Nucleon Structure

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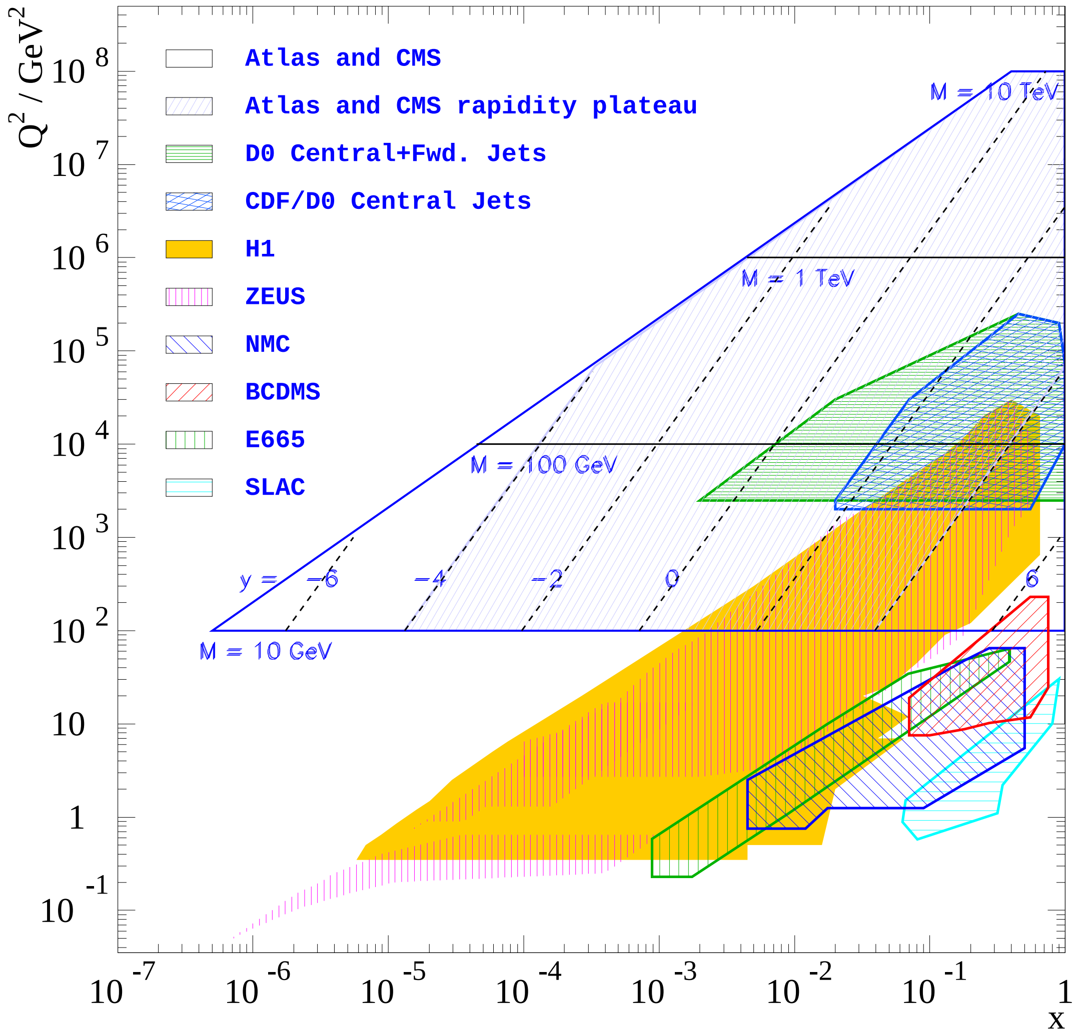
DESY

ICFA Seminar, CERN, October 2011.

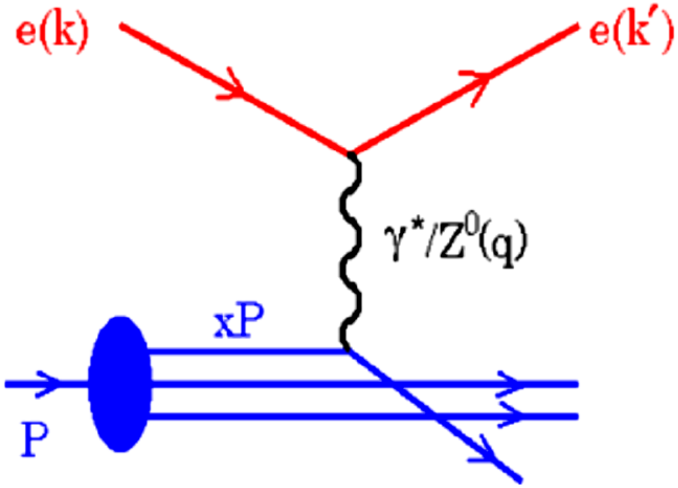
Overview of experimental data on the proton structure



- A number of *ep* and *pp* experiments cover a large kinematic range in Bjorken-x and momentum transfers Q^2.
- Accurate, ∼ 1% tests of the perturbative QCD picture.
- Broad consistency of *ep* and *pp* data, another triumph of SM, from the LHC.

→ signs of new physics may appear as (small) deviations vs SM at high scales, demanding new level of accuracy for proton structure, in particular at high x.

Probing proton structure



Neutral current Deep Inelastic Scattering (DIS) cross section:

$$\frac{d^2\sigma^\pm}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x}\sigma_r^\pm =$$

$$= \frac{2\pi\alpha^2 Y_+}{Q^4 x}\left[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3\right]$$

where factors $Y_\pm = 1 \pm (1-y)^2$ and y^2 define polarization of the exchanged boson and $y = Q^2/(S\,x)$.

Kinematics is determined by boson virtuality Q^2 and Bjorken x.

At leading order:

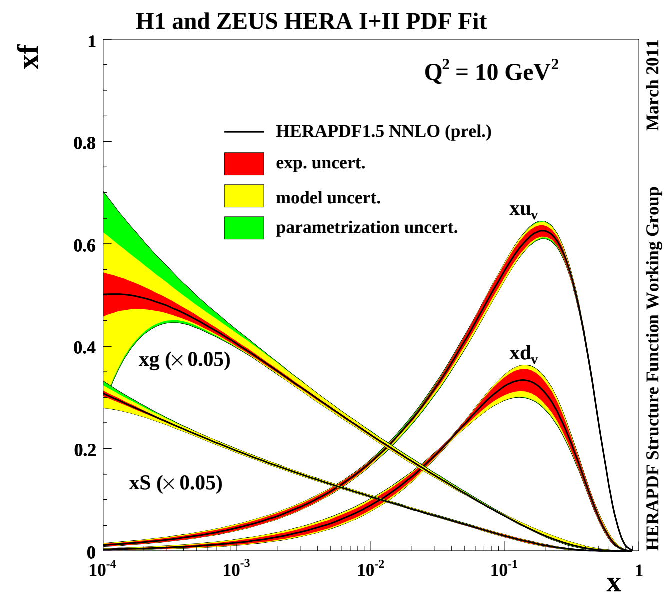
$$F_2 = x\sum e_q^2(q(x) + \bar{q}(x))$$

$$xF_3 = x\sum 2e_q a_q(q(x) - \bar{q}(x))$$

$$\sigma^+_{CC} \sim x(\bar{u} + \bar{c}) + x(1-y)^2(d+s)$$

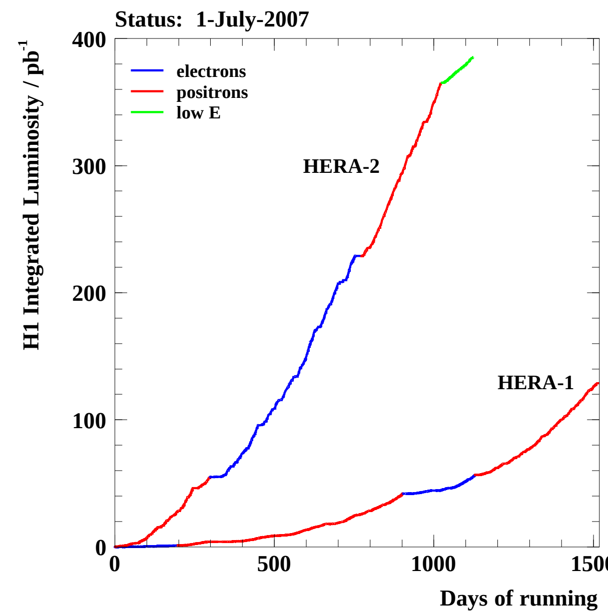
$$\sigma^-_{CC} \sim x(u+c) + x(1-y)^2(\bar{d} + \bar{s})$$

