A High Luminosity Electron - Ion Collider

Overview

Physics

Possible Accelerators

Possible Detectors

References / Acknowledgements

Study of the Fundamental Structure of Matter with an Electron-Ion Collider, Ann. Rev. Nucl. Part. Sci. 55 (2005) 165, A. Deshpande, R. Milner, R. Venugopalan, W. Vogelsang

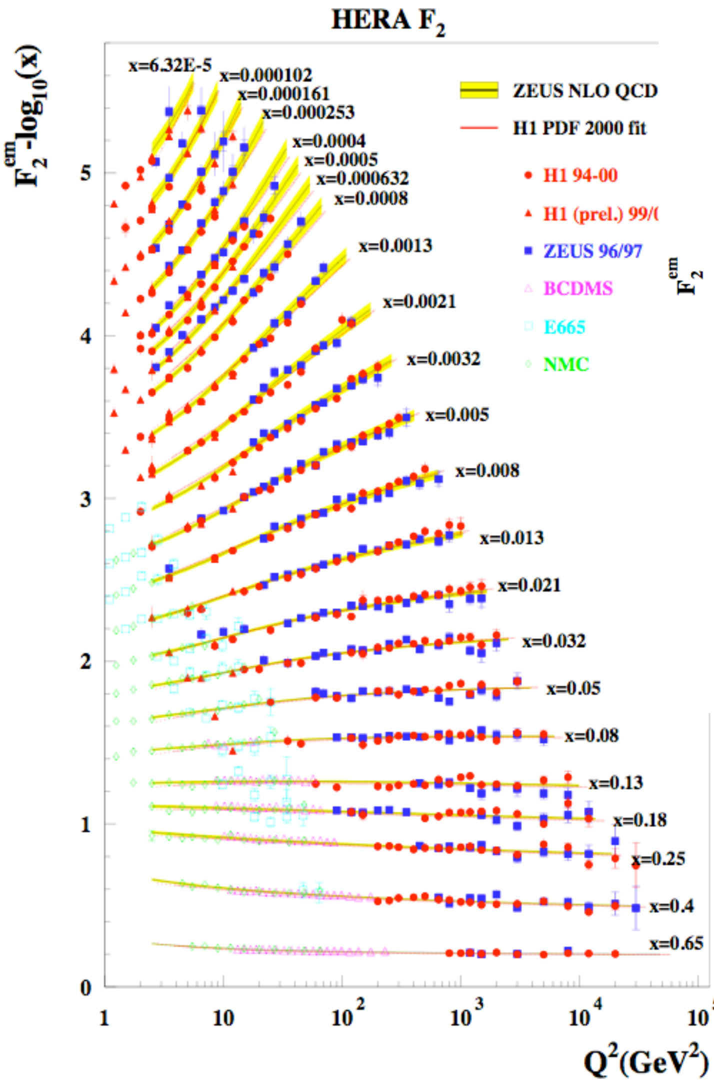
eRHIC - Zeroth Order Design Report, C-A/AP/142 March, 2004, BNL, MIT-Bates, BINP, DESY

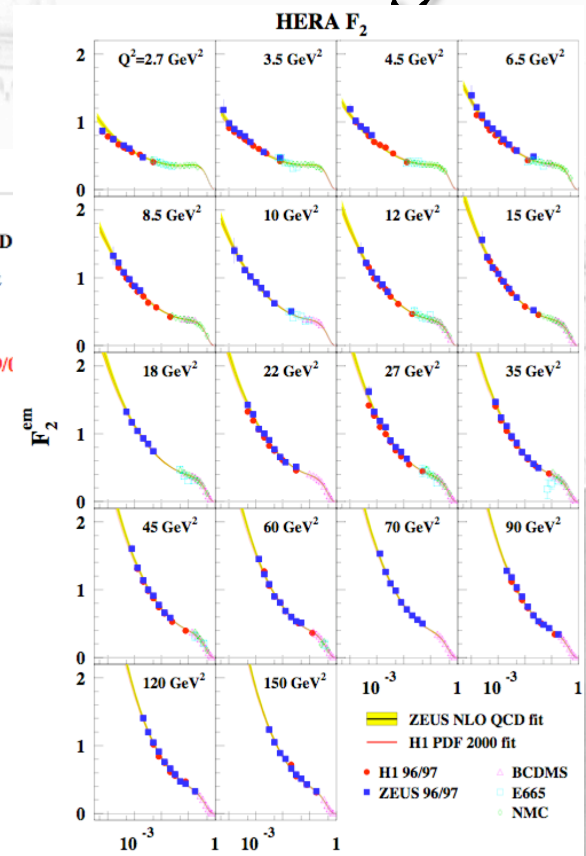
http://casa.jlab.org/research/elic/elic.shtml

Deep Inelastic Electron-Nucleon Scattering at the LHC, DESY 06-006, J.B. Dainton, M. Klein, P. Newman, E. Perez, F. Willike

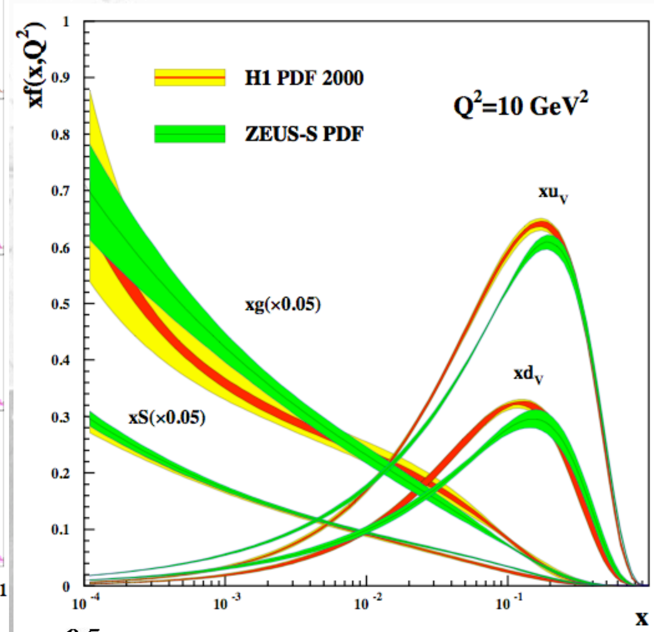
QCD Remarkably Successful

Bjorken scaling
DGLAP evolution



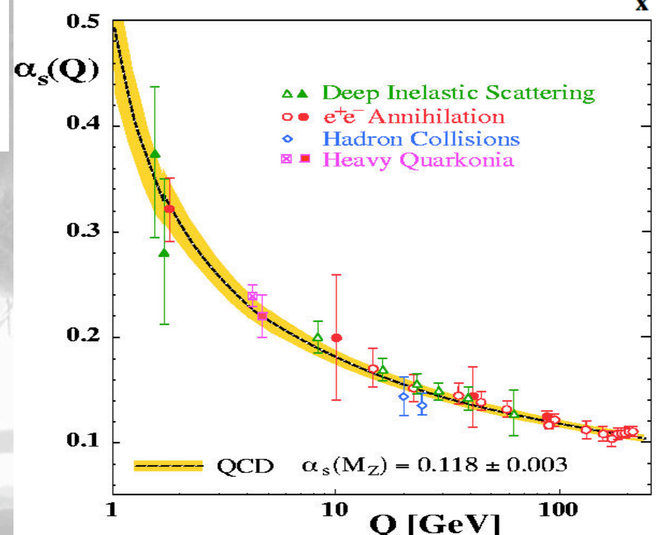


PDF's



Sea quarks

Running coupling α_s



On the Other Hand

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SCIENCE JOURNAL
By SHARON BEGLEY

Scientists Try to Put Right Spin on Quarks To Understand Matter

May 19, 2006; Page B1

Talk about accounting problems. In a quest that has its roots 2,400 years ago in Democritus' search for the smallest bit of matter, physicists thought they were doing pretty well when, in the 1960s, they discovered that the protons in atomic nuclei are each made of three even-smaller subatomic particles, which were given the whimsical name quarks.

But it quickly became clear that the numbers "don't add up," says physicist Douglas Beck of the University of Illinois, Urbana-Champaign. The total mass of the three quarks, for instance, is a mere 1.5% of the proton's. Try as they might to balance the books, no amount of creative accounting has turned up the sources of the missing mass, casting doubt on science's understanding of how the basic building blocks of the physical world are assembled into matter.

Wall Street Journal - 19/5/06

http://online.wsj.com/article_email/SB114798871342257010-lMyQjAxMDE2NDE3OTkxODk4Wj.html

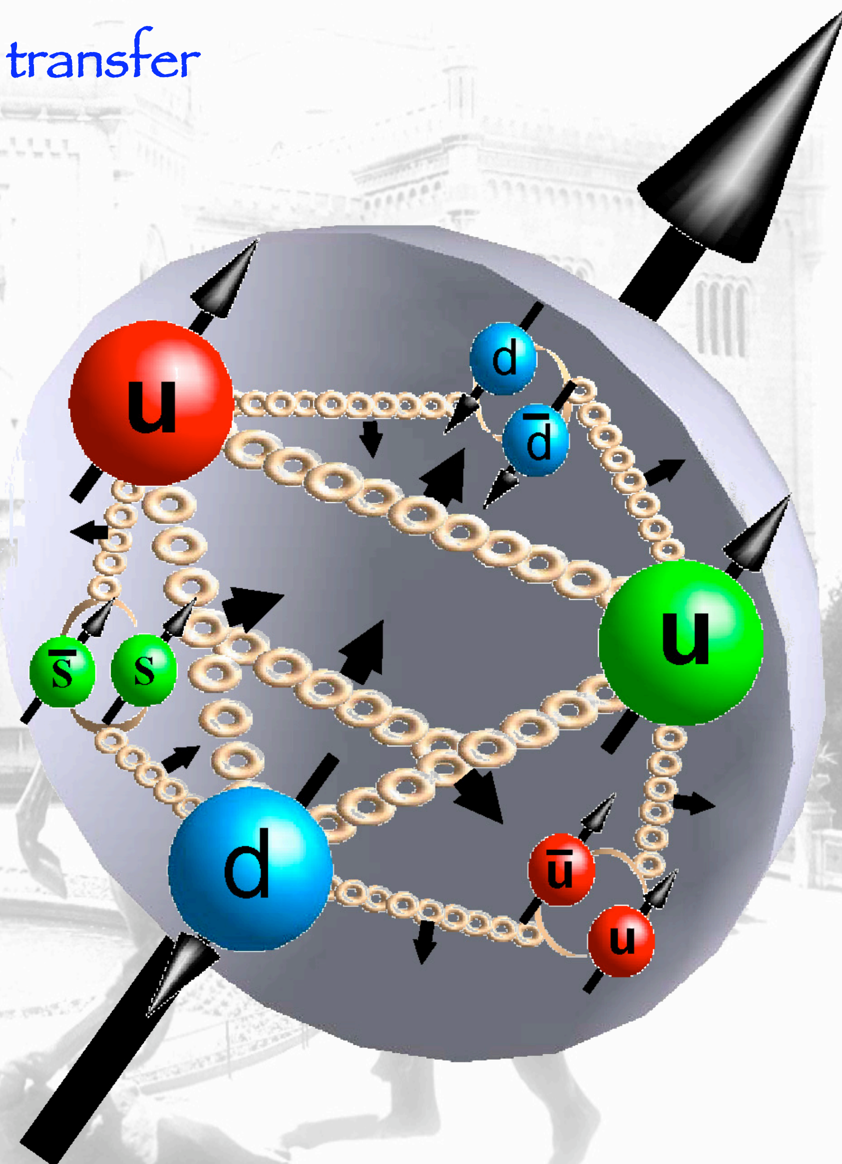
- Mass of nucleon
  - 1.5 % attributed to valence quarks
- Nucleon spin
  - 20-30 %
- Nucleon magnetic moment
  - 1/3
- Sea quarks ?
- Gluons ?

Still more to understand

pQCD only valid at large momentum transfer
- asymptotic freedom

Extension to normal matter difficult
- confinement obscures colour force
- lattice QCD ?

