Using Spin to Study the Strong Interaction

- Some perspective in honor of the distinguished career and achievements of Prof. Alan Krisch
- Motivate the next generation machine to study QCD – spin is essential

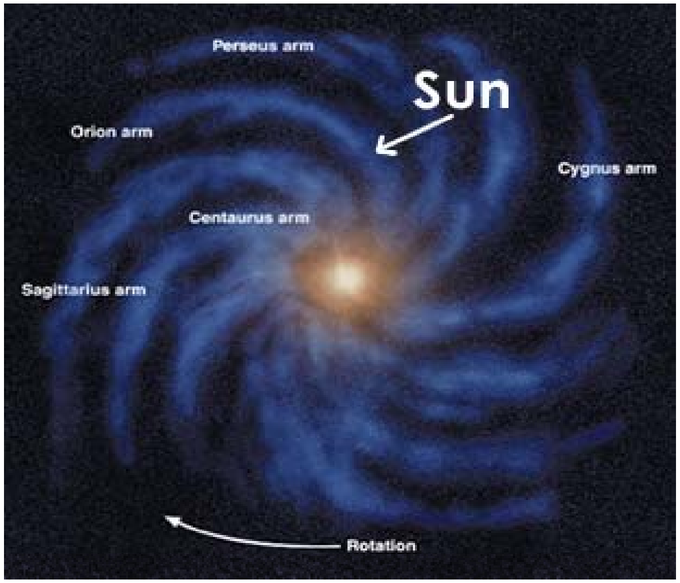
November 2009 CERN Courier

FUTURE FACILITIES

The EIC: exploring a new frontier in QCD

A worldwide effort to determine the best way to explore the frontier of understanding precisely how quarks and gluons form hadrons and nuclear matter in the context of QCD has determined that the ideal future facility would be a high-luminosity, high-energy polarized electron–ion collider. **Abhay Deshpande**, **Rolf Ent** and **Richard Milner** report.

The Fundamental Structure of Matter



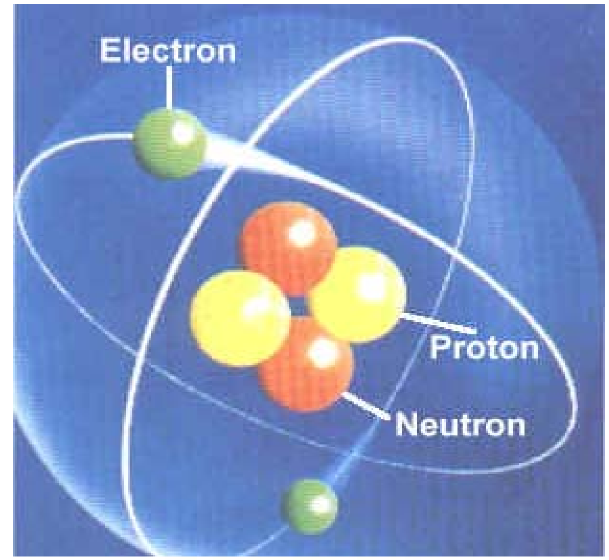
- Essentially all of the observable matter in the universe is made of protons and neutrons
- QCD describes these building blocks in terms of pointlike quarks and gluons.
- It has been a major goal of physicists to understand the structure and properties of the nucleon.
- Recent work has brought our understanding to a new level of precision.

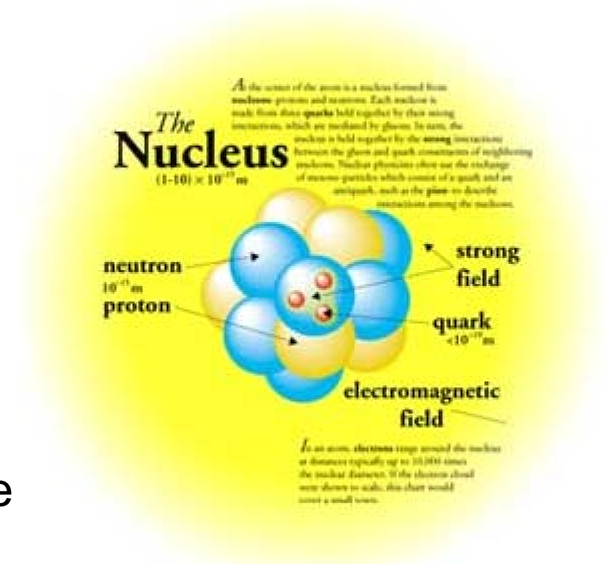
Recent history

• Balmer lines of hydrogen	1885
• Discovery of the electron	1897
• Discovery of the atomic nucleus	1911
• The Dirac equation	1928
• Discovery of the neutron	1932
• Hartree-Fock theory of the atom	1935
• **Q**uantum **E**lectro**D**ynamics	1947
• Shell model of the nucleus	1949
• Discovery of parity violation	1956
• Electroweak theory	1960's
• Discovery of quarks	1967
• **Q**uantum **C**hromo**D**ynamics	1970's
• Discovery of W, Z	1983

Standard Model of Structure of Matter

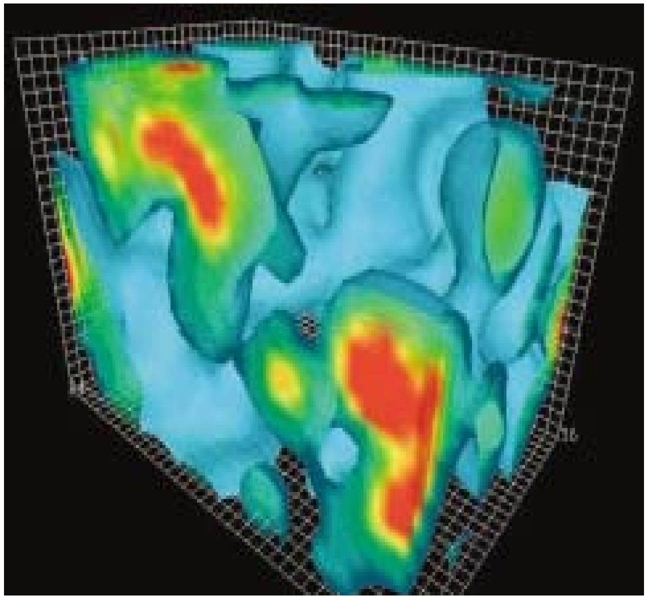
- Elementary constituents are fermions
- Interaction is mediated by bosons
- **Atom**: fermions are pointlike electrons interacting via QED with photon exchange
- Physics of the atom is well described by non-relativistic motion in a mean field.
- Electroweak theory generalizes to W, Z exchange and explains parity violation
- **Nucleus**: fermions are nucleons interacting via meson exchange
- Physics of the nucleus (at nucleon level) is well described by non-relativistic motion in a mean field.
- **Nucleon**: fermions are light (~ 5 MeV), pointlike quarks interacting via QCD with massless gluon exchange.
- Physics of the nucleon is completely relativistic with energy and virtual particles (sea quarks and gluons) dominating the structure.





Exploring QCD

- The QCD Lagrangian is known but not very useful for the foreseeable future
- We study the rich phenomenology of this new sub-nuclear world described by QCD
- We seek to understand the fundamental properties in terms of the quarks and gluons of QCD:
  - mass
  - spin
  - new phenomena, e.g. condensates
  - new techniques, e.g. imaging



- Experiment is essential
- Lattice QCD is important and increasingly powerful

QCD is unique

- It is the only fully consistent theory that we are certain that describes the real world: in the limit $m_q \rightarrow 0$, there are no free parameters
- All the interactions are a consequence of deep symmetry principles like gauge invariance and chiral symmetry
- Most of the visible phenomena are emergent

  quarks and gluons are not seen
- This makes QCD the only laboratory for exploring the dynamics of a non-trivial, consistent relativistic theory
- The virtual particles of QCD (sea quarks and gluons) are dominant but are largely unexplored and poorly understood

  1 GeV mass proton is built from ~ 5 MeV mass *up* and *down* valence quarks

Some critical perspectives

- **QCD is sacred**

  - it is unacceptable to `test QCD'

  - *in extremis*: we don't need experiment, we can calculate everything on the lattice

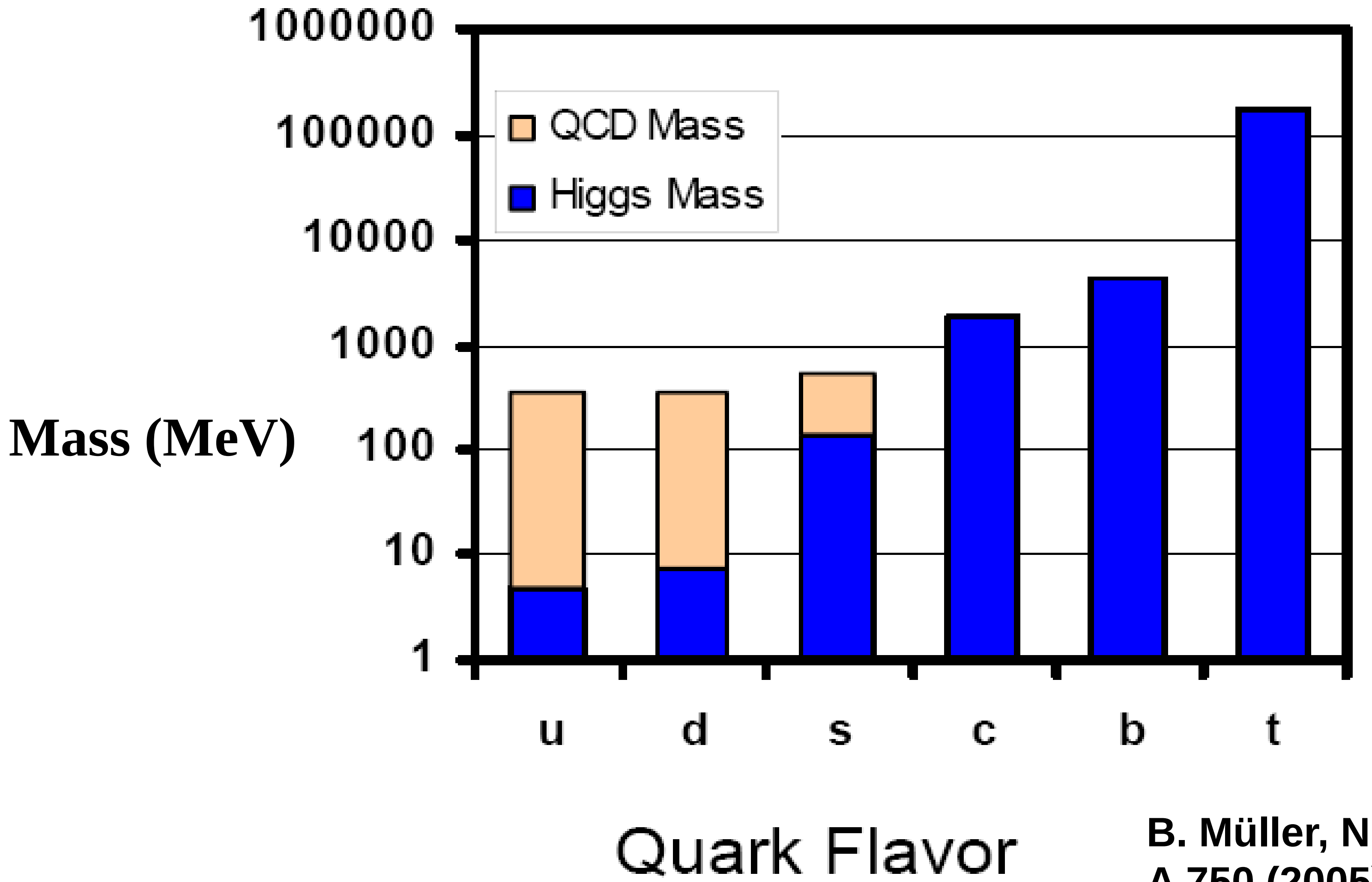
  Counterpoint: any physical theory is only as good as its experimental test

- **It is all stamp (structure function) collecting**

  - we have books of data at different kinematics, why do we need more?