$xg(x)$ — from F_2 scaling violation, jets and F_L



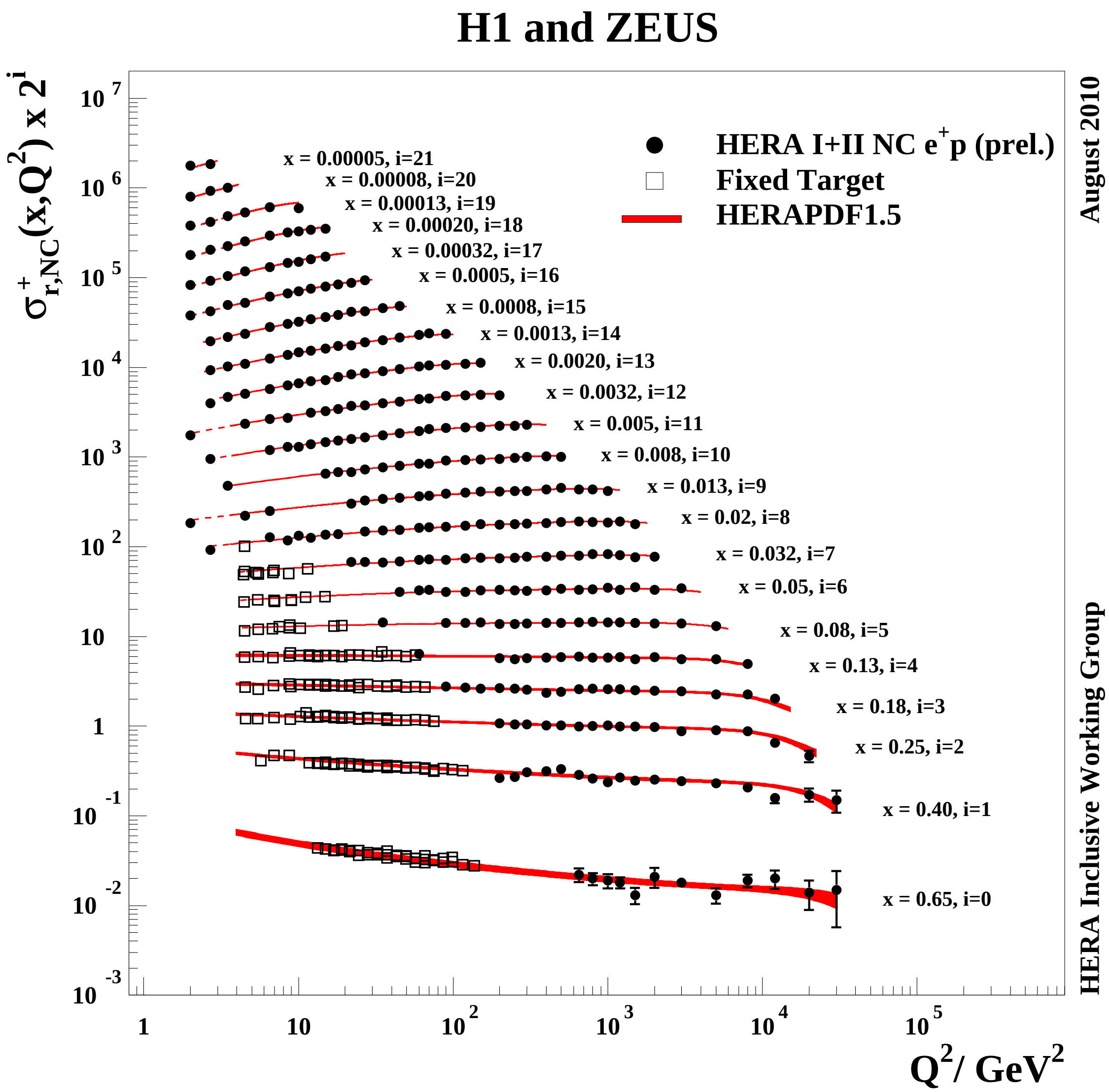
HERA, H1 and ZEUS.

$E_e \times E_p$=27.5×920 GeV^2
$\sqrt{s}$ = 318 GeV
L= 1...4·10^{31}cm^{-2}s^{-1}
e beam polarization.



Integrated luminosity: about 500 pb^{-1} per experiment.

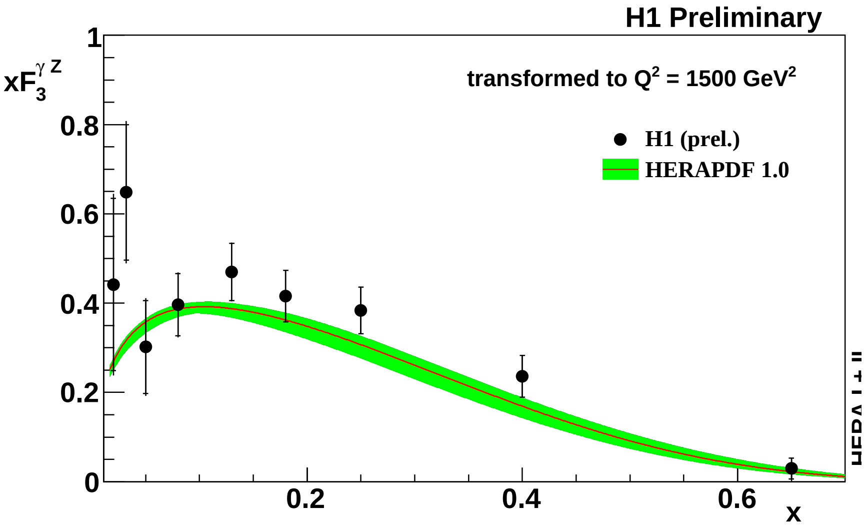
Combined HERAI and HERAII data (preliminary)

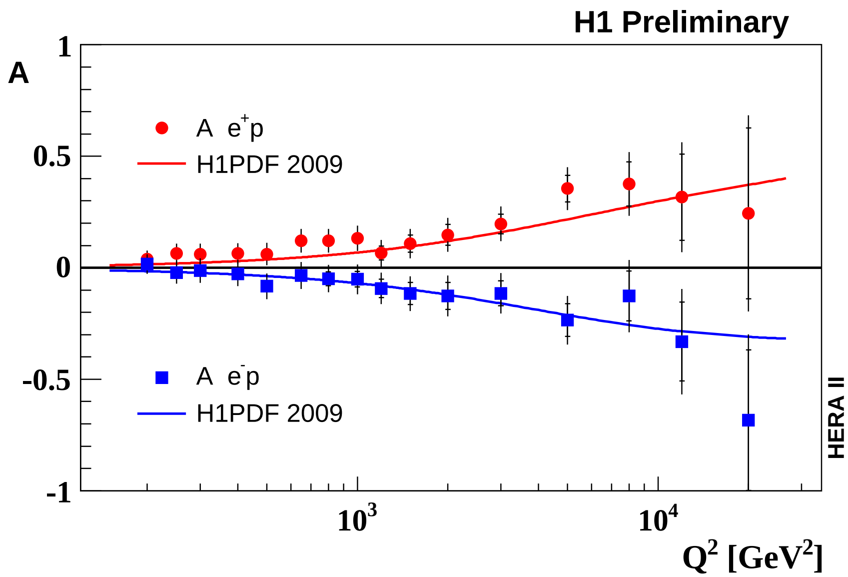


https://www.desy.de/h1zeus/combined_results/index.php?do=proton_structure

- Preliminary combination of complete HERA set
- Good agreement between DGLAP prediction and the data.
- Extrapolation to low Q^2 is consistent with fixed target data.

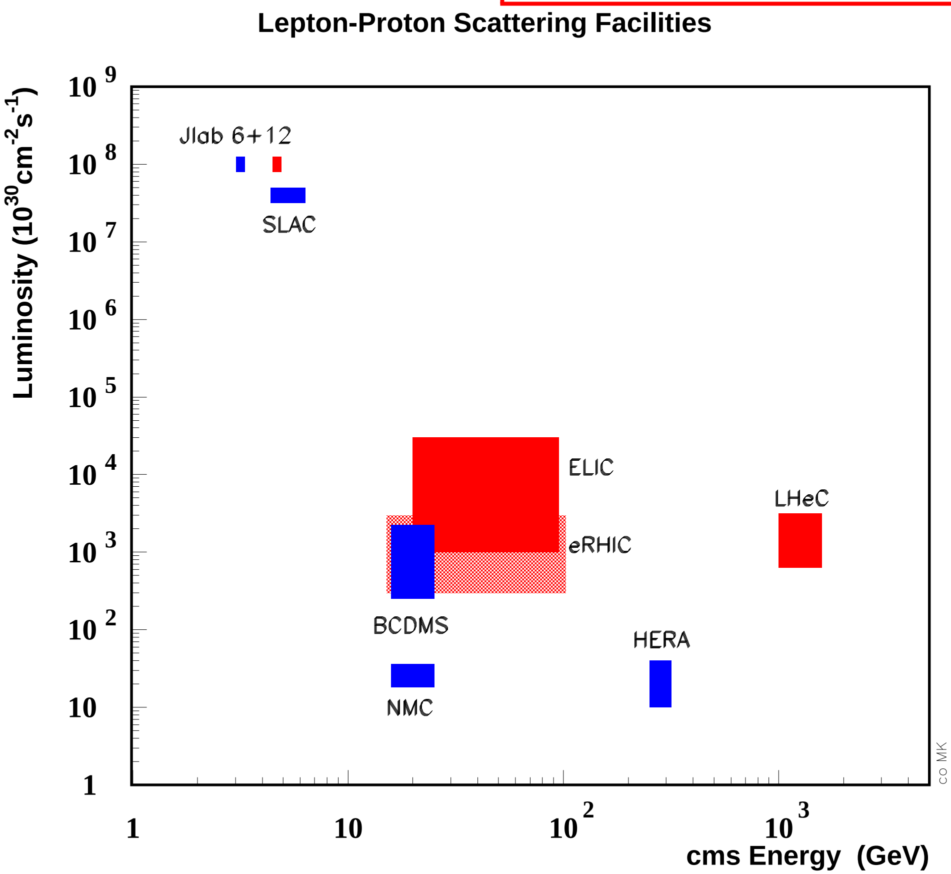
Measurements of $xF_3^{\gamma Z}$ and $F_2^{\gamma Z}$

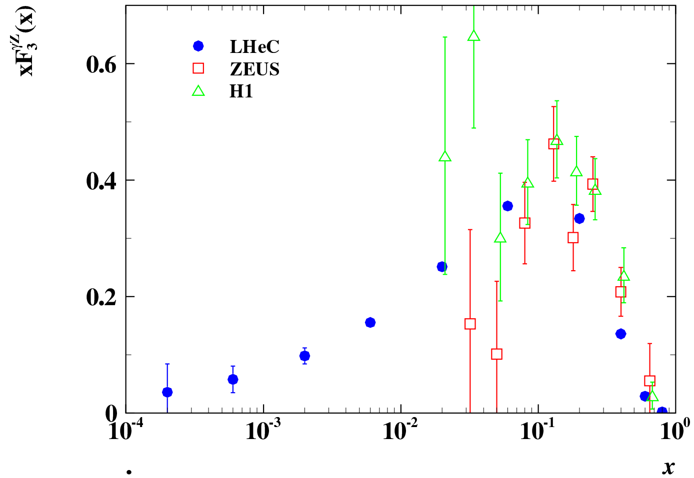




HERA uses $e^{\pm}$ asymmetry to measure $xF_3^{\gamma Z}$ and polarisation asymmetry to get access to $F_2^{\gamma Z}$. Measurements provide additional information on proton structure due to different γ vs Z couplings. Statistically limited: would become powerful with $\times 100$ luminosity.

