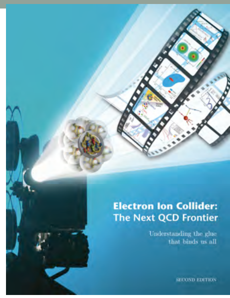
Tuesday, October 29

Session I **(Room: Ariadne) Chair: Latifa Elouadrhiri**		
15:00-15:45	EIC Science Overview	Abhay Deshpande (SBU)
15:45-16:30	EIC Accelerator Design Status	Vasily Morozov (JLab)
16:30-17:00	Coffee Break	
Session II **(Room: Ariadne) Chair: Latifa Elouadrhiri**		
17:00-17:45	EIC Detector Overview	Alexander Kiselev (BNL)
17:45-18:30	Polarized Light Ions	Wim Cosyn (Gent)

“The highest forms of understanding we can achieve are laughter and human compassion.”

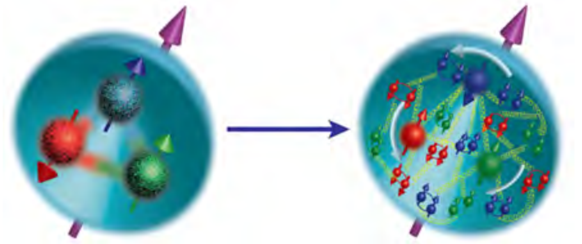
— **Richard P. Feynman**

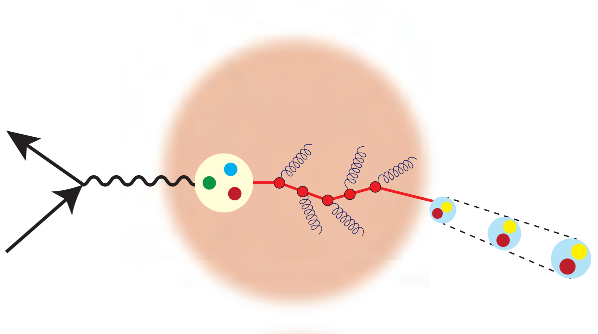


A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?





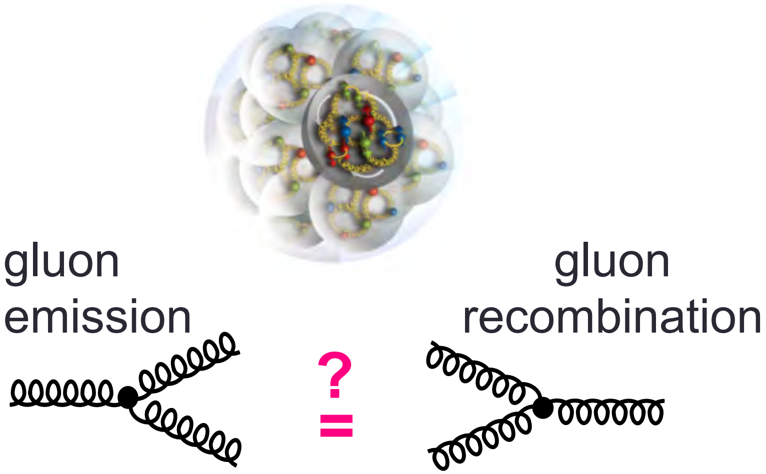
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



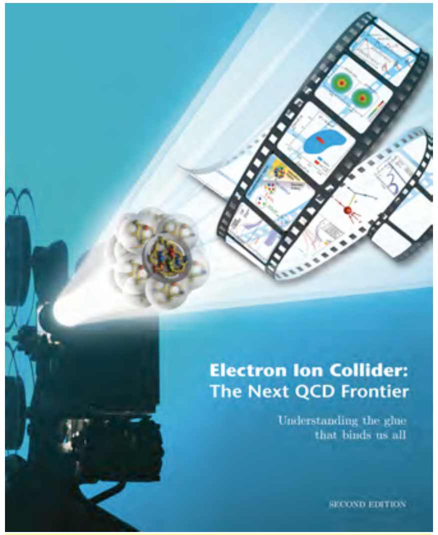
The Electron Ion Collider

For e-N collisions at the EIC:
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ $10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

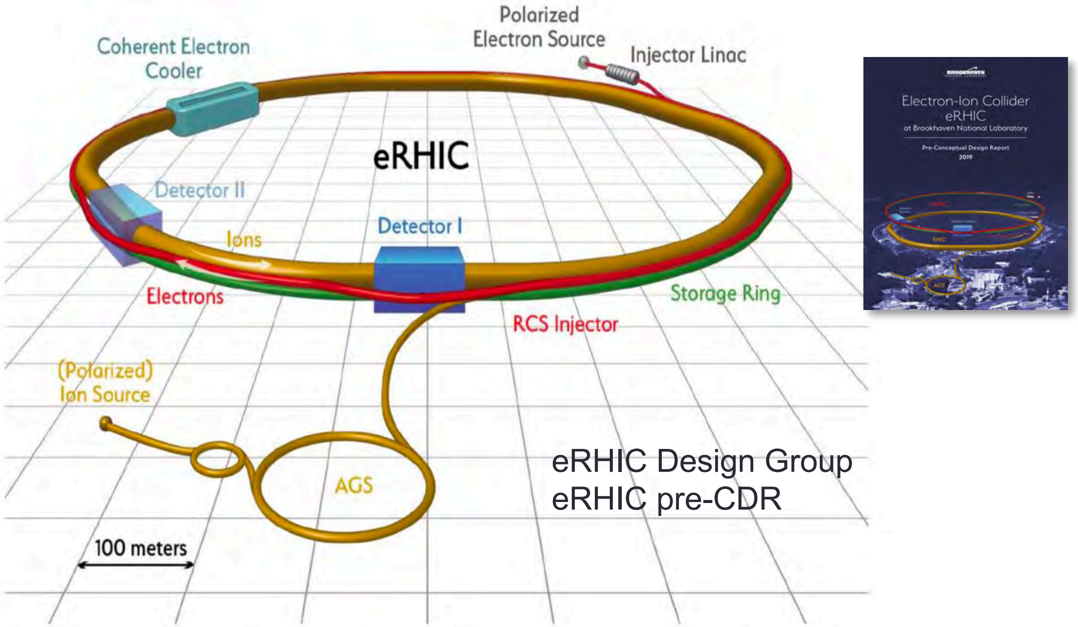
For e-A collisions at the EIC:
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Both designs use DOE's significant investments in infrastructure

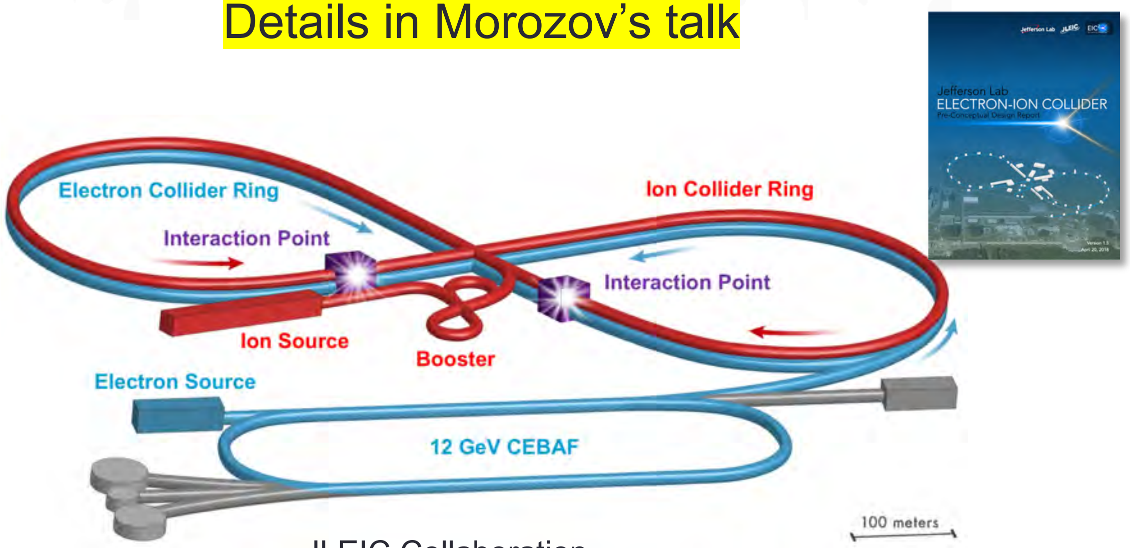


1212.1701.v3
A. Accardi et al
Eur. Phy. J. A, 52 9(2016)

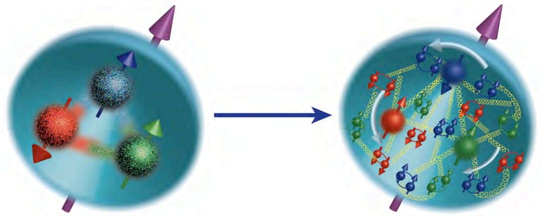


eRHIC Design Group
eRHIC pre-CDR

Details in Morozov's talk



JLEIC Collaboration
JLEIC Pre-CDR

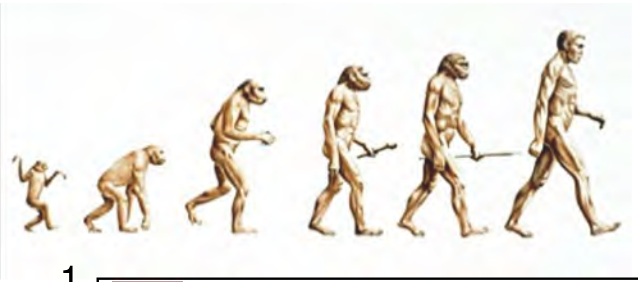


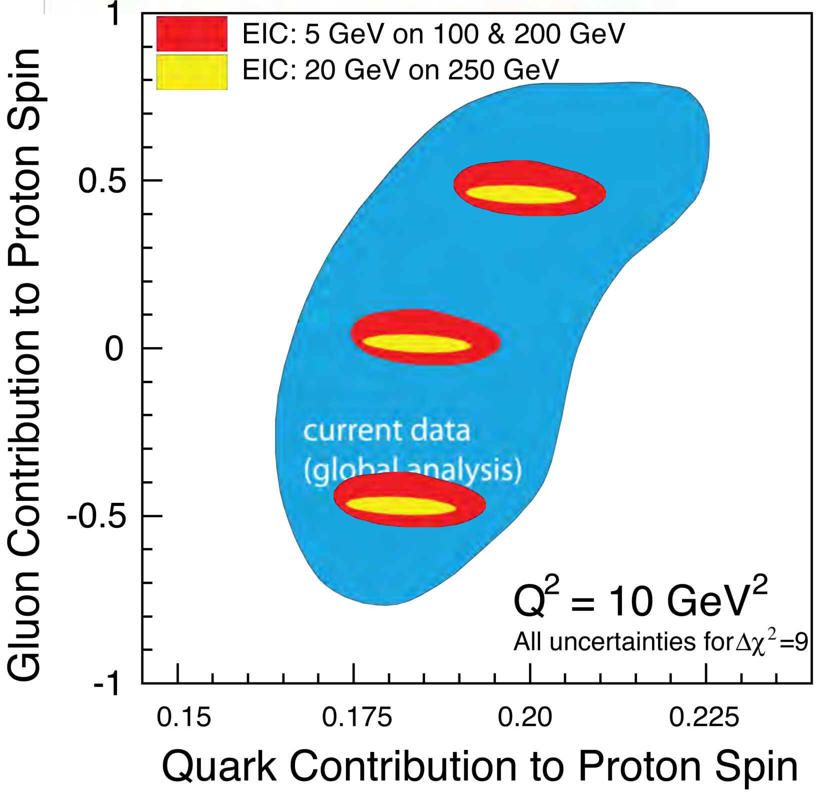
Understanding of Nucleon Spin

$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + \left[\Delta g + L_G\right]$$

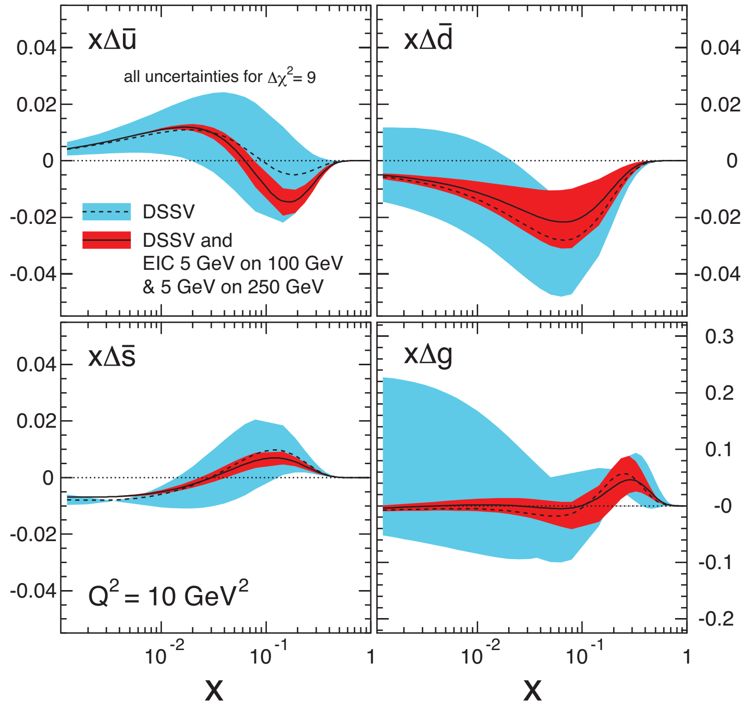
$\Delta\Sigma/2$ = Quark contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
Δg = Gluon contribution to Proton Spin
L_G = Gluon Orbital Ang. Mom

Precision in $\Delta\Sigma$ and Δg ➔ A clear idea Of the magnitude of L_Q+L_G





E. Sichtermann
B. Badelek
R. Fatemi



3-Dimensional Imaging Quarks and Gluons

Wigner functions $W(x,b_T,k_T)$

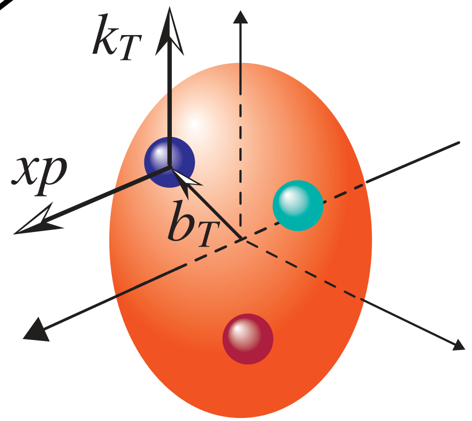
offer unprecedented insight into confinement and chiral symmetry breaking.

$W(x,b_T,k_T)$

Momentum space $\int d^2b_T$

$\int d^2k_T$ ***Coordinate space***

$f(x,k_T)$



$f(x,b_T)$

Spin-dependent 3D momentum space images from semi-inclusive scattering
→ **TMDs**

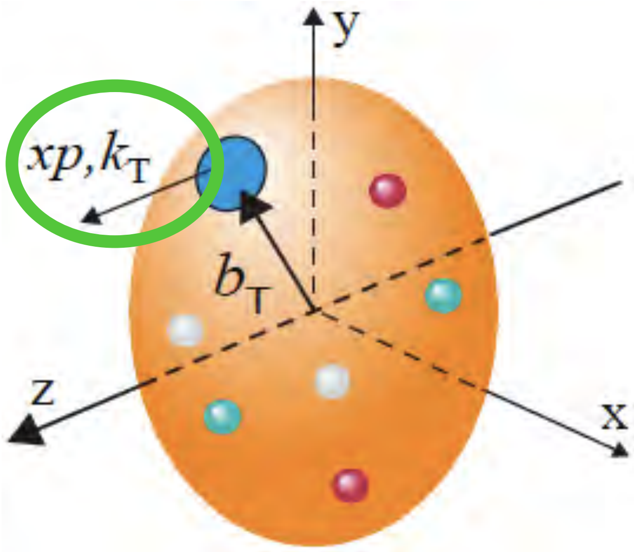
Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering (Deeply Virtual Compton Scattering and Deeply Virtual Vector Meson production)
→ **GPDs**

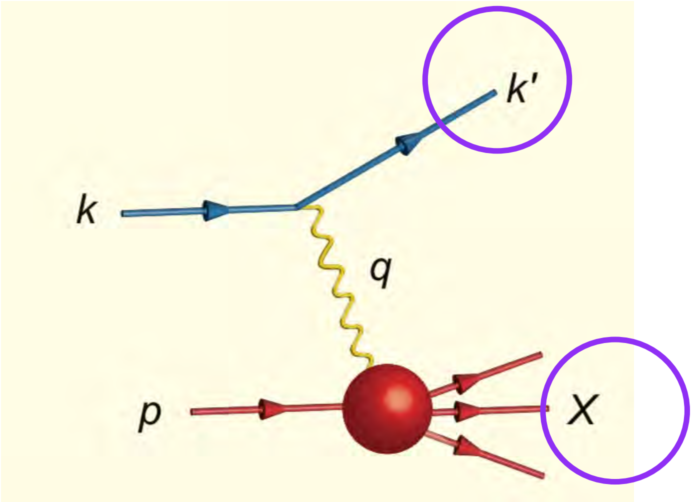
Position and momentum → Orbital motion of quarks and gluons

