CHALLENGES IN NUCLEAR FEMTOGRAPHY

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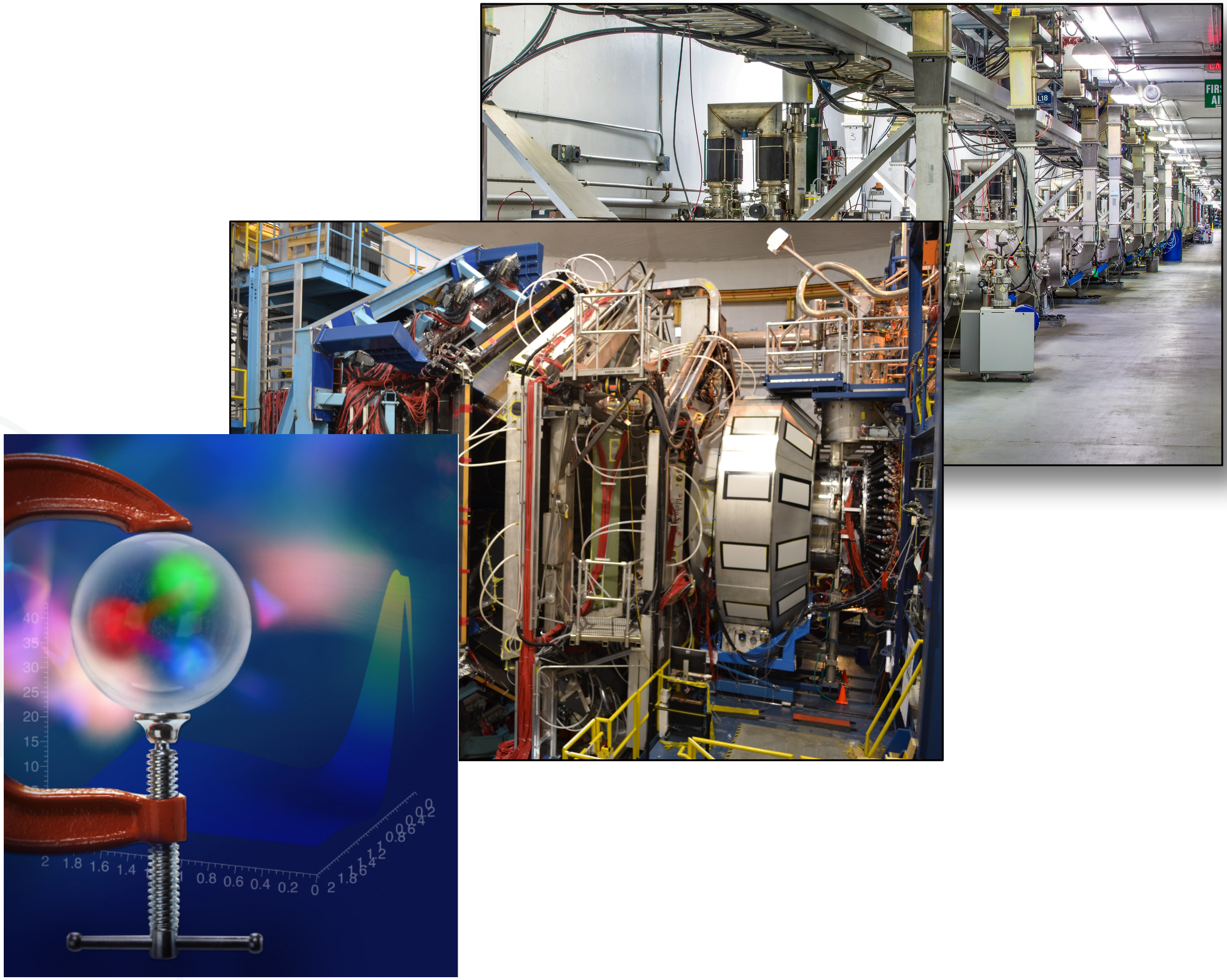
Jefferson Lab

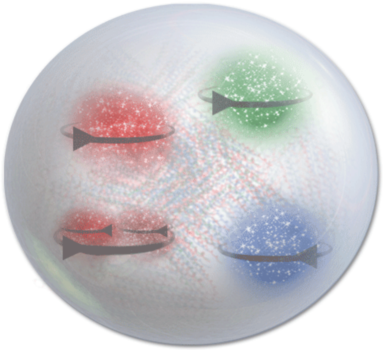
April 11, 2019



QCD Science Questions

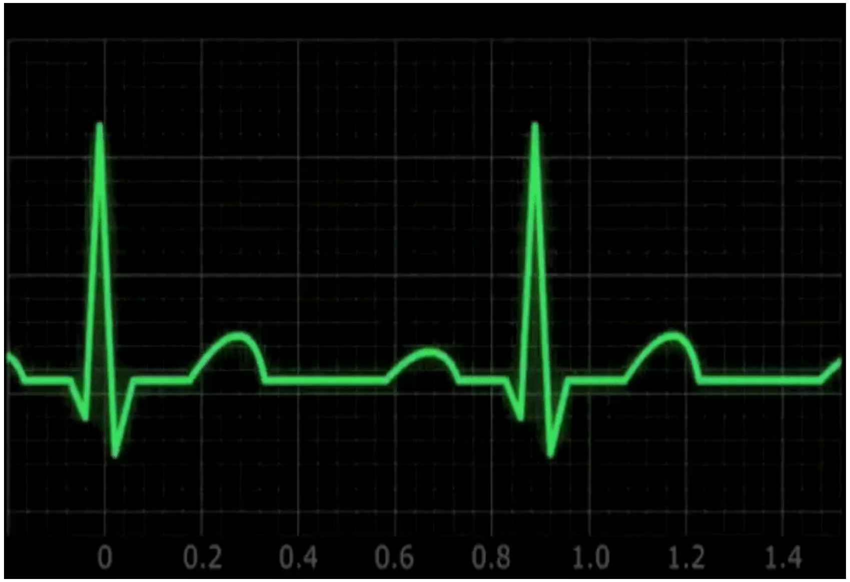
How are the quarks and gluons, and their intrinsic spins distributed in space & momentum inside the nucleon?

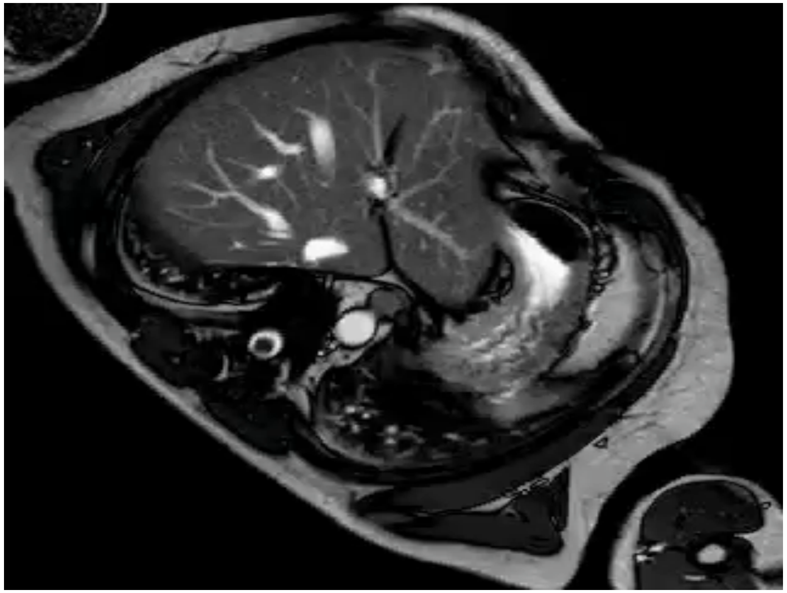
What is the role of orbital motion?



What are Pressure & Forces distributions??

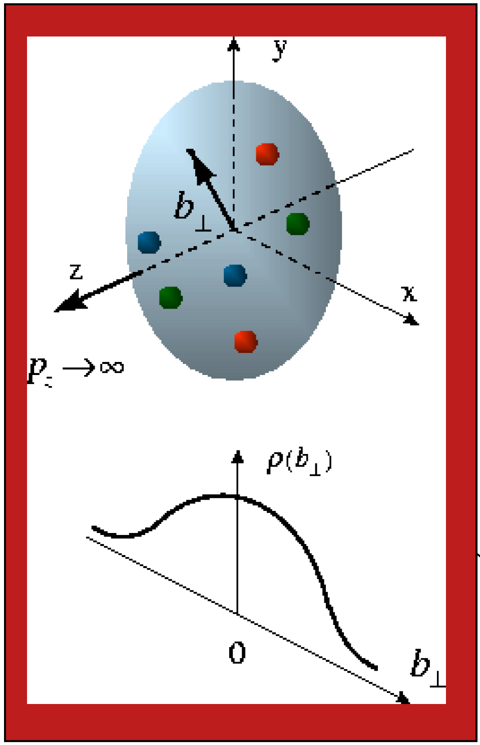
Color confinement & its origin?



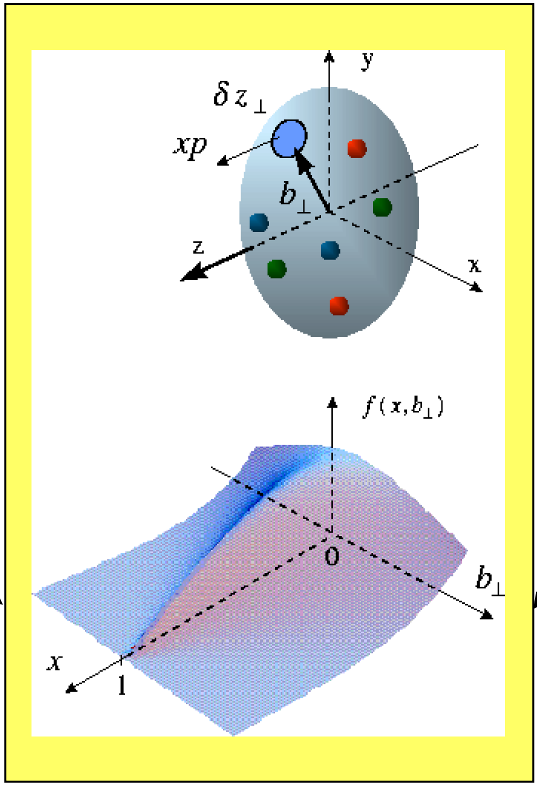


Generalized Parton Distributions

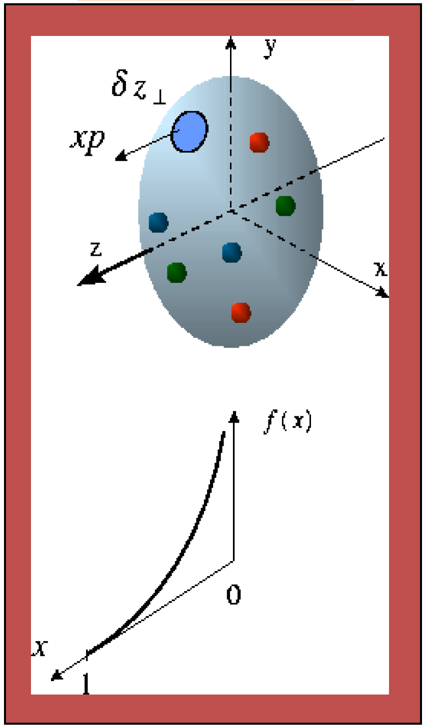
Last 60 years



Last 20 years



Last 45 years



Elastic form factors → **Transverse** charge & current densities $F_1(t)$, $F_2(t)$.

Deeply exclusive processes → GPD's and **3 D** images in transverse space and longitudinal momentum.
4 GPDs **H, E, $\tilde{H}$, $\tilde{E}$ (x,ξ,t)**

DIS structure functions → **Longitudinal** parton momentum & helicity densities, $F_2(x)$, $g_1(x)$.

