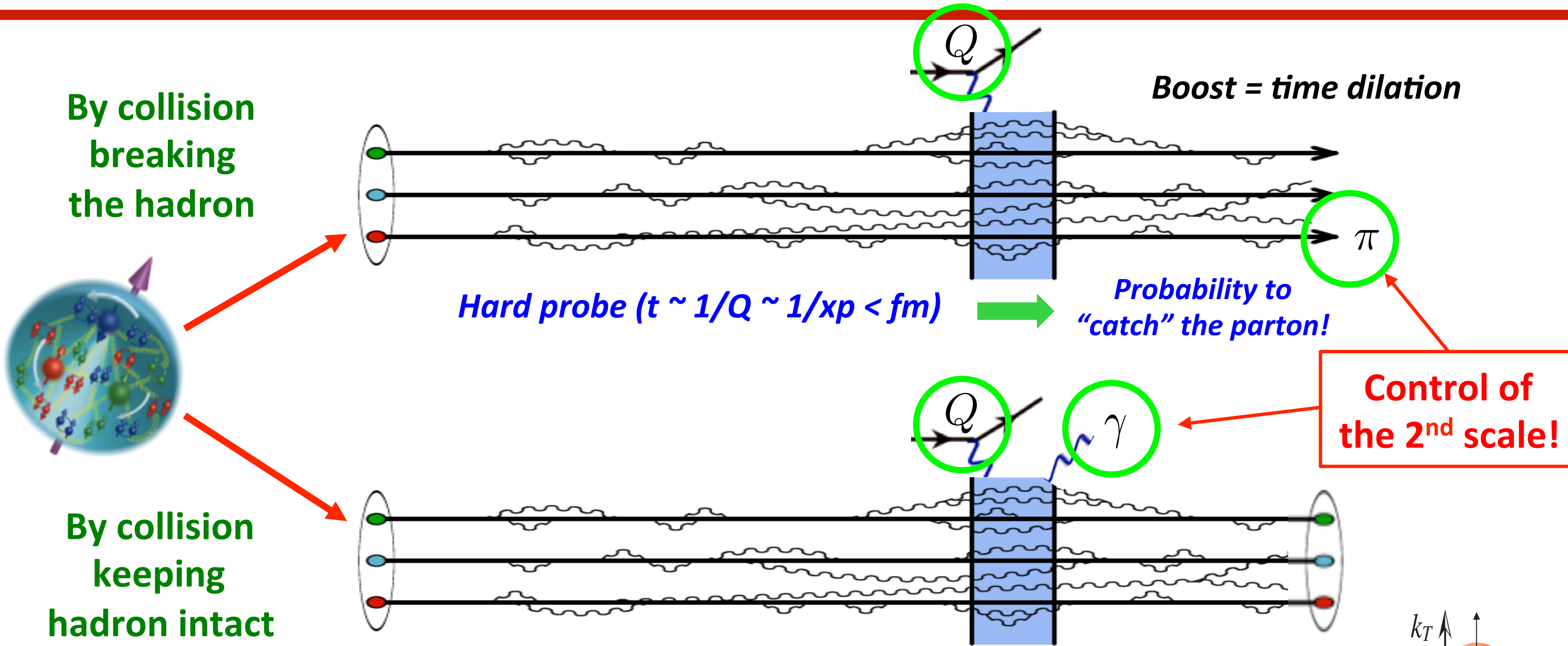


By collision keeping hadron intact

Boosted partonic structure is encoded in probability distributions: PDFs, TMDs, GPDs, … non-perturbative!



"See" the hadron structure



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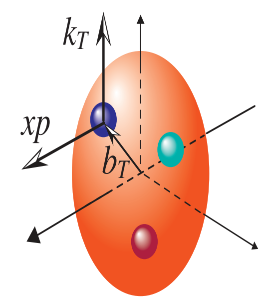
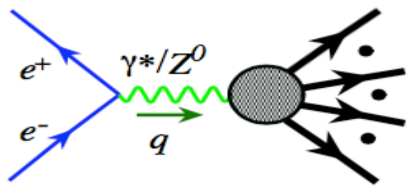


- Tools to "see" the hadron's partonic structure:
  - ✧ Experiment + QCD factorization + Global analysis/Phenomenology + Computing
  - ✧ Lattice QCD + QCD factorization + Global analysis/Phenomenology + Computing

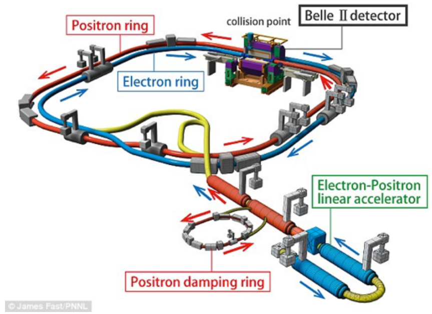
Complementary to each other, need each other, …

QCD needs lepton-hadron facility

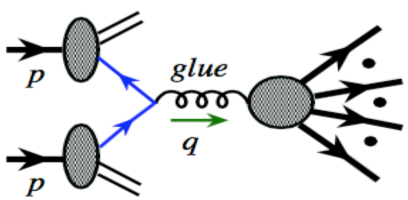
❑ **Hadrons are produced from the energy in e+e- collisions:**



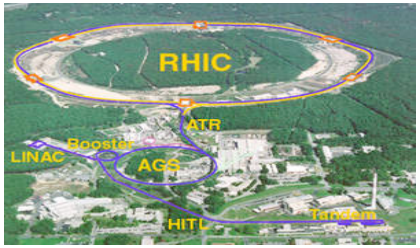
- *No hadron to start with*
- *Emergence of hadrons*



❑ **Hadrons are produced in hadron-hadron collisions:**

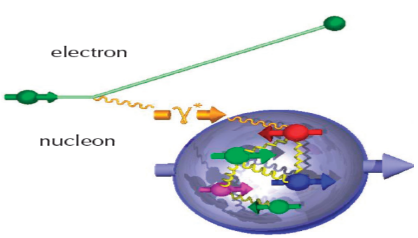


- *Partonic structure*
- *Emergence of hadrons*
- *Heavy ion target or beam(s)*



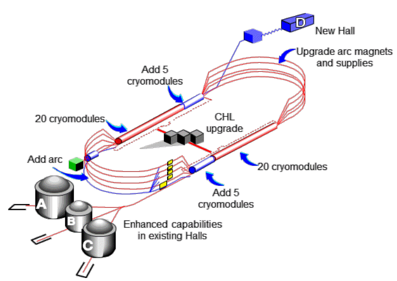
Also at the LHC

❑ **Hadrons are produced in lepton-hadron collisions:**



One facility covers all!

- *Colliding hadron can be broken or stay intact!*
- *Imaging partonic structure*
- *Emergence of hadrons*
- *Heavy ion target or beam*



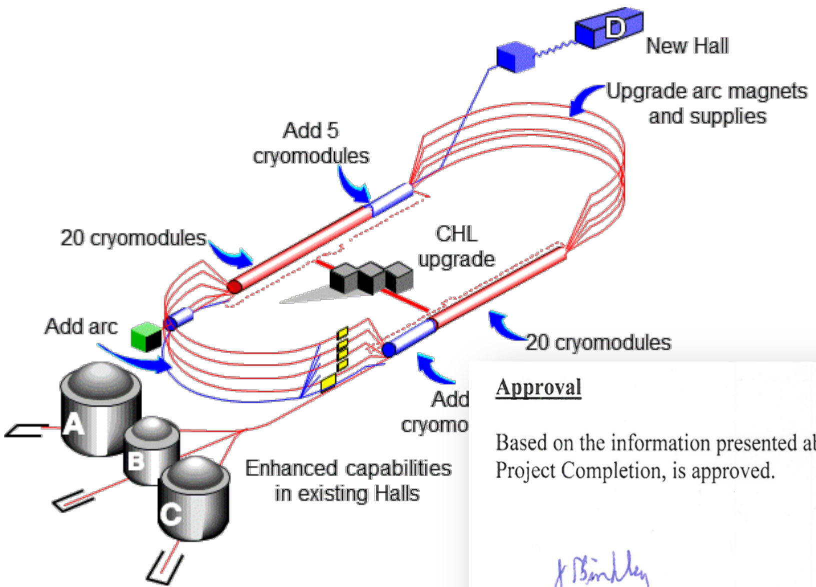
Also at COMPASS & future EIC

JLab 12 GeV ⟷ **EIC**

Valence — *Sea and glue*

Jefferson Lab

CEBAF 12 GeV Upgrade



Approval

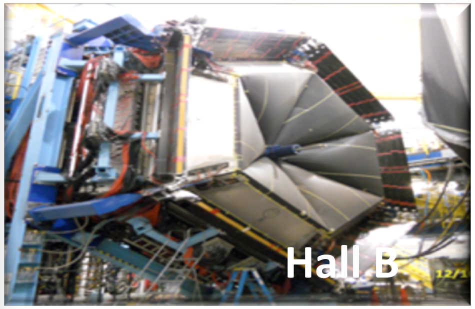
Based on the information presented above and at this review, Critical Decision 4, Approve Project Completion, is approved.

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 on September 27, 2017

All four Halls are in physics operations

JLab 12 GeV science era is here!

A critical step toward EIC!

A Lepton-Hadron Facility has the highest luminosity

Jefferson Lab

JLab12 Scientific Questions

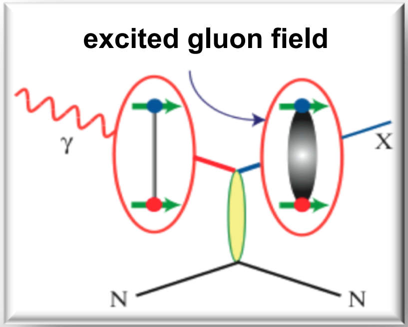
- **What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?**

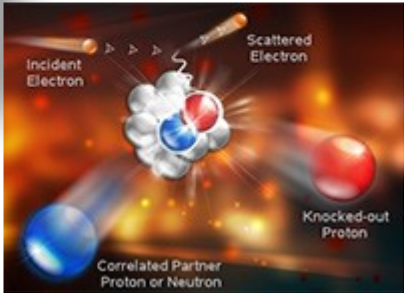
- **Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?**

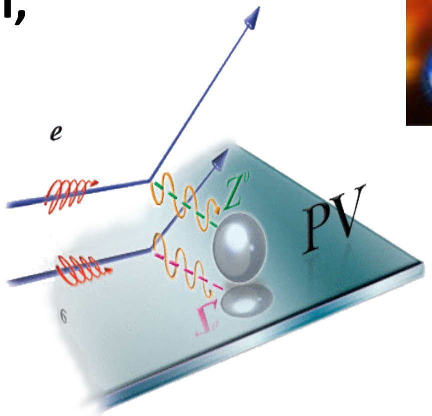
- **Can we reveal a novel landscape of nucleon substructure through 3D imaging at the femtometer scale?**

- **What is the relation between short-range N-N correlations, the partonic structure of nuclei, and the nature of the nuclear force?**

- **Can we discover evidence for physics beyond the standard model of particle physics?**



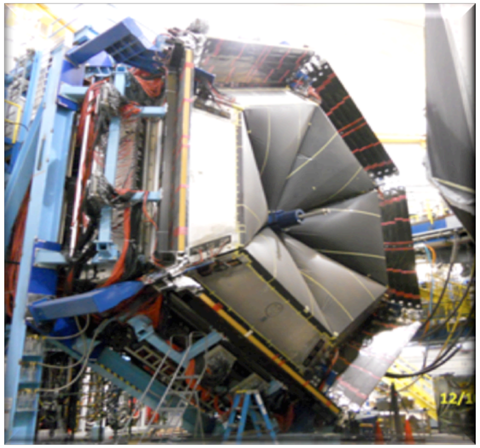




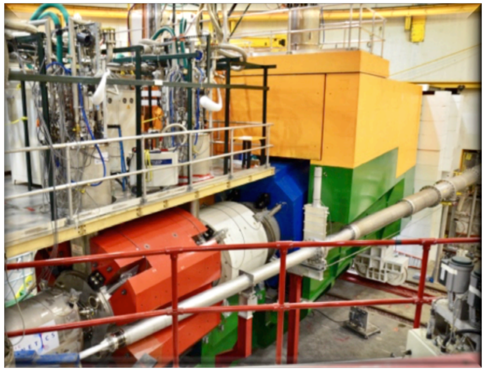
JLab12 Scientific Capabilities

V.D. Burkert’s talk on “Explore Strong QCD in the JLab Experiments …”

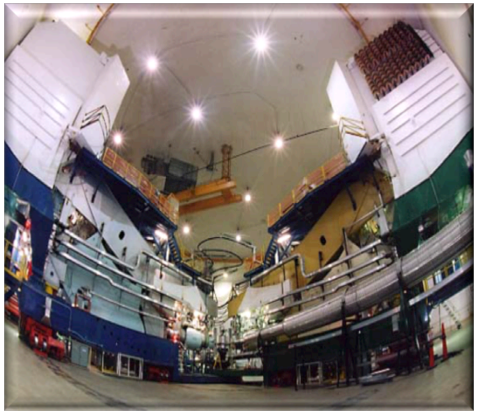
Hall D – exploring origin of **confinement** by studying **exotic mesons**



Hall B – understanding **nucleon structure** via **generalized parton distributions (GPDs)** and **transverse momentum dependent distributions (TMDs)**



Hall C – precision determination of **valence quark** properties in nucleons and nuclei



Hall A – short range correlations, form factors (SBS), hyper-nuclear physics, **future new experiments (e.g., SoLID and MOLLER)**

Strong QCD "Theory" at this conference

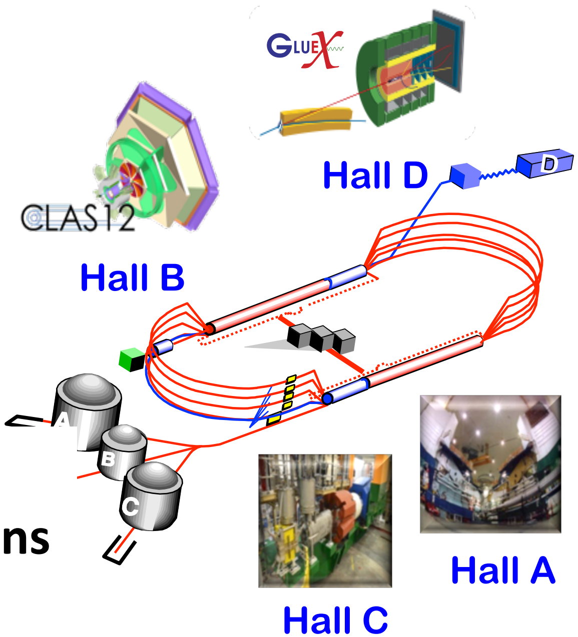
Nucleon Resonance, Spectroscopy, Exotics
Hiller-Blin, Gothe, Segovia, Szczepaniak, Thiel, …

Form factors, …
Cole, Kim,

From neutron to stars
Liuti, …

Solve QCD with controlled approximations
Roberts,
Rodriguez-Quitero, Mezrag, ..

QCD: a 50-year experience
Brodsky



Nuclear structure from QCD
Draayer

Nucleon structure in 3D
Vanderhaeghen, Ji, ..