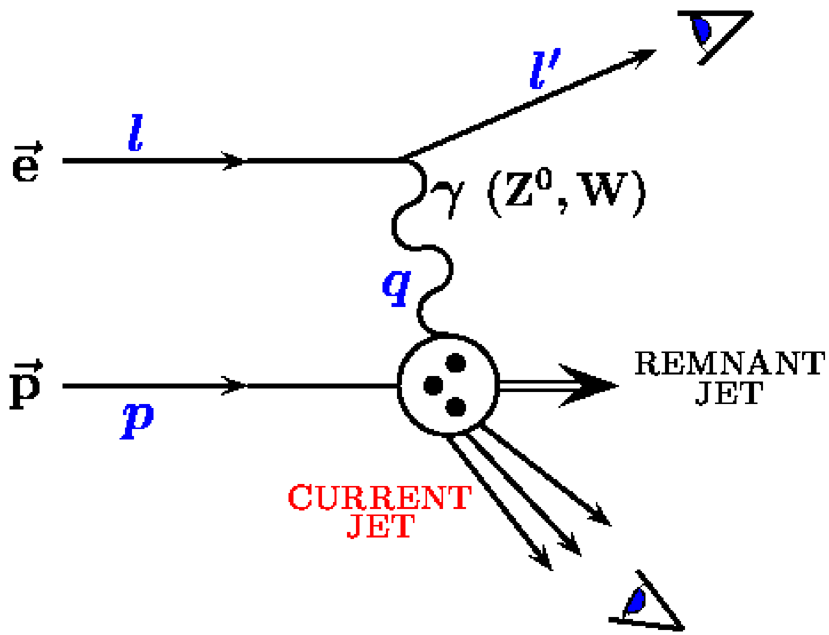
Counterpoint: experiments must be motivated to gain insight

Baryonic mass is dominated by QCD



B. Müller, Nucl. Phys. A 750 (2005) 84

High Energy Lepton Scattering



$$Q^2 = -q^2 = sxy$$

$$x = \frac{Q^2}{2p\cdot q}$$

$$y = \frac{p\cdot q}{p\cdot l}$$

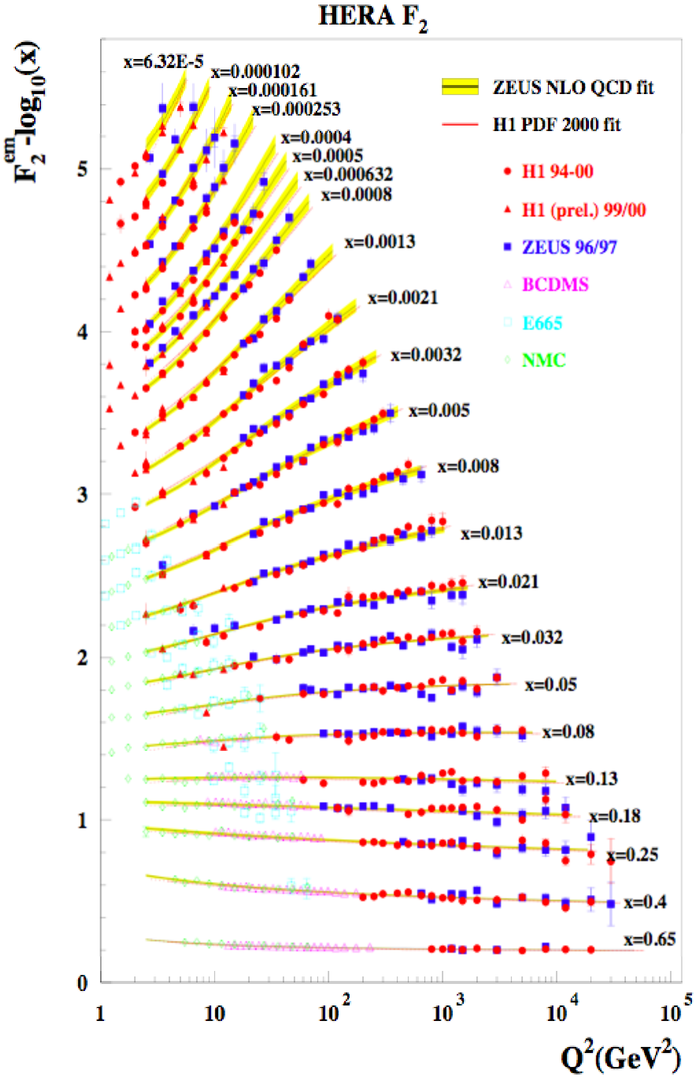
$$s = 4E_eE_p$$

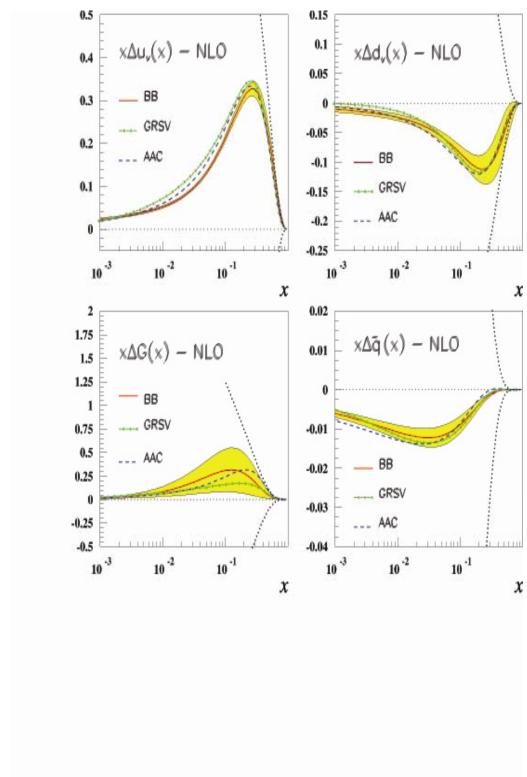
$$W = (q+p)^2$$

- Interpretable within a rigorous QCD framework
- Directly probes quarks and gluons
- Virtual photon imparts energy and momentum to quark in a completely controllable way

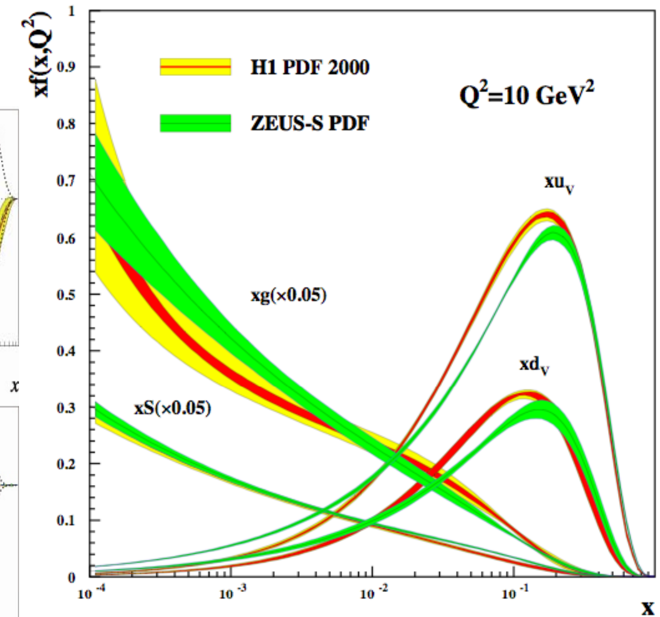
QCD remarkably successful

Bjorken scaling
DGLAP evolution

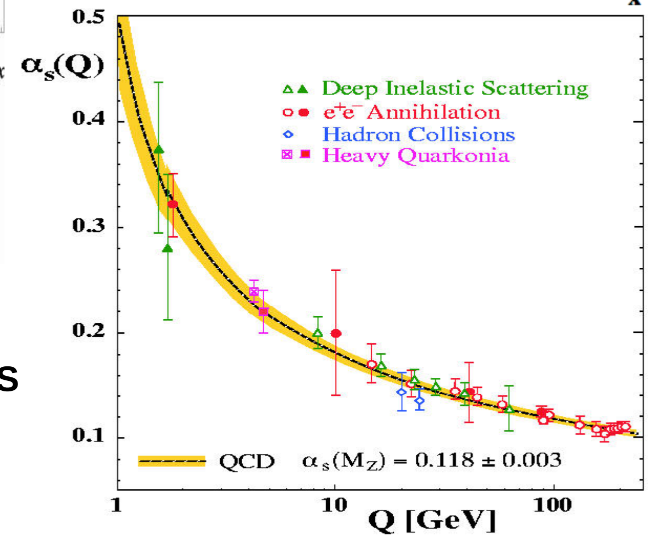




PDF's



Running coupling α_S



Scientific frontiers

- **Spin structure of nucleon**
  - $g^p_1(x)$ at low x **dramatic QCD prediction**
  - gluon and sea quark polarization
  - Bjorken sum rule **QCD test**
  - new (GPD, transversity) parton distributions

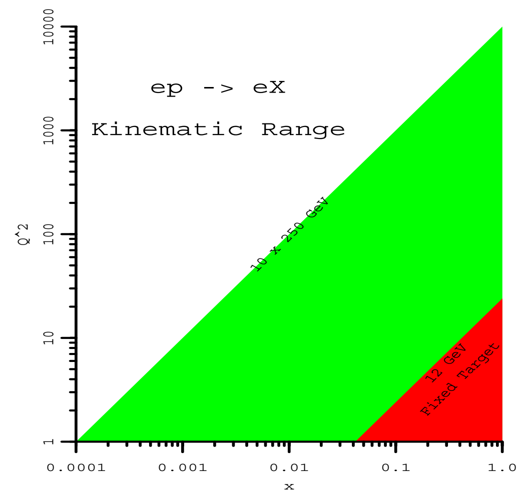
- **Partonic understanding of nuclei**
  - gluon momentum distribution in nuclei: **essential to understand hot QCD in RHI collisions**
  - fundamental explanation of nuclear binding
  - saturation

Why a high luminosity lepton-ion collider ?