Future *ep* colliders

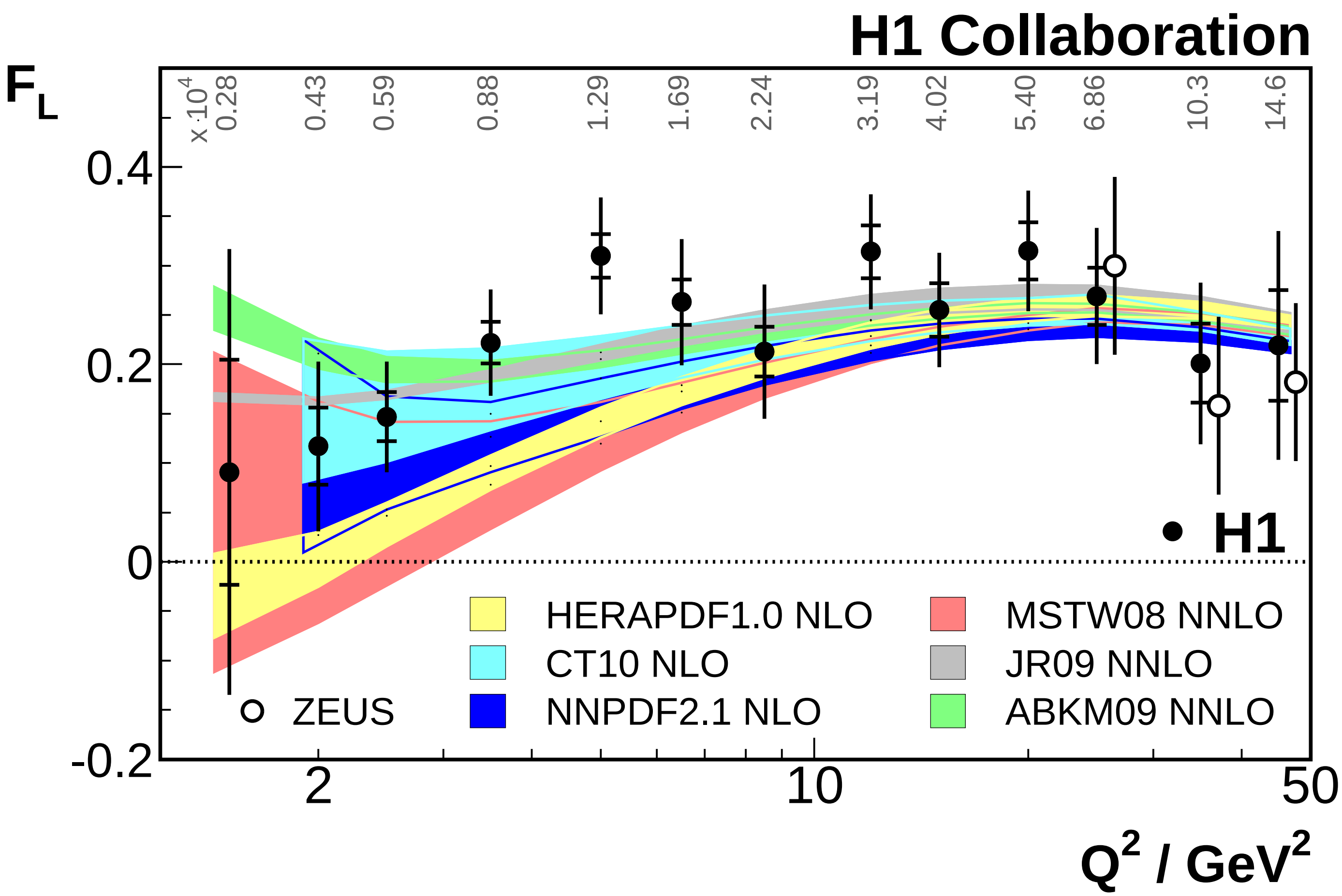




- xF_3 at LHeC can be measured much more accurately compared to HERA.

- Much increased luminosity for EIC and LHeC colliders compared to HERA.
- Increased center of mass energy for the LHeC allows for accurate measurements in EW regime.

Measurement of the Structure Function F_L

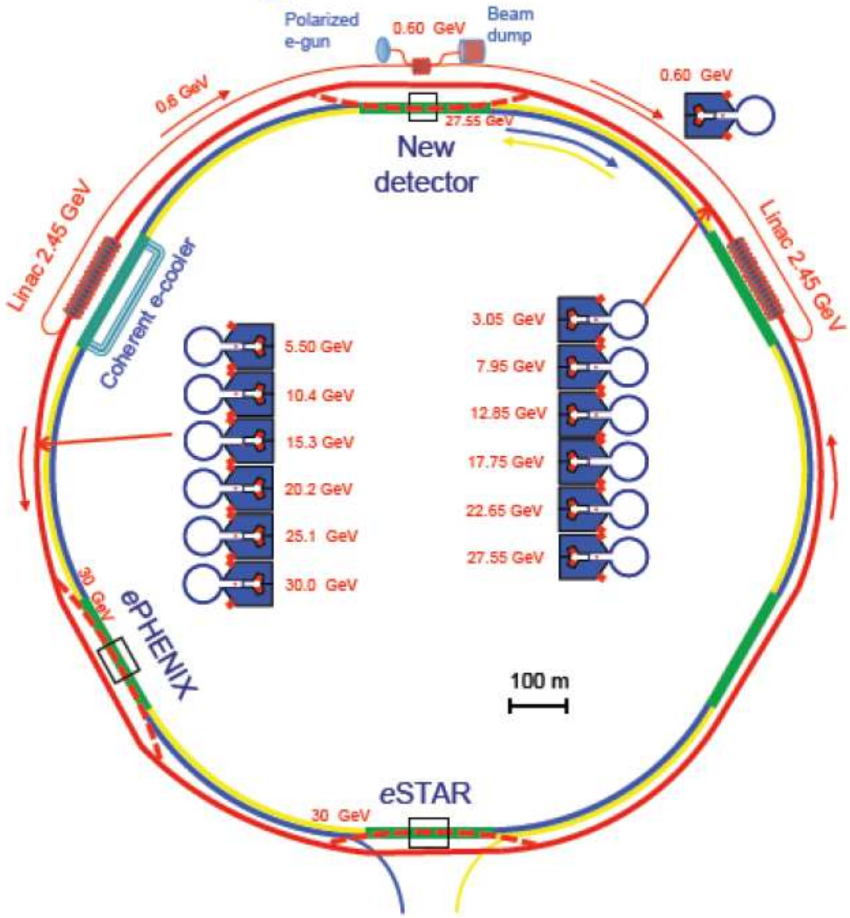


Measurement of the structure function F_L extended to $Q^2 \geq 1.5\ \mathrm{GeV}^2$ and compared to predictions from PDF groups. Good agreement, within the uncertainties. Critical test for gluon density.

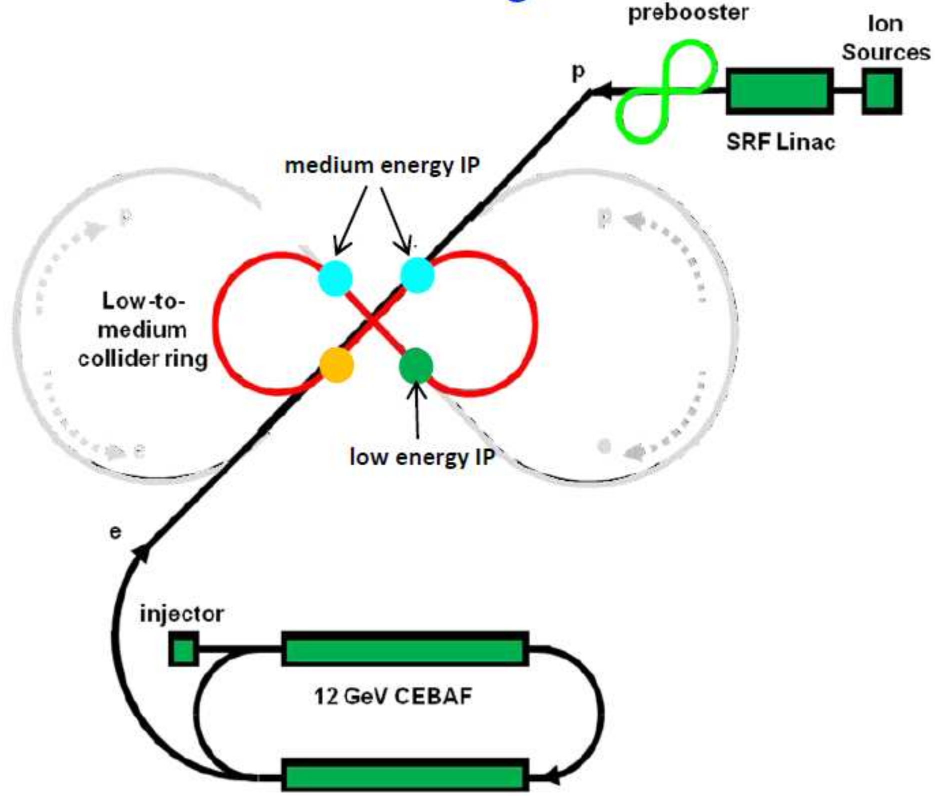
H1 Collaboratoin, F.D. Aaron *et al.*, Eur.Phys.J **C71** (2011) 1579

