Recent Progress of JLab Physics

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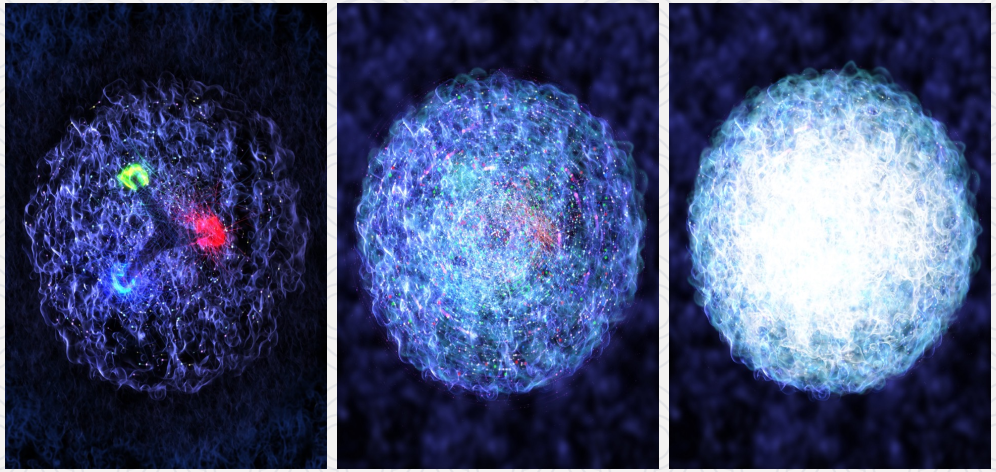
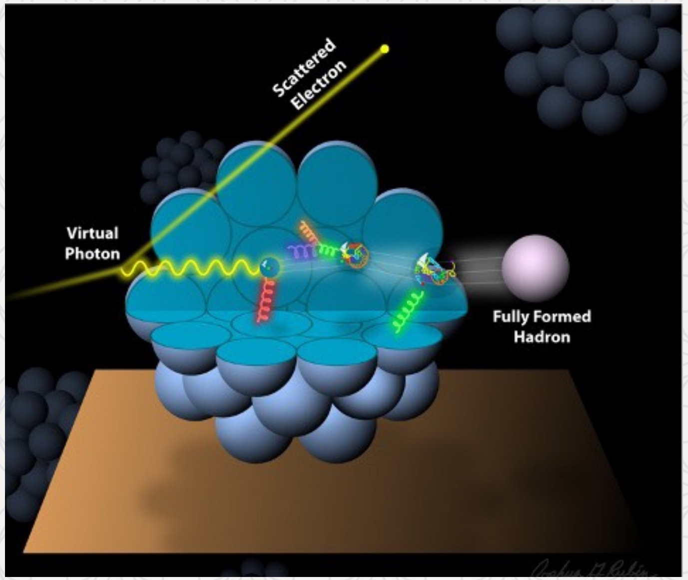
Outline

- Introduction
  - 2023 U.S. NSAC LRP
  - Jefferson Lab (JLab)
- Recent Progress
  - Nucleon structure and properties
  - Spectroscopy
  - QCD and Nuclei
- Selected activities for the future
- Summary

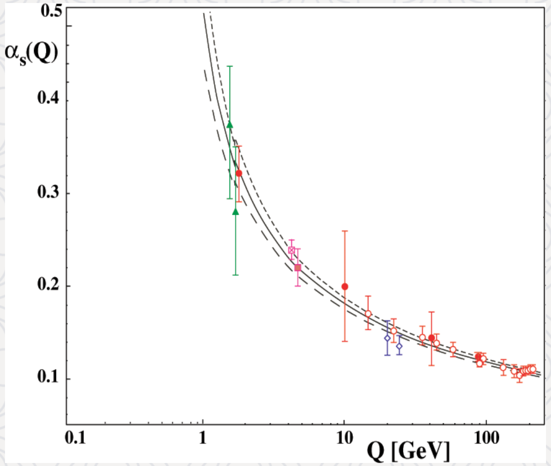




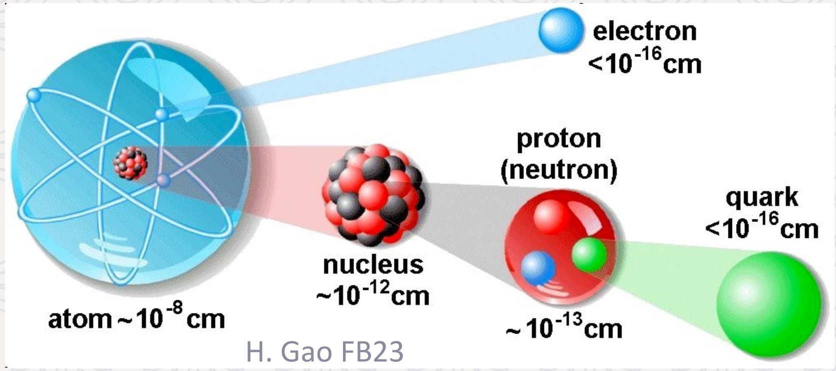
The Fundamental Structure of Visible Matter

- How does QCD generate the spectrum and structure of conventional and exotic hadrons?
- How do the mass and spin of the nucleon emerge from the quarks and gluons inside and their dynamics?
- How are the pressure and shear forces distributed inside the nucleon?
- How does the quark–gluon structure of the nucleon change when bound in a nucleus?
- How are hadrons formed from quarks and gluons produced in high-energy collisions?

Hadron properties and structure
Nuclei and QCD
Hadronization: forming QCD bound states
Spectrum of excited hadrons



https://science.osti.gov/-/media/np/nsac/pdf/202310/NSAC-LRP-2023-v12.pdf
https://arxiv.org/abs/2303.02579



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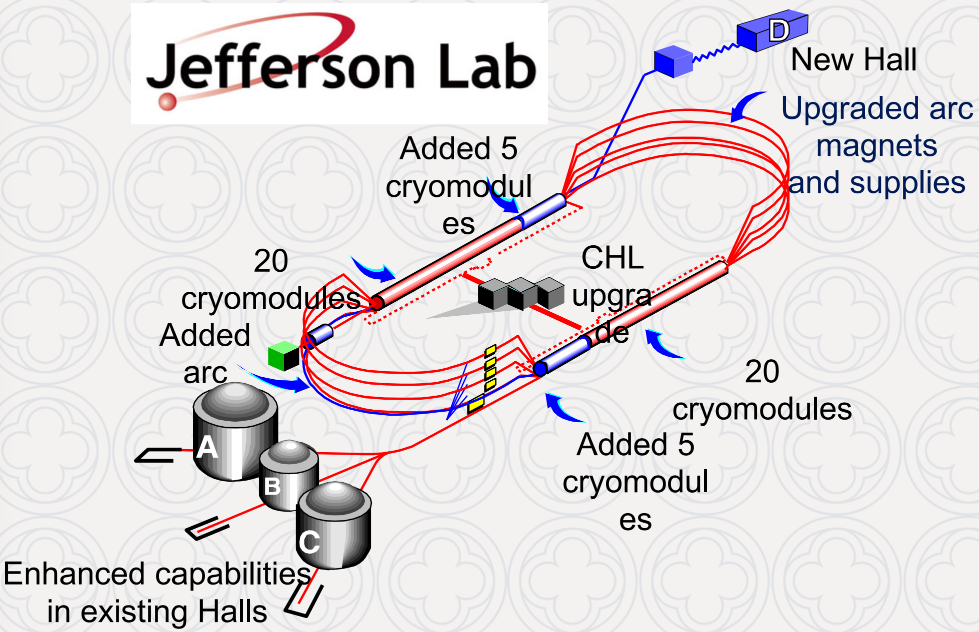
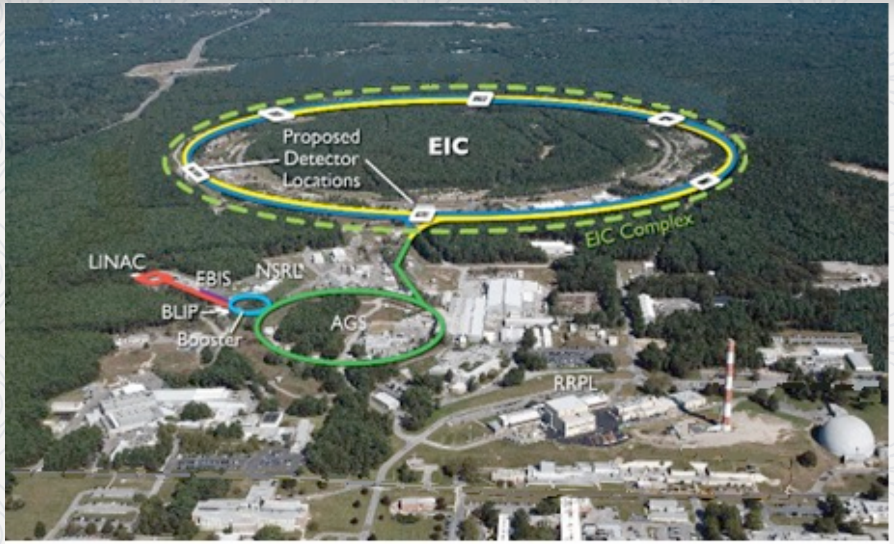
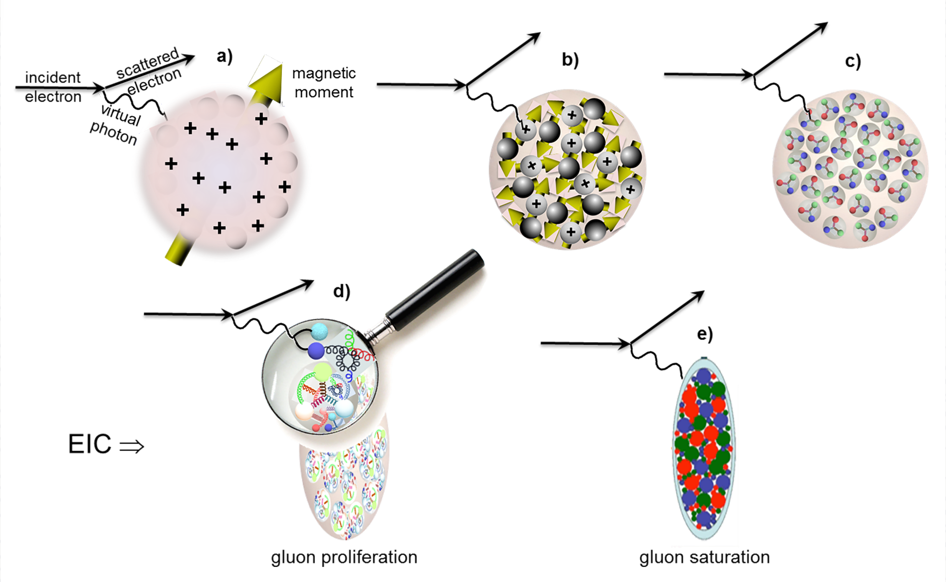
Structure of visible matter probed at JLab and the future EIC

- Newport News, Virginia, USA
- continuous polarized electron beam up to 12GeV
- Various fixed targets, both unpolarized and polarized
- *High luminosity*







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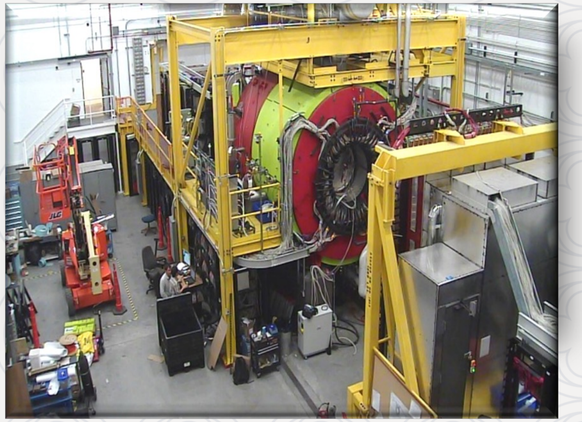
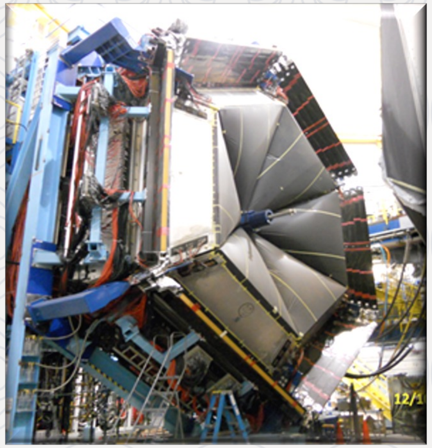
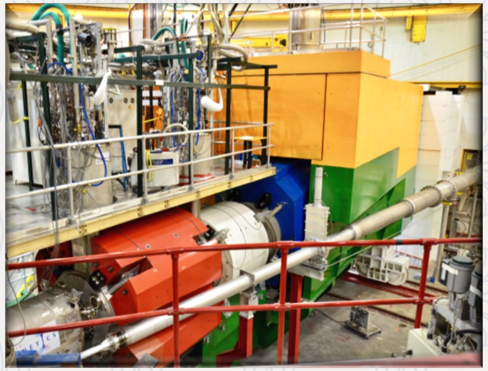
JLab 12 GeV Scientific Capabilities



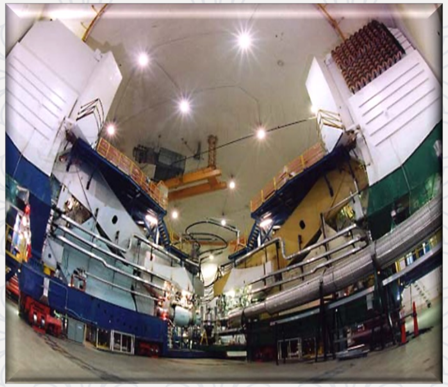
Hall D – exploring origin of confinement by studying exotic mesons



Hall B – understanding nucleon structure via generalized parton distributions and transverse momentum distributions



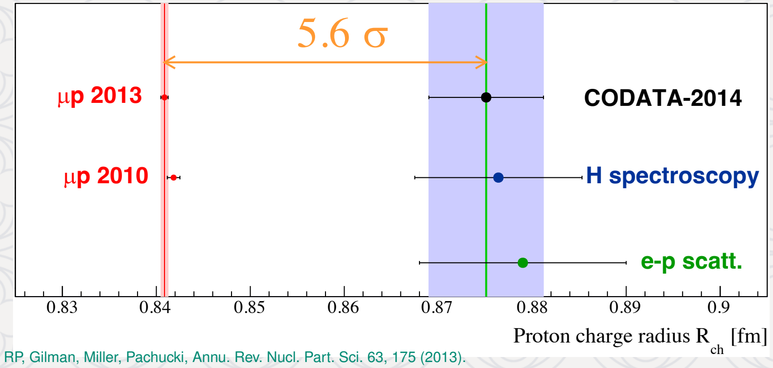
Hall C – precision determination of valence quark properties in nucleons and nuclei



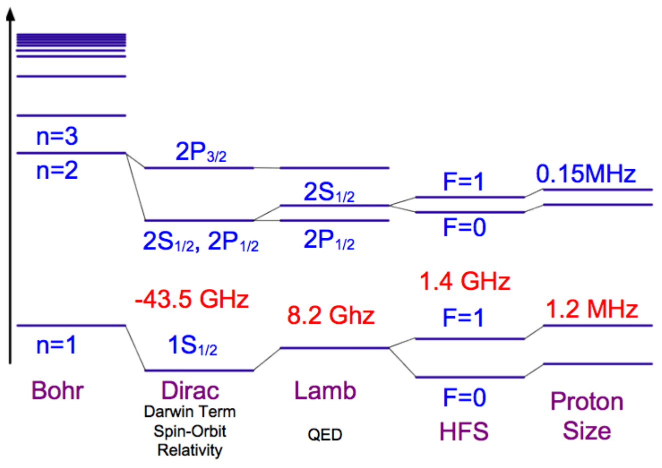
Hall A – short range correlations, form factors, hyper-nuclear physics, future new experiments (e.g., SoLID and MOLLER)

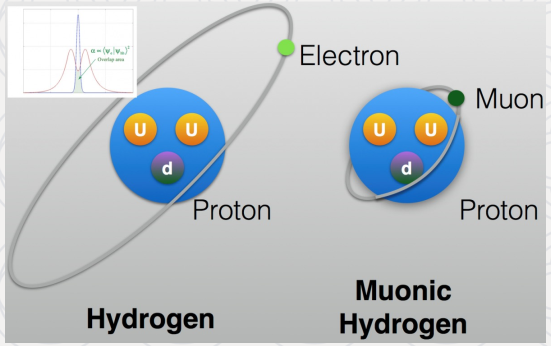
Size of the Proton: Charge Radius and the puzzle

- Proton charge radius:
  1. A fundamental quantity for proton
  2. Important for understanding how QCD works
  3. An important physics input to the bound state QED calculation, affects muonic H Lamb shift ($2S_{1/2} - 2P_{1/2}$) by as much as 2%, and critical in determining the Rydberg constant



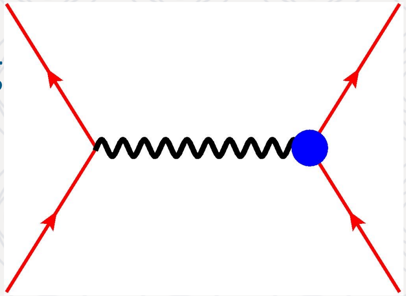
RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).





