Strong QCD from Hadron Structure Experiments

Nov. 6 - 9, 2019
Jefferson Lab
Newport News, VA USA

Summary and Outlook (Experiment)*

V.I. Mokeev, Jefferson Lab

Outcome of the Experiments with Electromagnetic Probes (Highlights)

- **Completion of the light (S=C=B=0) meson and baryon spectrum exploration from exclusive photo-, electro-, and hadro-production data finalizing the search for ``missing" resonances, new hybrid and multi-quark states.**

- **Considerable extension of the information on the 1D-structure of the ground state mesons and nucleons in terms of different meson form factors, nucleon elastic form factors, and PDFs getting insight to the process-independent QCD running coupling.**

- **A unique information on many facets of strong QCD in generation of the excited states of nucleon with different structural features from the results on transition $\gamma_v pN^*$ electrocouplings.**

- **Insight into the 3D-structure of the ground nucleons from semi-inclusive-DIS, DVCS , and DVMP data within the GPD and TMD concepts.**

- **Opportunity to map-out the energy-momentum tensor of the ground nucleons in terms of mass, angular momentum, and force (pressure) distributions determinedfrom the DVCS and DVMP data.**

Insight into the Strong QCD from the Synergy between Experiment, Phenomenology, and Theory

Experiment

Theory

Observables from the Experiments with the EM Probes:

- Differential cross sections
- Beam asymmetry
- Target asymmetries
- Recoil asymmetries
- Combinations of 2-fold and 3-fold asymmetries

Phenomenology:

- Amplitude analyses
- Reaction models

Elastic/Transition form factors
PDFs, PDA,TMD-functions
Compton form factors
Projection of GPD to observables

Strong QCD underlying the hadron generation $\alpha_s \sim 1$

QCD Lagrangian:

$$\mathcal{L}_{QCD} = \bar{\psi}(i \not{D}_a T_a - m)\psi - \frac{1}{4}F_a^{\mu\nu}F_{\mu\nu,a}$$

- Covariant derivative, gluon field tensor

$$D_a^\mu = \partial^\mu + igA_a^\mu$$
$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - g f_{abc} A_b^\mu A_c^\nu$$

- Color matrices and structure constants

$$[T_a^{(F)}, T_b^{(F)}] = i f_{abc} T_c^{(F)}, \quad (T_a^{(A)})_{bc} = -i f_{abc}$$

- Lattice QCD
- Continuum QCD

Light front quark models
AdS/CFT approaches
χ Quark-Soliton models
Hypercentral quark model
Covariant quark models
………………………………..

The Workshop Objectives and Highlights

Major objective: Forge the synergistic efforts between experimentalists, phenomenologists, and theorists in order to gain insight into strong QCD dynamics underlying the hadron generation from the data of the experiments with EM probes on the spectra and structure of the ground and excited hadrons.

Status and prospects for the experimental studies
V.D. Burkert, Exploring Strong QCD in the JLab Experiments of the 12 GeV era

Theoretical interpretation
J. Qiu, New Horizons for Strong QCD Theory in the 12 GeV era at Jlab
C.D. Roberts, Relating Experimental Studies of Hadron Structure to Strong QCD Within the Unified Continuum QCD Framework

Extending the nucleon structure studies in 3D
M. Vandergaedhen, Ground and Excited Nucleon Structure in 3D

Towards understanding of the atomic nuclear structure from QCD
J.P. Draayer, Paving the way to Understand Nuclear Structure from Strong QCD

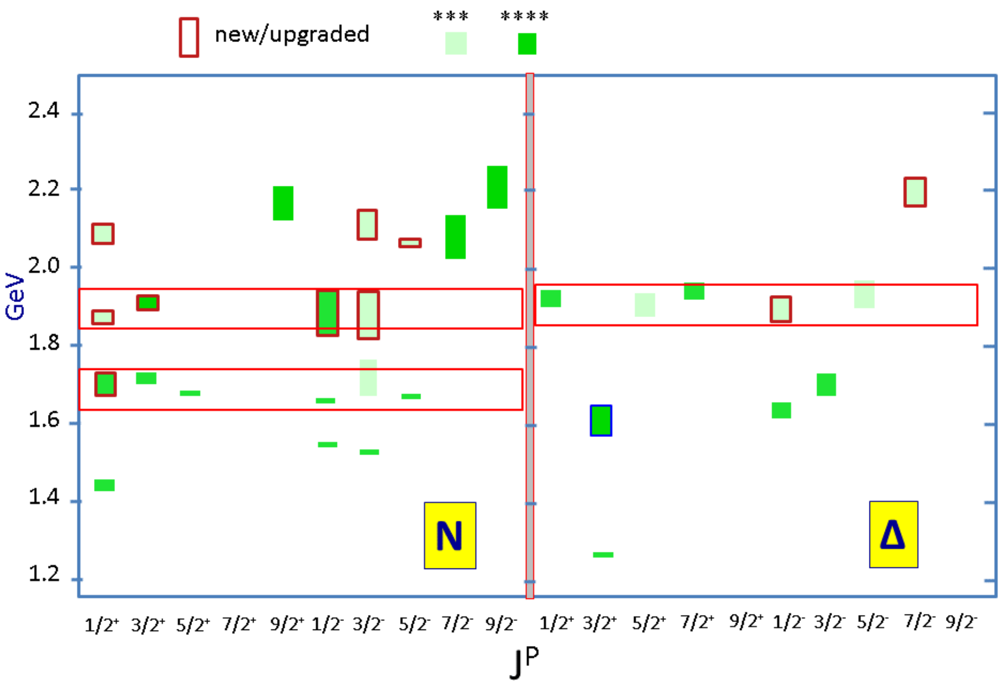
Preparing to the new era of experiments with the USA EIC
R.G. Milner, Studying QCD with the Electron-Ion Collider

Advances in Exploration of the N*-Spectrum

Several new nucleon resonances (``missing” states) have been discovered with the decisive impact of the CLAS open strangeness photoproduction data. A.V. Anisovich et al.,Phys. Lett. B782, 662(2018), V.D. Burkert, Few Body Syst. 59, 57 (2018).

V.D. Burkert

N^*/Δ^* Spectrum 2019



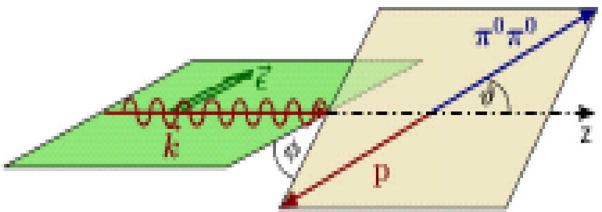
Nucleon resonances listed in Particle Data Group (PDG) tables

State N(mass)J^P	PDG pre 2016	PDG 2018*
$N(1710)1/2^+$	***	****
$N(1880)1/2^+$		***
$N(1895)1/2^-$		****
$N(1900)3/2^+$	**	****
$N(1875)3/2^-$		***
$N(2100)1/2^+$	*	***
$N(2120)3/2^-$		***
$N(2000)5/2^+$	*	**
$N(2060)5/2^-$		***
$\Delta(1600)3/2^+$	***	****
$\Delta(1900)1/2^-$	**	***
$\Delta(2200)7/2^-$	*	***

- **[70,2+] supermultiplet gets populated.**
- **Confirmation of the essential role of the SU(6) spin-flavor approximate symmetry in the generation of the N* spectrum**
- **Where are the other N* expected from SU(6) spin-flavor symmetry?**

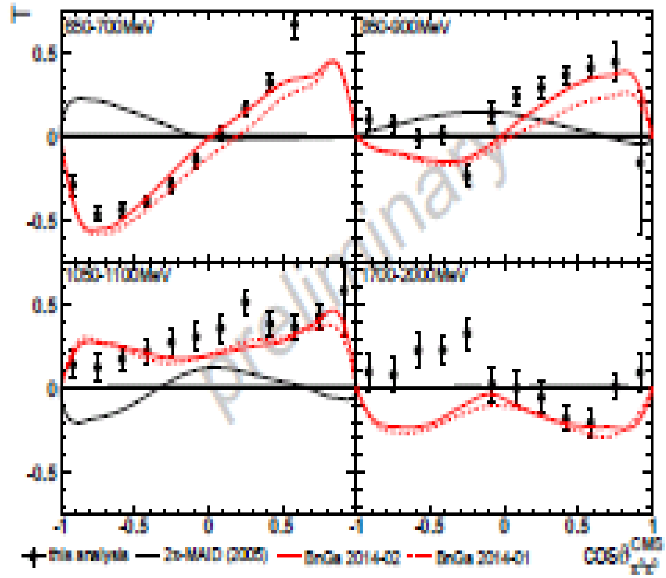
Here:

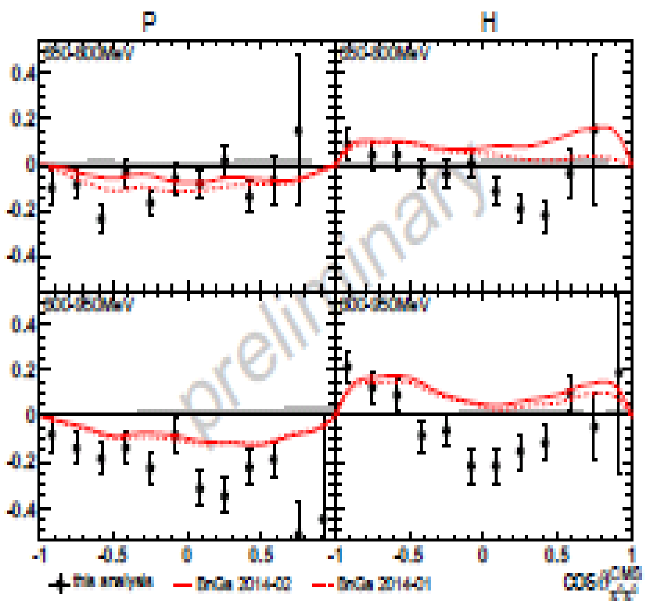
only results shown in quasi two-body kinematics



A. Thiel

T. Seifen





Observables also extracted for different kinematic variables

Full three-body kinematics allows the measurement of further observables.

