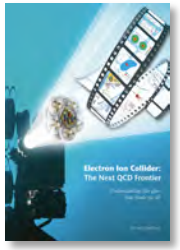
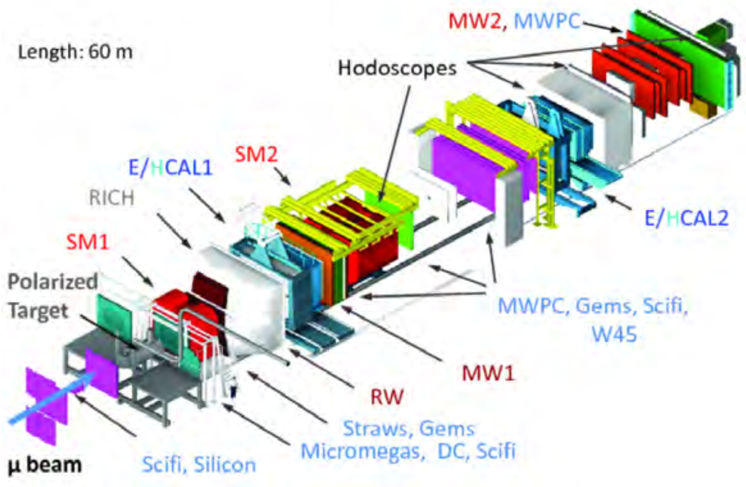
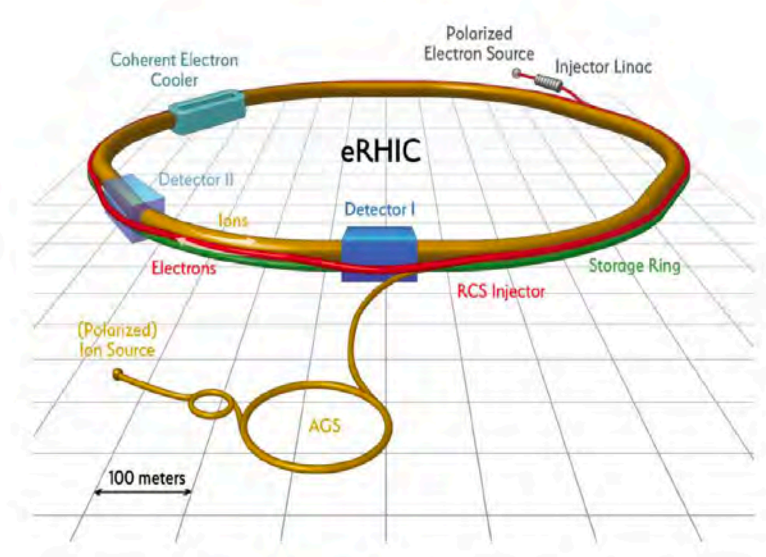
Center for Frontiers in Nuclear Science



From Fixed Target Muon DIS to the Polarized Electron Ion Collider

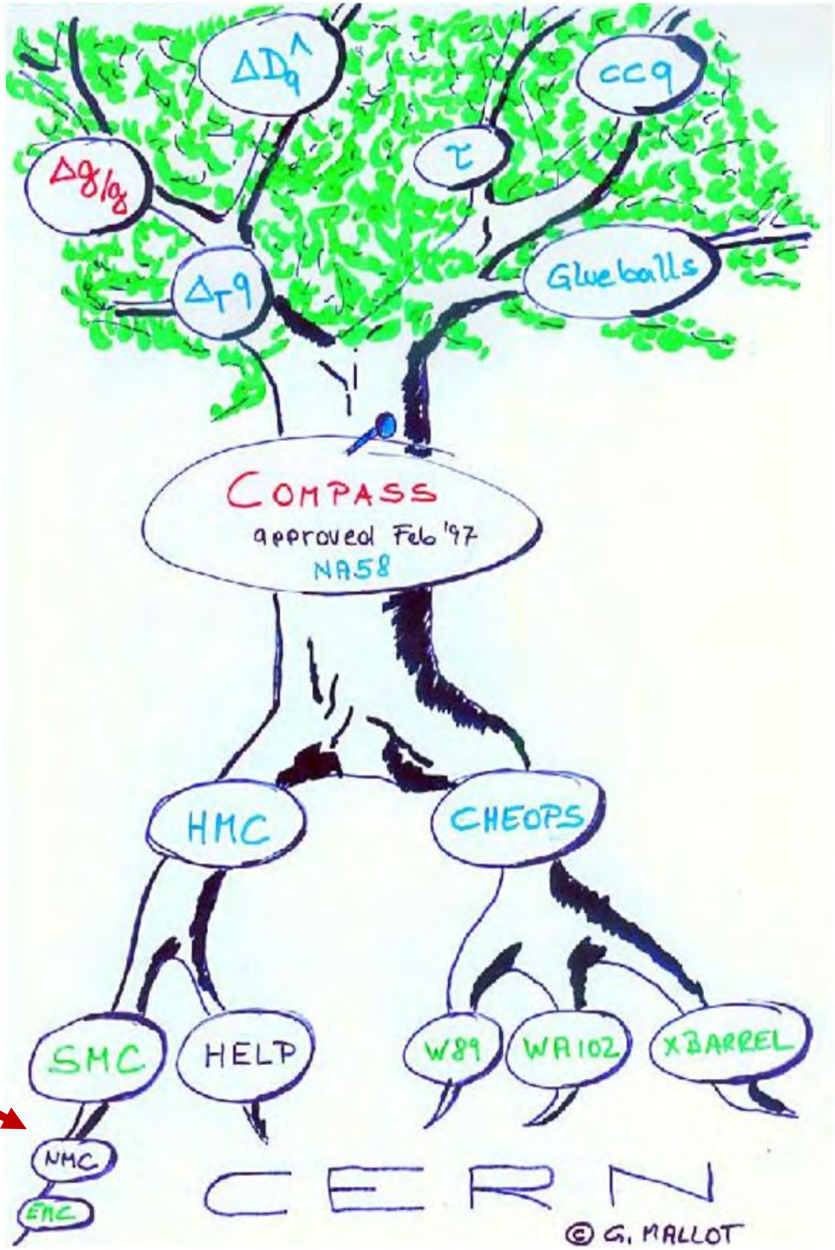
A Q^2 evolution of Gerd's Science





Stony Brook University
Abhay Deshpande
BROOKHAVEN NATIONAL LABORATORY

GERHARD K. MALLOT 'S SCIENCE



- Gerd's own view and artistic opinion of Gerd's science

Gerd's science timeline, started just after EMC

NMC
1986-1990

Precision nuclear (longitudinal) PDFs beyond EMC

SMC
1990-1999

Precision (longitudinal) spin PDFs beyond EMC

COMPASS
1995-Present (2020)

Precision flavor PDFs
and much more

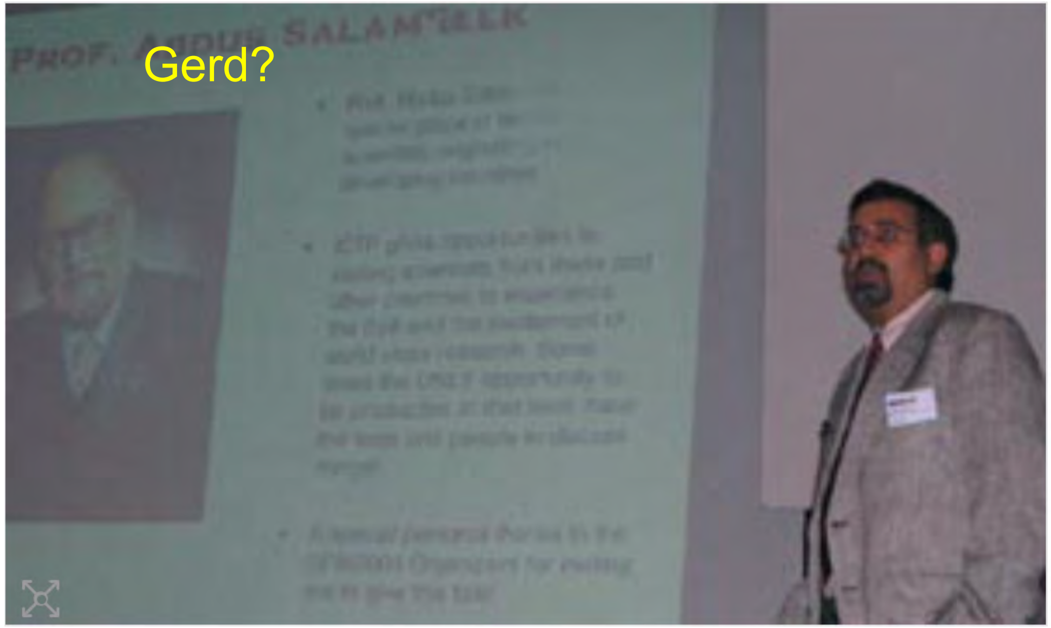
COMPASS++/AMBER
2018-??

Full exploration of 2+1 D
Flavor structure of hadrons

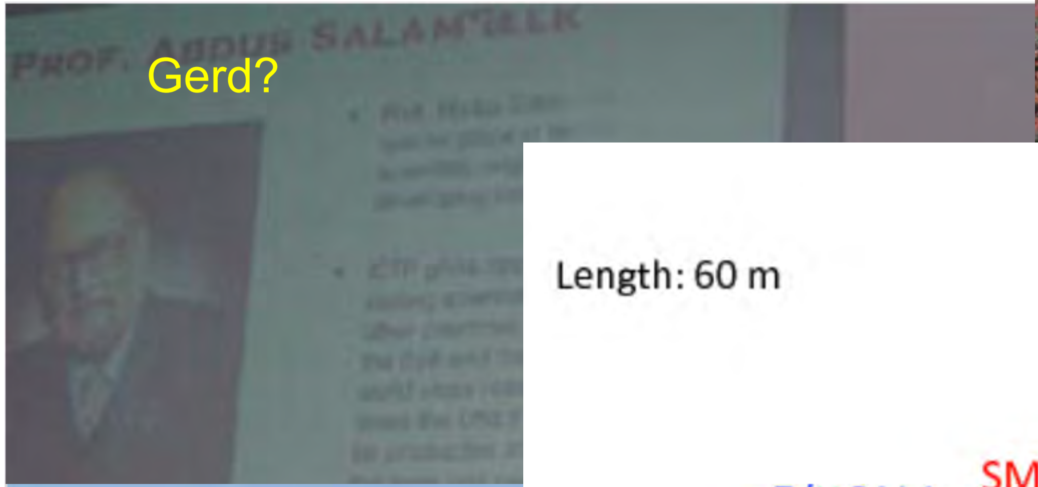
35+ years of world's best experimental studies with muons