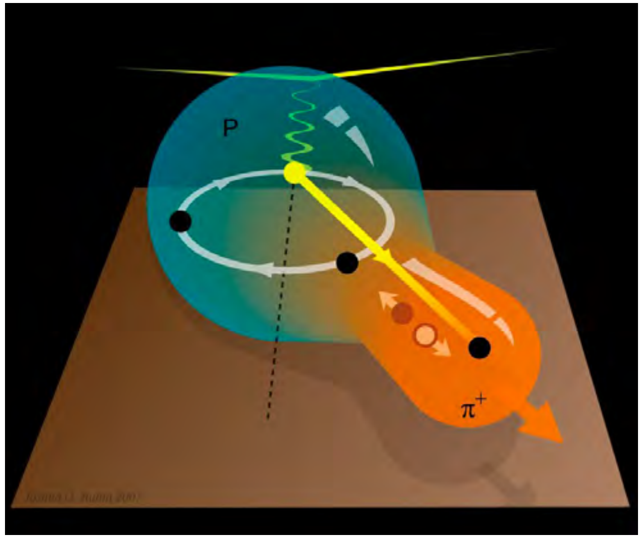
See:
Alexi Prokudin
Daria Sokhan

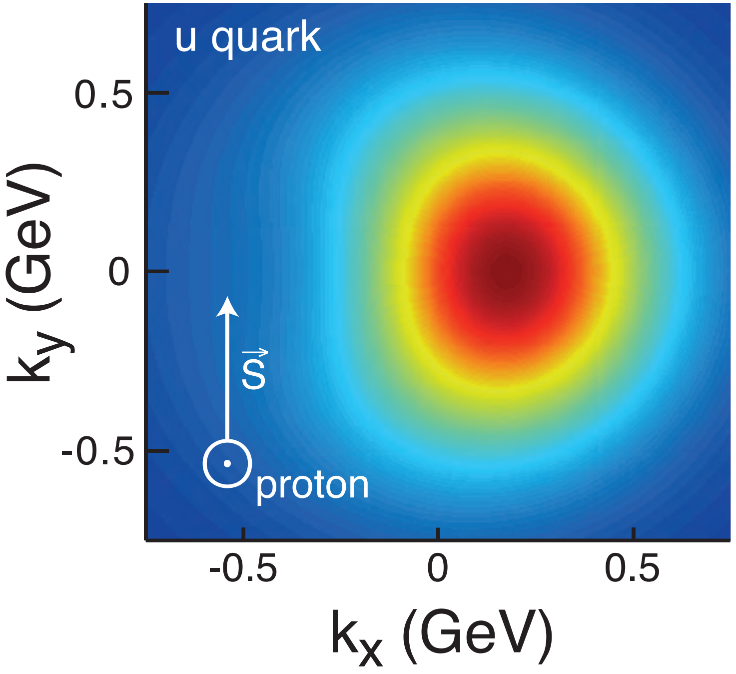
Measurement of Transverse Momentum Distribution

Semi-Inclusive Deep Inelastic Scattering







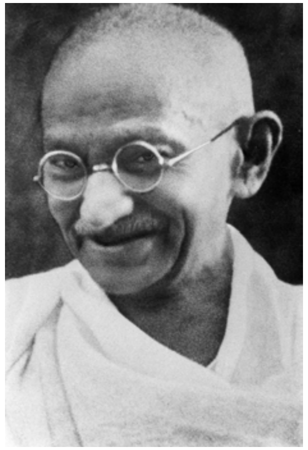


Spatial Imaging of quarks & gluons

Generalized Parton Distributions

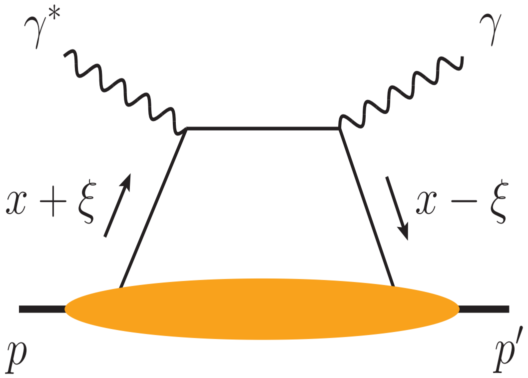
Historically, investigations of nucleon structure and dynamics involved breaking the nucleon…. (exploration of internal structure!)

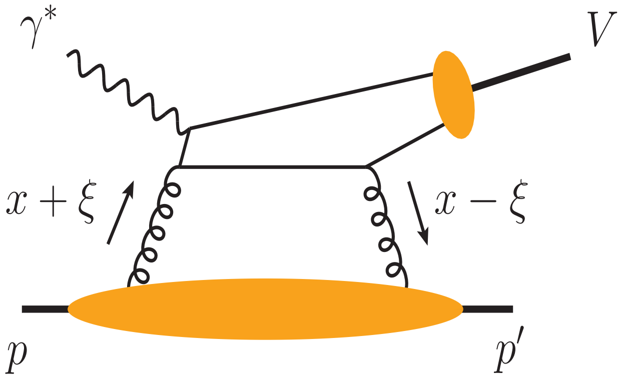
To get to the **orbital motion** of quarks and gluons we need **non-violent collisions**



Exclusive measurements → measure "everything"

Quarks Motion





Gluons: Only @ Collider

Deeply Virtual Compton Scattering
Measure all three final states
e + **p** → e'+ **p'**+ γ

Fourier transform of momentum transferred=(p-p') → Spatial distribution

SLAC-PUB-571
March 1969
(TH)

THEORETICAL IDEAS ON HIGH-ENERGY INELASTIC ELECTRON-PROTON SCATTERING*†

J. D. Bjorken

Stanford Linear Accelerator Center
Stanford University, Stanford, California

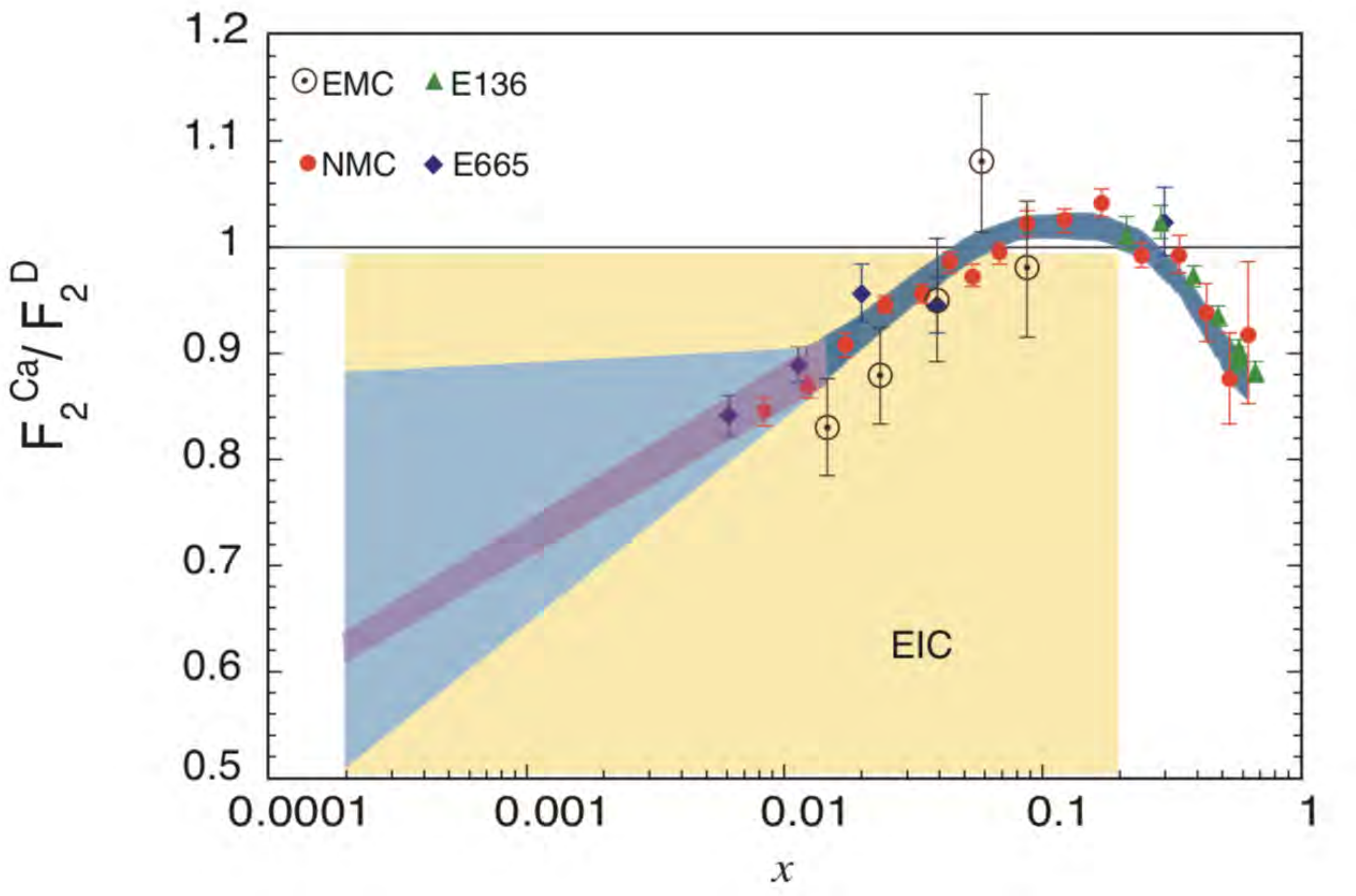
INTRODUCTION

The data on inelastic electron-proton scattering reported by the MIT-SLAC electron-scattering group[1] represents a study of the proton under conditions of extreme violence. The incident electron energy is 7 - 18 BeV, the transverse

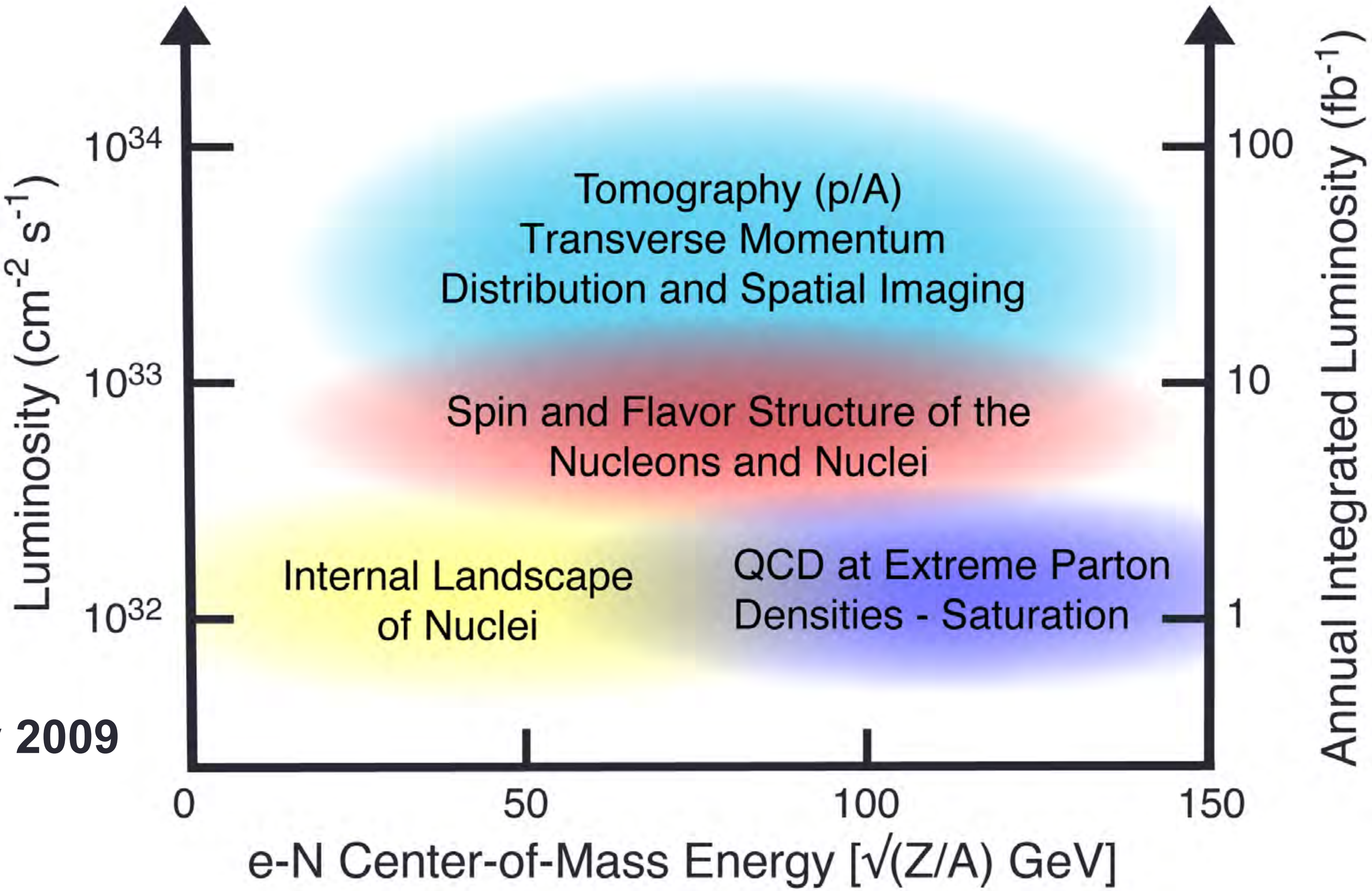
Nuclear PDFs (ratios)

Ratio of F_2 Structure functions of heavy vs. light nuclei
-- See Axel Schmidt's talk Lectures Day 1

No low-x date available. Those that exist are at very low-Q^2, where pQCD methods may not be reliable



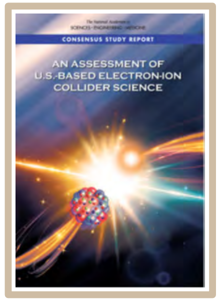
Summary: EIC Physics:
CM vs. Luminosity vs. Integrated luminosity



May 2009
GSI

NAS Consensus: EIC science compelling, fundamental, and timely

July 26, 2018



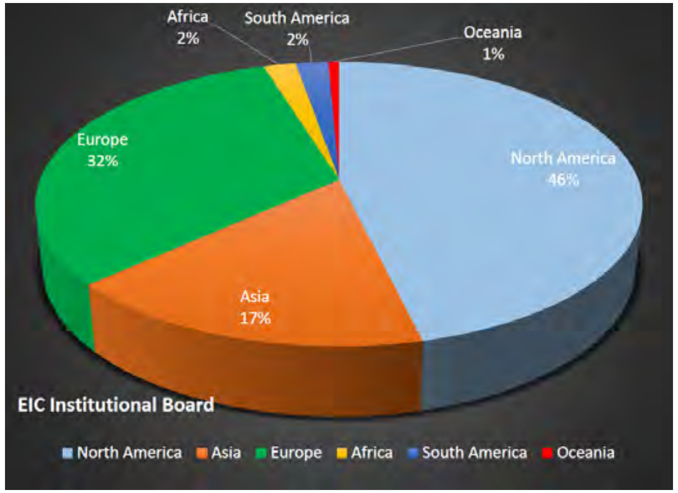
- **Finding 1**: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:
  - How does the mass of the nucleon arise?
  - How does the spin of the nucleon arise?
  - What are the emergent properties of dense systems 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.

Other findings:

An EIC would be a unique facility in the world

Leadership in the accelerator science and technology of colliders

US EIC Cost effective: takes advantage of existing accelerator infrastructure and expertise ➔ reduced risk



The EIC Users Group: EICUG.ORG

Formally established in 2016
~950 Ph.D. Members from 30 countries, 189 institutions

New:
Center for Frontiers in Nuclear Science (at Stony Brook/BNL)
EIC² at Jefferson Laboratory

EICUG Structures in place and active.
EIC UG Steering Committee, Institutional Board, Speaker's Committee

Task forces on:
-- Beam polarimetry, Luminosity measurement
-- Background studies, IR Design

Year long workshops: Yellow Reports for detector design

Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016)**, **Trieste (2017)**, **CAU (2018)**, **Paris (2019)**, **FIU (2020)**, **Warsaw (2021)**

Current Status and Path forward of EIC

Dir. Of office of NP
Tim Hallman's presentation

EICUG
Paris,
July
2019

The "wickets" are substantially aligned for a major step forward on the EIC

- A Mission Need Statement for an EIC has been approved by DOE
- An Independent Cost Review (ICR) Exercise mandated by DOE rules for projects of the projected scope of the EIC is very far along
- DOE is moving forward with a request for CD-0 (approve Mission Need)
- DOE has organized a panel to assess options for siting and consideration of "best value" between the two proposed concepts
- The Deputy Secretary is the Acquisition Executive for this level of DOE Investment
- **The FY 2020 President's Request includes $ 1.5 million OPC. The FY 2020 House Mark includes $ 10 million OPC and $ 1 million TEC.**

Summary:

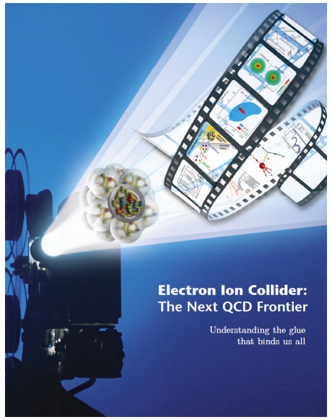
- Science of EIC: Gluons that bind us all… understanding their role in QCD
- EIC's precision, control and versatility will revolutionize our understanding QCD
  - ➢ 3D nucleon/nuclear structure, cold nuclear matter & physics high gluon density

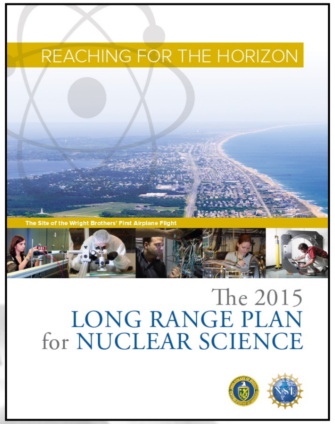
- The US EIC project has significant momentum on all fronts right now:
  - National Academy's positive evaluation → Science compelling, fundamental and timely
  - Funding agencies taking note of the momentum: not just in the US but also internationally

- The science of EIC, technical designs (eRHIC and JLEIC) moving forward
  - Pre-CDRs prepared by BNL (eRHIC) and JLab: machine & IR designs
  - Independent Cost Review underway ➔ CD0 anticipated soon. Siting decision process also underway.