- Methods to measure the proton charge radius:
  1. Hydrogen spectroscopy (atomic physics)
     - ➢ Ordinary hydrogen
     - ➢ Muonic hydrogen
  2. Lepton-proton elastic scattering (nuclear physics)
     - ➢ *ep* elastic scattering (like PRad)
     - ➢ *μp* elastic scattering (like MUSE, AMBER)

➢ Important point: the proton radius measured in lepton scattering is defined in the same way as in atomic spectroscopy (G.A. Miller, 2019)



$$\sqrt{<r^2>} = \sqrt{-6\frac{dG(q^2)}{dq^2}}\Big|_{q^2=0}$$

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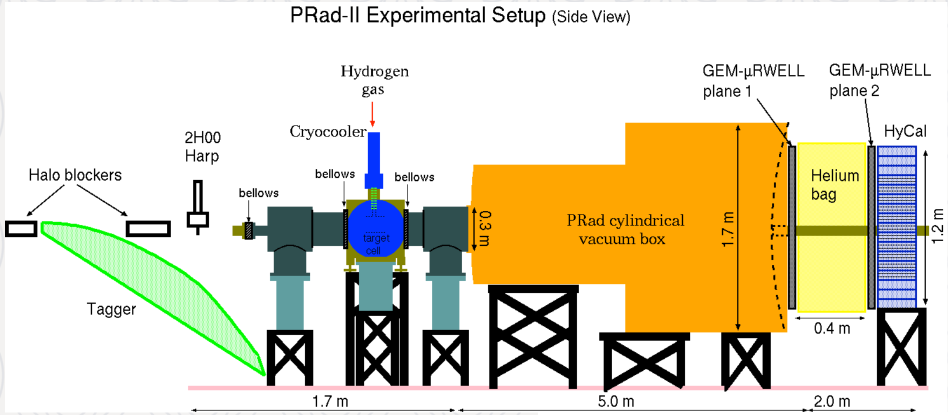
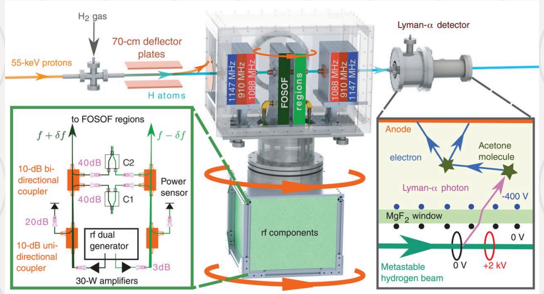
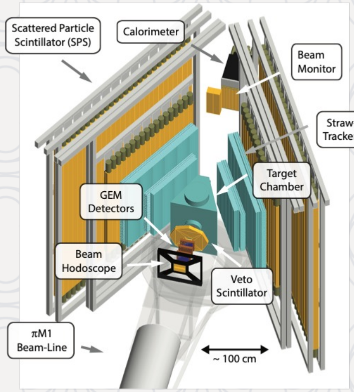
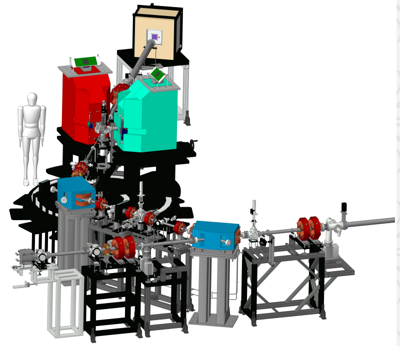
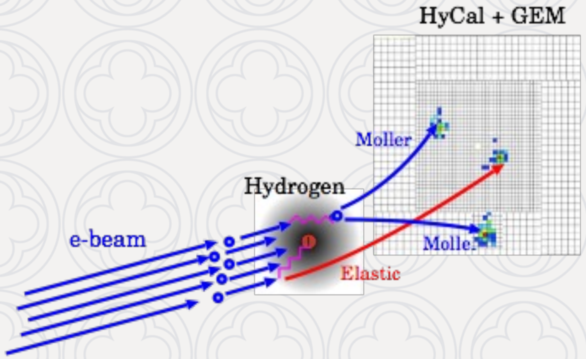
JLab PRad and PRad-II and World-wide effort on Proton Charge Radius





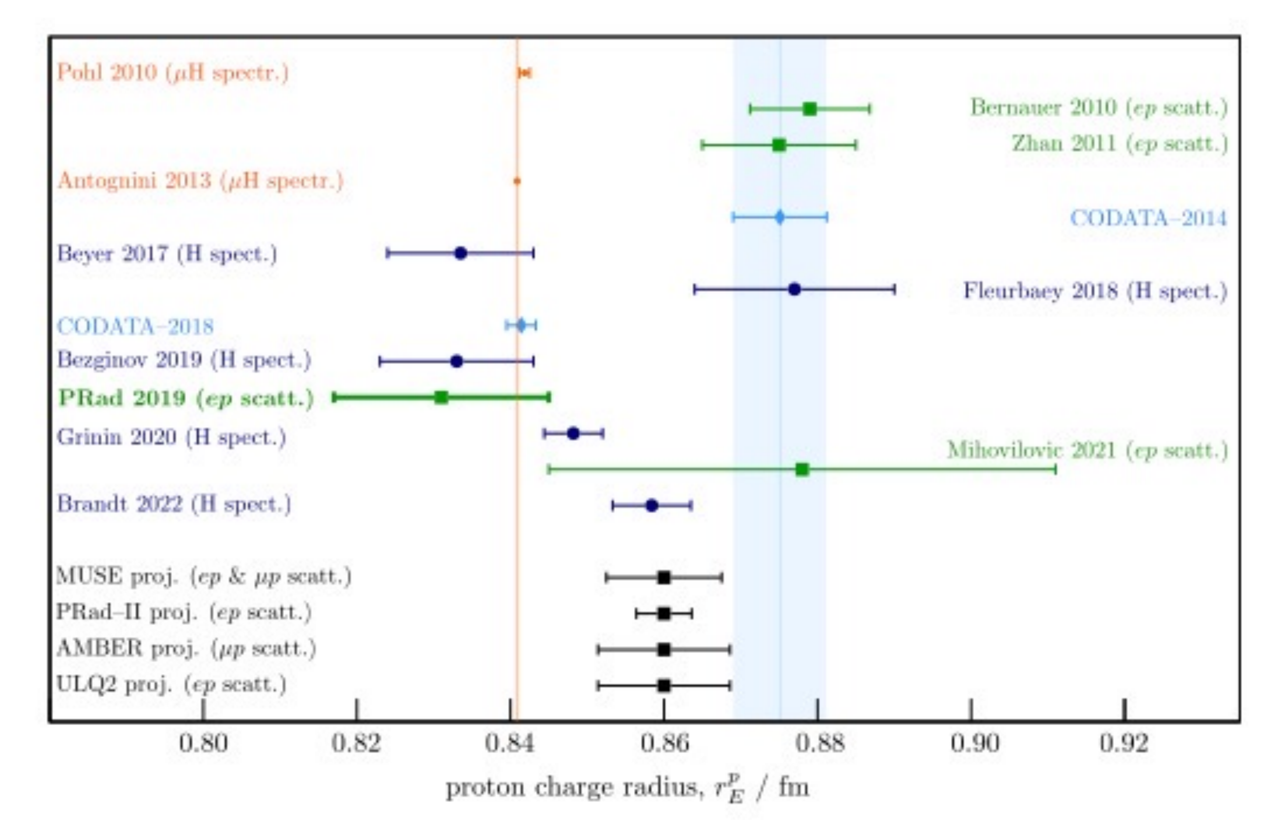




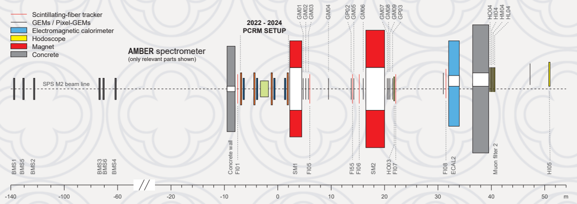


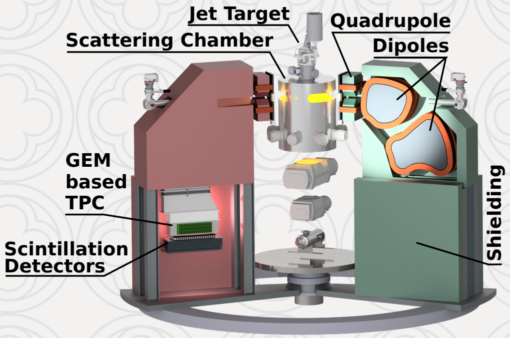
- High resolution, large acceptance, hybrid HyCal calorimeter ($PbWO_4$ and Pb-Glass)
- Windowless H_2 gas flow target
- Simultaneous detection of elastic and Moller electrons
- Q^2 range of 2×10^{-4} – 0.06 GeV^2
- XY – veto counters replaced by GEM detector
- Vacuum chamber

PRad: W. Xiong *et al.*, Nature 575, 147 (2019)



Gao & Vanderhaeghen Rev. Mod. Phys. 94, 015002 (2022)

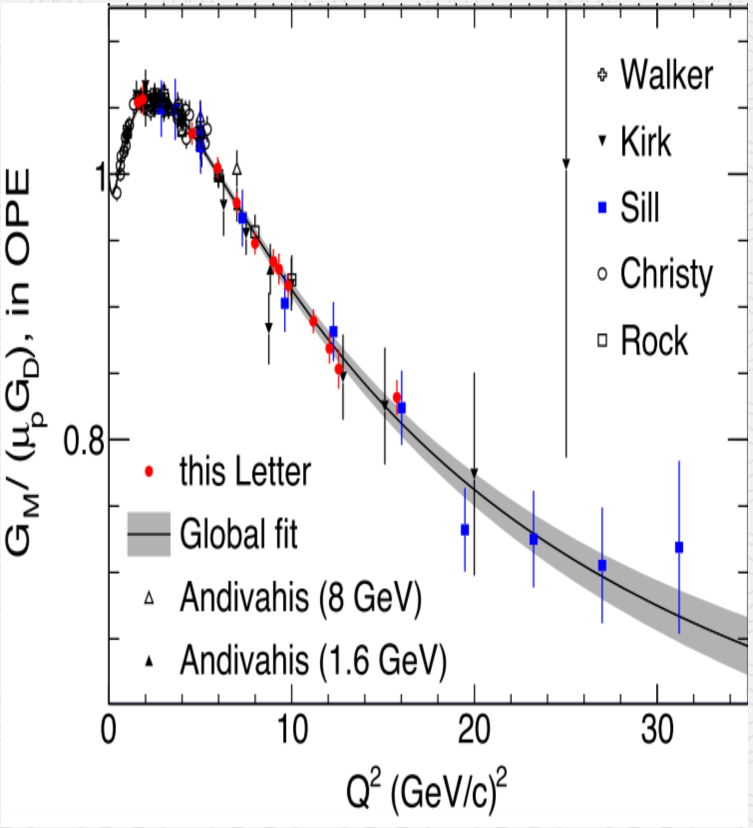


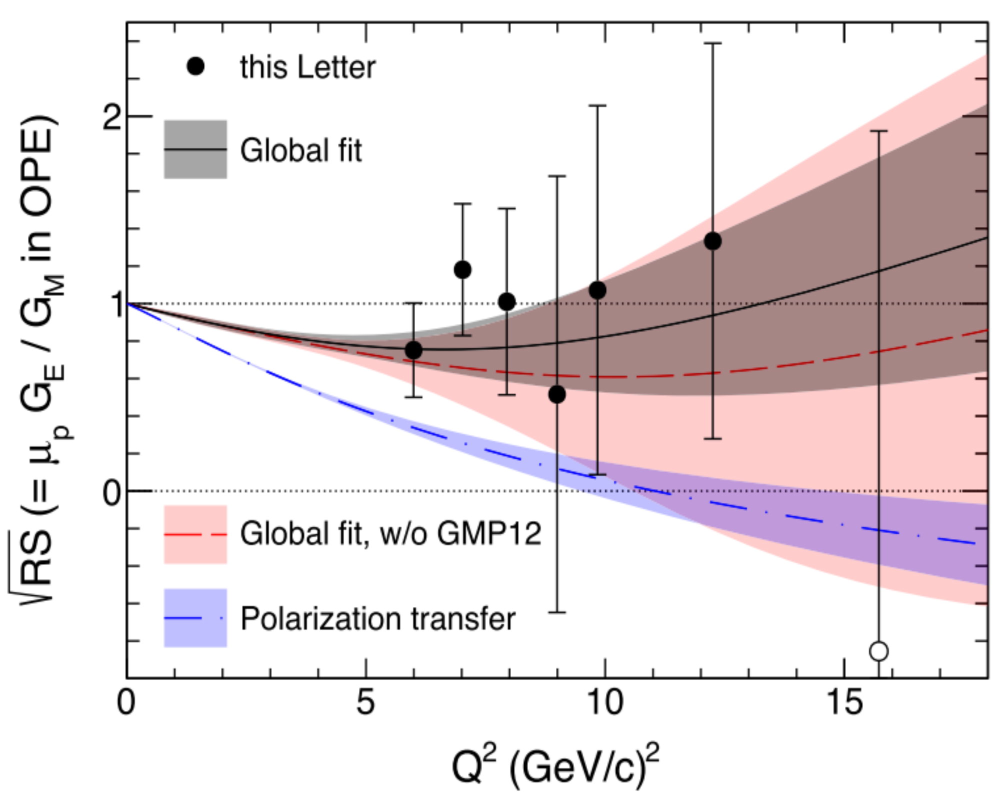


Recent Results from Hall A on Proton Form Factors at high Q^2

Proton magnetic form factor, G_M, at $Q^2 = 15.75$

- High luminosity and wide leverage in virtual photon polarization 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