QCD Phenomenology – QCD global analysis
Andres, Radici

Lattice QCD meets QCD Phenomenology
Briceno,
Lin, Radyushkin,

The Future: Electron-Ion Collider
Milner

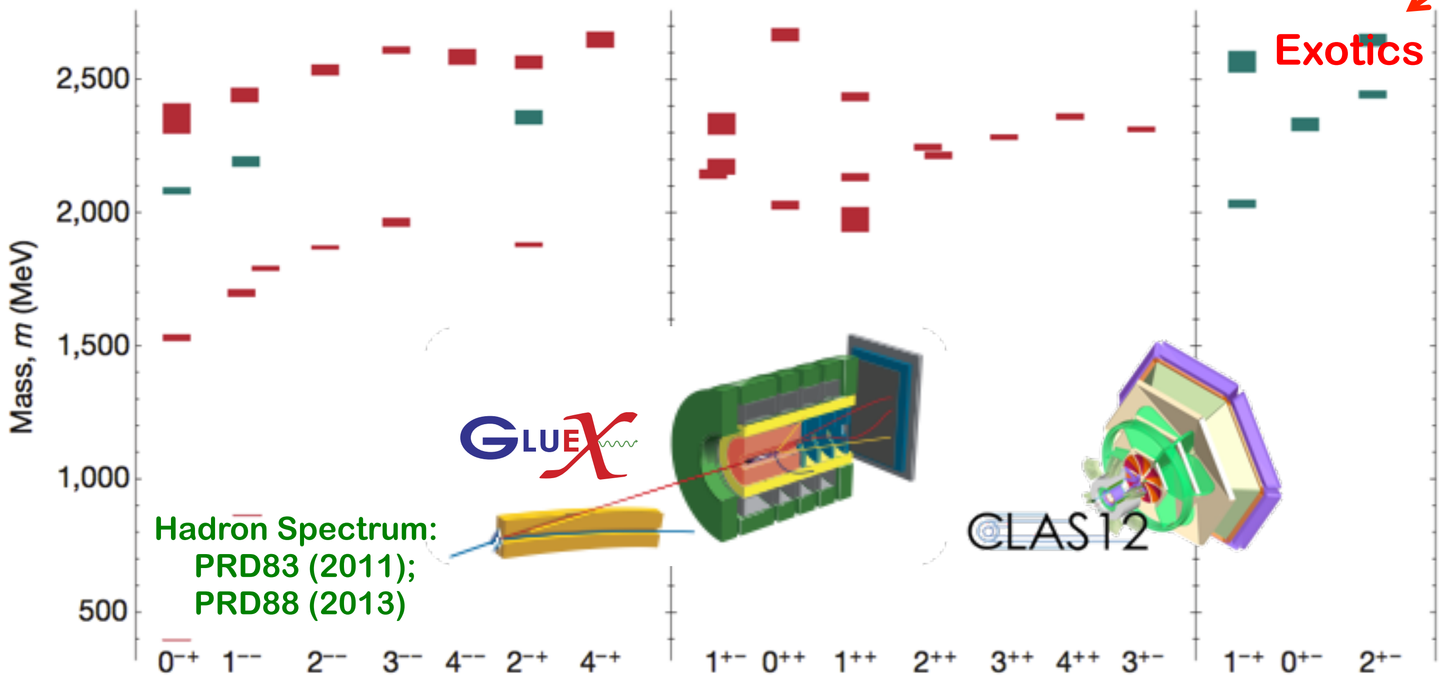
LQCD – beyond the mass spectrum

See talk by Briceno

- ✧ GlueX looking for exotic hybrid mesons in photoproduction
- ✧ Might appear as enhancement in πππ ~ πρ, πσ, πf0(980)…

Predicted

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



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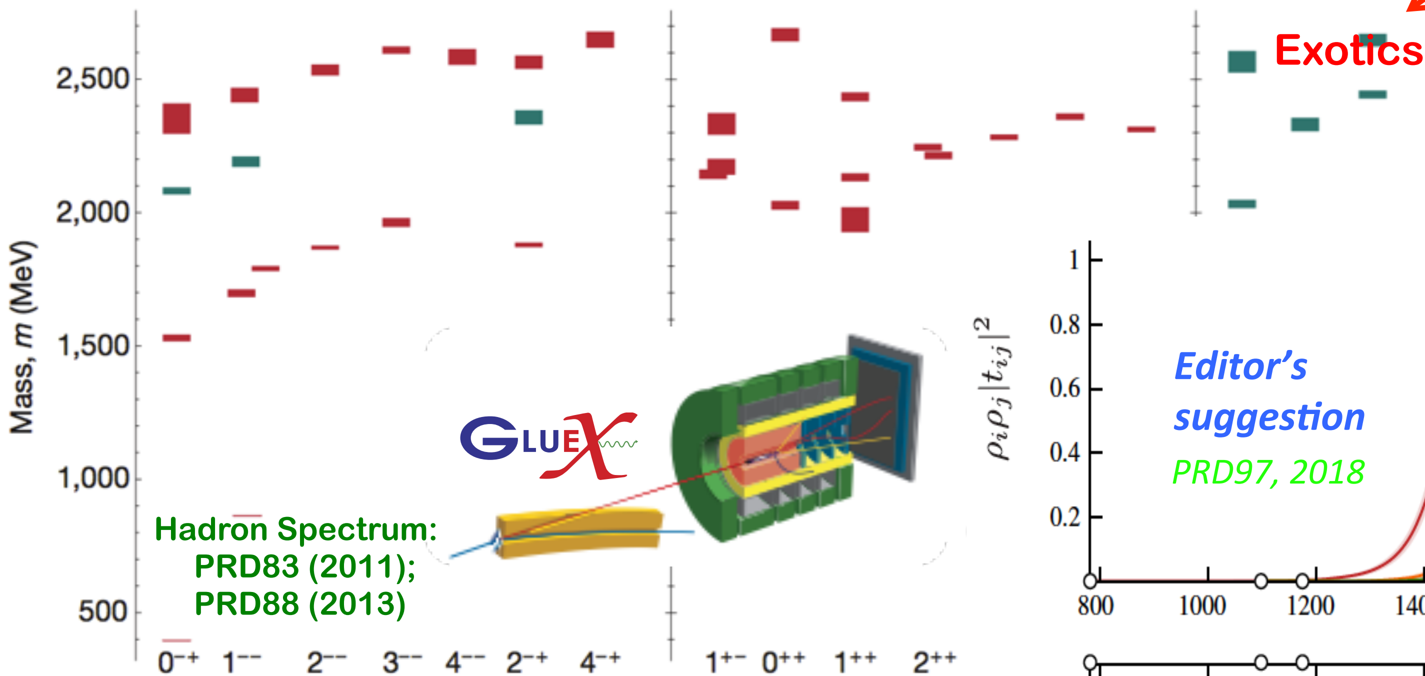
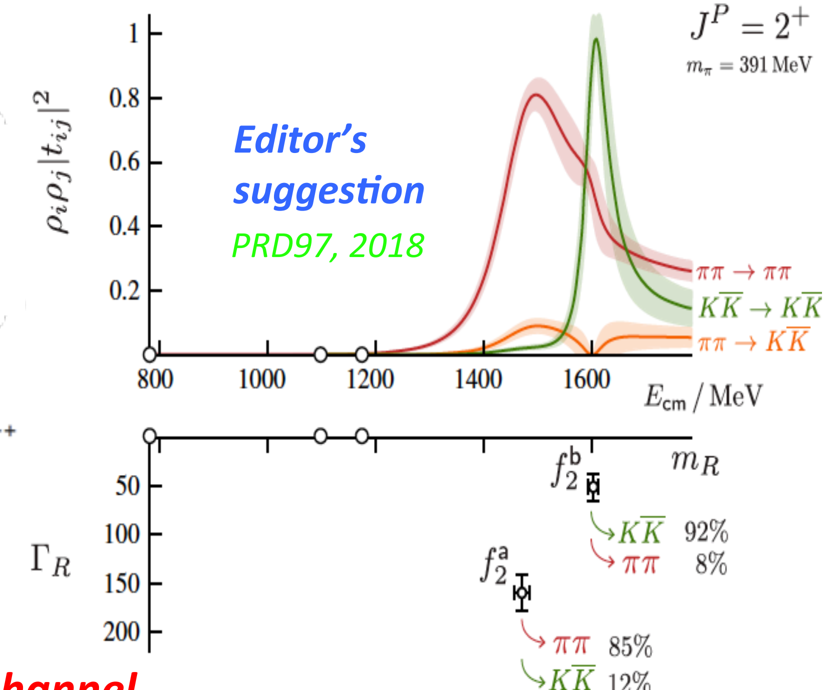


Decay rate



Motivation in GlueX PID upgrade proposal

GlueX actively calibrating in this channel

Jefferson Lab

Hadron Spectroscopy - JPAC

- Searching for the Exotics:

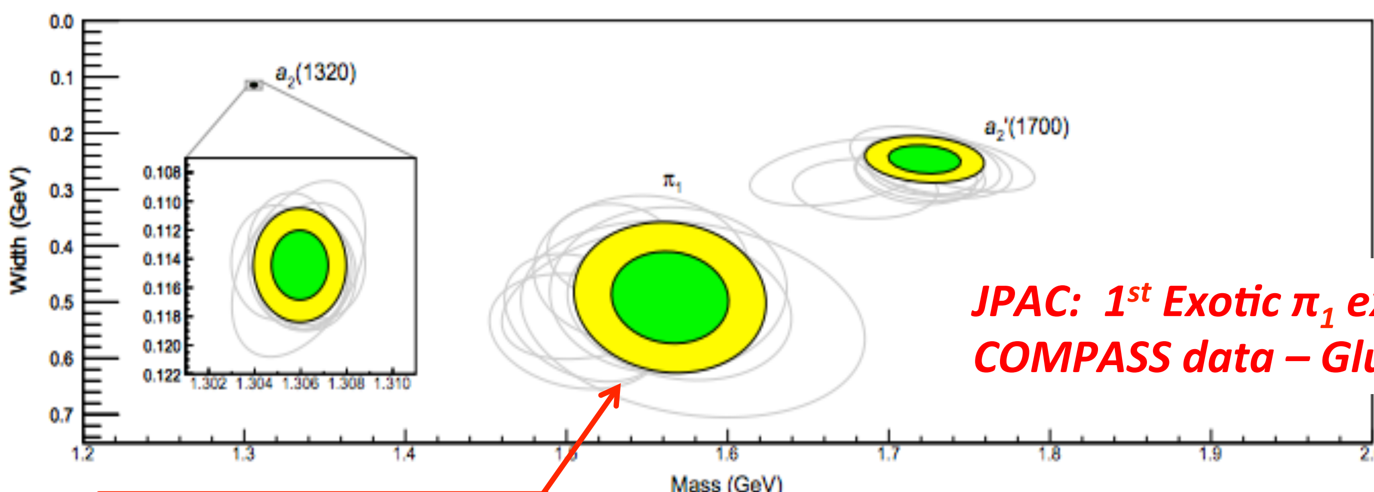
See talk by Szczepaniak

"Determination of the Pole Position of the Lightest Hybrid Meson Candidate"

Exotics in $\eta^{(\prime)}\pi$ – led to the 1st Exotic π_1

✧ For the first time pole parameters of the exotic π_1 resonance were extracted using a coupled channel fit to COMPASS $\eta^{(\prime)}\pi$ P- and D-waves

✧ Results compatible with the existence of a single π_1 meson, which solves a longstanding puzzle about two different $\pi_1(1400)$ and $\pi_1(1600)$, decaying separately into $\eta\pi$ and $\eta'\pi$



JPAC: 1st Exotic π_1 extracted from COMPASS data – GlueX data next!

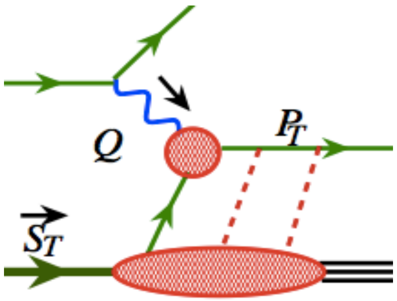
Mass: 1564 ± 24 ± 86
Width: 492 ± 54 ± 102

Jefferson Lab

"See" the 3D hadron structure

- Two-scale observables are natural in lepton-hadron collisions:

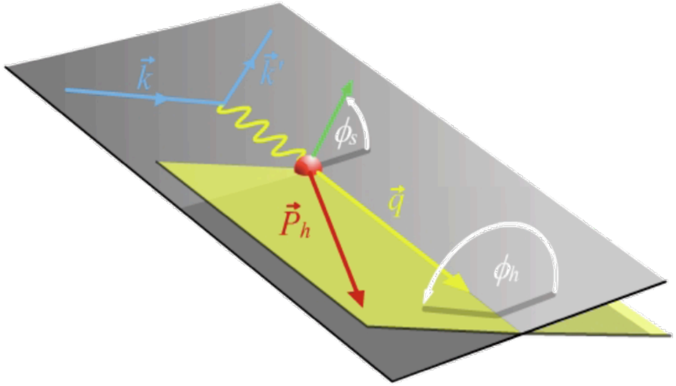
✧ Semi-inclusive DIS:



+ …

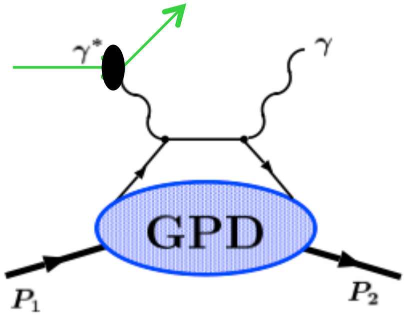
SIDIS: $Q \gg P_T$

Parton's confined motion encoded into TMDs



Two scales, two planes, Angular modulation, …

✧ Exclusive DIS:

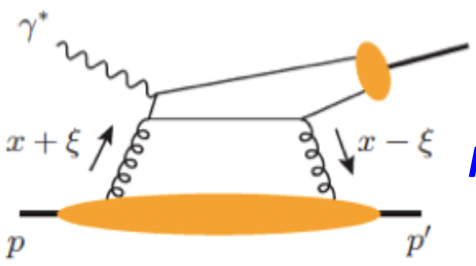


+ …

Imaging quarks

DVCS: $Q^2 \gg |t|$

Parton's spatial imaging from Fourier transform of GPDs' t-dependence



J/Ψ, Φ, …

Imaging gluons

Heavy quarkonium: $Q^2+M^2 \gg |t|$

Imaging the glue only at EIC
Need JLab12 to establish, …

Theory is solid for matching parton to hadron

- **Wigner distributions in 5D (or GTMDs):**

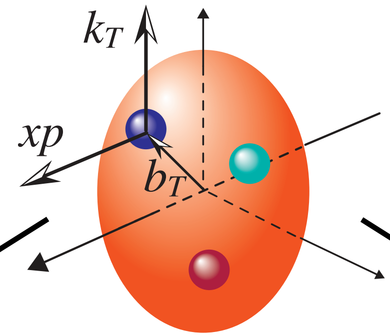
Momentum Space

TMDs

Confined motion

$\int d^2 b_T$

$f(x,k_T)$



Two-scales observables

$\int d^2 k_T$

$f(x,b_T)$

Coordinate Space

GPDs

Spatial distribution

- **TMDs & SIDIS as an example:**

  - **Low P_{hT} ($P_{hT} << Q$) – TMD factorization:**

$$\sigma_{\rm SIDIS}(Q, P_{h\perp}, x_B, z_h) = \hat{H}(Q) \otimes \Phi_f(x, k_\perp) \otimes \mathcal{D}_{f\to h}(z, p_\perp) \otimes \mathcal{S}(k_{s\perp}) + \mathcal{O}\left[\frac{P_{h\perp}}{Q}\right]$$

  - **High P_{hT} ($P_{hT} \sim Q$) – Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q, P_{h\perp}, x_B, z_h) = \hat{H}(Q, P_{h\perp}, \alpha_s) \otimes \phi_f \otimes D_{f\to h} + \mathcal{O}\left(\frac{1}{P_{h\perp}}, \frac{1}{Q}\right)$$

  - **P_{hT} Integrated - Collinear factorization:**

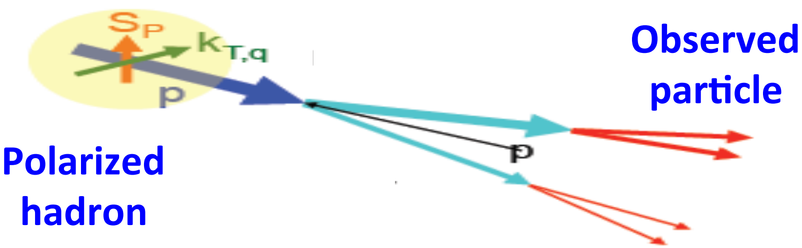
$$\sigma_{\rm SIDIS}(Q, x_B, z_h) = \tilde{H}(Q, \alpha_s) \otimes \phi_f \otimes D_{f\to h} + \mathcal{O}\left(\frac{1}{Q}\right)$$

  - **Very high $P_{hT} >> Q$ – Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q, P_{h\perp}, x_B, z_h) = \sum_{abc} \hat{H}_{ab\to c} \otimes \phi_{\gamma\to a} \otimes \phi_b \otimes D_{c\to h} + \mathcal{O}\left(\frac{1}{Q}, \frac{Q}{P_{h\perp}}\right)$$

First comprehensive study of the confined motion - JLab

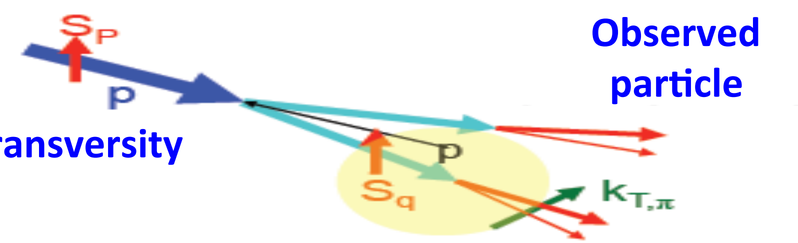
- Quantum correlation between hadron spin and parton motion:



Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

- Quantum correlation between parton's spin and its hadronization:



Collins effect – Collins function

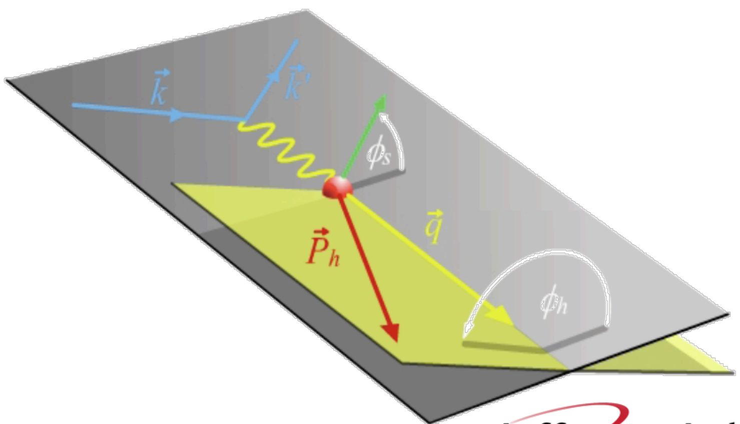
Parton's transverse polarization influences its hadronization

- SIDIS is ideal for probing TMDs:

$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

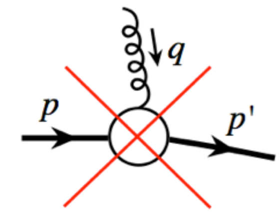


Another strength of lepton-hadron machine!