Both Lab managements are committed to working with the DOE, the EICUG and the international partners to realize the US EIC no matter its site (BNL or JLab)

Electron Ion Collider Requirements





Established in Community White Paper*, re-emphasized in 2015 NSAC LRP, and NAS study

- Polarized (~70%) electrons, protons, and light nuclei
  - High polarization essential to physics and delivering it in a timely manner
  - For many measurements statistical uncertainty ~ $1/(\mathbf{L} \times \mathbf{P}_e^{\mathbf{2}} \times \mathbf{P}_p^{\mathbf{2}})^{1/2}$
- Ion beams from deuterons to the heaviest stable nuclei
  - Protons, deuterons, light nuclei, through U or Pb
- Variable center of mass energies ~20-100 GeV, upgradable to ~140 GeV
  - Not a collider to achieve highest possible CoM energy
  - Highest luminosity demands in mid energy range
- High collision luminosity ~$10^{33\text{-}34}$ cm^{-2} s^{-1}
  - "Factory"-like luminosity, factor of 100-1000 beyond HERA
- Possibility of more than one interaction region

*A. Accardi et al. , "Electron Ion Collider: The Next QCD Frontier - Understanding the Glue that Binds Us All", Eur. Phys. J. A52 , p. 268 (2016), https://doi.org/10.1140/epja/i2016-16268-9

EIC Designs

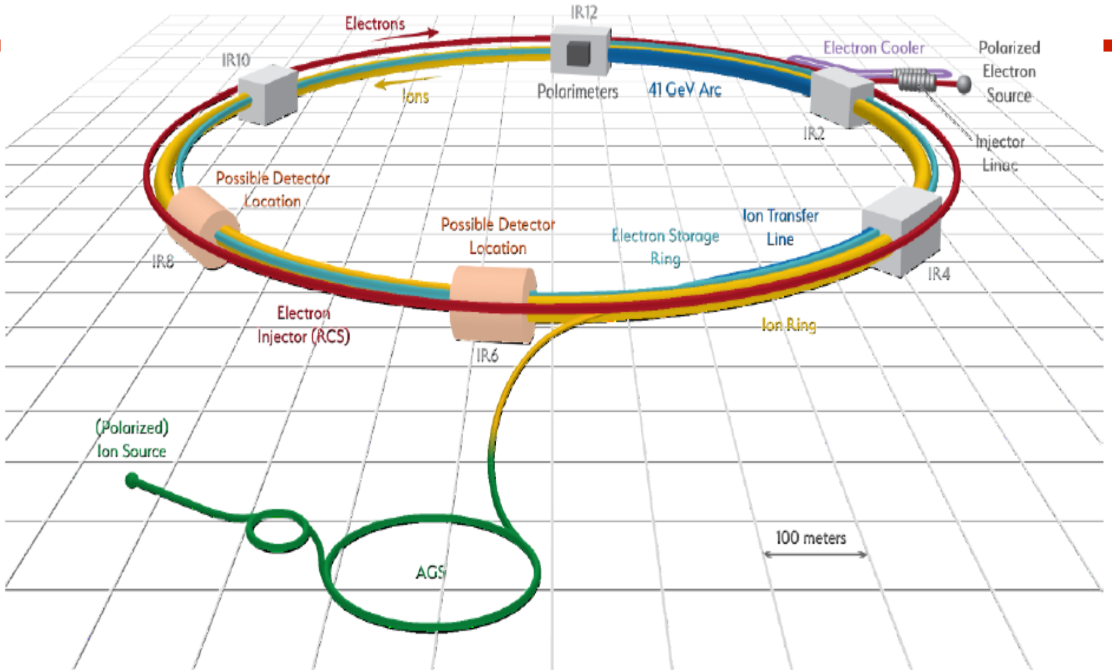
Both EIC concepts designed to meet the requirements set forth in NSAC Long Range Plan, which was emphasized by the NAS report:

- Highly polarized (~70%) electron and nucleon beams
- Ion beams from deuterons to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from ~20 - ~100 GeV, upgradable to ~140 GeV
- High collision luminosity ~10^{33} – 10^{34} $cm^{-2}s^{-1}$
- Possibilities of having more than one interaction region

Both designs based on ring-ring approach, both benefit from existing Nuclear Physics infrastructure and are based on the same accelerator principles:

Electron Storage Rings with frequent injection of fresh polarized beams
Hadron storage rings with strong cooling or alternatively frequent injections

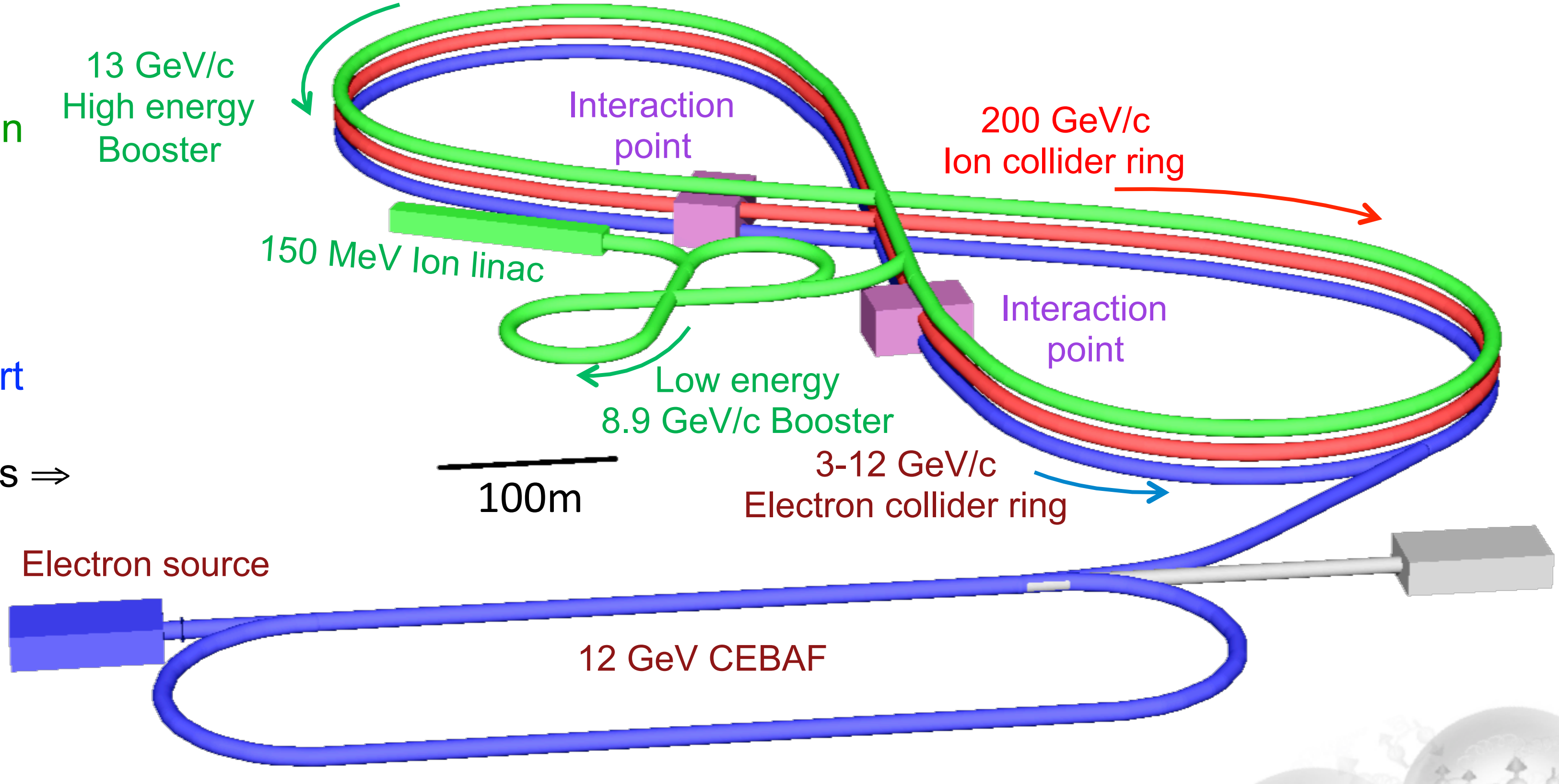
eRHIC Layout



- **Hadrons up to 275 GeV**
  - eRHIC is based upon the existing RHIC complex: Storage ring (Yellow Ring), injectors, ion sources, infrastructure
  - Need only few modifications for eRHIC
  - Today's RHIC beam parameters are close to what is required for eRHIC
- **Electrons up to 18 GeV**
  - Electron storage ring with up to 18 GeV ➔ E_{cm} = 20 GeV -141 GeV installed in RHIC tunnel. Beam current are limited by the choice of installed RF power 10 MW
  - Electron beams with a variable spin pattern accelerated in the on-energy, spin transparent injector: Rapid Cycling Synchrotron with 1-2 Hz cycle frequency in the RHIC tunnel
  - Polarized electron source and 400 MeV s-band injector linac in existing tunnel
  - Design meets the high luminosity goal of **$L = 10^{34} cm^{-2} s^{-1}$**

JLEIC Layout

- Full-energy top-up injection of highly polarized electrons from CEBAF ⇒ High stored electron current and polarization
- Full-size high-energy booster ⇒ Quick replacement of colliding ion beam ⇒ High average luminosity
- High-rate collisions of strongly-focused short low-charge low-emittance bunches similarly to record-luminosity lepton colliders ⇒ High luminosity
- Multi-stage electron cooling using demonstrated magnetized cooling mechanism ⇒ Small ion emittance ⇒ High luminosity



- Figure-8 ring design ⇒ High electron and ion polarizations, polarization manipulation and spin flip
- Integrated full acceptance detector with far-forward detection sections being parts of both machine and detector
- Upgradable to 140 GeV CM by replacing the ion collider 6T NbTi cosθ bending dipoles only with 12 T Nb3Sn magnets
- Design meets the high luminosity goal of **$L = 10^{34} cm^{-2} s^{-1}$**

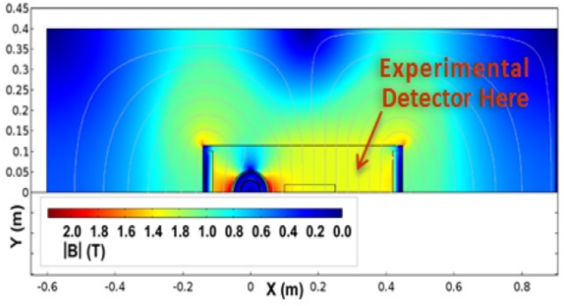
On-Going EIC R&D Effort

Component Development

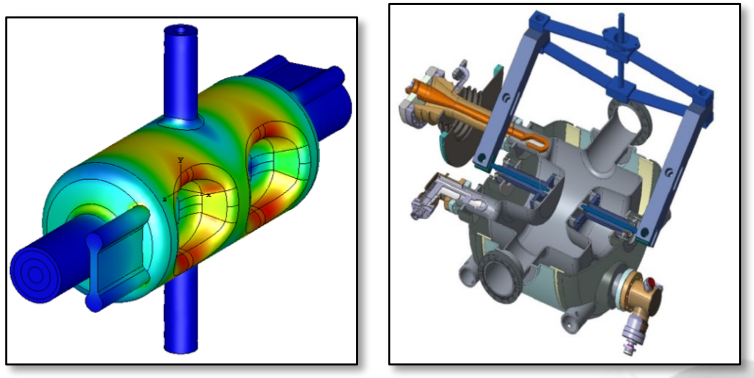
- Crab Cavity design development and prototyping
- IR magnet development and prototyping
- HOM damping for RF structure development
- Variable coupling high power forward power couplers development
- Effective in situ Cu coating of the beam pipe (BNL hadron only)
- High average current electron gun development
- Polarized ^{3}He source
- Bunch by bunch polarimetry

Accelerator Physics R&D

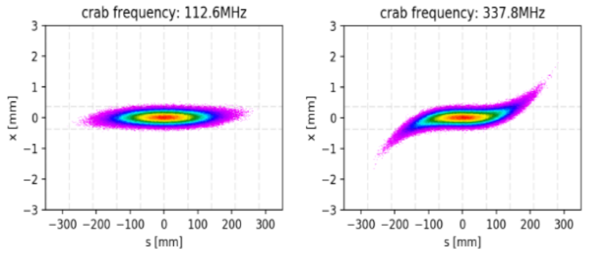
- Strong hadron cooling CeC, cooling development (simulation and experimental)
- Strong hadron cooling bunches electron beam cooling (simulation and experimental)
- ERL development for strong hadron cooling
- Test of suppression of intrinsic depolarizing resonances
- Experimental verification of figure-8 spin transparency
- Study of residual crab cavity effect on beam emittance



Instrumented accelerator magnet



Crab cavity prototypes developed for CERN SpS tests



Crabbed beam dynamics

EIC experimental program in one slide

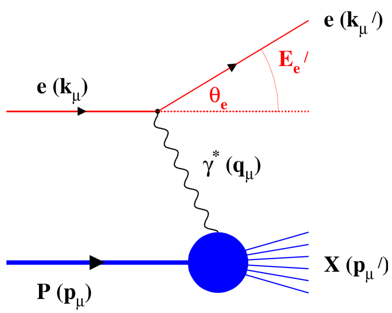
Parton Distributions in nucleons and nuclei

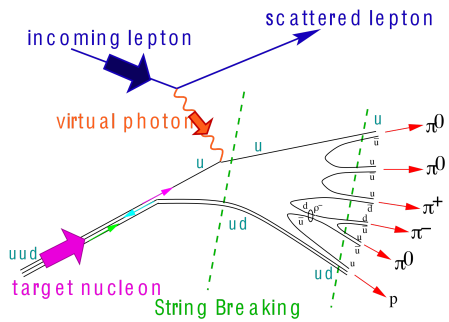
Spin and Flavor structure of nucleons and nuclei

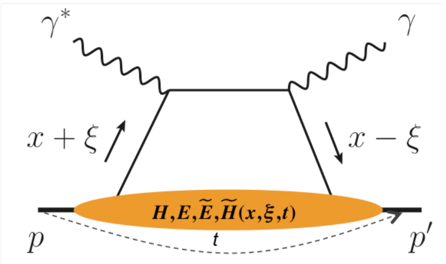
Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging







inclusive DIS

- measure scattered lepton
- two-dimensional binning: $\{x, Q^2\}$

→ reach to lowest x, Q^2 impacts Interaction Region design

~1 fb^{-1}

semi-inclusive DIS

- measure scattered lepton and hadrons in coincidence
- multi-dimensional binning: $\{x, Q^2, z, p_T, \Phi\}$

→ hadron identification over entire acceptance is critical

~10 fb^{-1}

exclusive processes

- measure all particles in event
- multi-dimensional binning: $\{x, Q^2, t, \Phi\}$
- proton p_t: 0.2 - 1.3 GeV/c

→ cannot be detected in main detector

→ strong impact on Interaction Region design

10-100 fb^{-1}

EIC Detector Concepts

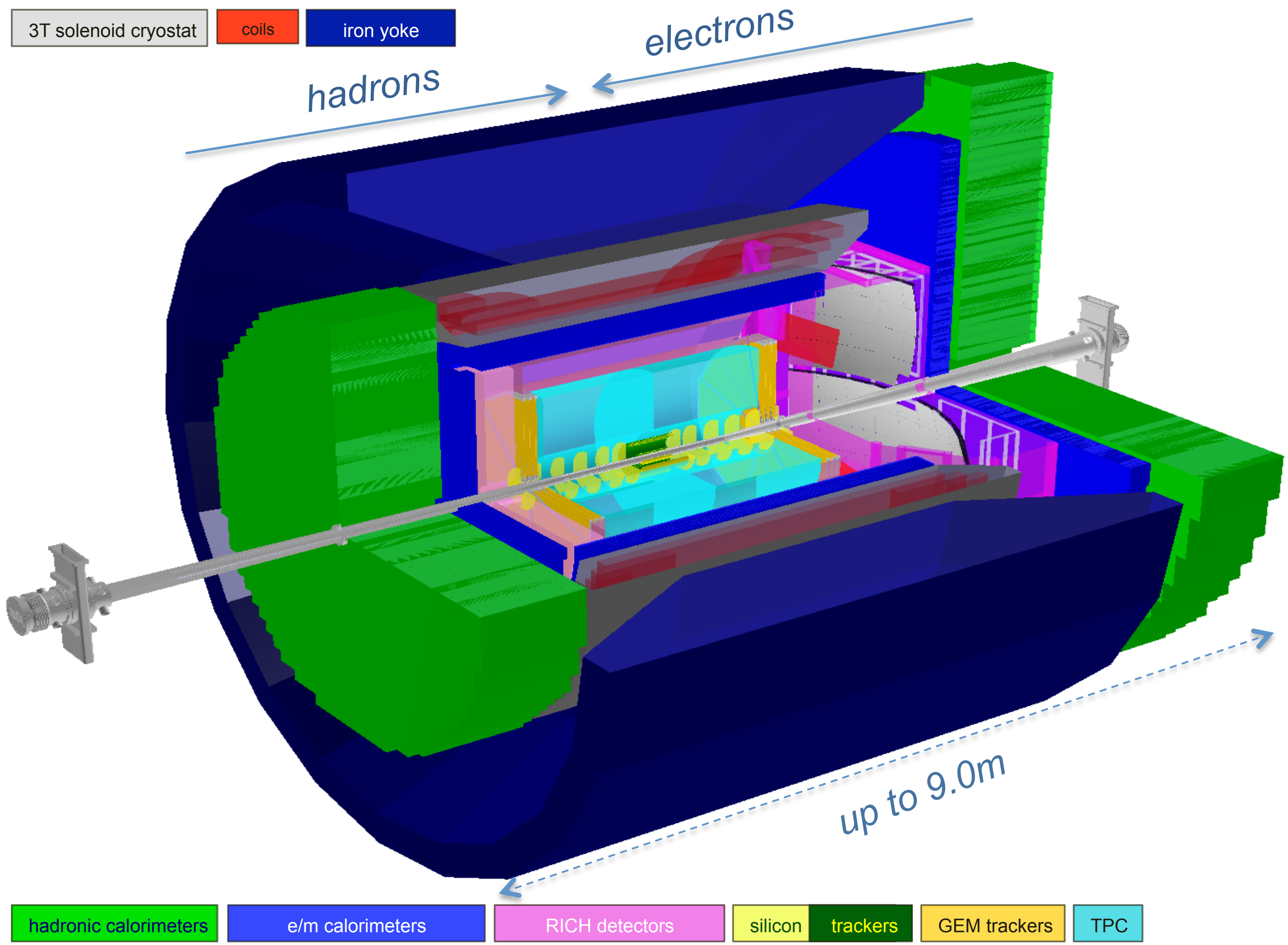
- **Common features:**
  - Compact design, driven by strong beam focusing at the IP
  - (Almost) 4π hermetic acceptance in tracking/calorimetry/PID