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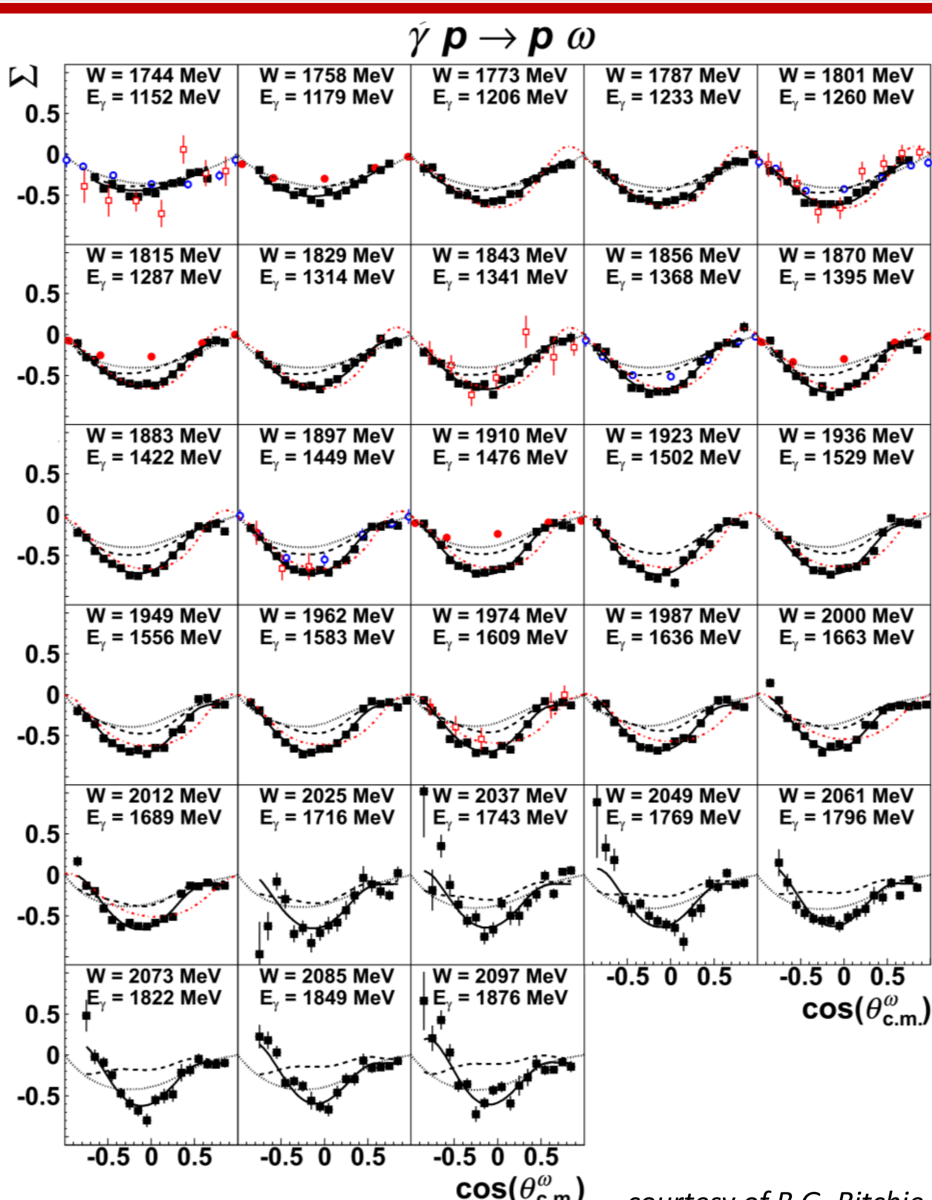
Latest ω photoproduction results



■ CLAS P. Collins *et al.*, PLB **773**, 112 (2017)
- 547 data points distributed over 28 *W* bins

○ GRAAL (2006)

● GRAAL (2015)

□ CB-ELSA/TAPS (2015)

E. Pasyuk

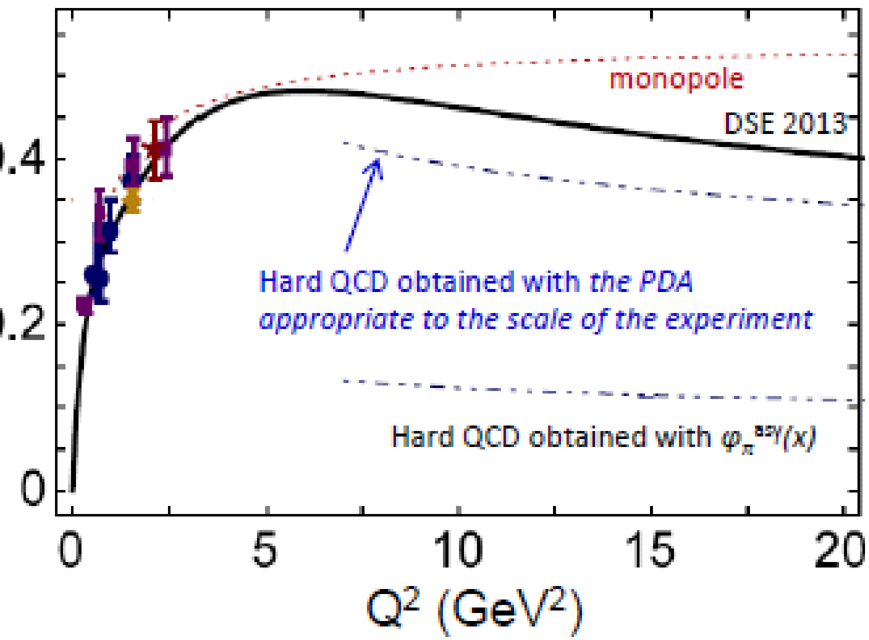
- BnGa fit with (black solid line) and without (black dashed line) incorporating these new data
- Close to threshold the process is dominated by $3/2^+$ and $5/2^+$ partial waves associated with $N(1720)3/2^+$ and $N(1680)5/2^+$

Implementation of new results from the less explored exclusive photoproduction channels into the global multichannel analyses facilitate further search for new baryon states shedding light on driving Symmetry for the N* spectrum

courtesy of B.G. Ritchie, ASU

Pion Form Factor (2019)

T. Horn



[L. Chang, et al., PRL 111 (2013) 141802; PRL 110 (2013) 1322001]

Compared to one calculation here – there are others, e.g.Braun et al.

Constraints from the data on pion BS amplitudes are of particular importance in order to shed light on hadron mass generation

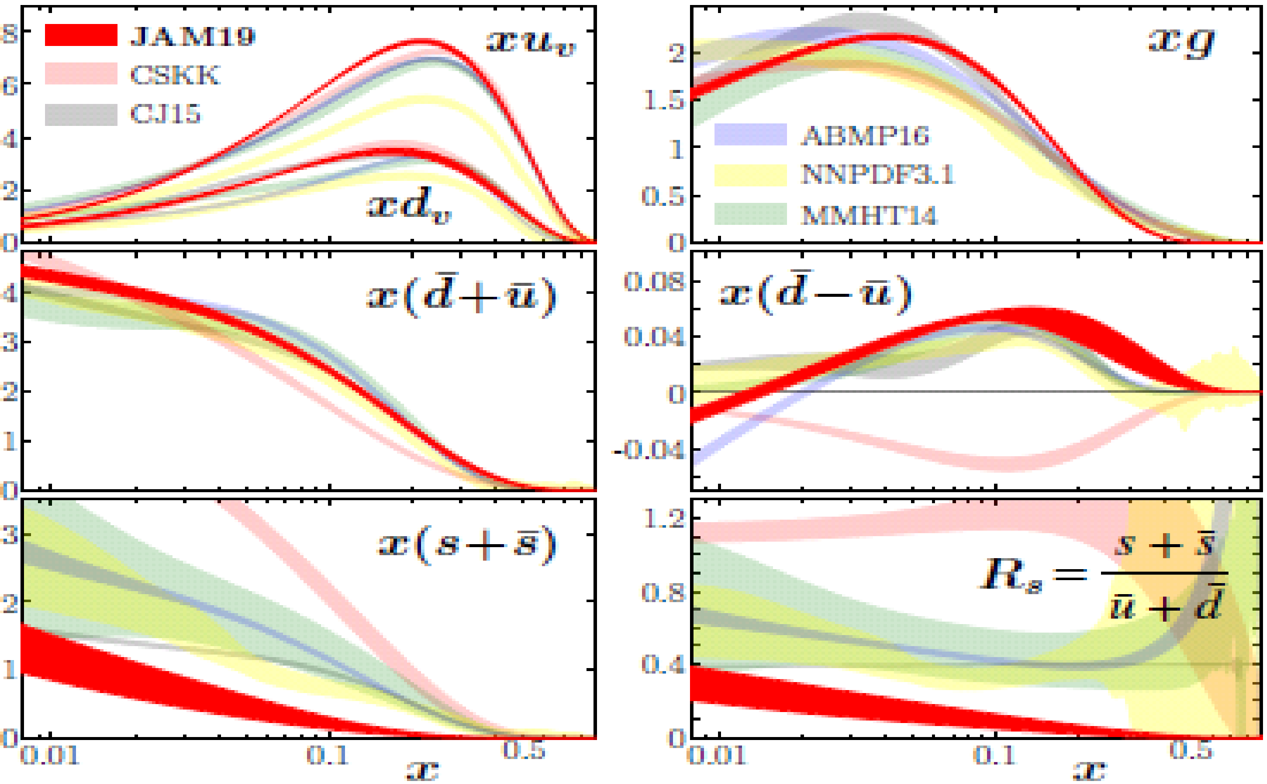
C. Aguilar et al., Eur. Phys. J. A55,190 (2019)

- J. Volmer et al., PRL **86** (2001) 1713 – 305 citations
  - Precision F_π results between Q^2=0.60 and 1.60 GeV^2
- T. Horn et al., PRL **97** (2006) 192001 – 236 citations
  - Precision F_π results at Q^2=1.60 and 2.45 GeV^2
- V. Tadevosyan, et al., PRC**75** (2007) 055205 – 200 ct's
- G. Huber et al., PRC**78** (2008) 045203 – 175 citations
  - Archival paper of precision F_π measurements 6 GeV
- H. P. Blok et al., PRC**78** (2008) 045202 – 101 citations
  - Archival paper of precision LT separated cross sections
- T. Horn et al., PRC**78** (2008) 058201 – 62 citations
  - L/T cross sections and F_π at Q^2=2.15 GeV^2 ,exploratory at Q^2~4.0 GeV^2
- Plus several spin-off papers on, e.g. L/T separations in π^- and ω production, high-t, transverse charge density (2012-present)

JAM19 PDFs

C.Andres

arXiv:1905.03788 [hep-ph]

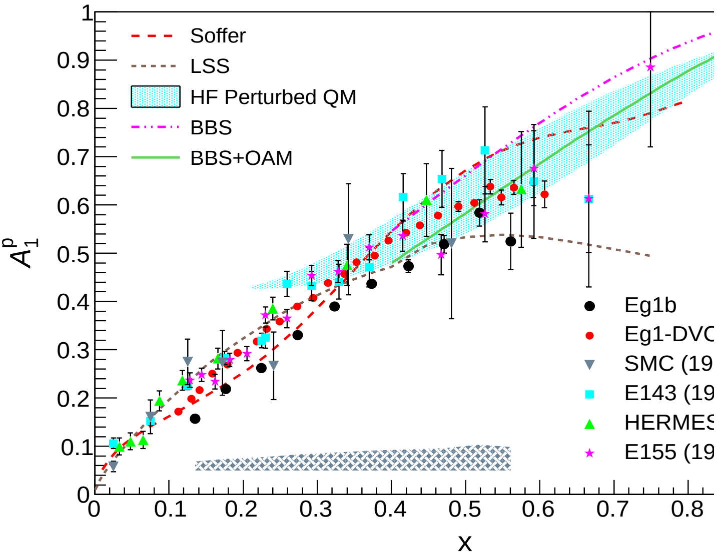


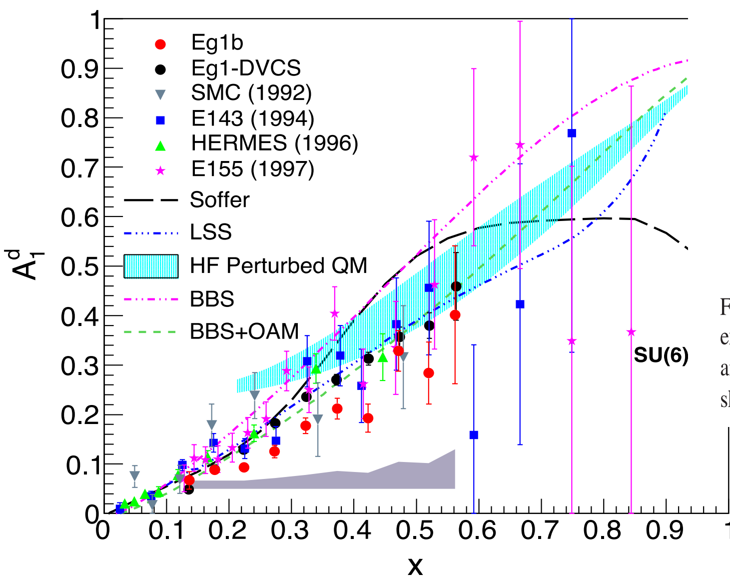
$$Q = m_c$$

DIS(p, d)
DY(pp, pd)
SIA$(\pi^{\pm}, K^{\pm})$
SIDIS$(\pi^{\pm}, K^{\pm})$

SPIN STRUCTURE FUNCTIONS IN THE LAST 40 YEARS

S. Kuhn





SATO, MELNITCHOUK, KUHN, ETHIER, and ACCARDI PHYSICAL REVIEW D **93,** 074005 (2016)

