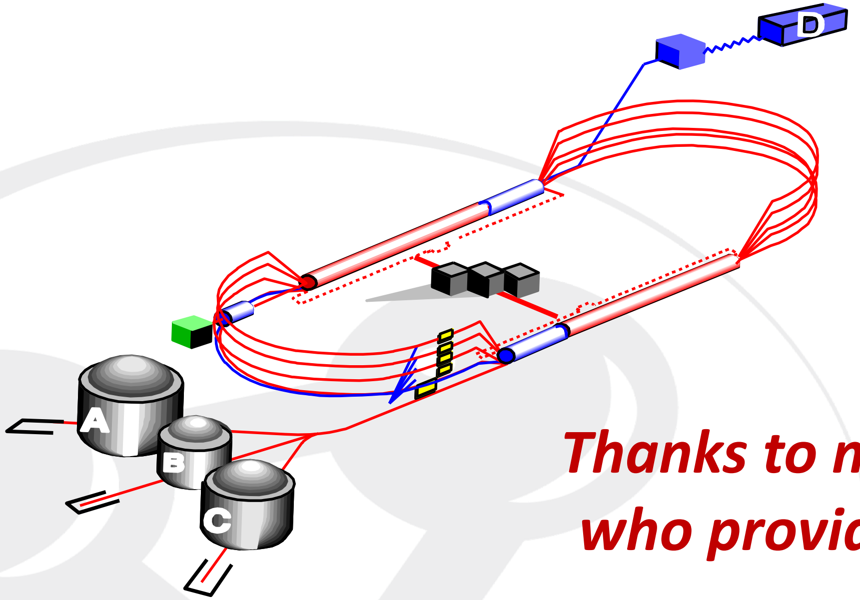
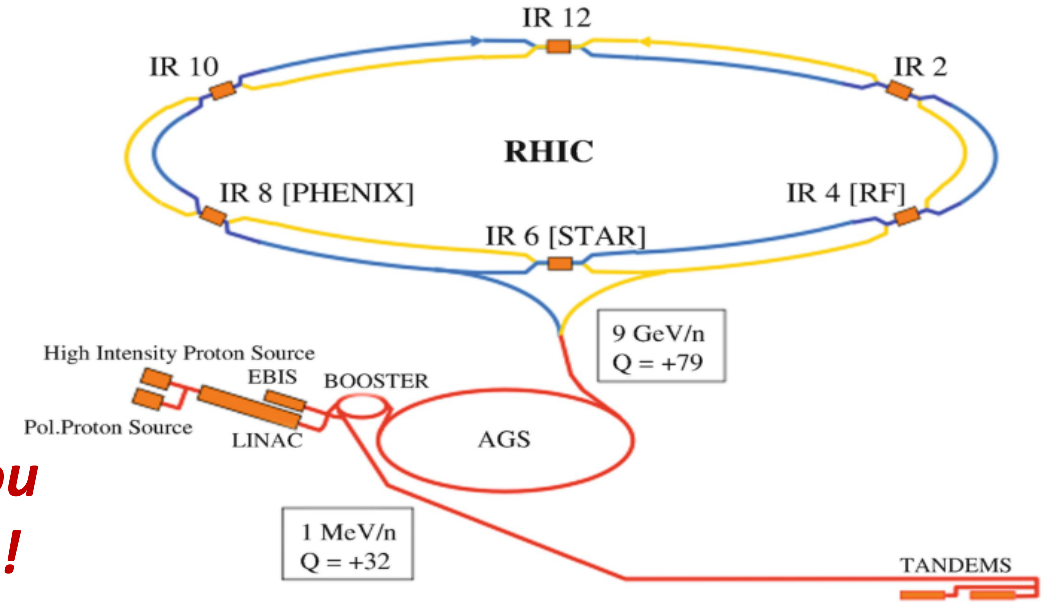
Cold QCD at JLab and RHIC: Theory Advances

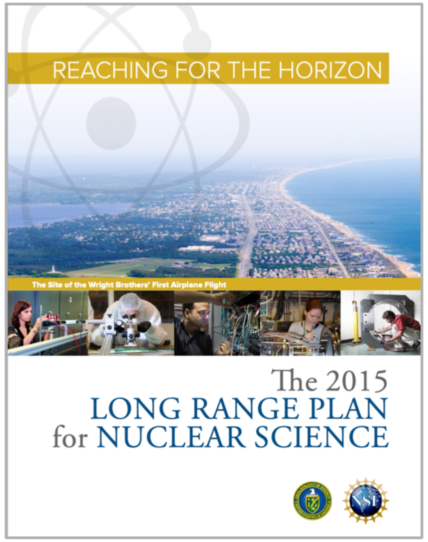




Thanks to many of you who provided inputs!

Jianwei Qiu
Jefferson Lab, Theory Center

Since the 2015 LRP, …



THE SCIENCE QUESTIONS

1. How did visible matter come into being and how does it evolve?
2. How does subatomic matter organize itself and what phenomena emerge?
3. Are the fundamental interactions that are basic to the structure of matter fully understood?
4. How can the knowledge and technical progress provided by nuclear physics best be used to benefit society?"

– 2015 Long Range Plan

For QCD community,

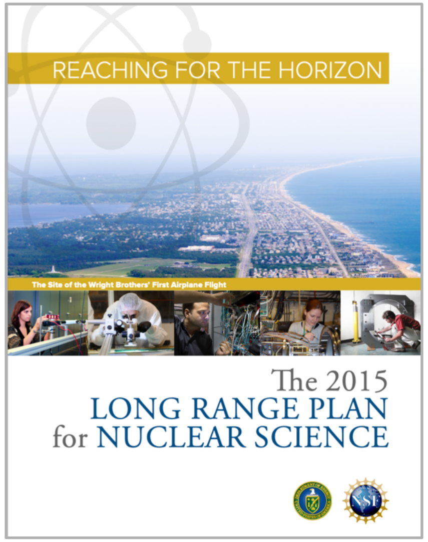
Existing facility:

RHIC & CEBAF in the U.S.

Future facility:

Electron-Ion Collider

Since the 2015 LRP, …



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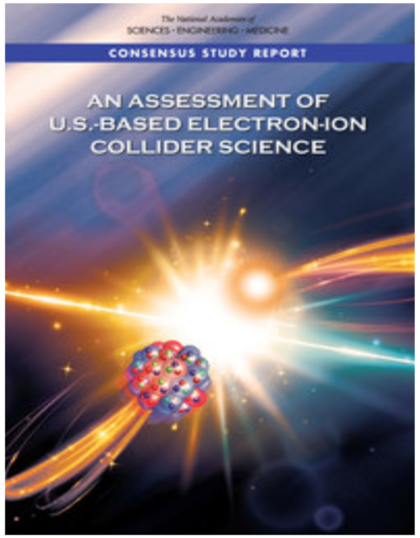
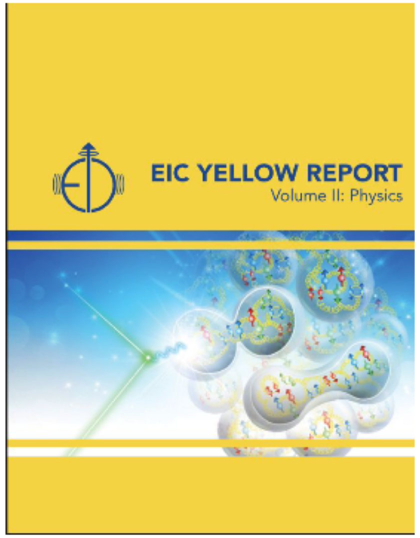
NAS Report:



EIC Yellow Report:



For QCD community,

Existing facility:

RHIC & CEBAF in the U.S.

Future facility:

Electron-Ion Collider

See many EIC talks so-far at this Town Hall meeting

NAS Report:

"… 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?

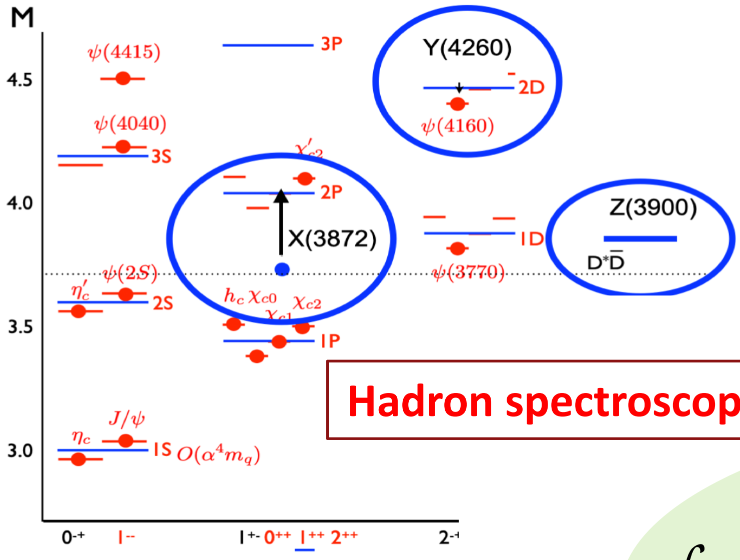
We believe we have the right Theory, …

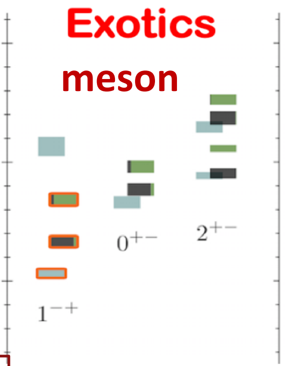
A theory of quarks & gluons

$$\mathcal{L}_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[(i\partial_\mu \delta_{ij} - gA_{\mu,a}(t_a)_{ij})\gamma^\mu - m_f \delta_{ij}\right] \psi_j^f - \frac{1}{4}\left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - gC_{abc}A_{\mu,b}A_{\nu,c}\right]^2$$

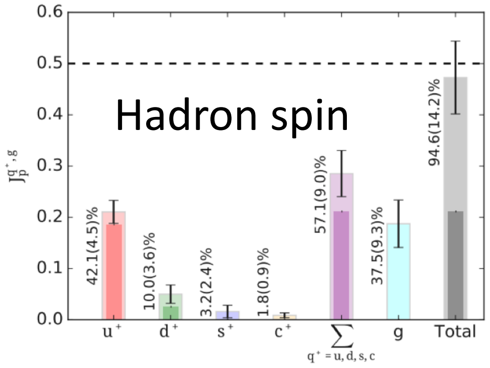
But, we saw none of them directly

We believe we have the right Theory, …





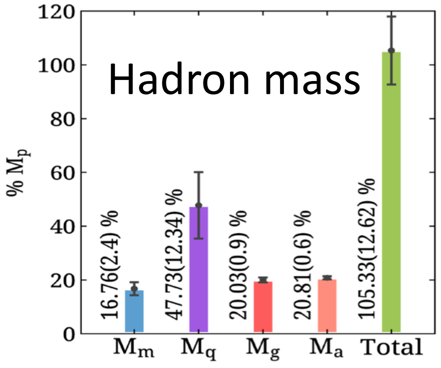
Hadron spectroscopy



$$\int_{0.01}^{1} dx\, \Delta\Sigma(x,Q^2) = 0.43 \pm 0.08$$

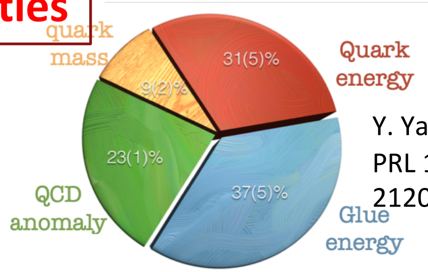
$$\int_{0.01}^{1} dx\, \Delta g(x,Q^2) = 0.3 \pm 0.1$$

@ 10 GeV²



C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

Hadron Properties



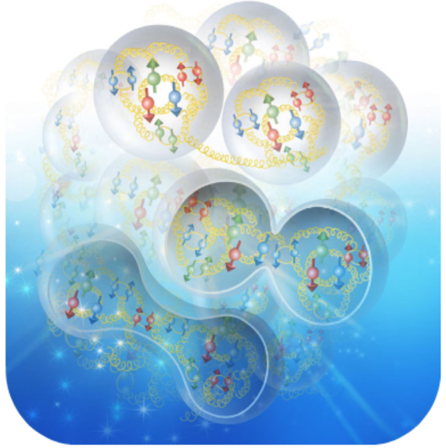
Y. Yang et al.
PRL 121, 212001

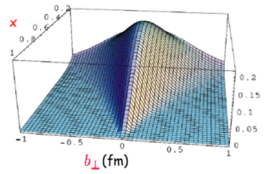
A theory of quarks & gluons

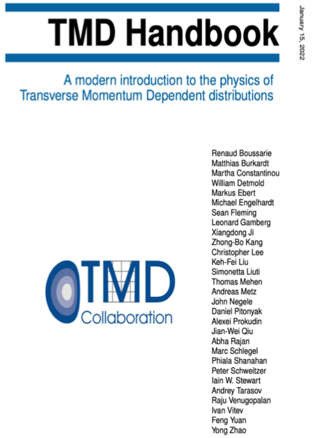
$$\mathcal{L}_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[(i\partial_\mu \delta_{ij} - g A_{\mu,a}(t_a)_{ij})\gamma^\mu - m_f \delta_{ij} \right] \psi_j^f - \frac{1}{4}\left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - g C_{abc} A_{\mu,b} A_{\nu,c}\right]^2$$

But, we saw none of them directly

Nuclear structure in the most fundamental way?



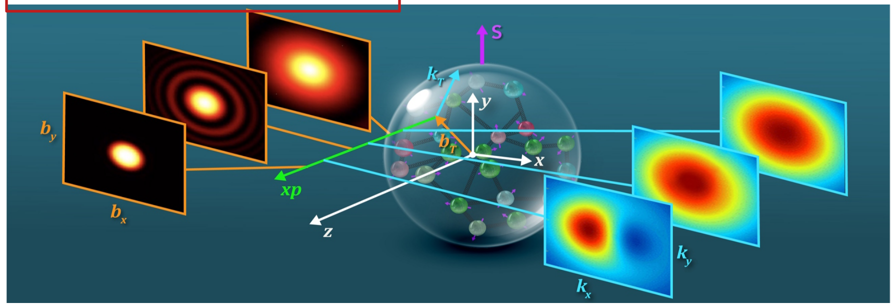




Q:
What a nucleus looks like if we only see quarks and gluons?

Q:
Does the color of nucleon "A" know the color of nucleon "B"?

Hadron structure



Need Theory to match what measured to what is happening!!!