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

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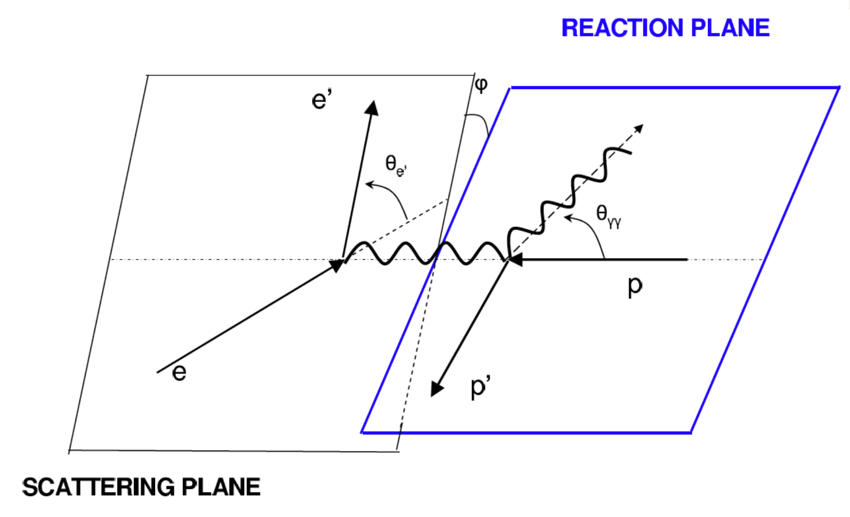
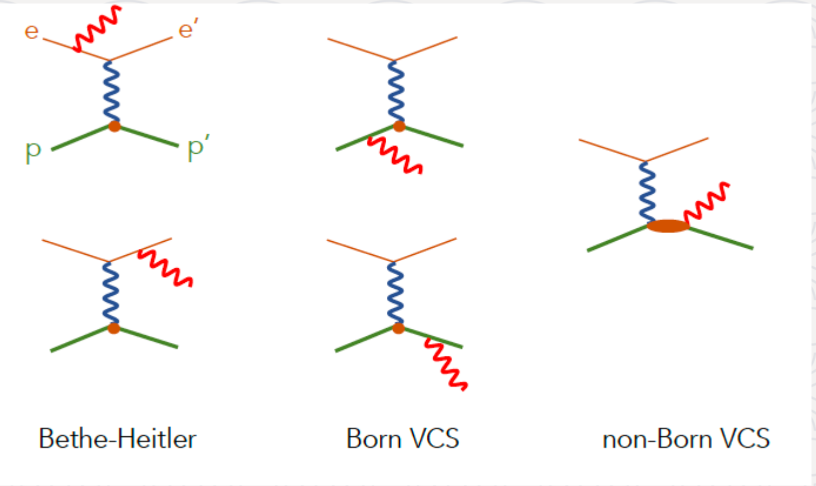
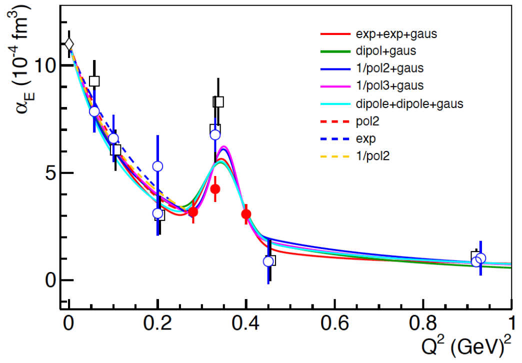
Virtual Compton Scattering and Proton Polarizability Radii

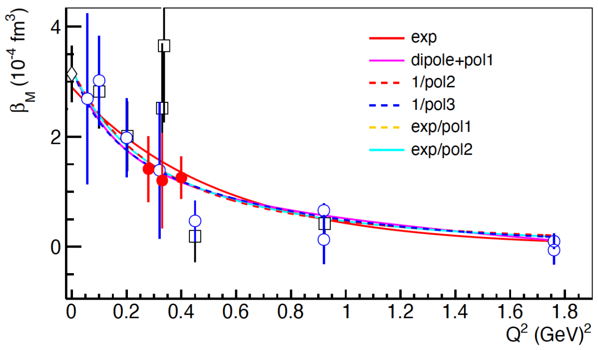


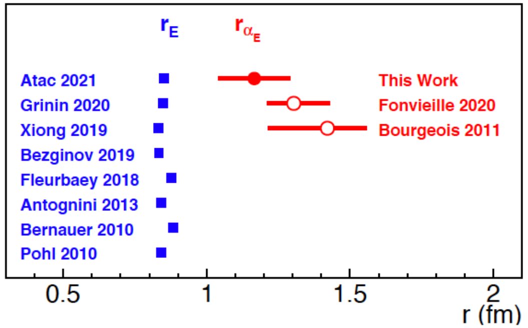


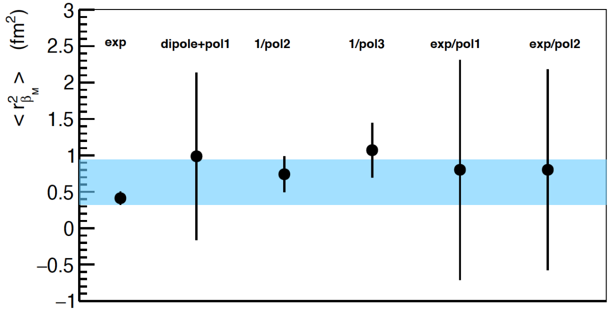
$$\langle r^2_{\alpha_E}\rangle = \frac{-6}{\alpha_E(0)}\cdot\frac{d}{dQ^2}\alpha_E(Q^2)\bigg|_{Q^2=0}$$

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









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

$$\langle r^2_{\beta_M}\rangle = 0.63 \pm 0.31\ \text{fm}^2$$

Elastic FFs **Generalized polarizabilities**

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

Real Compton Scattering experiments at Mainz and HIγS and nucleon EM and spin polarizabilities

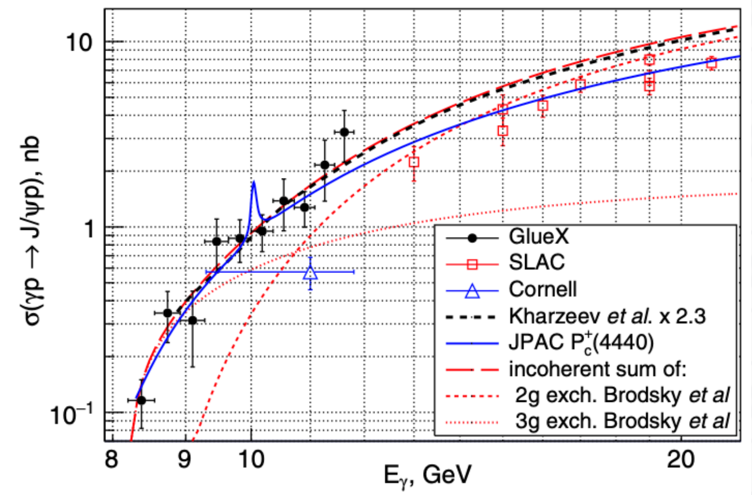
Nikos Sparveris, Spin 2023 Symposium and EINN 2023

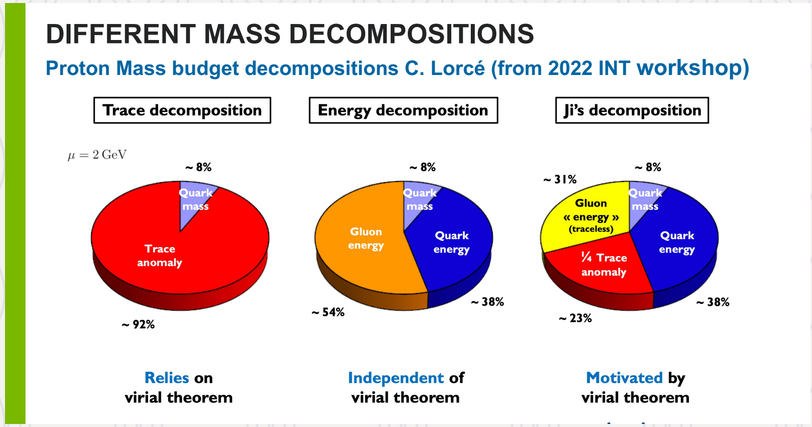
J/ψ Photoproduction at threshold

Hall D - GlueX

- Two-gluon exchange model doesn't reproduce σ
- **no evidence of 5quark** → model-dependent U.L. on on the branching fraction of the LHCb P_c^+ states

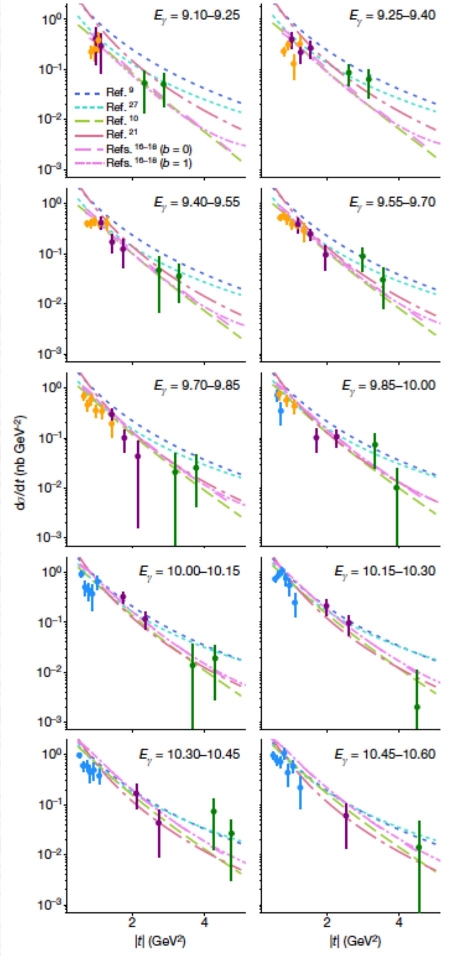
Phys. Rev. Lett. 123, 072001 (2019)



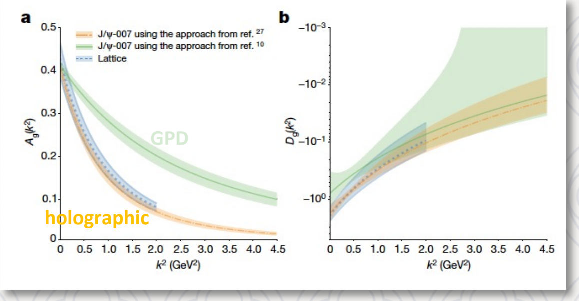


Hall C (E12-16-007)

- measured 5x more statistics → set more stringent limit on $\sigma(\gamma p \rightarrow P_c \rightarrow J/\psi p)$
- Data used to determine, in a model dependent way, the **gluonic gravitational form factors of the proton**



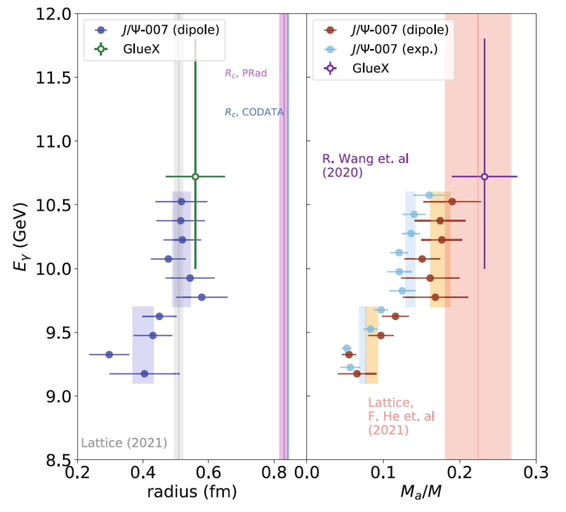
- Simultaneously fit of the **J/ψ dσ/dt** with the holographic and the GPD approaches to extract the gluonic gravitation form factors A(k) and D(k).



$$\langle r_m^2\rangle_g = 6\frac{1}{A_g(0)}\frac{dA_g(t)}{dt}\Big|_{t=0} - 6\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

$$\langle r_s^2\rangle_g = 6\frac{1}{A_g(0)}\frac{dA_g(t)}{dt}\Big|_{t=0} - 18\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

- **Mass Radius smaller than charge radius**

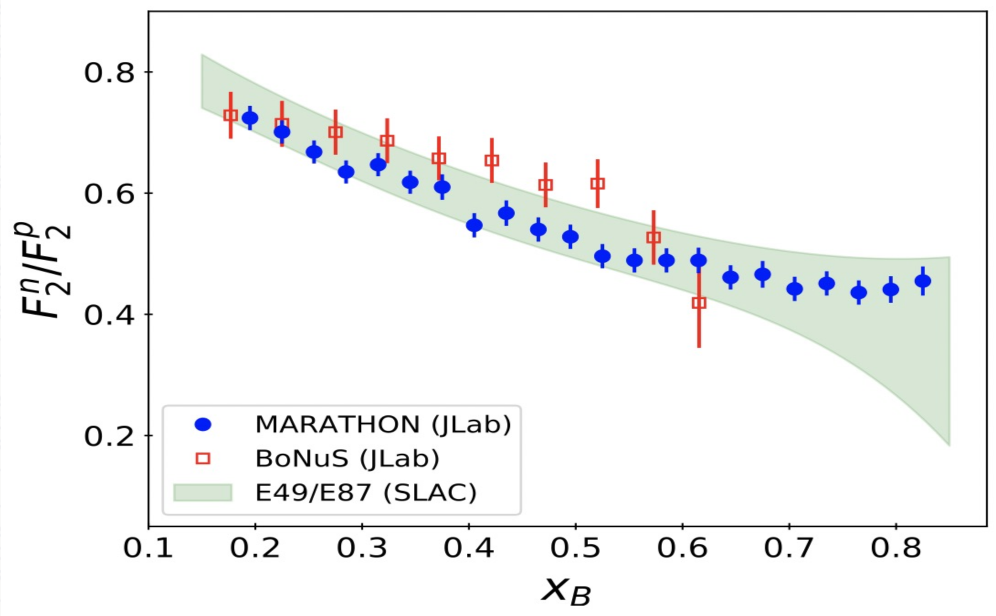


Nature volume 615, pages 813–816 (2023).

Recent Results on Parton Distribution Functions (PDFs)

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 fundamental QCD models of nucleon d/u structure Critical input to parton distribution functions, also relevant for high-energy collider data.

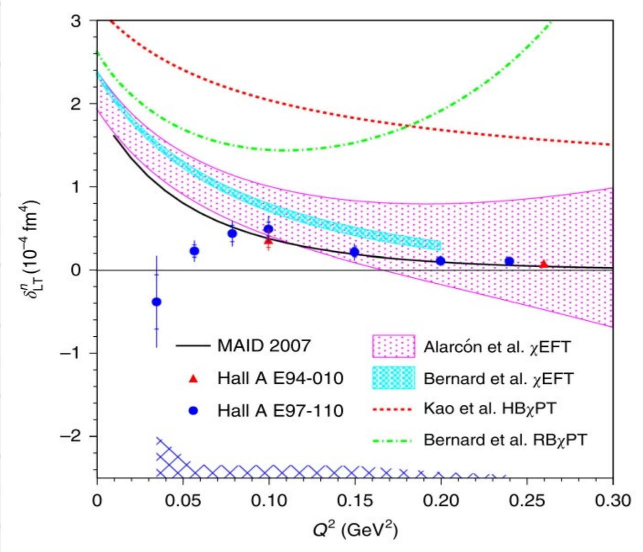


Phys. Rev. Lett. 128, 132003

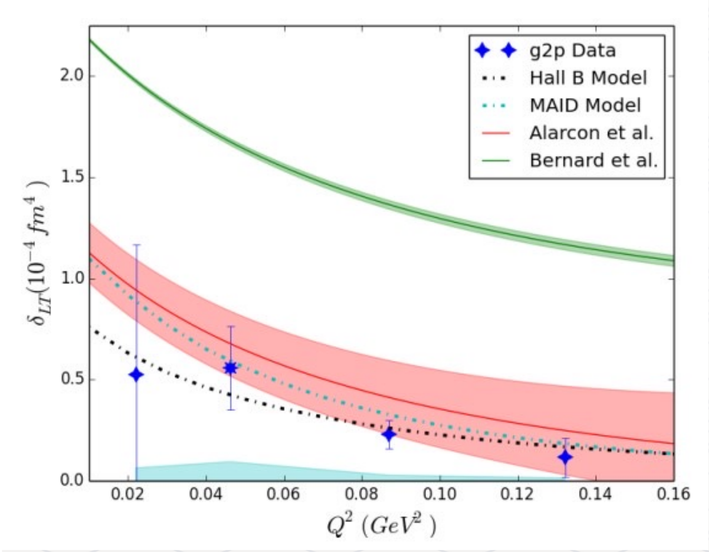
Test of Chiral Effective Field Theory at Low Q^2

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

Polarized Neutron



Polarized proton



- Nature Physics (2021) for neutron (E97-110 data)
- Nature Physics (2022) for proton (g2p data)