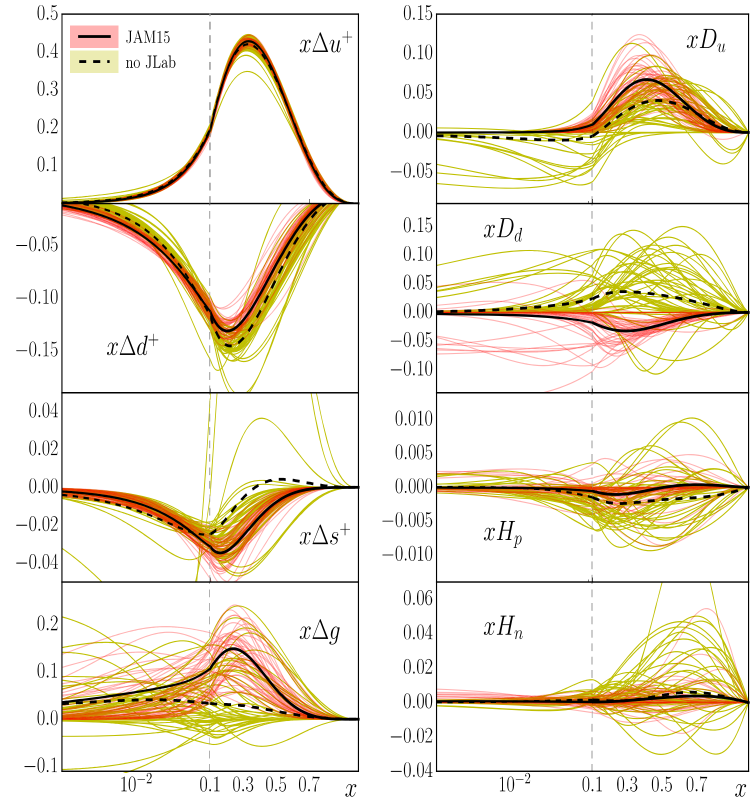


FIG. 15. Comparison of the JAM15 IMC fits (red curves, with the average indicated by the black solid curve) with corresponding fits excluding all Jefferson Lab data (yellow curves, with the average given by the black dashed curve) for the twist-2 PDFs Δu^+, Δd^+, Δs^+ and Δg, the twist-3 distributions D_u and D_d, and the twist-4 functions H_p and H_n at $Q^2 = 1$ GeV^2. Note that x times the distribution is shown. For illustration each distribution is represented by a random sample of 50 fits.

Nobuo Sato, W. Melnitchouk, S. E. Kuhn, J. J. Ethier, and A. Accardi:"Iterative Monte Carlo analysis of spin-dependent parton distributions", Phys. Rev. D **93**, 074005 (5 April 2016).

A. Deur, Y. Prok, V. Burkert, D. Crabb, F.-X. Girod, K. A. Griffioen, N. Guler, S. E. Kuhn, and N. Kvaltine: "High precision determination of the Q^2 evolution of the Bjorken sum", Phys. Rev. C **90**, 012009 (July 2014).

LQCD/PQCD – hadron/nuclear structure

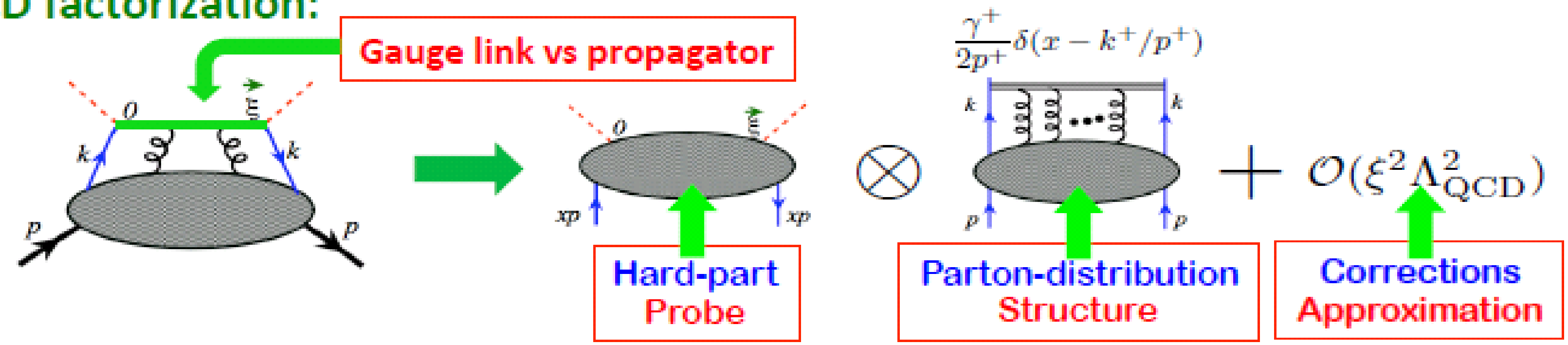
Ma and Qiu, arXiv:1404.6860

- **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:**

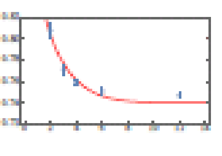


- **Tremendous potentials:**

  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!*

Jefferson Lab



Matching relations

- Basically, matching converts $\mathfrak{M}(\nu, z_3^2)$ into $\mathcal{I}(\nu, \mu^2)$, i.e. z_3^2-dependence of $\mathfrak{M}(\nu, z_3^2)$ into μ^2-dependence of $\mathcal{I}(\nu, \mu^2)$
- Matching condition between reduced pseudo-ITD and $\overline{\text{MS}}$ ITD (Y. Zhao 2017, A.R. 2017)

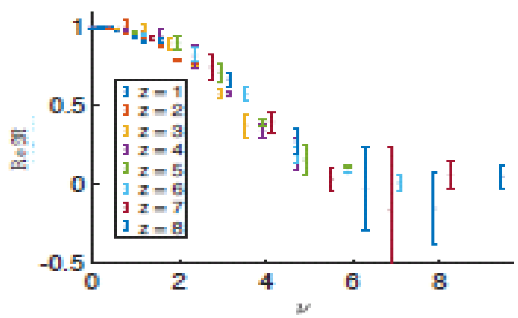
$$\mathfrak{M}(\nu, z_3^2) = \mathcal{I}(\nu,\mu^2) - \frac{\alpha_s}{2\pi} C_F \int_0^1 dw\, \mathcal{I}(w\nu,\mu^2) \times \left\{ B(w)\left[\ln\left(z_3^2\mu^2\frac{e^{2\gamma_E}}{4}\right)+1\right] + \left[4\frac{\ln(1-w)}{1-w} - 2(1-w)\right]_+ \right\}$$

A. Radyushkin

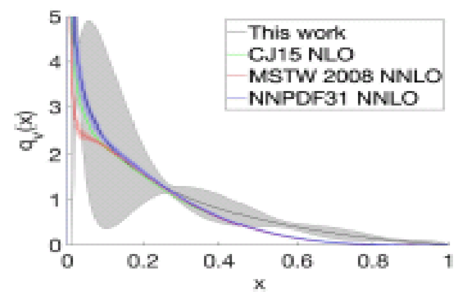
$$\mathfrak{M}(\nu,z_3^2) = \int_{-1}^1 dx \left[e^{ix\nu} - \frac{\alpha_s}{2\pi} C_F R(x\nu, z_3^2\mu^2)\right] f(x,\mu^2)$$

- Direct connection between lattice $\mathfrak{M}(\nu, z_3^2)$ and LC PDF $f(x, \mu^2)$

- $a = 0.094$ fm

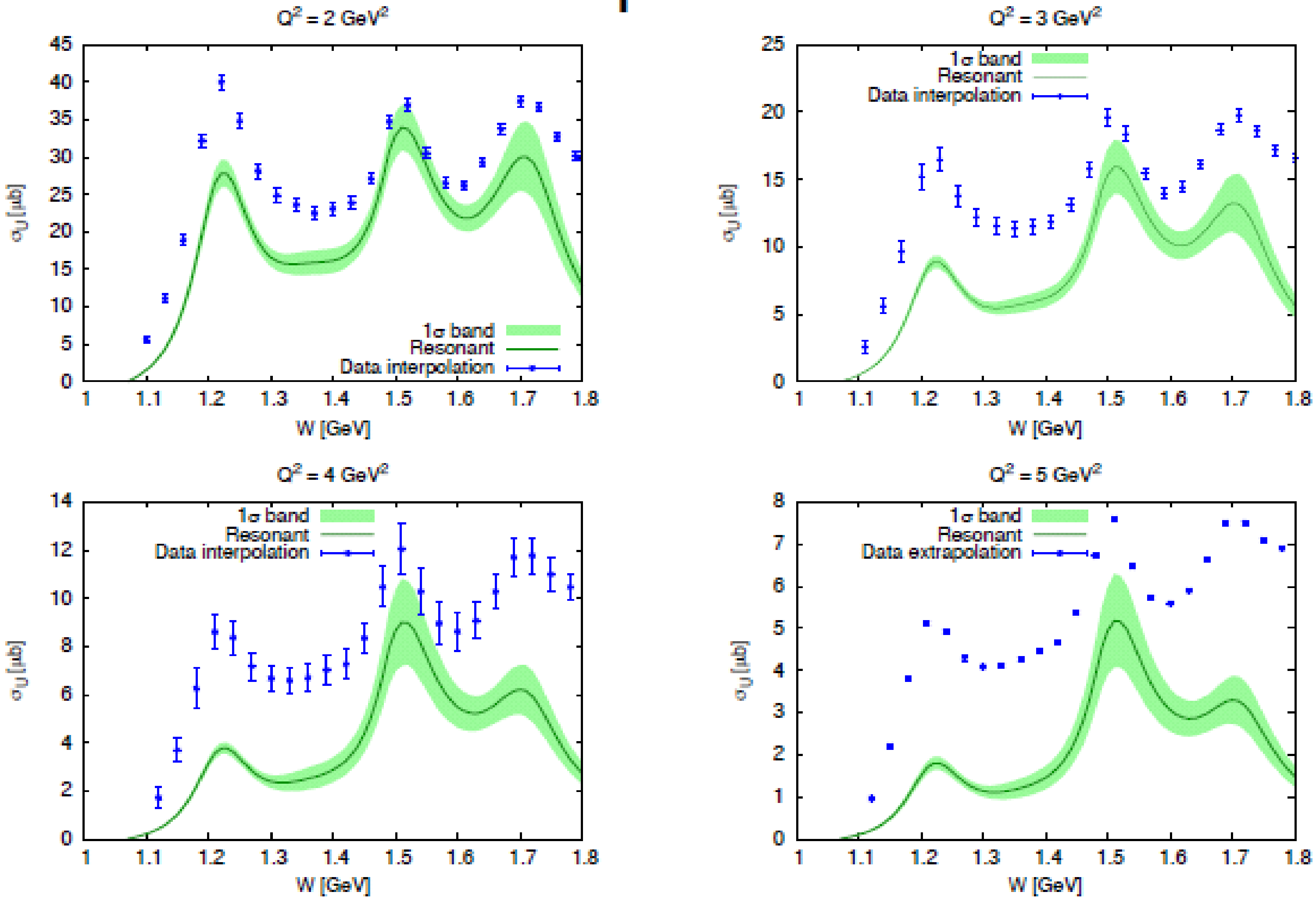


- PDF compared to global fits



- No intermediaries, like pseudo-PDFs or quasi-PDFs, are needed
- Work in progress on getting kernels for RI/MOM renormalization used in quasi-PDF applications