Jefferson Lab

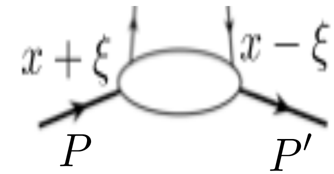
First comprehensive study of the spatial imaging - JLab

- **No color elastic nucleon form factor!**



➡ *Spatial distribution of quark/gluon densities – GPDs*

- **Quark "form factor":**



$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p'|\bar{q}(-\tfrac{1}{2}z)\gamma^+ q(\tfrac{1}{2}z)|p\rangle\Big|_{z^+=0,\mathbf{z}=0}$$

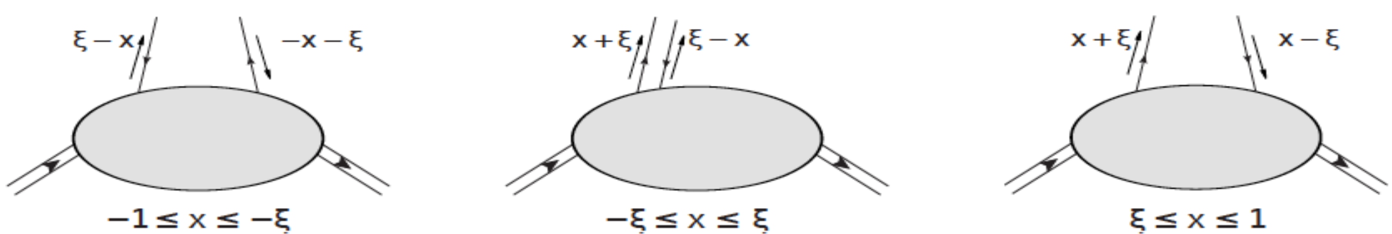
$$= \frac{1}{2P^+}\left[H^q(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}u(p)\right]$$

with $\xi = (P'-P)\cdot n/2$ and $t = (P'-P)^2 \Rightarrow -\Delta_\perp^2$ if $\xi \to 0$

Gauge link: $W[a,b] = P\exp\left(ig\int_b^a dx^-\, A^+(x^- n_-)\right)$

Mueller et al., 94;
Ji, 96;
Radyushkin, 96

- **Kinematics:**



Two more for quarks: $\tilde{H}_q(x,\xi,t,Q)$, $\tilde{E}_q(x,\xi,t,Q)$

with $\gamma\cdot n \longrightarrow \gamma\cdot n\,\gamma_5$

Jefferson Lab

Definition of GPDs

- **Gluon "form factor":**

Mueller et al., 94;
Ji, 96;
Radyushkin, 96

$$F^g = \frac{1}{P^+}\int \frac{\mathrm{d}z^-}{2\pi}\, e^{ixP^+z^-} \langle p'|G^{+\mu}(-\tfrac{1}{2}z)G_\mu{}^+(\tfrac{1}{2}z)|p\rangle\Big|_{z^+=0,\mathbf{z}=0}$$

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

Two more for gluons: $\tilde{H}^g(x,\xi,t)$ $\tilde{E}^g(x,\xi,t)$

with the two gluon field strength contracted anti-symmetrically

- **Forward limit – connection to collinear PDFs:**

$$H^q(x,0,0) = q(x), \quad \tilde{H}^q(x,0,0) = \Delta q(x) \qquad \text{for } x > 0$$

$$H^q(x,0,0) = -\bar{q}(-x), \quad \tilde{H}^q(x,0,0) = \Delta\bar{q}(-x) \quad \text{for } x < 0$$

$$H^g(x,0,0) = xg(x), \quad \tilde{H}^g(x,0,0) = x\Delta g(x) \quad \text{for } x > 0$$

The factorization scale dependence is suppressed

Foundation for the imaging and proton "radius" of quarks/gluons

Properties and Importance of GPDs

See talks by Elouadrhiri and Liuti for connection to pressure

- **QCD energy-momentum tensor:**

$$T^{\mu\nu} = \sum_{i=q,g} T_i^{\mu\nu} \quad \text{with} \quad T_q^{\mu\nu} = \bar{q}\gamma^{(\mu} \mathrm{i}\overleftrightarrow{D}^{\nu)} q, \qquad T_g^{\mu\nu} = G^{\mu\alpha} G_\alpha{}^\nu + \tfrac{1}{4} g^{\mu\nu} G^{\alpha\beta} G_{\alpha\beta}$$

- **Form factors:**

$$\langle p' | T_{q,g}^{\mu\nu} | p \rangle = A_{q,g}(t) \bar{u} P^{(\mu}\gamma^{\nu)} u + B_{q,g}(t) \bar{u} \frac{P^{(\mu} \mathrm{i}\sigma^{\nu)\alpha} \Delta_\alpha}{2m} u + C_{q,g}(t) \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu}\Delta^2}{m} \bar{u} u + \bar{C}_{q,g}(t) m g^{\mu\nu} \bar{u} u$$

- **Light-cone helicity operator:**

$$J^3 = \int \mathrm{d}x^- \, \mathrm{d}^2\mathbf{x} \, M^{+12}(x) \quad \text{with} \quad M^{\alpha\mu\nu} = T^{\alpha\nu} x^\mu - T^{\alpha\mu} x^\nu$$

- **Connection to the proton spin:**

Ji, PRL78, 1997

$$\langle J_q^3 \rangle = \tfrac{1}{2}[A_q(0) + B_q(0)] \,, \qquad \langle J_g^3 \rangle = \tfrac{1}{2}[A_g(0) + B_g(0)]$$

$$A_q(t) + B_q(t) = \int_{-1}^{1} \mathrm{d}x \, x [H_q(x,\xi,t) + E_q(x,\xi,t)]$$

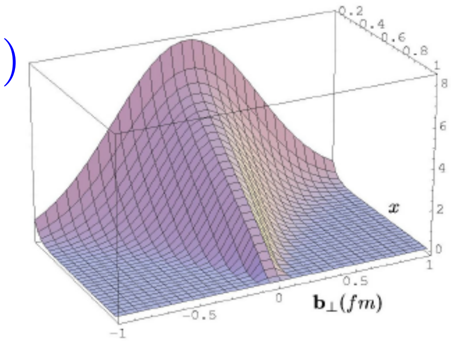
$$A_g(t) + B_g(t) = \int_{0}^{1} \mathrm{d}x [H_g(x,\xi,t) + E_g(x,\xi,t)]$$

Spatial imaging from GPDs

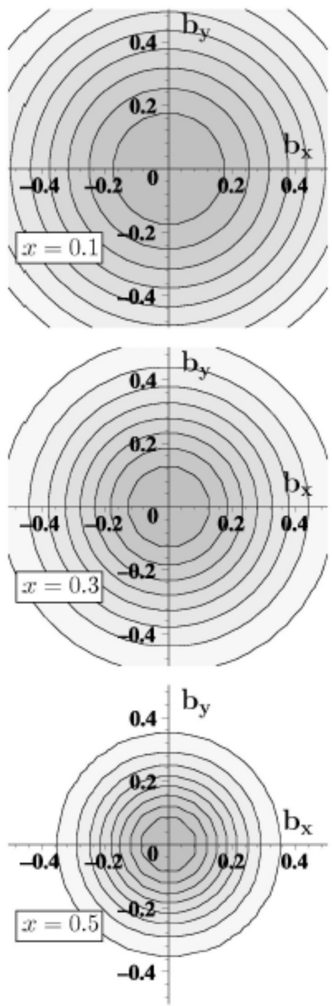
M. Burkdart, PRD 2000

❑ **Impact parameter dependent quark distribution:**

$$q(x, b_\perp, Q) = \int d^2\Delta_\perp e^{-i\Delta_\perp \cdot b_\perp} H_q(x, \xi = 0, t = -\Delta_\perp^2, Q)$$



$q(x, \mathbf{b}_\perp)$ for unpol. p



Unpolarized proton

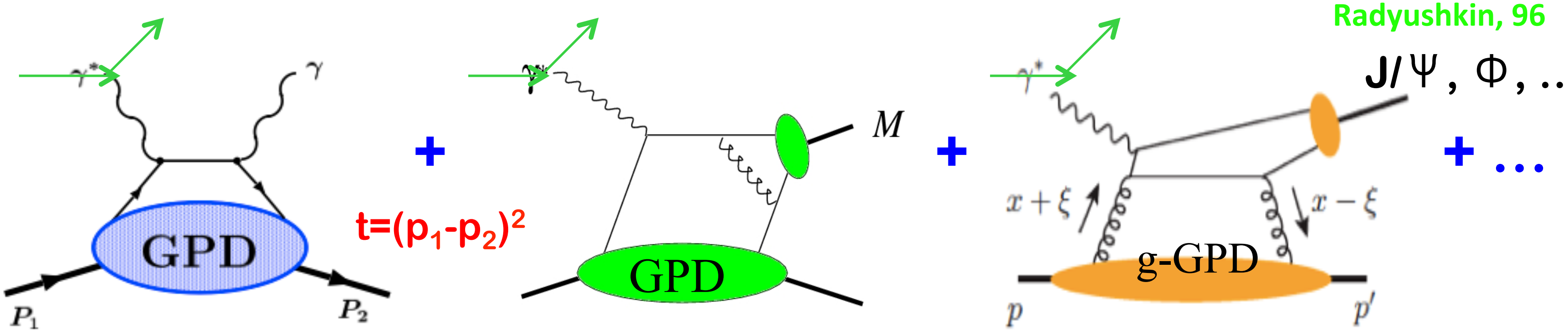
- $F_1(-\mathbf{\Delta}_\perp^2) = \int dx H(x, 0, -\mathbf{\Delta}_\perp^2)$
- x = momentum fraction of the quark
- $\mathbf{b}_\perp$ relative to $\perp$ center of momentum
- small x: large 'meson cloud'
- larger x: compact 'valence core'
- $x \to 1$: active quark becomes center of momentum

$\to$ $\vec{b}_\perp \to 0$ (narrow distribution) for $x \to 1$

Hunting for GPDs – Exclusive DIS

Mueller et al., 94;
Ji, 96;
Radyushkin, 96

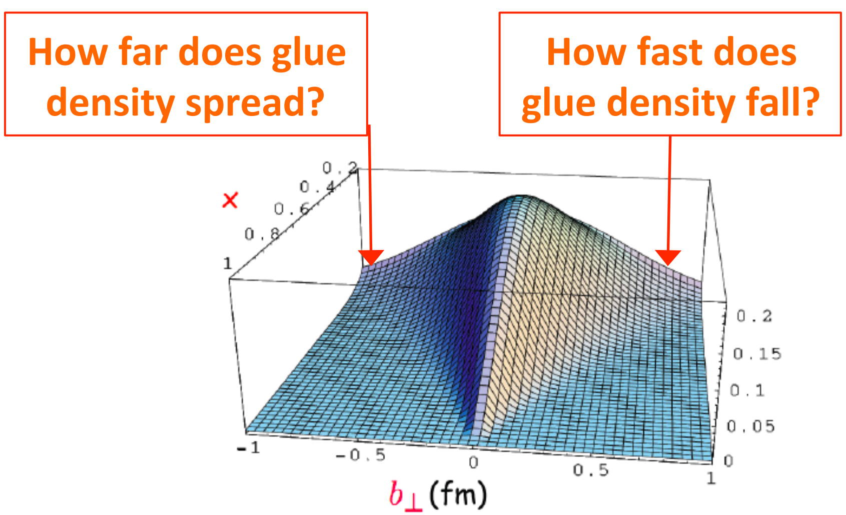
- **Experimental access to GPDs:**



DVCS: $Q^2 >> |t|$ DVEM: $Q^2 >> |t|$ EHMP: $Q^2 >> |t|$

- **Much more complicated – (x, ξ, t) variables:**
  - ✧ Challenge to derive GPDs from data

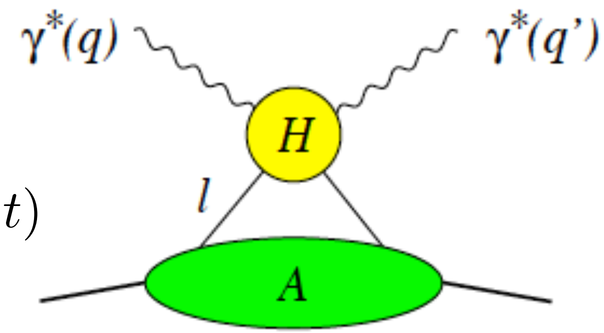
- **GPDs could tell us:**
  - ✧ Orbital contribution to proton's spin
  - ✧ Proton radius of quark & gluon density
  - ✧ Hints for color confining radius/mechanism
  - ✧ Origin of nuclear force, …
  - ✧ …



QCD factorization – Theory is solid

- **Deep Virtual Compton Scattering (DVCS):**

$$\gamma^*(q) + p(p) \to \gamma^*(q') + p(p')$$



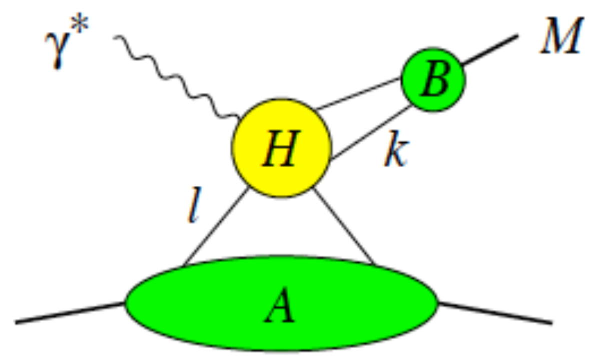
- **Factorization:**

$$\mathcal{A}(\gamma^* p \to \gamma p) = \sum_i \int_{-1}^{1} dx\, T^i(x, \xi, \rho, Q^2)\, F^i(x, \xi, t)$$

$$\rho = -(q + q')^2 / 2(p + p') \cdot (q + q')$$

- **Deep Virtual Meson Production (DVMP):**

$$\gamma^*(q) + p(p) \to M(q') + p(p')$$



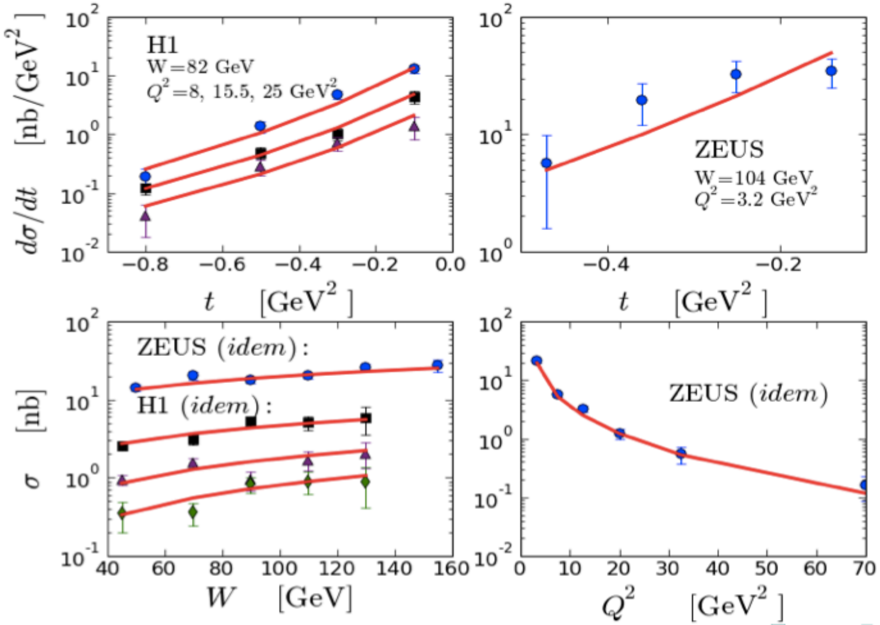
- **Factorization:**

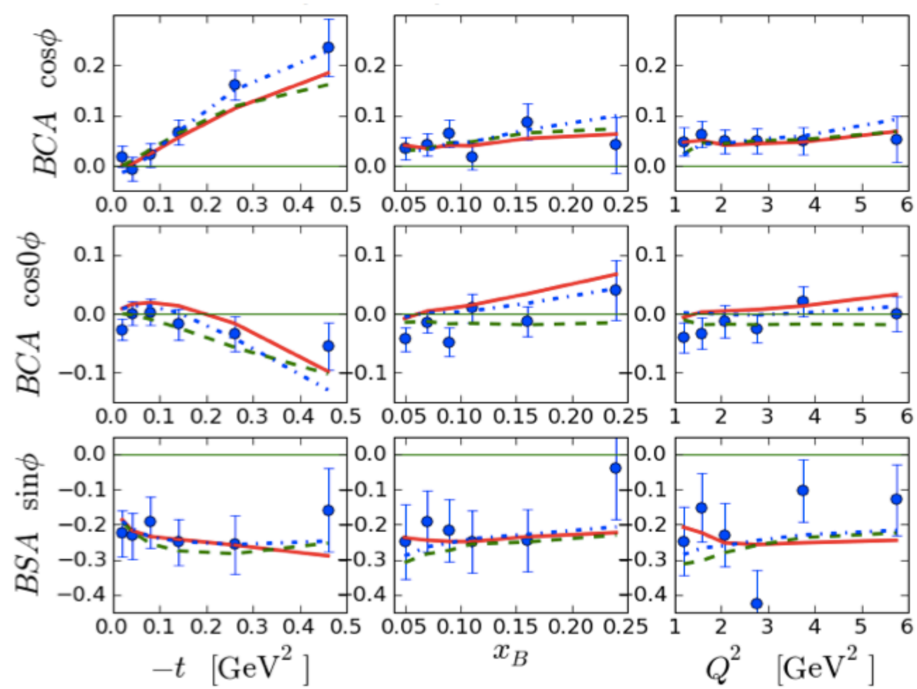
$$\mathscr{A}(\gamma_L^* p \to M_L p) = \frac{1}{Q} \sum_{ij} \int_{-1}^{1} \mathrm{d}x \times \int_0^1 \mathrm{d}z\, T^{ij}(x, \xi, z, Q^2) F^i(x, \xi, t) \Phi^j(z)$$