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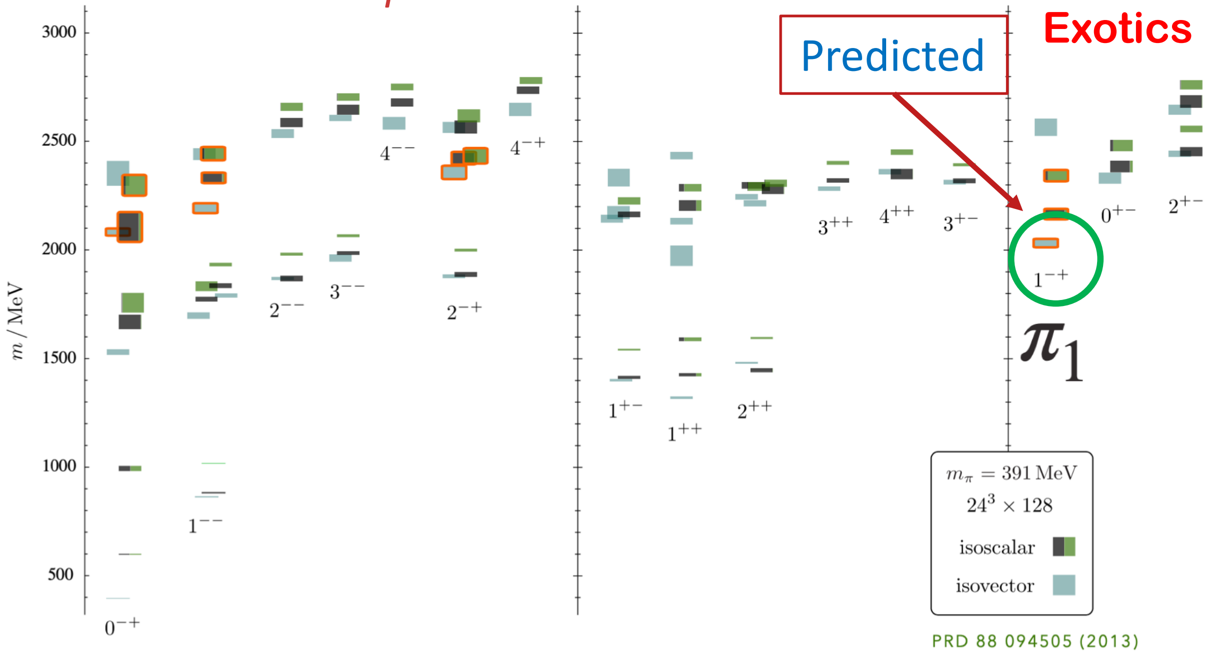
Modern way to study hadron spectroscopy

❑ Robust connection between real experiment & QCD

See J. Dudek's talk

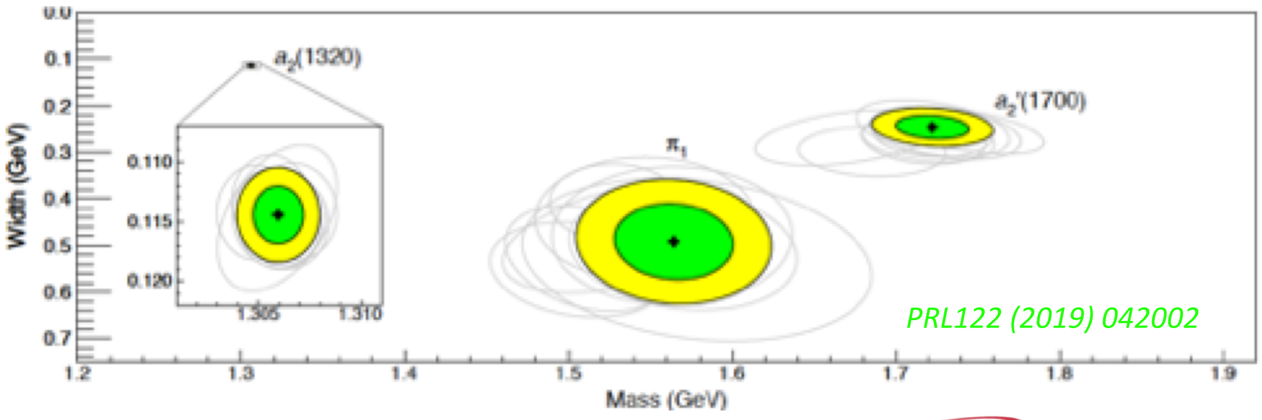
The lightest exotic hybrid meson

hadspec



PRD 88 094505 (2013)

JPAC analysis of COMPASS data resolve the puzzle between apparent "two" π_1 and the predicted "one" π_1



PRL122 (2019) 042002

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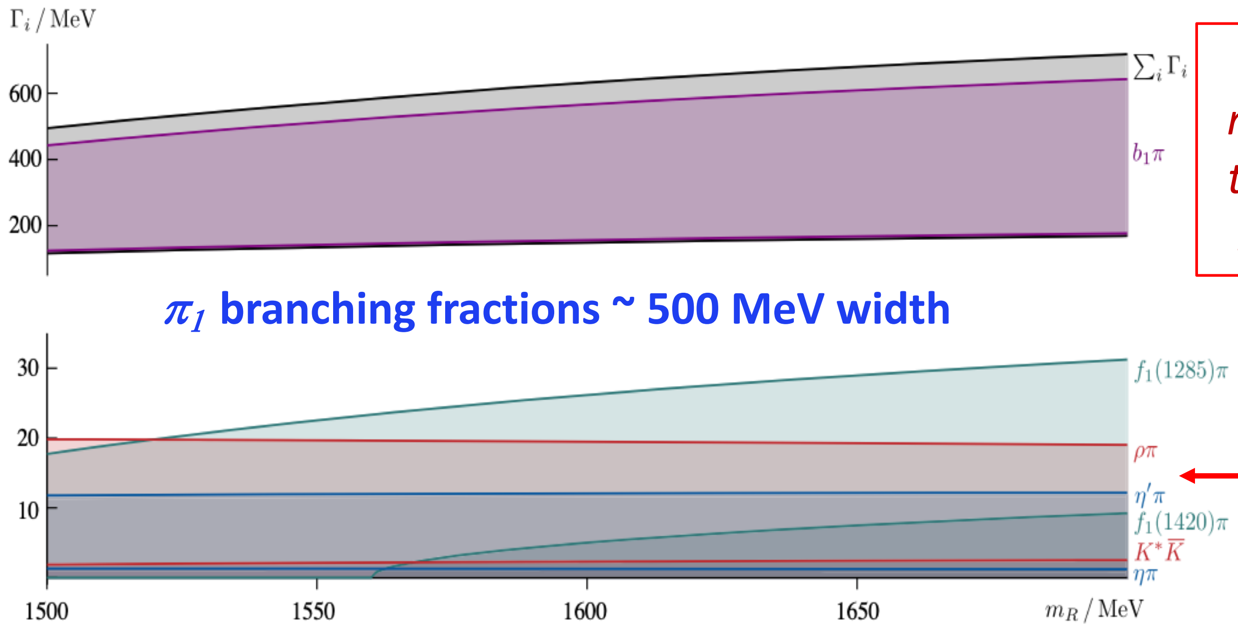
Searching for the exotics, …

❑ The lightest exotic hybrid mesons were predicted – where to find them?

First prediction for exotic π_1 full decay width from LQCD:



Exotic π_1 pole mass

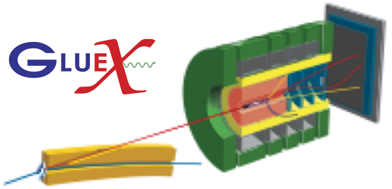
$b_1\pi$ width much larger than model suggested!

GlueX searching here

PHYSICAL REVIEW D **103,** 054502 (2021)

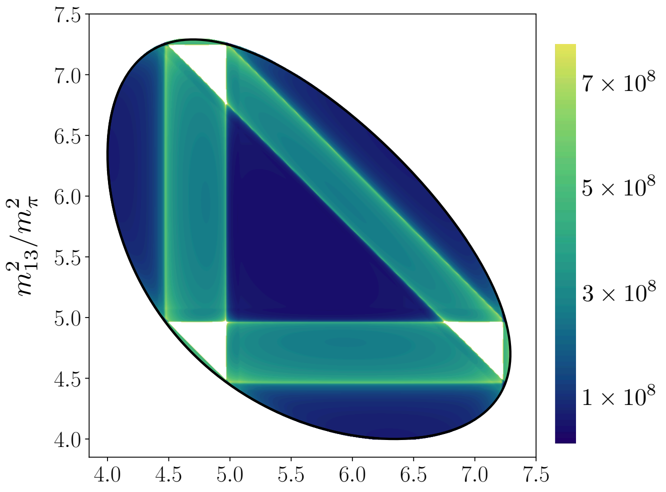
Decays of an exotic 1^{-+} hybrid meson resonance in QCD

Hadron Spectrum Collaboration



The first LQCD calculation of Dalitz plots (3-body decay)

Beyond two-particle decay



π–π–π amplitudes (Dalitz plot)

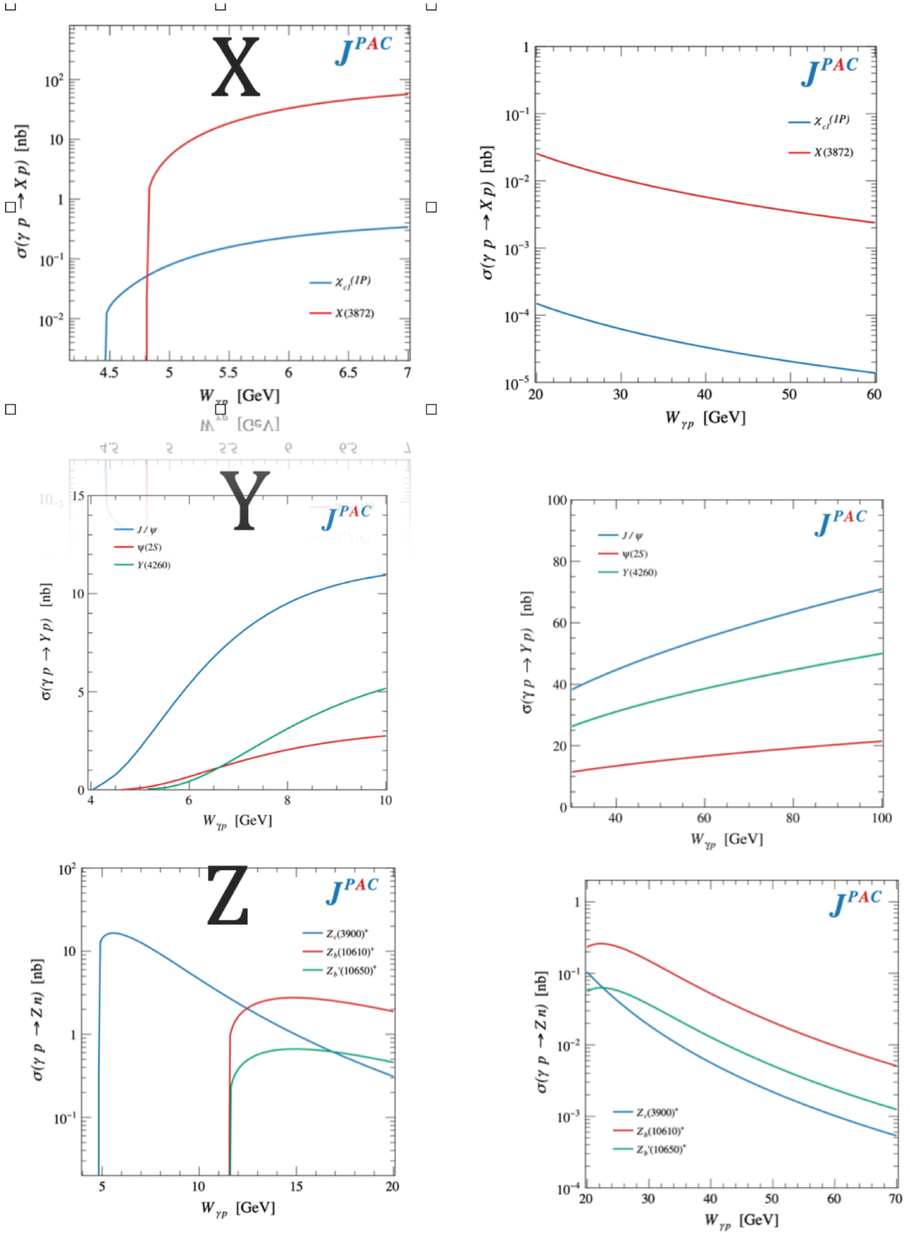
Hadron Spectrum Collaboration

Phys. Rev. Lett. 126 (2021) 012001

see Constantinou's talk for k-k-k plot

Jefferson Lab

XYZ explosion – renewed motivation on spectroscopy



A. Szcepaniak @ Theory pre-town hall

EIC/JLab++ explore the complementarity of diffraction, peripheral and/or direct production

XYZ yields – Compatible with e+e- @ 10^{34}

- X,Z production benefits form low CM energies
- Luminosity too low at 28 GeV
- Current simulations for 41 GeV configuration
  Luminosity assumed

Meson	Cross Section (nb)	Production rate (per day)	Decay Branch	Branch Ratio (%)	Events (per day)
$\chi_{c1}(3872)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	5	6.1 k
$Y(4260)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	1	1.2 k
$Z_c(3900)$	0.3	0.26 M	$J/\Psi\ \pi^+$	10	1.6 k
$X(6900)$	0.015	0.013 M	$J/\Psi\ J/\Psi$	100	46
$Z_{cs}(4000)$	0.23	0.20 M	$J/\Psi\ K^+$	10	1.2 k
$Z_b(10610)$	0.04	0.034 M	$\Upsilon(2S)\ \pi^+$	3.6	24

	17 GeV		24 GeV	
	produced	detected	produced	detected
$Z_c(3900)^+$	2.2 k	371	4.2 k	588
$X(3872)$	1.1 k	32	4.2 k	63

Comparable yields at the EIC or at a possible upgraded CLAS24

Emergent hadron properties: mass, spin, …

- **Mass – beyond lattice QCD – INT Workshop INT-20r-77:**

See S. Joosten's talk

"Origin of the Visible Universe: Unraveling the Proton Mass", June 13-17, 2022

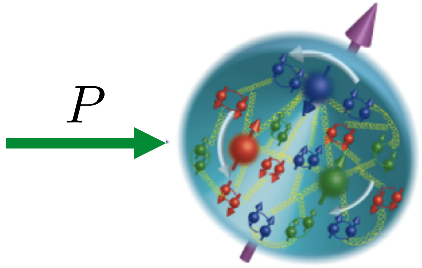
By I. Cloet, Z.E. Meziiani, B. Pasquini

Multi-pronged theory approach to explore the origin of nucleon mass:

- **Mass decomposition – roles of the constituents – but, not unique!**
  - **Matching individual terms to physical observables with controllable approximations – Factorization!**
- **Lattice QCD – calculations of individual terms**
- **Approximated analytical approach – model calculation, holographic light-front approach, …**

- **Decomposition of the trace of EMT:**

$$T^{\alpha}_{\ \alpha} = \underbrace{\frac{\beta(g)}{2g} F^{\mu\nu,a} F^{a}_{\mu\nu}}_{\text{QCD trace anomaly}} + \sum_{q=u,d,s} \underbrace{m_q (1+\gamma_m) \overline{\psi}_q \psi_q}_{\text{Chiral symmetry breaking}}$$



$$\beta(g) = -(11 - 2n_f/3)\, g^3/(4\pi)^2 + \ldots$$

Nucleon mass: ***Gluon quantum effect + Chiral symmetry breaking!***

The sigma-term can be calculated in LQCD, Need the trace anomaly to test the sum rule!

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Emergent hadron properties: mass, spin, …

- **Decompositions of "energy in the rest frame":** $M_n = \sum_{f=q,g} \frac{\langle P|T_f^{00}(0)|P\rangle}{2P^0}\Big|_{\text{cm}}$ ***Not unique!***

  - **Decomposition by Ji:**

See talk by M. Constantinou

$$T_a^{00} = \underbrace{\bar{T}_a^{00}}_{=\frac{3}{4}T_a^{00} + \frac{1}{4}\sum_i T_a^{ii}} + \underbrace{\hat{T}_a^{00}}_{=\frac{1}{4}T_a^{00} - \frac{1}{4}\sum_i T_a^{ii}} \qquad a = q, g$$

Quark Energy $\langle \bar{T}_q^{00}\rangle$ Gloun Energy $\langle \bar{T}_g^{00}\rangle$ Quark Mass $\langle \hat{T}_q^{00}\rangle$

$$M_n = \sum_{f=q,g} \frac{\langle P|T_f^{00}(0)|P\rangle}{2P^0}\Big|_{\text{cm}} = M_q + M_g + M_m + M_a$$

Trace Anomaly $\langle \hat{T}_g^{00}\rangle$

  - **Decomposition by Metz et al:**

Different interpretation!

$$M = \underbrace{\left[\langle \textstyle\int d^3r\, \bar{\psi}\gamma^0 iD^0\psi\rangle - \langle \textstyle\int d^3r\, \bar{\psi}m\psi\rangle\right]}_{\text{Quark kinetic and potential energy}} + \underbrace{\langle \textstyle\int d^3r\, \bar{\psi}m\psi\rangle}_{\text{Quark rest mass energy}} + \underbrace{\langle \textstyle\int d^3r\, \tfrac{1}{2}(\vec{E}^2 + \vec{B}^2)\rangle}_{\text{Gluon total energy}}$$

Understanding the trace anomaly is important for its own right!

