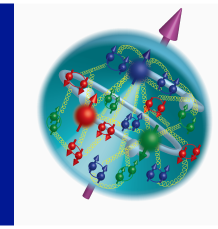
Overview on Experimental Studies of Nucleon Structure



ZEIN-EDDINE MEZIANI
Argonne National Laboratory

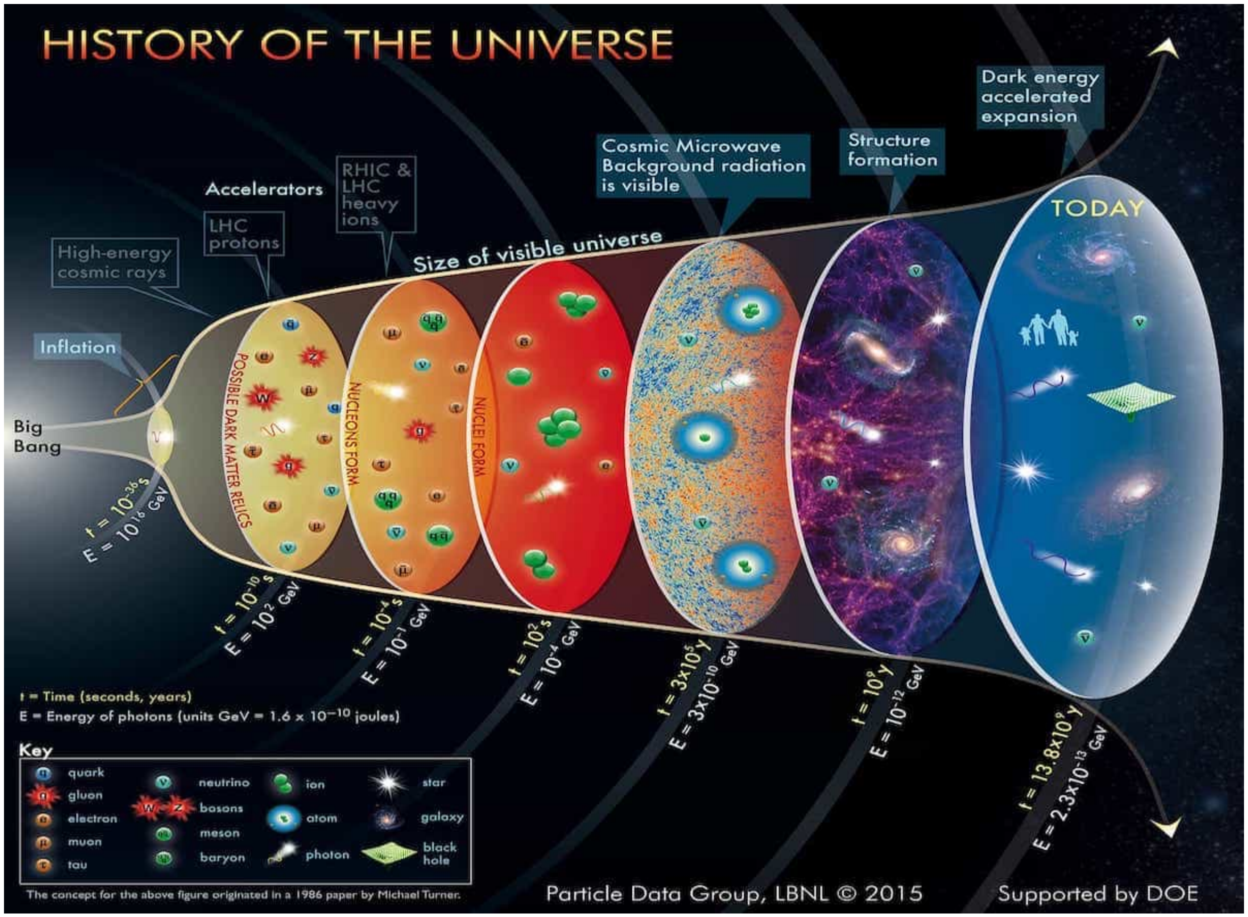
- **Origin of Mass**
  - Trace anomaly
  - Pion-nucleon sigma-term

- **Origin of Spin**
  - Electromagnetic form factors
  - Polarizabilities
  - 1D parton distributions
    - PDFs
  - 3D partonic structure of the nucleon
    - GPDs, TMDs

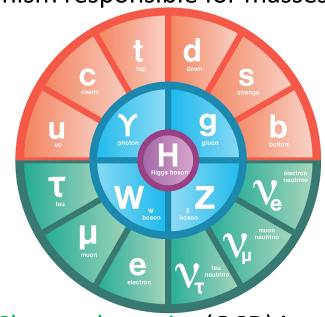
Disclaimer: This talk is not meant to be a complete overview, but gives a flavor of experimental activities/results

To know your future you must know your past

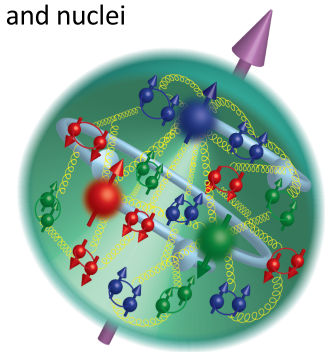
George Santanaya (American philosopher, poet and cultural critic: Born in Madrid, 1863-1952)



Standard Model of Particle Physics: Higgs mechanism responsible for masses

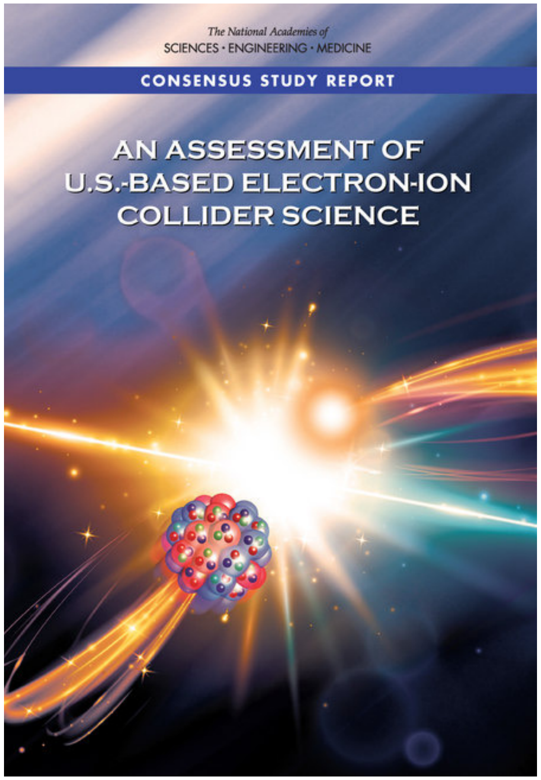


Quantum Chromodynamics (QCD) is responsible for most of the visible matter in the universe providing mass and spin to nucleons and nuclei



Nucleon: A fascinating strong interacting system of confined quarks and gluons. Chiral effective theories and lattice have played a key role in our progress.

EIC Science Assessment by NAS



Finding 1:

An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- 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?

How Does QCD generate its Mass & Spin?

"…QCD takes us a long stride towards
the Einstein-Wheeler ideal of mass without mass

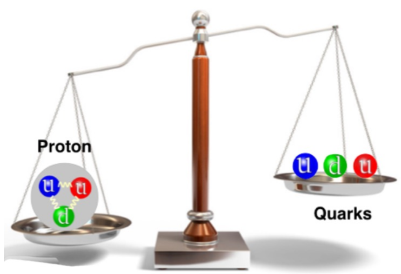
Frank Wilczek (1999, Physics Today)

Examples in nature: proton, blackhole

- What is the origin of hadron masses?
  - A case study: the proton.

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

The 2015 Long Range Plan for Nuclear Science

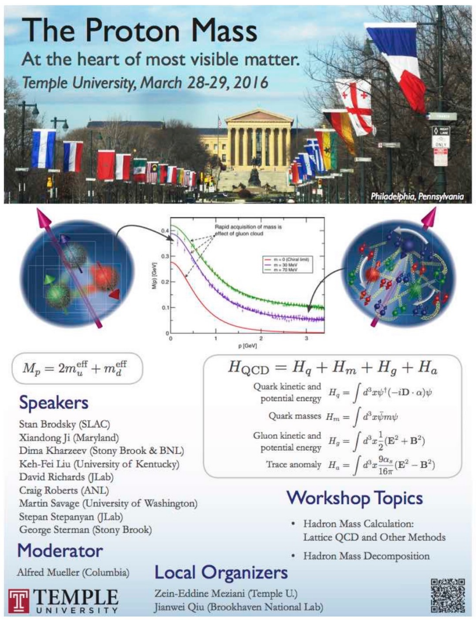


Threshold electro-photoproduction of quarkonium can probe the energy distribution of gluonic fields inside the proton and nuclei

The proton mass… a hot topic!

A precursor workshop before PR12-12-006 proposal was submitted was held in **2012**: http://quarks.temple.edu/~npcfiqcd

2016



2017

Jan. 2021

Credit: Z.-E Meziani

https://indico.phy.anl.gov/event/2/

Due to COVID-19 a 2020 INT proton mass workshop has been postponed to 2022 to become the 4th workshop in the series

- lattice QCD
- mass decomposition – roles of the constituents
- approximated analytical or model approaches

Access to the Quantum Anomalous Energy through elastic J/ψ and Upsilon production near threshold

How does QCD generates the nucleon mass?
Breaking of scale Invariance

See for example, **M. E. Peskin and D. V. Schroeder, An Introduction to quantum field theory, Addison-Wesley, Reading (1995), p. 682**

✧ **Trace of the QCD energy-momentum tensor:**

D. Kharzeev Proc. Int. Sch. Phys. Fermi 130 (1996)

$$T^\alpha_\alpha = \underbrace{\frac{\beta(g)}{2g} G^{\alpha\beta a} G^a_{\alpha\beta}}_{\text{QCD trace anomaly}} + \sum_{l=u,d,s} m_l \bar{q}_l q_l + \sum_{c,b,t} m_h \bar{Q}_h Q_h$$

with $\beta(g) = -b\frac{g^3}{16\pi^2} + ...,$ $\quad b = 9 - \frac{2}{3} n_h$

Gross, Wilczek & Politzer

At small momentum transfer, heavy quarks decouple:

M. Shifman et al., Phys. Lett. 78B (1978)

$$\sum_h \bar{Q}_h Q_h \to -\frac{2}{3} n_h \frac{g^2}{32\pi^2} G^{\alpha\beta a} G^a_{\alpha\beta} + ...$$

$$T^\alpha_\alpha = \underbrace{\frac{\beta(g)}{2g} G^{\alpha\beta a} G^a_{\alpha\beta}}_{\text{Field energy}} + \underbrace{\sum_{l=u,d} m_l \bar{q}_l q_l}_{\text{Pion-nucleon sigma term}} + m_s \bar{q}_s q_s + ...$$

✧ **Trace anomaly, chiral symmetry breaking, …**

$$M^2 \propto \langle P | T^\alpha_\alpha | P \rangle \xrightarrow[\text{Chiral limit}]{} \frac{\beta(g)}{2g} \langle P | G^2 | P \rangle$$

In the chiral limit we have a finite number for the nucleon and zero for the pion

Higgs Mass Contribution to the proton mass

Pion-Nucleon Sigma Term

$$\sigma_{\pi N} = \langle N(P)|m_u\bar{u}u + m_d\bar{d}d|N(P)\rangle = (59.1 \pm 3.5)\ \mathrm{MeV}$$

Strangeness content

$$\sigma_s = \langle N(P)|m_u\bar{s}s|N(P)\rangle = 41.0(8.4)\ \mathrm{MeV}$$

A talk by Ulf-G Meißner at the 3rd Proton Mass WorkshopS, Jan 14-2021

https://indico.phy.anl.gov/event/2/

Consequence for the proton mass: About 100 MeV from the Higgs, the rest is gluon field energy

Hoferichter, Ruiz de Elvira, Kubis, Ulf-GMeißner Phys. Rev. Lett. 115 (2015) 092301 [arXiv:1506.04142]
Phys. Rev. Lett. 115 (2015) 192301 [arXiv:1507.07552] Phys. Rept. 625 (2016) 1 [arXiv:1507.07552]

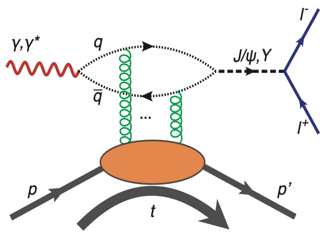
12 GeV experimental capabilities at Jefferson Lab

Argonne NATIONAL LABORATORY

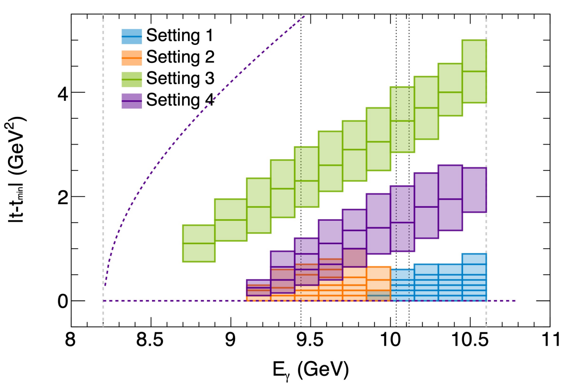
Z.-E. M, S. Joosten *et al.*, arXiv:1609.00676 [hep-ex]
K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141

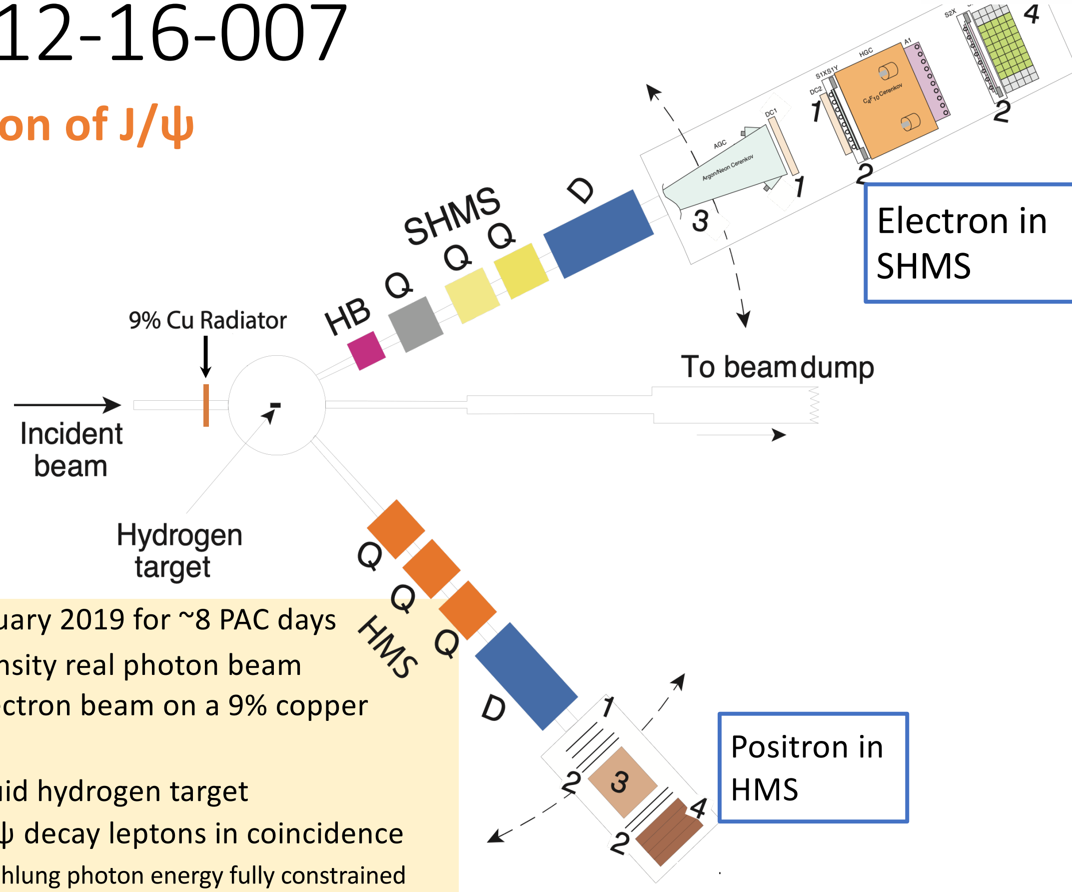
JLab experiment E12-16-007

Near threshold photoproduction of J/ψ



J/ψ threshold:
$W \approx 4.04\text{GeV}$
$E_\gamma^{lab} \approx 8.2\text{GeV}$
$t \approx -1.5\text{GeV}^2$





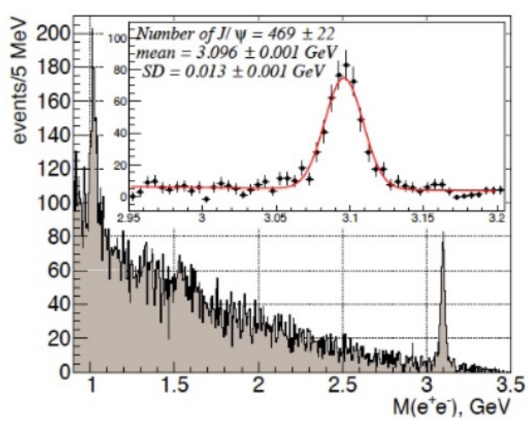
- Ran February 2019 for ~8 PAC days
- High intensity real photon beam (50μA electron beam on a 9% copper radiator)
- 10cm liquid hydrogen target
- Detect J/ψ decay leptons in coincidence
  - Bremsstrahlung photon energy fully constrained

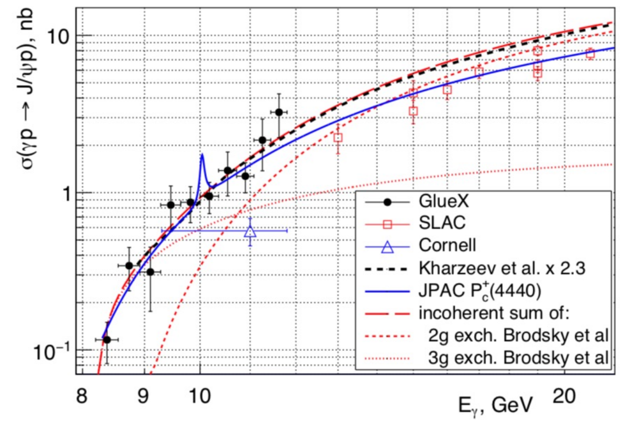
J/Ψ NEAR THRESHOLD IN HALL D

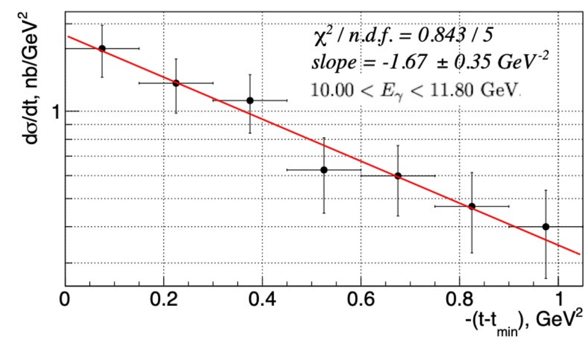
First J/ψ results from JLab, published in PRL 123, 072001 (2019)

- 1D cross section (~469 counts)
- Trends significantly higher than old measurements
- Also released a single 1D t-profile
- Published upper limits for s-channel pentaquark resonances at 90% confidence level
  - 1D limits on $\sigma(\gamma p \rightarrow P_c) \times \Gamma(P_c \rightarrow J/\psi\ p)$: resp. <4.6nb, <1.8nb, and <3.9nb at 90%
- Still consistent with pentaquark and molecular models
- 4x more statistics being analyzed