- The lepton probe provides the precision of the electroweak interaction but requires high luminosity to be effective
- Lepton scattering on hadron targets in new regimes has consistently yielded new insights, e.g. DIS, EMC effect, Glue
- High $E_{cm} \Rightarrow$ large range of x, Q^2 $\quad$ $Q_{max}^2 = E_{CM}^2 \bullet x$

  x range: valence, sea quarks, glue

  Q^2 range: utilize evolution equations of QCD



- High polarization of lepton, nucleon achievable
- Complete range of nuclear targets
- Collider geometry allows complete reconstruction of the final state

EIC is needed to complete the study of

the fundamental structure of matter

EIC evolution

- Substantial international interest in high luminosity (~$10^{33}cm^{-2}s^{-1}$) polarized lepton-ion collider over more than a decade
- Workshops

Seeheim, Germany	1997	MIT, USA	2000
IUCF, USA	1999	BNL, USA	2002
BNL, USA	1999	JLab, USA	2004
Yale, USA	2000	BNL,USA	2006

- In early 2007 an EIC Collaboration was formed

http://web.mit.edu/eicc

- Recent EICC meetings approx. every six months

2007: MIT, Stony Brook   2008: Hampton, Berkeley

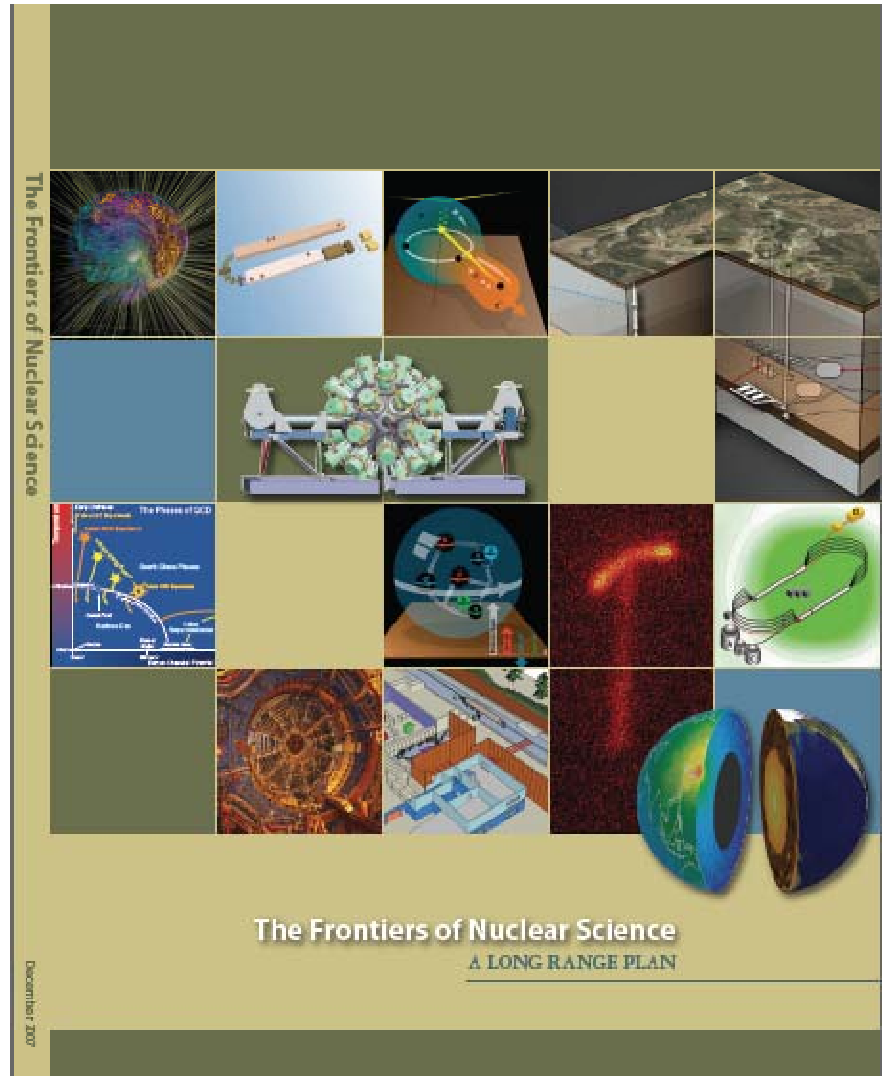
2009: GSI, Germany   2010: Stony Brook

- Over the last decade, EIC has become established as the leading candidate for the next QCD machine
- EIC viewed as part of the future at both BNL and JLab.
- See `*The EIC's route to a new frontier in QCD*' by A. Deshpande. R. Ent and R.M. in November 2009 CERN Courier.

NSAC 2007 Long Range Plan

"An **Electron-Ion Collider (EIC)** with polarized beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia. In support of this new direction:

We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton."



Overview

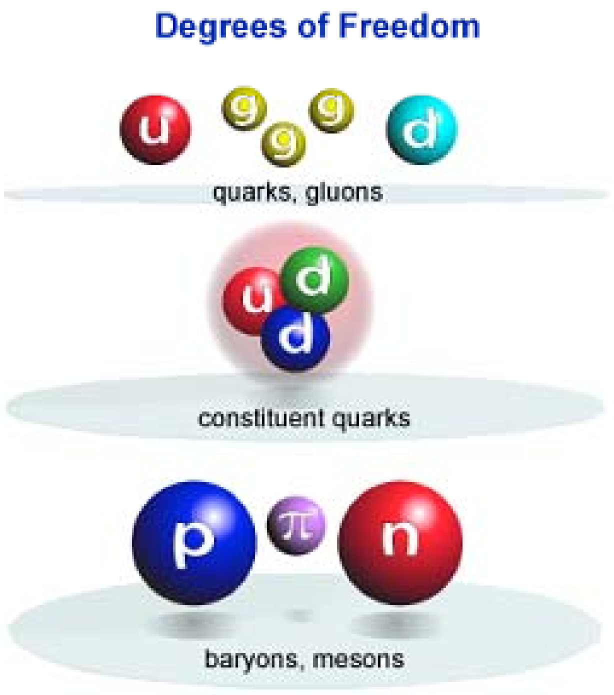
The EIC will explore the most compelling issues in nuclear science and technology.

- ***The structure of visible matter***
- ***The role of gluons in hadronic matter***
- ***Fundamental symmetries of nature***

This will require a new generation of accelerator and detectors.

Goal of the Electron-Ion Collider: To explore the structure of visible matter

- **What is the internal landscape of the hadron?**
  - Benchmark: Spatial, spin, flavor and gluonic structure
- **What is the nature of the nuclear force that binds protons and neutrons into nuclei?**
  - Frontier: QCD properties of nuclear force
  - Mysteries: QCD effects in nuclei



Understanding the proton spin

Where is the Spin of the proton?

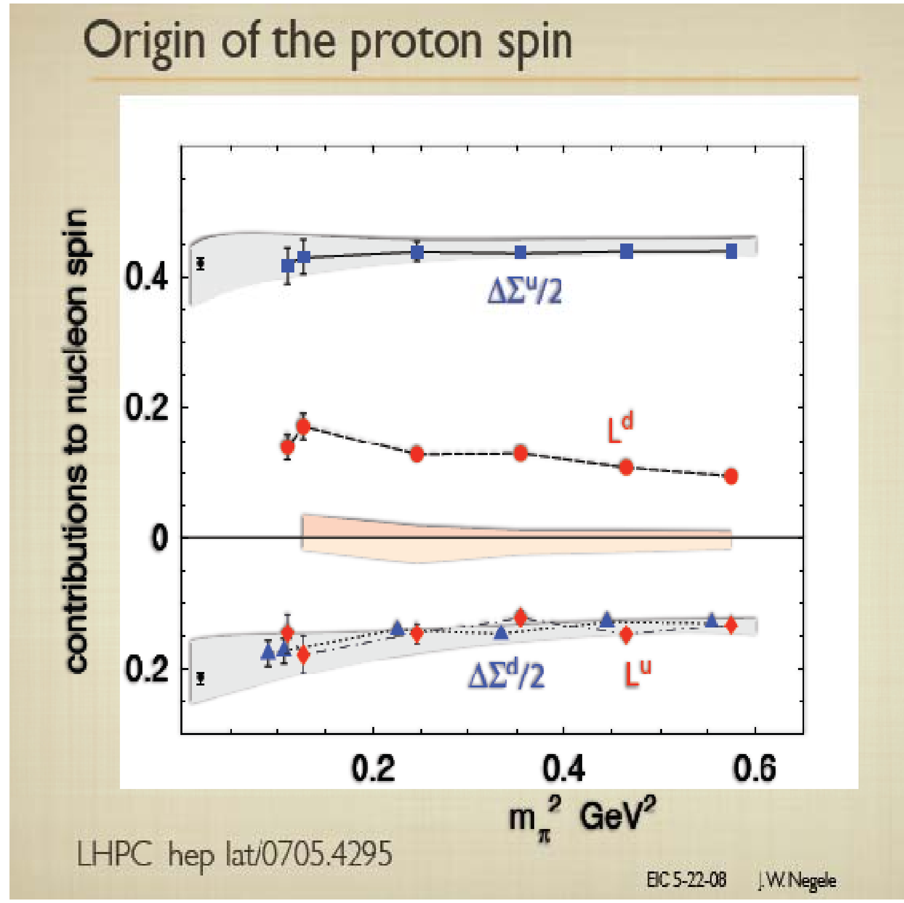
- Modern data yields:
  $\Sigma = 0.33 \pm 0.03 \pm 0.05$

  (c.f. $0.14 \pm 0.03 \pm 0.10$ originally)

- In addition, there is little or no polarized glue
  - COMPASS: $g^D_1 = 0$ to $x = 10^{-4}$
  - A_{LL} (π^0 and jets) at PHENIX & STAR $\rightarrow \Delta G \sim 0$
  - Hermes, COMPASS and JLab: $\Delta G / G$ small

• ALL effects, relativity and OGE and the pion cloud have the effect of swapping quark spin for valence orbital angular momentum and anti-quark orbital angular momentum (>60% of the spin of the proton)