Emergent hadron properties: mass, spin, …

❑ The first LQCD calculation:

F. He, P. Sun, Y. Yang
PRL 104 (2021)074507

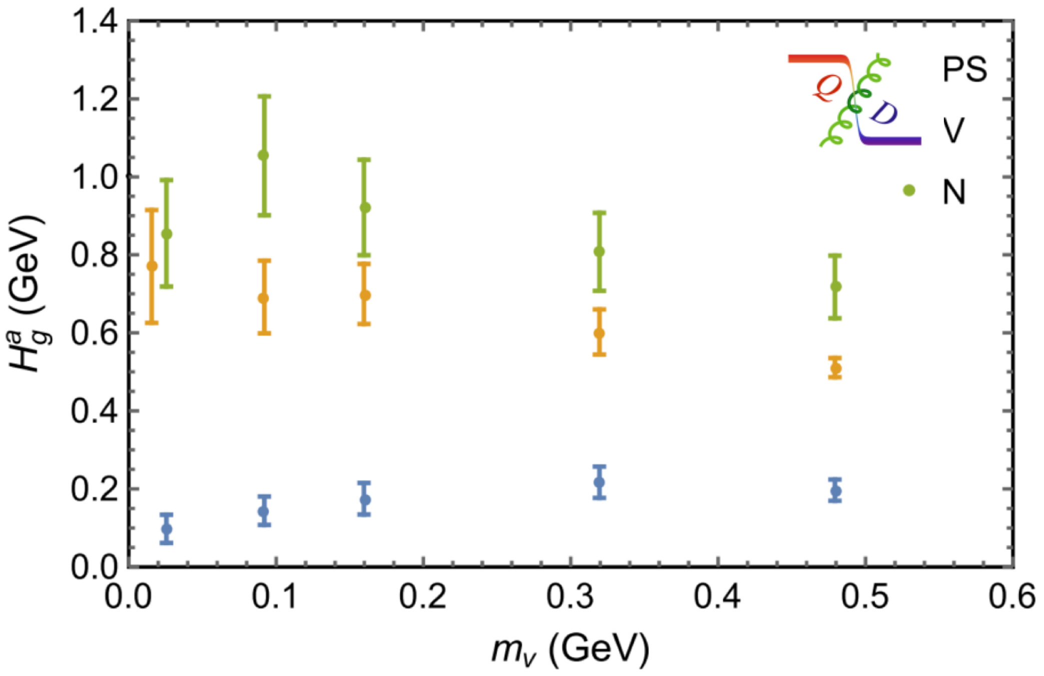
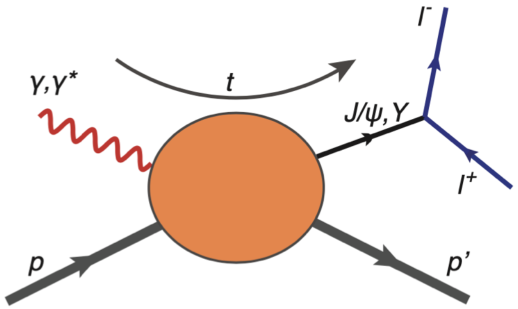


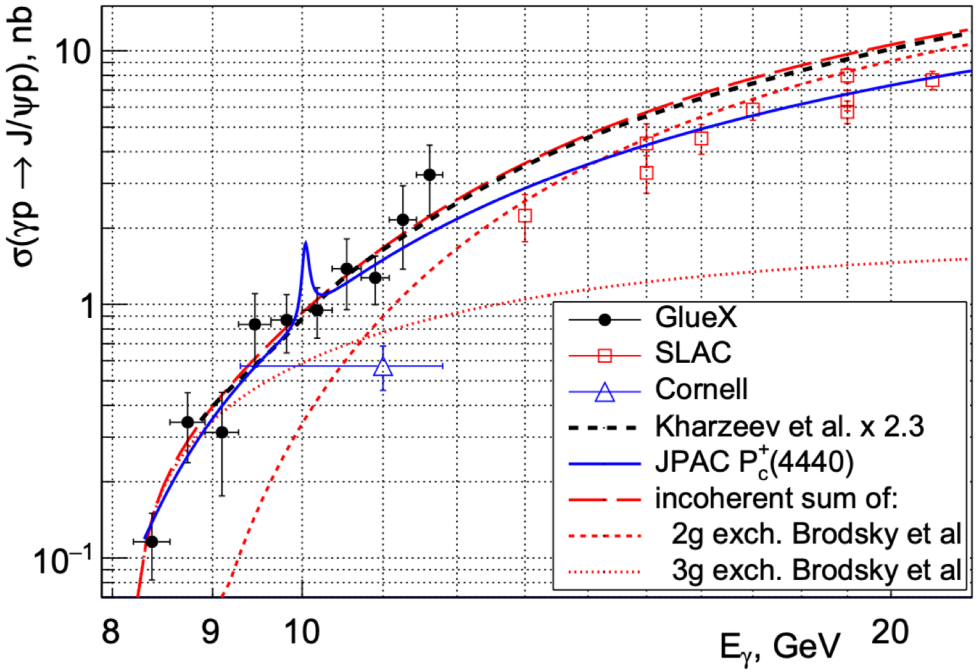
FIG. 3. The gluon trace anomaly contribution to the hadron mass. For five different quark masses, the corresponding pion masses are 0.340, 0.647, 0.864, 1.277, and 1.640 GeV. We can see that it is always small for the PS meson, while it approaches ~800 MeV for the nucleon and vector mesons in the chiral limit $m_v \to 0$.

(χQCD Collaboration)

❑ The first J/ψ near-threshold measurement:



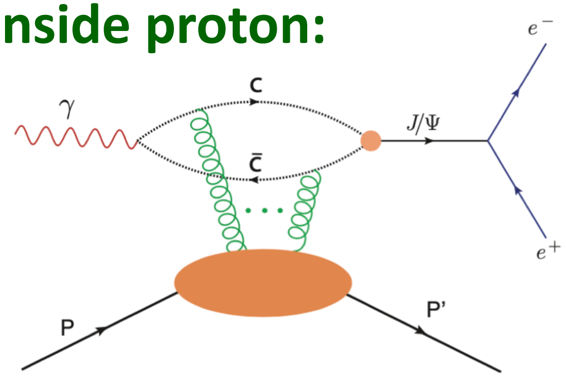
A. Ali, GlueX,
Phys.Rev.Lett.123, 072001



Emergent hadron properties: mass, spin, …

Mass distribution inside proton:

D. Kharzeev, Phys.Rev. D105 (2021) 054032



$$\mathcal{M}_{\gamma P\to\psi P}(t) =$$

$$\frac{d\sigma_{\gamma P\to\psi P}}{dt} = \frac{1}{64\pi s}\frac{1}{|\mathbf{p}_{\gamma cm}|^2}|\mathcal{M}_{\gamma P\to\psi P}(t)|^2$$

- Scattering amplitude of threshold photoproduction is approximated to be proportional the scalar gravitational formfactor: G(t)
- Mass radius: $\langle R_\mathrm{M}^2\rangle = \frac{6}{M}\frac{dG}{dt}\Big|_{t=0}$
- GlueX data fits a dipole formfactor $G(t) = \frac{M}{(1-t/M_s^2)^2}$

$R_\mathrm{m} \equiv \sqrt{\langle R_\mathrm{m}^2\rangle} = 0.55 \pm 0.03$ fm proton mass radius

< $\bar{\mathrm{R}}_\mathrm{c} \equiv \sqrt{R_c^2} = 0.8409 \pm 0.0004$ fm proton charge radius

Gravitational form factors = moments of GPDs *Come back later!*

Pressures and energy density inside a pion:

- Pion nearly massless—requires **light front** description.
- Densities by 2D Fourier transforms:

$$T^{ij}_{\mathrm{pure}}(\mathbf{b}_\perp) = \int\frac{\mathrm{d}^2\mathbf{\Delta}_\perp}{(2\pi)^2}\frac{\mathbf{\Delta}^i_\perp\mathbf{\Delta}^j_\perp - \delta^{ij}\mathbf{\Delta}^2_\perp}{2}D(-\mathbf{\Delta}^2_\perp)e^{-i\mathbf{\Delta}_\perp\cdot\mathbf{b}_\perp}$$

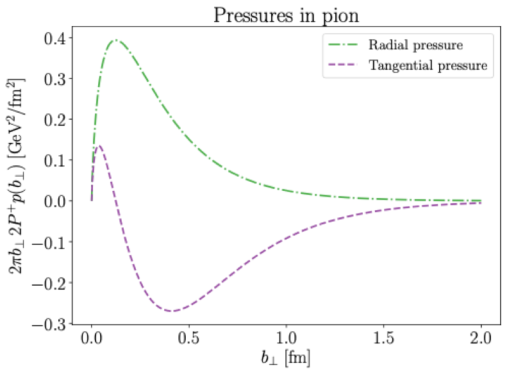
$$\mathcal{E}(\mathbf{b}_\perp) = \int\frac{\mathrm{d}^2\mathbf{\Delta}_\perp}{(2\pi)^2}\left(m_\pi^2 - \frac{\mathbf{\Delta}^2_\perp}{4}\right)A(-\mathbf{\Delta}^2_\perp)e^{-i\mathbf{\Delta}_\perp\cdot\mathbf{b}_\perp} - \delta_{ij}T^{ij}_{\mathrm{pure}}(\mathbf{b}_\perp)$$

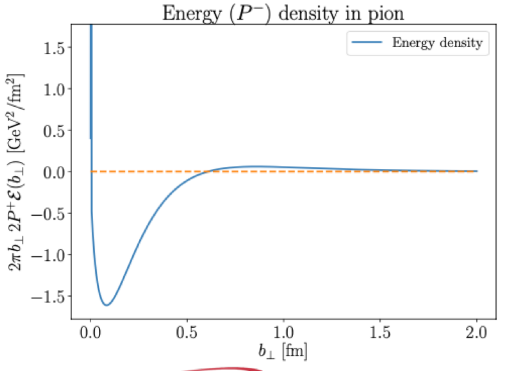
Upcoming work (Freese & Miller) for more info!

- Phenomenological form factors:

$$A(t) = \frac{1}{1-t/m_{f_2}^2} \qquad m_{f_2} = 1270\ \mathrm{MeV}$$

$$D(t) = \frac{-1}{(1-t/m_{f_2}^2)(1-t/m_\sigma^2)} \qquad m_\sigma = 630\ \mathrm{MeV}$$





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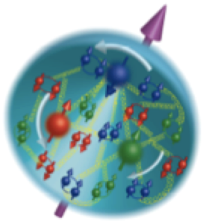
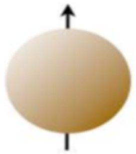
Emergent hadron properties: mass, spin, …

❑ Proton's Spin:

Spin is the Angular Momentum of the proton when it is at the Rest!



Spin = Spin of quarks and gluons + Orbital Angular Momentum



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Jaffe, Manohar, 1990
Ji, 1996

- **Enormous progress on helicity PDFs has been made over past ~ decade:**

$$\int_{0.01}^{1} dx\, \Delta\Sigma(x, Q^2) = 0.43 \pm 0.08 \qquad \int_{0.01}^{1} dx\, \Delta g(x, Q^2) = 0.3 \pm 0.1$$

@ 10 GeV^2 See talk by W. Vogelsang

- **Consistency among all phenomenological global fits:**

$$\int_{0.05}^{1} dx \Delta G(x, Q^2 = 10\text{GeV}^2) = 0.20^{+.06}_{-.07}$$ DSSV

$$\int_{0.05}^{0.2} dx \Delta G(x, Q^2 = 10\text{GeV}^2) = 0.17 \pm 0.06$$ NNPDF

$$\int_{0.05}^{1} dx \Delta G(x, Q^2 = 10\text{GeV}^2) = 0.23 \pm 0.03$$ JAM

See talk by Y. Hatta

Total angular momentum $J_{q,g}(Q)$ = moments of GPDs

Would not have been achieved without the RHIC spin program!

But, it is still an incomplete story – more opportunity!

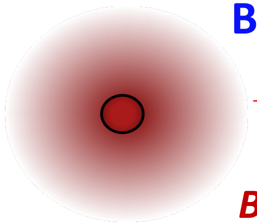
Small x region – EIC + Theory advances

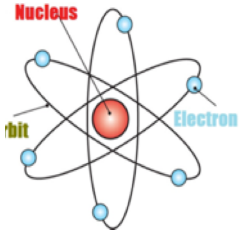
See talk by Y. Kovchegov

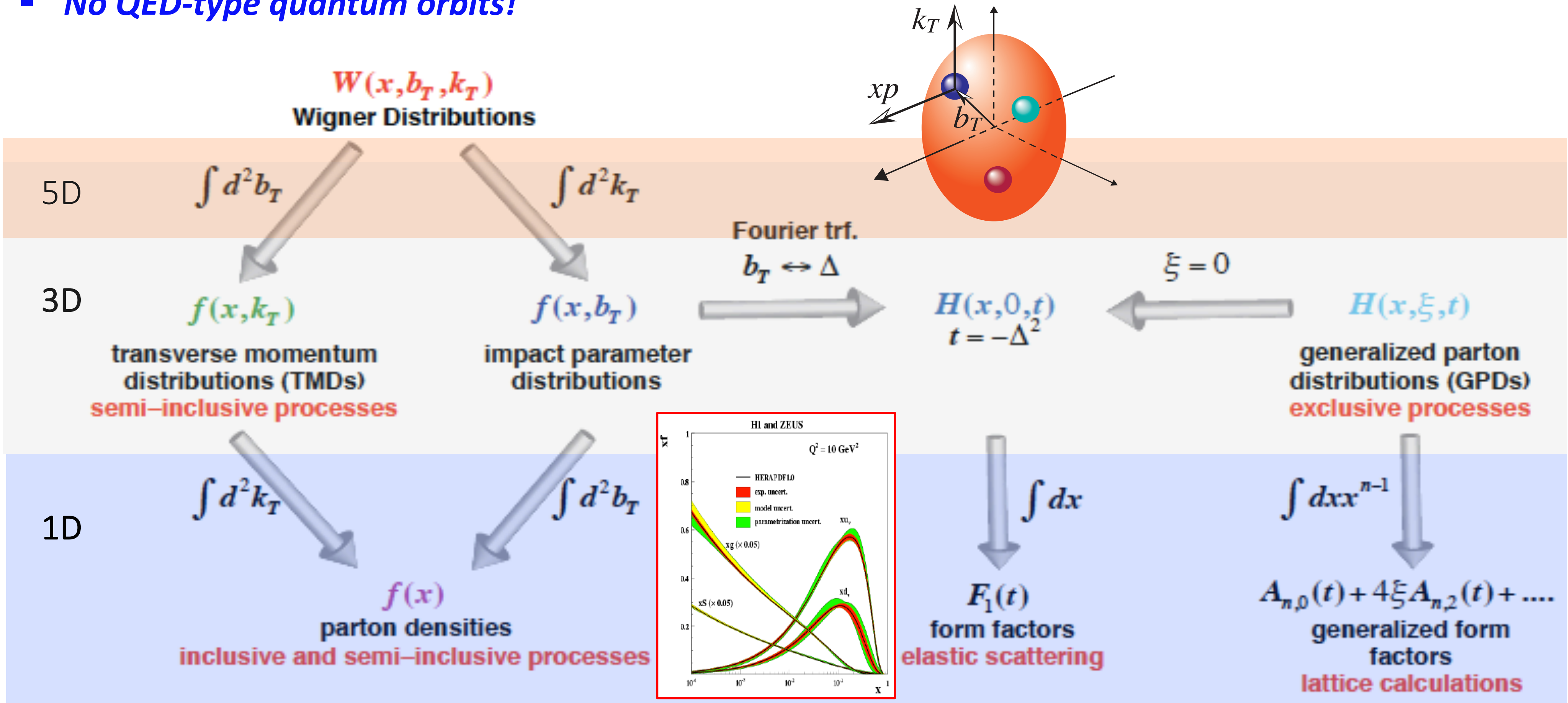
➡ **Parton transverse motion & Partonic structure!**

Hadron structure and internal landscape, …

- **Hadrons are not static, rather, dynamics bound states of quarks and gluons:**
  - *Quarks and gluons are moving relativisticaly, color is fully entangled!*
  - *Partonic structure = "Quantum correlations functions":* $\langle P,S|\mathcal{O}(\overline{\psi},\psi,A^\mu)|P,S\rangle$
  - *No QED-type quantum orbits!*

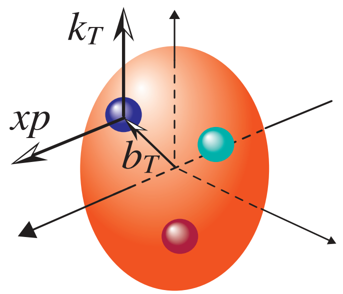


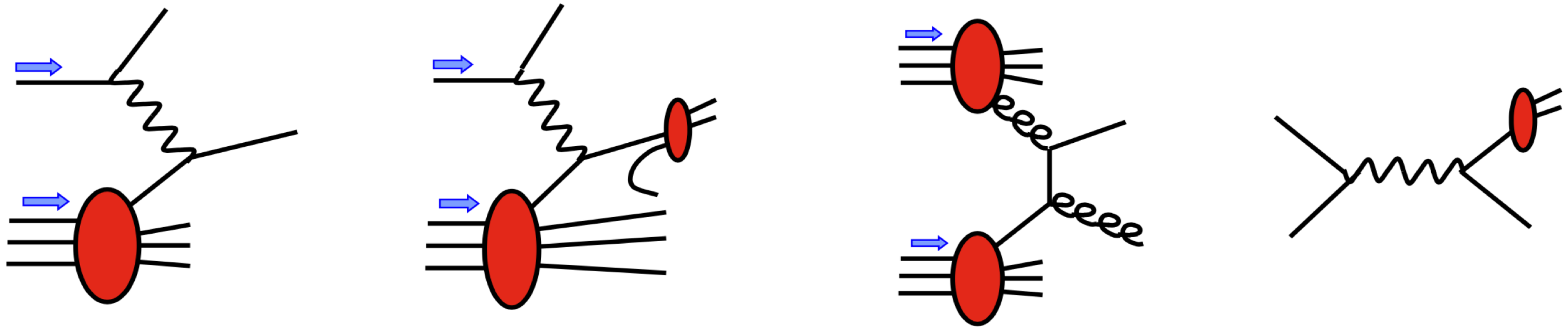




Hadron structure and internal landscape, …

- **1D hadron structure (flavor, momentum, helicity, …):**
  - **Single hard collision** with a momentum transfer >> 1/fm
  - Integrate over d^2k_T or d^2b_T ➡ Parton distribution functions (PDFs) – initial-state
    Fragmentation functions (FFs) – final state