Inclusive unpolarized cross sections



A. Hiller Blin

ANHB et al., PRC100 (2019) 035201

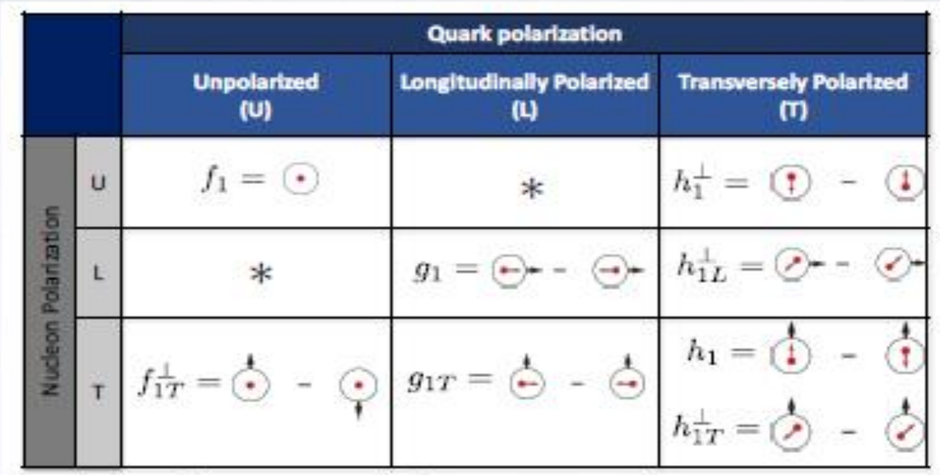
Opportunity for the extraction of parton distributions accounting for the resonant contributions computed from the experimental results on $\gamma_v pN^*$ electrocouplings

Parton Distributions in the Ground Nucleon from SIDIS

M. Radici

quark

nucleon



Sivers | T worm gear

at leading twist

Boer-Mulders

L worm gear

transversity

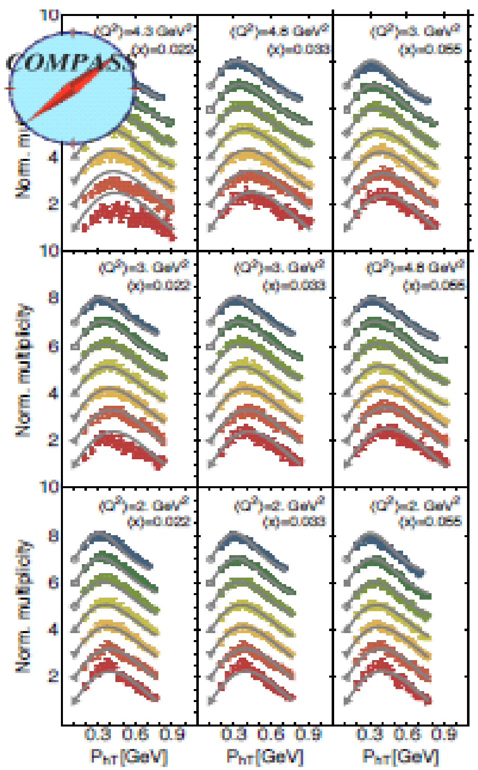
pretzelosity

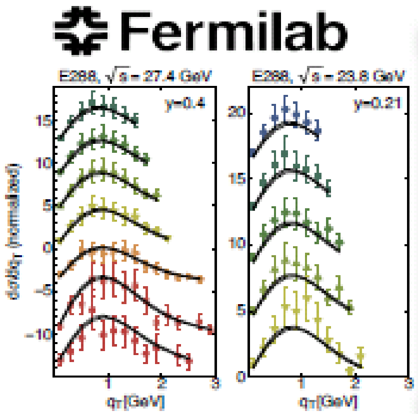
3D maps of

- partonic quantum correlations: spin-spin, spin-momentum (orbit)
- quantum correlations between partonic motion and macroscopic nucleon properties (spin)
- partonic orbital motion (most TMDs vanish with no L^q)
- color-gauge invariance and time-reversal symmetry of QCD

The Pavia 2017 fit

first fit putting together SIDIS, Drell-Yan, and Z production

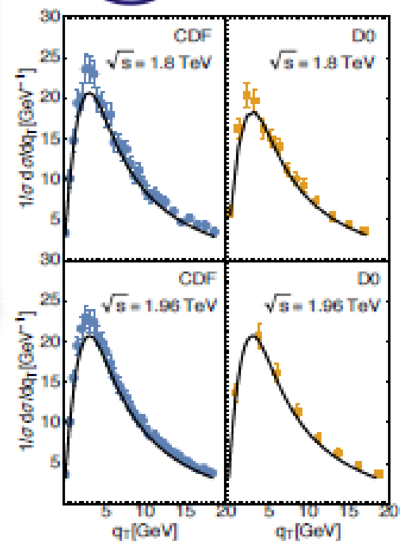




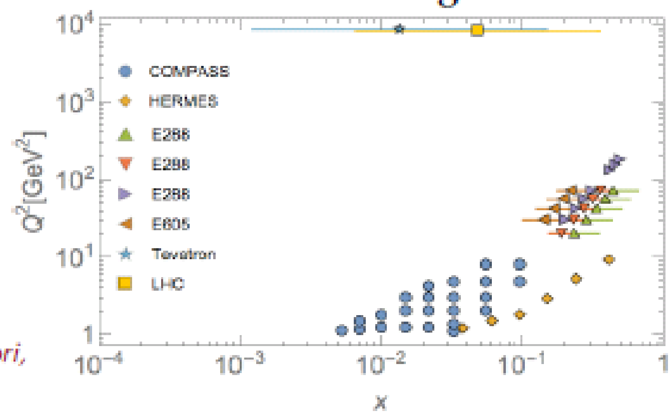
data points
8059

\# fit parameters
11

global χ^2/d.o.f.
1.55 ± 0.05



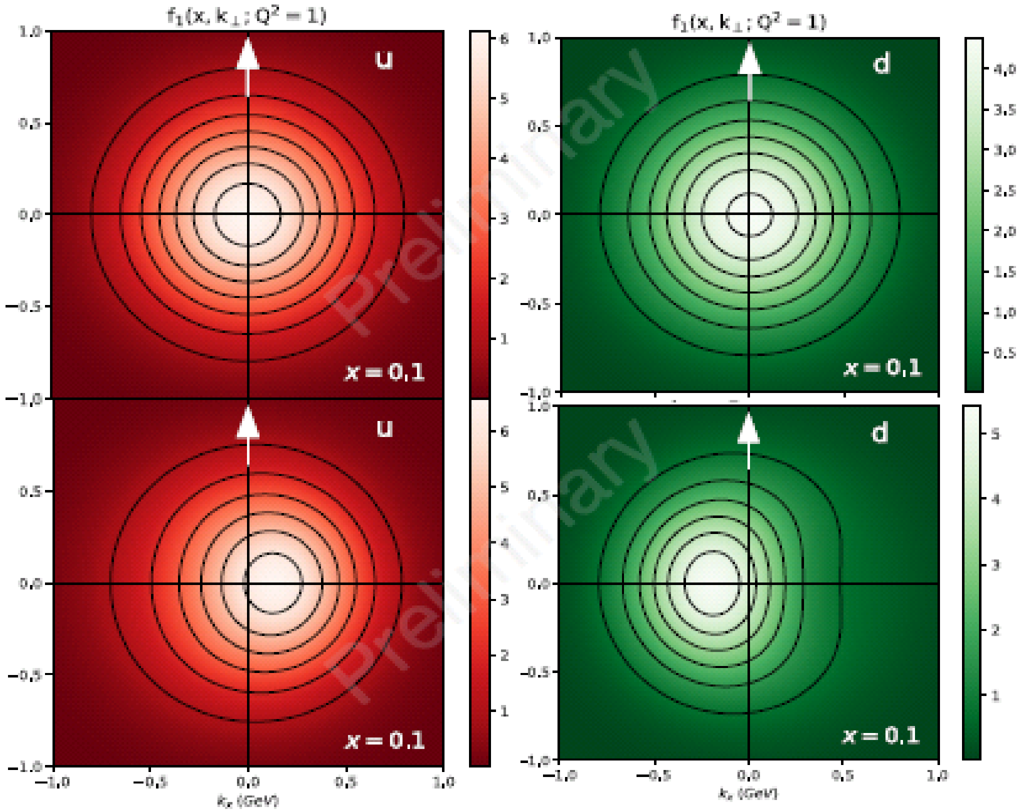
data coverage



Bacchetta, Delcarro, Pisano, Radici, Signori,
JHEP ***1706*** *(17) 081, arXiv:1703.10157*

Ground Nucleon 3D-image in the Momentum Space

The Pavia 2019 fit of Sivers $f_{1T}^{\perp}$ (preliminary)



Bacchetta, Delcarro, Pisano, Radici, in preparation

$$f_{q/p^{\uparrow}}(x, \boldsymbol{k}_T) = f_1^q(x, \boldsymbol{k}_T)$$

$$f_{q/p^{\uparrow}}(x, \boldsymbol{k}_T) = f_1^q(x, \boldsymbol{k}_T) - f_{1T}^{\perp q}(x, \boldsymbol{k}_T)\, \boldsymbol{S} \cdot \left(\frac{\hat{\boldsymbol{P}}}{M} \times \boldsymbol{k}_T \right)$$

M. Radici

(distorted) plots entirely based on data

Ground States are *Easy*. Equally, Ground States are Insufficient

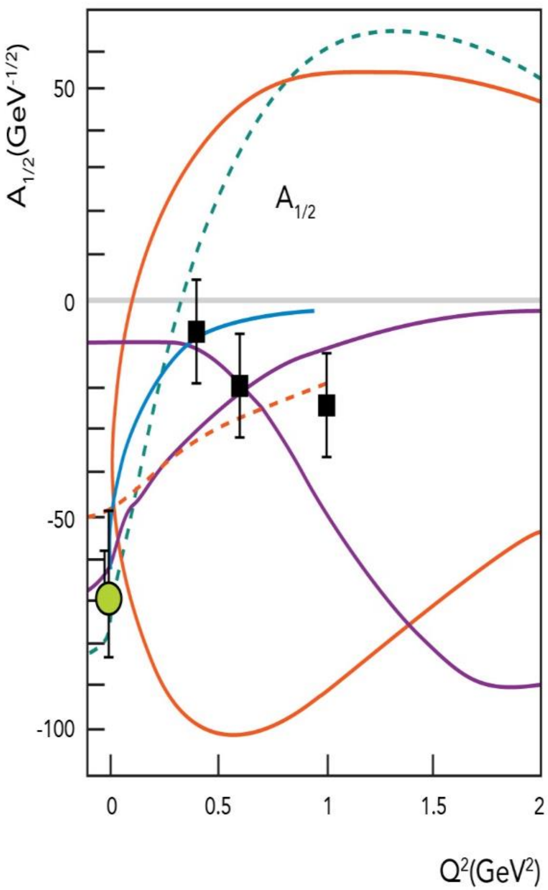
C.D. Roberts

- Results on N* structure and those for ground state nucleons & mesons cannot be divorced.
- To validate any explanation, one must expose & study the properties of all systems that can be produced by the theory & insist that the approach provide a truly unifying explanation
- True for meson & baryon & hybrid & exotic sectors.
- Any claim to understand QCD must explain all these things simultaneously, *e.g*.
  - How is emergent mass expressed in different bound-states?
  - Are any differences readily understood?
  - Are correlations an essential feature of *all* $n \geq 3$ valence-parton systems?
- ***A focus on ground-states alone is like throwing out the baby and keeping the bathwater***