GPDs and QCD

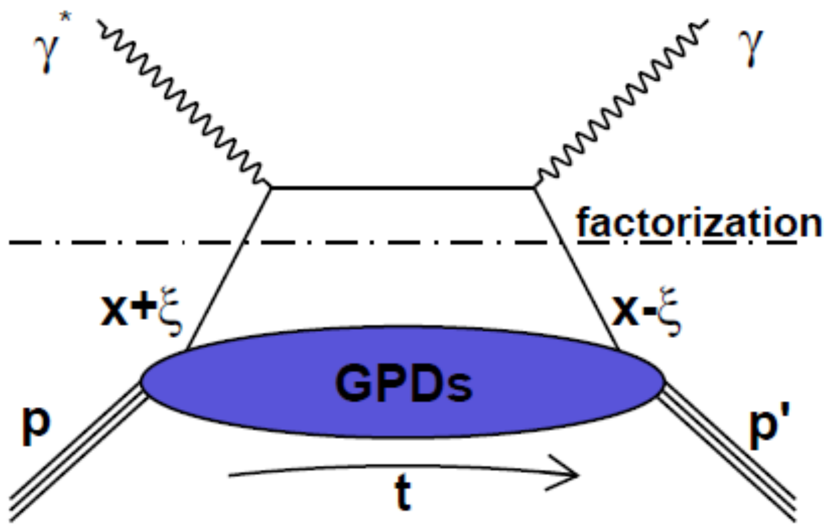
The Generalized Parton Distributions (GPDs) provide the theoretical framework to interpret the experimental data

Breakthrough in theory of **QCD** (1990s): developing **D**eeply **V**irtual **C**ompton **S**cattering (**DVCS**) as a tool to characterize the structure of the nucleon within **QCD** and showing how its properties can be probed through experiments.

D. Mueller (1994), X.Ji (1996), A.Radyushkin (1996)

Deeply Virtual Compton Scattering (DVCS) and GPDs

DVCS and Generalized Parton Distributions



$$\gamma^* p \to \gamma p'$$

Bjorken regime :
$Q^2 \to \infty$, x_B fixed

t fixed $\ll Q^2$, $\xi \to \frac{x_B}{2-x_B}$

$$\frac{P^+}{2\pi}\int dy^-\, e^{ixP^+y^-}\langle p'|\bar{\psi}_q(0)\gamma^+(1+\gamma^5)\psi(y)|p\rangle$$

$$= \bar{N}(p')\left[H^q(x,\xi,t)\gamma^+ + E^q(x,\xi,t)i\sigma^{+\nu}\frac{\Delta_\nu}{2M}\right.$$

$$\left. + \tilde{H}^q(x,\xi,t)\gamma^+\gamma^5 + \tilde{E}^q(x,\xi,t)\gamma^5\frac{\Delta^+}{2M}\right]N(p)$$

x: average fraction of quark longitudinal momentum

ξ fraction of longitudinal momentum transfer

H, E, $\widetilde{H}$, $\widetilde{E}$: **G**eneralized **P**arton **D**istributions (**GPDs**)

3-D Imaging conjointly in transverse impact parameter and longitudinal momentum

UNRAVELING CONFINEMENT FORCES IN PROTON

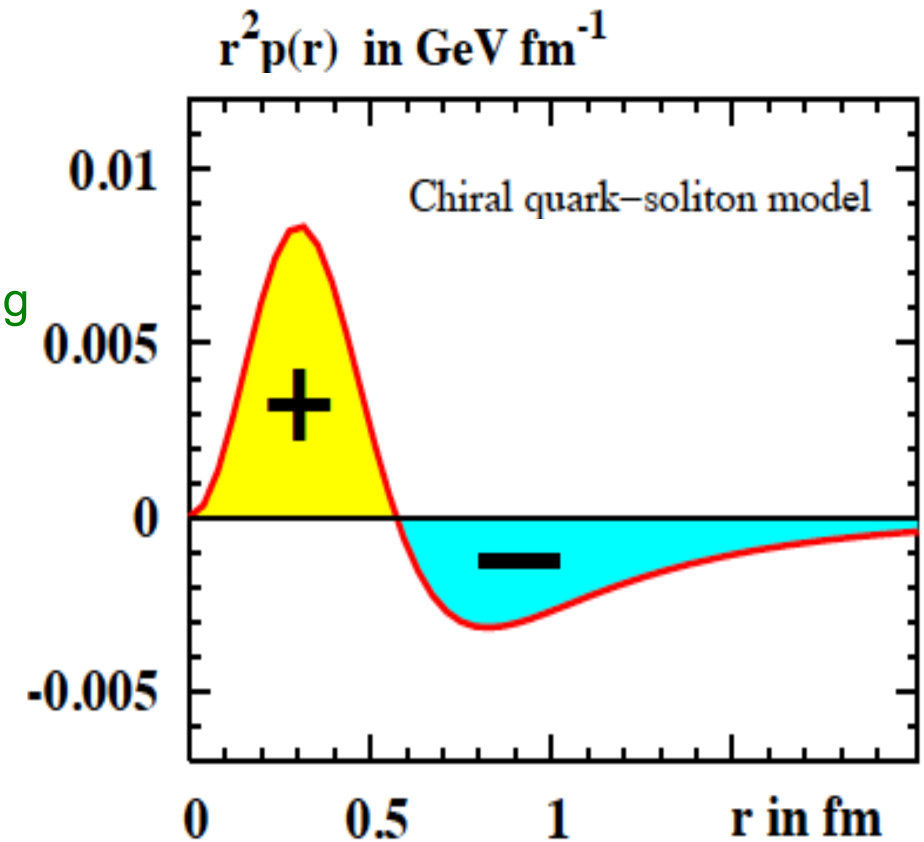
Nucleon matrix element of Energy Momentum Tensor (EMT) contains:

$M_2(t)$: Mass distribution inside the nucleon
$J(t)$: Angular momentum distribution
$d_1(t)$: Shear forces and pressure distribution

Measure directly in graviton-proton scattering

$$\int \mathrm{d}x\, x H(x,\xi,t) = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

$$\mathrm{Re}\mathcal{H}(\xi,t) \stackrel{\mathrm{LO}}{=} D(\xi,t) + \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) \mathrm{Im}\mathcal{H}(\xi,t)$$



From measurement of D(t), we learn about confinement forces in the proton.

FACILITIES & EQUIPMENT TO EXPLORE HADRON STRUCTURE

- **Facilities and equipment to Explore Hadron Structure became possible with all the advancement in detector, Electronics and Computing technologies**

- **Unprecedented capabilities:**
  - High Intensity
  - High Duty Factor
  - High Polarization
  - Parity Quality Beams
  - Large acceptance detectors
  - State-of-the-art polarized targets
  - **High luminosity**

- **Facilities and laboratories working together**

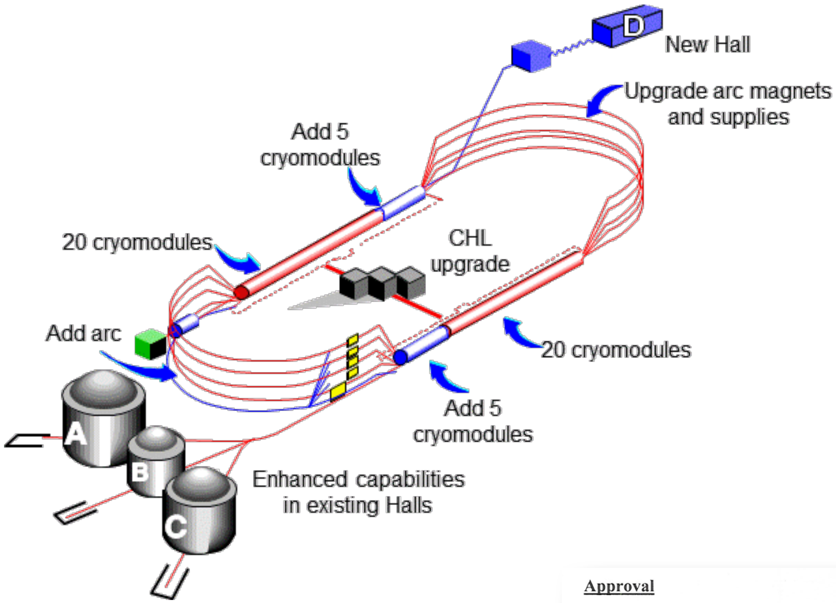
Jefferson Lab Overview

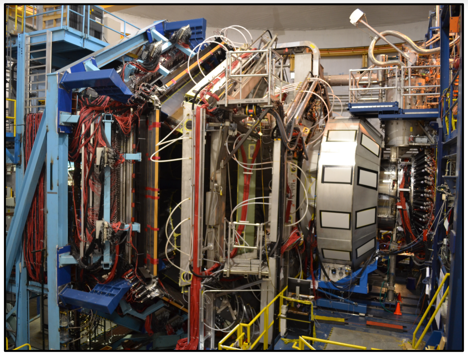
- One of 17 U.S. Department of Energy National Laboratories
  - Single program focus on Nuclear Physics
- Created to build and operate the Continuous Electron Beam Accelerator Facility (CEBAF), world-unique user facility for Nuclear Physics
- Mission is to gain a deeper understanding of the structure of matter
  - Through advances in fundamental research in nuclear physics
  - Through advances in accelerator science and technology
- In operation since 1995
- **Managed for DOE by Jefferson Science Associates, LLC (JSA)**

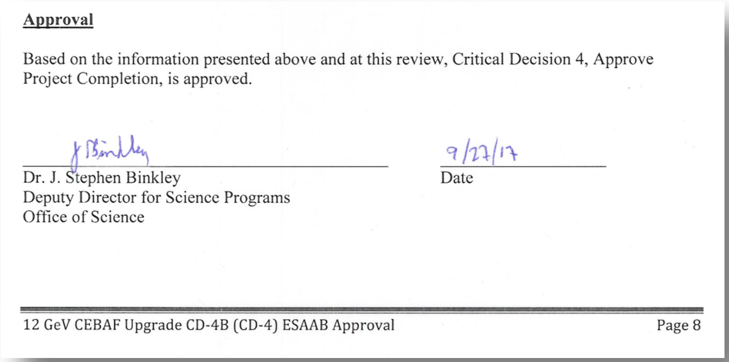
Jefferson Lab by the numbers:

- 700 employees
- 169 acre site
- 1,600 Active Users
- 27 Joint faculty
- **608 PhDs granted to-date (211 in progress)**
- K-12 programs serve more than 12,000 students and 950 teachers annually

12 GeV CEBAF Upgrade Project is Complete, On-time and On-Budget!






Approval

Based on the information presented above and at this review, Critical Decision 4, Approve Project Completion, is approved.

9/27/17

Dr. J. Stephen Binkley
Deputy Director for Science Programs
Office of Science

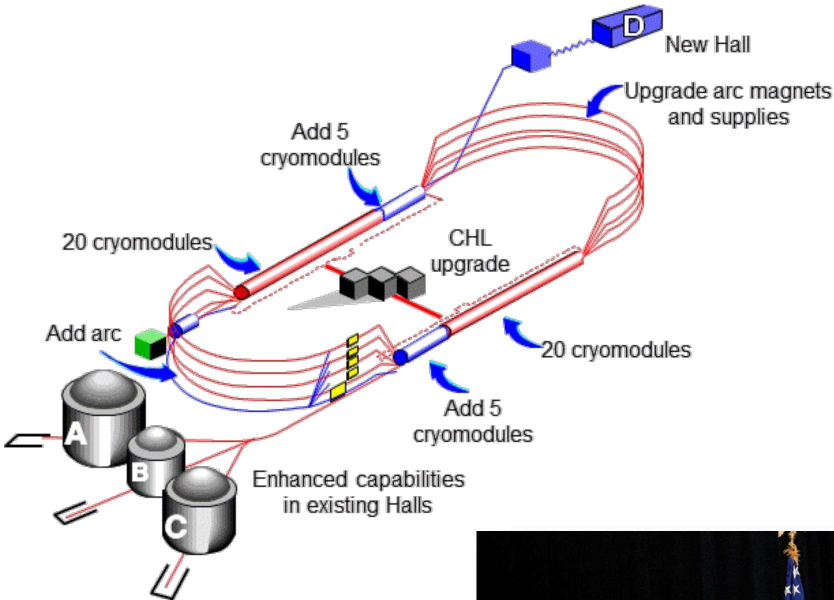
Date

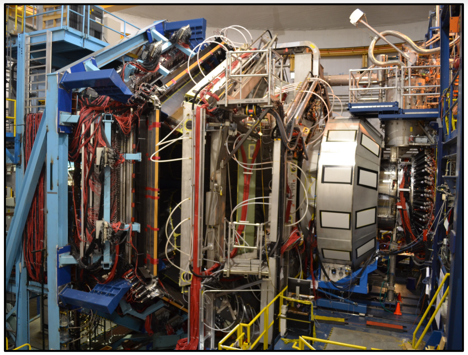
12 GeV CEBAF Upgrade CD-4B (CD-4) ESAAB Approval — Page 8

Project Completion Approved September 27, 2017

Jefferson Lab

12 GeV CEBAF Upgrade Project is Complete, On-time and On-Budget!

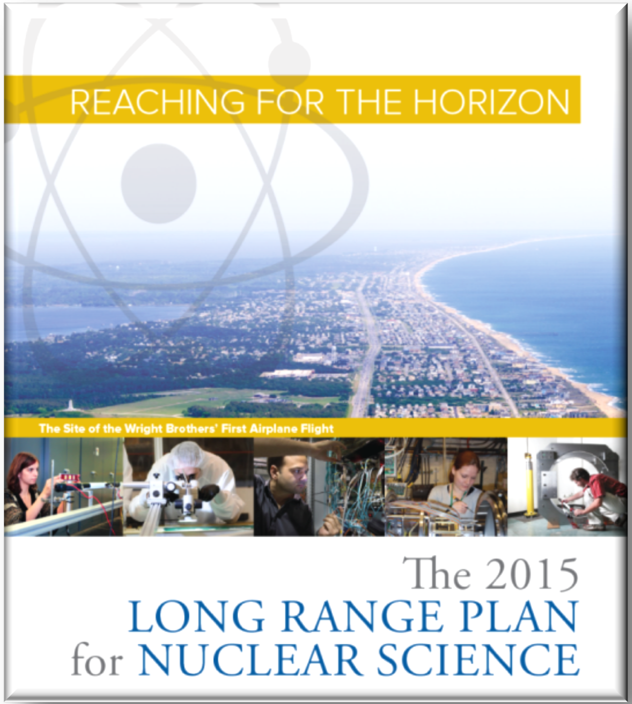




Secretary of Energy Project Management Achievement Award

Project Completion Approved September 27, 2017

The 2015 Long Range Plan for Nuclear Science



RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in the 2015 Plan is to capitalize on the investments made.

