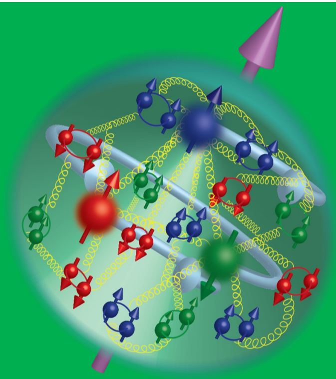
EXPERIMENTAL PERSPECTIVES ON ELECTROMAGNETIC HADRON PHYSICS



ZEIN-EDDINE MEZIANI
Argonne National Laboratory

Disclaimer: This talk cannot capture all the exciting experimental results in 30 min, thus it is incomplete and biased

EINN-2023 Pafos, Cyprus

Thanks to P. Achenbach, H. Avakian, E. Chudakov, J.-P. Chen, M. Jones, S. Joosten, C. Keppel, H. Avakian, S. Prasad, B. Parsamyan, E. Aschenauer, M. Zurek

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OUTLINE

Jefferson Lab, RHIC Spin at BNL, COMPASS, Mainz, PSI

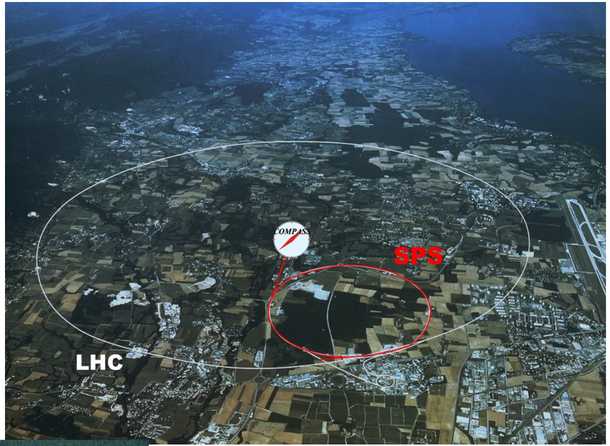
- Form Factors
  - Electromagnetic and gravitational form Factors (Lepton scattering, J/psi production)
  - Generalized Polarizabilities through low Q^2 experiments (Lepton scattering)
- Structure Functions (Inclusive DIS, Drell-Yan)
  - Unpolarized structure functions
  - Polarized structure functions (Inclusive DIS, Drell-Yan,...)
- Generalized Parton Distributions (GPDs)
  - DVCS experiments & Compton form factors (JLab Halls A & B, COMPASS)
  - DVMP experiments & differential cross sections(JLab, COMPASS, RHIC)
- Transverse Momentum Dependent Distributions (TMDs)
  - SIDIS experiment with di-hadrons in the final state (JLab, COMPASS)
- Conclusion

OUTLINE

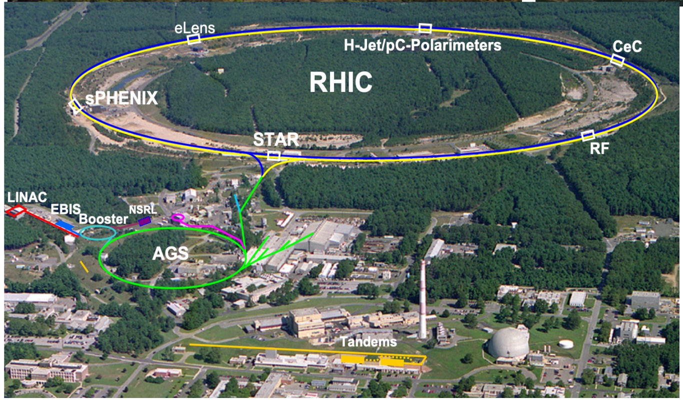
JLab (Hall A, B, C, D), BNL (RHIC-Spin STAR), CERN(COMPASS, Mainz(Hall A), PSI(MUSE)

JLab

COMPASS



Mainz (MAMI, MESA)



RHIC

PSI

US LONG RANGE PLAN FOR NUCLEAR PHYSICS

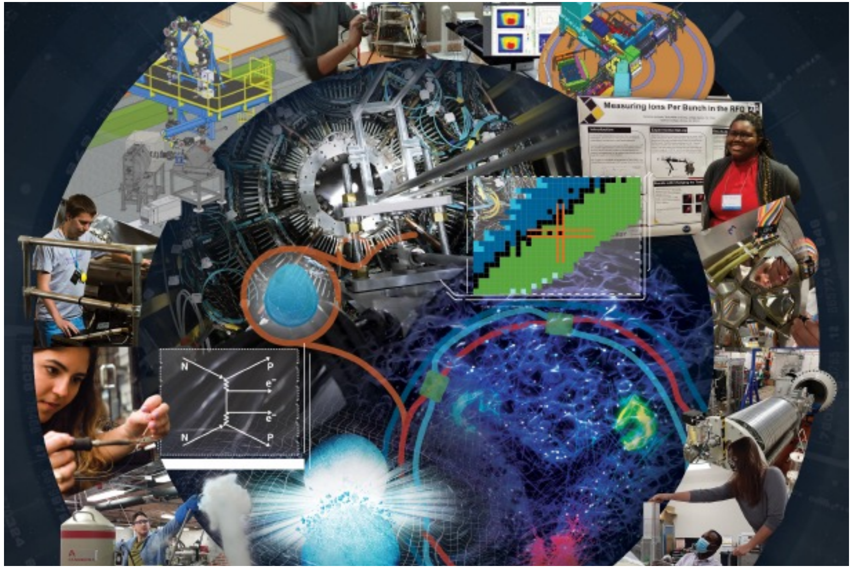
Since EINN2021, the LRP a Major Process in the US

https://indico.mit.edu/event/538/timetable/?view=standard

- September, 2022

Hot & CoLD QCD Town Hall Meeting at MIT

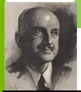
https://nuclearsciencefuture.org/



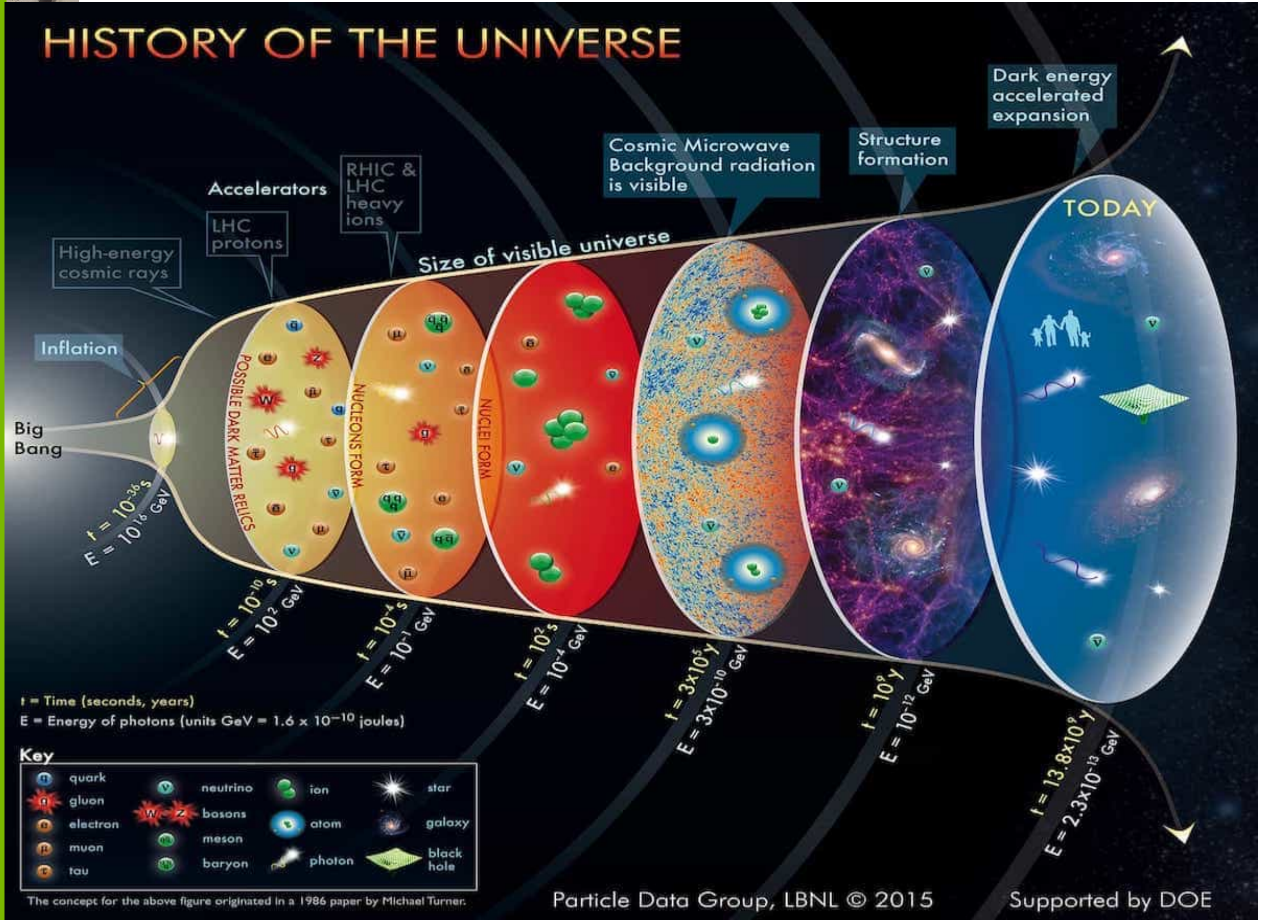
- October 2023

Release of the Long Range Plan Document by NSAC

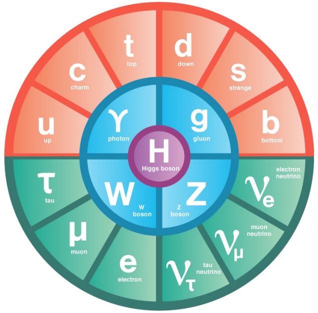
TO KNOW YOUR FUTURE YOU MUST KNOW YOUR PAST



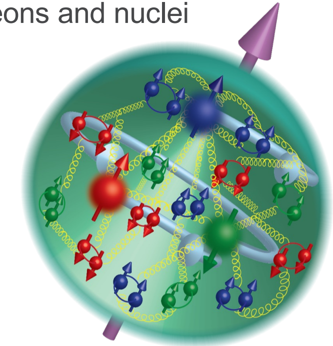
George Santayana (American philosopher, poet and cultural critic: Born in Madrid, 1863-1952)



Standard Model of Particle Physics



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

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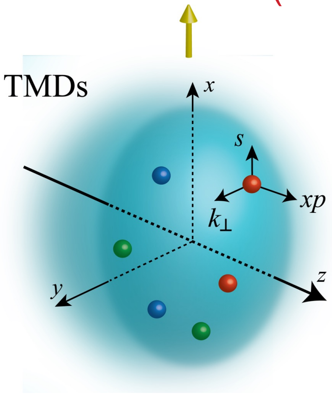
Unified View of Nucleon Structure

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

Transverse Momentum Dist. (TMD)

Tomography

Generalized Parton Dist. (GPD)

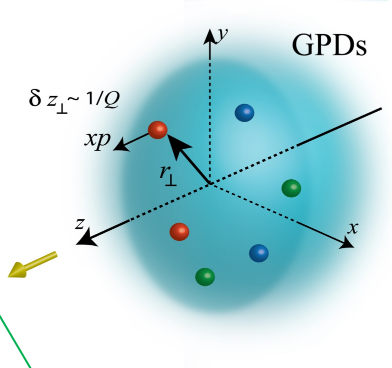


dr_T

d^2k_T

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

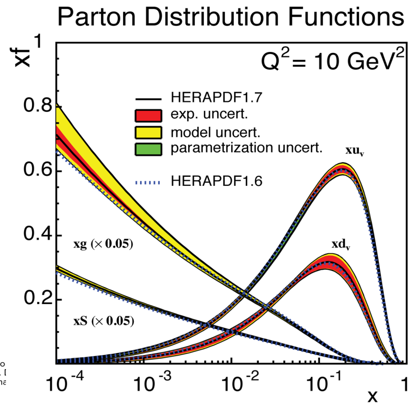
GPD



d^2k_T

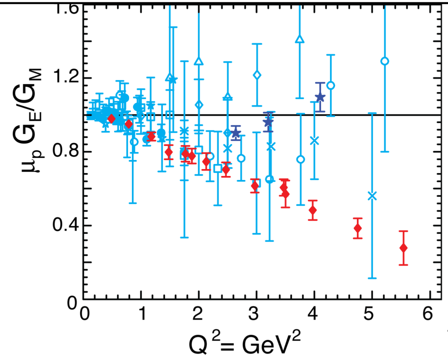
d^2r_T

dx & Fourier Transformation



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

Electromagnetic Form Factor $G_E(Q^2)$, $G_M(Q^2)$



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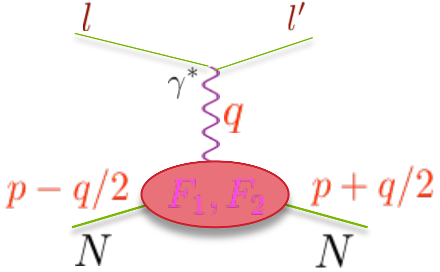
The Proton Electromagnetic Form Factors

Talks: A. Puckett (parallel Workshop 1), A. Denig (Wednesday, plenary)

ELASTIC ELECTRON SCATTERING & ELECTROMAGNETIC FORM FACTORS

- Elastic e p → e p scattering used for more than 60 years to investigate nucleon structure
- In 1-photon exchange approximation:

  nucleon structure parameterized by two form factors



$$
\begin{aligned}
A^{\mu}_{\lambda\lambda'} &= \langle p + \frac{1}{2}q, \lambda' \mid J^{\mu}(0) \mid p - \frac{1}{2}q, \lambda\rangle \\
&= \bar{u}(p + \frac{1}{2}q, \lambda') \left[F_1(Q^2)\gamma^{\mu} + F_2(Q^2)\frac{i}{2m}\sigma^{\mu\nu}q_{\nu} \right] u(p - \frac{1}{2}q, \lambda)
\end{aligned}
$$

Dirac Pauli

F_1 helicity conserving, F_2 helicity flip form factors

Robert Hofstadter (1961) Nobel Prize

- In experiments we measure the Sachs form factors

$$
\frac{d\sigma}{d\Omega}(E,\theta) = \sigma_M \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2(\frac{\theta}{2}) \right]
$$

Rosenbluth Formula

$$
\sigma_M = \frac{\alpha^2 E' \cos^2(\frac{\theta}{2})}{4E^3 \sin^4(\frac{\theta}{2})}
$$

$$
\tau = \frac{Q^2}{2M}
$$

$$
\begin{aligned}
G_E(Q^2) &= F_1(Q^2) - \tau F_2(Q^2) \\
G_M(Q^2) &= F_1(Q^2) + F_2(Q^2)
\end{aligned}
$$

