Jefferson Lab in the 12 GeV Era

NNPSS 2019,
University of Tennessee,
Knoxville,
July 08-09, 2019

Rolf Ent (Jefferson Lab)

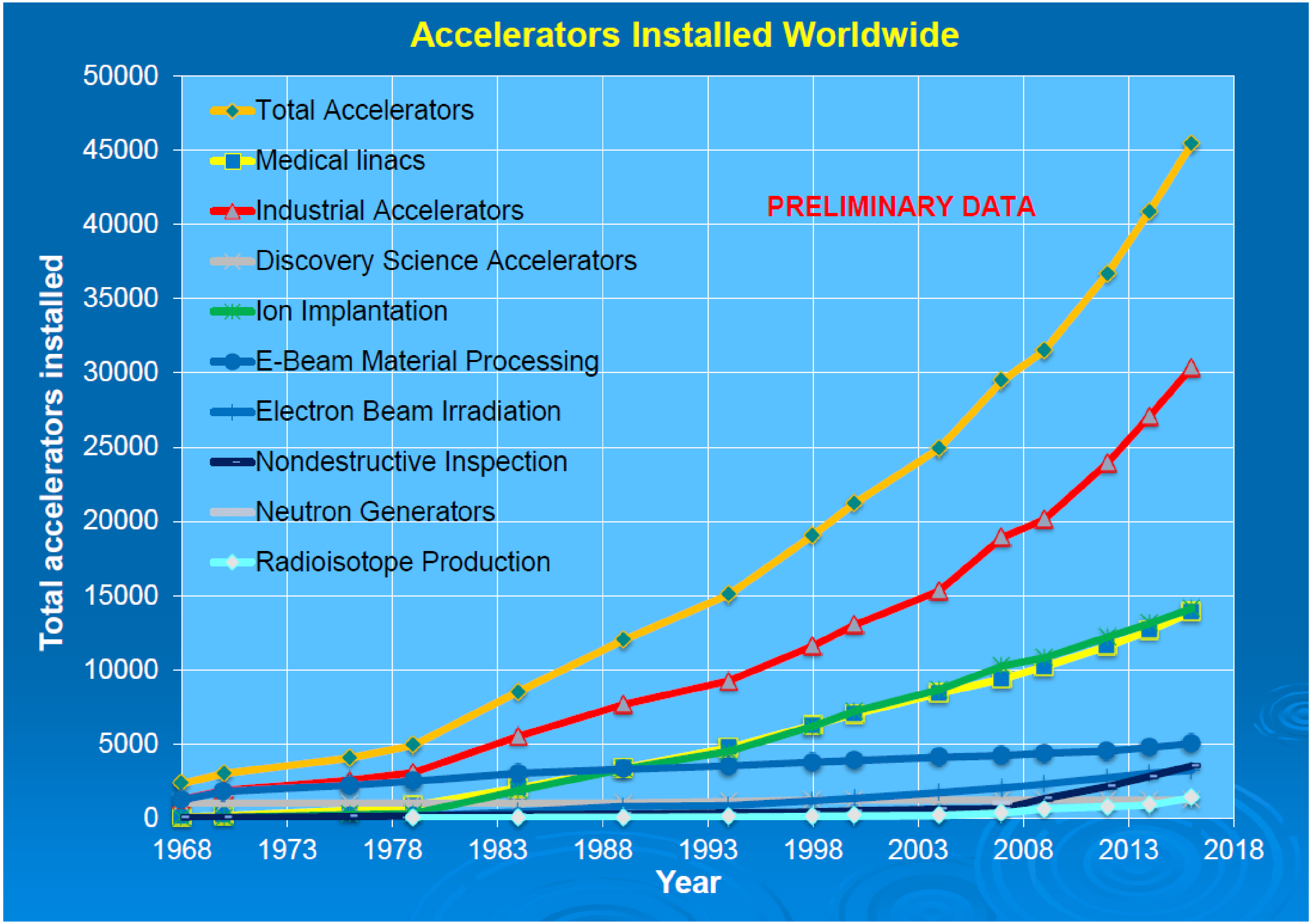
Outline

- Cool Facts about QCD and Nuclei
- Introduction to QED and QCD
- The Quest to Understand the Fundamental Structure of Matter
- Why Electron Scattering?
- Electron Scattering Formalism – the Era before Jefferson Lab

- Introduction to Jefferson Lab
- The 6-GeV Science Program – what did we learn?

- Gluons and QCD – The Need for 3D Atomic Structure
- JLab @ 12 GeV – Towards a New Paradigm for Structure
  - Femtography of valence quarks in nucleons and nuclei
  - Role of gluonic excitations in the spectroscopy of light mesons
  - Search for new physics Beyond the Standard Model
- The US-Based Electron-Ion Collider (EIC) – The Role of Gluons
- JLab @ 12 GeV (& EIC) – A Portal to a New Frontier

Growing Relevance of Accelerators Worldwide



From: Dr. Robert W. Hamm

The Structure of the Proton

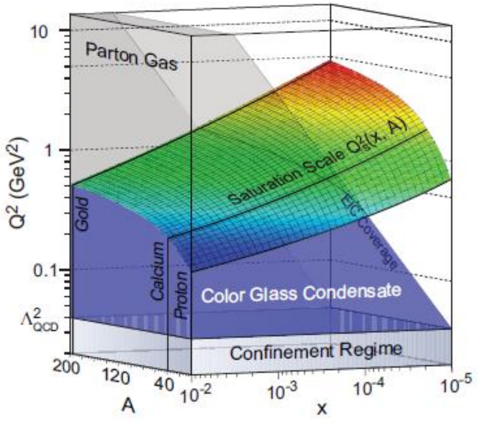
Naïve Quark Model: proton = uud (valence quarks)

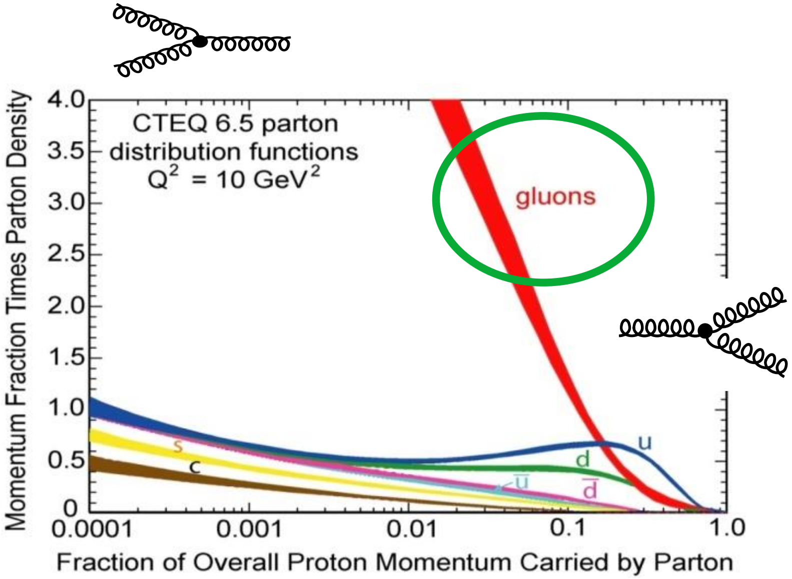
QCD: proton = uud + u$\bar{u}$ + d$\bar{d}$ + s$\bar{s}$ + …

The proton sea has a non-trivial structure: $\bar{u} \neq \bar{d}$

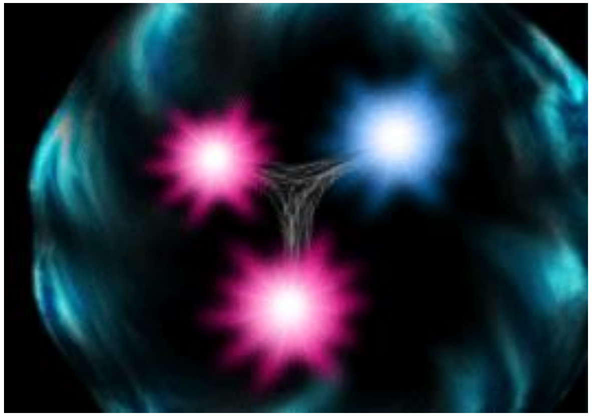
& gluons are abundant

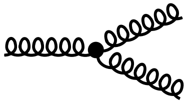
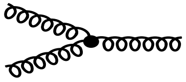
gluon dynamics





Non-trivial sea structure



- ❑ The proton is **far more** than just its up + up + down (valence) quark structure
- ❑ Gluon $\neq$ photon: Radiates  and recombines: 

Results Published in 2017/2018 in Nature

nature
International weekly journal of science

- *Precision measurement of the weak charge of the proton*, Qweak collaboration,
  Published: Nature 557, 207–211 (2018)
- *The pressure distribution inside the proton,* Burkert, Elouadrhiri, Girod,
  Published: Nature 557 (2018) no.7705, 396-399
- *A per-cent-level determination of the nucleon axial coupling for quantum chromodynamics*, Berkowitz et. al., Published: Nature 558, 91-94 (2018)
- *Ultrafast Nucleons in Asymmetric Nuclei,* M. Duer et. al., CLAS Collaboration,
  Published: Nature 560 (2018) no.7720, 617-621
- *A glimpse of gluons through deeply virtual compton scattering on the proton*, Dufurne et. al., Published: Nature Communications 8, 1408 (2017)

DAILY NEWS 16 May 2018

We've measured the pressure inside a proton and it's extreme

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NEWS PHYSICS 10 MAY 2018

Revealed: the weak charge of a proton

New measurement limits search for as-yet-undiscovered fundamental particles. Andrew Masterson reports.

NEWS AND VIEWS · 09 MAY 2018

Weak charge of the proton measured

The proton's weak charge defines the strength of certain interactions between protons and other particles. A precise determination of this quantity provides a stringent test of the standard model of particle physics.

Xiaochao Zheng

Subatomic particles interact through fo
only two of these forces have effects on
keeps us grounded on Earth, and electr
stormy days. We are not directly influen
the weak and strong forces. Similarly, it
at the root of gravitational interactions
magnetic moments are central to electr
properties that describe the strength of
known as weak and colour charges, resp
paper in Nature, the Jefferson Lab Q_{weak}

Oldest known lizard fossil pushes group's origins back 75 million years

The first Americans could have taken a coastal route into the New World

Finally, a plan on how to include pregnant women in clinical trials

Hurricane Maria killed at least 4,645 people in Puerto Rico, a study estimates

Astronomers scrutinized last year's eclipse. Here's what they've learned

Hard-to-burn 'smart' wallpaper even triggers alarms

The history of heredity makes for a fascinating, and chilling, read

NEWS PARTICLE PHYSICS

The inside of a proton endures more pressure than anything else we've seen

For the first time, scientists used experimental data to estimate the pressure inside a proton

BY EMILY CONOVER

FEELING THE PRESSURE Extreme pressures are found within the proton, scientists report. The proton contains three particles called quarks (illustrated) as well as gluons, which hold the particle together.

Jefferson Lab

JLab: 21st Century Science Questions

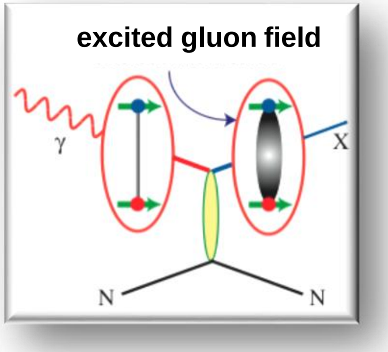
- What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?

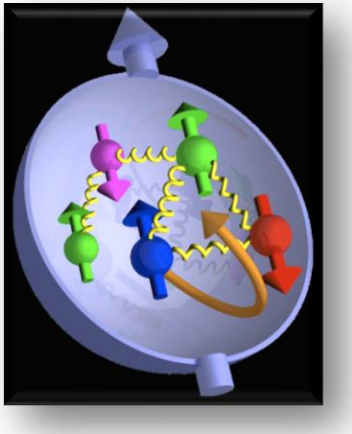
- Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?

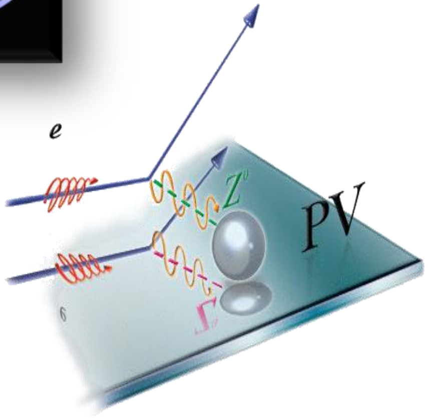
- Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?

- What is the relation between short-range N-N correlations, the partonic structure of nuclei, and the nature of the nuclear force?

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

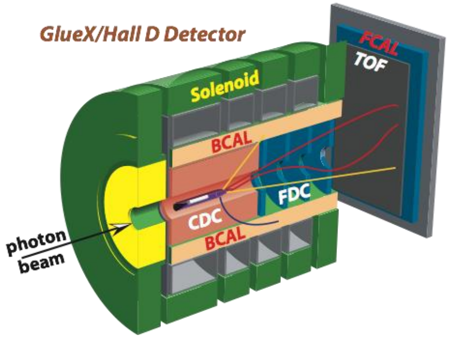


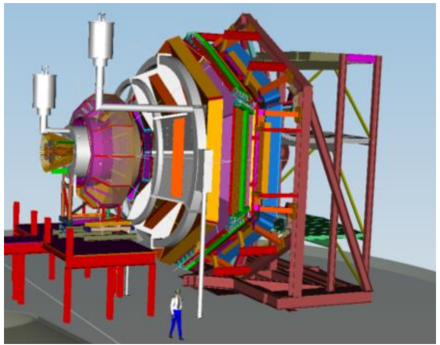


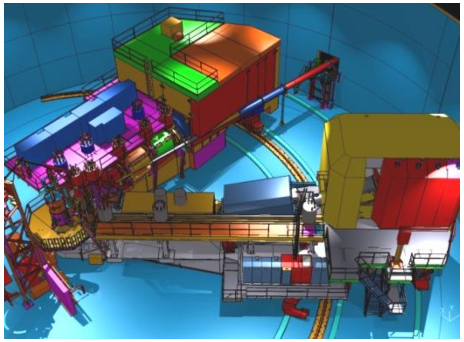


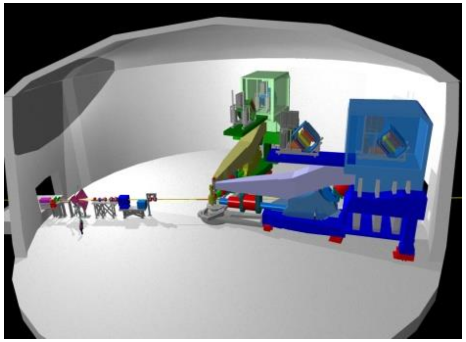
Jefferson Lab

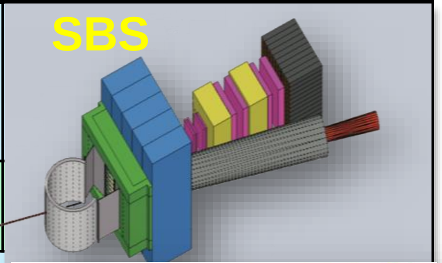
Detector Requirements: Complementarity

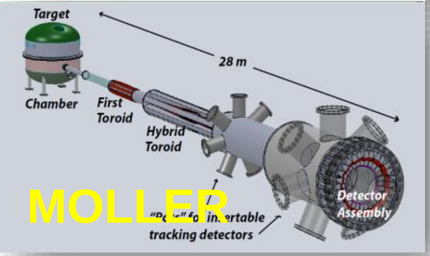




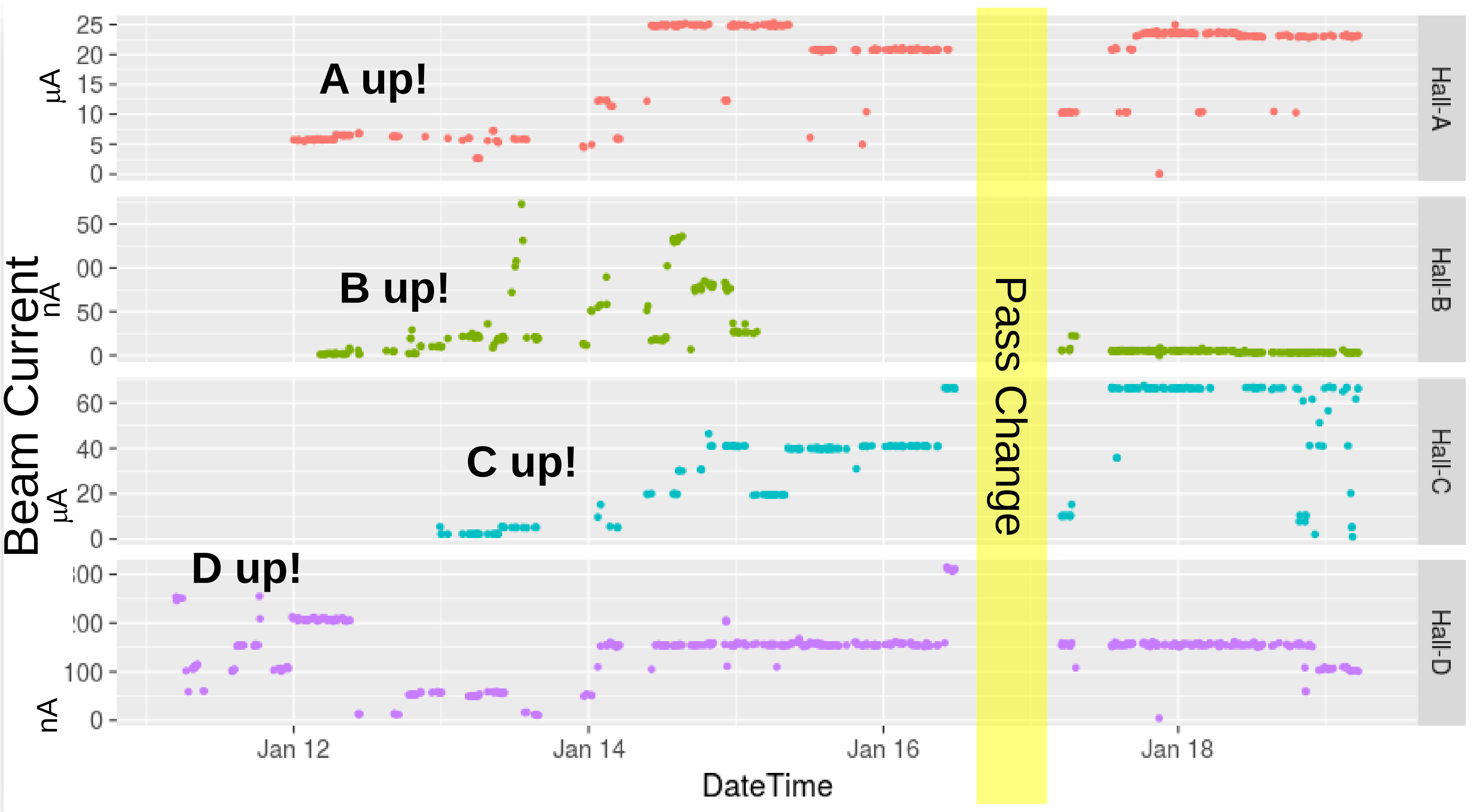




Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10^{35}	energy reach	
polarized photons	hermeticity	precision	
E_γ~8.5-9 GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent moment	
high multiplicity reconstruction		luminosity u	
particle ID			



INITIATED FOUR HALL OPERATION



Simultaneous 4-Hall Beam Delivery since Jan 18, 2018

Now operating total 900 kW CW beam power to 4 Halls

QCD

Asymptotic Freedom

Small Distance
High Energy

Confinement

Large Distance
Low Energy

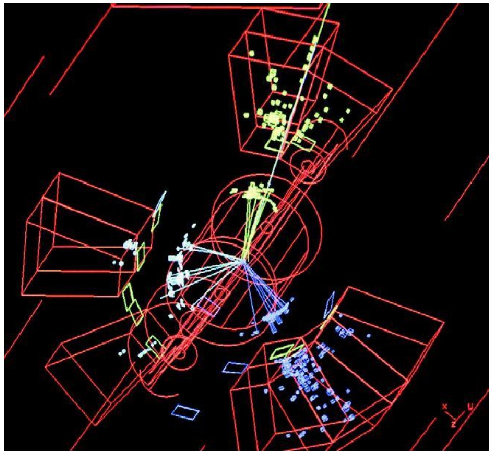
Perturbative QCD

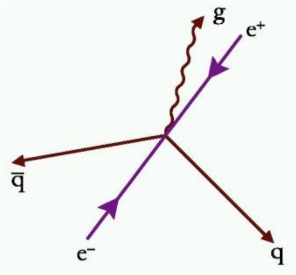
High Energy Scattering

no signature of gluons???

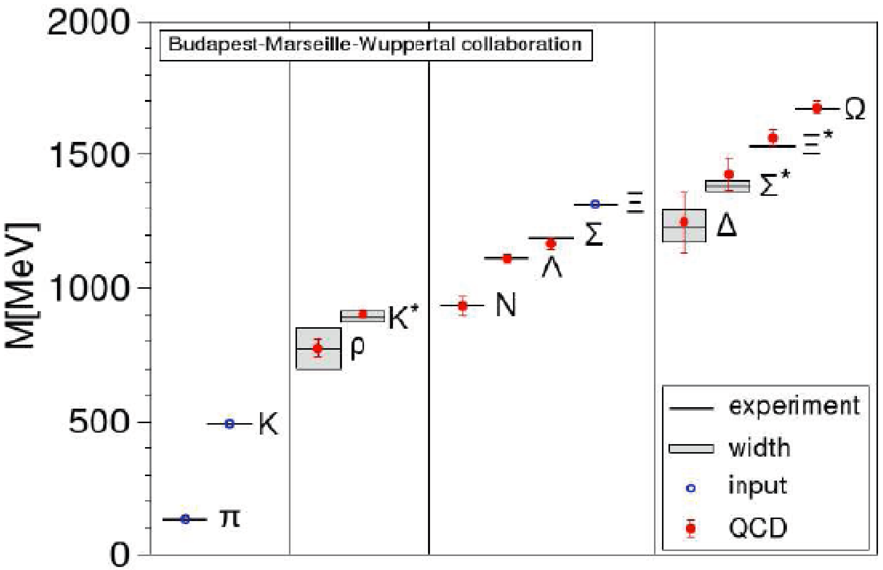
Strong QCD

Hadron Spectrum



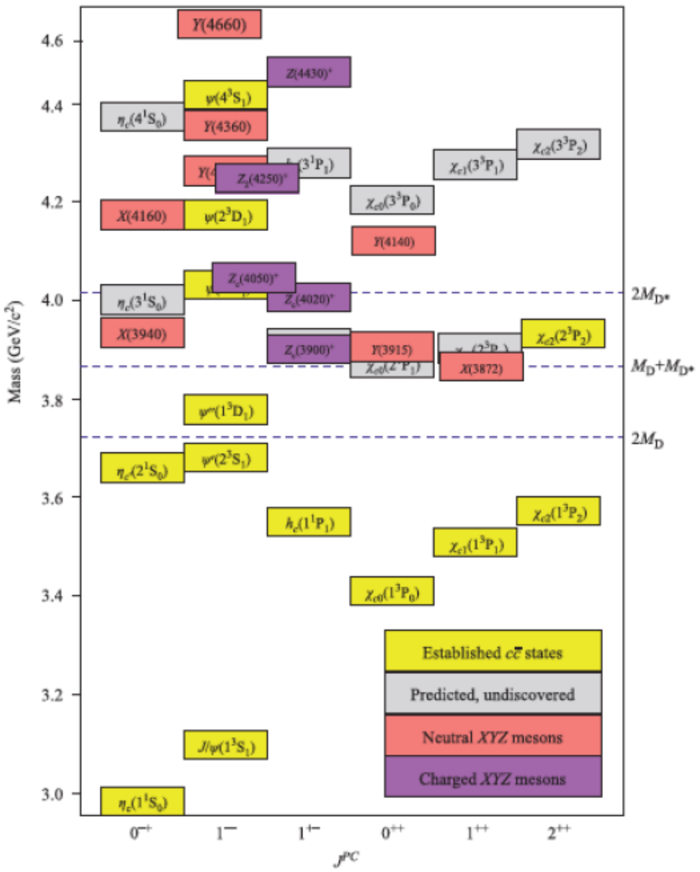


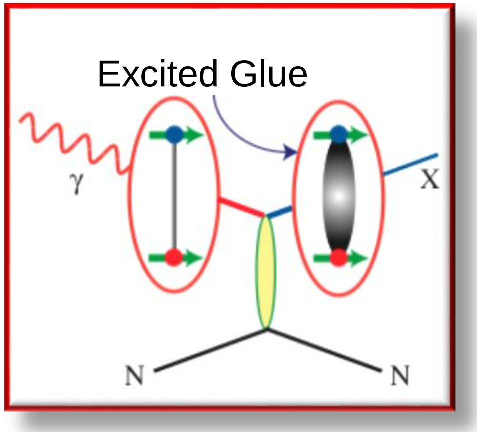
Gluon Jets Observed



Hadron Spectroscopy in the 21st Century

**Heavy quarks:
XYZ states in the charmonium sector**



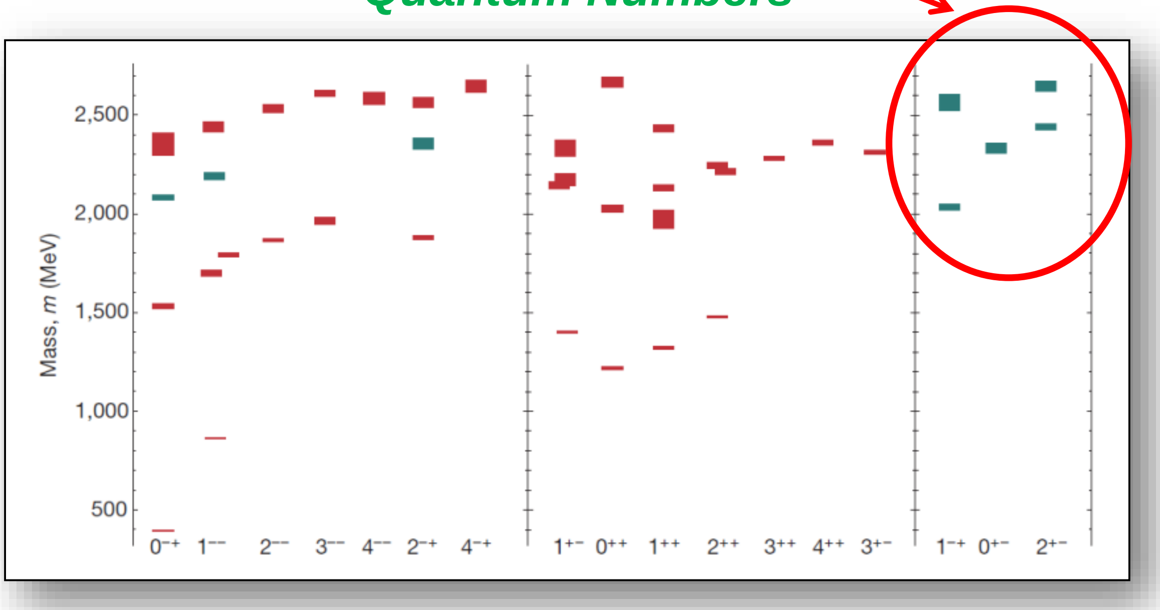


nature International weekly journal of science

Searching for the rules that govern hadron construction

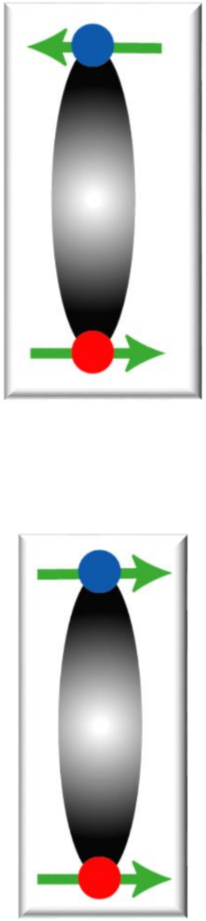
M. R. Shepherd, J. J. Dudek, R. E. Mitchell