γp → p J/ψ → pe⁺e⁻

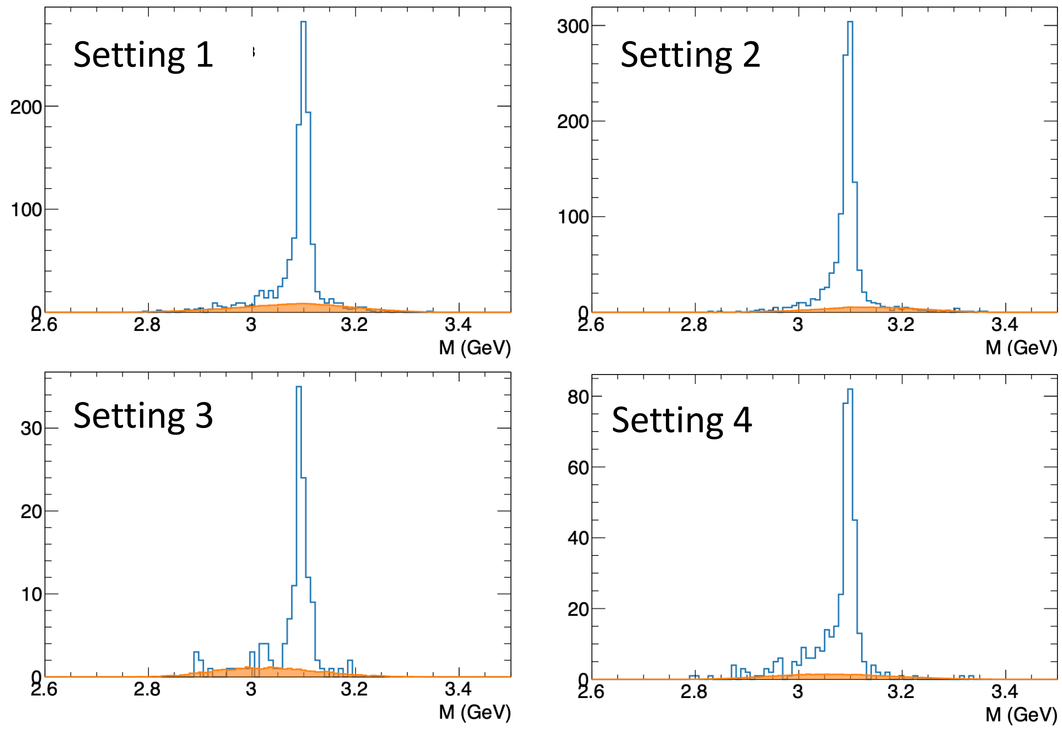






Clear J/ψ signal with minimal background

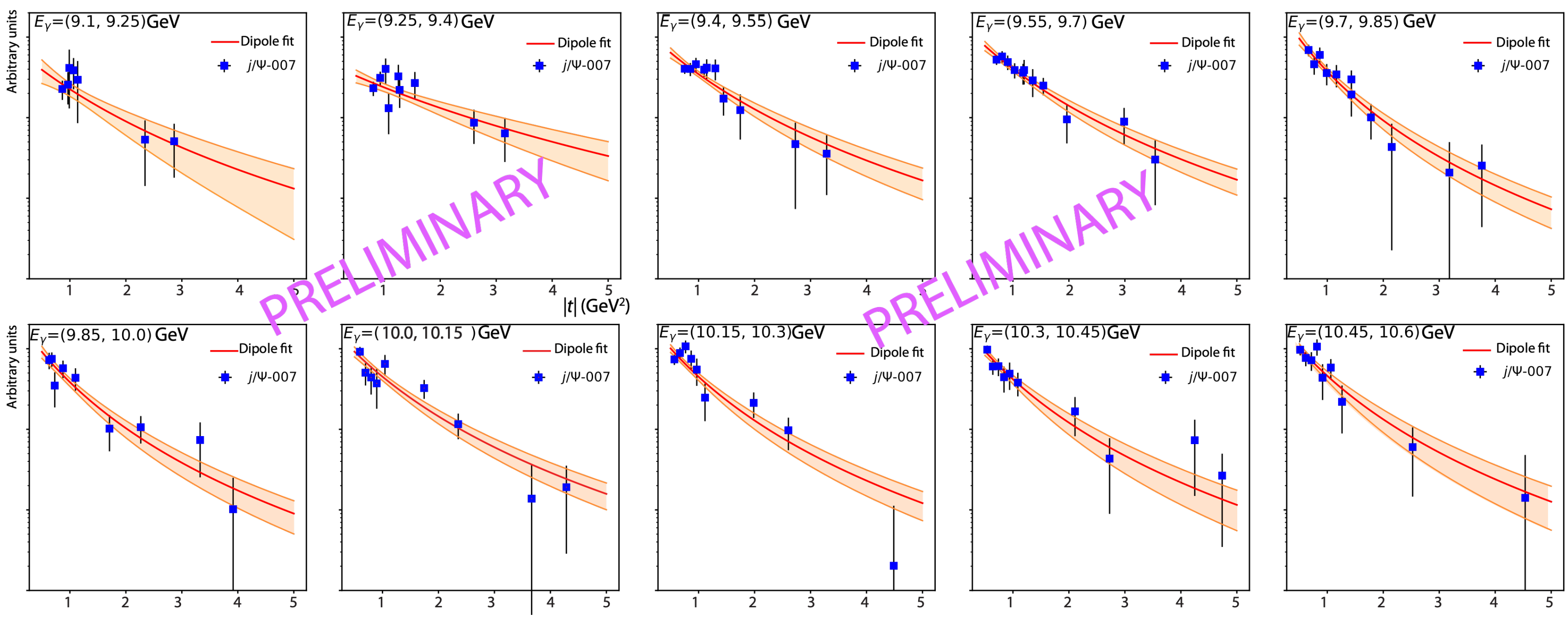
settings	HMS	SHMS	target	charge [C]	goal
setting 1	19.1° at +4.95GeV	17.0° at -4.835GeV	LH2 with radiator dummy with radiator LH2, no radiator	5.2 0.6 0.1	low-t and high energy target wall electroproduction
setting 2	19.9° at +4.6GeV	20.1° at -4.3GeV	LH2 with radiator dummy with radiator	8.2 0.3	low-t and low energy target wall
setting 3	16.4° at +4.08GeV	30.0° at -3.5GeV	LH2 with radiator	13.8	high-t
setting 4	16.5° at +4.4GeV	24.5° at -4.4GeV	LH2 with radiator dummy with radiator	6.9 0.2	medium-t target wall



Lepton-pair Invariant mass

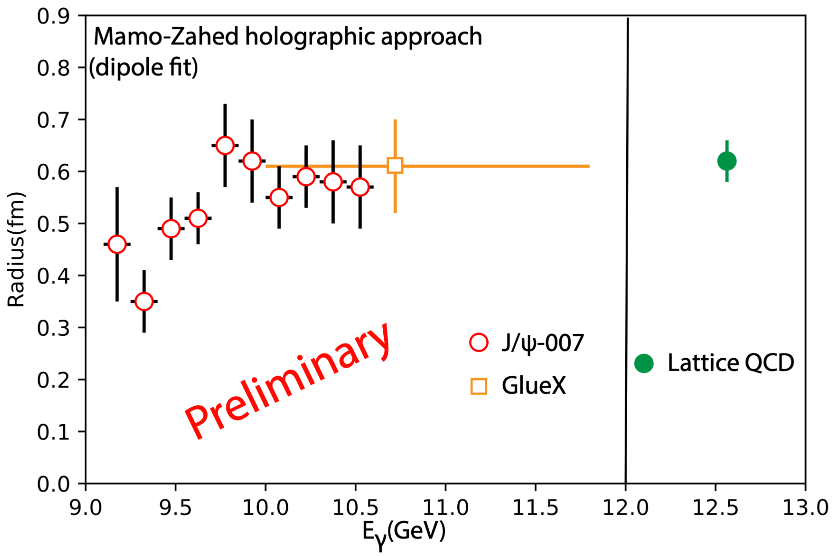
2D J/ψ cross section results in a.u.

t-dependence consistent with a dipole slope



An energy scan of the gluon radius

First ever access of the energy dependence of the gluon radius in two models



- Mass radii can be extracted for each of the 10 energy bins by means of a dipole fit
- Figure shows results following the approach from Mamo-Zahed (Phys. Rev. D 101, 086003, 2020).
- Similar results are obtained following D. Kharzeev's approach (Phys. Rev. D 104, 054015, 2021)
- Data can also be used to constrain the gravitational form factors falling the approach from Guo-Ji-Liu (Phys. Rev. D 103, 096010, 2021)
- The results can also be used to study the energy-momentum tensor of QCD following the approach from Hatta-Rajan-Yang (Phys. Rev. D 100, 014032, 2019)

- Lattice from Shanahan & Detmold (*Phys.Rev.D* 99 (2019) 1, 014511)

Impact on the trace anomaly extraction

X. Ji PRL 74, 1071 (1995) & PRD 52, 271 (1995)

$$H_{QCD} = \int d^3x T^{00}(0, \vec{x})$$

$$H_q = \int d^3x \, \psi^\dagger \left(-iD \cdot \alpha\right) \psi$$ Quarks & anti-quarks kinetic and potential energy

$$H_m = \int d^3x \, \psi^\dagger m \psi$$ Quarks masses

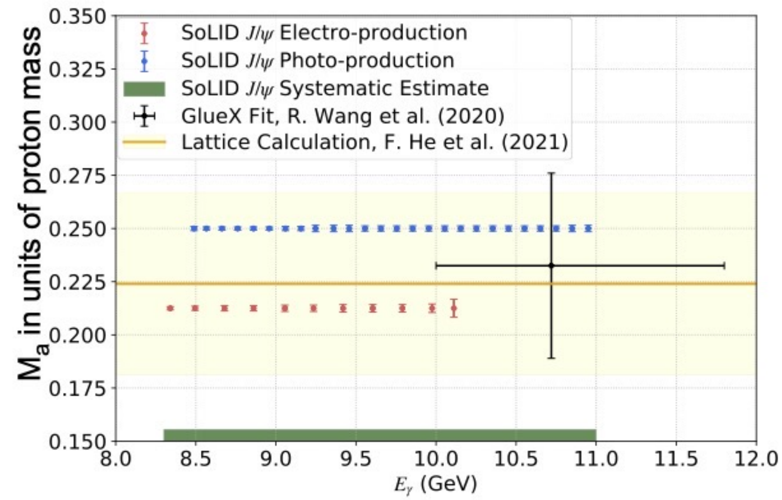
$$H_g = \int d^3x \, \frac{1}{2} \left(E^2 + B^2\right)$$ Gluons kinetic and potential energy

$$H_a = \int d^3x \, \frac{9\alpha_s}{16\pi} \left(E^2 - B^2\right)$$ Trace anomaly

$$M_N = \frac{\langle P|H_{QCD}|P\rangle}{\langle P|P\rangle}$$

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right) M_N \qquad M_g = \frac{3}{4}\left(1-a\right) M_N$$

$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)} b M_N \qquad M_a = \frac{1}{4}\left(1-b\right) M_N$$



Following: R. Wang, J. Evslin and X. Chen, Eur. Phys. J. C **80**, no.6, 507 (2020)

$$M_a = 23.3\% \pm 4.25\%$$

$$\boxed{M_N = M_q + M_m + M_g + M_a}$$

- *a(μ)* related to PDFs, well constrained
- ***b(μ)* related to quarkonium-proton scattering amplitude $T_{\psi p}$ near threshold**