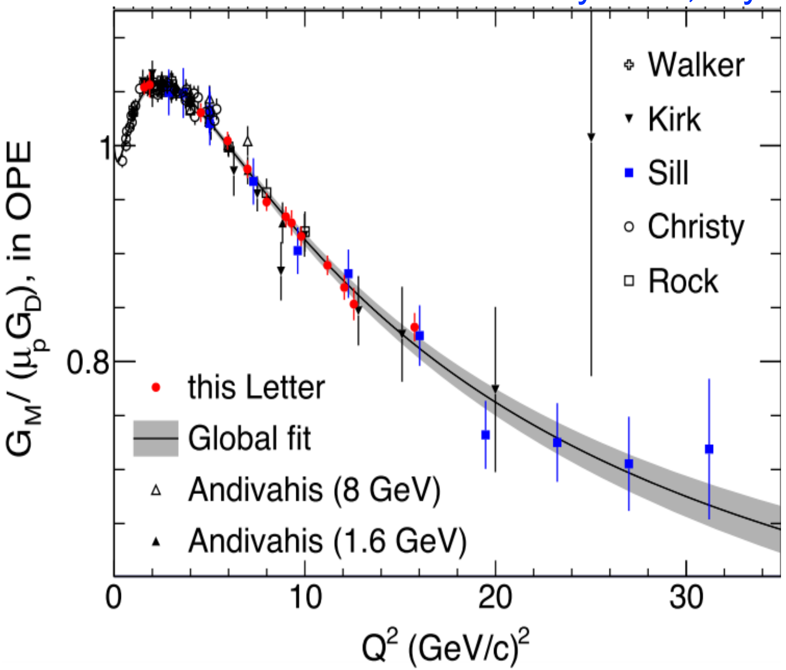
Proton Radius

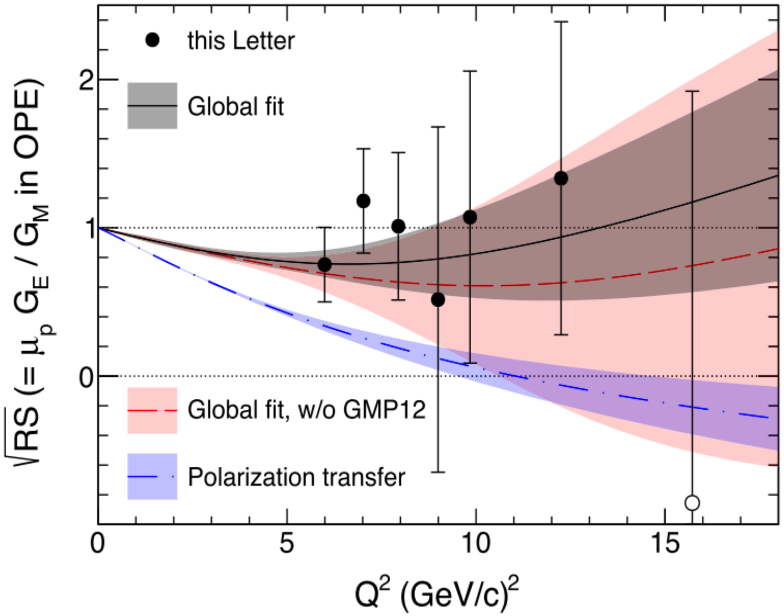
$$
\langle {r_E^p}^2 \rangle = -\frac{6}{G_E^p(0)} \frac{dG_E^p(Q^2)}{dQ^2}\Big|_{Q^2=0}
$$

JLab Hall A : Proton magnetic form factor, G_M, up to Q^2 = 15.75

- High luminosity needed to do longitudinal-transverse separation. Electric form factor has small contribution to cross section at large Q^2
- Hard two-photon exchange effects at large Q^2 quantified.

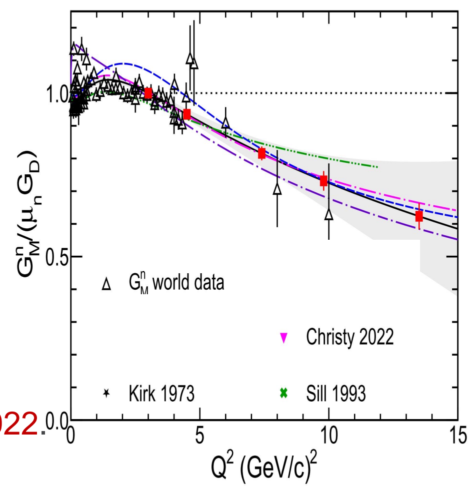
E. Christy et al.,Phys. Rev. Lett. 128 (2022) 102002

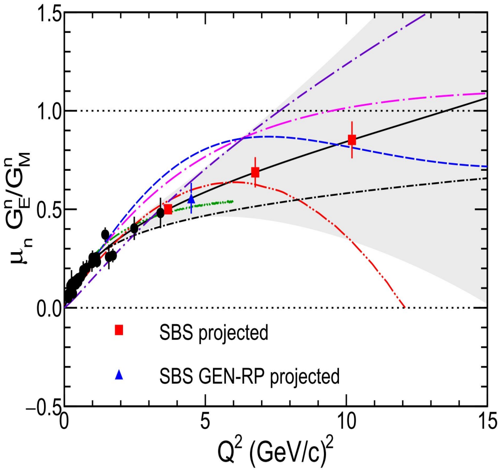




JLab Hall A: Nucleon Form Factors at large Q^2

Red points projected errors





Neutron Magnetic Form Factor to Q^2 = 13.5

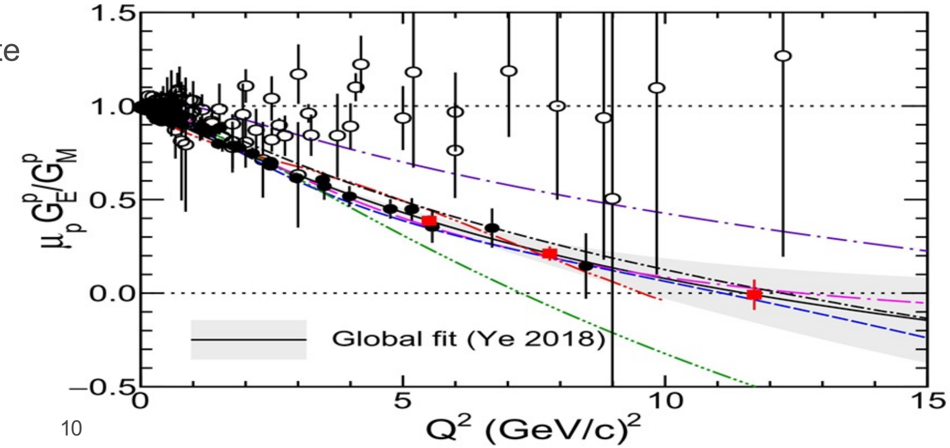
- Ratio of D(e,e'n)/D(e,e'p) yield sensitive to G_M^n
- At Q^2= 4.5 GeV^2, data at two beam energies to measure two-photon exchange in neutron.
- Completed data taking in Spring 2022.

Neutron Electric Form Factor to Q^2 = 10

- Polarized helium target with L=60cm, P =50% at 45uA.
- Beam-target asymmetries measured G_E^n to Q^2= 10.
- Completed the Q^2 = 3.0 and 6.8 kinematics in Winter 2022.
- Presently running the Q^2 = 10 kinematics
- Recoil polarization by charge exchange (GEN-RP) to measure G_E^n at Q^2 = 4.5GeV^2. Cross check with separate technique. Run experiment in April 2024.

Proton Electric Form Factor to Q^2 = 12

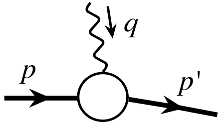
- Measure ratio of transverse to longitudinal recoil polarization in elastic scattering to extract GEp/GMp.
- With measurement of all 4 form factors to Q^2 = 10 GeV^2, one can extract the up and down quark from factors (assumption strange FF = 0).
- Plan to start experiment in Oct 2024.

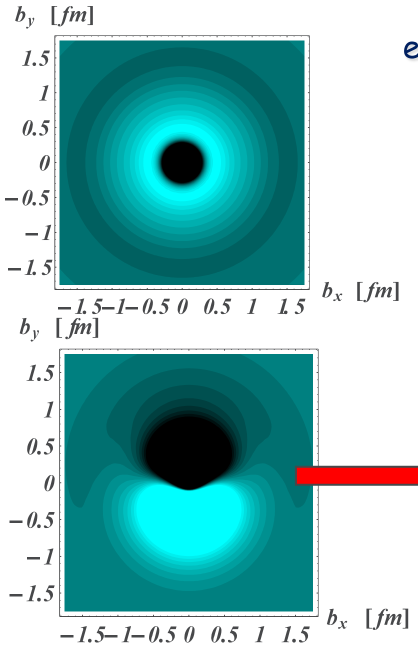


How are charge & magnetization distributed inside the proton?

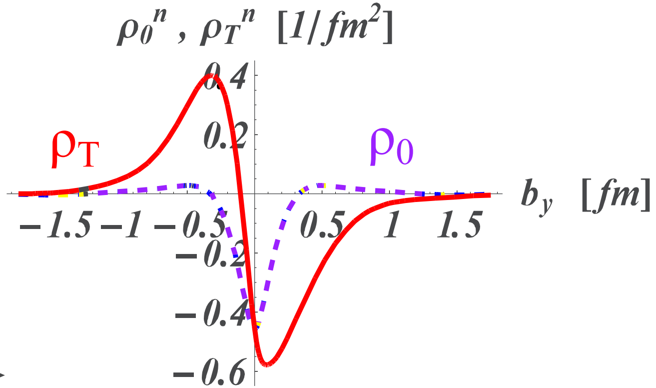
- Electric charge distribution:

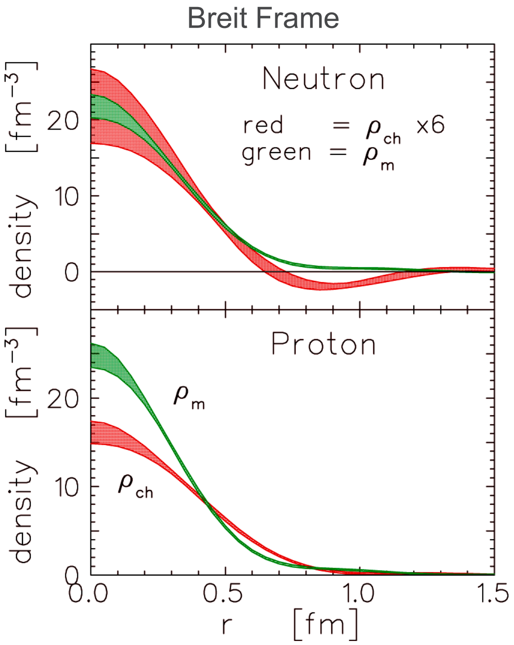
Elastic electric form factor
→ Charge distribution