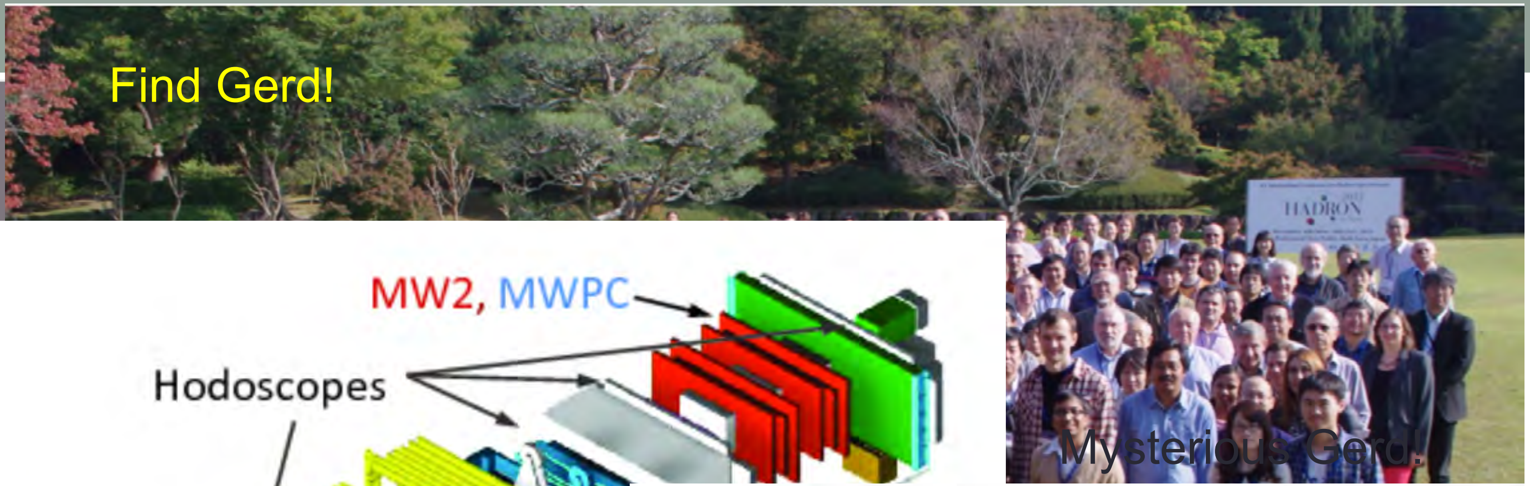
Hardly any pictures of Gerd around…

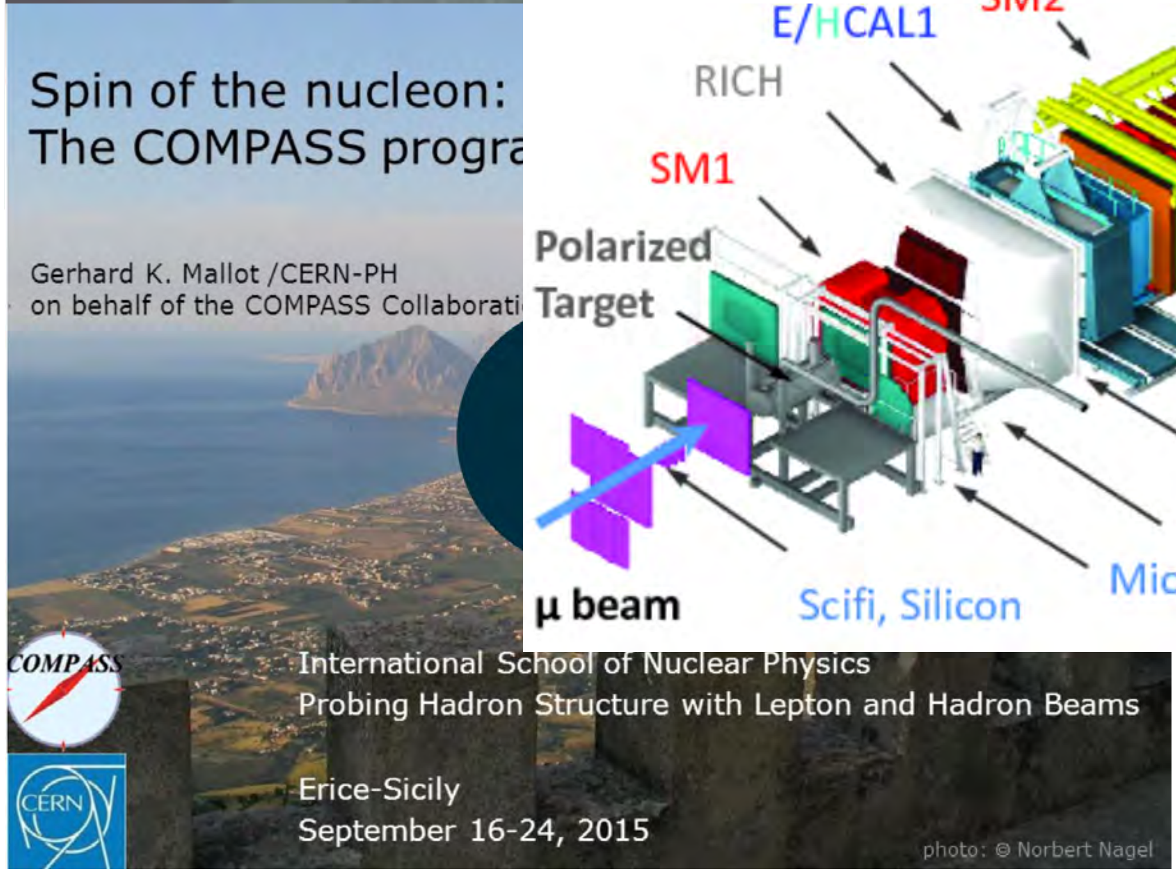
Wanted to put them with the time line of his experiments earlier.

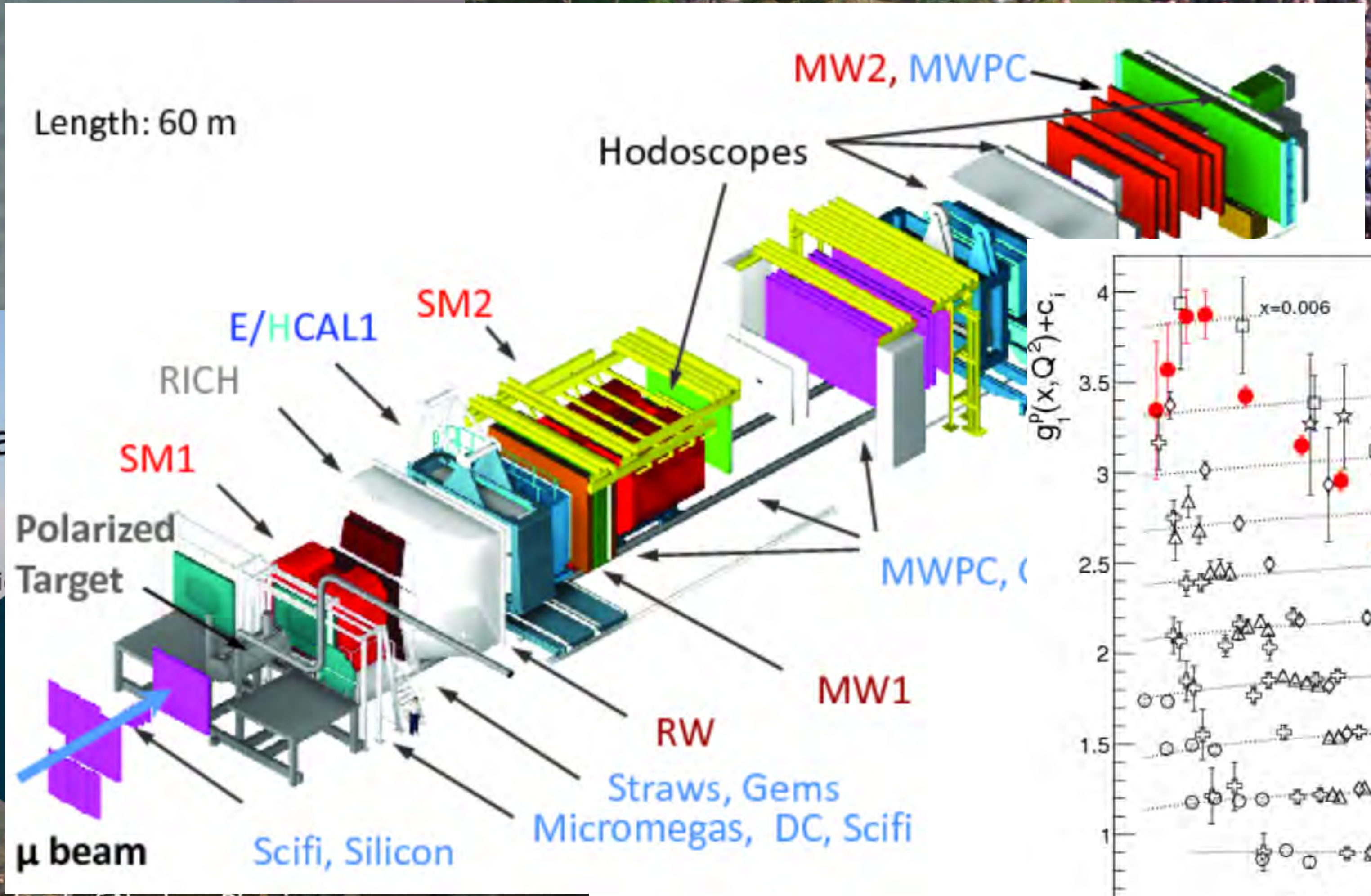


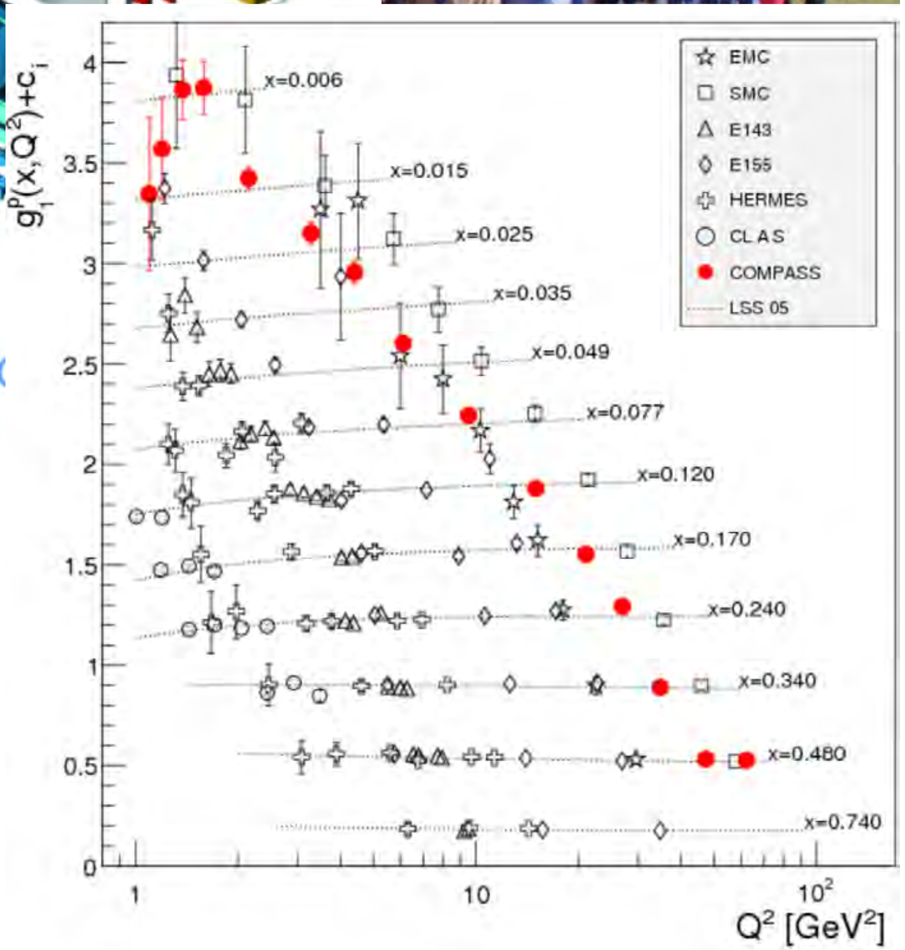
The future measurement of transversity at the FAIR facility at GSI was a hot matter of discussion, in particular between Raimondo Bertini (left) and Mauro Anselmino of INFN Torino.


PROF. ABDUS SALAM TALK
Gerd?


Find Gerd!
HADRON
Mysterious Gerd!


Spin of the nucleon:
The COMPASS progra
Gerhard K. Mallot /CERN-PH
on behalf of the COMPASS Collaborati
COMPASS
CERN
International School of Nuclear Physics
Probing Hadron Structure with Lepton and Hadron Beams
Erice-Sicily
September 16-24, 2015
photo: © Norbert Nagel

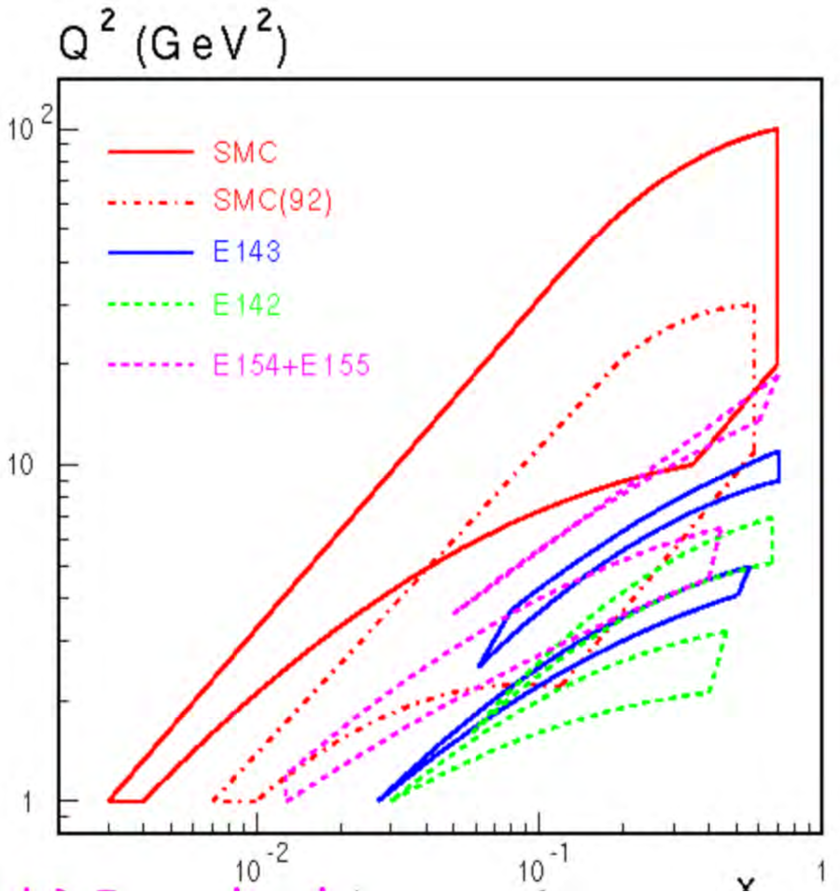

Length: 60 m
MW2, MWPC
Hodoscopes
E/HCAL1
SM2
RICH
SM1
Polarized
Target
MWPC, (
MW1
RW
Straws, Gems
Micromegas, DC, Scifi
μ beam
Scifi, Silicon


$g_1^p(x,Q^2)+c_i$
Q^2 [GeV^2]
EMC
SMC
E143
E155
HERMES
CLAS
COMPASS
LSS 05
x=0.006
x=0.015
x=0.025
x=0.035
x=0.049
x=0.077
x=0.120
x=0.170
x=0.240
x=0.340
x=0.480
x=0.740

Seeds of future polarized collider were sown at SMC1995-1999

SMC Physics Analysis to study low-x uncertainties

1st NLO pQCD analysis (home grown) and in collaboration with Altarelli, Ball, Forte, Ridolfi