  - Vertex + central + forward/backward + far forward tracker layout

  - Low material budget in the tracker volume
  - Strong central solenoid field

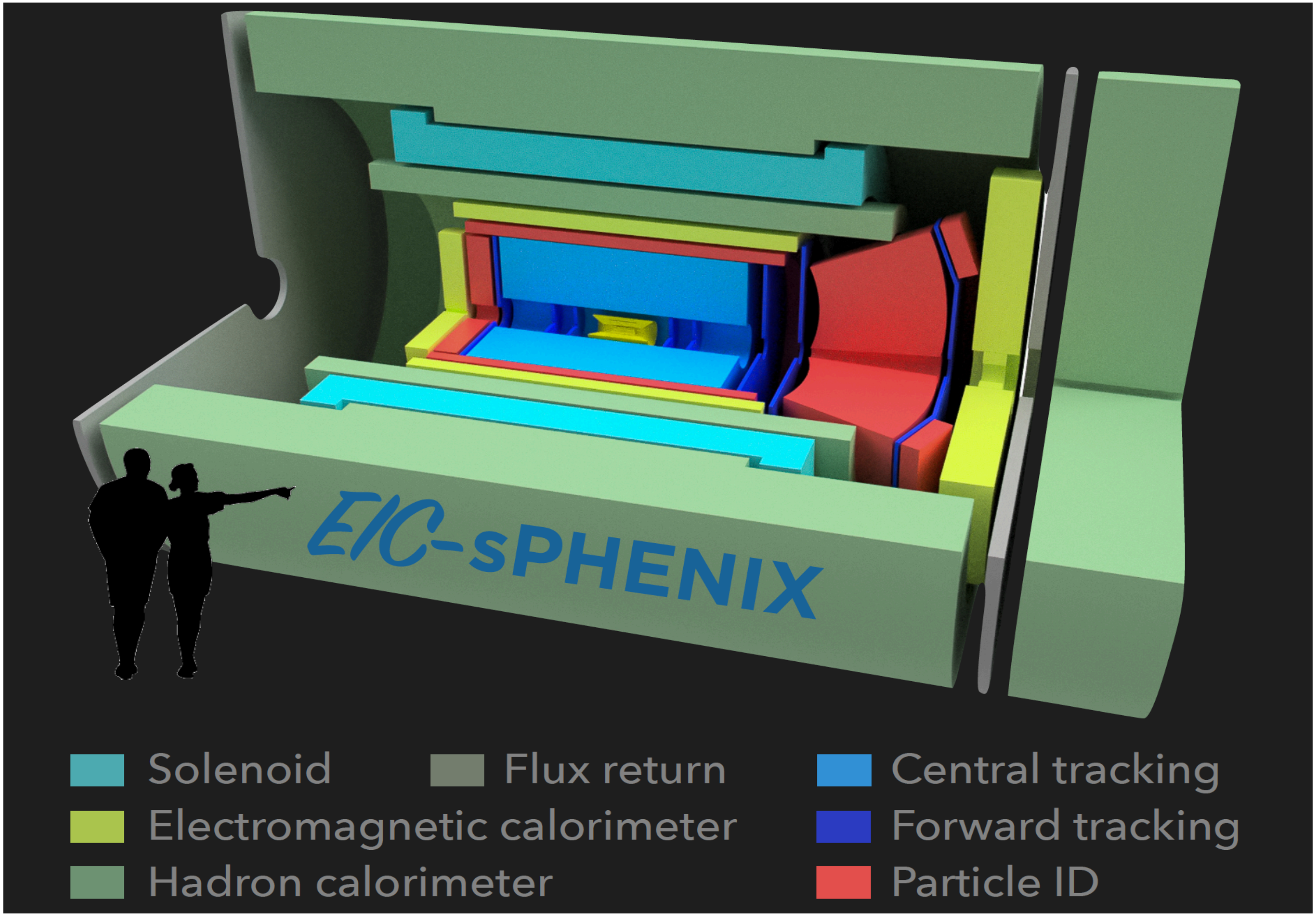
  - Moderate momentum resolution (~1% level)
  - Moderate EmCal and HCal energy resolution

BeAST



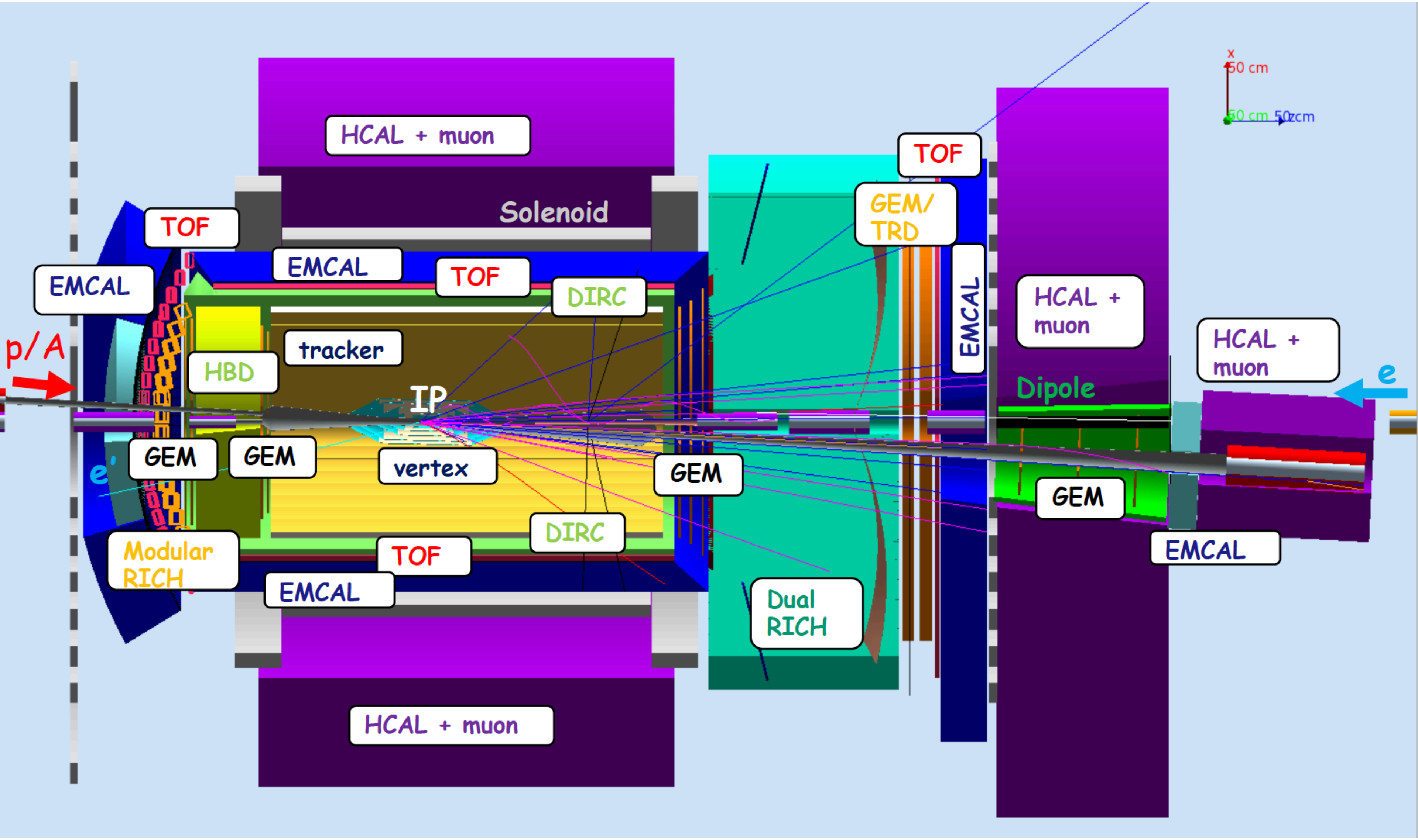
- **Brookhaven Laboratory (BNL) “green field” detector**

ePHENIX



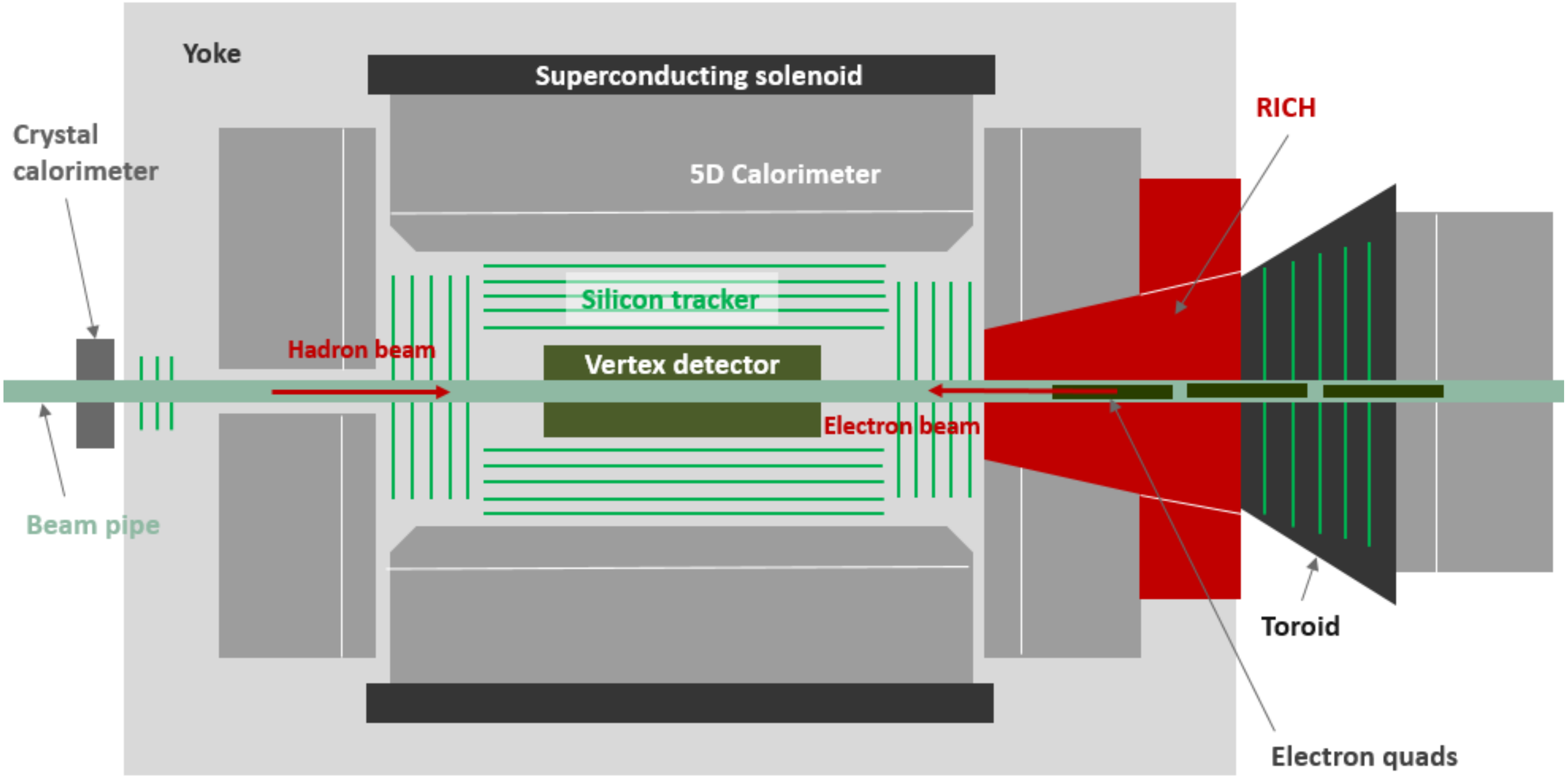
- **Brookhaven Laboratory sPHENIX-based implementation**

JLEIC



- **Jefferson Laboratory (JLab) "green field" detector**

TOPSiDE



- **Argonne Laboratory (ANL) all-silicon implementation**

Interaction Region (IR) design goals

- Focus both beams to small spot sizes for maximum luminosity
  - Deal with a very confined machine-element-free region around the IP
- Minimize beam divergence as it is equivalent to P_t smearing
  - This is in conflict with maximizing the luminosity
- Run with a high collision frequency to increase the luminosity
  - Bunch-by-bunch luminosity and polarization measurements become challenging

- Provide early beam separation and minimize synchrotron radiation
  - Use crossing angle -> introduce crabbing to recover the luminosity
- Pass synchrotron radiation through the detector with minimal losses
  - Have to increase the diameter of the beam pipe at the IP & find space for masks

- Provide clear close-to-beam-line acceptance and separation for several types of secondary particles
  - This causes numerous conflicts between the IR subsystems

-> Need to find a working compromise between mutually exclusive requirements

Why focus on light ions at an EIC?

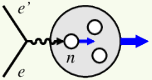
- Measurements with light ions address essential parts of the EIC physics program
  - neutron structure
  - nucleon interactions
  - coherent phenomena

- Light ions have unique features
  - polarized beams
  - breakup measurements & tagging
  - first principle theoretical calculations of initial state

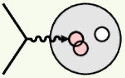
- Intersection of two communities
  - high-energy scattering
  - low-energy nuclear structure

Use of light ions for high-energy scattering and QCD studies remains relatively unexplored

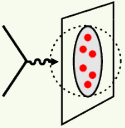
Light ions at EIC: physics objectives



- **Neutron** structure
  - flavor decomposition of quark PDFs/GPDs/TMDs
  - flavor structure of the nucleon sea
  - singlet vs non-singlet QCD evolution, leading/higher-twist effects



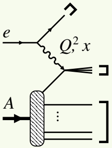
- Nucleon **interactions** in QCD
  - medium modification of quark/gluon structure
  - QCD origin of short-range nuclear force
  - nuclear gluons
  - coherence and saturation

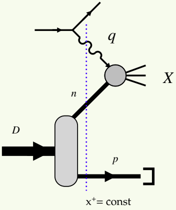


- **Imaging** nuclear bound states
  - imaging of quark-gluon degrees of freedom in nuclei through GPDs
  - clustering in nuclei

Need to control nuclear configurations that play a role in these processes

Theory: high-energy scattering with nuclei





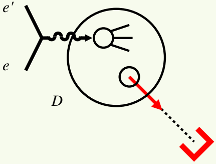
- Interplay of two scales: high-energy scattering and low-energy nuclear structure. Virtual photon probes nucleus at fixed lightcone time $x^+ = x^0 + x^3$

- Scales can be separated using methods of light-front quantization and QCD factorization

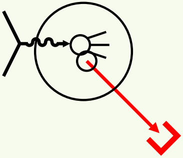
- Tools for high-energy scattering known from *ep*

- Nuclear input: light-front momentum densities, spectral functions, overlaps with specific final states in breakup/tagging reactions
  - framework known for deuteron, can be extended to ^{3}He
  - still **low-energy** nuclear physics, just formulated differently

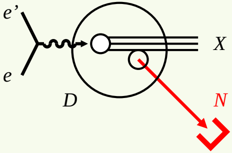
Tagging: EMC effect



average-size



small-size



Final−state interactions

- Medium modification of nucleon structure embedded in nucleus (EMC effect)
  - dynamical origin?
  - caused by which momenta/distances in nuclear WF
  - spin-isospin dependence?
- tagged EMC effect
  - recoil momentum as extra handle on medium modification (off-shellness, size of nuclear configuration) away from the on-shell pole
  - EIC: Q^2 evolution, gluons, spin dependence!
- Interplay with final-state interactions!
  - use $\tilde{x} = 0.2$ to constrain FSI
  - constrain medium modification at higher $\tilde{x}$

Wednesday, October 30

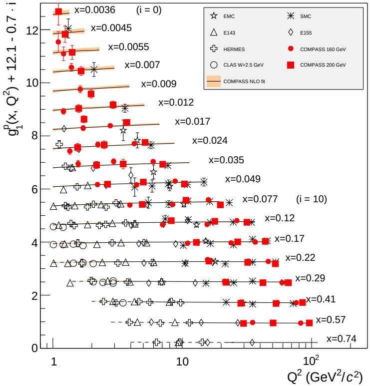
Session I **(Room: Ariadne) Chair: Ernst Sichtermann**		
15:00-15:45	Nucleon Longitudinal Spin Structure	Barbara Badelek (Warsaw)
15:45-16:30	Imaging the Proton	Daria Sokhan (Glasgow)
16:30-17:00	Coffee Break	
Session II **(Room: Ariadne) Chair: Ernst Sichtermann**		
17:00-17:45	Nuclear PDFs	Jacob Ethier (Amsterdam)
17:45-18:30	New Scientific Opportunities with Spin-dependent Electron Scattering from Polarized He-3	Richard Milner (MIT)

g_1^{p} and g_1^{d}, $Q^2 >1$ (GeV/c)^2, COMPASS full statistics

COMPASS NLO QCD fit to the world data at $W^2 > 10$ (GeV/c^2)^2

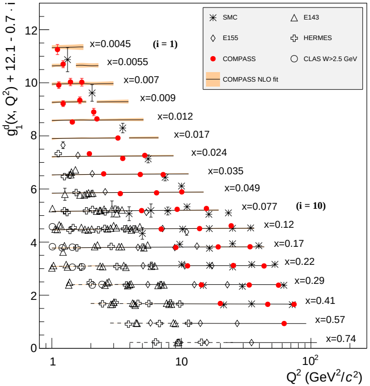
dashed line: extrapolation to $W^2 < 10$ (GeV/c^2)^2

proton



Phys.Lett.B753(2016)18

deuteron



COMPASS PL B769 (2017) 034

COMPASS measurements at high Q^2 important for the QCD analysis! but little sensitive to Δg

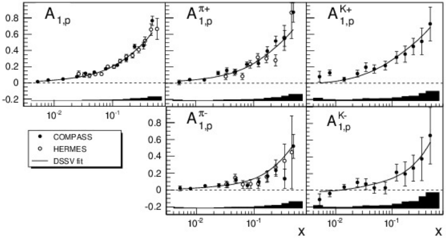
Semi-inclusive asymmetries, A_1^{h} and parton distributions

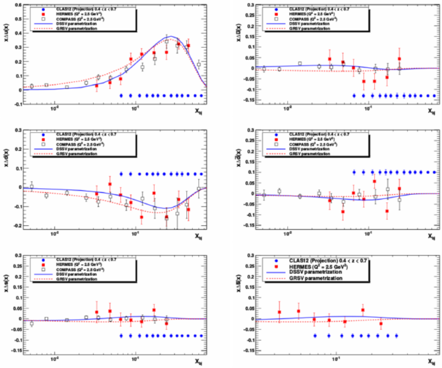
- COMPASS: measured on both proton and deuteron targets
for identified, positive and negative pions and (for the first time) kaons

CLAS12, Update to E12-09-007

COMPASS, Phys. Lett. B **693** (2010) 227

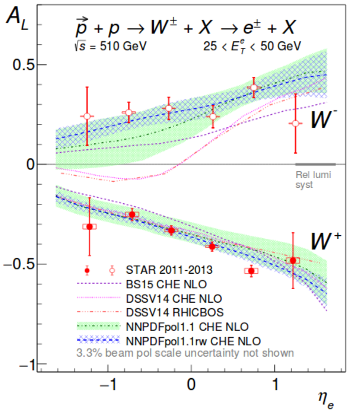
DSSV, Phys. Rev. D **80** (2009) 034030



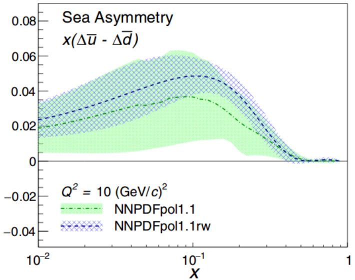


- COMPASS: LO DSS fragm. functions and LO unpolarised MRST assumed here.
- NLO parameterisation of DSSV describes the data well.