- *With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.*

→ **Operate 12 GeV CEBAF – highest priority**

RECOMMENDATION II

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

RECOMMENDATION III

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

→ **Jefferson Lab EIC (JLEIC) development**

→ **BNL (eRHIC) development**

→ **National Academy of Sciences report**

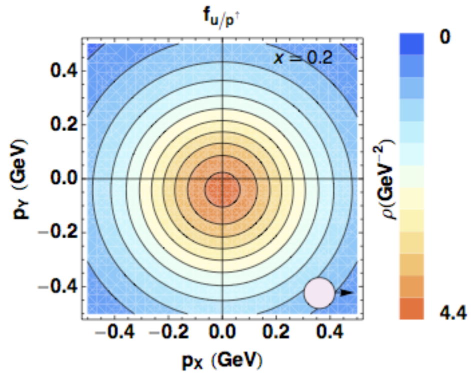
RECOMMENDATION IV

We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

Quantum phase-space distributions of quarks

$W_p^q(x,k_T,r)$ Wigner distributions

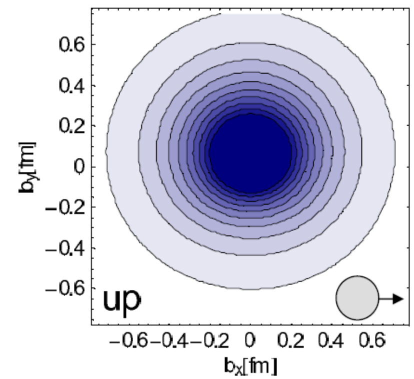
Probability to find a quark q in a nucleon P with a certain polarization in a position r & momentum k



d^3r

d^2k_T

[Wigner (1932)] QM
[Belitsky, Ji, Yuan (04)] QFT (Breit frame)
[Lorce', BP (11)] QFT (light cone)



TMD PDFs: $f_p^u(x,k_T)$,…

GPDs: $H_p^u(x,x,t)$, …

Semi-inclusive measurements
Momentum transfer to quark
Direct info about momentum distribution

d^2k_T

$\xi=0, t=0$

Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

PDFs $f_p^u(x)$,…

$$J_q = \frac{1}{2}\Delta\Sigma + L_q = \lim_{t\to 0}\int_{-1}^{1} dx\, x\,\left[H(x,\xi,t)+E(x,\xi,t)\right]$$

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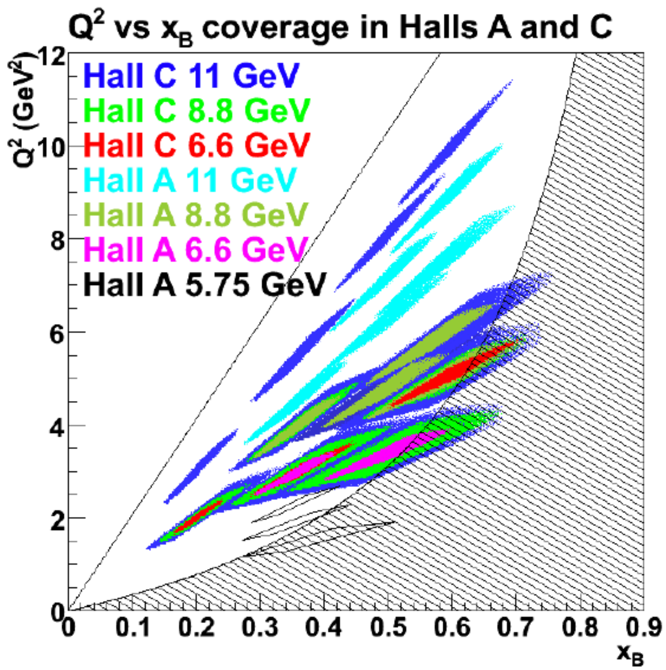
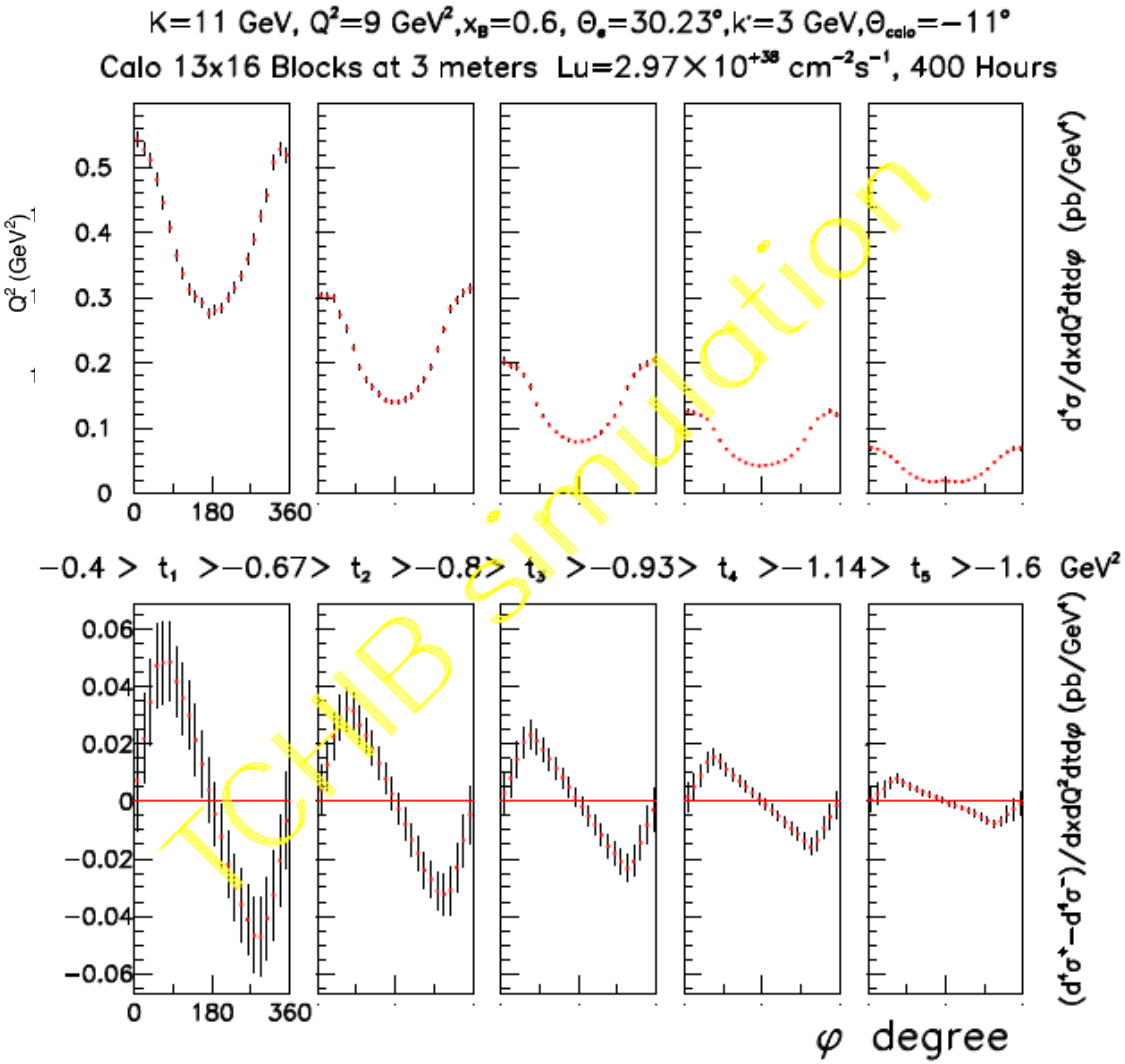
DVCS WITH POLARIZED E$^-$ BEAM IN HALL A/C

E12-06-114





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The CLAS12 Detector

Baseline equipments

Forward Detector (FD)

- TORUS magnet (6 coils)
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Pre-shower calorimeter
- E.M. calorimeter

Central Detector (CD)

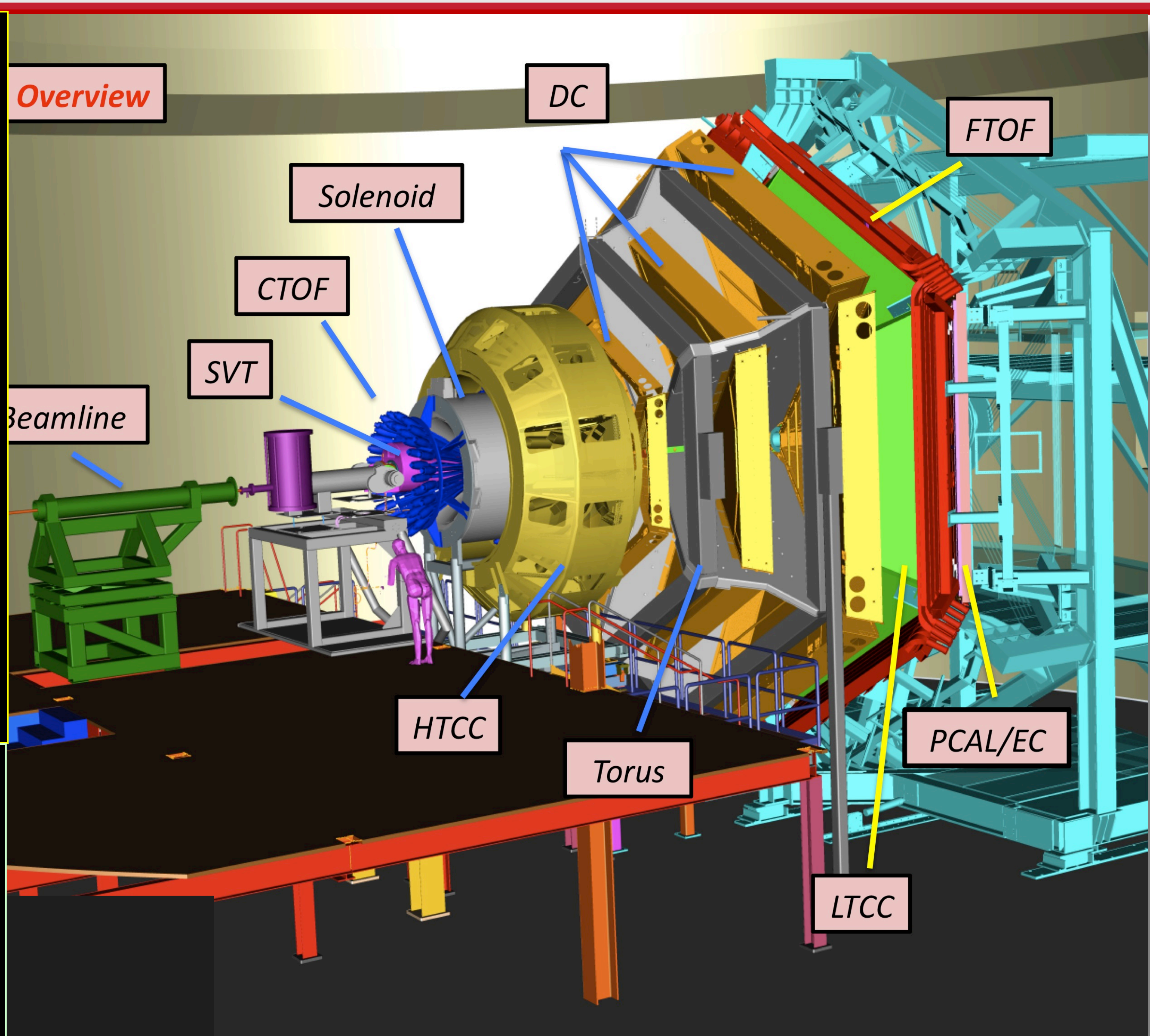
- SOLENOID magnet
- Barrel Silicon Tracker
- Central Time-of-Flight

Beamline

- Polarized target (transv.)
- Moller polarimeter
- Photon Tagger

Upgrades to the baseline & under construction

- RICH detector (FD)
- Forward Tagger (FD)
- Neutron detector (CD)
- Micromegas (CD)
- Polarized target (long.)