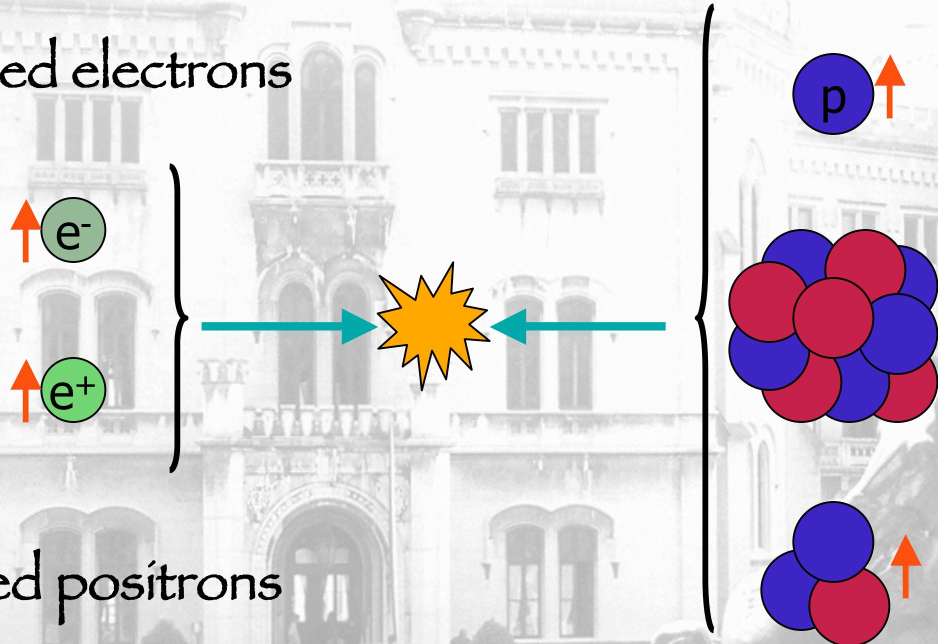
Need to know more:
- spin distributions
- flavour distributions
- distributions in nuclei
- further tests of QCD



Electron-Ion Collider Concept

Polarized electrons

Polarized positrons



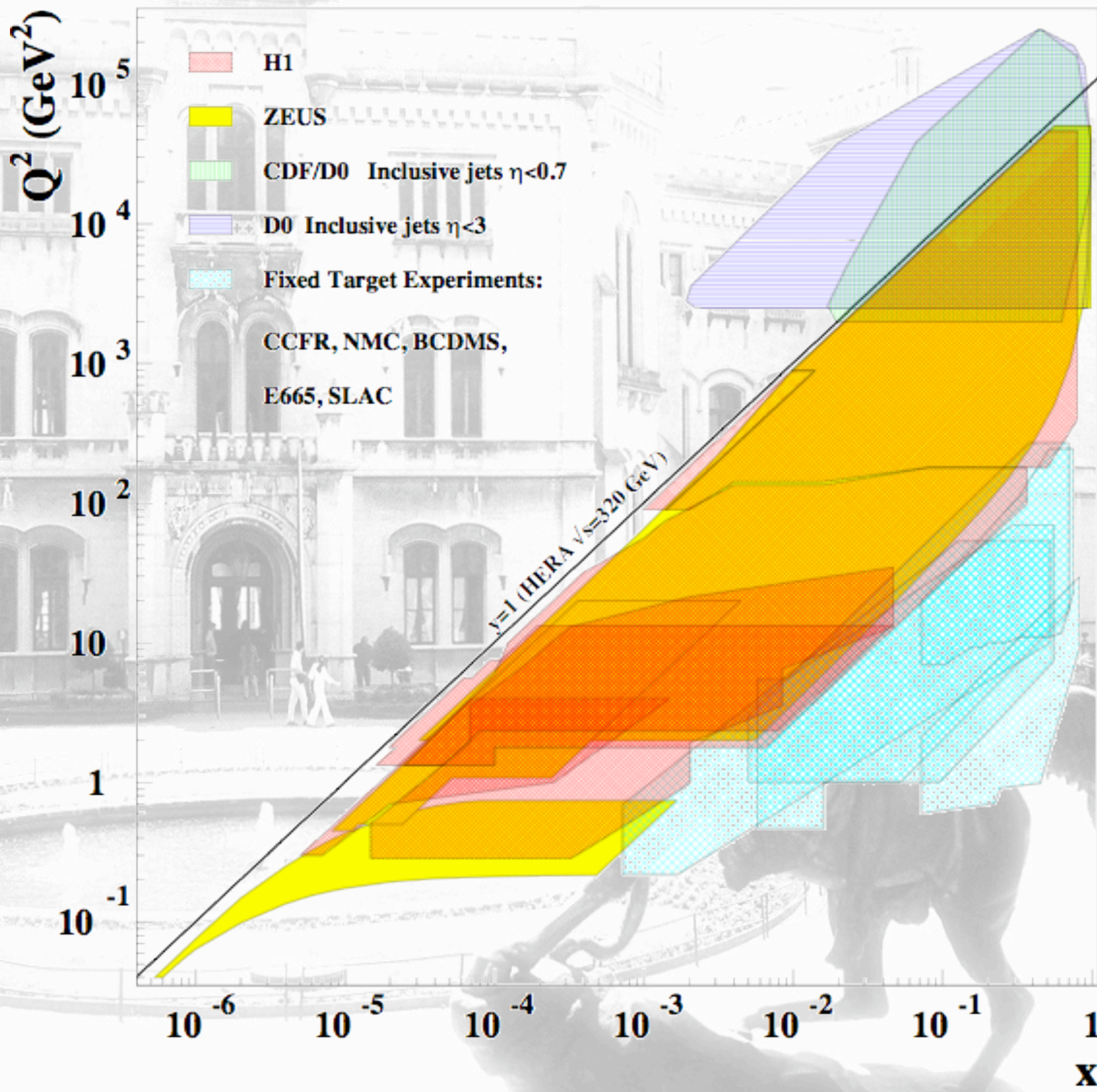
Polarized protons

Heavy ions (Au)

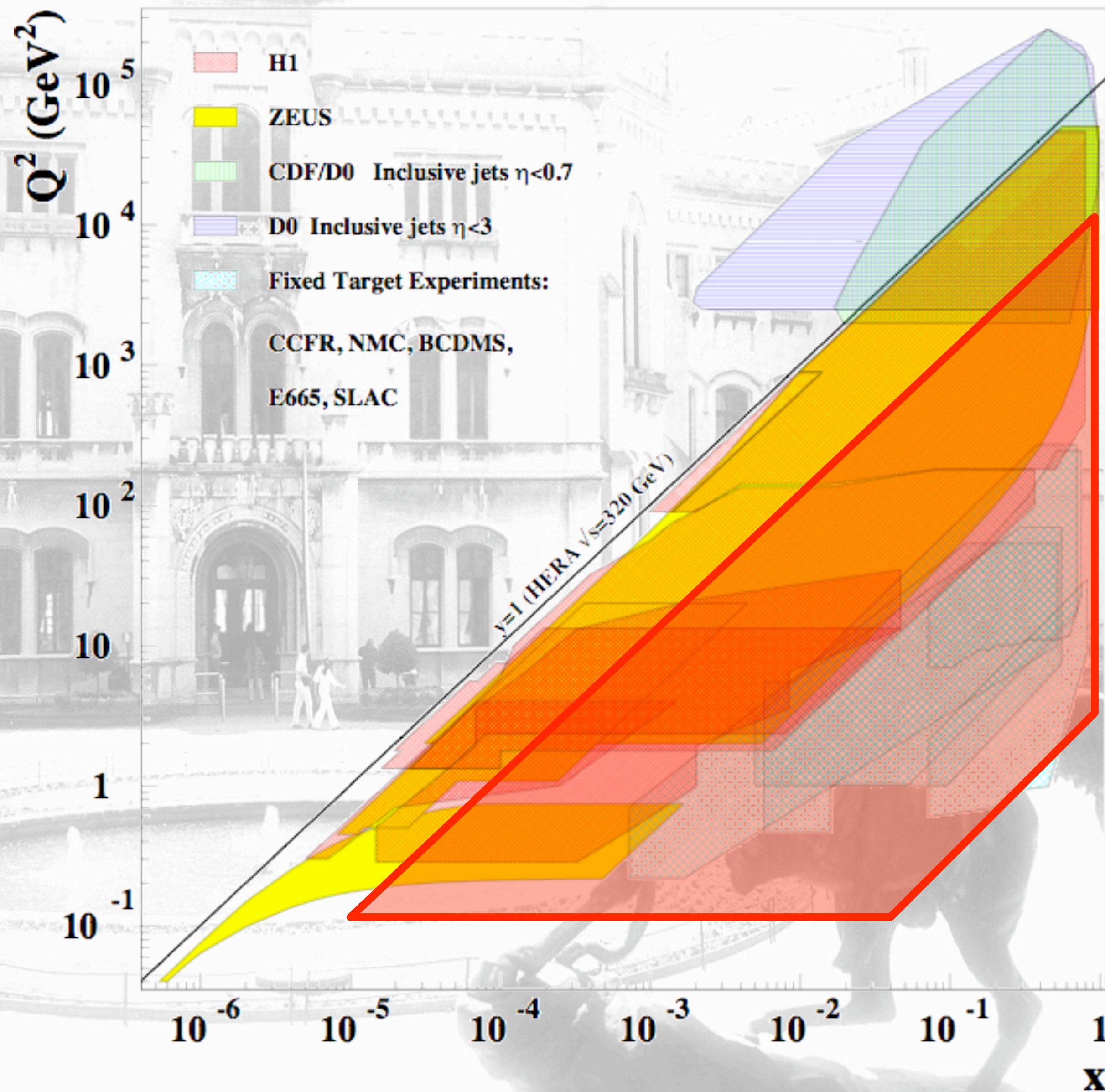
Polarized light ions
D, ^{3}He
Effective neutron

Range of centre of momentum energies

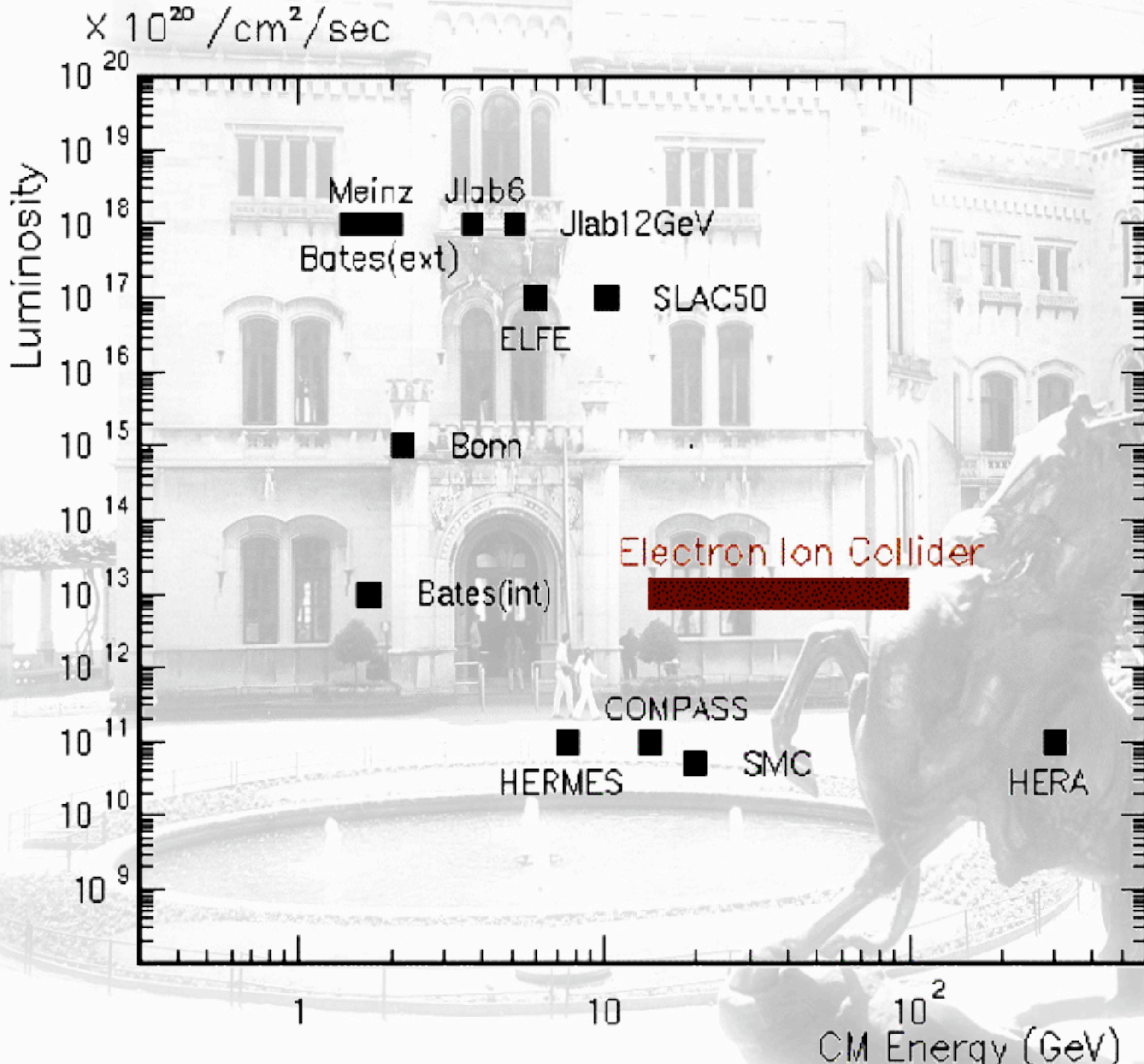
Existing Kinematic Range - Mostly Unpolarised



