JLab 5-year physics agenda

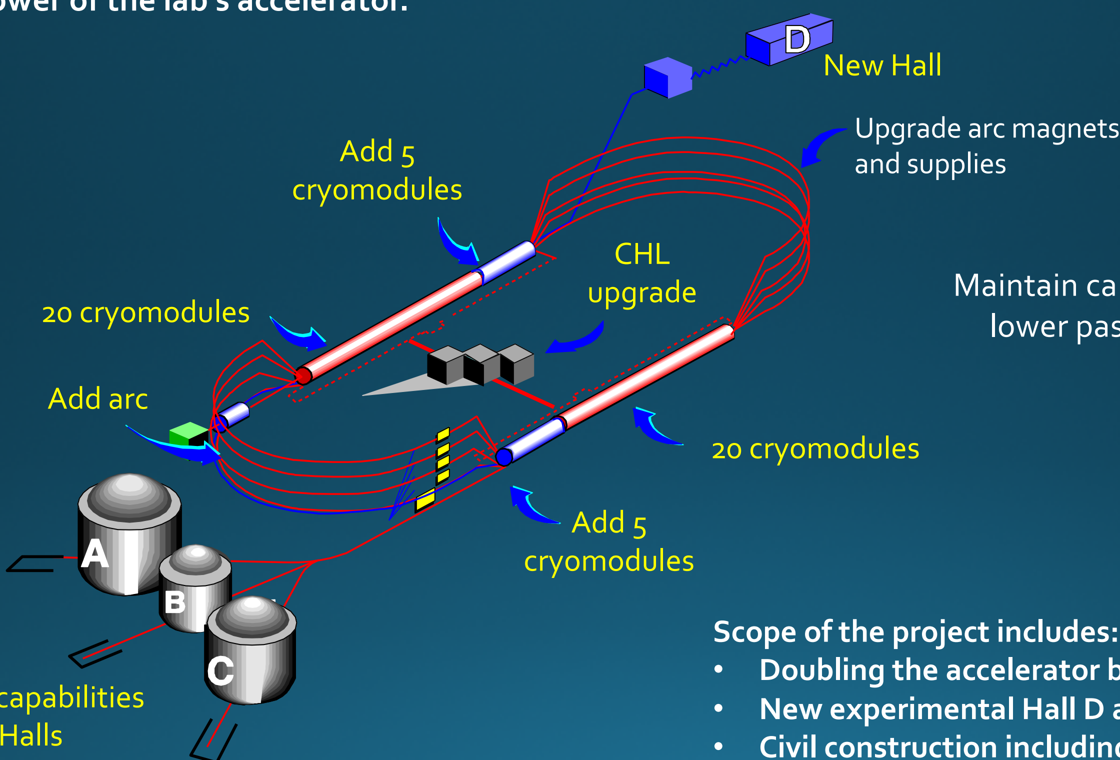
Outline:

- Overview of JLab science program
- A paradigm shift: 3D Imaging of quarks in the proton
- Towards the EIC, lessons from JLab 12 GeV upgrade.

Jefferson 12 GeV Upgrade Project

The 12 GeV Upgrade greatly expands the research capabilities of Jefferson Lab, adding a fourth experimental hall – D, upgrading existing halls and doubling the power of the lab's accelerator.

TPC=$338M
99% complete!

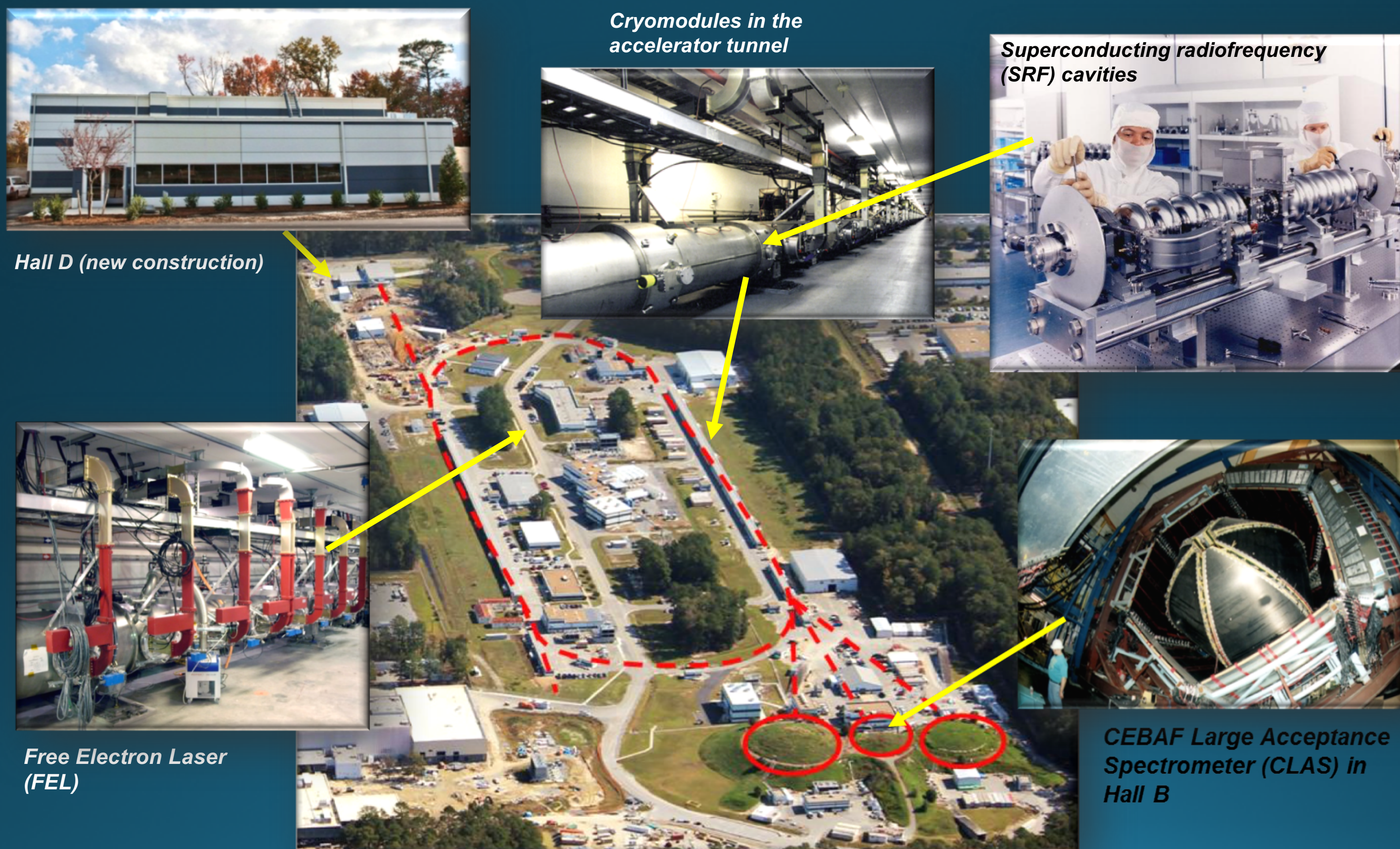


Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6….

