Future Initiatives in QCD

(with emphasis on DIS related physics and initiatives)

1. Introduction
2. New Facilities
3. Selected Physics at the New Facilities
   - Some Comments on QCD@LHC
   - Unpolarized Parton Distributions of the Proton
   - High Energy Domain of QCD (DIS)
   - Spatial Mapping of Quarks and Gluons in the Nucleon
   - Spatial Mapping of Nuclei
   - Spin Mapping of Quarks and Gluons in the Nucleon
4. Outlook and Summary

Introduction

QCD: From a "simple" Lagrangian

$$L_{QCD} = \overline{\psi}_i (i\gamma^\mu \partial_\mu - m)\psi_j - gG^a_\mu \overline{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \tfrac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - gf^{abc} G^b_\mu G^c_\nu$$

follow incredibly rich and complex phenomena

We all believe in QCD! Why future initiatives? What are the questions?

So far the main emphasis: testing QCD
→ understanding + detailed exploring of new domains of QCD

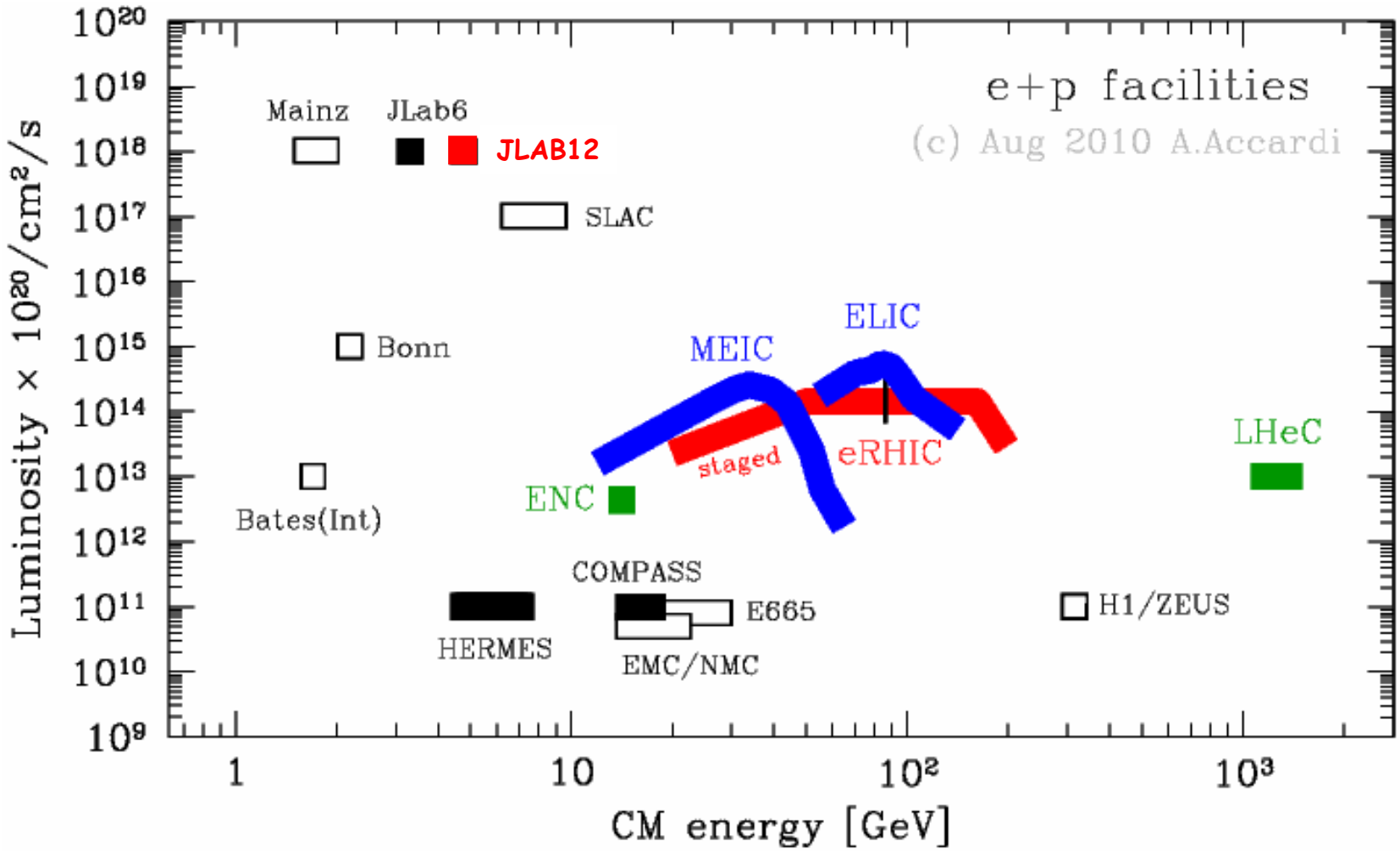
+ precision input (structure of hadrons and nuclei, hadronization, α_S, bound-state effects, h-h-scattering) is required for New Physics at LHC, in rare decays, for g-2, etc.

Scattering expts. in particular DIS an essential main tool of particle physics

→ Rutherford (1911) → SLAC (1967) → HERA († 2007) → **future initiatives**

The Facilities

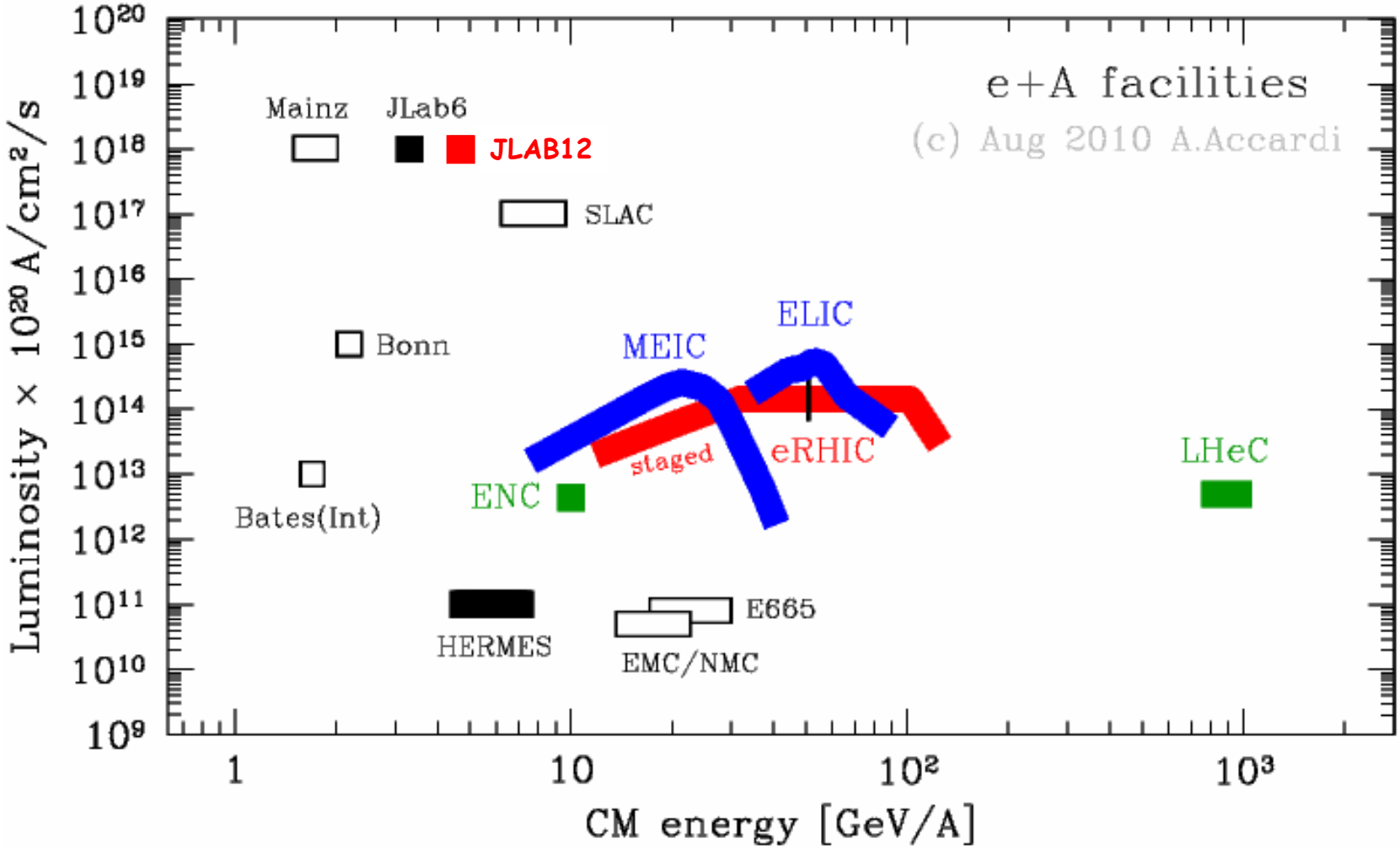
E_{CM} vs. L_{int}-plane for ep [μp]:



A.Accardi

The Facilities

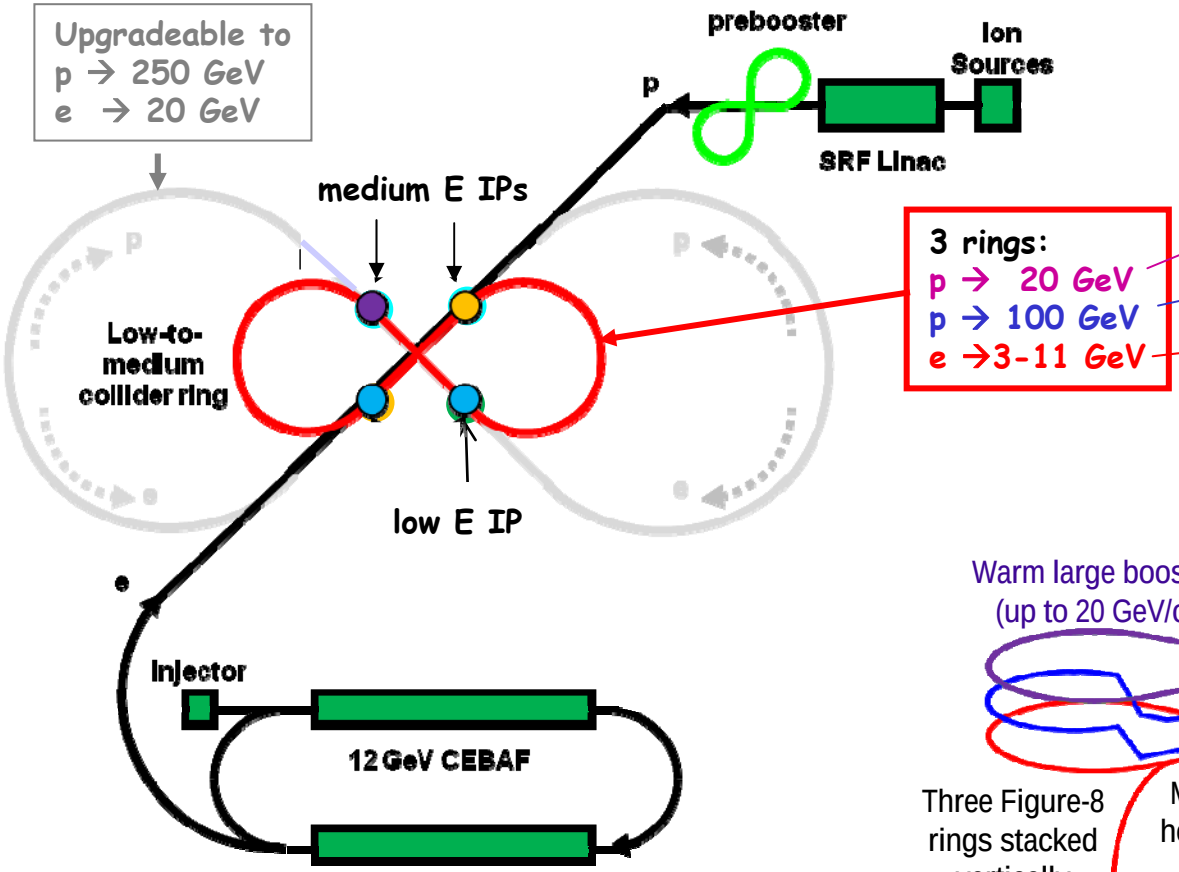
E_{CM} vs. L_{int}-plane for eA [μA] :