Roper Resonance in 2002 & 2019

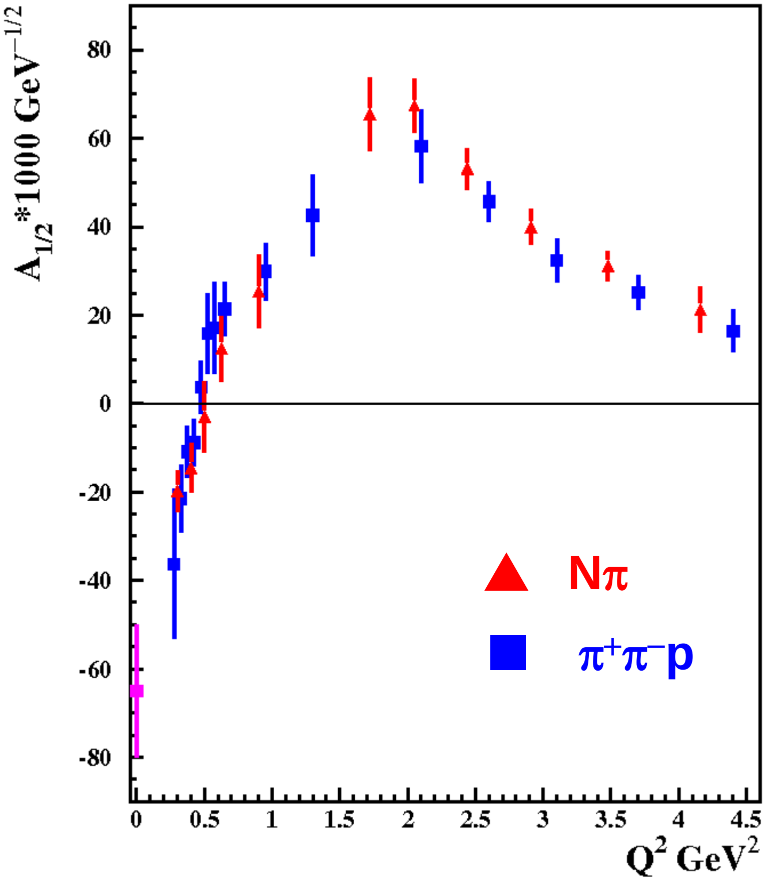
R.W. Gothe

2002



Baryons 2002

2019



Strong QCD Workshop 2019

Summary of Results on $\gamma_v pN^*$ Electrocouplings from CLAS

Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v pN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$	0.16-6.0
	$N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$	0.30-4.16
$\pi^+ n$	$N(1675)5/2^-$, $N(1680)5/2^+$ $N(1710)1/2^+$	1.6-4.5
ηp	$N(1535)1/2^-$	0.2-2.9
$\pi^+\pi^- p$	$N(1440)1/2^+$, $N(1520)3/2^-$	0.25-1.50
	$\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$	0.5-1.5

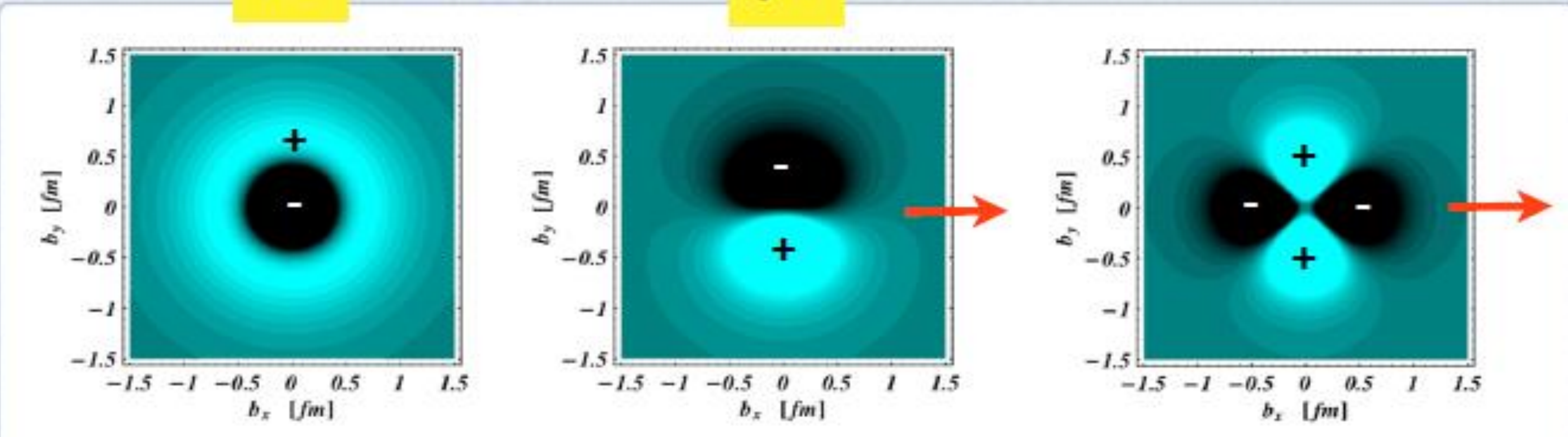
The website with numerical results and references:
https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

$N \rightarrow \Delta(1232)$ transition densities

M.Vanderhaeghen

$$
\begin{aligned}
\rho_T^{N\Delta}(\vec{b}) &\equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp\cdot\vec{b}} \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, s_\perp^\Delta = +\frac{1}{2} \,|\, J^+(0) \,|\, P^+, -\frac{\vec{q}_\perp}{2}, s_\perp^N = +\frac{1}{2} \rangle \\
&= \int_0^\infty \frac{dQ}{2\pi} \frac{Q}{2} \Big\{ J_0(b\,Q)\, G^+_{+\frac{1}{2}+\frac{1}{2}} \quad \longrightarrow \text{monopole} \\
&\quad - \sin(\phi_b - \phi_S)\, J_1(b\,Q) \left[\sqrt{3} G^+_{+\frac{3}{2}+\frac{1}{2}} + G^+_{+\frac{1}{2}-\frac{1}{2}} \right] \longrightarrow \text{dipole} \\
&\quad - \cos 2(\phi_b - \phi_S)\, J_2(b\,Q) \sqrt{3}\, G^+_{+\frac{3}{2}-\frac{1}{2}} \Big\} \quad \longrightarrow \text{quadrupole}
\end{aligned}
$$

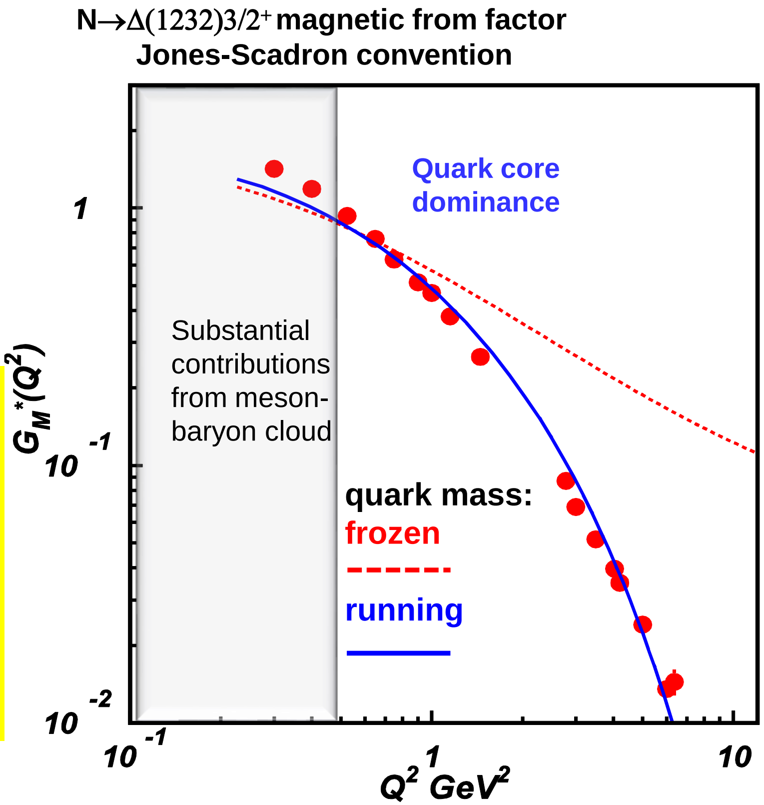
ρ_0 P -> Δ^+ ρ_T quadrupole term

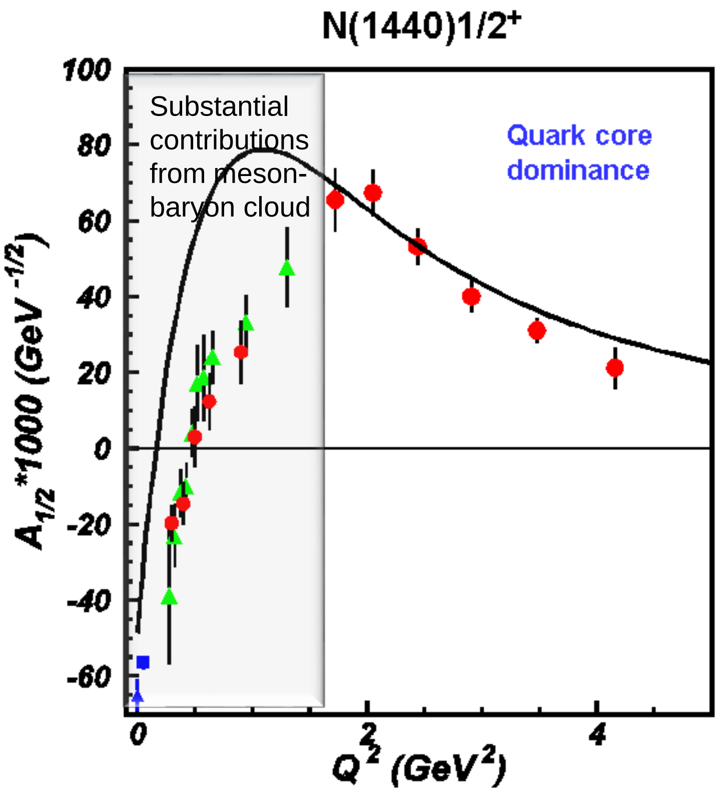


Carlson, Vdh(2007)

14

J. Segovia, R.W Gothe





Dyson-Schwinger Equations (DSE):

- **J. Segovia et al., Phys. Rev. Lett. 115, 171801 (2015).**
- **J. Segovia et al., Few Body Syst. 55, 1185 (2014).**

- **Good data description at Q^2>2.0 GeV^2 with the same dressed quark mass function for the ground and different excited nucleon states validate the DSE results on generation of dressed quarks as the relevant degree of freedom in the structure of the ground and excited nucleons.**

- **γ_vpN* electrocoupling data offer access to the strong QCD dynamics underlying the hadron mass generation.**

Faddeev amplitude of the ground nucleon can be evaluated with the dressed quark mass function and di-quark correlations checked against the data on gvpN* electrocouplings

Synergy in the Studies of the Ground and Excited Nucleon Structure

- **Faddeev amplitude encoded a full information on the ground nucleon structure**
- **GPDs/TMDs can be evaluated from Faddeev amplitudes, plugged into the reaction models for evaluation of the DVCS,DVMP/SIDIS observables and confronted with the data**
- **Successful description of the DVCS,DVMP/SIDIS observables with the dressed quark mass function and di-quark correlation amplitudes checked against the data on $\gamma_v pN^*$ electrocouplings will confirm credible insight into the strong QCD dynamics underlying the ground nucleon generation. will shed light on emergence of hadron mass and quark-gluon confinement from QCD.**

Talks by: L. Elouadrhiri, S. Liuti, M. Vanderhaeghen, A.Kim, M. Ben Ali, C. Mezrag, Z-E. Mezziani (experiment/phenomenology advances)