Recent results from STAR on sea polarisation



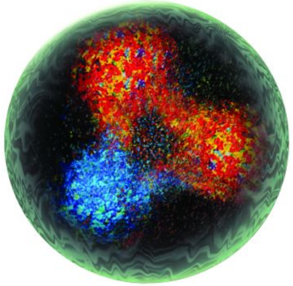
STAR, PR D99 (2019) 051102



- The polarised sea is probably unsymmetric (STAR) contrary to COMPASS result
- This is opposite to spin-averaged quark sea asymmetry

Take away menu

- Measurements of $g_1^{\mathrm{p}}(x, Q^2)$ and $g_1^{\mathrm{d}}(x, Q^2)$ for DIS ($Q^2 >$1 (GeV/c)^2) and nonperturbative ($Q^2 <$1 (GeV/c)^2) regions cannot be improved $\Longrightarrow$ EIC !
- The $g_1^{\mathrm{p}}(x)$ at low x and low Q^2 is clearly positive ($g_1^{\mathrm{d}}(x)$ is consistent with zero) $\Longrightarrow$ first observation of the spin effect at such low x
- The $g_1^{\mathrm{p}}(x)$ at low x is positive (and $g_1^{\mathrm{d}}(x) \approx 0$) also at $Q^2 >$1 (GeV/c)^2
- NLO QCD fit of g_1 world data gave well constrained quark distributions; gluons poorly determined. Quark helicity contribution to nucleon spin: $0.26 < \Delta\Sigma < 0.36$ but hope is in global fits (PDFs and FFs)
- Need to understand hadron multiplicites $\Longrightarrow$ FFs !
- From the COMPASS data alone:
  - first moments determined and Bjorken sum rule verified to 9% accuracy
  - flavour-singlet axial charge a_0 extracted:
    $a_0(Q^2$ = 3 (GeV/c)^2)= 0.32 $\pm 0.02_{\mathrm{stat.}} \pm 0.04_{\mathrm{syst.}} \pm 0.05_{\mathrm{evol.}}$
    (in $\overline{\mathrm{MS}}$ identified with total contribution of quark helicities to the nucleon spin)

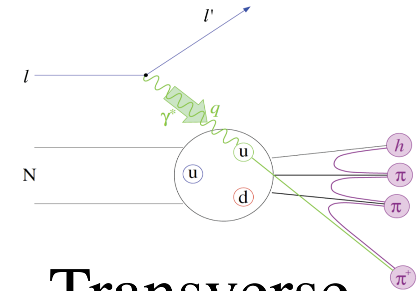


Wigner function: full phase space parton distribution of the nucleon

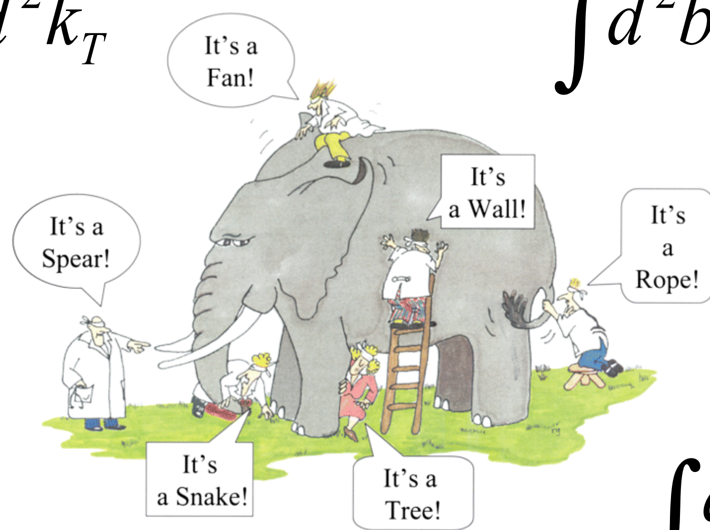
Generalised Transverse Momentum Distributions (GTMDs)

$\int d^2k_T$

$\int d^2b_T$

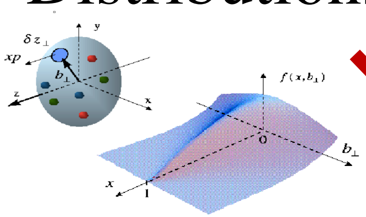


Transverse Momentum Distributions (TMDs)



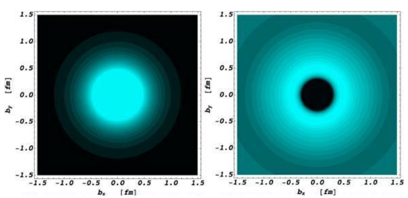
G. Renee Guzlas, artist.

Generalised Parton Distributions (GPDs)



$\int dx$

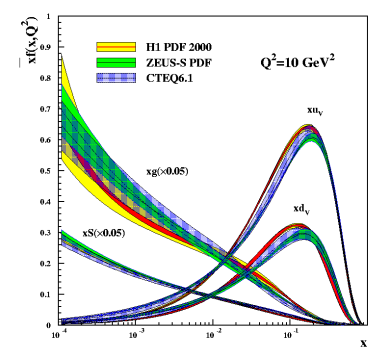
$\int d^2k_T$



Form Factors

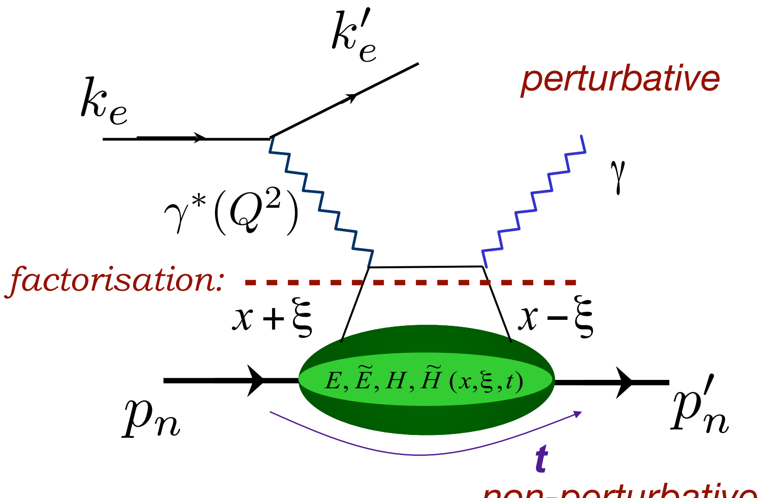
eg: G_{E}, G_{M}

Parton Distribution Functions (PDFs)



Deeply Virtual Compton Scattering

the "golden channel" for GPD extraction



"Handbag" diagram

$$Q^2 = -(\mathbf{k}-\mathbf{k}')^2 \qquad t = (\mathbf{p_n'} - \mathbf{p_n})^2$$

Bjorken variable: $x_B = \dfrac{Q^2}{2\mathbf{p_n}\cdot\mathbf{q}}$

$x \pm \xi$ *longitudinal momentum fractions of the struck parton*

Skewness: $\xi \cong \dfrac{x_B}{2-x_B}$

- At high exchanged Q^2 and low t access to four parton helicity-conserving, chiral-even GPDs:

$$E^q, \tilde{E}^q, H^q, \tilde{H}^q(x,\xi,t)$$

- Can be related to PDFs:

$$H(x,0,0) = q(x) \qquad \tilde{H}(x,0,0) = \Delta q(x)$$

and form factors:

$$\int_{-1}^{+1} H dx = F_1 \qquad \int_{-1}^{+1} \tilde{H}\, dx = G_A$$

$$\int_{-1}^{+1} E\, dx = F_2 \qquad \int_{-1}^{+1} \tilde{E}\, dx = G_P$$

(Dirac and Pauli) *(axial and pseudo-scalar)*

- Small changes in nucleon transverse momentum allows mapping of transverse structure at large distances.

John Bercow, Speaker of the House
(*BT.com*)

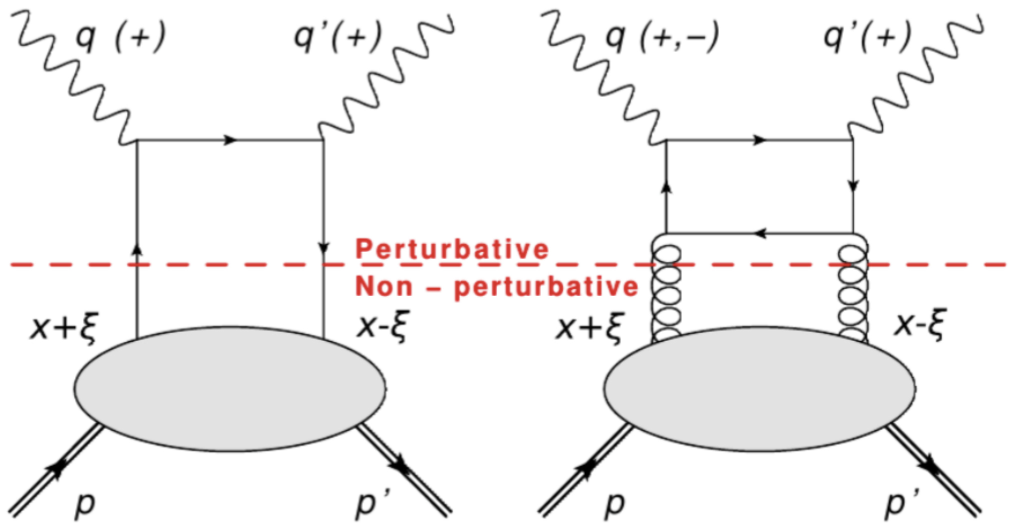
Order and Twist

- Twist: powers of $\frac{1}{\sqrt{Q^2}}$ in the DVCS amplitude. Leading-twist (LT) is twist-2.

- Order: introduces powers of α_s

Leading order (LO)

Next-to-leading order (NLO)



- Leading Order (LO) requires $Q^2 >> M^2$ (M: target mass)

CLAS12

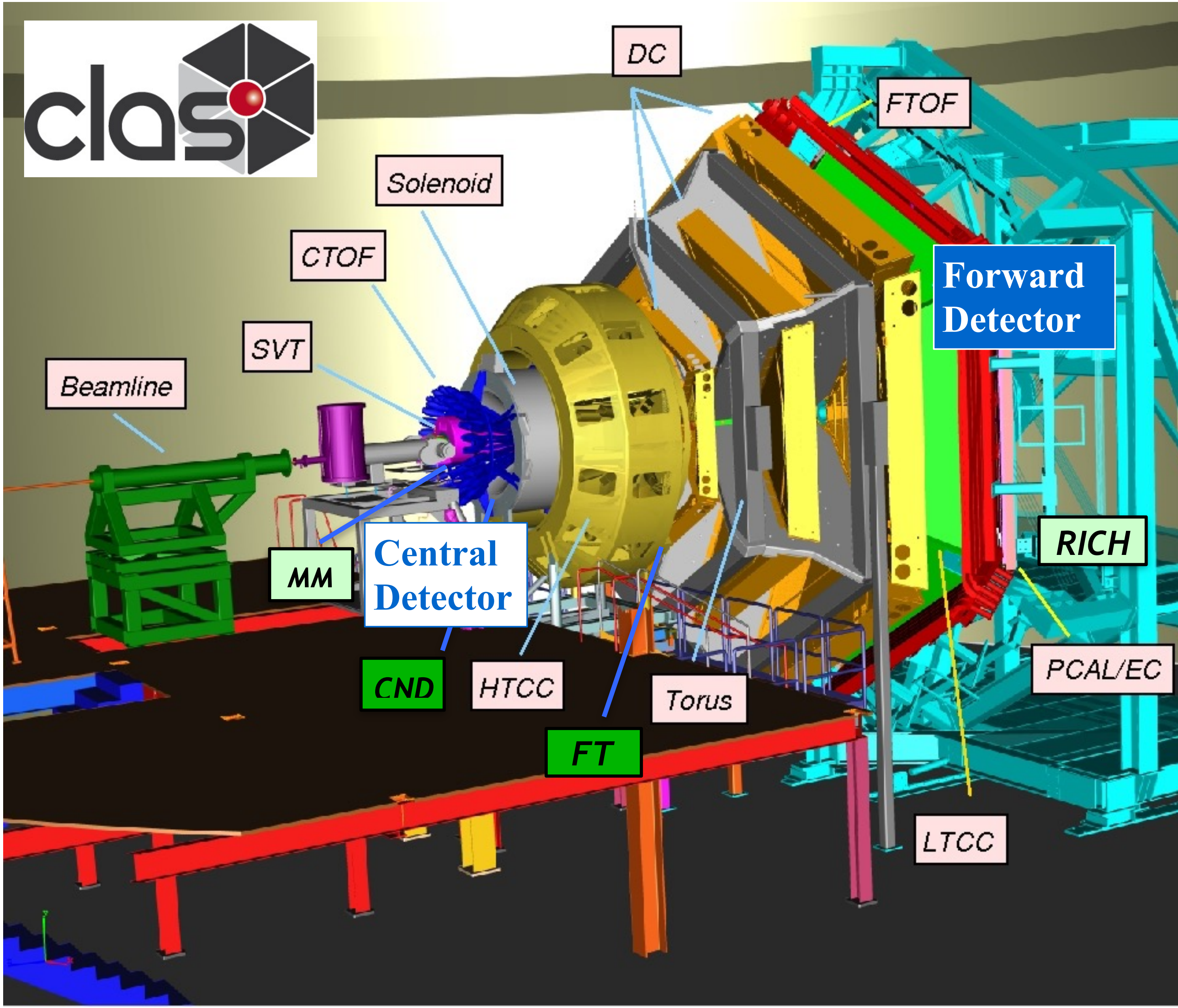
Design luminosity
$L \sim 10^{35}\ cm^{-2}\ s^{-1}$

High luminosity & large acceptance:
Concurrent measurement of exclusive, semi-inclusive, and inclusive processes

Acceptance for photons and electrons:
- $2.5^o < \theta < 125^o$

Acceptance for all charged particles:
- $5^o < \theta < 125^o$

Acceptance for neutrons:
- $5^o < \theta < 120^o$



DVCS at lower energies with CLAS12

Experiment E12-16-010B

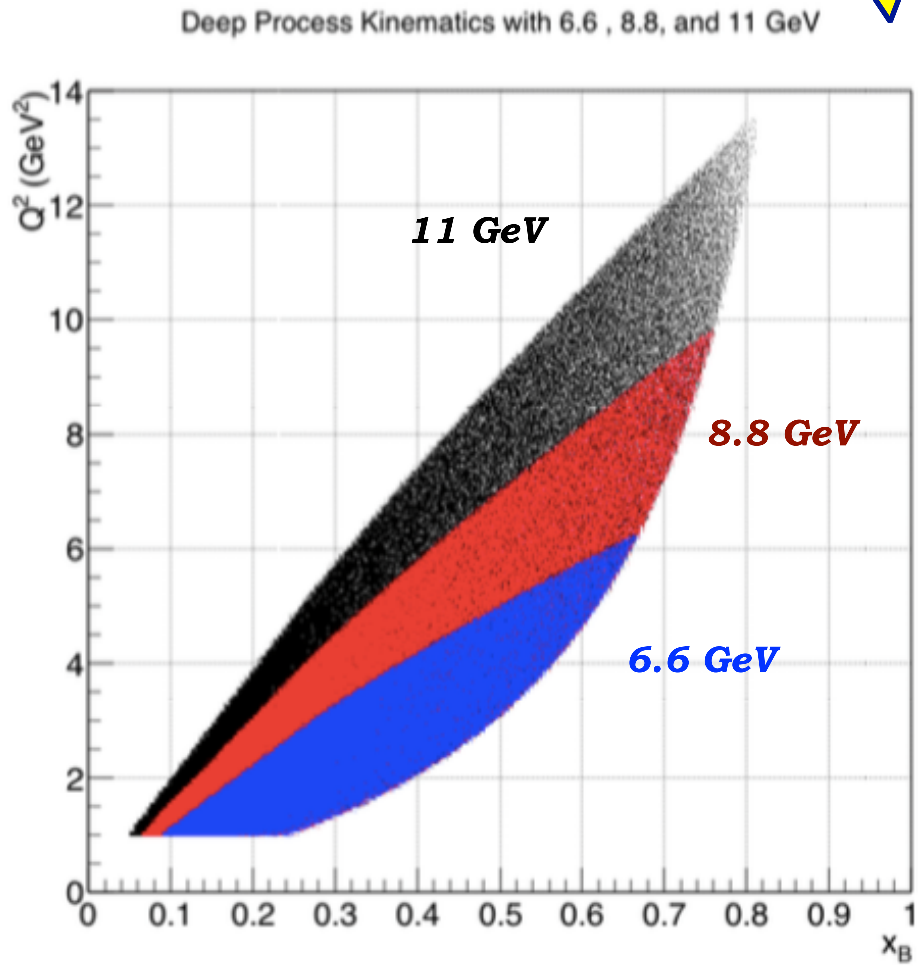
Unpolarised liquid H_2 target:

- Beam energies: 6.6, 8.8 GeV
- Simultaneous fit to beam-spin and total cross-sections.