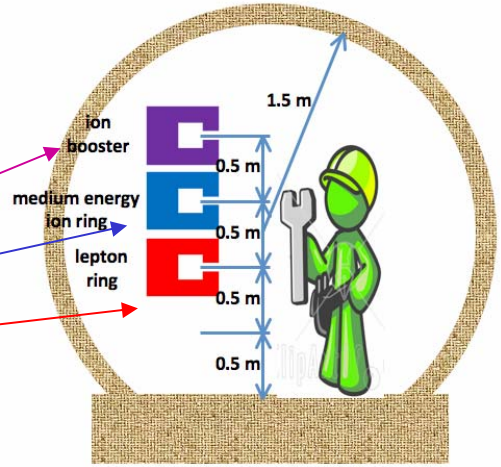
A.Accardi

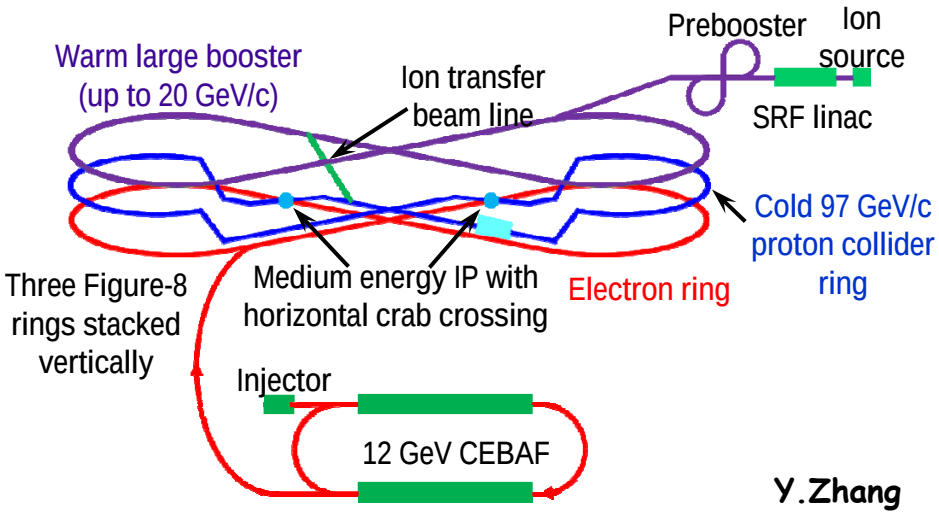
Future Facilities: E(L)IC @ JLAB

High luminosity for ep and eA over a wide energy range



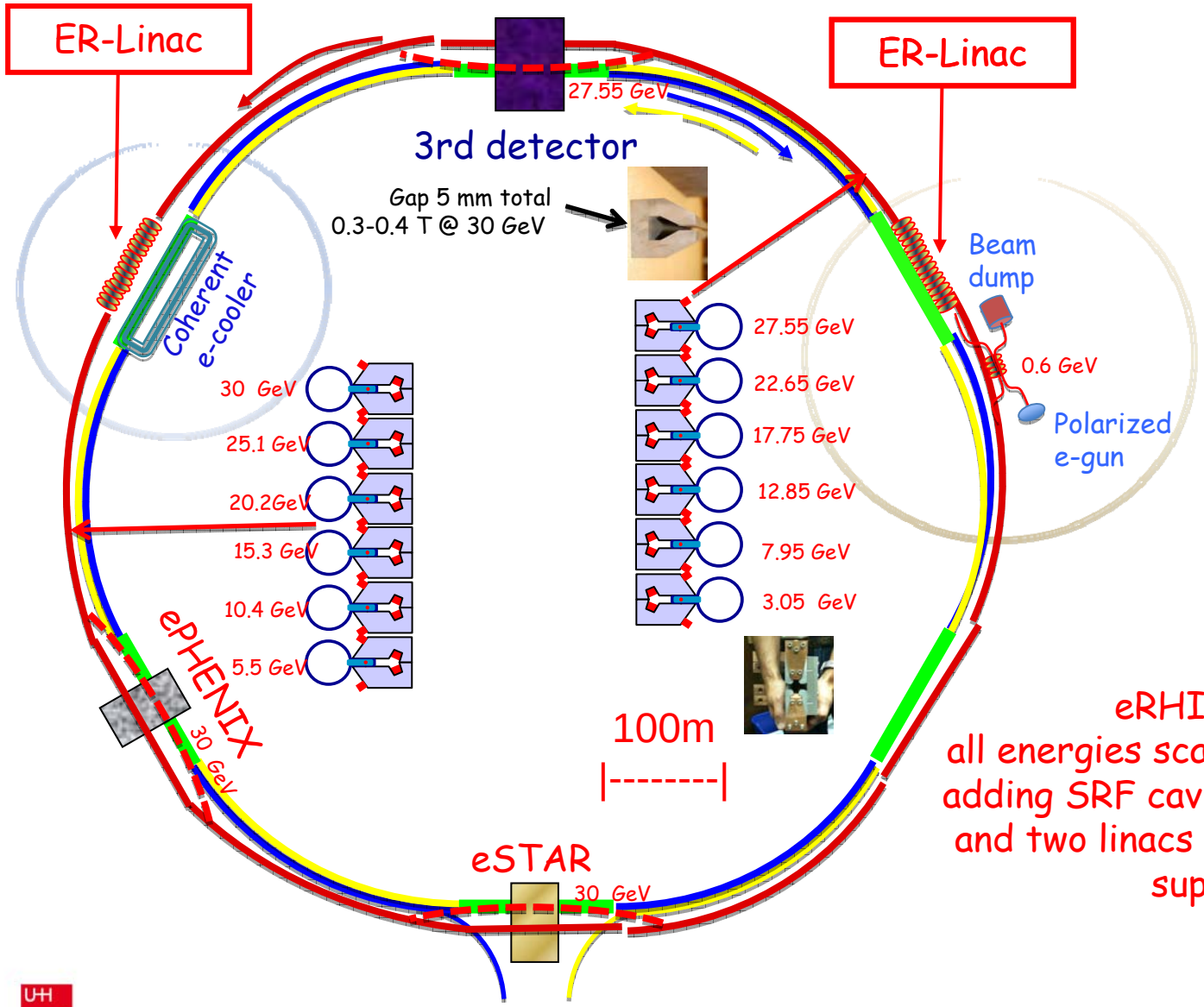
3 rings:
p → 20 GeV
p → 100 GeV
e →3-11 GeV





Y.Zhang
DIS 2011

Future Facilities: e(RH)IC @ BNL



eRHIC staging:
all energies scale proportionally by adding SRF cavities to the injector and two linacs and cranking power supplies up

N.Litvinenko
DIS 2011

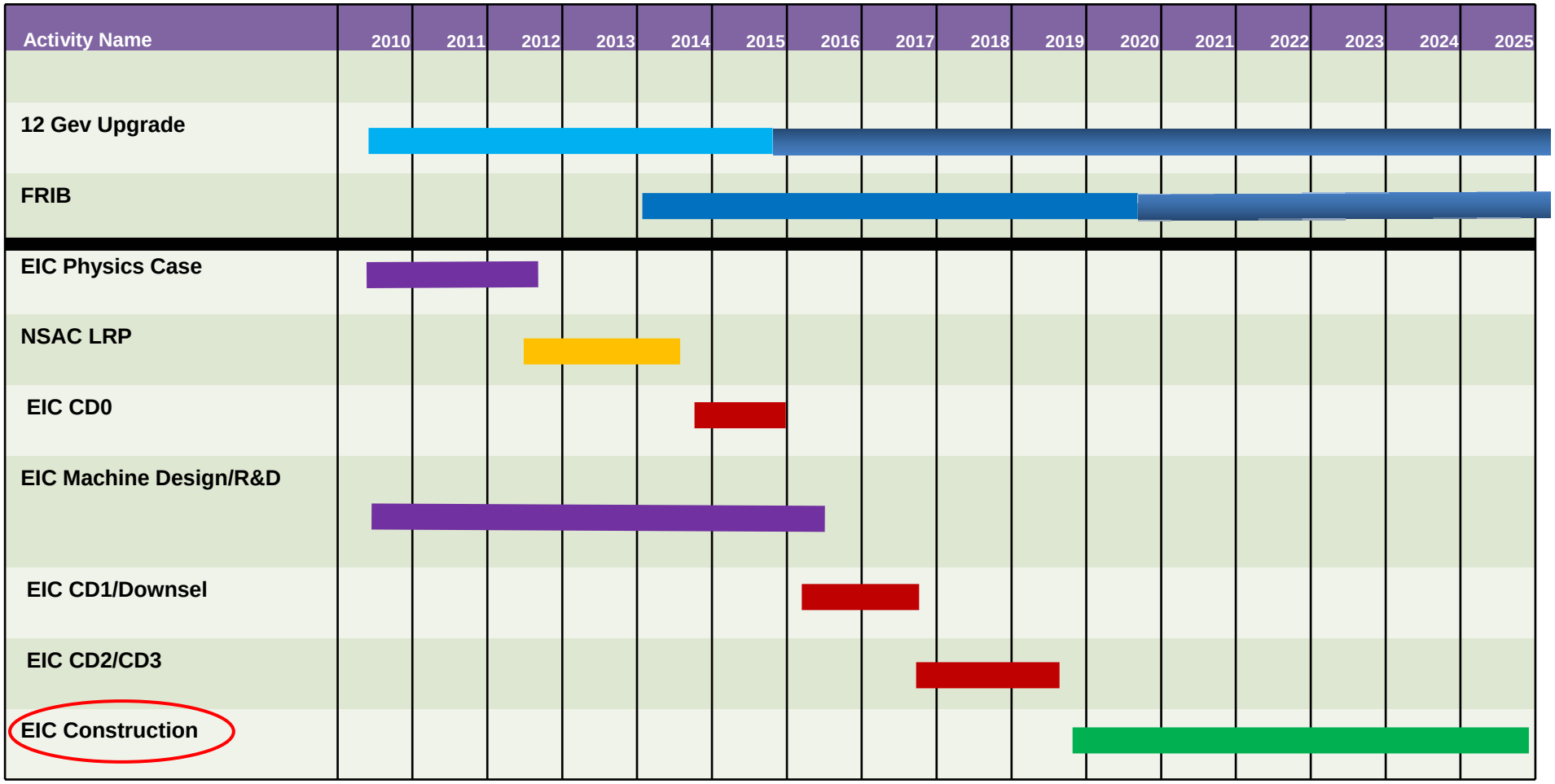
Design Goals EICs (and more)

- Staged designs, with impressive physics program already for phase I
- Physics requirements → similar design goals for both projects

Item	MEIC @ JLAB	eRHIC @BNL
electrons	3-11 GeV; 80% pol.	5-30 GeV; 80% pol.
protons	2-100 (250) GeV; ~70% pol.	50-250 (325) GeV; ~70% pol.
nuclei	p,d,^{3}He → A~200; 12-40GeV/u	p,d,^{3}He → U; 12-40GeV/u
currents	I_e=3A, I_p=0.5A	I_e=0.05A, I_p=0.42A
luminosity	5.6 (14.2) x10^{33} for ep @ 5x60	14.6 x 10^{33} for ep @ 20x325
interaction regions	3	3
distance bunches	1.3 ns	74 ns

- Convergence in specifications (difference in energies)
- Both design represent major challenges for accelerator and detectors
  → planning and R&D is underway/has started