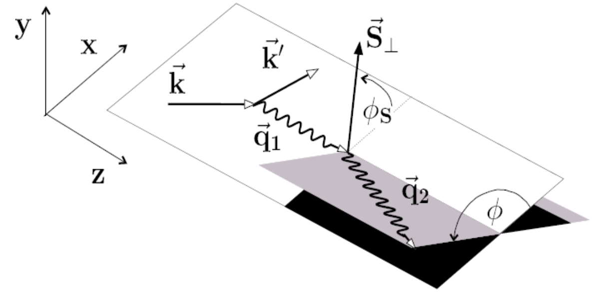


A path towards extracting GPDs

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

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

$k = t/4M^2$



Polarized beam, unpolarized target:

$\Delta\sigma_{LU} \sim \sin\phi \, \{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\} d\phi$ → $H(\xi,t)$

Unpolarized beam, longitudinal target:

$\Delta\sigma_{UL} \sim \sin\phi \, \{F_1 \tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi) E)\} d\phi$ → $\tilde{H}(\xi,t)$

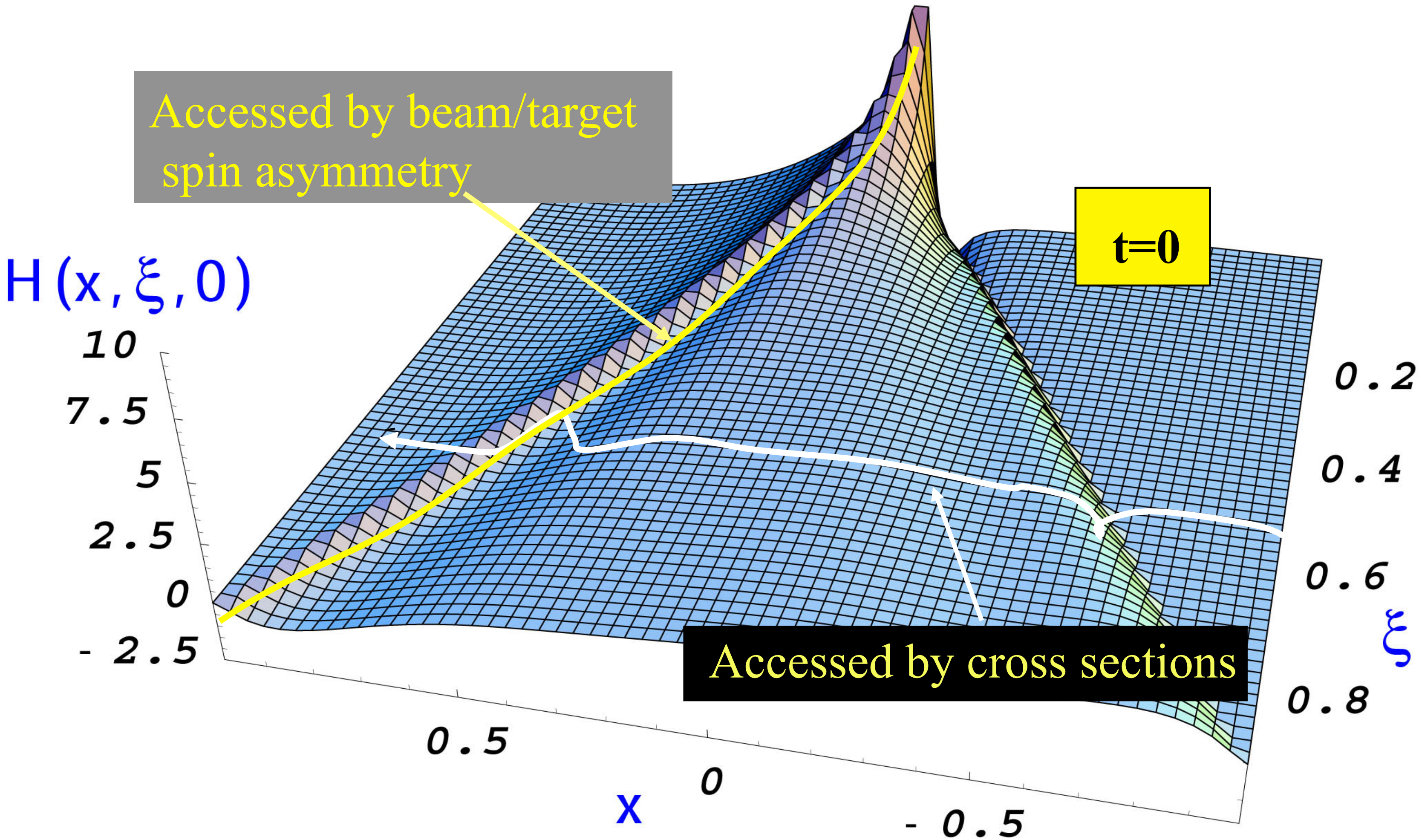
Unpolarized beam, transverse target:

$\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s-\phi)\{k(F_2 H - F_1 E)\} d\phi$ → $E(\xi,t)$

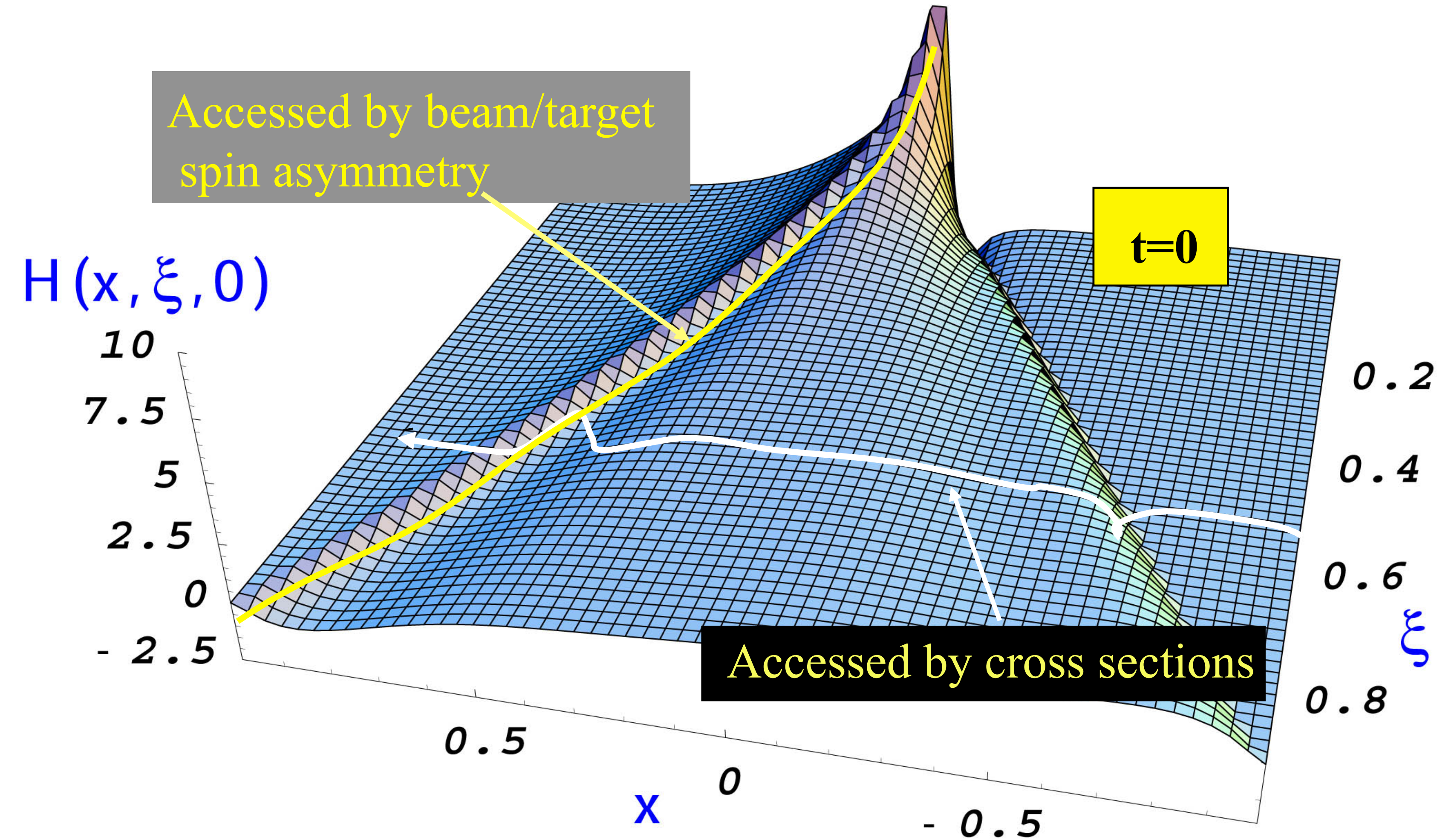
Unpolarized total cross section:

Separates h.t. contributions to DVCS → $\mathcal{R}e(T^{DVCS})$

GPDS KINEMATICS



GPDS KINEMATICS

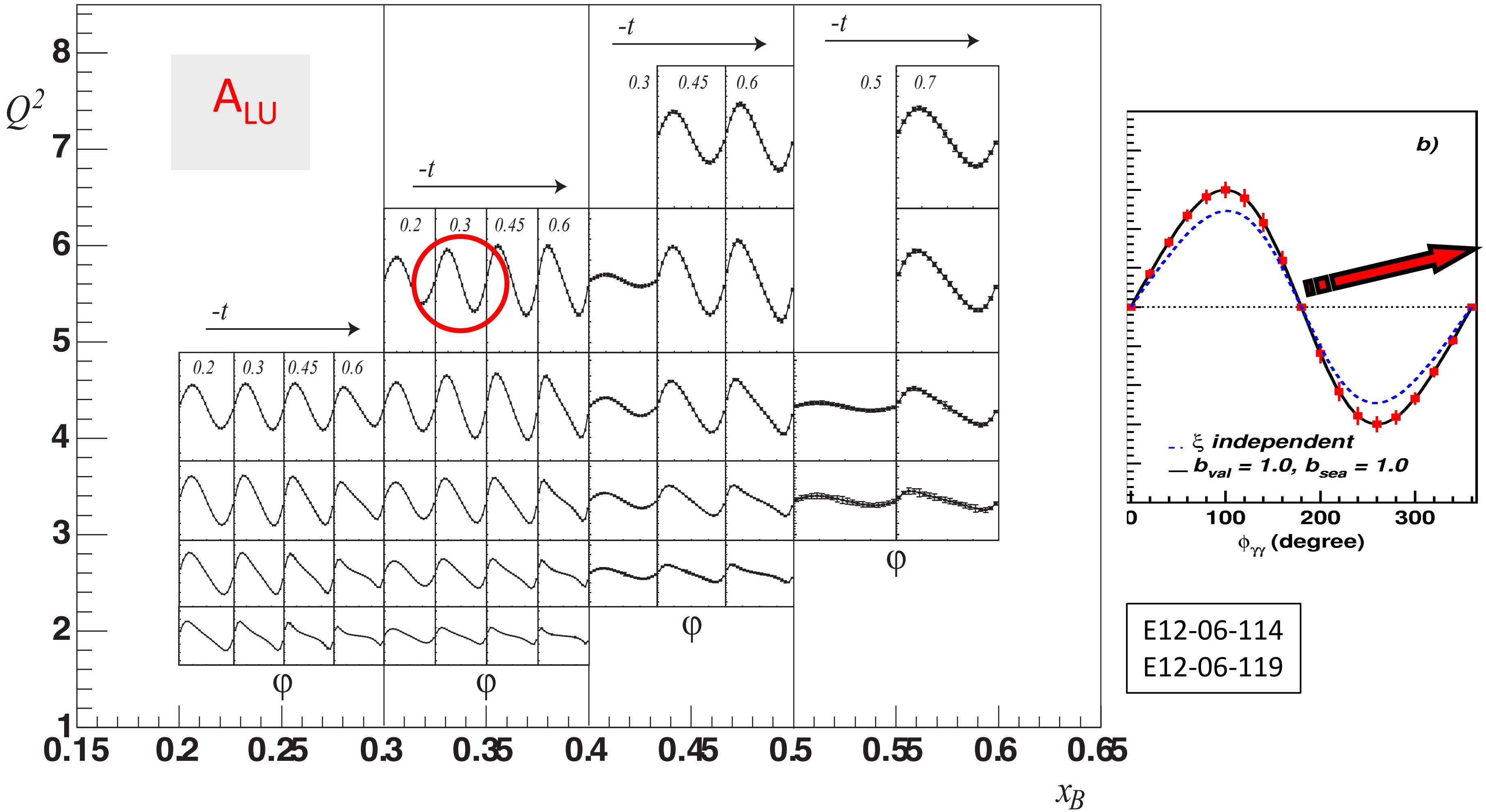


Mapping GPDs requires large kinematical coverage

A_{LU} Projections for 12GeV

$\Delta\sigma_{LU} \sim \sin\phi\ \{F_1 \mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} + kF_2 \mathcal{E}\}d\phi$