* Rosenbluth separation of interference and $|T_{DVCS}|^2$ terms in the cross-section

* Scaling tests of the extracted CFFs

Compare with measurements from Halls A and C: cross-check model and systematic uncertainties.



Data currently under analysis

CLAS12

Proton & neutron DVCS with a longitudinally polarised target

Experiments: E12-06-119
E12-06-109A

A_{UL} characterised by imaginary parts of CFFs via:

$$F_1\tilde{H} + \xi G_M\left(H + \frac{x_B}{2}E\right) - \frac{\xi t}{4M^2}F_2\tilde{E} + \dots$$

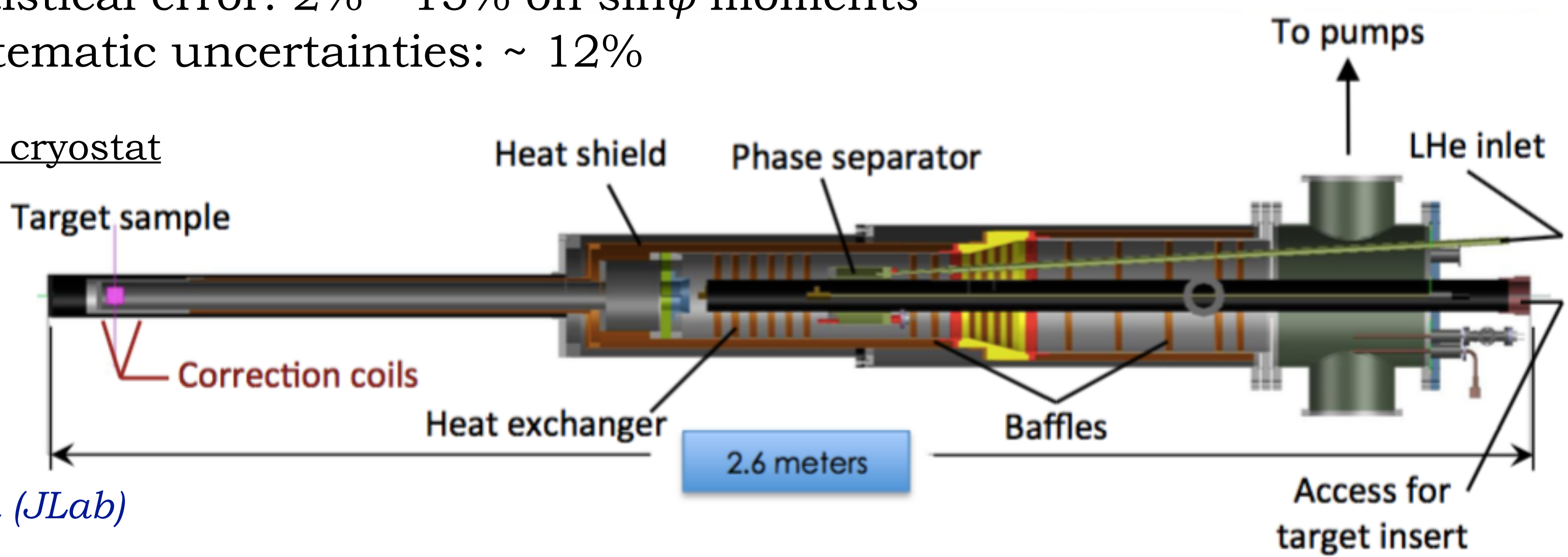
Longitudinally polarised NH_3 and ND_3 targets:

- Dynamic Nuclear Polarisation (DNP) of target material, cooled to 1K in a *He* evaporation cryostat.
- $P_{proton} > 80\%$
- $P_{deuteron}$ up to 50%
- Statistical error: 2% - 15% on sinφ moments
- Systematic uncertainties: ~ 12%

→ ***Im***$(\widetilde{\mathrm{H}}_p)$
Im(H_n)

Tentative schedule: ~2021

Target cryostat



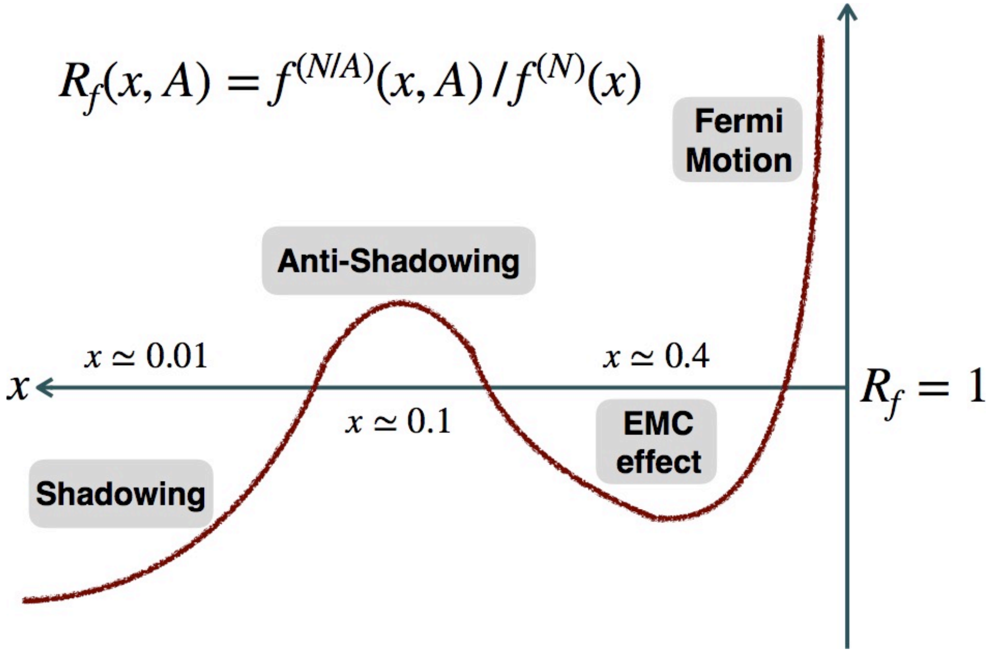
C. Keith (JLab)

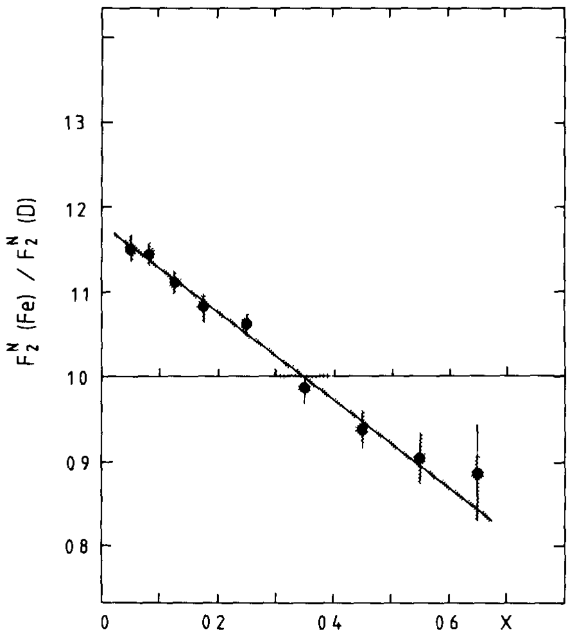
Motivation

- Deep-inelastic scattering of leptons from nuclei cannot be described by free nucleon formalism (EMC effect), e.g.

DIS structure functions: $$F_2^A \neq Z F_2^p + (A - Z) F_2^n$$

- Parton structure is modified in bound systems





J.J. Aubert et. al. Phys. Lett. B 123B (1983)

- Mechanisms that originate nuclear effects still not well understood

nPDFs from Global QCD Analyses

- Empirical determination of in-medium modifications to parton structure
- Relevant for interpretation of heavy ion collisions at RHIC and LHC
- Relies on collinear factorization formalism analogous to free proton PDF fits, e.g.

$$d\sigma^A(x,Q^2) \simeq \sum_f \int_x^{M_A/M} \frac{d\xi}{\xi} \underbrace{f^A(\frac{x}{\xi},Q^2)}_{\text{Parton distribution function (PDF) of nucleus with atomic mass } A} \underbrace{d\hat{\sigma}_f(\xi,Q^2)}_{\text{Hard scattering}}$$

- Scattering from nuclei treated as incoherent from single bound nucleon

$$d\sigma^A(x,Q^2) \simeq Z d\sigma^{p/A} + (A-Z) d\sigma^{n/A}$$

$$d\sigma^{N/A}(x,Q^2) \simeq \sum_f \int_x^1 \frac{d\xi}{\xi} f^{N/A}(\frac{x}{\xi},Q^2) d\hat{\sigma}_f(\xi,Q^2)$$

- nPDFs are parameterized and fitted to global lepton-nucleus and hadron-nucleus scattering measurements

nPDFs from Global QCD Analyses

- Can reveal onset of non-linear evolution effects at low x and Q^2

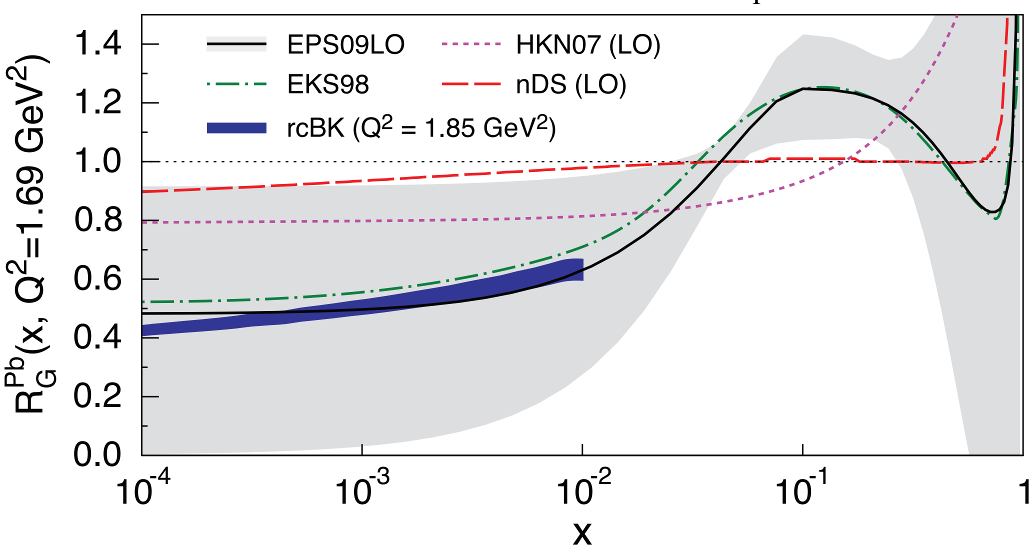
  → Enhancement for heavier nuclei – saturation region expected to begin at larger x

- Effect given in ratio of nuclear to proton PDFs:

$$R_G^A = \frac{g^{(p/A)}(x, Q^2, A)}{g^{(p)}(x, Q^2)}$$

- Existing nuclear PDF information contains large uncertainties in the saturation region

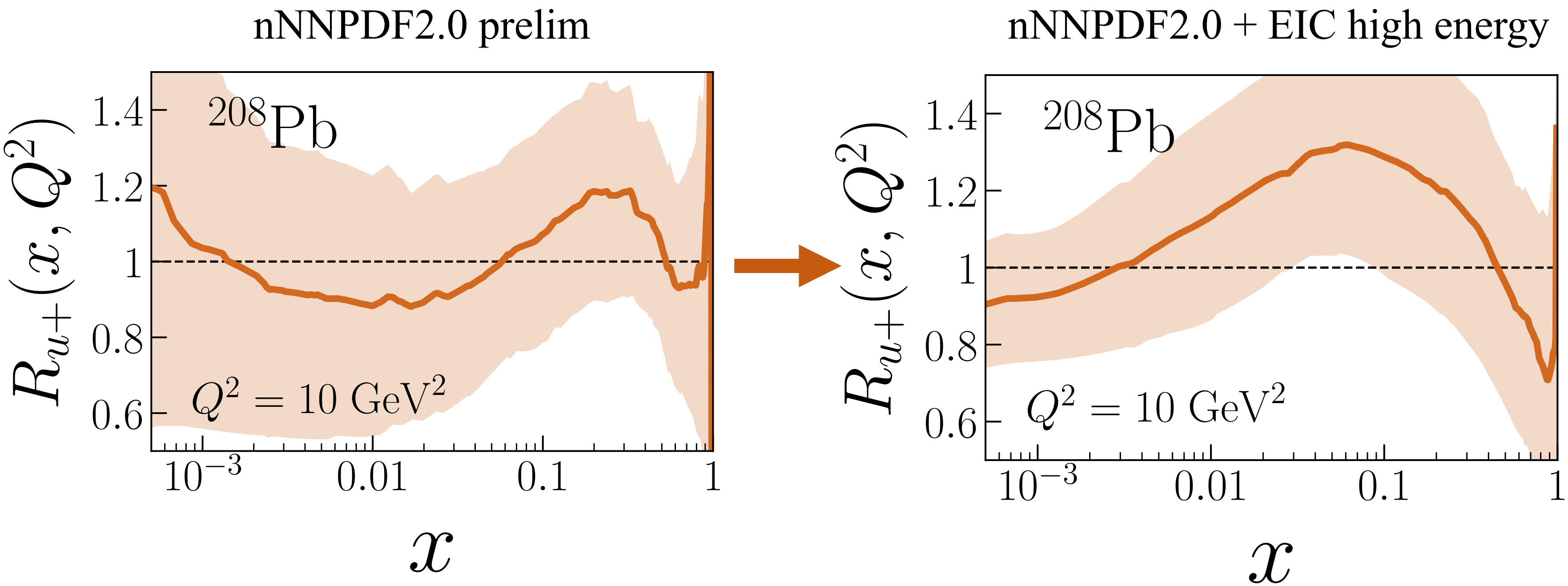
A. Accardi et. al. EIC White Paper *arXiv:1212.1701*



- Precise determination of nuclear PDFs is highly relevant for Electron-Ion Collider

Re-analysis of EIC Impact

- Analysis of high energy EIC pseudo-data (constructed with prelim 2.0)



- ~20% reduction in 90% CL levels for Pb ratio at low *x*!
- Can help pin down flavor separation at low *x*

Summary and Outlook

- Machine learning + Monte Carlo methods are important for robust extractions of nPDFs and their uncertainties
- Methodology improvements in nuclear PDF analysis:

  → Neural networks optimized with stochastic gradient descent in TensorFlow

- Highlights from first Monte Carlo nPDF fit

  → Significant impact of A=1 boundary condition for low-A nuclei

  → High energy EIC scenario can constrain nPDFs down to $x \sim 10^{-4}$

- Towards nNNPDF2.0

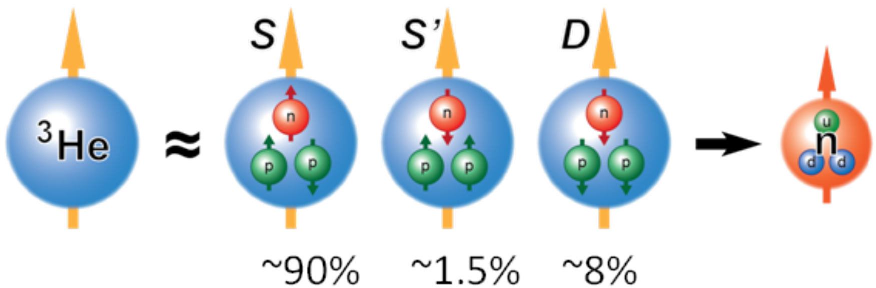
  → Inclusion of additional observables (VB production from LHC p+Pb collisions, CC DIS) for flavor separation and uncertainty reduction

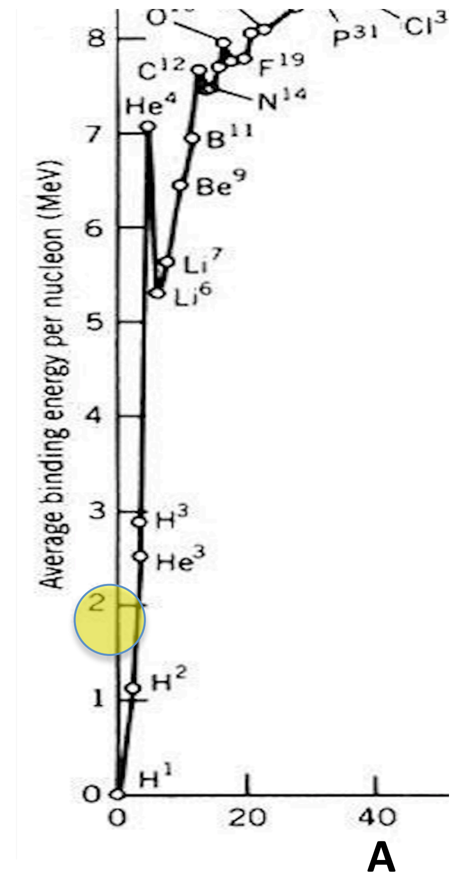
  → New proton BC (not contaminated with heavy nuclear target data)

  → Positivity constraints

THANK YOU!