E(L)IC: Decision + Construction Timeline

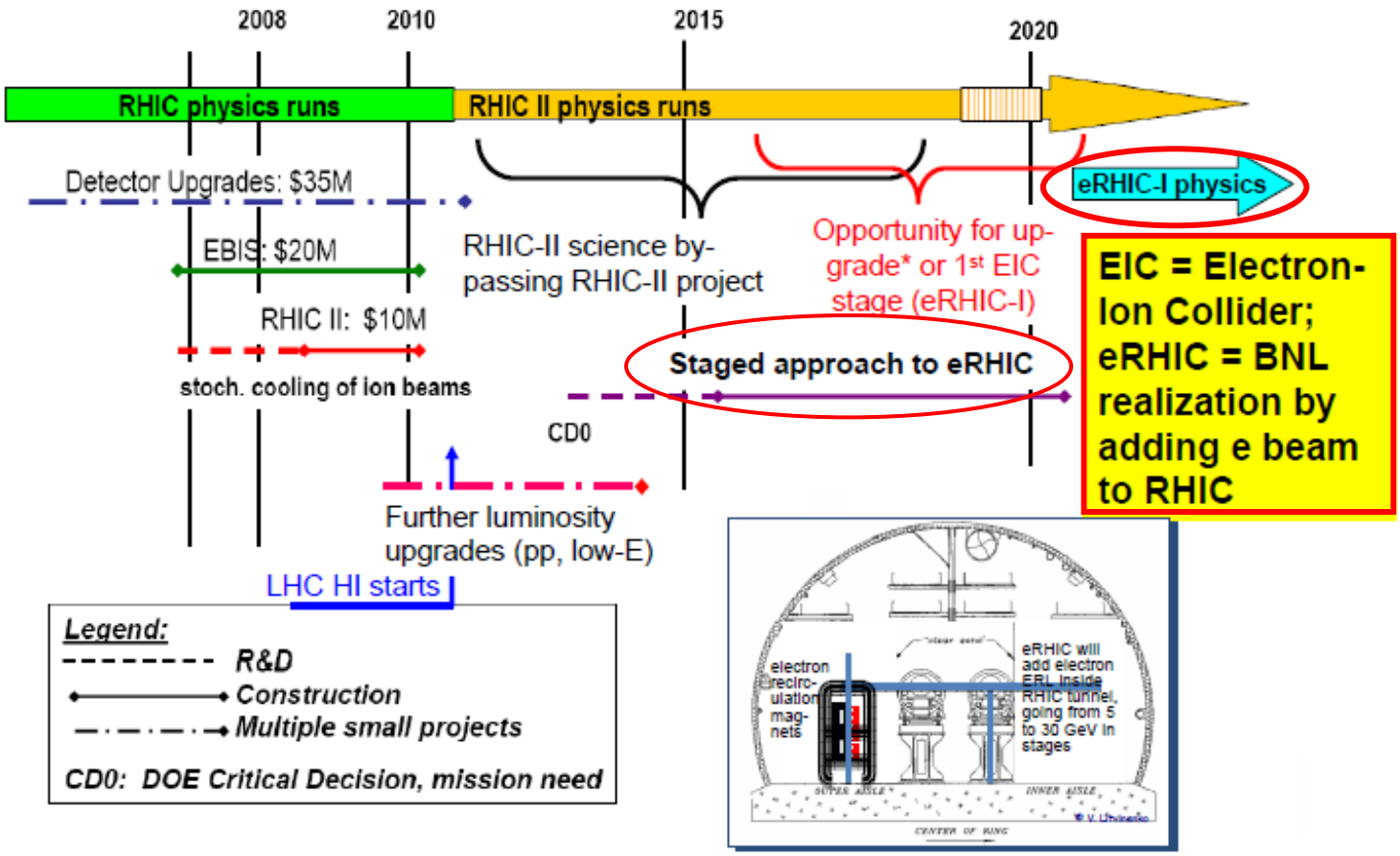


H.Montgomery
INT Nov.10

E(RH)IC: Construction Timeline

S. Vigdor, BNL Associate Director

A Long Term (Evolving) Strategic View for RHIC



EIC = Electron-Ion Collider; eRHIC = BNL realization by adding e beam to RHIC

* New PHENIX and STAR Decadal Plans provide options for this period.
Dedicated storage ring for novel charged-particle EDM measurements another option

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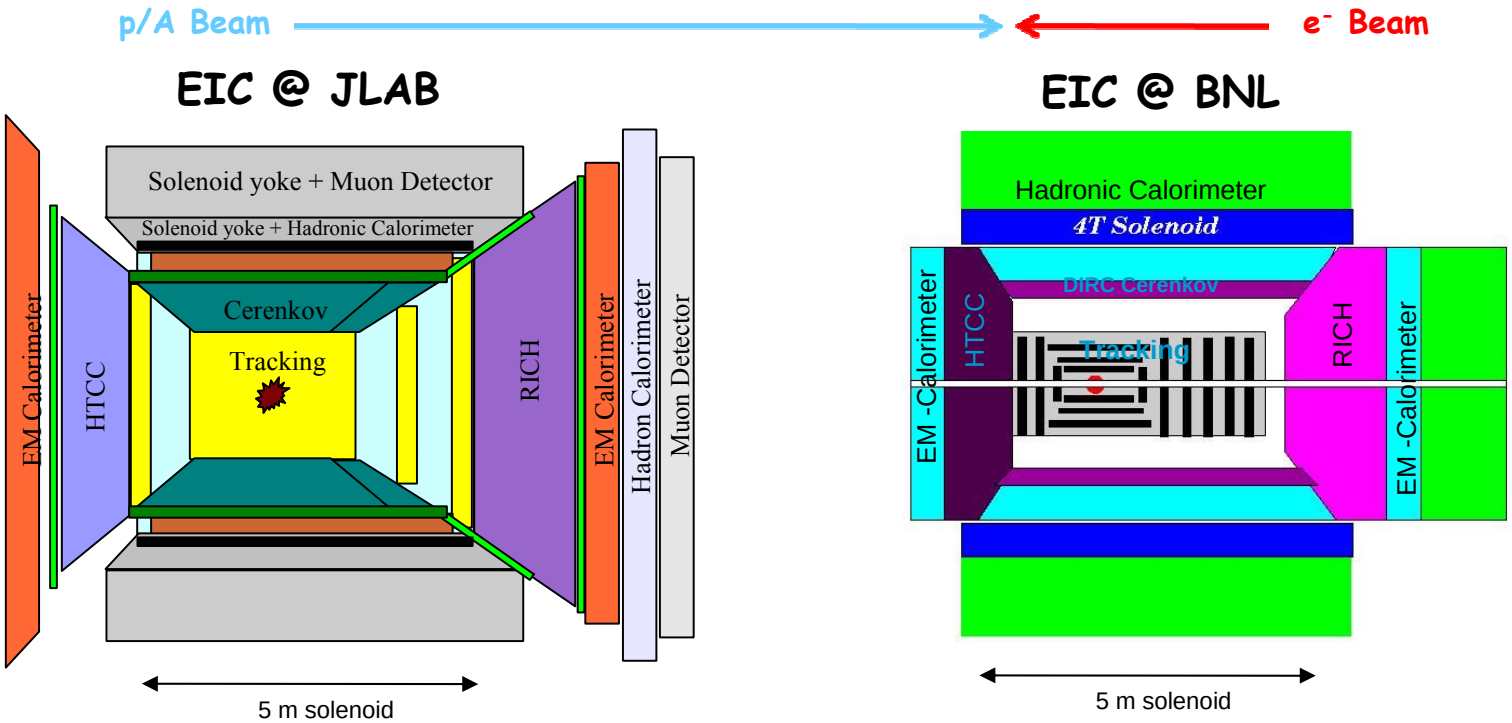
S. Vigdor
Apr. 2011

EIC: Detector Concepts



- Convergence (also) of detector concepts
- In addition:
  - p/A-downstreams: dipole(s), 0° neutron CAL, Roman pots, tagging counters
  - e-downstreams: e-taggers (to tag photoproduction)
- Simulations and optimizations started + Call for detector R&D proposals

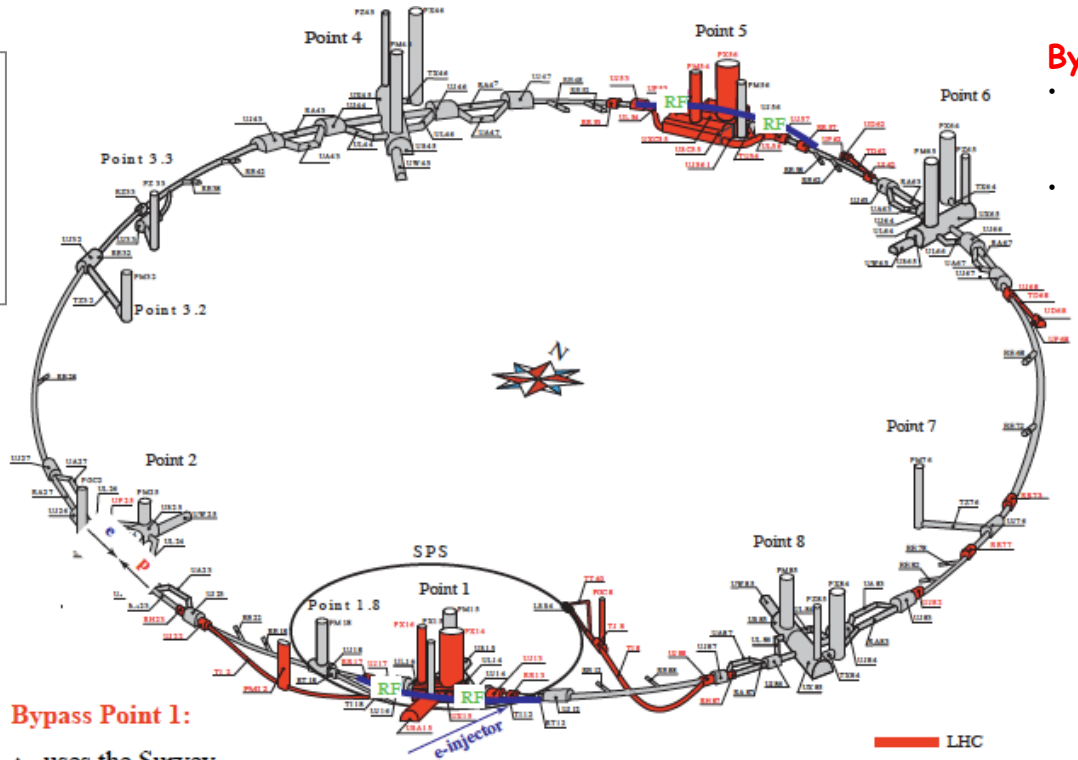
Future Facilities: LHeC

3 Options: 100 MW power limit → 60 GeV (e) x 7 TeV (p) [+ eA]

- **Ring-Ring**: $L = 2\times10^{33}cm^{-2}s^{-1}$ (100xHERA) → $L_{int} = O(100)\ fb^{-1}$, Pol.(e) = 40%
- **Pulsed Linac-Ring**: $L = 1\times10^{32}cm^{-2}s^{-1}$, Pol.(e) = 90%
- **Energy Recov. Linac-Ring**: ($\beta^* = 0.1m$) → $L = 1\times10^{33}cm^{-2}s^{-1}$, Pol.(e) = 90%

example for:
60 GeV e-ring
with 10 GeV e-
linac injector

Decision L vs. R
after completion
of design work

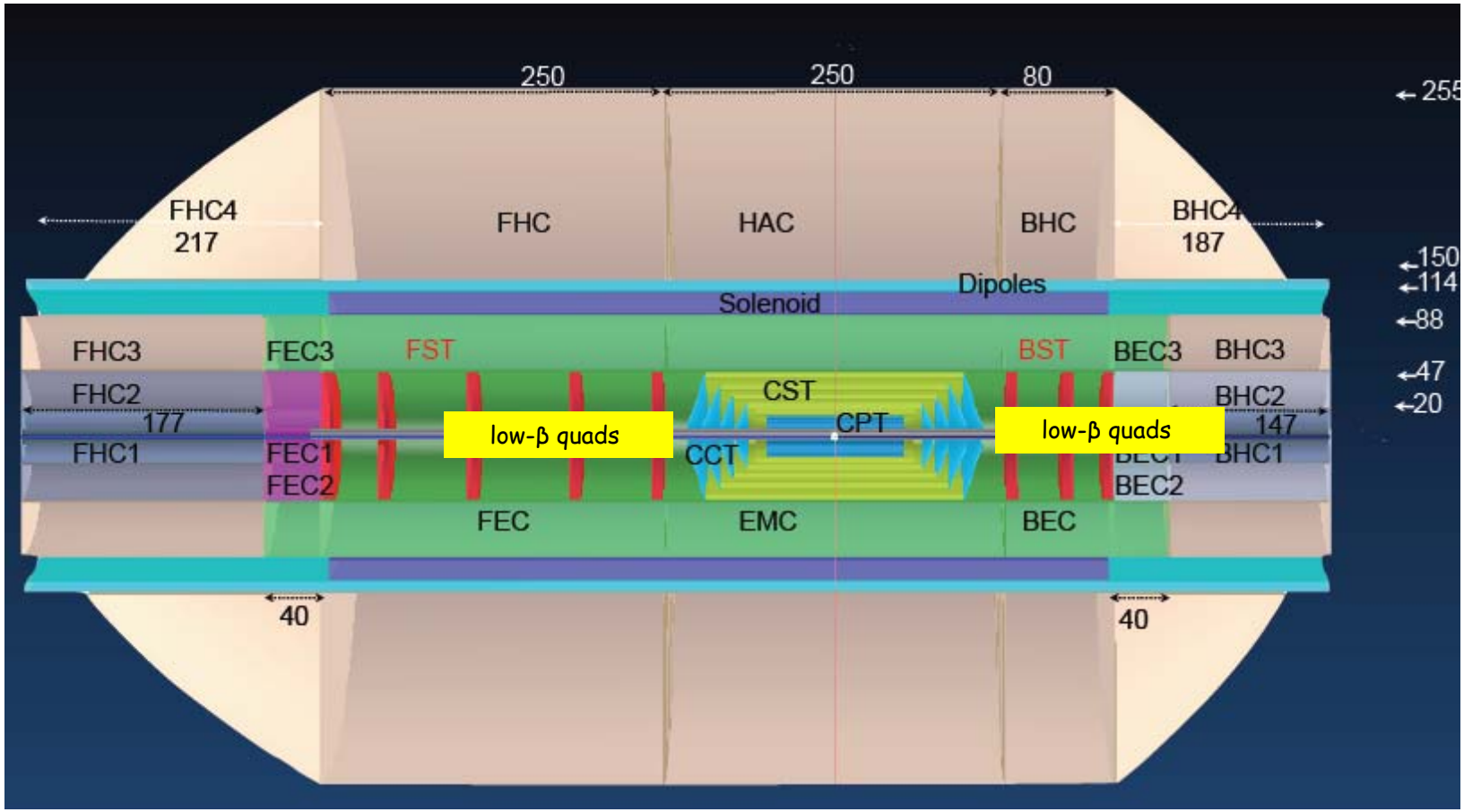


Bypass Point 5:
- adjustment of the circumference by varying separation
- Δ = 20.56 m