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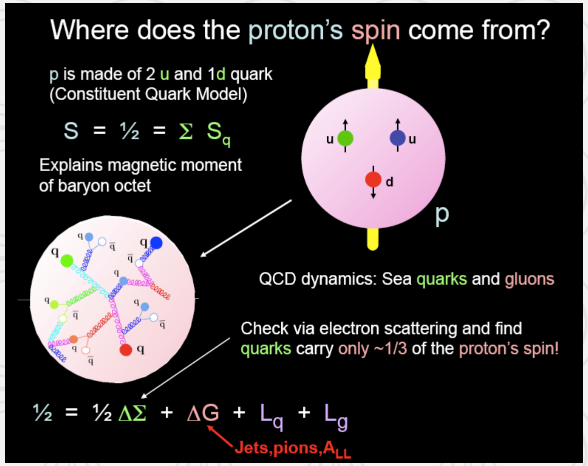
Nucleon Structure from 1D to 3D & orbital motion



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

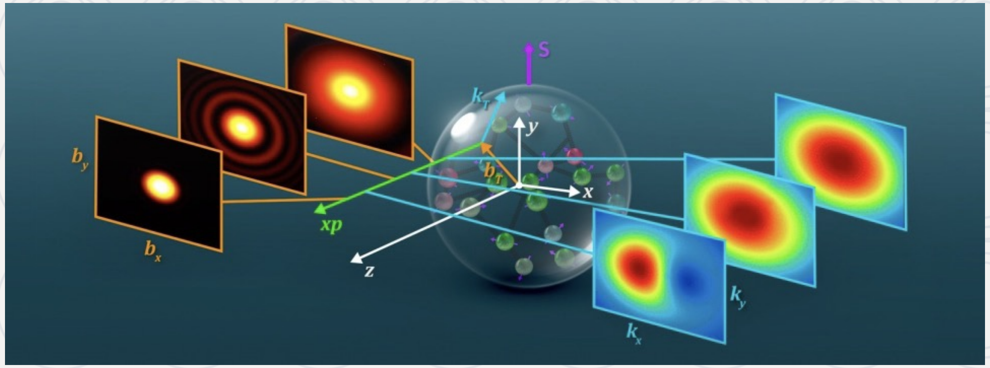
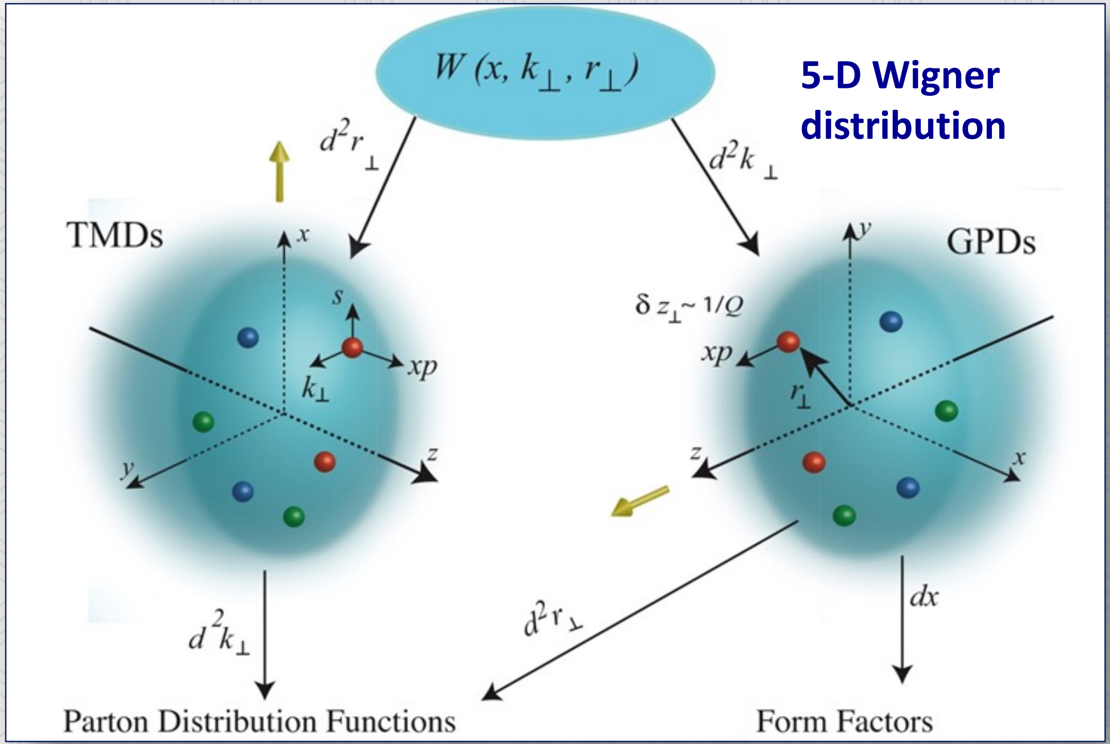


Image from 2023 NSAC LRP

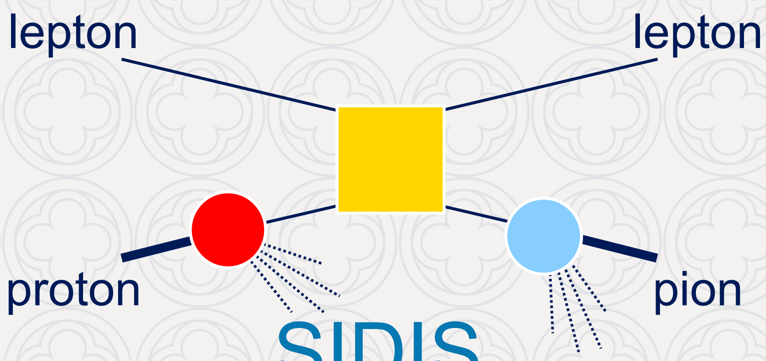
Generalized parton distribution (GPD)
Transverse momentum dependent parton distribution (TMD)



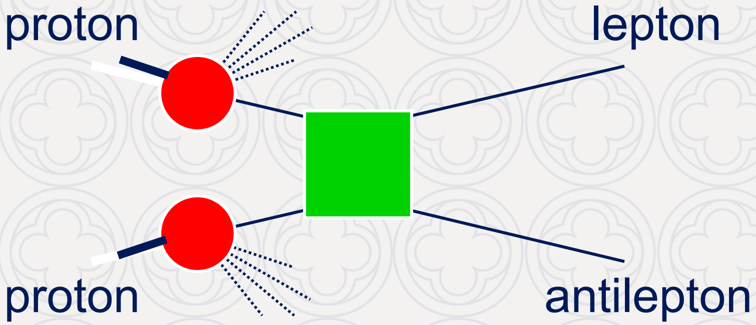
X.D. Ji, PRL91, 062001 (2003);
Belitsky, Ji, Yuan, PRD69,074014 (2004)

Image from J. Dudek et al., EPJA 48,187 (2012)

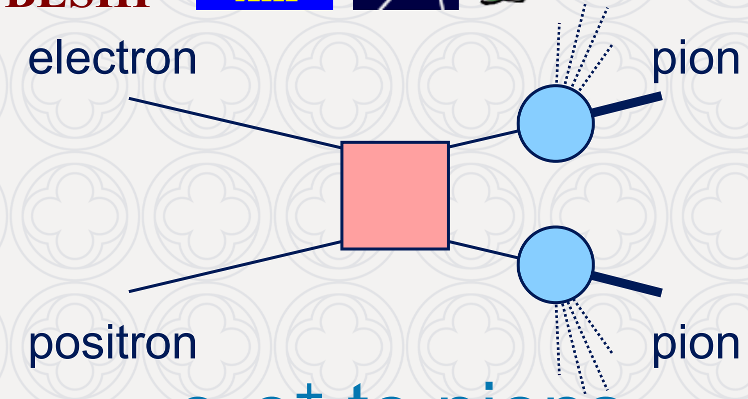
Access TMDs through Hard Processes



SIDIS



Drell-Yan



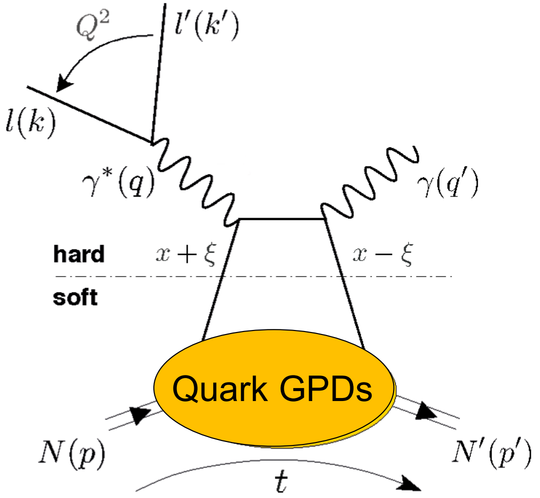
$e^{-}e^{+}$ to pions

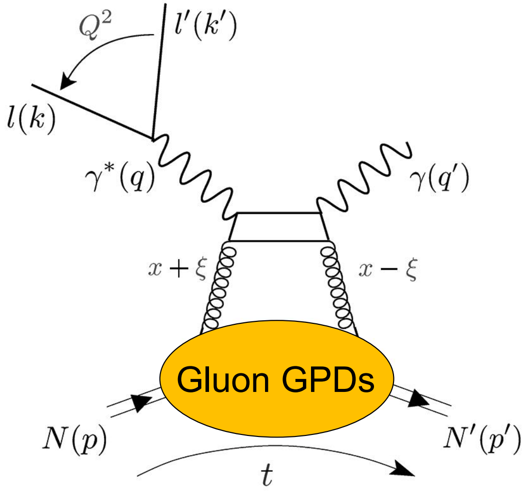
- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

$$f_{1T}^{\perp q}(\text{SIDIS}) = -f_{1T}^{\perp q}(\text{DY})$$

$$h_1^{\perp}(\text{SIDIS}) = -h_1^{\perp}(\text{DY})$$

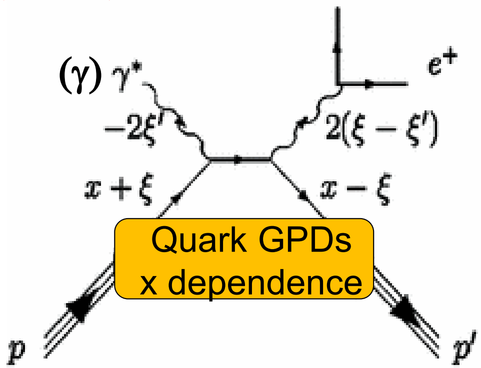
Exclusive reactions giving access to GPDs

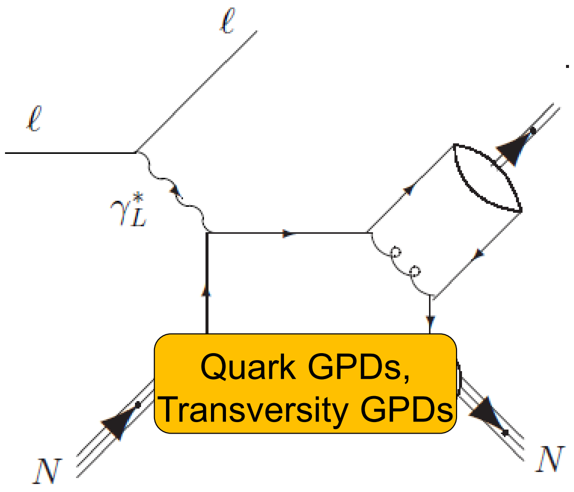




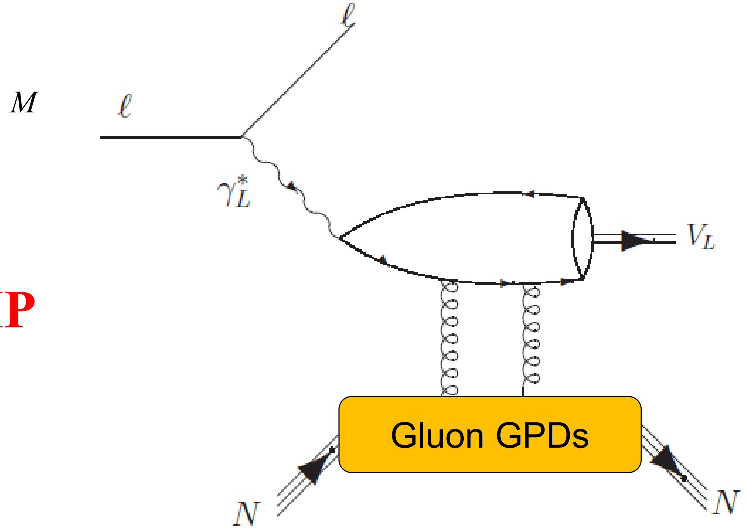
DVCS

(TCS), DDVCS





DVMP



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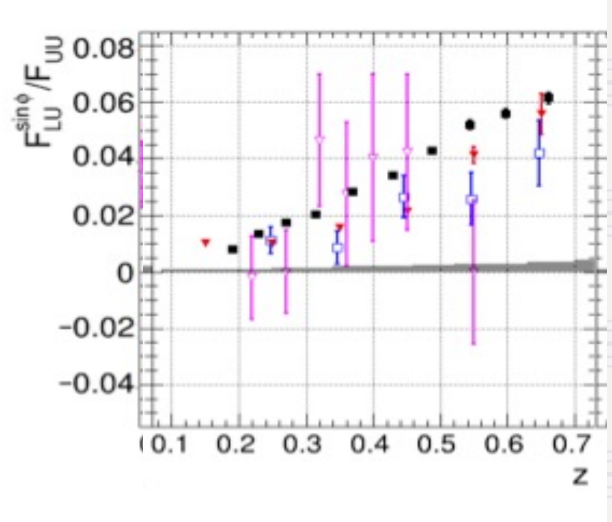
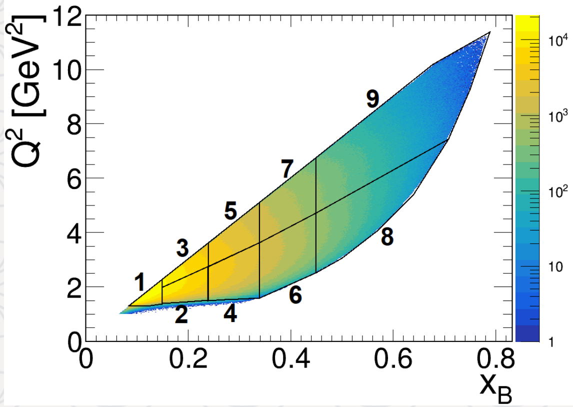
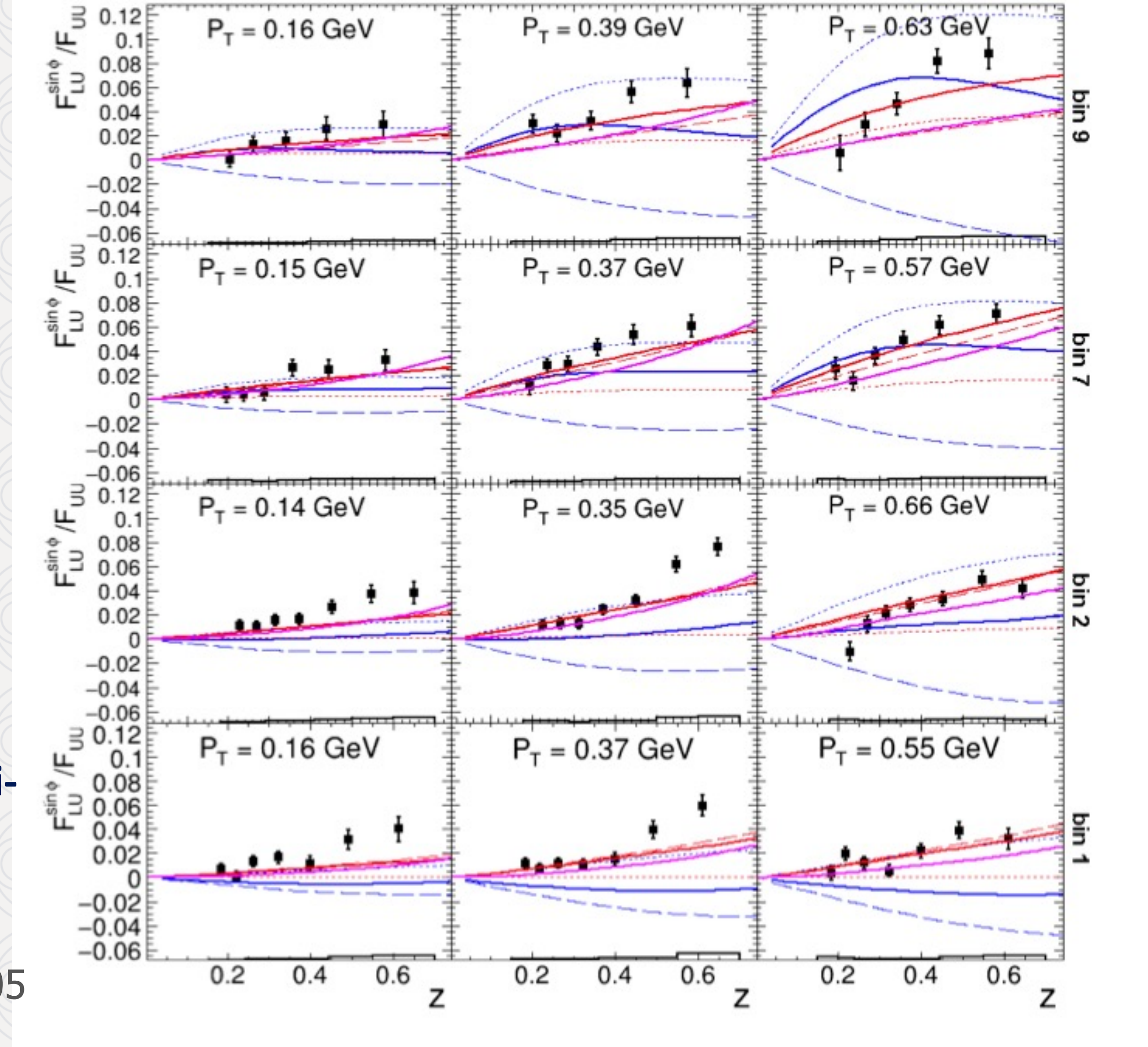
State-of-the-art from CLAS 12

multi-dimensional binning with precision – reduces systematics, constrain models, forms of TMDs, disentangle correlations, isolate phase-space region with large signal strength (CLAS12)