Scope of the project includes:

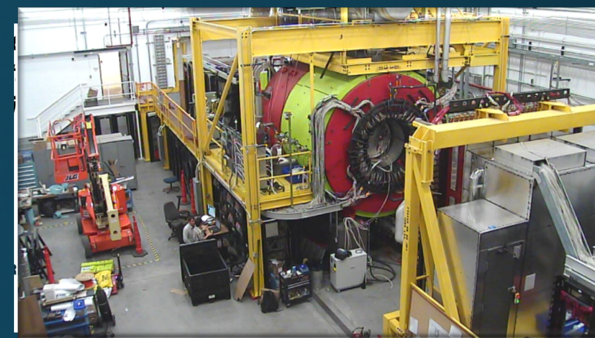
- **Doubling the accelerator beam energy - Done**
- **New experimental Hall D and beam line - Done**
- **Civil construction including utilities - Done**
- **Upgrades to existing Experimental Halls B& C - ~99% Done**

Jefferson Lab Accelerator Complex

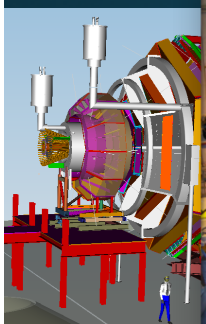


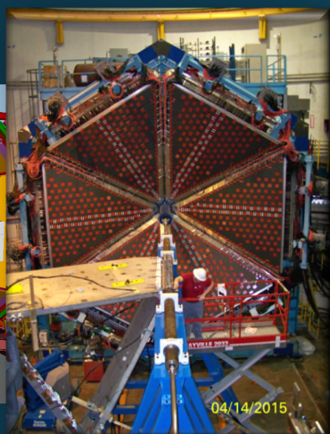
An aerial view of the recirculating linear accelerator and 4 experimental halls

12 GeV Scientific Capabilities



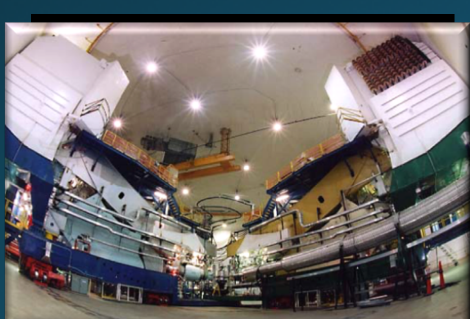
Hall D – exploring origin of confinement by studying exotic mesons





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)

The Intellectual Challenge in this Field!

- Facts:
  - ✧ We probe with leptons/hadrons and measure/detect leptons and hadrons
  - ✧ No modern machine (detector) has been able to produce (see) quarks and gluons in isolation!
- The challenge:

  How to probe the quark-gluon dynamics, quantify the hadron structure, study the emergence of hadrons, …, when we cannot see quarks and gluons?
- In response, facing the challenge:

  Theory advances:

  QCD factorization – matching the quarks/gluons to hadrons with controllable approximations!
  Unified picture of hadron structure, Wigner distributions, GTMDs
  Lattice QCD *ab initio* calculations

  Experimental breakthroughs:

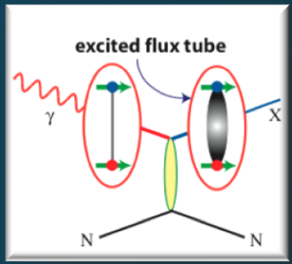
  Advances in luminosity and detection – Unprecedented resolution, event rates, and precision probes, especially EM probes, …

  Quarks – *Need a probe to "see" their existence, …*

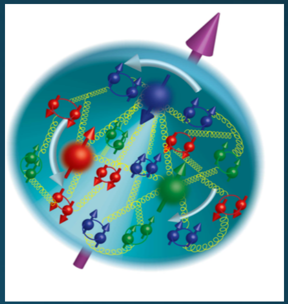
  Gluons – *Varying the probe's resolution to "see" their effect, …*

Jefferson Lab @ 12 GeV Science Questions

- What is the role of gluonic excitations in the spectroscopy of light mesons?

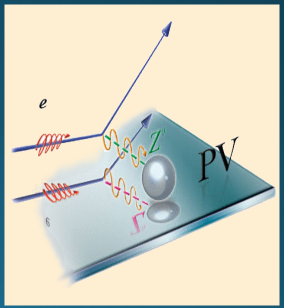


- Where is the missing spin in the nucleon? *Role of orbital angular momentum?*



- Can we reveal a **novel landscape of nucleon** substructure through **3D imaging** at the femtometer scale?

- Can we discover evidence for physics beyond the standard model of particle physics?



12 GeV Approved Experiments by Physics Topics

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD (GlueX and heavy baryon and meson spectroscopy)		2	1	3		6
The transverse structure of the hadrons (Elastic and transition Form Factors)	5	3	3	1		12
The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions)	2	3	6			11
The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)	5	9	7			21
Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body experiments)	7	3	7		1	17
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1		1	1	6
TOTAL	22	21	24	5	2	74

A Decade of Experiments

PAC41 "High Impact" Selection

PAC Days
Boldface = days designated High Impact
Parentheses=days not counting toward High Impact total

Row Color
Yellow=High Impact
Green=backup expt

Exp#	Exp name	Hall	Run Group/ Days	PAC Days	PAC grade	Comments
	TOPIC 1 : SPECTROSCOPY					
E12-06-102	**GlueX** : Mapping the Spectrum of Light Quark Mesons and Gluonic Excitations with Linearly Polarized Photons	**D**		(120) approved **★90**	A	GlueX - assumed half commissioning/half physics **★plus (30) commissioning days**
	TOPIC 2 : FORM FACTORS					
E12-06-101	Measurement of the Charged **Pion Form Factor** to High Q2	**C**		**52**	A	Requires fully commissioned SHMS
E12-07-109	**GEp/GMp** : Large Acceptance Proton Form Factor Ratio Meas's at 13 and 15 (GeV/c)2 Using Recoil Polarization Method	**A**		**45**	A-	Requires SBS and high power cryo target
E12-11-106	High Precision Measurement of the **Proton Charge Radius**	**B**		**15**	A	Non-CLAS12 experiment, Prad
	TOPIC 3 : PDFs					
E12-06-113	**BONuS** : The Structure of the Free Neutron at Large x-Bjorken	**B**	F/40	(40) approved **★21** ↓	A	Requires BONuS Radial TPC upgrade **★42 days High Impact for the experiment**
E12-10-103	**MARATHON** : Measurement of the F2n/F2p, d/u Ratios and A=3 EMC Effect in DIS off the Tritium and Helium Mirror Nuclei	**A**	Tritium target group/61	↑ **★21** (42) approved	A	**that runs first; experiments are equally important & both are essential**
E12-06-110	**A1n HallC–3He** : Meas of Neutron Spin Asymmetry A1n in the Valence Quark Region Using an 11 GeV Beam and a Polarized 3He Target in Hall C	**C**		**36**	A	Requires high luminosity 3He

Valence Quarks Imaging

Stepping Stone Experiments to an EIC!

TOPIC 4T : TMDs

C12-11-111	**TMD CLAS–HDIce** : SIDIS on Transverse polarized target	**B**	G/110	**110** concurrent	A	Requires transversely polarized HDIce with electron beam
C12-12-009	**Dihadron CLAS-HDIce** : Measurement of transversity with dihadron production in SIDIS with transversely polarized target	**B**	G/110	(**110**) concurrent	A	Requires transversely polarized HDIce with electron beam C1 Proposal
E12-06-112	**TMD CLAS-H(Unpol)** : Probing the Proton's Quark Dynamics in Semi-Inclusive Pion Production at 12 GeV	**B**	A/139	(60) approved **★10**	A	Hall B commissioning + 10 days **★plus (50) commissioning days**

TOPIC 4G : GPDs

E12-06-114	**DVCS HallA–H(UU,LU)** : Measurements of Electron-Helicity Dependent Cross Sections of DVCS with CEBAF at 12 GeV	**A**	Early: DVCS & GMp/62	(100) approved **★70**	A	Hall A commissioning
C12-12-010	**DVCS CLAS–HDIce** : DVCS at 11 GeV with transversely polarized target using the CLAS12 Detector	**B**	G/110	(**110**) concurrent	A	Requires transversely polarized HDIce with electron beam C1 Proposal
E12-11-003	**DVCS CLAS–D(UU,LU)** : DVCS on the Neutron with CLAS12 at 11 GeV	B	B/90	(90) approved	A	Requires D target; central neutron detector ready in 2016 **★Backup GPD-E meas if HDIce delayed**