States with Exotic Quantum Numbers



MESON SPECTROSCOPY: THE FUTURE

Quarks ⊕ **Excited Gluon Field** → **Hybrid Meson**



$S = 0$

$L = 0$

$J^{PC} = 0^{-+}$

like π, K

$$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$$

$$J^{PC} = \begin{cases} 1^{--} \\ 1^{++} \end{cases}$$

$S = 1$

$L = 0$

$J^{PC} = 1^{--}$

like γ, ρ

$$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$$

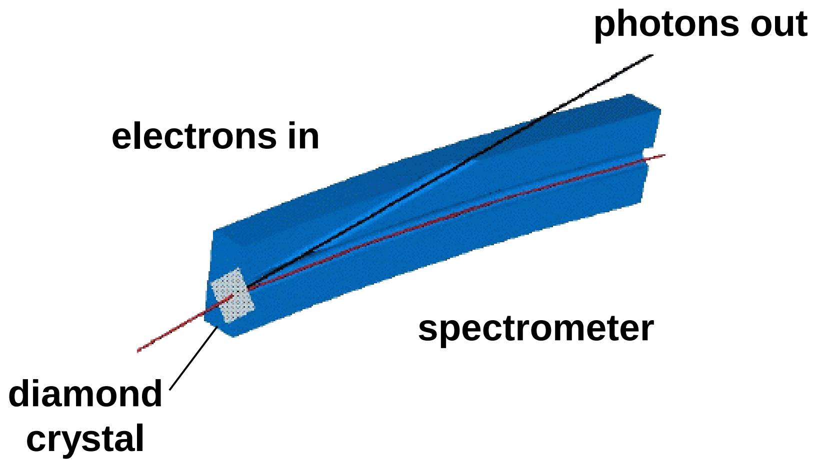
Exotic

$$J^{PC} = \begin{cases} 0^{-+} \quad \boxed{1^{-+}} \quad 2^{-+} \\ \boxed{0^{+-}} \quad 1^{+-} \quad \boxed{2^{+-}} \end{cases}$$

Gluonic excitation (and parallel quark spins) lead to exotic J^{PC}

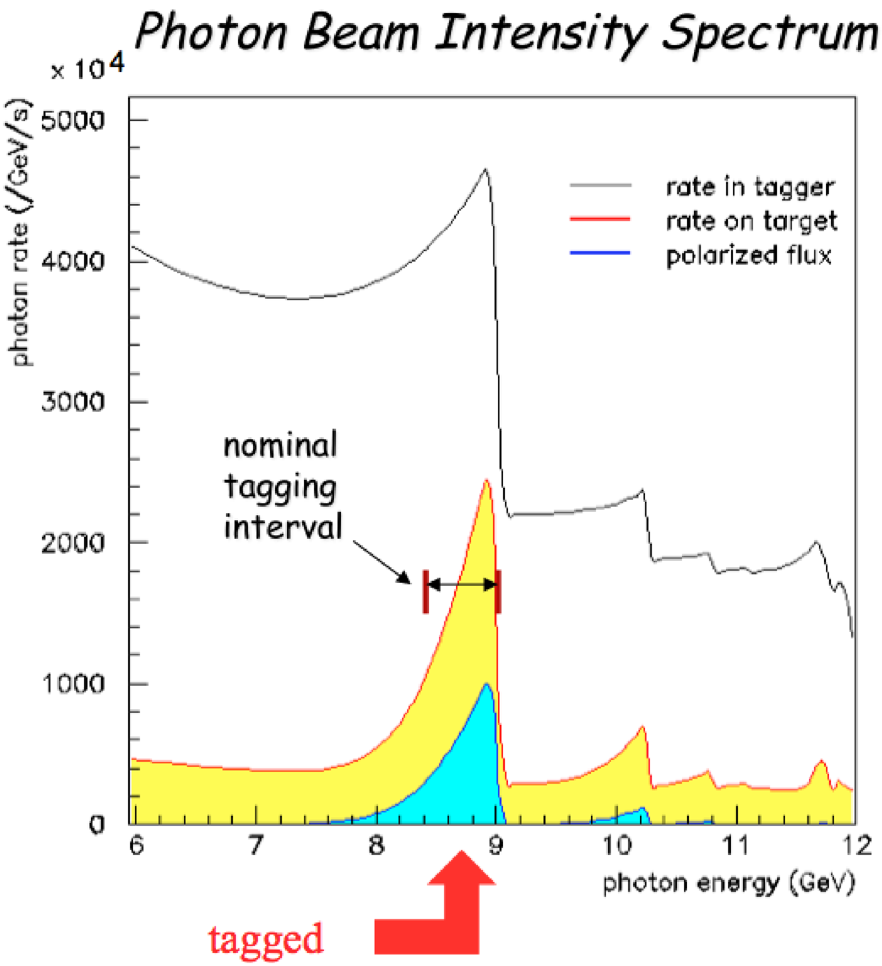
HALL D STRATEGY: COHERENT BREMSSTRAHLUNG

- Use 8-9 GeV polarized photons (12 GeV electron beam)
- Use hermetic detector with large acceptance
- Perform amplitude analysis



This technique provides requisite energy, flux and polarization

(gain of 10,000 versus existing photo-production data)



tagged

$\delta E/E = 0.1\%$

Pol = 40%

photon energy (GeV)

Gluonic Excitations and the mechanism for confinement

QCD predicts a rich spectrum of as yet to be discovered gluonic excitations - whose experimental verification is crucial for our understanding of QCD in the confinement regime.

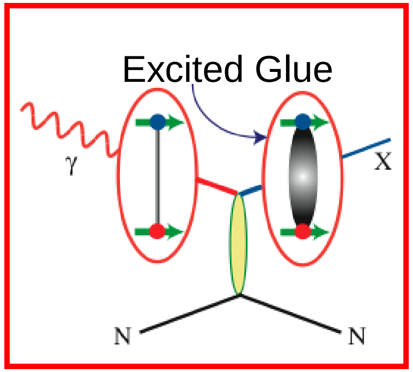
With the upgraded CEBAF, a linearly polarized photon beam, and the **GlueX detector**, Jefferson Lab will be uniquely poised to:

- discover these states
- map out their spectrum
- measure their properties

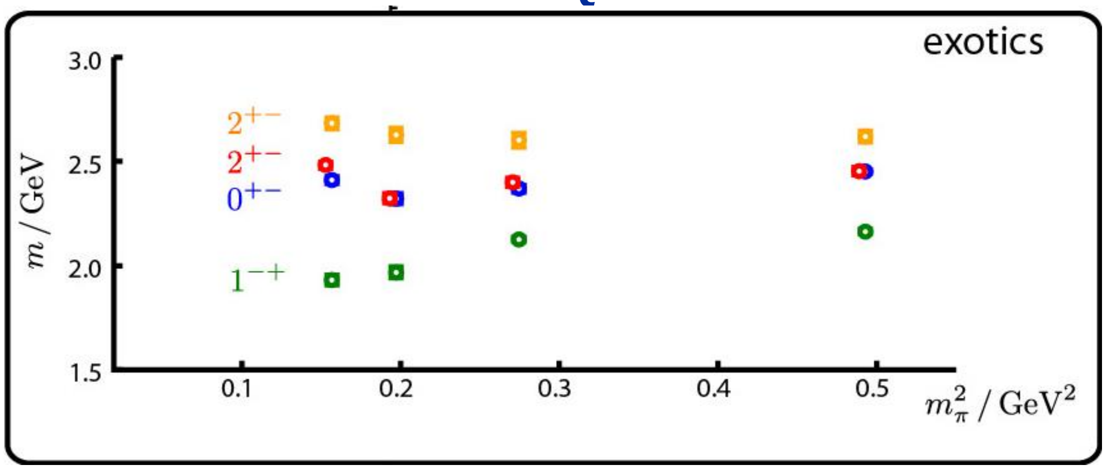
12 GeV electrons

States with Exotic Quantum Numbers

γ beam



Dudek et al.

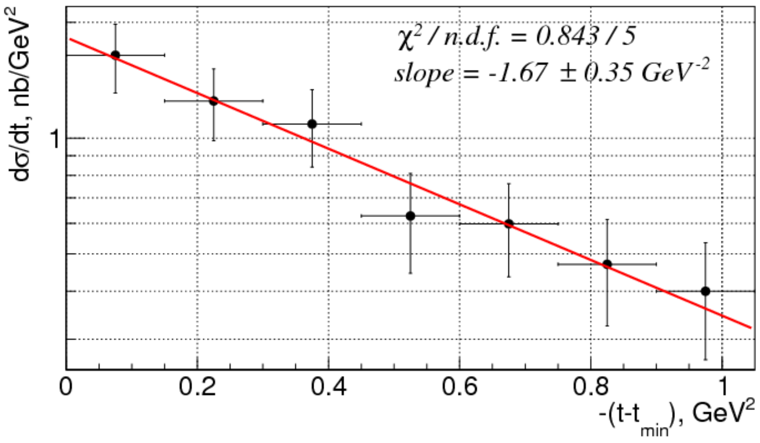


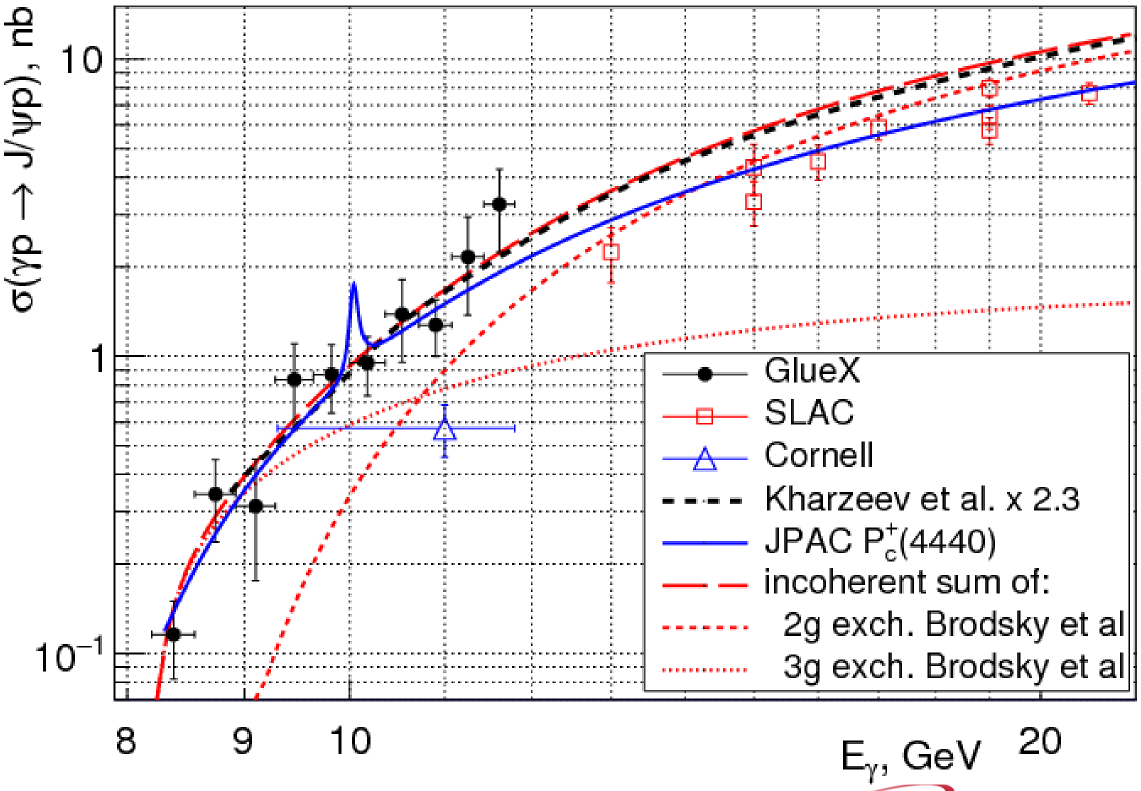
DIRC-based Cherenkov will allow access to decay channels with charged kaons

J/Ψ PHOTOPRODUCTION NEAR THRESHOLD

GlueX Collaboration, A.Ali *et al* “First Measurement of near-threshold J/ψ exclusive photoproduction off the proton” arXiv:1905.10811 (May 2019)

- Probes gluonic field in the nucleon: measured cross section is larger than expected
  - Already cited by: Y.Hatta et al arXiv:1906.00894 – calculation involving the “trace anomaly” related to the gluonic contribution to the proton mass
- Limits on the LHCb pentaquark BR to J/ψp of about 2% at 90%CL
  - Already cited by: M.Voloshin arXiv:1905.13156 : Interpretation of the XYZ states



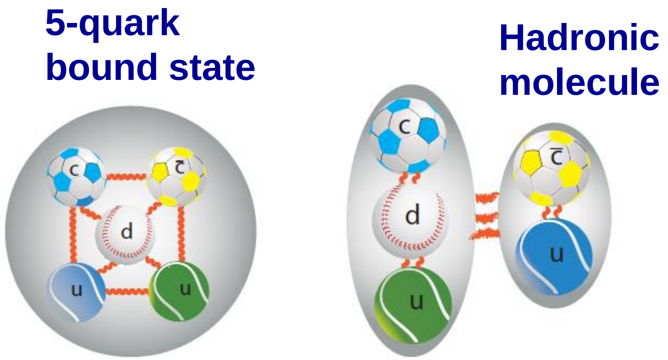


FY19 HALLS C & B – NATURE OF CHARMED PENTAQUARK

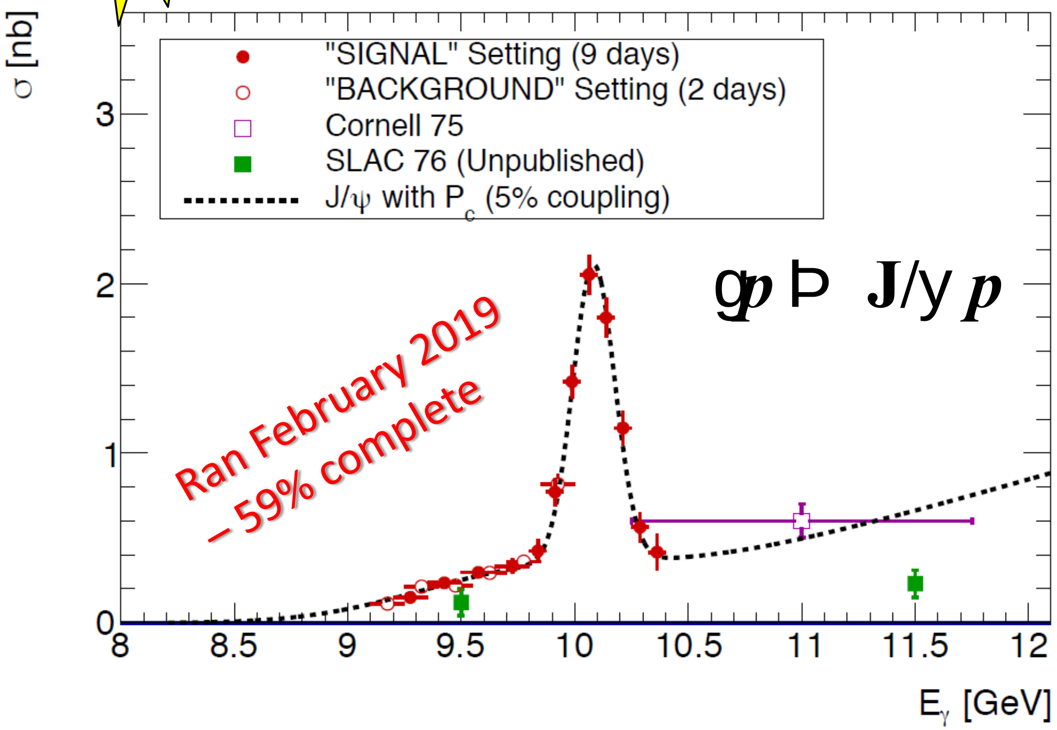
What is the exact nature of the *charmed pentaquark* states discovered by the LHCb collaboration at CERN?

P_c Þ $J/y\ p$

high impact

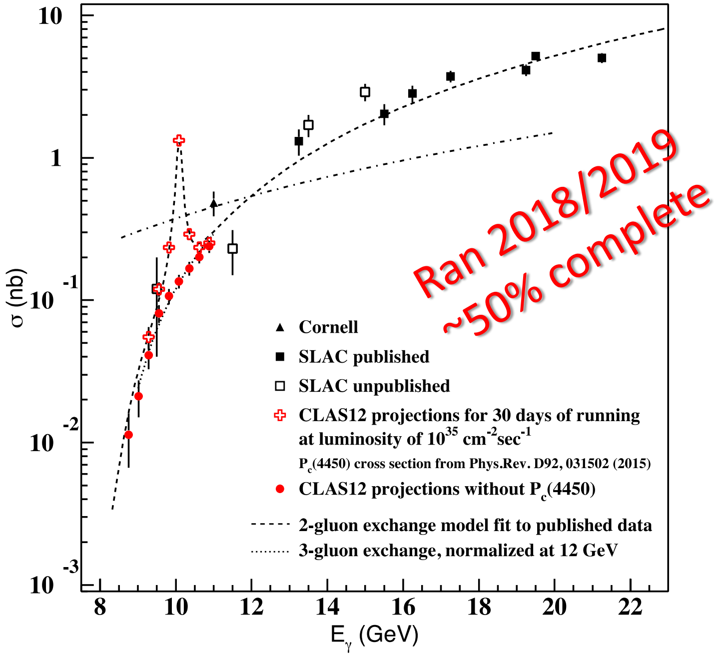


Hall C



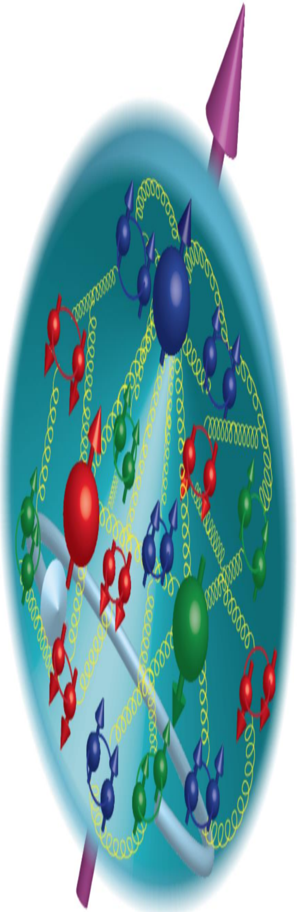
Ran February 2019
– 59% complete

Hall B



Ran 2018/2019
~50% complete

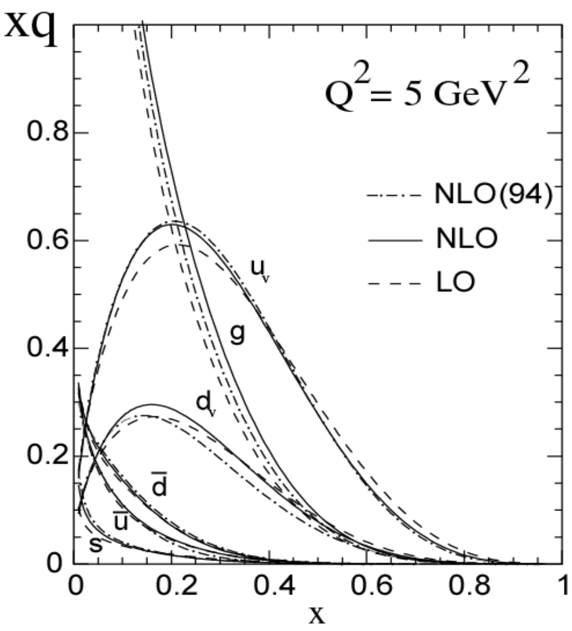
Proton Viewed in High Energy Electron Scattering:
1 Longitudinal Dimension



MEASURING HIGH-X STRUCTURE FUNCTIONS

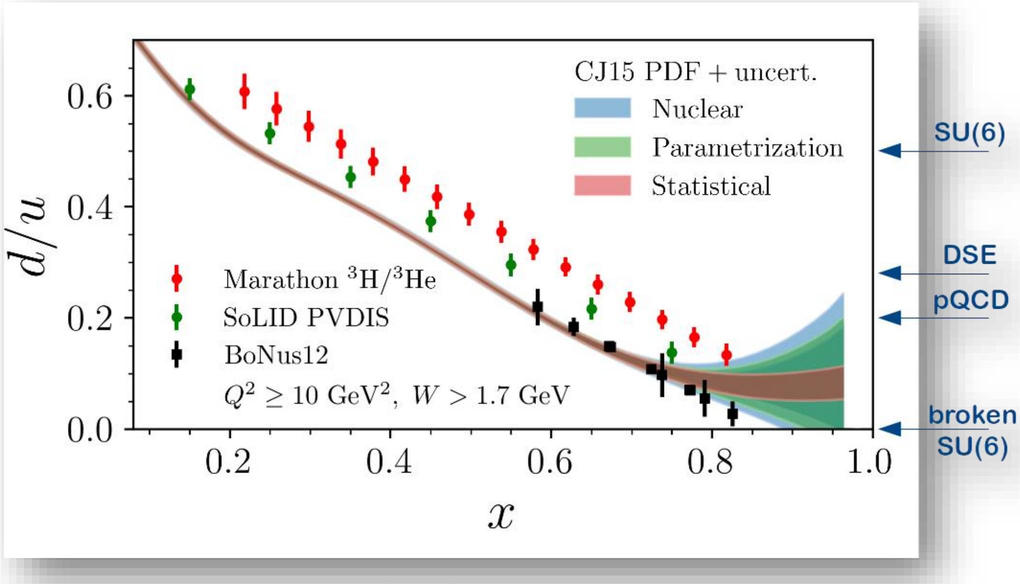
REQUIRES:

- High beam polarization
- High electron current
- High target polarization
- Large solid angle spectrometers



12 GeV will access the regime (x > 0.3), where valence quarks dominate

Projected JLab 12 GeV *d/u* Extraction



Marathon ^{3}H/^{3}He completed!

x →1 predictions	**F_2^n/F_2^p**	**d/u**	**A_1^n**	**A_1^p**
SU(6)	**2/3**	**1/2**	**0**	**5/9**
Diquark Model/Feynman	**1/4**	**0**	**1**	**1**
Quark Model/Isgur	**1/4**	**0**	**1**	**1**
Perturbative QCD	**3/7**	**1/5**	**1**	**1**
QCD Counting Rules	**3/7**	**1/5**	**1**	**1**

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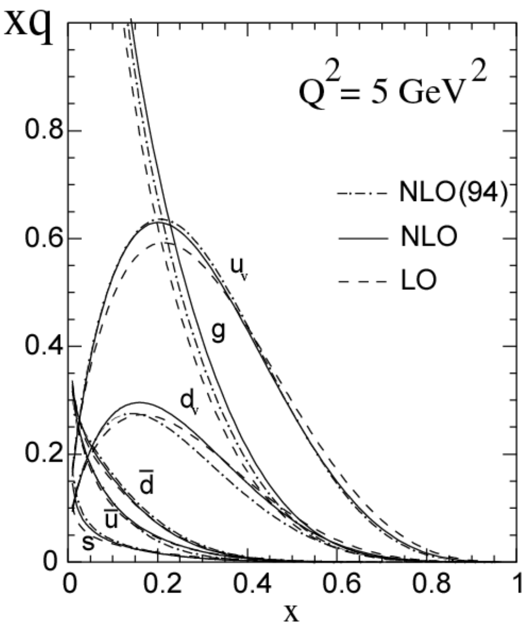
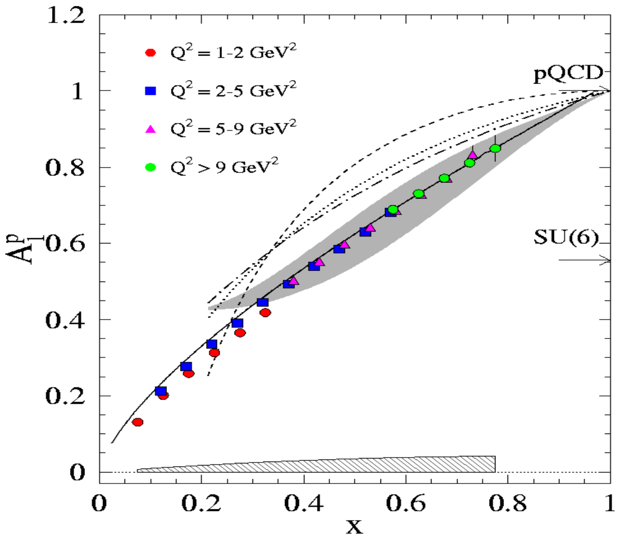
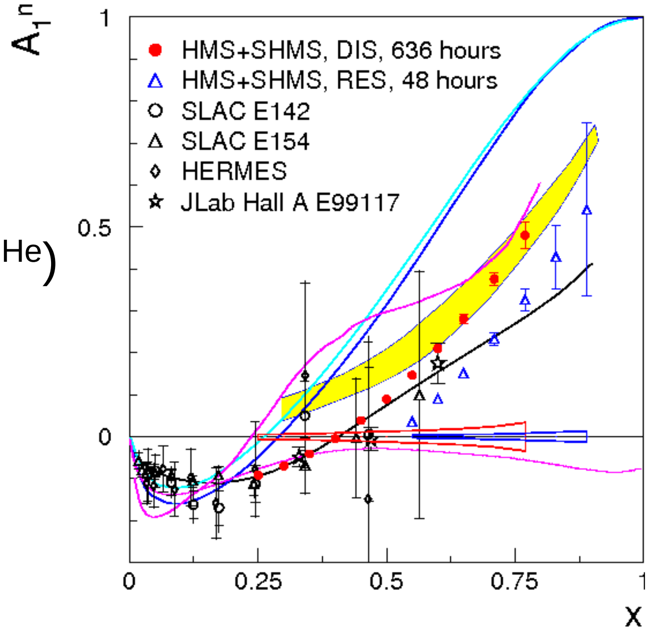


12 GeV will access the regime (x > 0.3), where valence quarks dominate

Hall B: A_1^p
(and A_1^d)



Hall C: A_1^n
(from A_1^{3He})



MEASURING HIGH-X STRUCTURE FUNCTIONS

REQUIRES:

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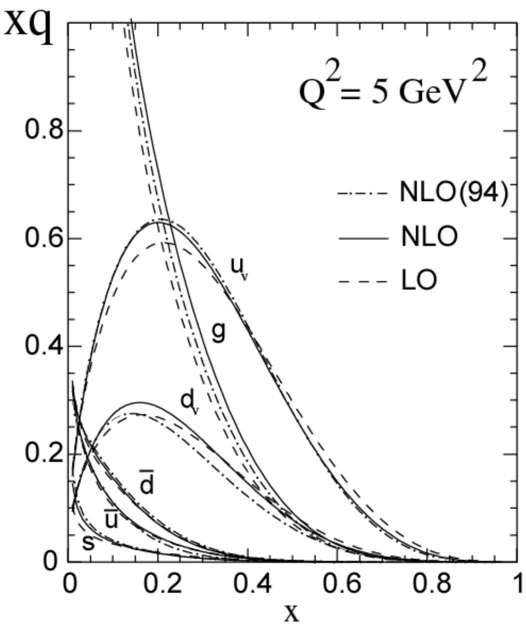
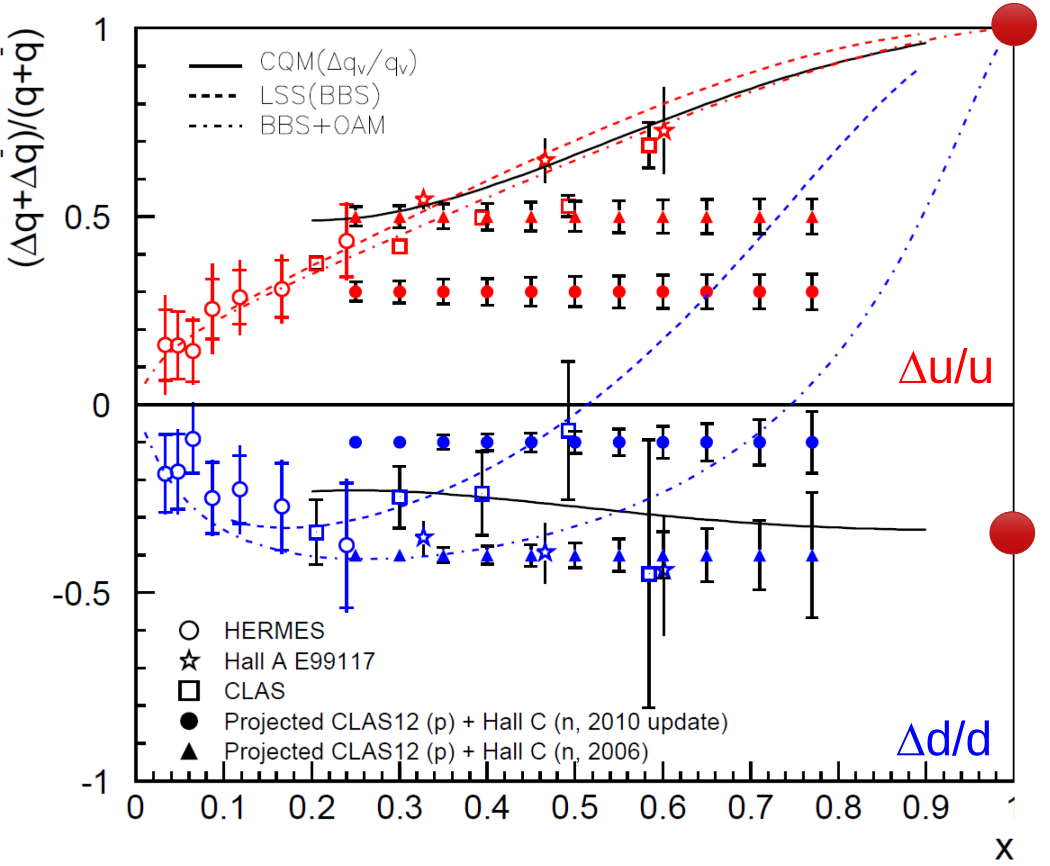


12 GeV will access the regime (x > 0.3), where valence quarks dominate

Combine Hall B A_1^p and Hall C A_1^n

→ extract Δu/u and Δd/d

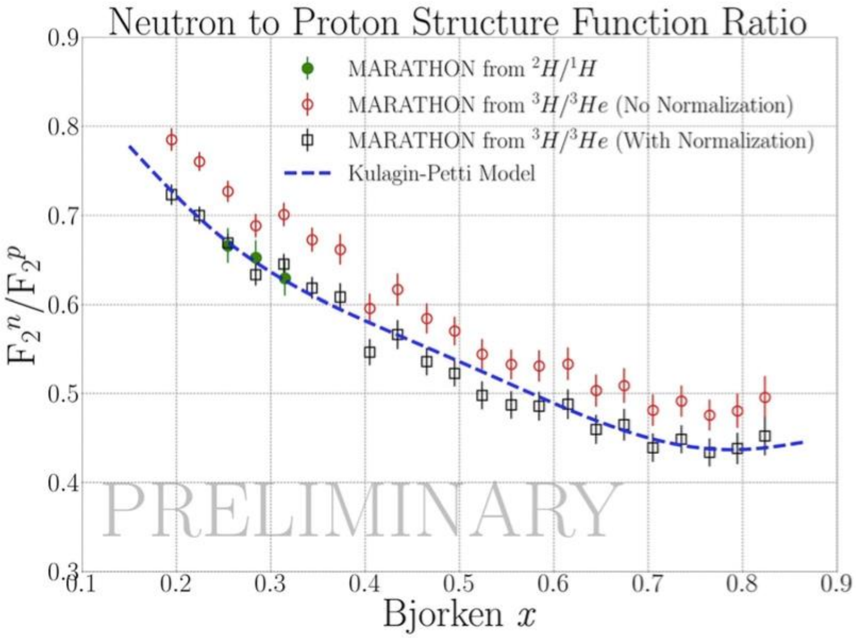
(constrained by knowledge of A_1^n → requires polarized ^{3}He performance!)