empirical quark transverse densities in Neutron

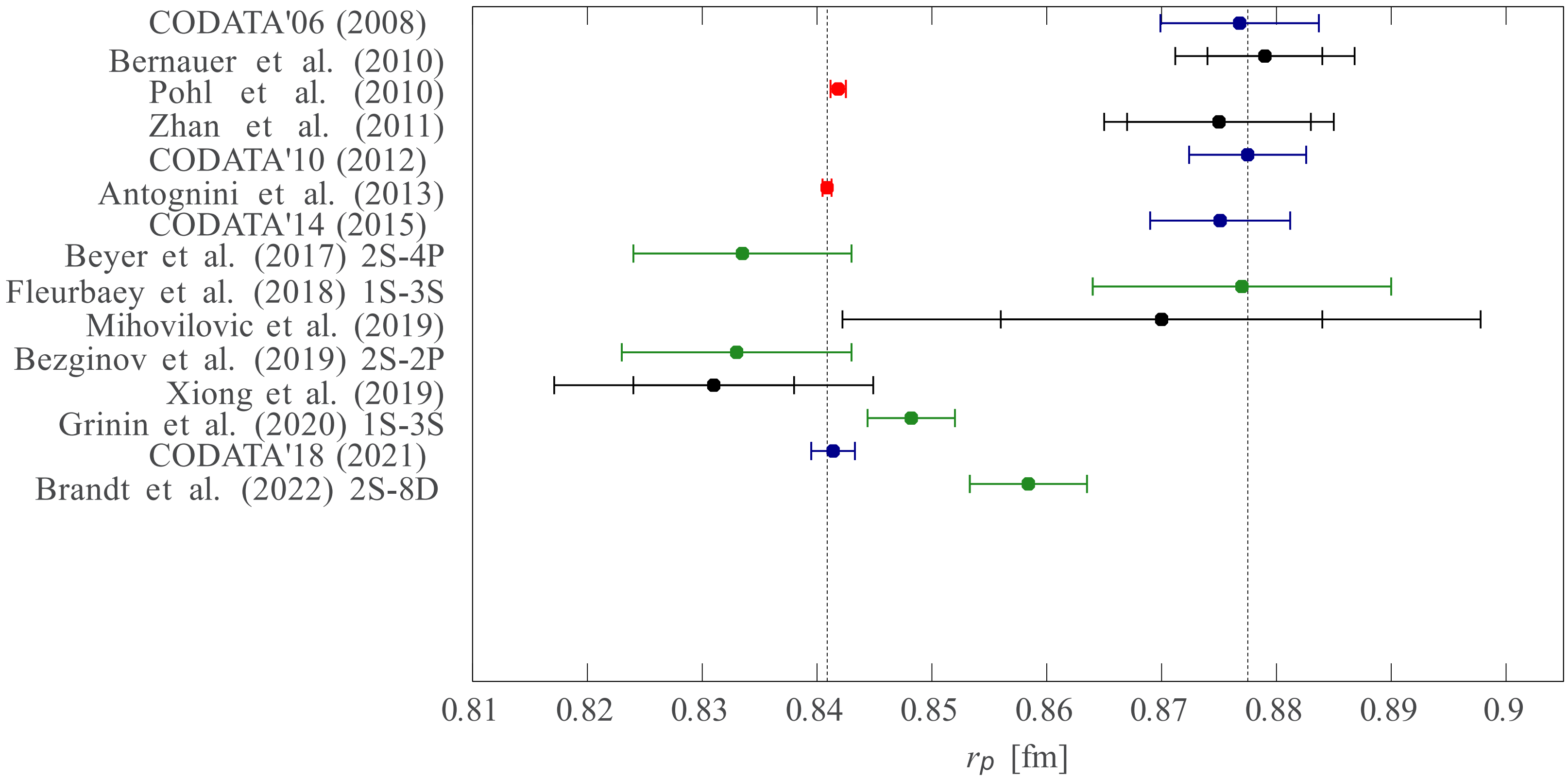




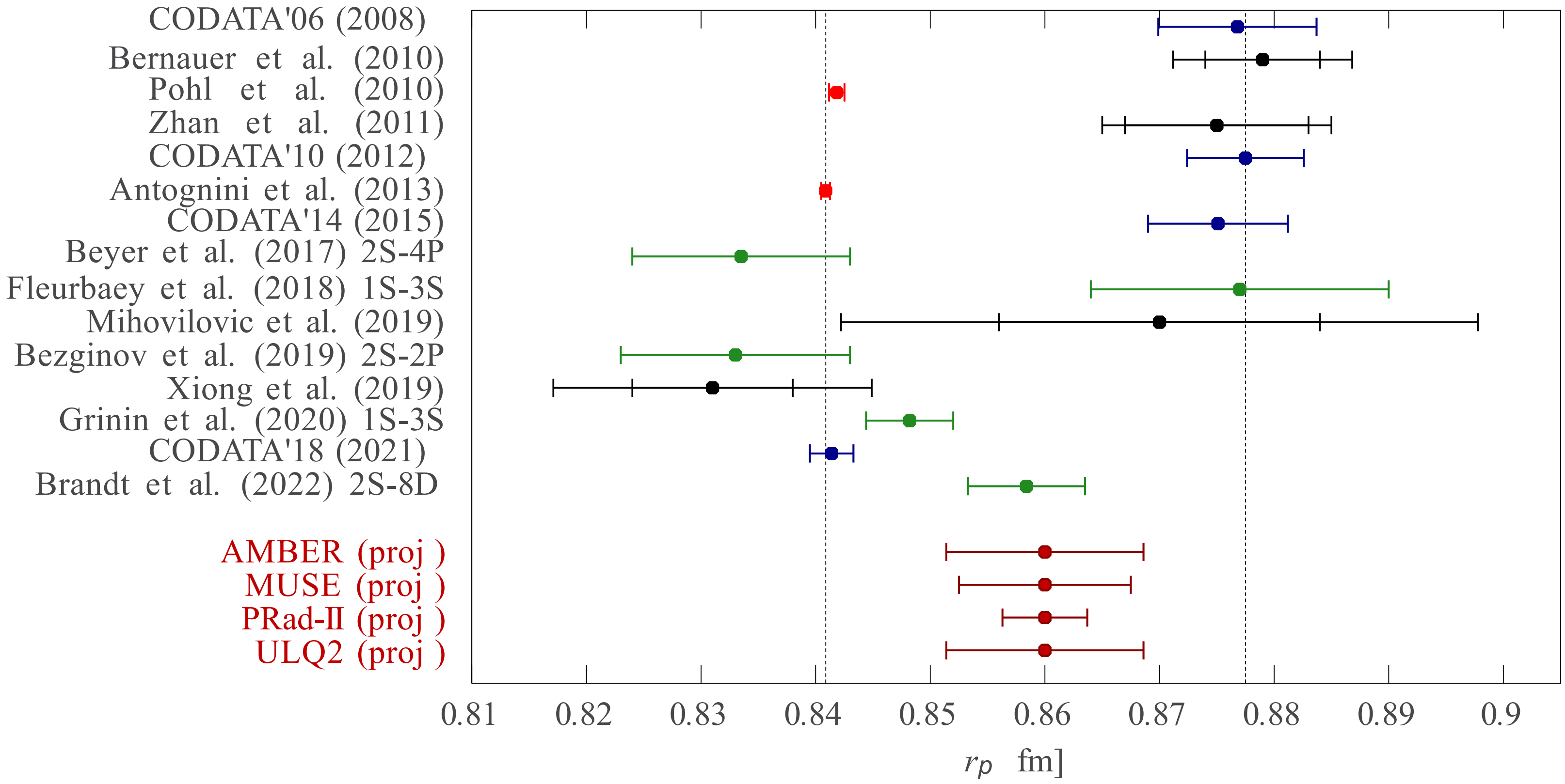
densities : Miller (2007); Carlson, Vanderhaeghen (2007)

induced EDM : $d_y = F_{2n}(0) . e / (2 M_N)$

EXPERIMENTAL STATUS OF THE PROTON CHARGE RADIUS



PROTON ELECTRIC CHARGE RADIUS PROJECTIONS



The Nucleon Generalized Polarizabilities

Talks: N. Sparveris (Thursday Plenary)

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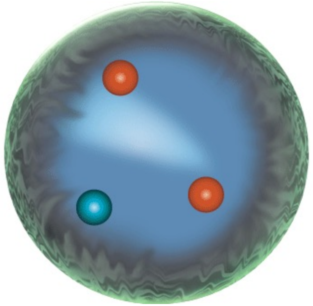
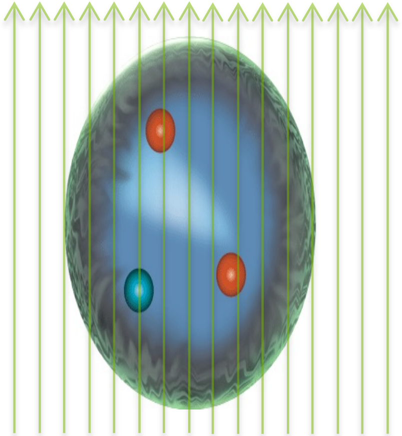
Scalar Polarizablities

Response of internal structure to an applied EM field

Interaction of the EM field with the internal structure of the nucleon



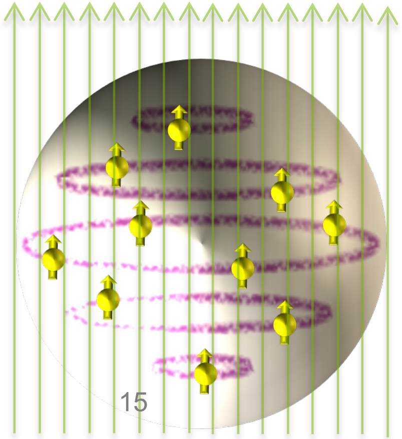


$\vec{E}$

"stretchability"

$\vec{d}_{E\ induced} \sim \alpha \vec{E}$

External field deforms the charge distribution



$\vec{B}$

"alignability"

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

$\beta_{para} > 0$

$\beta_{diam} < 0$

Paramagnetic: proton spin aligns with the external magnetic field

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

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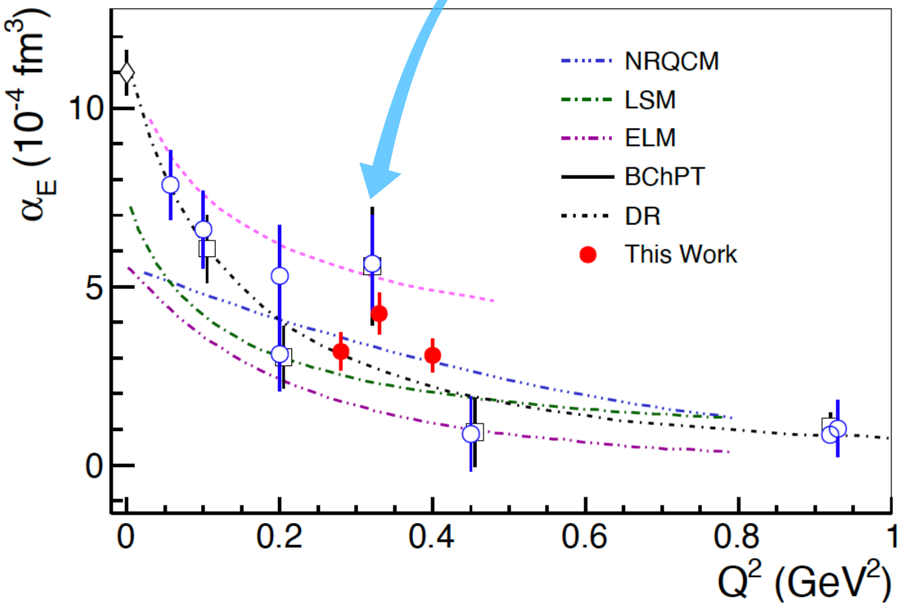
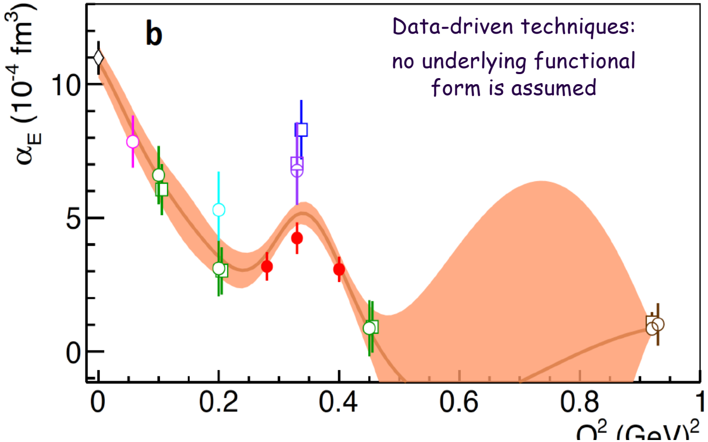
Electric Generalized Polarizability (Q^2)

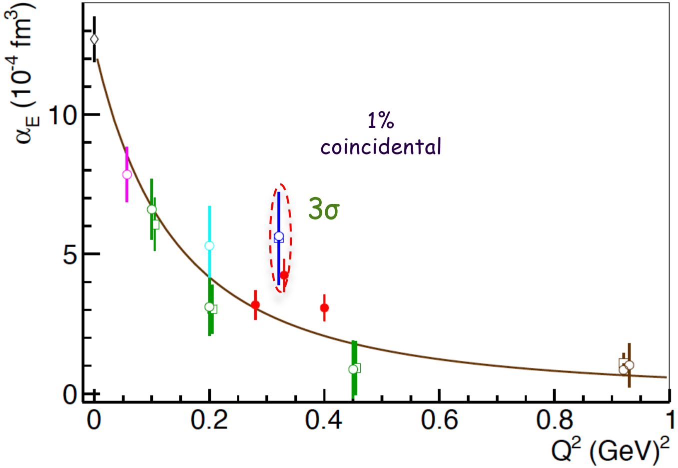
Nature 611, 265 (2022)

VCS-I Experiment (E12-15-001) in Hall C

MAMI-I re-analysis (unpublished)







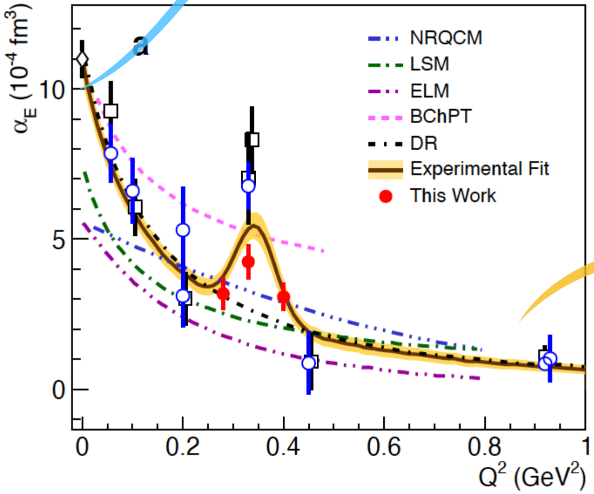
Electric Generalized Polarizability (Q^2) : Radius

R. Li et al. Nature 611, 265 (2022)

$$\langle r^2_{\alpha_E} \rangle = \frac{-6}{\alpha_E(0)} \cdot \frac{d}{dQ^2} \alpha_E(Q^2) \Big|_{Q^2=0}$$

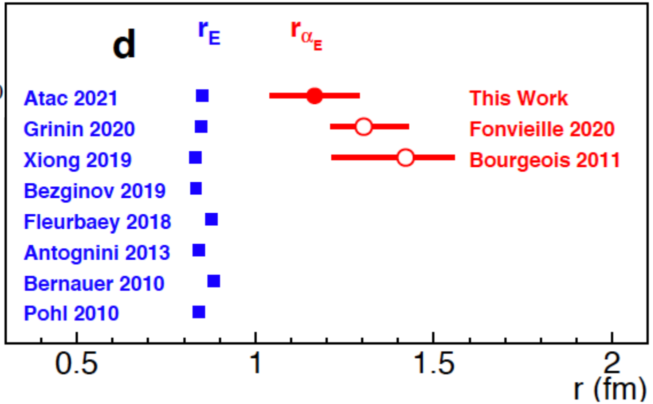
$$\langle r^2_{\alpha_E} \rangle = 1.36 \pm 0.29 \text{ fm}^2$$

Slope of α_E

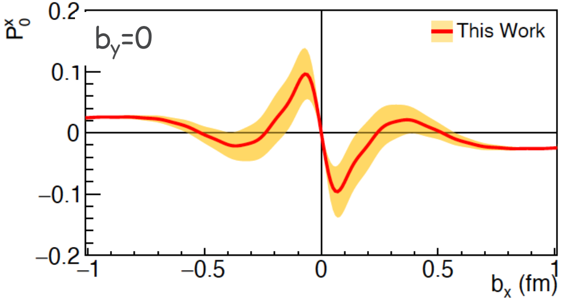


Experimental Fit

Electric polarizability radius



Induced polarization in a proton when submitted to an e.m. field



x-y defines the transverse plane with the z-axis being the direction of the fast-moving proton

Phys. Rev. Lett. 104, 112001 (2010)

M. Gorchtein, C. Lorce, B. Pasquini, M. Vanderhaeghen

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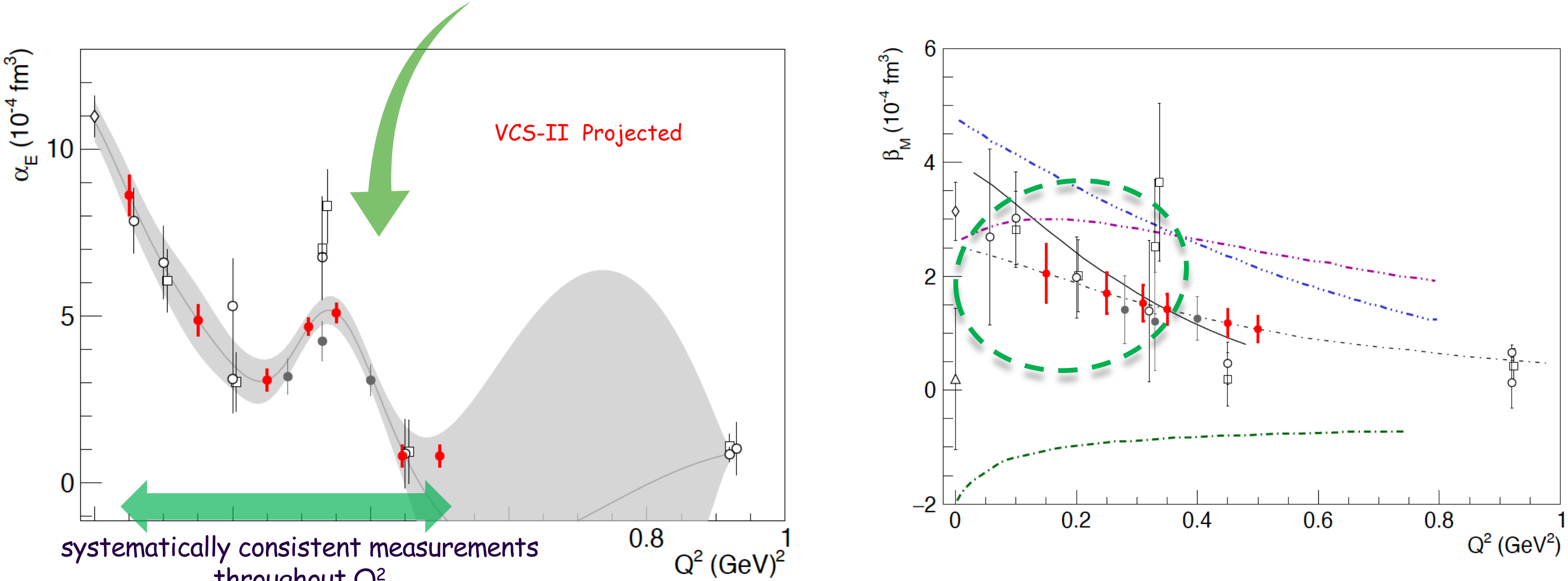
VCS-II Projected Measurements : PAC51 Approved E12-23-001@JLAB