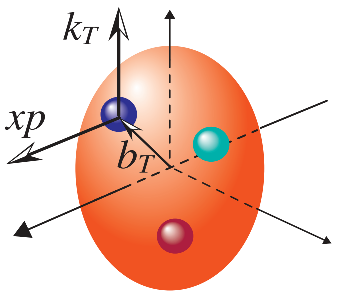




Jefferson Lab

Hadron structure and internal landscape, …

❑ 1D hadron structure (flavor, momentum, helicity, …):



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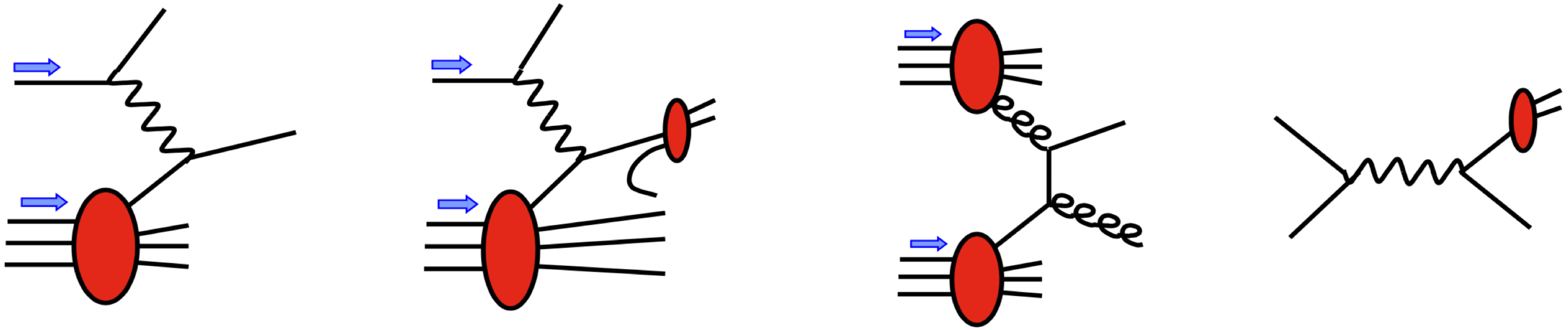


❑ QCD global analysis:

Jefferson Lab, KEK, CERN, BROOKHAVEN NATIONAL LABORATORY, Fermilab

Experimental data

} $= \int \cdots \int$ **Factorization Theory**

PQCD Calculation ⊗ PDFs, FFs Unknown ➡ **To extract PDFs, FFs From limited data**

Matching hadrons to partons

Very difficult inverse problem!

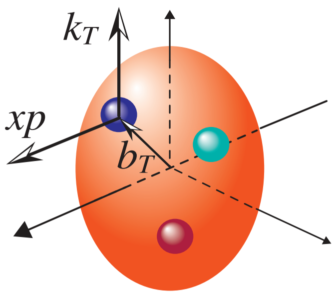
See talks by N. Sato & W. Vogelsang

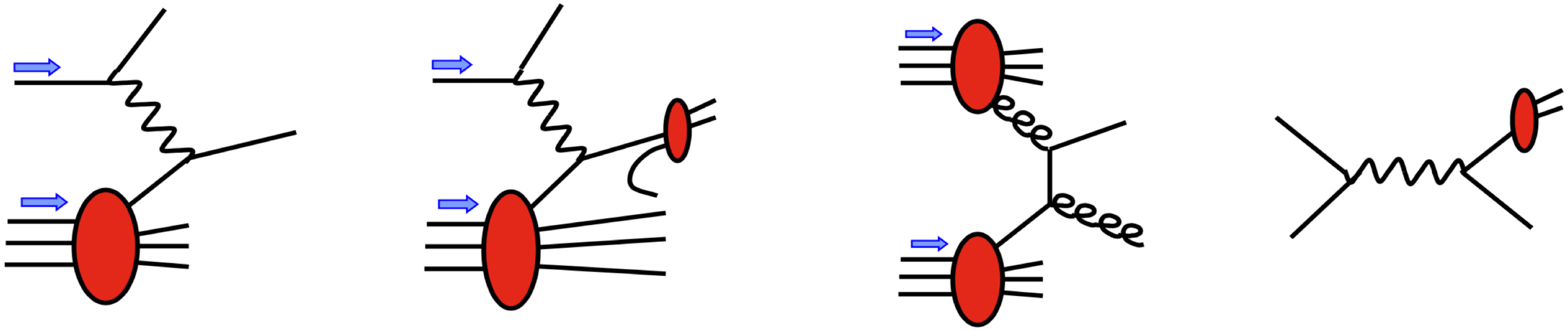
Hadron structure and internal landscape, …

❑ 1D hadron structure (flavor, momentum, helicity, …):

- **Single hard collision with a momentum transfer >> 1/fm**
- **Integrate over d^2k_T or d^2b_T ➡ Parton distribution functions (PDFs) – initial-state**

  Fragmentation functions (FFs) – final state



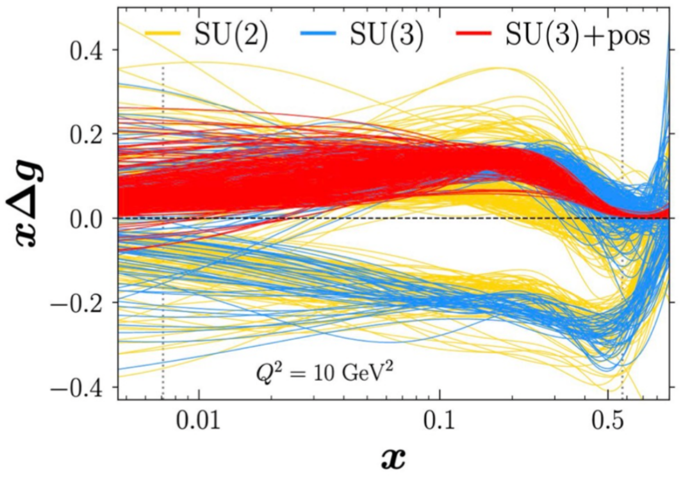


❑ Challenges to QCD global analysis:

Limited observables, limited data, …

If measured A_{LL} is dominated by data sensitive to $\Delta G(x_1) \otimes \Delta G(x_2)$,

➡ Sign of $\Delta G(x)$?



Solutions:

- New observables,
- Better kinematic reach,
- LQCD – single hadron matrix element,

…. Model calculation, …

See talk by Y. Zhao

Hadron structure and internal landscape from LQCD, …

❑ LQCD cannot calculate x-dependent PDFs directly!

Ji, arXiv:1305.1539

- **A great idea from Xiangdong Ji – Calculate matrix elements at "equal-time" in LQCD**

$$\text{“}\sigma^{\text{LQCD}}(\nu,\xi^2,\mu_R^2)\text{”} \equiv \frac{\langle h(p)|\overline{\psi}_q(\xi)\gamma^\nu\Phi(\{\xi,0\})\psi(0)|h(p)\rangle}{Z_{RS}(\xi^2,\mu_R^2)}$$

Calculable in LQCD!

- **Large momentum effective theory (LaMET) approach – Quasi-PDFs:**

$$\widetilde{q}(\widetilde{x},\mu_R^2) = \int \frac{d\nu}{2\pi}\, e^{i\widetilde{x}\nu}\, \text{“}\sigma^{\text{LQCD}}(\nu,\xi^2,\mu_R^2)\text{”}$$
$$= \int \frac{dx}{x}\, f_{q_v/h}(x,\mu^2)\, C_{RS}(x/\widetilde{x},\mu_R^2,\mu^2) + \mathcal{O}(1/xp_z) + \ldots \qquad \nu = p_z\,\xi_z$$

Power correction, not universal!

$$\widetilde{x}\, p_z\, \xi_z \sim \mathcal{O}(1)$$

- **"Short-distance" factorization approach – Pseudo-PDFs, …**

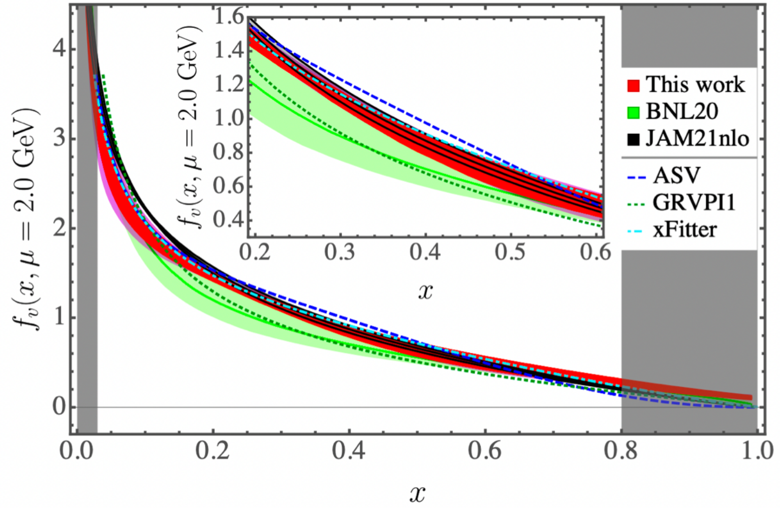
$$\text{“}\sigma^{\text{LQCD}}(\nu,\xi^2,\mu_R^2)\text{”} \equiv \frac{\langle h(p)|\overline{\psi}_q(\xi)\gamma^\nu\Phi(\{\xi,0\})\psi(0)|h(p)\rangle}{Z_{RS}(\xi^2,\mu_R^2)} = \int_{-1}^{1} \frac{dx}{x}\, f_{q_v/h}(x,\mu^2) \otimes K_{RS}^{\nu}(x\nu,\xi^2,\mu^2) + \mathcal{O}(z^2)$$

- **Great progresses have been made since last LRP, not limited by parton-parton correlators!**
  - **– matching to NNLO!**
  - **– Idea extended far beyond 1D PDFs!**

See talks by M. Constantinou & Y. Zhao

Hadron structure and internal landscape from LQCD, …

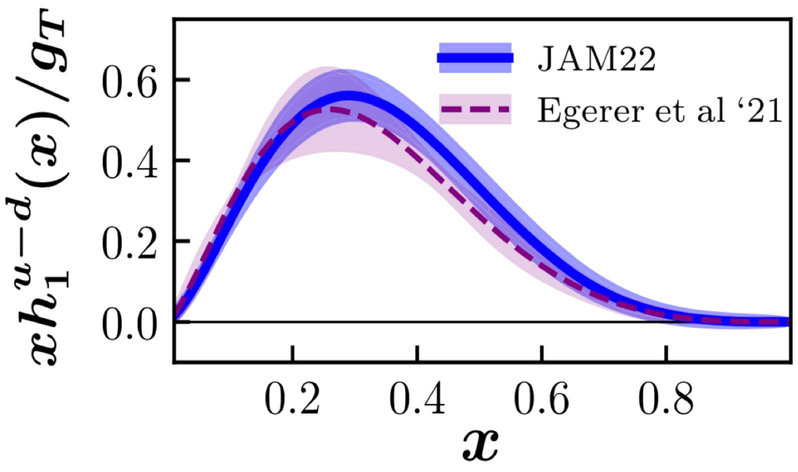
- **Structure of QCD Goldstone bosons:**



Yong Zhao et al., Phys. Rev. Lett. 128, 142003 (2022)

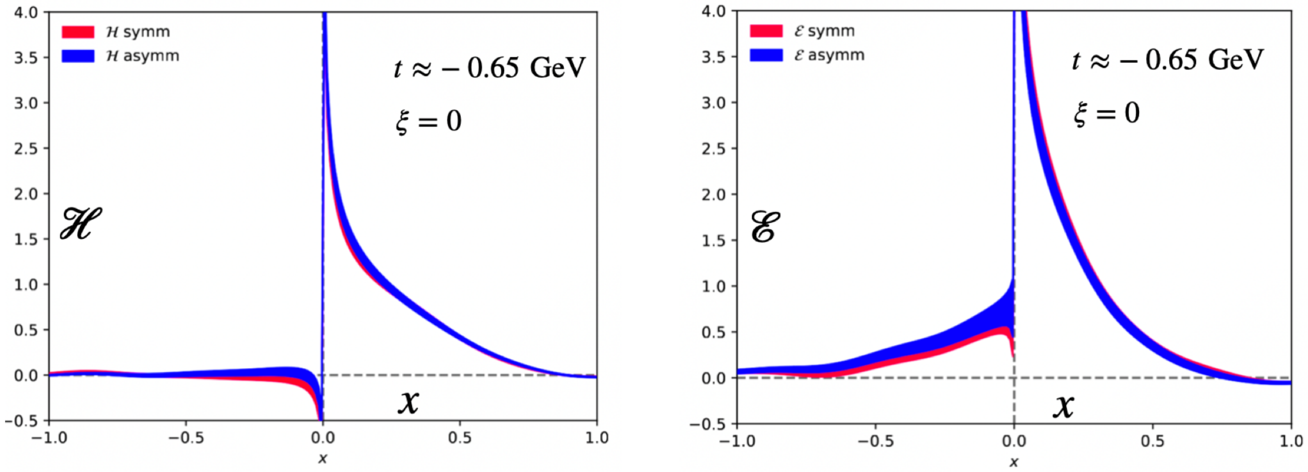
- **Transversity distribution:**

See talks by M. Constantinou & Y. Zhao



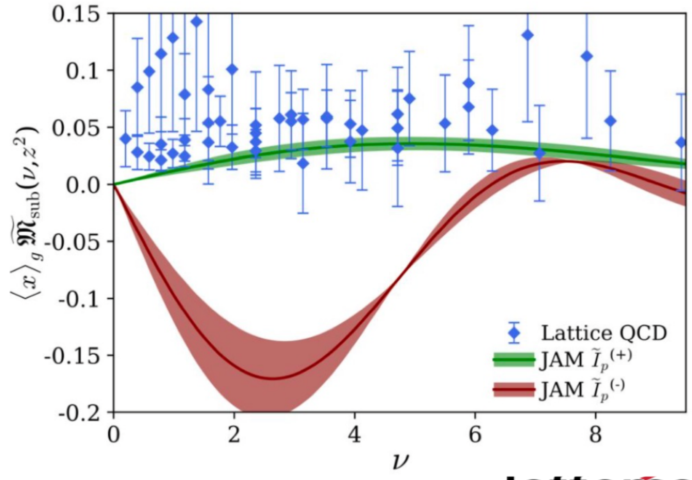
C. Egerer et al. (HadStruc), Phys.Rev.D **105**, 034507 (2022)

- **Beyond PDFs – GPDs:**



Bhattacharya, Constantinou, *et al.*, arXiv: 2209.05373

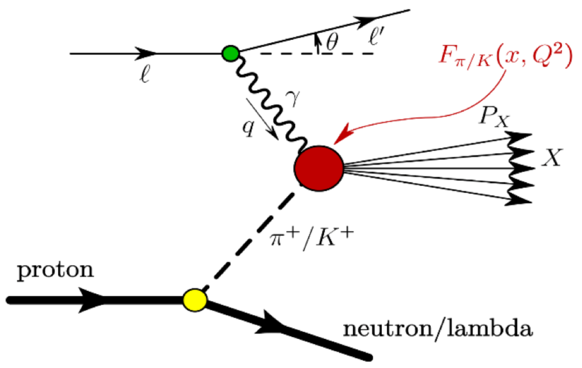
- **Help solve the $\Delta G(x)$ puzzle?**