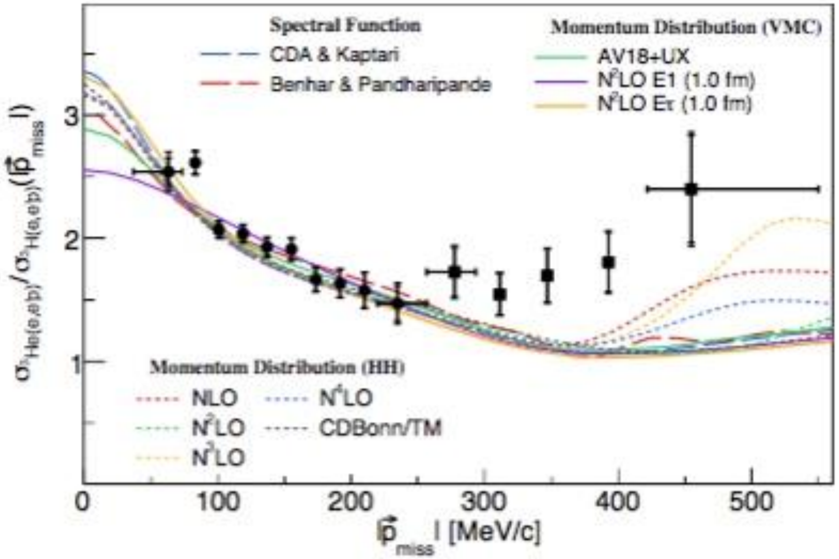


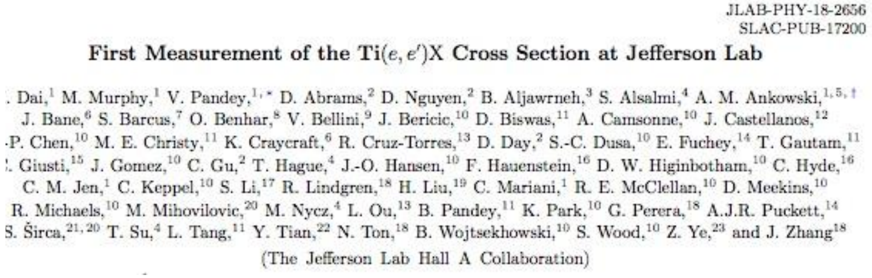
HALL A TRITIUM (and Argon) RUNNING COMPLETED

First tritium target used for electron scattering in three decades!

MARATHON preliminary results presented at April 2019 APS in Denver







JLAB-PHY-18-2656
SLAC-PUB-17200

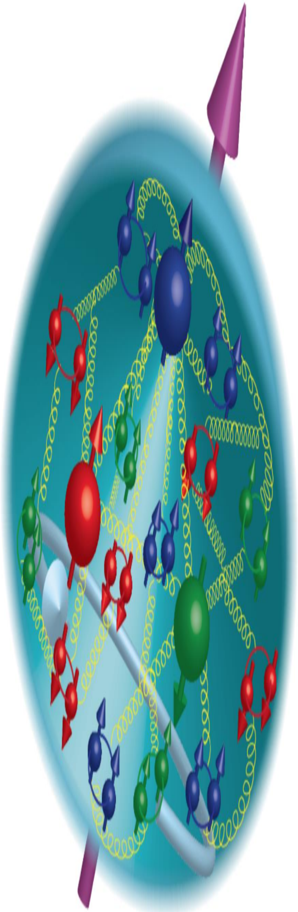
First Measurement of the Ti(e,e')X Cross Section at Jefferson Lab

Dai,[1] M. Murphy,[1] V. Pandey,[1,*] D. Abrams,[2] D. Nguyen,[2] B. Aljawrneh,[3] S. Alsalmi,[4] A. M. Ankowski,[1,5,†]
J. Bane,[6] S. Barcus,[7] O. Benhar,[8] V. Bellini,[9] J. Bericic,[10] D. Biswas,[11] A. Camsonne,[10] J. Castellanos,[12]
P. Chen,[10] M. E. Christy,[11] K. Craycraft,[6] R. Cruz-Torres,[13] D. Day,[2] S.-C. Dusa,[10] E. Fuchey,[14] T. Gautam,[11]
Giusti,[15] J. Gomez,[10] C. Gu,[2] T. Hague,[4] J.-O. Hansen,[10] F. Hauenstein,[16] D. W. Higinbotham,[10] C. Hyde,[16]
C. M. Jen,[1] C. Keppel,[10] S. Li,[17] R. Lindgren,[18] H. Liu,[19] C. Mariani,[1] R. E. McClellan,[10] D. Meekins,[10]
R. Michaels,[10] M. Mihovilovic,[20] M. Nycz,[4] L. Ou,[13] B. Pandey,[11] K. Park,[10] G. Perera,[18] A.J.R. Puckett,[14]
S. Širca,[21,20] T. Su,[4] L. Tang,[11] Y. Tian,[22] N. Ton,[18] B. Wojtsekhowski,[10] S. Wood,[10] Z. Ye,[23] and J. Zhang[18]
(The Jefferson Lab Hall A Collaboration)

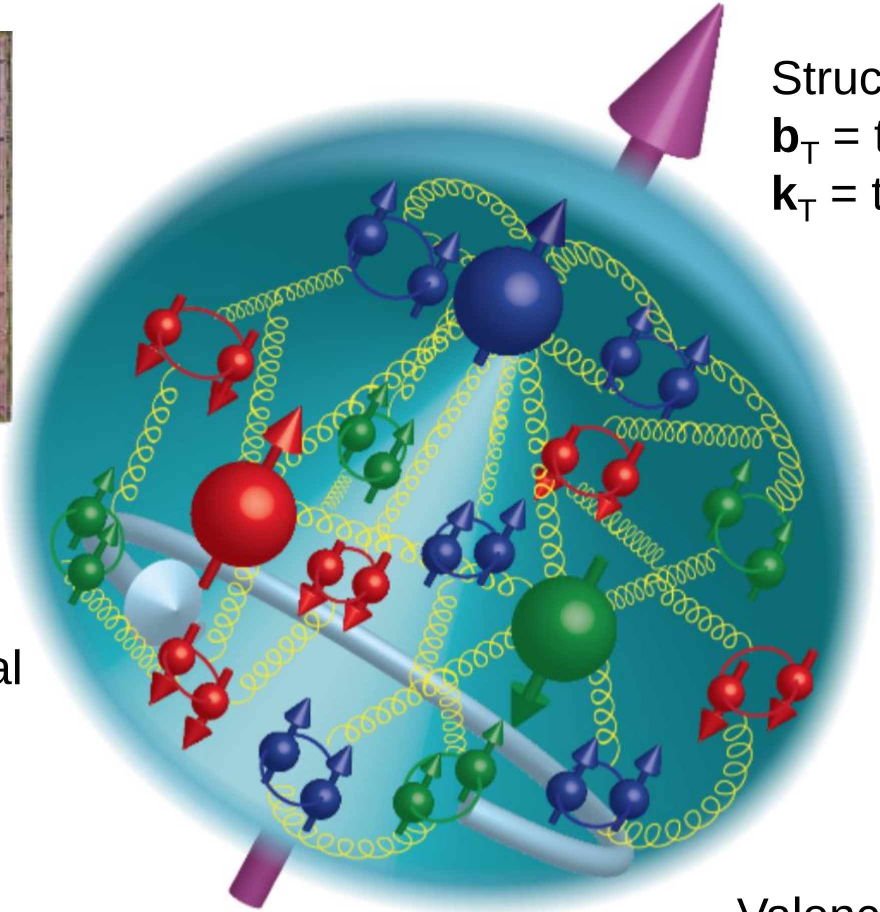
Phys. Rev. C 98 (2018) no.1, 014617
Phys.Rev. C99 (2019) no.5, 054608

Short Range Correlation (e.e'p) publication *submitted*, arXiv:1902.06358v1

Proton Viewed in High Energy Electron Scattering: 1 Longitudinal Dimension



Proton Tomography: 2 New Dimensions Transverse to Longitudinal Momentum



Structure mapped in terms of
b$_T$ = transverse position
k$_T$ = transverse momentum

Nuclei!

Goal:
Unprecedented
21st Century Imaging
of Hadronic Matter

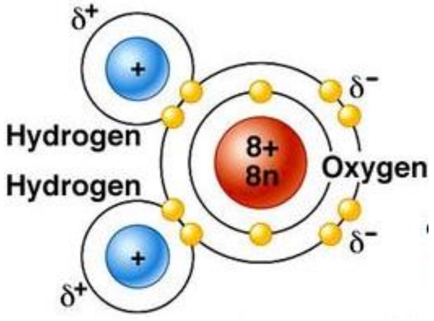
Direction of longitudinal momentum normal to plane of slide

Valence Quarks: JLab 12 GeV
Sea Quarks and Gluons: EIC

Nuclear Femtography – Subatomic Matter is Unique

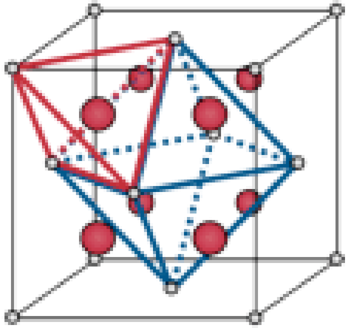
- ☐ Localized mass and charge centers – vast “open” space:

Molecule:



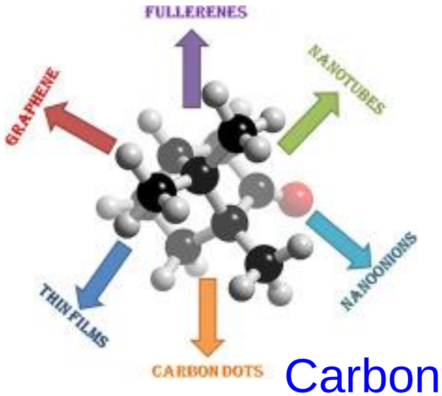
“Water”

Crystal:



Rare-Earth metal

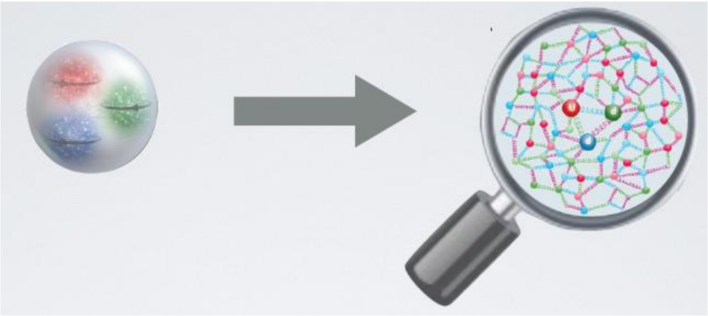
Nanomaterial:



Carbon-based

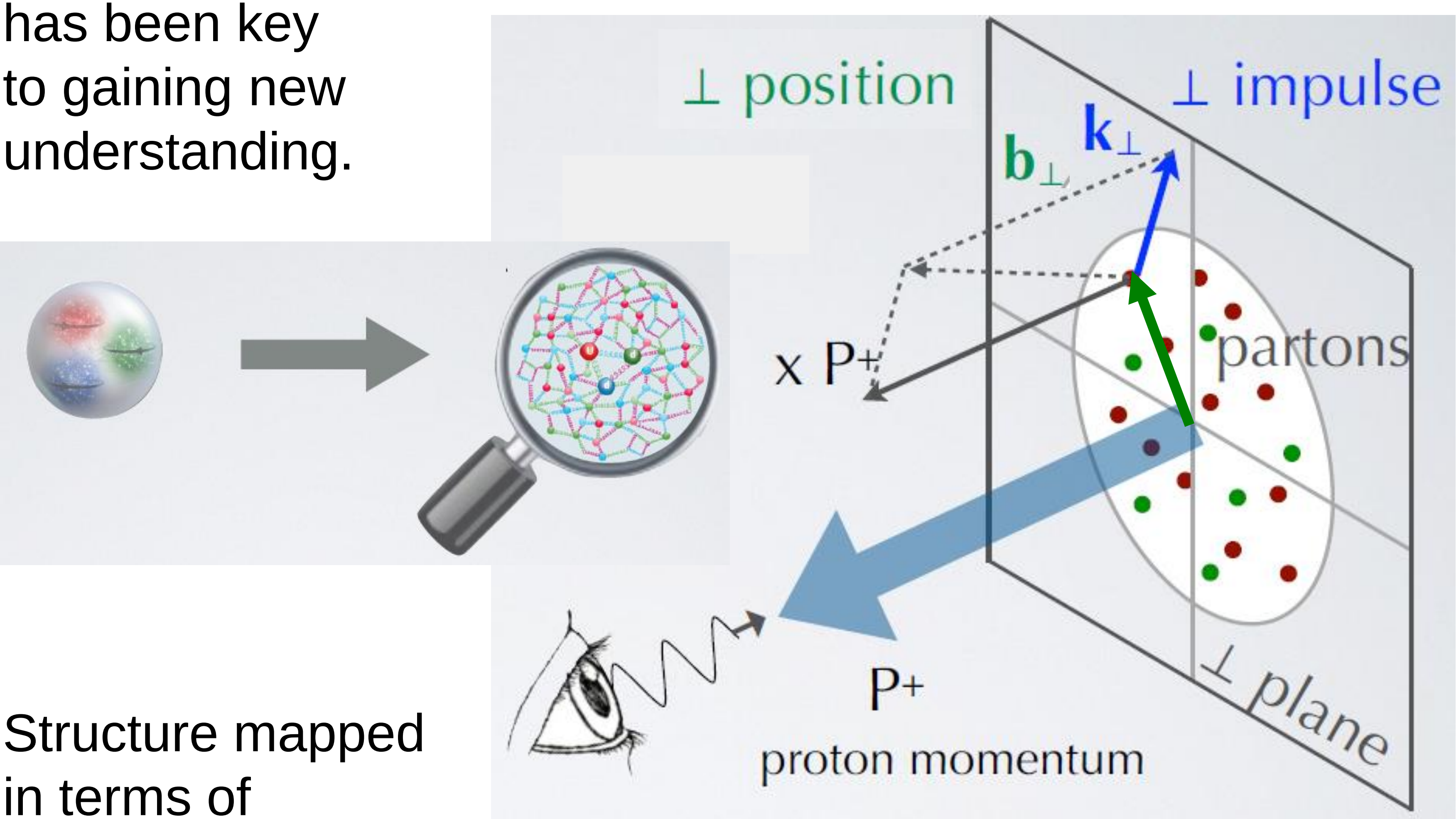
Interactions and structure are mixed up in nuclear matter: Nuclear matter is made of quarks that are bound by gluons that also bind themselves. Unlike with the more familiar atomic and molecular matter, the interactions and structures are inextricably mixed up, and the observed properties of nucleons and nuclei, such as mass & spin, emerge out of this complex system.

- ☐ Not so in proton structure!



Nuclear Femtography - Imaging

In other sciences, imaging the physical systems under study has been key to gaining new understanding.



Structure mapped in terms of

b_T = transverse position

k_T = transverse momentum

Exploring the 3D Nucleon Structure

- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction (x_{Bj}) picture of the nucleon.
  - High luminosity, large acceptance experiments with polarized beams and targets.
  - Theoretical description of the nucleon in terms of a 5D Wigner distribution that can be used to encode both 3D momentum and transverse spatial distributions.

- **Deep Exclusive Scattering (DES)** cross sections give sensitivity to electron-quark scattering off quarks with longitudinal momentum fraction (Bjorken) x at a transverse location b.

- **Semi-Inclusive Deep Inelastic Scattering (SIDIS)** cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum (k_T) of a parton and transverse momentum (p_T) created during the [parton → hadron] fragmentation process.

Nuclear Femtography

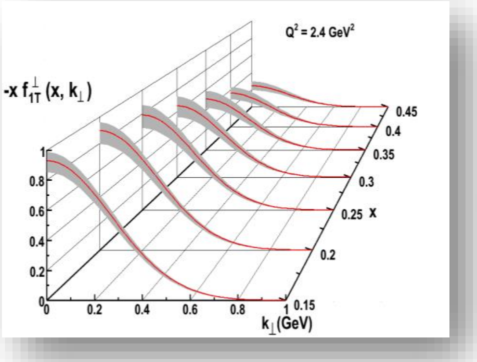
3D IMAGING OF THE NUCLEON

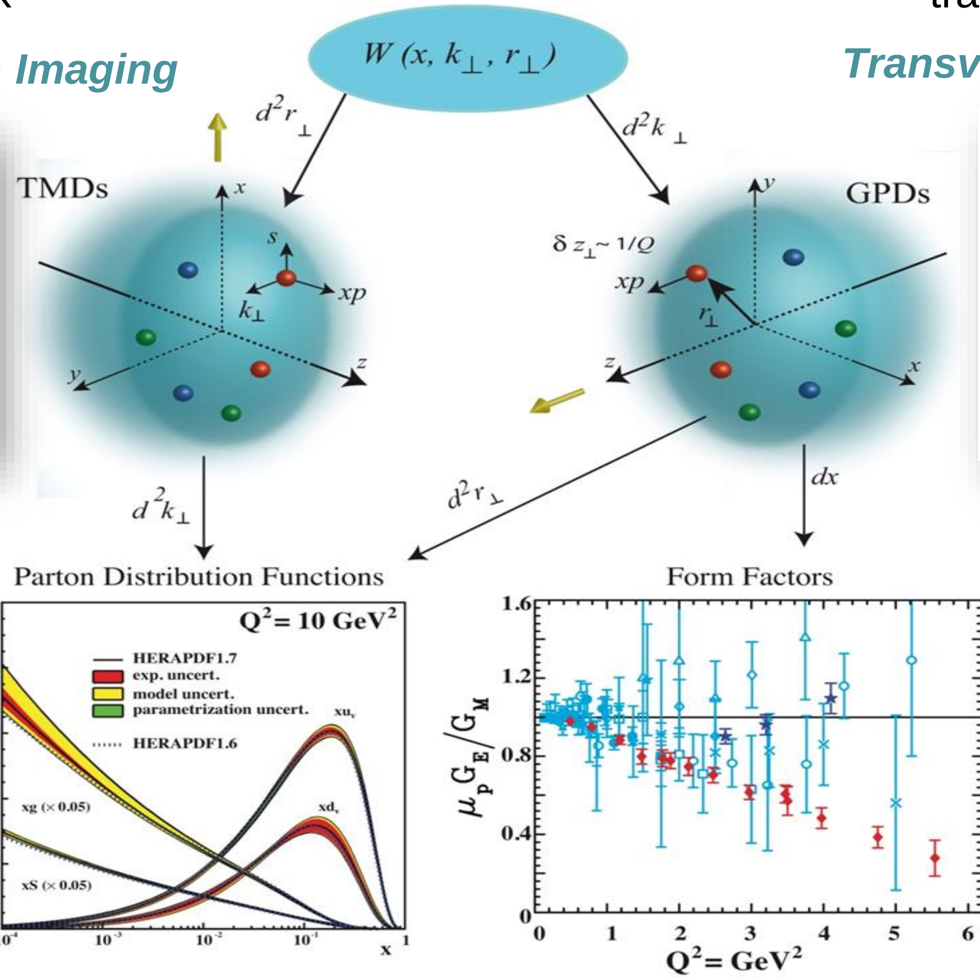
TMDs: Longitudinal momentum fraction x and transverse momentum k

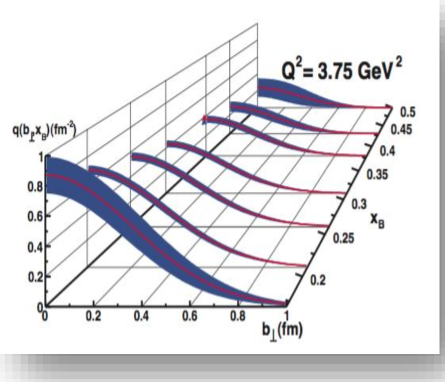
GPDs: Longitudinal momentum fraction x at transverse location b

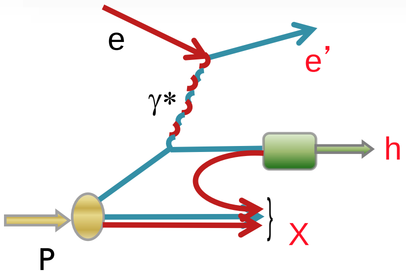
Transverse Momentum Imaging

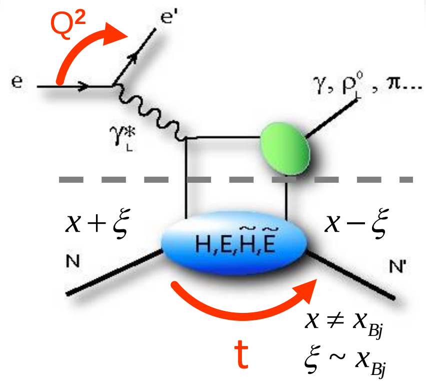
Transverse Spatial Imaging



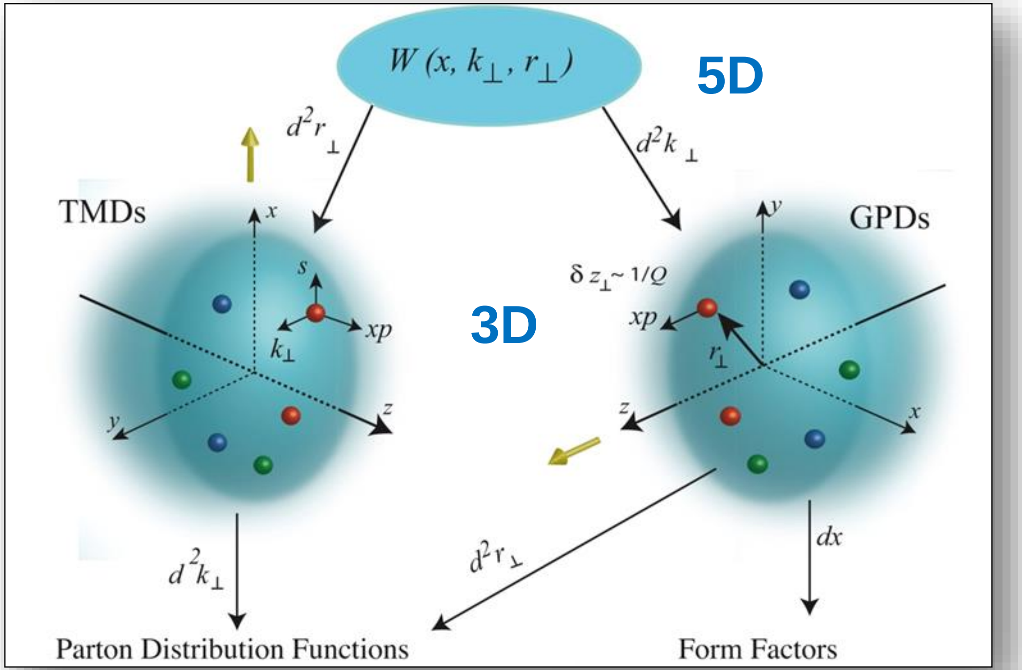


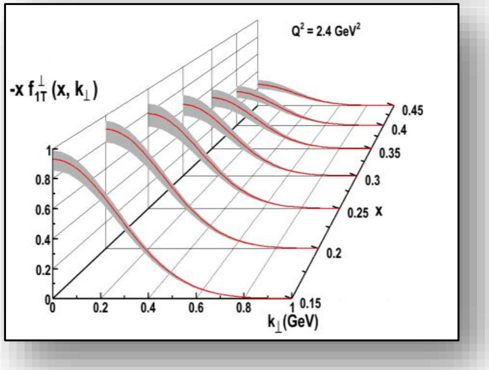


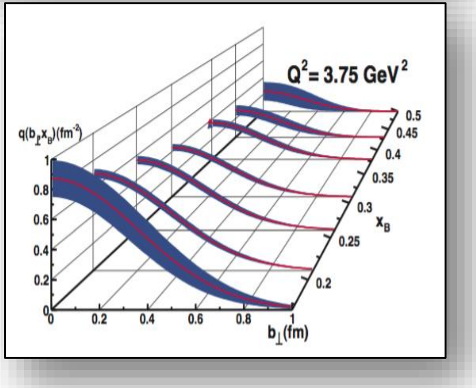




New Paradigm for Nucleon Structure







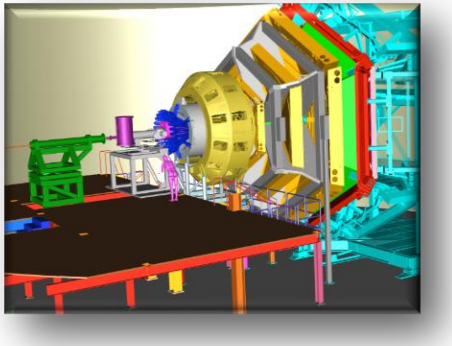
- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- GPDs
  - Spatial imaging (exclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets
  - Sophisticated detector systems