First multidimensional, high precision measurements of semi-inclusive π+ beam single spin asymmetries from the proton over a wide range of kinematics

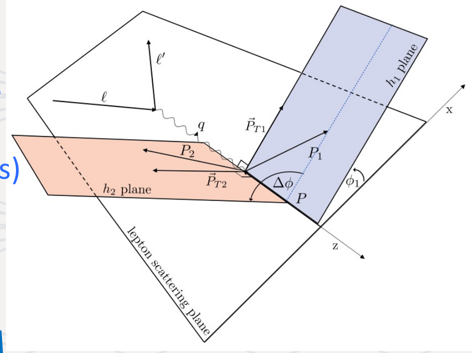
S. Diehl *et al.* (CLAS Collaboration), Phys. Rev. Lett. **128**, 062005

CLAS12 First-ever Measurements

Observation of Correlations between Spin and Transverse Momenta in Back-to-Back Dihadron production at CLAS12

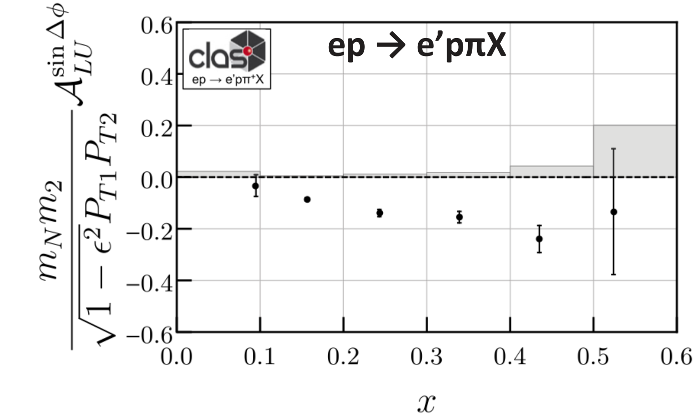
H. Avakian et al. (CLAS Collaboration)
Phys. Rev. Lett. 130, 022501 (2023)

Two hadrons in opposite hemispheres (current and target-fragm. regions)



- Direct access to leading twist **Fracture Functions** which gives conditional probability to eject a longitudinally polarized quark with the additional hadron in the target fragment

$$\mathcal{A}_{LU} = -\sqrt{1-\epsilon^2}\,\frac{|\vec{P}_{T1}||\vec{P}_{T2}|}{m_N m_2}\,\frac{\mathcal{C}[w_5 \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]}\sin\Delta\phi$$

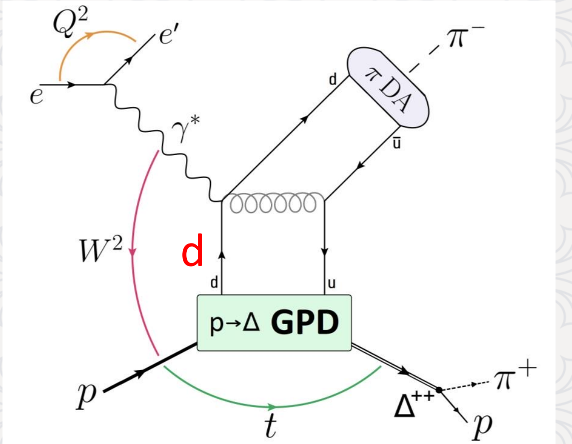


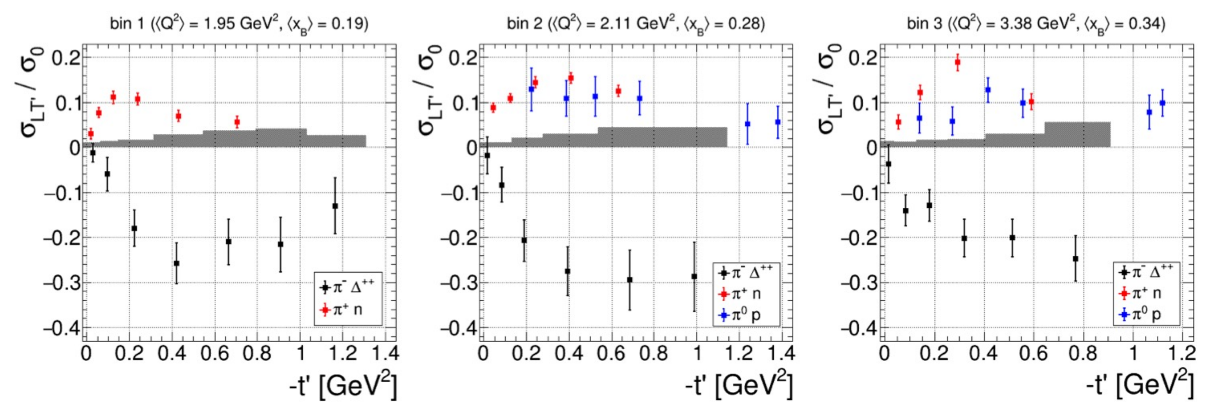
A_{LU} increases with x → correlation of final-state hadrons most significant in the valence quark region

First measurement of hard exclusive $\pi^-\Delta^{++}$ electro-production BSA off protons

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

- Provides access to p-Δ transition GPDs
- Provides access to the d-quark content of the nucleon



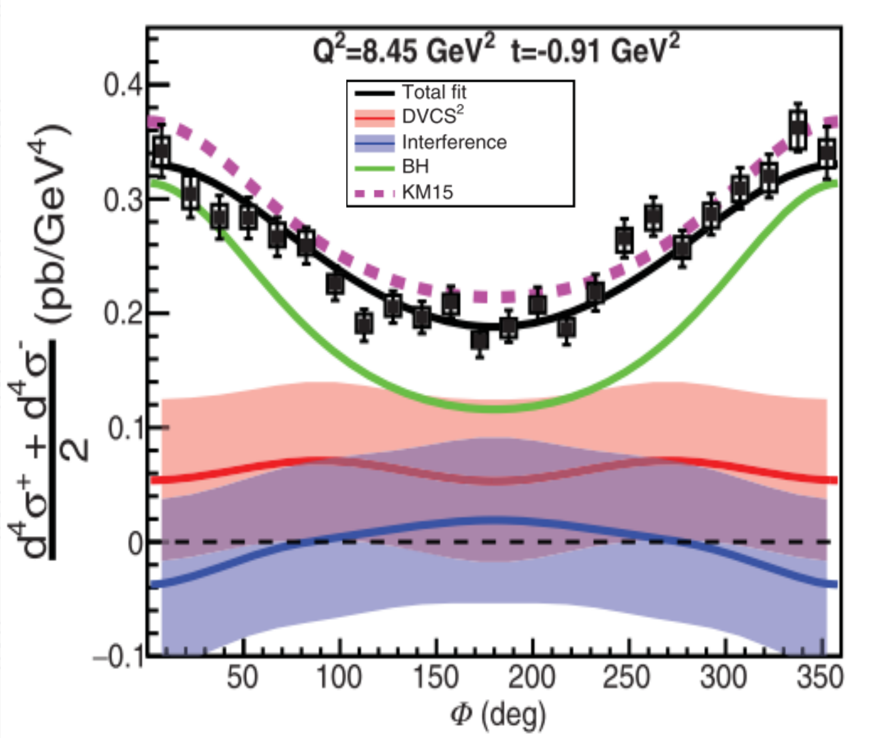


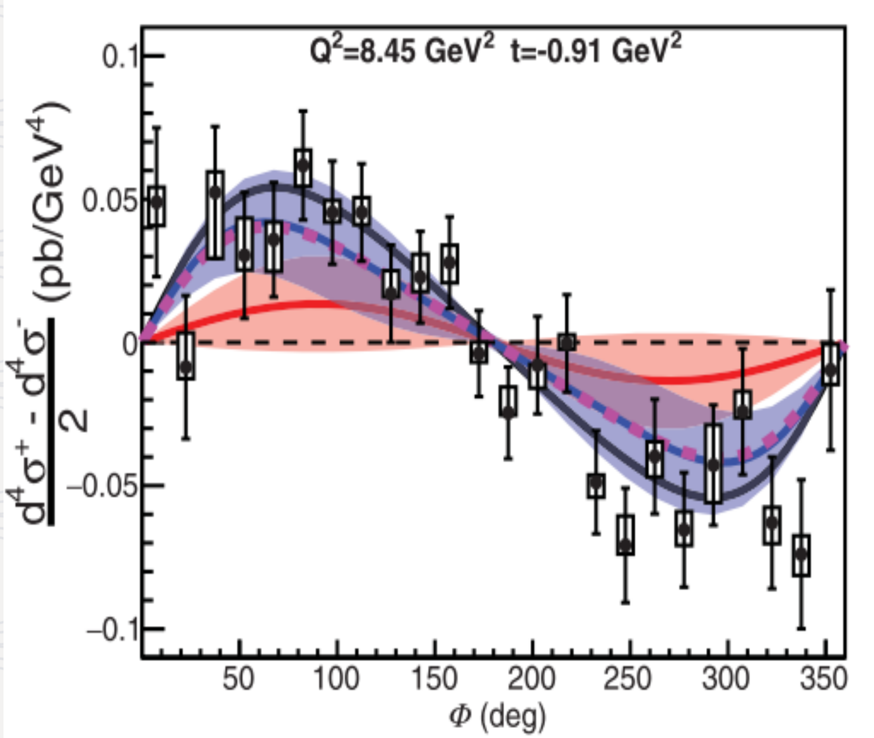
BSA clearly negative and ~ 2 times larger than for the hard exclusive π^+ /π^0 production → Polarized u quarks (π^+n, π^0p) has positive asymmetry, d quarks ($\pi^-\Delta^{++}$) negative asymmetry

Recent Results on Compton Form Factors from Hall A

First Experimental Extraction of All Four Helicity-Conserving Compton Form Factors (CFF)

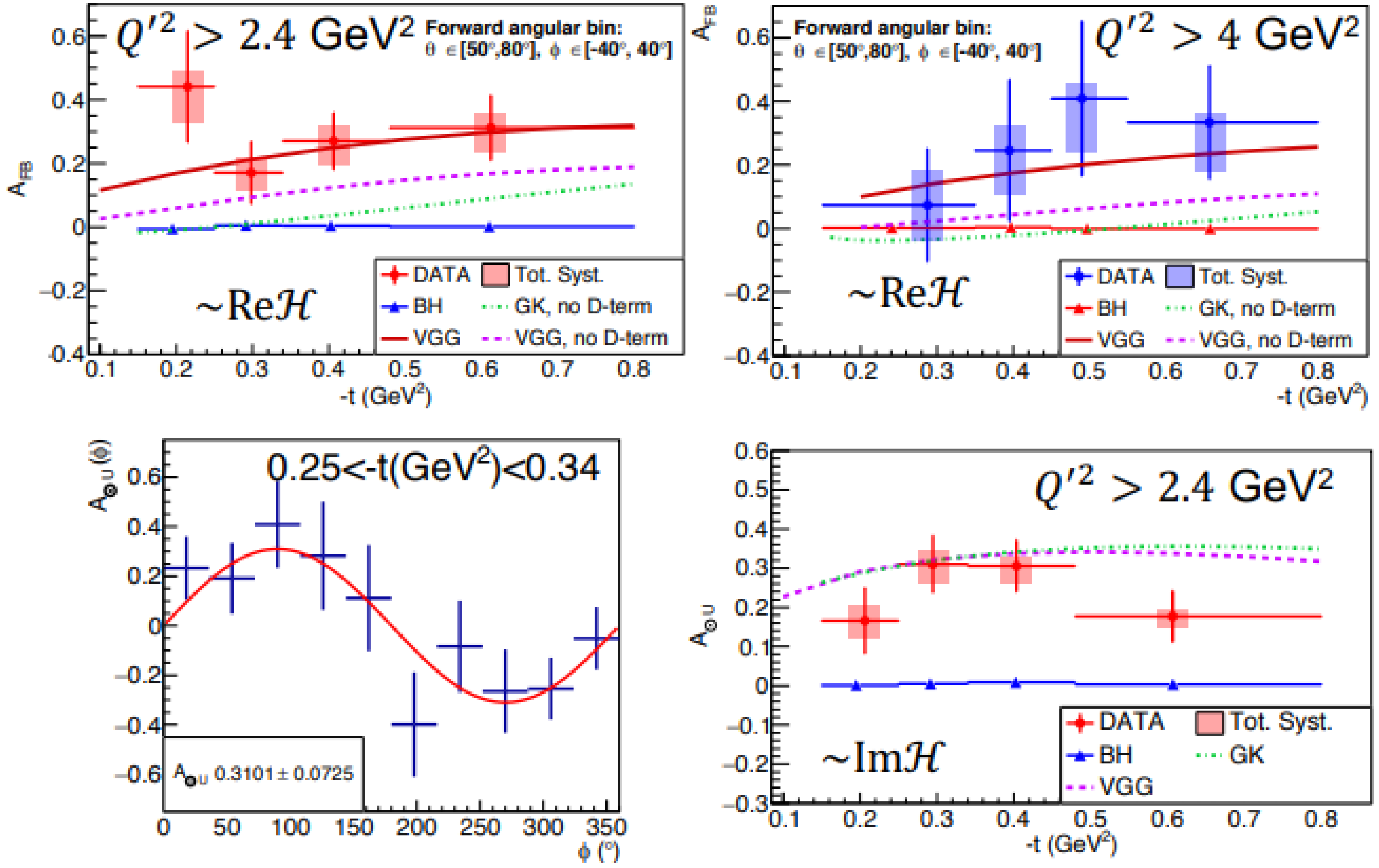
- DVCS is the prime reaction to determine CFFs which are convolution integrals of Generalized Parton Distributions (GPDs).
- Fit cross section data over large range of x_B, Q^2 and t.
- Determined some poorly known CFFs.