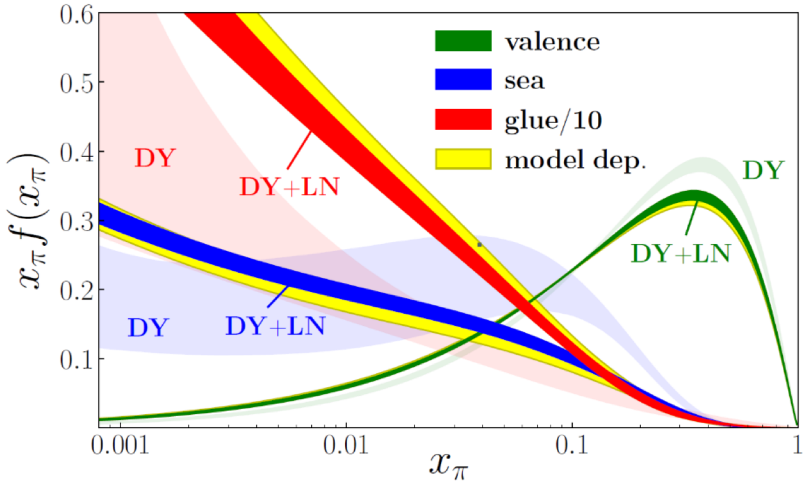


Hadron structure and internal landscape, …

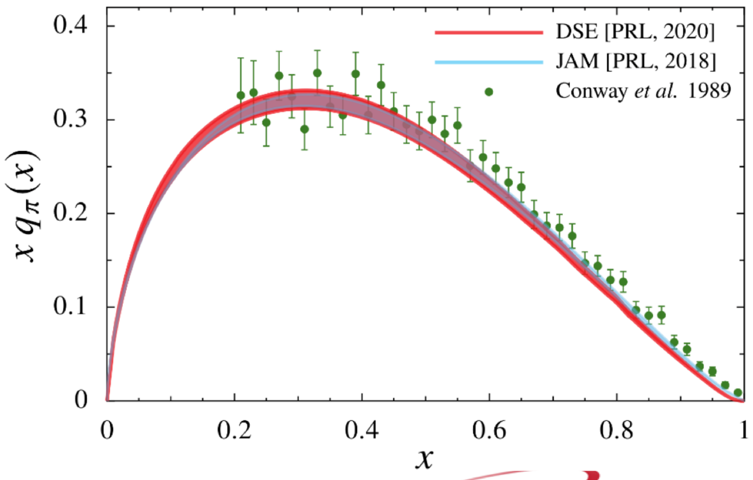
I. Cloet

- **Jefferson Lab/EIC provides access to partonic structure of pion & kaon via Sullivan process**
  - **Contrast with proton PDFs provides insights into QCD dynamics; strange quark in kaon sheds light on flavor breaking effects; and quark/gluon momentum fractions provide link to origin of hadron mass, etc.**
- **Long time interest in behavior of pion PDF as $x \longrightarrow 1$, that is, $q(x) \sim (1-x)^{\beta}$, where $1 \leq \beta \leq 2$**
- **Early partonic models predict $\beta \approx 2$** *[Farrar, Jackson (1975), Soper (1979), Berger, Brodsky (1979), Yuan (2004)]*
  - **Existing Drell-Yan (Fermilab, 1989) and leading neutron (HERA, 2010) data find $\beta \approx 1$, confirmed by JAM global analysis [PRL 2018], including with threshold resummation [PRL 2021] using preferred double Mellin method**
  - **Dyson-Schwinger calculation illustrates there may be no contradiction between previous expectations and experiment — $\beta \approx 2$ behavior sets in at extremely large x, otherwise good agreement with data and JAM analysis**
- **Important to revisit measurements of pion & kaon structure at Jefferson Lab and EIC**





Barry, Sato, *et al.* [JAM], PRL (2018)

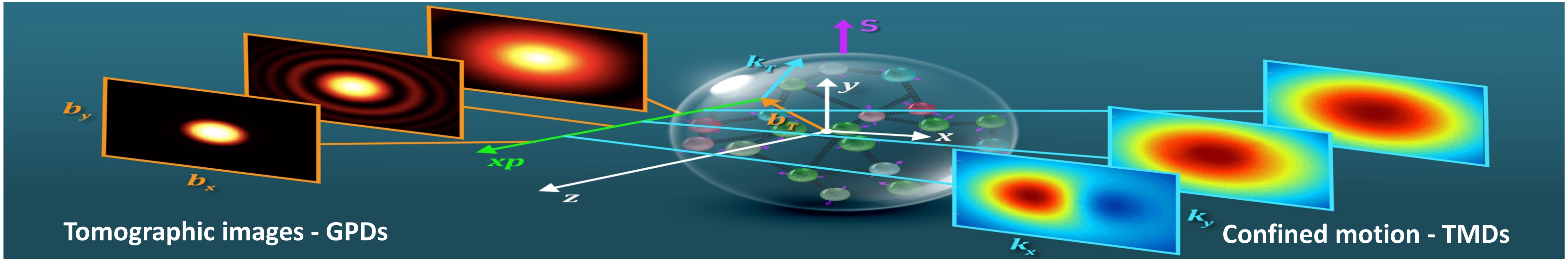


Jefferson Lab

Hadron structure and internal landscape, …

❑ 3D hadron structure:

NO quarks and gluons can be seen in isolation!



Hadron structure and internal landscape, …

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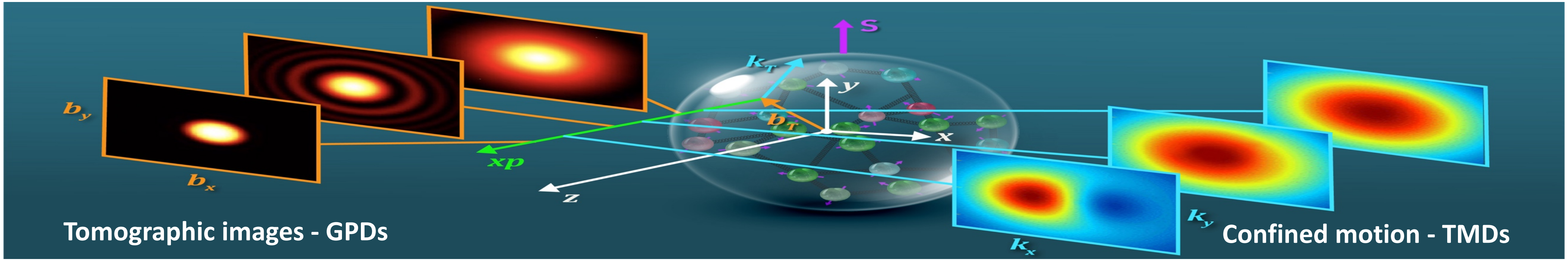
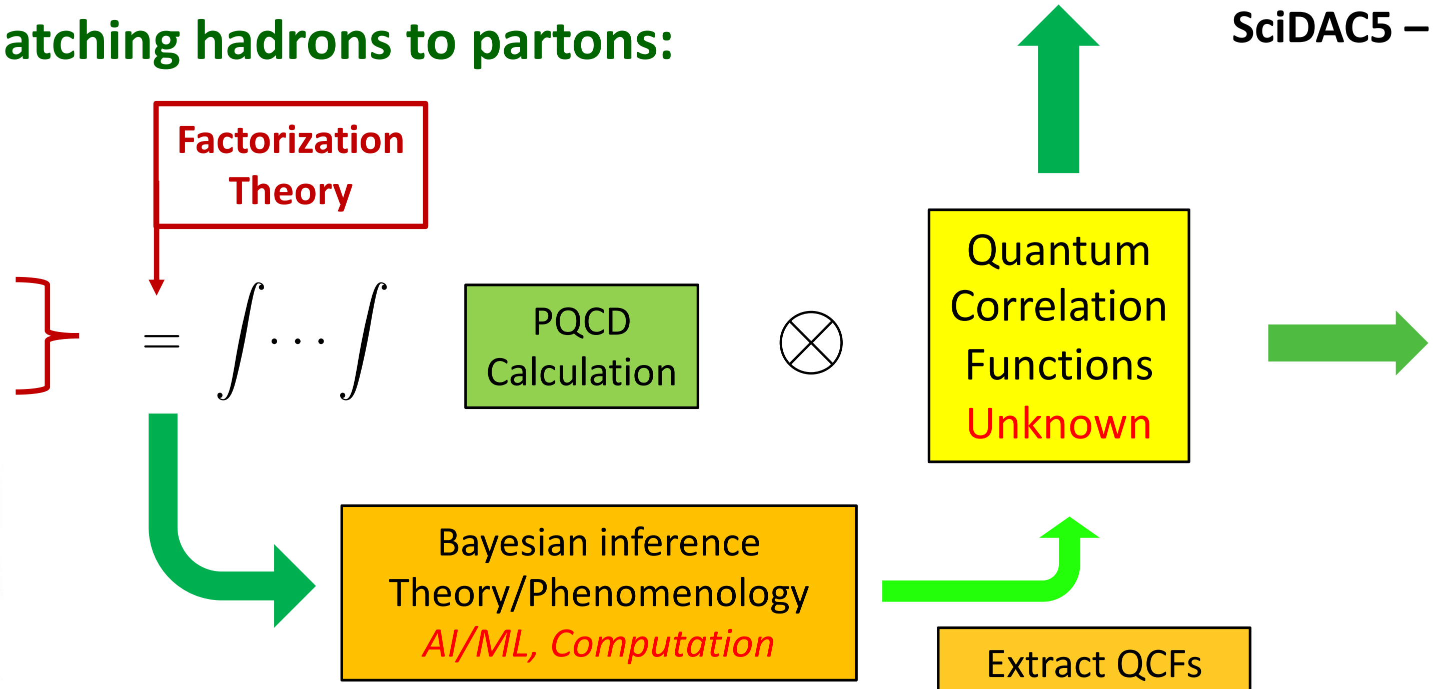
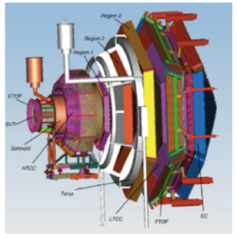
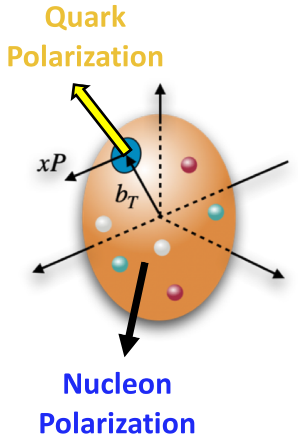


SciDAC5 – QuantOm Collab.

❑ QCD factorization – Matching hadrons to partons:



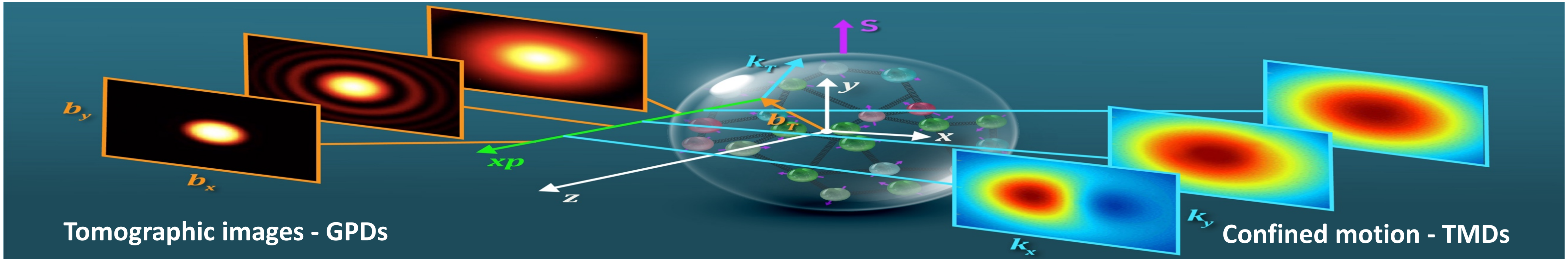




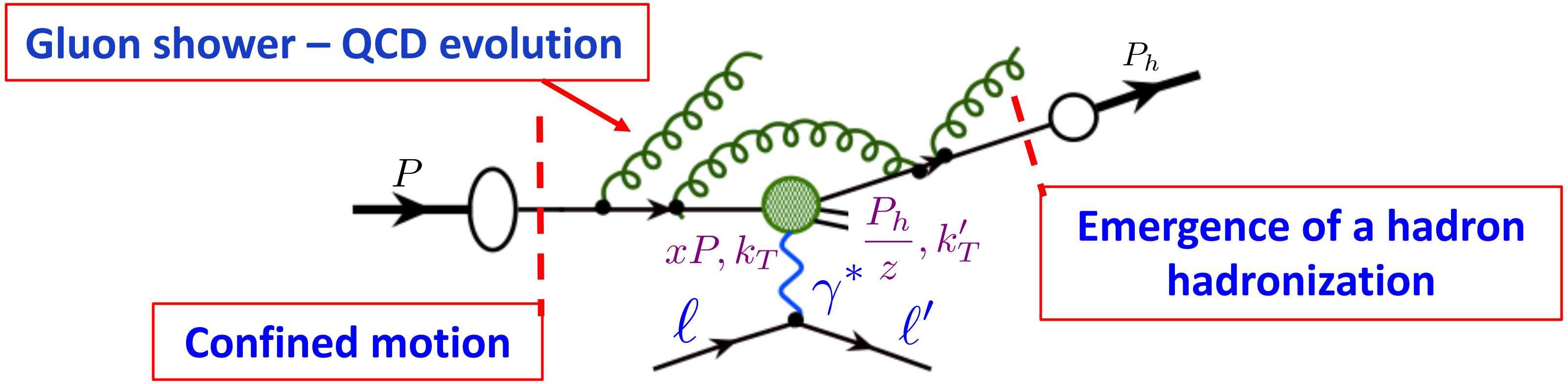
Hadron structure and internal landscape, …

- **3D hadron structure:**

NO quarks and gluons can be seen in isolation!



- **If the proton is broken, e.g., in SIDIS, …**



Transverse momentum broadening:

$$\Delta k_T^2 \propto \Lambda_{\rm QCD}^2 \times \alpha_s(C_F, C_A) \times \log(Q^2/\Lambda_{\rm QCD}^2) \times \log(s/Q^2) \quad \Big\} \gtrsim 1$$

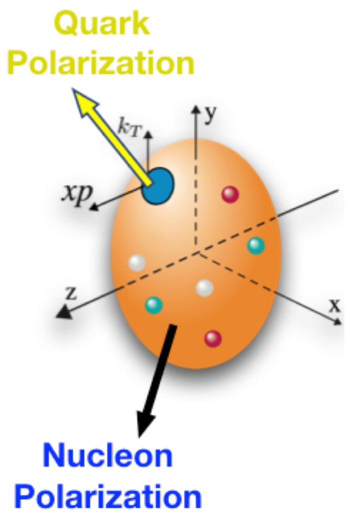
Structure information is diluted by the collision induced shower!

- *Measured k_T is NOT the same as k_T of the confined motion!*
- *Structure information vs. collision effects*

Transverse momentum dependent PDFs (TMDs)

❑ Quark TMDs with polarization:

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$		$h_1^\perp(x,k_T^2)$ - Boer-Mulders
	L		$g_1(x,k_T^2)$ - Helicity	$h_{1L}^\perp(x,k_T^2)$ - Long-Transversity
	T	$f_1^\perp(x,k_T^2)$ - Sivers	$g_{1T}(x,k_T^2)$ - Trans-Helicity	$h_1(x,k_T^2)$ - Transversity $h_{1T}^\perp(x,k_T^2)$ - Pretzelosity



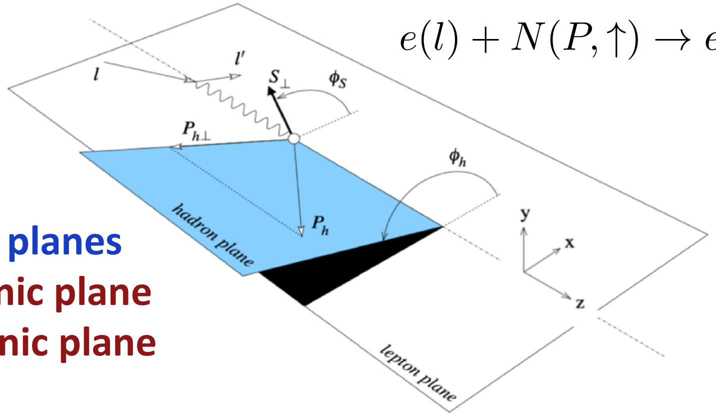
See talk by Z.B. Kang

Analogous tables for:

- Gluons $f_1 \to f_1^g$ etc
- Fragmentation functions
- Nuclear targets $S \neq \frac{1}{2}$

❑ Polarized SIDIS:

$$e(l) + N(P,\uparrow) \to e(l') + h(P_h) + X$$



Two planes
Leptonic plane
Hadronic plane

Single Transverse-Spin Asymmetry

$$A_{UT} = \frac{1}{P}\frac{\sigma_{lN(\uparrow)} - \sigma_{lN(\downarrow)}}{\sigma_{lN(\uparrow)} + \sigma_{lN(\downarrow)}}$$

In photon-hadron frame:

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

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

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

Angular modulation provides the best way to separate TMDs

Transverse momentum dependent PDFs (TMDs)