$\vec{e}p \to ep\gamma$



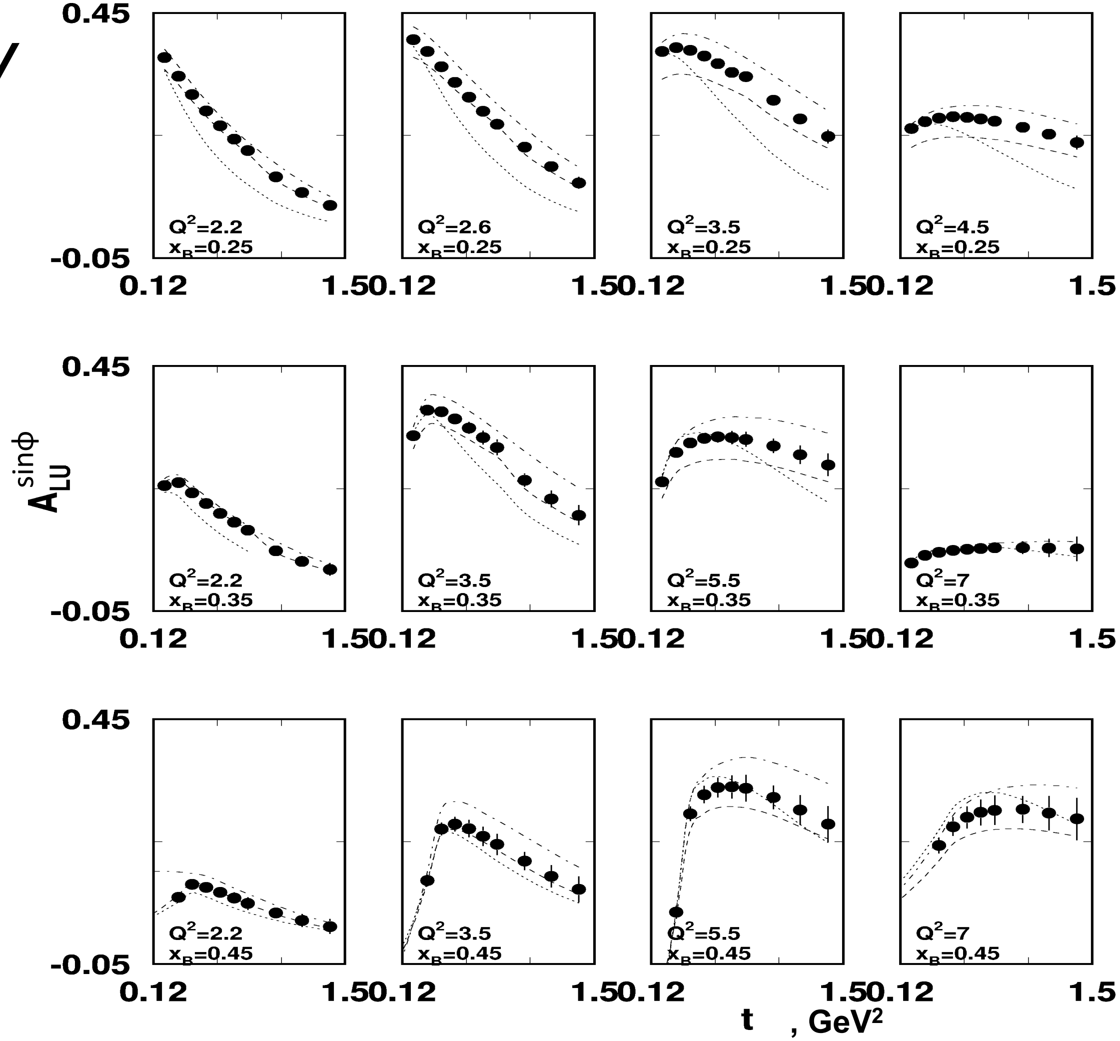
E12-06-114
E12-06-119

A_{LU} - Projections for protons

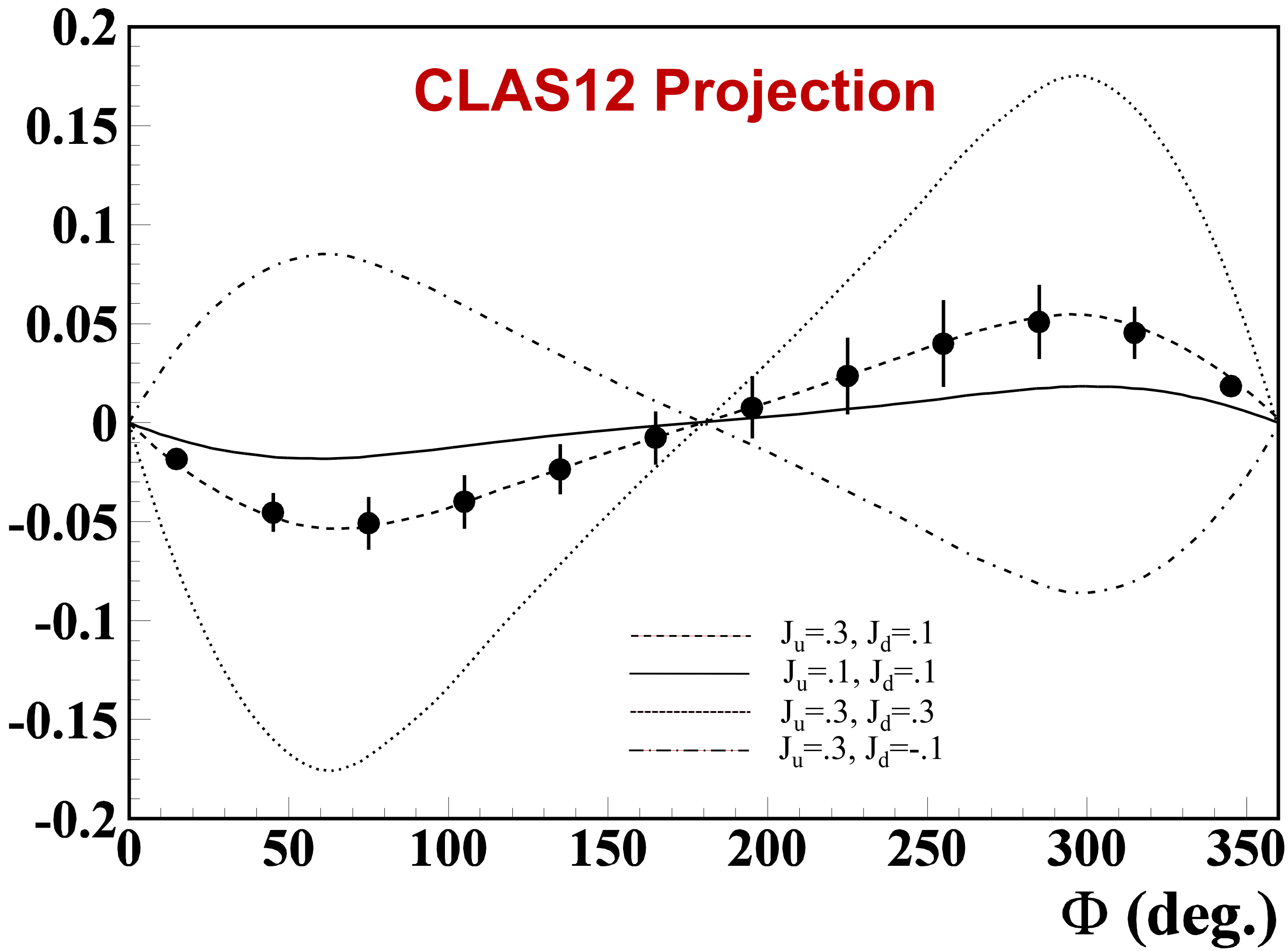
$\vec{e}p \longrightarrow ep\gamma$

$\Delta\sigma_{LU} \sim \sin\phi\ \{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} + kF_2\mathcal{E}\}d\phi$

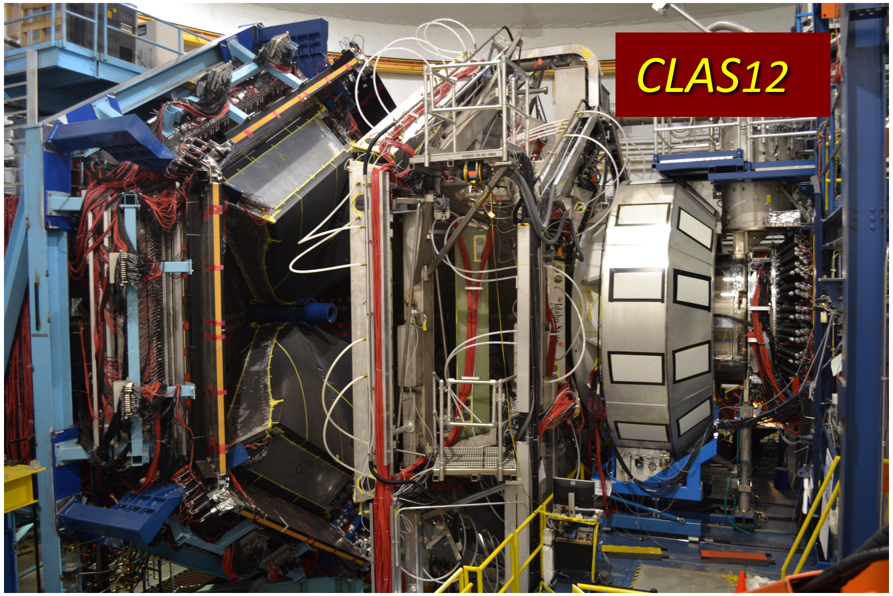
$E_e = 11 GeV$



Beam-spin asymmetry for nDVCS

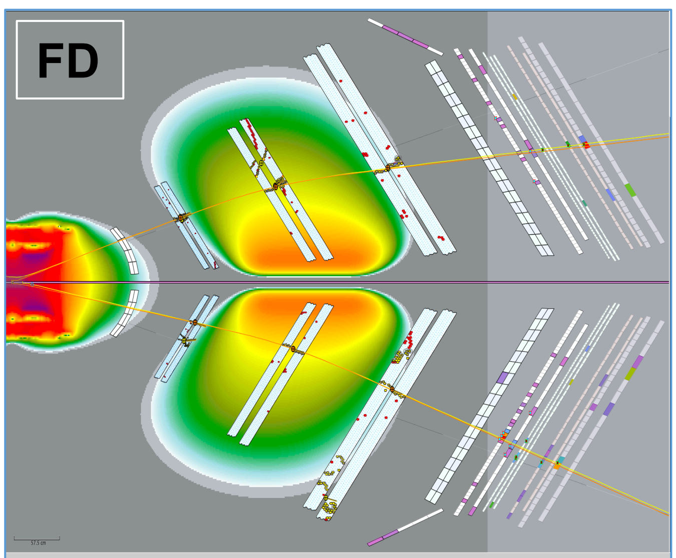


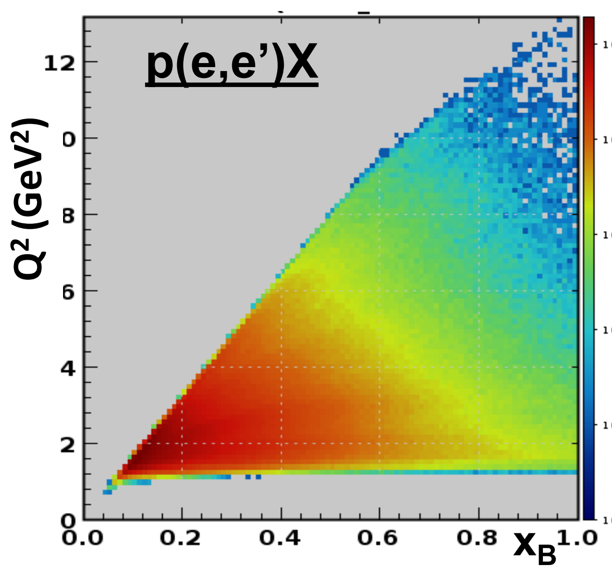
CLAS12 @ JLAB12

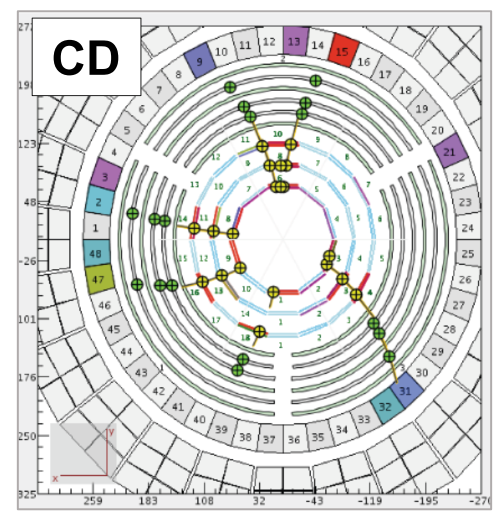


Broad science program at 11 GeV

- N* physics at short distances
- Imaging of nucleon quark structure
- GPDs, TMDs
- Exotic hadrons
- Strong interaction in nuclei
- Gravitational structure of the proton