F. Georges *et al.*, Phys. Rev. Lett. 128, 252002 (2022)

First-ever measurement of Timelike Compton Scattering (CLAS12)



γp→γ*p→(e')e⁺e⁻p

- Quasi-real photo-production (Q^2~0)
- The beam helicity asymmetry of TCS accesses the imaginary part of the CFF in the same way as in DVCS and probes the universality of GPDs
- The forward-backward asymmetry is sensitive to the real part of the CFF → direct access to the Energy-Momentum Form Factor $d_q(t)$ (linked to the D-term) that relates to the mechanical properties of the nucleon (quark pressure distribution)
- This measurement proves the importance of TCS for GPD physics.
- Limits: very small cross section → high luminosity is necessary for a more precise measurement
- Imminent doubling of statistics thanks to data reprocessing with improved reconstruction

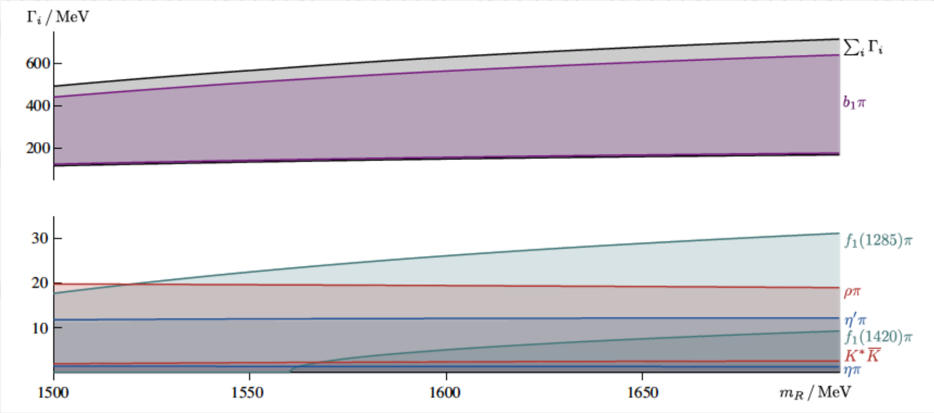
P. Chatagnon et al. (CLAS), Phys. Rev. Lett. 127 (2021) ***Talk by P. Chatagnon***

Search for Hybrid Mesons at GlueX

Focus on π_1 (1600)

- Set upper limit on photoproduction x-section
- Perform partial wave analyses on $\eta\pi$ and $\eta'\pi$ to confirm COMPASS data

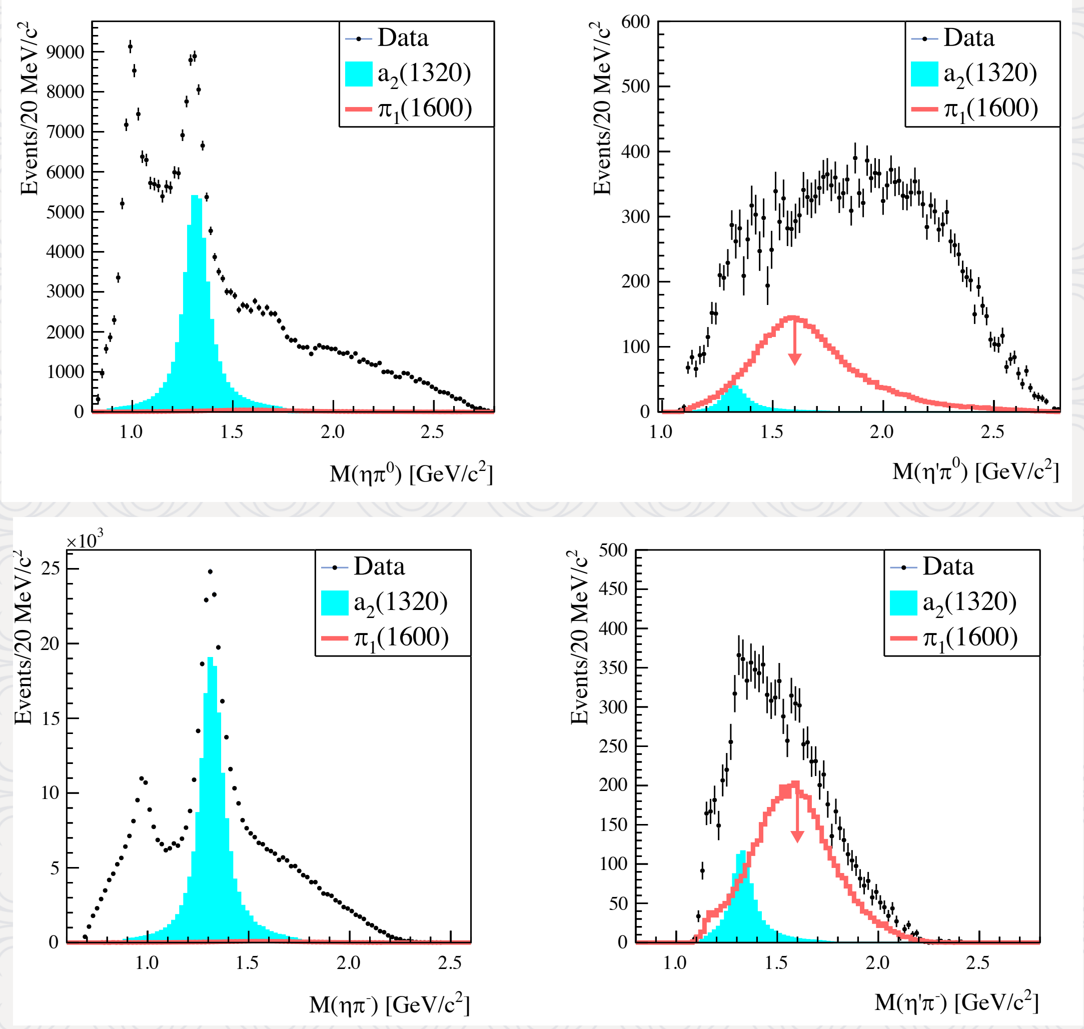
π_1 Branching Fractions from Lattice QCD
(PRD 103 054502, 2021)



the $\pi_1 \to b_1\pi \to \omega\pi\pi$ decay channel is used to set an upper limit on photoproduction, setting the scale of possible contributions in $\eta\pi$ and $\eta'\pi$

F. Afzal *et al.* (GlueX), arXiv:2407.03316, submitted to PRC
H. Gao FB23

π_1 Upper Limit - Projections to $\eta\pi$ and $\eta'\pi$

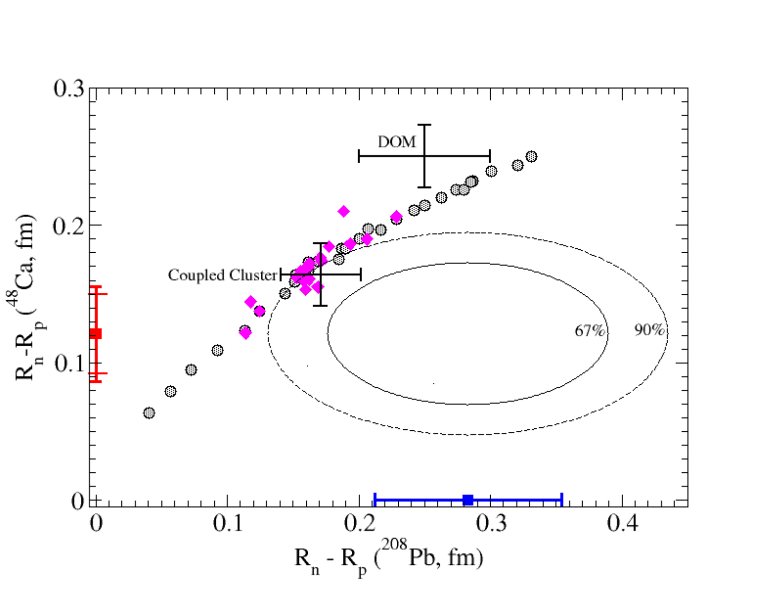


- π_1 not a large fraction of $\eta\pi$
- π_1 could saturate $\eta'\pi^-$ distribution

Recent Results on Nuclear Physics

From Nuclei to Neutron Stars

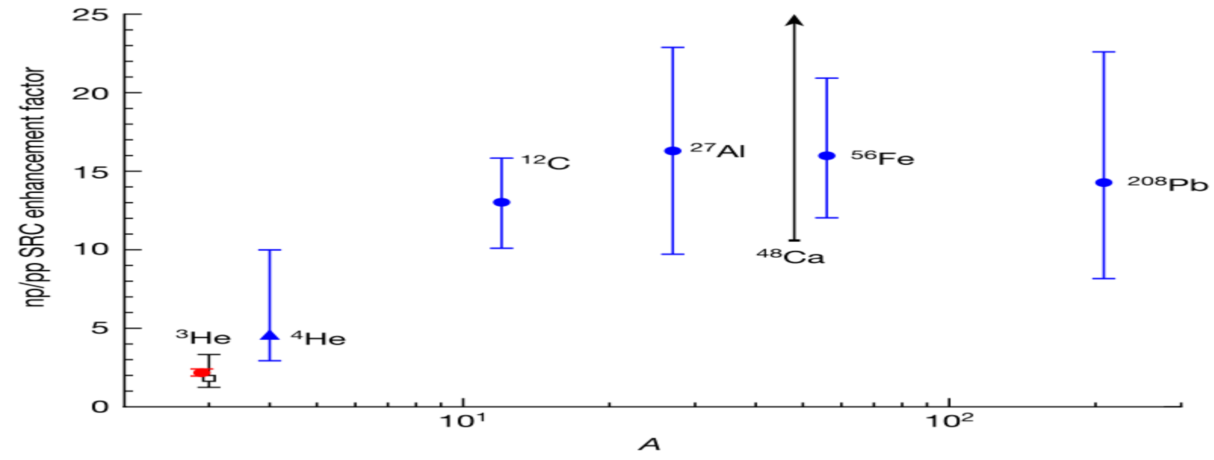
- Parity-violating electron scattering measurement of neutron skins in comparison to nuclear models, ab-initio calculations.
- Models used in calculation of neutron star mass limits



D. Adhikari *et al.* (CREX Collaboration)
Phys. Rev. Lett. 129, 042501 – Published 20 July 2022

Nuclear Studies of Light Mirror Nuclei

- In heavy nuclei, np pairs dominant Short-Range Correlations over pp pairs.
- Inclusive electron scattering on 3H and 3He to determine the mass-3 SRC and find the np/pp SRC enhancement is much smaller (red data point) compared to heavy nuclei.

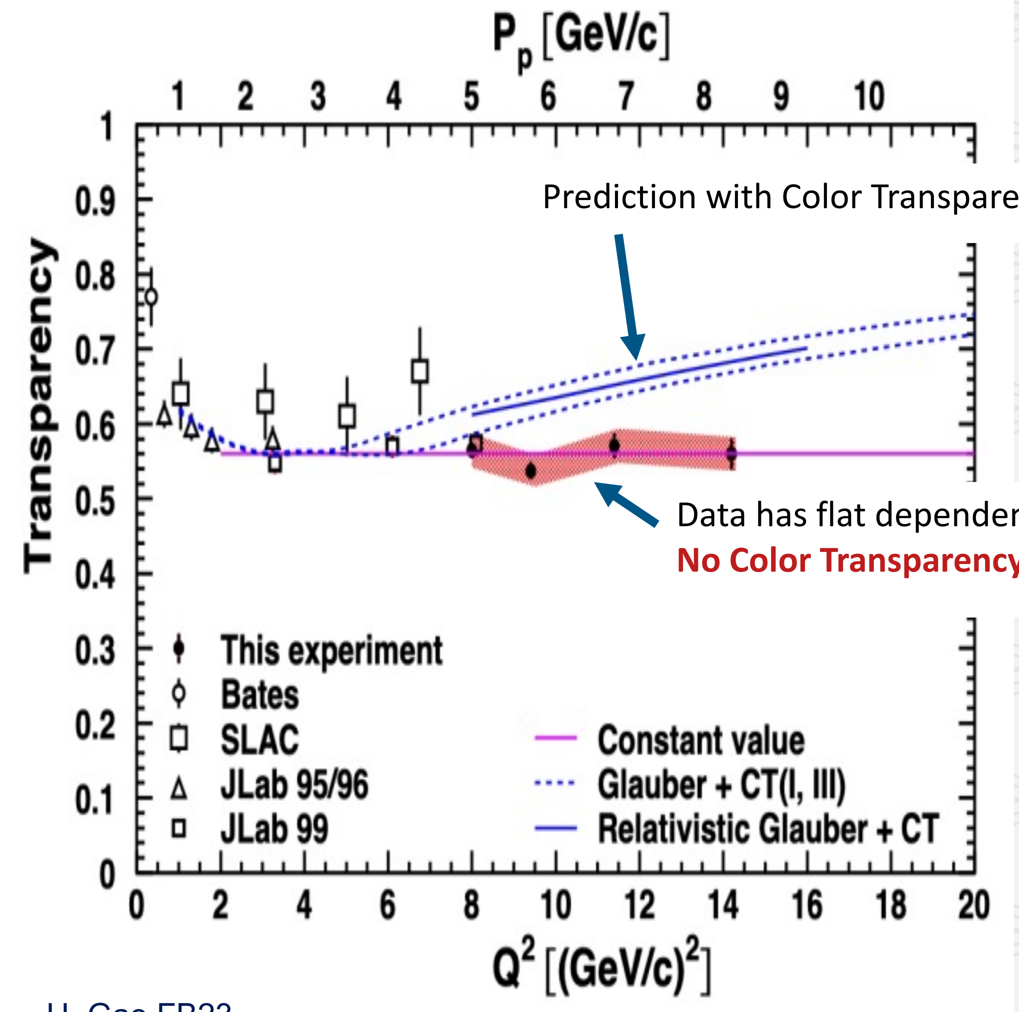


S. Li, *et al.*, Nature 609, 41-45 (2022)

New nuclear data challenge theory – Hall C

Ruling out color transparency in quasi-elastic $^{12}C(e,e' p)$ up to Q^2 of 14.2 $(GeV/c)^2$

Phys. Rev. Lett. 126, 082301



Prediction with Color Transparency

Data has flat dependence

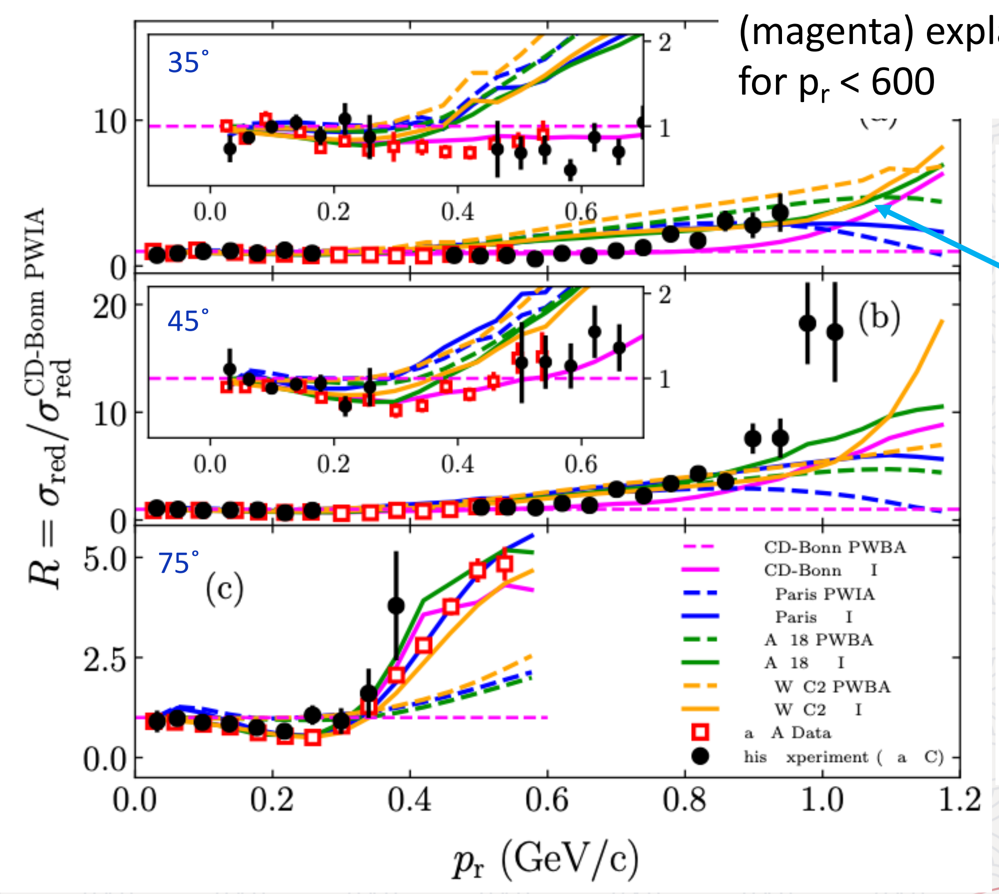
No Color Transparency !