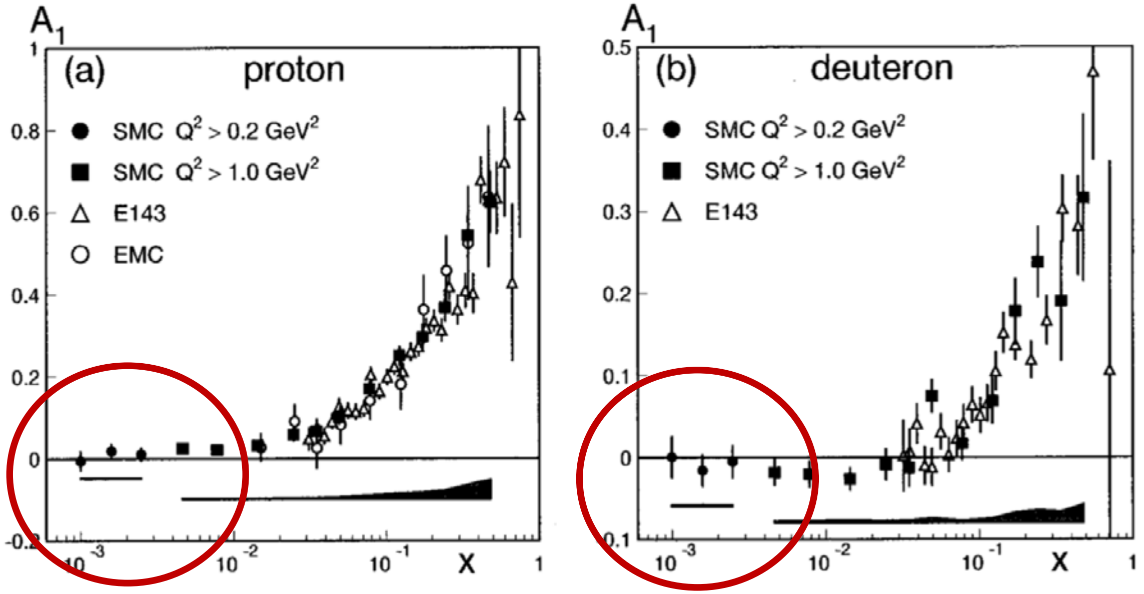


FIG. 7. The optimal set of SMC results for A_1 together with the results from other experiments. Statistical errors are shown as error bars, while the shaded bands below indicate the systematic uncertainty for the SMC measurements.

B. ADEVA *et al.* PHYSICAL REVIEW D **58** 112001

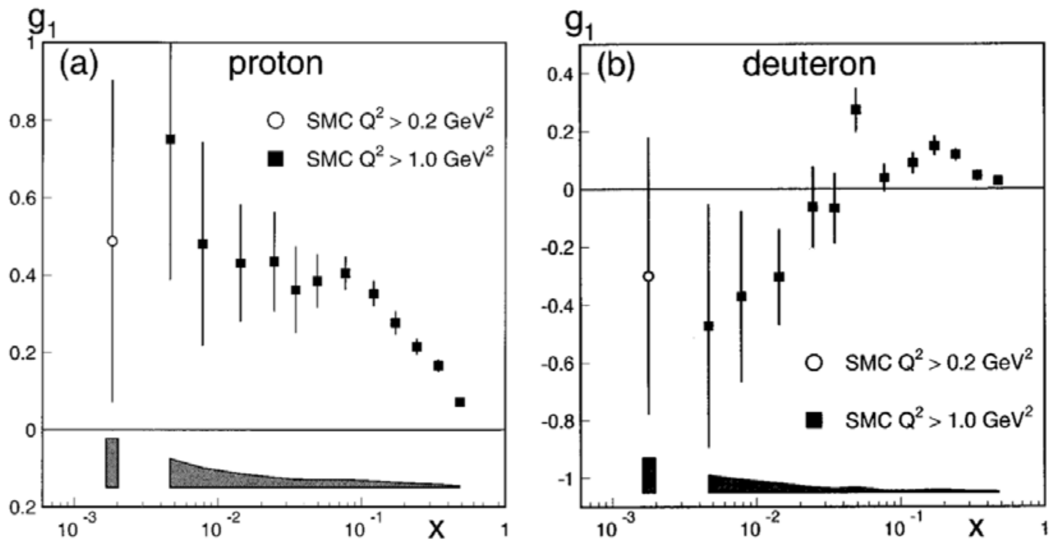
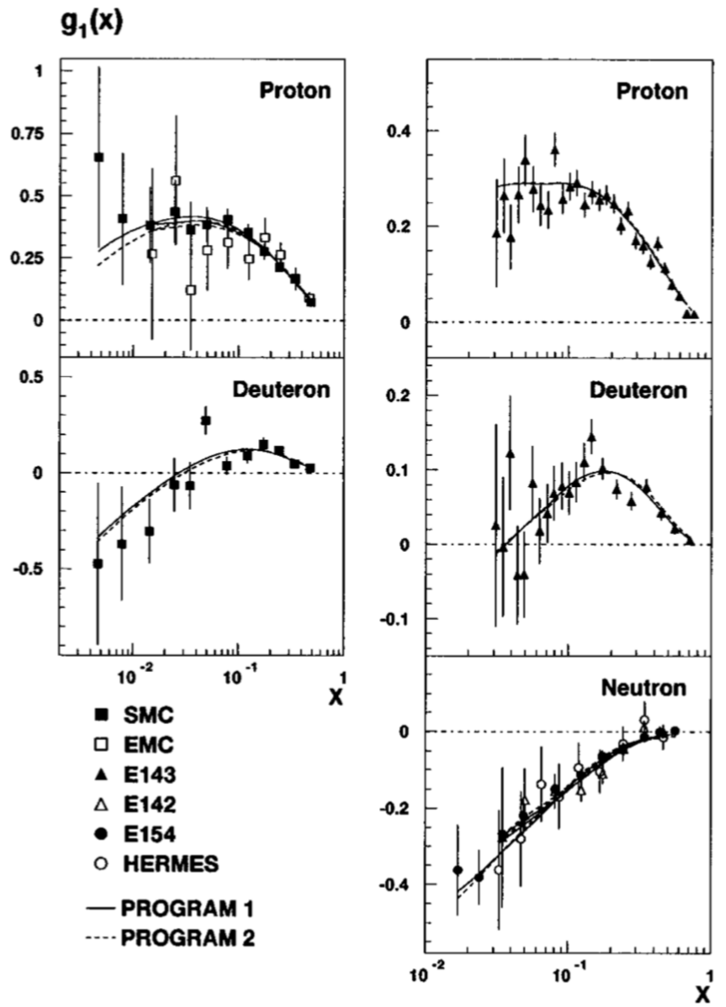


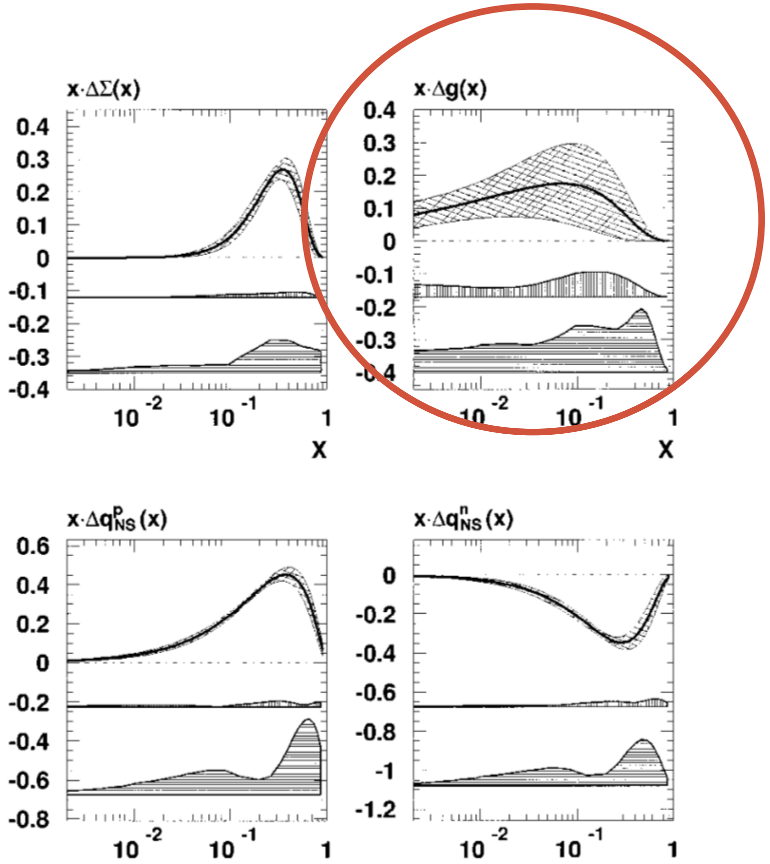
FIG. 10. The optimal set of SMC results of g_1: (a) for proton and (b) for deuteron. Statistical errors are shown as error bars while the shaded band below indicates the systematic uncertainty. The $Q^2 > 0.2$ GeV^2 result was obtained by combining the lowest three A_1 bins.

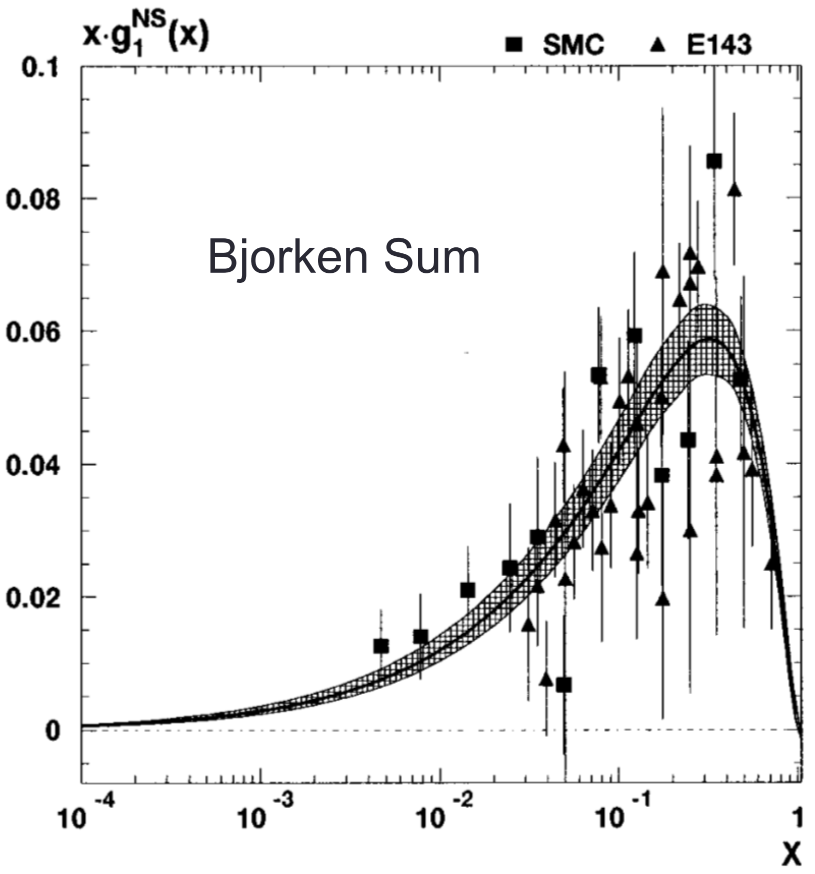
SMC Final results 1998

SMC Final results 1998

PHYSICAL REVIEW D 58 112002

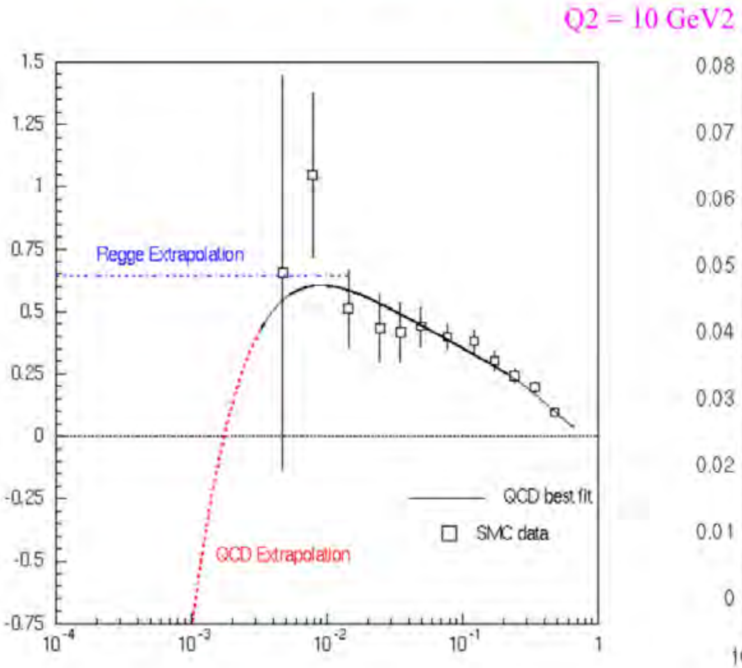


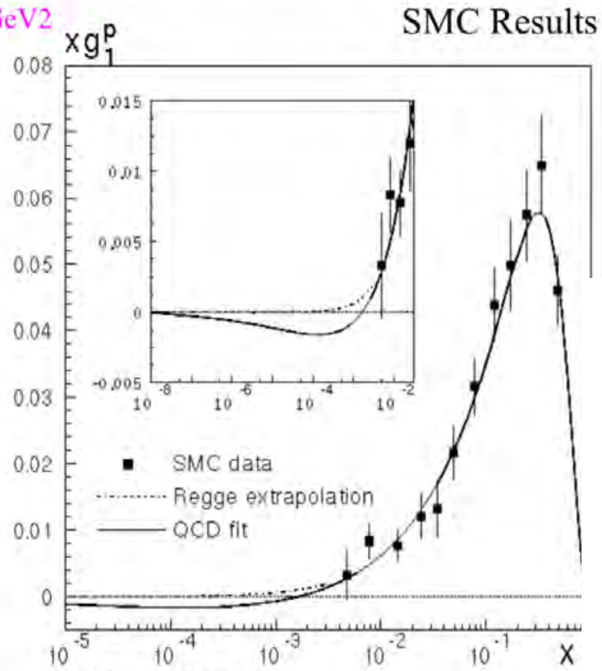




Also determined Alpha_S, but sensitivity due to polarized or unpolarized data? Gerd's important observation. Altarelli later commented on it in his own paper.