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FIRST LOOK AT BEAM-SPIN ASYMMETRY FROM CLAS12

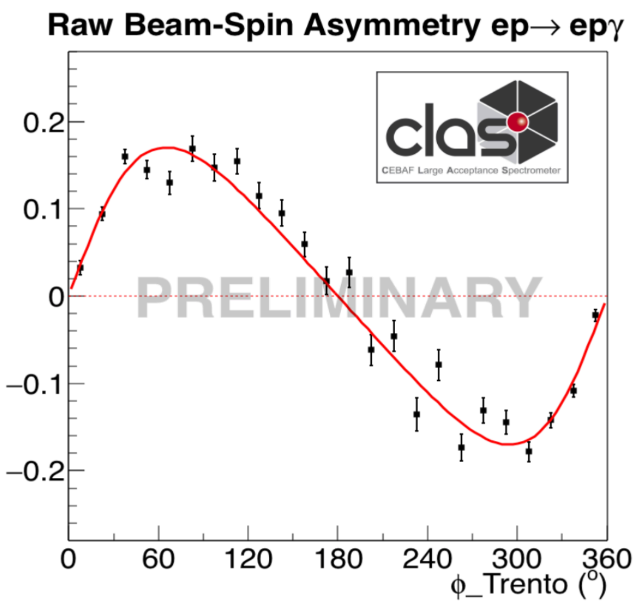
Preliminary asymmetry:

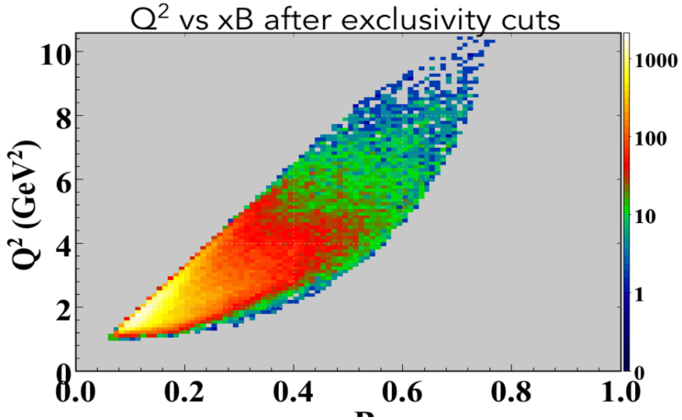
$$A_{LU} = \frac{1}{P}\frac{N^{+}(\phi_{trento}) - N^{-}(\phi_{trento})}{N^{+}(\phi_{trento}) + N^{-}(\phi_{trento})}$$

P polarization

N^{+} / N^{-} number of events with helicity + / -

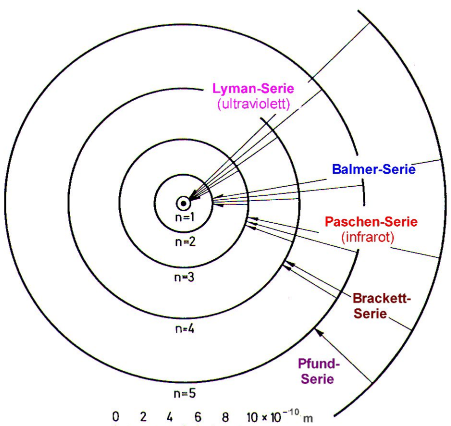
- Residual background not yet subtracted
- Only statistical errors
- Integrated over all kinematic domain



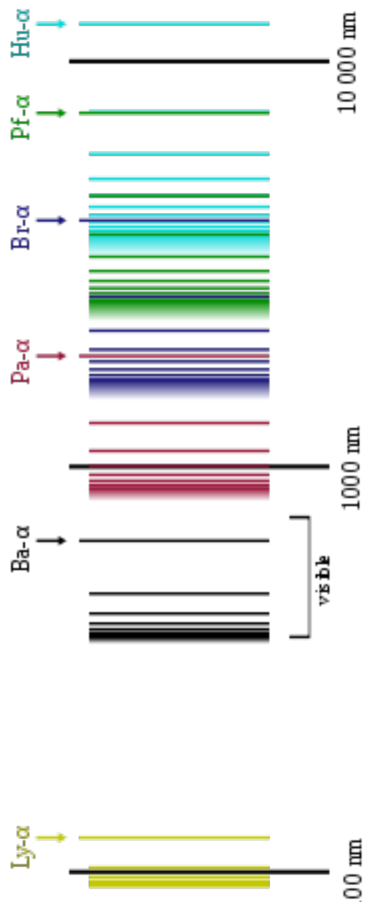


FROM THE H SPECTRUM TO THE N* SPECTRUM

Niels Bohr, model of the hydrogen atom, 1913.



Spectral series of hydrogen



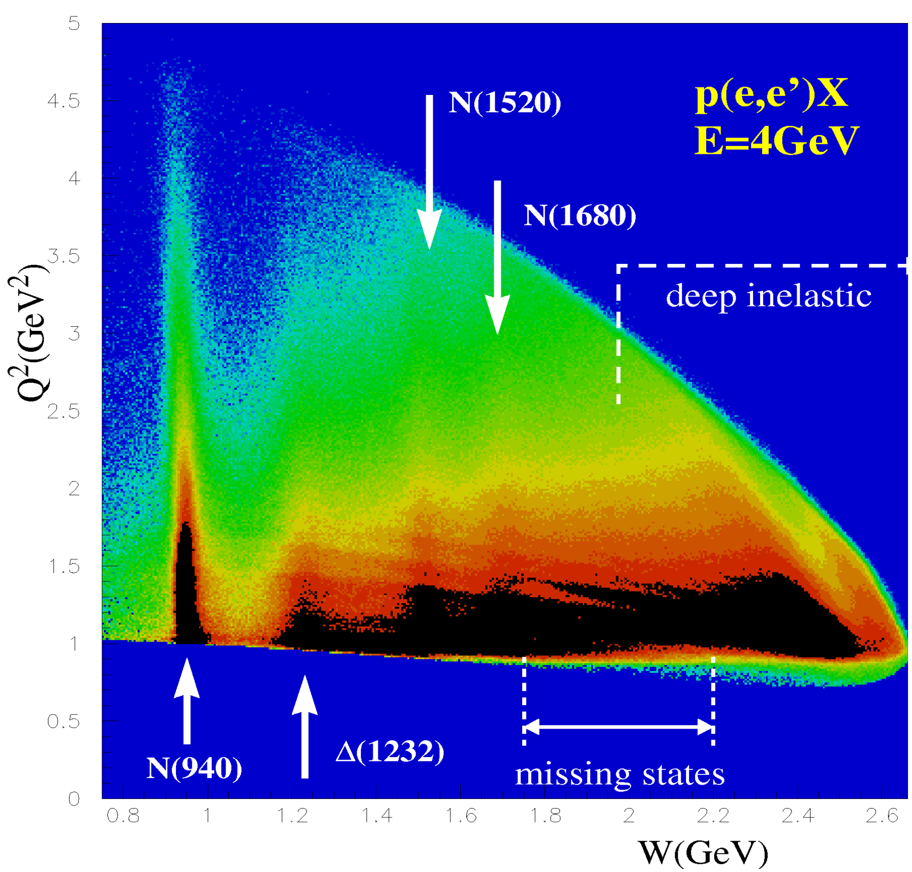
- Understanding the hydrogen atom requires understanding its spectrum of *sharp energy levels*
  -> From the *Bohr model* to ***QED***

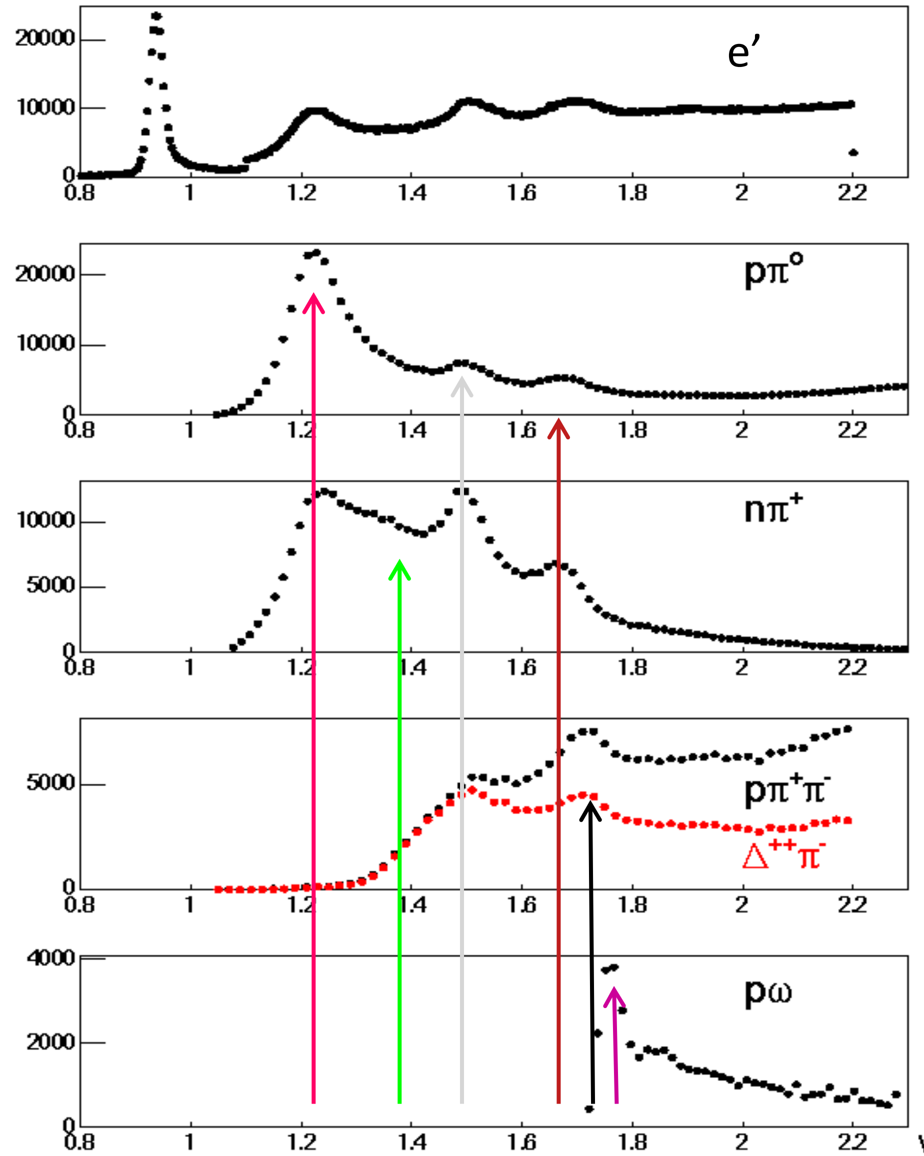
- Understanding the proton requires understanding its energy spectrum of *broad energy levels*
  -> From the *quark model* to **strong *QCD***

We have the theory and need to apply it to the excited states of the proton.