Polarized Electron - Ion Collider



Luminosity versus Q^2

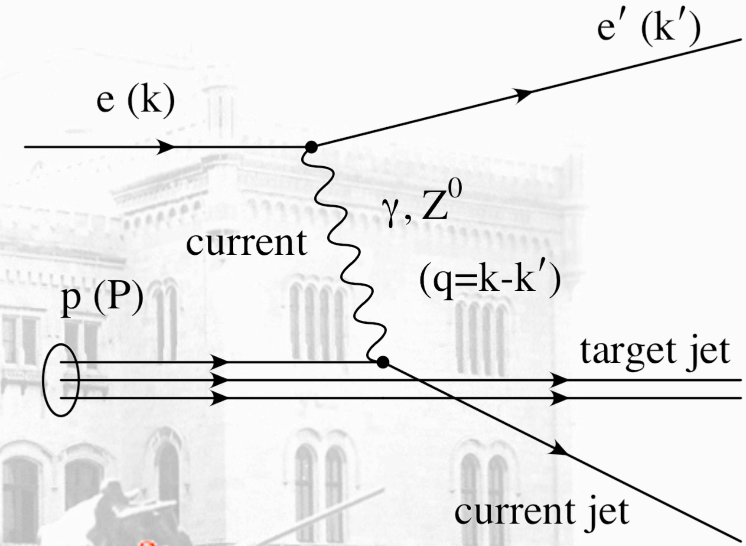


$10^{33} cm^{-2} s^{-1}$

Corresponds to
86.4 pb^{-1} / day
605 pb^{-1} / week
2.6 fb^{-1} / month

For 100% machine and detector efficiency

Why Lepton - Ion Collider



$$\frac{d^2\sigma}{dxdy} \propto \mathcal{L}_{\mu\nu}(k,q,s)\mathcal{W}^{\mu\nu}(P,q,S)$$

$$\begin{aligned}
\mathcal{W}^{\mu\nu}(P,q,S) \;=\; & -g^{\mu\nu}F_1(x,Q^2) + \frac{P^\mu P^\nu}{Pq}F_2(x,Q^2) \\
& -\imath\epsilon^{\mu\nu\rho\sigma}\frac{q_\rho P_\sigma}{2Pq}F_3(x,Q^2) \\
& +\imath\epsilon^{\mu\nu\rho\sigma}q_\rho\left[\frac{S_\sigma}{Pq}g_1(x,Q^2) + \frac{S_\sigma(Pq)-P_\sigma(Sq)}{(Pq)^2}g_2(x,Q^2)\right] \\
& +\left[\frac{P^\mu S^\nu + S^\mu P^\nu}{2Pq} - \frac{Sq}{(Pq)^2}P^\mu P^\nu\right]g_3(x,Q^2) \\
& +\frac{Sq}{(Pq)^2}P^\mu P^\nu g_4(x,Q^2) - \frac{Sq}{Pq}g^{\mu\nu}g_5(x,Q^2)
\end{aligned}$$

Unpolarized DIS at EIC

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha_{em}^2}{Q^4}\left[\left(1+(1-y)^2\right)F_2(x,Q^2) - y^2 F_L(x,Q^2)\right]$$

$$F_2(x,Q^2) = \sum_q e_q^2\left(xq(x,Q^2) + x\bar{q}(x,Q^2)\right)$$

Measurements will add to F_2 data set

Longitudinal structure function F_L

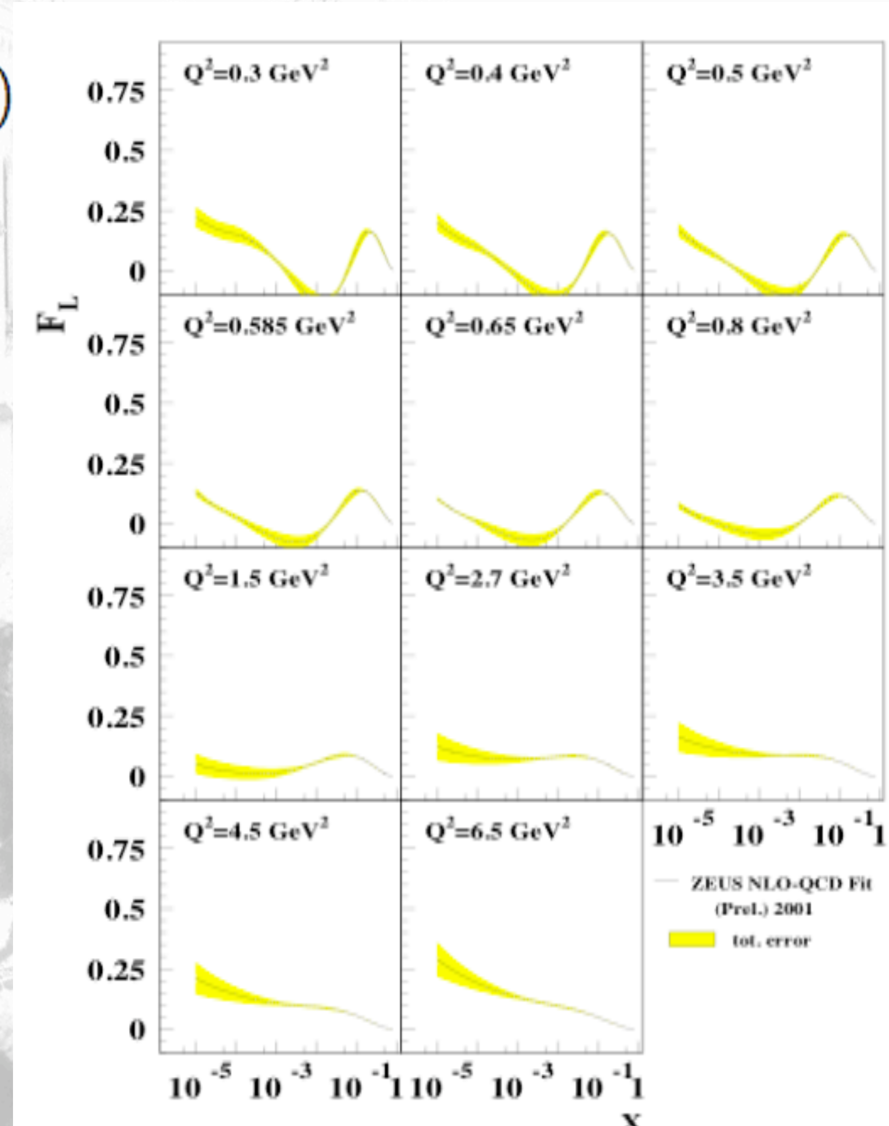
$$F_L = F_2 - 2xF_1$$

Can be determined from scaling violations

$$F_L \propto \alpha_S xG(x,Q^2)$$

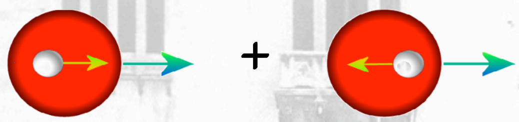
Negative gluon distributions at low Q^2

Possible direct measurement at EIC by varying centre of momentum energy



Spin Structure of Nucleons

$$F_1(x) = \frac{1}{2}\sum_q e_q^2\,(q(x) + \bar{q}(x))$$

q(x) ≈ 

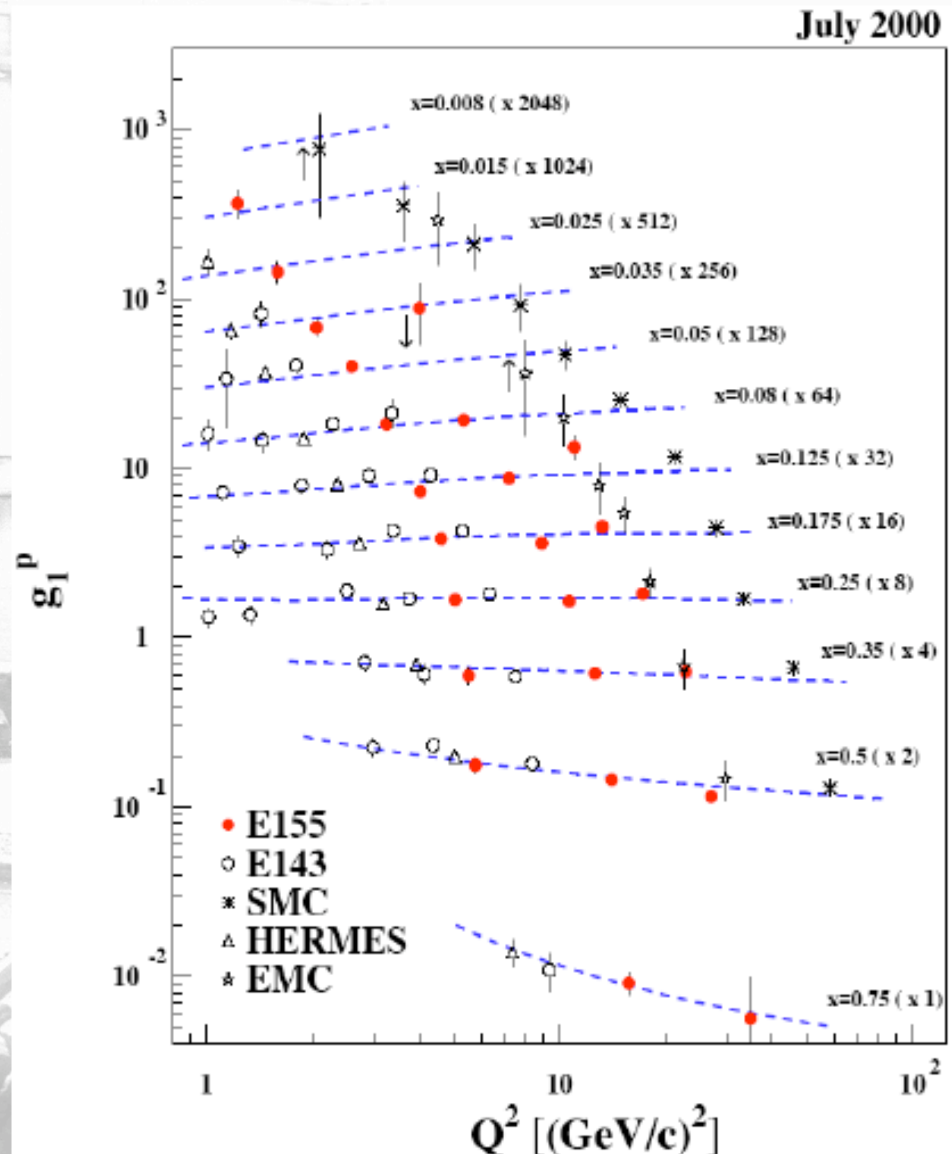
$$g_1(x) = \frac{1}{2}\sum_q e_q^2\,(\Delta q(x) + \Delta\bar{q}(x))$$