Bypass Point 1:
- uses the Survey Gallery
- Δ=16.25 Meter

LHeC Detector Concepts

Low x optimised (e-linac): tracking → > 1° + low material + high precision + forward p: p, n, d,... -tagging + backward e: γ-tagging



High Lumi-Q² optimised (e-linac): low-β quads → tracking → > 10°

P.Kostka
DIS-2011

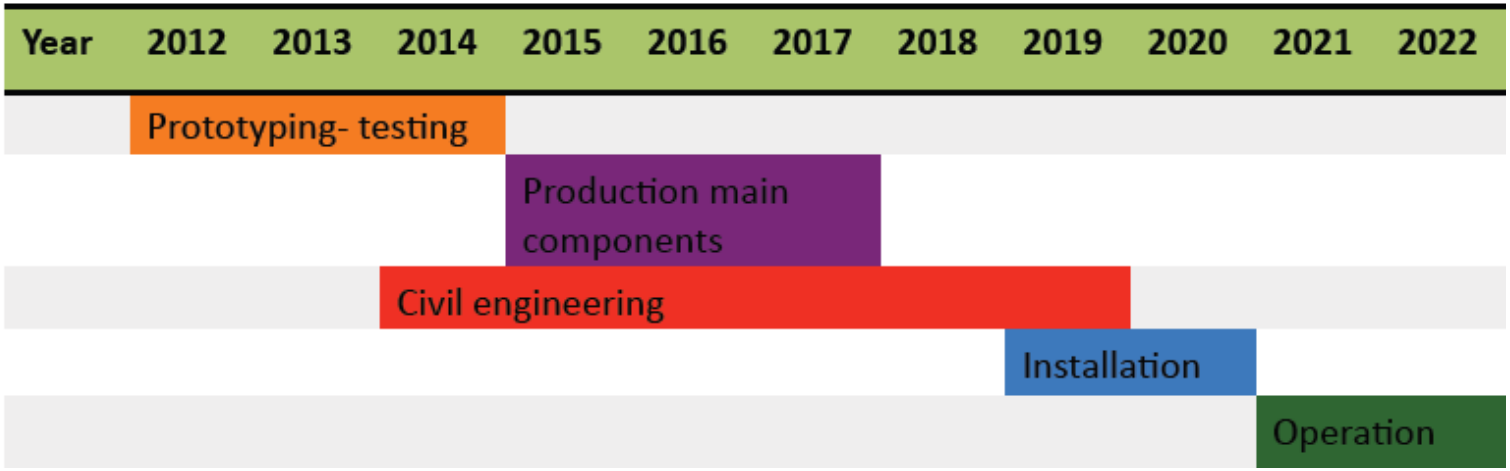
LHeC Timeline

CDR organisation: **Aim for spring 2011**

- Scientific Advisory Committee: Chair A.Caldwell MPI-Munich)
- Steering Committee: Chair M.Klein (Liverpool)
- 5 Working Groups + CERN has appointed referees

LHeC_DRAFT_Timeline

Based on LHC constraints, ep/A programme, series production, civil engineering etc



M.Klein
ECFA 26.Nov.10

More Facilities + Upgrades

FAIR@GSI

- hadron structure and spectroscopy in $\bar{p}p$ interactions
- hadrons and quarks in compressed nuclear matter
- ENC (not part of the modularised start-up version → after ~2019):
  - 3.3 GeV e(↑) x 15 GeV in p(↑) PANDA
  - L(ep) ~ $10^{33}cm^{-2}s^{-1}$
  - L(ed) ~ 1.8 x $10^{33}cm^{-2}s^{-1}$

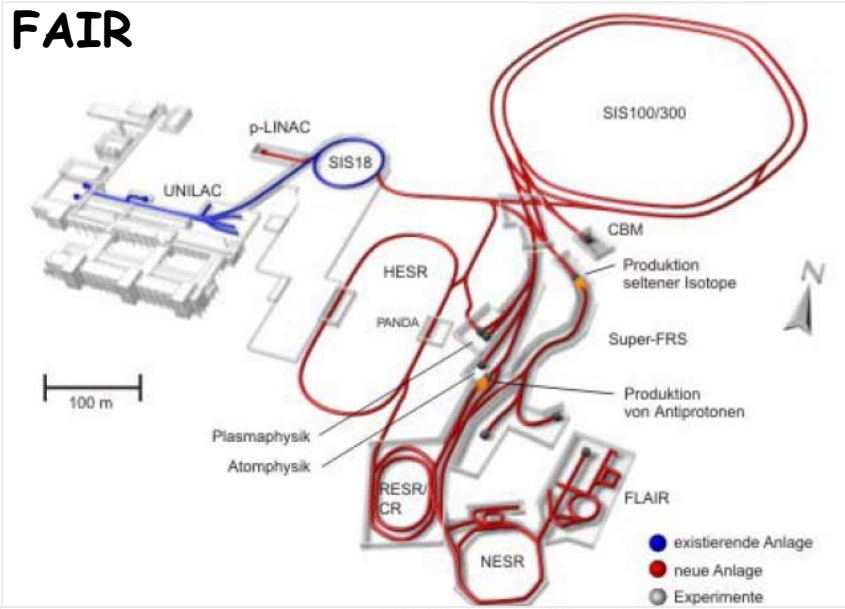
Upgrade of RHIC detectors

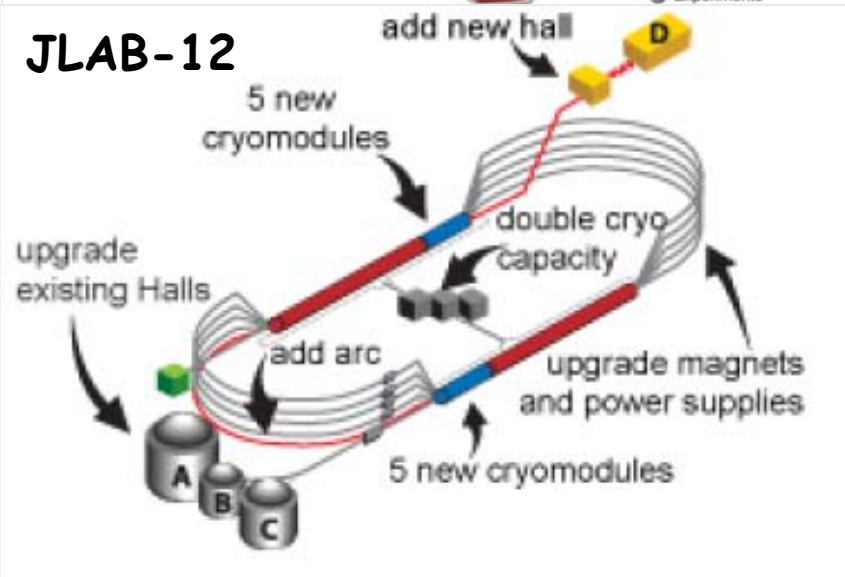
AnDY @ RHIC (?)

COMPASS-II @ CERN

Upgrade LHC + LHC detectors

MINERvA @ FNAL, OLYMPUS





Summary: Facilities for QCD

After completion of the "old fixed target" program with e, μ and ν, of Hermes and of the first ep-collider HERA, presence + near future:

- QCD high energy frontier: LHC and RHIC
- QCD high intensity frontier: JLAB 6 → 12
- QCD polarisation frontier: JLAB, COMPASS, RHIC
- new QCD regimes: RHIC and LHC

Ideas and plans for new facilities, to

- extend the high energy frontier: LHeC
- bridge the gap between fixed target and HERA energies with high intensities and polarisation: EIC
- new QCD regimes (using protons and nuclei): LHeC, EIC, FAIR

We should not forget:

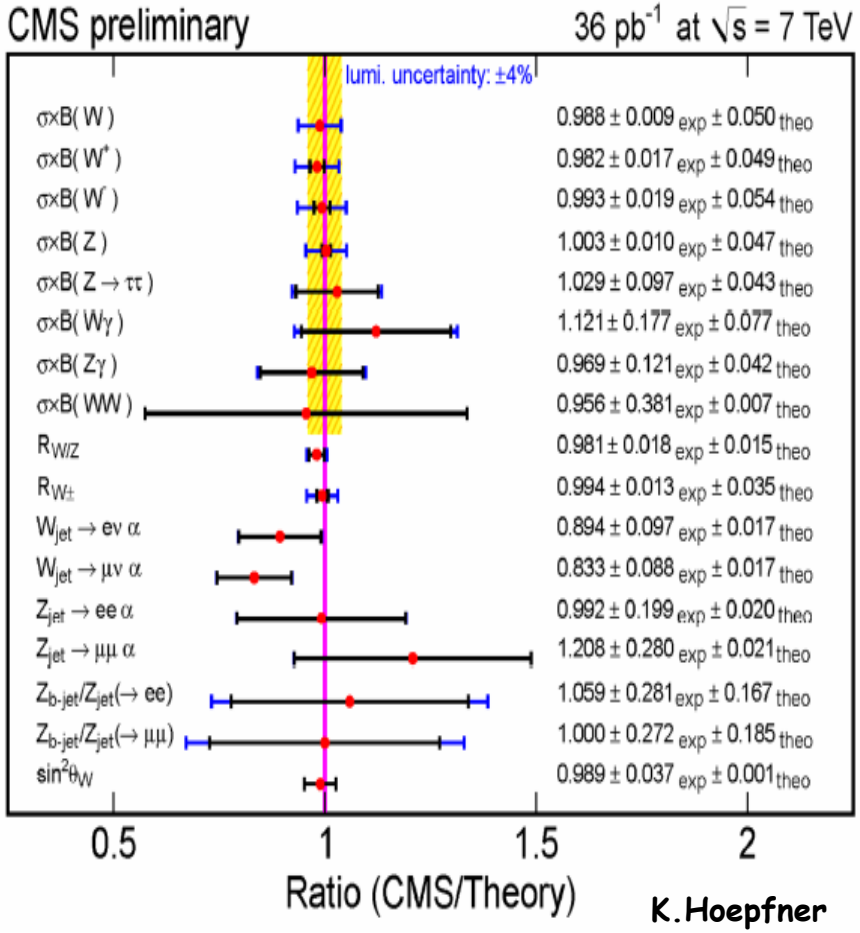
- hadron spectroscopy: FAIR, LHC, e^+e^-, JLAB
- phenomenology, higher order calculations and QCD on the lattice ! (strong theoretical support is **absolutely** essential)

Selected Physics at the New Facilities

Some Comments on QCD @ Hadron Colliders

Results presented are most impressive: Confirm SM in a new E-regime

- An outstanding achievement by experimenters and theorists
- Results now used for MC-tuning and understanding of QCD
- The heroic efforts on complete NNLO calculations are essential
- Is effort on understanding MPI (multi-particle i.a) sufficient ?
- First surprises: long range particle correlations "ridge"
  + more insight in "jet quenching"
  → regime of high density QCD effects ?