Lack of low x data… consequences





- Regge extrapolation:

$$\int_0^{0.003} g_1^p(x, Q_0^2)dx = 0.002 \pm 0.00$$

- QCD fit extrapolation:

$$\int_0^{0.003} g_1^p(x, Q_0^2)dx = -0.011 \pm 0.01$$

$$g_1(x \to 0) \propto x^{\alpha} \quad \text{as } 0 < \alpha < 0.5$$

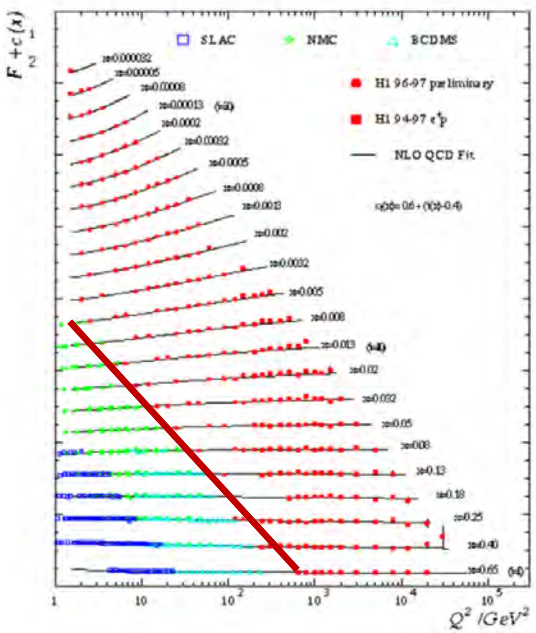
Regge/QCD

In these discussions, while many focused on the low-x extrapolations (only), Gerd focused on whether the low-x asymmetries being measurable. Worry about systematics etc.

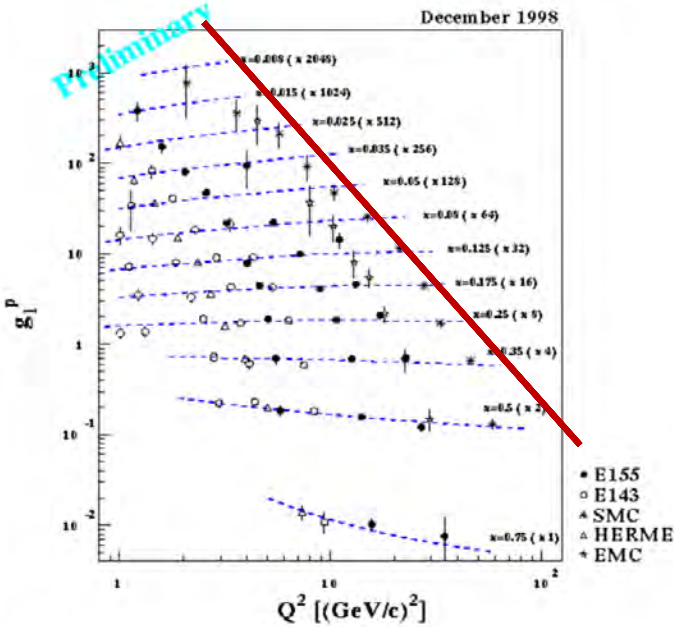
Seeds for a **polarized collider**

How far does polarized DIS have to go!

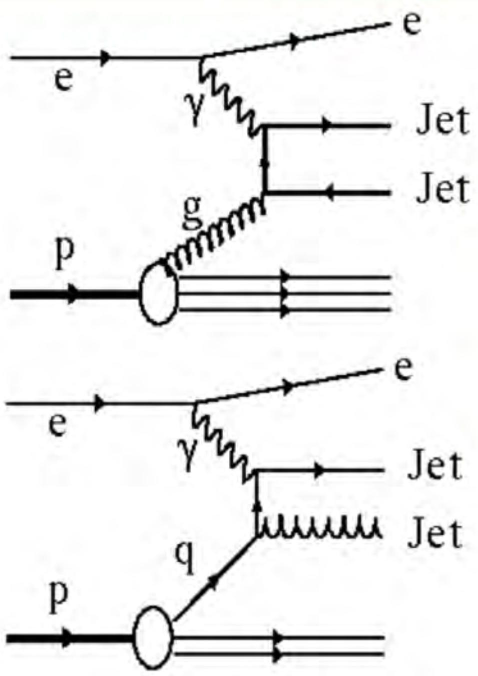
World data on F_1^p



World data on g_1^p

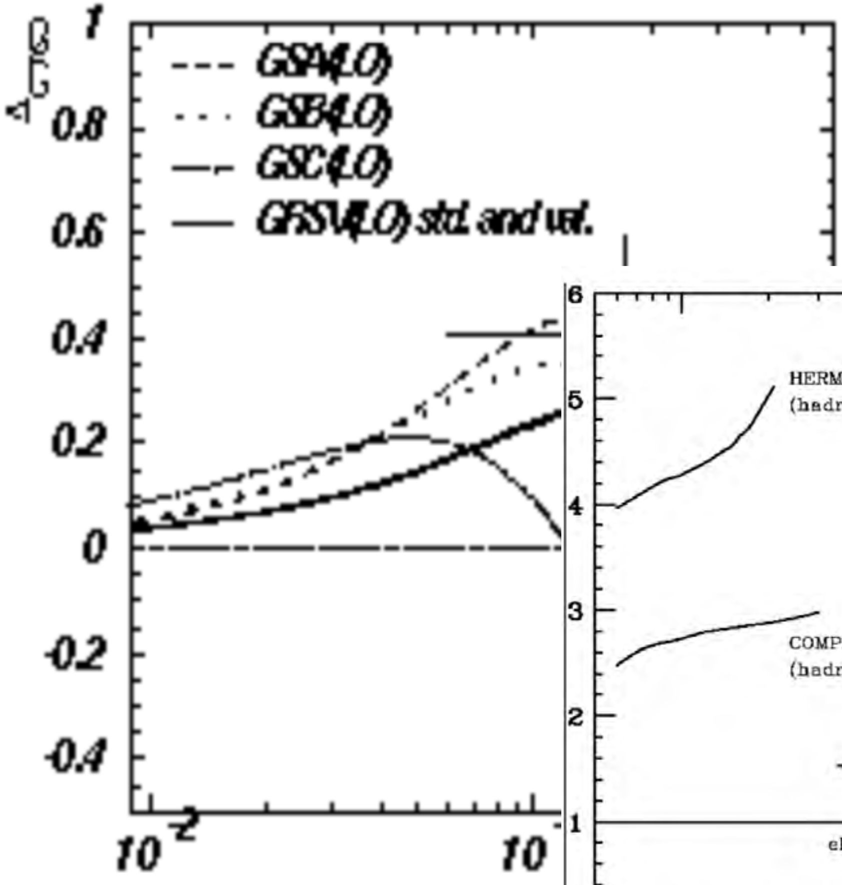


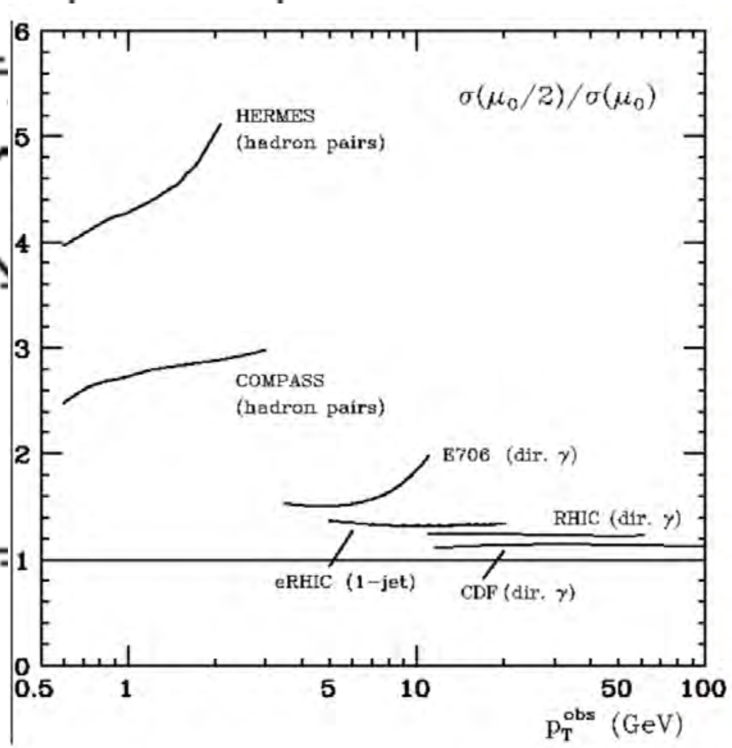
ΔG from Photon-Gluon-Fusion (PGF)



All figures from archived talks from late 1990's and early 2000's.

HERMES Results





Scale dependencies

- M. Stratmann & W. Vogelsang Proceedings of SPIN2000, Osaka, Japan.
- At low energies (such as HERMES/COMPASS) result strongly dependent on the value of the scale
- *At higher energies the scale dependence of the result significantly reduced… look at curves for eRHIC, HERA, RHIC, Tevatron…*

Need a polarized high energy collider!

Ideas for a polarized DIS collider were first discussed in this context

Input on possible use of Siberian Snakes from RHIC

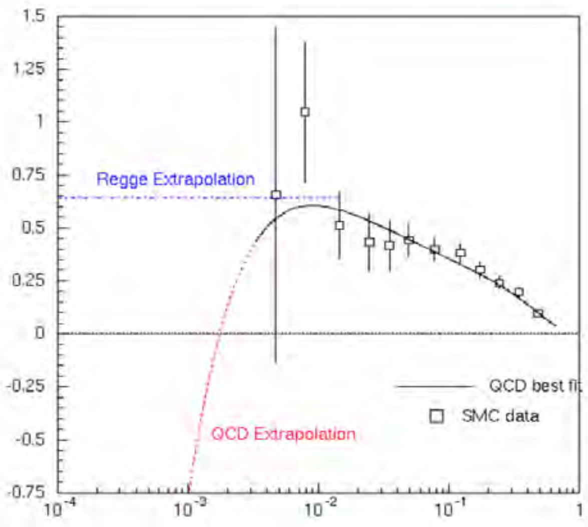
Evolved into a letter of interest in **polarized HERA**

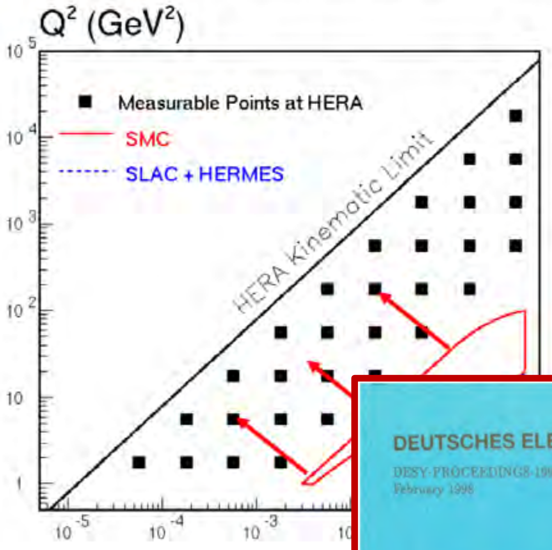
A "*competing group*" proposed an **e-Nucleus Collider at HERA**

The Legacy of **EMC** @ CERN → Moving on

Low x behavior of $g_1(p)$!