Δq(x) ≈ 

Analogous to unpolarised DIS

QCD predicts evolution

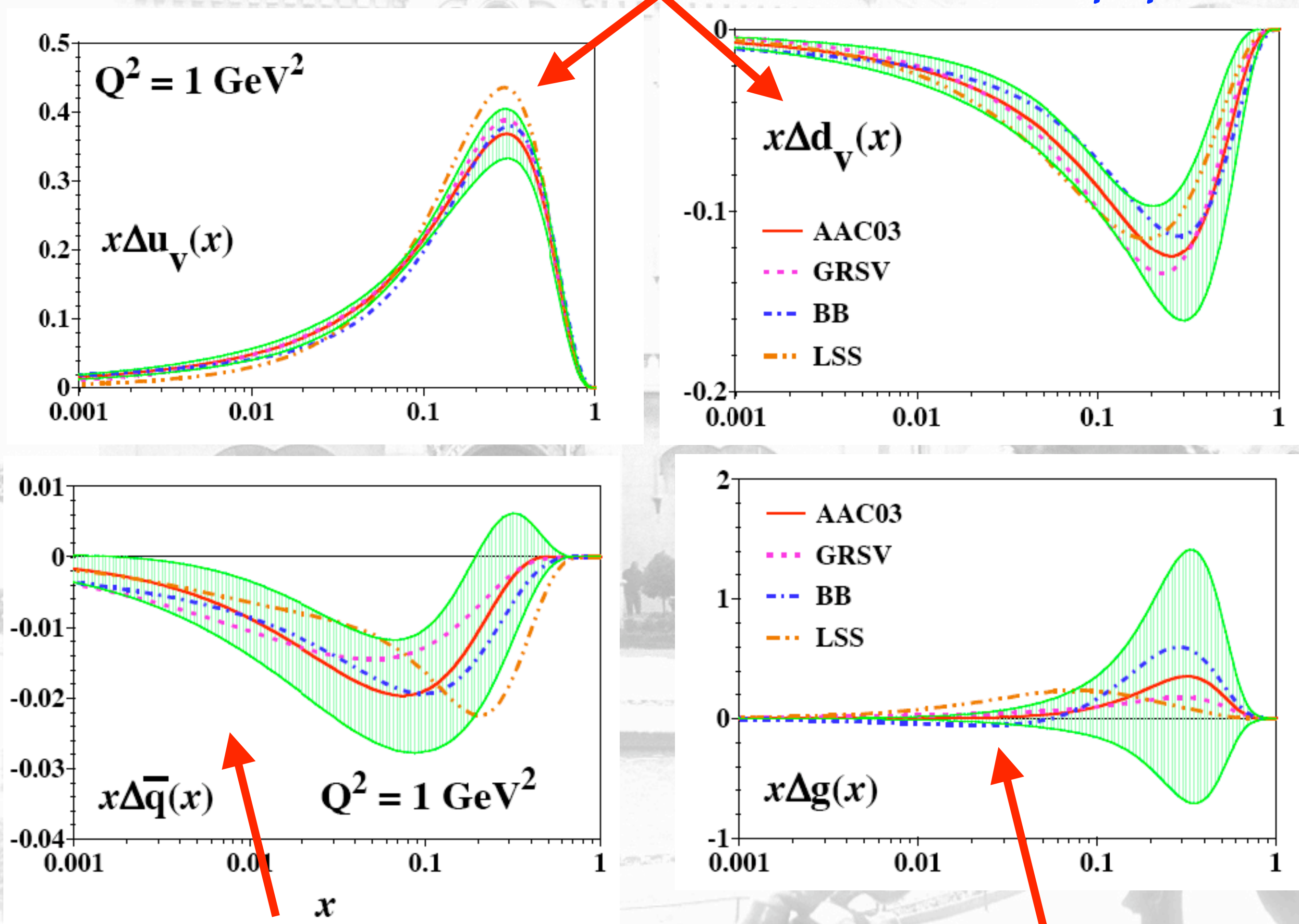
Able to extract polarised parton densities including gluon



Parton Spin Distributions

Hirai, Kumano, Saito

Valence distributions $q-\bar{q}$



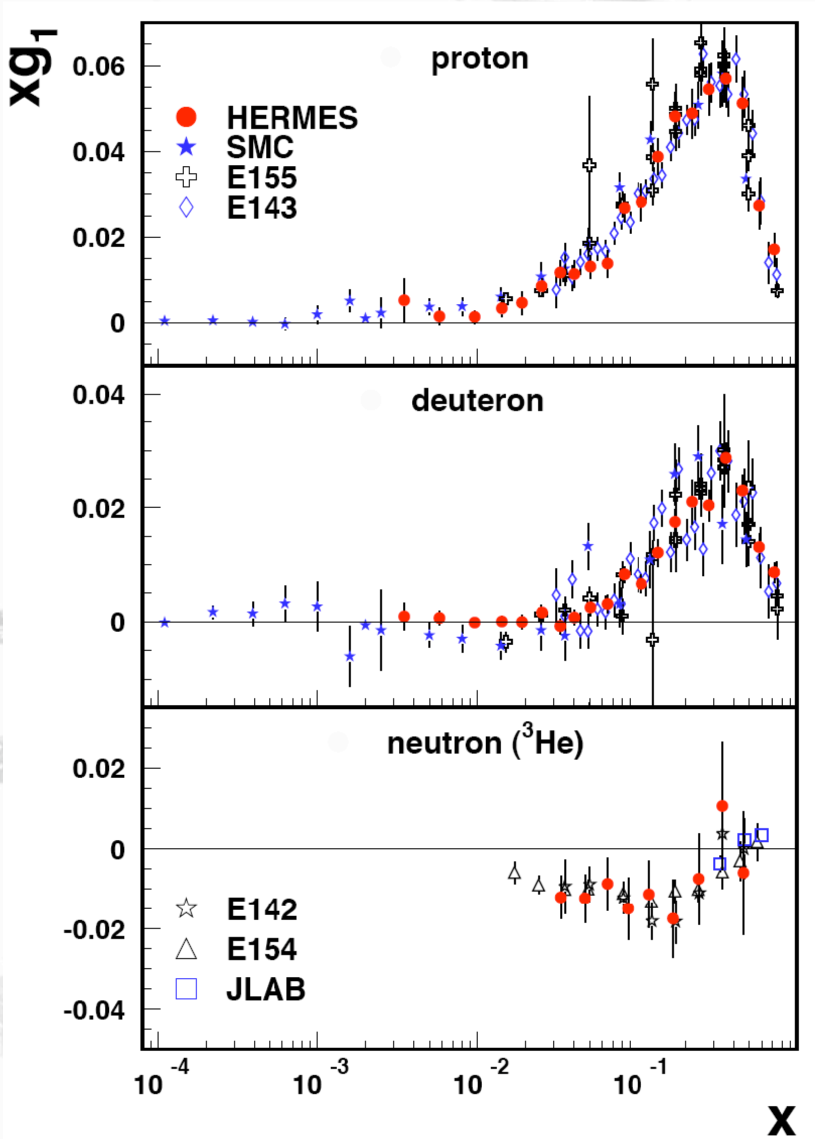
Results limited by range of Q^2

EIC extend range
$5 \times 10^{-5} < x < 0.7$
$0.5 < Q^2 < 3000$

Limited information on sea

Weak constraints from scaling violation

p, n, d Spin Structure Functions

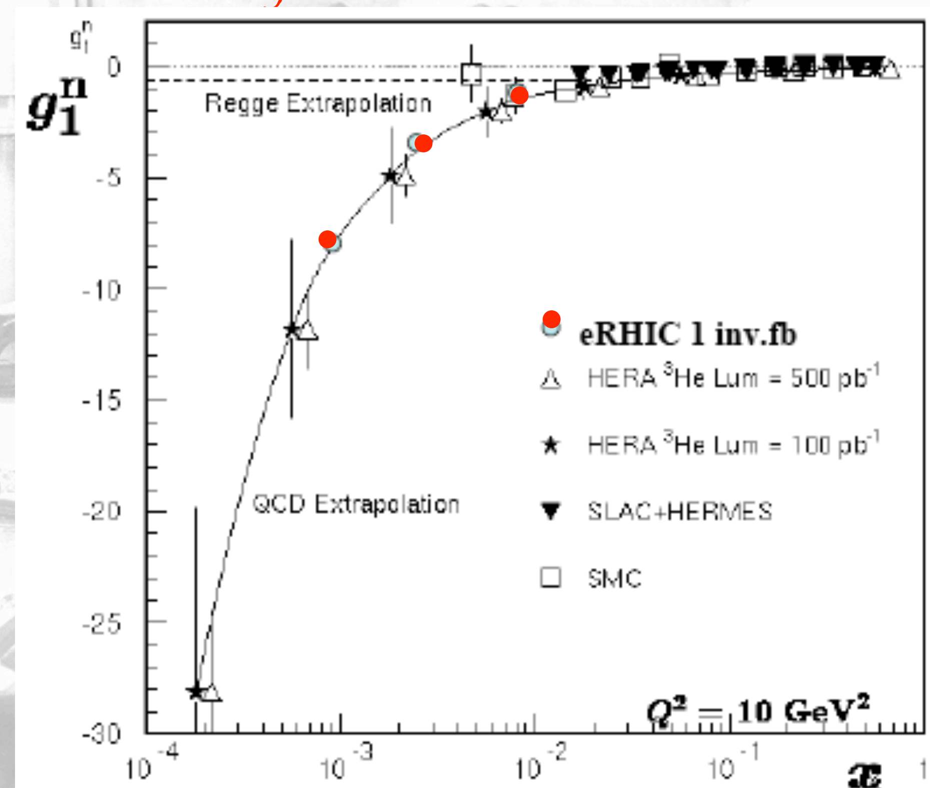


Available data limited in range, Q^2

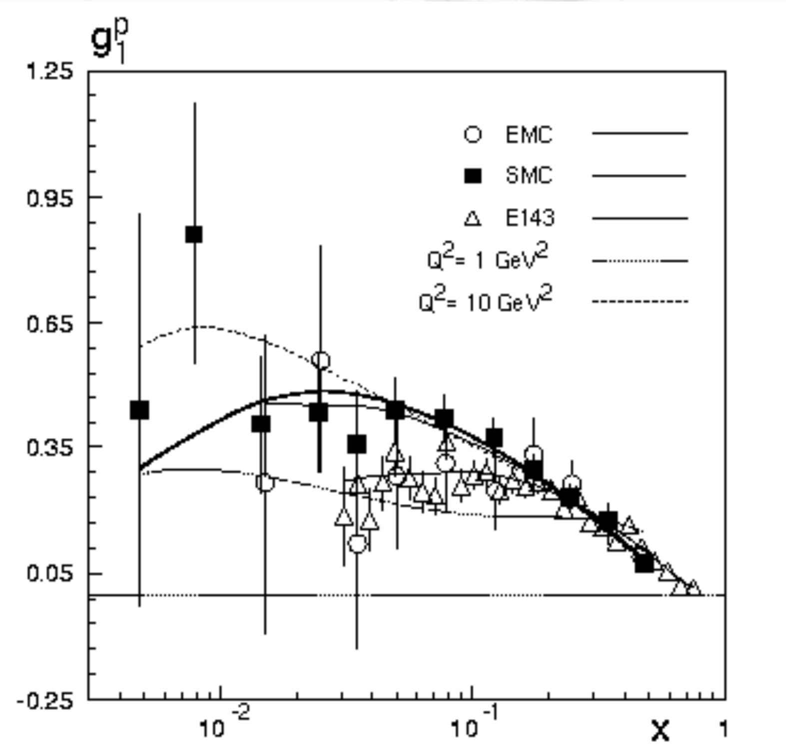
Particularly g_1^n

At EIC – p, d, ^{3}He

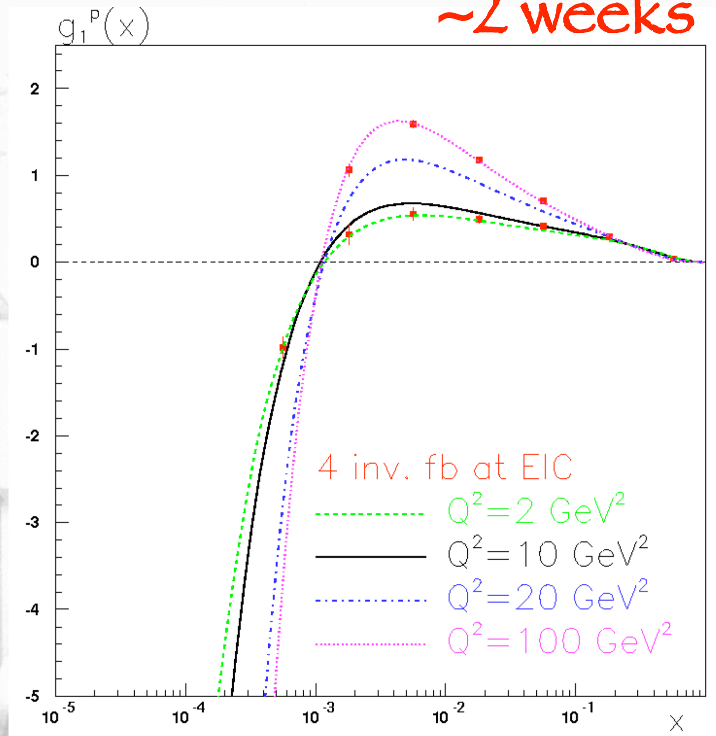
After just ~2 weeks at 10^{33} cm^{-2}s^{-1}