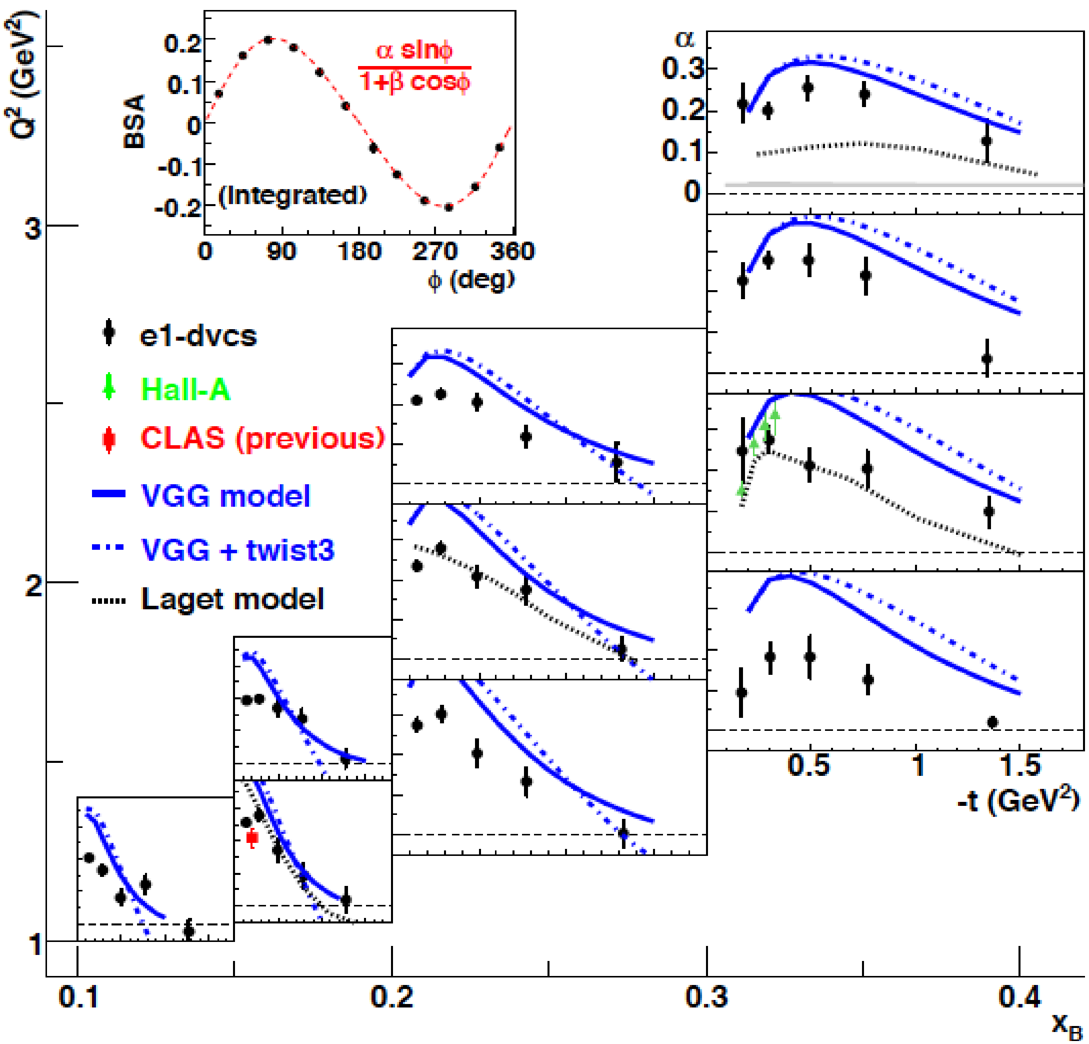
- Studies of unpolarized DVCS/DVMP cross sections and beam, beam-target asymmetries for different orientations of the target-proton spin are needed

- Offer access to the GPDs at $x=\xi$ or to the integrals from GPDs

- The models are needed in order to gain insight into the GPDs in an entire range of x, ξ, t

DVCS BEAM SPIN ASYMMETRY

F.X. Girod et al. Phys.Rev.Lett. 100 162002 (2008)



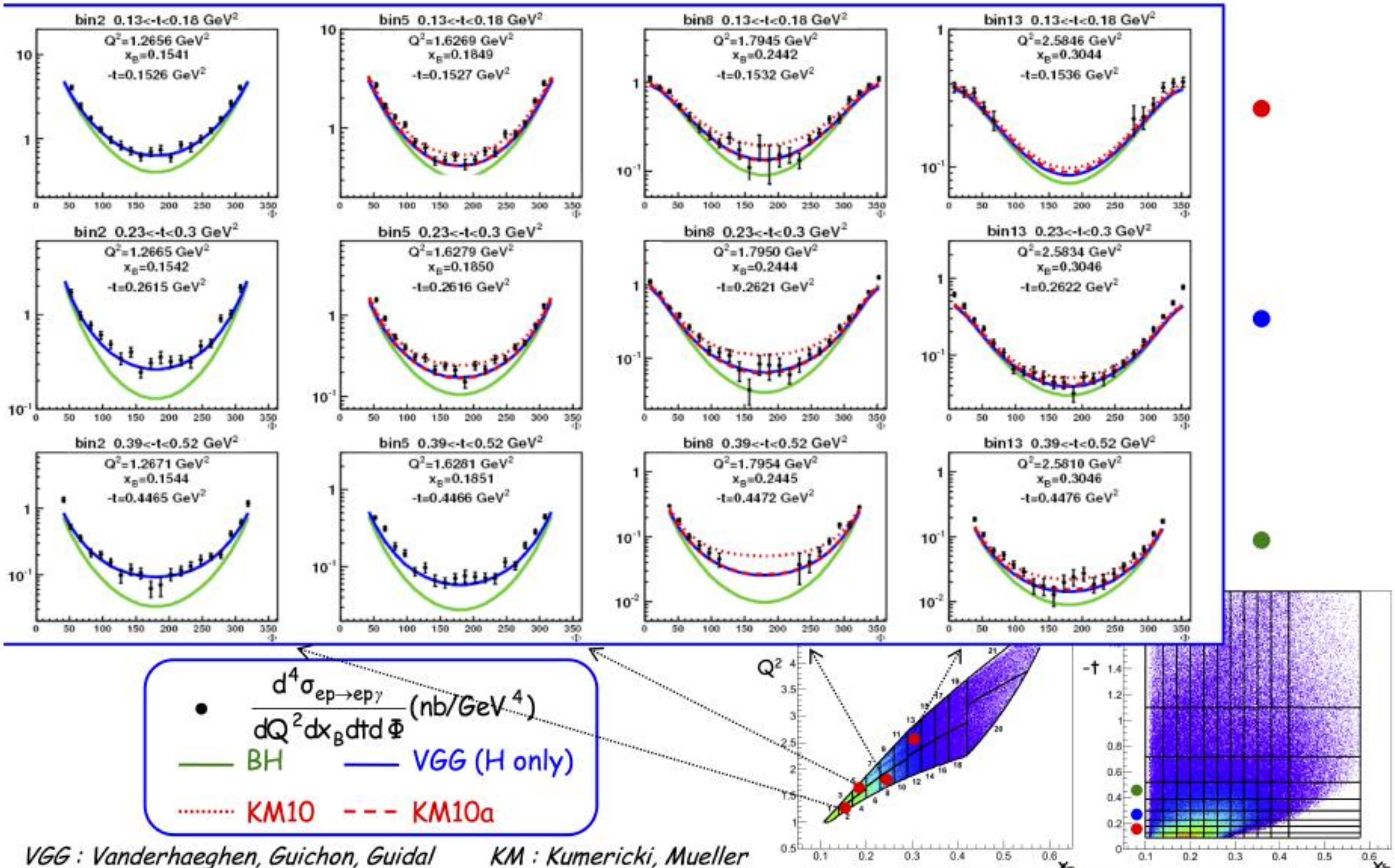
Measurements in a large phase space Q^2, x_B, t

$$A = \frac{d^4\vec{\sigma} - d^4\overleftarrow{\sigma}}{d^4\vec{\sigma} + d^4\overleftarrow{\sigma}}$$

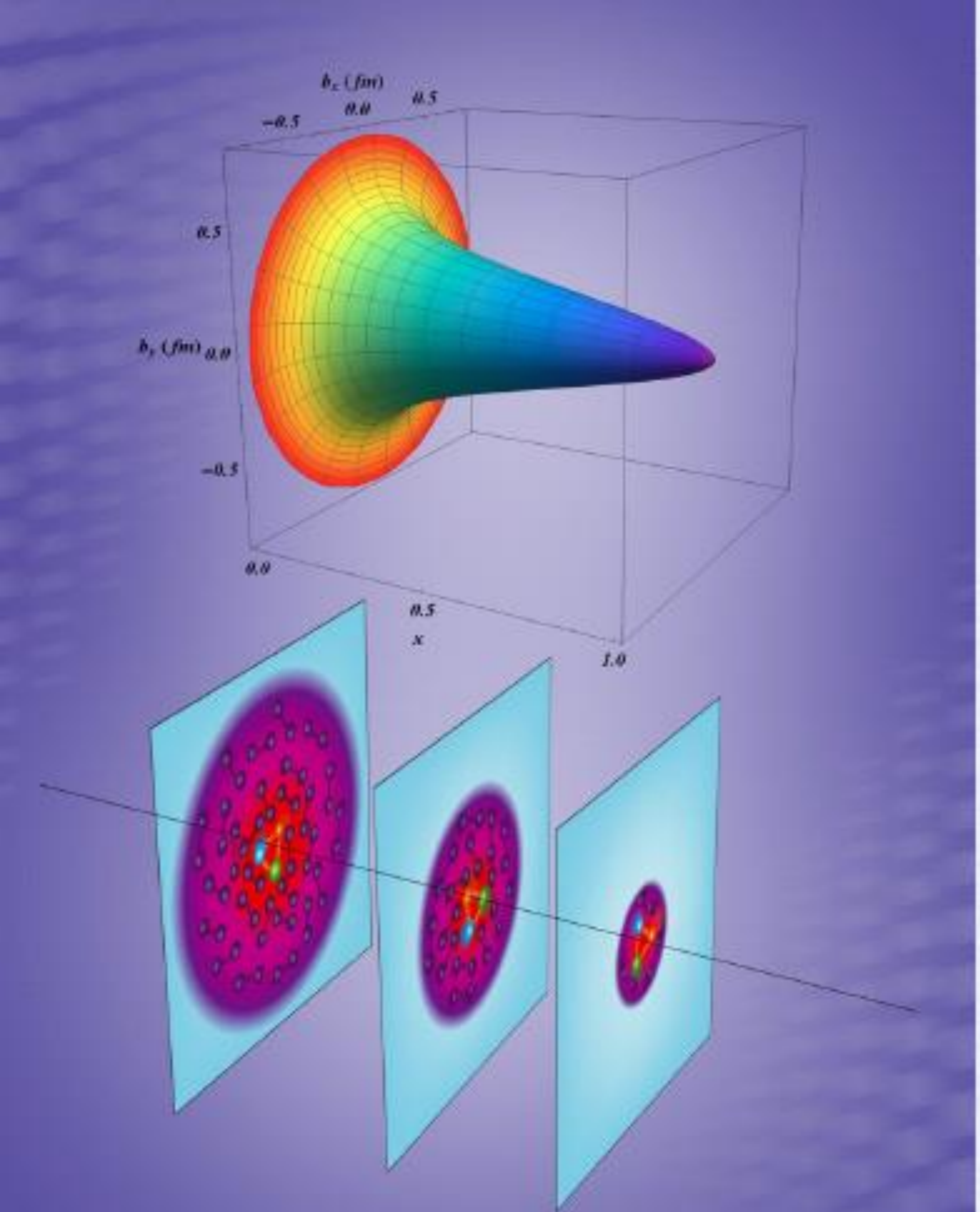
$$F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$

small & suppressed

DVCS UNPOLARIZED CROSS-SECTIONS



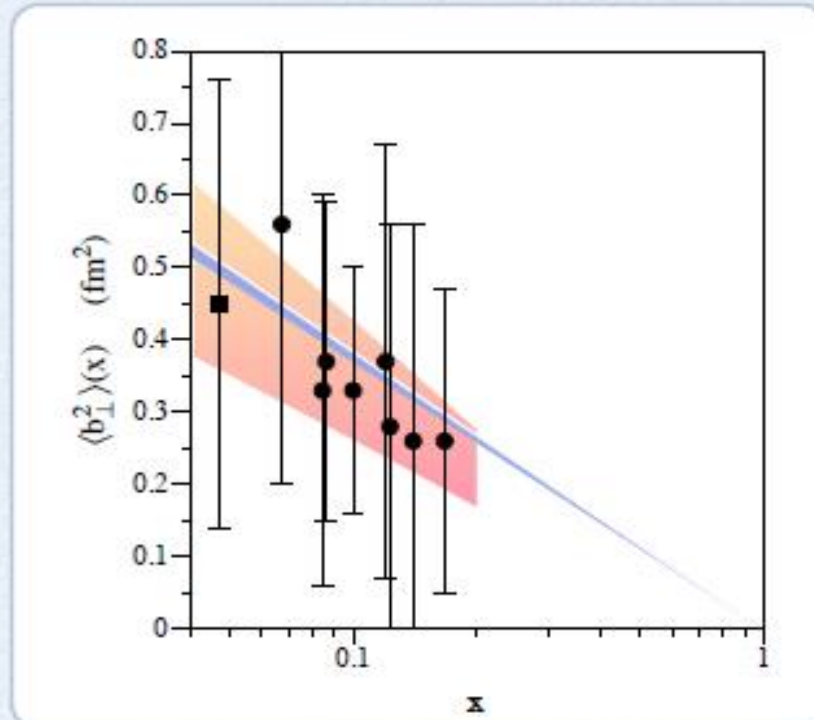
H.-S. Jo *et al.*, PRL 115 212003 (2015)