Major new capability with JLab12

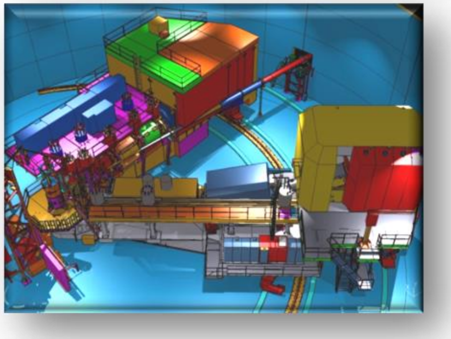
3D Imaging With JLab @ 12 GeV

Generalized Parton Distributions (GPDs) and Transverse Momentum Distributions (TMDs)

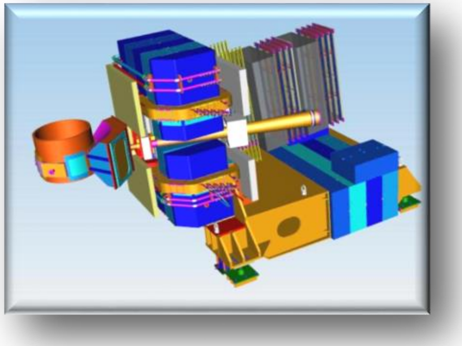
- CEBAF Large Acceptance Spectrometer (CLAS12) in Hall B: general survey experiments, large acceptance and medium luminosity



- SHMS, High Momentum Spectrometer (HMS) and Neutral-Particle Spectrometer (NPS) in Hall C: precision cross sections for L-T studies and ratios, small acceptance and high luminosity



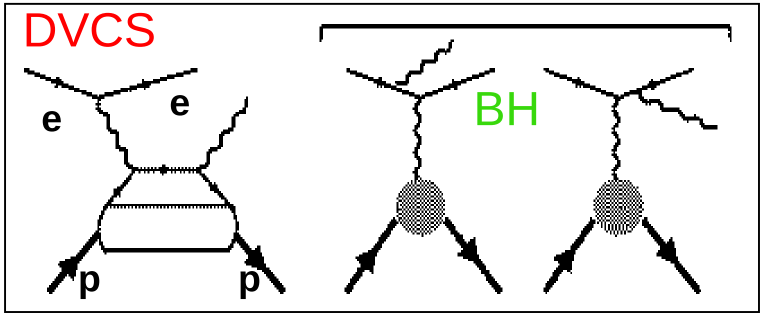
- Super Bigbite Spectrometer (SBS) in Hall A : dedicated large-x TMD study
medium acceptance and high luminosity



- Future: Solenoidal Large Intensity Device (SoLID) in Hall A: large acceptance and high luminosity

TOWARDS THE 3D STRUCTURE OF THE PROTON

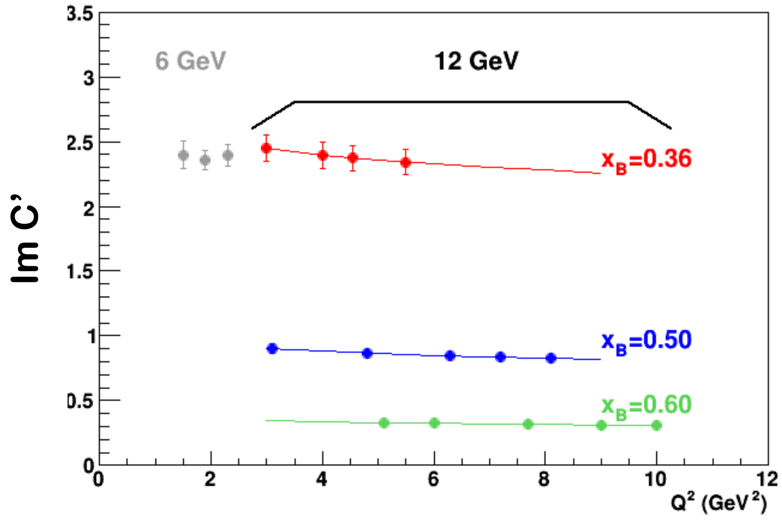
Simplest process: **e + p → e' + p + γ (DVCS)**



- Polarized beam, unpolarized target: $H(\xi,t)$
- Unpolarized beam, long. polarized target: $\tilde{H}(\xi,t)$
- Unpolarized beam, transv. polarized target: $E(\xi,t)$

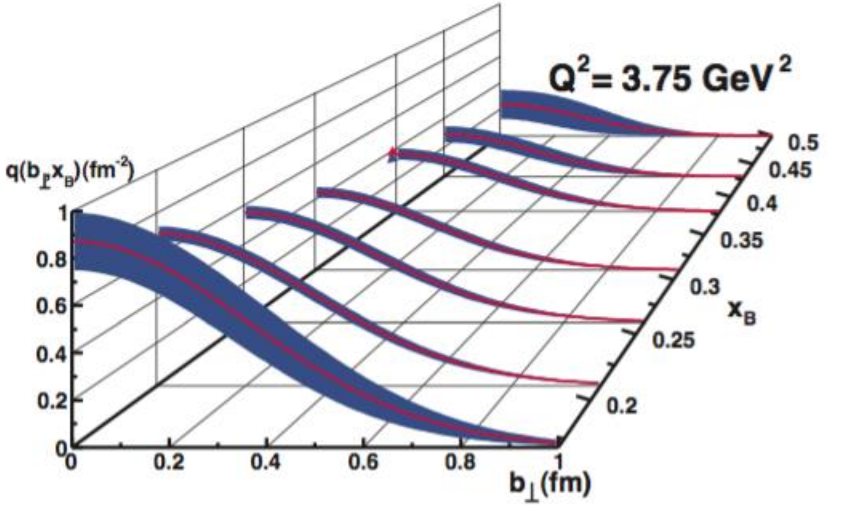
Hall A data for Compton form factor (over *limited* Q^2 range) agree with hard-scattering

12 GeV projections: confirm formalism

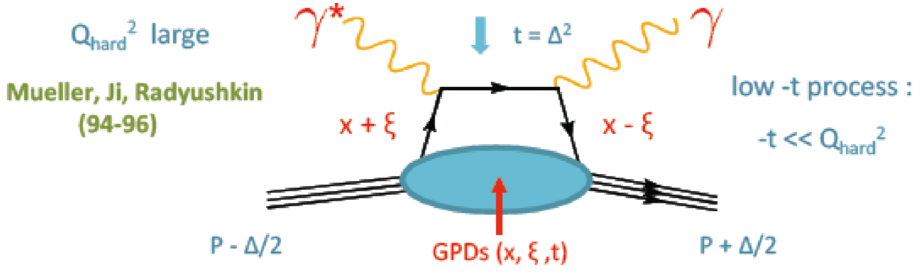


Hall B beam-spin asymmetry and cross section data show potential for imaging studies from analysis in x, Q^2 and t

12 GeV projections: transverse spatial maps

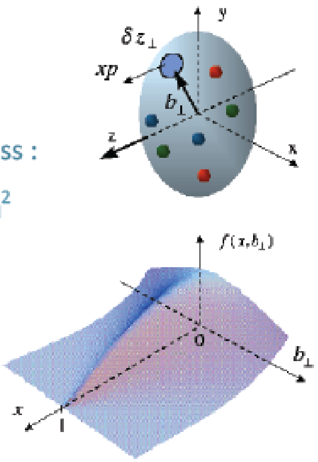


Deeply Virtual Compton Scattering @ 11 GeV



Mostly H for unpolarized proton target

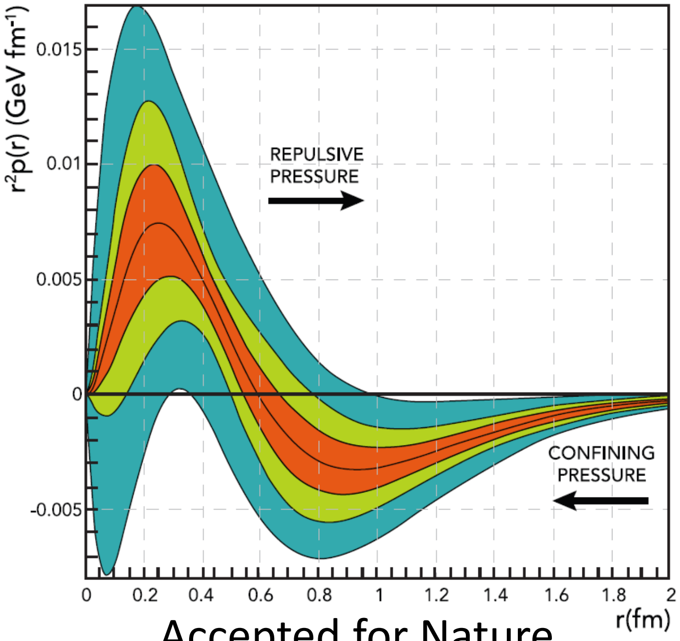
Mostly $\tilde{H}$ for polarized proton target



Hall A DVCS scaling check completed

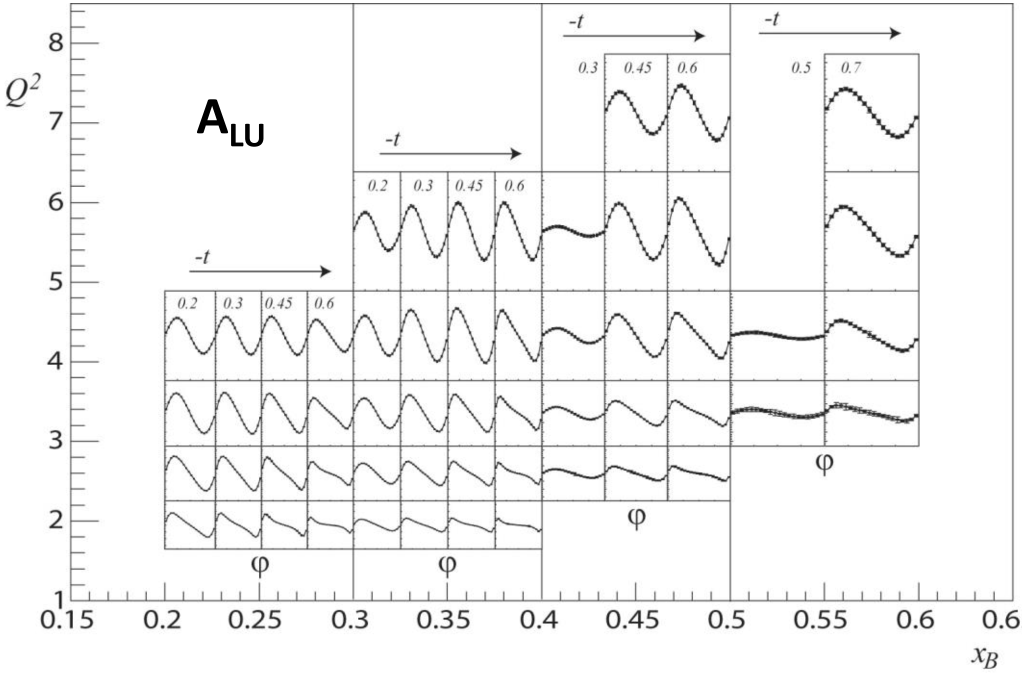
Hall B DVCS on H 50% complete

CLAS DVCS data sample at 6 GeV



Accepted for Nature

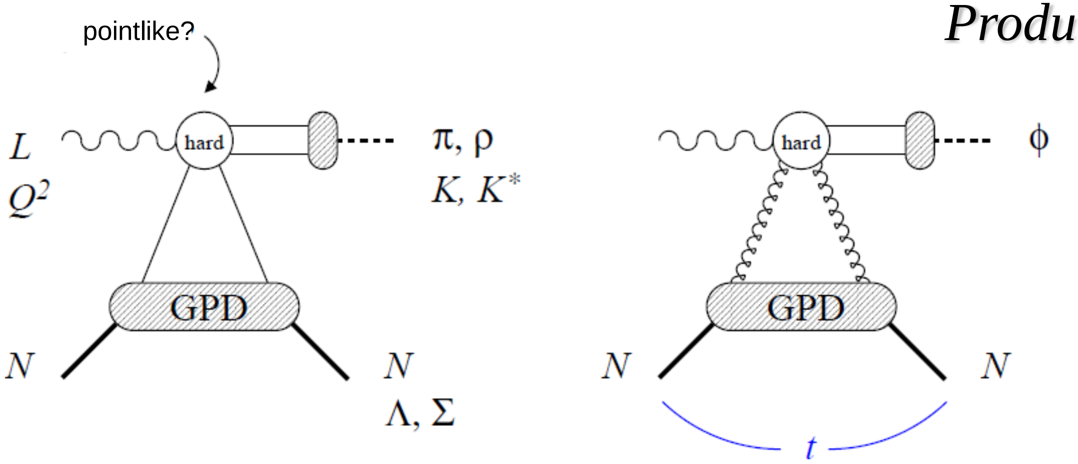
CLAS12 (projected)



TOWARDS SPIN/FLAVOR SEPARATION

Exclusive Reactions: $\gamma^* N \longrightarrow M + B$

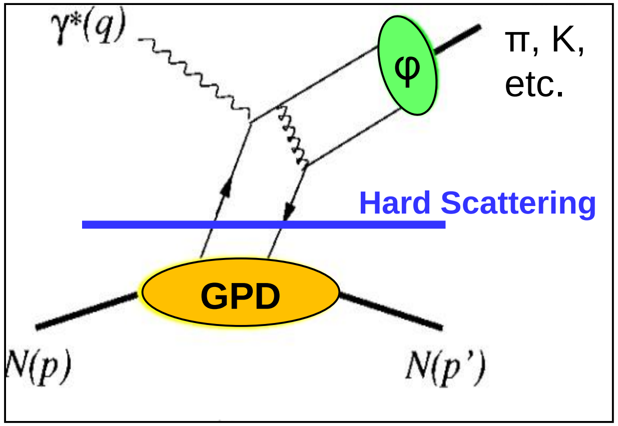
Deep Virtual Meson Production (DVMP)

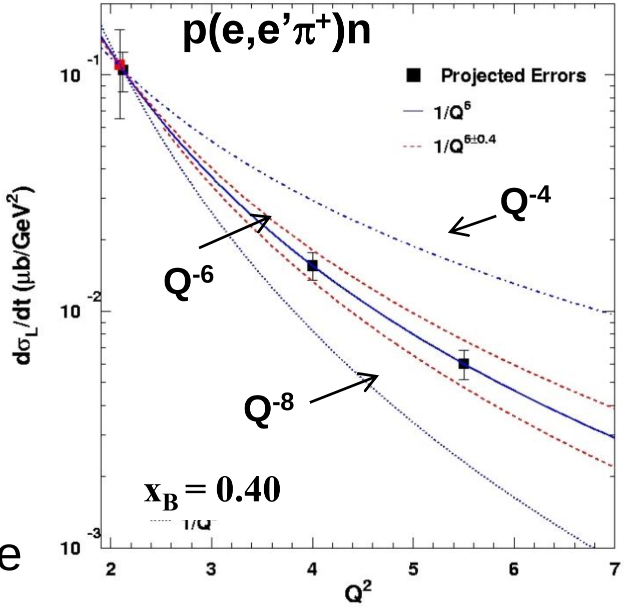


- Nucleon structure described by 4 (helicity non-flip) GPDs:
  - –*H, E* (unpolarized), ,$\tilde{H}$ $\tilde{E}$ (polarized)
- Quantum numbers in DVMP probe individual GPD components selectively
  - –Vector : $\rho^o/\rho^+/K^*$ select *H, E*
  - –Pseudoscalar: π,η,*K* select the polarized GPDs, $\tilde{H}$ and $\tilde{E}$
- Need good understanding of reaction mechanism
  - –QCD factorization for mesons
  - –Can be verified experimentally through L/T separated cross sections

Factorization Tests in π^+ and K^+ Electroproduction

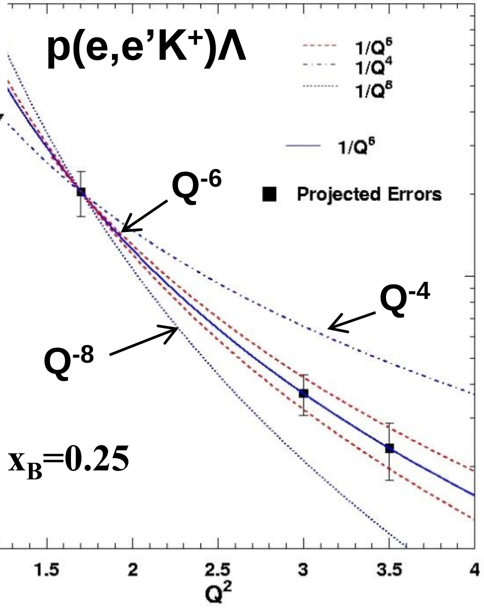
$$\sigma = \Gamma(\sigma_T + \varepsilon\sigma_L + \varepsilon\cos(2\phi)\sigma_{TT} + [\varepsilon(\varepsilon+1)/2]^{1/2}\cos(\phi)\sigma_{LT})$$





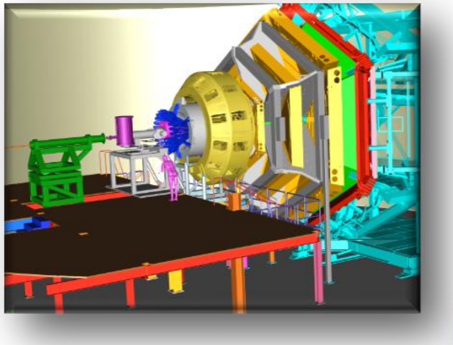
π^+: up to $Q^2 = 10$
K^+: up to $Q^2 = 6$

Fit: $1/Q^n$



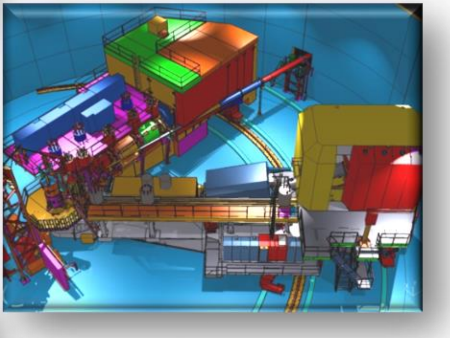
- One of the most stringent tests of factorization is the Q^2 dependence of the π and K electro-production cross section
  - σ_L scales to leading order as Q^{-6}
- Experimental validation of factorization essential for reliable interpretation of results from the JLab GPD program at 12 GeV for meson electro-production
- K and π together provide quasi model-independent study

TOGETHER STRONGER: 3D MOMENTUM IMAGING



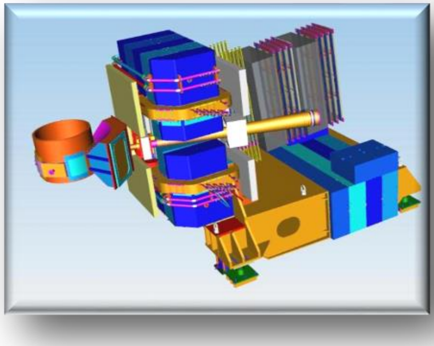
- **CLAS12 in Hall B**

  General survey, medium lumi



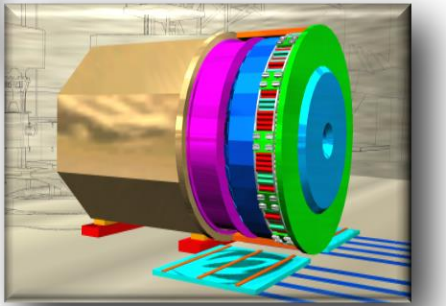
- **SHMS, HMS, NPS in Hall C**

  L-T studies, precise $\pi^+/\pi^-/\pi^0$ ratios



- **SBS in Hall A**

  High x, High Q^2, 2-3D



- **SOLID in Hall A**

  High lumi and acceptance – 4D

Features of 3D Distributions/TMDs

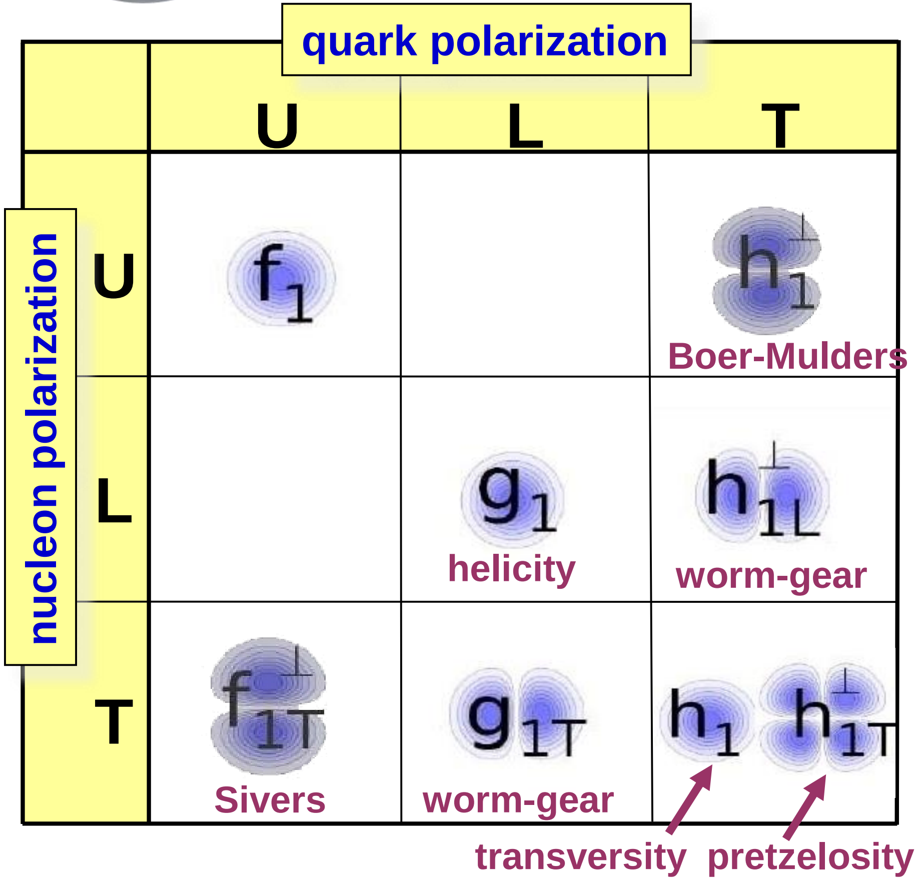
$$f^a(x, k_T^2; Q^2)$$

Ex. TMD PDF for a given combination of parton and nucleon spins

$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

↓

$$f^a(x, k_T^2; Q^2)$$

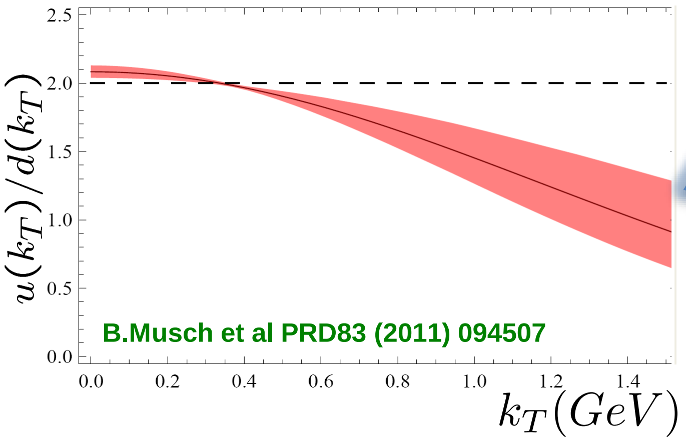


		quark polarization		
		U	L	T
nucleon polarization	U	f_1		$h_1^\perp$ Boer-Mulders
	L		g_1 helicity	$h_{1L}^\perp$ worm-gear
	T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 $h_{1T}^\perp$

transversity pretzelosity

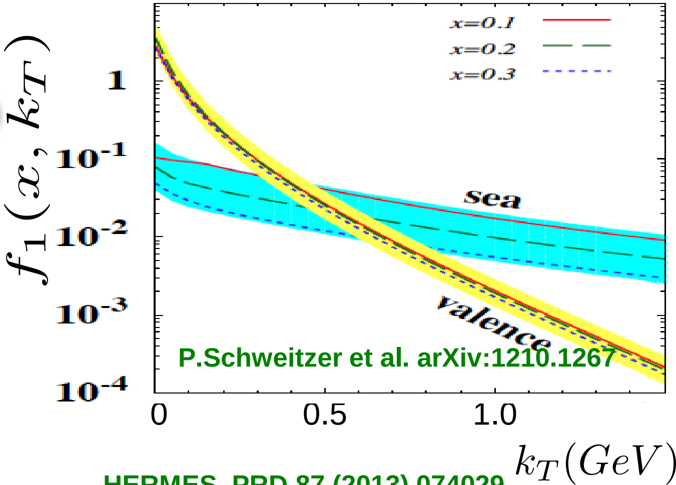
- transverse position and momentum of partons are correlated with the spin orientations of the parent hadron and the spin of the parton itself
- transverse position and momentum of partons depend on their flavor
- transverse position and momentum of partons are correlated with their longitudinal momentum
- spin and momentum of struck quarks are correlated with remnant
- quark-gluon interaction play a crucial role in kinematical distributions of final state hadrons, both in semi-inclusive and exclusive processes

PROBING THE FLAVOR-DEPENDENCE OF K_T-DISTRIBUTIONS



B.Musch et al PRD83 (2011) 094507

Higher probability to find more sea & d-quarks at **large k_T**

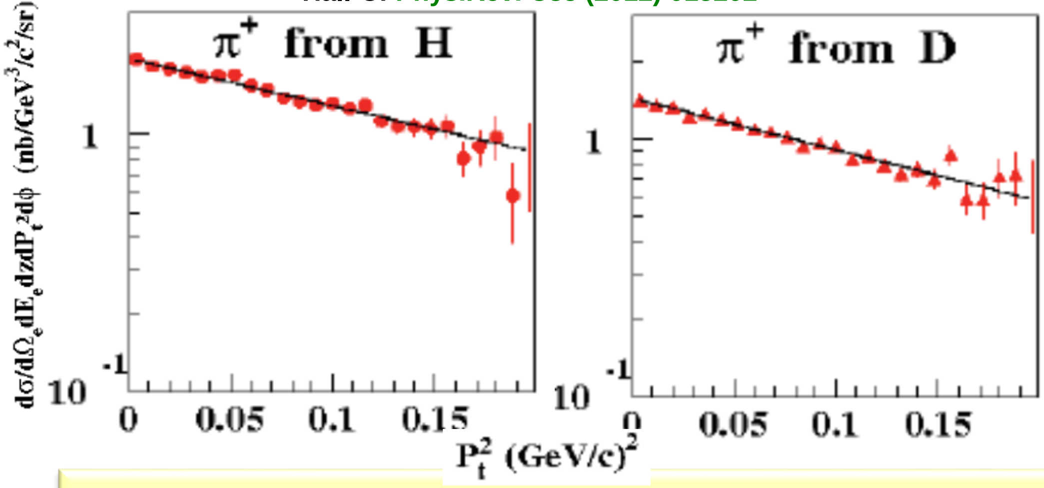


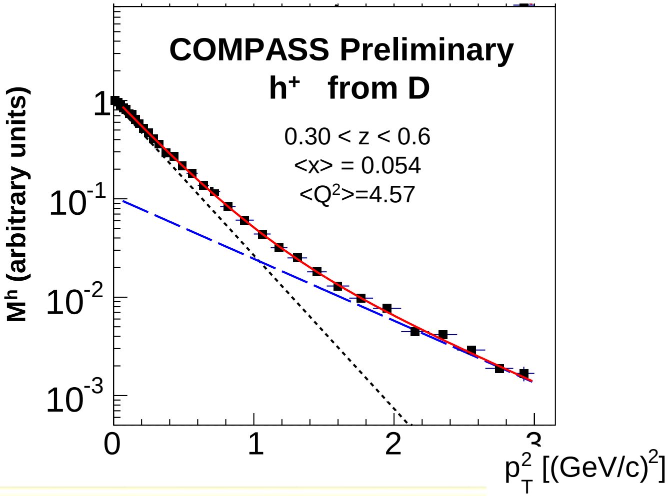
P.Schweitzer et al. arXiv:1210.1267

Measurements of hadronic multiplicities provide a crucial input for studies of k_T dependence of spin independent distributions

HERMES, PRD 87 (2013) 074029
COMPASS, EPJC 73 (2013) 2531

Hall-C: Phys.Rev. C85 (2012) 015202



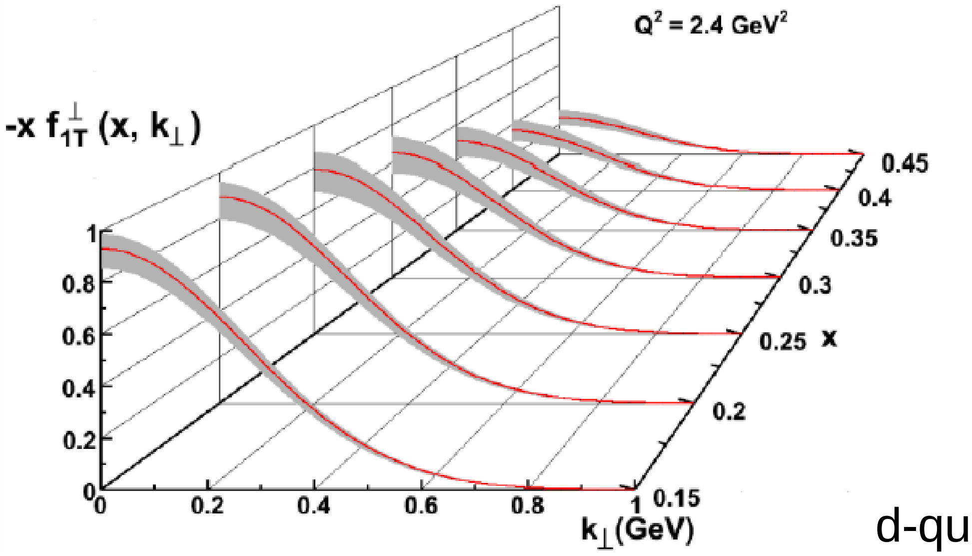


There are indications from both theory (lattice, chiral constituent quark model) and experimental data of the k_T dependence of quark flavor distribution.