Spin Structure Function g_1^p at Low x



~2 weeks



Bjorken sum rule

$$\int_0^1 dx(g_1^p - g_1^n) = \frac{1}{6} g_A[1 + O(\alpha_S)]$$

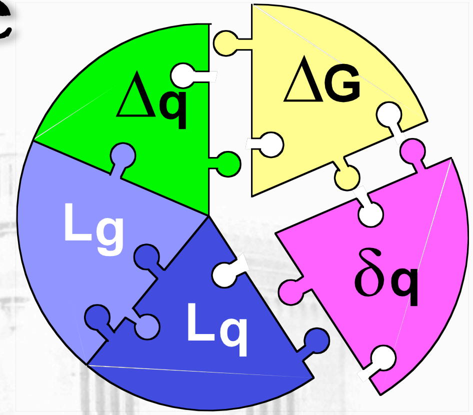
Currently known to ~10%

EIC would verify to ~1%

Improved measure of α_s

Nucleon Spin Puzzle

Nucleon spin = $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$

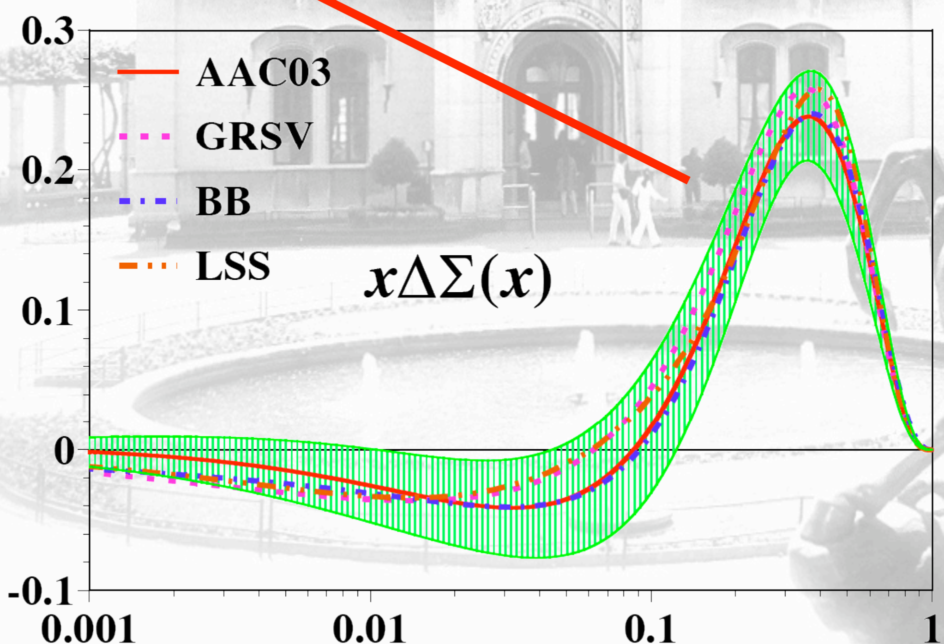


Quark contribution

$$\Delta\Sigma = \int_0^1 dx(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s})$$

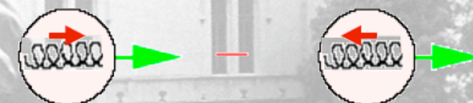
$\Delta\Sigma \approx 0.2$

Hirai, Kumano, Saito



Gluon contribution

$$\Delta G = \int_0^1 dx \Delta g(x)$$

$\Delta g(x) =$ 

Currently

$1.0 \pm 1.0(stat) \pm 0.4(sys) \pm 1.4(th)$

Many experiments underway on ΔG

COMPASS, STAR

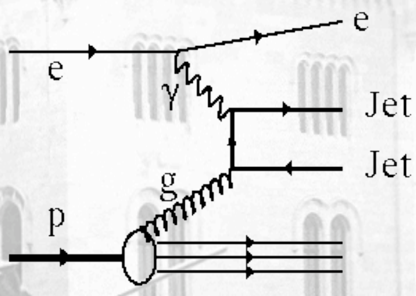
ΔG at EIC

Determination from scaling violations of $g_1(x,Q^2)$

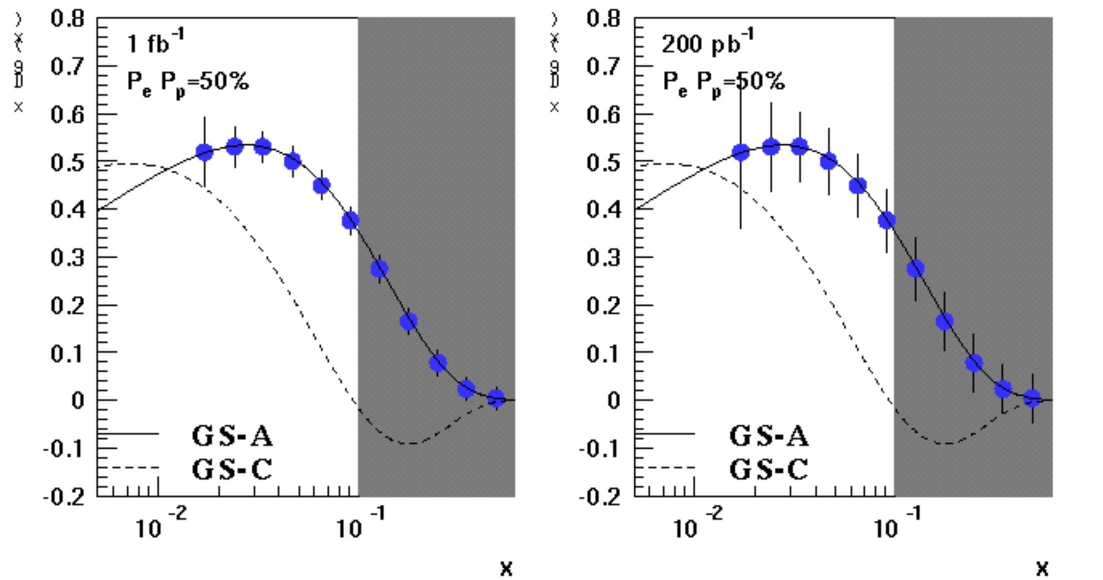
- EIC will extend range in x and Q^2
- improve existing measurement factor of 3 in 1 week

Direct measure via photon-gluon fusion

- di-jets, high P_T hadrons
- Successfully used at HERA
- NLO calculations exist
- Constrains shape in mid x region



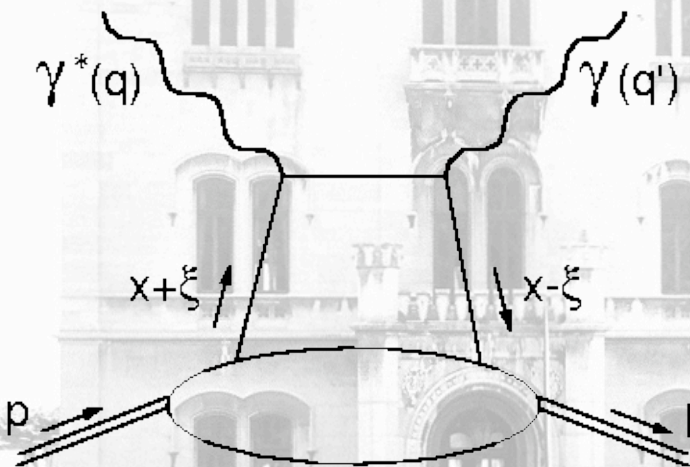
A.De Roeck,A.Deshpande, V. Hughes, J. Lichtenstadt, G. Radel



1 fb^{-1} in 2 week at EIC

Scaling violation data plus di-jet analysis will yield total uncertainty 5-10% after 1 year

DVCS - Vector Meson Production



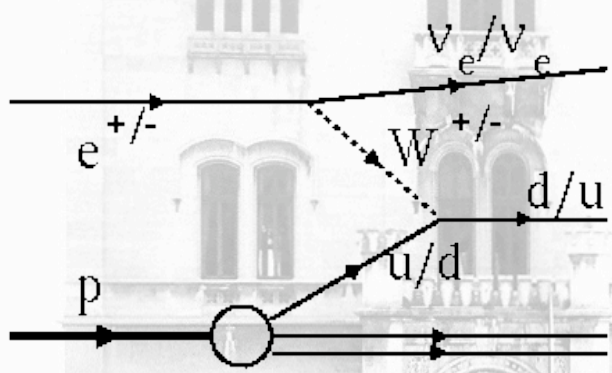
- Hard exclusive process
- Photon or vector meson out
- Possible access to skewed or off-forward PDF's
- Access to quark orbital angular momentum
- Theoretical debate continues

$$\int xdx\,[H(x,t,\xi)+E(x,t,\xi)] = 2J_q = \Sigma + 2L_q$$

Parity Violating Structure Function g_5

Use asymmetry between electrons
and positrons in CC reactions

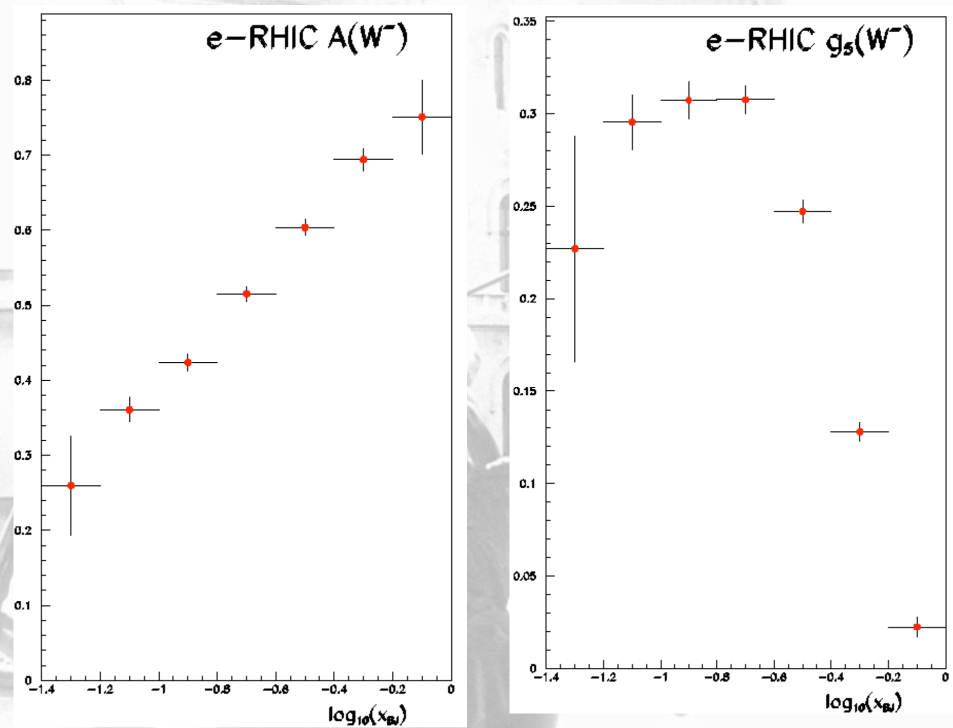
J. Contreras, A. De Roeck



$$A^{W^+} = \frac{-2bg_1 + ag_5}{aF_1 - bF_3}$$

$$A^{W^-} = \frac{2bg_1 + ag_5}{aF_1 + bF_3}$$

Extract g_5



Unique measurement at EIC

Polarised Electron - Ion Collider Proposals

Not all machines will be discussed here.