EIC

eRHIC @ BNL: *add electron Energy Recovery Linac in RHIC tunnel*



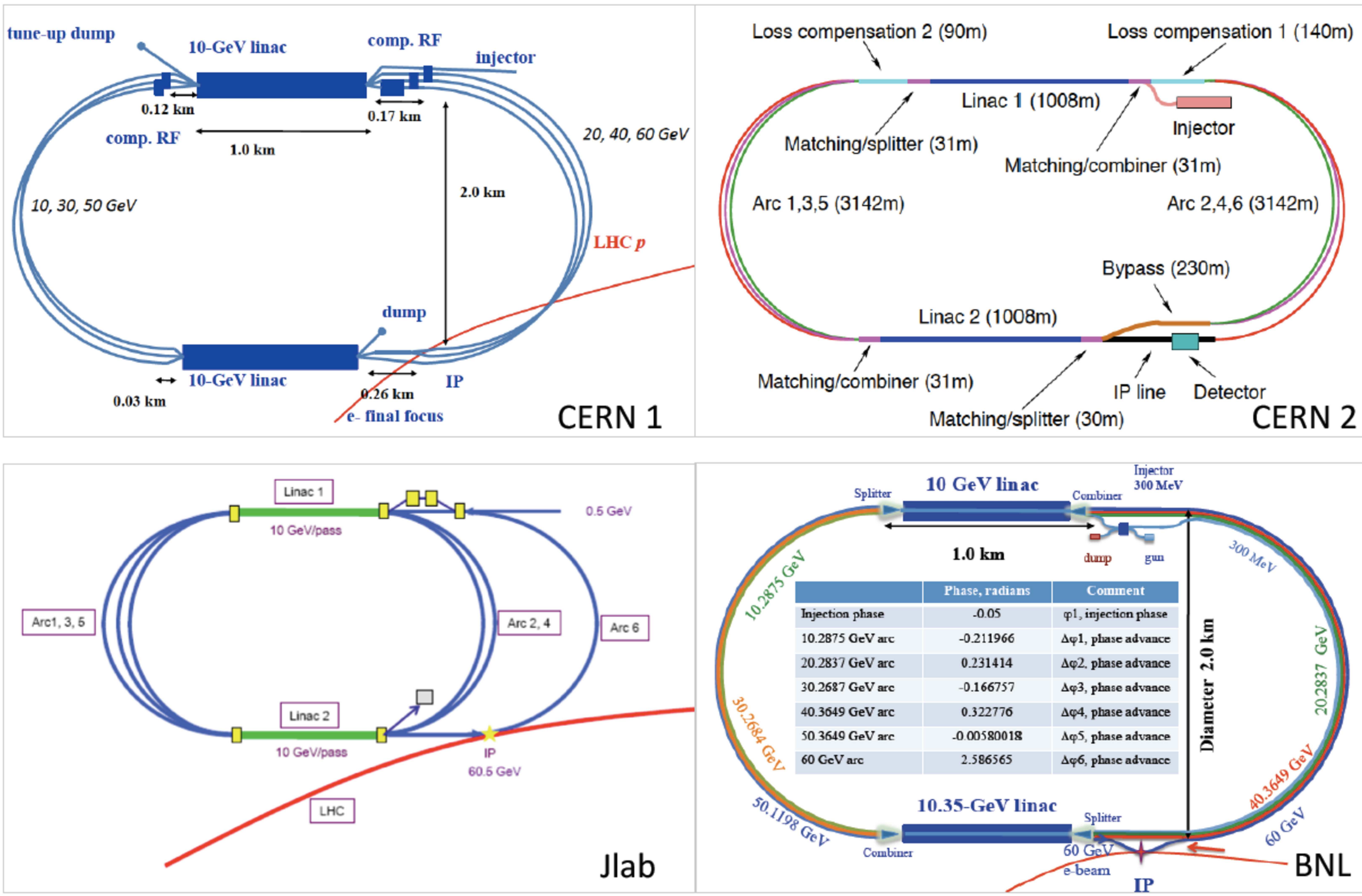
ELIC @ JLab: *add figure-8 hadron & electron rings to CEBAF*



Two designs for EIC collider. Both designs consider flexible setting for E_p, to measure F_L accurately.

LHeC

60 GeV Energy Recovery Linac

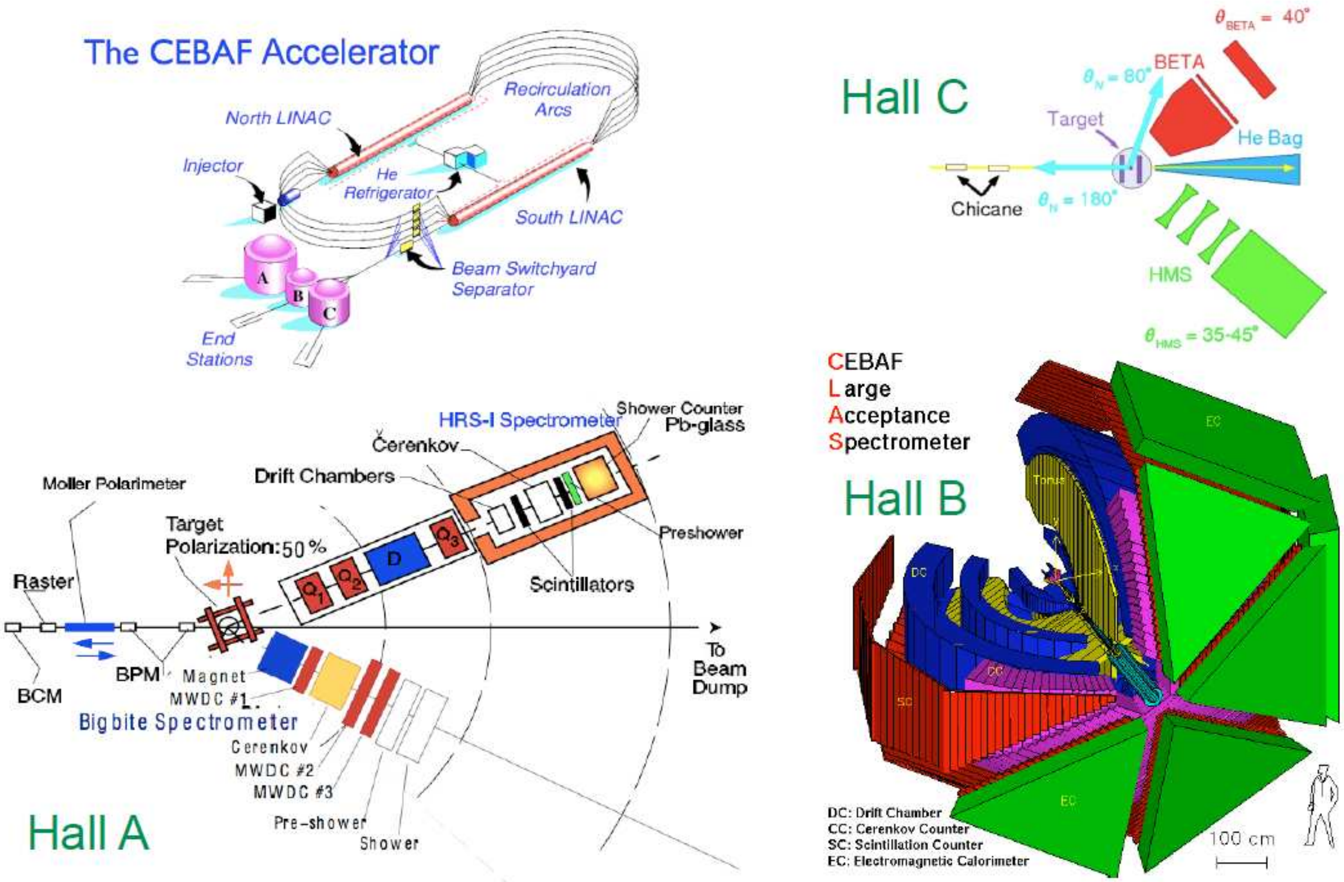


	Phase, radians	Comment
Injection phase	-0.05	φ1, injection phase
10.2875 GeV arc	-0.211966	Δφ1, phase advance
20.2837 GeV arc	0.231414	Δφ2, phase advance
30.2687 GeV arc	-0.166757	Δφ3, phase advance
40.3649 GeV arc	0.322776	Δφ4, phase advance
50.3649 GeV arc	-0.00580018	Δφ5, phase advance
60 GeV arc	2.586565	Δφ6, phase advance

Two 10 GeV energy recovery Linacs, 3 returns, 720 MHz cavities

Simultaneous operation of *pp* and *ep* colliders.