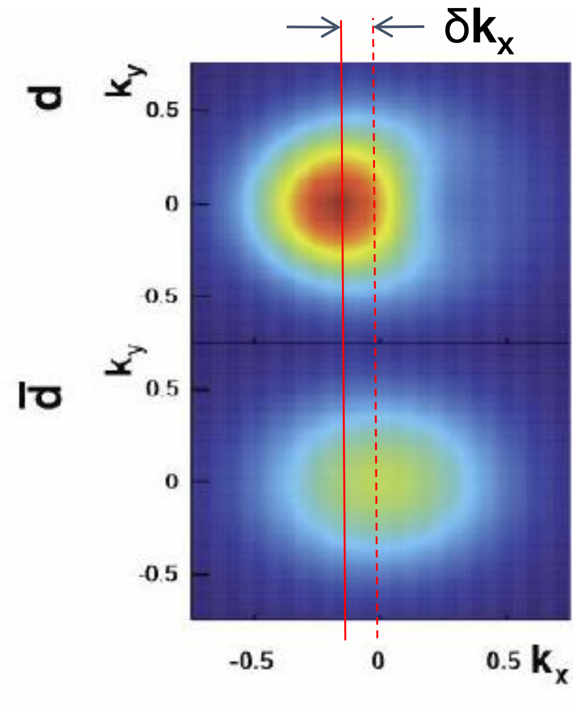
MOMENTUM TOMOGRAPHY WITH TMDS @ 11 GEV

JLab/12 GeV Goal → Precision in 3D Momentum Imaging of the Nucleon!

Sivers function for d-quarks extracted from model simulations with a transverse polarized ^{3}He target.



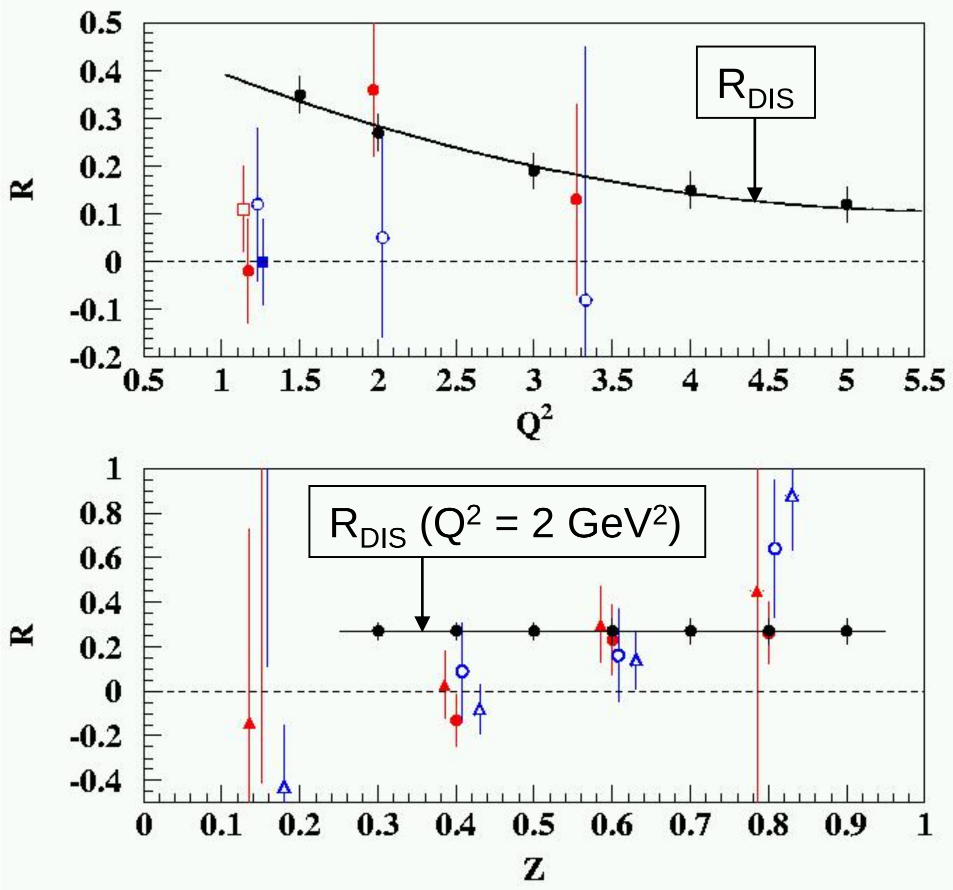
12 GeV ~ Valence Quark Region (x > 0.1)



d-quark momentum tomography for Sivers function. The d-quark momentum density shows a distortion and shift in $\mathbf{k_x}$. A non-zero $\delta \mathbf{k_x}$ value requires a non-zero orbital angular momentum.

LONGITUDINAL CROSS SECTION: $R = \sigma_L/\sigma_T$ IN SIDIS

- R_{DIS} is in the naïve parton model related to the parton's transverse momentum: $R = 4(M^2x^2 + \langle k_T^2\rangle)/(Q^2 + 2\langle k_T^2\rangle)$.
- $R_{DIS} \rightarrow 0$ at $Q^2 \rightarrow \infty$ is a consequence of scattering from free spin-½ constituents



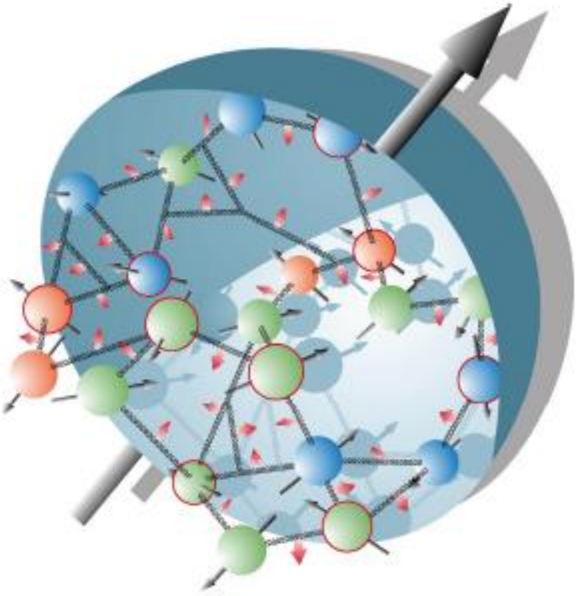
Cornell 70's existing (H and D, π^+ and π^-)
JLab 12-GeV projected (H and D, π^+ and π^-)

- Knowledge on R_{SIDIS} is non-existing
- R_{SIDIS} may (will!) vary with z, and with p_T
  (JLab E12-06-104 will scan versus p_T too)

- Knowledge on R_{SIDIS} needed for any TMD-related asymmetry

- Even if one can relate R_{SIDIS} to a flavor-dependent average transverse momentum in a naïve parton model (W. Melnitchouk *et al*, in progress), R_{SIDIS} can not easily be integrated in a global TMD analysis as it is sensitive to gluon and HT effects.

The Incomplete Nucleon: Spin Puzzle



- Proton has spin-1/2
- Proton is a composite system consisting of spin-1/2 quarks and spin-1 gluons

This implies that the sum of angular momentum of quarks and gluons together must amount to 1/2. Can be due to:

Quark spin ~0.25	Quark orbital momentum
Gluon spin ~0.25	Gluon orbital momentum

Classical: ~ **r** x **p**

Needs a cross-product or something three-dimensional!

THE INCOMPLETE NUCLEON: SPIN PUZZLE

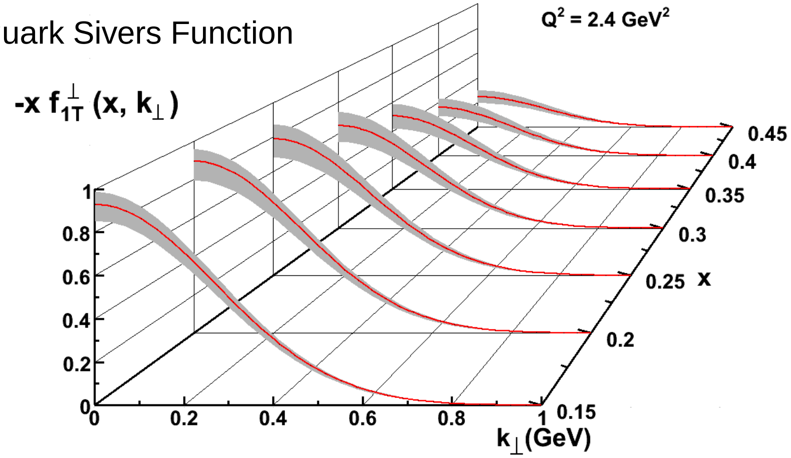
Needs a cross-product or something three-dimensional!

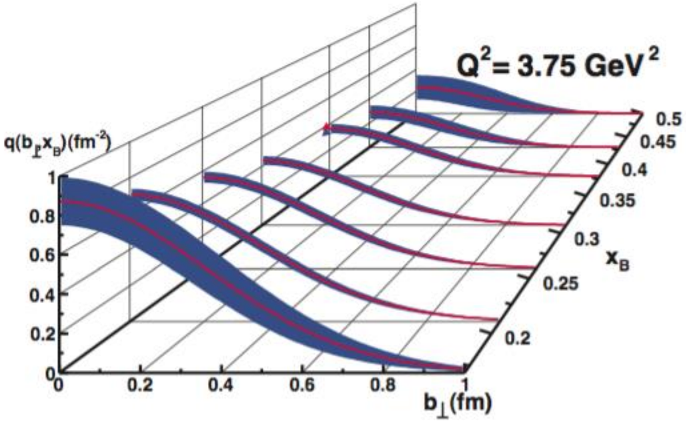
Quark orbital momentum

Longitudinal momentum fraction x and transverse momentum images

Longitudinal momentum fraction x and transverse spatial images

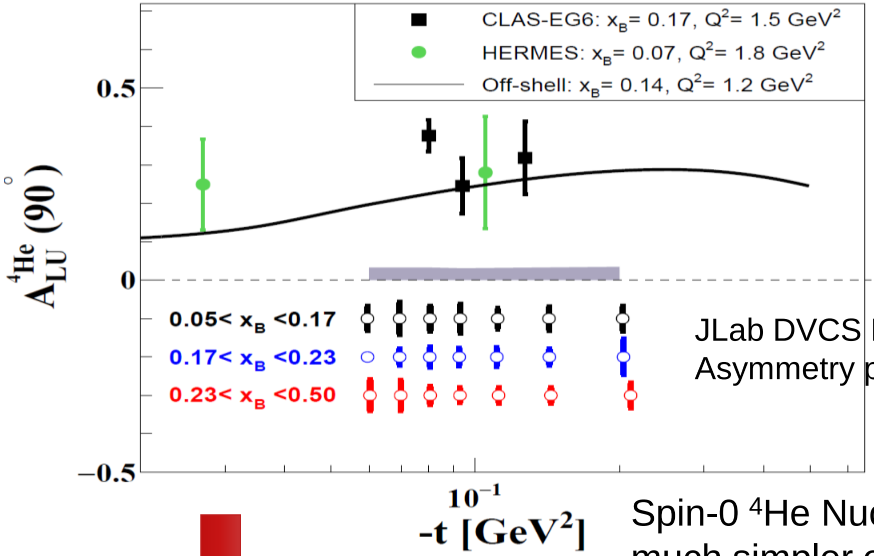
Up quark Sivers Function



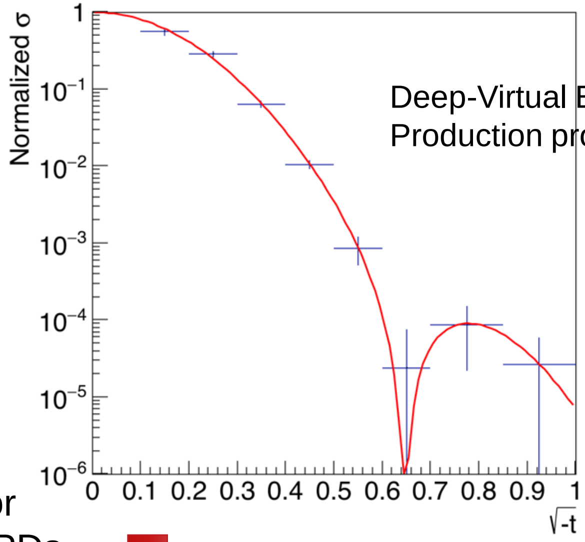


12 GeV projections: valence quarks well mapped

TOMOGRAPHY OF ^{4}HE NUCLEUS @ 11 GEV



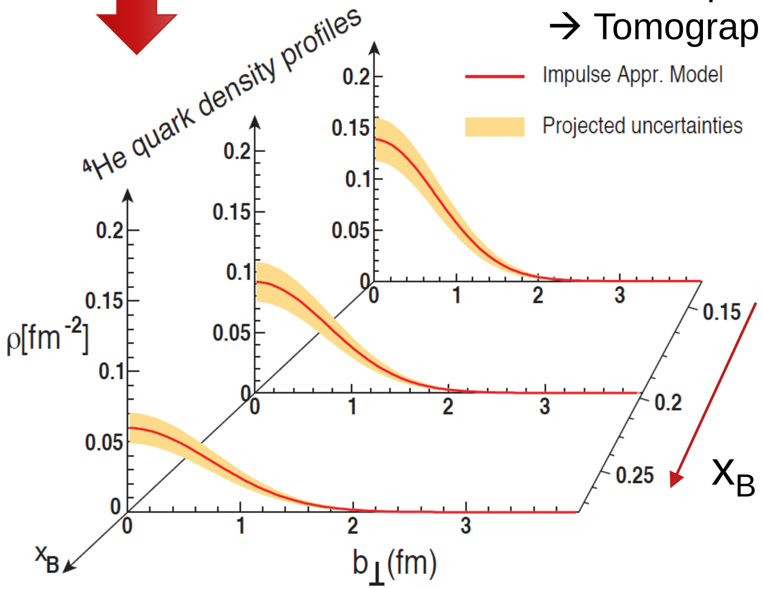
JLab DVCS Beam-Spin Asymmetry projections



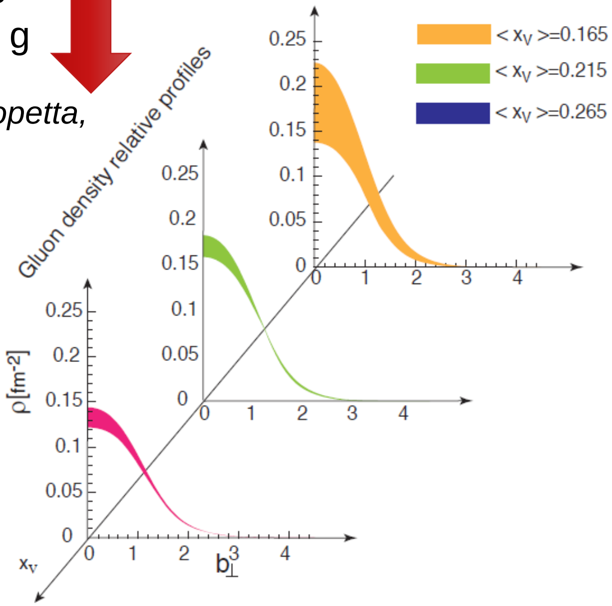
Deep-Virtual Exclusive ϕ Production projections

Spin-0 ^{4}He Nucleus makes for much simpler extraction of GPDs

→ Tomography in terms of q and g



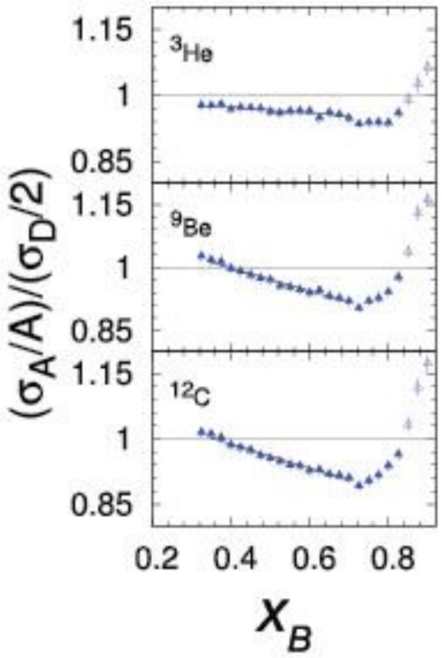
(R. Dupre and S. Scopetta, EPJA 52 (2016) 159)

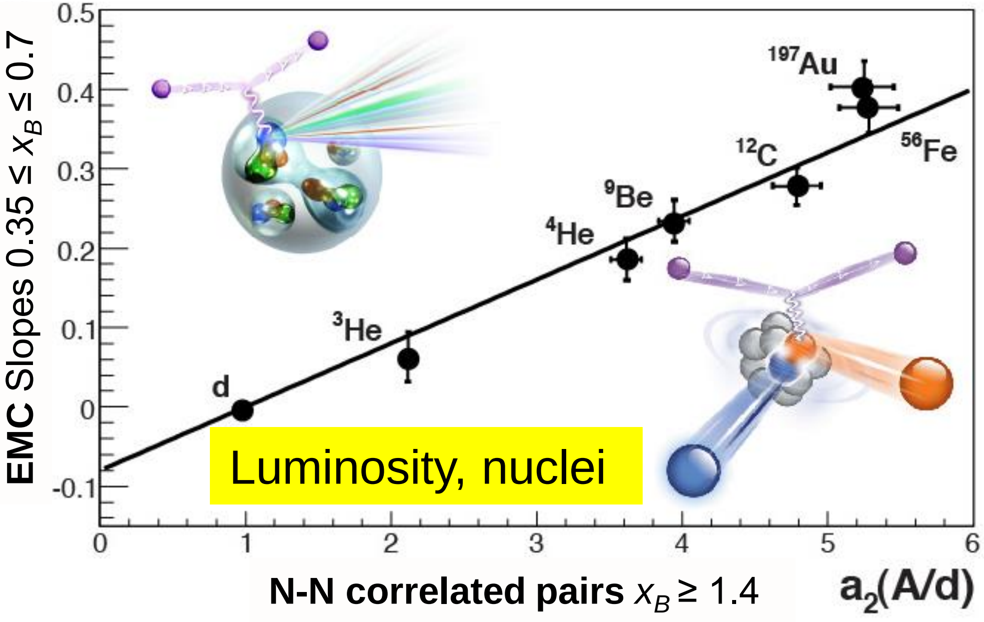


PARTON DYNAMICS AND N-N CORRELATIONS

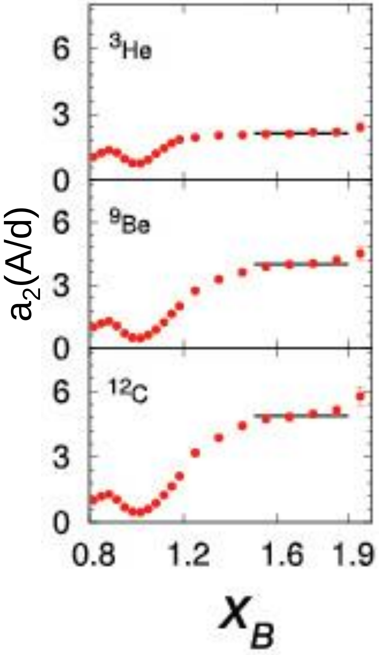
EMC effect: quark momentum in nucleus is altered

N-N Correlations: pairing due to tensor force and strong repulsive core





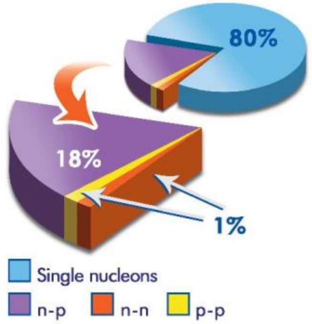
Luminosity, nuclei



^{9}Be ~
$\alpha\alpha$n

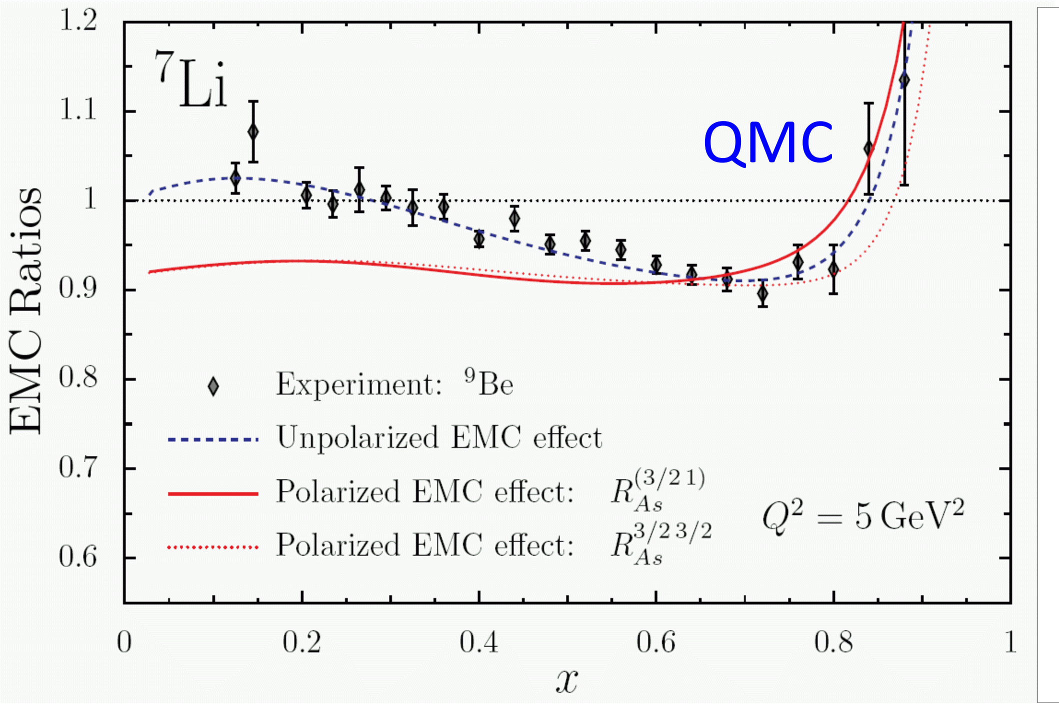
12 GeV science quest: Hall C ^{9}Be, ^{10,11}B data in

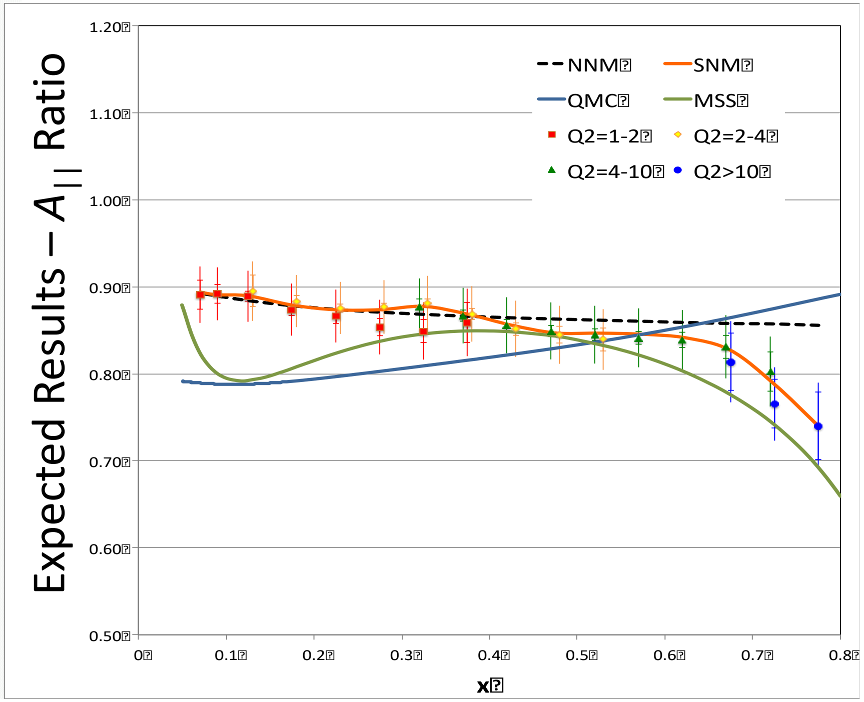
- isospin dependence: ^{3}H, ^{3}He, ^{6,7}Li, ^{9}Be ^{10,11}B, ^{40,48}Ca
- initial spin dependence (^{7}Li)
- “tagged” deep-inelastic scattering off ^{2}H with both slow and fast protons



$g_1(A)$ – “Polarized EMC Effect”

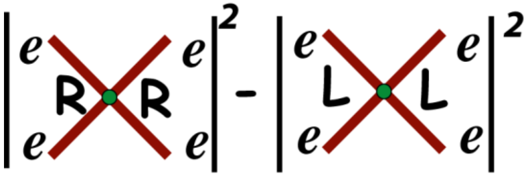
- Calculations indicate larger effect for polarized structure function ratio than for unpolarized: scalar field modifies lower components of Dirac wave function
- Spin-dependent parton distribution functions for nuclei nearly unknown