Will briefly describe:

- eRHIC - BNL ring-ring option
- eRHIC - BNL linac-ring option
- ELIC - JLAB
- LHeC - CERN

eRHIC

C-A/AP/142
March 2004

eRHIC

Zeroth-Order Design Report

BNL
L. Ahrens, D. Anderson, M. Bai, J. Beebe-Wang, I. Ben-Zvi, M. Blaskiewicz, J.M. Brennan, R. Calaga, X. Chang, E.D. Courant, A. Deshpande, A. Fedotov, W. Fischer, H. Hahn, J. Kewisch, V. Litvinenko, W.W. MacKay, C. Montag, S. Ozaki, B. Parker, S. Peggs, T. Roser, A. Ruggiero, B. Surrow, S. Tepikian, D. Trbojevic, V. Yakimenko, S.Y. Zhang

MIT-Bates
W. Franklin, W. Graves, R. Milner, C. Tschalaer, J. van der Laan, D. Wang, F. Wang, A. Zolfaghari and T. Zwart

BINP
A.V. Otboev, Yu.M. Shatunov

DESY
D.P. Barber

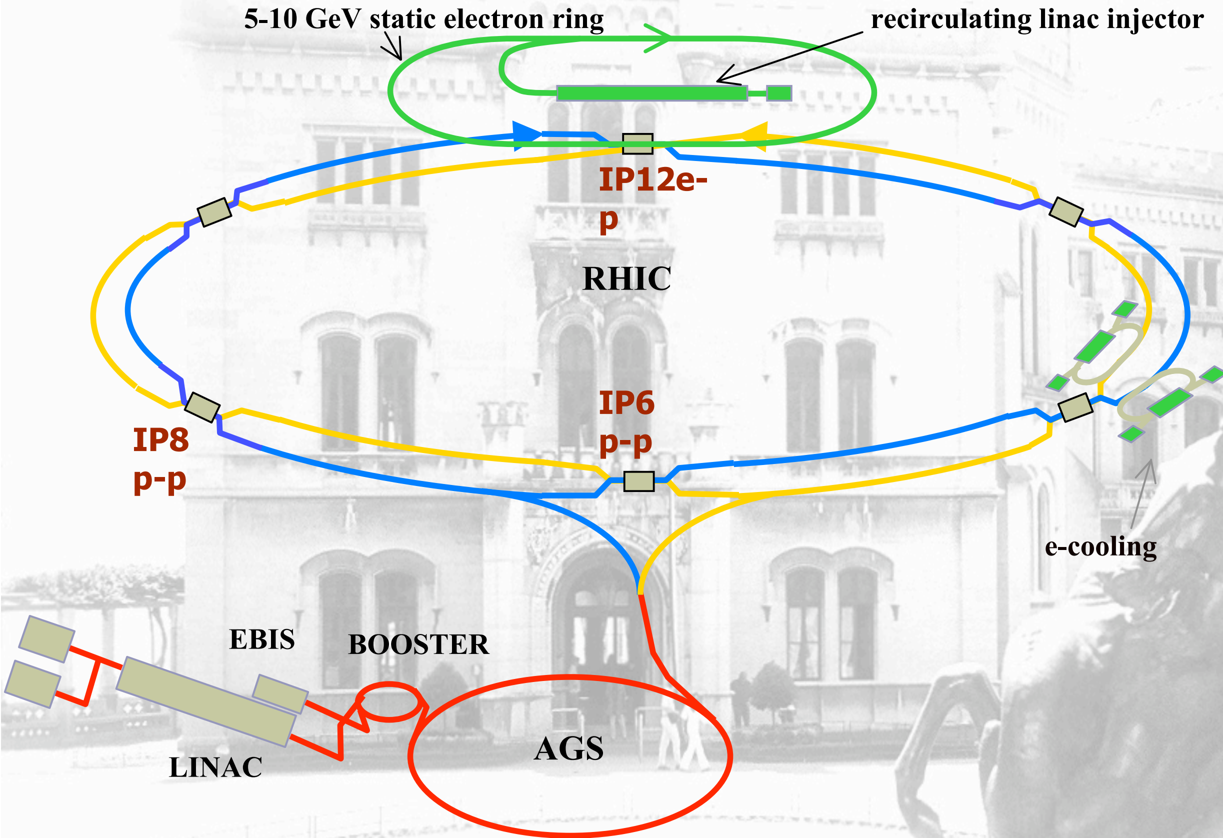
Editors: M. Farkhondeh (MIT-Bates) and V. Ptitsyn (BNL)

Detailed design report on accelerators and interaction region for both
- Ring-ring
- Linac-ring

Joint effort by BNL, MIT-Bates, Novosibirsk, and DESY

www.agsrhichome.bnl.gov/eRHIC/eRHIC_ZDR.htm

eRHIC - Ring-Ring Design



Luminosity limited by beam-beam tune shifts
High luminosity requires cooling
and
increase of 120 ⇒ 360 bunches

Linac injects into electron storage ring at full energy
- 2-10 GeV
- 0.5 A

RHIC can run in parallel

Polarized electrons and positrons

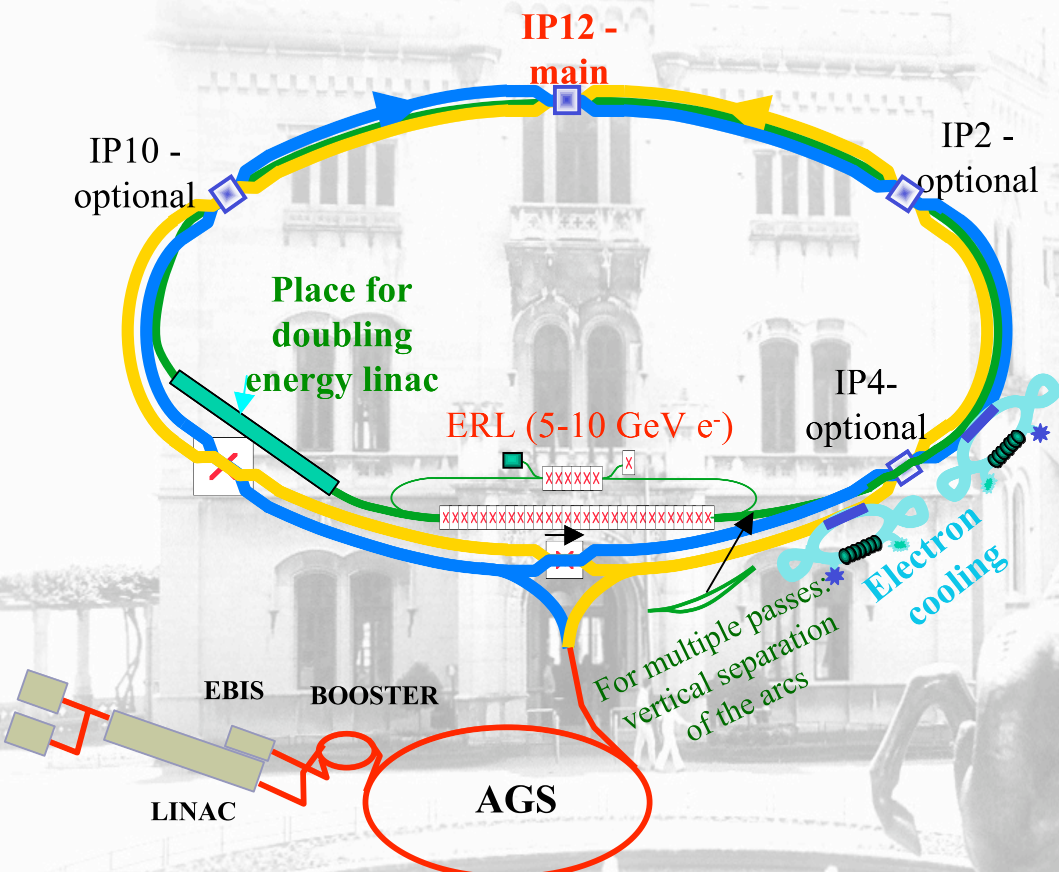
Similar to PEP II
- Same components ?

Single interaction point

Requires spin rotators

±3 m IP to nearest magnet

eRHIC - Linac-Ring Design



Superconducting, energy recovery linac feeds directly into IP

Possible multiple IP's

Rapid reversal of polarisation

No depolarizing energy regions

Spin rotators not needed

±5 m IP to nearest magnet

No positrons

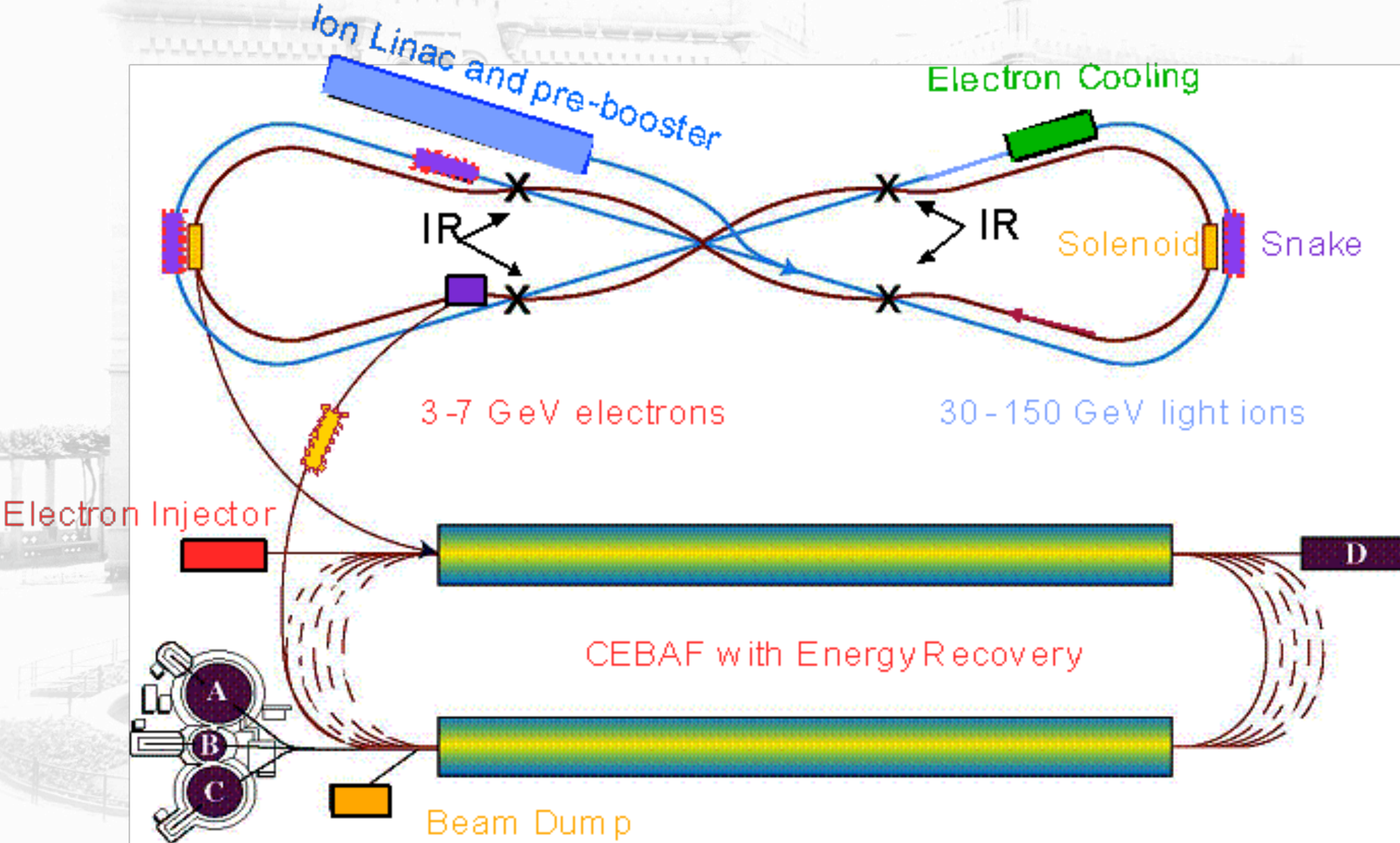
Luminosity not limited by beam-beam interaction