JLab experimental halls

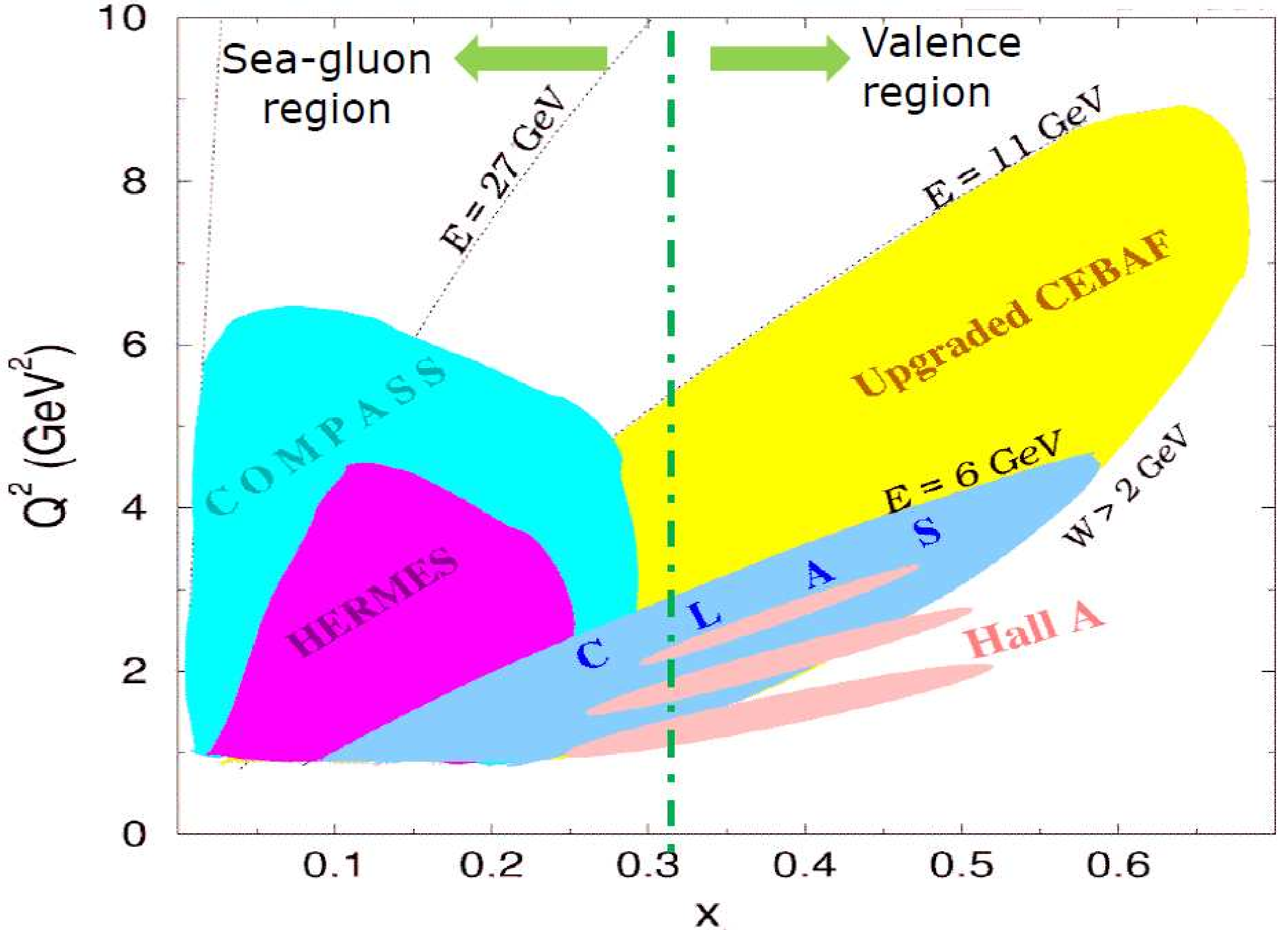


- 6 GeV → 12 GeV electron beam.
- Longitudinal beam polarisation.

Halls A,C: dedicated small angle spectrometers.
Hall B: large acceptance spectrometer CLAS.

Hall D: under construction for photon beam experiments.

High x kinematic plane



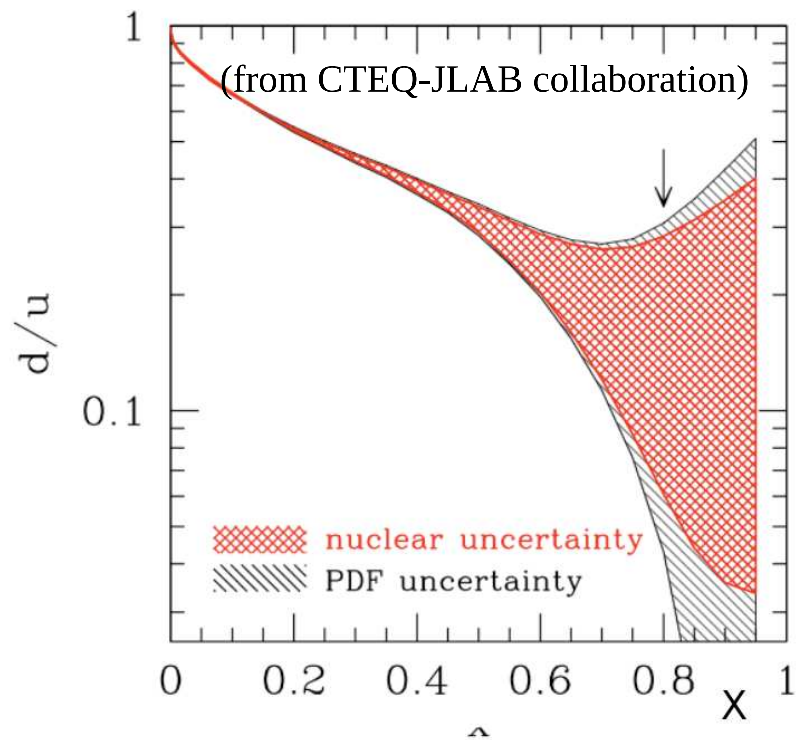
High x domain is currently being explored by CEBAF. 12 GeV upgrade allows to reach larger Q^2 and x for $W > 2$ GeV.

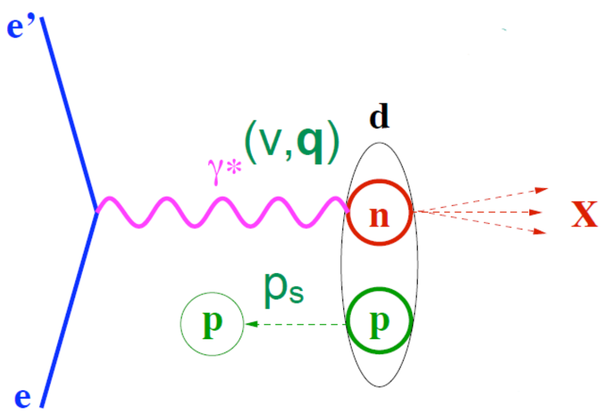
Measurement of the neutron structure — tagged proton

- d/u limit for $x \to 1$ probes different theory predictions, important for high energy predictions (e.g. jet rates, W-mass).
- Measured using F_2^n/F_2^p assuming isospin symmetry:

$$\frac{F_2^n}{F_2^p} = \frac{u + \bar{u} + 4(d + \bar{d}) + s + \bar{s}}{4(u + \bar{u}) + d + \bar{d} + s + \bar{s}}$$

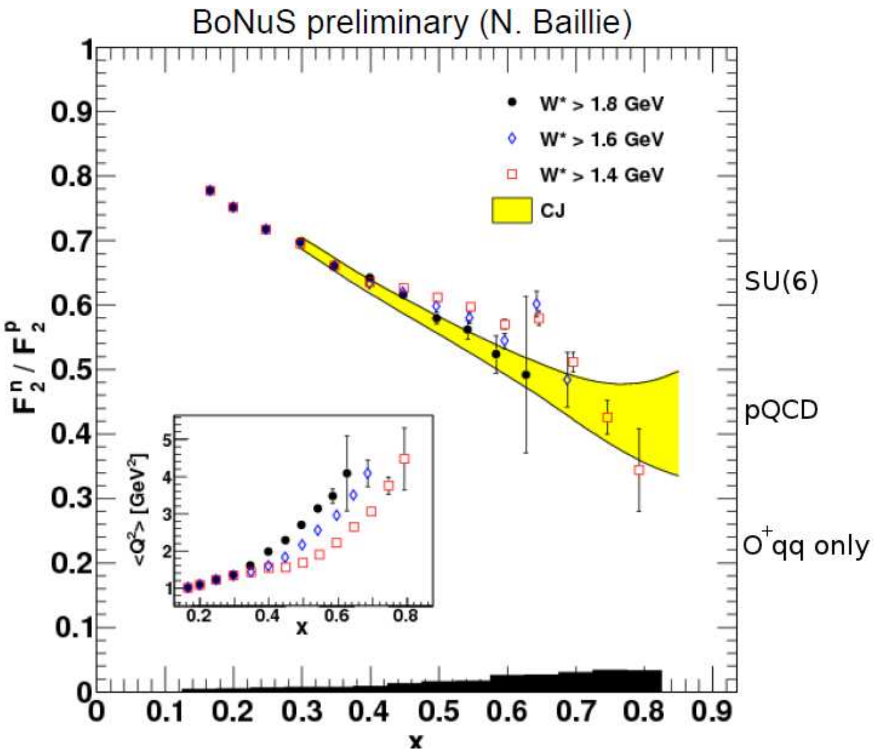
However, large uncertainties due to nuclear corrections (EMC effect).





Detect the spectator proton from deuterium following en scattering. Use spectator proton momentum to correct kinematics. This can be done at colliders, EIC and LHeC, too.
BoNuS experiment using CLAS.

BoNuS and MARATHON



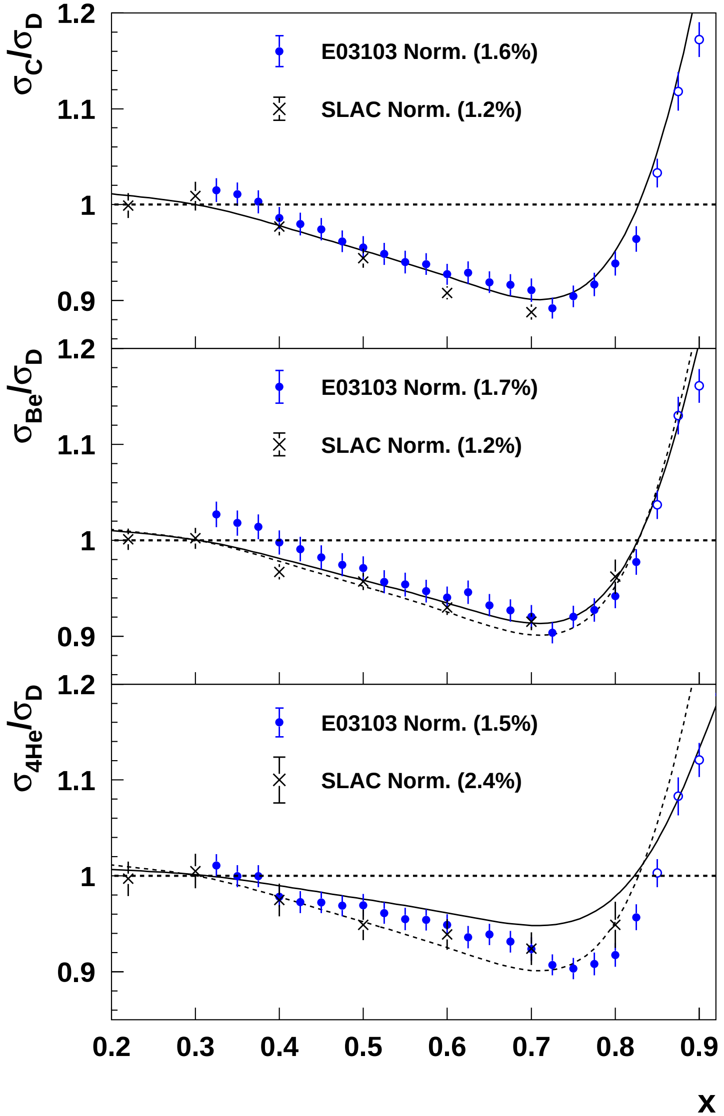
- First results from the BoNuS collaboration, using CLAS at hall B.
- Results approximately agree with CTEQ-JLAB analysis
- Higher beam energy is needed to measure at higher x and $W > 2$ GeV.