- After 30 years, still no universally accepted model of the EMC-effect
- Spin degrees of freedom access specific nuclear orbitals and dynamical mechanisms
- Part of four-pronged EMC effect attack at 12-GeV: precision (while varying n/p ratio), extraction of F_2^n, tagging, polarized

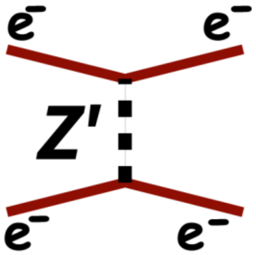
MØLLER PARITY-VIOLATING EXPERIMENT: NEW PHYSICS REACH
(EXAMPLE OF LARGE INSTALLATION EXPERIMENT WITH 11 GEV BEAM ENERGY)

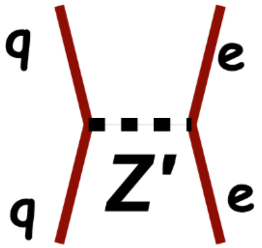


New Contact Interactions

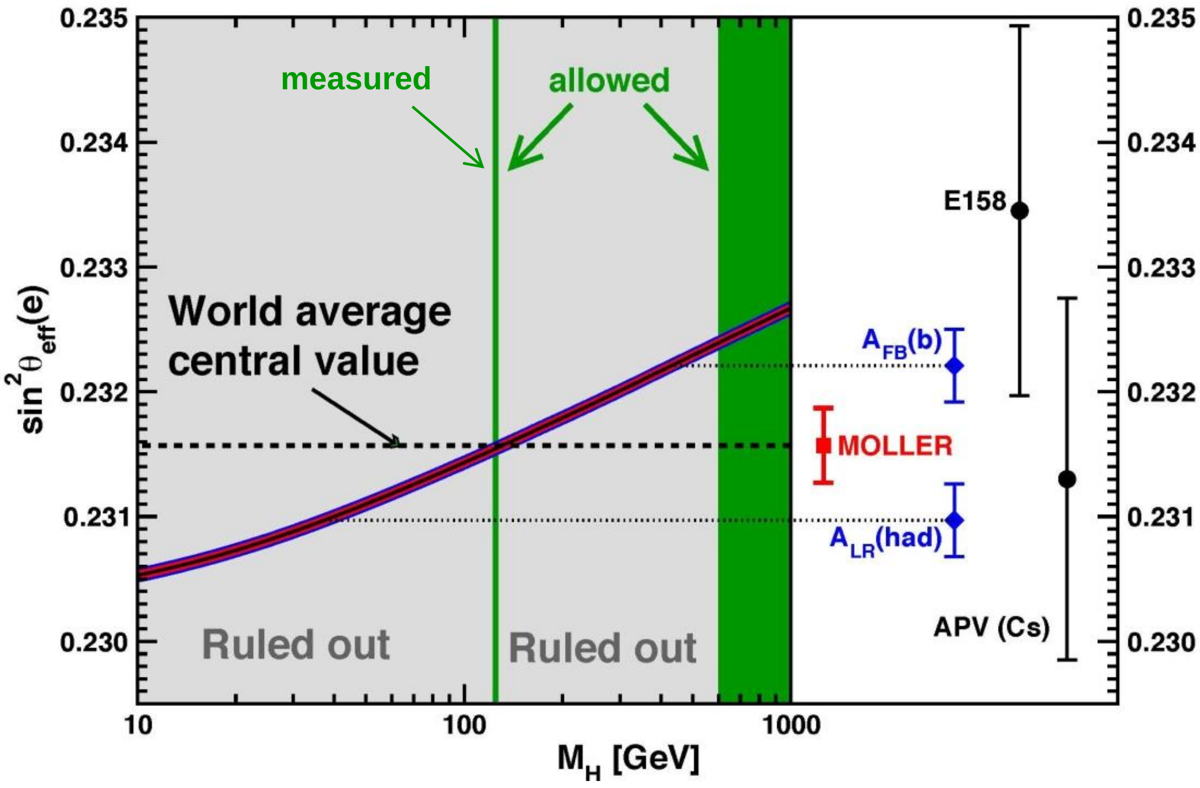
JLab Møller

Λ_{ee} ~ 27 TeV





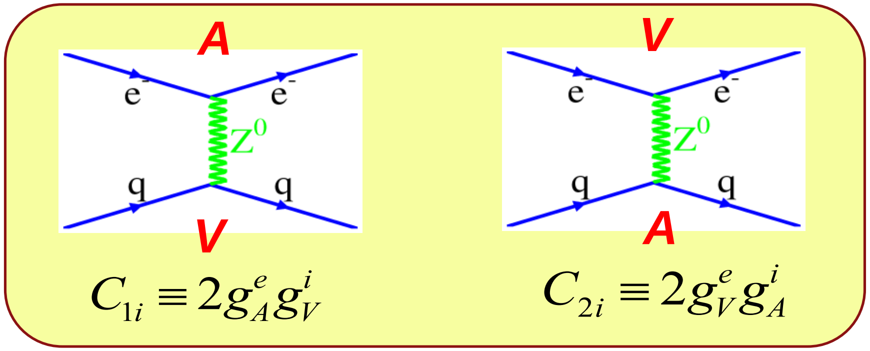
LHC



Known Higgs mass now fixes the SM curve → Not "just another measurement" of $\sin^2(\Theta_W)$

- A_{FB}(b) measures the product of e- and b-Z couplings
- A_{LR}(had) measures purely the e-Z couplings
- Proposed A_{PV}(b) measures purely the e-Z couplings at a different energy scale

USE PRECISION JLAB DATA TO UNRAVEL THE C_{1Q} & C_{2Q} COUPLINGS



$$C_{1i} \equiv 2 g_A^e g_V^i \qquad C_{2i} \equiv 2 g_V^e g_A^i$$

Vector quark couplings *Axial-vector quark couplings*

$$A_{LR} = A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{\gamma}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

$$\mathbf{x}\ (\alpha\ [2C_{1u} - C_{1d}] + \beta\ [2C_{2u} - C_{2d}])$$

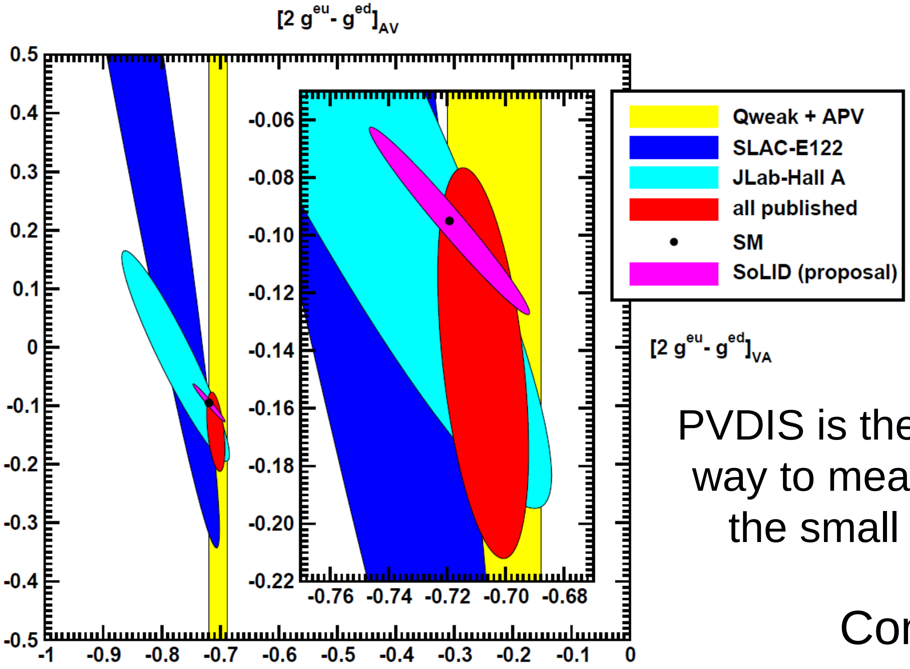
Nature 506, 67–70 (06 February 2014)

The Jefferson Lab PVDIS Collaboration

See also News & Views, *Nature* 506, 43–44 (06 February 2014)

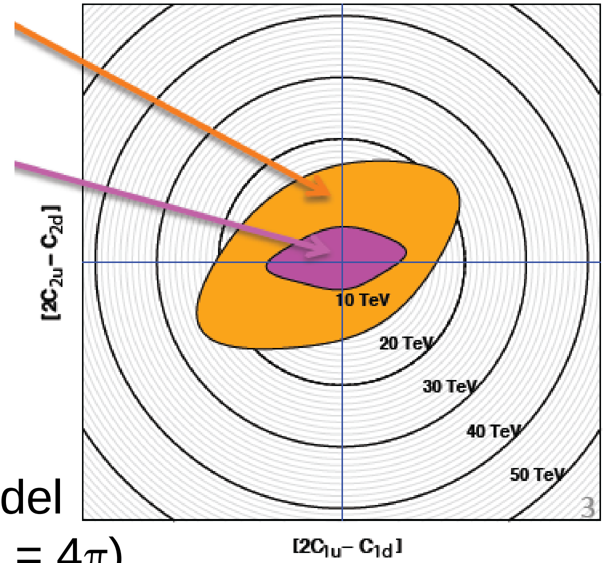
$2C_{2u} - C_{2d} = 0.145 \pm 0.068$

With SoLID: $\delta(2C_{2u}-C_{2d}) = 0.003$



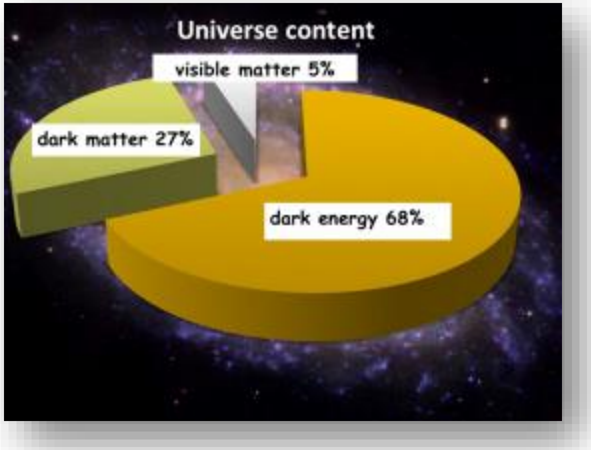
6 GeV (+ SoLID@12 GeV)

PVDIS is the only way to measure the small C_2

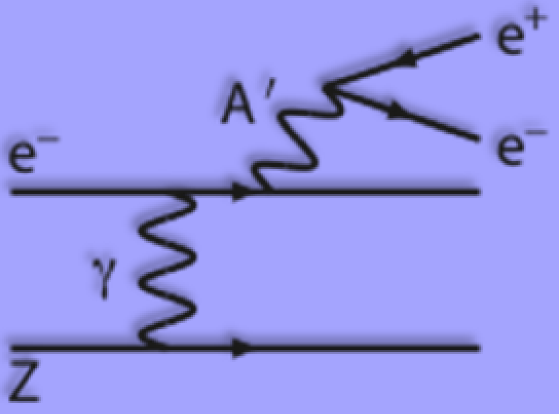


Composite model mass limits ($g^2 = 4\pi$)

HEAVY PHOTON SEARCH



Search for a U(1) Heavy Gauge Boson following up on cosmological observations (PAMELA, AMS)

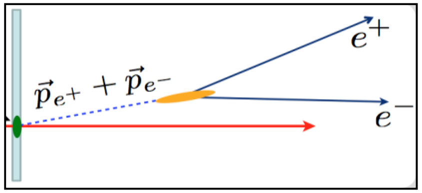


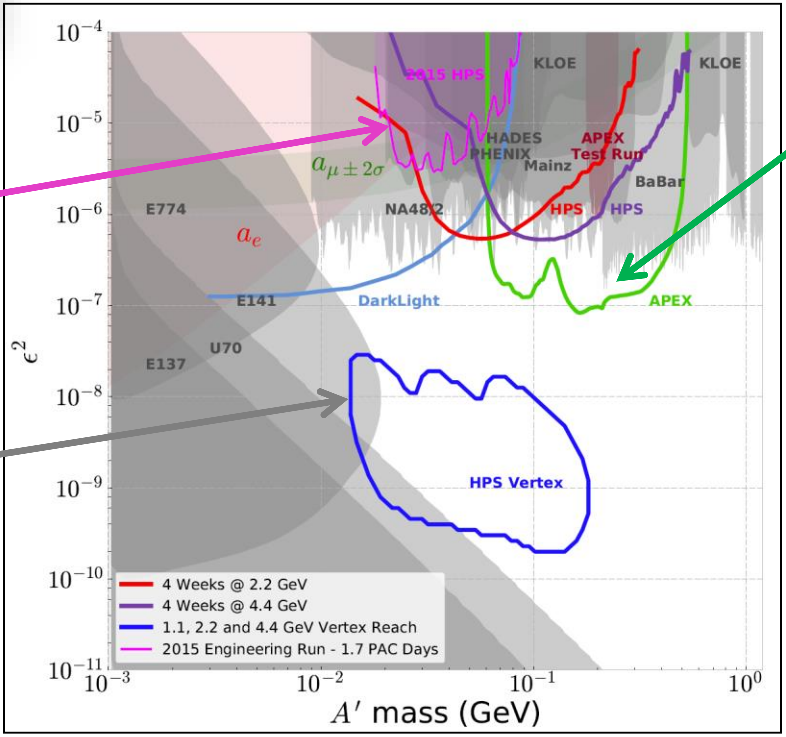
HPS (Hall B)

2015 Engineering Run
1.7 PAC days @ 1.05 GeV

2 GeV data taken in 2016, under analysis

Displaced decay vertex search





APEX (Hall A)

Search for 50-500 MeV A' decaying promptly to e^+e^- pairs

2019 Program: HPS (upgraded), APEX

WHY SHOULD YOU BE INTERESTED IN PIONS AND KAONS?

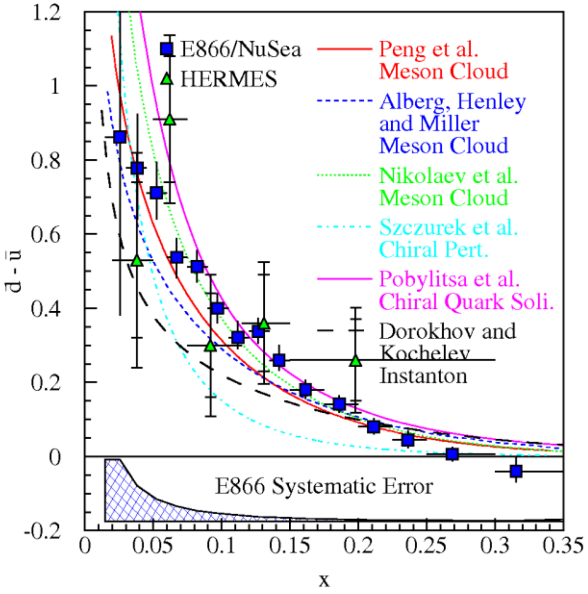
Protons, neutrons, pions and kaons are the main building blocks of nuclear matter

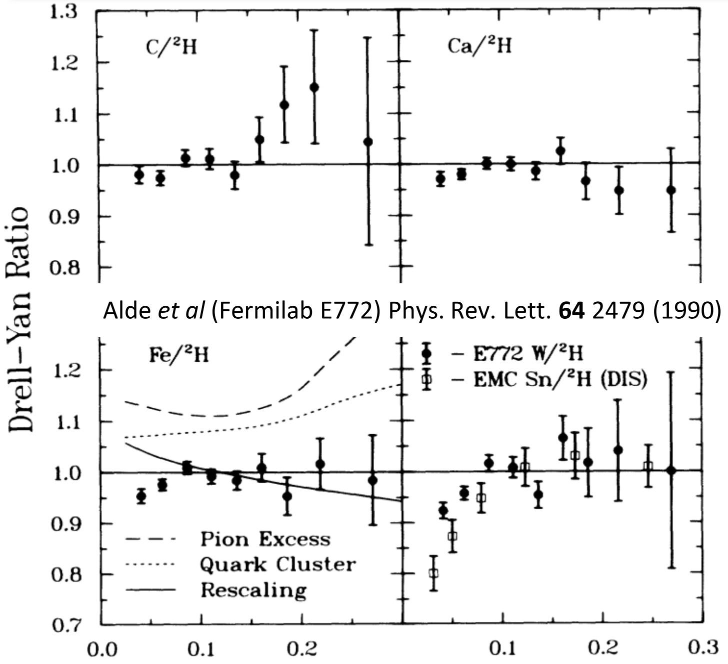
1) The pion, or a meson cloud, explains light-quark asymmetry in the nucleon sea

2) Pions are the Yukawa particles of the nuclear force – but no evidence for excess of nuclear pions or anti-quarks

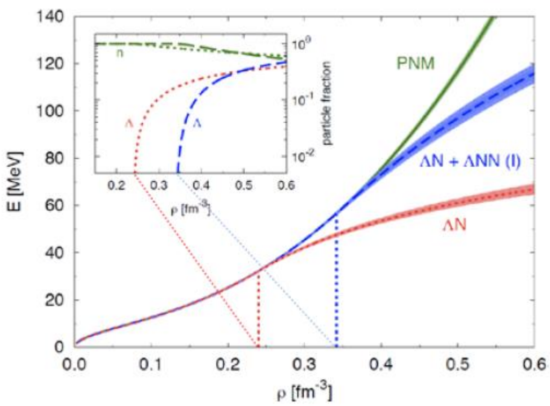
3) Kaon exchange is similarly related to the ΛN interaction – correlated with the Equation of State and astrophysical observations

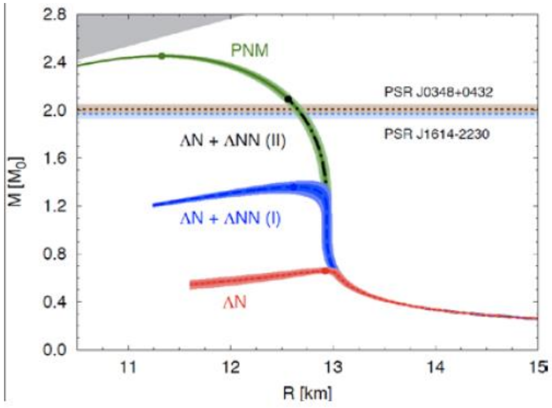
4) Mass is enigma – cannibalistic gluons vs massless Goldstone bosons





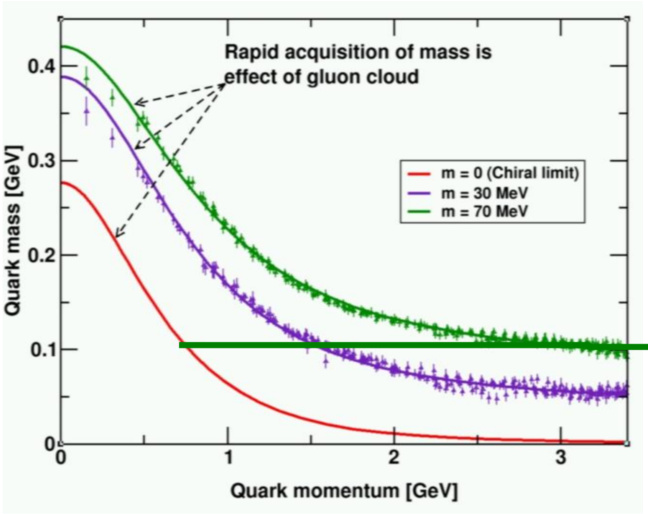
Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

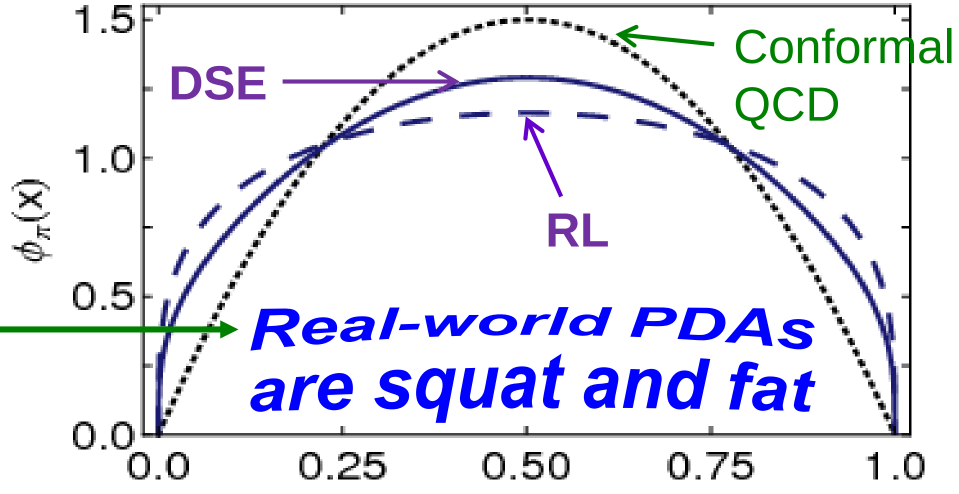




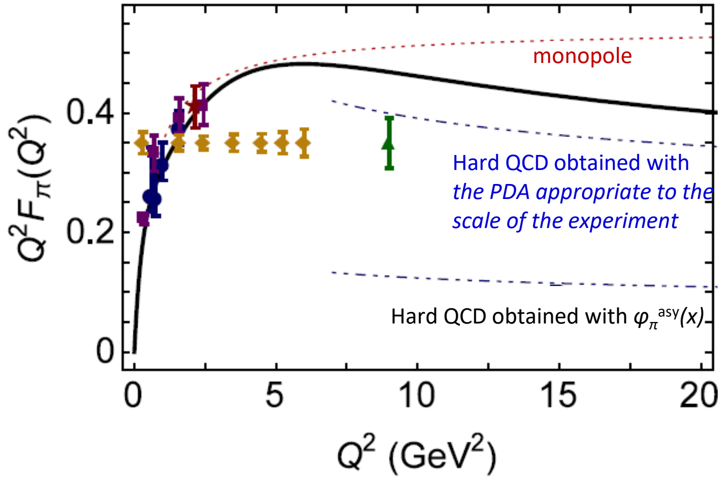
Jefferson Lab

PION FORM FACTOR AND STRUCTURE FUNCTION





Real-world PDAs are squat and fat



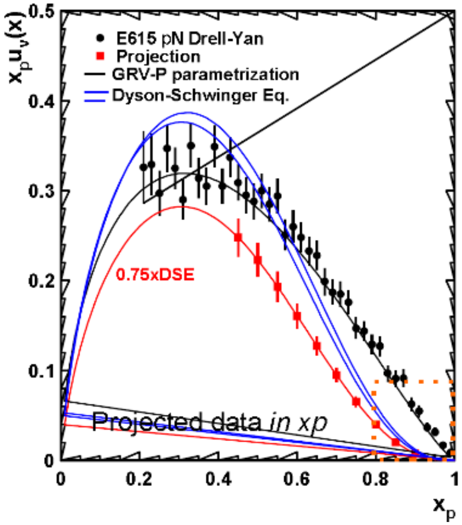
Pion FF – first quantitative access to hard scattering scaling regime?

Implications if so: two longstanding puzzles could be solved

1. Magnitude of pion form factor in hard scaling regime
2. Power of pion parton behavior at large x

Also implications for nucleon and N form factor interpretation (not shown here).*

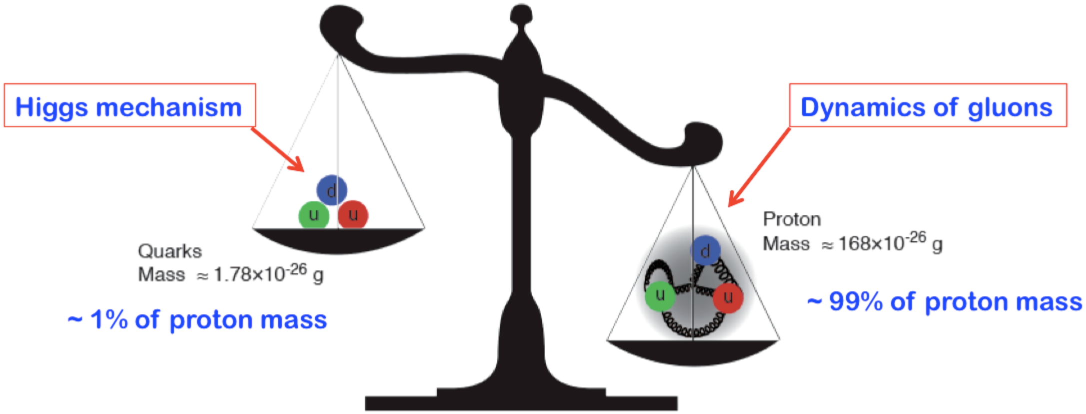
and kaon



Pion SF – $(1-x)^1$ or $(1-x)^2$ dependence at large x?

THE INCOMPLETE HADRON: MASS PUZZLE

"Mass without mass!"