- **QCD factorization – Works for many observables at JLab, RHIC, EIC, …:**

See talk by Z.B. Kang
M. Constantinou, &
I. Stewart @ Theory
Pre-townhall

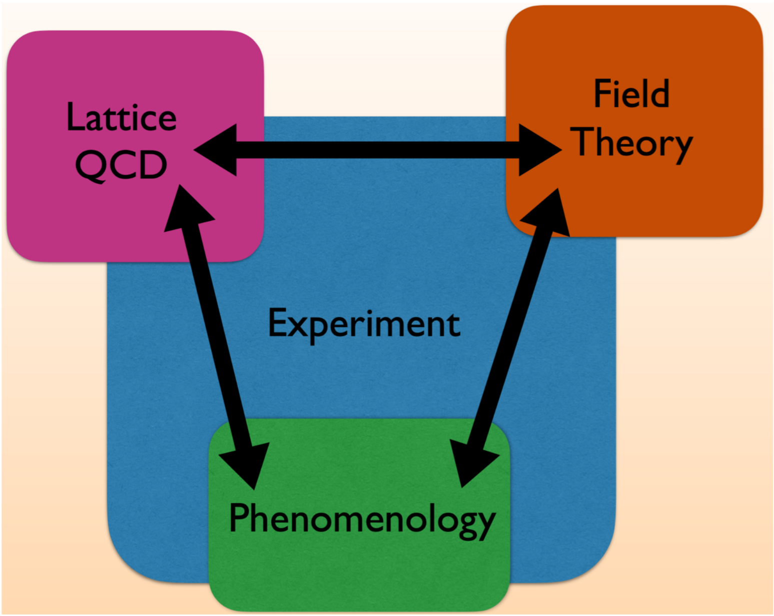
Unlike PDFs, TMD evolution is not purely perturbative!

$$f_q(x, \vec{b}_T, \mu, \zeta) = \exp\left[\int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'} \gamma_\mu^q(\mu', \zeta_0)\right] \exp\left[\frac{1}{2}\gamma_\zeta^q(\mu, b_T) \ln \frac{\zeta}{\zeta_0}\right] f_q(x, \vec{b}_T, \mu_0, \zeta_0)$$

CS kernel   Boundary condition

- **SCET or PQCD for perturbative evolution**

Accuracy	$H, \mathcal{J}$	$\Gamma_{\rm cusp}(\alpha_s)$	$\gamma_H^q(\alpha_s)$	$\gamma_r^q(\alpha_s)$	$\beta(\alpha_s)$
LL	Tree level	1-loop	–	–	1-loop
NLL	Tree level	2-loop	1-loop	1-loop	2-loop
NLL′	1-loop	2-loop	1-loop	1-loop	2-loop
NNLL	1-loop	3-loop	2-loop	2-loop	3-loop
NNLL′	2-loop	3-loop	2-loop	2-loop	3-loop
$\mathrm{N^3LL}$	2-loop	4-loop	3-loop	3-loop	4-loop
$\mathrm{N^3LL'}$	3-loop	4-loop	3-loop	3-loop	4-loop
$\mathrm{N^4LL}$	3-loop	5-loop	4-loop	4-loop	5-loop
$\mathrm{N^4LL'}$	4-loop	5-loop	4-loop	4-loop	5-loop



12 chapters
470 pages
(soon to be released)

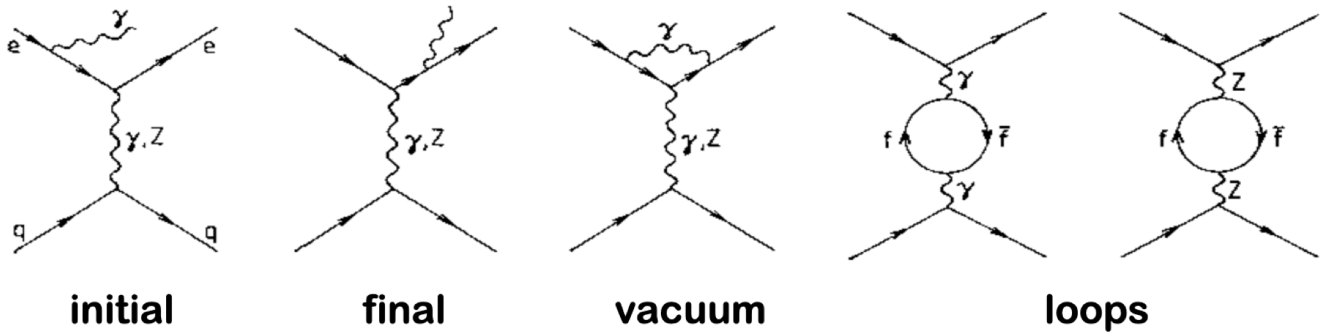
- **Lattice QCD for non-perturbative evolution:**
- **Phenomenology – Global fitting**

Topical Collaboration!

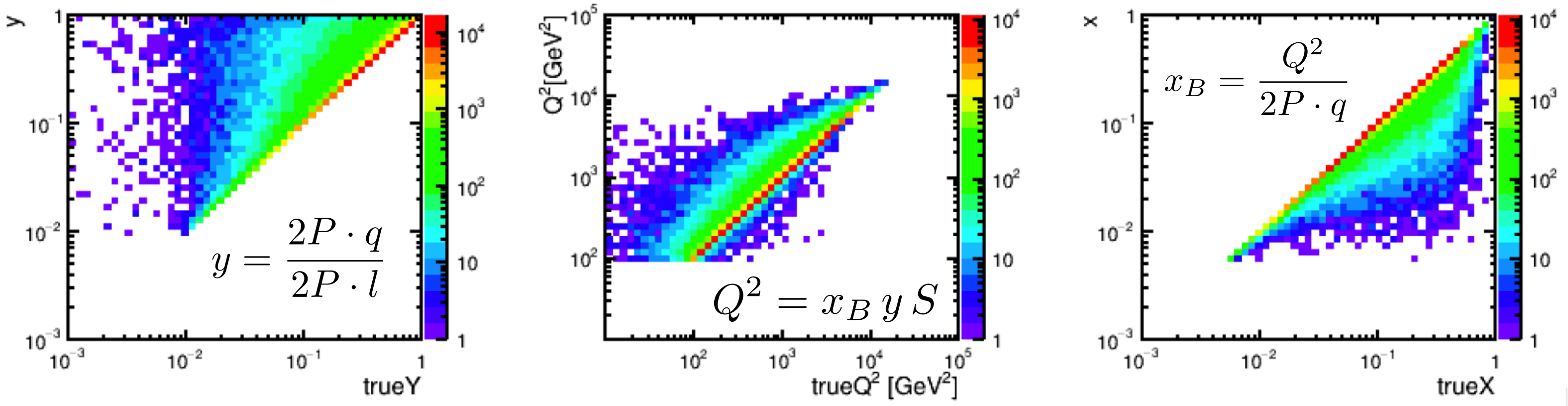
Collision with a large momentum transfer induces strong QED radiation

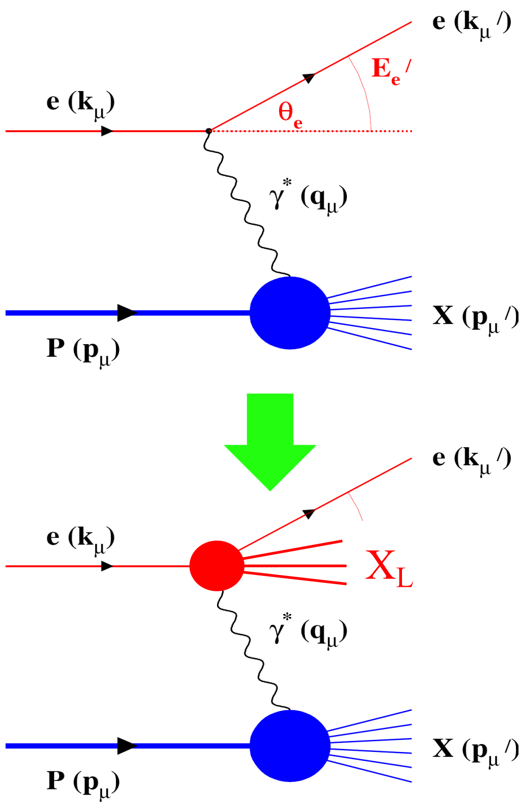
❑ "Probe" for the hadron is smeared by the induced QED radiation:

Data sample : Int L = 10 fb^{-1}, Kinematics settings: $0.01<y<0.95$, 10^2 GeV^2 < Q^2 < 10^5 GeV^2



See Xiaoxuan Chu @2nd EIC YR workshop





$$q_\mu \rightarrow \hat{q}_\mu$$

$$Q^2 = -q^2 \rightarrow \widehat{Q}^2 = -\hat{q}^2$$

$$x_B = \frac{Q^2}{2P\cdot q} \rightarrow \hat{x}_B = \frac{\widehat{Q}^2}{2P\cdot\hat{q}}$$

Instead of a straight line – linear correlation,

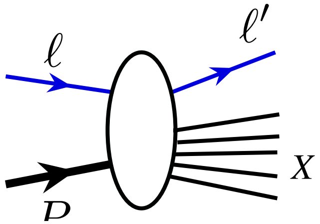
the kinematic variables, y, Q^2 , x_B, from the leptons are smeared so much to make them different from what the scattered "quark" experienced!

Ill-defined "photon-hadron" frame?!

Inclusive lepton-hadron deep inelastic scattering (DIS)

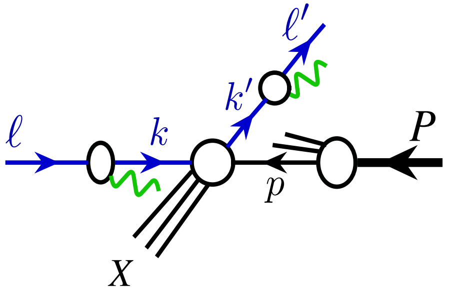
❑ Inclusive production of single high p_T lepton in lepton-hadron collision:

Liu, Melnitchouk, Qiu, Sato
2008.02895, 2108.13371



$$e(\ell,\lambda_\ell) + N(P,S) \to e(\ell') + X$$

$$d\sigma_{\ell(\lambda_\ell)P(S)\to\ell' X} = \frac{1}{2s}\left|M_{\ell(\lambda_\ell)P(S)\to\ell' X}\right|^2 d\mathrm{PS}$$



$$E'\frac{d\sigma_{\ell P\to\ell' X}}{d^3\ell'} \approx \frac{1}{2s}\sum_{ija}\int_{\zeta_{\min}}^1 \frac{d\zeta}{\zeta^2}\int_{\xi_{\min}}^1 \frac{d\xi}{\xi} D_{e/j}(\zeta,\mu^2)\, f_{i/e}(\xi,\mu^2)$$

$$\times \int_{x_{\min}}^1 \frac{dx}{x} f_{a/N}(x,\mu^2)\, \widehat{H}_{ia\to jX}(\xi\ell, xP, \ell/\zeta, \mu^2) + \cdots$$

Collinear QED & QCD factorization

Lepton distribution functions (LDFs): $f_{i/e}(\xi,\mu^2)$

Lepton fragmentation functions (LFFs): $D_{e/j}(\zeta,\mu^2)$ $\quad i.j = e, \gamma, \bar{e}, ..., q, g, ...$

Parton distribution functions (PDFs): $f_{a/N}(x,\mu^2)$ $\quad a = q, g, \bar{q}, e, \gamma, \bar{e}, ...$

Short-distance hard coefficients: $\widehat{H}_{ia\to jX}(\xi\ell, xP, \ell/\zeta, \mu^2)$

$$\approx \widehat{H}^{(m,n)}_{ia\to jX}(\xi\ell, xP, \ell/\zeta, \mu^2) \approx \mathcal{O}(\alpha^m\alpha_s^n)$$

Photon is charge neutral
QED factorization works

- **No DIS "Structure Functions"!**

  Concept of one-photon exchange

- **QED & QCD contribution are factorized at the same scale: μ**

  $$(x_B, Q^2) \to (y, \ell'_T)$$

- **Corrections suppressed by power**

  $$(1/\ell'_T)^\alpha$$

Nayak, Qiu, Sterman, Phys.Rev.D 72 (2005) 114012

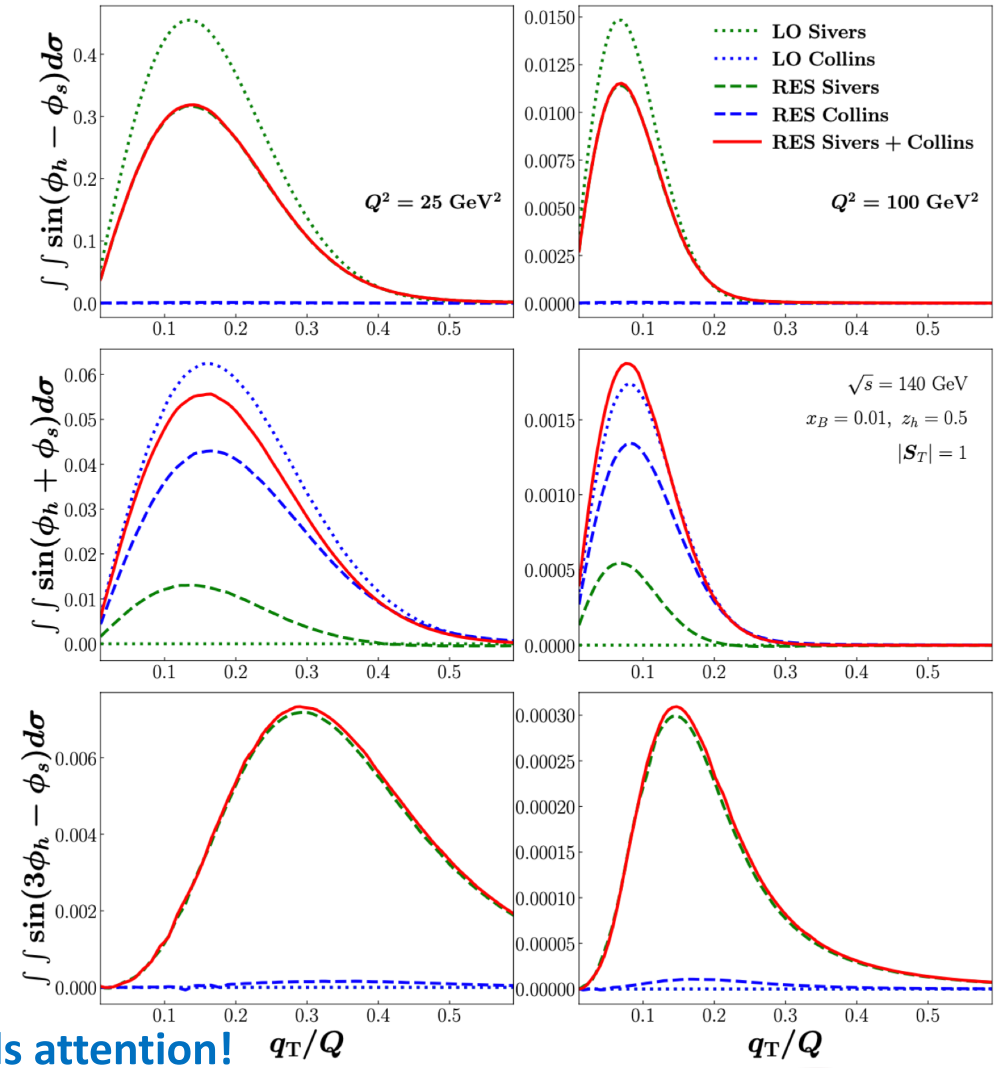
Jefferson Lab

Lepton-hadron semi-inclusive deep inelastic scattering (SIDIS)

❑ Case study – single transverse spin asymmetry:

Liu, Melnitchouk, Qiu, Sato
2008.02895, 2108.13371

$$
\begin{aligned}
\frac{d\sigma}{dx\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = &\\
\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right) \Big\{ & F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{UU}^{\cos\phi_h} \\
& + \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\,\varepsilon(1-\varepsilon)}\, \sin\phi_h\, F_{LU}^{\sin\phi_h} \\
& + S_\parallel \left[\sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h} \right] \\
& + S_\parallel \lambda_e \left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_h\, F_{LL}^{\cos\phi_h} \right] \\
& + |\boldsymbol{S}_\perp| \Big[\sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \right) \\
& \quad + \varepsilon\, \sin(\phi_h + \phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\, \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \\
& \quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin(2\phi_h - \phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Big] \\
& + |\boldsymbol{S}_\perp| \lambda_e \Big[\sqrt{1-\varepsilon^2}\, \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_S\, F_{LT}^{\cos\phi_S} \\
& \quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos(2\phi_h - \phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)} \Big] \Big\}
\end{aligned}
$$



Angular modulation needs attention!