3D imaging of proton

M.Vanderhaeghen

black circles: CFF fit of JLab data



narrow band: $B_0(x) = a_{B_0} \ln(1/x)$

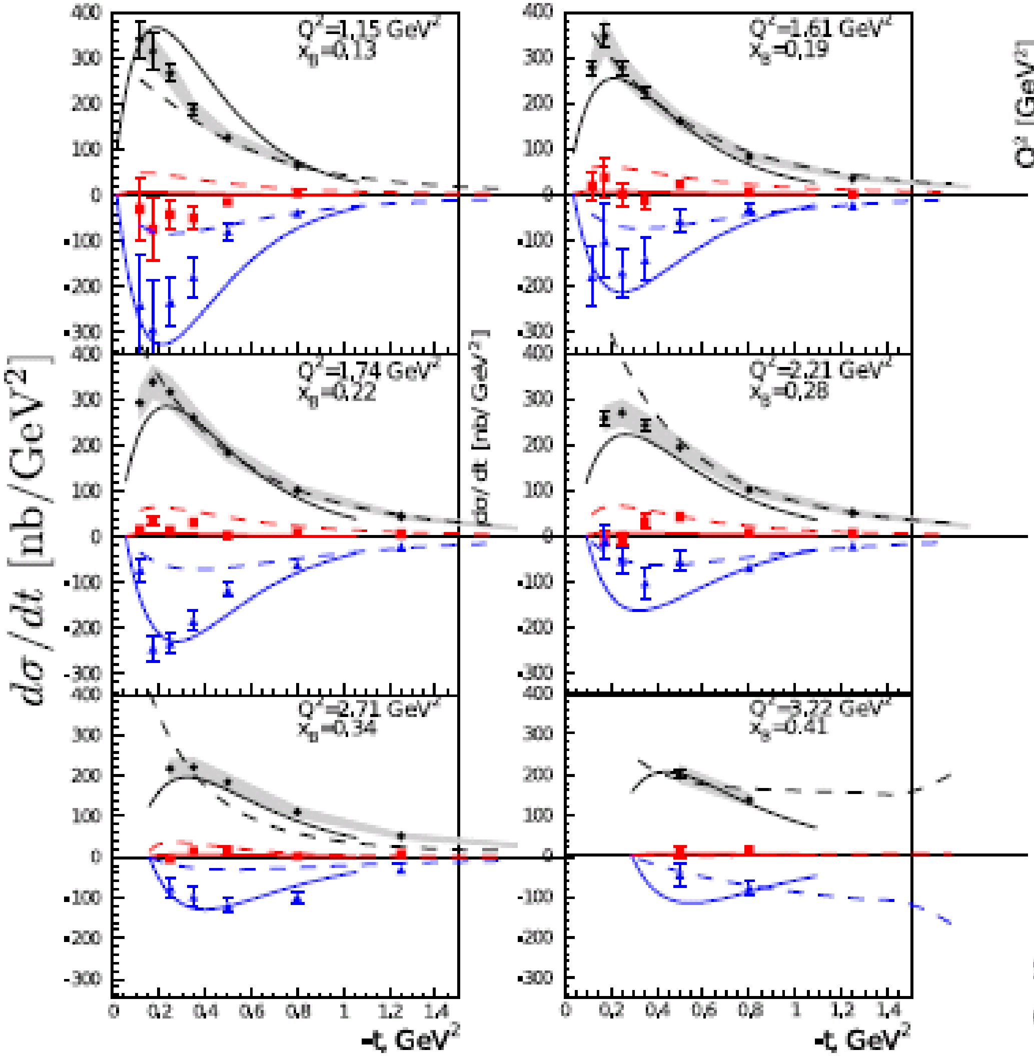
a_{B_0} fixed from elastic scattering

Dupré, Guidal, Niccolai, Vdh(2017)

Can the image be computed under connection to QCD? See the talks by J.Qiu

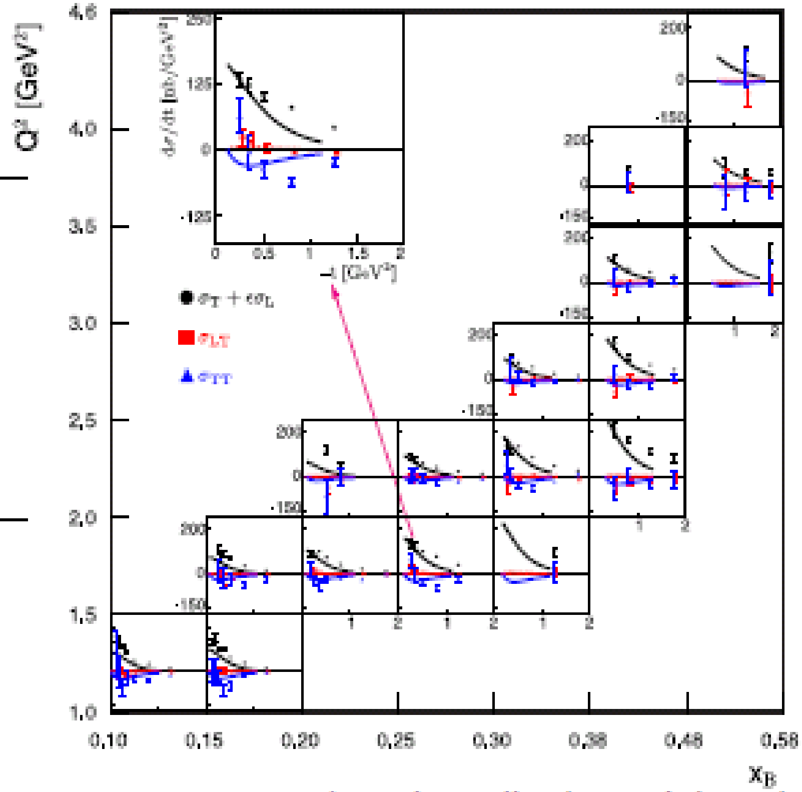
π^0/η structure functions from CLAS

π^0 electroproduction



PRL109:112001 (2012) I. Bedlinskiy et al. (CLAS collaboration)

η electroproduction



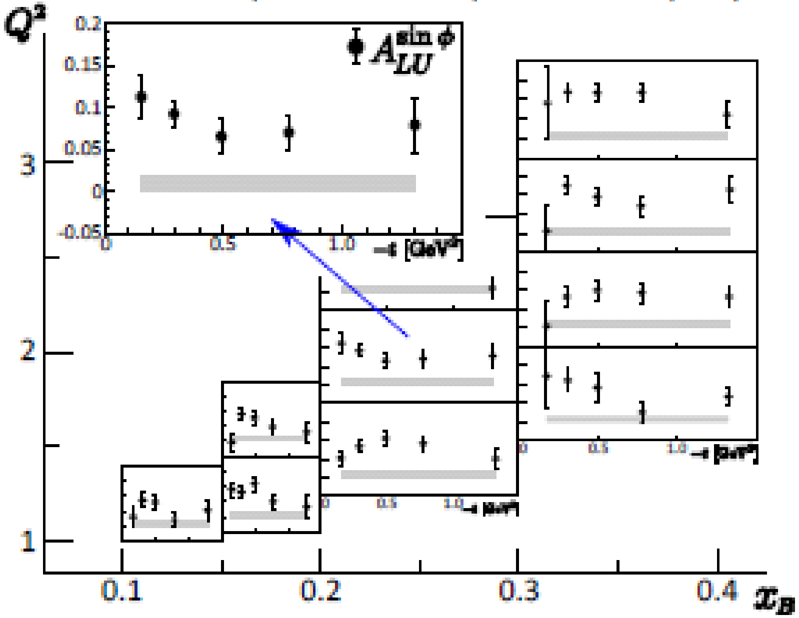
PRL95: 035202 (2017) I.Bedlinsky et al. (CLAS)