High precision measurements
combined with a fine mapping in Q^2



systematically consistent measurements
throughout Q^2

JLab Hall A: Test of Chiral Effective Field Theory at Low Q^2

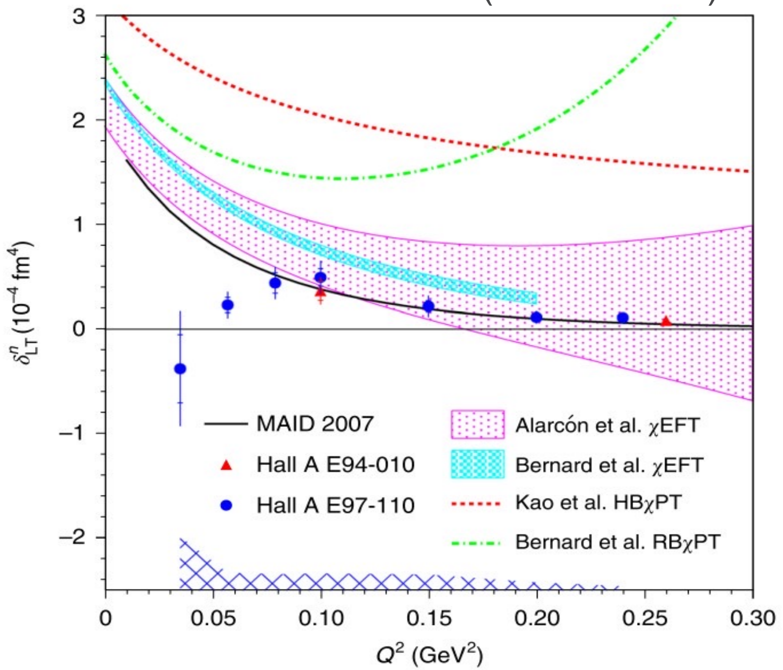
δ^n_{LT} (Q^2) puzzle" remains!

$$\delta_{LT} = \frac{4e^2 M^2}{\pi Q^6} \int x^2 (g_1 + g_2) dx$$

- Spin observables to test QCD-based theories.
- Different models predict different neutron and proton transverse-longitudinal spin polarizabilities, δ_{LT}

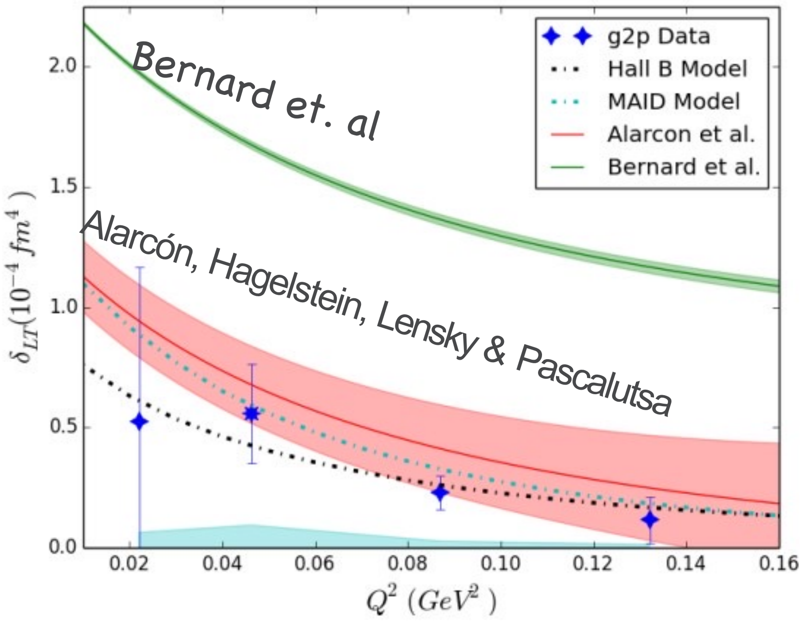
V. Sulkosky et al., Nature Physics, 17, 736-741 (2021)

Polarized Neutron (E97-110 data)



D. Ruth et al., Nature Physics 18, 1441 (2022)

Polarized Proton (g2p data)



The Proton Gravitational Form Factors

Nucleon mechanical properties, Mass, Pressure Shear

Talks: Sylvester Joosten (Tuesday pleanary session), Dimtra Pefkou (Tuesday parallel workshop 2), Shohini,

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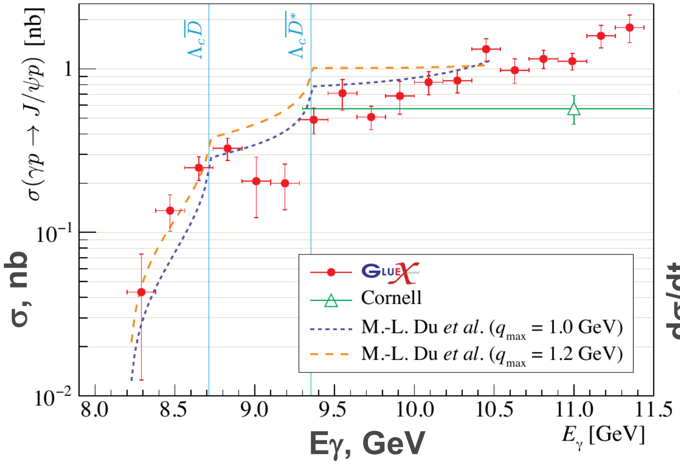
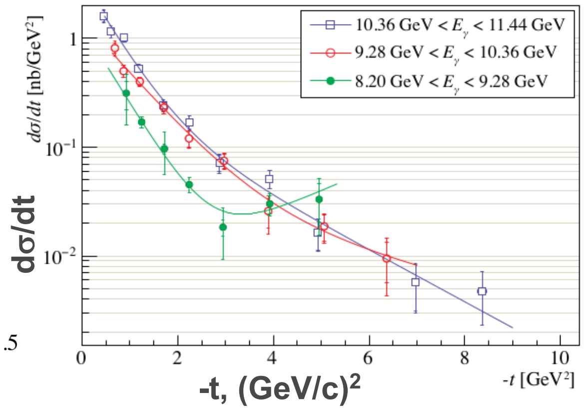
JLab Hall D GlueX Experiment: recent results

Photoproduction of γp→J/ψp close to threshold

1. *GlueX Coll. Ali et al, PRL 123 (2019)* **>170 citations**
2. *GlueX Coll. Adhikari et al, PRC 108 (2023)* , (×4 data)





GlueX –
4π acceptance spectrometer

Recent highlights

- σ(E), dσ/dt measured
Structure at σ(9GeV) may indicate an open charm contribution at ~2.6σ significance
- Rise in dσ/dt at high t, close to threshold: not a t-channel feature

Outlook

- More data are needed to study the production mechanism
- GlueX-II: ×4 more data to expect in 3 years

Large theoretical interest!

Under assumptions of 2-gluon exchange, large m_C, factorization

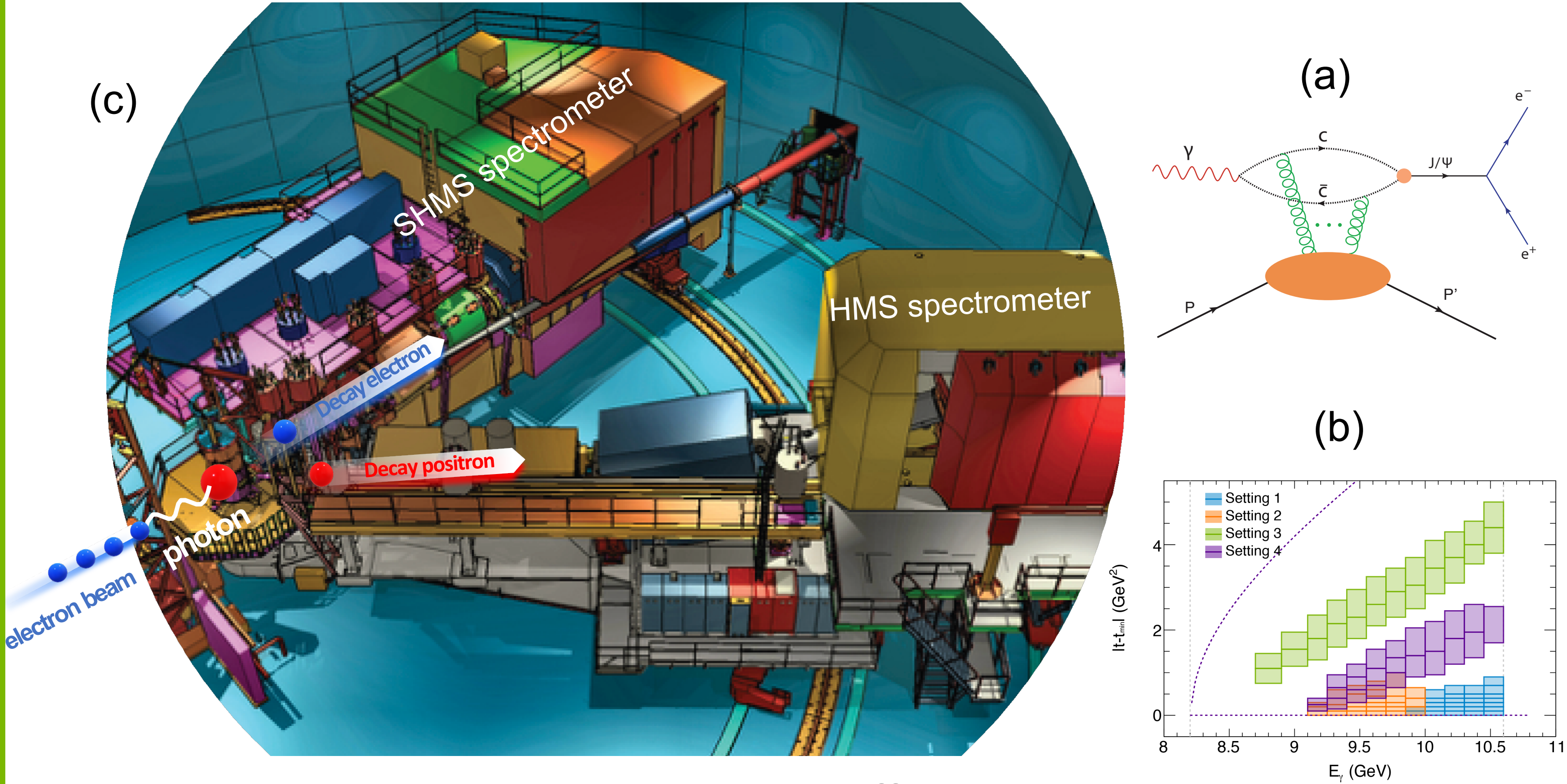
- 2-gluon exchange probes the gluonic structure of the nucleon
- Relation of dσ/dt to *gravitational form factors* of the nucleon
- Relation to the *EMT trace anomaly* and *nucleon mass*
- Probing the nature of LHCb Pentaquark (P →J/ψp): BR<few %

Other production mechanism proposed: open charm exchange

Precise measurements → verification of the assumptions

JLAB EXPERIMENT E12-16-007 IN HALL C AT JLAB

Near threshold photoproduction of J/ψ



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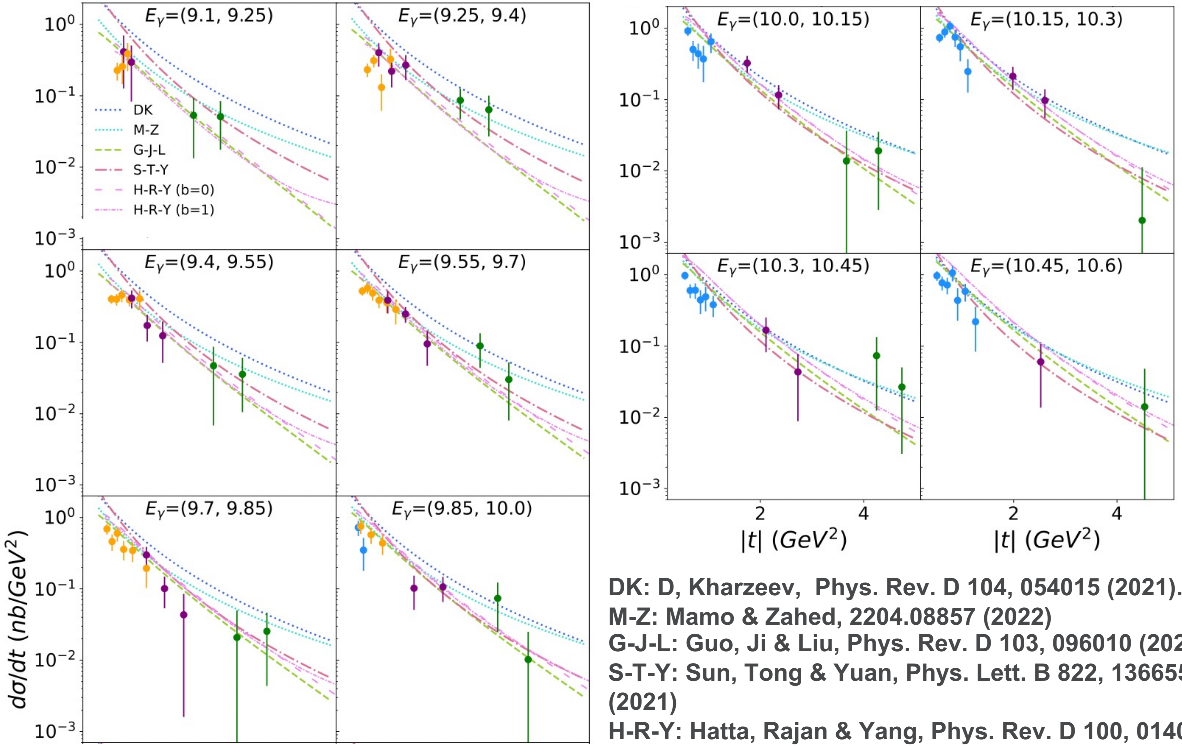
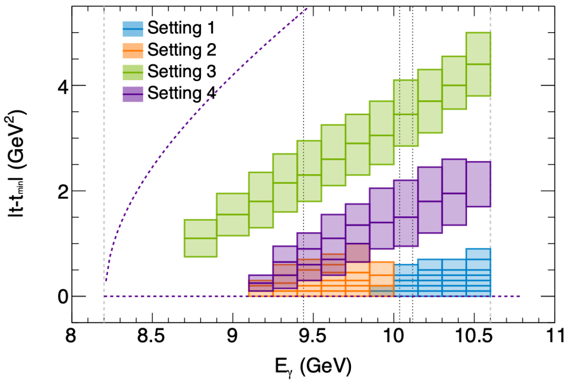
2D J/Ψ CROSS SECTION RESULTS FROM 007$^{J/\psi}$

B. Duran, et al., Nature **615**, no.7954, 813-816 (2023)



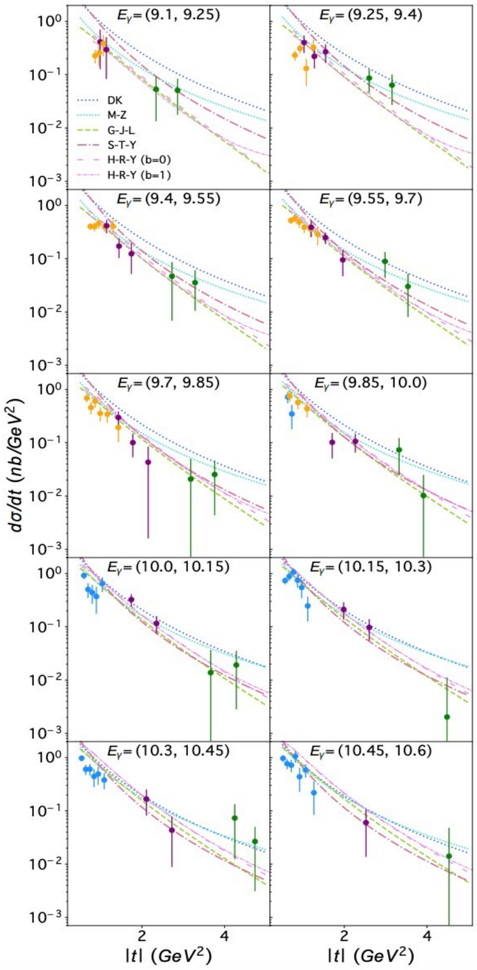


DK: D, Kharzeev, Phys. Rev. D 104, 054015 (2021).
M-Z: Mamo & Zahed, 2204.08857 (2022)
G-J-L: Guo, Ji & Liu, Phys. Rev. D 103, 096010 (2021)
S-T-Y: Sun, Tong & Yuan, Phys. Lett. B 822, 136655 (2021)
H-R-Y: Hatta, Rajan & Yang, Phys. Rev. D 100, 014032 (2019)