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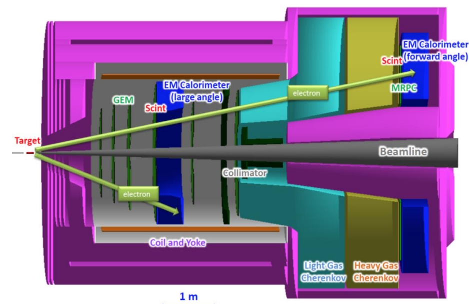
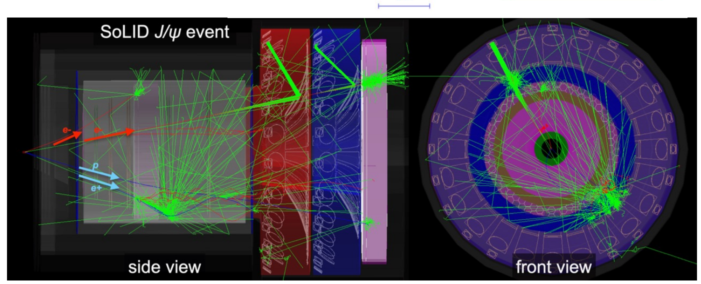
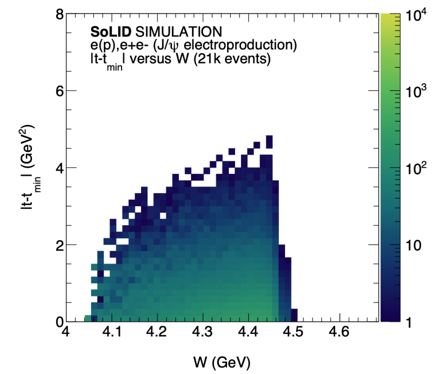
Future solid experiment at JLab

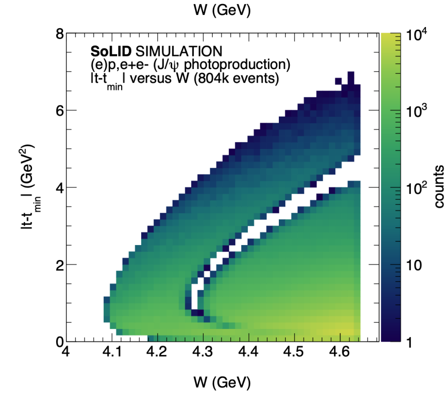
Ultimate experiment for near-threshold J/ψ production

- General purpose large-acceptance spectrometer
- 50 days of **3μA** beam on a **15cm** long LH2 target ($10^{37}/cm^2/s$)
- Ultra-high luminosity: 43.2ab^{-1}
- 4 channels:
  - **Electroproduction** (e, e-e+)
  - **Photoproduction** (p, e-e+)
  - **Inclusive** (e-e+)
  - **Exclusive** (ep, e-e+)



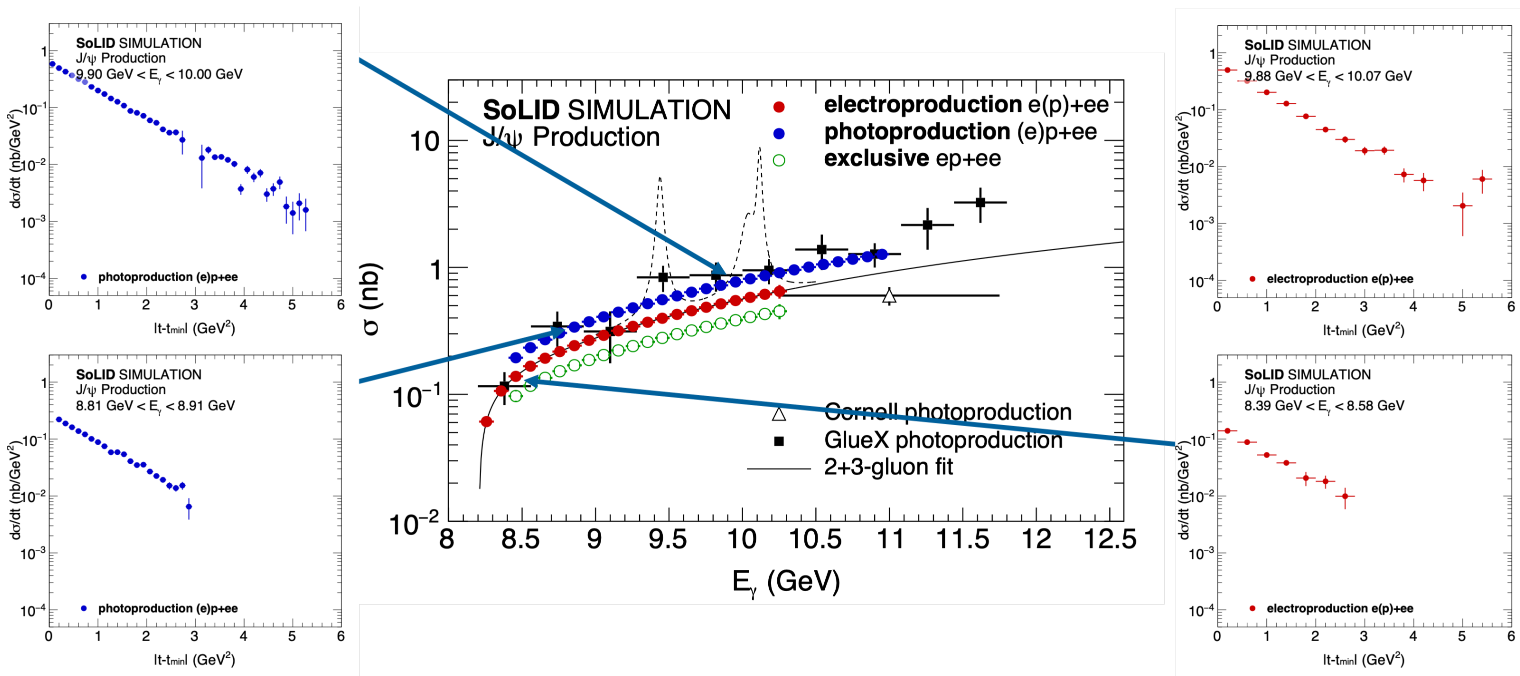






Future solid experiment at JLab

Precision measurement of J/psi near threshold



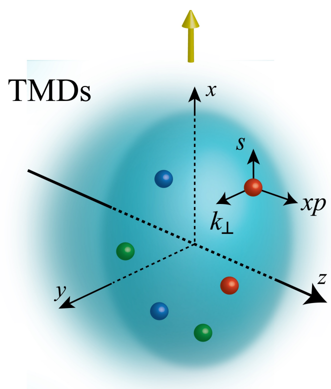
Unified View of Nucleon Structure

$W_p^u(x,k_T,r_T)$ Wigner distributions

Transverse Momentum Dist. (TMD)

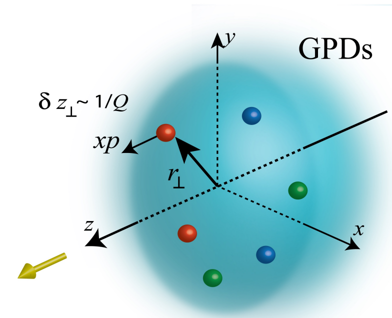
Tomography

Generalized Parton Dist. (GPD)



dr_T

d^2k_T



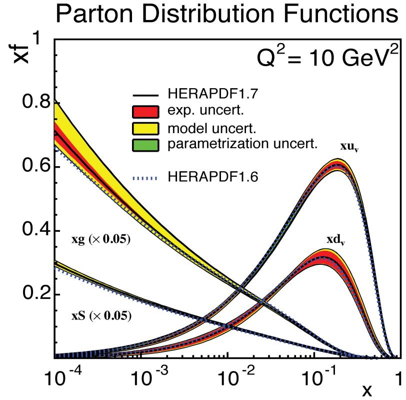
TMD $f_1^u(x,k_T)$, $h_1^u(x,k_T)$

GPD

d^2k_T

d^2r_T

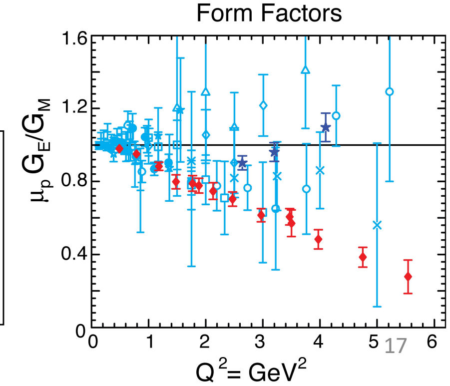
dx & Fourier Transformation



PDFs
$f_1^u(x)$, ..
$h_1^u(x)$

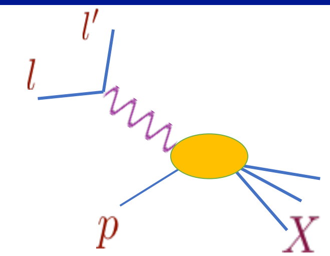
1D

Form Factors
$G_E(Q^2)$,
$G_M(Q^2)$

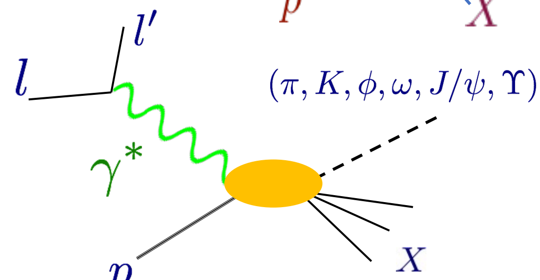


Experimental tools: GPDs & TMDs and Form Factors (Charge and Gravitational)

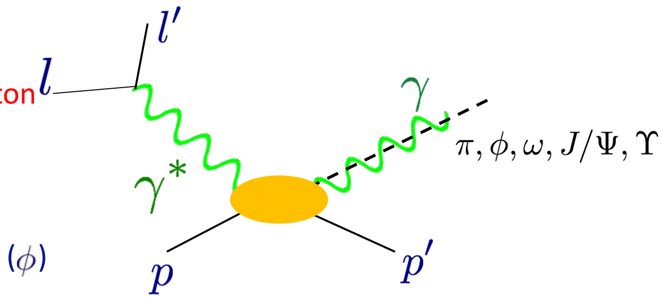
- Inclusive reactions:
  - Deep Inelastic scattering



- Semi-Inclusive reactions: *e+p/A → e'+h(π,K,...)+X*
  - *Detect scattered lepton in coincidence with identified hadrons or jets*
    Semi-Inclusive Deep Inelastic Scattering (SIDIS)
  - Challenge:
    - High polarized luminosity combined with large acceptance detectors
    - 5 key variables x,Q^2, z, p_T and angle between leptonic and hadronic plane
    - Fine binning needed