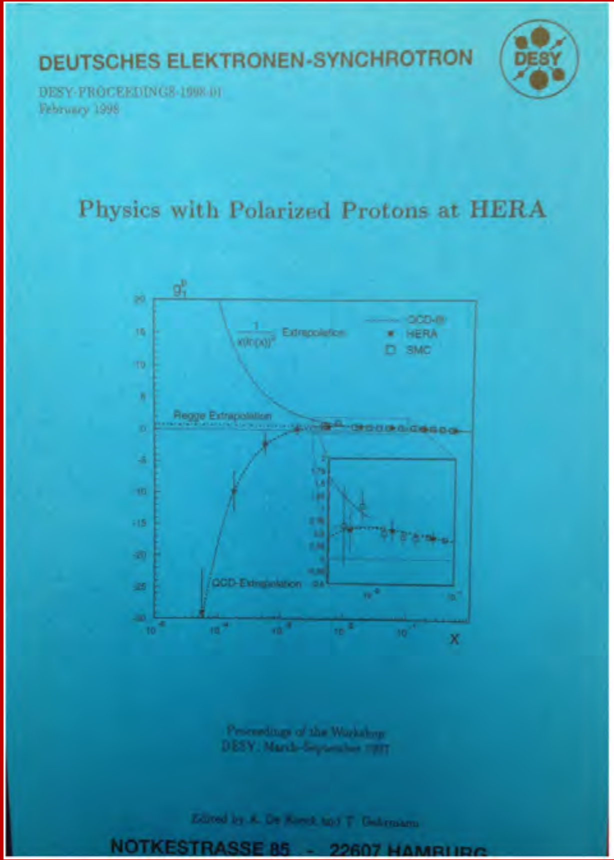
A. Deshpande & V. W. Hughes
~1995 SMC (internal) analysis meeting





Regge : $g_1(x \to 0) \sim x^{-\alpha}$; $0 < \alpha < 0.5$

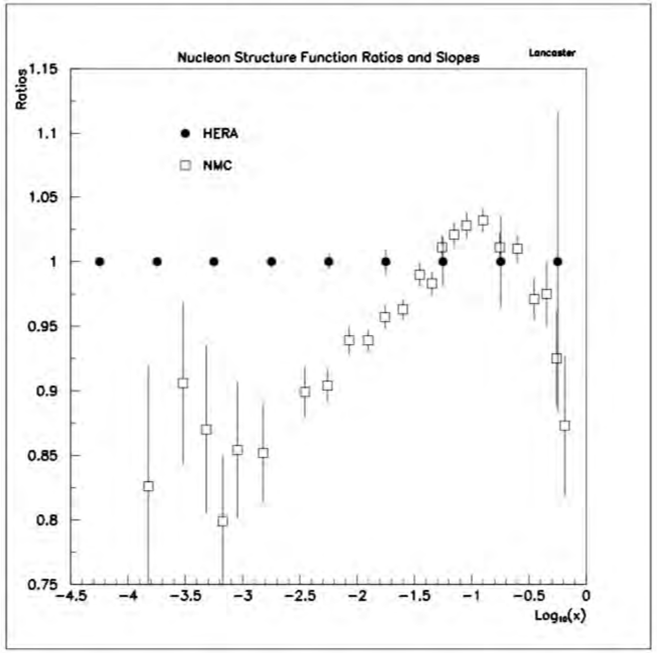
Clear need for
low x measurements!



Encouraged by
B. Wiik, R. Klanner (DESY),
&
A. Caldwell, F. Sciulli (Columbia)

The Yale group (A.D., V. Hughes & S. Dhawan) joined ZEUS and together with **A. De Roeck** & J. Feltesse (H1) and theorist **T. Gehrmann** ran the 1999 workshop on Physics with Polarized Proton Beams at HERA.

Accelerator Experts: D. Barber, G. Hoffstaedter & M. Vogt
External advisors: Mei Bai & Thomas Roser



Nuclear beams in HERA

M.Arneodo[a], A.Bialas[b], M.W.Krasny[c], T.Sloan[d] and M. Strikman[e]

Università di Torino, I 10125 and INFN Cosenza, Italy
Institute of Physics, Jagellonian University, Cracow, Poland
LPNHE, Universités Paris VI and VII, IN2P3 CNRS, Paris, France
School of Physics and Chemistry, University of Lancaster, Lancaster LA1 4YB, UK
Pennsylvania State University, University Park, PA 16802, USA

Abstract: A study has been made of the physics interest and feasibility of experiments with nuclear beams in HERA. It is shown that such experiments widen considerably the horizon for probing QCD compared to that from fr… gets. In addition there is some sensitivity to physics beyond the st… Hence the option to include circulating nuclear beams in HERA allo… of physics processes to be studied and understood.

Strikman and McLerran organized a letter signed by Bjorken, Mueller supporting e-A

Neutralized by Vernon Hughes by an identical letter for polarized e-p signed by Bjorken and Mueller

Letter to Director Wiik
From
Bjorken, McLerran and Mueller
Page 2 with their signatures could not be found

Courtesy: Mark Strikman

olumbia University in the City of New York | New York, N.Y. 10027

PARTMENT OF PHYSICS
…oretical Physics Group

538 West 120th Street
Fax: 212-932-3169

December 10, 1996

Professor Bjorn Wiik, Director
DESY
Notkestrasse 85
D-22607 Hamburg
Germany

Dear Bjorn:

We write to you concerning the future physics program at HERA. The two-volume report "Future Physics at HERA" has given a remarkably thorough presentation of the possibilities that lie ahead. In surveying that report we have been struck by the fact that one particular proposal, having nuclear beams in HERA, builds on the most impressive results of the present HERA program and extends the range and scope of these experiments in a very significant way.

The rapid increase of F_2 at small values of x observed at HERA has been one of the most important physics discoveries of the 1990's. This increase means that at the smallest available values of x, and at moderate values of Q^2, the gluon number density, $xG(x, Q^2)$ is likely between 20 and 30. While this number of gluons is remarkably large it is not yet large enough to see gross violations of the linear evolution equations of QCD due to unitarity and parton saturation. The onset of such nonlinear effects marks the boundary of a completely new regime of QCD, a regime where gluon densities become so large that the parton model and perturbative QCD break down, even while α_s is small. It is the fact that HERA may already be approaching this regime that has excited so many of us.

Of course, it would be nice to have data at even smaller values of x. While this is clearly not possible, one can get much the same effect using ions. An increase in gluon number density per unit area equivalent to a factor of 10^{-2} reduction of x can be obtained by going from a proton beam to a heavy ion beam. In addition to giving lower effective values of x, nuclear beams also furnish their own special observables. This includes an old favorite of yours, the A-dependence of diffractive vector meson electroproduction, which will help to observe the phenomenon of color transparency in a direct way. In addition, the A-dependence of the properties of rapidity gap events, as discussed in the "Future Physics at HERA" report, will be sensitive to the high parton density regime of QCD, and will greatly clarify the interpretation of this important phenomenon, already such an important specialty of the HERA program.

Investigation of these new features of QCD will help our understanding about non-

DESY had other things on their mind

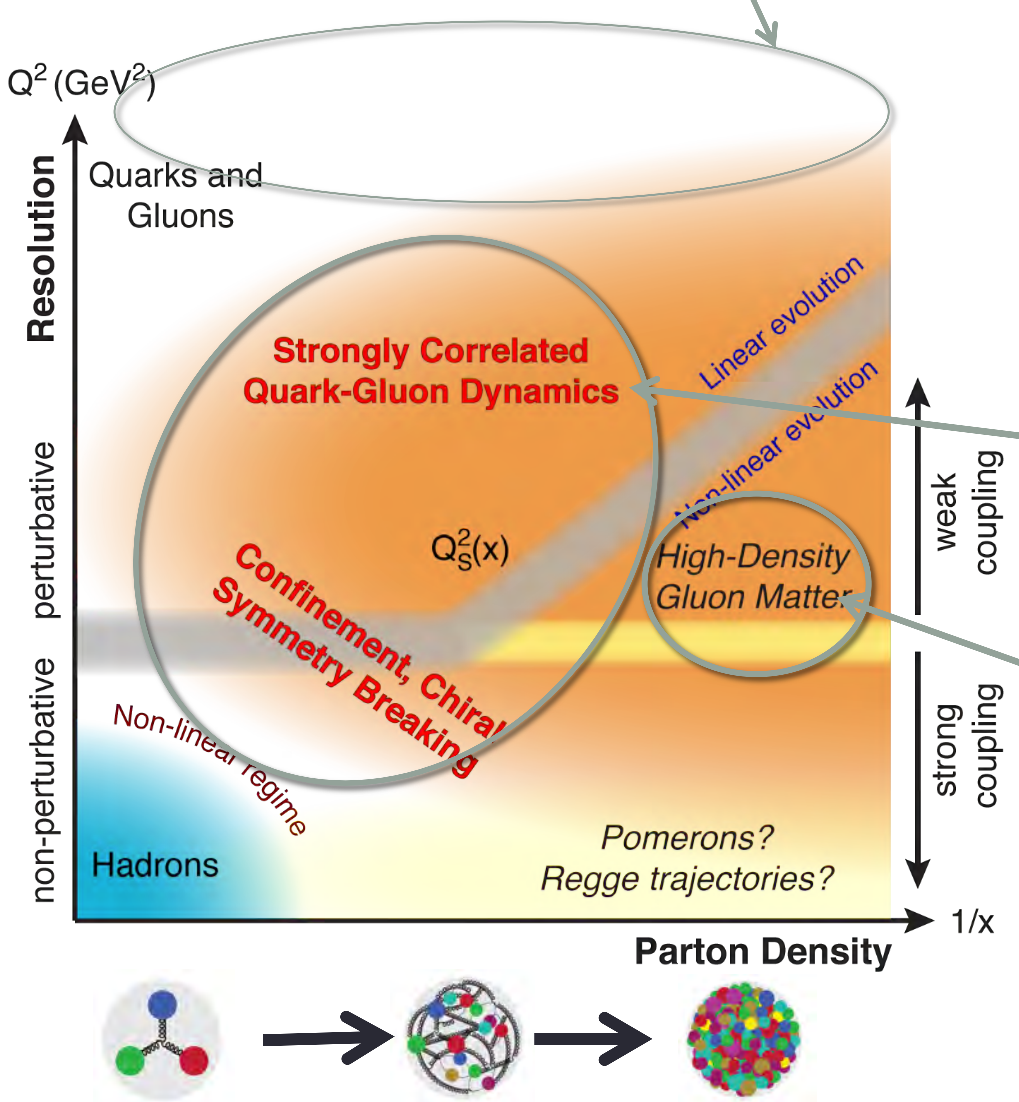
Bjorn Wiik’s untimely demise did not help either….

In search of new possibilities the proponents moved to the US

The Electron Ion Collider

QCD Landscape to be explored by a future facility

QCD at high resolution (Q^2) —weakly correlated quarks and gluons are well-described



arXiv: 1708.01527

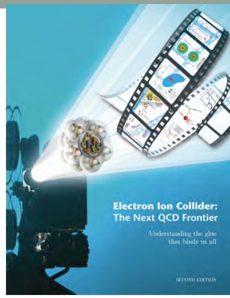
Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

Systematically explore correlations in this region.

An exciting opportunity: Observation of a new regime in QCD of weakly coupled high-density matter

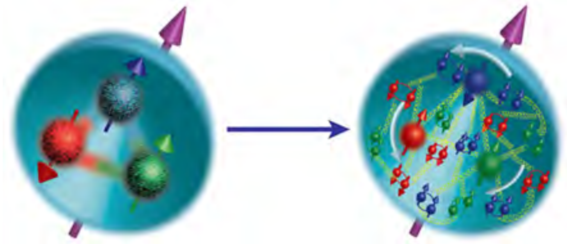
Need Precision and Control in technique
And spin whenever possible

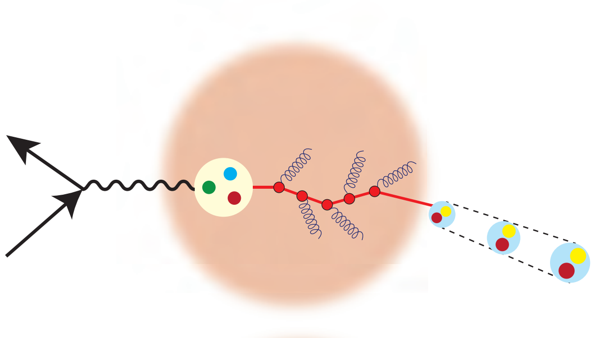
A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter



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?

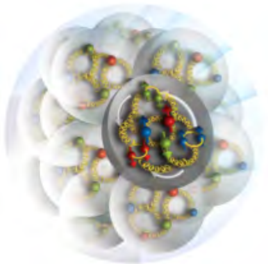




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

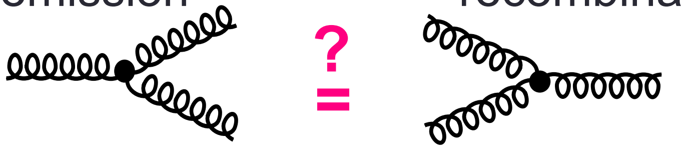
How do the confined hadronic states emerge from these quarks and gluons?