solid: P.Kroll & S.Goloskokov
dashed: G.R. Goldstein, J.O. Gonzalez & S.Liuti

Spin asymmetry variables

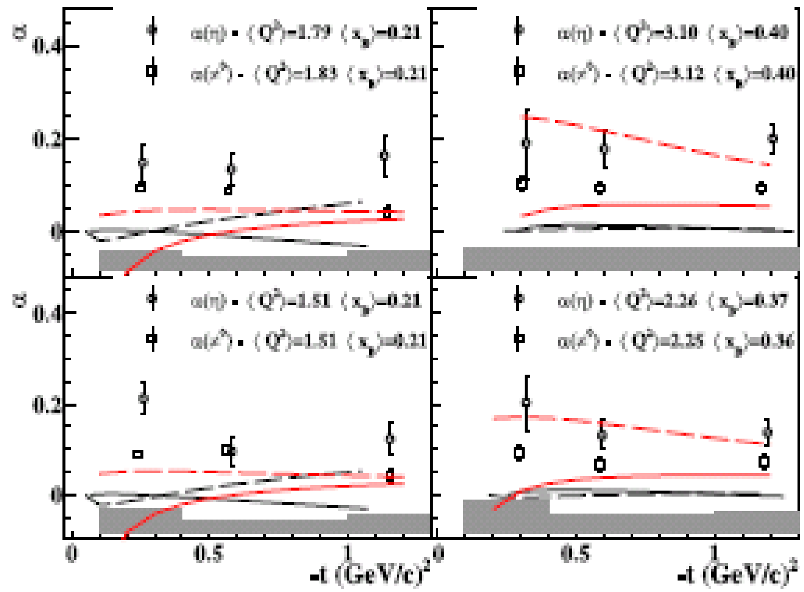
π^0 Beam Spin Asymmetries

R. De Masi *et al.* (CLAS collaboration) PRC77: 042201 (2008)



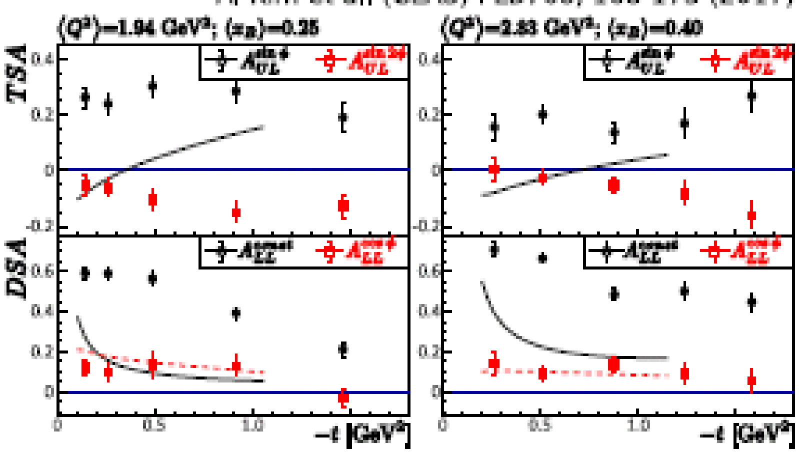
η Beam Spin Asymmetries

B. Zhao, A. Kim et al. (CLAS) submitted to PLB, 2018



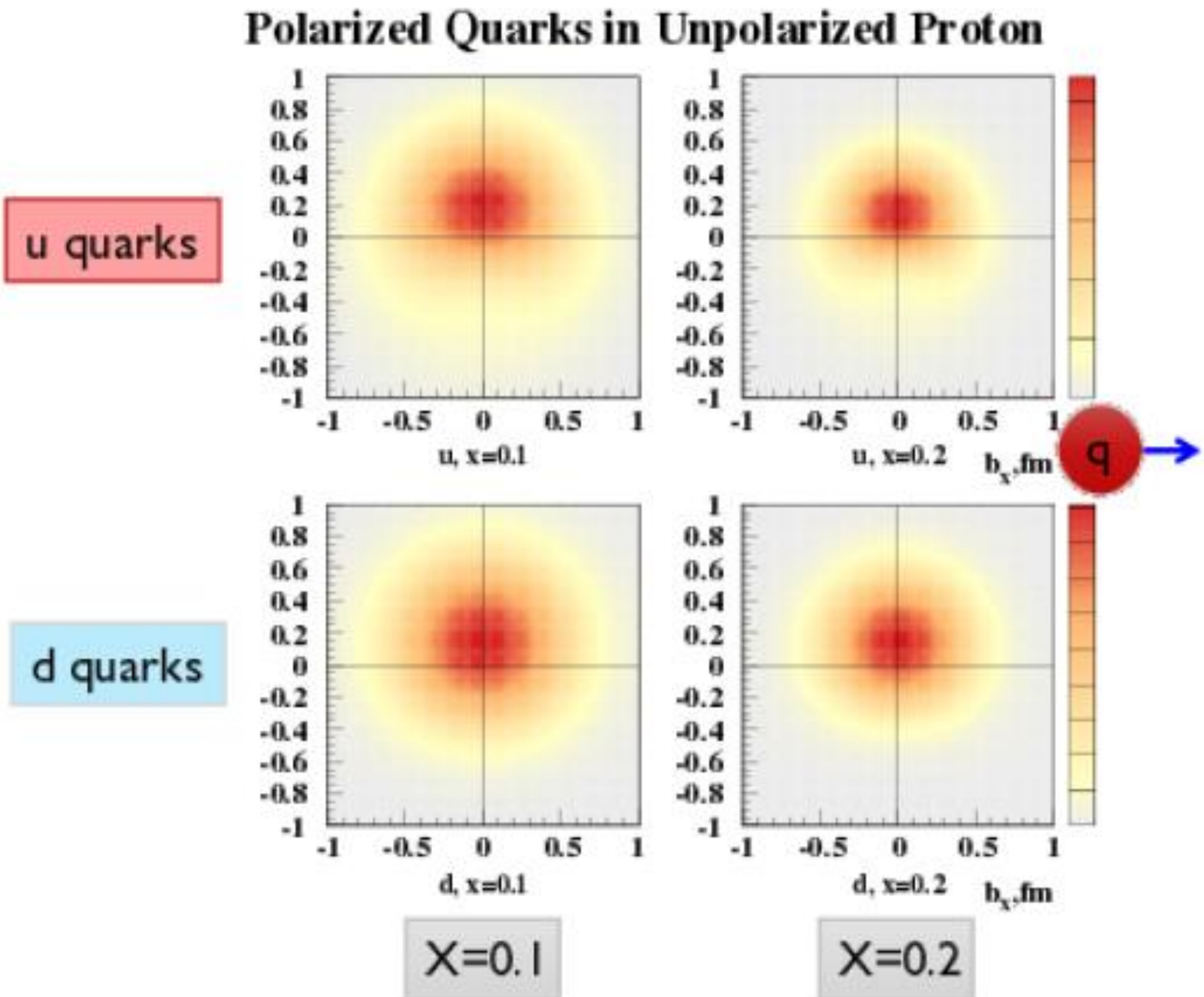
π^0 Target and Double Spin Asymmetries

A. Kim et al. (CLAS) PLB768, 168-173 (2017)



- Large number of single and double spin asymmetries were measured over wide kinematic range
- Asymmetries are harder to interpret since they involve convolutions of chiral even and chiral odd GPDs

Transverse densities for u and d quarks in the proton



THE GPDS AND GRAVITATIONAL FORM FACTORS

Nucleon matrix element of the Energy-Momentum Tensor contains three scalar form factors (R. Pagels, 1966) and can be written as (X. Ji, 1997):

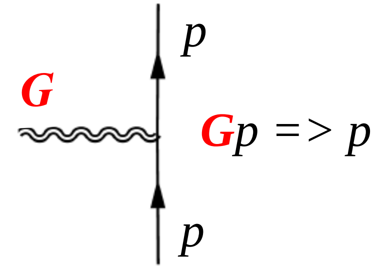
$$\langle p_2|\hat{T}^q_{\mu\nu}|p_1\rangle = \bar{U}(p_2)\left[M_2^q(t)\frac{P_\mu P_\nu}{M} + J^q(t)\frac{i(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M} + d_1^q(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M}\right]U(p_1)$$

$M_2(t)$: Mass distribution inside the nucleon

$J(t)$: Angular momentum distribution

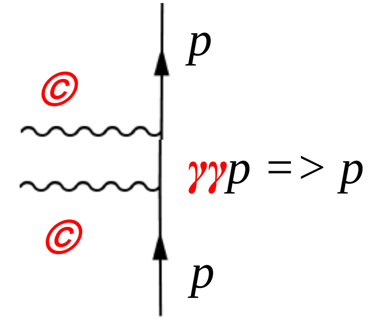
$d_1(t)$: Forces and pressure distribution

Graviton scattering



GPDs ⟺ GFFs

DVCS



$$\int dx\, x\,[H(x,\xi,t) + E(x,\xi,t)] = 2J(t)$$

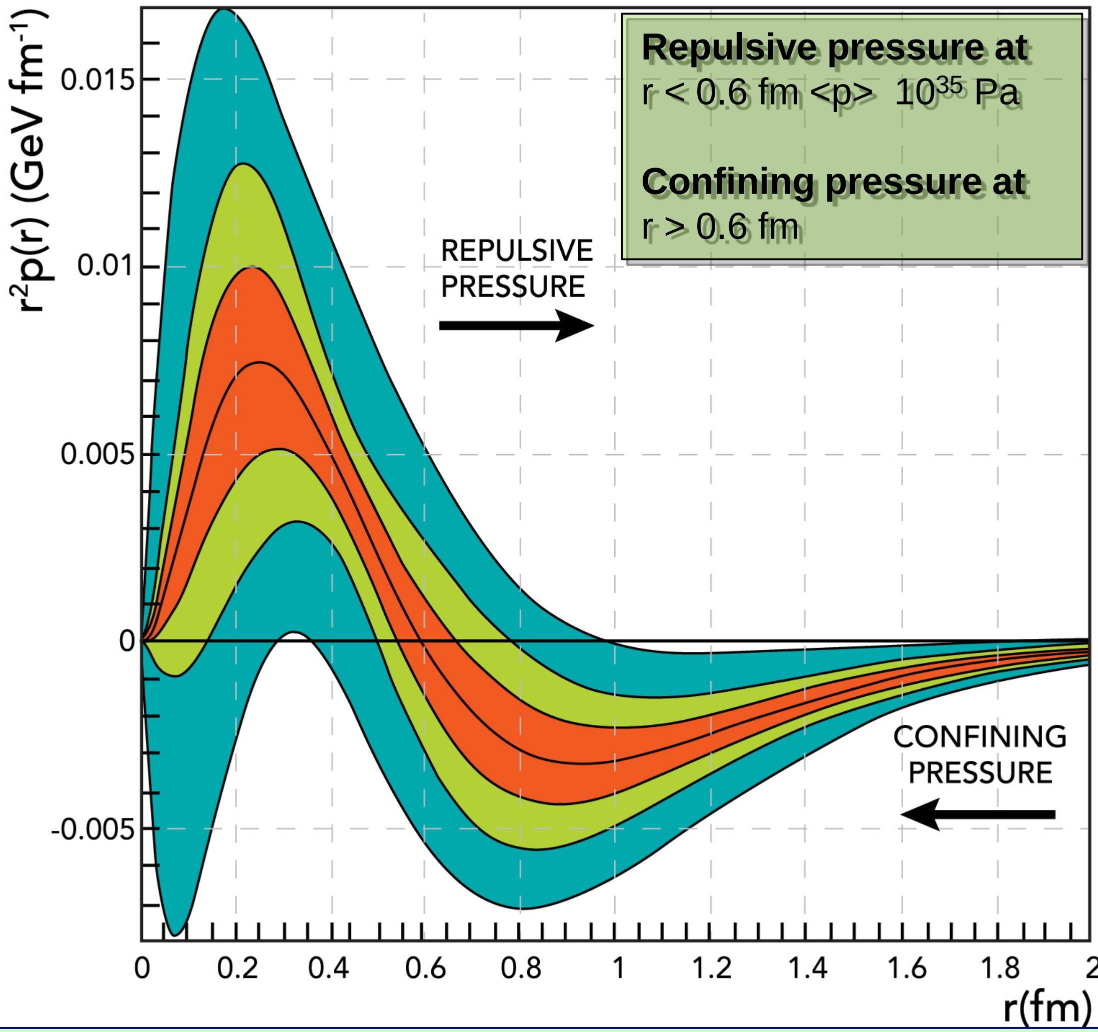
$$\int dx\, x H(x,\xi,t) = M_2(t) + \frac{4}{5}\xi^2 d_1(t),$$

X. Ji, Phys. Rev. Lett. 78, 610 (1997)

X. Ji, Phys. Rev. D55, 7114 (1997)

Jefferson Lab

THE PRESSURE DISTRIBUTION INSIDE THE PROTON



nature

International weekly journal of science

Nature 557 (2018) no.7705, 396-399

V. Burkert, L. Elouadrhiri, F.X. Girod

This work opens up a new area of research on the fundamental gravitational properties of protons, neutrons and nuclei, which can provide access to their physical radii, the internal shear forces acting on the quarks and their pressure distributions.

How the balance between repulsive and confining pressure comes from QCD?

Jefferson Lab

Synergy in the Studies of the Ground and Excited Nucleon Structure

- **Different data sets from experiments with electromagnetic probes from the measurements in the N* and DIS-regions with a focus on exploration of both ground and excited hadron structure offer an excellent opportunity to gain insight into strong QCD undelying the hadron generation from quarks and gluons**

- **Synergistic efforts between experimentalists phenomenologists and theorists is needed.**

- **Roadmap forward:**
  a) publication of the ``Strong QCD from Hadron Structure Experiments" with a goal to facilitate the new research projects on exploration of strong QCD from the experimental data on spectra and structure of the ground and excited hadrons;

  b) continuation of the Workshops with the planned next Workshop in the first half of 2021 in Nanjing University, China under C.D. Roberts leadership

NANJING UNIVERSITY

sQCD 2021

Experiment and Theory for Strong QCD

Craig Roberts … http://inp.nju.edu.cn/