- Exclusive reactions: *e+p/A → e'+ p'/A'+ (γ,π,K,...)*
  - *Detect all final states including recoiling nucleon or nucleus*
    Deep Virtual Compton Scattering (DVCS/VCS) when detecting the real photon
    Deep Virtual Meson Production (DVMP) when detecting $\pi, \phi, \omega, J/\Psi, \Upsilon$
  - Challenge:
    - High polarized luminosity combined with large acceptance detectors
    - 4 key variables x,Q^2,t and angle between leptonic and production plane (ϕ)
    - Fine binning needed



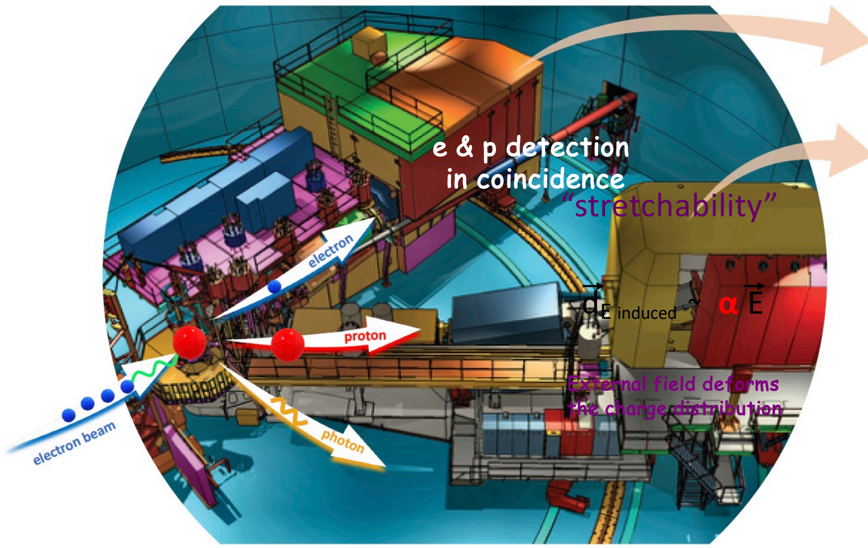
VCS and generalized polarizabilities of the proton

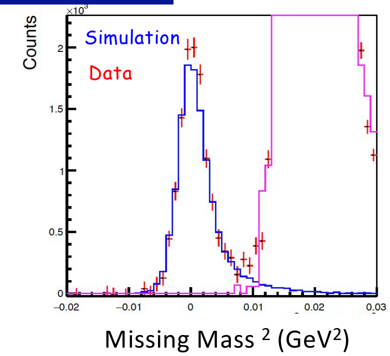
N. Sparveris et al.
JLab-E12-15-001

“stretchability”

$\vec{d}_{E\ \mathrm{induced}} \sim \boldsymbol{\alpha}\,\vec{E}$

External field deforms
the charge distribution





Hall C:
SHMS, HMS
4.56 GeV
20 μA
Liquid hydrogen 10 cm

“alignability”

$\vec{d}_{M\ \mathrm{induced}} \sim \boldsymbol{\beta}\,\vec{B}$

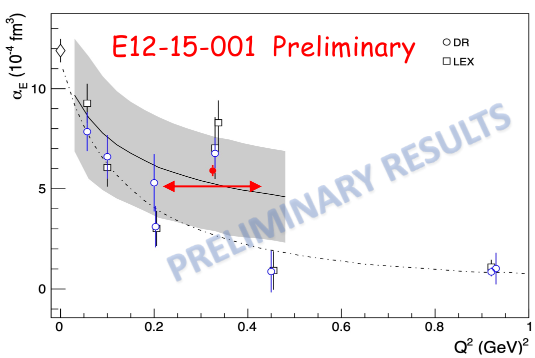
$\beta_{para} > 0$

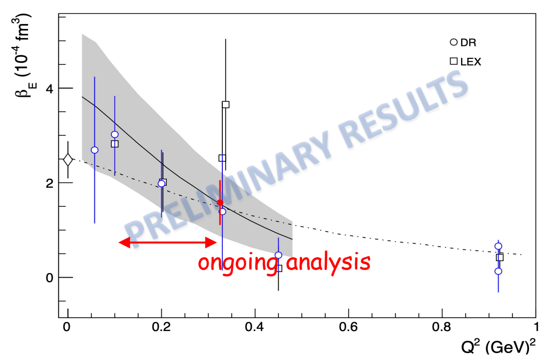
$\beta_{diam} < 0$

Paramagnetic: proton spin aligns
with the external magnetic field

Diamagnetic: π-cloud induction produces
field counter to the external one

Q^2=0.33 GeV^2

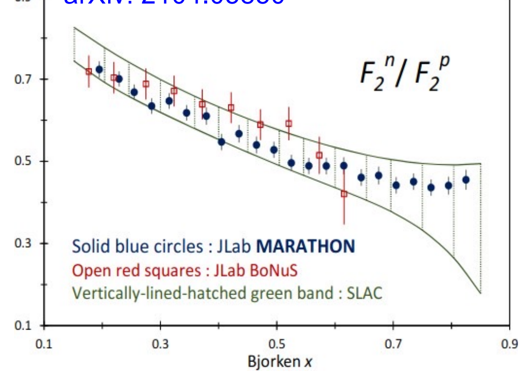


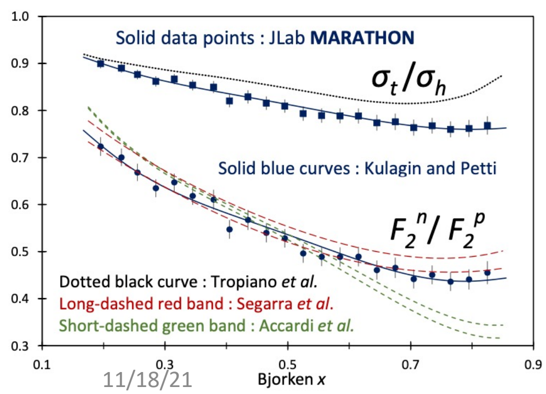


Proton valence quarks ratio through Inclusive DIS

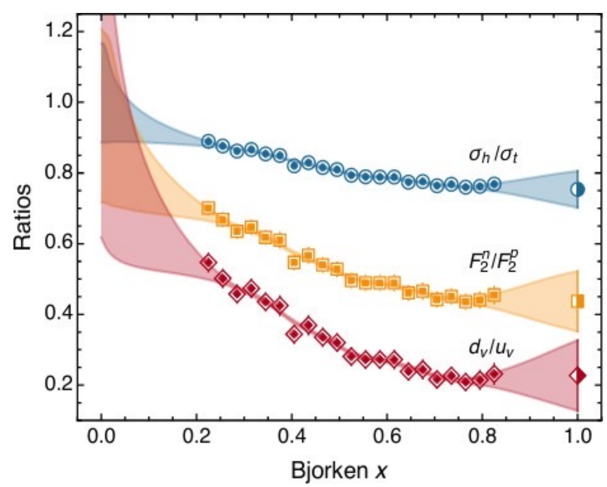
MARATHON at JLab Hall-A DIS experiment: 10 GeV electrons off ³He and ³H targets

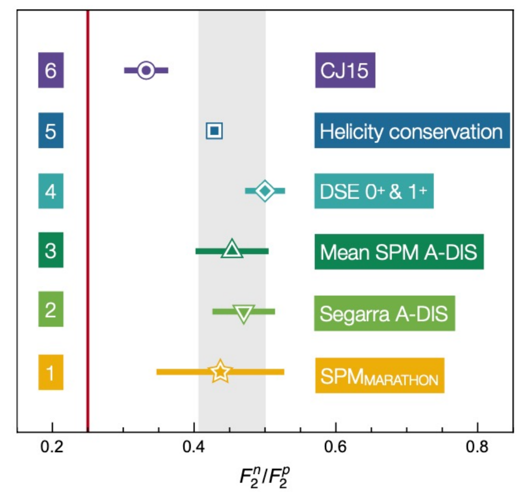
arXiv: 2104.05850





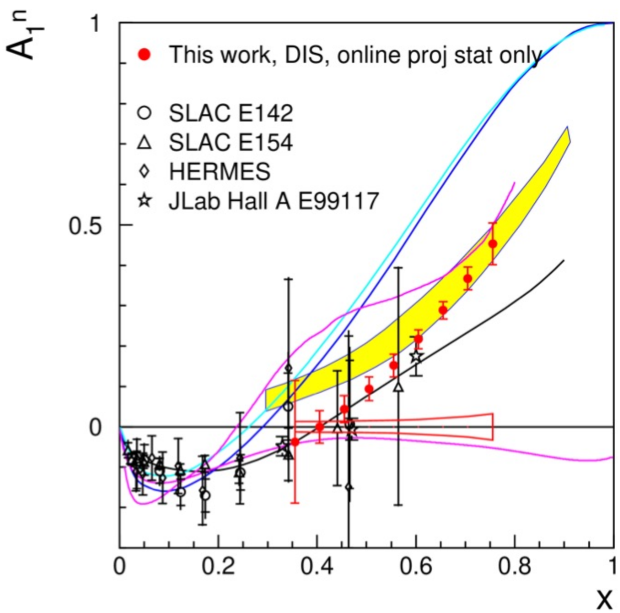
Cui Zhu-Fang et al.: arXiv:2108.11493

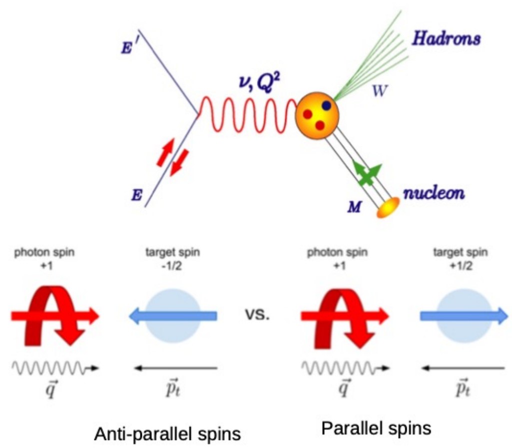




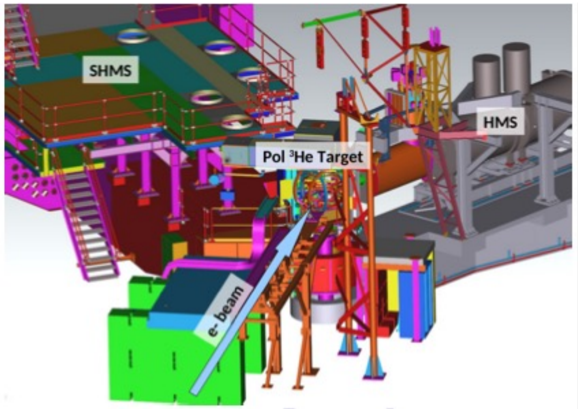
Neutron Spin Structure in the Valence Region