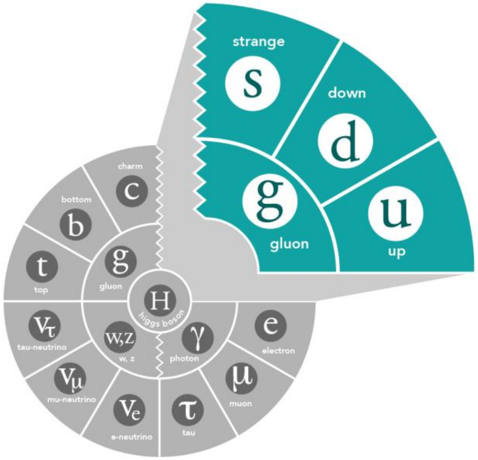


Higgs mechanism

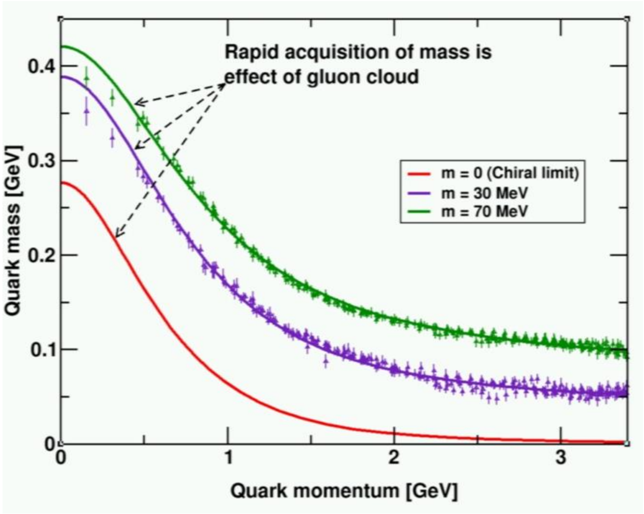
~ 1% of proton mass

Dynamics of gluons

~ 99% of proton mass



Bhagwat & Tandy/Roberts et al



Proton: Mass ~ 940 MeV

preliminary LQCD results on mass budget,

or view as mass acquisition by DcSB

Kaon: Mass ~ 490 MeV

at a given scale, less gluons than in pion

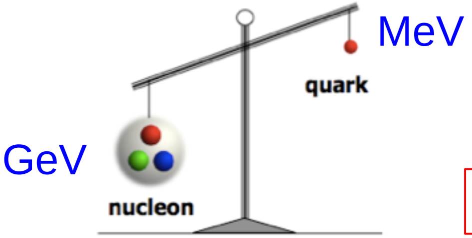
Pion: Mass ~ 140 MeV

mass enigma – gluons vs Goldstone boson

THE INCOMPLETE HADRON: MASS PUZZLE

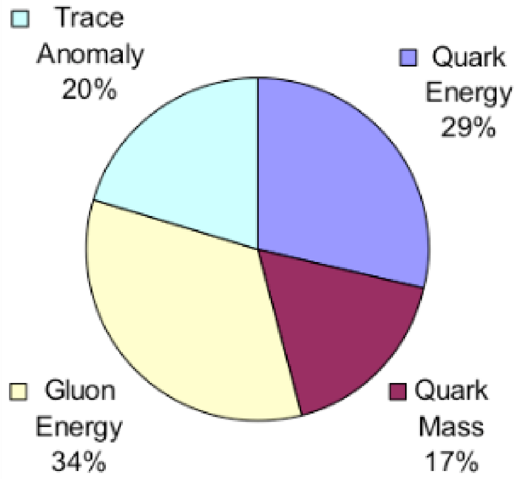
"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

❑ Proton mass:



$$M = \overbrace{\underbrace{E_q}_{\text{Quark Energy}} + \underbrace{E_g}_{\text{Gluon Energy}}}^{\text{Relativistic motion}} + \overbrace{\underbrace{\chi m_q}_{\text{Quark Mass}} + \underbrace{T_g}_{\text{Trace Anomaly}}}^{\text{Quantum fluctuation}}$$

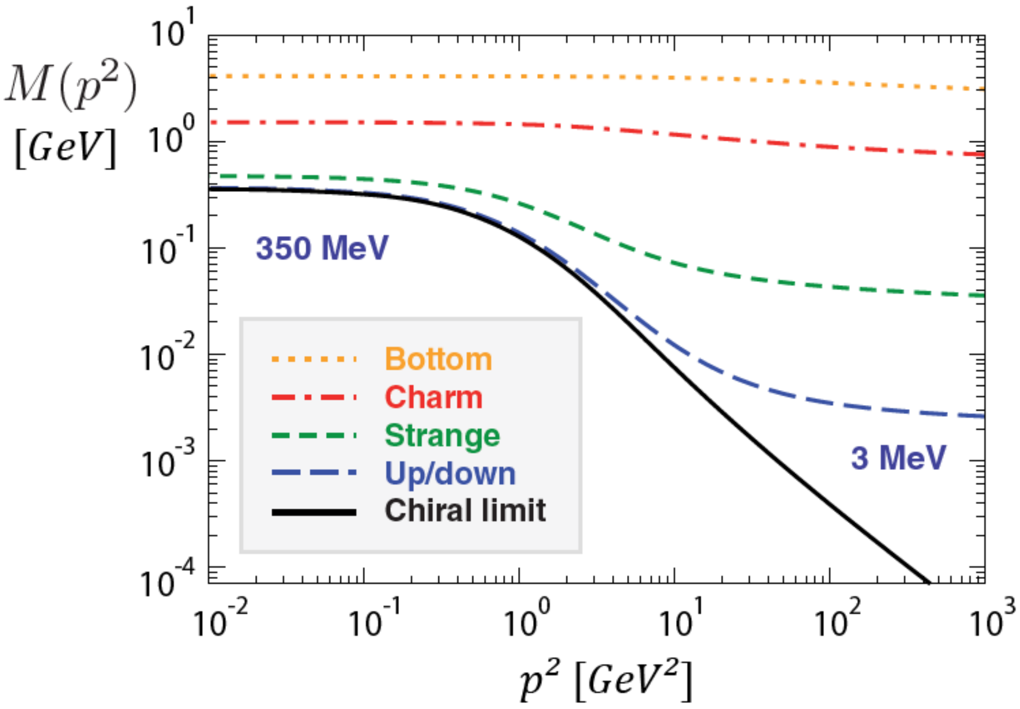
❑ Preliminary Lattice QCD results:



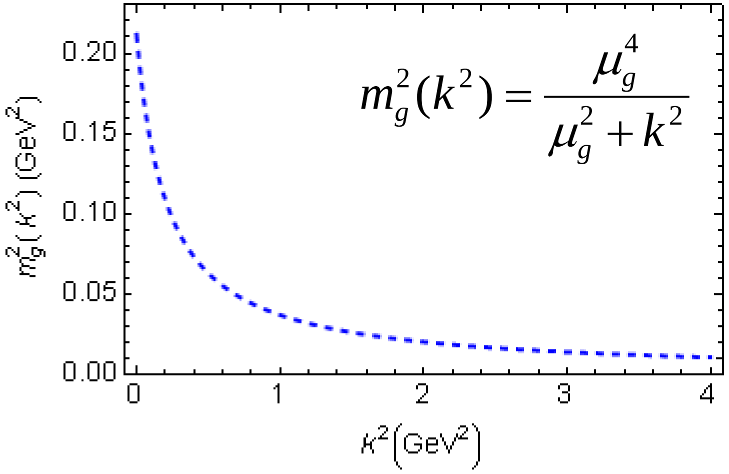
Not unambiguous: Physical interpretation of the proton mass decomposition has to be done with care, as one seemingly treats gluons in the trace anomaly and in kinetic and potential energy as separate entities (C. Lorcé, Eur. Phys. J. C 78 (2018) 120).

MASS OF THE VISIBLE UNIVERSE

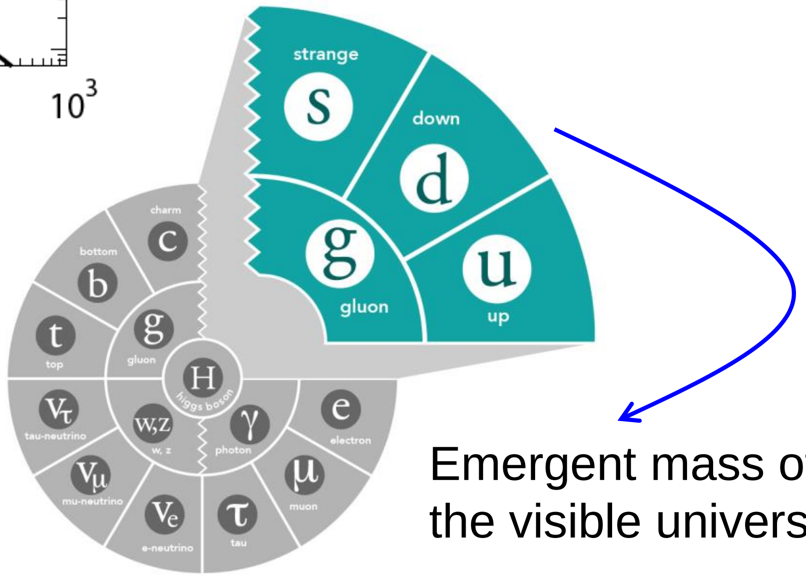
“Mass without mass!”



Gluon mass-squared function

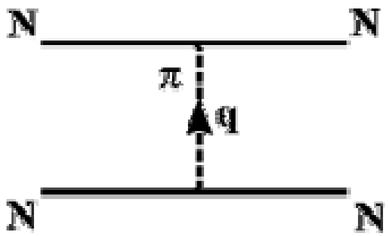


The strange quark is at the boundary - both emergent-mass and Higgs-mass generation mechanisms are important.



Emergent mass of the visible universe

ORIGIN OF MASS OF QCD'S PSEUDOSCALAR GOLDSTONE MODES



- The pion is responsible for the long-range part of the nuclear force, acting as the basis for meson exchange forces and playing a critical role as an elementary field in nuclear structure Hamiltonians
- The pion is both the lightest bound quark system with a valence $q\bar{q}$ structure and a Nambu-Goldstone boson
- There are exact statements from QCD in terms of current quark masses due to PCAC
  (Phys. Rep. 87 (1982) 77; Phys. Rev. C 56 (1997) 3369; Phys. Lett. B420 (1998) 267)

$$f_\pi m_\pi^2 = (m_u^\zeta + m_d^\zeta)\rho_\pi^\zeta$$
$$f_K m_K^2 = (m_u^\zeta + m_s^\zeta)\rho_K^\zeta$$

- Pseudoscalar masses are generated **dynamically**
  - The mass of bound states increases as √m with the constituent masses – $m_\pi^2 \sim \sqrt{m_q}$
  - In contrast, in quantum mechanical models, *e.g.*, constituent quark models, the mass of bound states rises linearly with the mass of the constituents
  - *E.g.*, with constituent quarks Q: in the nucleon $m_Q \sim ⅓m_N \sim$ 310 MeV, in the pion $m_Q \sim ½m_\pi \sim$ 70 MeV, in the kaon (with one s quark) $m_Q \sim$ 200 MeV – **This is not real**.
  - In both DSE and LQCD, the mass function of quarks is the same, regardless what hadron the quarks reside in – **This is real**. It is the Dynamical Chiral Symmetry Breaking (DcSB) that makes the pion and kaon masses light.

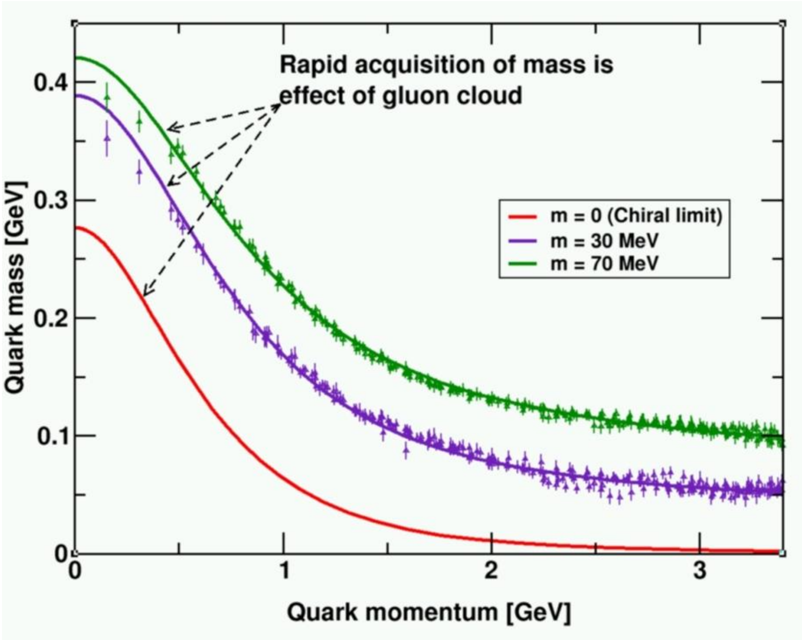
THE ROLE OF GLUONS IN PIONS

Pion mass is enigma – cannibalistic gluons vs massless Goldstone bosons

$$f_\pi E_\pi(p^2) = B(p^2)$$

Adapted from Craig Roberts:

- The most fundamental expression of Goldstone’s Theorem and DCSB in the SM
- Pion exists if, and only if, mass is dynamically generated – “because of B, there is a pion”
- On the other hand, in absence of the Higgs mechanism, the pion mass m_π = 0 – the pion mass^2 is entirely driven by the current quark mass (for reference, for the ρ, only 6% of its mass^2 is driven by this).



Rapid acquisition of mass is effect of gluon interactions

What is the impact of this for gluon parton distributions in pions vs nucleons?
One would anticipate a different mass budget for the pion and the proton

THE ROLE OF GLUONS IN THE CHIRAL LIMIT

In the chiral limit, using a parton model basis: *the entirety of the proton mass is produced by gluons and due to the trace anomaly*

$$\langle P(p)|\Theta_0|P(p)\rangle = -p_\mu p_\mu = m_N^2$$

In the chiral limit, for the pion ($m_\pi = 0$):

$$\langle \pi(q)|\Theta_0|\pi(q)\rangle = -q_\mu q_\mu = m_\pi^2 = 0$$

Sometimes interpreted as: *in the chiral limit the gluons disappear and thus contribute nothing to the pion mass*.

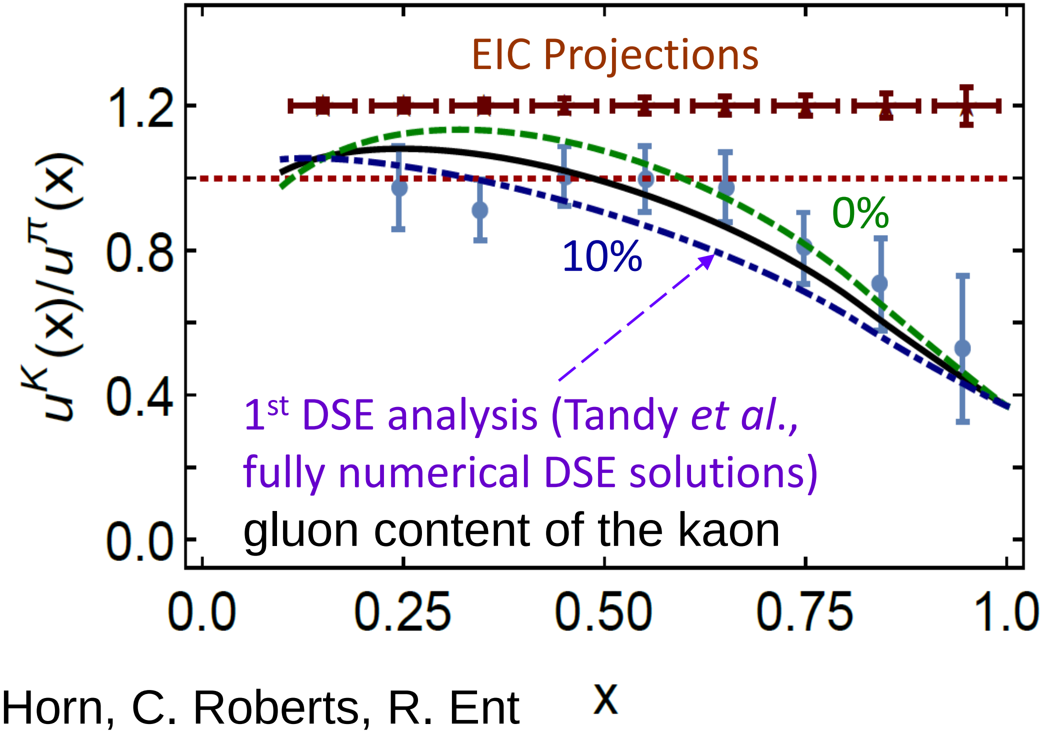
This is unlikely as quarks and gluons still dynamically acquire mass – this is a universal feature in hadrons – so more likely a cancellation of terms leads to “0”

Nonetheless: are there gluons at large Q^2 in the pion or not?

KAON STRUCTURE FUNCTIONS – GLUON PDFS

Based on Lattice QCD calculations and DSE calculations:

- Valence quarks carry some 52% of the pion’s momentum at the light front, at the scale used for Lattice QCD calculations, or ~65% at the perturbative hadronic scale
- At the same scale, valence-quarks carry ⅔ of the kaon’s light-front momentum, or roughly 95% at the perturbative hadronic scale

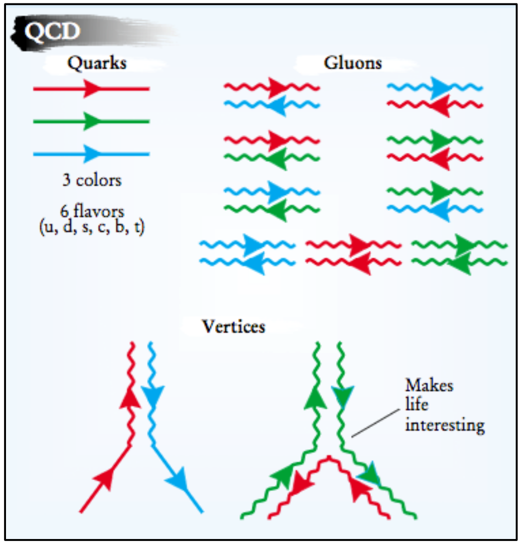


T. Horn, C. Roberts, R. Ent

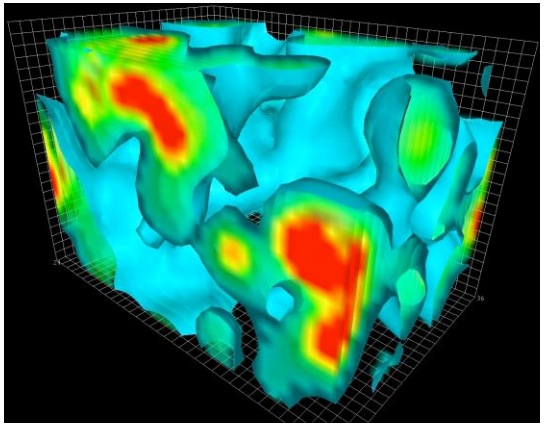
Thus, at a given scale, there is far **less glue in the kaon than in the pion**:

- ☐ heavier quarks radiate less readily than lighter quarks
- ☐ heavier quarks radiate softer gluons than do lighter quarks
- ☐ Landau-Pomeranchuk effect: softer gluons have longer wavelength and multiple scatterings are suppressed by interference.
- ☐ Momentum conservation communicates these effects to the kaon's u-quark.

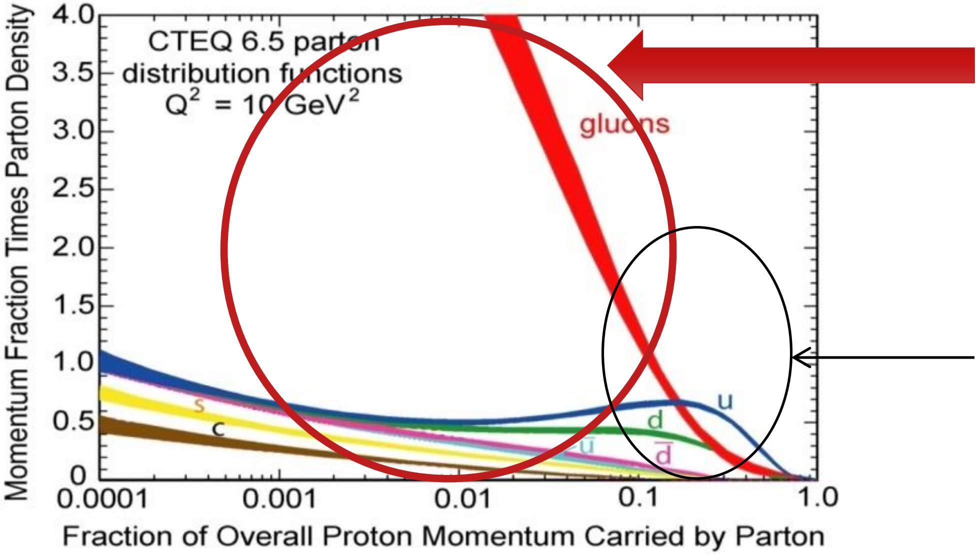
Subatomic Matter is Unique



Interactions and Structure are entangled because of gluon self-interaction.



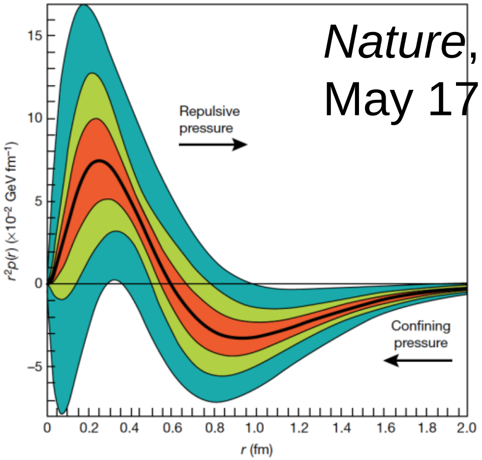
Observed properties such as mass and spin emerge from this complex system.



EIC needed to explore the gluon dominated region

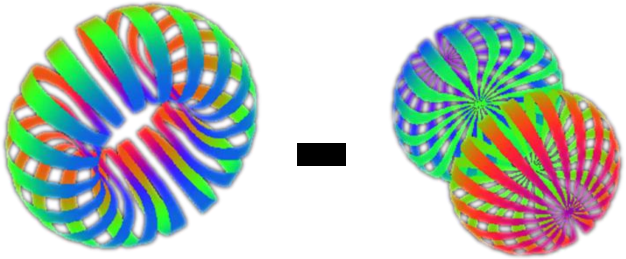
JLAB 12 to explore the valence quark region

New Avenues

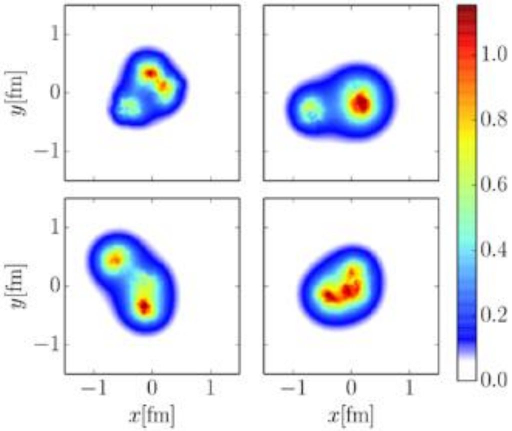


Nature, **557**, May 17, 2018

- **Pressure in the Proton**
    - First determination using DVCS (Deeply Virtual Compton Scattering) data
    - Interior pressure in proton is > pressure inside a neutron star! ***Who knew that!***
    - Lattice calculation motivates determination of gluon GPDs at EIC



- **Polarized Deuteron Structure**
    - Inclusive Deep Inelastic Scattering on a Tensor-Polarized Deuteron Beam
    - Map the Structure Function b1
    - Are quarks sensitive to the doughnut or dumbbell shape of the nucleus?

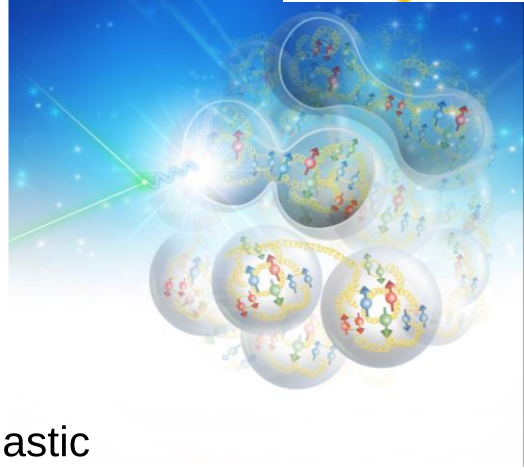


- **Hot Spots in the Nucleus**
    - Simulated proton density fluctuations x = 10^{-3}
    - Accessible with 3D tomography
    - Responsible for ridge behavior found in Heavy-Ion reactions at high energies?

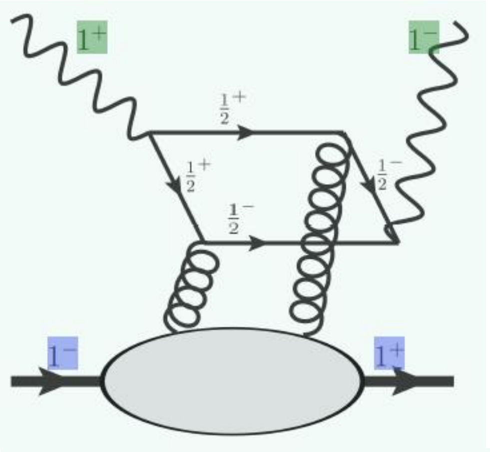
Exotic Glue in Nuclei

Exotic Glue in Nuclei =

- gluons **not** associated with individual nucleons in nucleus
- operator in nucleon = 0 & operator in nuclei ≠ 0



Targets with J ≥ 1 have leading twist gluon contribution
$\Delta(x,Q^2)$: double helicity flip (Jaffe and Manohar, 1989)
Changes both photon and target helicity by two units…



$$\Delta(x,Q^2) = A_{+-,-+}$$

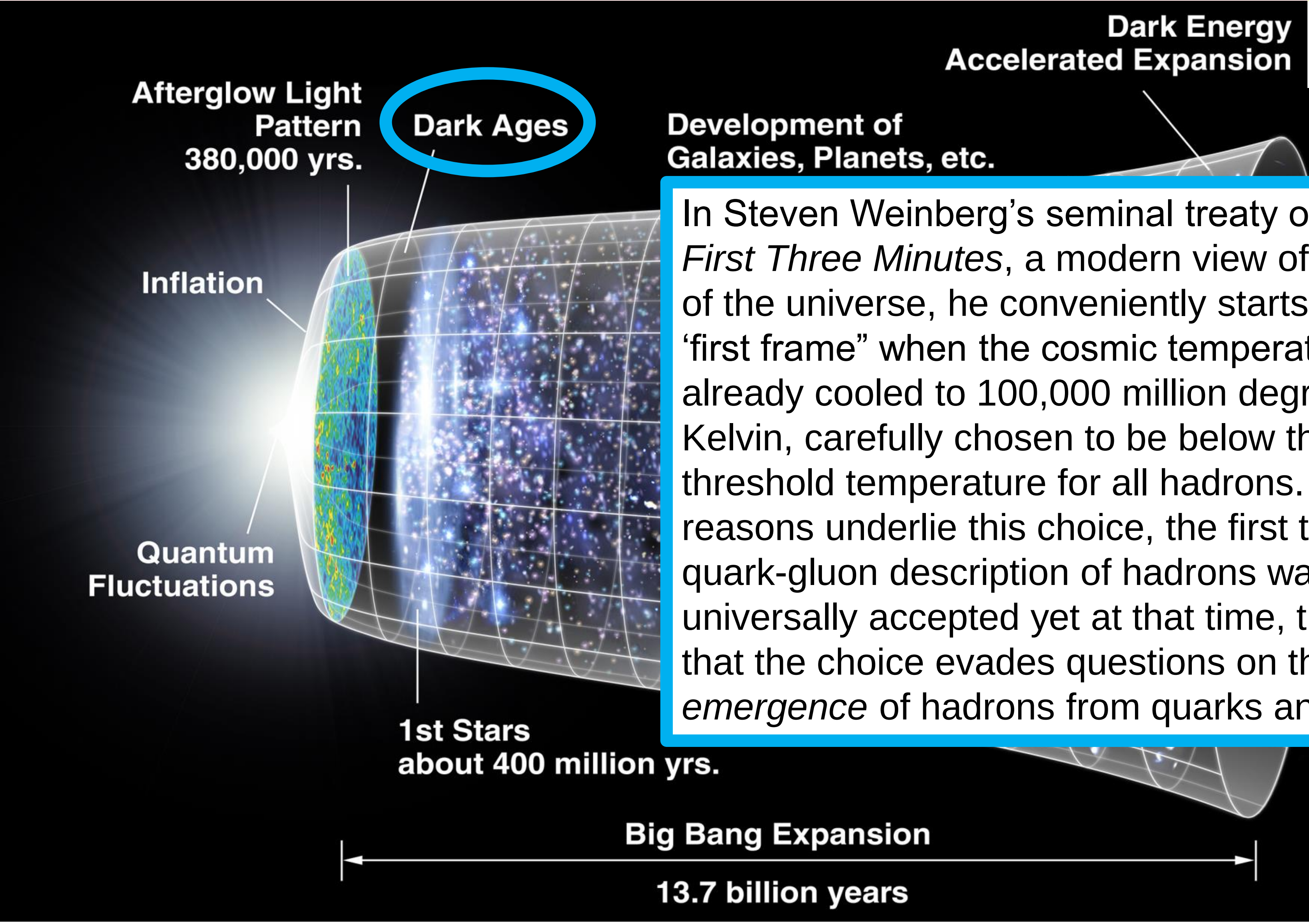
Measurable in unpolarized Deep Inelastic Scattering with a **transversely polarized J ≥ 1 target like the deuteron** as azimuthal variation.

Parton model interpretation:
$\Delta(x,Q^2)$ informs how much more momentum of a transversely polarized particle is carried by a gluon with spin aligned rather than perpendicular to it in the transverse plane.

Shanahan, Detmold, et al.

LQCD calculation: gluon transversity distribution in the deuteron, m_π = 800 MeV
→ **First evidence for non-nucleonic gluon contributions to nuclear structure**

Timeline of the Universe



In Steven Weinberg’s seminal treaty on *The First Three Minutes*, a modern view of the origin of the universe, he conveniently starts with a ‘first frame” when the cosmic temperature has already cooled to 100,000 million degrees Kelvin, carefully chosen to be below the threshold temperature for all hadrons. Two reasons underlie this choice, the first that the quark-gluon description of hadrons was not universally accepted yet at that time, the second that the choice evades questions on the *emergence* of hadrons from quarks and gluons.

ONGOING

Decade of Experiments Approved
Start of 12-GeV Science!