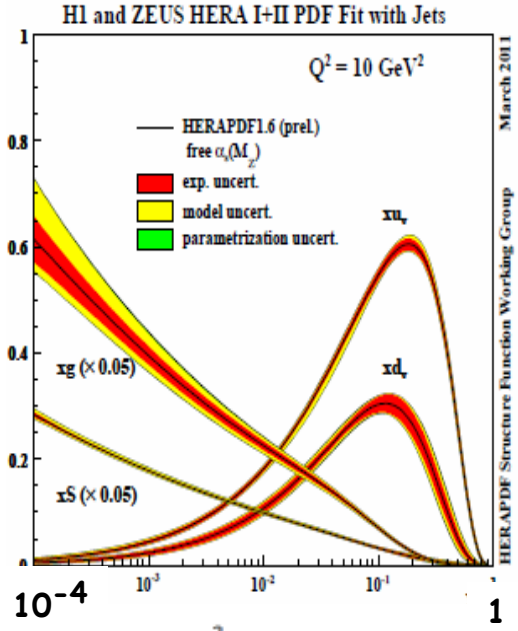


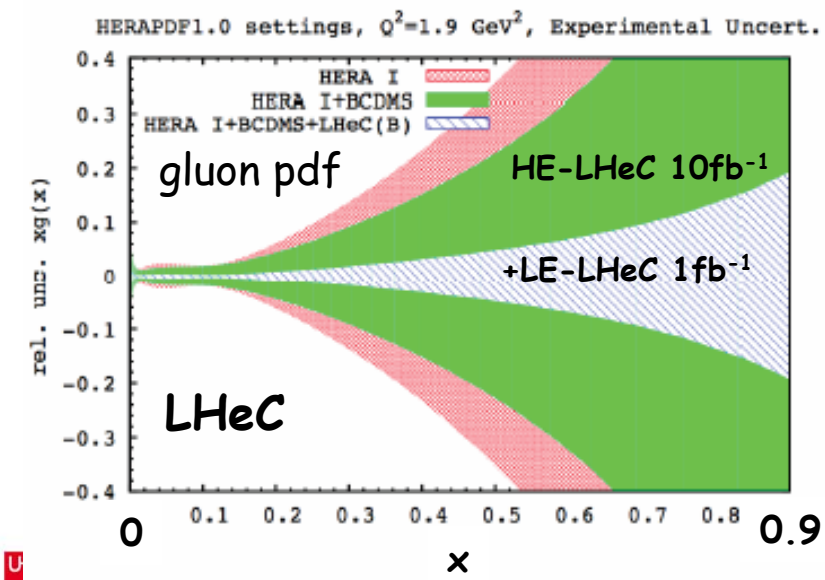
K.Hoepfner DIS 2011

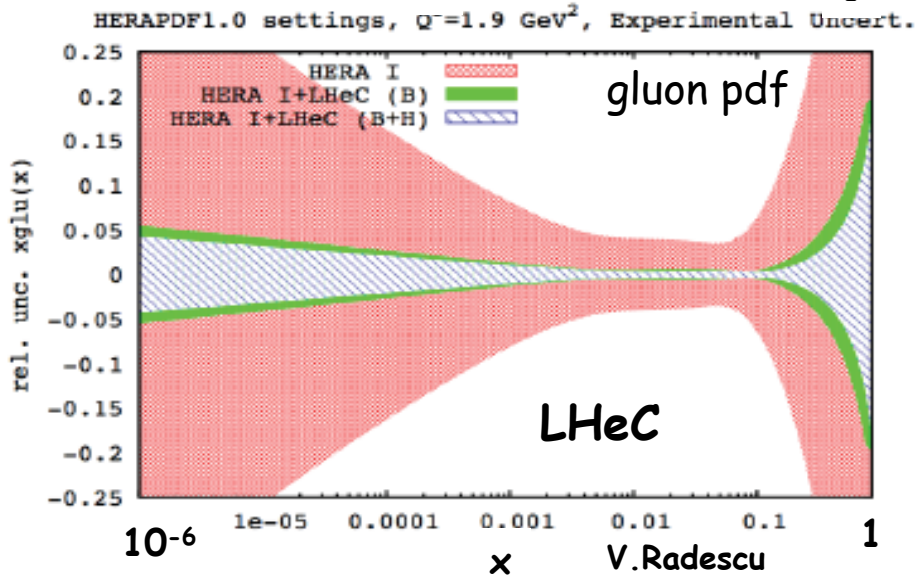
Unpolarized Proton PDFs

Big progress – role of HERA !

- further improvements **HERA** (final analyses + jets + heavy flavours
- improvements **PDFs** needed for **x > 0.1** and for **x < 10^{-4}**
- high x (high mass at LHC): **JLAB, LHC and LHeC**
- low x (gluon saturation in p): **LHeC**







V.Radescu
DIS 2011

Gluon Density in the High-E Limit

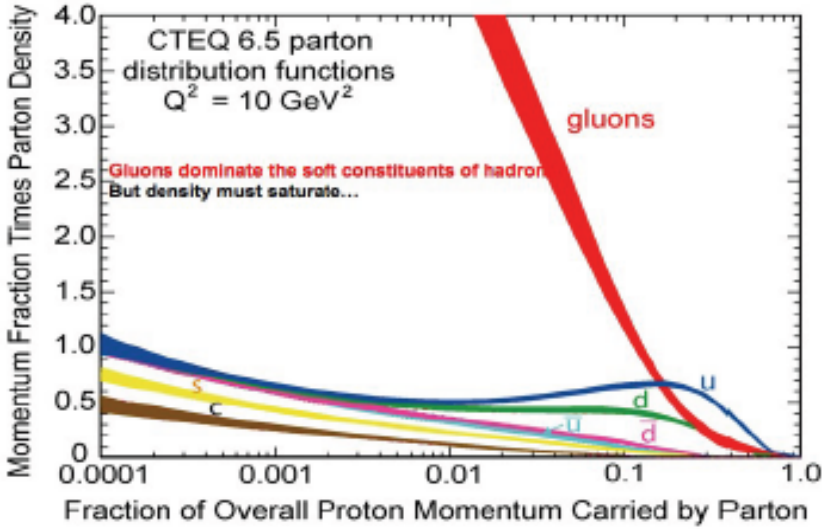
Unpolarised longitudinal parton distr.

→ gluons dominate for **x < 0.1**

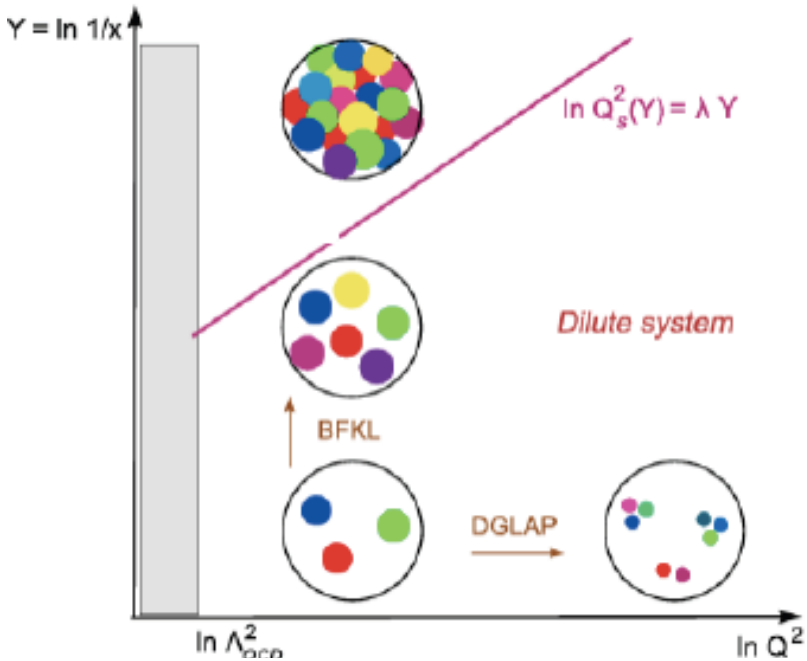
When do saturation effects appear ?

→ a new regime of **p**QCD (Q^2)

recombination ?



Gluons dominate the proton wavefunction

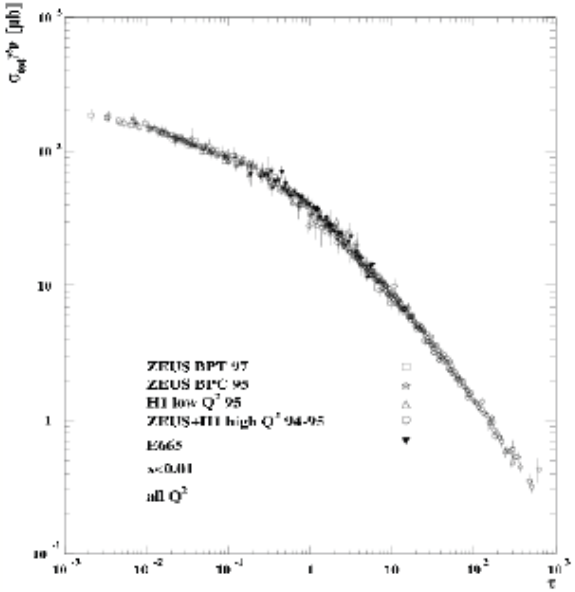


Hints from HERA, RHIC and LHC – interpretation model dependent

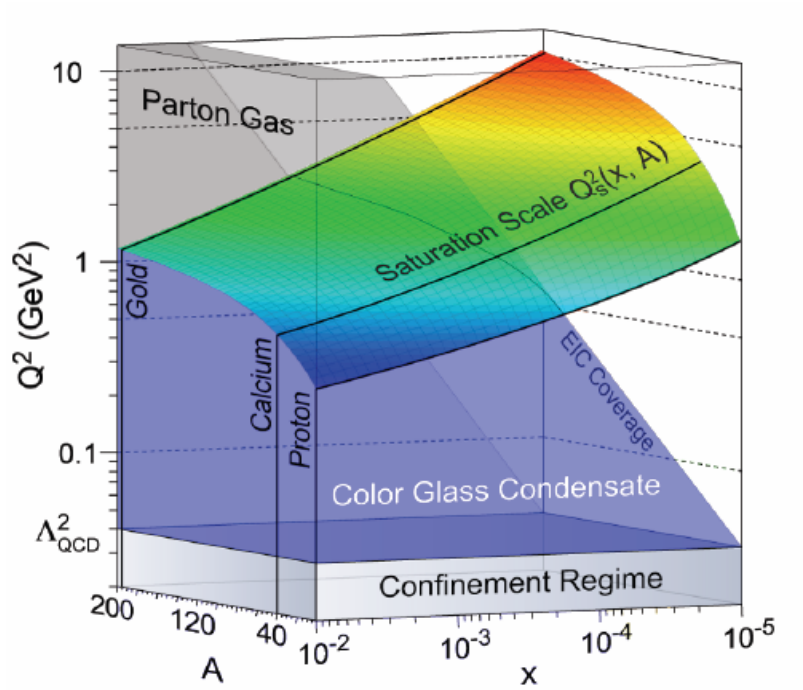
Gluon Density in the High-E Limit

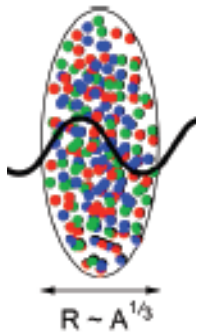
For x < 0.1 observe scaling in τ

→ described e.g. by
Colour Glass Condensate
(saturation not necessarily needed)



Expectation sat. scale: $Q_s^2 \approx Q_0^2 \cdot [A/x]^{1/3}$





Exploration in ep and eA at **LHeC**: for ep (60·7000)GeV²: x ~ $2 \cdot 10^{-7}$ @ 1 GeV²
and in eA at **EIC** (high E_{CM} a big bonus !)

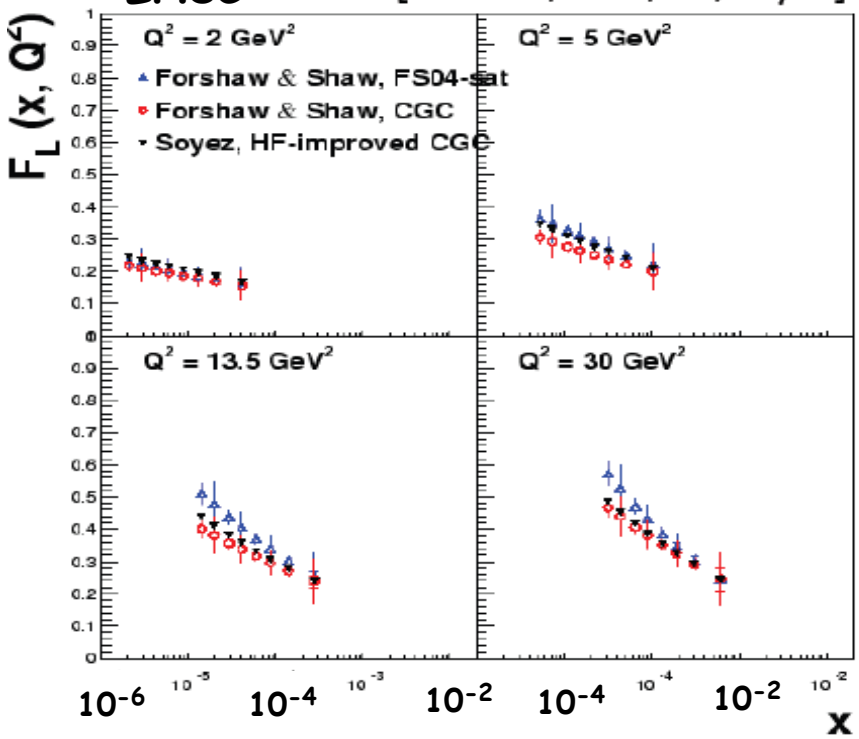
Proof of saturation → another big step in unraveling the richness of QCD

Precision measurement of F_L

$F_L \sim \alpha_S \cdot$ gluon density → essential to confirm saturation effects (F_2^c ???)