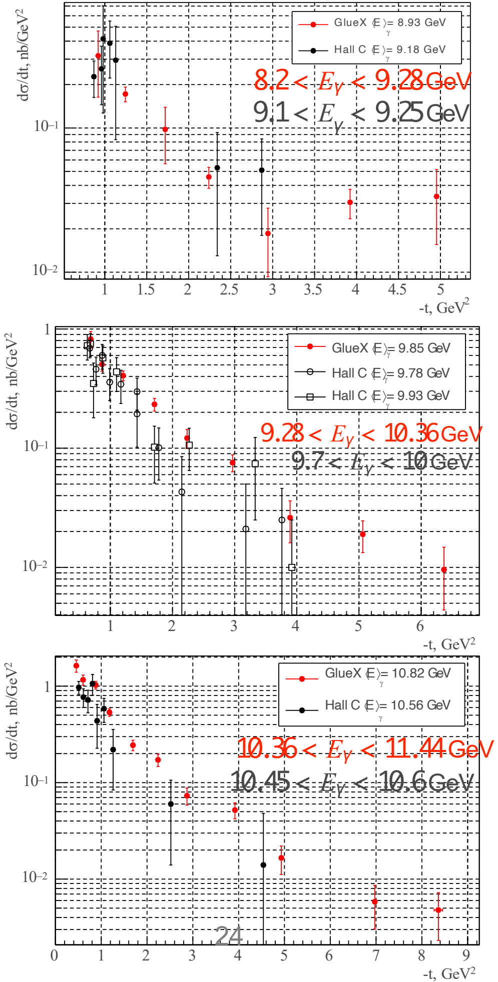
- Unfolded 2D cross section results compared to various model predictions informed by the 2019 1D GlueX results
- All models work reasonably well at higher energies but deviate at lower energies

DIFFERENTIAL CROSS SECTIONS FROM J/Ψ- 007 AND GLUEX

B. Duran et al. (J/ψ-007), Nature 615 (2023)



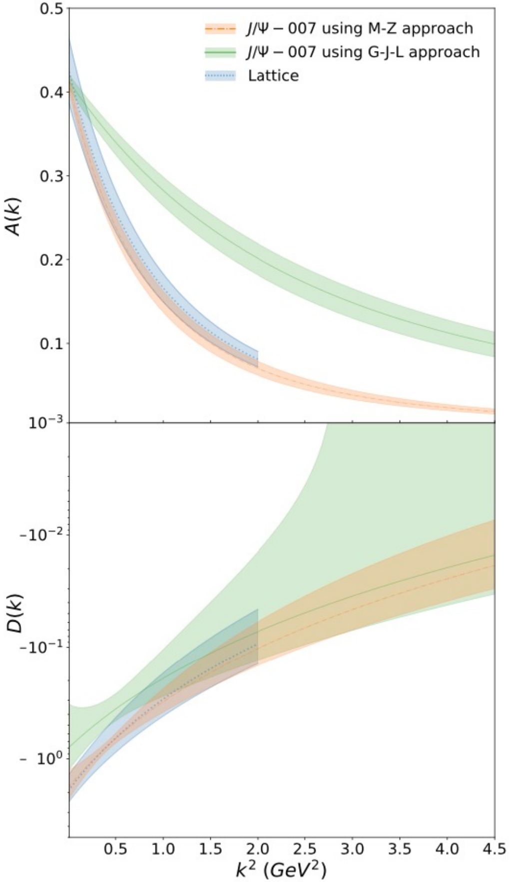
S.Adhikari et al. (GlueX), Phys. Rev. C 108, 025201



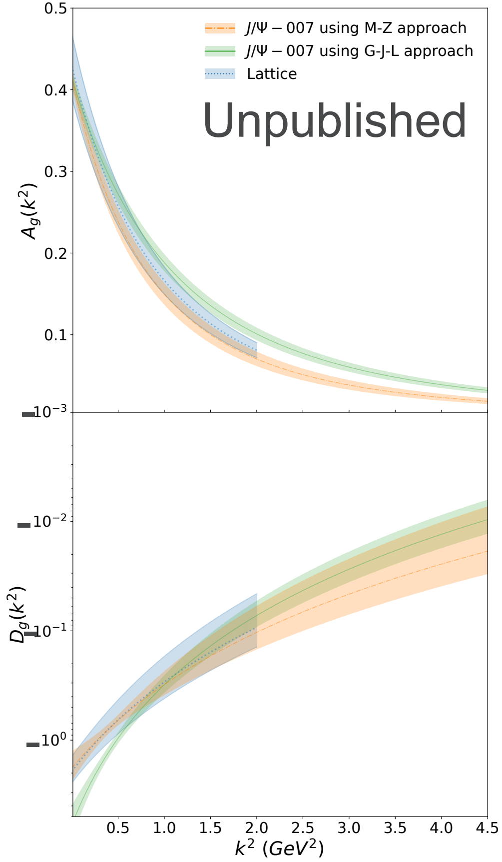
- 10 photon energy bins of 150 MeV in *J/ψ-007*
- Results for the three **GlueX energy bins** compared to the closest Hall C
- Scale uncertainties: 20% in GlueX and 4% in Hall C *J/ψ-007* differential cross section results
- Good agreement within errors; note also differences in average energies

EXTRACTED GLUONIC GRAVIATATIONAL FORM FACTORS FROM J/PSI-007

S.Prasad, ANL



B.Duran, et al., proton, Nature **615**, no.7954, 813-816 (2023)



G-J-L analysis update Phys. Rev. D **108** (2023) no.3, 034003 arXiv:2305.06992 [hep-ph]

SRUCTURE OF THE NUCLEON

Parton Distributions unpolarized/polarized

Talks: W. Vogelsang (Tuesday, parallel workshop 2), N. Pavel (Wednesday, plenary)

U.S. DEPARTMENT OF ENERGY
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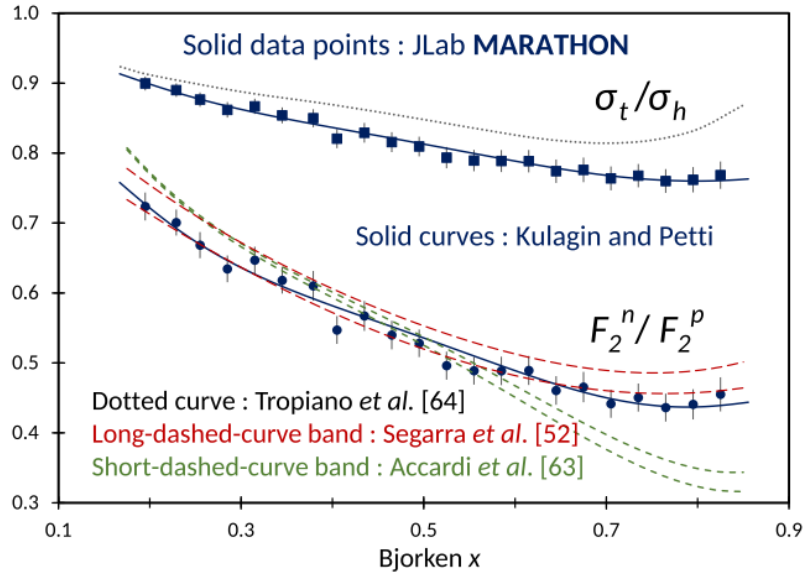
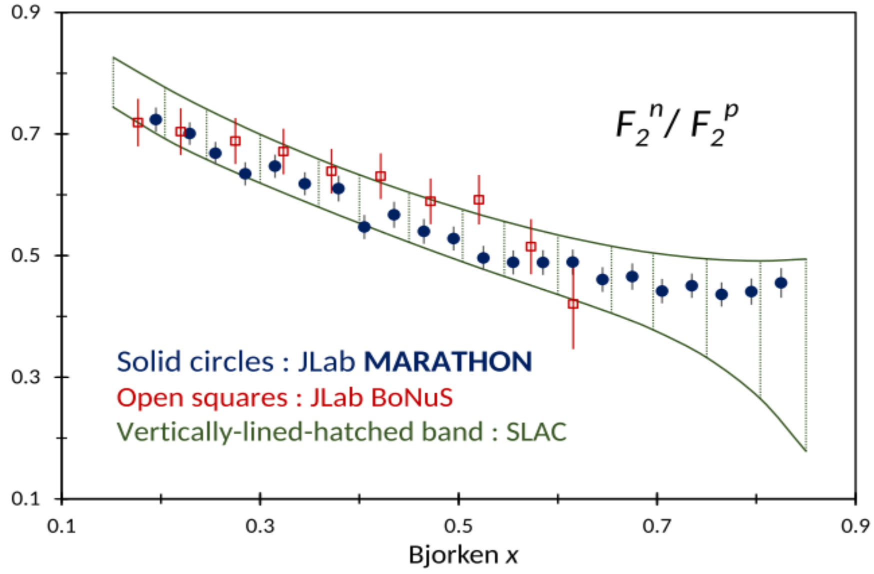
JLab Hall A : Precise Determination of the Nucleon F_2^n/F_2^p at Large x_B

- Electron DIS from the mirror nuclei ^3H and ^3He gives unique access to the neutron/proton ratio.
- Tests predictions of a wide variety of QCD models.
- Improves PDF fits at large x_B which is relevant for high-energy collider data.

D. Abrams et al., Phys. Rev. Lett. 128 (2022) 132003





@ x = 1 $F_2^n/F_2^p \rightarrow 1/4$ ($d/u \rightarrow 0$) for scalar diquarks

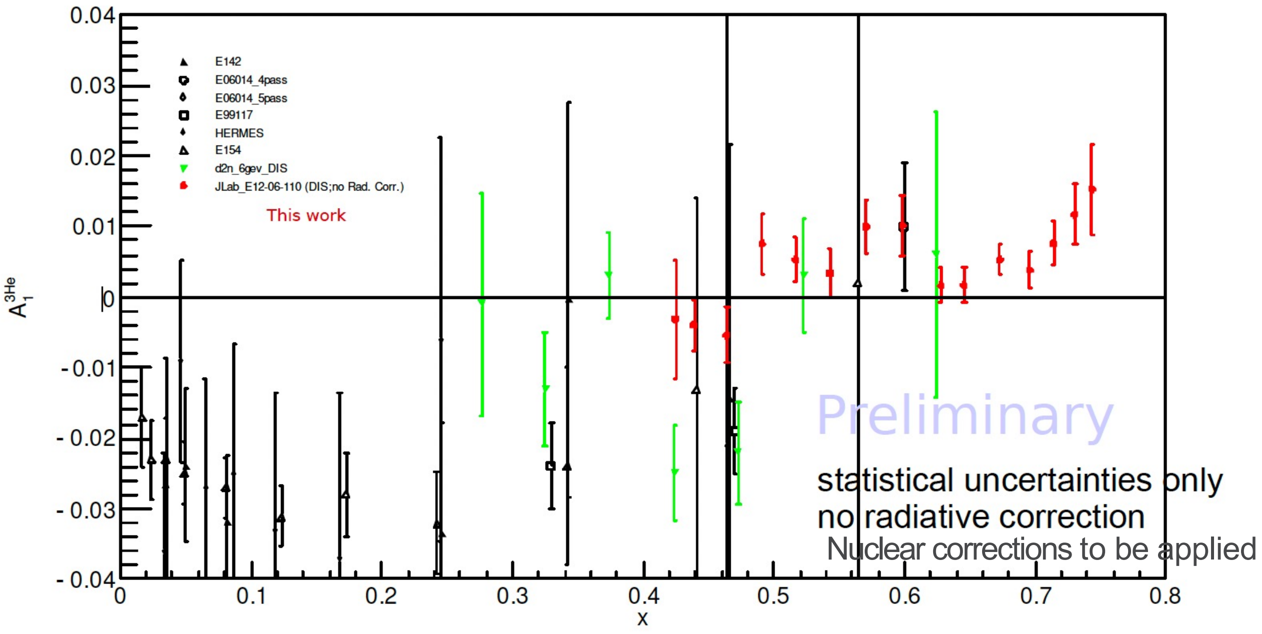
$F_2^n/F_2^p \rightarrow 3/7$ ($d/u \rightarrow 1/5$) for hard gluon exchange

HALL C: A_1^N@HIGH-X: PRELIMINARY RESULTS (E12-06-110)

Asymmetry A_1^{3He}

with DIS W>2 GeV cut

$$A_1 = \frac{A_\parallel}{D(1+\eta\xi)} - \frac{\eta A_\perp}{d(1+\eta\xi)}$$

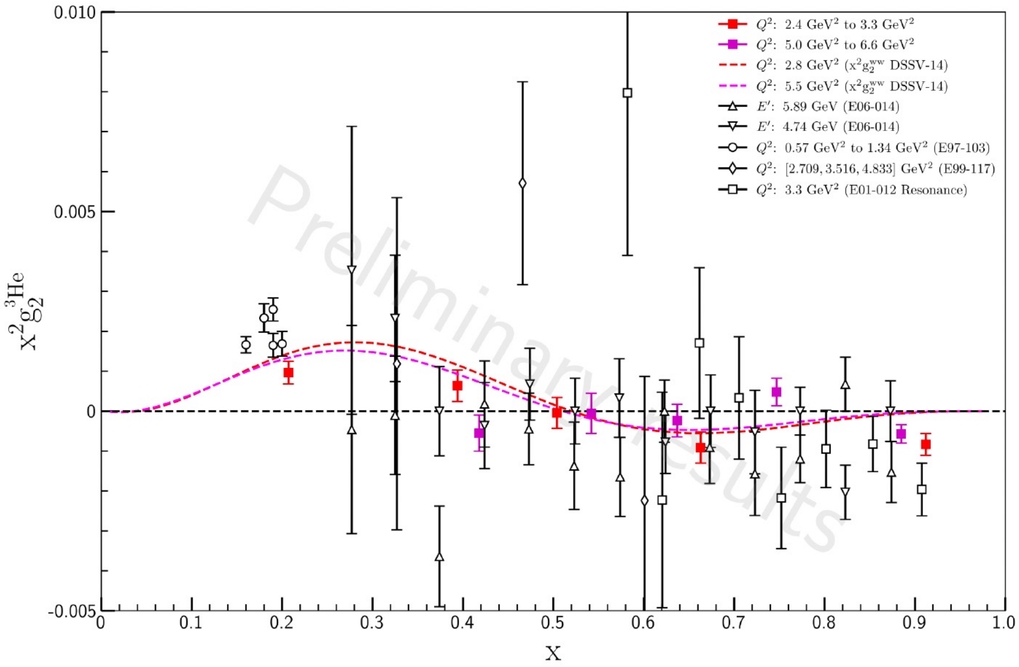


- Credit to Mingyu Chen (UVA)