H. Gao FB23

Probing the Deuteron at Very Large Internal Momenta

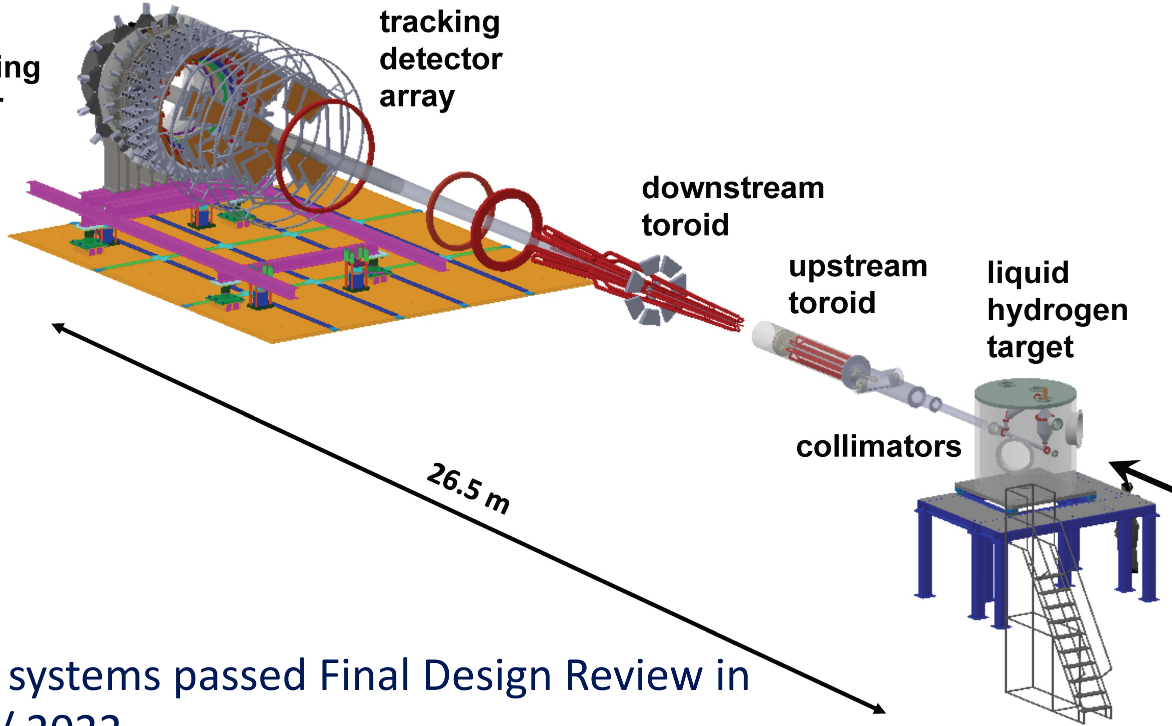
Phys. Rev. Lett. 125, 262501 (2020)

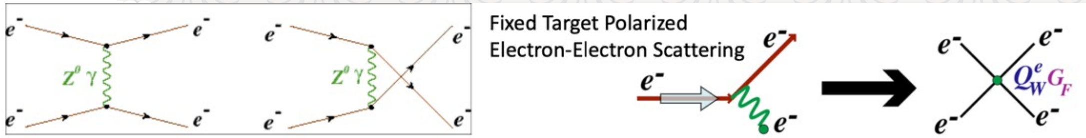
CD-BONN theory (magenta) explains data for p_r < 600



- None of the calculations, including the CD-BONN theory, can explain data for $p_r > 0.6$
- Completed experiment to explore if trend continues to $p_r >$ 1.1

MOLLER: World-leading Measurement of e-e PV

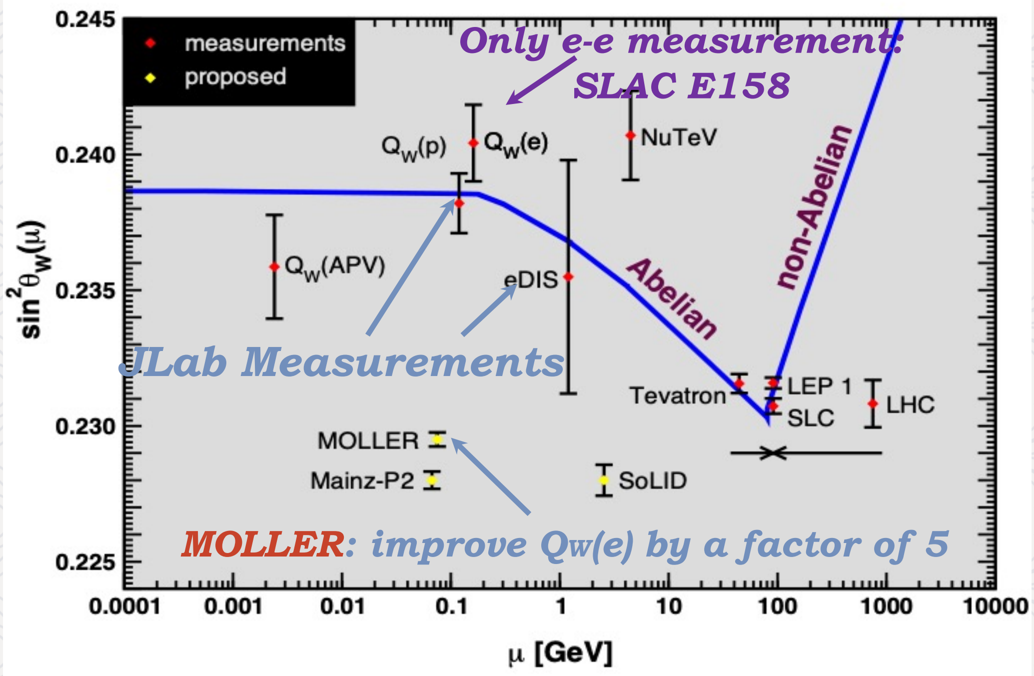




$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}Q_W^e \qquad Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075$$

A_{PV} ~ 32 ppb $\delta(A_{PV})$ ~0.8 ppb

$\delta(Q^e{}_w)$ = ±2.1% (stat) ± 1.1% (syst.)



- All systems passed Final Design Review in 12/ 2022
- Nearly all of the needed funding has been appropriated
- Achieved CD-3A, Approve Long Lead Procurements, in March 2023
- CD-2/3, Start of Construction, approved in May 2024
- Early CD-4 finish in Q2FY27

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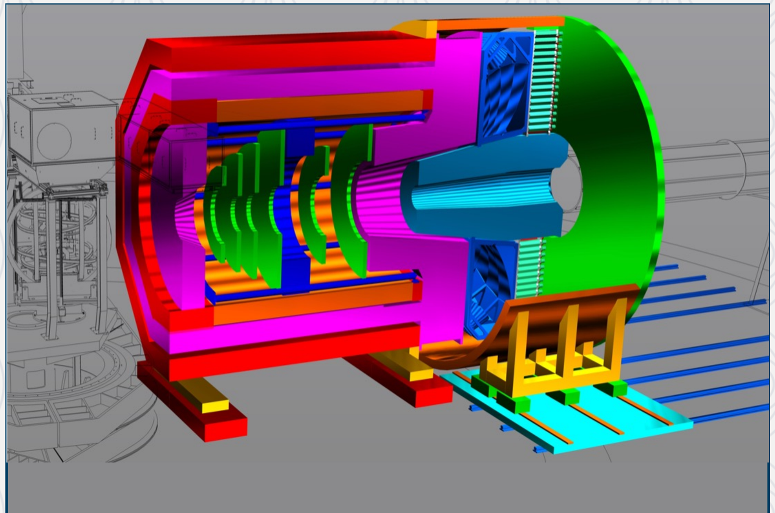
SoLID@JLab: QCD at the intensity frontier

SoLID will ***maximize*** the science return of the 12-GeV CEBAF upgrade by **combining…**

High Luminosity
$10^{37\text{-}39}$ /cm^2/s
[>100x CLAS12][>1000x EIC]

+

Large Acceptance
Full azimuthal ϕ coverage

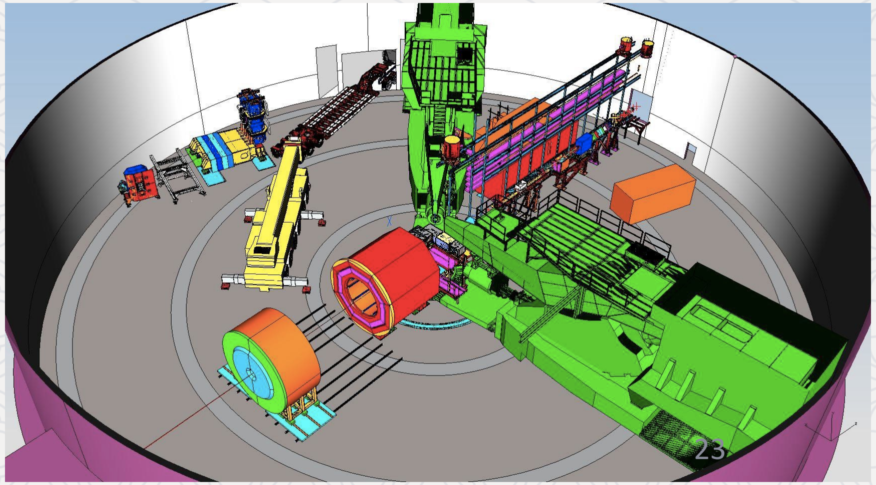


SoLID in Hall A at JLab

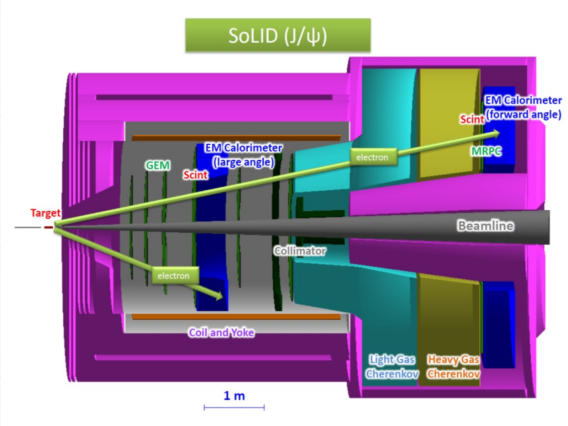
Research at **SoLID** will have the ***unique*** capability to **explore** the QCD landscape while **complementing** the research of other key facilities

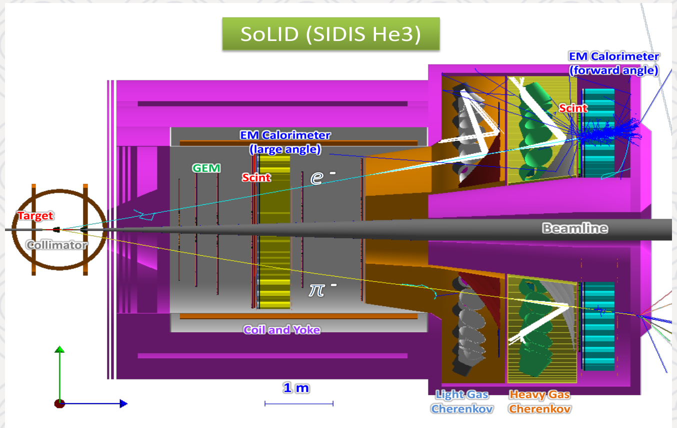
- Pushing the phase space in the search of new physics and of hadronic physics
- 3D momentum imaging of a relativistic strongly interacting confined system (**nucleon spin**)
- Superior sensitivity to the differential electro- and photo-production cross section of J/ψ near threshold (**proton mass**)

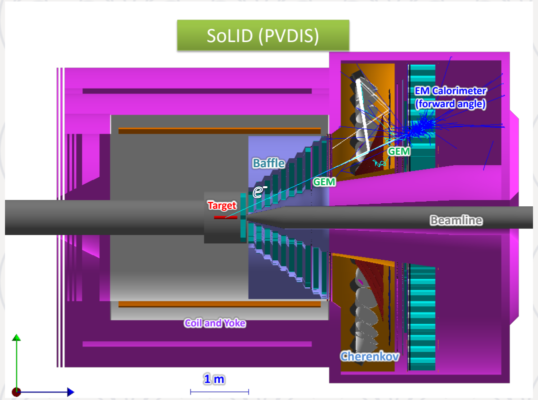
Synergistic with the pillars of EIC science (**proton spin** and **mass**) through high-luminosity valence quark tomography and precision J/ψ production near threshold

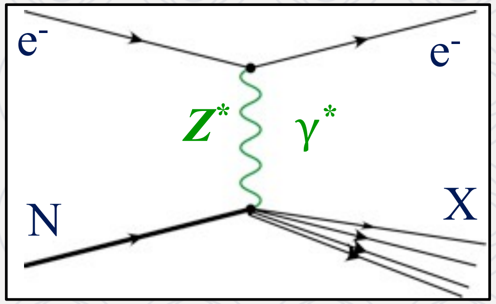


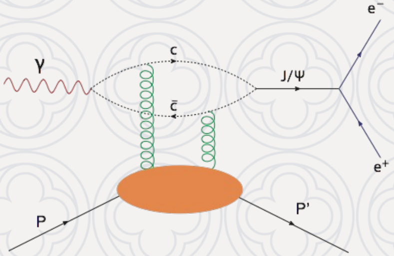
SoLID@JLab: QCD at the intensity frontier