→ requires F_2 measurements at widely spaced E_{CM}

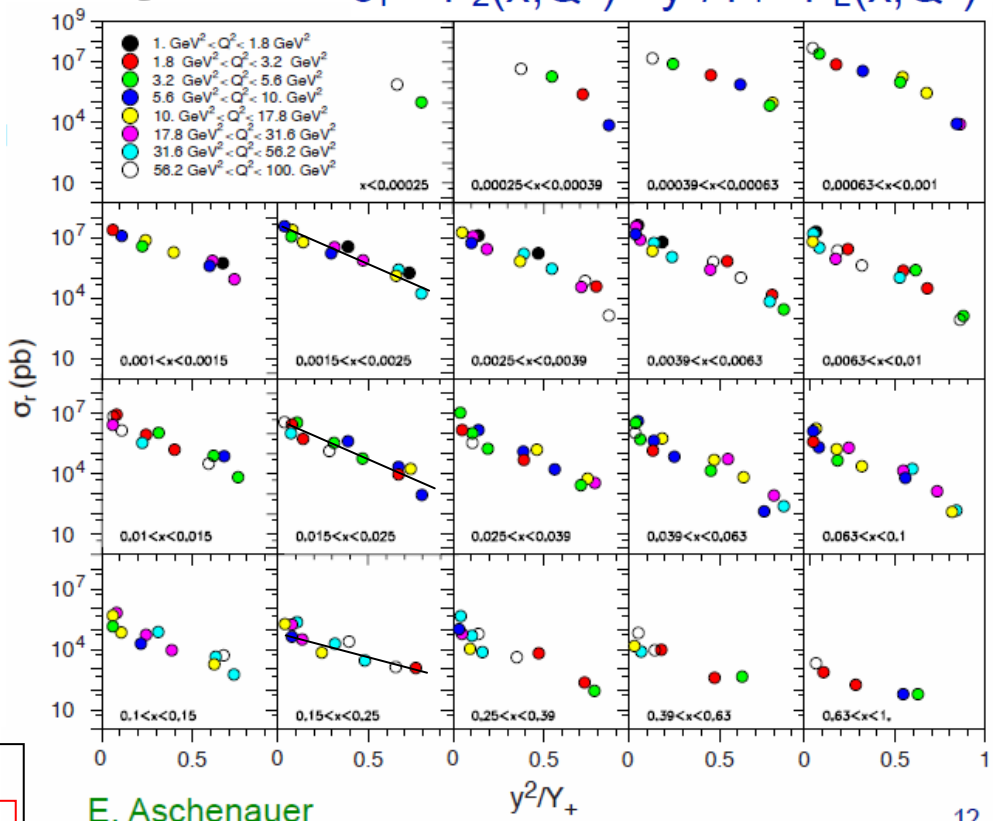
LHeC [Forshaw, Klein, PN, Soyez]



LeHC with E_p=7TeV;Lint=1fb^{-1}		
E_e=60 GeV	4	0.8
	2	0.2
	1	0.05

→$\delta F_L \sim 5\%$

EIC $\sigma_r = F_2(x,Q^2) - y^2/Y_+ \cdot F_L(x,Q^2)$



E. Aschenauer 12

→ first studies on F_L started for EIC (difficult measurement due to low E_e)

Map of Spatial Structure of Nucleon

Exclusive reactions at $Q^2 > 1\ GeV^2$: $\gamma^* p \rightarrow \gamma p$ (DVCS); $\gamma^* p \rightarrow \rho^0 p$; $\gamma^* p \rightarrow J/\psi(\varphi) p$, ...

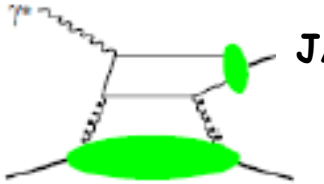
Transverse imaging by mom. transfer t of proton → Fourier transform

(requires the measurement of the recoils – for collider for small t: a few mm from beam)

singlet quarks,
gluons in NLO

ρ^0

sea quarks
and gluons

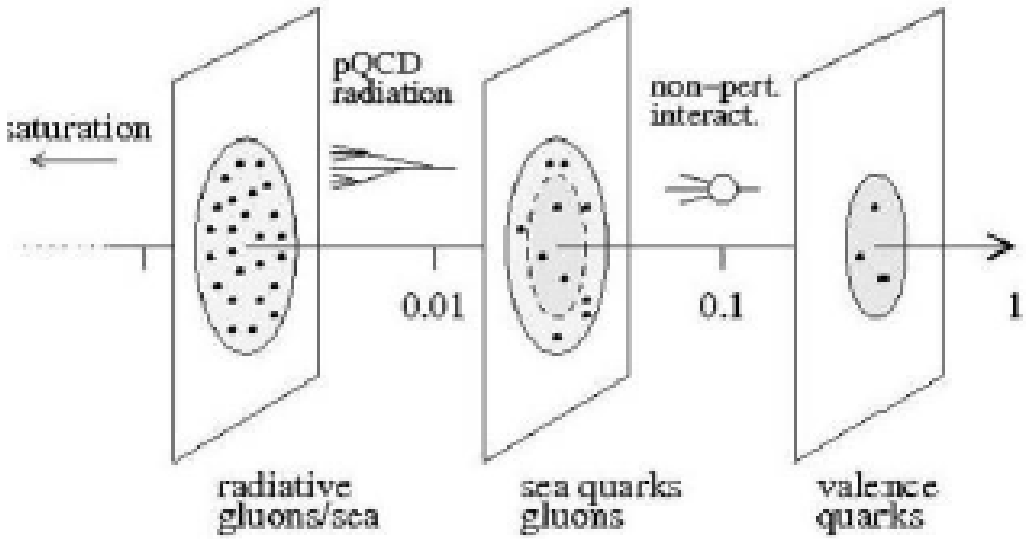


$J/\psi,\varphi$

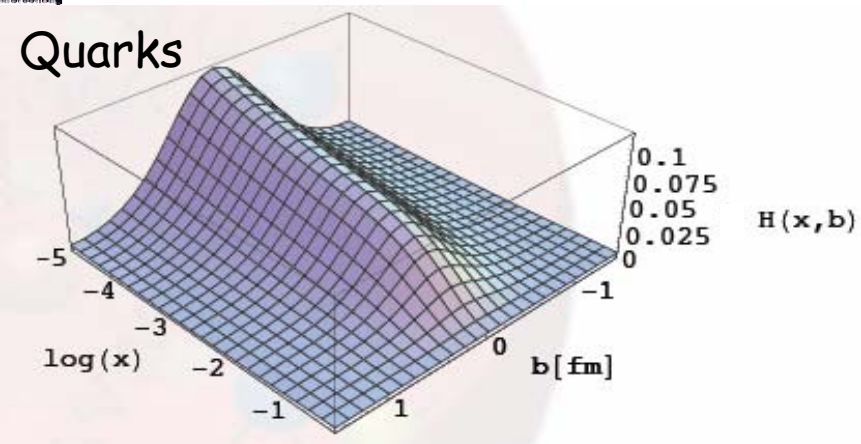
gluons

etc.

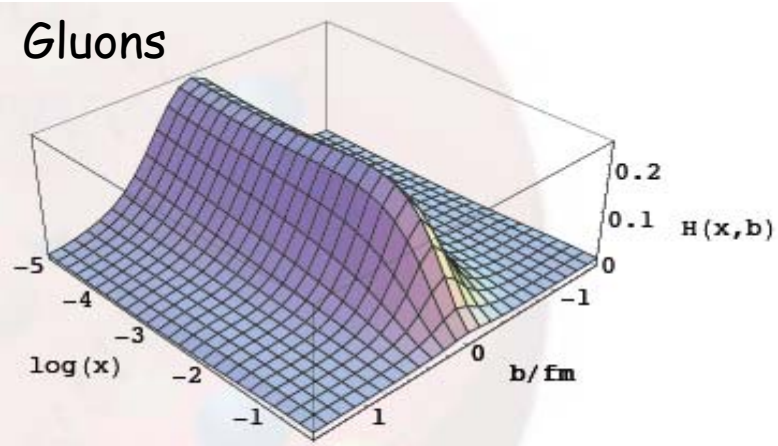
+ Measurement vs x → 3 d image



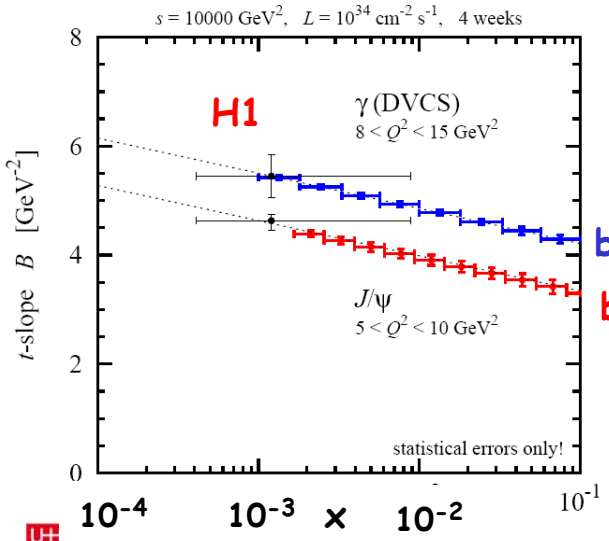
Map of Gluons and Quarks inside of Nucleon



GPD fit to the DVCS data from HERA, Kumerick-D.Mueller, 09,10



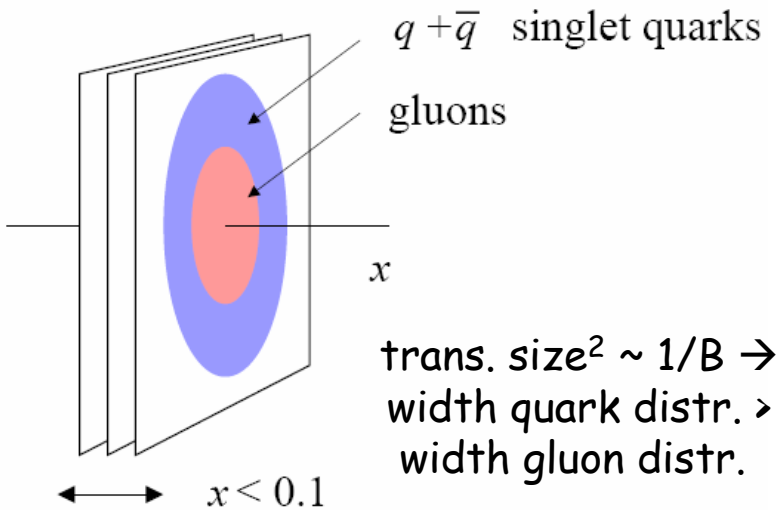
GPD fit to the DVCS data from HERA, Kumerick-Mueller, 09,10



b-slope γ

b-slope J/ψ

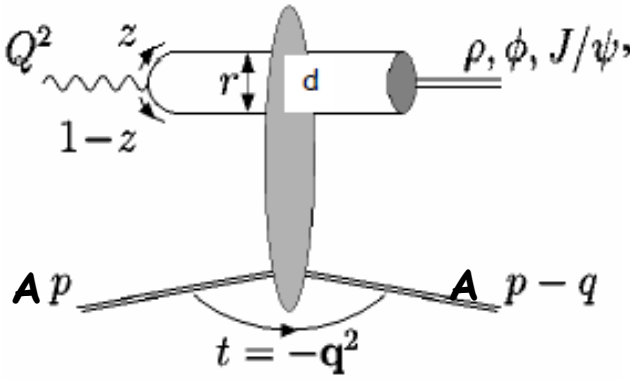
GPD-fit →



trans. size² ~ 1/B → width quark distr. > width gluon distr.