The A_1^n experiment in Hall C





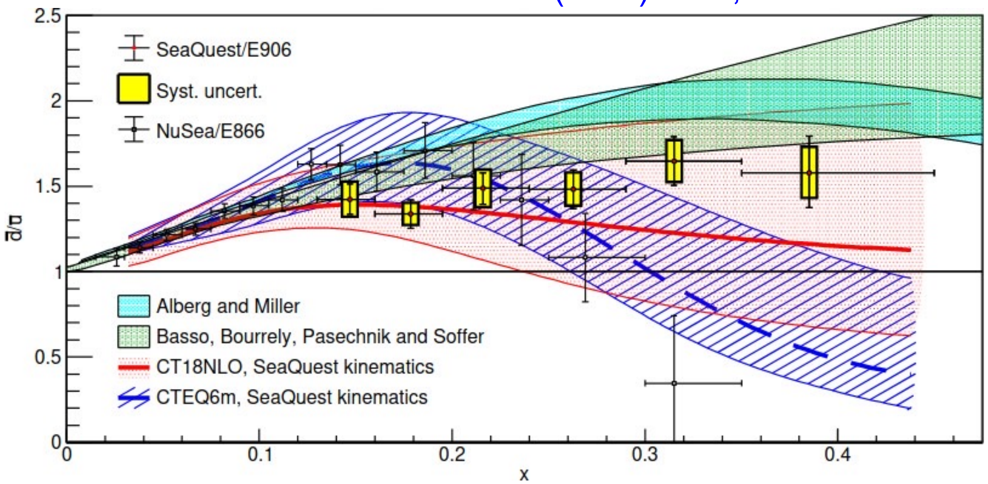
- Precision measurement of the neutron spin asymmetry A_1^n in the far valence region ($0.61 < x < 0.77$)
- Explore Q^2 dependence of A_1^n in the valence region
- Access flavor dependent helicity PDF ratios at large x by combining with proton results from CLAS12



- Experiment ran in FY20, with a 30μA electron beam on a 40cm high-pressure polarized ^{3}He target.
- Analysis in an advanced state

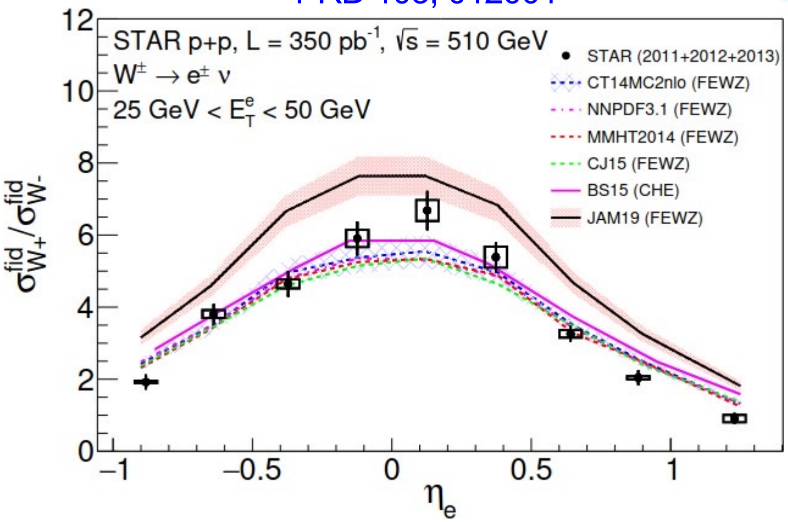
Light sea asymmetry in the proton

Nature 590 (2021) 7847, 561-565



SeaQuest: 120 GeV proton-induced Drell-Yan on Hydrogen and Deuterium targets.

PRD 103, 012001



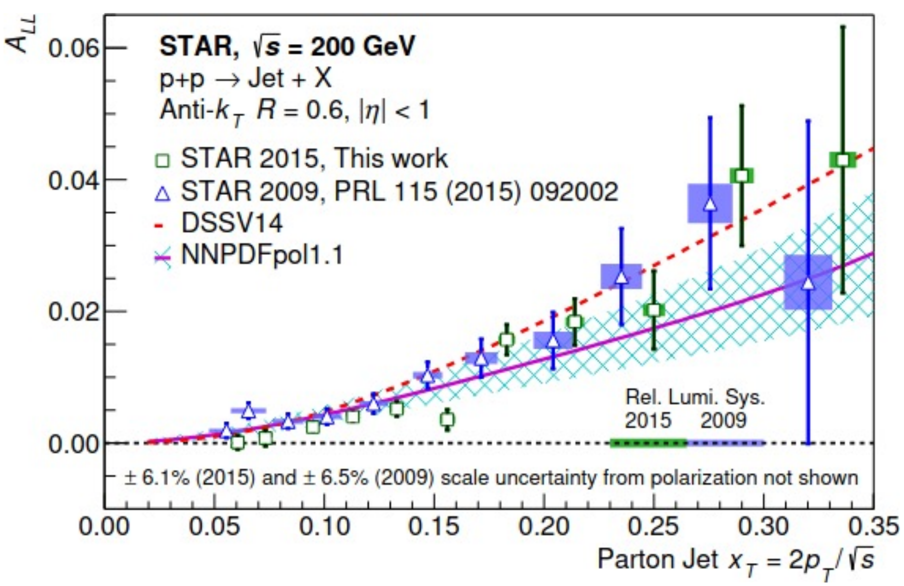
- Behavior of the ratio of d-bar/u-bar better constrained
- Consistent with predictions of statistical model

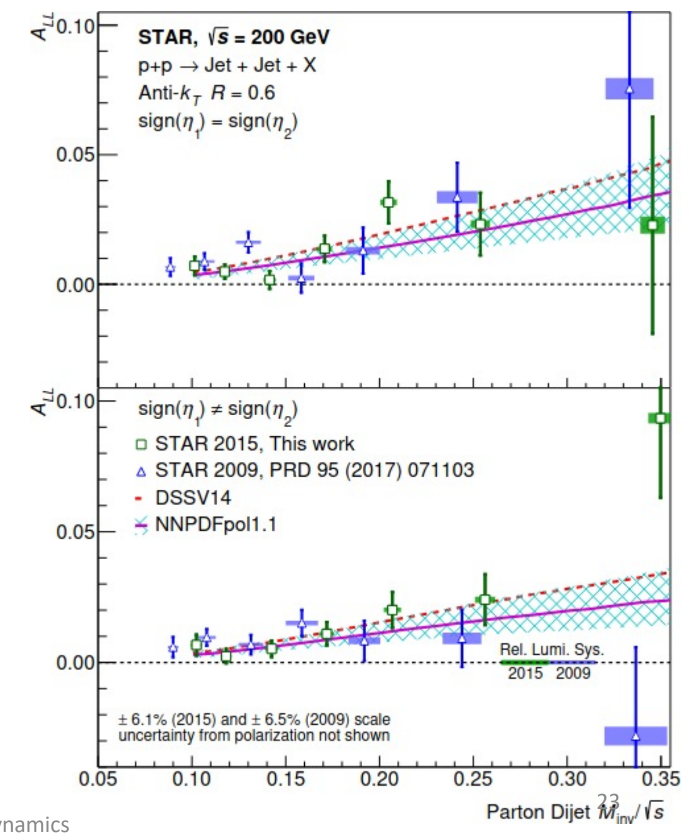
7

Longitudinal double spin asymmetries

Inclusive jet and dijet data: sensitivity to gluon helicity in $0.05 < x_g < 0.5$

arXiv:2103.05571





Further evidence that
$\Delta g(x,Q^2)$ is positive for $x_g > 0.05$

Probing TMDs

- **TMDs - rich quantum correlations:**

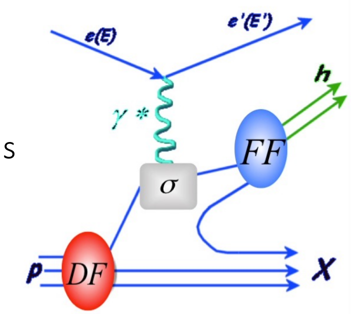
Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	$f_1 =$		$h_1^{\perp} =$ — Boer-Mulders
L		$g_{1L} =$ — Helicity	$h_{1L}^{\perp} =$ —
T	$f_{1T}^{\perp} =$ — Sivers	$g_{1T}^{\perp} =$ —	$h_1 =$ — Transversity $h_{1T}^{\perp} =$ —

Nucleon Spin

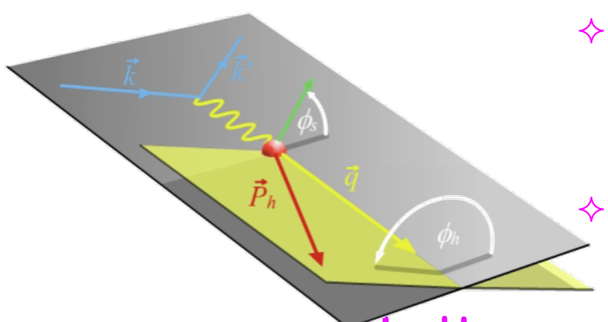
Quark Spin

Similar for gluons

SIDIS



- **Naturally, two scales and two planes:**



✧ Two scales:

high Q - localized probe

Low p_T - sensitive to confining scale

✧ Two planes:

angular modulation to separate TMDs

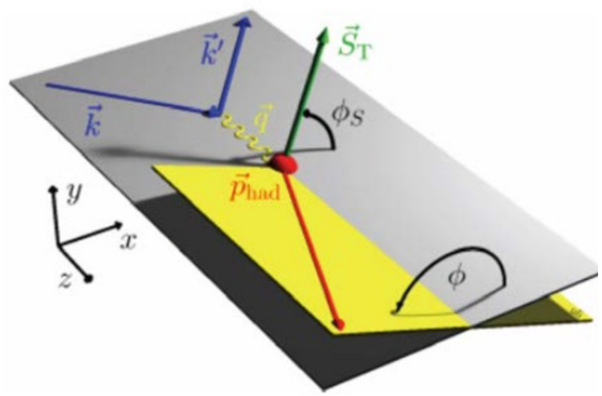
Hard to separate TMDs in hadronic collisions