TOPIC 5 : NUCLEAR

E12-13-005	**Bubble Chamber** : Measurement of 16O(^{3},±)12C with a bubblechamber and a bremsstrahlung beam	**INJ**		**14**	A-	Our guess: 2017
E12-11-101	**PREx-II** : Precision Parity-Violating Measurement of the Neutron Skin of Lead	**A**		**35**	A	Requires septum, Pb target, 1% Moller polarimetry
E12-06-105	**SRC–hiX** : Inclusive Scattering from Nuclei at $x > 1$ in the quasielastic and deeply inelastic regimes	**C**		**32**	A-	
E12-11-112	**SRC–Tritium** : Precision measurement of the isospin dependence in the 2N and 3N short range correlation region	**A**	Tritium target group/61	**19**	A-	

Fundamental Symmetries

TOPIC 6 : FUNDAMENTAL SYMMETRIES

E12-11-006	**HPS** : Status of the Heavy Photon Search Experiment at Jefferson Laboratory (Update on PR12_11_006)	**B**	H/180	(155) approved **★39**	A	non-CLAS12 experiment, HPS **★25 pre-CLAS engr + 14 physics @ 4.4 GeV**
E12-10-009	**APEX :** Search for new Vector Boson A1 Decaying to e+e-	**A**		**34**	A	Requires new septum and target system

<<< SUMMARY of "HIGH IMPACT" DAYS >>>

by Topic	**1**	**2**	**3**	**4GT**	**5**	**6**	**total post-commissioning**
	90	112	78	190	100	73	643
by Hall		**A**	**B**	**C**	**D**	**INJ**	
		224	195	120	90	14	643

In summary

5 years of high impact experiments

Paradigm shift: 3D Imaging of Nucleons & Nuclei
Transformational!

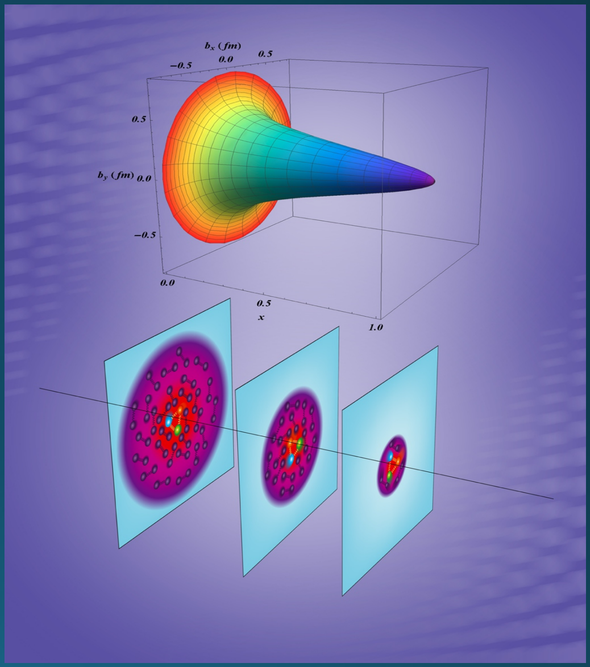
- Valence quarks
  - Jefferson Lab 12 GeV

➢ New theoretical framework within QCD
  - ✓ Non-local matrix elements linked to measurements
  - ✓ Wigner distribution for a unified picture
  - ✓ GPDs, TMDs: 3D images in space and momentum

➢ Proof of principle achieved using Jlab 6 GeV data

➢ Intimately linked to orbital angular momentum
➢ of the nucleon

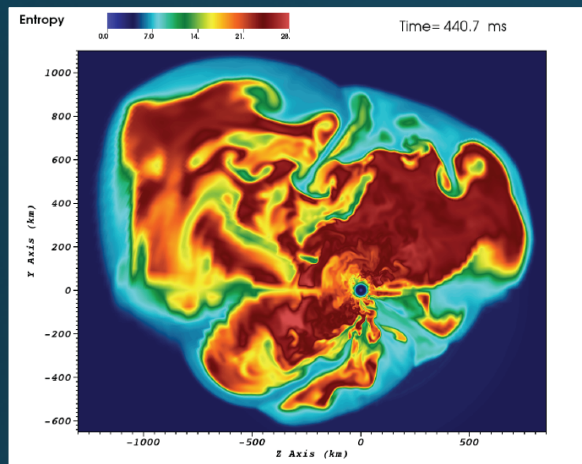
➢ Precursor for sea quarks and gluon imaging at an EIC



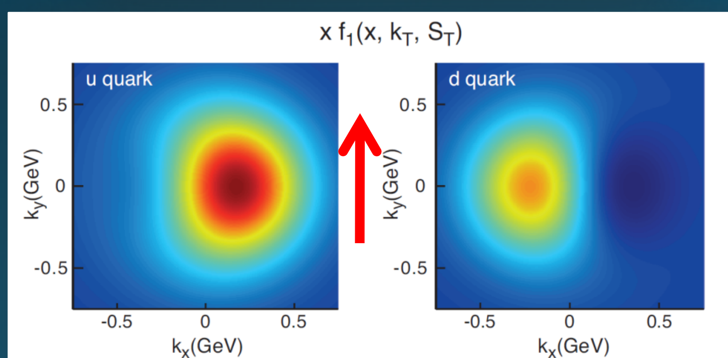
2D+1 quark spatial distribution in a proton accessible with JLab @ 12 GeV

Science in 3-Dimensions

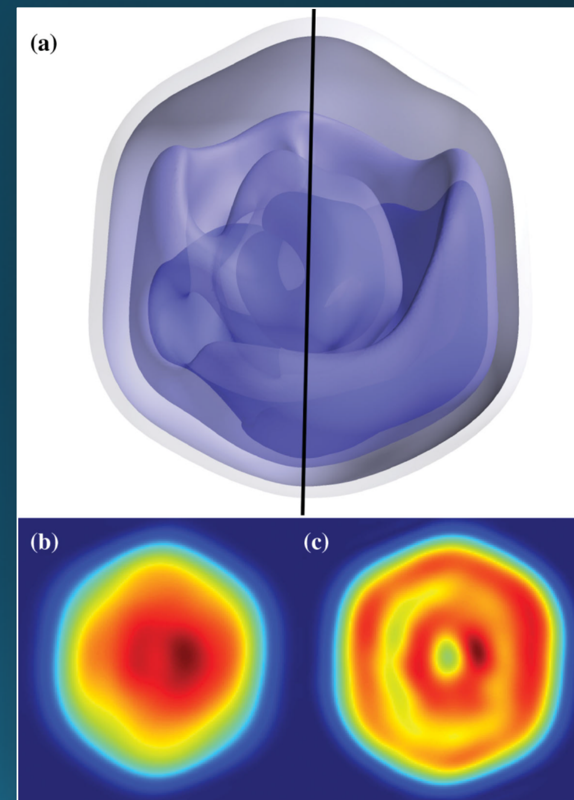
3D simulation of $15M_{\odot}$ supernova (ORNL)



Predicted quark Transverse Momentum Distributions for a polarized proton (accessible with JLab @ 12 GeV)



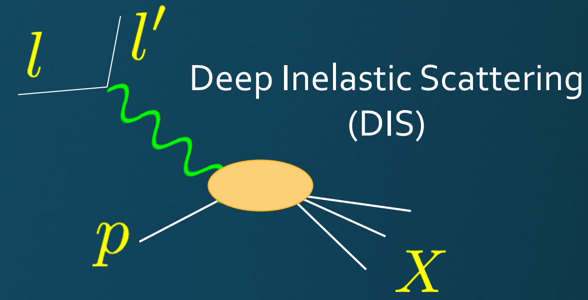
X=0.1



Mimivirus imaged at LCLS (SLAC)

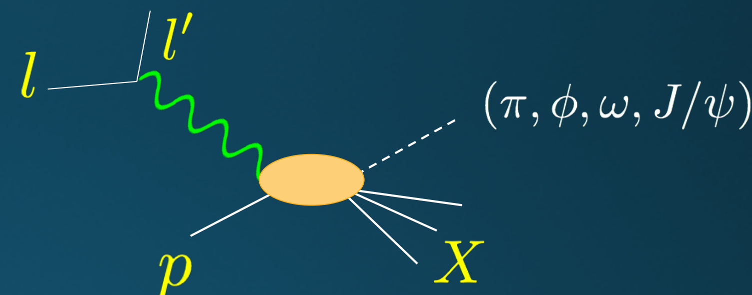
Experimental Tools: Scattering

- Inclusive reactions: e+p/A → e′+X
  - Detect only the scattered lepton in the detector