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

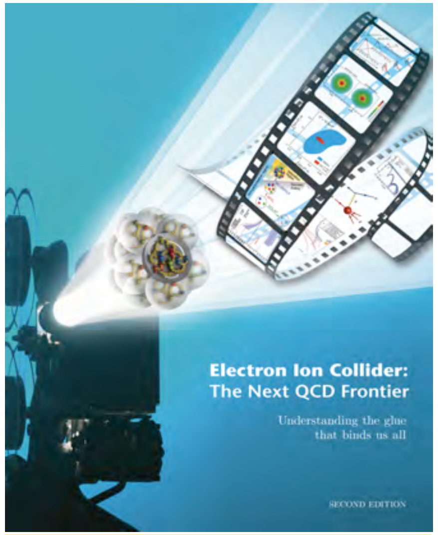
2003-2019

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

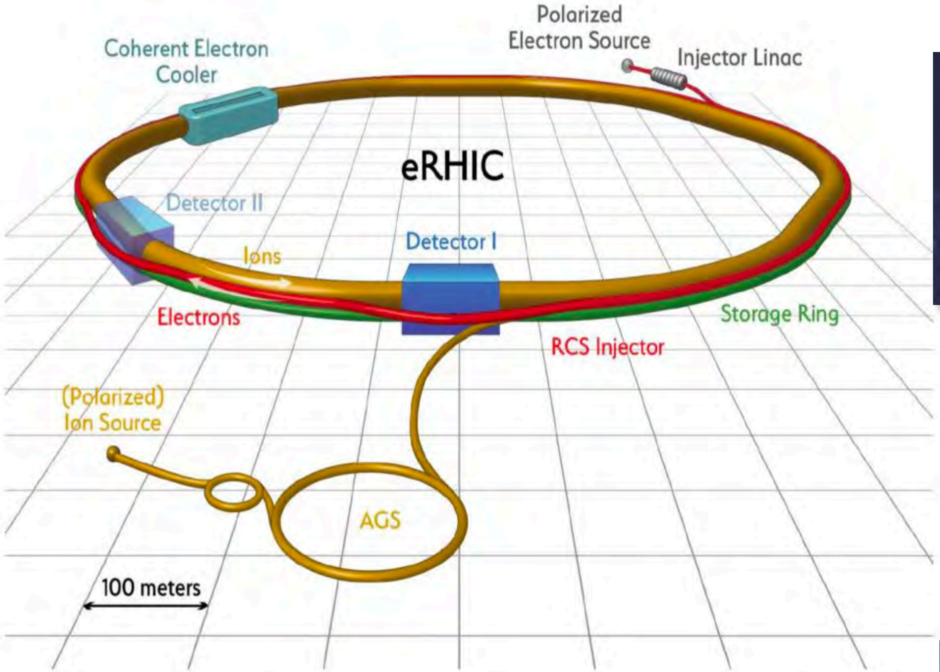
For e-A collisions at the EIC:
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

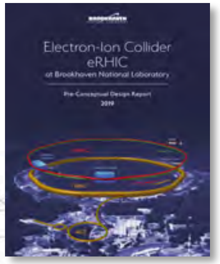
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

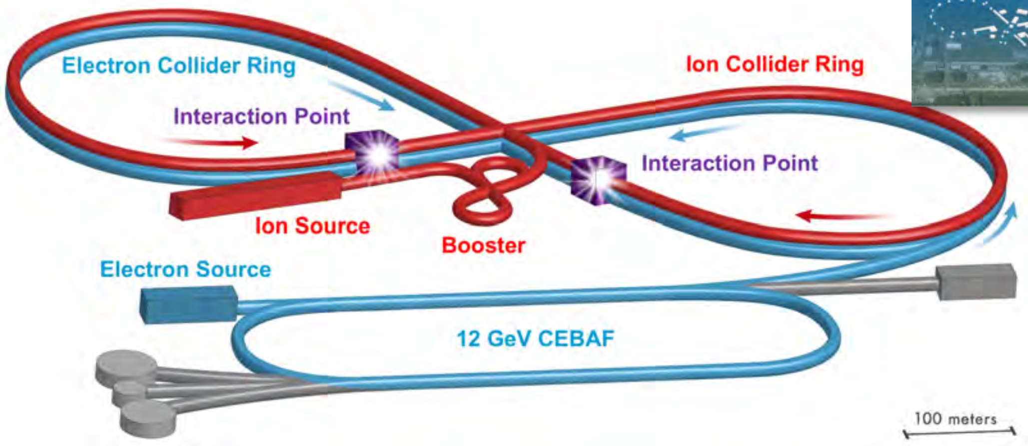
Both designs use DOE's significant investments in infrastructure



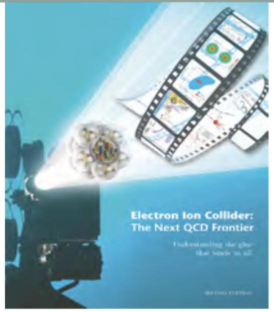
1212.1701.v3
A. Accardi et al
Eur. Phy. J. A, 52 9(2016)

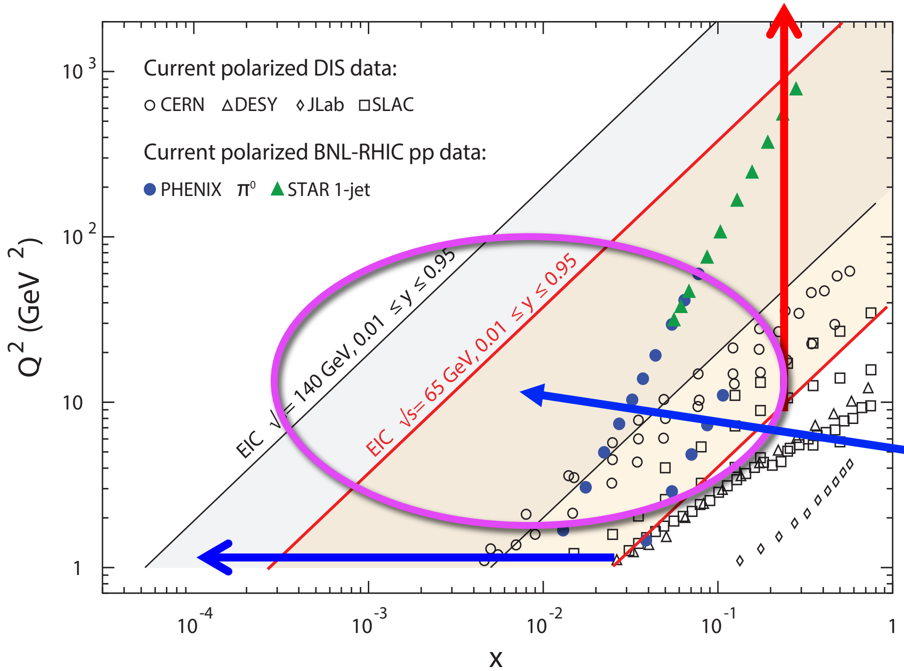






EIC: Kinematic reach & properties





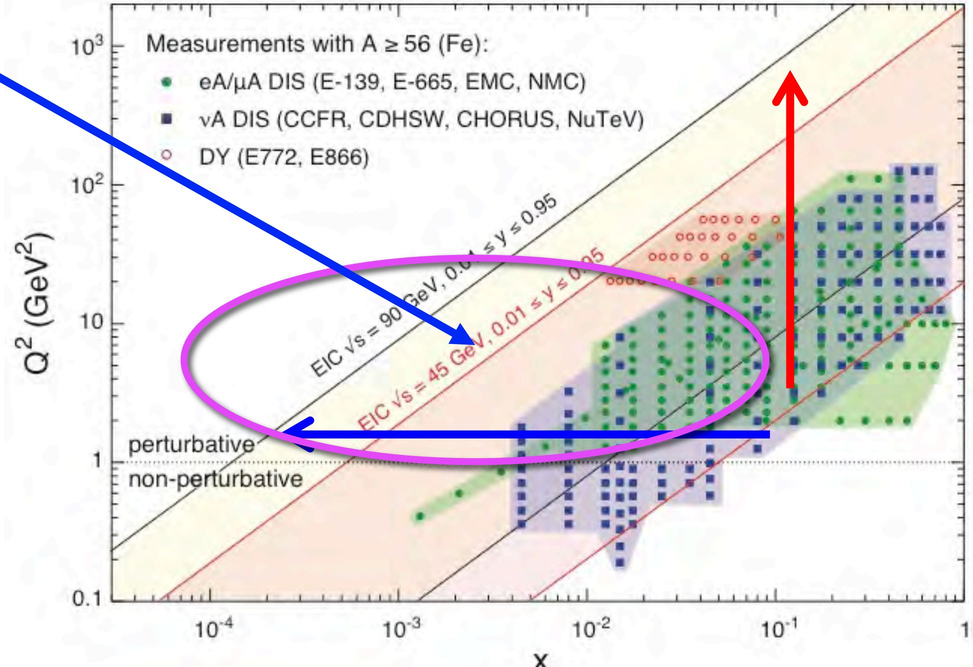
For e-N collisions at the EIC:

- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

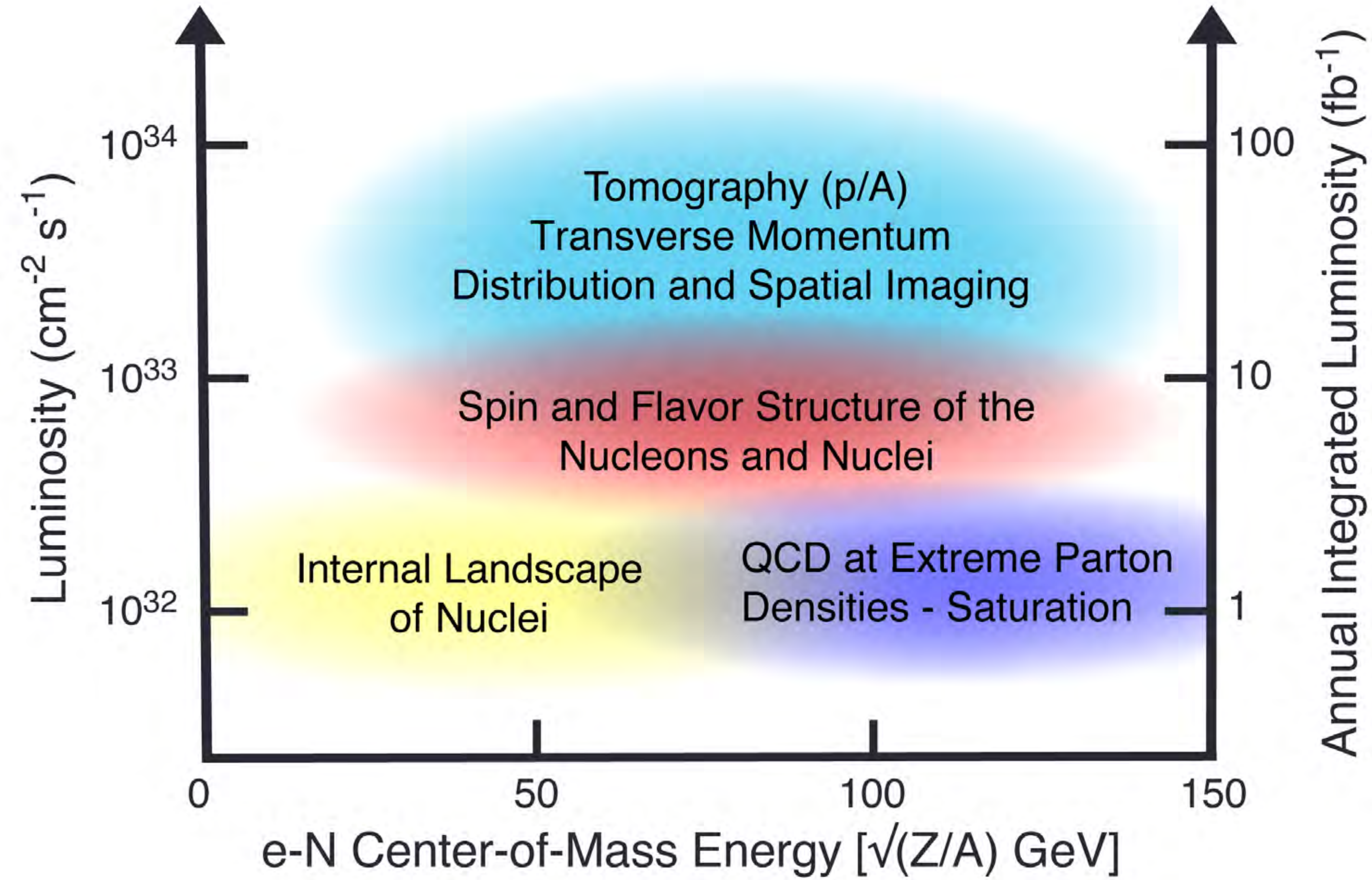
A Q^2 and x evolution of Gerd's science

For e-A collisions at the EIC:

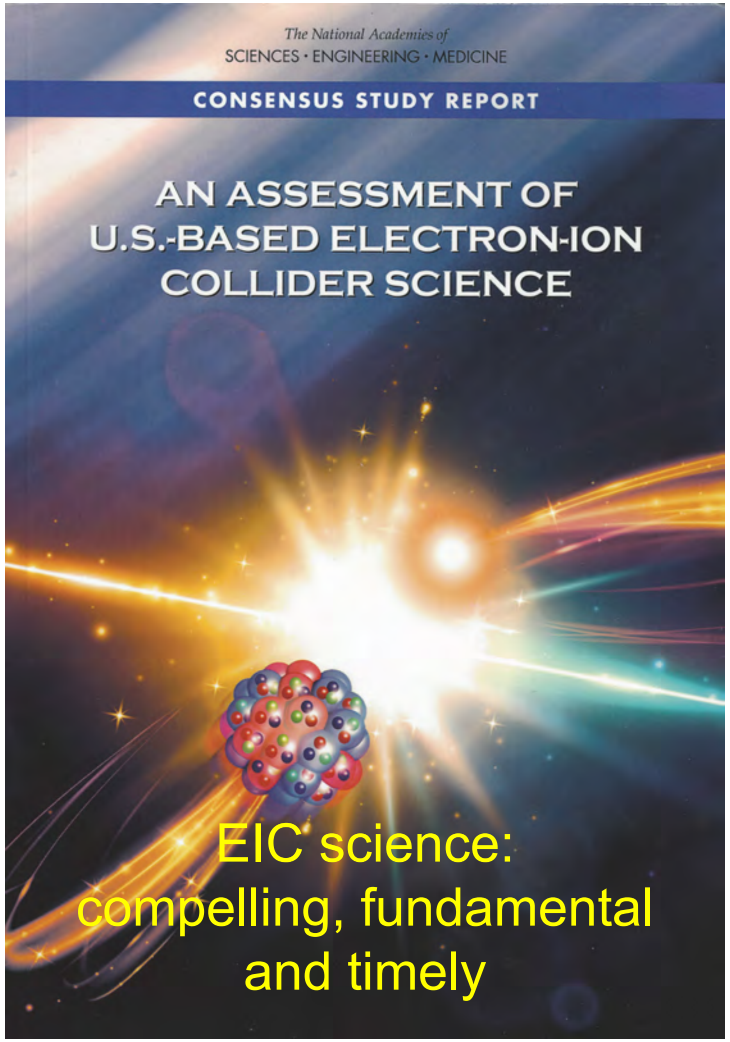
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)