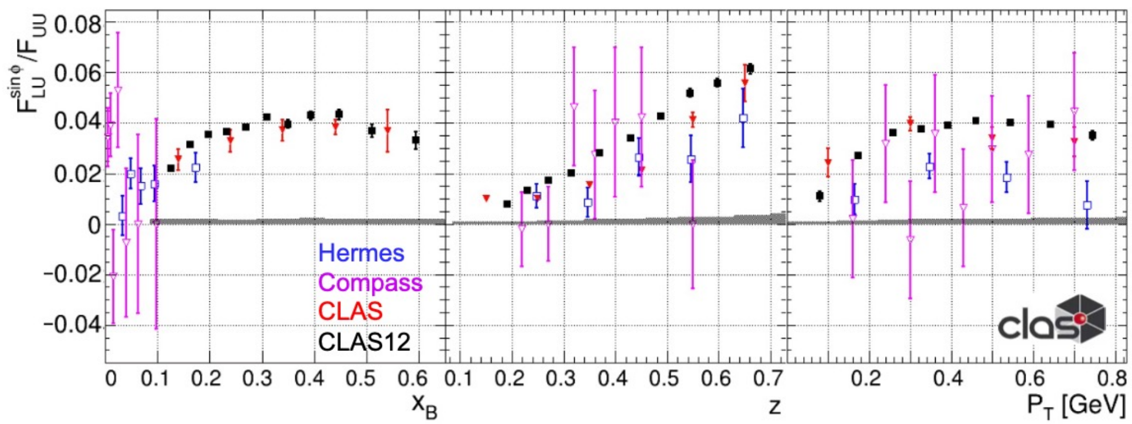
SIDIS at CLAS12: Pion Beam Spin Asymmetry

arXiv:2101.03544, submitted to PRL

- Spin asymmetries in semi-inclusive pion production directly related to TMDs and FFs
- Single-spin asymmetries (eg. BSA) sensitive to twist-3 quark correlations

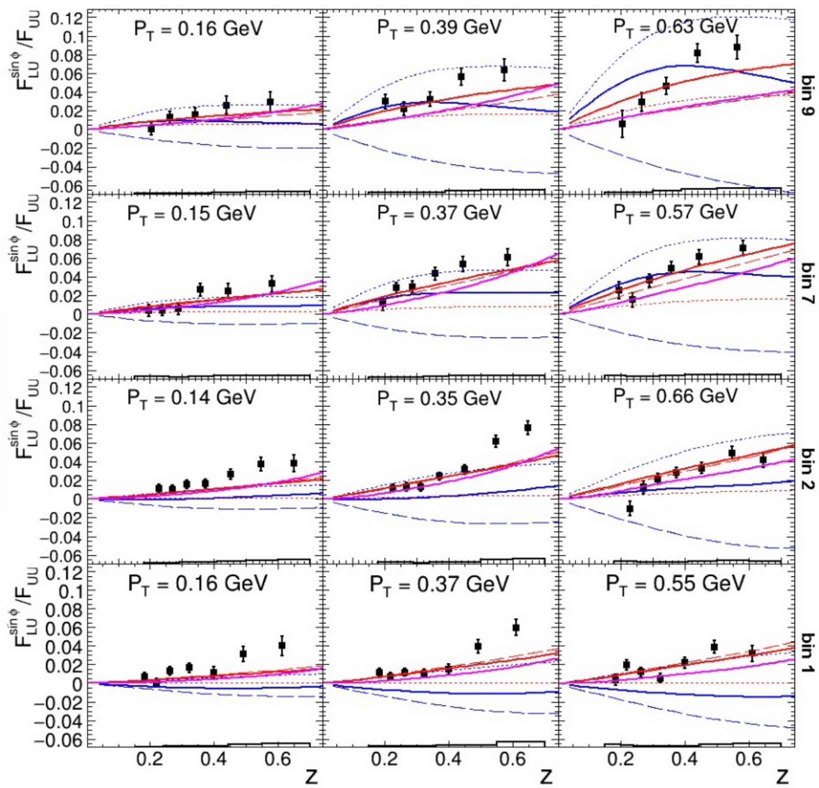
- First multi-dimensional mapping of the π+ BSA on a hydrogen target at CLAS12
- Dramatic improvement on precision compared to previous measurements
- Sufficient precision for a multi-dimensional approach





SIDIS at CLAS12: Pion Beam Spin Asymmetry

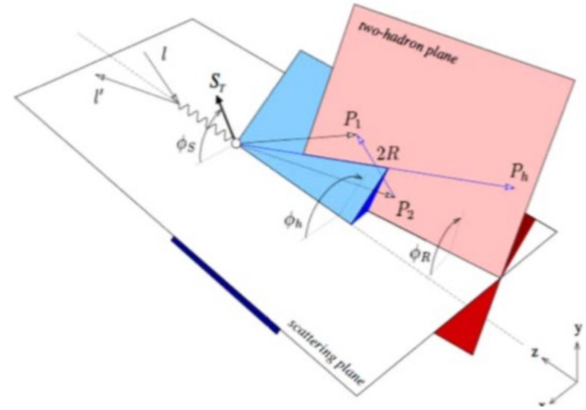
arXiv:2101.03544, submitted to PRL

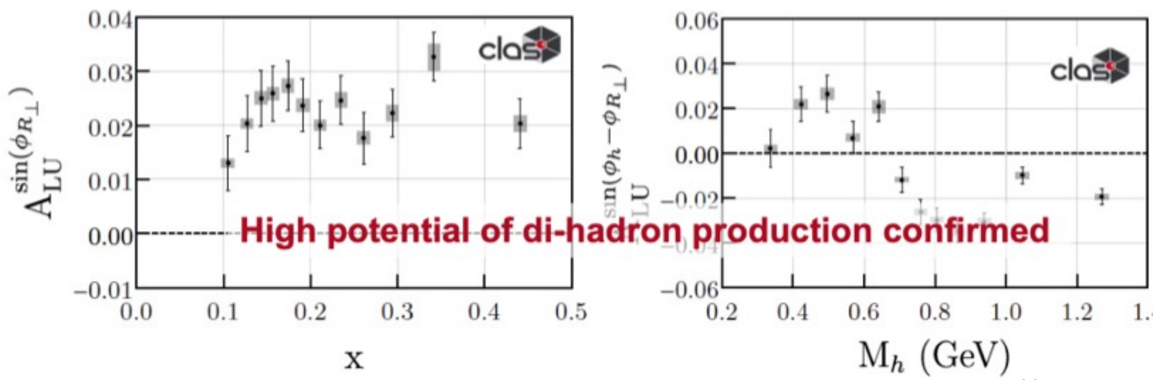


SIDIS at CLAS12: di-hadron production

Phys. Rev. Lett. 126, 152501 (2021)

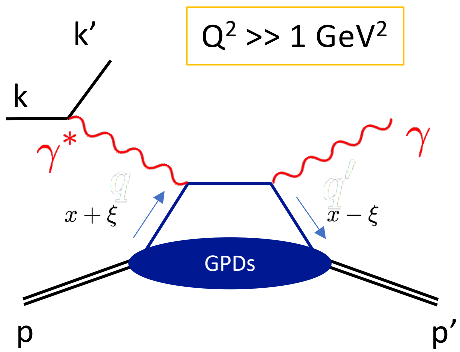
- Ideal process to access the collinear PDF e(x), sensitive to the interaction between quarks and gluons
- First time access to the Helicity-dependent di-hadron fragmentation function G^1
- Access through the azimuthal angles of the final-state hadrons $\perp$



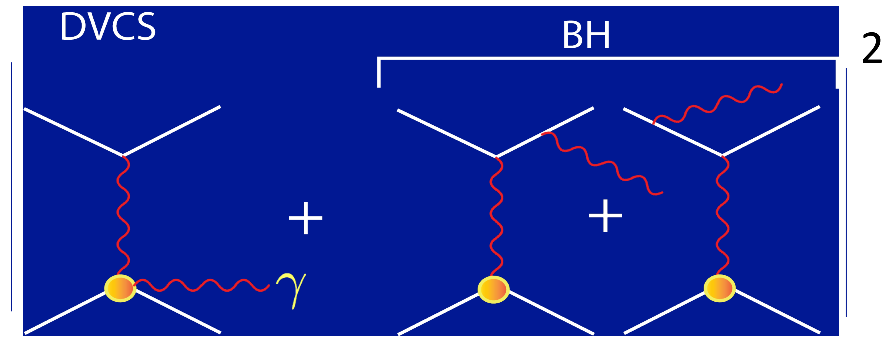


High potential of di-hadron production confirmed

Deeply Virtual Compton Scattering



$$\sigma(ep \longrightarrow ep\gamma) \propto$$



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

$$Q^2 = -q^2 = -(k - k')^2$$
$$t = (p' - p)^2$$
$$x_B = Q^2/2p \cdot q$$
$$t \ll Q^2 \quad , \xi \rightarrow \frac{x_B}{2 - x_B}$$

- At large Q^2: QCD factorization theorem
- At twist-2: 4 quark helicity conserving GPDs: $H_q(x, \xi, t, Q^2), E_q(x, \xi, t, Q^2), \ldots$
- Key: Q^2 leverage needed to test QCD scaling
- High statistics required for a clean extraction

Separating GPDs Through Polarization Measurements of Compton FF

ep ⟶ epγ

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$\xi = x_B/(2-x_B)$

$k = -t/4M^2$

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

Kinematically suppressed

⟹ H, $\tilde{H}$, E

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi\{F_1\tilde{H}+\xi(F_1+F_2)(H + \ldots\}d\phi$$

⟹ H, $\tilde{H}$

Unpolarized beam, transverse target:

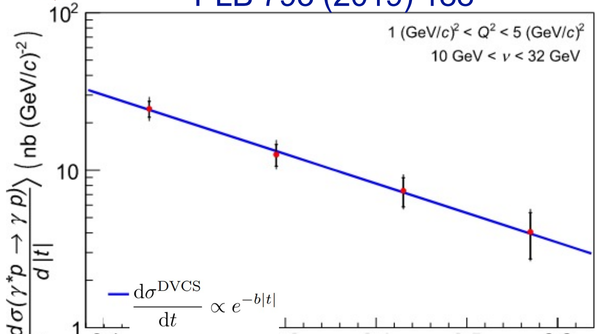
$$\Delta\sigma_{UT} \sim \sin\phi\{k(F_2 H - F_1 E) + \ldots\}d\phi$$