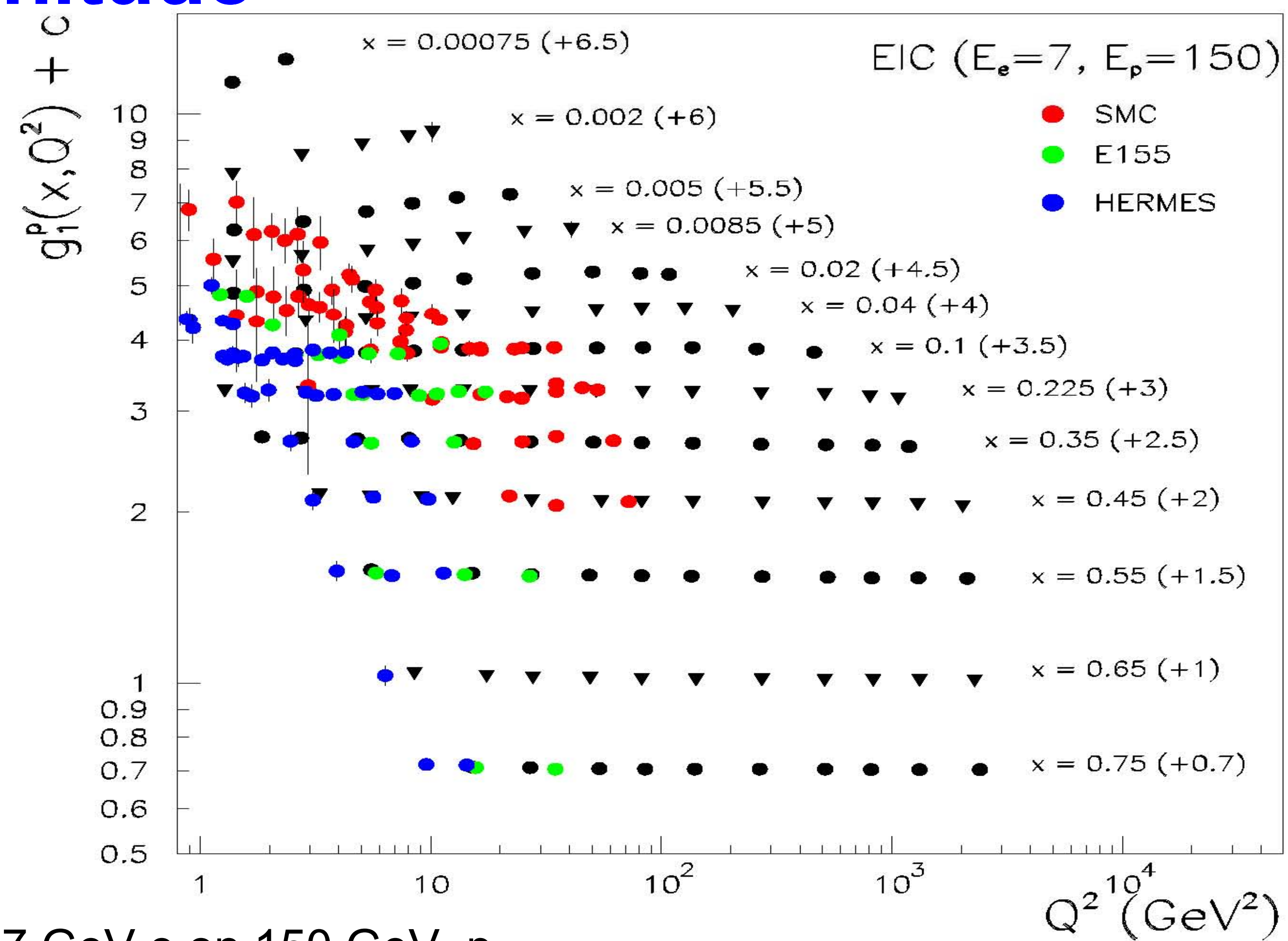
Myhrer & Thomas, hep-ph/0709.4067



A. Thomas: gluon contribution small

J. Negele: Quark orbital A.M. small

EIC will extend reach of spin-dependent inclusive measurements by several orders of magnitude

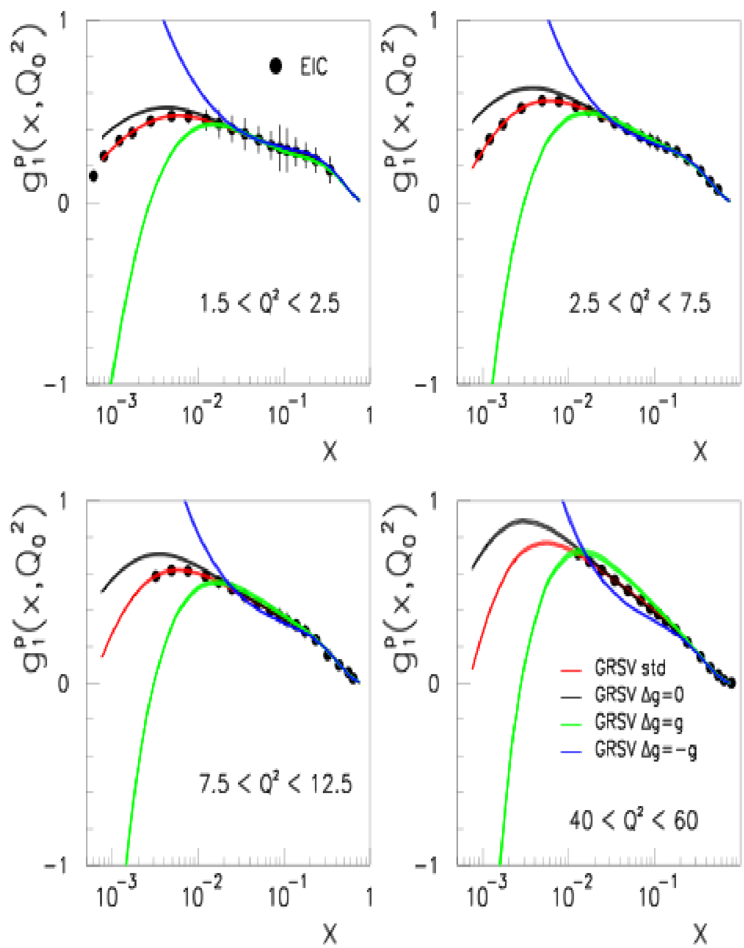


A. Bruell
R. Ent

7 GeV e on 150 GeV p
5 fb^{-1} integrated luminosity

Scaling violations directly observed!

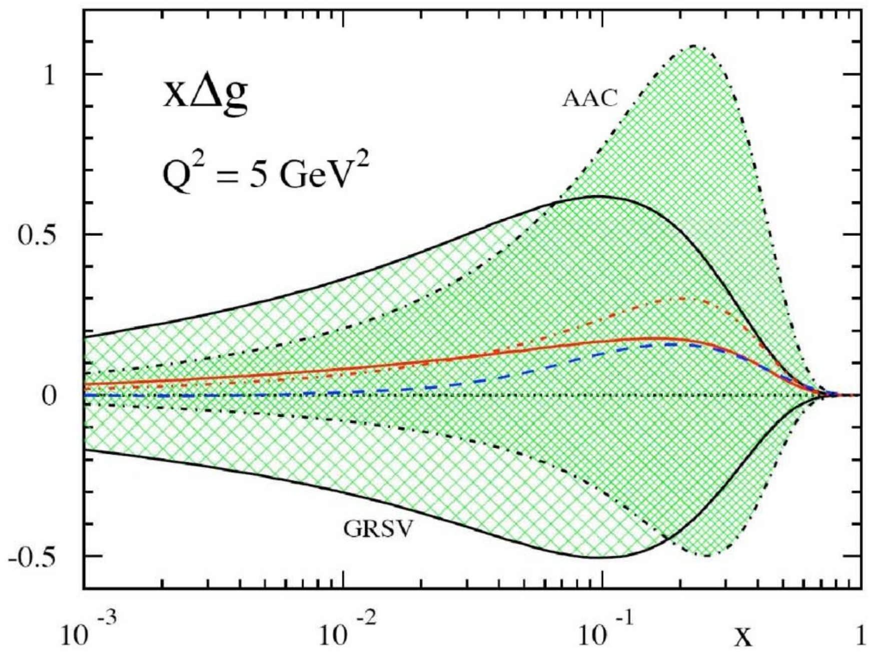
Unprecedented inclusive spin-dependent DIS measurements



7 GeV e on 150 GeV p
5 fb^{-1} integrated luminosity

A. Bruell
B. R. Ent

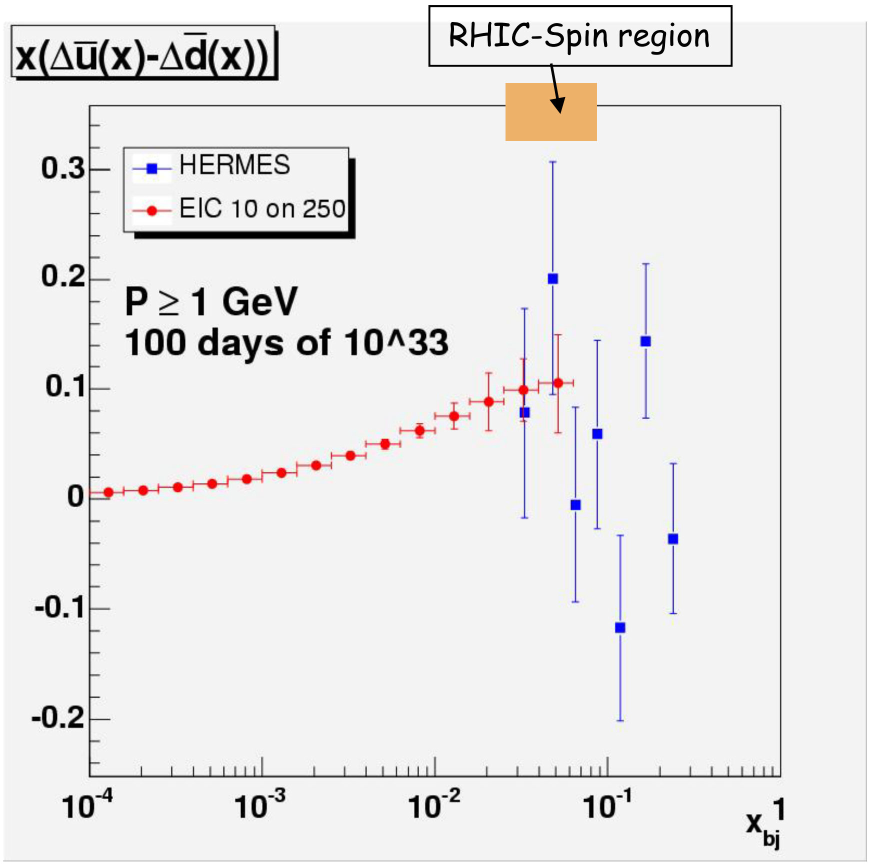
x-dependence of gluon polarization



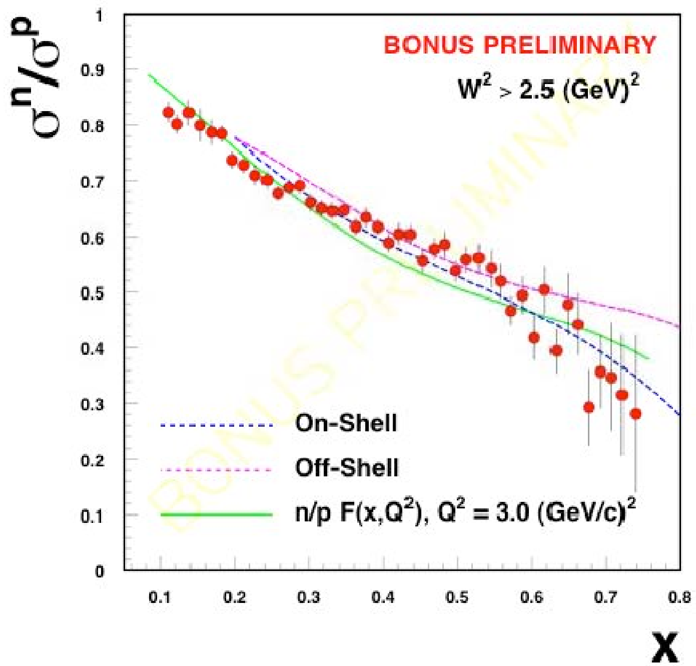
Note substantial gluon polarization in some models at high x ~ 0.5