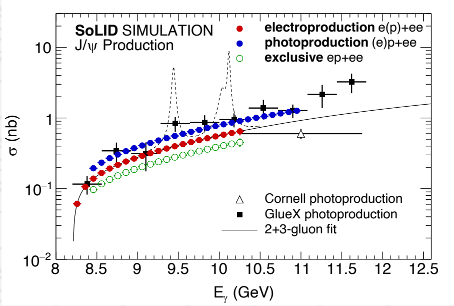


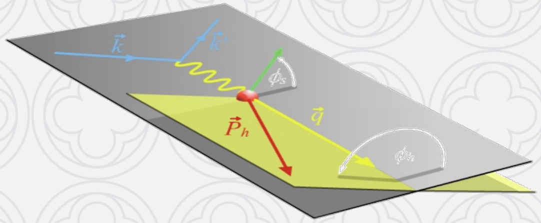


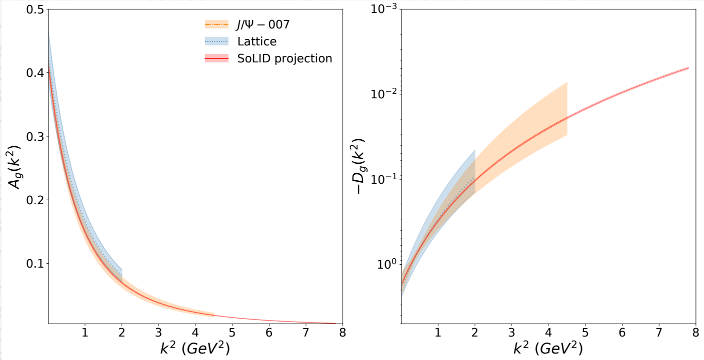


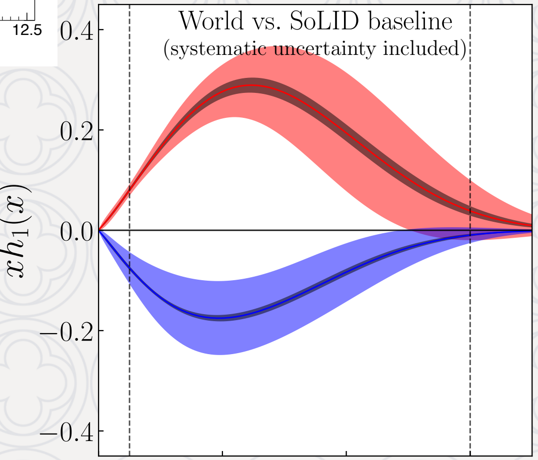


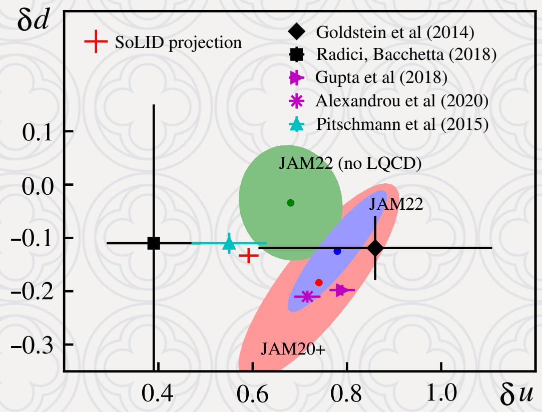


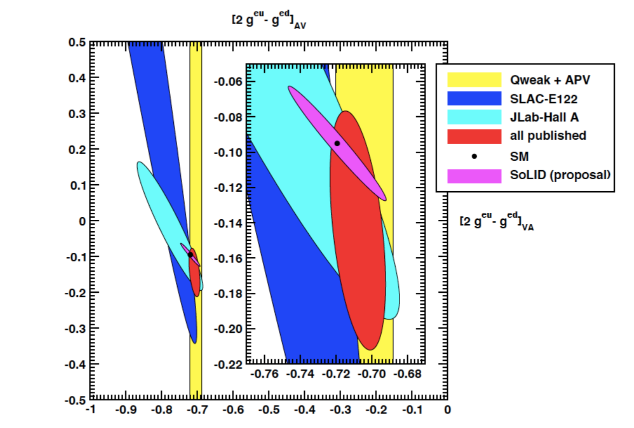












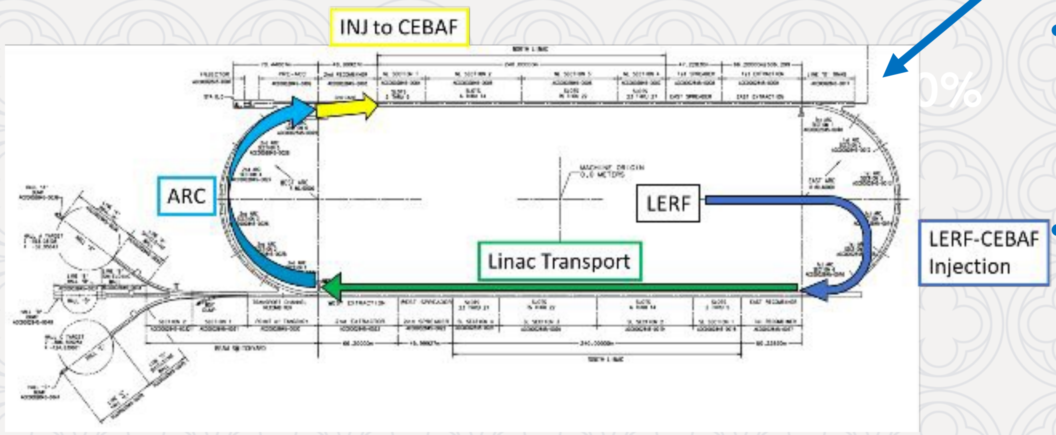
Arrington *et al*., J. Phys. G: Nucl. Part. Phys. 50, 110501 (2023)

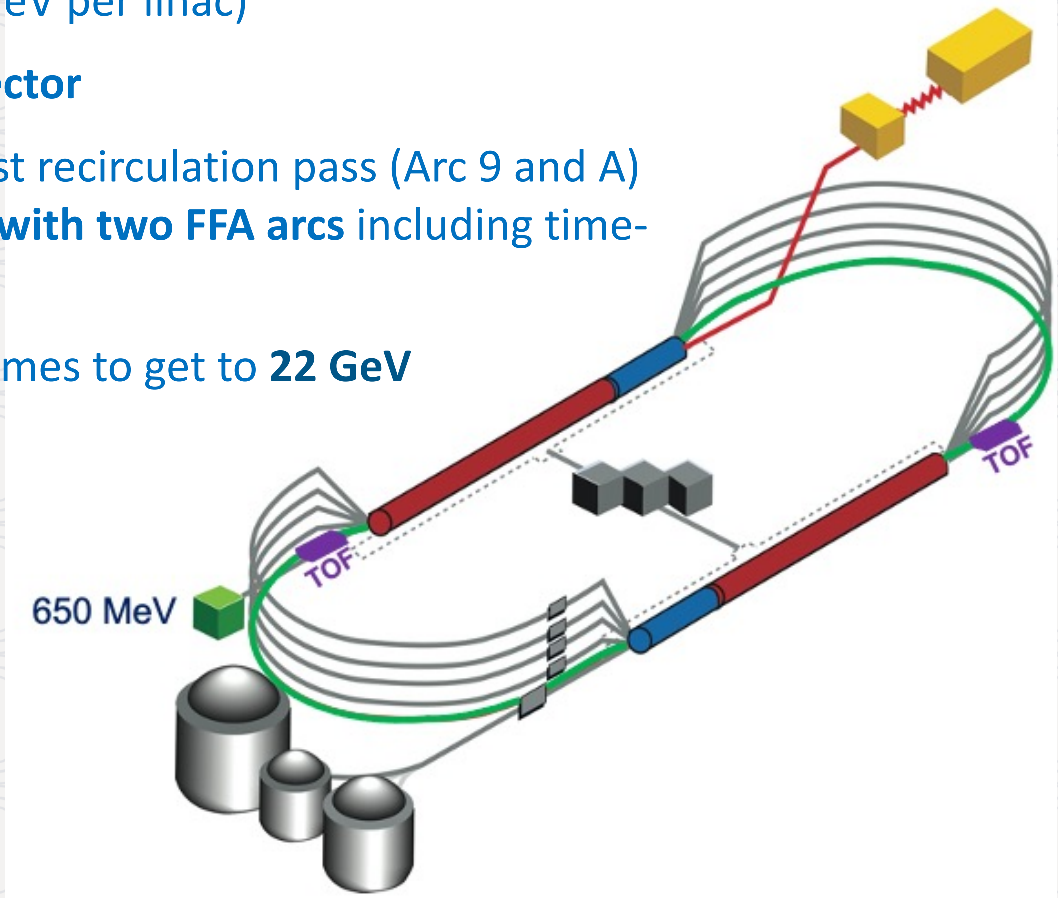
Feasible, Cost effective, Innovative Path from e^+ to 22 GeV

Capitalize on recent science insights and US-led accelerator science and technology innovations to develop a **staged program at the luminosity frontier**

- CEBAF @ 22 GeV
- Positron beam

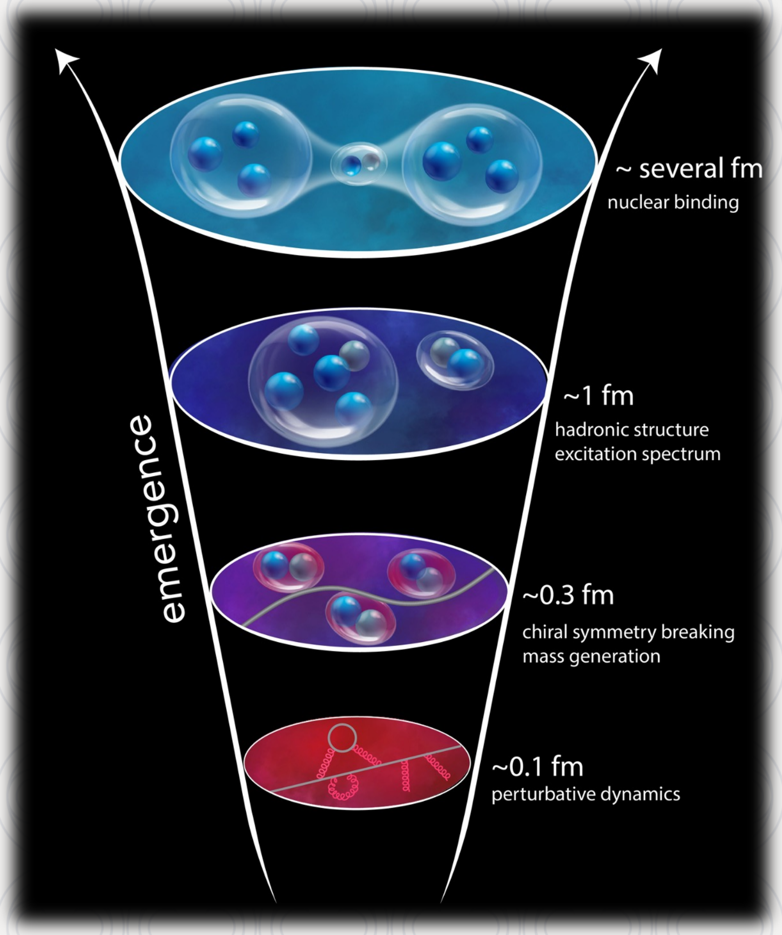
- Starting with 12 GeV CEBAF
- NO new SRF (1.1 GeV per linac)
- **New 650 MeV injector**
- Remove the highest recirculation pass (Arc 9 and A) and **replace them with two FFA arcs** including time-of-flight chicane
- Recirculate 4.5+6times to get to **22 GeV**





- **Positrons (e+) in the LERF with transport to CEBAF**
- Injection energy upgrade for 650 MeV Electron (e-) in LERF

Why CEBAF @ 22 GeV?



Emergence of hadron structure

Complex non-pQCD problem which demands different approaches and measurements to access multiple observables

What a 22 GeV upgrade will bring:

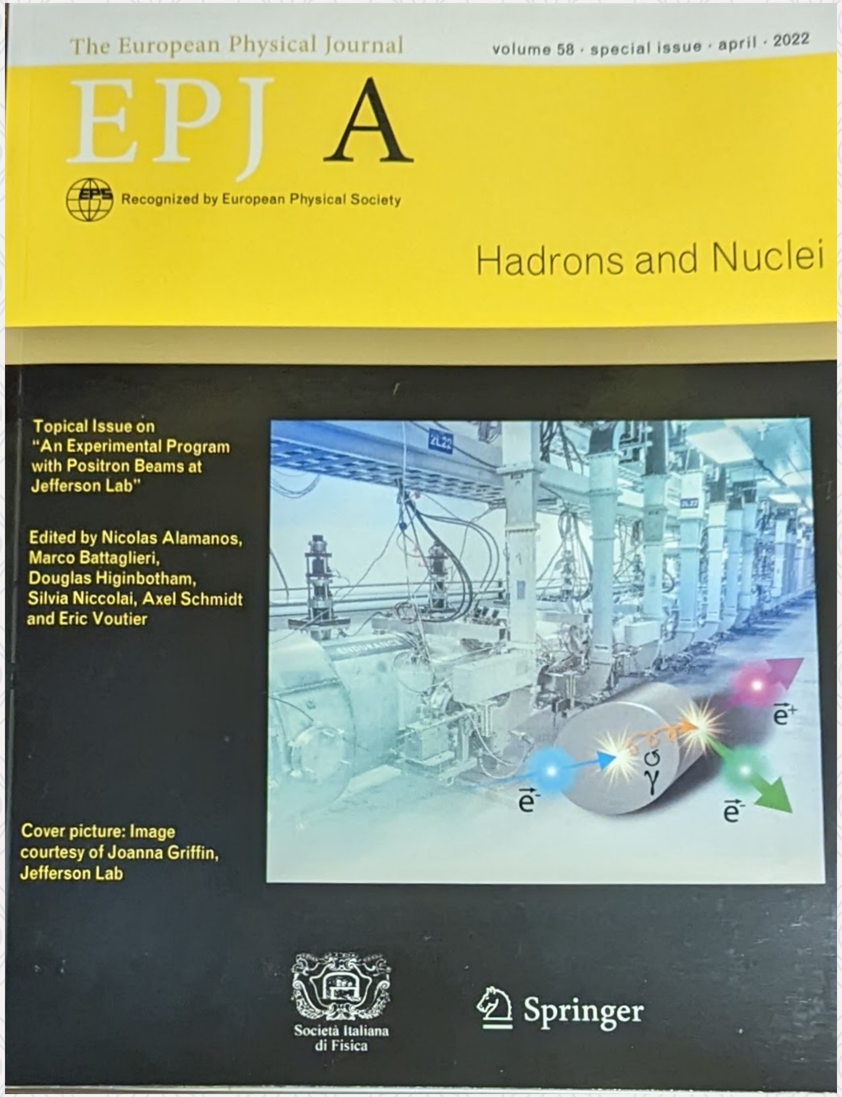
- **some important thresholds would be crossed → charm, nuclear distances, in fundamental symmetries, etc..**
- **An energy window which sits between JLab @ 12 GeV and EIC**
  → test and validation of our theory from lower to higher energy

- **A rich physics program is under development, leveraging on existing or already-planned infrastructure and on the uniqueness of CEBAF HIGH LUMINOSITY**

The Proposed Positron Program at JLab

Experiment Label (EPJ A)	Experiment Short Name	Hall	Detector	Target	Polarity	p (GeV/c)	P (%)	I (μA)	Time (d)	PAC Grade
					Two Photon Exchange Physics					
57:144	$H(e, e'p)$	B	CLAS12$^+$	H_2	$+/-_s$	2.2/3.3/4.4/6.6	0	0.060	53	
57:188	$H(\vec{e}, e'\vec{p})$	A	ECAL/SBS	H_2	$+/-_p$	2.2/4.4	60	0.200	121	
57:199	r_p	B	PRad-II	H_2	+	0.7/1.4/2.1	0	0.070	40	
	r_d			D_2		1.1/2.2		0.010	39	
57:213	$\vec{H}(e, e'p)$	A	BB/SBS	$N\vec{H}_3$	$+/-_s$	2.2/4.4/6.6	0	0.100	20	
57:290	$H(e, e'p)$	A	HRS/BB/SBS	H_2	$+/-_s$	2.2/4.4	0	1.000	14	
57:319	SupRos	A	HRS	H_2	$+/-_p$	0.6−11.0	0	2.000	35	
58:36	$A(e, e')A$	A	HRS	He	$+/-_p$	2.2	0	1.000	38	
					Nuclear Structure Physics					
57:186	p-DVCS	B	CLAS12	H_2	$+/-_s$	2.2/10.6	60	0.045	100	C2
57:226	n-DVCS	B	CLAS12	D_2	$+/-_s$	11.0	60	0.060	80	
57:240	p-DDVCS	A	SoLID$^\mu$	H_2	$+/-_s$	11.0	(30)	3.000	100	
57:273	He-DVCS	B	CLAS12/ALERT	^{4}He	$+/-_s$	11.0	60			
57:300	p-DVCS	C	SHMS/NPS	H_2	+	6.6/8.8/11.0	0	5.000	77	C2
57:311	DIS	A/C	HRS/HMS/SHMS		$+/-_s$	11.0				
57:316	VCS	C	HMS/SHMS	H_2	$+/-_s$		60			
					Beyond the Standard Model Physics					
57:173	C_{3q}	A	SoLID	D_2	$+/-_s$	6.6/11.0	(30)	3.000	104	D
57:253	LDM	B	PADME	C	+	11.0	0	0.100	180	
			ECAL/HCAL	$PbW0_4$					120	
57:315	CLFV	A	SoLID$^\mu$	H_2	+	11.0				
								Total (d)	**1121**	

CLAS12$^+$ ≡ CLAS12 implemented with an Electromagnetic Calorimeter in the Central Detector
SoLID$^\mu$ ≡ SoLID complemented with a muon detector
+ Secondary positron beam
$-_s$ Secondary electron beam
$-_p$ Primary electron beam
(30) Do not require polarization but would take advantage if available at the required beam intensity



https://doi.org/10.1140/epja/s10050-022-00699-6

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Summary

- JLab program is fully aligned with the U.S. NSAC Nuclear Science Long Range Plan priorities
- Exciting and insightful results from all areas of QCD physics coming out from the vibrant JLab 12-GeV program
- New opportunities on the horizon with MOLLER being built and SoLID (hope) to be built
- Longer-term future of JLab may involve positron and 20+ GeV beams, complementary to the EIC

Acknowledgement: I thank Thia Keppel, Zein-Eddine Meziani, and Patrizia Rossi for sharing their slides and all who contributed to the successful JLab science program. This work is supported in part by the U.S. Department of Energy under contract number DE-FG02-03ER41231.