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



The National Academy of Sciences, Engineering and Medicine 2018



Consensus Study Report on the US based Electron Ion Collider

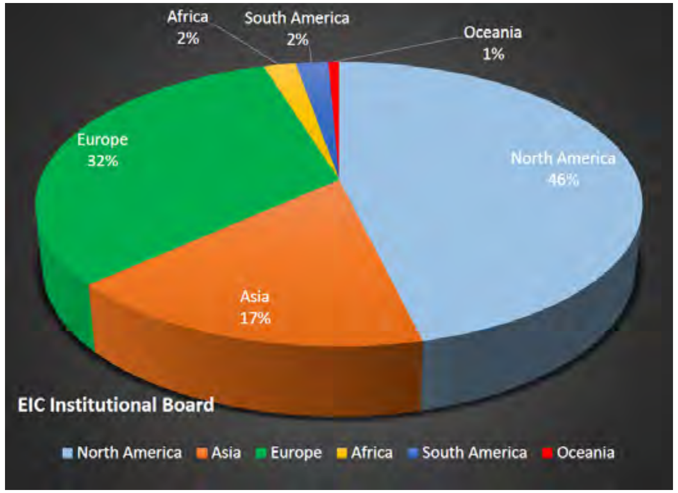
Summary:

The science questions that an EIC will answer *are central* to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would *advance accelerator science and technology* in nuclear science; it would as well *benefit other fields of accelerator based science and society*, from medicine through materials science to elementary particle physics

The EIC Users Group: EICUG.ORG

Formally established in 2016
~1100+ Ph.D. Members from 31 countries, 210 institutions

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



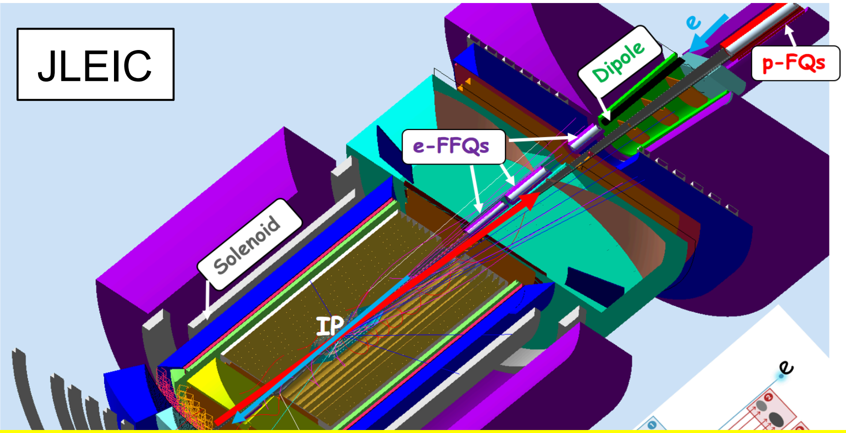
EICUG Structures in place and active.
EIC UG Steering Committee, Institutional Board, Speaker's Committee

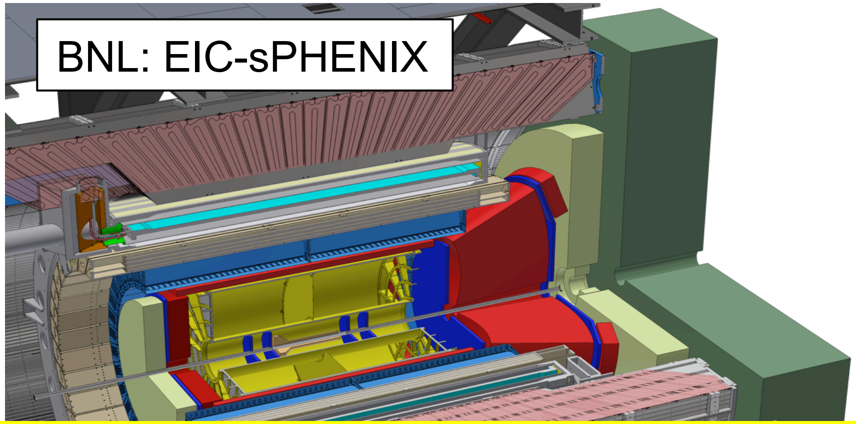
Task forces on:
-- Beam polarimetry, Luminosity measurement
-- Background studies, IR Design

Year long workshops: Yellow Reports for detector design

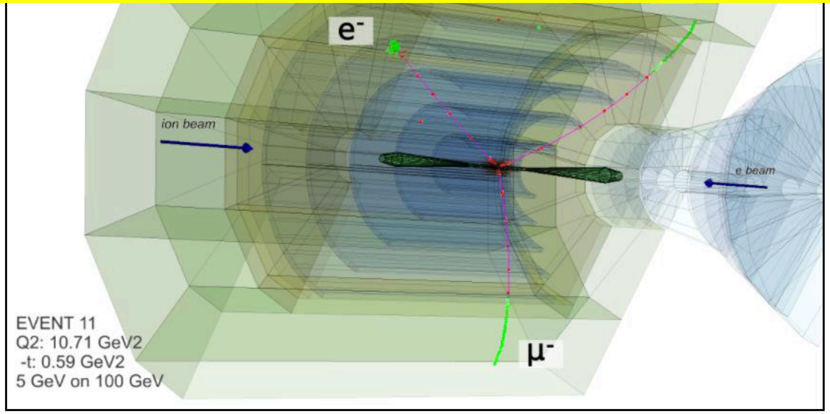
Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016)**, **Trieste (2017)**, **CAU (2018)**, **Paris (2019)**, **FIU (2020)**, **Warsaw (2021)**

Current EIC detector concepts

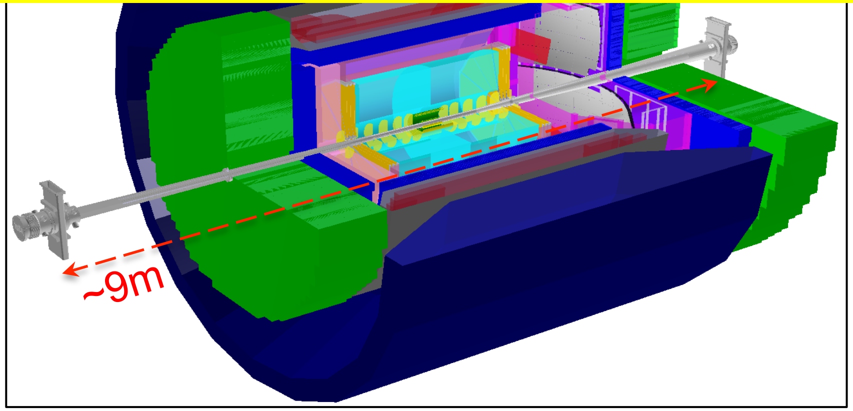




The EIC Users Group has just started a YELLOW REPORT writing activity that will help us move toward Technical Design Reports



Time OPtimized Silicon Detector for EIC



[Defining features](#)

Click here

January 9, 2020

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Department of Energy

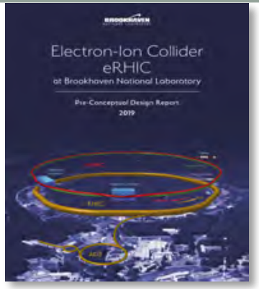
U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JANUARY 9, 2020

Home » U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

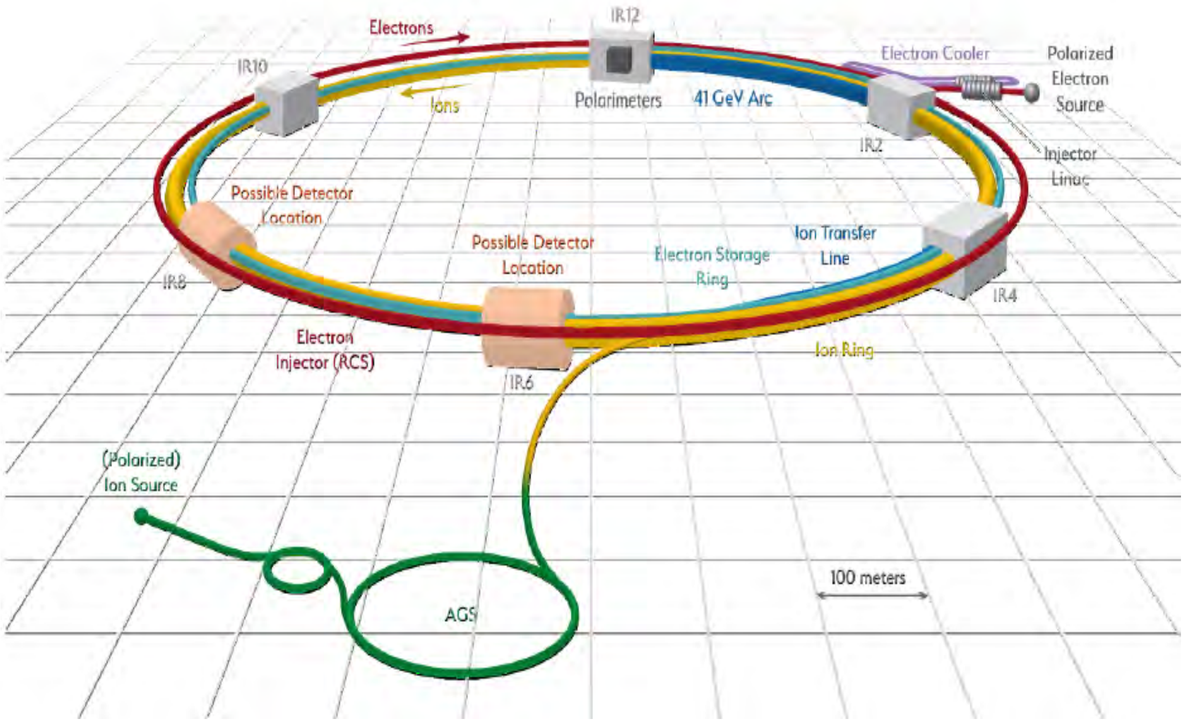
WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

In the same also announced CD0 on December 19, 2019



As of Jan 9, 2020

The US Electron Ion Collider



- ❖ Electron storage ring with frequent injection of fresh polarized electron bunches
- ❖ Hadron storage ring with strong cooling or frequent injection of hadron bunches

Hadrons up to 275 GeV

- ➢ Existing RHIC complex: Storage (Yellow), injectors (source, booster, AGS)
- ➢ Need few modifications
- ➢ RHIC beam parameters fairly close to those required for EIC@BNL

Electrons up to 18 GeV

- ➢ Storage ring, provides the range sqrt(s) = 20-140 GeV. Beam current limited by RF power of 10 MW
- ➢ Electron beam with variable spin pattern (s) accelerated in on-energy, spin transparent injector (Rapid-Cycling-Synchrotron) with 1-2 Hz cycle frequency
- ➢ Polarized e-source and a 400 MeV s-band injector LINAC in the existing tunnel

Design optimized to reach 10^{34} $cm^{-2}sec^{-1}$

EIC Hadron Polarization

Measured RHIC Results:

- Proton Source Polarization 83 %
- Polarization at extraction from AGS 70%
- Polarization at RHIC collision energy 60%

Planned near term improvements:

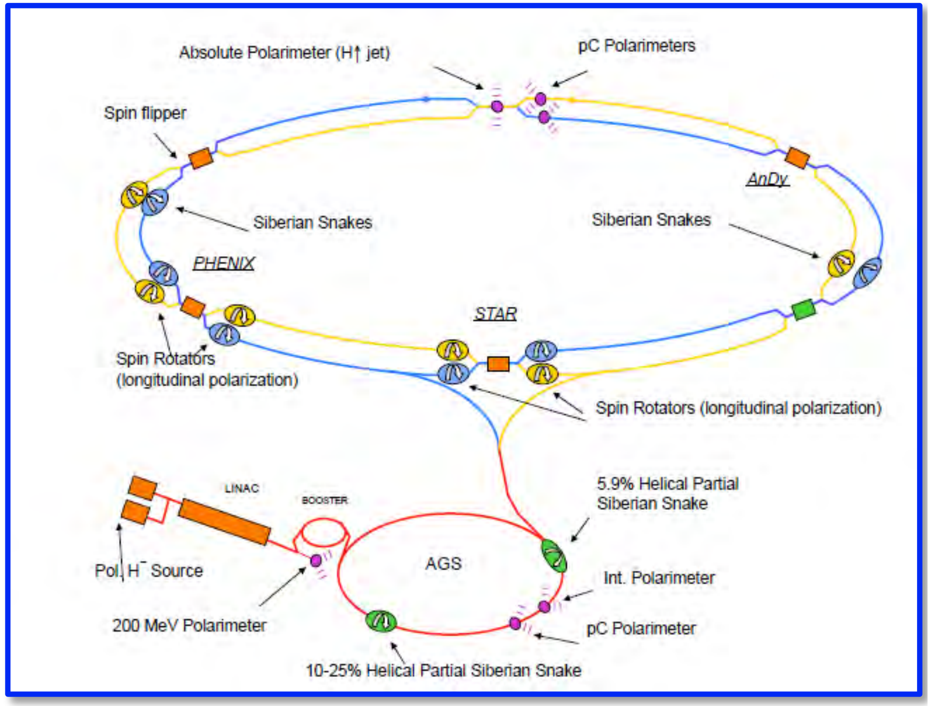
AGS: Stronger snake, skew quadrupoles, increased injection energy
➔expect 80% at extraction of AGS
RHIC: Add 2 snakes to 4 existing no/reduce polarization loss
➔ expect 80% in Polarization in RHIC and EIC
Expected simulations results benchmarked against RHIC operations