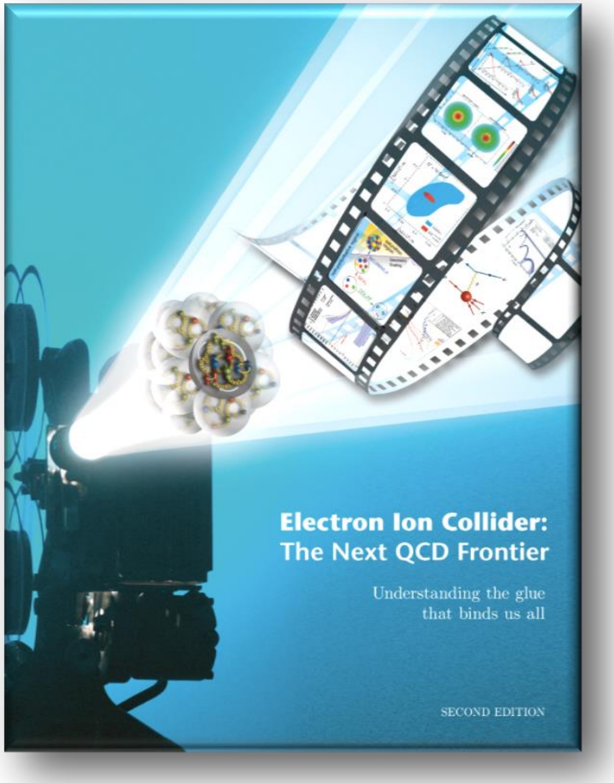
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Physics Opportunities with
the 12 GeV Upgrade at Jefferson Lab

- **Confinement**
- **Hadron structure**
- **Nuclear Structure and Astrophysics**
- **Fundamental Symmetries**

FUTURE

Seeking Realization
The Next QCD Frontier



Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

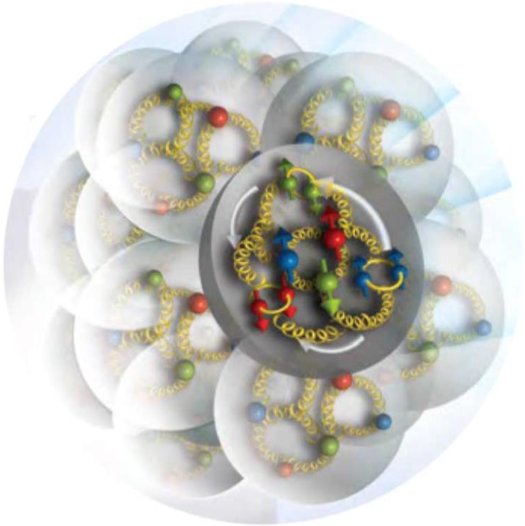
SECOND EDITION

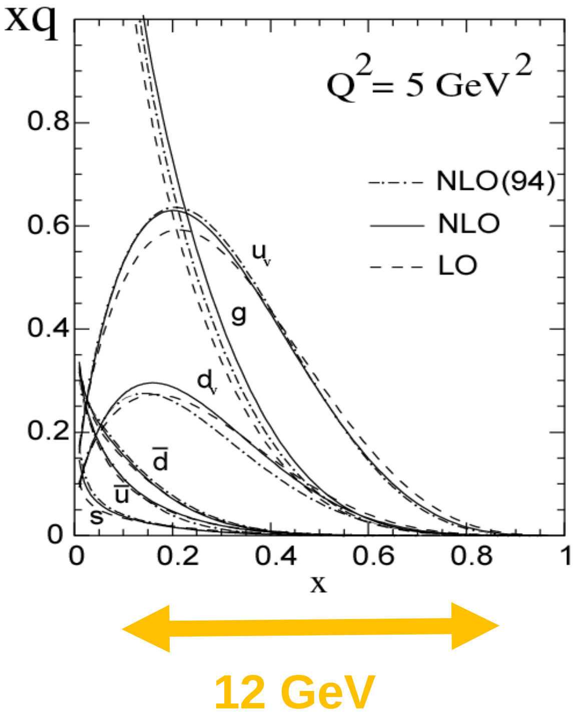
Role of Quark Sea and Gluons in Nucleon and Nuclear Structure

Nuclear Femtography

Science of mapping the position and motion of quarks and gluons in the nucleus.

Artist's Conception of Quark and Gluons in a proton and nucleus





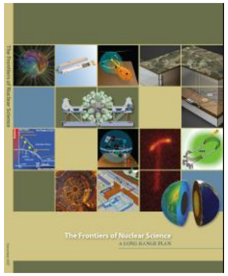
.. is just beginning → **EIC**

REQUIRES:

- *High beam polarization*
- *High electron current*
- *High target polarization*
- *Large solid angle spectrometers*

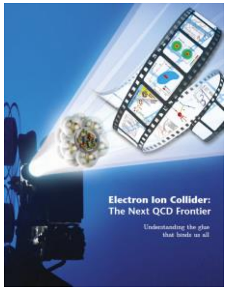
Jefferson Lab

U.S. Electron-Ion Collider Planning 2007-18


The Frontiers of Nuclear Science
A LONG RANGE PLAN

2007 Nuclear Science Advisory Committee (NSAC) Long-Range Plan

“An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier”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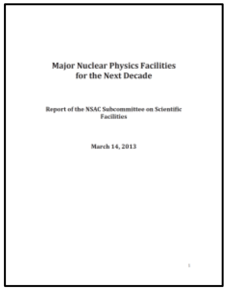

Major Nuclear Physics Facilities
for the Next Decade

Report of the NSAC Subcommittee on Scientific Facilities

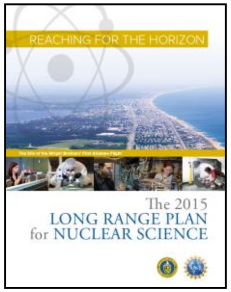
March 14, 2013

2013 Electron Ion Collider White Paper

(Writing committee convened by Jefferson Lab and BNL)

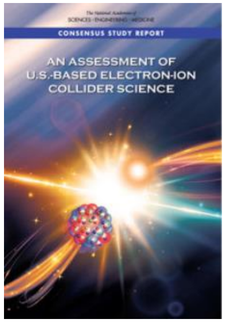
2013 NSAC Subcommittee on Future Facilities

Identified EIC as **absolutely central** to the nuclear science program of the next decade


REACHING FOR THE HORIZON
The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

2015 NSAC Long-Range Plan

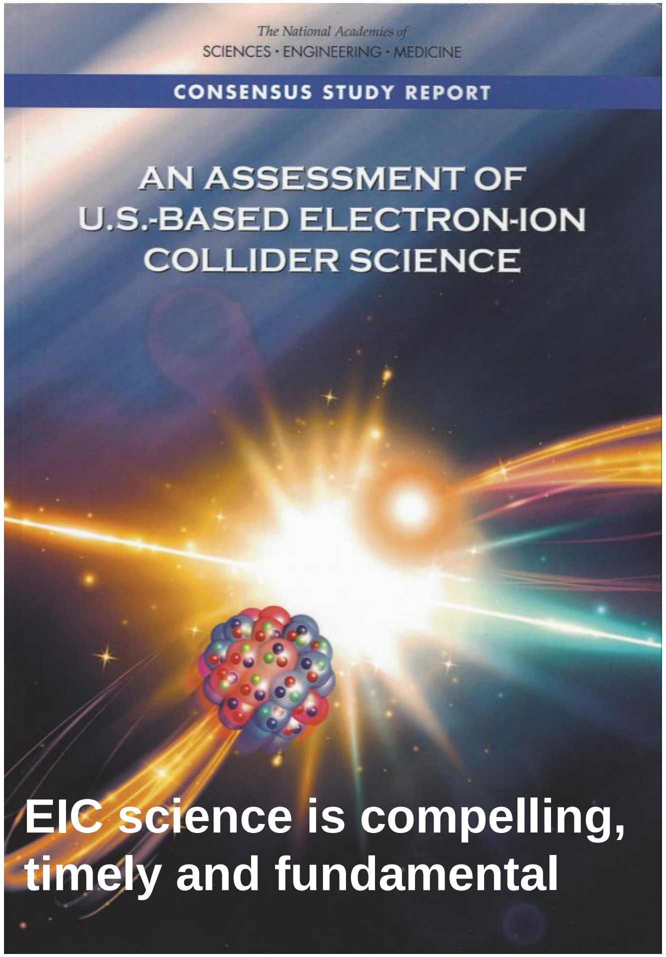
“We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.”


The National Academies of SCIENCES · ENGINEERING · MEDICINE
CONSENSUS STUDY REPORT
AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE

2018 National Academy of Sciences (NAS) – Assessment of U.S. Based Electron-Ion Collider Science

“…the committee finds a compelling scientific case for such a facility. The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today.”

Findings of the NAS committee



The National Academies of
SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

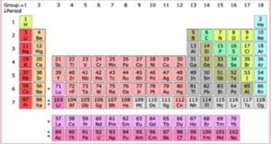
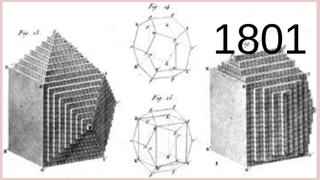
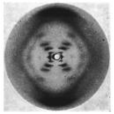
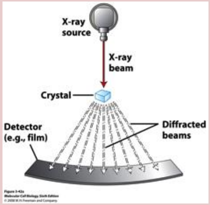
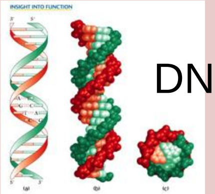
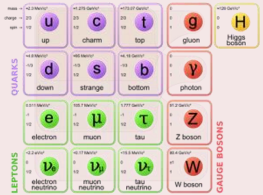
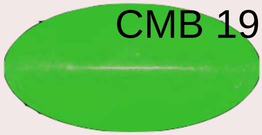
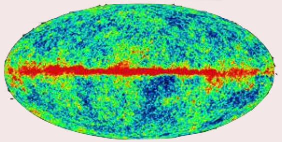
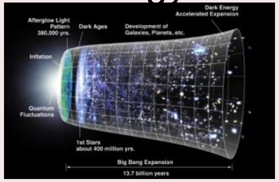
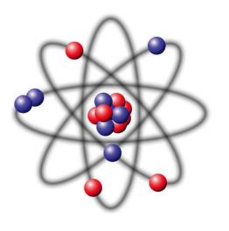
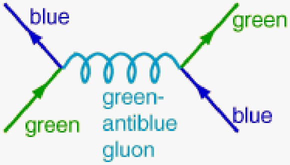
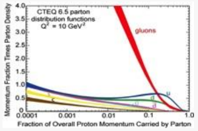
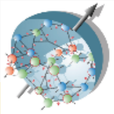
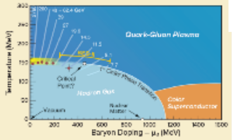
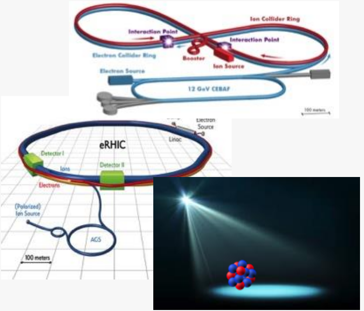
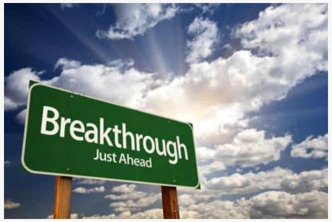
AN ASSESSMENT OF
U.S.-BASED ELECTRON-ION
COLLIDER SCIENCE

EIC science is compelling, timely and fundamental

Developed by NAS committee with broad science perspective

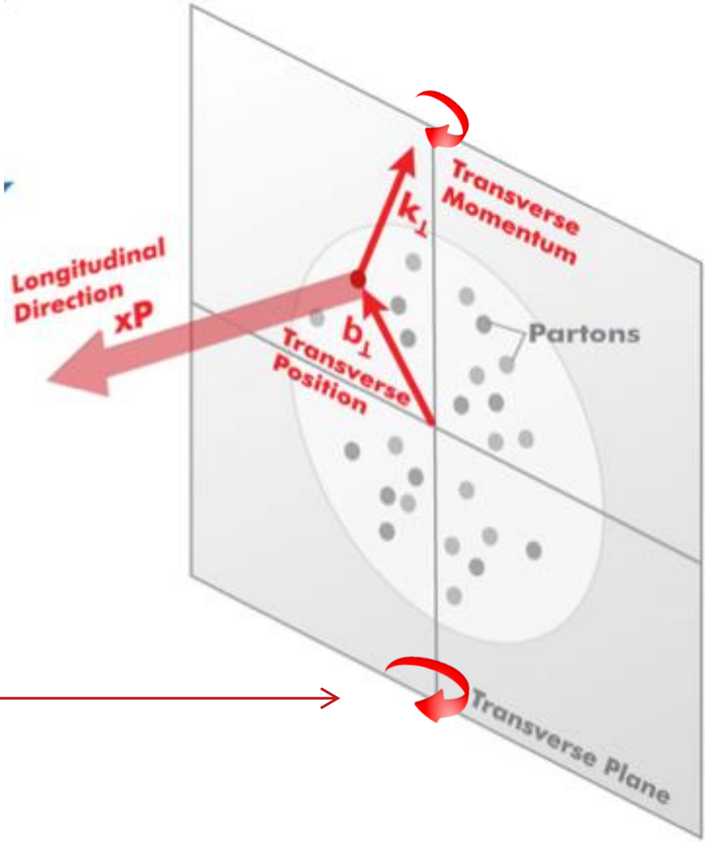
- **Finding 1:** An EIC can uniquely address three profound questions about nucleons — neutrons and protons — and how they are assembled to form the nuclei of atoms:
  - How does the **mass** of the nucleon arise?
  - How does the **spin** of the nucleon arise?
  - What are the **emergent properties** of dense systems of gluons?
- **Finding 2:** These three high-priority science questions can be answered by an EIC with **highly polarized beams** of electrons and ions, with sufficiently high **luminosity** and sufficient, and variable, center-of-mass **energy**.
- **Finding 3:** An EIC would be a unique facility in the world and would maintain U.S. leadership in nuclear physics.
- **Finding 4:** **An EIC would maintain U.S. leadership in the accelerator science and technology of colliders and help to maintain scientific leadership more broadly.**

Imaging Physical Systems is Key to New Understanding

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure  1801	X-ray Diffraction (~1920)   	Solid state physics Molecular biology  DNA
Universe 	General Relativity Standard Model  	Quantum Gravity, Dark matter, Dark energy. Structure  CMB 1965	Large Scale Surveys CMB Probes (~2000)  	Precision Observational Cosmology 
Nuclei and Nucleons 	Perturbative QCD Quarks and Gluons $\mathcal{L}_{QCD} = \overline{\psi}(i\partial\!\!\!/ - g A\!\!\!/)\psi - \frac{1}{2}\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu}$  	Non-perturbative QCD. Structure  2017   	Electron-Ion Collider (2025+)  	Structure & Dynamics in QCD 

3D Structure of Nucleons and Nuclei

- EIC is a machine to completely map the 3D structure of the nucleons and nuclei
- We need to measure positions and momenta of the partons transverse to its direction of motion.
- These quantities (k_T, b_T) are of the order of a few hundred MeV.
- Also their polarization!



k_T, b_T (~100 MeV)

Proton and Ion Beam

Need to keep $[100\ \mathrm{MeV}]_T/E_{\mathrm{proton,Ion}}$ manageable (~ >10^{-3}) ➔ E_{proton} ~< 100 GeV

Electron-Ion Collider: Cannot be HERA or LHeC: proton energy too high

EIC: 21st Century QCD Laboratory

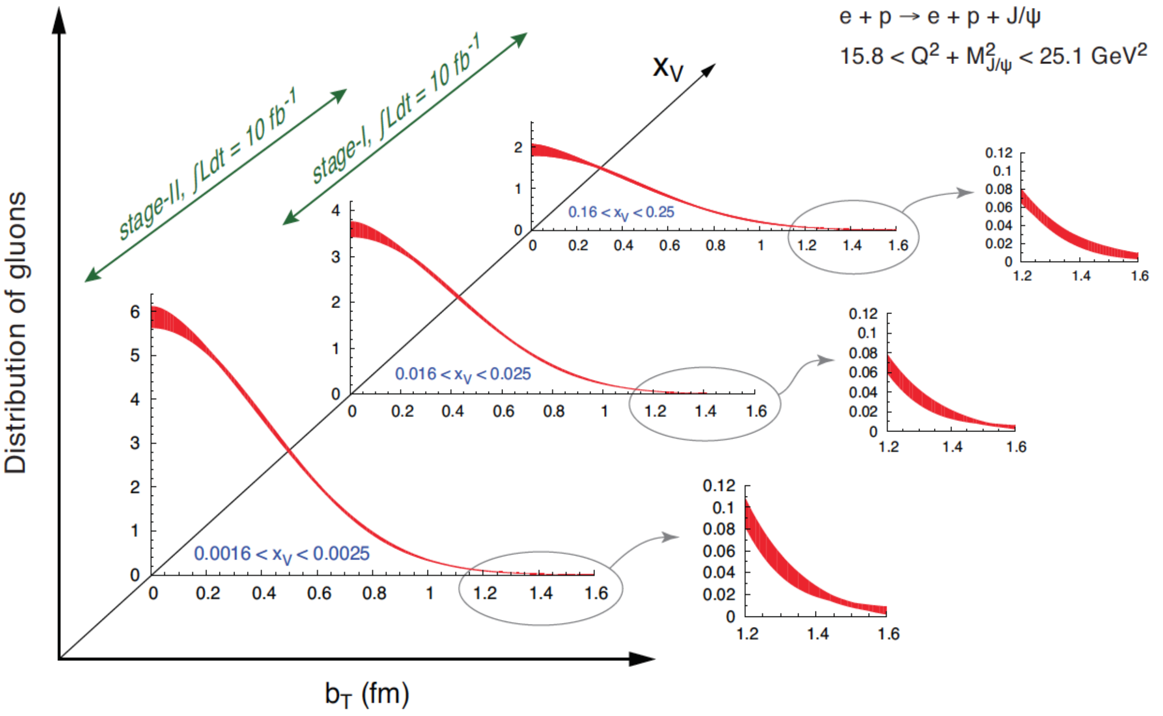
- To explore the fundamental structure and dynamics of the matter in the visible world

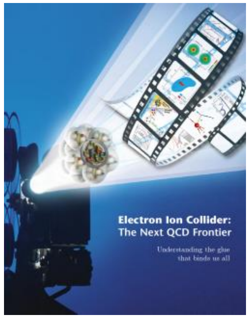
$$L_{QCD} = \sum_{j=u,d,s,\ldots} \bar{q}_j \left[i\gamma^\mu D_\mu - m_j \right] q_j - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}$$

$$D_\mu = \partial_\mu + ig\tfrac{1}{2}\lambda^a A^a_\mu, G^a_{\mu\nu} = \partial_\mu A_\nu + \partial_\nu A_\mu \boxed{+\boldsymbol{igf^{abc}A^b_\mu A^c_\nu}}$$

- Interactions arise through fundamental symmetry principles
- Properties of the visible universe emerge through complex structure of the QCD vacuum
- The proton is a highly relativistic system described by QCD, a fully relativistic quantum field theory.
- Lattice QCD is an increasingly powerful means to carry out *ab initio* QCD calculations of hadron structure in the rest frame.
- The goal of the EIC is to provide us with an understanding of the internal structure of the proton and more complex atomic nuclei that is comparable to our knowledge of the electronic structure of atoms themselves, which lies at the heart of modern technologies.

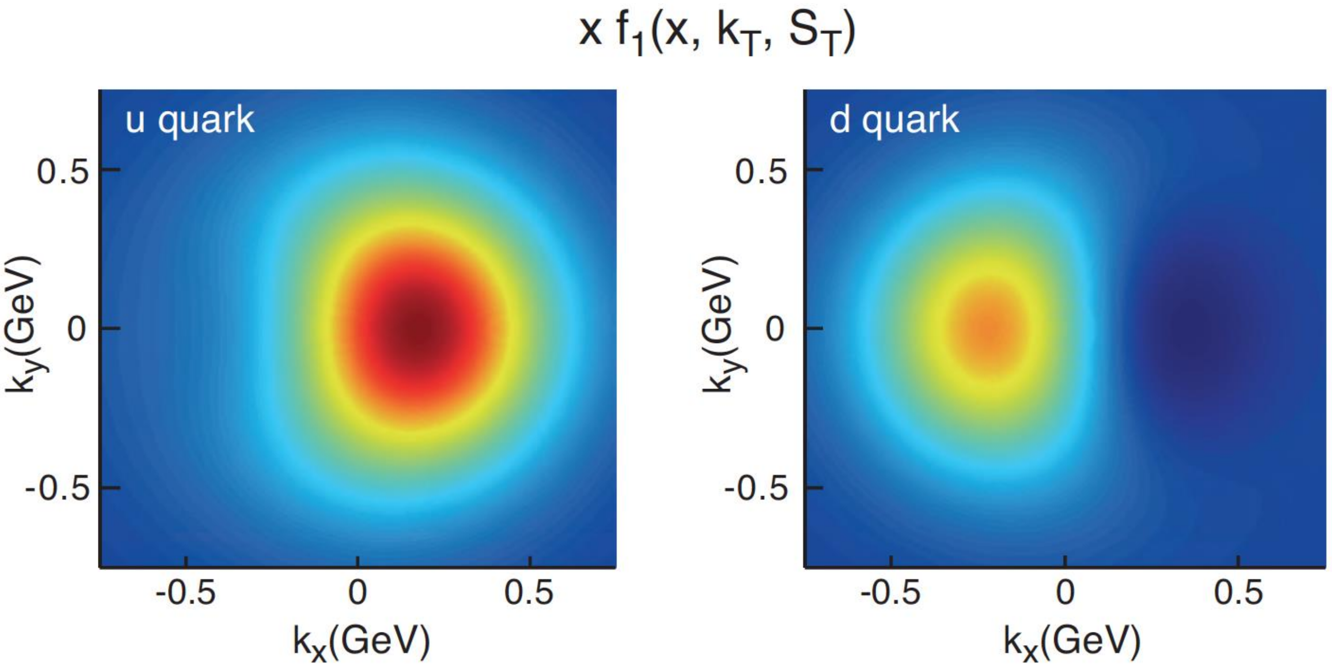
Transverse Spatial Distribution of Gluons

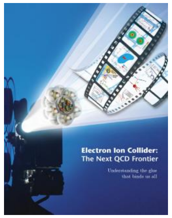




- How are gluons spatially distributed in a proton or a nucleus?
- Is the distribution smooth?
- How does it differ from the charge distribution?
- **First ever tomographic images of ocean of gluons within matter !**

Transverse Momentum Distributions





- Spin and the ability to look at transverse momentum together give a powerful new window into QCD
- TMDs directly related to orbital motion
- For example, we can explore for the first time **interference in quantum phases due to color force – impossible with purely longitudinal experiments**

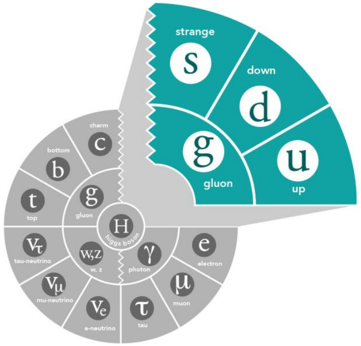
THE INCOMPLETE HADRON: MASS PUZZLE

“Mass without mass!”

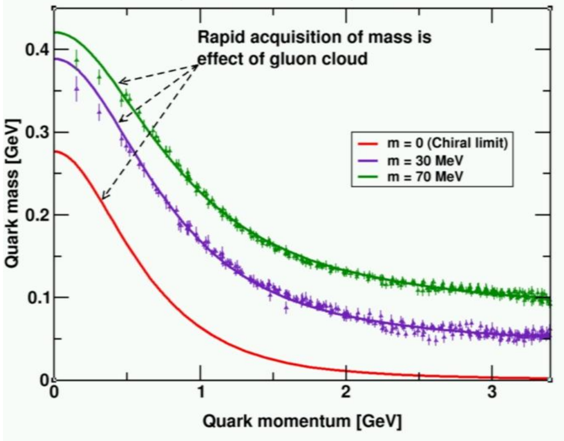
Proton: Mass ~ 940 MeV
constituents acquire mass by DχSB,
most of mass generated by dynamics

Kaon: Mass ~ 490 MeV
boundary between emergent-mass and
Higgs-mass generation mechanisms

Pion: Mass ~ 140 MeV
exists only if mass dynamically generated



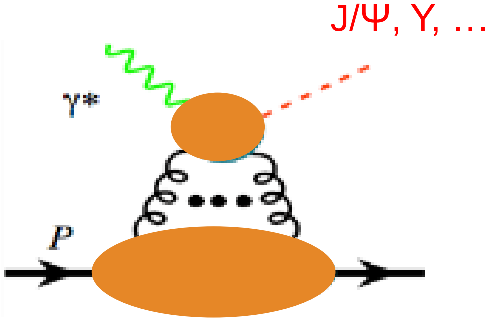
Bhagwat & Tandy/Roberts et al



❑ EIC expected contributions in:

✧ trace anomaly:

Upsilon production near the threshold

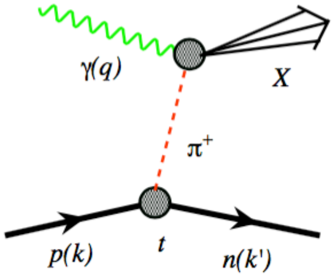


❑ EIC’s expected contributions in:

✧ Quark-gluon energy:
∝ *quark-gluon momentum fractions*

In N with DIS and SIDIS

In π and K with Sullivan process



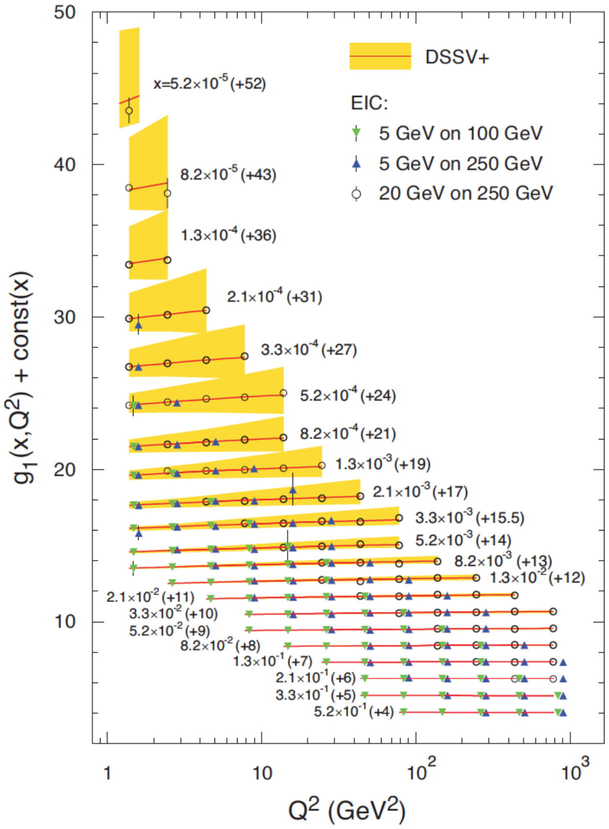
The trace anomaly’s contribution to the masses of the proton and pion could be interpreted as that at large renormalization scales the **proton is full of gluons, whereas the pion is empty of gluons**. On the other hand, from phenomenological view, at a given scale, there is **far less glue in the kaon than in the pion**… This can all be measured at an EIC.

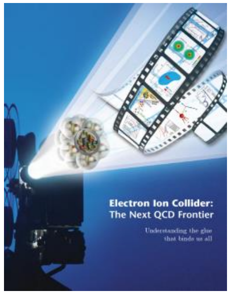
THE INCOMPLETE HADRON: SPIN PUZZLE

“Helicity sum rule”

$$\frac{1}{2}\hbar = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quark contribution}} + \underbrace{\Delta G}_{\text{gluon contribution}} + \underbrace{\sum_q L_q^z + L_g^z}_{\text{orbital angular momentum}}$$

EIC projected measurements:
Precise determination of polarized PDFs of quark sea and gluons ➔ precision ΔG and ΔΣ
➔ Determination of $L_q + L_g$

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