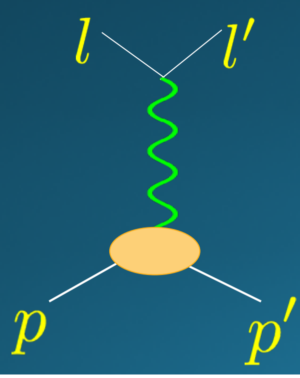


Deep Inelastic Scattering (DIS)

- Semi-Inclusive reactions: e+p/A → e′+h(p,π,K)+X
  - Detect the scattered lepton in coincidence with identified hadrons (mesons)



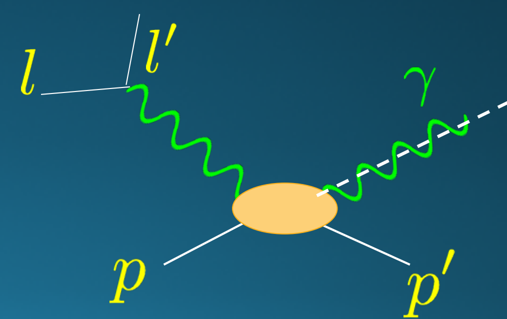
- Exclusive reactions: e+p/A → e′+ p′/A′+ (γ π,K,…)
  - Detect all final states including proton (or its fragments)



Elastic Scattering

Deep Virtual Compton Scattering: γ

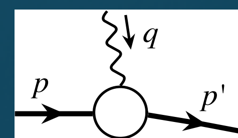
Deep Virtual Meson Production (DVMP)$(\pi, \phi, \omega, J/\psi)$

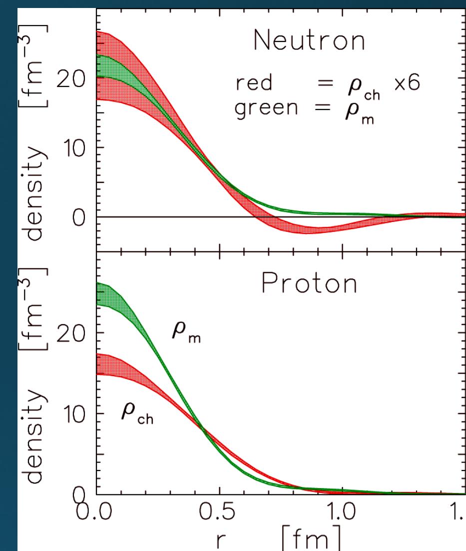


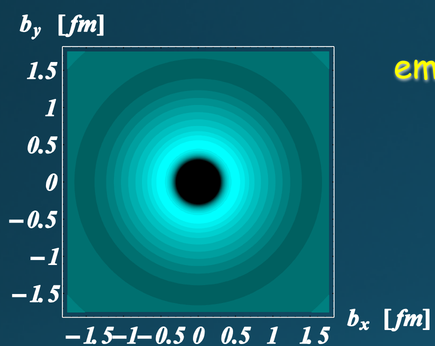
How is charge distributed inside the proton?

- Electric charge distribution:

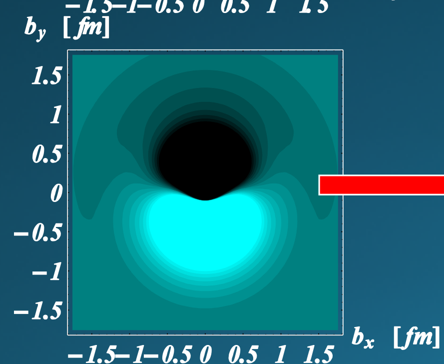
Elastic electric form factor
➡ Charge distributions

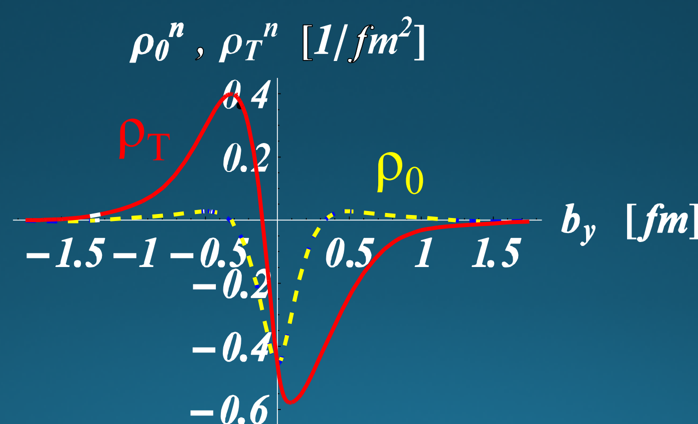






empirical quark transverse densities in Neutron





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

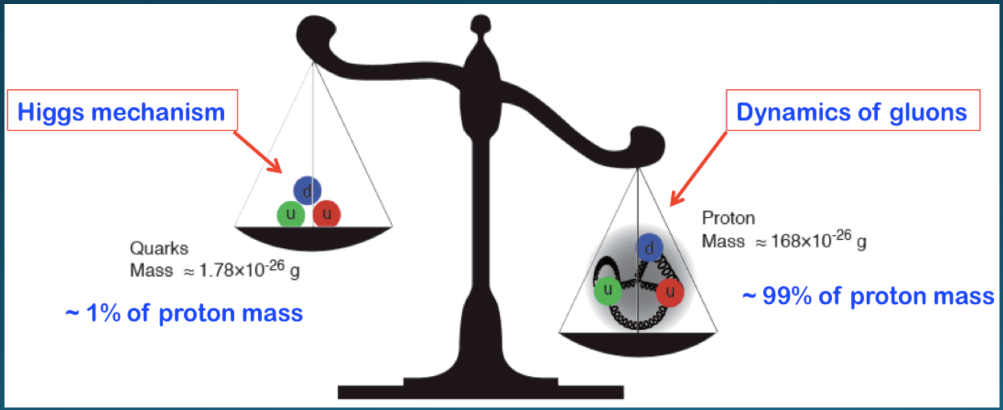
induced EDM : $d_y = F_{2n}(0) . e / (2 M_N)$

How does QCD generate its Mass & Spin?

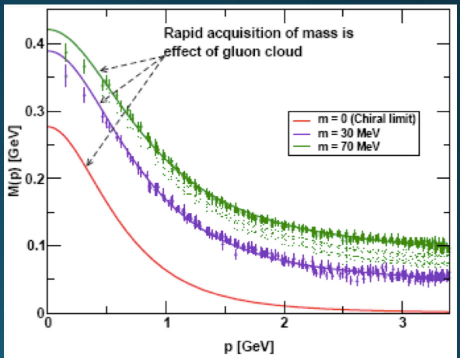
"…QCD takes us a long stride towards the Einstein-Wheeler ideal of mass without mass Frank Wilczek (1999, Physics Today)

Close examples in nature: proton

✧ Massless, yet, responsible for nearly all visible mass



"Mass without mass!"