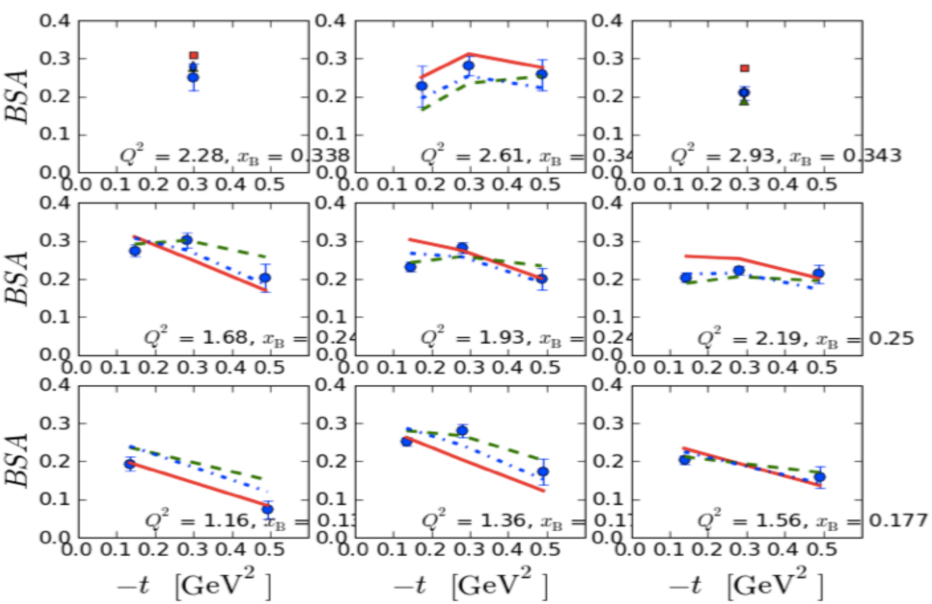
- **Evolution:**

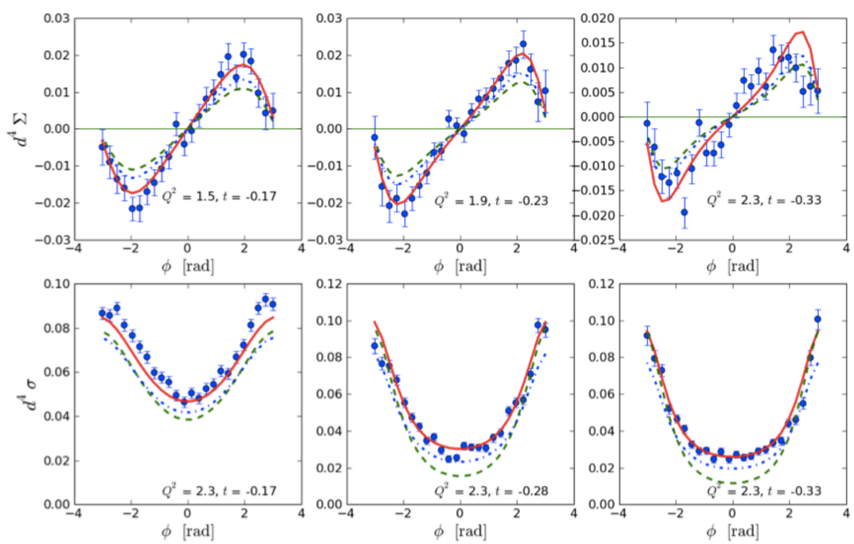
Factorization nationally lead to evolution equations for GPDs

Data: Just the beginning



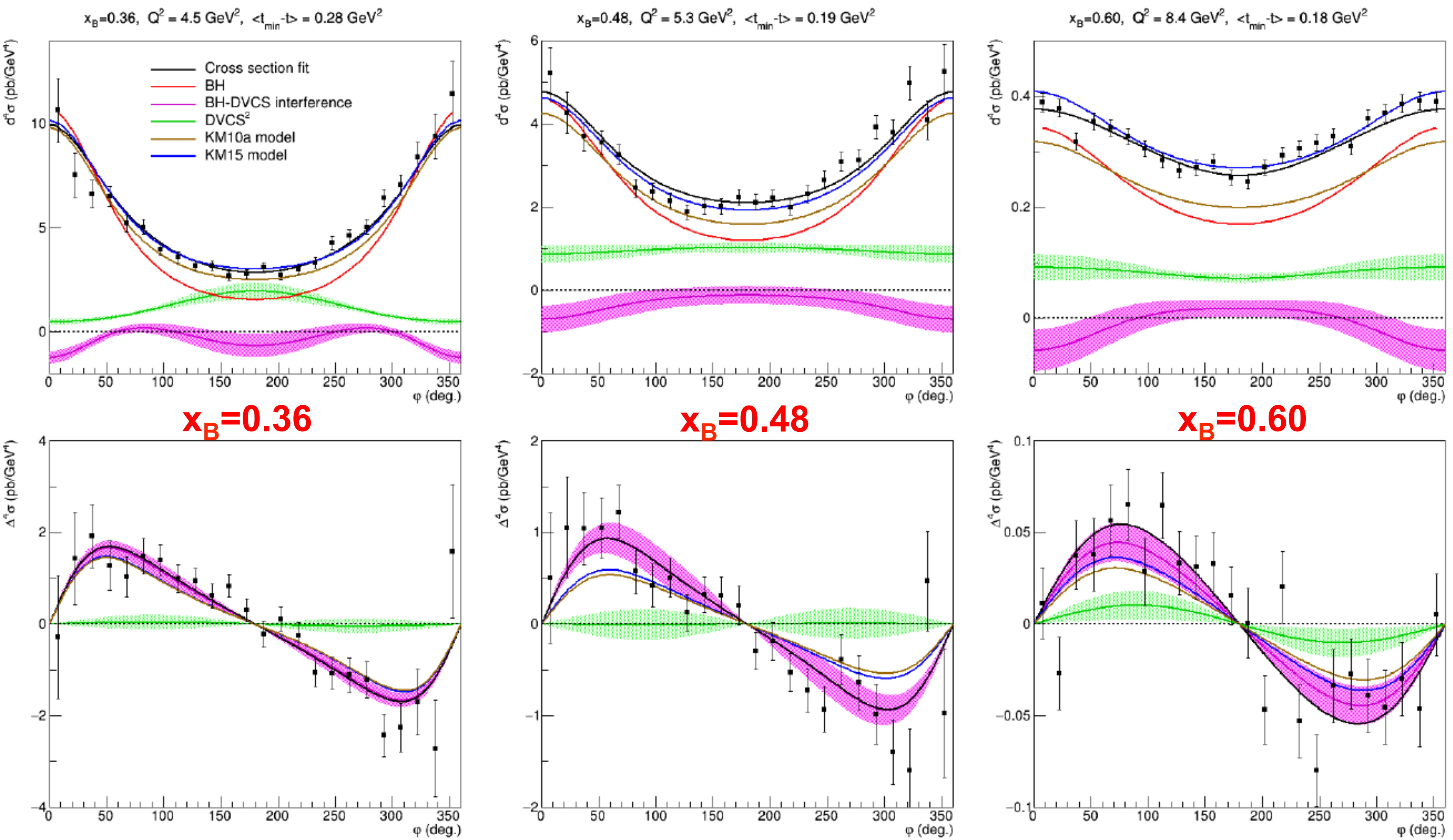






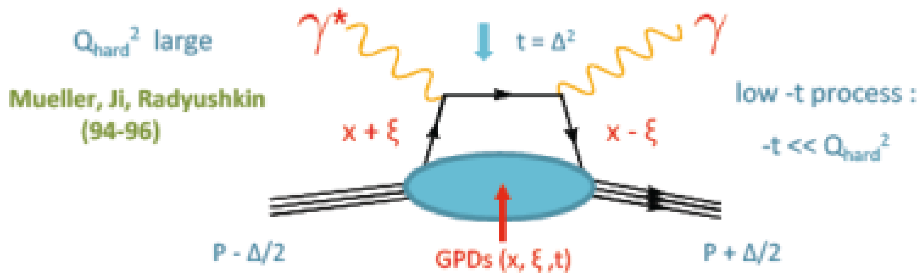
JLab E12-06-114 DVCS/Hall A Experiment at 11 GeV

Sample of cross-section results:



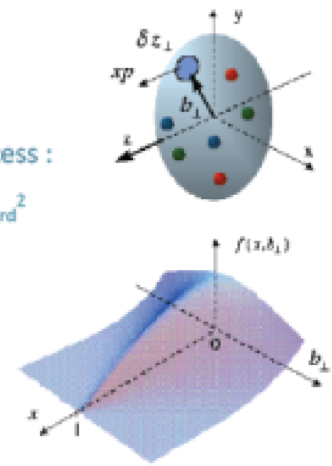
Jefferson Lab

JLab DVCS/Hall B Experiment at 11 GeV



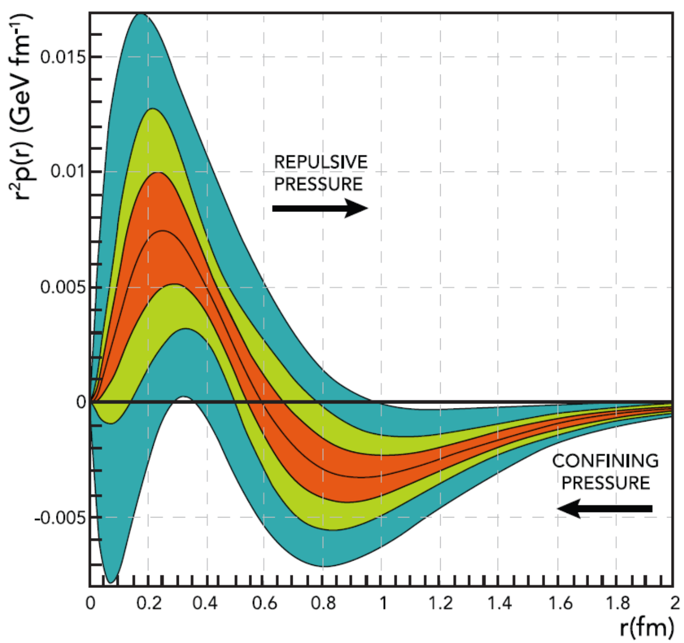
Mostly H for unpolarized proton target

Mostly $\tilde{H}$ for polarized proton target



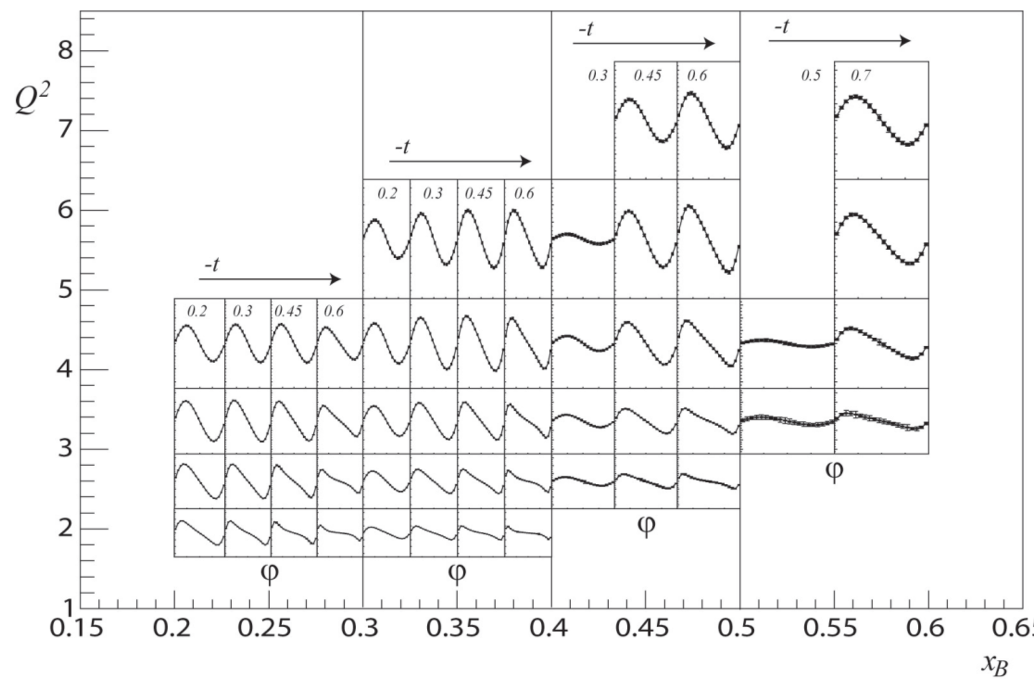
Hall A DVCS scaling check completed

Hall B DVCS on H 50% complete



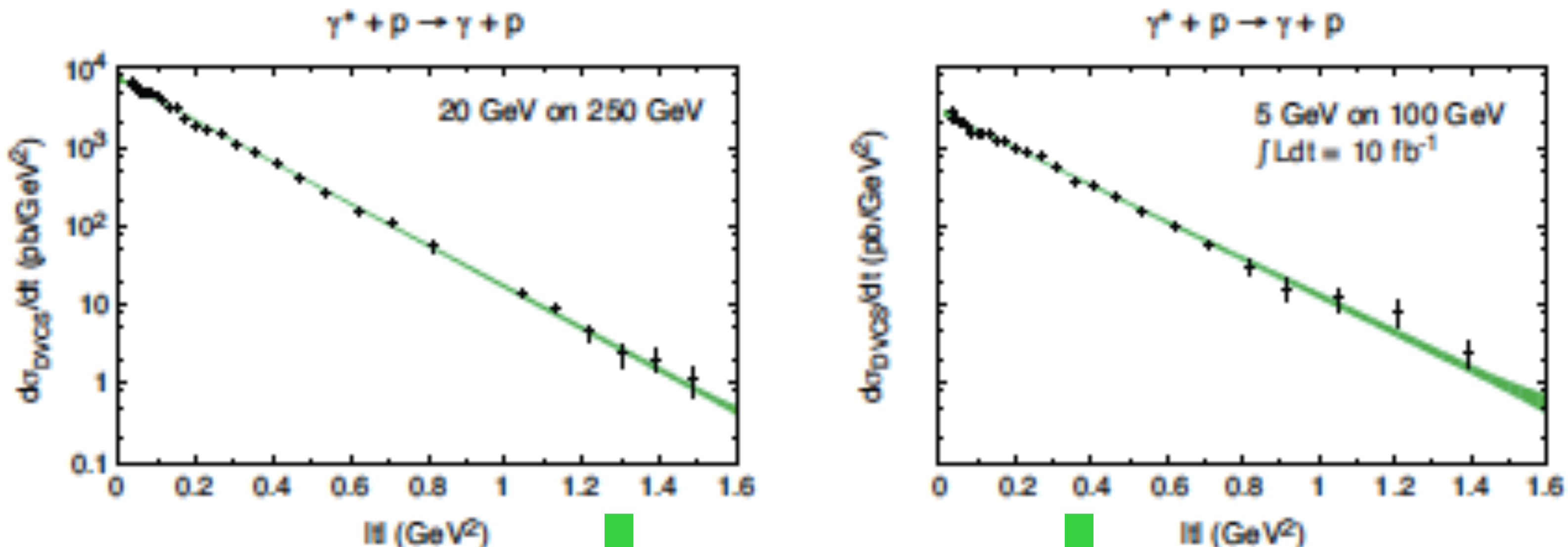
Nature **557**, 396-399 (2018)

CLAS12 (projected)

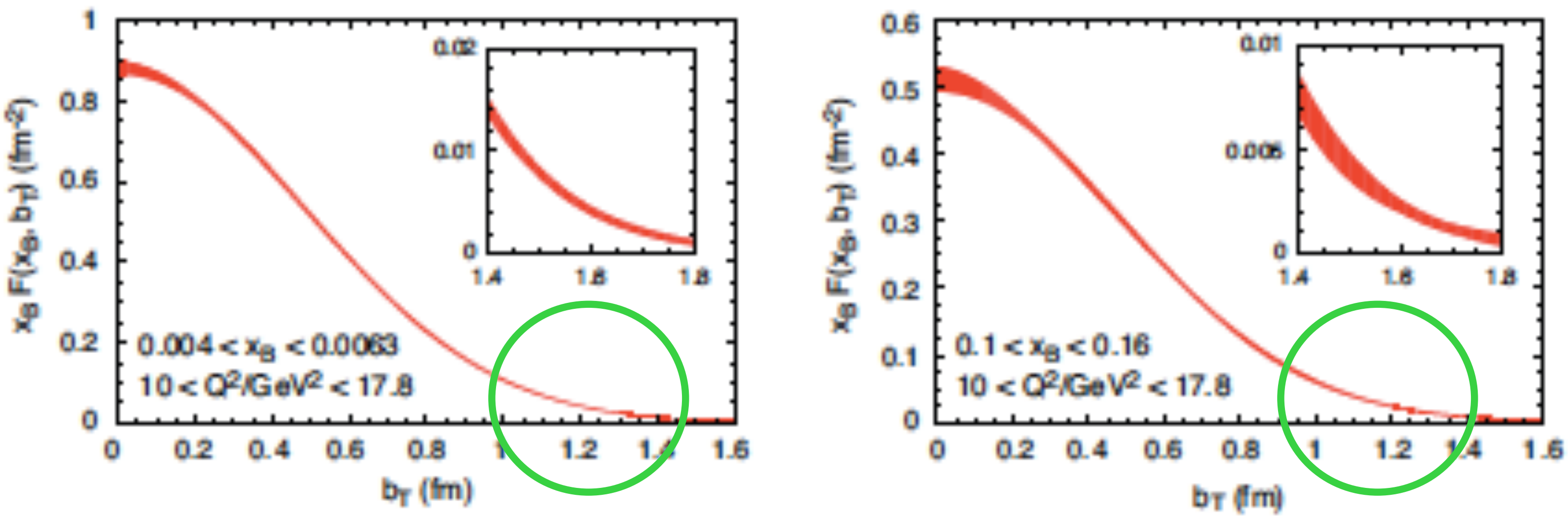


DVCS at future EIC (White Paper)