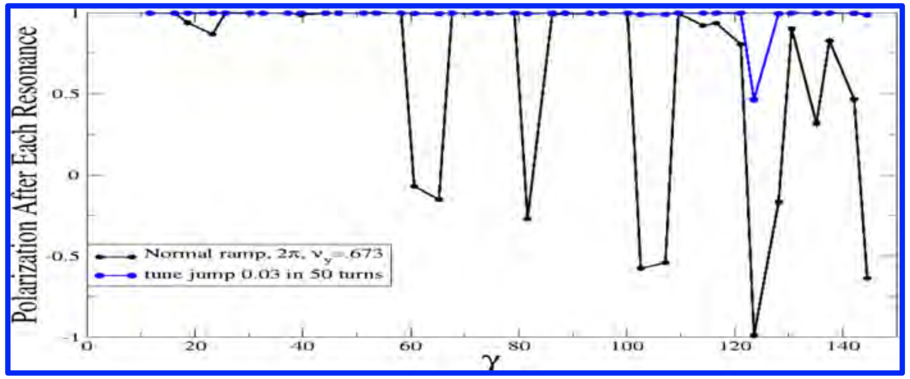
^{3}He in eRHIC with six snakes

Achieved 85% polarization in 3He ion source
Polarization preserved with 6 snakes for up to twice the design emittance

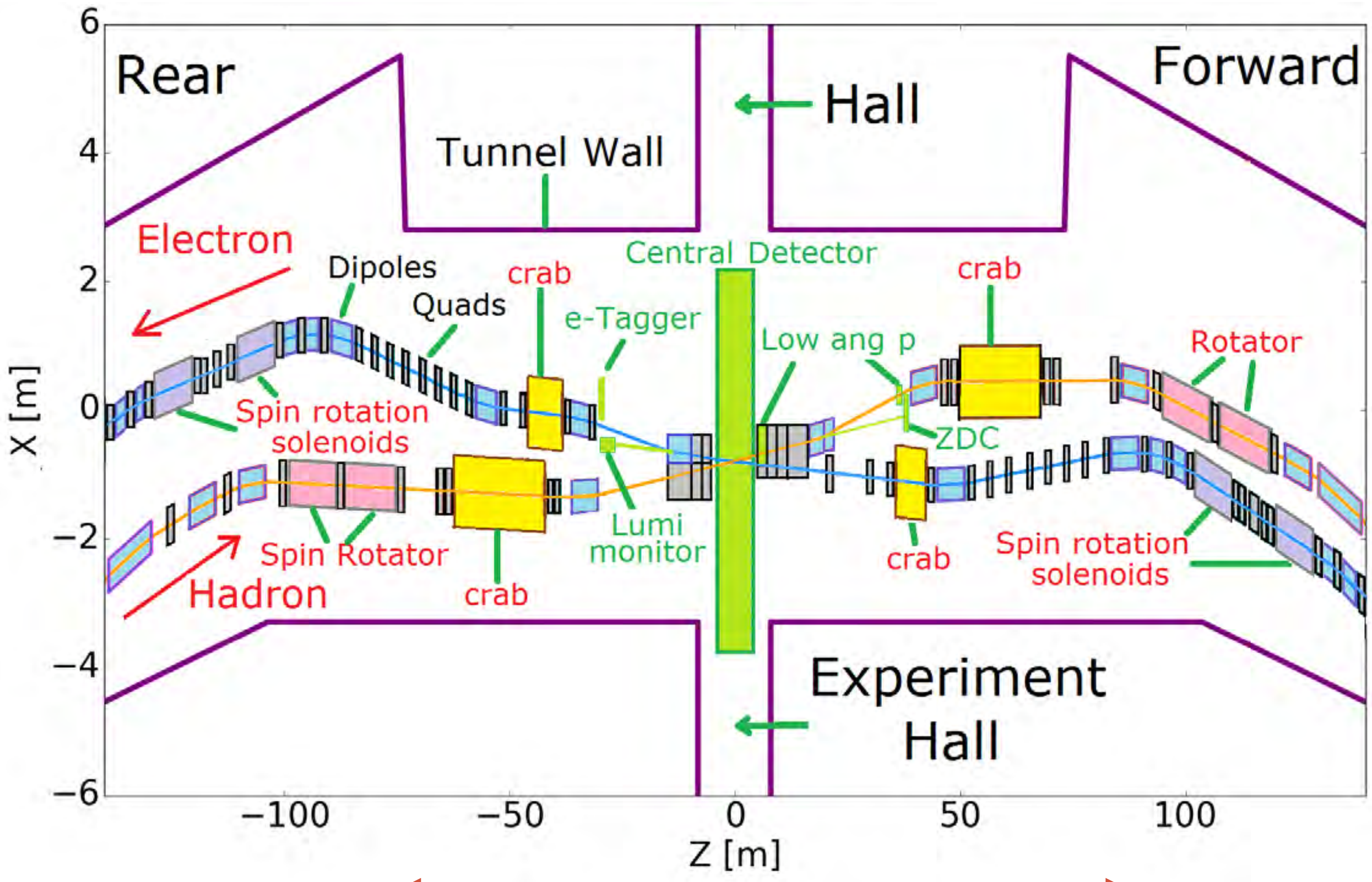
Deuterons in eRHIC:

Requires tune jumps in the AGS, then
benchmarked simulation show 100% Spin transparency
No polarization **loss** expected in the EIC hadron ring





Full Acceptance EIC Interaction Region Layout



Detector Components
Far beyond the central detector

Design

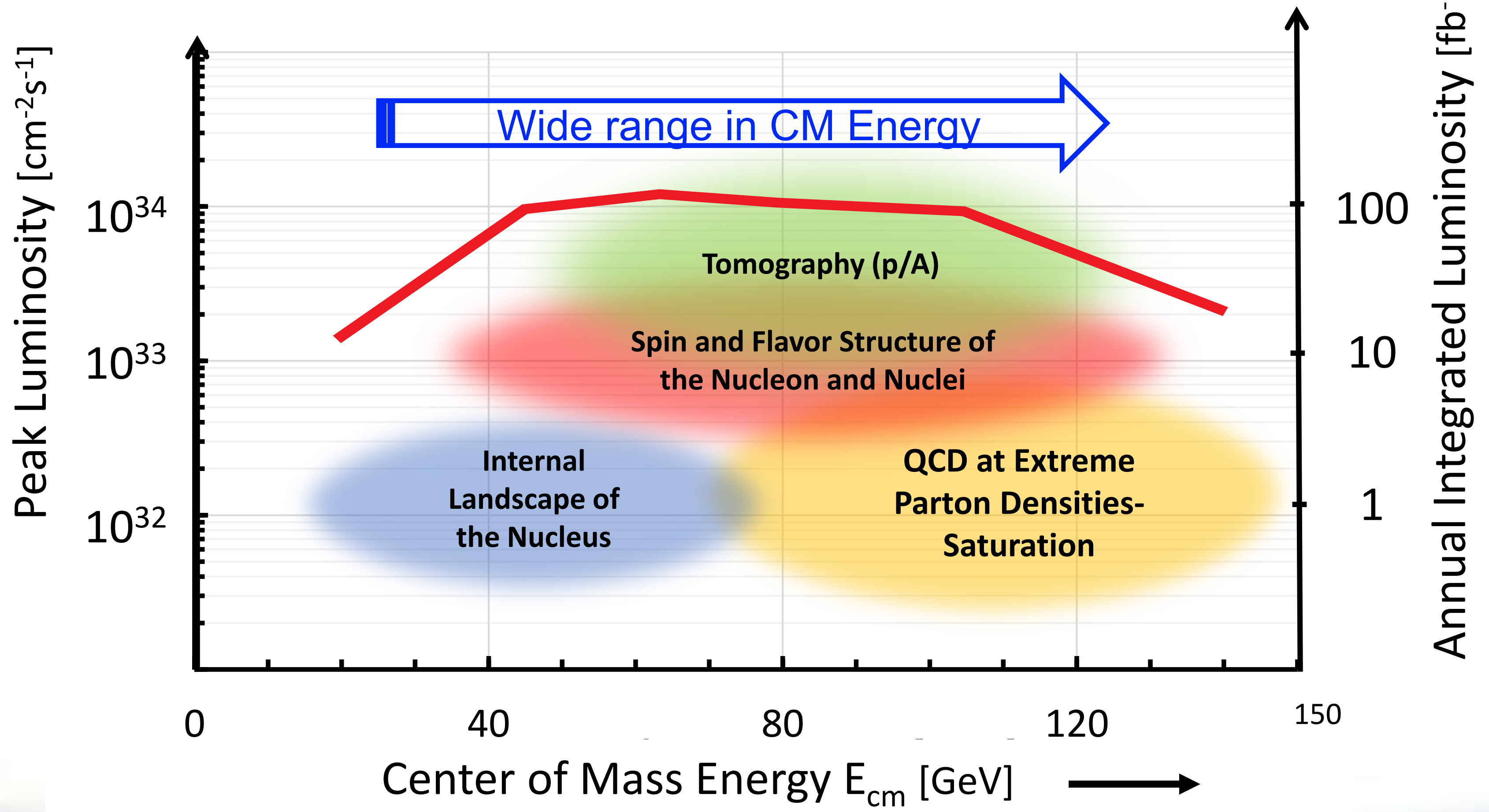
- All superconducting magnets
  - ➢ Only 5 magnets need collared Nb-Ti coils
  - ➢ All other magnets can be built with **direct wind** of Nb-Ti wire
- Full acceptance e.g. P_t =200 MeV/c-1.3 GeV/c
  - ➢ Neutrons 4 mrad
- Large Aperture Dipole w/ instrumented gap
- Modest IR chromaticity
- Hadrons up to β<200m

➔ Manageable dynamic aperture optimization

Broad CM energy range without much loss in luminosity

Collider capability envelope

- Based on design choice of 10 MW synchrotron radiation



Emergent Physics @ the EIC beyond the EIC White Paper:

New Studies with proton or neutron target:

- Impact of precision measurements of unpolarized PDFs at high x/Q^2, for LHC (AD et a. CFNS/LPC-FNAL)
- *What role would TMDs in e-p play in W-Production at LHC?*
- *Gluon TMDs at low-x!*
- Heavy quark and quarkonia (c, b quarks) studies beyond HERA, with 100-1000 times luminosities (??) Does polarization of hadron play any role?

Physics with nucleons and nuclear targets:

- *Quark Exotica: 4,5,6 quark systems…?*
- Study of jets: Internal structure of jets (
  Studies with jets: Jet propagation in nuclei… energy loss in cold QCD medium
- Initial state affects QGP formation!….. p-A, d-A, A-A at RHIC and LHC:
- Polarized light nuclei in the EIC
- Entanglement entropy in nuclear medium and its connections to fragmentation, hadronization and confinement

Precision electroweak and BSM physics:

- Electroweak physics and searches beyond the Standard Model

Outlook: Past ends and future begins…

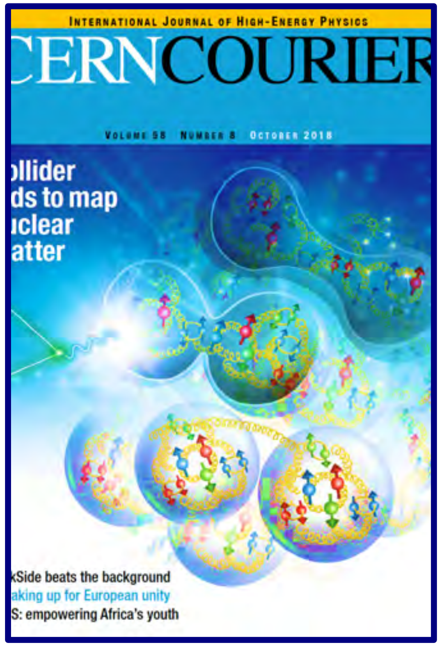
- EIC science is about *non-linear parton interactions & dynamics* in nucleons and nuclei: at the heart of which is to study the **role of gluons in QCD: Low-x and low-to-high Q^2**

- *US NAS Academy: EIC Science "compelling and timely"*
- *As of January 9, 2020: CD0 at hand, Site is BNL. Timeline for 1st collisions ~2030.*

- **Gerd's science has evolved well…and will continue for the next three decades**

Thank you Gerd and hope you have a very happy and relaxed retirement with family and friends.

R. Ent, T. Ullrich, R. Venugopalan
Scientific American (2015)
Translated in to multiple languages



E. Aschenauer
R. Ent
October 2018

A. Deshpande
& R. Yoshida
June 2019
Translated in to Chinese (Taiwan), Italian and other languages