Bhagwat & Tandy/Roberts et al

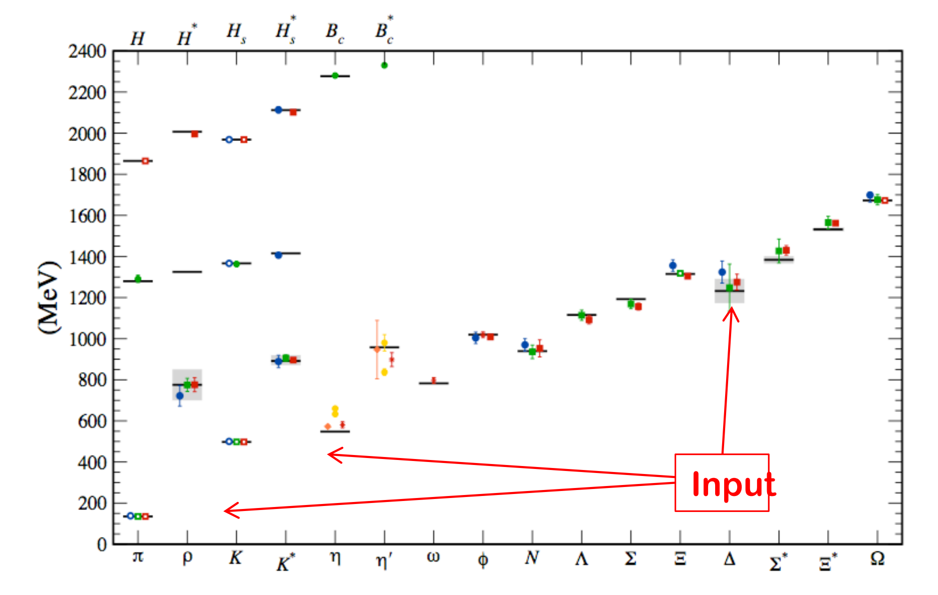
What Susskind has to say about proton mass and the Higgs mechanism.

- https://youtu.be/JqNg819PiZY?t=2403

How does QCD generate the nucleon mass?

"… 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***

❑ Hadron mass from Lattice QCD calculation:



How does QCD generate this? The role of quarks vs that of gluons?

If we do not understand proton mass, we do not understand QCD

How does QCD generate nucleon mass?

- **Four-pronged approach to explore the origin of hadron mass**
  - **Lattice QCD**
  - **Mass decomposition – roles of the constituents**
  - **Model calculation – approximated analytical approach**
  - **Measurements of the parts in a decomposition**

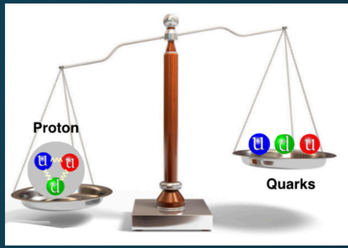
https://phys.cst.temple.edu/~meziani/proton-mass-workshop-2016/

How does QCD generate its Mass & Spin?

- ❑ **Three-pronged approach to explore the origin of hadron mass**
  - ✧ **Lattice QCD**
  - ✧ **Mass decomposition – roles of the constituents**
  - ✧ **Model calculation – approximated analytical approach**
  - ✧ **Measurements of the parts in a decomposition**

http://www.ectstar.eu/node/2218

How does QCD generates the nucleon mass?



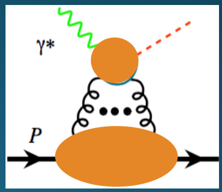
- Role of quarks and gluons?
  - **QCD energy-momentum tensor:** $$T^{\mu\nu} = \frac{1}{2}\bar{\psi} i \overleftrightarrow{D}^{(\mu}\gamma^{\nu)}\psi + \frac{1}{4}g^{\mu\nu}F^2 - F^{\mu\alpha}F^{\nu}_{\alpha}$$
  - Trace of the QCD energy-momentum tensor:

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

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

  - **Mass, trace anomaly, chiral symmetry breaking, …**

$$m^2 \propto \langle p|T^{\alpha}_{\alpha}|p\rangle \xrightarrow{\text{Chiral limit}} \frac{\beta(g)}{2g}\langle p|F^2|p\rangle$$



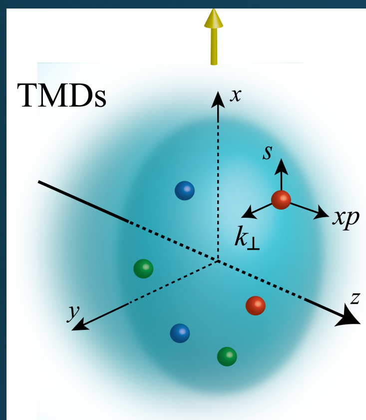
➡ Heavy quarkonium production near the threshold, from JLab12 to EIC

Unified View of Nucleon Structure

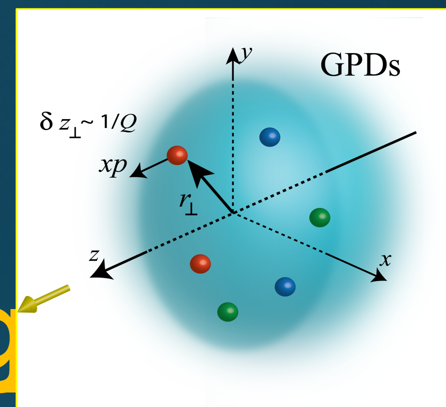
$W_p^u(x,k_T,r_T)$ Wigner distributions

5D Dist.

Transverse Momentum Dist.



Generalized Parton Dist.



dr_T

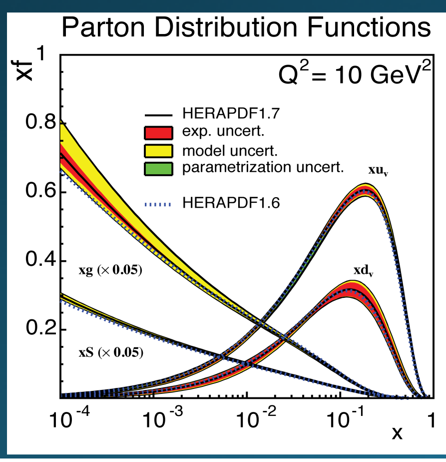
d^2k_T

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

GPD

"3D" imaging

dx &Fourier Transformation



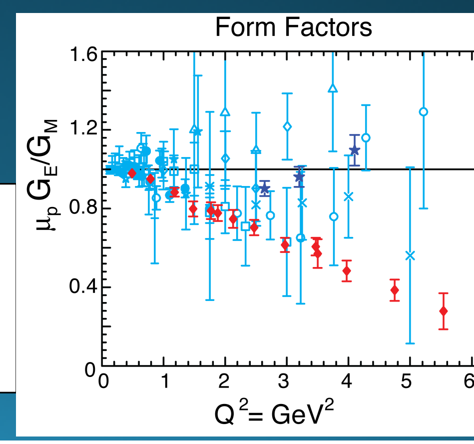
d^2k_T

d^2r_T

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

1D

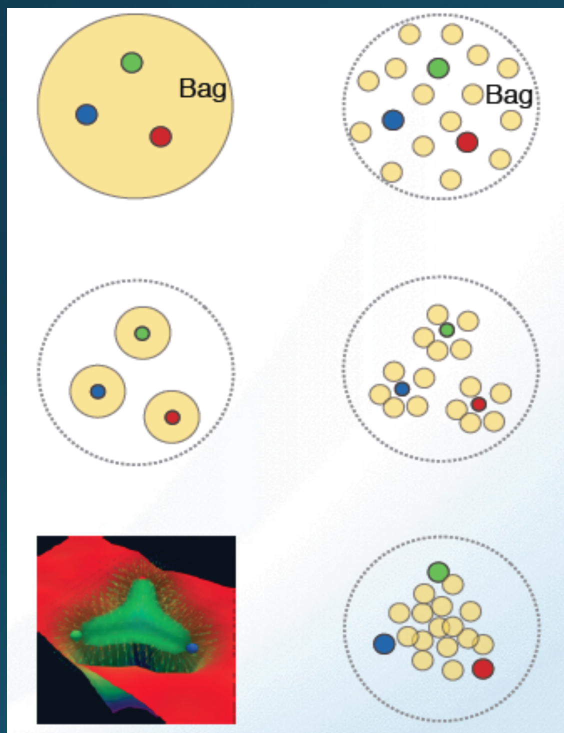
Form
Factors
$G_E(Q^2)$,
$G_M(Q^2)$



Why 3D nucleon structure?

❑ Spatial distributions of quarks and gluons:

Static Boosted



Bag Model:

Gluon field distribution is wider than the fast moving quarks.

Gluon radius > Charge Radius

Constituent Quark Model:

Gluons and sea quarks hide inside massive quarks.