Stratmann and Vogelsang
hep-ph/07020831

Light quark structure – chiral properties



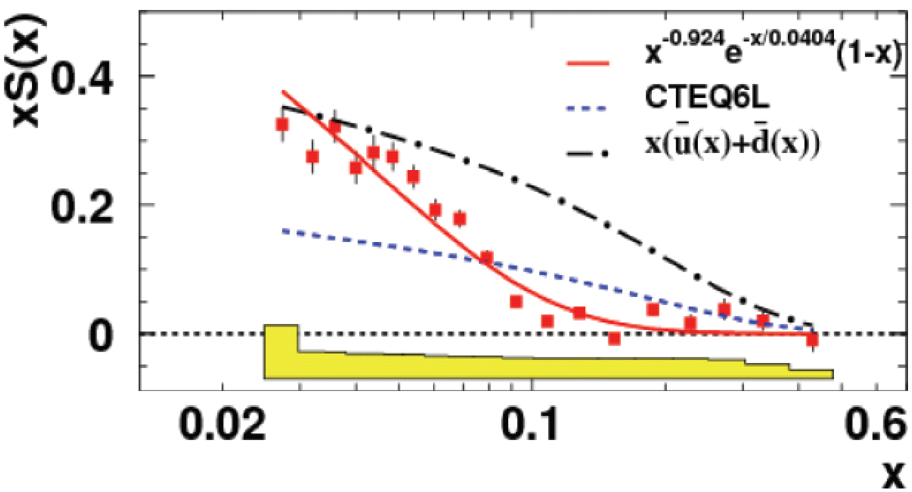
Tagged structure functions to reach x > 0.9

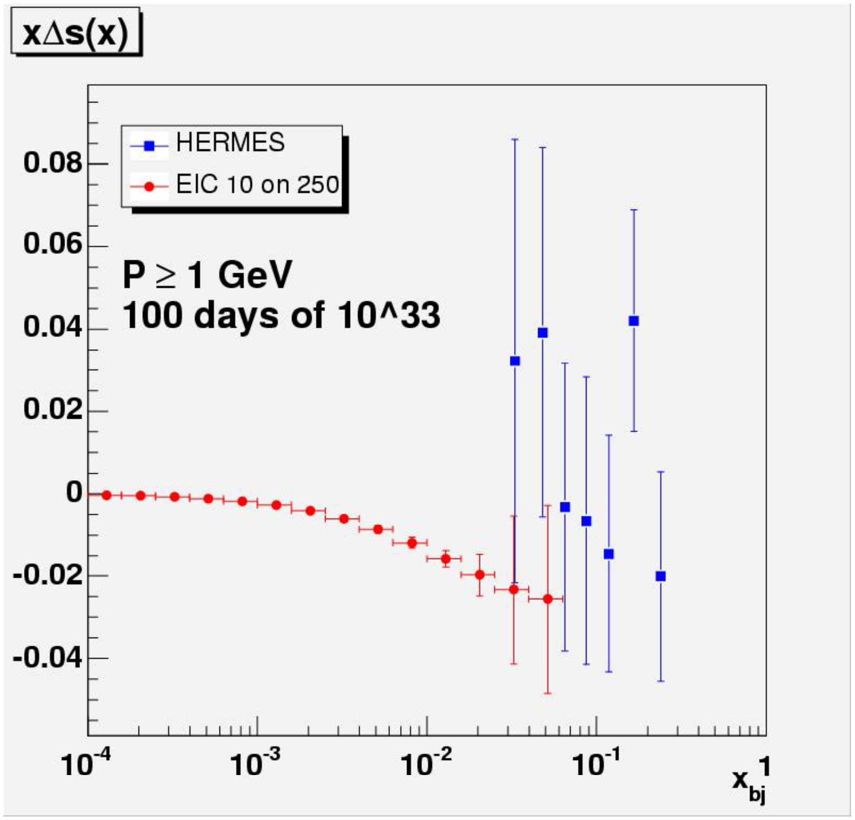


Spectator forward tagging to minimize deuteron structure –similar requirements as exclusive, DVCS, diffraction

Strange quark distributions

HERMES data





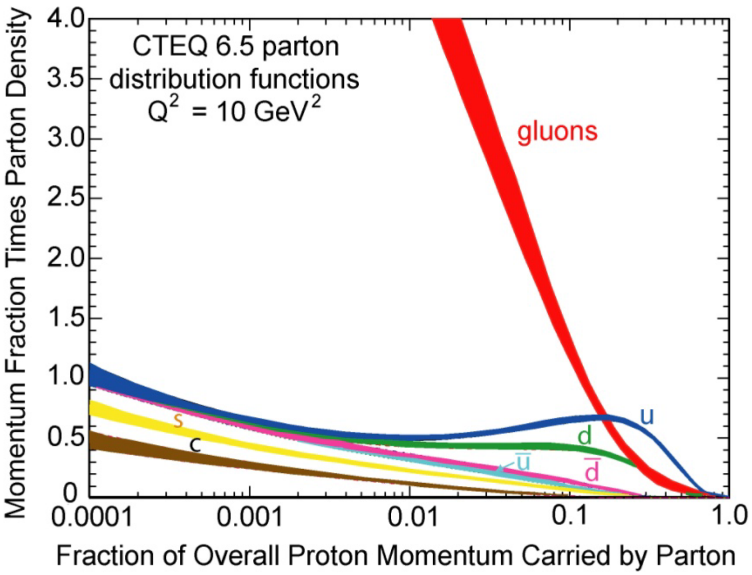
- Asymmetric strange-antistrange sea can explain NuTeV anomaly
- Data on same time scale as disconnected diagrams in lattice calculations.
- What about charm quark contributions?

Explore gluon-dominated matter

- **What is the role of gluons and gluon self-interactions in nucleons and nuclei? NSAC-2007**
  - **Gluon dominance in the proton**

Gluon distribution $G(x,Q^2)$

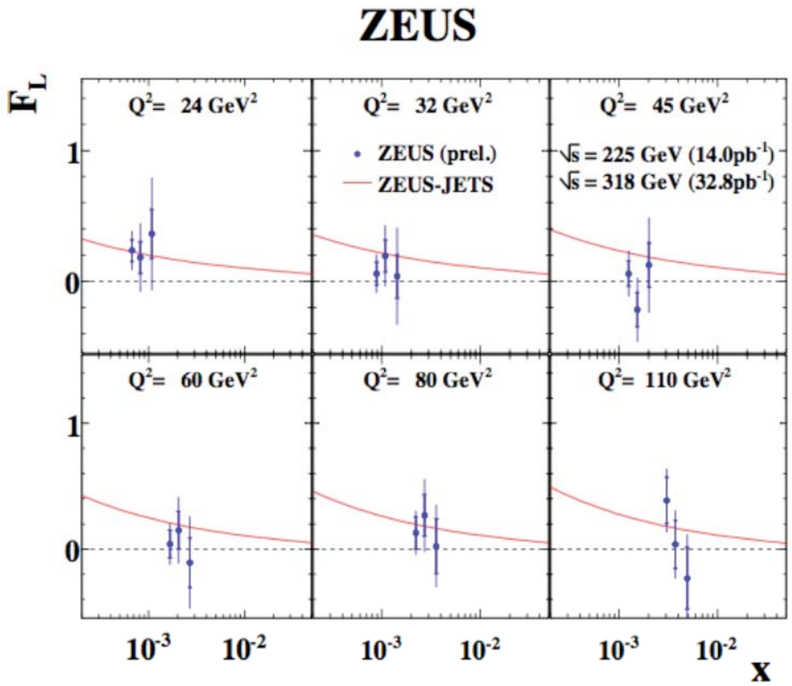
- **Scaling violation in F_2: $dF_2/d\ln Q^2$**
- **$F_L \sim a_s\, G(x,Q^2)$**
- **inelastic vector meson production (e.g. J/ψ)**
- **diffractive vector meson production $\sim [G(x,Q^2)]^2$**
- **...**