Neutron Spin Structure Function $g_1^n(x,Q^2)$





Neutron polarization: 87%
Proton polarization: 2.7%

- Has been successfully used at MIT-Bates, IUCF, AmPS, SLAC, Mainz, HERMES, JLab
- Quasielastic (e,e’n) scattering yields elastic neutron FF: $G_M^n(Q^2)$, $G_E^n(Q^2)$
- In inclusive spin-dependent electron scattering, precision measurements of $g_1^n(x,Q^2)$ can be made
- Together with measurements of $g_1^p(x,Q^2)$, the Bjorken Sum Rule can be tested.
- ***In spin-dependent DIS if one tagged the spectator proton and deuteron, could one access the spin structure functions of the deuteron and proton in ^{3}He?***

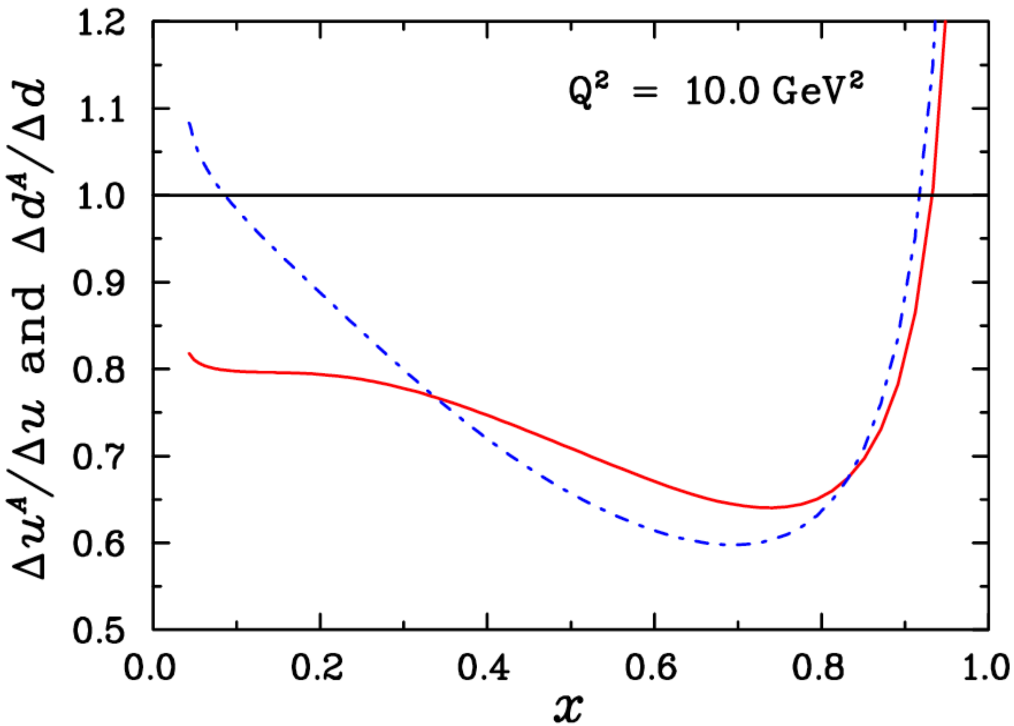
- **Tagged deuteron:** Scattering from the $|0,0>$ state cannot contribute. Thus, measurement of $\overrightarrow{^3\mathrm{He}}(\vec{e}, e'd_{\mathrm{spectator}})$ in DIS kinematics is equivalent to scattering from a negatively polarized proton 66% of the time and 33% of the time from a positively polarized proton. This is equivalent to scattering from the polarized proton in ^{3}He with -33% polarization. This makes polarized ^{3}He an effective polarized proton target.

- **Tagged proton:** 50% of the time, the scattering arises from the $|1,1>$ state, 25% from the $|1,0>$ state and 25% from the $|0,0>$ state. In forming the spin-asymmetry A in the DIS process $\overrightarrow{^3\mathrm{He}}(\vec{e}, e'p_{\mathrm{spectator}})$ there will be a contribution from scattering from the deuteron A_{ed}, the contribution arising from the $|1,0>$ state will cancel and there will a correction arising from a contribution A_{corr} from scattering from the np pair in the $|0,0>$ state, i.e.

$$A \sim \frac{2}{3}A_{ed} + \frac{1}{3}A_{corr} \ . \tag{29}$$

How large is A_{corr}?

Spin-dependent EMC Effect



Cloet et al, PRL 95, 052302 (2005)

FIG. 4 (color online). Ratio of the quark distributions in nuclear matter to the corresponding free distributions, at a scale of $Q^2 = 10\ \text{GeV}^2$. The solid line represents $\Delta u^A(x)/\Delta u(x)$ and the dot-dashed line $\Delta d^A(x)/\Delta d(x)$. Note, these distributions are the full quark distributions and hence include antiquarks generated through Q^2 evolution.

Neutron GPDs from ^{3}He

M. Rinaldi and S. Scopetta
Phys. Rev. C **87**, 035208 (2013)

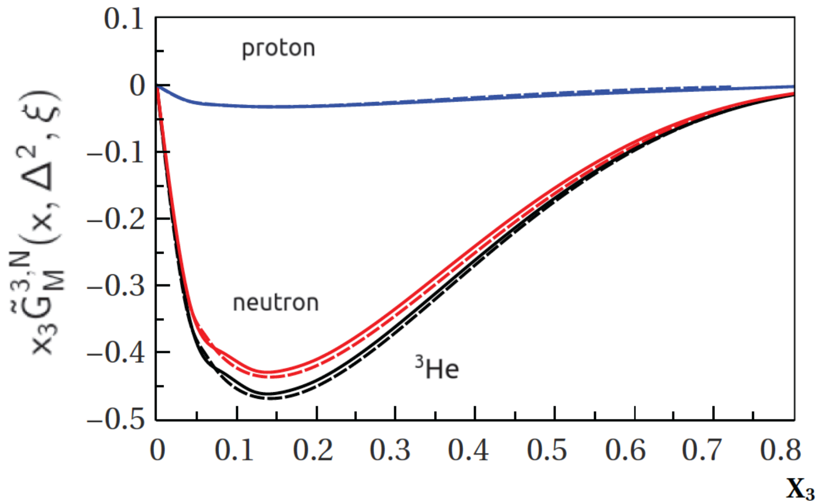


FIG. 6. (Color online) The quantity $x_3\tilde{G}^3_M(x,\Delta^2,\xi)$ of ^{3}He in the forward limit, together with the proton and neutron contribution (solid lines), compared with the approximations to these quantities given by the factorized form of Eq. (21) (dashed lines).

For later convenience, let us define the following auxiliary function, given simply by the sum of the GPDs H_q^A and E_q^A for a given target A of spin-$\frac{1}{2}$:

$$\tilde{G}_M^{A,q}(x,\Delta^2,\xi) = H_q^A(x,\Delta^2,\xi) + E_q^A(x,\Delta^2,\xi). \quad (3)$$

This function, owing to Eq. (2), fulfills obviously the following relation:

$$\int_{-1}^{1} dx\, \tilde{G}_M^{A,q}(x,\Delta^2,\xi) = F_1^{A,q}(\Delta^2) + F_2^{A,q}(\Delta^2) \equiv G_M^{A,q}(\Delta^2), \quad (4)$$

$G_M^{A,q}(\Delta^2)$ being the contribution of the quark of flavor q to the magnetic ff of the target A.

A fundamental result is Ji's sum rule (JSR) [3], according to which the forward limit of the second moment of the unpolarized GPDs is related to the component, along the quantization axis, of the total angular momentum of the quark q in the target A, J_q^A, according to

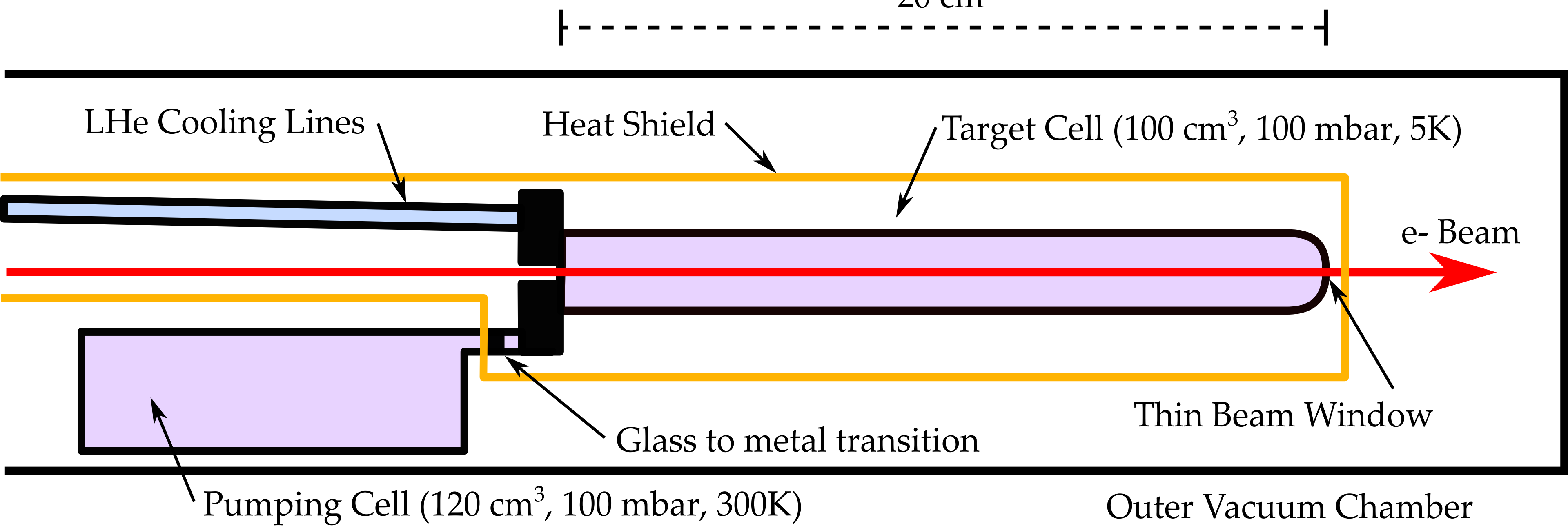
$$J_q^A = \int_{-1}^{1} dx\, x\, \tilde{G}_M^{A,q}(x,0,0). \quad (5)$$

The combination $\tilde{G}_M^{N,q} = H_q^N + E_q^N$ is therefore needed to study the angular momentum content of the nucleon N, through the JSR, and OAM could be obtained from J_q^A, being the helicity content measurable in DIS and SiDIS.

James Maxwell
Richard Milner

Side view

CLAS12 Polarized 3He Target



Thursday, October 31

Session I (Room: Ariadne) Chair: Axel Schmidt		
14:30-15:00	First extraction of A, B and D gravitation-al form factors from global DVCS analysis	Arkadusz Trawinski
15:00-15:30	Exclusive single photon production in muon-proton scattering at COMPASS	Johannes Giarra (Mainz)
15:30-16:00	Electrons for Neutrinos	Afroditi Papadopoulou (MIT)
16:00-16:30	Leading order corrections to the Bethe-Heitler process	Matthias Heller (Mainz)
16:30-17:00	Coffee Break	

In classical continuum mechanics the energy-momentum tensor

$$T^{\mu\nu}(\boldsymbol{x},t) = \left(\begin{array}{c|ccc} T^{00} & T^{01} & T^{02} & T^{03} \\ \hline T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{array}\right),$$

where:
T^{00} - energy density,
T^{ii} - (not summed) represents pressure,
T^{ij} - $i \neq j$ represent shear stress,
T^{0i} - momentum flux,
T^{i0} - mass (energy) flux.
Classically $T^{\mu\nu} = T^{\nu\mu}$.

Matrix elements of the general local asymmetric energy–momentum tensor for a spin-1/2 target read

$$\left\langle p', s' \middle| \hat{T}^{\mu\nu}_{\mathrm{QCD}}(0) \middle| p, s \right\rangle =$$

$$= \bar{u}(p', s') \left\{ \frac{P^\mu P^\nu}{M} A(t) + \frac{\Delta^\mu \Delta^\nu - \eta^{\mu\nu}\Delta^2}{M} C(t) + M\eta^{\mu\nu} \bar{C}(t) \right.$$

$$+ \frac{P^\mu i\sigma^{\nu\lambda}\Delta_\lambda}{4M} \left[A(t) + B(t) + D(t) \right]$$

$$\left. + \frac{P^\nu i\sigma^{\mu\lambda}\Delta_\lambda}{4M} \left[A(t) + B(t) - D(t) \right] \right\} u(p, s) \, .$$

X.-D. Ji, Phys.Rev.Lett.78 (1997) 610
B.L.G. Bakker, E. Leader, T.L. Trueman, Phys.Rev.D70 (2004) 114001

PARTONS software

http://partons.cea.fr

PARTONS

PARtonic Tomography Of Nucleon Software

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Main Page

What is PARTONS?

PARTONS is a C++ software framework dedicated to the phenomenology of Generalized Parton Distributions (GPDs). GPDs provide a comprehensive description of the partonic structure of the nucleon and contain a wealth of new information. In particular, GPDs provide a description of the nucleon as an extended object, referred to as 3-dimensional nucleon tomography, and give an access to the orbital angular momentum of quarks.

PARTONS provides a necessary bridge between models of GPDs and experimental data measured in various exclusive channels, like Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP). The experimental programme devoted to study GPDs has been carrying out by several experiments, like HERMES at DESY (closed), COMPASS at CERN, Hall-A and CLAS at JLab. GPD subject will be also a key component of the physics case for the expected Electron Ion Collider (EIC).

Table of Contents

- What is PARTONS?
- Get PARTONS
- Configure PARTONS
- How to use PARTONS
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- License
- Contact and newsletter

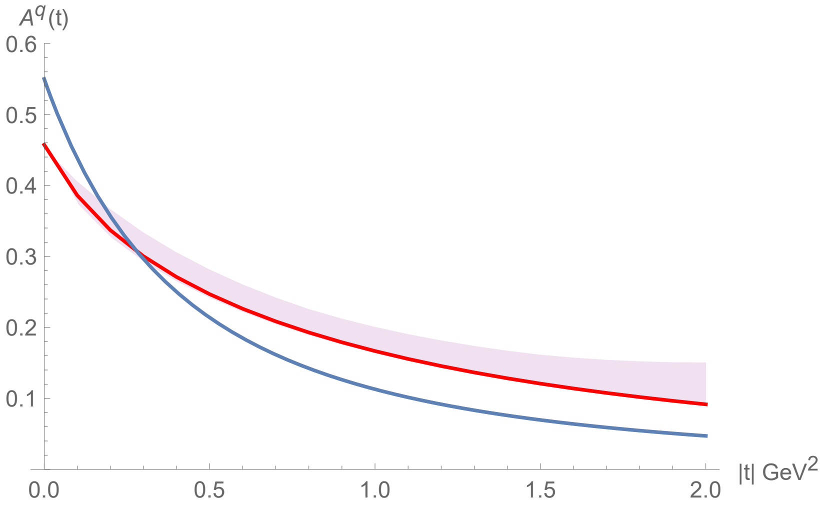
PARTONS is useful to theorists to develop new models, phenomenologists to interpret existing measurements and to experimentalists to design new experiments.

Get PARTONS

Here you can learn how to get your own version of PARTONS. We offer two ways:

- You can use our provided virtual machine with an out-of-the-box PARTONS runtime and development environment. This is the easiest way to start your experience with PARTONS.
- You can also build PARTONS by your own on GNU/Linux. This is useful if you want to have PARTONS on your computer without using the virtualization technology or if you want to use PARTONS on computing farms.

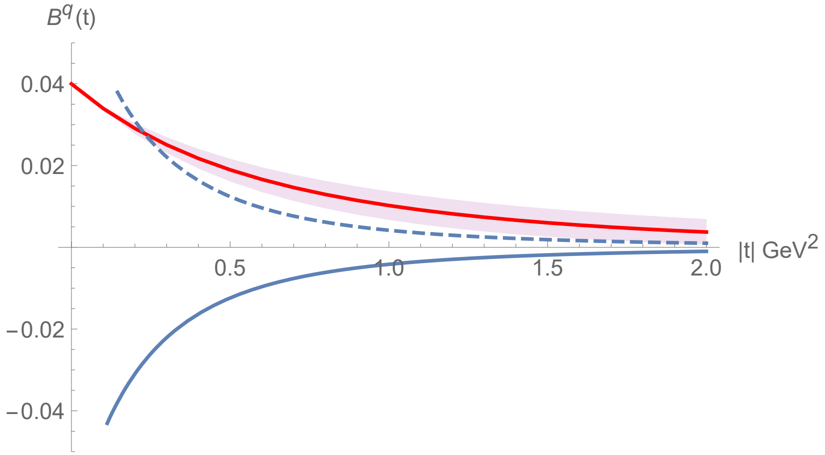
GFF $A^q(t)$



C. Lorcé, H. Moutarde, A.P. Trawiński (in preparation)

C. Lorcé, H. Moutarde, A.P. Trawiński, Eur.Phys.J. C79 (2019) 89

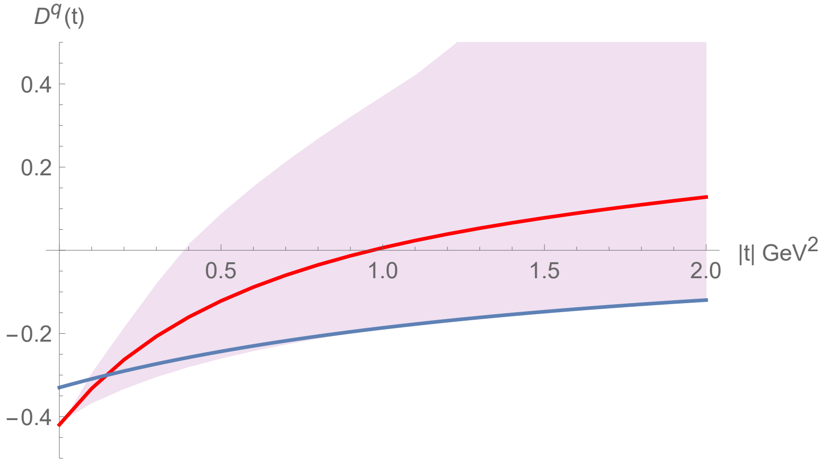
GFF $B^q(t)$



C. Lorcé, H. Moutarde, A.P. Trawiński (in preparation)

C. Lorcé, H. Moutarde, A.P. Trawiński, Eur.Phys.J. C79 (2019) 89

GFF $D^q(t)$ – axial form factor



C. Lorcé, H. Moutarde, A.P. Trawiński (in preparation)

C. Lorcé, H. Moutarde, A.P. Trawiński, Eur.Phys.J. C79 (2019) 89

Summary

The study of the EMT is important because:

- $T^{\mu\nu}$ is a fundamental quantity, which allows to access for example pressures and a spin decomposition.
- DVCS gives a way to experimentally measure $T^{\mu\nu}$, *e.g.* JLab.
- Its form factors have a clear interpretation as spatial densities ($\vec{\Delta}$ is related to $\vec{r}$).
- GFFs and GPDs constrain each other.