Map of Gluons and Quarks inside of Nucleus

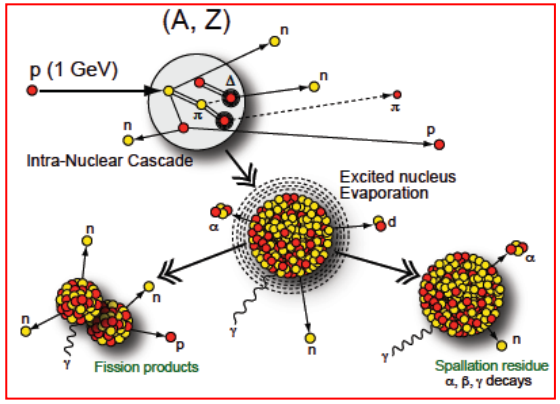
Similar for Nucleus:



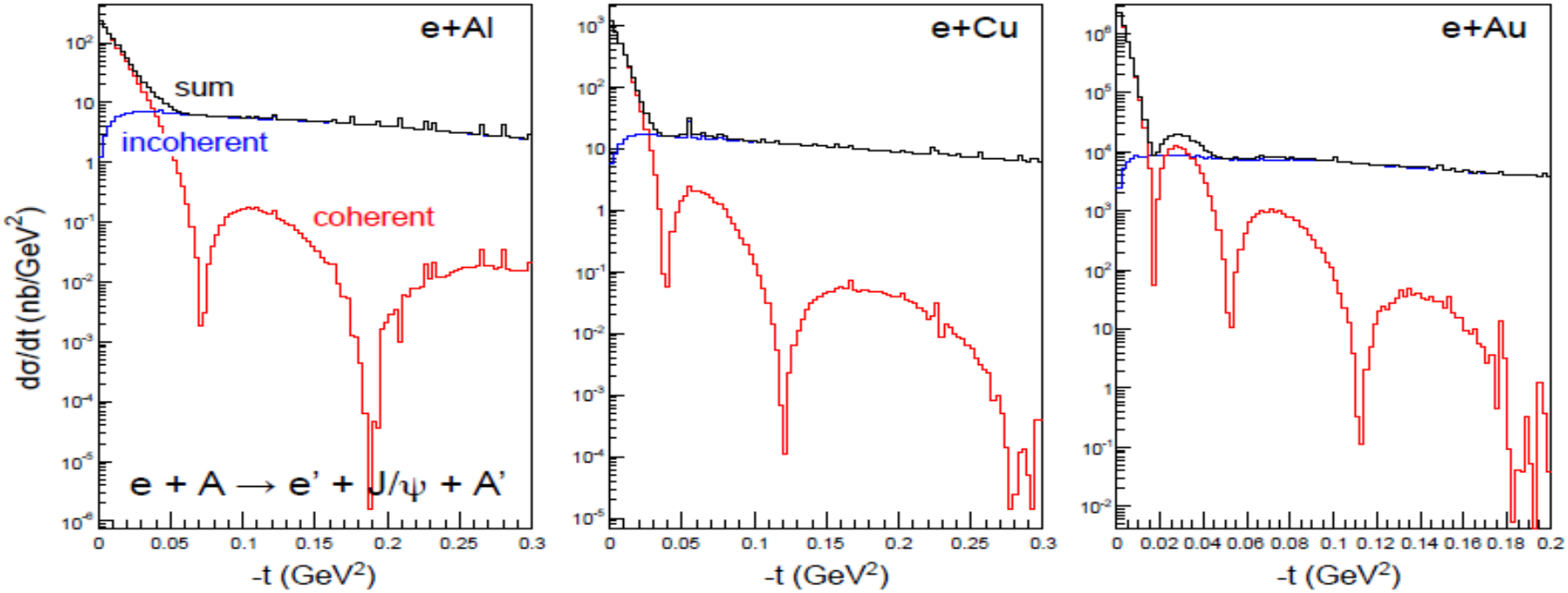
however:

- rejection 10^{-5} of incoherent scattering
- excellent t-resolution required

→ study started



T.Ullrich
DIS 2011



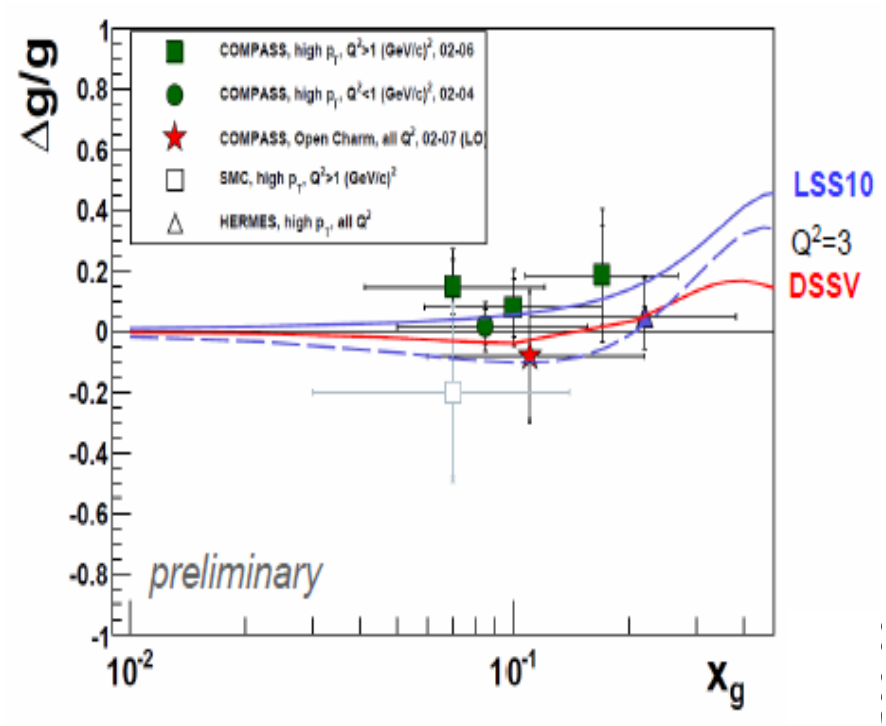
Spin of the Nucleon

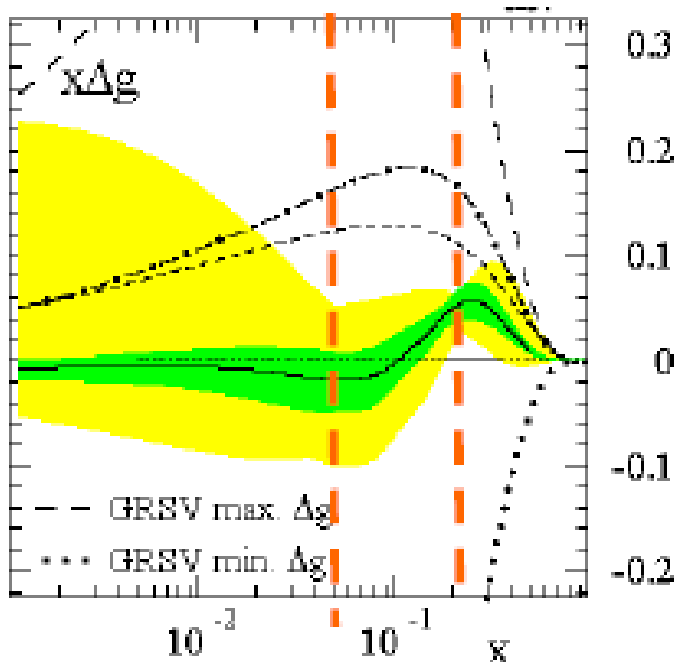
Nucleon Spin: $\frac{1}{2}\Delta\Sigma + \Delta G + L = \frac{1}{2}$ [quarks + gluons + orbital angular momentum]

$$\Delta\Sigma = u + d + s + \bar{u} + \bar{d} + \bar{s};\ \Delta q = \vec{q} - \overleftarrow{q}$$

World data: $\Delta\Sigma \sim 0.3$ and
$\Delta G/G(LO) \sim 0$ for 0.05 < x < 03

ΔG from global fits (DSSM)





Full flavour separation from semi-inclusive DIS-data (HERMES, COMPASS)

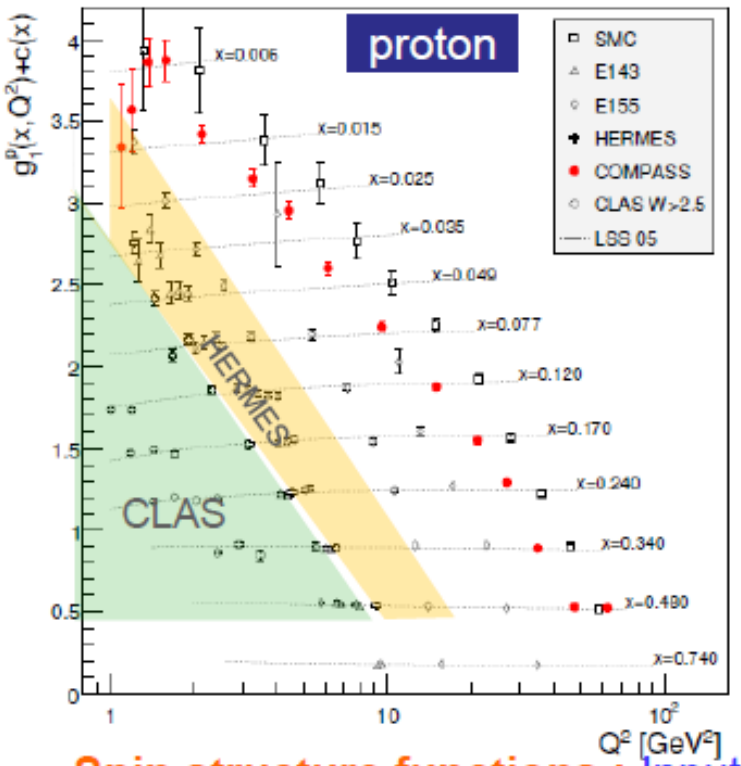
Spin of the Nucleon

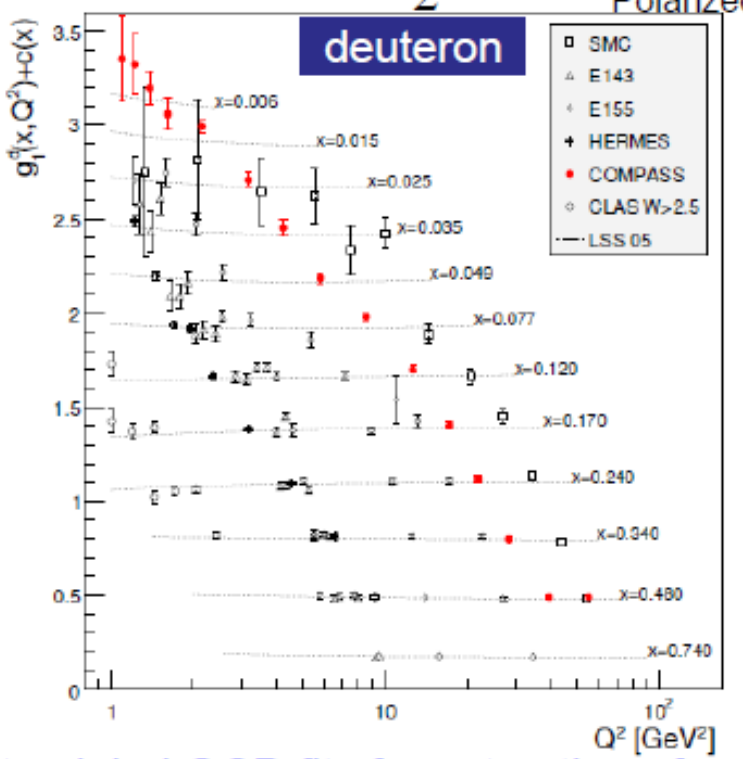
Situation highly unsatisfactory → desperate need of new data

Polarized DIS, spin structure function g_1

$$\sigma_{DIS}^{inclusive} \propto g_1(x) \propto \frac{1}{2}\Sigma e_q^2\left(\Delta q(x) + \Delta\bar{q}(x)\right)$$

Polarized PDFs





Spin structure functions : Input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta G(x)$ using evolution equations.