Preliminary Results on g_2^{3He}

- Measurement of g_1 and g_2 structure functions and d_2 moments at 3 GeV^2 < Q^2 < 5.5 GeV^2 for the neutron using a polarized ^{3}He target
- Study quark-gluon correlations (twist-3) and provide a benchmark test of LQCD calculations.
- Completed data taking in 2020

$$\int_0^1 x^2\{2g_1 + 3g_2\} = d_2$$



Interpretations of d_2

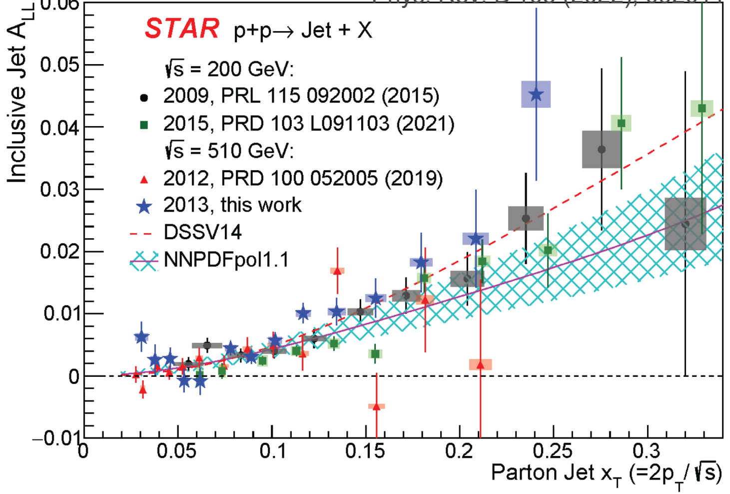
- Color polarizabilities X. Ji 95, E. Stein et al. 95)
- Average color Lorentz force (M. Burkhardt 2013)

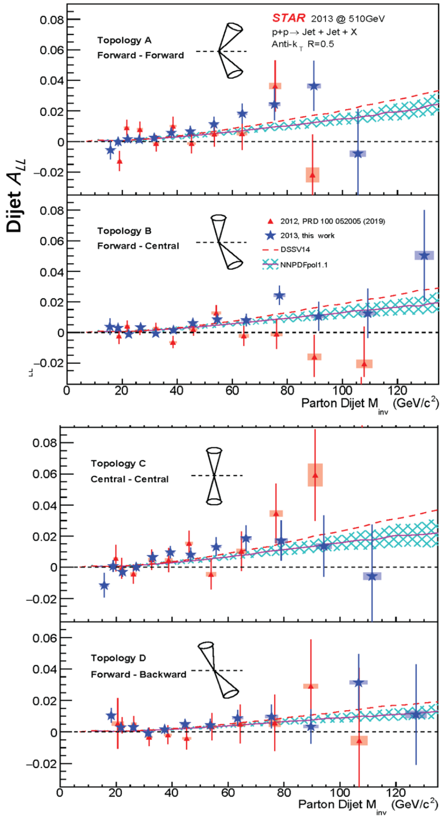
HELICITY PDFS: ΔG

Golden probes for Δg:
Double spin asymmetry A_{LL} for jets, di-jets and meson-production
Increase x-range covered: go to higher √s (200 GeV → 500 GeV)
go to higher rapidity: $-1<\eta<1$ → $-1 <\eta<1.8$)

Di-jets: constrain the shape of the Δg(x,Q2)

Phys. Rev. D 105 (2022), 092011



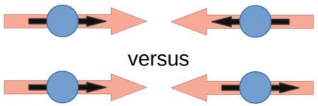


GLUON HELICITY

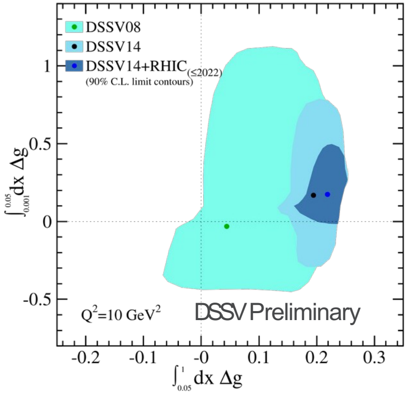
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} \hat{a_{LL}} \otimes D}{\Sigma f_a \otimes f_b \otimes \hat{\sigma} \otimes D}$$

LO for illustration

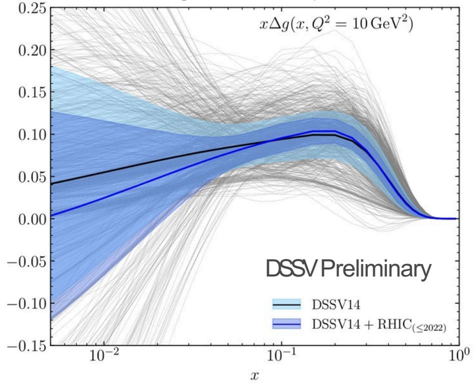
$$\vec{p} + \vec{p} \rightarrow \text{jet/dijet/hadrons} + X$$



- At RHIC energies: sensitivity to qg and gg – Access to **Δg(x)/g(x)**
- Cross-section measurement to support the NLO pQCD interpretation of asymmetries
- Data included in global pQCD analysis provided evidence for **positive gluon polarization for x > 0.05 at Q^2 = 10 GeV^2**



The RHIC Cold QCD Program, White Paper, arXiv:2302.00605



ΔG = 0.218(27), x > 0.05, Q^2 = 10 GeV^2 (68% C.L.)

DSSV14+RHIC≤2022: newest RHIC data included (STAR jets and dijets, PHENIX π)

See talk by W. Vogelsang

3D SRUCTURE OF THE NUCLEON

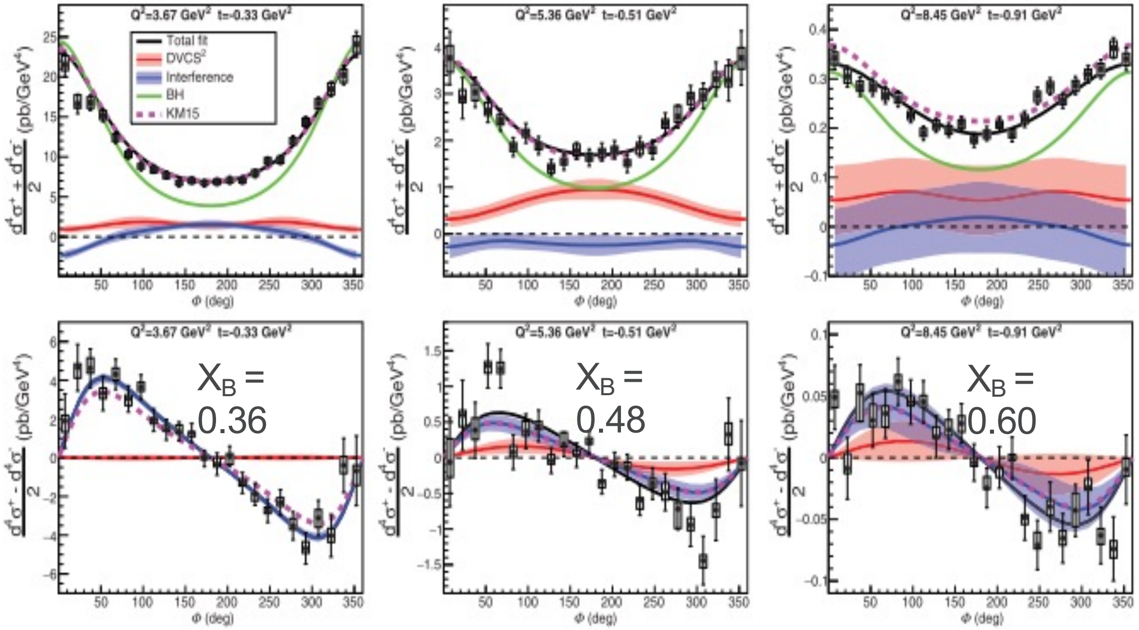
Generalized Parton Distributions (GPDs)

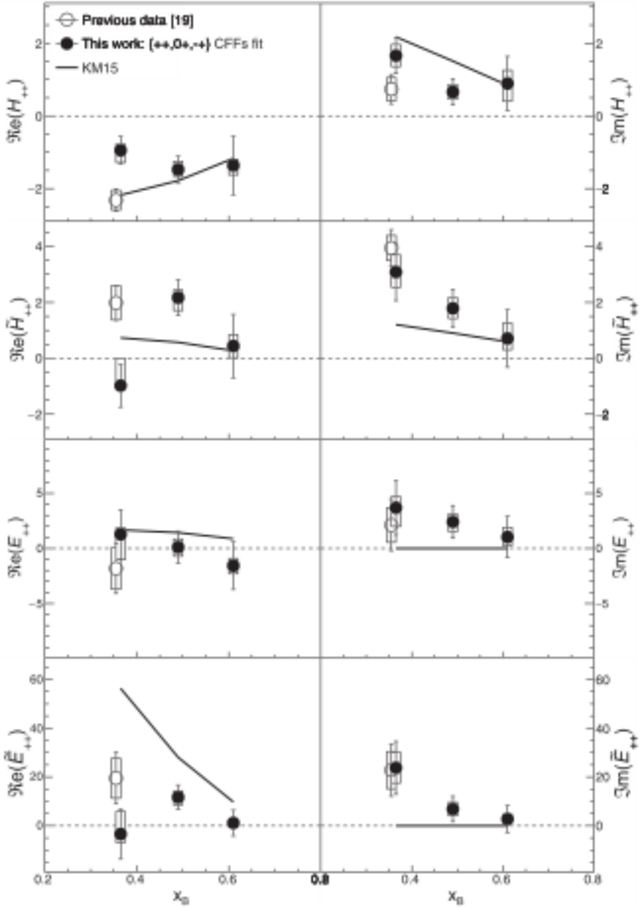
Talks:C. Reidl (Wednesday plenary), S. Niccolai (Workshop 1), V. Braun (Workshop 2), H. Adam (Workshop 2), A. Metz (Thursday), V. Bertone (Workshop 2)

Jlab Hall A: Extraction of All Four Helicity-Conserving Compton Form Factors

- DVCS is the prime reaction to determine CFFs which are convolutions of GPDs
- Fit cross section data over large range of x_B, Q^2 and t.
- Determined some poorly known CFFs. F. George et al. Phys. Rev. Lett. (2022).

- Deep Exclusive π^0 data published in Phys. Rev. Lett. (2021)





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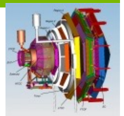
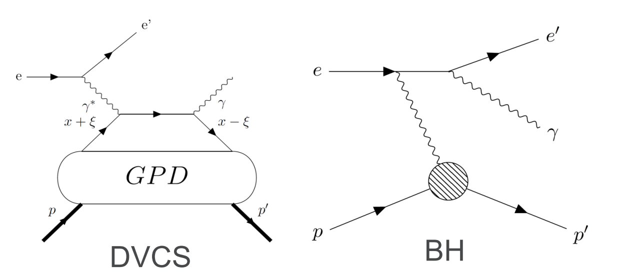
Hall B: First Measurement of the DVCS Process in the Extended Valence Region



G. Christiaens *et al.* (CLAS Collaboration), Phys. Rev. Lett. 130, 211902 (2023)

Deeply Virtual Compton Scattering: the golden process to access GPDs

- Reaction of interest: *ep → e'p'γ*
- In the factorization regime $-t \ll Q^2$ GPD describe the soft structure of the proton



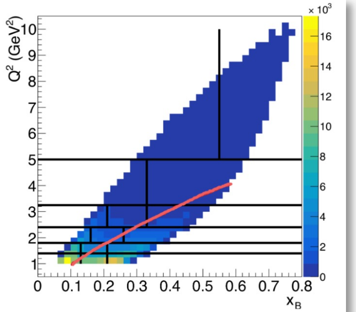
Representing only 25% of the beam time allocated to the CLAS12 experiment for DVCS on an unpolarized proton.

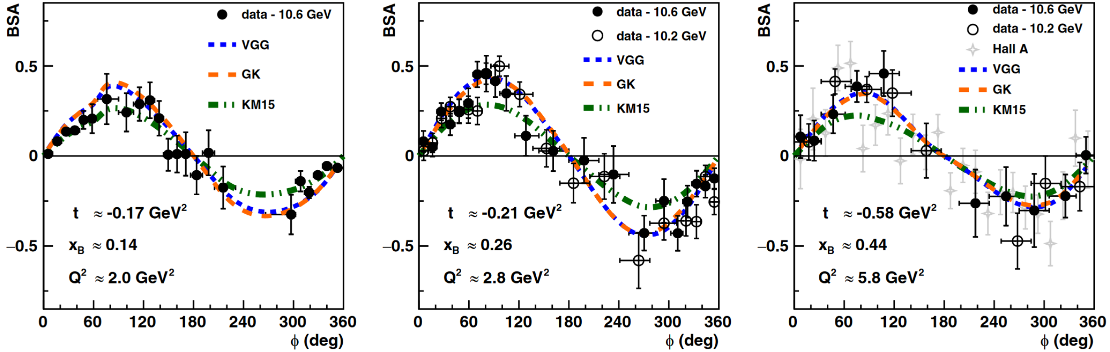
Beam spin asymmetries in wide phase space

- Addressing Compton Form Factors, constraints on GPDs, and proton's mechanical properties

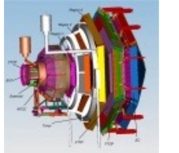
$$A_{LU} \propto Im\left[F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right]$$

- 1600 new data points
- 25% of the total beam time for CLAS12 DVCS experiment on unpolarized proton



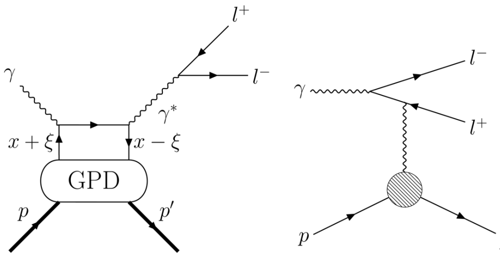


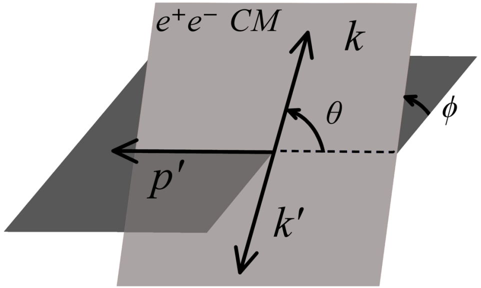
TIME-LIKE COMPTON SCATTERING AT JLAB HALL B



First measurement of time-like Compton scattering processes from CLAS12

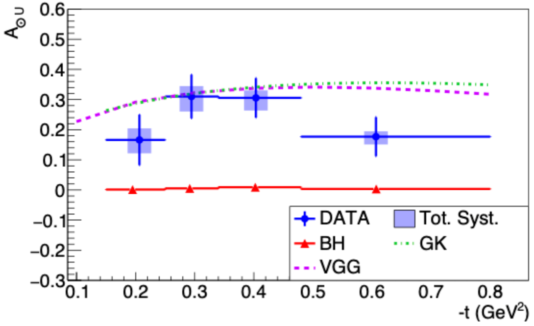
P. Chatagnon *et al.* (CLAS Collaboration), Phys. Rev. Lett. 127, 262501 (2021)