But need high intensity ion source

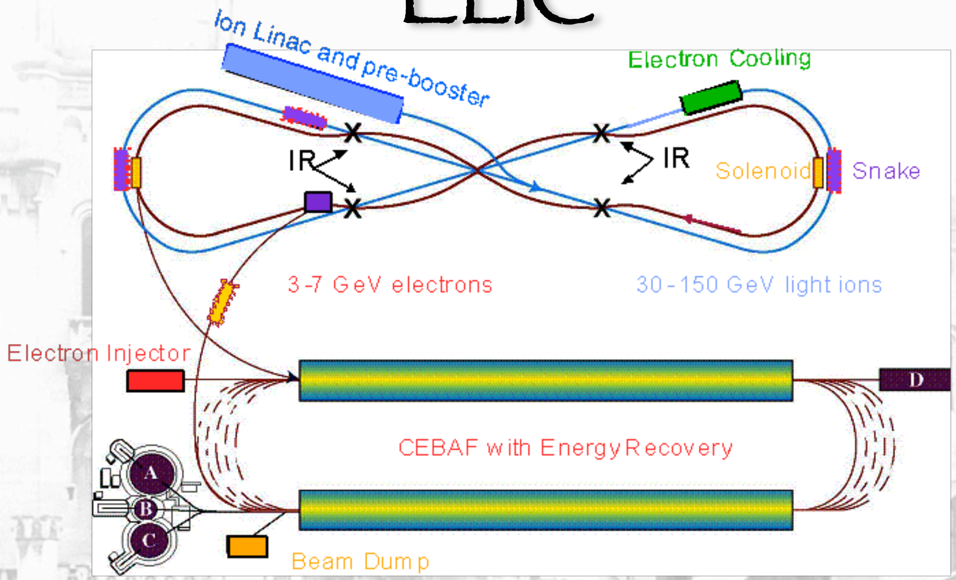
kW IR laser ERL-FEL (significant R&D)

ELIC

http://casa.jlab.org/research/elic/elic.shtml



ELIC



- Based on existing CEBAF but with 5 GeV upgrade
  - Replace 5 cell cryomodules with 7 cell cryomodules
  - Use 1 accelerating and 1 decelerating pass to get E_{CM}=20-65 GeV
- New figure 8 electron ring, new light ion linac, booster, and storage ring
  - New rings ease requirements for high intensity ion source and ERL from that of eRHIC linac-ring but significant R&D still necessary
- Possible to run 25 GeV fixed target experiments simultaneously
- Luminosity up to 10^{35} $cm^{-2}s^{-1}$ with crab crossing
- 4 possible interaction points

LHeC

DESY 06-006
Cockcroft-06-05

Deep Inelastic Electron-Nucleon Scattering at the LHC*

J. B. Dainton[1], M. Klein[2], P. Newman[3], E. Perez[4], F. Willeke[2]

[1] Cockcroft Institute of Accelerator Science and Technology, Daresbury International Science Park, UK
[2] DESY, Hamburg and Zeuthen, Germany
[3] School of Physics and Astronomy, University of Birmingham, UK
[4] CE Saclay, DSM/DAPNIA/Spp, Gif-sur-Yvette, France

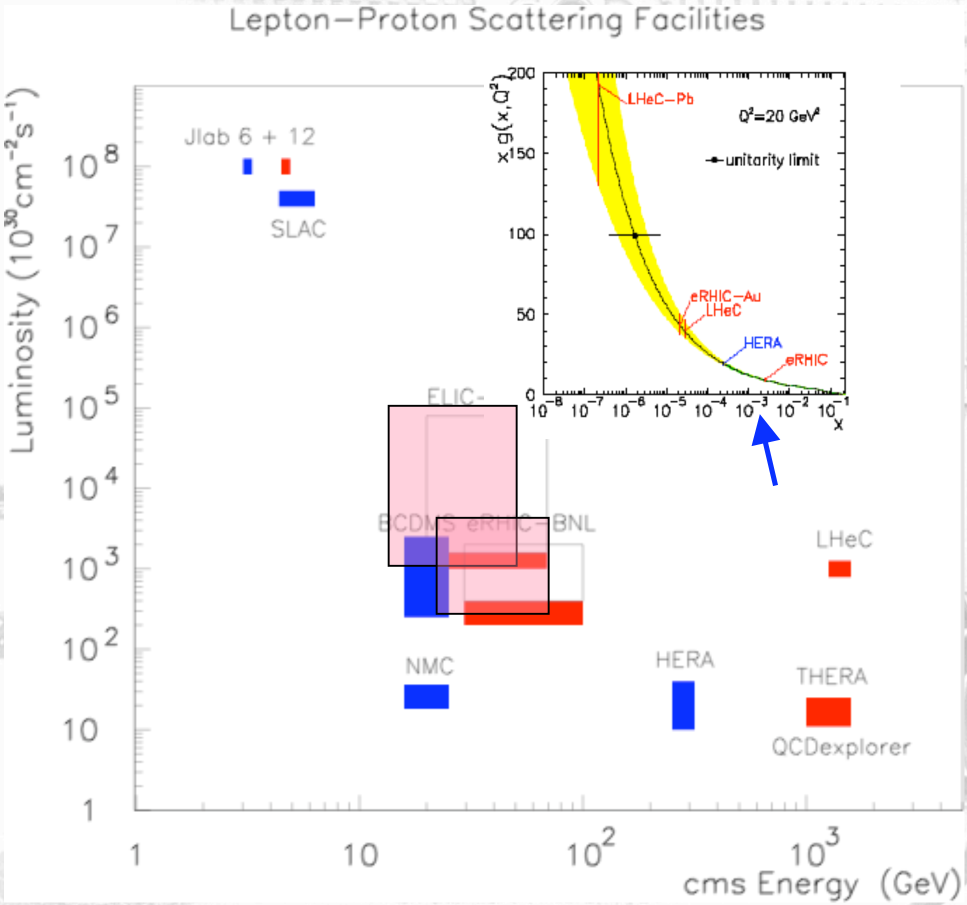
Abstract

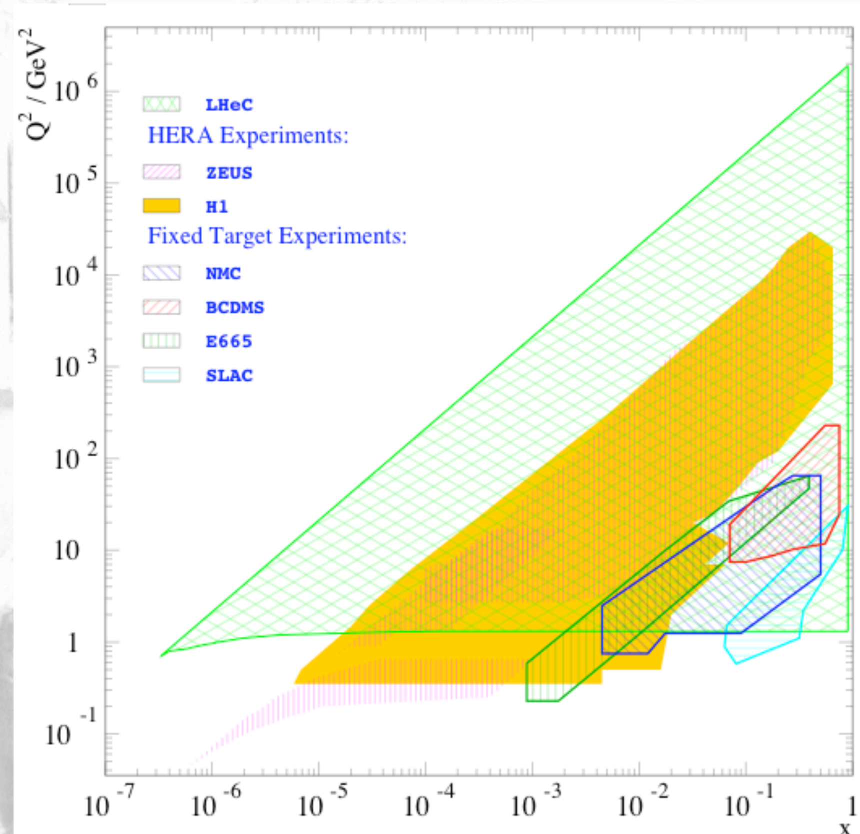
The physics, and a design, of a Large Hadron Electron Collider (LHeC) are sketched. With high luminosity, $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and high energy, $\sqrt{s} = 1.4$ TeV, such a collider can be built in which a 70 GeV electron (positron) beam in the LHC tunnel is in collision with one of the LHC hadron beams and which operates simultaneously with the LHC. The LHeC makes possible deep-inelastic lepton-hadron (ep, eD and eA) scattering for momentum transfers Q^2 beyond $10^6\,\mathrm{GeV}^2$ and for Bjorken x down to the 10^{-6}. New sensitivity to the existence of new states of matter, primarily in the lepton-quark sector and in dense partonic systems, is achieved. The precision possible with an electron-hadron experiment brings in addition crucial accuracy in the determination of hadron structure, as described in Quantum Chromodynamics, and of parton dynamics at the TeV energy scale. The LHeC thus complements the proton-proton and ion programmes, adds substantial new discovery potential to them, and is important for a full understanding of physics in the LHC energy range.

*Contributed to the Open Symposium on European Strategy for Particle Physics Research, LAL Orsay, France, January 30^{th} to February 1^{st}, 2006.