More works are needed for analyzing JLab/EIC data

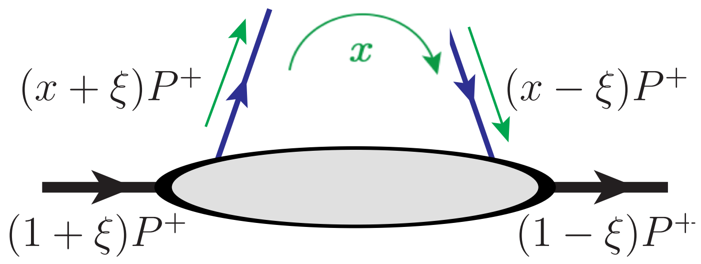
Jefferson Lab

How to explore internal structure of hadron without breaking it?

❑ Generalized PDFs (GPDs):

$$F^q(x,\xi,t) = \int \frac{dz^-}{4\pi} e^{-ixP^+z^-} \langle p'|\bar{q}(z^-/2)\gamma^+ q(-z^-/2)|p\rangle$$
$$= \frac{1}{2P^+}\left[H^q(x,\xi,t)\,\bar{u}(p')\gamma^+ u(p) - E^q(x,\xi,t)\,\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}u(p)\right],$$
$$\widetilde{F}^q(x,\xi,t) = \int \frac{dz^-}{4\pi} e^{-ixP^+z^-} \langle p'|\bar{q}(z^-/2)\gamma^+\gamma_5 q(-z^-/2)|p\rangle$$
$$= \frac{1}{2P^+}\left[\widetilde{H}^q(x,\xi,t)\,\bar{u}(p')\gamma^+\gamma_5 u(p) - \widetilde{E}^q(x,\xi,t)\,\bar{u}(p')\frac{\gamma_5\Delta^+}{2m}u(p)\right].$$

$$\Delta^+ = 2\xi P^+$$

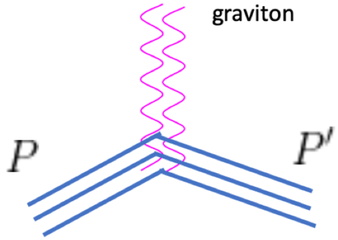


$$P^+ = \frac{p^+ + p'^+}{2}$$
$$\Delta = p - p'$$

Similar definition for gluon GPDs

❑ Nucleon Form Factors of energy-momentum tensor:

$$\langle P'|T^{\mu\nu}_{q,g}|P\rangle = \bar{u}(P')\left[A_{q,g}\gamma^{(\mu}\bar{P}^{\nu)} + B_{q,g}\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M} + D_{q,g}\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M} + \bar{C}_{q,g}Mg^{\mu\nu}\right]u(P)$$



See talk by Y. Hatta

All the form factors are interesting!

$A_{q,g}$, $B_{q,g}$ } Ji sum rule $J_{q,g} = \frac{1}{2}(A_{q,g} + B_{q,g})$ for proton spin

$D_{q,g}$ `pressure' inside proton

$\bar{C}_{q,g}$ trace anomaly, gluon condensate

1 graviton ≈ 2 photons

EM form factors ⟶ proton charge radius

1 graviton ≈ 2 gluons

Gravitational form factors ⟶ proton mass radius

Hadron structure and internal landscape, …

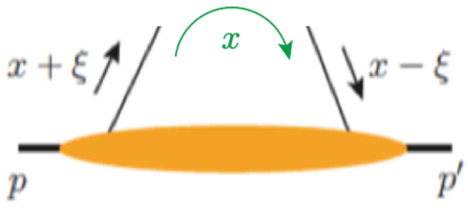
M. Burkdart, PRD 2000

❑ **Impact parameter dependent parton density distribution – 3D tomography:**

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

Quark density in $\mathrm{d}x\, \mathrm{d}^2 \boldsymbol{b}_T$

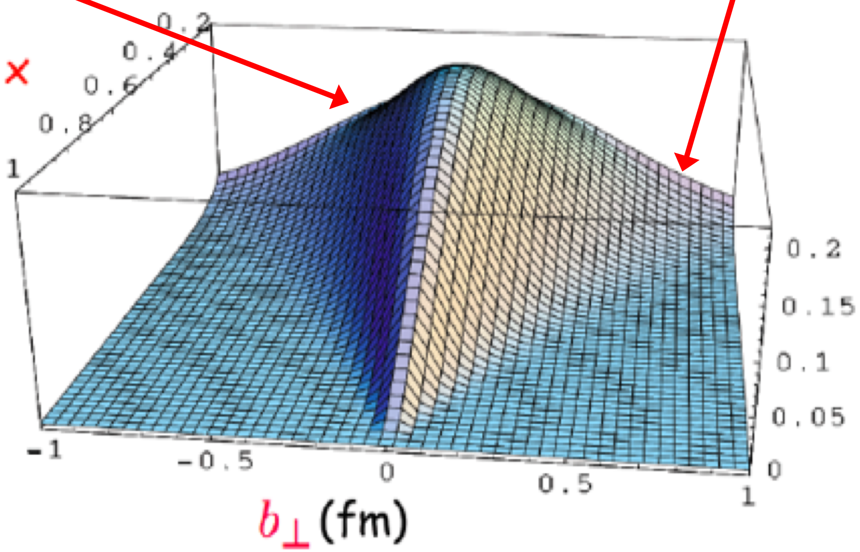
Unpolarized proton



How fast does glue density fall?

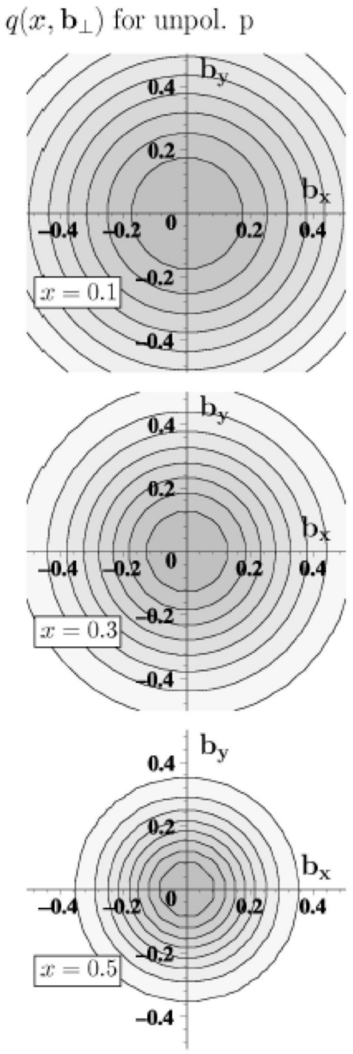
3D image

How far does glue density spread?



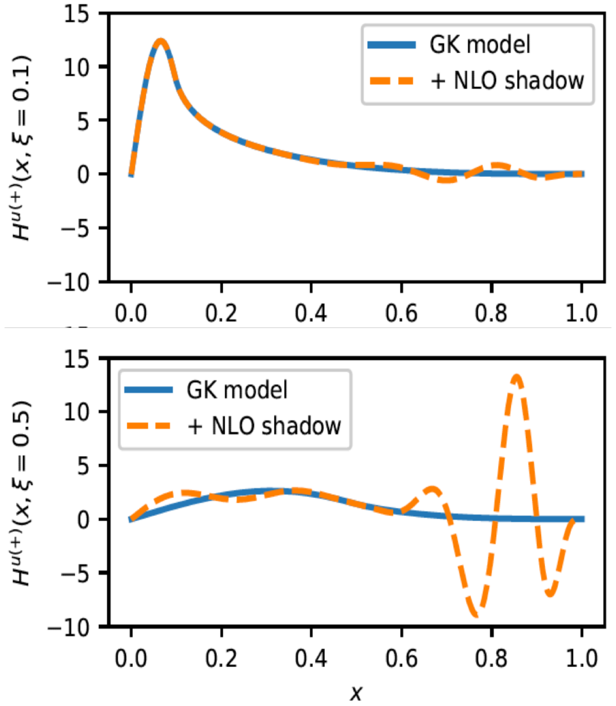
➡ **Proton radii of quark and gluon spatial density distribution, $r_q(x)$ & $r_g(x)$**

- Should $r_q(x)$ > $r_g(x)$, or vice versa?
- Could $r_g(x)$ saturates as $x \to 0$
- How do they compare with known radius (EM charge radius, mass radius, …)?
- Tomographic images in slides of different x value!



It is difficult to extract the x-dependence of GPDs – Why?

❑ "Shadow GPDs"



Blue and dashed
Fit the same CFFs !

PRD103 (2021) 114019

❑ Amplitude nature: exclusive processes

$x \sim$ loop momentum

$$\mathcal{M} \sim \int_{-1}^{1} \mathrm{d}x F(x, \xi, t) \cdot C(x, \xi; Q/\mu)$$

never pin down to some x

❑ Sensitivity to x comes from $C(x, \xi; Q/\mu)$

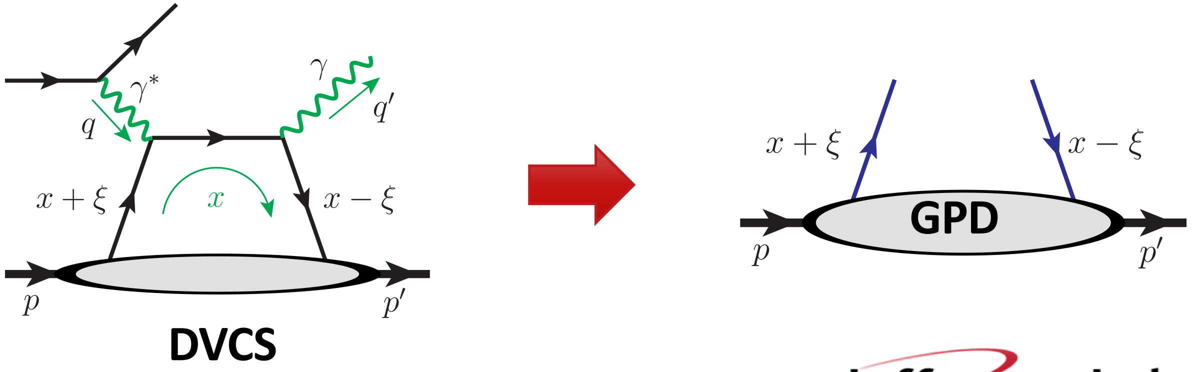
At LO, DVCS hard coefficient factorizes

$$C(x, \xi; Q/\mu) = C_Q(Q/\mu) \cdot C_x(x, \xi) \propto \frac{1}{x - \xi + i\varepsilon} \cdots$$

$$\Rightarrow \quad i\mathcal{M} \propto \int_{-1}^{1} \mathrm{d}x \frac{F(x, \xi, t)}{x - \xi + i\varepsilon} \equiv \text{“}F_0(\xi, t)\text{”}$$

- **also true for most other processes**
- **x-dependence is only constrained by a "moment"**
- **easy to fit to the data**

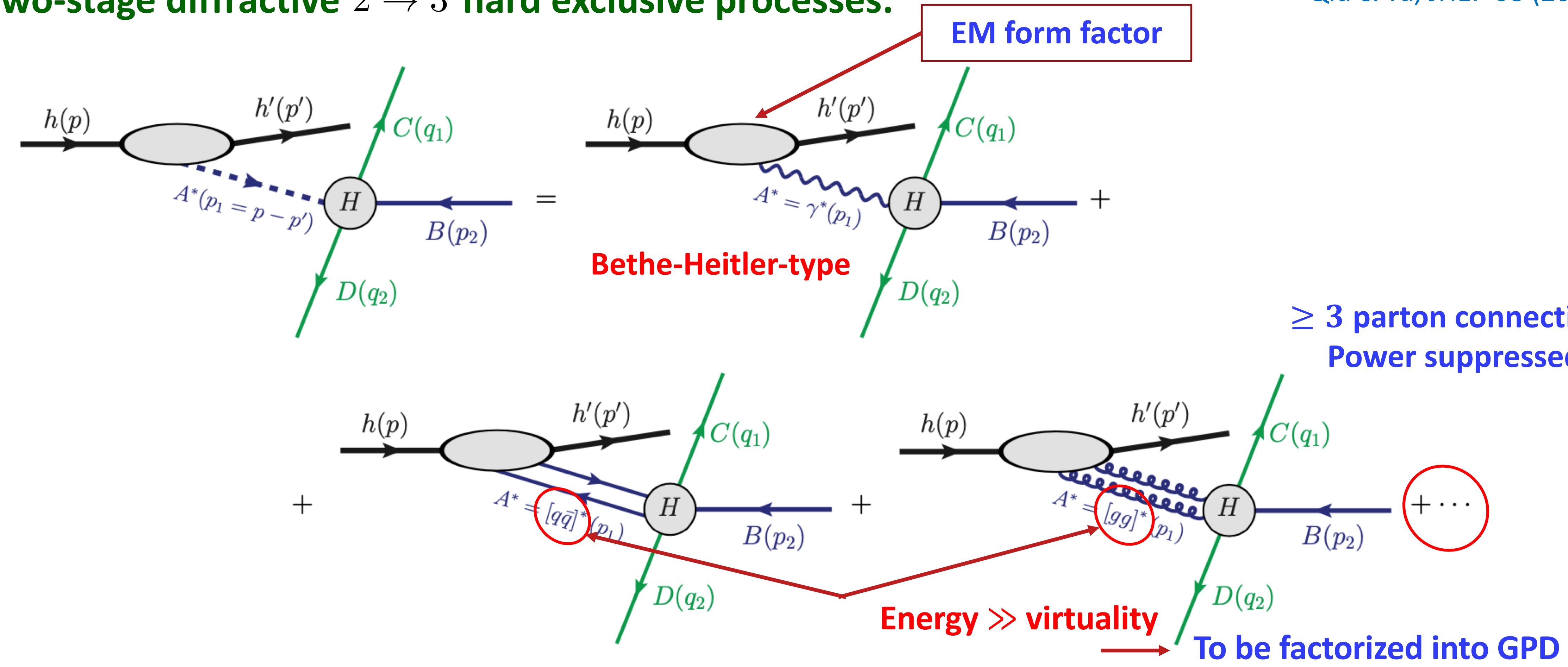
Qiu & Yu, JHEP 08 (2022) 103



Single-Diffractive Hard Exclusive Processes (SDHEP)

❑ **Two-stage diffractive $2 \to 3$ hard exclusive processes:**

Qiu & Yu, JHEP 08 (2022) 103



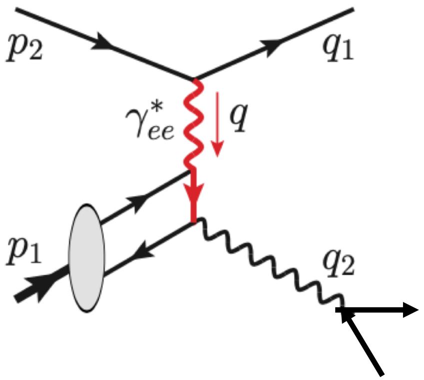
The exchanged state $A^*(p\text{-}p')$ is a sum of all possible partonic states, $\sum_{n=1,2,..}$, allowed by

- **Quantum numbers of $h(p) - h'(p')$**
- **Symmetry of producing non-vanishing H**

More Opportunities with SDHEP, …

- **DDVCS is sensitive to the x-dependence of GPDs – Needs luminosity!**

Qiu & Yu, JHEP 08 (2022) 103



Transverse momentum flow from the final-state lepton and the virtual photon is sensitive to the virtuality of the dilepton

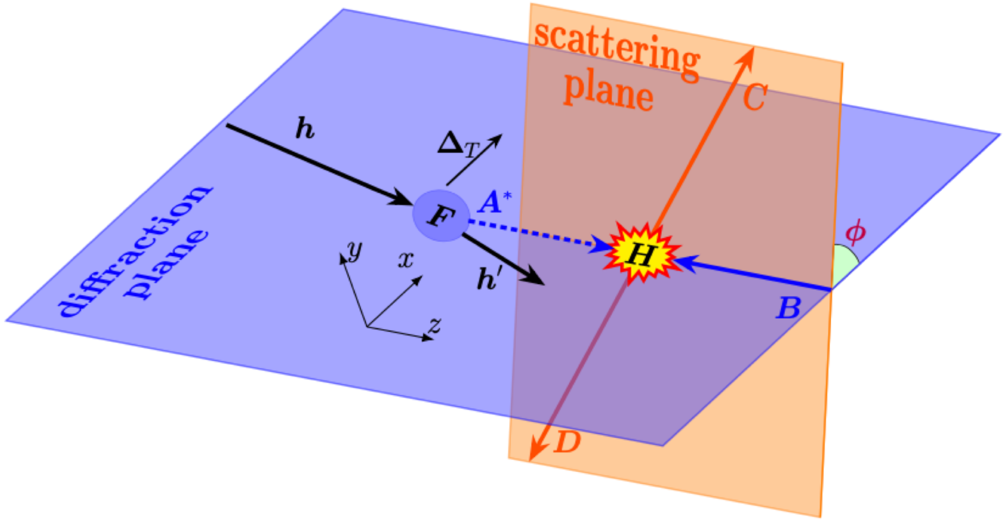
$$Q'^2 \equiv q'^2 = \left(\frac{2\xi}{x_B(1+\xi)} - 1\right)$$

Direct sensitive to external variable, x_B, directly sensitive to q_T

Experimental challenge to distinguish the scattered lepton !