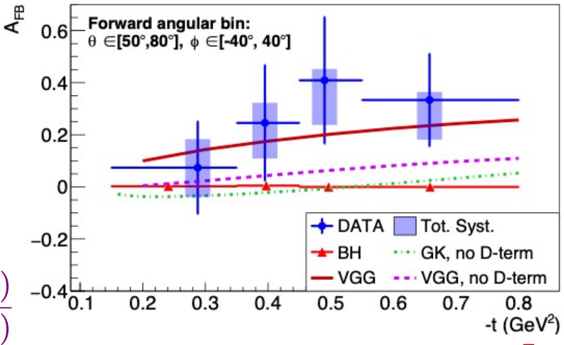


$$\sigma(\gamma p \to p' e^+ e^-) = \sigma_{BH} + \sigma_{TCS} + \sigma_{INT}$$

Photon polarization asymmetry



Forward-backward asymmetry



$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = A\frac{1+\cos^2\theta}{\sin\theta}[\cos\phi \,\mathrm{Re}\tilde{M}^{--} - \nu\cdot\sin\phi\,\mathrm{Im}\tilde{M}^{--}],$$

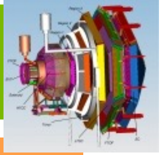
$$\tilde{M}^{--} = \left[F_1\mathcal{H} - \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4m_p^2}F_2\mathcal{E}\right]$$

$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-},$$

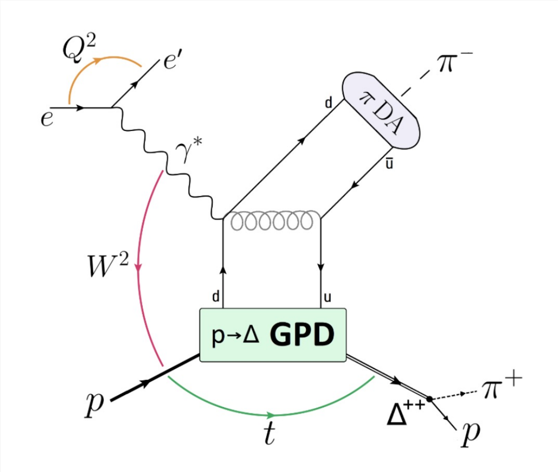
$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180° - \theta, 180° + \phi)}{d\sigma(\theta,\phi) + d\sigma(180° - \theta, 180° + \phi)}$$

- Test of GPD universality via beam spin asymmetry that is sensitive to the imaginary part of the Compton form factors
- Access to real part of Compton form factors via forward/backward asymmetry and thus to *D*-term in parametrization of GPDs that links to the mechanical properties of the proton

CLAS12 First Measurement of a Transition GPD in the N to Δ++ Reaction



16 transition GPDs in N → Δ processes

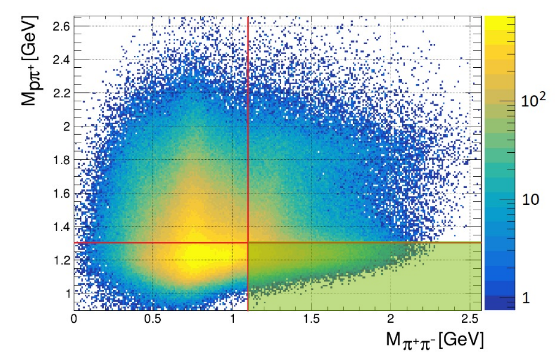


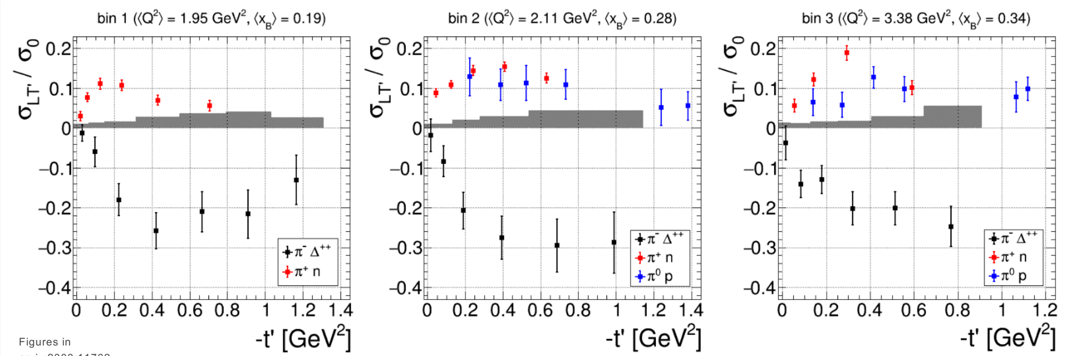
Opens a path for 3D structure of resonances from future measurements of the $N \rightarrow N^*$ DVCS process, as well as other $N \rightarrow N^*$ DVMP channels at JLab and at the future electron ion collider (EIC) with an extension to the strangeness sector.

Exploratory measurement of beam-spin asymmetries in these processes

- $ep \rightarrow e' p\, \pi^-(\pi^+)$
- Access to *d*-quark content
- No other world data

$$BSA = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi}$$



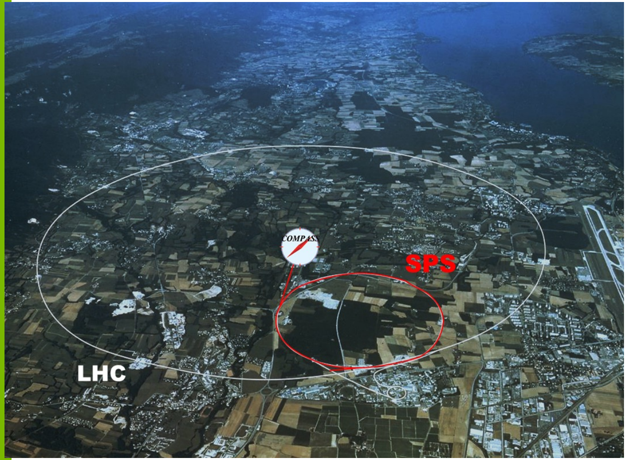


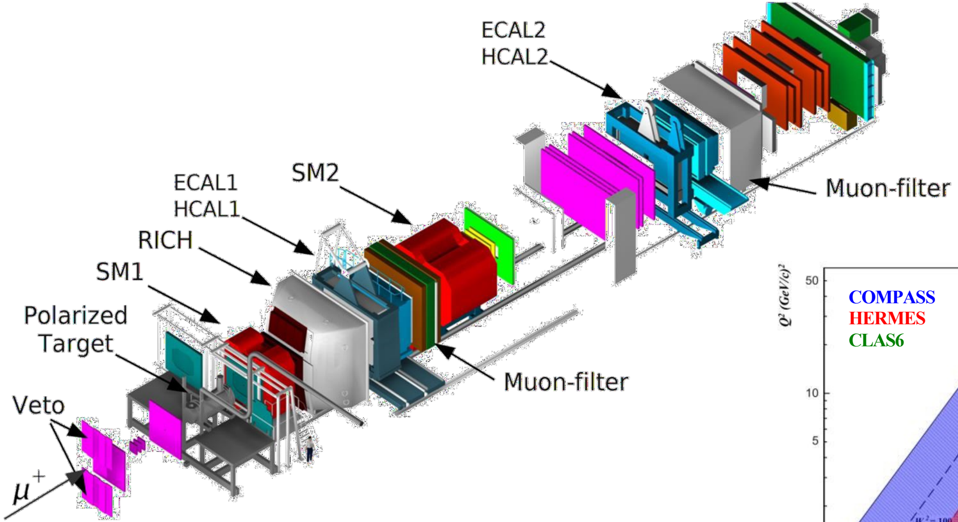
Figures in arxiv:2303.11762

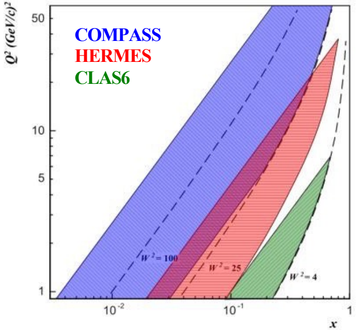
S. Diehl *et al.* (CLAS Collaboration), Phys. Rev. Lett. 131, 021901 (2023)

COMPASS AT CERN

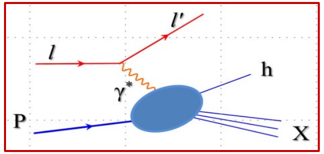
COMPASS EXPERIMENTAL SETUP



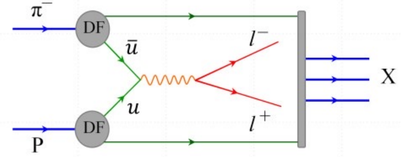


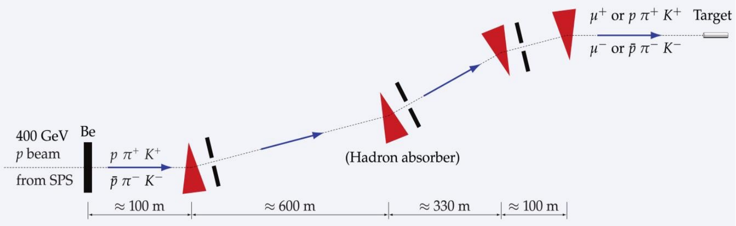


Transverse SIDIS



Drell-Yan



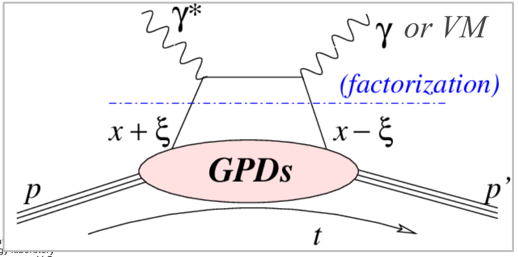


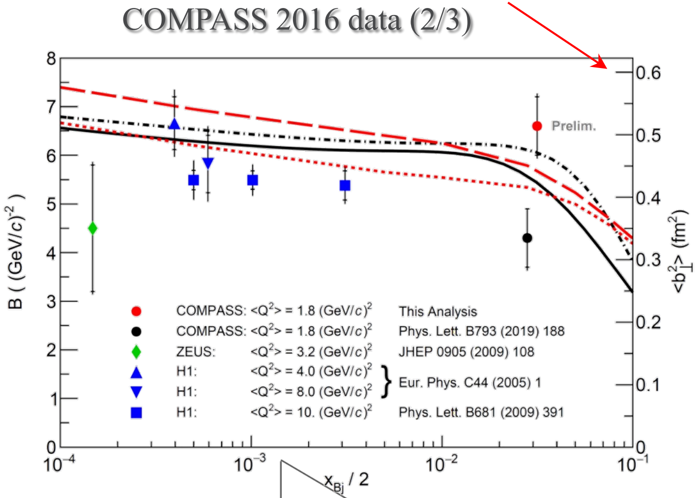
COMPASS DATA TAKING CAMPAIGNS

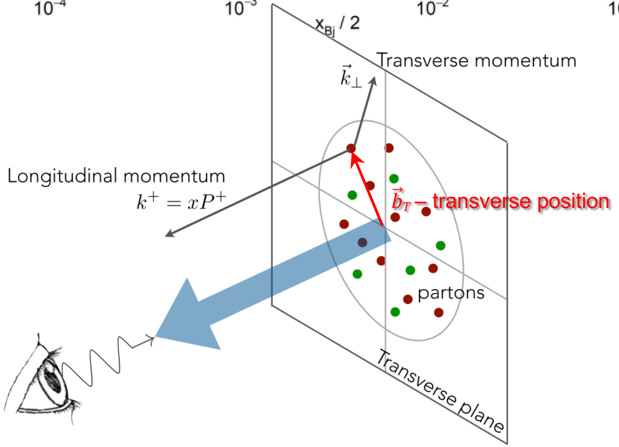
Beam	Target	year	Physics programme
μ^+	Polarized deuteron (^6LiD)	2002 2003 2004	80% Longitudinal | 20% Transverse SIDIS
μ^+	Polarized deuteron (^6LiD)	2006	Longitudinal SIDIS
μ^+	Polarized proton (NH_3)	2007	50% Longitudinal | 50% Transverse SIDIS
π | K | p	LH_2, Ni, Pb, W	2008 2009	Spectroscopy
μ^+	Polarized proton (NH_3)	2010	Transverse SIDIS
μ^+	Polarized proton (NH_3)	2011	Longitudinal SIDIS
π | K | p	Ni	2012	Primakoff
$\mu^\pm$	LH_2	2012	Pilot DVCS & HEMP & unpolarized SIDIS
π^-	Polarized proton (NH_3)	2014	Pilot Drell-Yan
π^-	Polarized proton (NH_3)	2015 2018	Transverse Drell-Yan
$\mu^\pm$	LH_2	2016 2017	DVCS & HEMP & unpolarized SIDIS
μ^+	Polarized deuteron (^6LiD)	2021 2022	Transverse SIDIS

NUCLEON 3D STRUCTURE

- Transverse position $\vec{b}_T$ of partons
  - Correlation between $\vec{b}_T$ and x
  - Complementary to TMD PDFs
- 8 generalized parton distribution functions (GPDs)
  - Contain information about parton orbital angular momentum
  - Mostly unknown
- COMPASS exclusive process measurements:
  - Deeply virtual Compton scattering (DVCS): $\mu + N \rightarrow \mu + \gamma + N$
  - Hard exclusive meson production (HEMP): $\mu + N \rightarrow \mu + VM + N$ with $VM = \pi^0, \rho(770), \omega(782)$,..





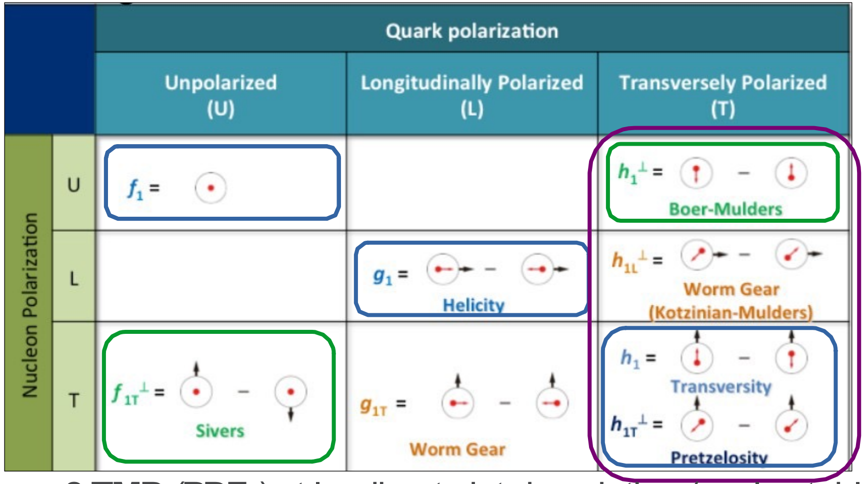


3D SRUCTURE OF THE NUCLEON

Transverse Momentum Dependent Distributions (TMDs)

Talks:C. Reidel (Wednesday, Pleanary)

LEADING TWIST TMDS



TMDs surviving integration over k_T

Naive time-reversal odd TMDs describing strength of spin-orbit correlations.