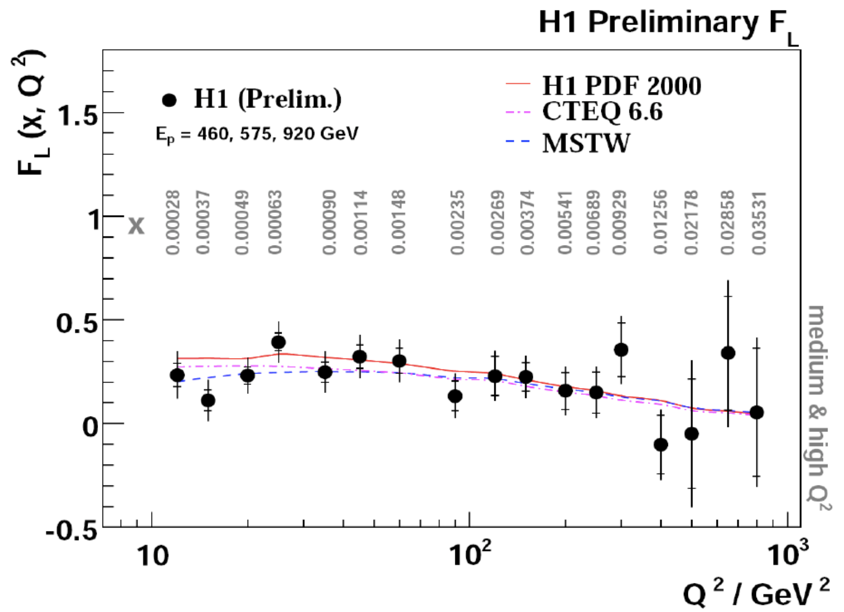


EIC: most precise measure of gluon densities

Recent progress – direct F_L measurements from HERA

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

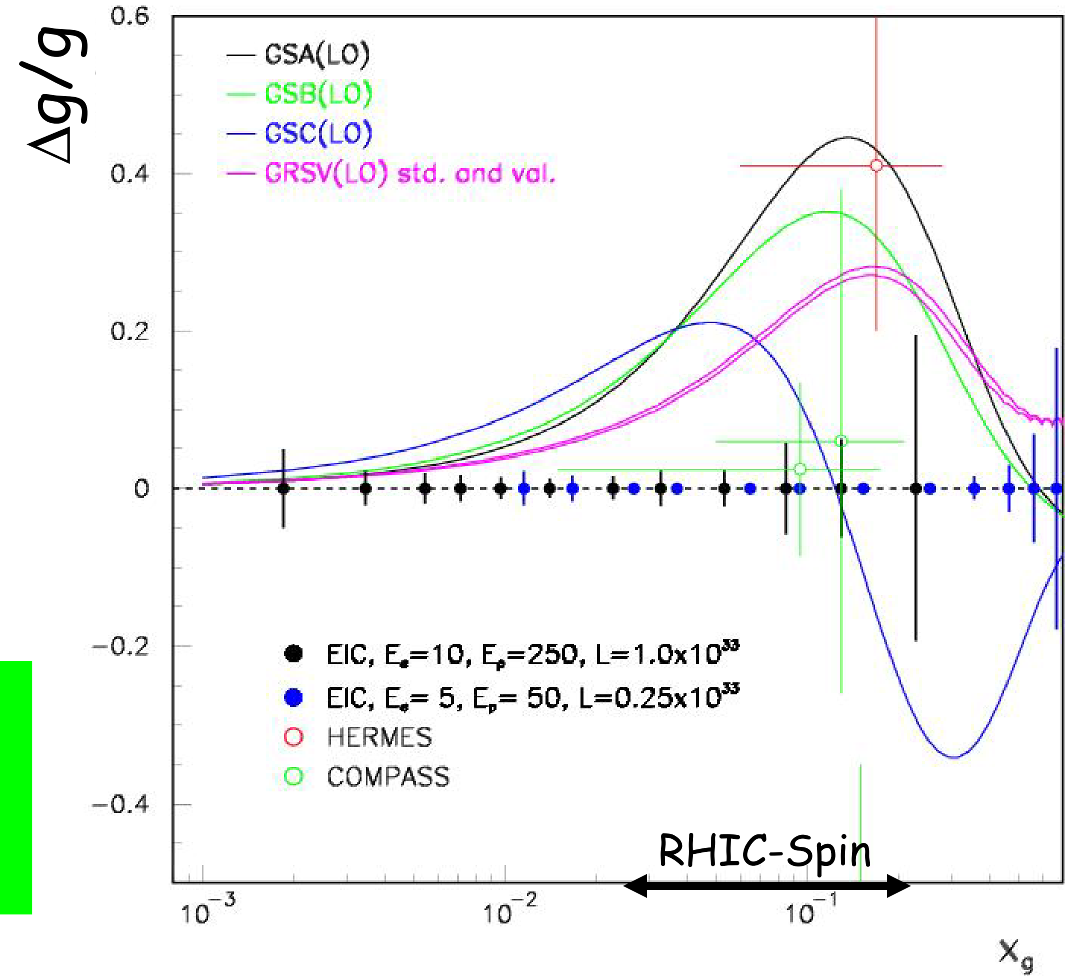




EIC – an F_L factory

Gluon Contribution to the Proton Spin

Projected data on Dg/g with an EIC, via g + p → D^0 + X
↳ K^- + p^+



Advantage: measurements directly at fixed Q^2 ~ 10 GeV^2 scale!

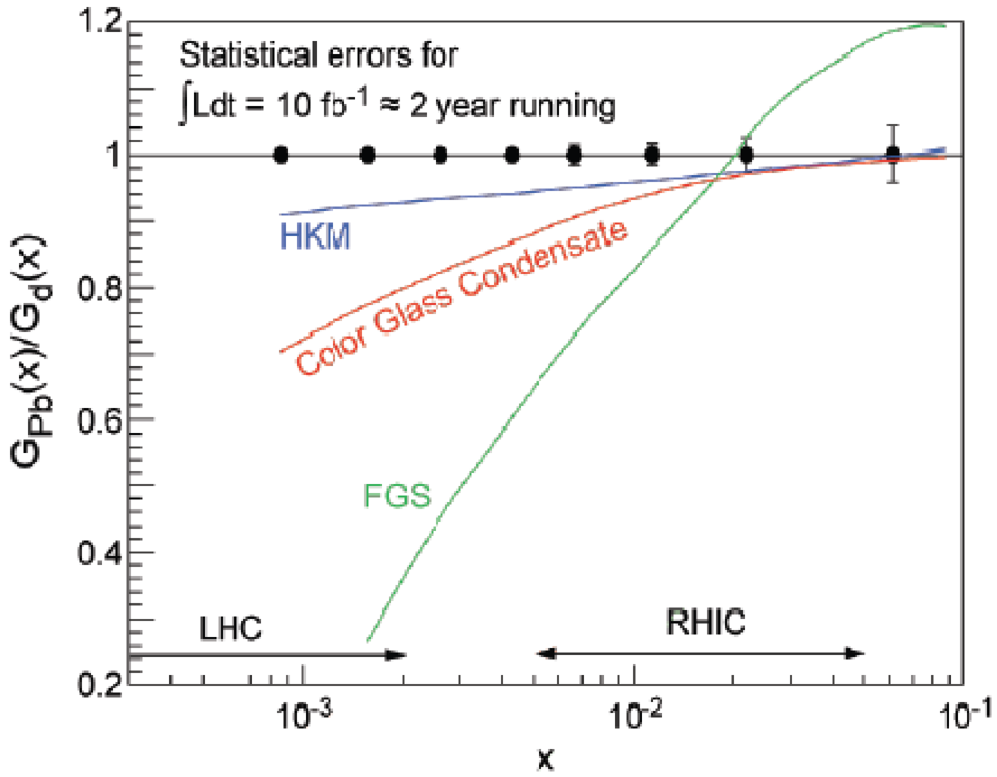
Explore gluon-dominated matter

- **What is the role of gluons and gluon self-interactions in nucleons and nuclei? NSAC-2007**
  - **The nucleus as a “gluon amplifier”**

At high gluon density, gluon recombination should compete with gluon splitting ⇒ density saturation.

Color glass condensate

- **Oomph factor stands up under scrutiny.**
- **Nuclei greatly extend x reach:** **$x_{EIC} = x_{HERA}/18$ for 10+100 GeV, Au**

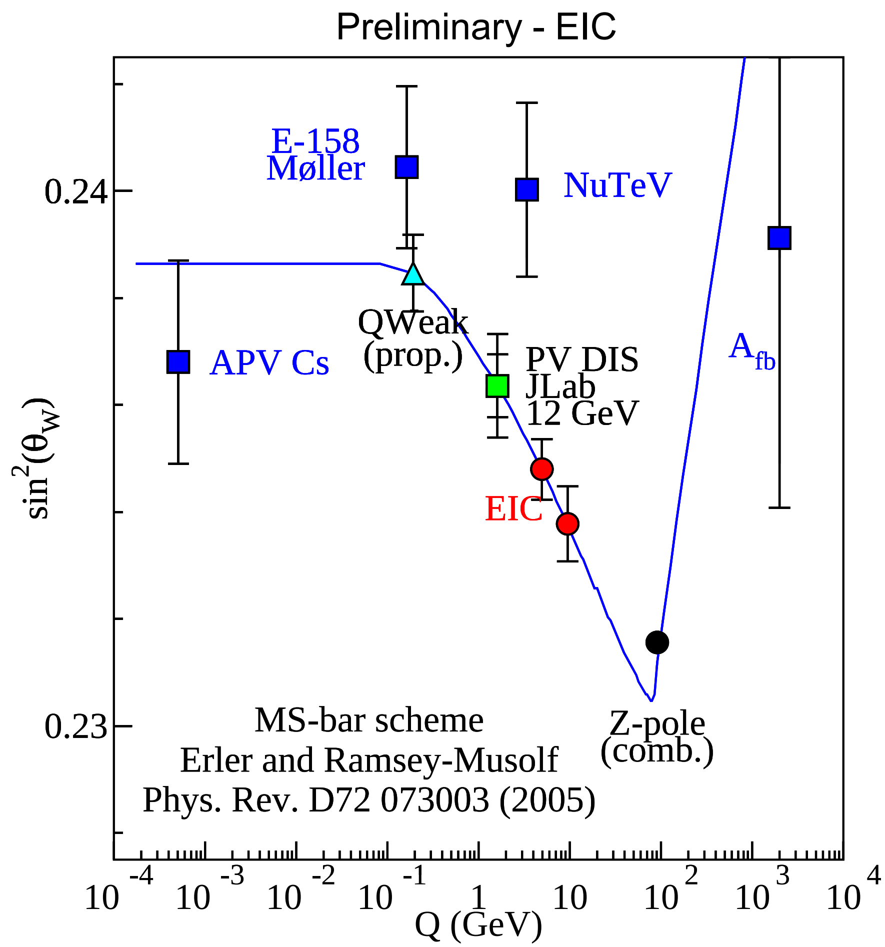


Explore the low energy precision frontier

“The task of the physicist is to see through the appearances down to the underlying, very simple, symmetric reality.”
- S. Weinberg

What are the unseen forces present at the dawn of the Universe but have disappeared from view as the universe evolved? *precision electroweak experiments*: *sin^2q_W* **, …**

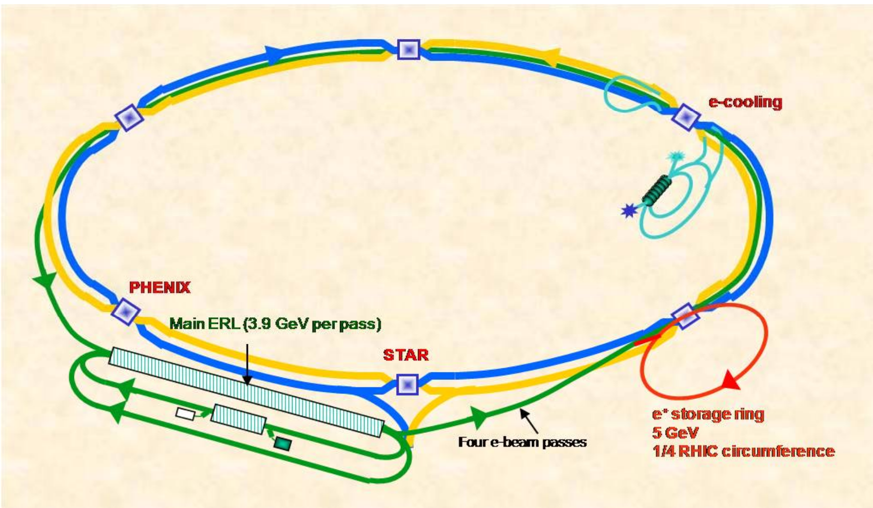
Questions for the Universe, Quantum Universe, HEPAP, 2004; NSAC Long Range Plan, 2007



R. Holt
- **5 GeV polarized e on 50 GeV unpolarized deuteron**
- **~ 500 fb^{-1} integrated luminosity**
- **full simulation required**