- **More opportunities:**
  - Diffractive plane
  - Exclusive hard scattering plane
  - Angular modulation between the two planes

→ ***Selection from different exchange state A* (or different GPDs)***



It is the x-dependence of GPDs that allows us to calculate various moments of GPDs – total angular momentum, gravitational form factors (2nd moments), …

Jefferson Lab

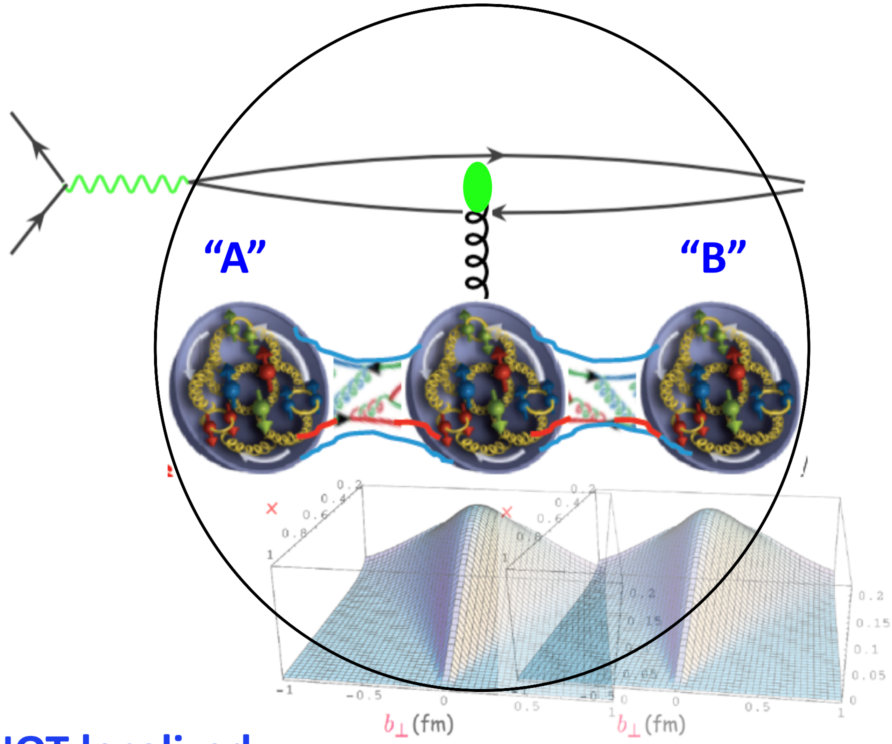
What does a nucleus look like if we only see quarks and gluons ?

- ❑ **Does the colored glue of nucleon "A" know the color of a gluon in nucleon "B"?**

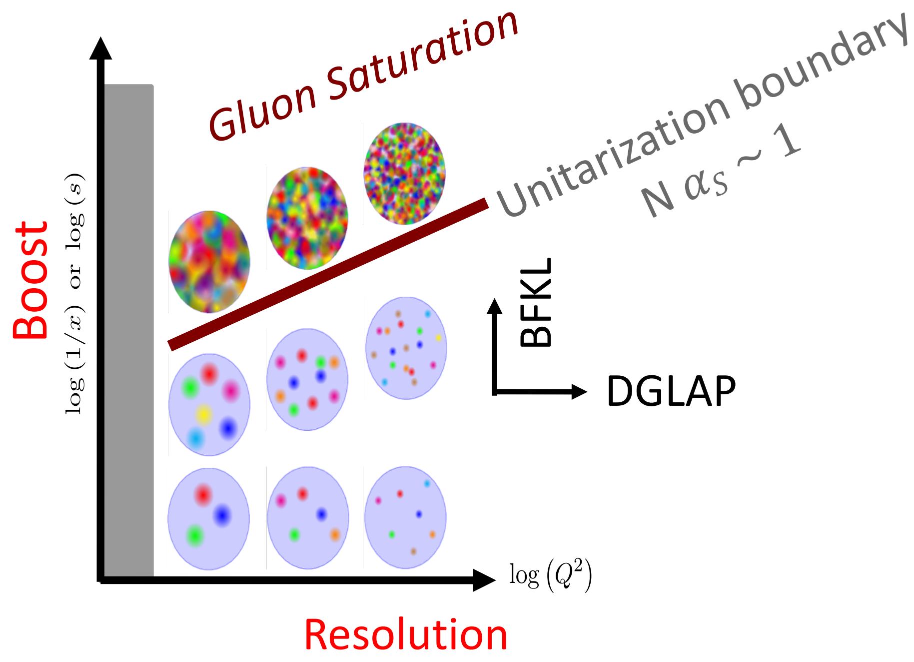
  IF YES, Nucleus could act like a bigger proton at small-x, and could reaching the saturation much sooner!

  IF NOT, Observed nuclear effect in cross-section is a coherent collision effect

EIC can tell !



- ❑ **Landscape of the strong interaction**

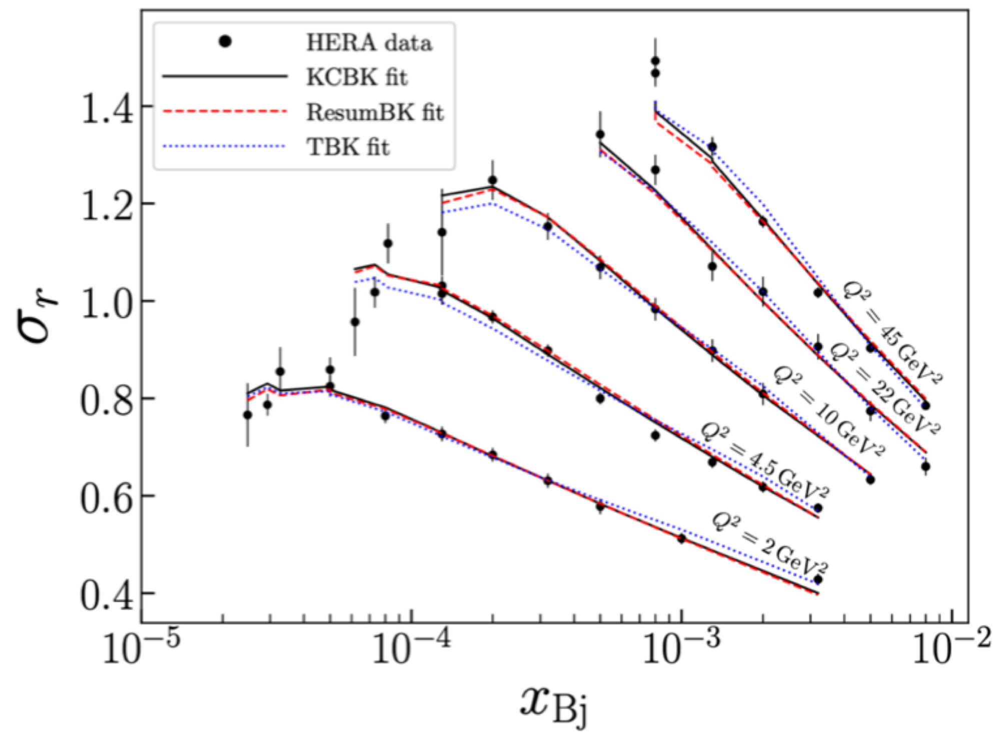


- **Hard probe at small-x is NOT localized in the longitudinal direction!**
- **The probe can interact with gluons from different Nuclson coherently – collision effect to the cross section**
- **If gluons from "A" coherently interact with gluons from "B", nucleus could be viewed as "bigger" nucleon at small x!**

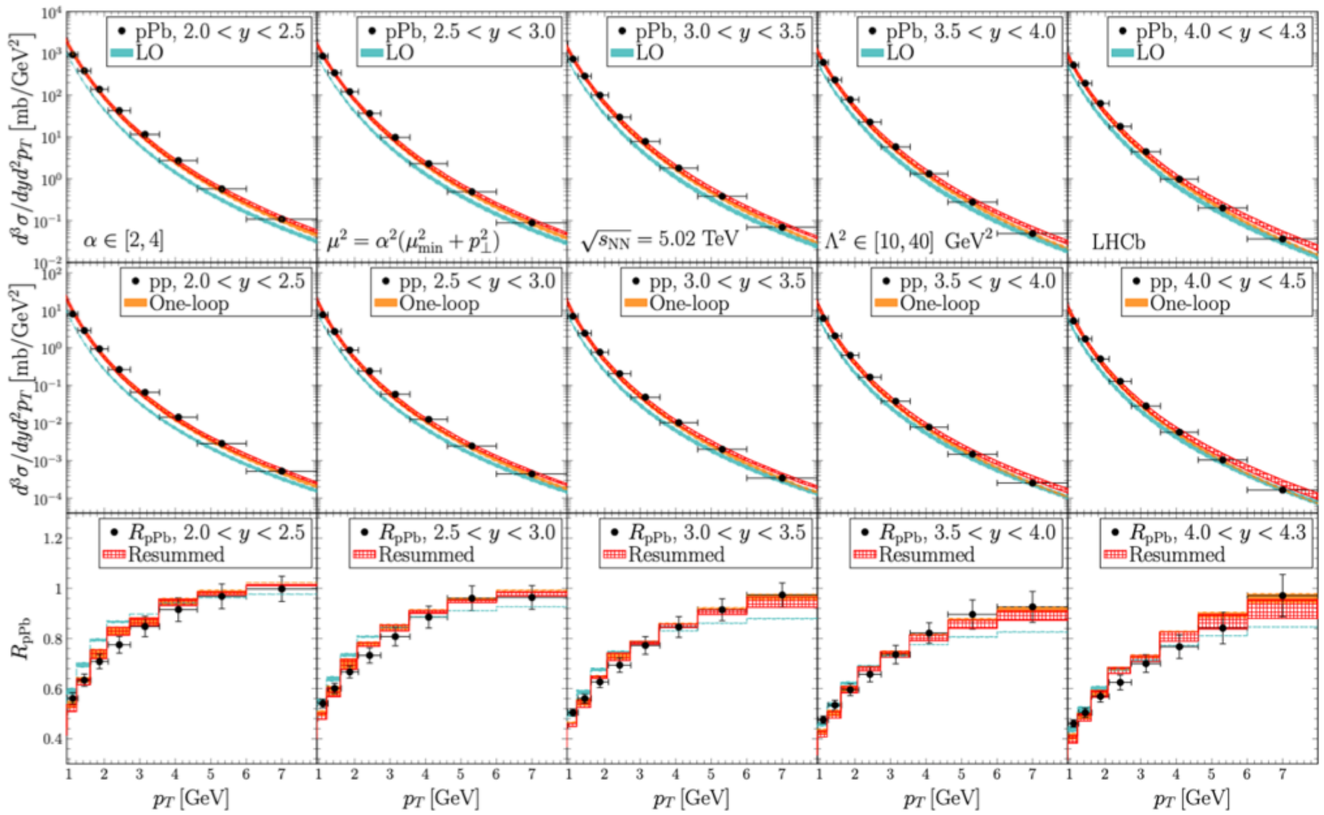
Jefferson Lab

Impact of saturation physics?

❑ From LO+LLx to NLO+NLLx: Saturation phenomenology



Beuf,Hanninen,Lappi,Mantysaari, arXiv:2007.01645



Shi,Wang,Wei,Xiao, arXiv:2112.06975

Significant progress towards global analysis in p+A and e+A: goal is to extract universal many-body dipole and quadrupole correlators

Match to parton TMDs at larger Q^2 and larger x

Summary and Outlook

- ❑ **We have the right Theory – QCD, but, unprecedented challenges**

  Trying to understand the emergent phenomena of QCD without being to see quarks and gluons

- ❑ **We have some Tools, but, need more: Computing, SciDAC, AI/ML. Topical Collaboration, …**

  We made a lot Theory Advances since the 2015 LRP, we need more DATA from JLab/RHIC to get ready for the EIC!

- ❑ **To get ready for the future EIC era,**

  CFNS workshop: "EIC Theory in the next decade", Sept.20-22, 2022, MIT

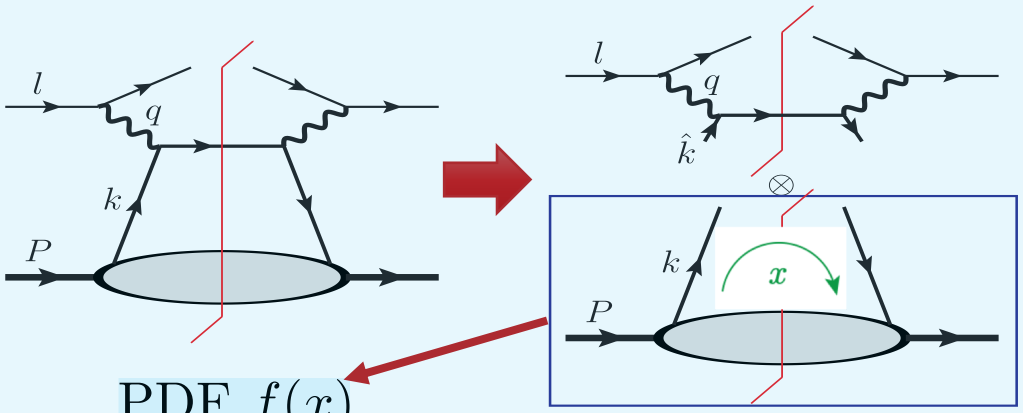
  Organizers: Peter Petreczky (BNL), Ian Cloët (ANL), Dmitri Kharzeev (Stony Brook University/BNL), Xiangdong Ji (University of Maryland), Jianwei Qiu (JLab), Phiala Shanahan (MIT), Iain Stewart (MIT), Ivan Vitev (LANL), Feng Yuan (LBNL)

  Resolution:
  "We recommend the establishment of a national EIC theory alliance to enhance and broaden the theory community needed to advance EIC physics goals and the experimental program. This theory alliance will develop a diverse workforce through a competitive national EIC theory fellow program and tenure-track bridge positions, including appointments at minority serving institutions."

Thanks!

Inclusive Process vs. Exclusive Process

❑ Deeply Inelastic Scattering (DIS):



PDF $f(x)$

$x = k^+/P^+$

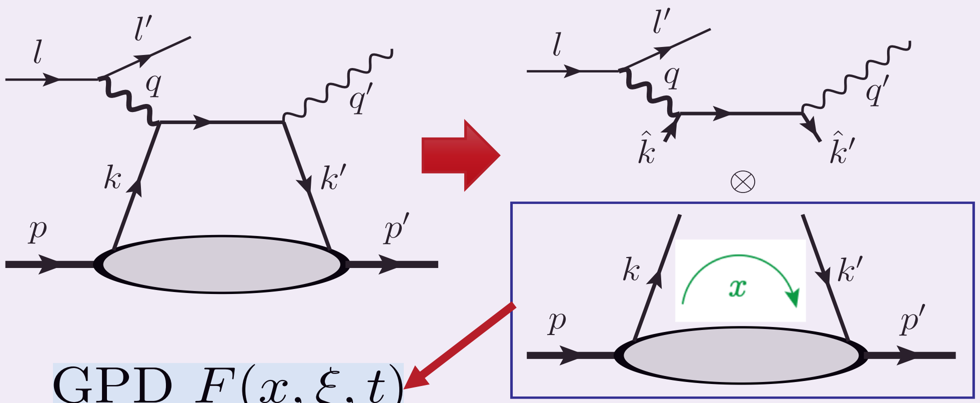
Cross section: Cut diagrams

$$\sigma_{\rm DIS} \simeq \int_{x_B}^{1} {\rm d}x\, f(x)\, \hat{\sigma}(x/x_B)$$

- PDF ~ probability
- At LO: $x = x_B$ $\quad \hat{\sigma}^{(\rm LO)}(x/x_B) \propto \delta(x - x_B)$
- Beyond LO: $x \in [x_B, 1]$

x-dependence: Part of measurement

❑ Deeply Virtual Compton Scattering (DVCS)



GPD $F(x, \xi, t)$

$$x = \frac{(k+k')^+}{(p+p')^+}$$

$$\xi = \frac{(p-p')^+}{(p+p')^+}$$

$$t = (p-p')^2$$

Amplitude: Uncut diagrams

$$\mathcal{M}_{\rm DVCS}(\xi, t) \simeq \int_{-1}^{1} {\rm d}x\, F(x, \xi, t)\, \hat{\mathcal{M}}(x, \xi)$$

- GPD ~ amplitude
- $k^+ = (x + \xi)\, P^+$ is loop momentum
- At any order: $x \in [-1, 1]$

x-dependence: Hard to measure