Electron Scattering ep→e'X

$Q^2=-(e-e')^2$; $W^2 = M_X{}^2=(e-e'+p)^2$





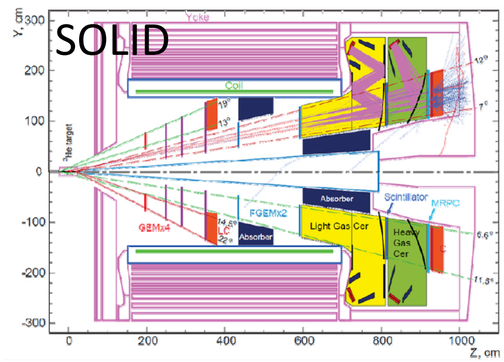
Resonances cannot be uniquely separated in inclusive scattering → exclusive processes

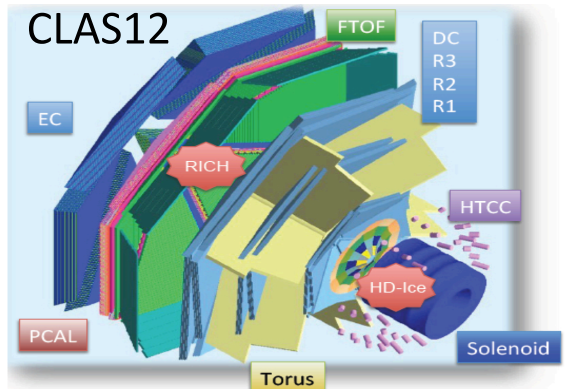
Incorporate NN* GPDs in general framework?

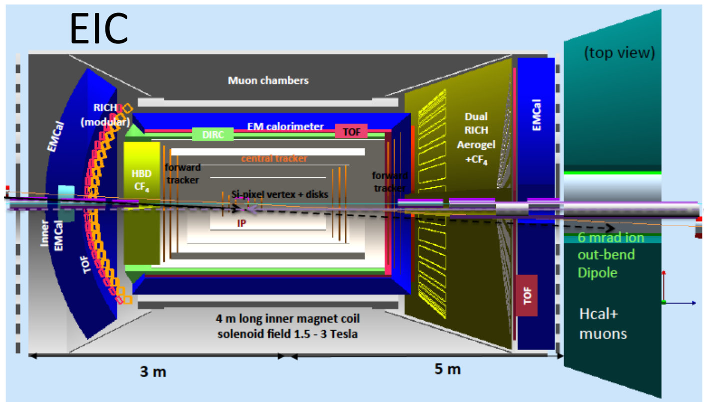
- Need to develop transition GPD formalism for NN* transitions in N*DVCS.

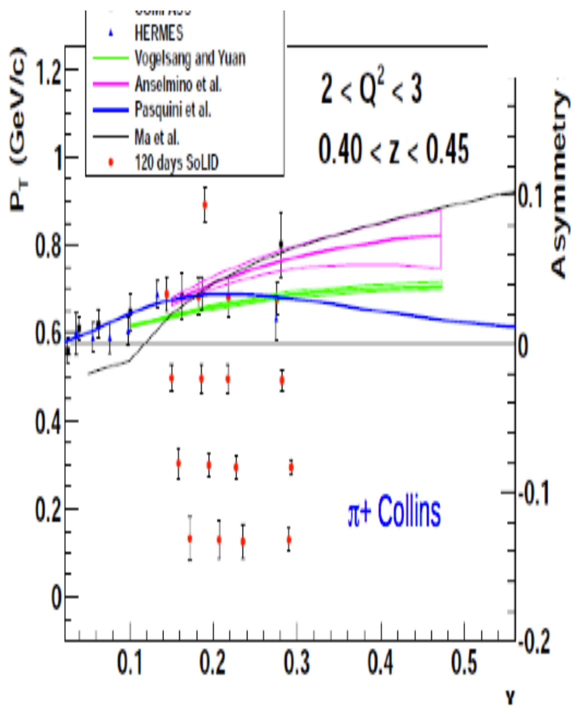
- Channels of interest for experiments $p(e,e'\gamma p\pi^0)$, $p(e,e'\gamma p\eta)$, $p(e,e'\gamma n\pi^+)$, $n(e,e'\gamma p\pi^-)$ for low mass states, and $p(e,e'\gamma\, p\pi^+\pi^-)$ for high mass states.

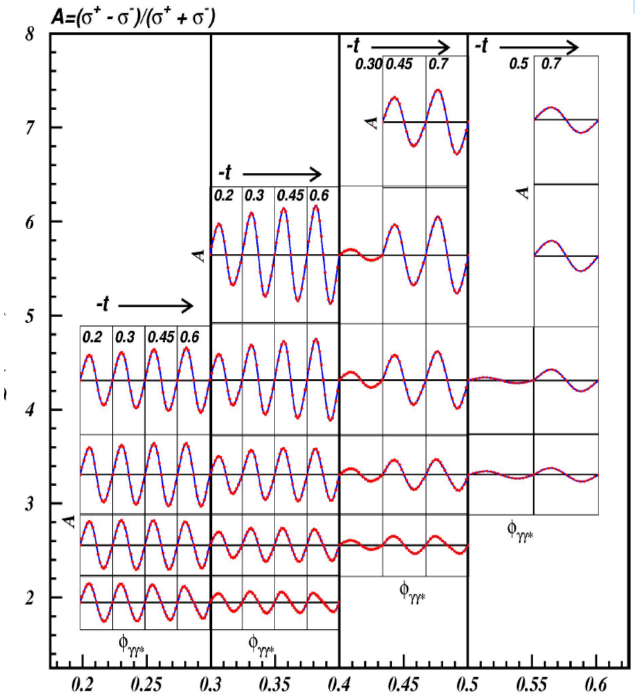
STATE OF THE ART EXPERIMENTAL APPARATUS

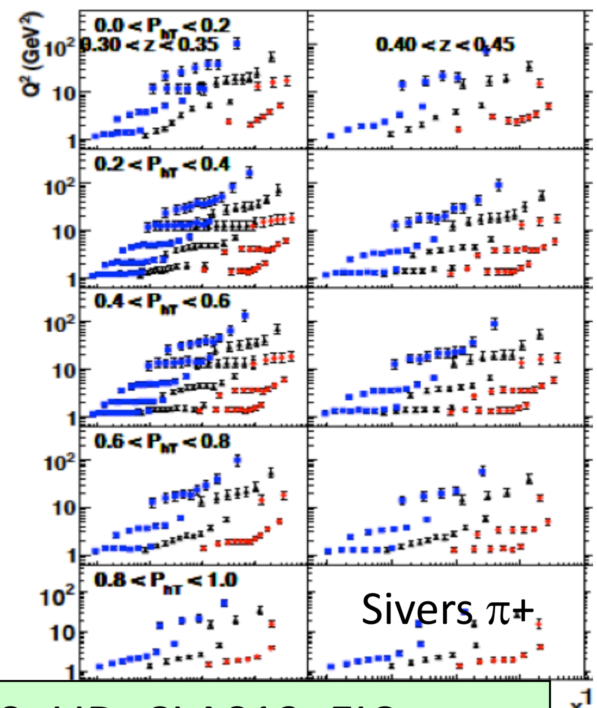




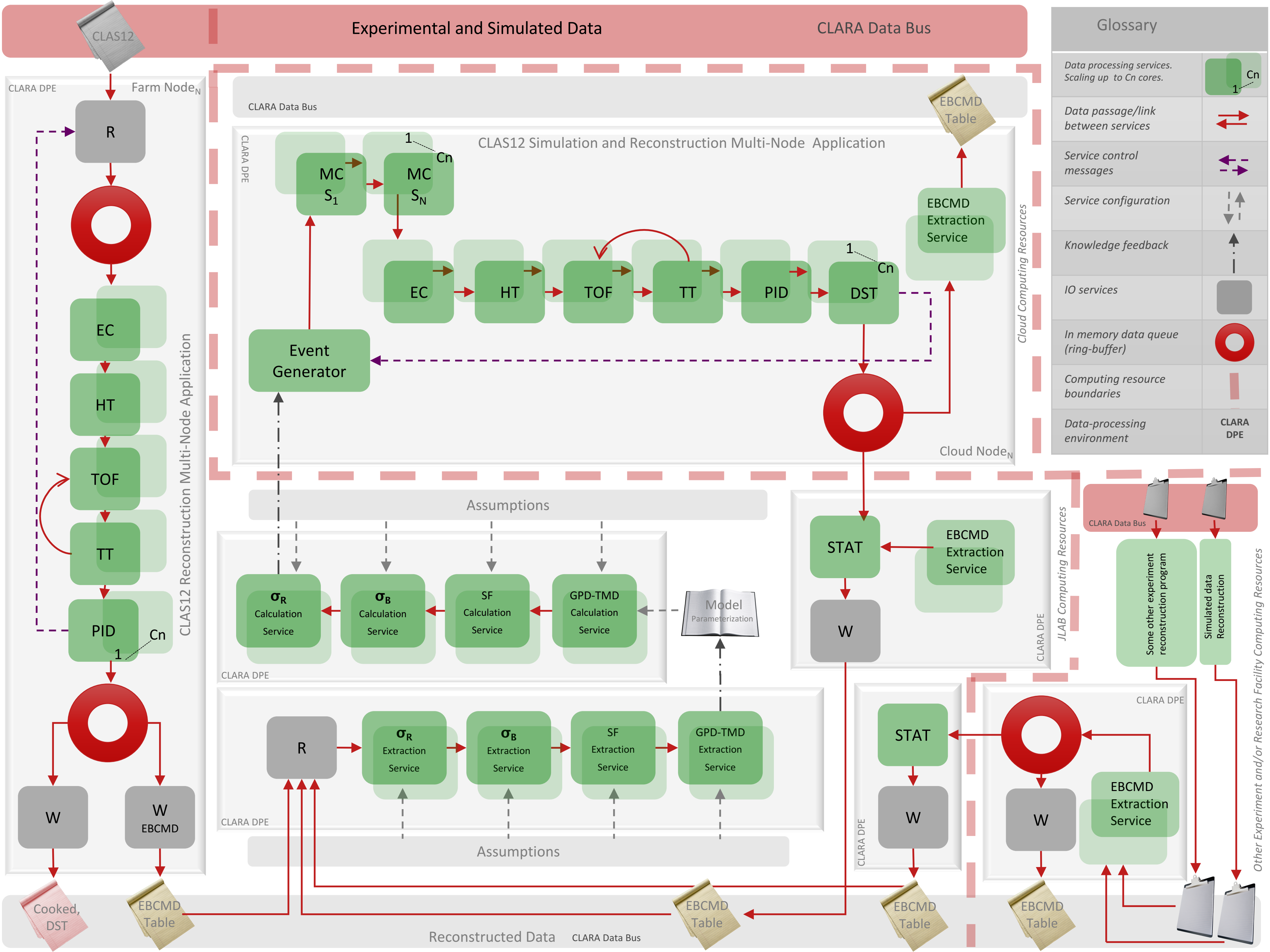








Precision multi-dimensional mapping of 3D PDFs using SoLID, CLAS12, EIC,…



CLAS12
Experimental and Simulated Data
CLARA Data Bus
Glossary
Data processing services. Scaling up to Cn cores.
Data passage/link between services
Service control messages
Service configuration
Knowledge feedback
IO services
In memory data queue (ring-buffer)
Computing resource boundaries
Data-processing environment
CLARA DPE
CLARA DPE
Farm Node$_N$
R
EC
HT
TOF
TT
PID
Cn
1
W
W
EBCMD
CLAS12 Reconstruction Multi-Node Application
Cooked, DST
EBCMD Table
CLARA Data Bus
EBCMD Table
CLARA DPE
CLAS12 Simulation and Reconstruction Multi-Node Application
MC S_1
MC S_N
1
Cn
EC
HT
TOF
TT
PID
DST
1
Cn
EBCMD Extraction Service
Event Generator
Cloud Node$_N$
Cloud Computing Resources
Assumptions
σ_R Calculation Service
σ_B Calculation Service
SF Calculation Service
GPD-TMD Calculation Service
Model Parameterization
CLARA DPE
STAT
EBCMD Extraction Service
W
CLARA DPE
JLAB Computing Resources
CLARA Data Bus
Some other experiment reconstruction program
Simulated data Reconstruction
Other Experiment and/or Research Facility Computing Resources
R
σ_R Extraction Service
σ_B Extraction Service
SF Extraction Service
GPD-TMD Extraction Service
CLARA DPE
Assumptions
STAT
W
CLARA DPE
CLARA DPE
W
EBCMD Extraction Service
EBCMD Table
EBCMD Table
EBCMD Table
Reconstructed Data
CLARA Data Bus

Center for Nuclear Femtography (CNF)

The science of imaging the interior of the atomic nucleus is in its infancy. With new tools at our disposal, we are poised to make major progress in the near future.