⟹ H, E

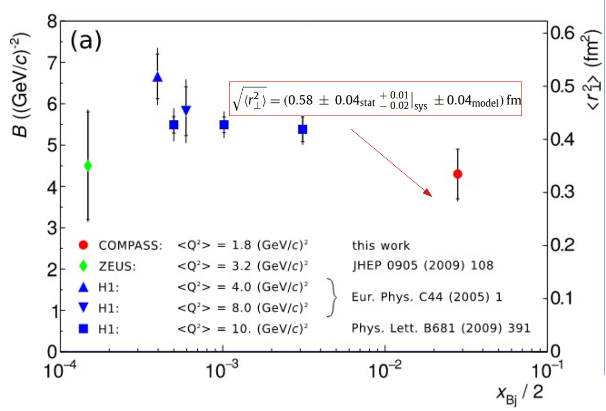
Global analysis of polarized and unpolarized data needed for GPDs separation

Transverse extension of partons in the proton

PLB 793 (2019) 188

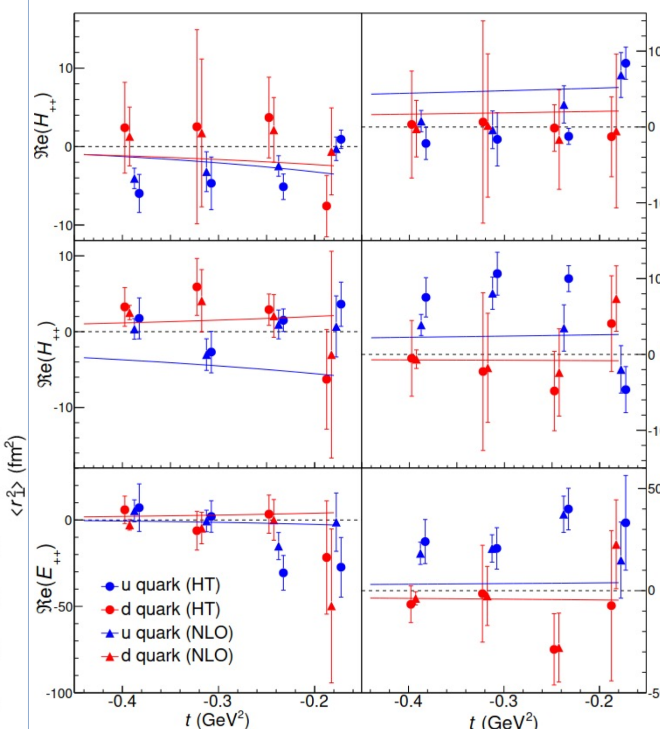


$\langle r_\perp^2(x_{Bj}) \rangle \approx 2B(x_{Bj})$ At small x_{Bj} | (GeV/c)^2



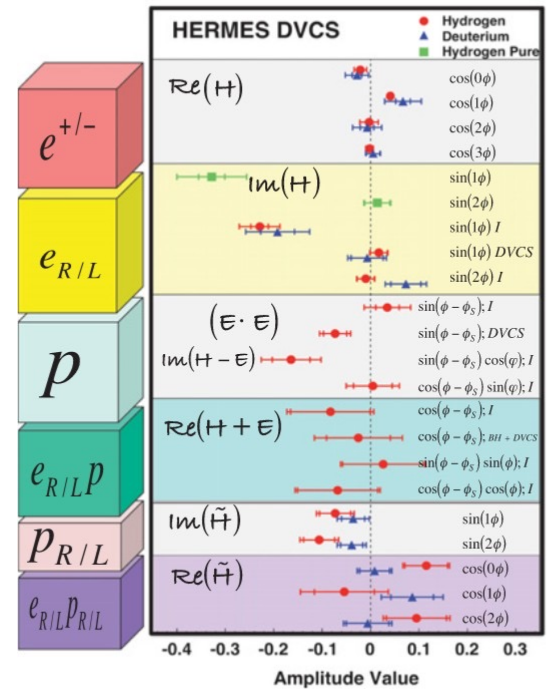
Flavor separation of Helicity conserved CFFs

Nat. Phys. 16, 191–198 (2020)



JLab Hall-A n & p DVCS

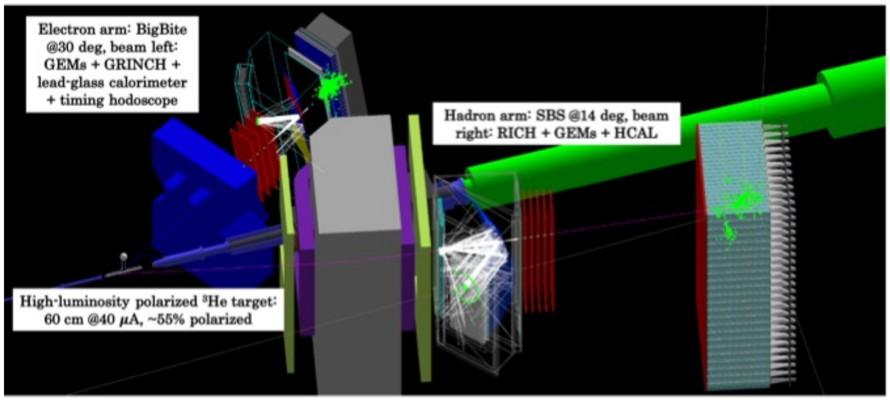
DOI: 10.1051/epjconf/20147302014



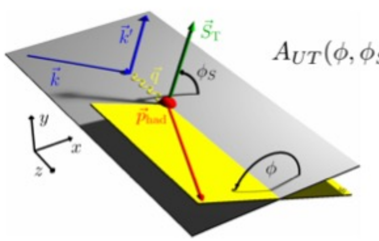
Pioneering measurements from HERMES

Future: transversity at SBS

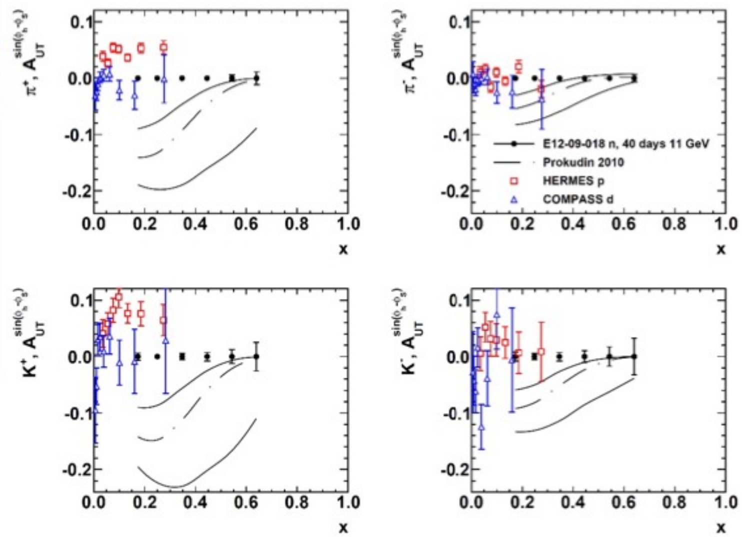
Experiment elastic form factors and SIDIS



- **E12-09-018** in Hall A: 40 (20) days production at E = 11 (8.8) GeV. **Approved by PAC38 for 64 beam-days, A- rating**
- Reach high x (up to ~0.7) and high statistical FOM (~1,000X Hall A E06-010 @6 GeV)



$$
\begin{aligned}
A_{UT}(\phi,\phi_S) &= \frac{1}{P_T}\frac{d\sigma(\phi,\phi_S)-d\sigma(\phi,\phi_S+\pi)}{d\sigma(\phi,\phi_S)+d\sigma(\phi,\phi_S+\pi)} \\
&= A_{UT}^{Collins}\sin(\phi+\phi_S)+ \\
&\quad A_{UT}^{Sivers}\sin(\phi-\phi_S)+ \\
&\quad A_{UT}^{Pretz}\sin(3\phi-\phi_S)
\end{aligned}
$$

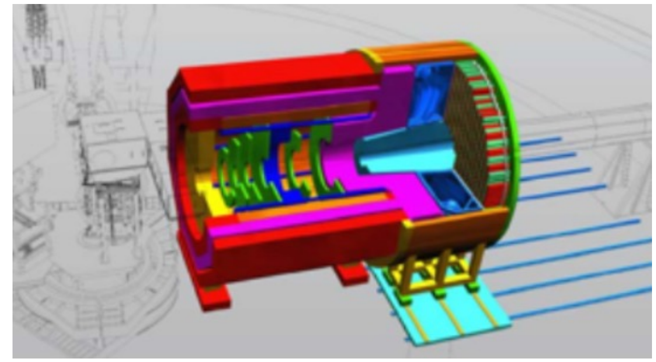


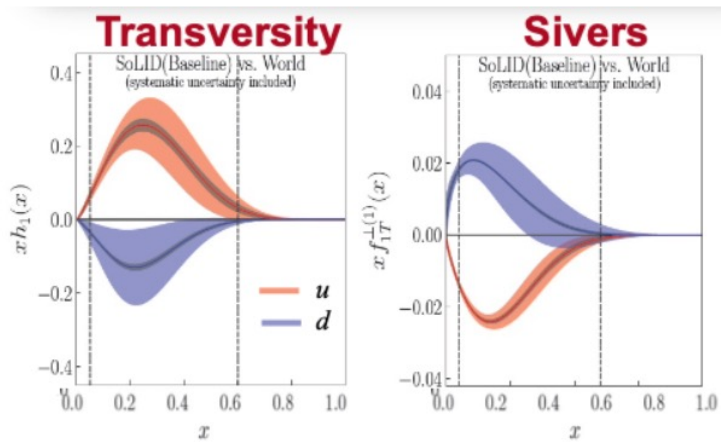
Example of projected E12-09-018 precision: neutron Sivers moments for charged pions and Kaons (11 GeV data only)

Can run as soon as 2023!

Future: TMDs at SoLID

- Solenoidal Large Intensity Device
- Unique combination of high luminosity (10^{37}-10^{39} $cm^{-2}s^{-1}$) and large acceptance
- Rich physics program with as main pillars the study of nucleon spin (through SIDIS), nucleon mass (through near-threshold J/psi production), and physics beyond the standard model.
- SoLID went through DOE science review this year
- Detector in advanced pre-R&D phase, awaiting CD0 approval





Summary

- J/psi Production is a promising probe to understanding the origin of the proton mass.
- The 3D landscape of the nucleon is challenging but many processes will help unravel it.
- Lattice QCD and effective field theories should be benchmarked against data but should also guide us in the corners of the phase space not accessible by experiments as well as making new predictions.

- JLab 12 GeV, COMPASS, AMBER, SPINQUEST and EIC(s) are poised to advance our understanding of nucleons and nuclei within QCD.

This work is supported in part by the U.S. Department of Energy, under Contract No. DE-AC02-06CH11357