Another approach: use SuperRation R^*:

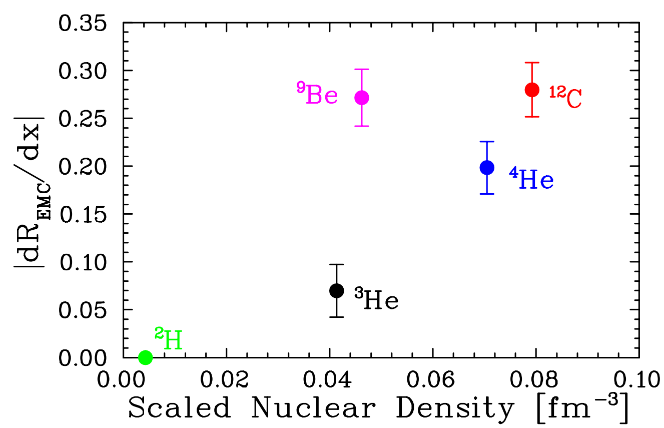
$$\frac{\sigma^{He^3}}{\sigma^{H^3}} \approx \frac{F_2^{He^3}}{F_2^{H^3}} = R^* \frac{2F_2^P + F_2^n}{F_2^p + 2F_2^n}$$

which is expected to be close to 1 to $< 1.5\%$. Proposed to be measured by MARATHON with $E_e = 12$ GeV.

EMC effect for light nuclei

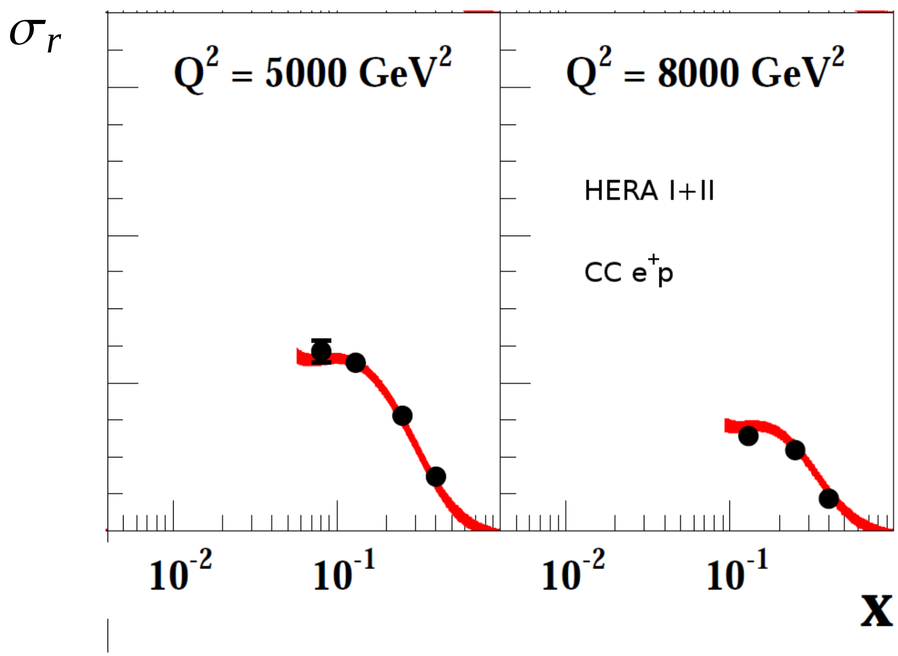


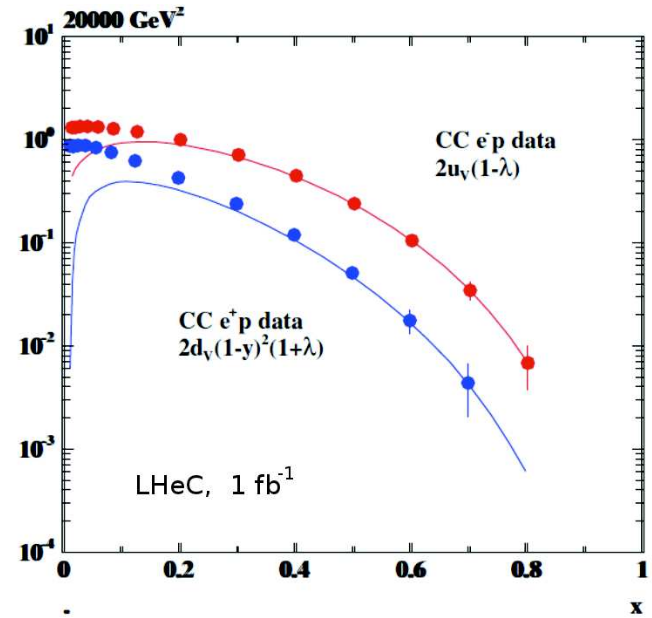
- Suppression of the per-nucleon structure function F_2 at $0.3 < x < 0.8$ for heavy nuclei, observed by EMC collaboration.
- Theoretical models predict average nuclear density or nuclear mass dependence, work well for large A.
- Measurements of EMC effect at JLAB, parametrized as a linear slope for $0.35 < x < 0.7$, suggest local environment dependence.

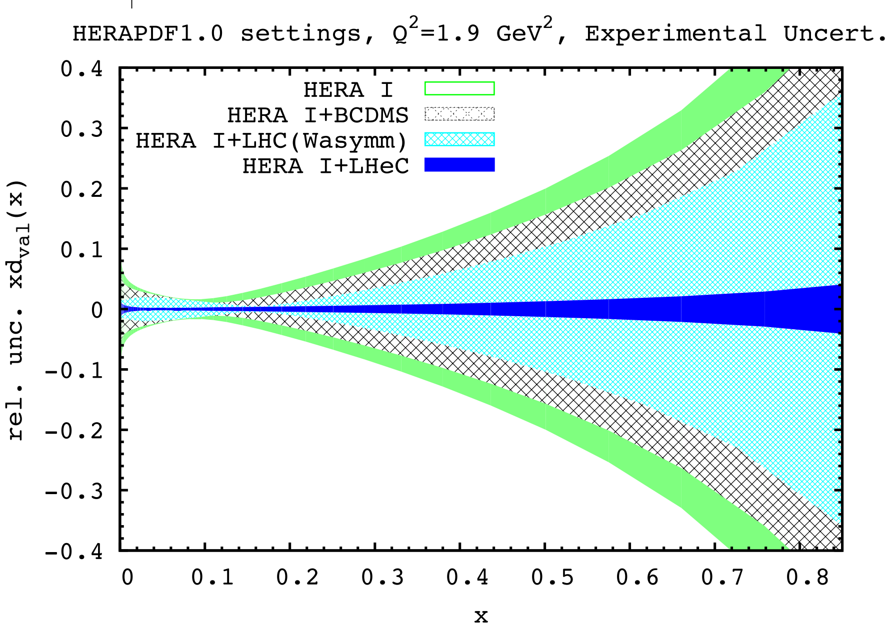


PRL 103, 202301 (2009)

CC measurement at HERA and LHeC

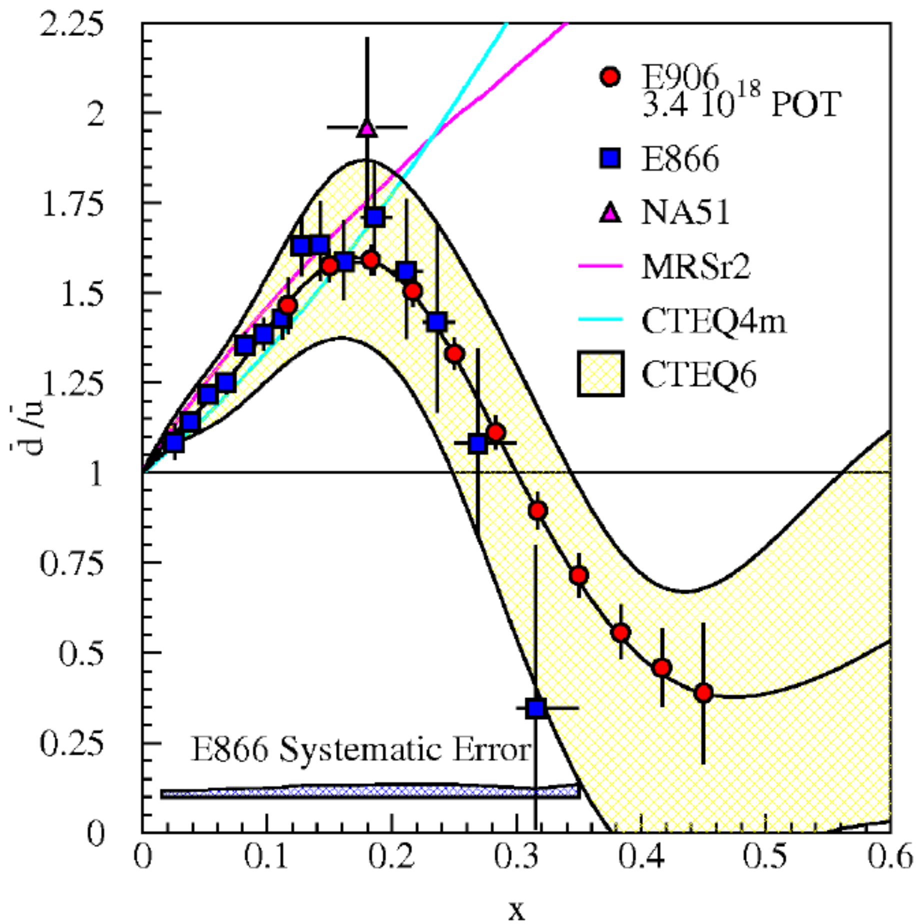






Another way to measure *d* density is by using CC process which has different couplings.
LHeC could bring significant reduction of uncertainty at high *x*.
Measurements can be also done by Minerνa neutrino scattering experiment at Fermilab.