Gluon radius ~ Charge Radius

Lattice Gauge theory (with slow moving quarks):

Gluons more concentrated inside the quarks

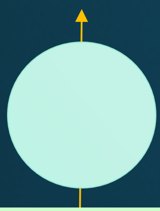
Gluon radius < Charge Radius

3D Confined Motion (TMDs) + Spatial Distribution (GPDs)

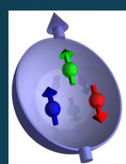
Relation between charge radius, quark radius (x), and gluon radius (x)?

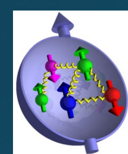
How does QCD generate the Nucleon Spin?

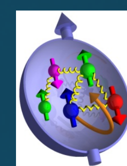
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g) = \sum \langle P,S|\hat{J}_f^z(\mu)|P,S\rangle$$



Proton Spin







Quark Helicity
Best known from DIS

$$\frac{1}{2}\int dx(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s})$$

$$\sim 30\%$$

Gluon helicity
Start to know

$$\Delta G = \int dx \Delta g(x)$$

$$\sim 20\% (\text{with RHIC data})$$

Orbital Angular Momentum of quarks and gluons
Little known?

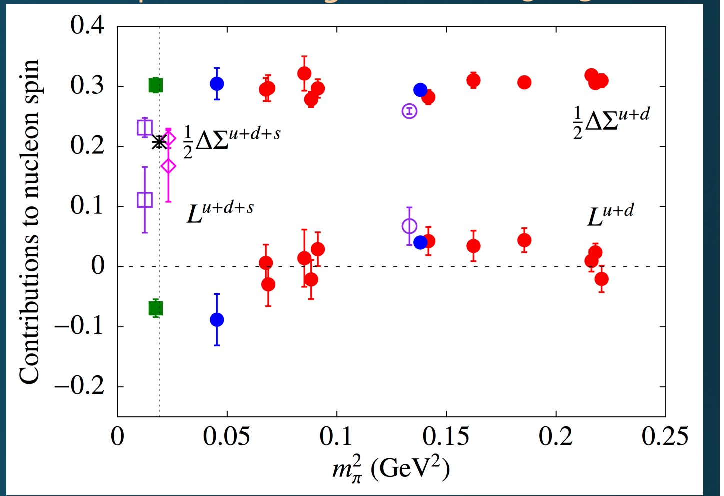
If we do not understand proton spin, we do not understand QCD

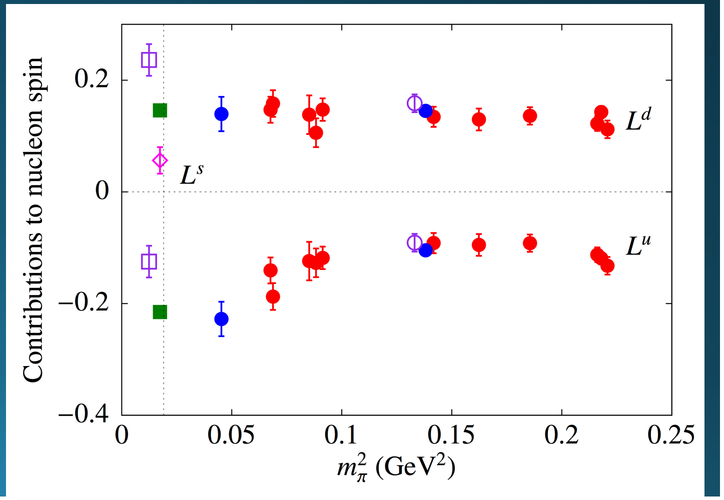
Lattice QCD and Nucleon Spin

https://arxiv.org/abs/1611.09163M.

- Lattice calculations are now performed at the physical pion mass.
- Large orbital angular momentum components for valence quarks are obtained. Up and down quark cancel their orbital contribution. Flavor decomposition is important.
- Also the down quark spin contribution cancels the orbital angular momentum contribution
- The contribution of the sea quarks is not small
- Rapid progress in evaluating directly the parton distributions

$$J^q(t) = \frac{1}{2}\int_{-1}^{+1} dxx\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$$

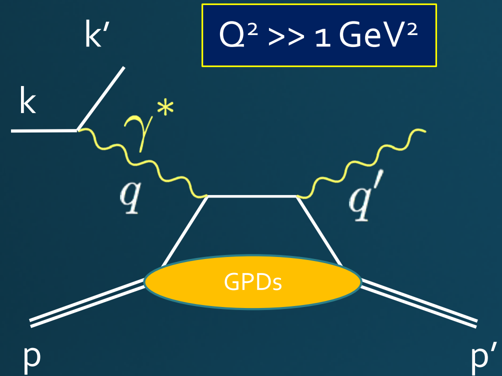




Deeply Virtual Compton Scattering

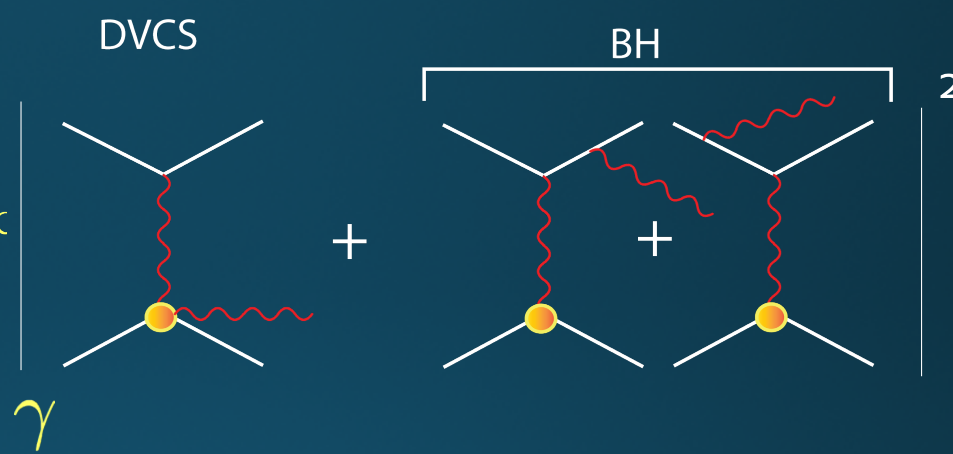
A clean probe of GPDs

Q² >> 1 GeV²



$$Q^2 = -q^2 = -(k-k')^2$$
$$t = (p-p')^2$$
$$x_B = Q^2/2p\cdot q$$

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



$$A_{LU} = \frac{BH * \mathrm{IM}(DVCS) * \sin\phi}{(BH^2 + DVCS^2)}$$

- At large Q^2: QCD factorization theorem
- At twist-2: 4 quark helicity conserving GPDs
- Key: Q^2 leverage needed to test QCD scaling

Separating GPDs Through Polarization

$ep \longrightarrow ep\gamma$

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

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

$k = -t/4M^2$

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

$\Rightarrow$ $H, \tilde{H}, E$

Unpolarized beam, longitudinal target:

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

$\Rightarrow$ $H, \tilde{H}$

Unpolarized beam, transverse target:

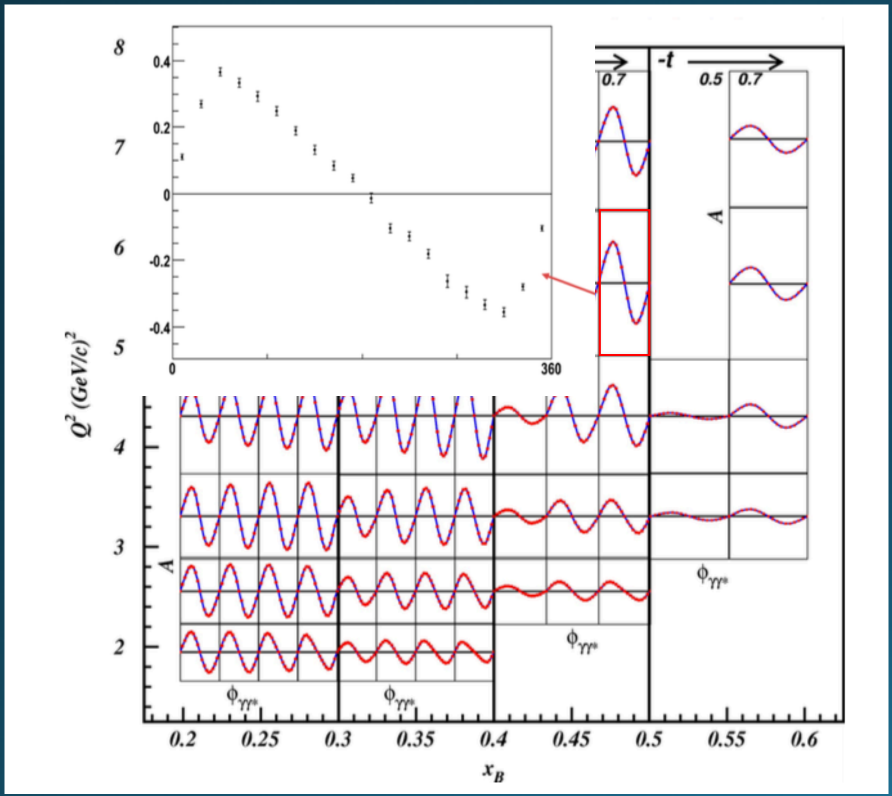
$$\Delta\sigma_{UT} \sim \sin\phi\{k(F_2 H - F_1 E) + \ldots\}d\phi$$

$\Rightarrow$ H, E

Global analysis of polarized and unpolarized data needed for GPD separation

Proton Beam Spin Asymmetry DVCS A_{LU} *in CLAS 12* *E12-06-009*

80 days at L=10^{35} cm^{-2} s^{-1} with 85% polarized beam

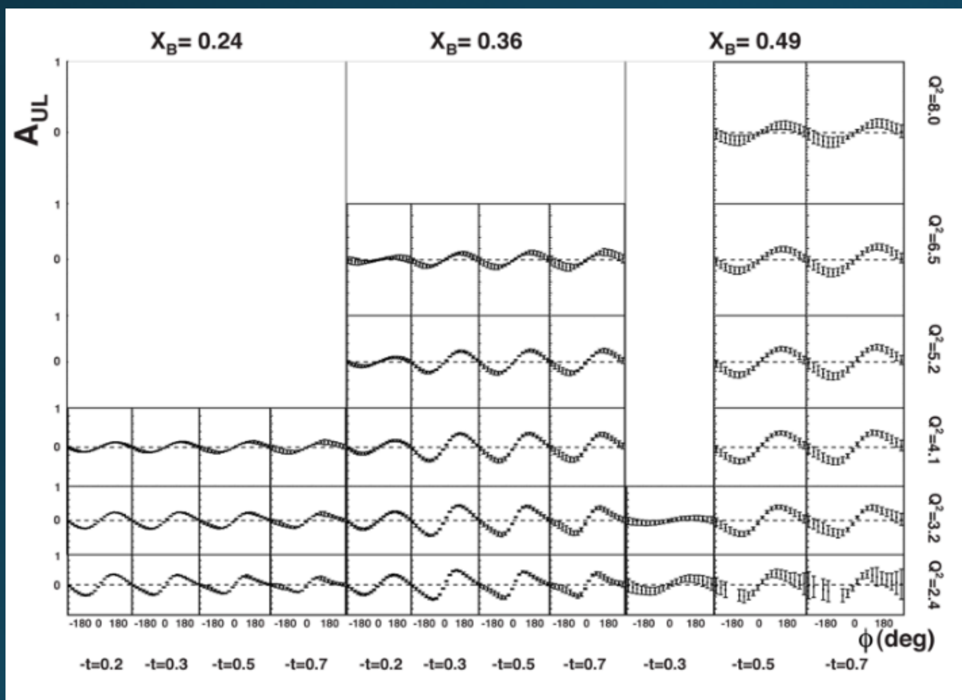


$$A_{LU} \propto F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$

- Beam spin asymmetry dependence ϕ
- Statistical uncertainties: from 1 % (low Q^2) to 10 % (high Q^2)
- Unprecedented statistics over the full ϕ range up to x= 0.6

Proton Target Spin Asymmetry DVCS A_{UL} *in CLAS 12* *E12-06-009*

120 days at $L=10^{35}$ cm^{-2} s^{-1} with 85% polarized NH_3

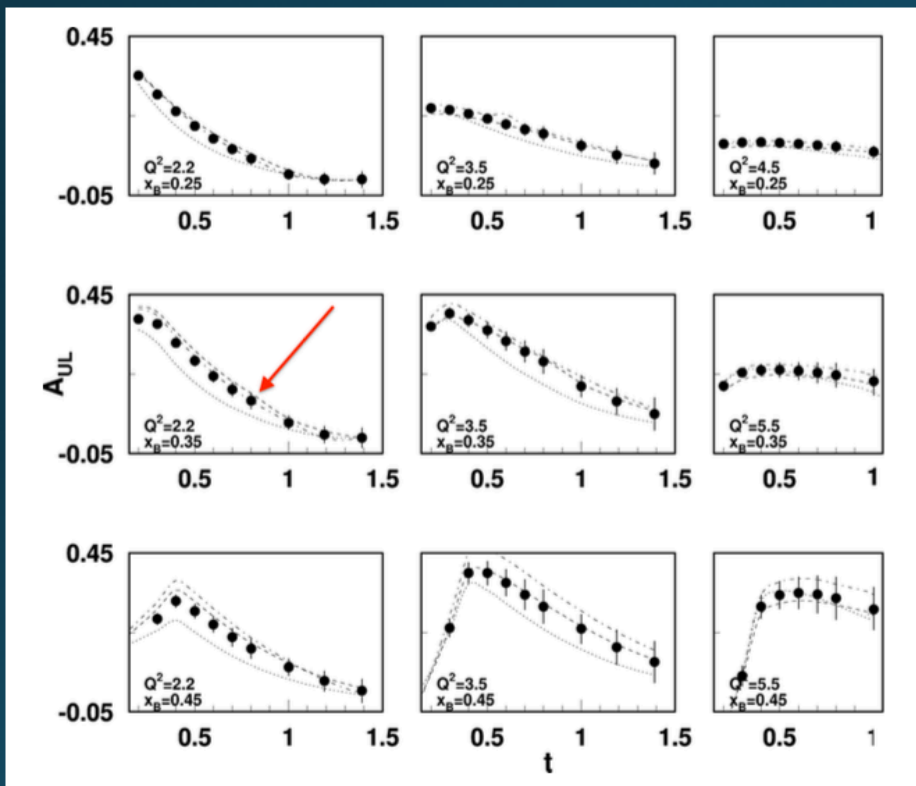


$$A_{UL} \propto F_1 \tilde{\mathcal{H}} + \xi G_M (\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}) - \ldots$$

- Beam spin asymmetry dependence ϕ
- Statistical uncertainties: from 2 % (low Q^2) to 30 % (high Q^2)
- Unprecedented statistics over the full ϕ range up to *x*= 0.6