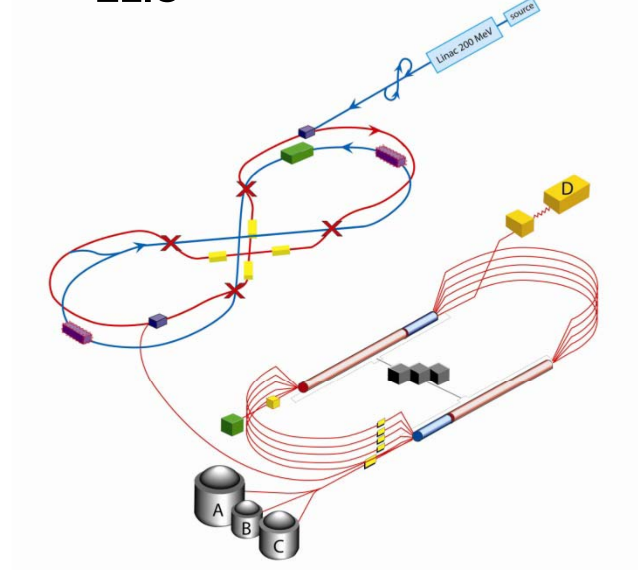
EIC accelerator concepts

eRHIC



Peak lumi ~ 2.6 x 10^{33}cm^{-2}s^{-1}

ELIC



Peak lumi ~ 6 x 10^{34}cm^{-2}s^{-1}

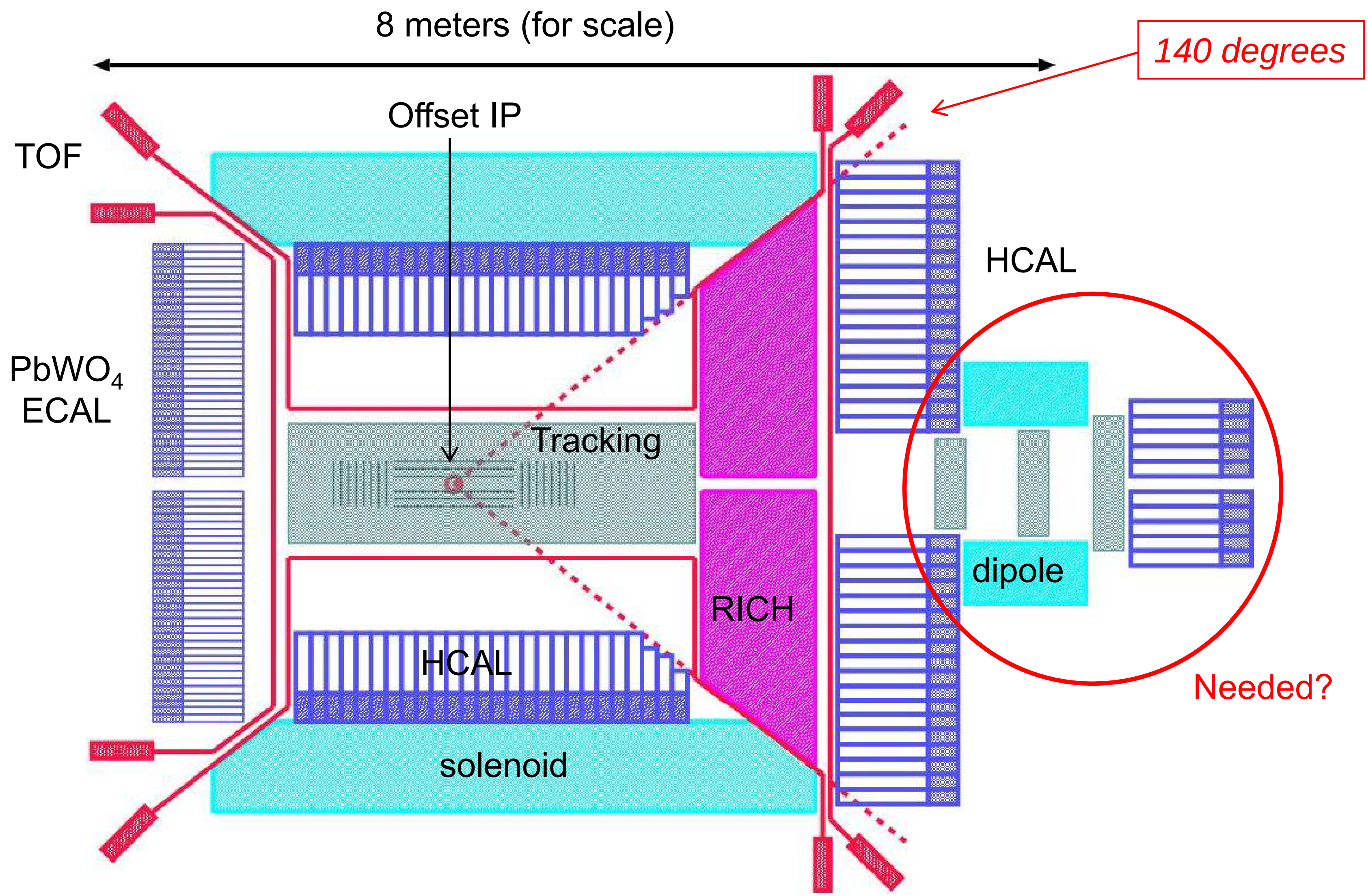
"We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron-Ion Collider."

NSAC LRP 2007

EIC accelerator R&D is underway

- **Electron beam R&D for ERL-based design**:
  - **High intensity polarized electron source**
    - **Development of large cathode guns with existing current densities ~ 50 mA/cm^2 with good cathode lifetime.**
  - **Energy recovery technology for high power beams**
    - **Multicavity cryomodule development; BNL test ERL; loss protection; instabilities.**
  - **Development of compact recirculation loop magnets**
    - **Design, build and test a prototype of a small gap magnet and its vacuum chamber.**
  - **Evaluation of electron-ion beam-beam effects, including the kink instability and e-beam disruption**
- **Ion beam R&D**:
  - **Polarized ^3He production (EBIS) and acceleration**
  - **Increasing number of bunches, number of ions/bunch in RHIC**
- **Cooling:**
  - **Cooling of ion beam**

Emerging detector concept



Issues: 1) would need to change (E)TOF with HTCC if 500 MHz operation
2) need add'l Particle Id. (RICH/DIRC) for large angle π/K/p?
3) conflict with charm measurements that require low central field?

A Detector for Forward Physics at eRHIC

Feasibility Study

I. Abt, A. Caldwell, X. Liu, J. Sutiak

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

July 20, 2004

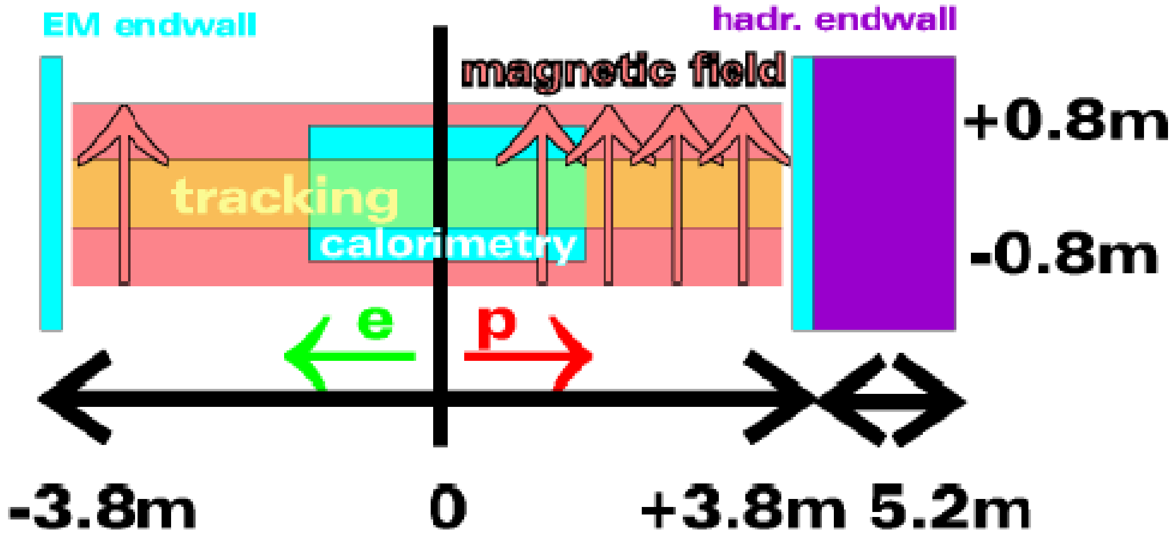


Figure 6: Conceptual layout of the detector with a 7m long dipole field and an interaction region without machine elements extending from -3.8 m to +5.2 m

Staging of EIC

- Can one consider an initial stage of EIC where
  - cost is a fraction of that of full EIC
  - it can be realized on a significantly faster timescale than the full EIC?
- It must have a strong science case, i.e. it must open up a dramatic new capability.
- It should naturally evolve to the full EIC.
- Considerations include
  - luminosity ~ 3×10^{32} $cm^{-2}s^{-1}$
  - center of mass energy ~ 4 Gev $e^{\pm}$ on 250 GeV RHIC
  - polarized nucleon and nuclear beams
- Staged EIC concepts being developed at both BNL and JLab

Summary

- The Electron-Ion Collider is the next generation accelerator concept for the study of QCD in the U.S.
- In Europe, LHeC as a future evolution for CERN and ENC@GSI/FAIR are under discussion.
- It is essential to lay the foundations for the next U.S. nuclear physics long range plan exercise in ~ 2013.
  - It will be necessary to broaden and deepen the science case.
  - Strong, international support is required.
  - It is highly desirable to have a single EIC accelerator design by ~ 2012.
- Study of staged eRHIC, ELIC scenarios is underway.
- R&D on the accelerator and detector must have a high priority.
- While the path to the full EIC is uncertain, considerable progress has been made by a determined group of highly motivated people.
- We look forward to the next meeting at Stony Brook University, New York on January 10-12, 2010