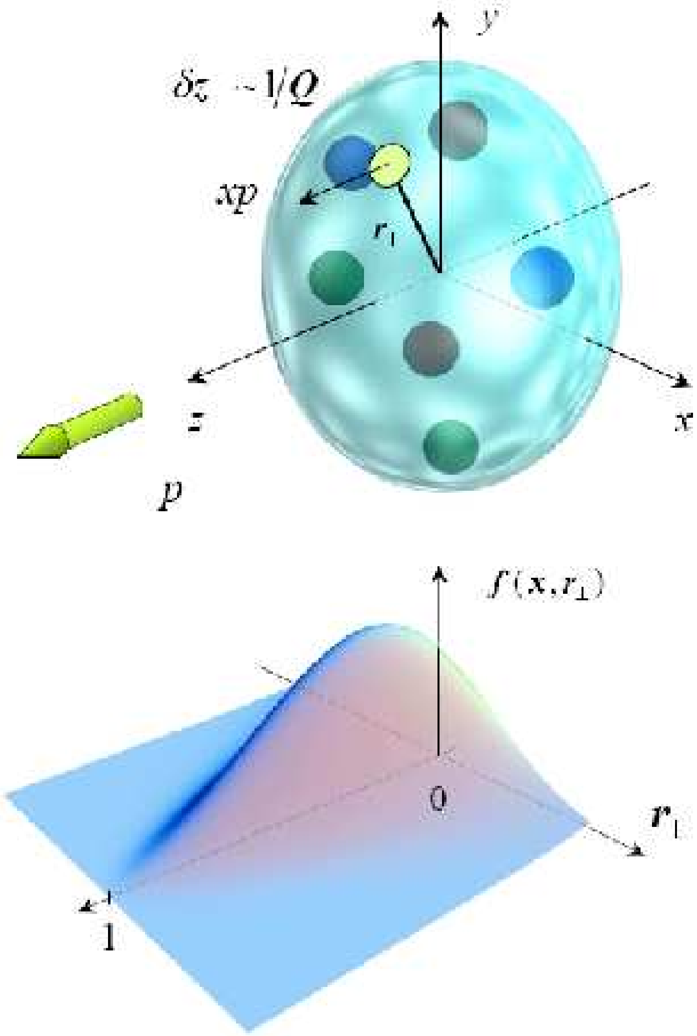
Measurement of $\bar{d}/\bar{u}$, SeaQuest E-906



- Anti-quarks at large x are very important for pp phenomenology.
- Measure $\bar{d}/\bar{u}$ using DY process for scattering off H, d targets.
- E906 experiment at Fermilab, using $E_p = 120$ GeV protons from the main injector in the former KTeV hall, to extend to higher x compared to E866 measurement.

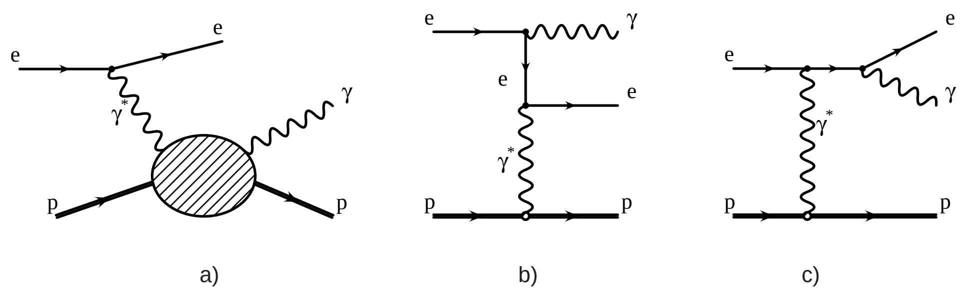
Lower s compared to E866 allows to collect $50\times$ higher statistics for planned 2 year run.

Generalized parton distribution functions.

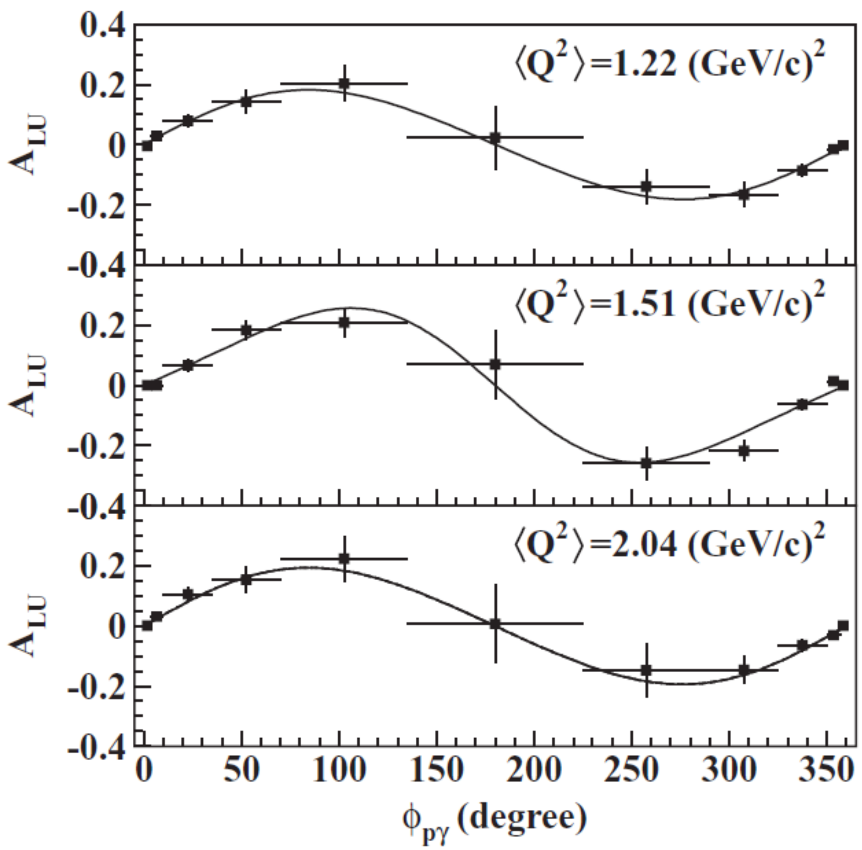


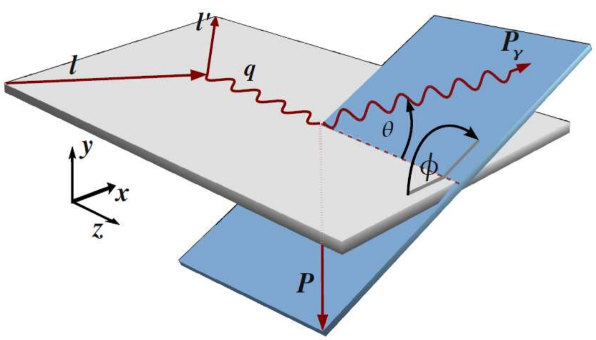
- Generalization of PDFs in collinear limit, and Form Factors, as moments of GPDs.
- Provide correlated information on longitudinal momentum xp and transverse spacial position $r_\perp$.
- Several GPDs H, $\tilde{H}$ E, $\tilde{E}$, for different nucleon helicity. Target polarisation to disentangle, require knowledge of nucleon form factors.
- Can be measured using vector/pseudoscalar mesons, however the cleanest way is DVCS, DVCS interfere with BH processes: use beam charge/polarisation asymmetry to measure.

DVCS Results: CLAS



← DVCS process (a) interferes with BH (b,c). Measure asymmetries to access amplitudes.

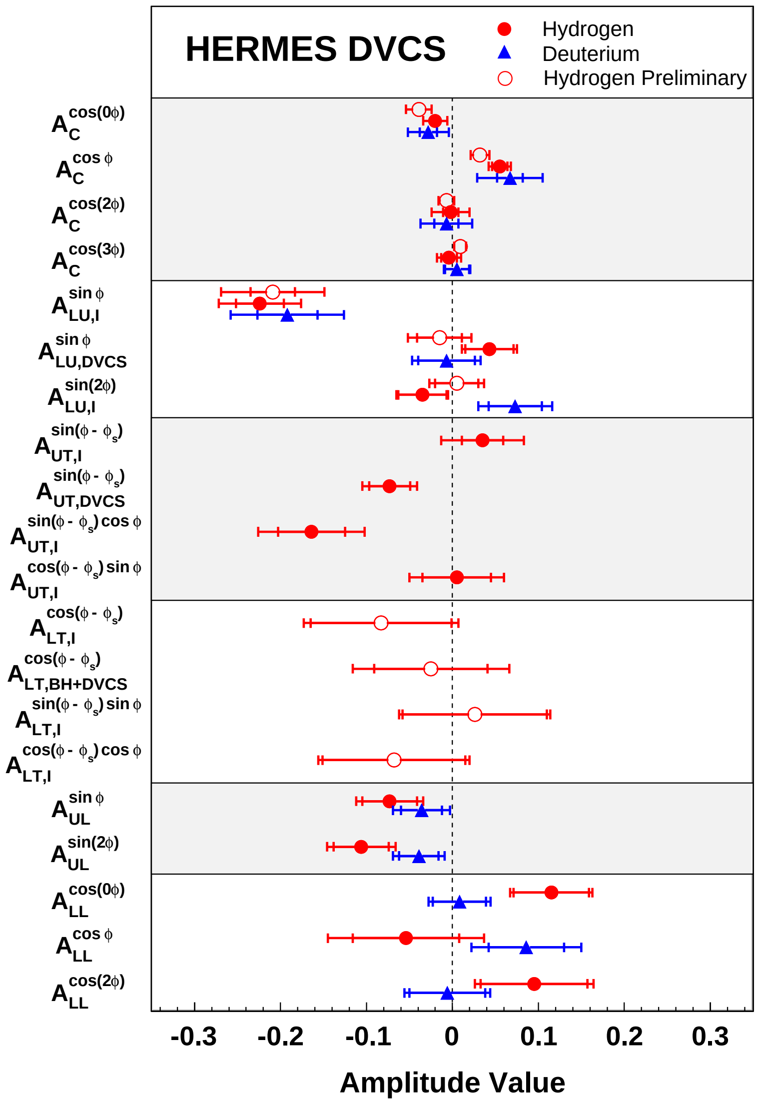




CLAS resent result (Phys. Rev. C**80**, 035206 (2009)) of the longitudinal beam polarisation asymmetry, vs $\phi_{\rho\gamma}$.