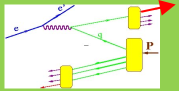
Chiral odd TMDs

- **8 TMD** (PDFs) at leading-twist description (analog table for **fragmentation functions**) Off-diagonal part vanishes without parton's transverse motion

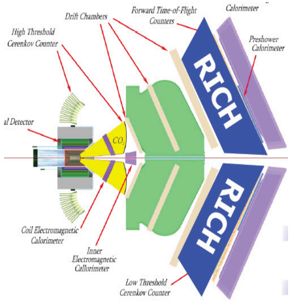
- **Sivers effect:** correlations between the nucleon transverse spin direction and parton transverse momentum in the polarized nucleon

- **Collins effect:** fragmentation of a transversely polarized parton into a final-state hadron

- **Boer-Mulders effect:** correlations between the parton transverse spin direction and parton transverse momentum in the polarized nucleon



SIDIS AT JLAB12



Proton

CLAS12

E12-16-010C

E12-06-112: π^+,π^-,π^0
E12-09-008: K^+, K^-, K^0

E12-07-107: π^+,π^-,π^0
E12-09-009: K^+, K^-, K^0

C12-11-111: π^+,π^-,π^0 K^+, K^-

H_2, NH_3, HD

Quark spin polarization / Nucleon polarization

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

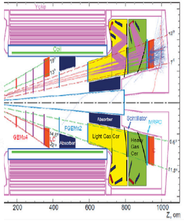
Hall C | Hall A

E12-09-017: π^+,π^-, K^+,K^-
C12-11-102: π^0
HMS SHMS

E12-06-104
E12-23-014

C12-11-108: π^+,π^-
Solid

H_2 | NH_3



E12-16-010C

D_2

CLAS12

E09-008: π^+,π^-,π^0 K^+, K^-, K^0

E07-107: π^+,π^-,π^0
E09-009: K^+, K^-, K^0

D_2, ND_3

C12-20-002
π^+,π^-,π^0,K+

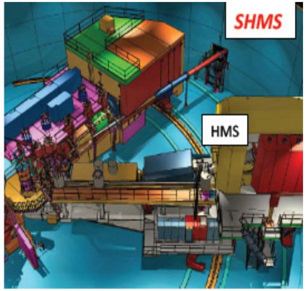
Quark spin polarization / Nucleon polarization

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall C

E12-09-017: π^+,π^-, K^+,K^-
C12-11-102: π^0
HMS SHMS

D_2



^3He

Quark spin polarization / Nucleon polarization

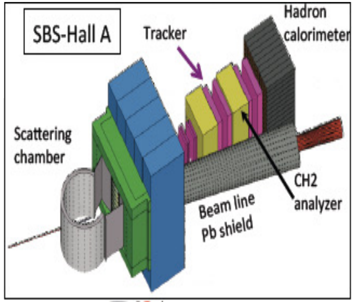
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall A

E12-07-007: π^+,π^- Solid

E10-006: π^+,π^- Solid
E12-09-018: π^+,π^-, K^+,K^- SBS

^3He

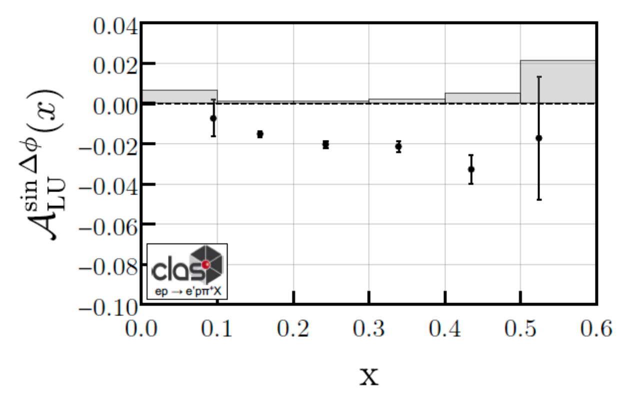


H. Avakian (SPIN2023)

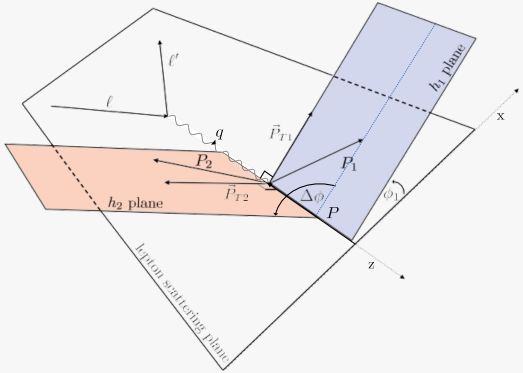
First Measurement of Asymmetries in Back-to-Back Dihadron Electroproduction

H. Avakian *et al.* (CLAS Collaboration), Phys. Rev. Lett. 130, 022501 (2023)

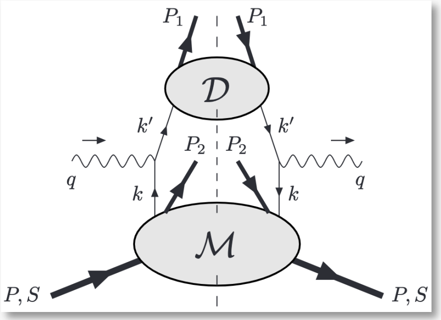
$$A_{LU} \propto \frac{\mathcal{C}[w_5\, \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]} \sin \Delta\phi$$



Unique access to longitudinally polarized quarks in unpolarized nucleons



$$ep \longrightarrow ep\pi^+X$$



- First SIDIS detection of a hadron in current-fragmentation region in coincidence with a hadron in target-fragmentation region
- Structure function contains a convolution of fracture and fragmentation functions
- Asymmetry significant at large *x*, where valence quarks dominate

CAHN EFFECT IN SIDIS

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left(\ldots + \sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \ldots\right)$$

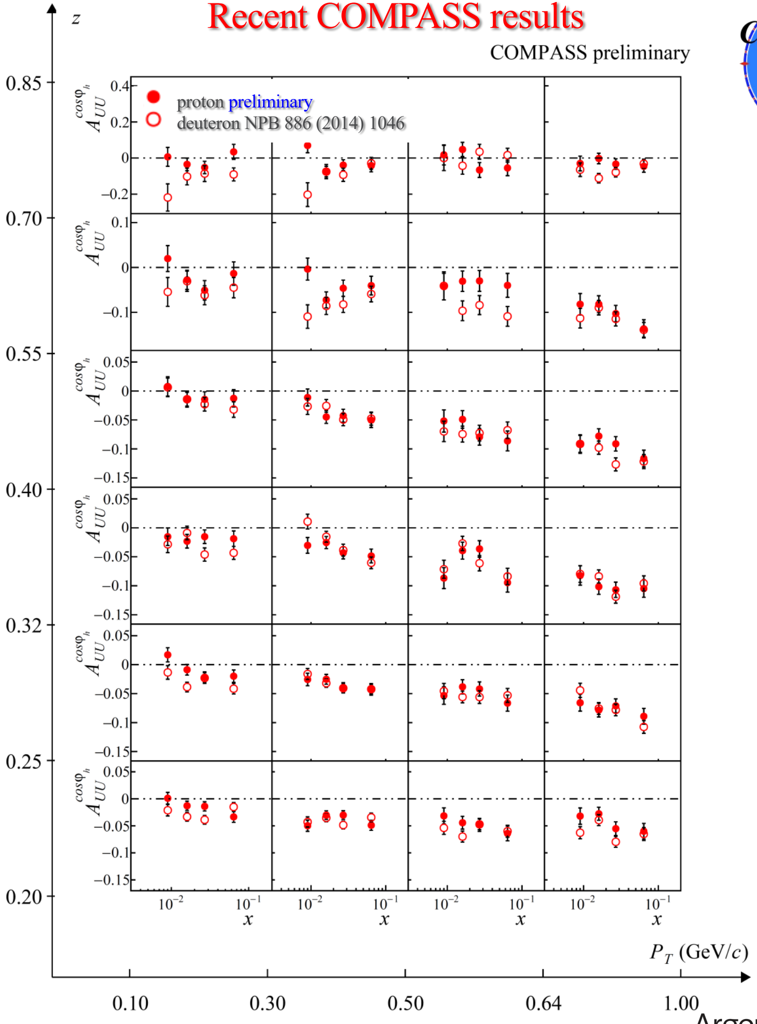
Cahn effect

$f_1^q(x, \boldsymbol{k}_T^2)$
number density

As of 1978 – simplistic kinematic effect:
- non-zero k_T induces an azimuthal modulation

As of 2023 – complex SF (twist-2/3 functions)
- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no comprehensive interpretation
- A set of complex corrections:
  - Acceptance, diffractively produced VMs, radiative corrections (RC), etc.
- Strong Q^2 dependence – unexplained
  - Do not seem to come from RCs
  - Transition between TMD↔collinear regions?

Recent COMPASS results



B. Parmasyan (SPIN2023)

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Argonne ... U.S. Dep... managed by UChicago Argonne, LLC.
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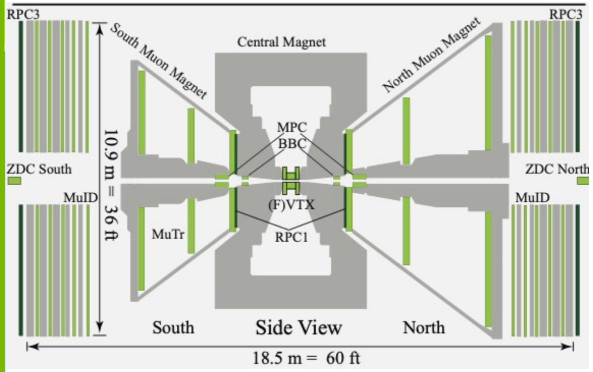
THE RHIC EXPERIMENTS

PHENIX

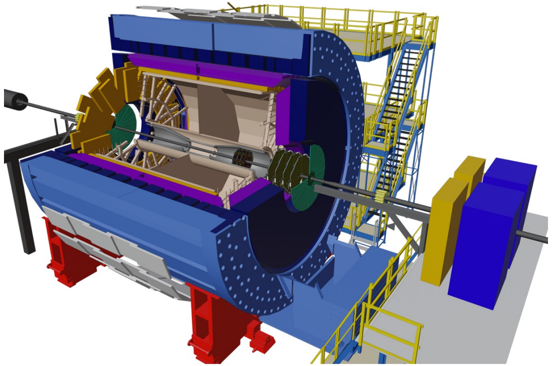


$-0.35 < \eta < 0.35$
$1.2 < |\eta| < 2.4$ muon arms
$|\eta| < 3$ vertex trackers

e/h separation,
μ, γ, π^0 Identification

2000 to 2016

STAR

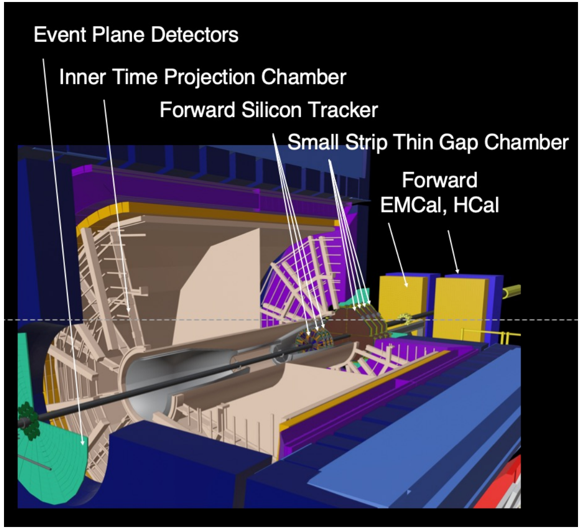


Rapidity coverage
$-1 < \eta < 4$

Particle Identification
e/h separation,
μ, γ, π^0 Identification
π,K,p PID via dE/x, ToF

Data Taking
2000 to 2025

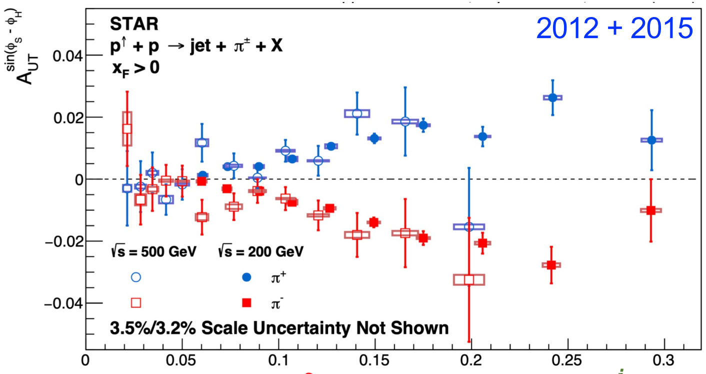
STAR Upgrades

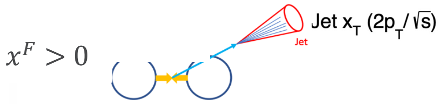


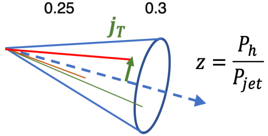
- Event plane detectors
- Inner time projection chamber
- Forward silicon tracker
- Small strip thin gap chamber
- Forward EMCal, HCal

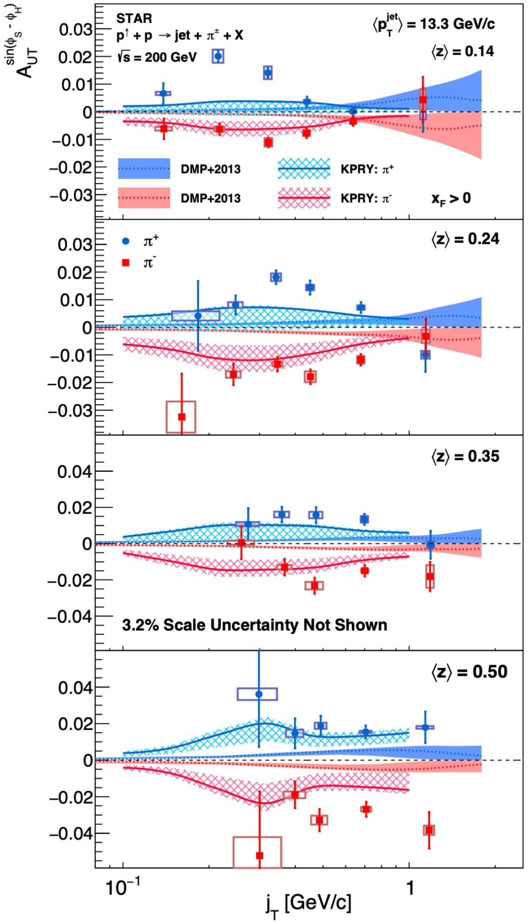
COLLINS ASYMMETRY FOR $\pi^{\pm}$ IN JETS (MID-RAPIDITY)

STAR: Phys.Rev.D 106 (2022) 7, 072010 arXiv:2205.1180









- ❑ Collins asymmetries of $\pi^{\pm}$ measured with extremely high precision; agree at 0.06 <x_T< 0.2, Q^2 differ by a factor of 6
- ❑ Collins asymmetry has a weak energy dependence in hadronic collisions;
- ❑ Collins TMD FF is sensitive to the (j_T, z); z and j_T dependences of the Collins FF are closely related.
- ❑ Results slightly favor the KPRY model than DMP+2013;
- ❑ Sizable differences between data and both theoretical calculations.

CONCLUSION

- ❑Many exciting results since the last edition of EINN! Serious progress was achieved in many fronts but still a lot to do.
- ❑1D studies still offer many opportunities to understand the structure of the nucleon
- ❑ A lot of progress in spatial and momentum 3D imaging of the proton, still a long road with much promise
- ❑We'll hear about the exciting future of the field with the EIC and opportunities for high luminosity SoLID, positron beams & 20+ GeV upgrade at JLab.
- ❑Finally, after 50 years of QCD we have not yet solved the confinement problem. But some hope & positive news a "Simons Collaboration on Confinement and QCD Strings" was recently established at Princeton. This points to the importance of our field recognized by those who moved from it in the last 40 years.

https://simonsconfinementcollaboration.org/

Thank you!

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