- 70 GeV electron/positron ring on top of LHC ring
- Assumes nominal LHC parameters
- Posible multiple IP's
- 74 mA electron current
- 25 ns bunch spacing
- $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity

LHeC Kinematics





Accelerator Summary

eRHIC - BNL

- 2-10 GeV electrons/positrons
- 25-250 GeV protons
- E_{CM}: 20 - 100 GeV^2
- Protons, light ions, heavy ions
- Two configurations:

Ring-Ring

- Luminosity: 10^{33} $cm^{-2}s^{-1}$
- Single IP, 3m

Linac-Ring

- Luminosity: 10^{34} $cm^{-2}s^{-1}$
- Multiple IP's possible, 5 m

ELIC - JLAB

- 3-7 GeV electrons
- 30-150 GeV protons
- E_{CM}: 20-65 GeV
- Protons, light-medium ions
- Luminosity: 10^{35} $cm^{-2}s^{-1}$
- 4 IP's

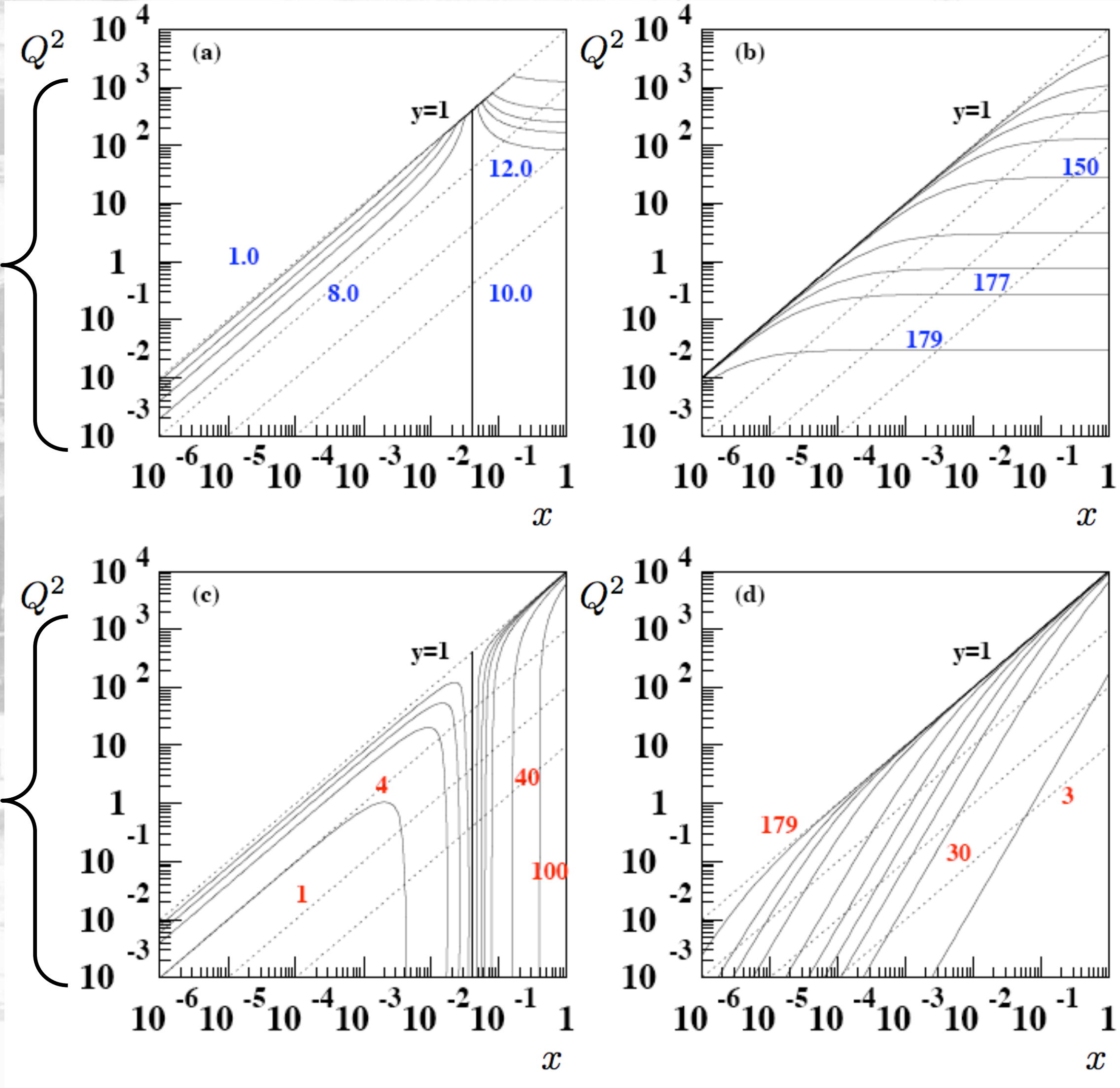
LHeC - CERN

- 70 GeV electrons/positrons
- 7,000 GeV protons
- E_{CM}: 1,400 GeV
- Protons, light ions
- Luminosity: 10^{33} $cm^{-2}s^{-1}$
- Multiple IP's

10 GeV Electrons on 250 GeV Protons

Lines of constant electron energy (E'_e)

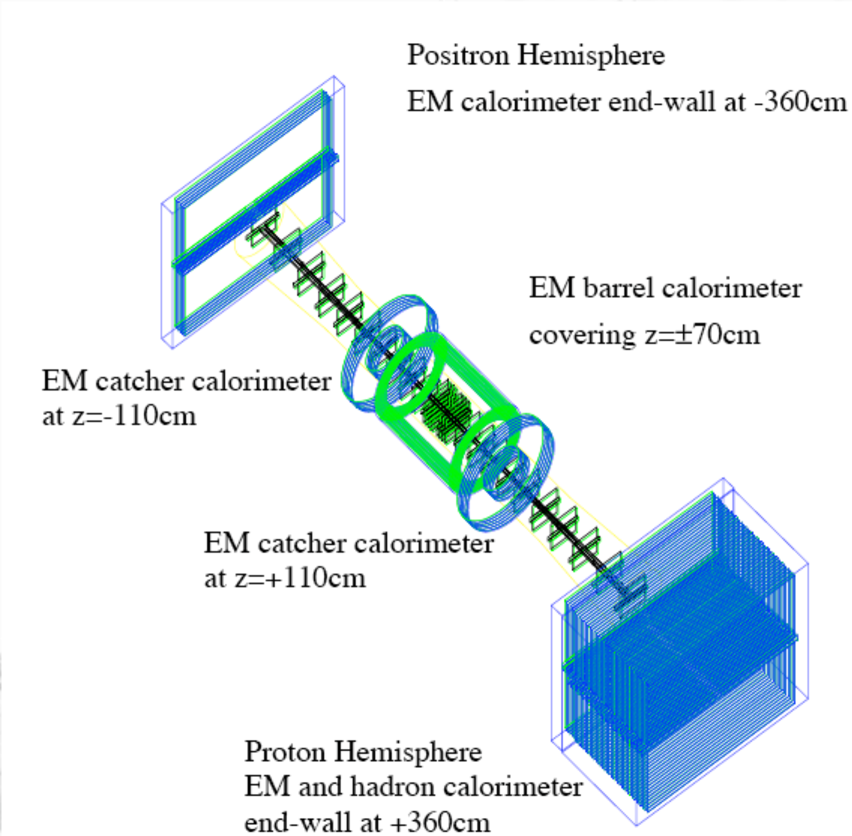
Lines of constant electron angle (ϑ'_e)



Lines of constant hadron energy (F)

Lines of constant hadro angle (γ)

Forward Angle Detector



I. Abt, A. Caldwell, X. Liu, J. Sutiak, MPP-2004-90, hep-ex 0407053

Long inner dipole field

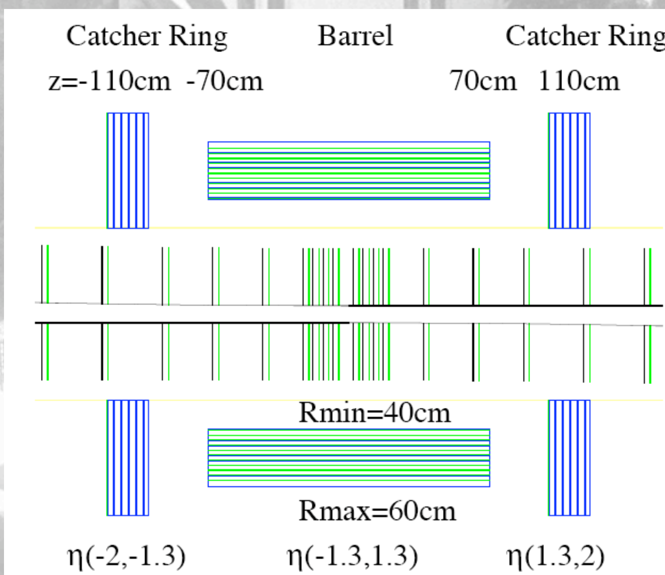
Central barrel Si-W, EM calorimeter

Forward and rear EM calorimeters

Forward hadron calorimeter

Specialized to enhance acceptance of forward scattered electrons and hadronic final state

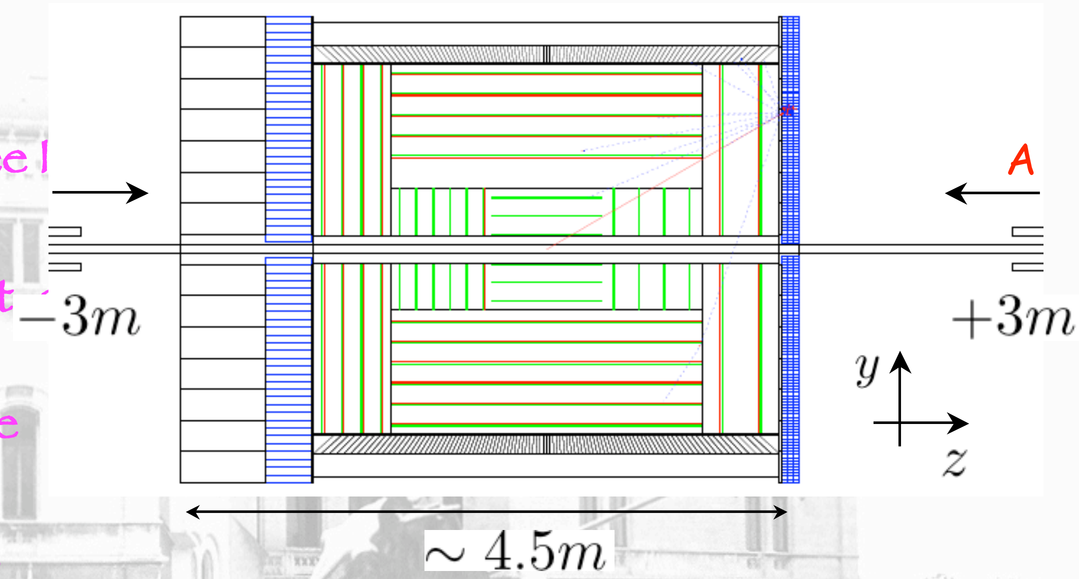
- Can run with lower luminosity
- 28 40x40 cm² double sided, Si-strip stations
  - 20 micron resolution
- Tracking down to $0.75 < \eta < 6$
- $\Delta P_T/P_T \approx 2\%$

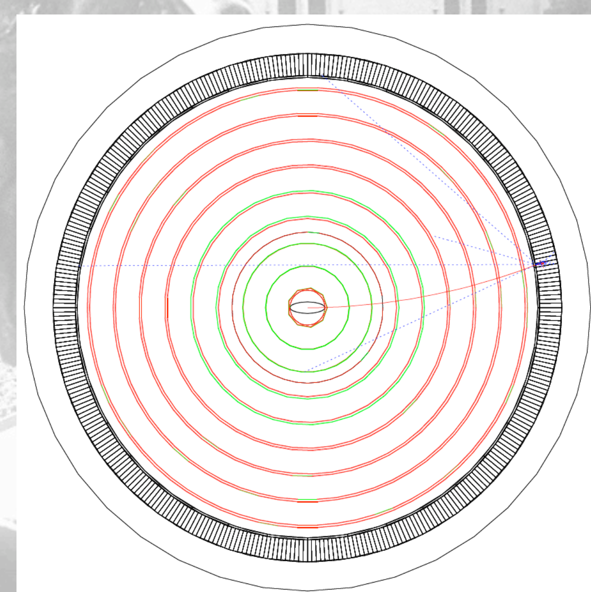


ELECTRA

General purpose, 4π detector

- inside ±3 m machine element free l
- Barrel and rear EMC - Si-W
- Forward EMC and HC Pb-scint -
  U-scint.
- Tracking and barrel EMC inside solenoidal magnetic field
- Tracking based on Si inner and micro-pattern (triple GEM outer)





General Detector IP Issues

Integration of accelerator elements and detector

- Keep IP as free as possible
- Quadrupoles as far away as possible
  - Impact on luminosity
- Combine separation dipole with detector solenoidal field

Synchrotron radiation

- Experience from HERA upgrade
- May radiation pass through, shield back scatter
- Maintain high vacuum

Small angle forward detectors

- Tag protons (remnants)
- Zero degree neutron detector

Luminosity monitors

- Zero degree photon detector

Polarimetry

DAQ / Trigger

- Typically 25 ns bunch crossing

If only 1 IP

- Staging different detectors
  - Start with forward tracking det
  - Electra later with high lumi

Conclusion

- Unpolarised valence quark region has been well explored and understood.
- Frontier research in QCD demands a concerted experimental effort directed towards the role of gluons and sea quarks.
- Spin dependent data is essential to understand the fundamental nature of matter.
- A new, polarised electron-ion collider can address these issues in an efficient, comprehensive manner.

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A new, polarised electron-ion collider can address these issues in an efficient, comprehensive manner.