Cross Sections:

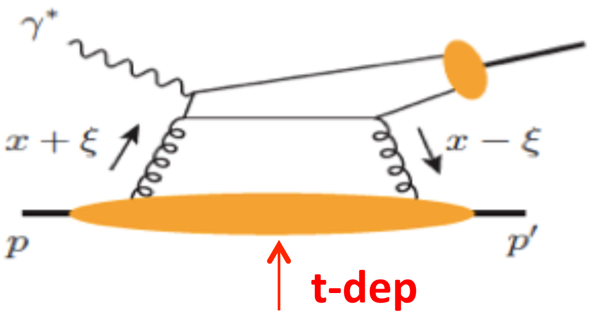


Spatial distributions:



Imaging the gluon (White Paper)

- Exclusive vector meson production:



J/Ψ, Φ, …

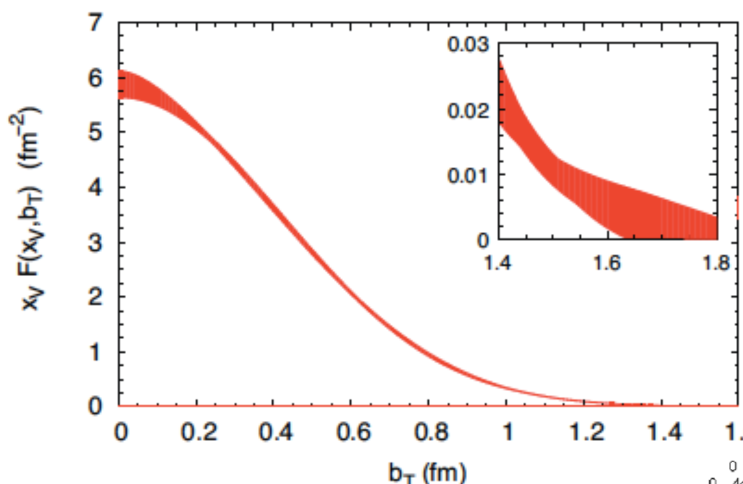
$$\frac{d\sigma}{dx_B dQ^2 dt}$$

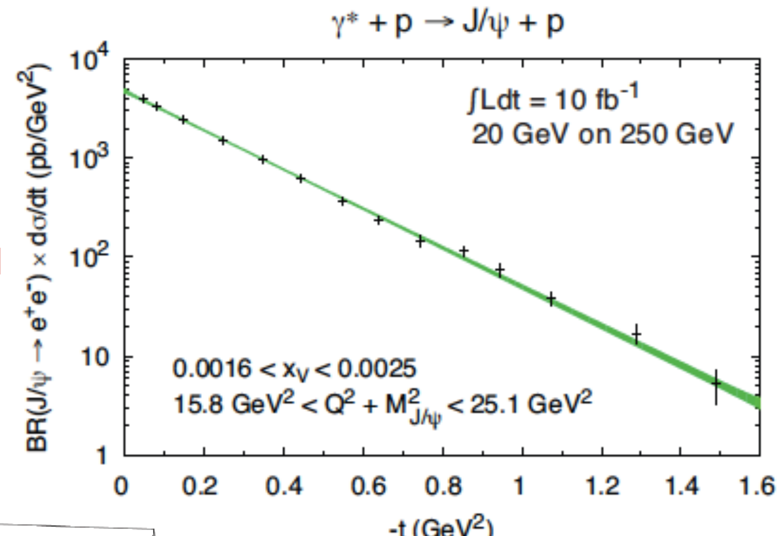
✧ Fourier transform of the t-dep

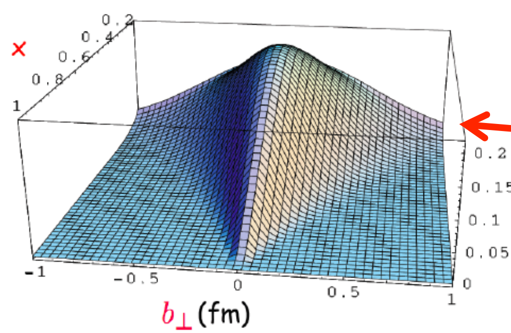
➡ Spatial imaging of glue density

✧ Resolution ~ 1/Q or $1/M_Q$

- Gluon imaging from simulation:







Only possible at the EIC

Proton radius of glue (x)?

How spread at small-x?

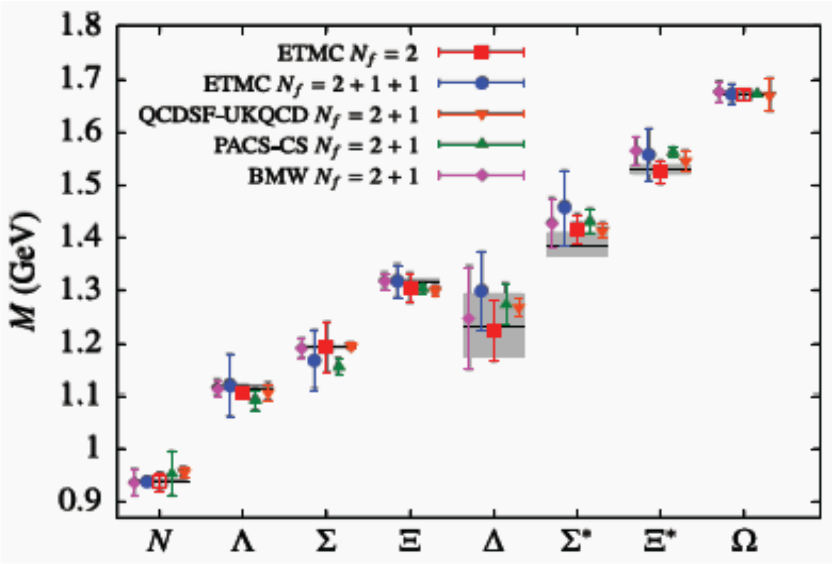
Color confinement

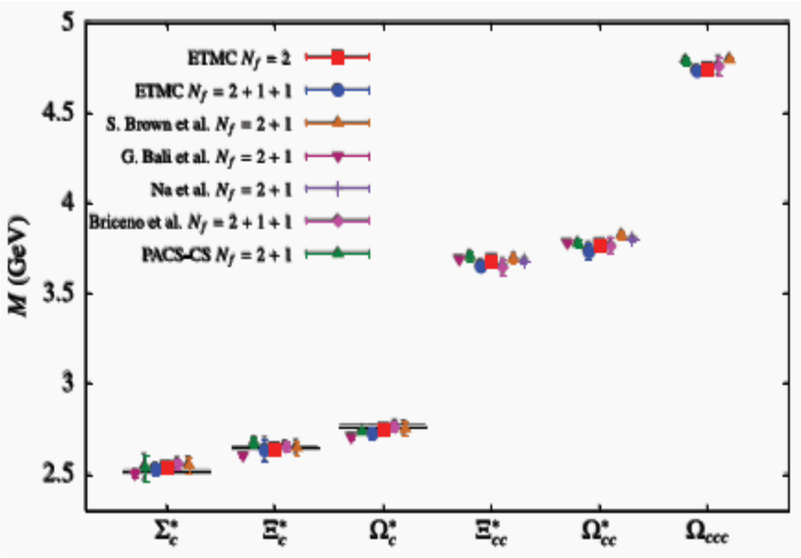
Jefferson Lab

Lattice QCD – ab initio Simulation of QCD

- Baryon spectrum:

arXiv:1704.02647





Reproduction of light baryon masses:

- Agreement between lattice discretizations
- Reproduction of experimental results

Prediction of yet to be observed baryons

- Agreement between lattice schemes

- Lattice "time" is Euclidean: $\tau = i\,t$

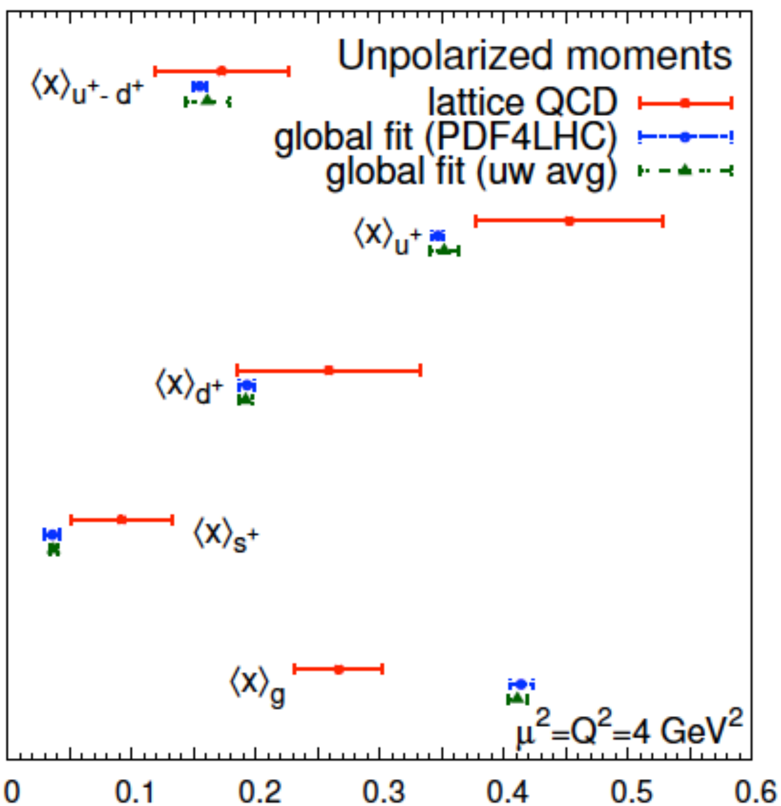
Lattice cannot calculate PDFs, TMDs, GPDs, …, directly, whose operators are time-dependent!

Lattice meets Phenomenology: Moments

- **Moments of PDFs – matrix elements of local operators:**

$$\langle x^n(\mu^2)\rangle_q \equiv \int_0^1 dx\, x^n\, q(x,\mu^2) \qquad q^{\pm} \equiv q \pm \bar{q} \quad \text{and} \quad \Delta q^{\pm} \equiv \Delta q \pm \Delta\bar{q}$$

- **Unpolarized:**



Moment	Lattice QCD	Global Fit	PDF4LHC
$\langle x\rangle_{u^+-d^+}$	0.119–0.226	0.161(18)	0.155(5)
$\langle x\rangle_{u^+}$	0.453(75)†	0.352(12)	0.347(5)
$\langle x\rangle_{d^+}$	0.259(74)†	0.192(6)	0.193(6)
$\langle x\rangle_{s^+}$	0.092(41)†	0.037(3)	0.036(6)
$\langle x\rangle_{g}$	0.267(35)†	0.411(8)	0.414(9)

† Single lattice result [PRL 119 (2017) 142002].

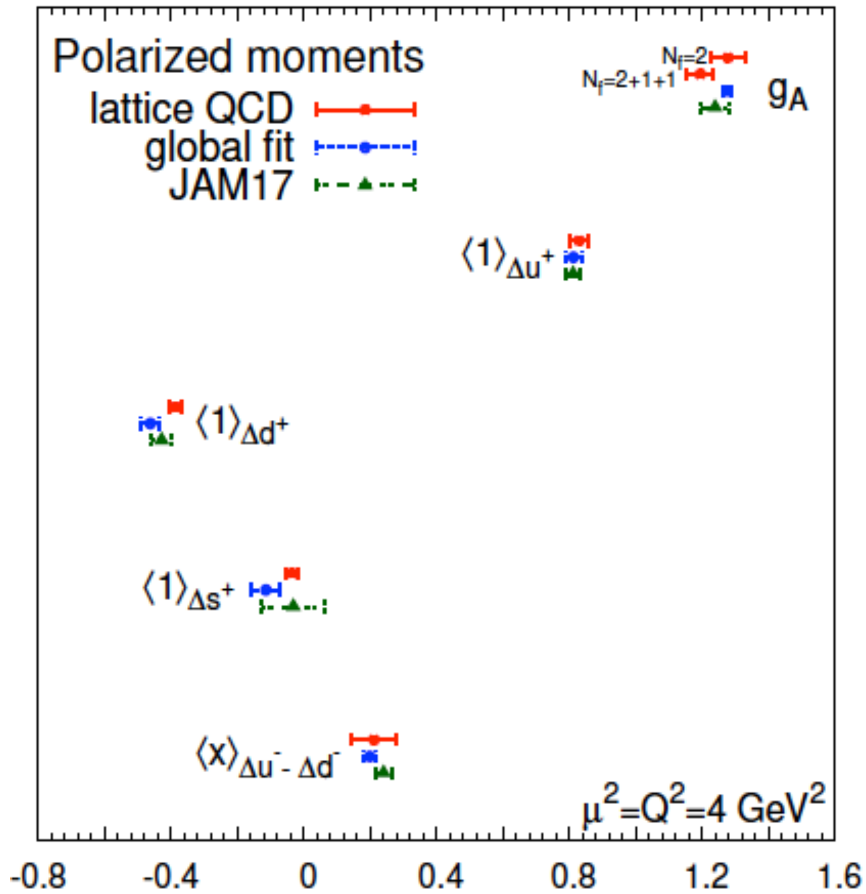
$q^{\pm} = q \pm \bar{q}$, $q = u, d, s$; $Q = 2$ GeV.

For details, see [Prog.Part.Nucl.Phys. 100 (2018) 107].

arXiv: 1711.07916

Lattice meets Phenomenology: Moments

- Polrized:



Moment	Lattice QCD	Global Fit	JAM17
g_A	1.195(39)* 1.279(50)**	1.275(12)	1.240(41)
$\langle 1\rangle_{\Delta u+}$	0.830(26)†	0.813(25)	0.812(22)
$\langle 1\rangle_{\Delta d+}$	-0.386(17)†	-0.462(29)	-0.428(31)
$\langle 1\rangle_{\Delta s+}$	-0.052−-0.014	-0.114(43)	-0.038(96)
$\langle x\rangle_{\Delta u^- - \Delta d^-}$	0.146–0.279	0.199(16)	0.241(26)

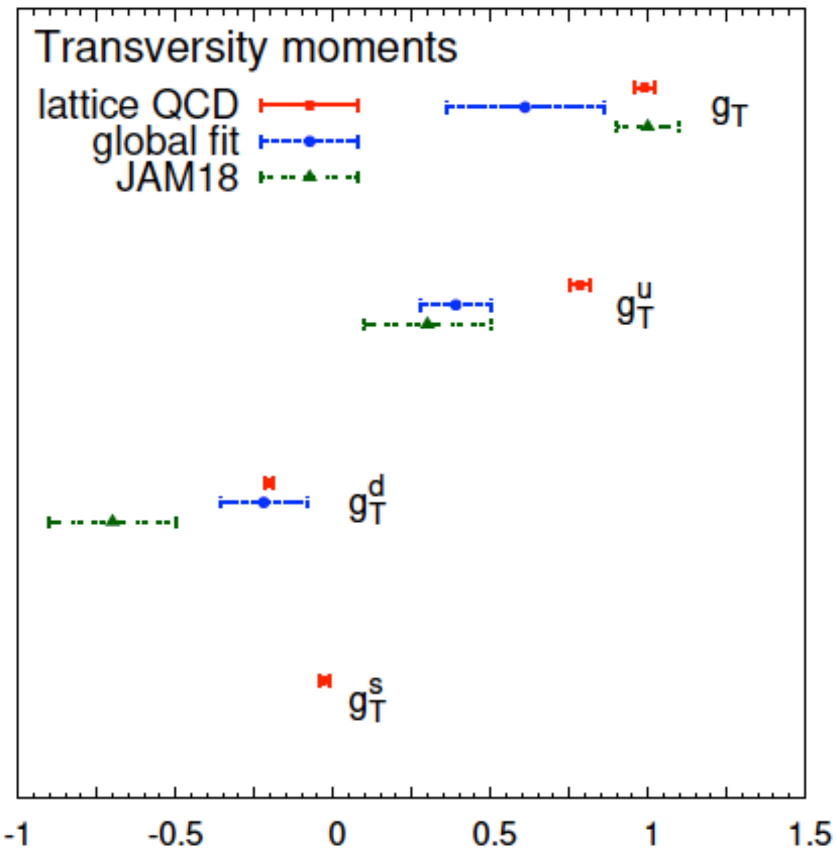
* $N_f = 2$.
** $N_f = 2 + 1 + 1$.
† Single lattice result [PRL 119 (2017) 142002].