E. Leader, C. Lorcé, Phys.Rept.541 (2014) 163

Results of DVCS measurement at COMPASS

Johannes Giarra

on behalf of the COMPASS collaboration

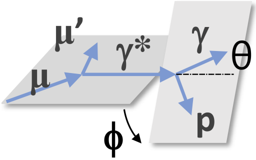
EINN2019

27. Oct - 02. Nov.

Paphos, Cyprus

Kinematic dependencies:

- Q^2 : 4-momentum of γ^*
- ν : Energy of γ^*
- t : Momentum transfer to proton
- ϕ : Angle between scattering plane (γ^*) and production plane (γ)



⇒ Measure **angular distribution of real photon**

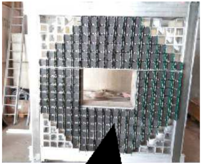
Identify exclusive photon events:

$$\left.\begin{array}{l}\text{Incoming muon}\\ \text{Scattered muon}\\ \text{Recoil proton}\\ \text{Real photon}\end{array}\right\}\ \text{overconstrained}$$

Data taking @COMPASS:

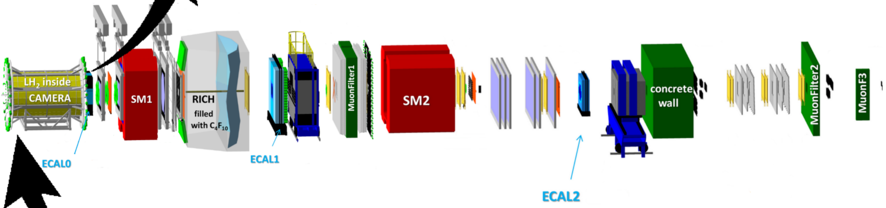
- 2012 test run for 4 weeks
  → Analysis finished and published
- Long runs dedicated to DVCS in 2016/17
  → Analysis ongoing

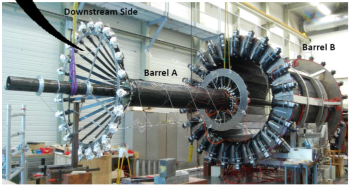
COMPASS spectrometer setup (2016/17)



ECAL0:

Sampling calorimeter (lead scintillator sandwich)
$\sim$ 2 x 2 m^2, hole 60cm x 84cm
194 modules each 9 cells (4 x 4 cm^2)





CAMERA:

Inner & outer ring each 24 scintillator slabs
TOF measurement

Analyse the t-slope of the cross section

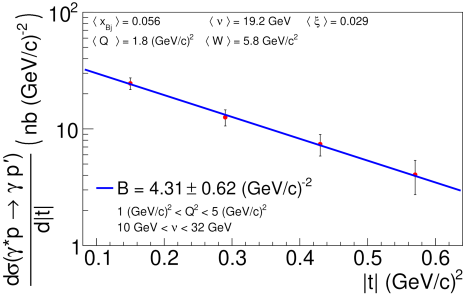
To go from μp to $\gamma^* p$:

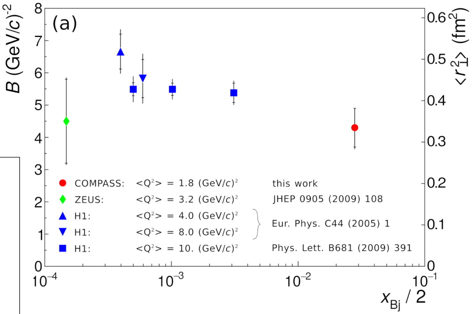
$$\frac{d\sigma^{\mu p}}{dQ^2 d\nu d\Phi dt} \rightarrow \frac{d\sigma^{\gamma^* p}}{dt d\phi} \text{ by multiplying with } \frac{1}{\Gamma(Q^2,\nu,E_\mu)}$$

$\Gamma(Q^2, \nu, E_\mu)$: Flux of transverse virtual photons

No ϕ dependence observed
$\Rightarrow$ add up ϕ bins

fit $\propto e^{B|t|}$





arXiv:1802.02739

Analyse the t-slope of the cross section

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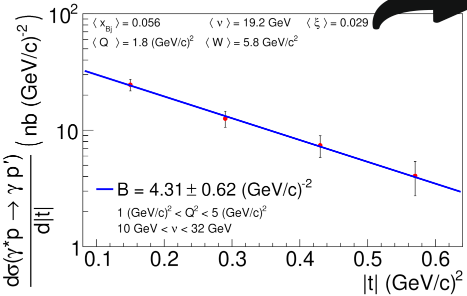
$$\frac{d\sigma^{\mu p}}{dQ^2 d\nu d\Phi dt} \rightarrow \frac{d\sigma^{\gamma^* p}}{dt d\phi} \text{ by multiplying with } \frac{1}{\Gamma(Q^2,\nu,E_\mu)}$$

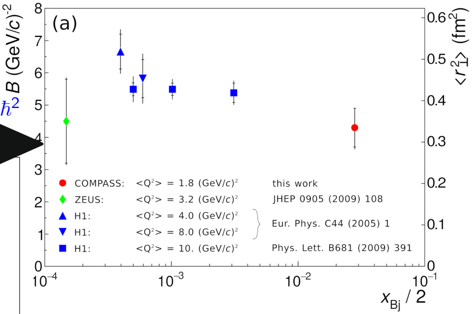
$\Gamma(Q^2,\nu,E_\mu)$: Flux of transverse virtual photons

No ϕ dependence observed
$\Rightarrow$ add up ϕ bins

fit $\propto e^{B|t|}$

$\langle r_\perp^2 \rangle = 2\langle B(x_{Bj})\rangle \hbar^2$

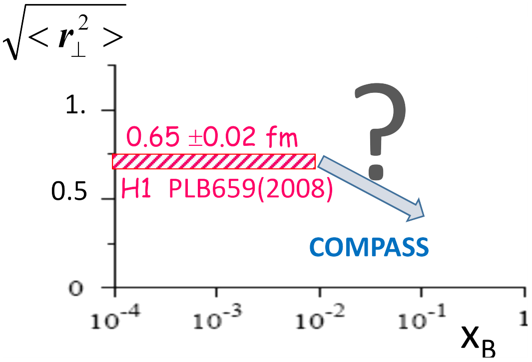




$$\sqrt{\langle r_\perp^2 \rangle} = (0.58 \pm 0.04_{stat} \,{}^{+0.01}_{-0.02}|_{sys} \pm 0.04_{model})\text{fm}$$

arXiv:1802.02739

Future results



e4ν Objective

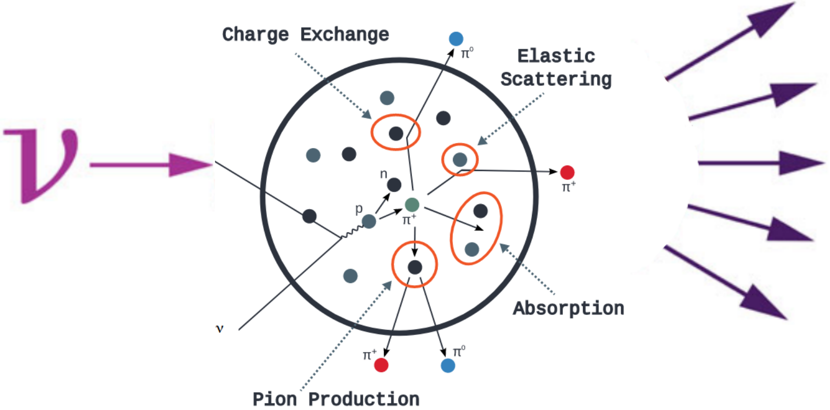
- Accuracy of ν energy reconstruction methods using e-scattering data

- Benchmarking of ν event generator models against e-scattering data

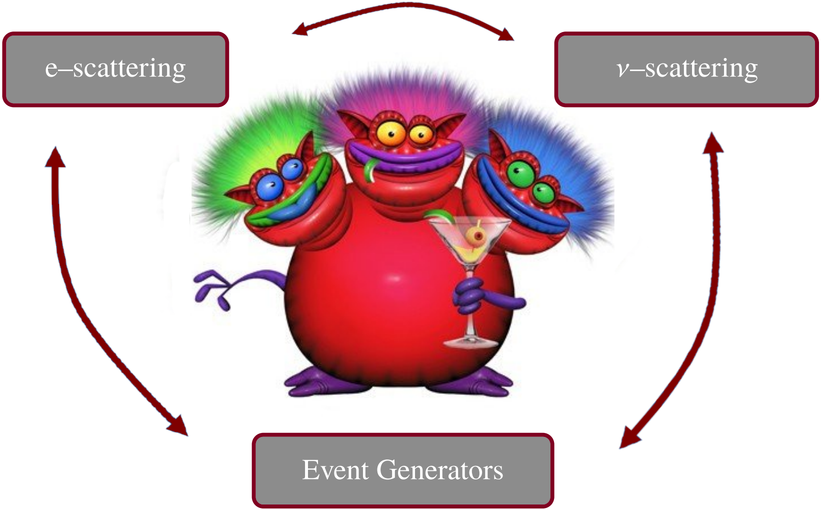
Generator Modeling

Models: Effective. Often Empirical. Semi–classical (no interference terms)

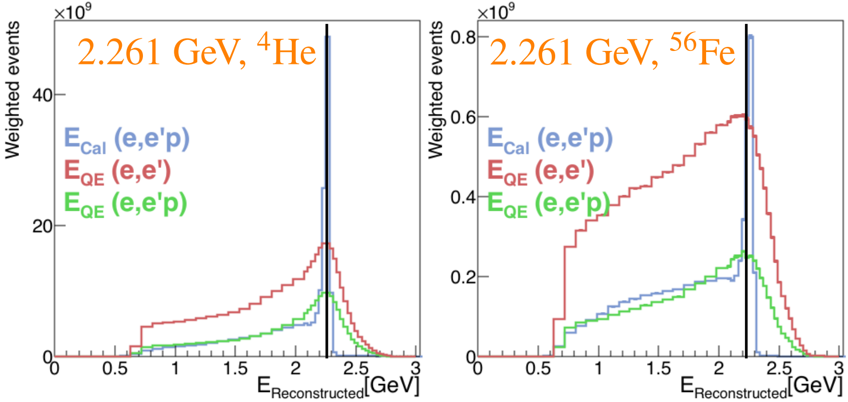
⇒ **MUST tune to data!**



Attacking from all sides

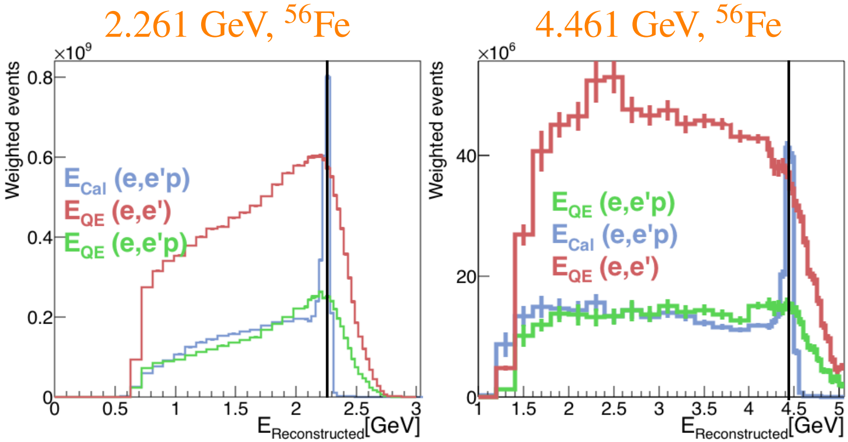


Large A dependence



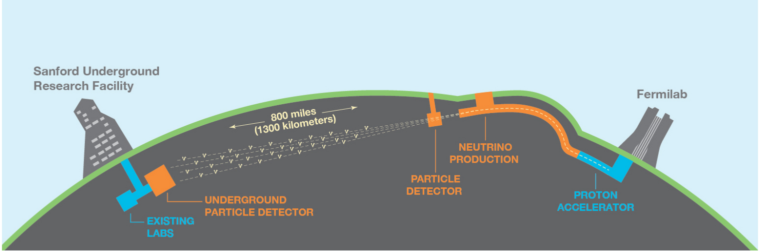
- ^{56}Fe is predominantly tail
- ^{56}Fe is worse than ^{4}He

Large E dependence



Better reconstruction at lower energies

DUNE Goals



Extraction of oscillation parameters

with an accuracy of ~ 5 %

But energy reconstruction deviations & data–MC disagreement

Is

DOOMED?

Attacking from all sides

Not yet!

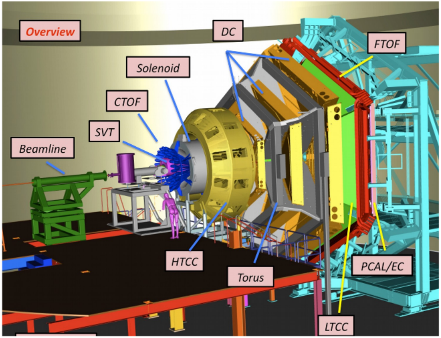
e–scattering

ν–scattering

Event Generators

New Proposal

High statistics for semi–inclusive and exlusive data sets on multiple targets at multiple energies



New Proposal

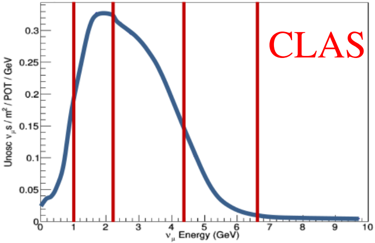
Targets

^{4}He, ^{12}C, ^{16}O, ^{40}**Ar**, ^{120}Sn

Beam Energies

1.1, 2.2, 4.4, 6.6 GeV

DUNE Spectrum

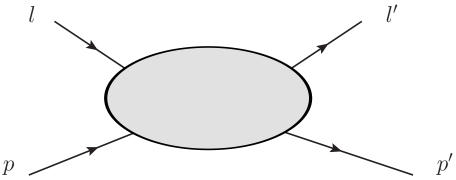


Test of lepton universality

- Assume universal proton form factor for all leptons
  $\rightarrow$ same proton radius for muons and electrons

- Broken universality could be an explanation for proton radius puzzle

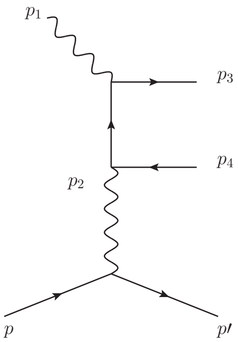
- Test this with upcoming experiments:
  - MUSE @ PSI (electron vs muon scattering)
  - COMPASS @ CERN (high energy muon scattering off the proton)
  - MAMI $\gamma p \rightarrow e^- e^+ p$ vs. $\gamma p \rightarrow \mu^- \mu^+ p$



Bethe-Heitler process

$2 \to 3$ process has 5 indepenedent kinematic invariants

$$
\begin{aligned}
(p_3 + p_4)^2 &= s_{ll} \\
(p_3 - p_1)^2 &= t_{ll} \\
(p_3 - p_2)^2 &= u_{ll} \\
(p_1 + p)^2 &= s \\
(p - p_3)^2 &= u \\
p_2^2 = (p - p')^2 &= t \\
s_{ll} + t_{ll} + u_{ll} &= 2m^2 + t
\end{aligned}
$$

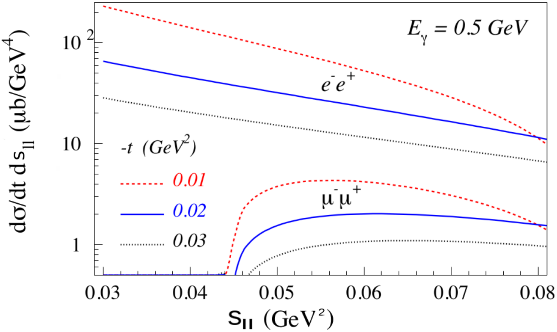


Lab quantities: $E_\gamma, E_{p'}, \theta_{p'}, \phi_{ll}^{\text{lab}}, \theta_{ll}^{\text{lab}}$

Bethe-Heitler process

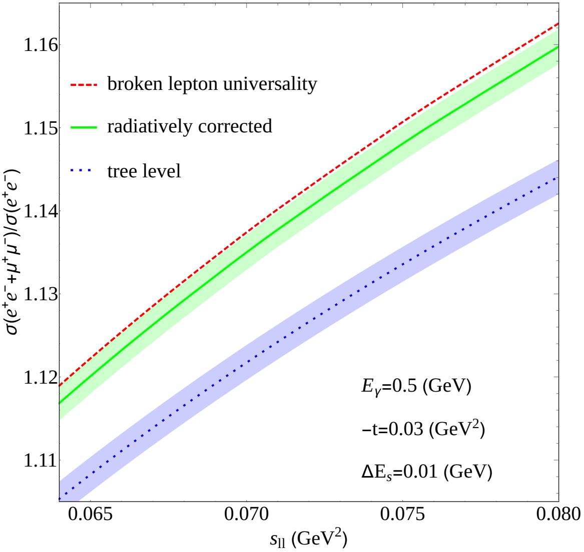
Comparison of cross sections for $l = e$ and $l = \mu$ can be used to test lepton universality:

$$R(s_{ll}, s_{ll}^0) \equiv \frac{[\sigma(\mu^+\mu^-)]\,(s_{ll}) + [\sigma(e^+e^-)](s_{ll})}{[\sigma(e^+e^-)](s_{ll}^0)}$$



Pauk and Vanderhaeghen, PRL 115 (2015)

Effect on ratio of cross sections



Conclusion and Outlook

- we calculated full one-loop QED corrections on lepton side of Bethe-Heitler process
- hadronic corrections are negligible at required level of precision
- upcoming experiment at MAMI (Mainz) aims to test lepton universality
- complementary $\gamma p \to l^+ l^- p$ experiment could shed light on the proton radius puzzle
- next step: calculation for initial photon off-shell (electron-scattering)