Proton Target Spin Asymmetry DVCS A_{UL} *in CLAS 12* *E12-06-009*

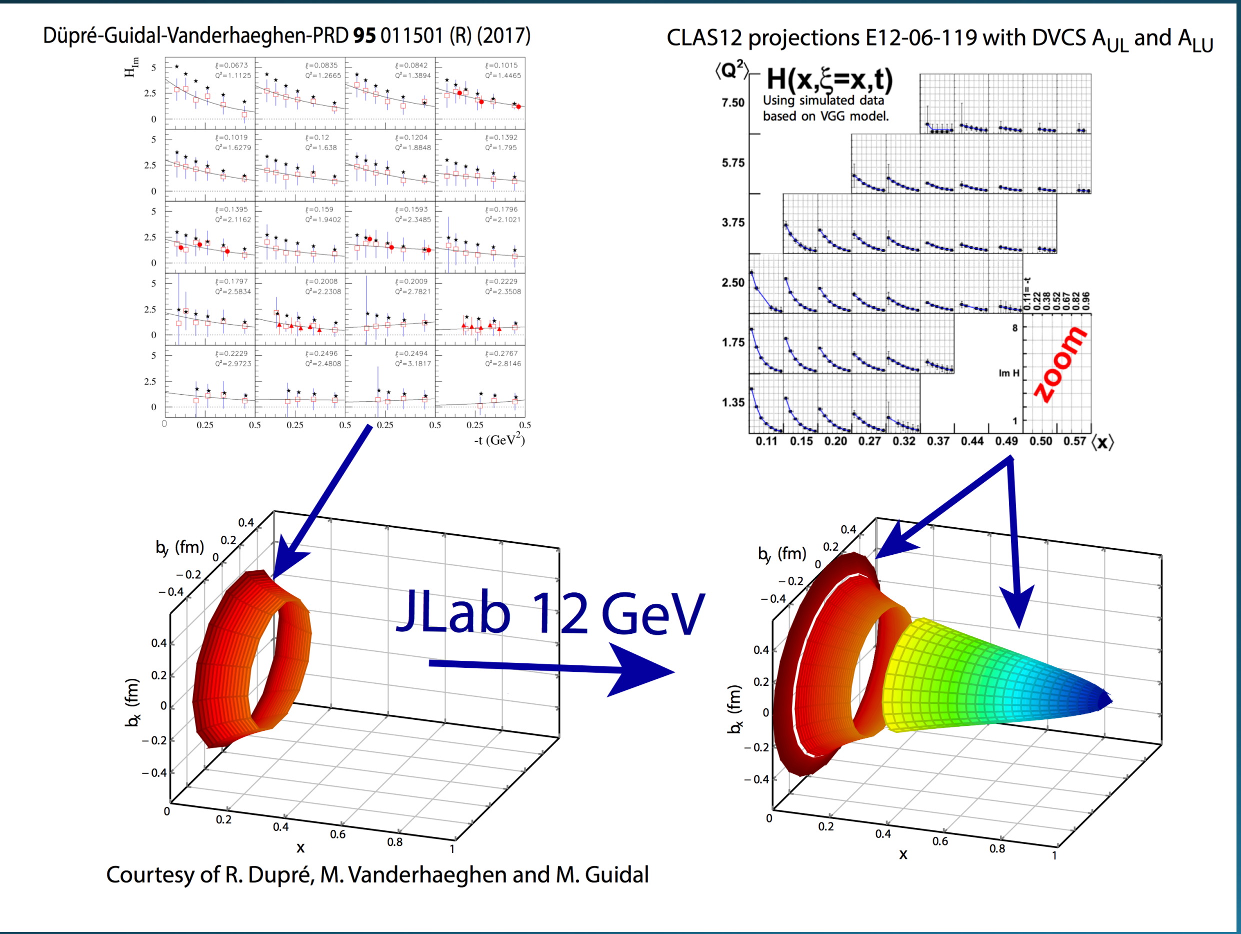
120 days at L=10^{35} cm^{-2} s^{-1} with 85% polarized NH_3



$$A_{UL} \propto F_1 \tilde{\mathcal{H}} + \xi G_M (\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}) - \ldots$$

- TSA t-slopes
- Sample kinematics for target asymmetries
- Change of t-slope with x_B implies imaging $\Delta q(x_B, b_\perp)$

Global Analysis of JLab 6 GeV Data and Projections for 12 GeV



- Proof of principle achieved with Jlab 6 GeV
- With 12 GeV data will be accessed to complete the valence picture
- Even gluons imaging in the valence region will be attempted.
- **A powerful preparation for the EIC**

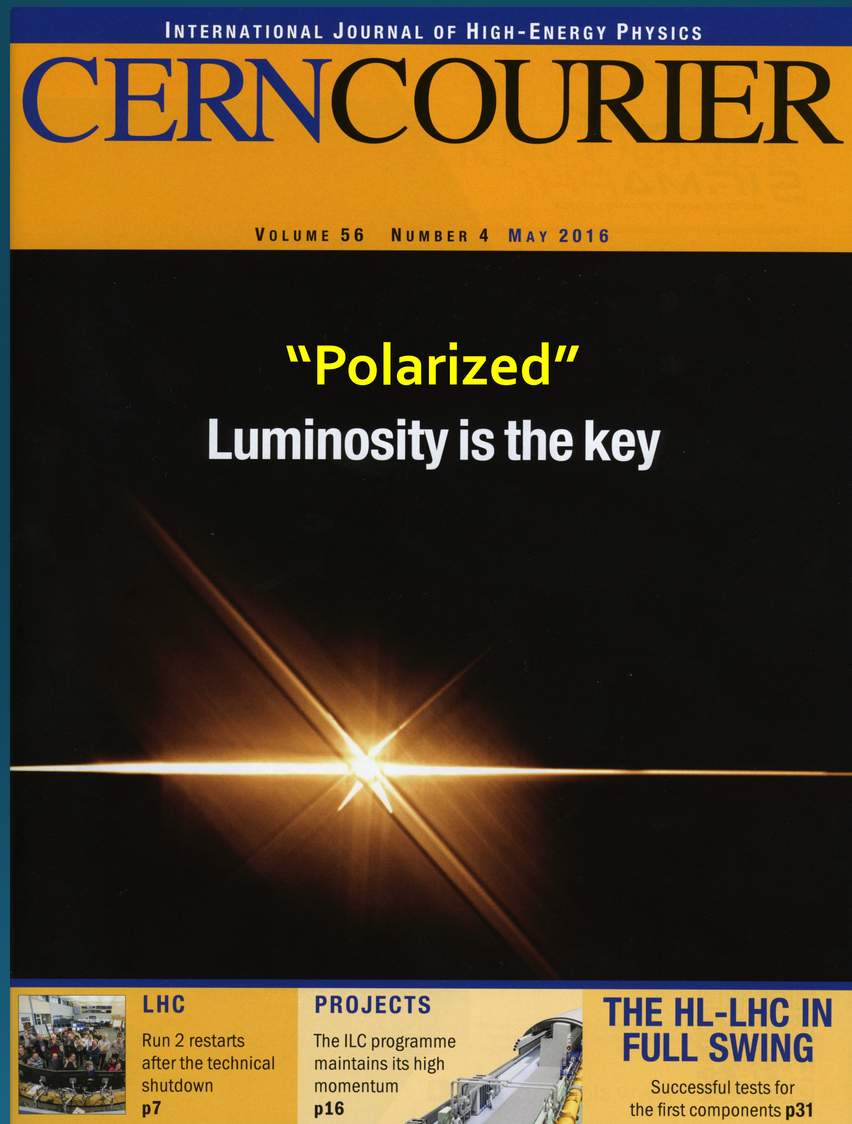
12 GeV JLab – The Potential

- Opportunity to discover and study new exotic mesons to elucidate the mechanism of confinement.
- Open a new landscape of nucleon tomography, with potential to identify the missing angular momentum. Proof of principle performed at 6 GeV
- Establish the quantitative foundation for the short-distance behavior in nuclei, underpinning the development of precision nuclear structure studies.
- Provide stringent new tests of the standard model and extensions, complementing the information obtained at LHC.
- Establish a firm basis for higher energy studies with a future **Electron Ion Collider**

Conclusions

- In the proton, charge and energy density distributions are intimately related to its confinement radius
- Proton imaging provides access to the total angular momentum contribution of quarks. A flavor decomposition will be carried too.
- Paradigm shift into a 3D view of the proton where polarized luminosity is key to gather precise enough data for GPD global extractions.
- TMDs and momentum imaging will provide key information on the confined motion of quarks in the proton. Spin-orbit couplings are strong signature of the role of orbital angular momentum of quarks.

- Jefferson Lab 12 GeV is the precursor and natural launch pad for the EIC imaging science. For EIC glue and sea quarks are key!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