$\Delta q^{\pm} = \Delta q \pm \Delta\bar{q}$, $q = u, d, s$; $Q = 2$ GeV.
For details, see [Prog.Part.Nucl.Phys. 100 (2018) 107]

arXiv: 1711.07916

Lattice meets Phenomenology: Moments

- Transversity:



Moment	Lattice QCD	Global Fit	JAM18
g_T	0.989(32)(10)	0.61(25)	1.0(1)
g_T^u	0.784(28)(10)	0.39(11)	0.3(2)
g_T^d	-0.204(11)(1)	-0.22(14)	-0.7(2)
g_T^s	-0.027(16)	—	—

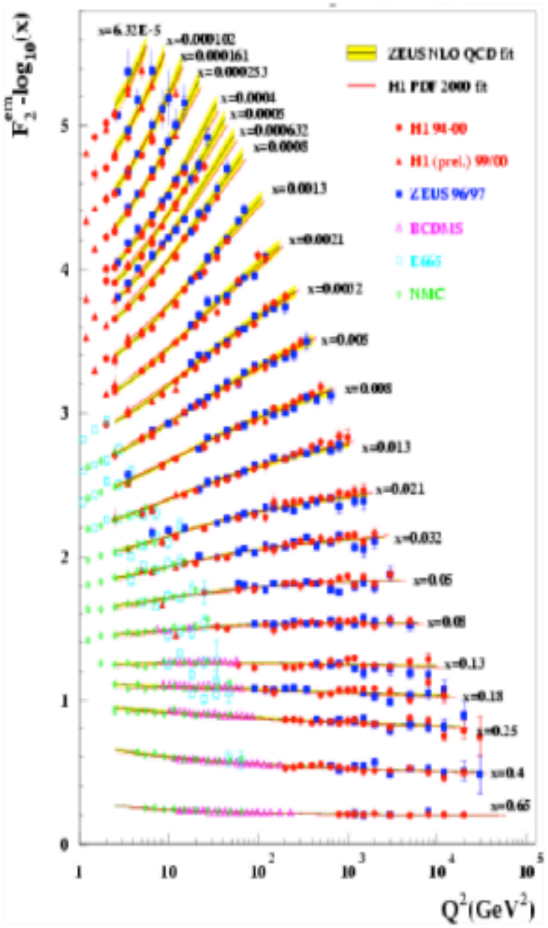
$q^+ = q + \bar{q}$, $q = u, d, s$; $Q = 2$ GeV.
Lattice results from the 2019 FLAG review.
Global fit [PRD 93 (2016) 014009]
JAM18 [PRL 120 (2018) 152502]

arXiv: 1711.07916

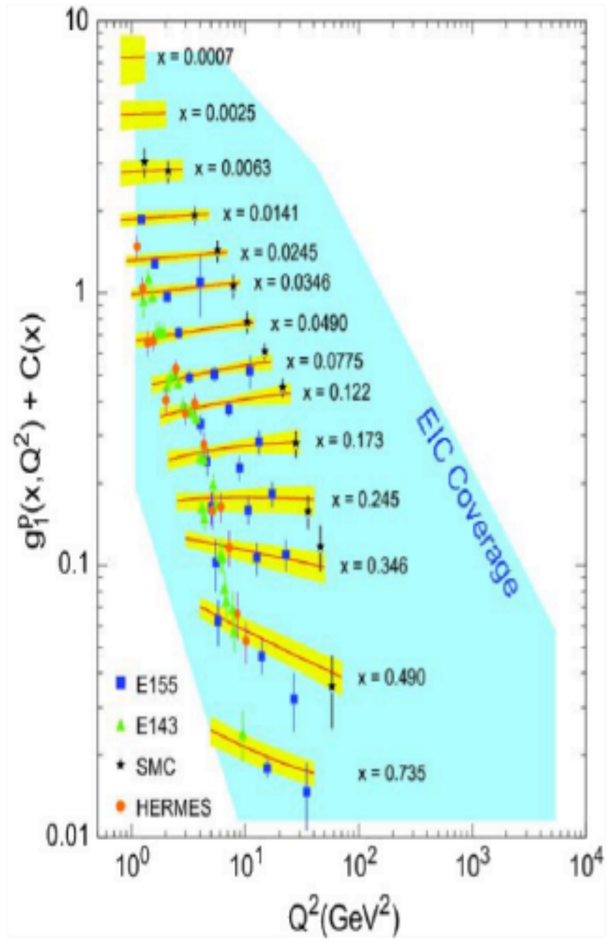
Lattice meets Phenomenology: Data accuracy

Nocera
@EINN2019

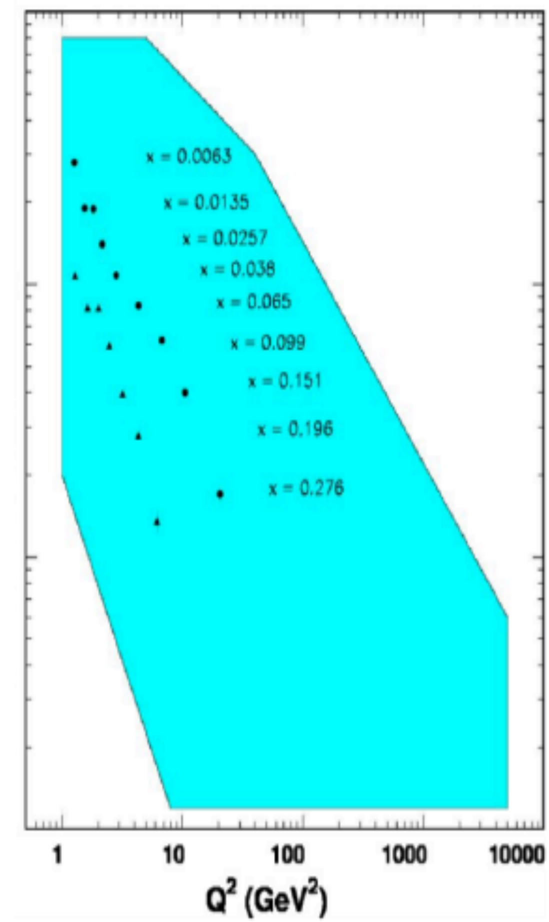
World data for $F_2{}^p$	World data for $g_1{}^p$	World data for **h₁**



Fits of f
from **thousands** of data
CT, MMHT, NNPDF, . . .



Fits of Δf
from hundreds of data
DSSV, JAM, NNPDF, . . .



Fits of δf
from tens of data
Kang; Anselmino; Bacchetta

Lattice meets Phenomenology: PDFs

- **Quasi-PDFs:**

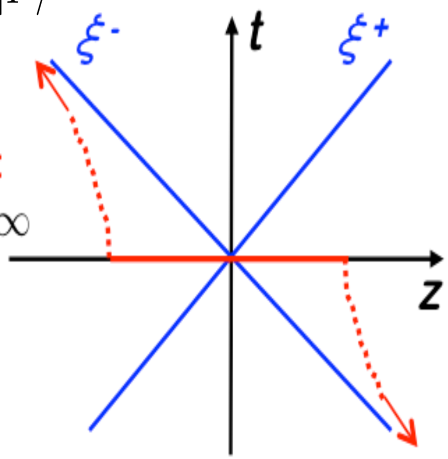
Ji, arXiv:1305.1539

$$\tilde{q}(\tilde{x},\mu_R^2,P_z) \equiv \int \frac{d\xi_z}{4\pi} e^{-i\tilde{x}P_z\xi_z} \langle P|\overline{\psi}(\frac{\xi_z}{2})\gamma_z \exp\left\{-ig\int_0^{\xi_z} d\eta_z A_z(\eta_z)\right\}\psi(\frac{-\xi_z}{2})|P\rangle$$

Idea – Large Momentum Effective Theory (LaMET):

Quasi-PDFs are not boost invariant.

$$\tilde{q}(\tilde{x},\mu_R^2,P_z) \longrightarrow q(x,\mu^2) \quad \textbf{when } P_z \to \infty$$



Note: **In Lattice QCD calculation, difficult to take** $P_z \to \infty$ **limit**

Proposed matching:

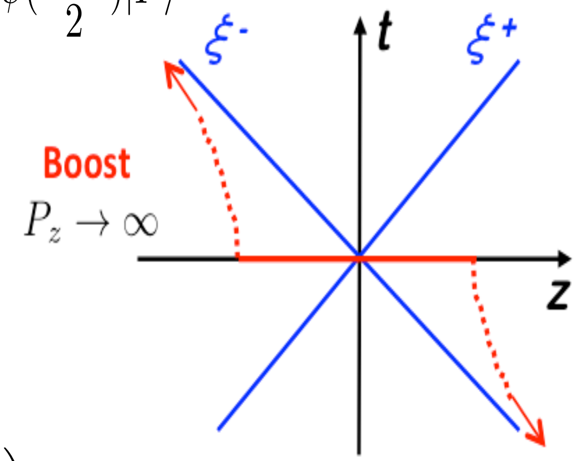
$$\tilde{q}(x,\mu^2,P_z) = \int_x^1 \frac{dy}{y} Z\left(\frac{x}{y},\frac{\mu}{P_z}\right) q(y,\mu^2) + \mathcal{O}\left(\frac{\Lambda^2}{P_z^2},\frac{M^2}{P_z^2}\right)$$

Ma, Qiu arXiv:1404.6860

Lattice meets Phenomenology: PDFs

- **Quasi-PDFs:** Ji, arXiv:1305.1539

$$\tilde{q}(\tilde{x},\mu_R^2,P_z) \equiv \int \frac{d\xi_z}{4\pi} e^{-i\tilde{x}P_z\xi_z} \langle P|\overline{\psi}(\frac{\xi_z}{2})\gamma_z \exp\left\{-ig\int_0^{\xi_z} d\eta_z A_z(\eta_z)\right\}\psi(\frac{-\xi_z}{2})|P\rangle$$



Idea – Large Momentum Effective Theory (LaMET):

Quasi-PDFs are not boost invariant.

$$\tilde{q}(\tilde{x},\mu_R^2,P_z) \longrightarrow q(x,\mu^2) \quad \textbf{when} \quad P_z \to \infty$$

Note: In Lattice QCD calculation, difficult to take $P_z \to \infty$ limit

Proposed matching:

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

Ma, Qiu arXiv:1404.6860

- **Pseudo-PDFs:** A. Radyushkin, arXiv:1705.01488

✧ **Lattice calculation with $\alpha = 0$:** Ioffe time: $\nu = p\cdot\xi \to -p_z\xi_z$

$$\mathcal{M}^\alpha(\nu = p\cdot\xi,\xi^2) \equiv \langle p|\overline{\psi}(0)\gamma^\alpha\Phi_v(0,\xi,v\cdot A)\psi(\xi)|p\rangle \quad \text{with } \xi^2 < 0$$

$$\equiv 2p^\alpha\mathcal{M}_p(\nu,\xi^2) + \xi^\alpha(p^2/\nu)\mathcal{M}_\xi(\nu,\xi^2) \approx 2p^\alpha\mathcal{M}_p(\nu,\xi^2)$$

Fourier transform of ν

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

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

LQCD/PQCD – hadron/nuclear structure

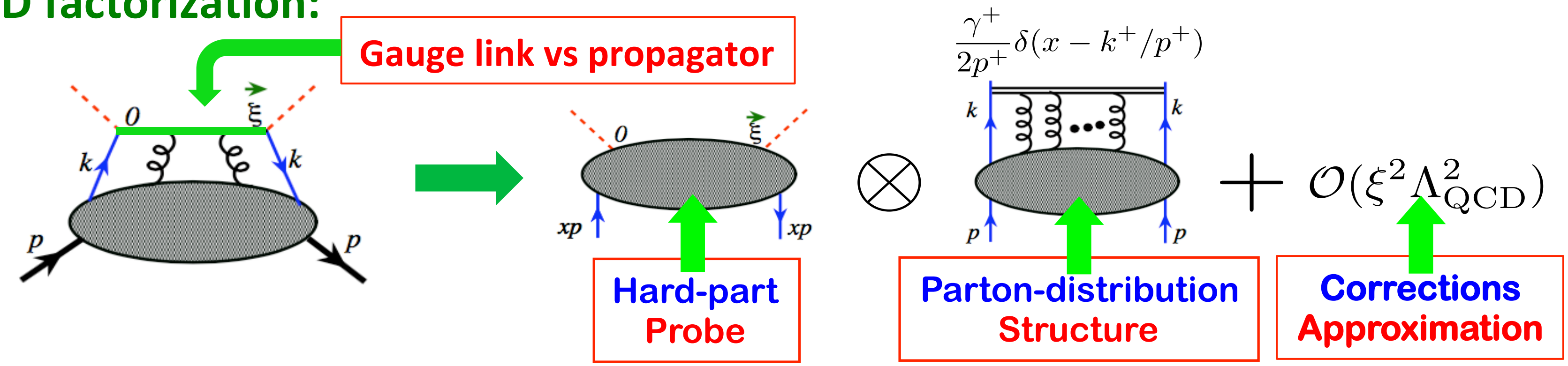
Ma and Qiu, arXiv:1404.6860

- **Good lattice cross sections:**

  $\sigma_n(\omega, \xi^2, P^2) = \langle P|T\{\mathcal{O}_n(\xi)\}|P\rangle$ **with** $\omega \equiv P\cdot\xi,\ \xi^2 \neq 0,\ \text{and}\ \xi_0 = 0;$ **and**

  1) **can be calculated in lattice QCD with precision,**
     has a well-defined continuum limit (UV+IR safe perturbatively), and
  2) **can be factorized into universal matrix elements of quarks and gluons**
     with controllable approximation $P \to \sqrt{s}$ ***and*** $\xi \to 1/Q$ ***define collision kinematics***

- **QCD factorization:**



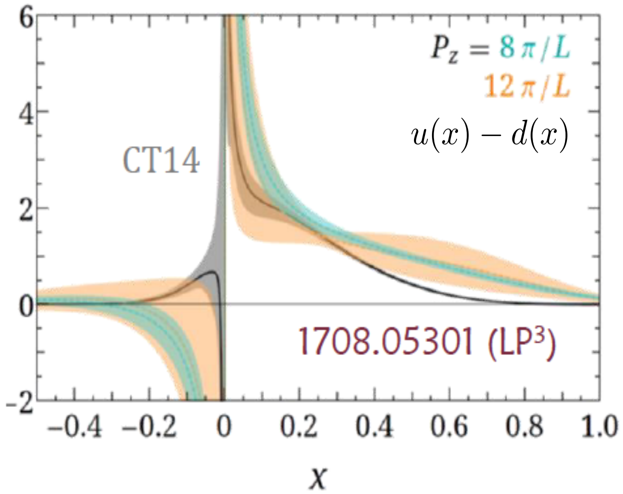
- **Tremendous potentials:**

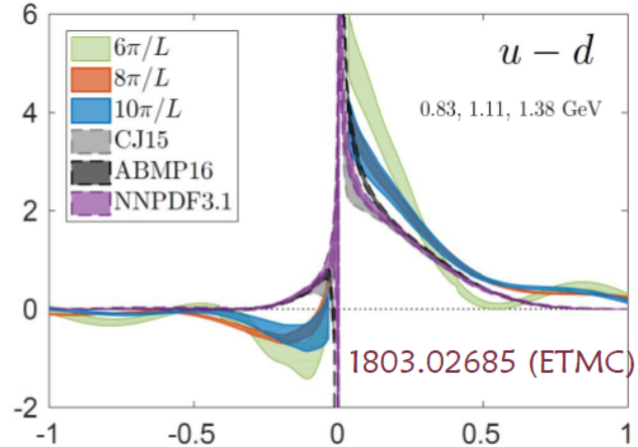
  Access to large-x region, …
  Neutron PDFs, … (no free neutron target!)
  Meson PDFs, such as pion, kaon, …
  More direct access to parton flavor, …

→ ***1st LQCD calculation of pion valence PDFs!***

Lattice QCD calculated PDFs – Quasi-PDFs approach

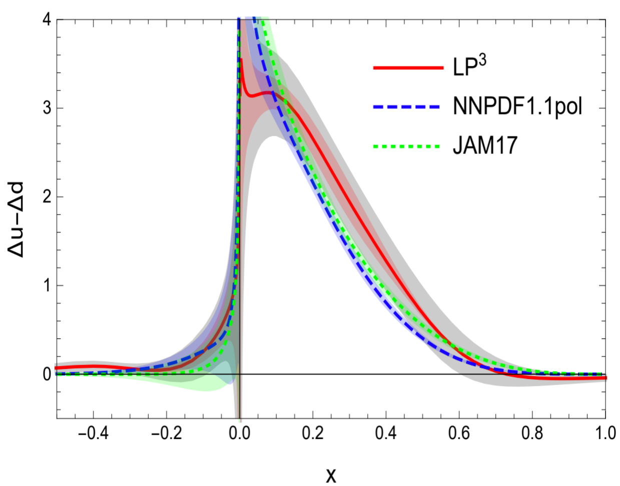
❑ **Unpolarized: Both LP3 and ETMC obtained their results at physical pion**