$E_e = 4.8$ GeV, $\mathcal{L} \sim 1.3$ fb^{-1}.

DVCS Results from HERMES



(HERMES-11-004a)

A number results from HERMES, using various asymmetries, allows to map out GPDs:

- Beam charge and beam helicity asymmetry measure H, e.g. beam helicity:

$$\sigma_{LU} \sim sin\phi \left[F_1 H + \xi(F_1 + F_2)\tilde{H} + kF_2 E\right]$$

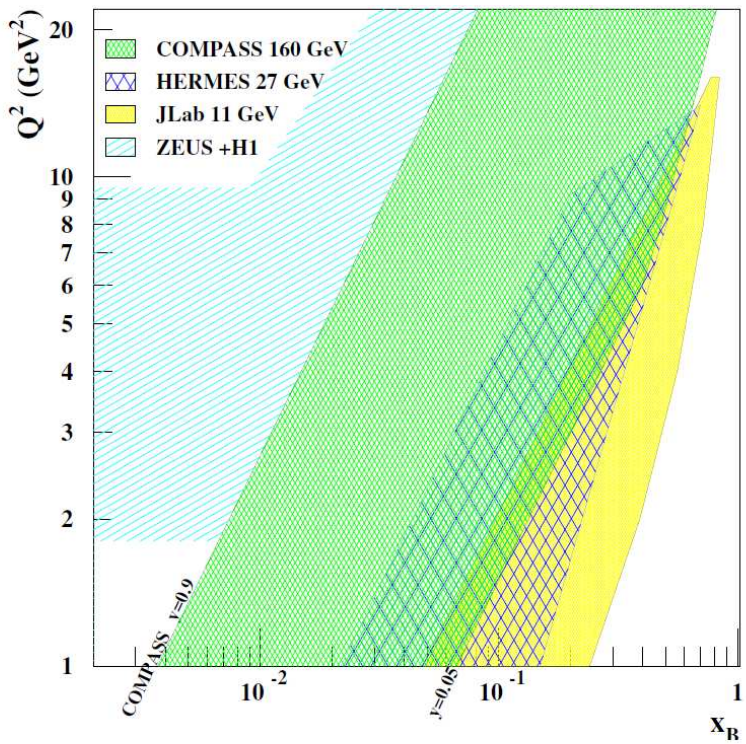
- Transverse target spin asymmetry adds information on E:

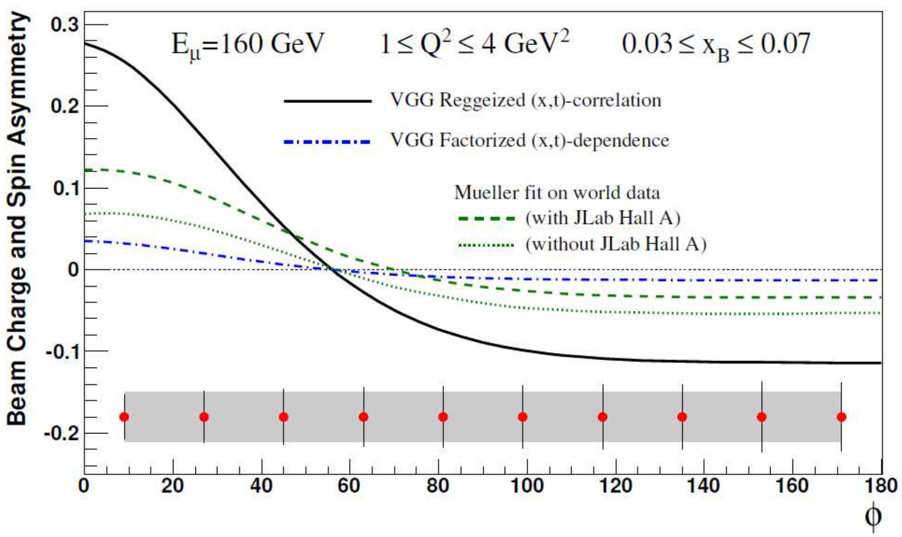
$$\sigma_{UT} \sim cos\phi \sin(\phi_s - \phi)\,[k(F_2 H - F_1 E)]$$

- Longitudinal target spin asymmetry can be used to separate $\tilde{H}$

$$\sigma_{UL} \sim sin\phi \left[F_1 \tilde{H} + \xi(F_1 + F_2)(H + \frac{\xi}{1+\xi}E)\right]$$

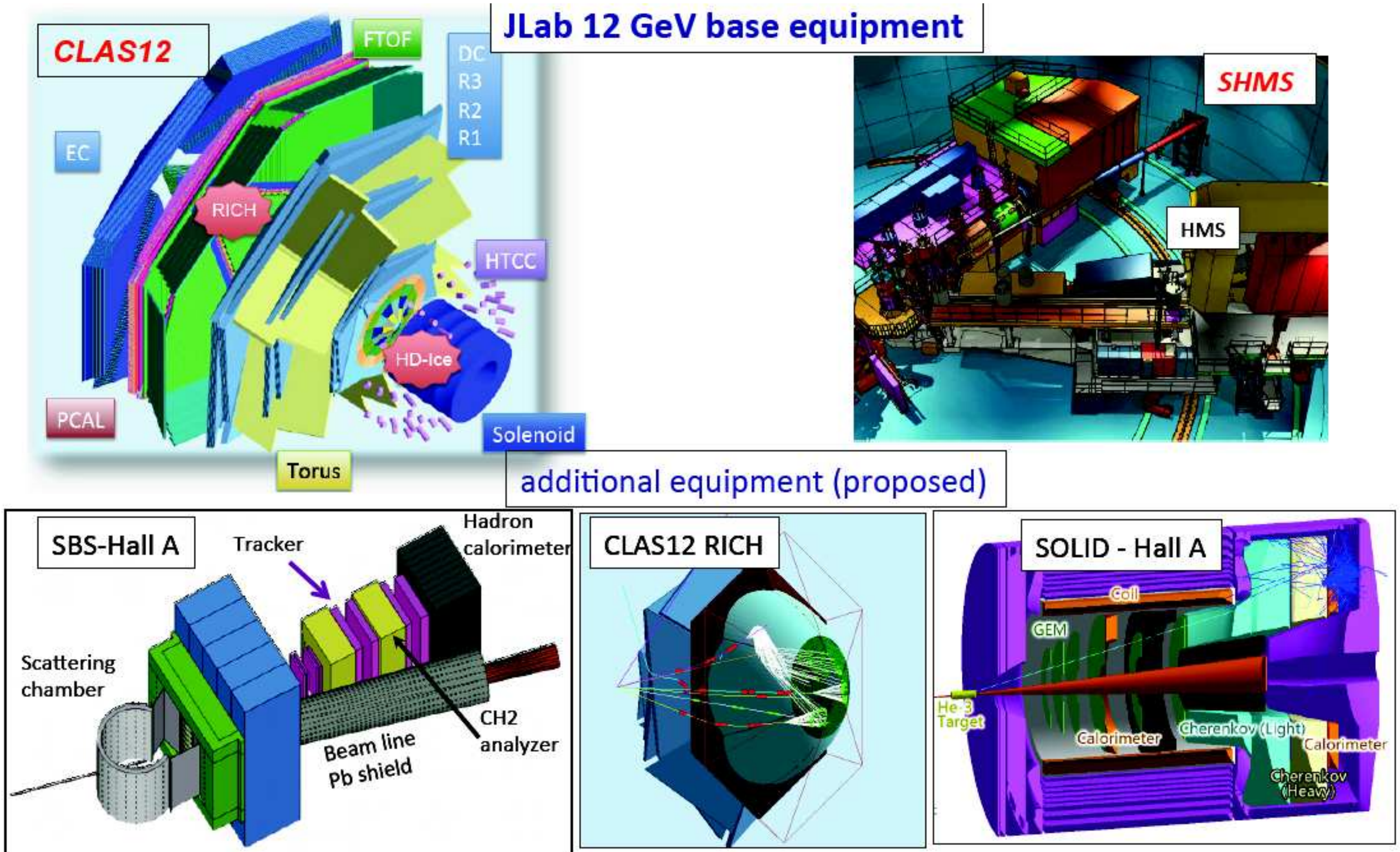
Compass-II





- Using longitudinally polarized $\mu^{\pm}$ beams with the energy of $E_\mu = 160$ GeV Compass covers unexplored region at medium x
- Upgrade of EM calorimeters, 2.5 m liquid hydrogen target and proton recoil detector.
- High accuracy for proposed 70 days μ^+ and 210 days μ^- run.

JLab 12 GeV Upgrades



(from talk of V.D. Burkert, Transversity 2011)

$E_e = 12$ GeV experiments will use existing infrastructure with a number of proposed upgrades.

Hall A expects initial beam in October 2013, Hall D: April 2014, Hall C,B: October 2014.

Summary

- HERA-II analyzes are being finalized, result in accurate determination of the proton structure over a wide range in x and Q^2.
- JLab provides unique information at high x using modern experimental techniques. The ratio d/u at high x is studied using tagged protons; high statistics measurements of DVCS process give 3D view on the proton structure.
- Upgrade of JLab energy to $E_e = 12$ GeV extends the kinematic range of the observables, allows to measure at $x > 0.6$ in the DIS regime with $W > 2$ GeV.
- A new generation of ep/A colliders is under preparation. EIC: emphasis on polarised structure and GPDs LHeC: emphasis on precision QCD/eweak and saturation both will explore nuclear structure.