- Development of 3D formalism for nuclear structure
- New state of the art experimental tools becoming available

Need/Require a multidisciplinary approach

➔ **Center for Nuclear Femtography**

Center for Nuclear Femtography

Initial Phase funded by Commonwealth to "…..*to facilitate the application of modern developments in data science to the problem of imaging and visualization of sub-femtometer scale structure of protons, neutrons, and atomic nuclei"*

- **Multi-disciplinary,** *bringing together nuclear theorists and experimentalists, mathematicians, computer scientists,… … and architects and artists!*

- **Consortium of VA universities, Jefferson Lab, others?**

Latifa Elouadrhiri & David Richards - Steering-Committee Co-Chairs

FIRST STEP TOWARDS THE CENTER

- Symposium at the University of Virginia in **December 2018** (*S. Liuti Chair).*The symposium brought together scholars and researchers from universities and research institutes from around the world to discuss recent developments and future opportunities in the **imaging and visualization** of scientific data across a spectrum of disciplines and how these could be applied to advance Nuclear Femtography.

1. Collect interested parties, experts from nuclear physics and other disciplines

2. Exchange information on expertise, capabilities relevant to Nuclear Femtography

3. Identify areas of potential collaboration

4. Discuss the development of the Center and near-term activities

CNF – NEXT STEP

As next step, CNF funded near-term projects (7) that can both seed future activities at the center, and can contribute to a future proposal to the Commonwealth of Virginia aimed at the long-term establishment of a world-leading Center. These projects included, but were not restricted to:

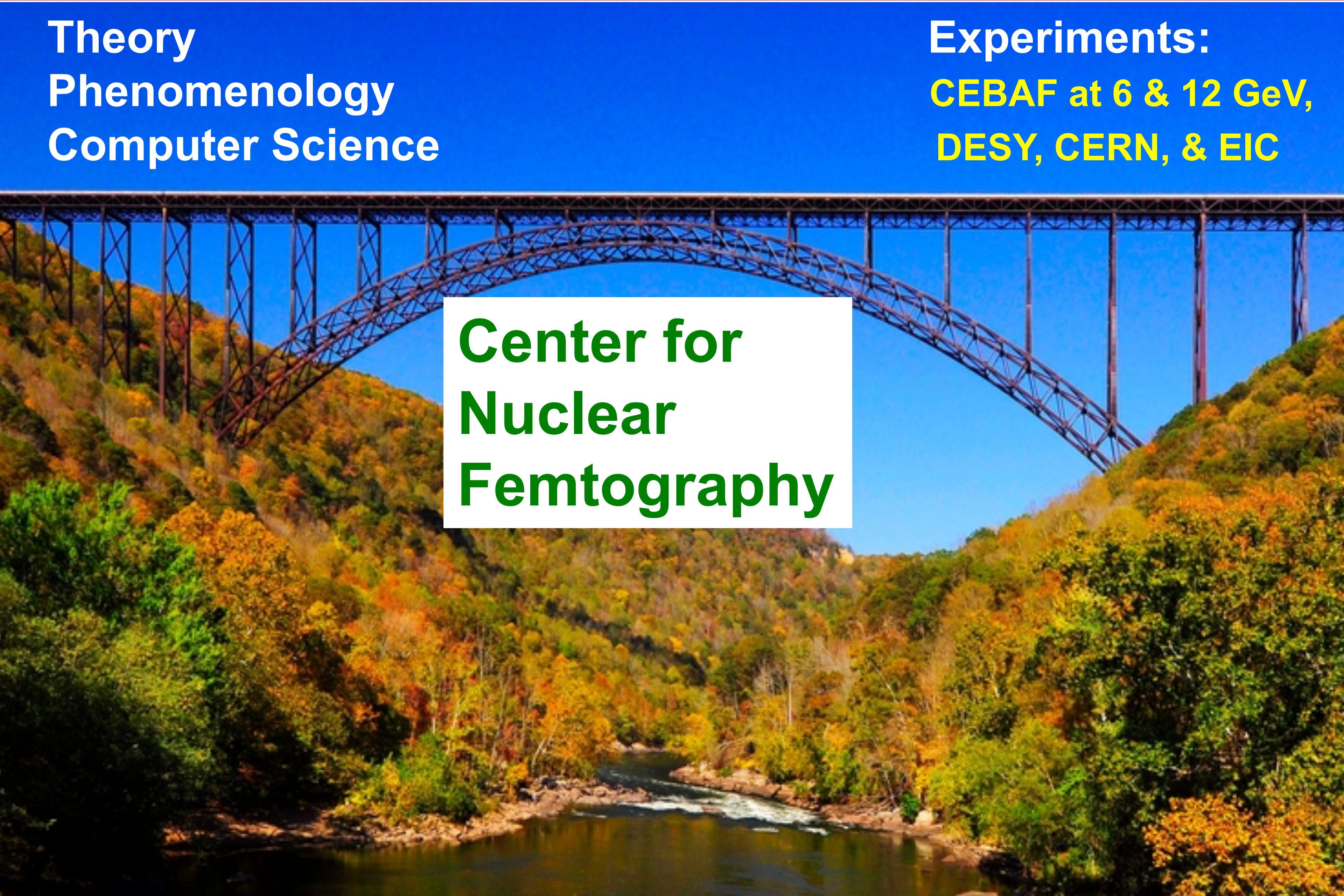
1. The construction of a QCD-inspired reference model for the nucleon, including that of the Wigner Distribution.

2. The development of images of the nucleon through fitting to experimental data with theoretical input, reflecting constraints arising from limitations both in experiment and theory.

3. The use of Visualization both as a means of imaging the nucleon, and of refining our analysis methodology.

4. Applications of Machine Learning to data analysis, interpretation and classification.

5. The development and application of computational and mathematical methods, and the associated computational infrastructure.


Theory
Phenomenology
Computer Science
Experiments:
CEBAF at 6 & 12 GeV,
DESY, CERN, & EIC
Center for
Nuclear
Femtography

Thank You

@latifaelou

What is inside the proton/neutron?

1933: Proton's magnetic moment

Nobel Prize
In Physics 1943

Otto Stern

"for … and for his discovery of the magnetic moment of the proton".

$g \neq 2$

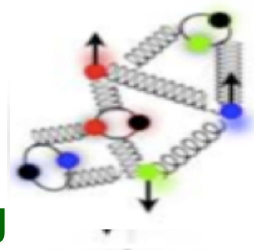
1960: Elastic e-p scattering

Nobel Prize
In Physics 1961

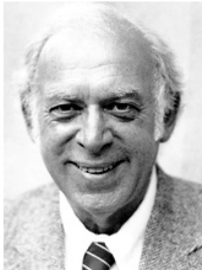
Robert Hofstadter

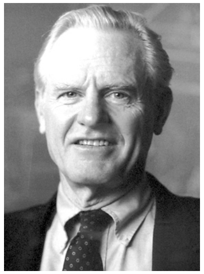
"for … and for his thereby achieved discoveries concerning the structure of the nucleons"

Form factors $\rightarrow$ Charge distributions



1969: Deep inelastic e-p scattering



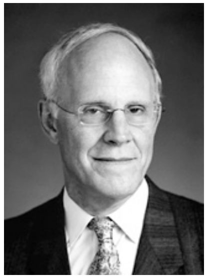


Nobel Prize in Physics 1990

Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

"for their pioneering investigations concerning deep inelastic scattering of electrons on protons …".

1974: QCD Asymptotic Freedom

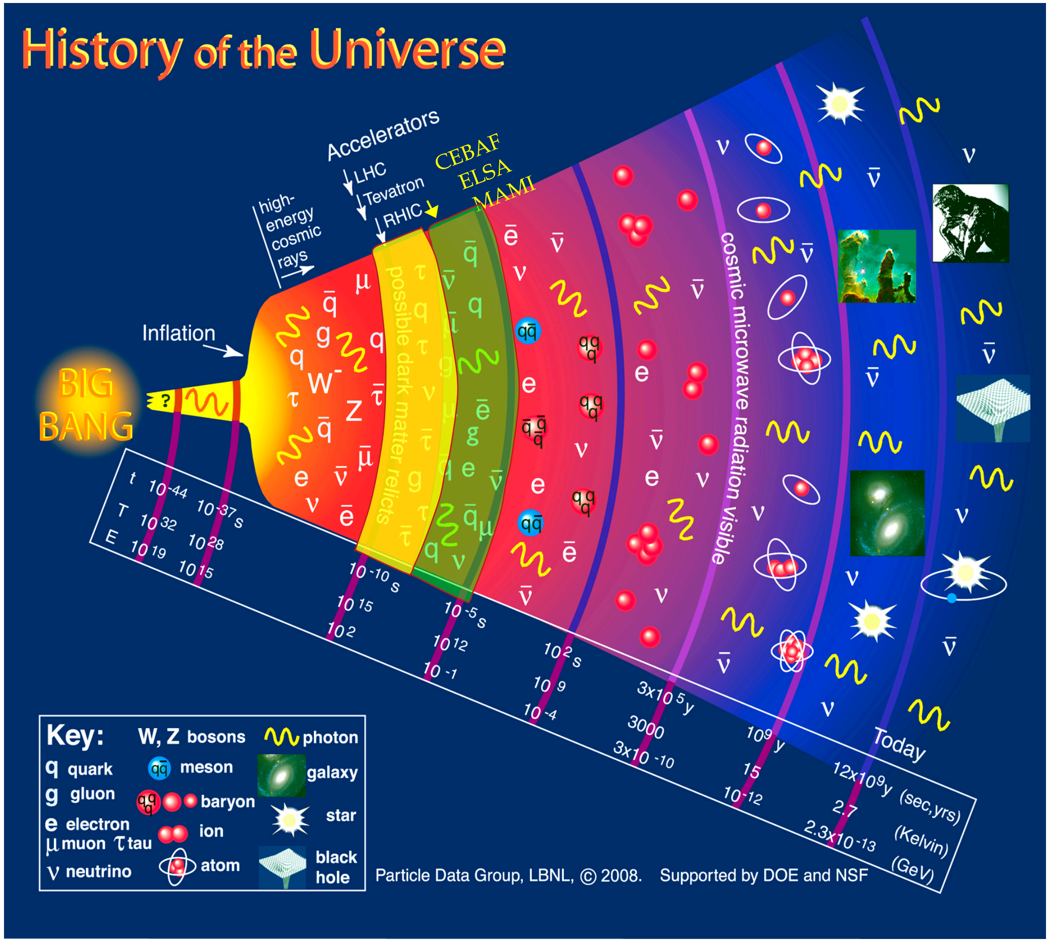


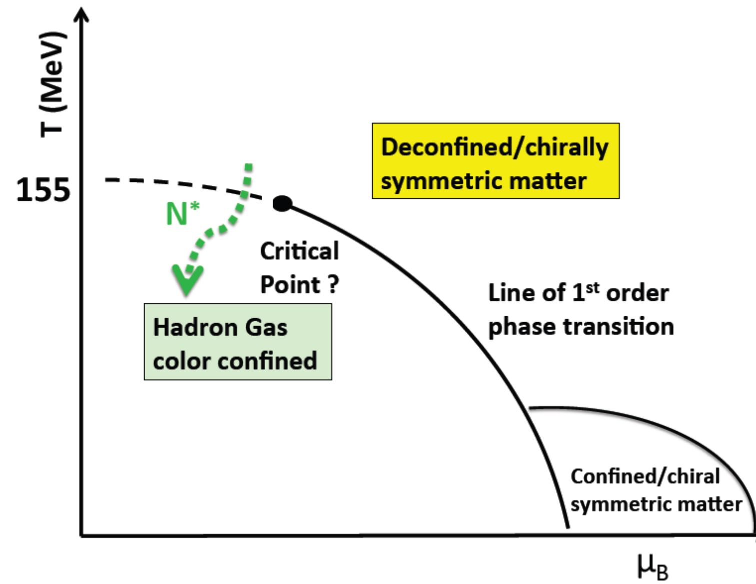
Nobel Prize in Physics 2004

David J. Gross, H. David Politzer, Frank Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction".

The Emergence of Confinement





Dramatic events in the μsec old universe

- Chiral symmetry is broken
- Quarks attain masses dynamically
- Quark confinement occurs

QGP ➡ Hadron gas phase

With electron machines we explore these events to unravel the mechanisms of confinement