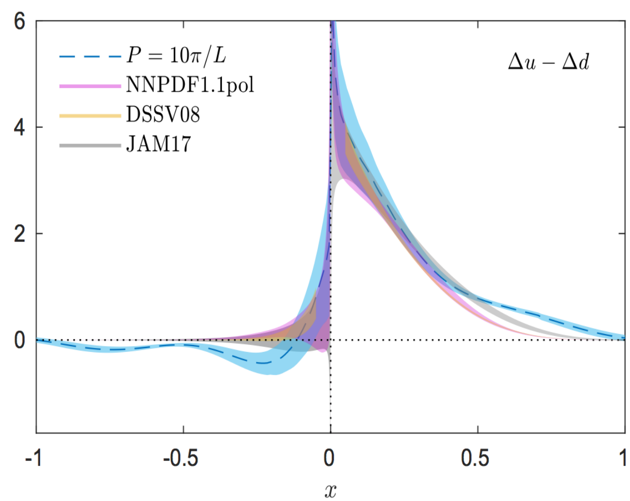




One-loop matching
Target mass corrections

❑ **Helicity distributions:**





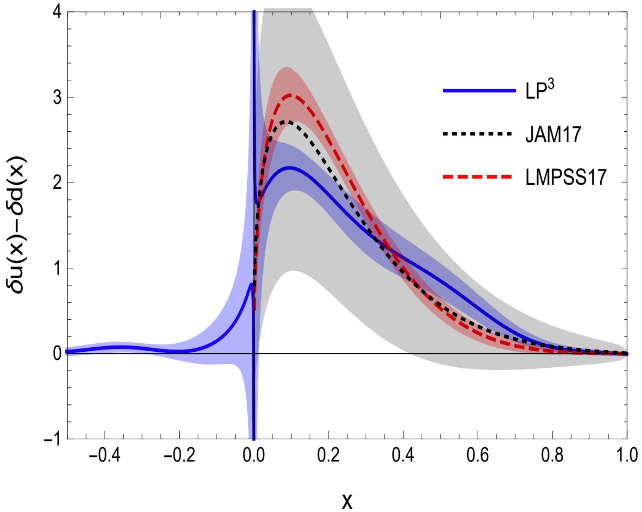
See also talk by Lin

[H.-W. Lin et al. (LP3), PRL 121 (2018) 242003]

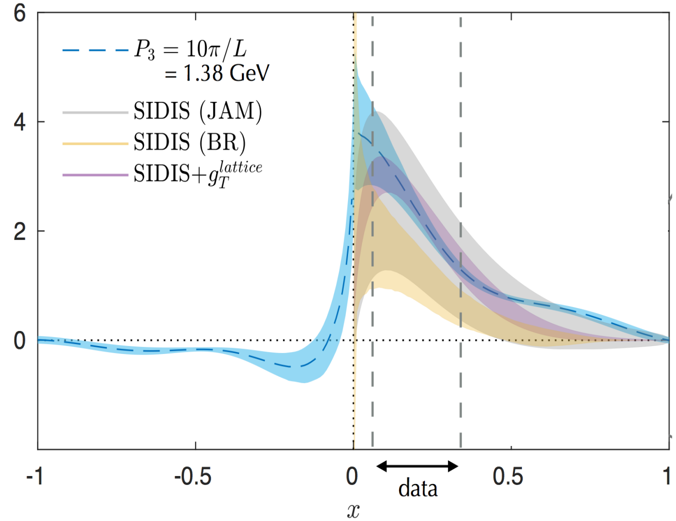
[C. Alexandrou et al. (ETMC), PRL 121 (2018) 112001]

Lattice QCD calculated PDFs – Quasi-PDFs approach

- **Transversity distribution:**



[Y.-S. Liu et al. (LP3), arXiv:1807.00232]



[C. Alexandrou et al. (ETMC), arXiv:1807.00232]

One-loop matching

Target mass corrections

See also talk by Lin

Jefferson Lab

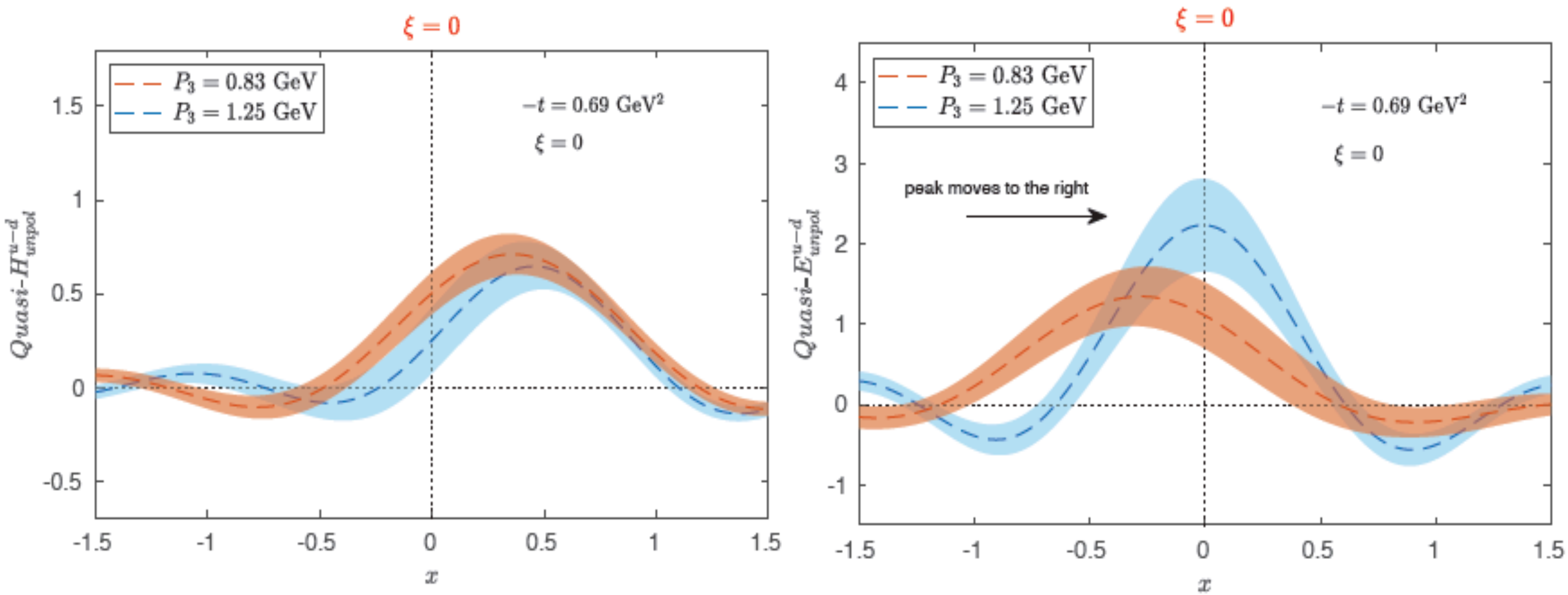
Lattice QCD calculation of GPDs – Quasi-PDFs approach

Unpolarized quasi-GPDs

Scapeliato
@EINN2019

Upon Fourier transform

$$\tilde{q}^{GPD} = \frac{2P_3}{4\pi} \sum_{z=-z_{\rm max}}^{z=z_{\rm max}} e^{-ixP_3 z} ME^{GPD}(z,t,\xi)$$



- Quasi-H and -E affected differently on the momentum boost
  - quasi-H is compatible within errors
  - quasi-E becomes symmetric in x (larger momenta will shed light on the behavior of the quasi-E)

Still non-physical results, matching is needed

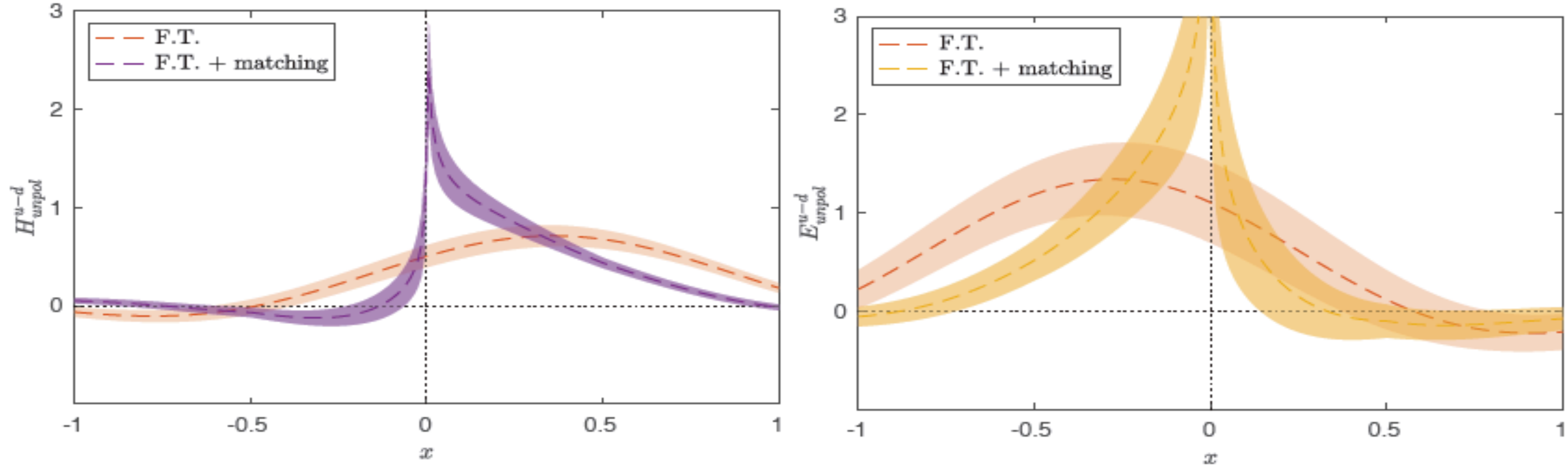
Lattice QCD calculation of GPDs – Quasi-PDFs approach

Matching effect on the GPDs

Scapeliato @EINN2019

- We apply the RI$\rightarrow \overline{\text{MS}}$ matching [Y-S Liu et al., Phys.Rev. D100 (2019) no.3, 034006]

$$P_3 = 0.83 \text{ GeV}, \ -t = 0.69 \text{ GeV}^2, \ \xi = 0$$



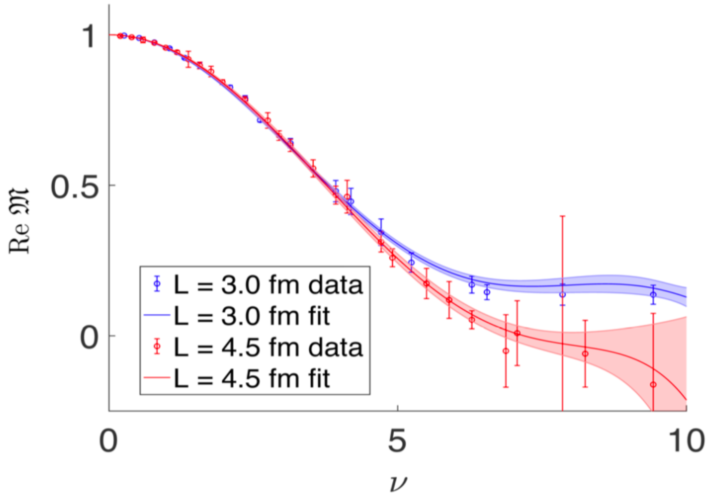
- Matching affects both H and E largely

Lattice QCD calculated PDFs – Pseudo-PDFs approach

❑ **Volume effect:**

[B. Joo et al. (JLab-W&M), arXiv:1908.09771]

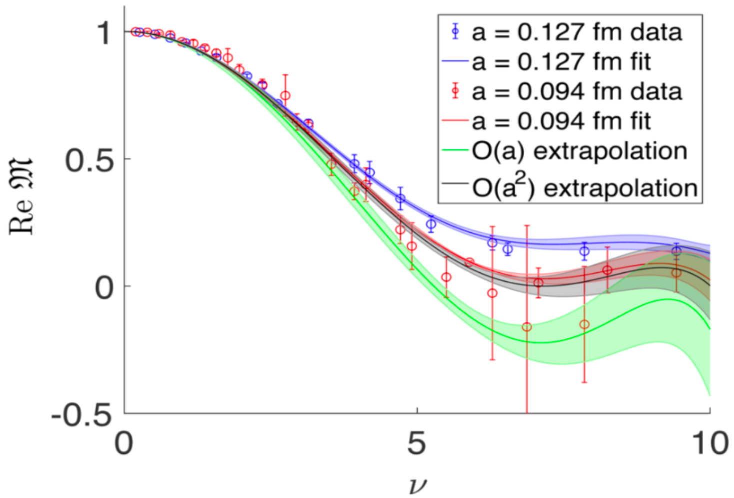
See talk by Rudyshkin



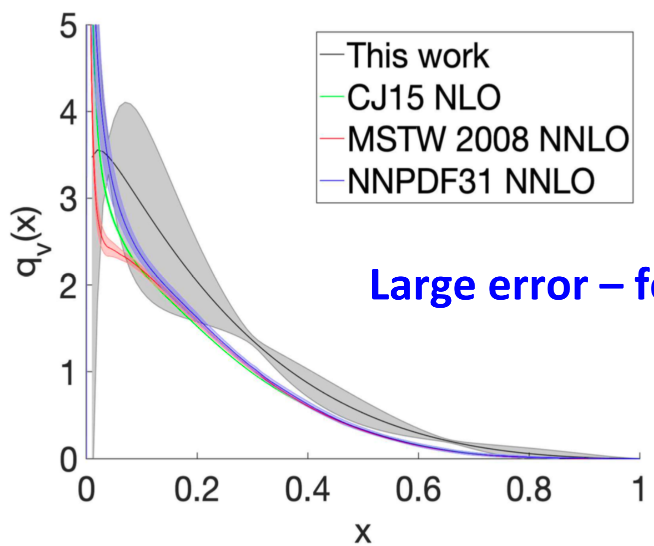
$a(\mathrm{fm})$	$M_\pi(\mathrm{MeV})$	$L^3 \times T$
0.127(2)	415(23)	$24^3 \times 64$
0.127(2)	415(23)	$32^3 \times 96$
0.094(1)	390(71)	$32^3 \times 64$

N_f=2+1 clover fermions
(3 ensembles):

❑ **Discretization effect:**



❑ **Extract/fit PDF from lattice data with a functional form similar to CJ and MSTW**



Large error – few data

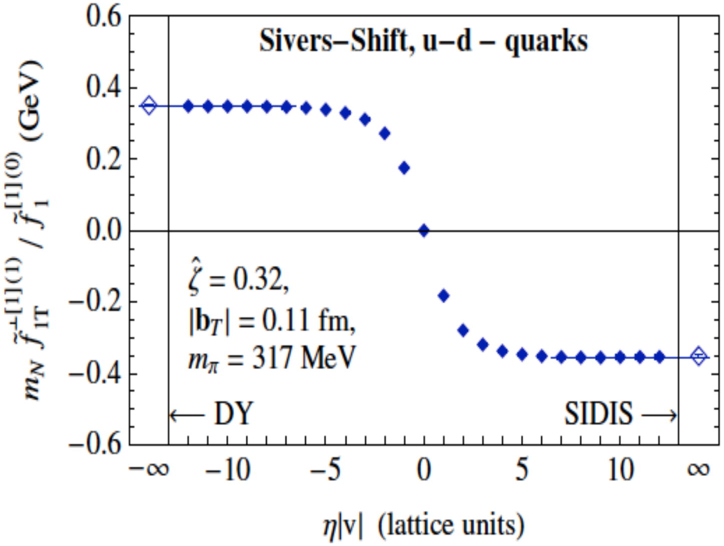
Too strong "L" & "a" dependence
– limited the range of ν!

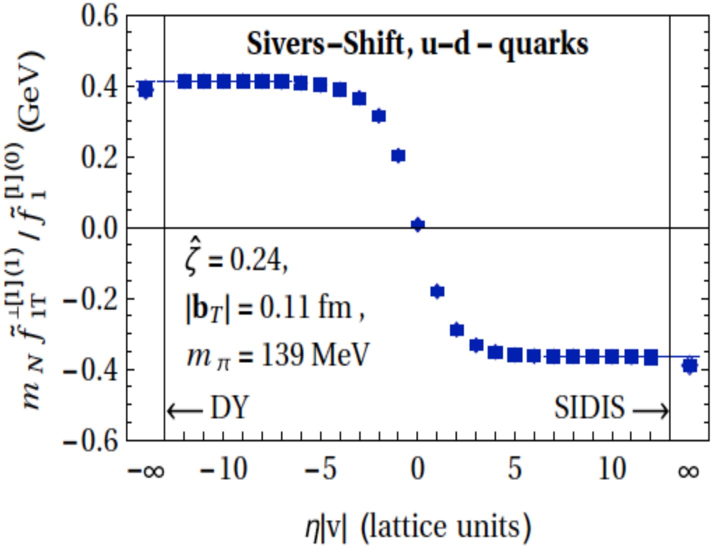
Challenges due to lattice limitation
Results are encouraging!