The International Picture

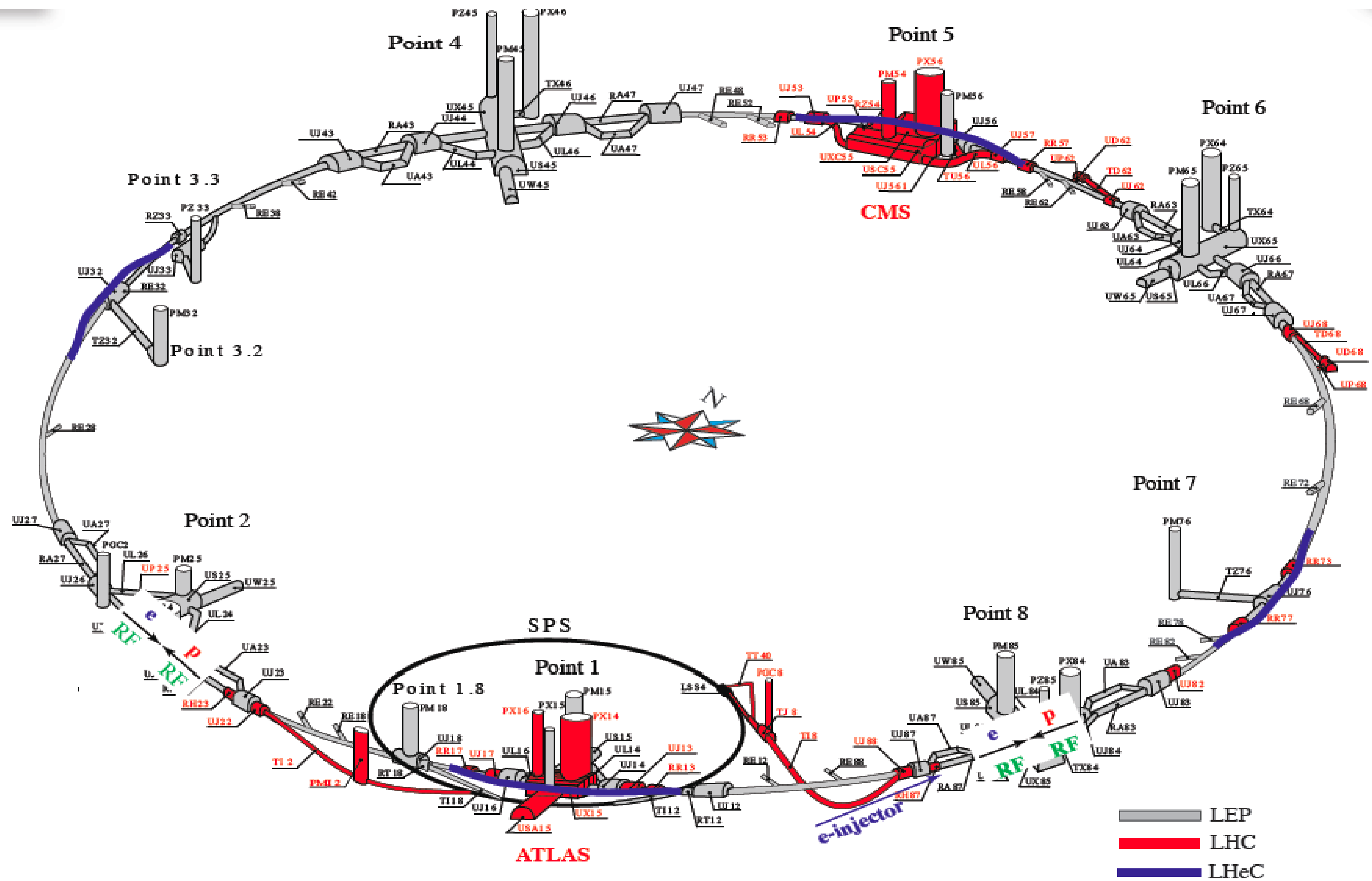
QCD a major research focus on three Continents

- J-PARC 50 GeV proton beams
- JLAB@12 GeV starts ~ 2013
- RHIC lumi upgrade until ~ 2015
- FAIR in ~ 2015

FOUR EIC concepts

- **eRHIC at BNL**
- **ELIC at JLab**
- **L**arge **H**adron **e**lectron **C**ollider at the LHC
- **ENC at GSI/ FAIR**

LHeC



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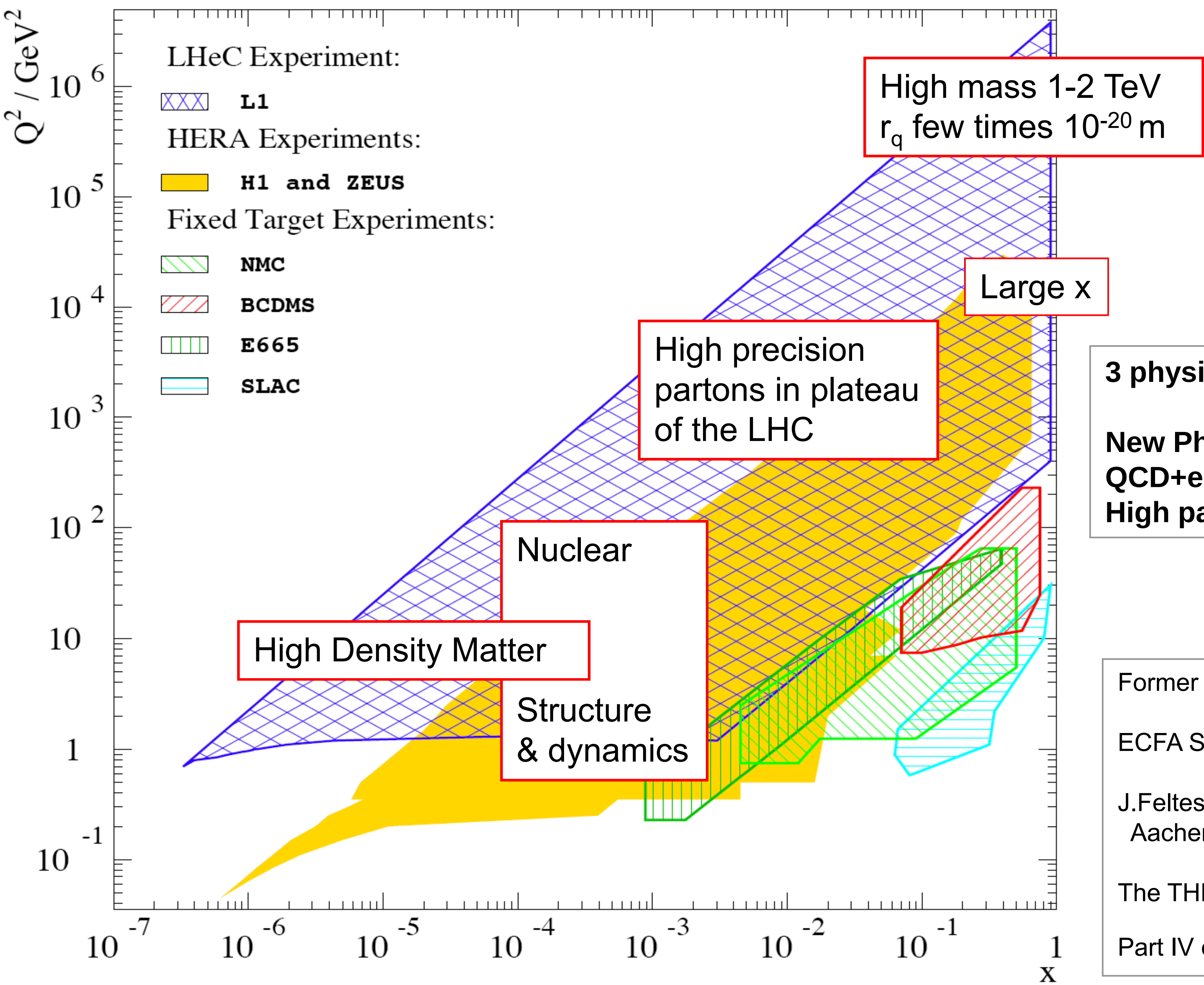


3 physics subjects:

New Physics
QCD+electroweak
High parton densities

Former considerations:

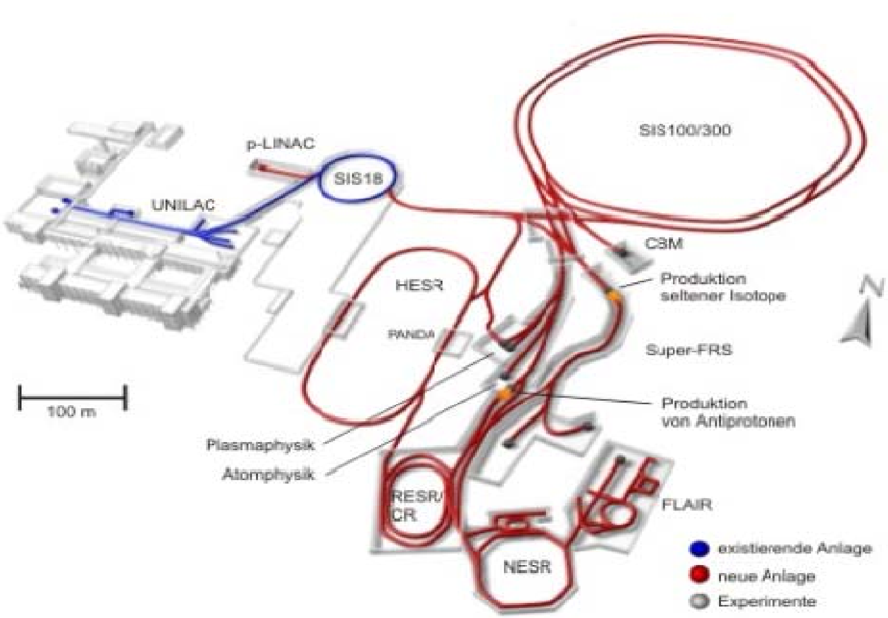
ECFA Study 84-10

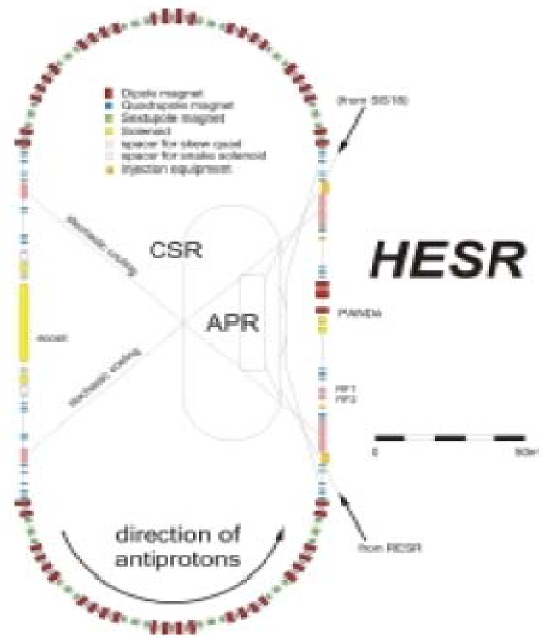
J.Feltesse, R.Rueckl: Aachen Workshop (1990)

The THERA Book (2001)&

Part IV of TESLA TDR

ENC@ FAIR





Q^2-Range: $1 < Q^2 < 100\,GeV^2$

HERMES: $s = 58\,GeV^2$, $\mathcal{L} \approx 10^{31} cm^{-2} s^{-1}$

COMPASS: $s = 320\,GeV^2$,$\mathcal{L}_{eff} \approx 10^{31} cm^{-2} s^{-1}$

Wanted: $s \approx 100 - 200$,$\mathcal{L} \approx 10^{33} cm^{-2} s^{-1}$

Energy. between HERMES and COMPASS ,$s = 60 - 300$

Luminosity 100 times HERMES or COMPASS, $\mathcal{L} = 100 \times 10^{31} = 10^{33} cm^{-2} s^{-1}$