Lattice QCD calculation of TMDs:

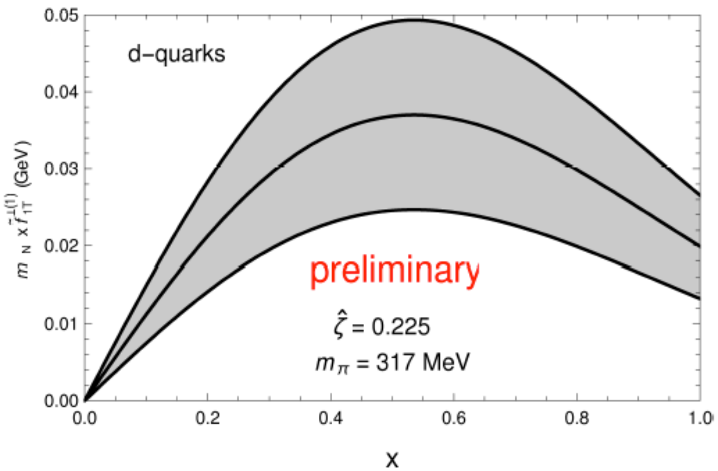
Engelhardt @EINN2019

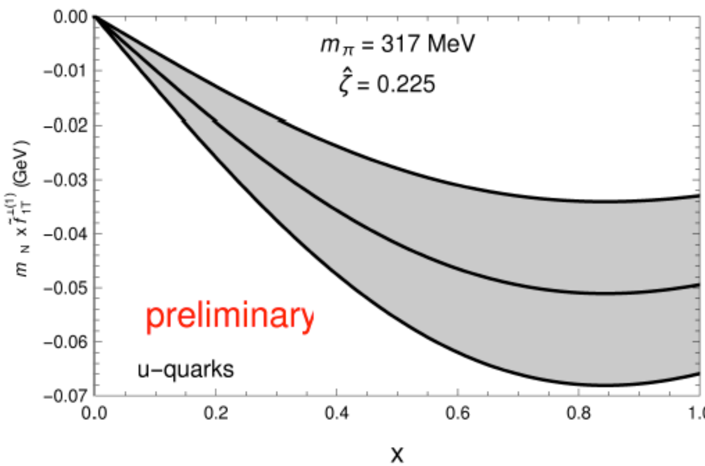
- Sivers' sign change:





- Advertisement – x-dependent TMDs:



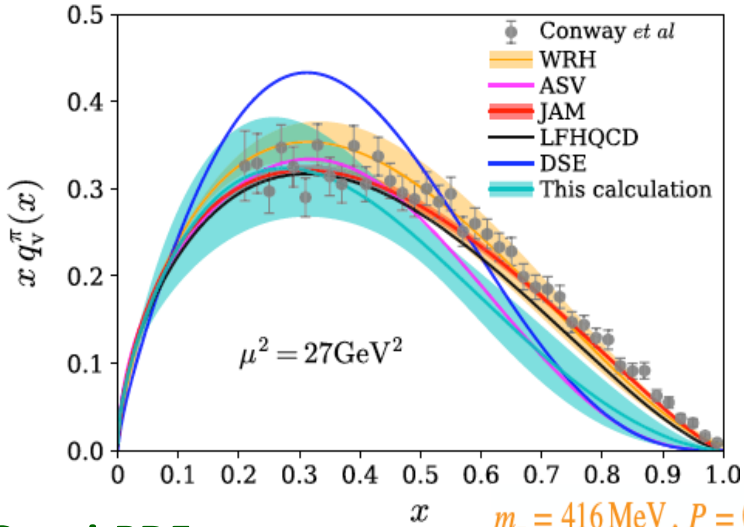


son Lab

Lattice QCD calculated pion distribution

❑ "Lattice cross section":

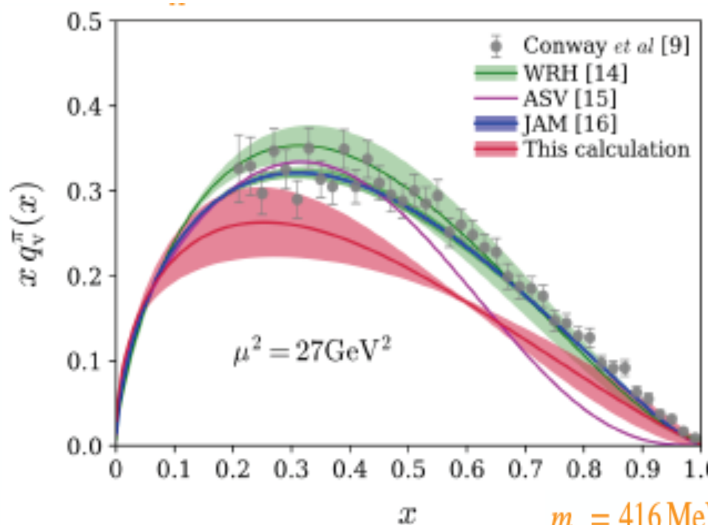
[R. Sufian et al. (JLab - W&M), Phys. Rev. D 99 (2019) 074507]



$m_\pi = 416\,\mathrm{MeV}$, $P = 0.6 - 1.5$

❑ Pseudo-PDF:

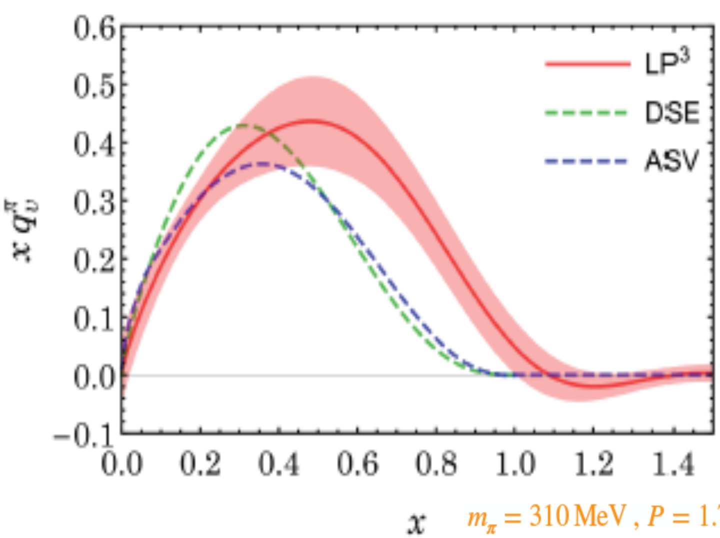
[B. Joo et al. (JLab-W&M), arXiv:1909.08517]



$m_\pi = 416\,\mathrm{MeV}$, $\nu \leq 4.7$

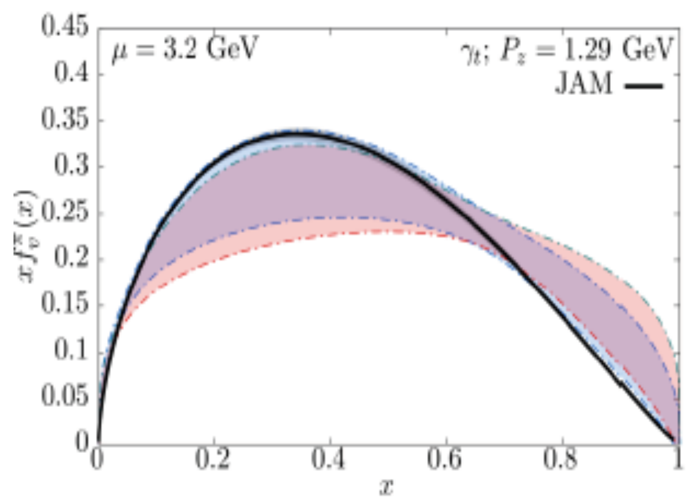
❑ Quasi-PDF:

[J.-H. Zhang et al. (LP3),Phys. Rev. D 100, 034505 (2019)]



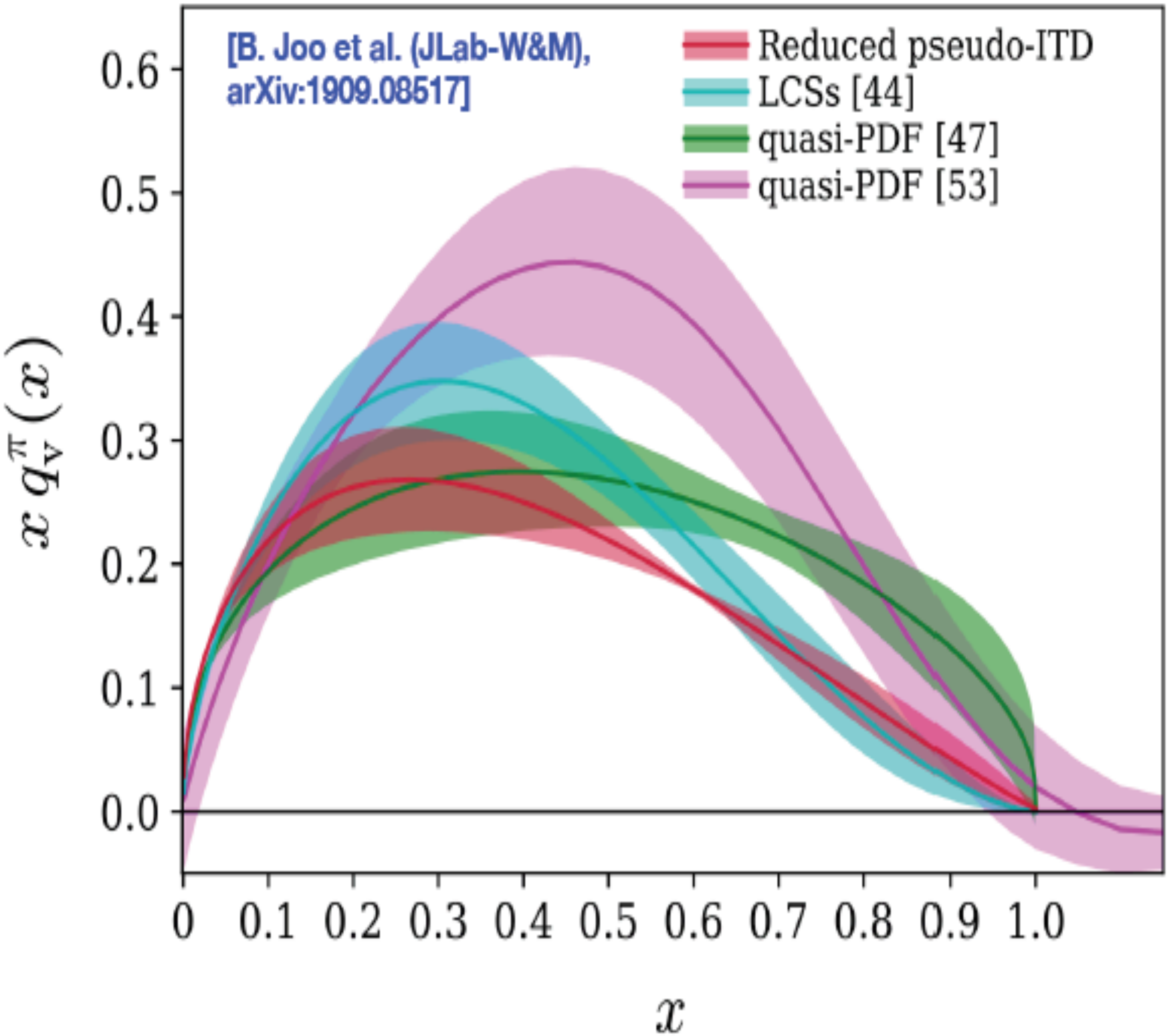
$m_\pi = 310\,\mathrm{MeV}$, $P = 1.74\,\mathrm{GeV}$

[T. Izubuchi et al. (BNL-SBU-UConn), Phys. Rev. D 100, 034516 (2019)]



$m_\pi = 300\,\mathrm{MeV}$, $P = 1.29\,\mathrm{GeV}$

Lattice QCD calculated pion distribution



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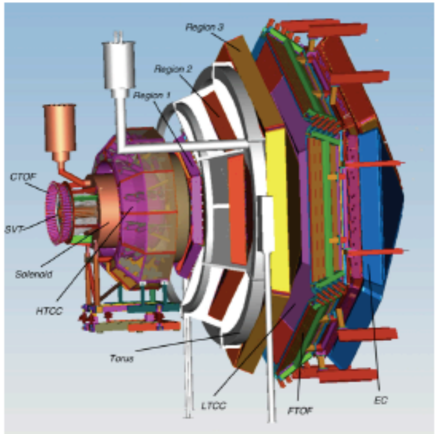
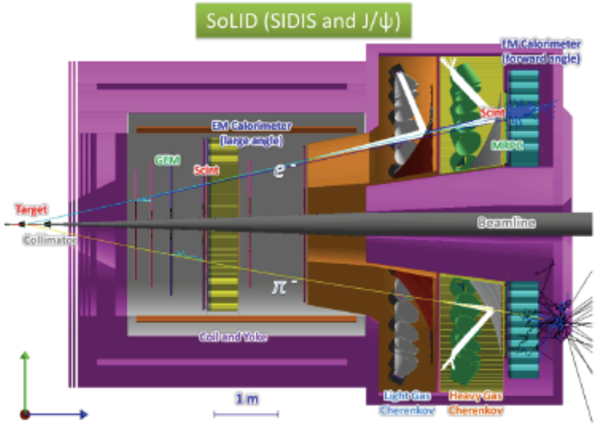
From JLab12 to EIC:



Lattice QCD



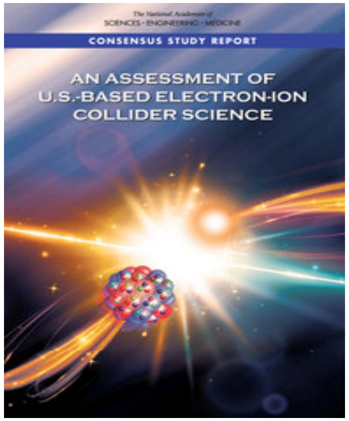
DVCS

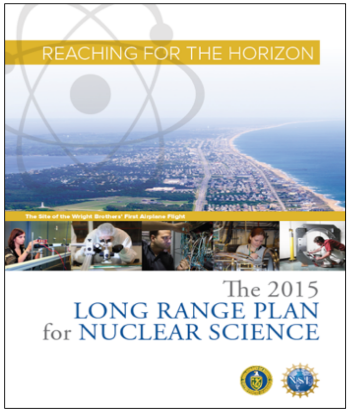
SIDIS

Imaging the Quarks

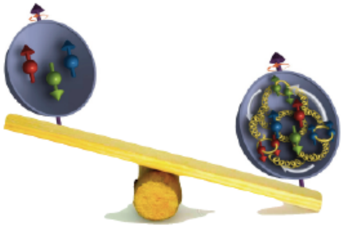
Electron-Ion Collider

Imaging the Gluons





Understand the glue that binds us all: The Next QCD Frontier in Nuclear Physics



CENTER for NUCLEAR FEMTOGRAPHY

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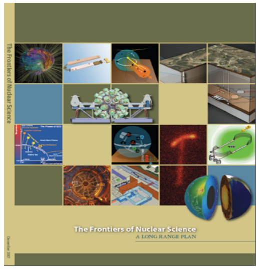
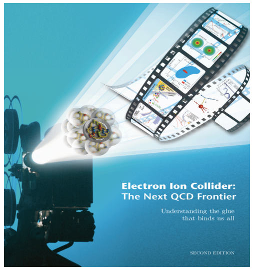
The future for Strong QCD

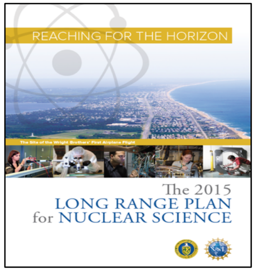
❑ **Electron-Ion Collider: the best future facility for Strong QCD:**

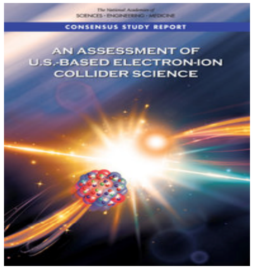
See talk by Milner

…









…

"… answer science questions that are compelling, fundamental, and timely, and help maintain U.S. scientific leadership in nuclear physics."

… three profound questions:

How does the mass of the nucleon arise?
How does the spin of the nucleon arise?
What are the emergent properties of dense systems of gluons?

Explore the emergent phenomena of QCD – the Strong QCD!
Starting at JLab12, …

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What EIC can do, but, HERA & other colliders cannot do?

- **Why is so special about the Lepton-Hadron Collider?**

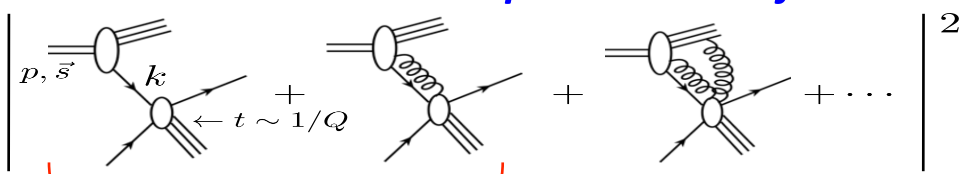
  Hit the proton with a well-controlled hard probe without breaking it!

- **Quantum imaging:**
  - ✧ **HERA discovered: 15% of e-p events is diffractive – Proton not broken!**
  - ✧ **US-EIC: 100-1000 times luminosity – *Critical for 3D tomography!***

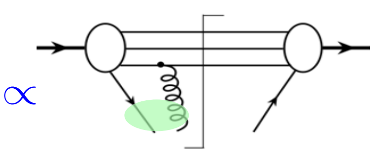
- **Quantum interference & entanglement – dual role of hadron spin:**
  - ✧ **US-EIC: Highly polarized beams – *Origin of hadron property: Spin, …***

    Direct access to chromo-quantum interference!

$\sigma(Q, \vec{s}) \propto$



$\sigma(s) - \sigma(-s)$ ➡ **Quantum interference** ➡ $T^{(3)}(x, x) \propto$



- **Nonlinear quantum dynamics – dual role of nuclei:**
  - ✧ **US-EIC: Light-to-heavy nuclear beams – *Origin of nuclear force, …***

    Catch the transition from chromo-quantum fluctuation

    to chromo-condensate of gluons, …

    Emergence of hadrons (femtometer size detector!),

    – "a new controllable knob" – Atomic weight of nuclei

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Summary and outlook

- QCD at the Fermi-Scale is the most interesting, rich, and complex, but mysterious and challenging regime of the theory

- QCD needs the lepton-hadron facility:
  - Theory advances – controlled two-scale observables
  - Lattice QCD is now able to meet with phenomenology
  - Technology and Facility advances – JLab 12 to EIC
  - New emergent science – Nuclear femtography

Also facilities from other countries

- EIC is a ultimate QCD machine, could study major Nuclear Science issues that other existing facilities, even with upgrades, cannot do

- US-EIC is sitting at a sweet spot for the rich QCD dynamics
  – capable of exploring the science of nuclear femtography!

- It is a new era for the Strong QCD – QCD at the Fermi-Scale

Thanks!

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