However x and Q^2 coverage not yet sufficient

Use constraint from pp data (DSSV)

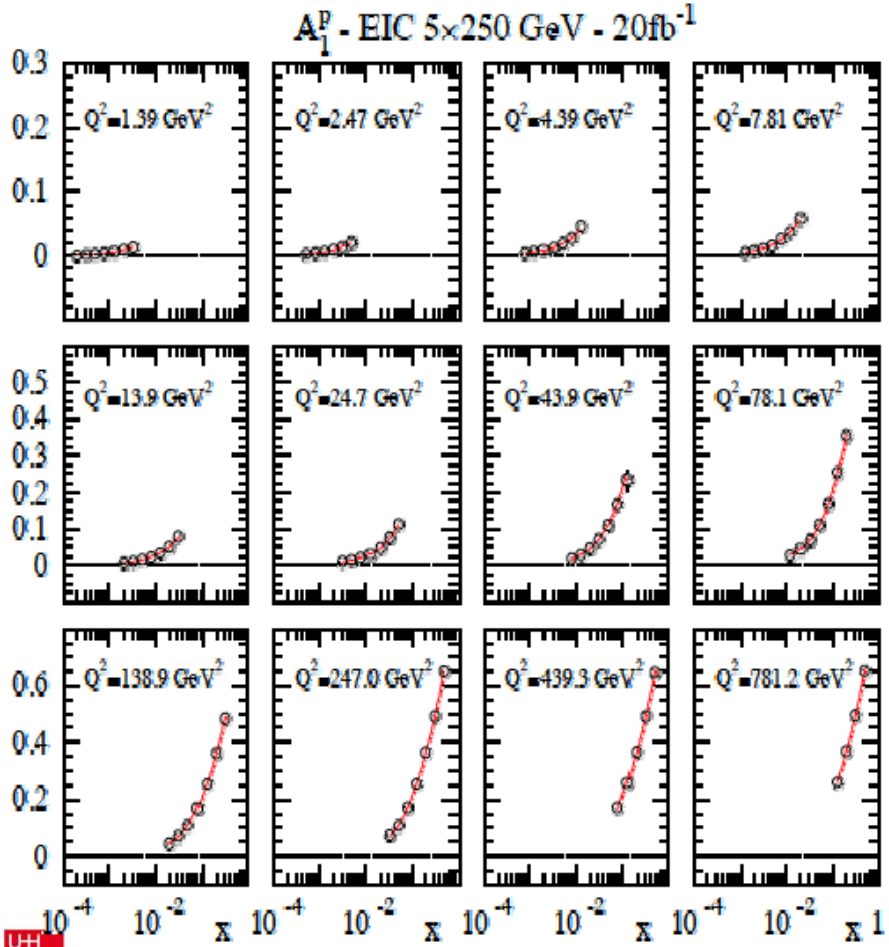
F. Kunne
DIS 2011

EIC and the Spin of the Nucleon

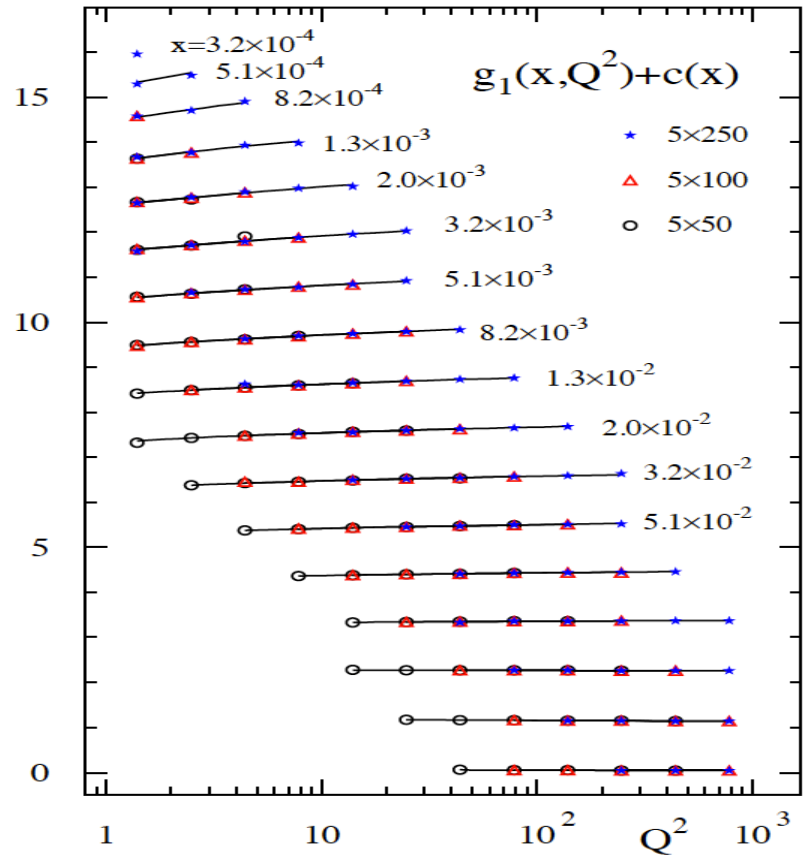
EIC → Simulation has started

Aims: access to lower x + similar precision of polarised SFs as HERA non-pol.

study: Lumi + det. performance required using pseudo-data in global QCD-fits

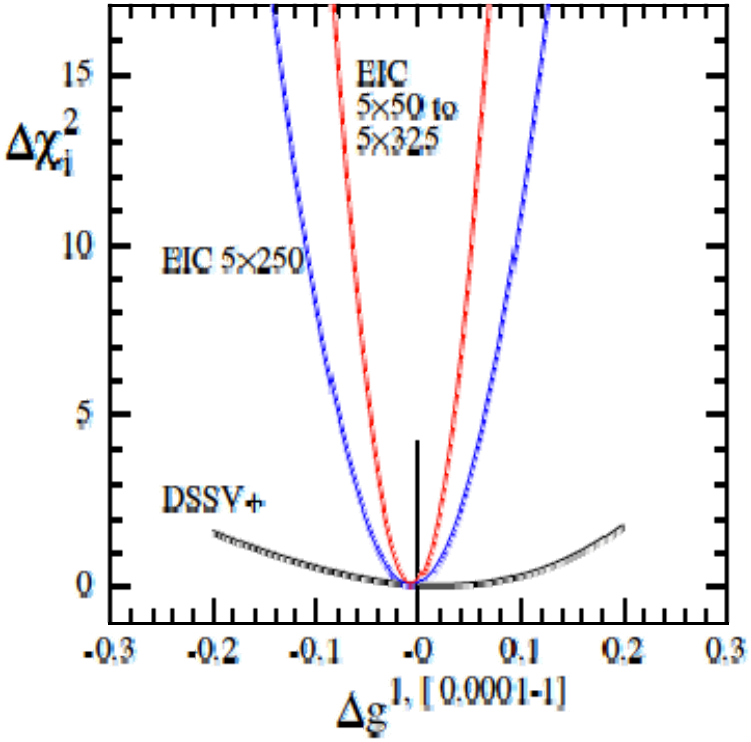


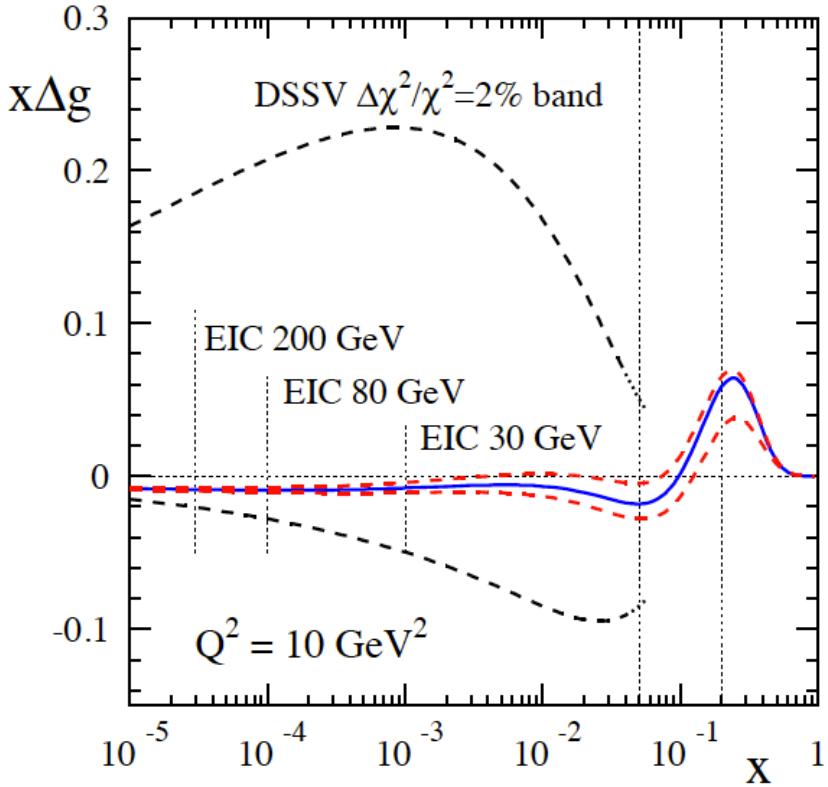
3 x ~1 mo. running of EIC



EIC and the Nucleon Spin

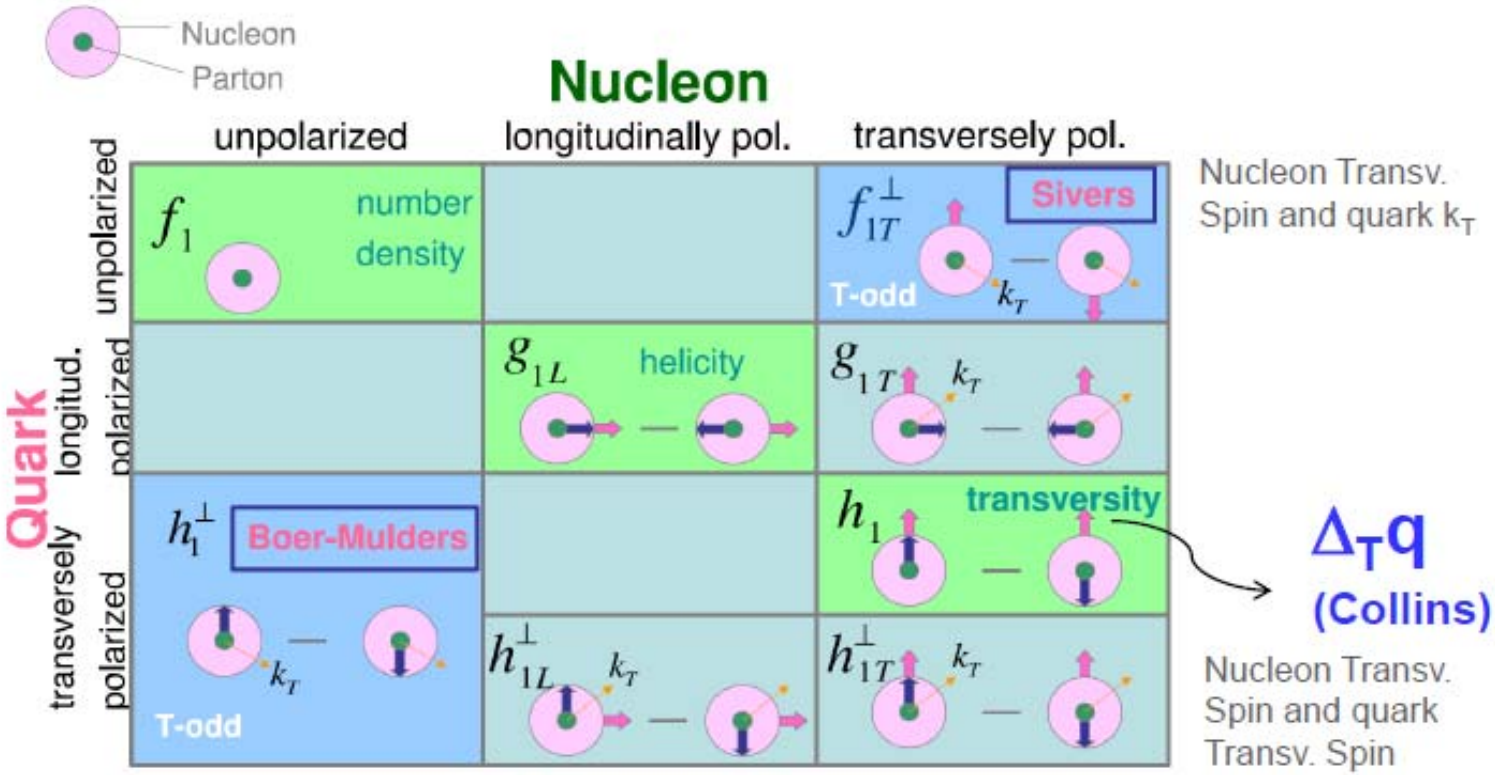
Accuracy of ΔG for ~ 3 mo. EIC running





In addition many tools for reliable flavour separation →
from semi-inclusive DIS ... to ... charged current DIS

Spin of the Nucleon: Many more SFs



Off diagonal: Transverse Momentum (k_T) Dependent

- TMDs express correlations between spin, momentum,…
- Experimentally: azimuthal modulations of outgoing hadron in SIDIS cross section *lp* → *lp h*

Summary: Mapping of Spin and Partons

- A rich, complex and fascinating program – in spite of long-term effort: **We are just at the beginning !**
- Program requires high luminosity and fancy, high quality detectors
- Promising results available from JLAB, HERMES, COMPASS, RHIC and H1/ZEUS
- JLAB12, COMPASS-II and RHIC will make the necessary next big step
- but lots of work will remain for an **EIC** with high luminosity + high energies + high polarization, and detectors with excellent particle identification and large acceptance (also for t → 0).

→ Is the present engagement of experimentalists sufficient to make EIC a reality ???

Outlook and Summary

DIS 2011 has been a most exiting and stimulating workshop

- Attendance 360; O(1) talk/attendant; many young scientists
- Many new expt. results: HERA, RHIC, COMPASS, JLAB, LHC
- Hard and successful work by the theoretical community
- Strong exchanges and interactions between communities

The progress achieved convincingly demonstrates

- New facilities are required to achieve a fuller understanding of the complexity of QCD. DIS is essential for future progress in hep
- Given the time scales (+other boundary conditions) a big step in planning the future has to happen NOW
- Planning = Lots of work on
  - sharpening the physics case (impressive work by theor.colleagues)
  - demonstrating the feasibility of the measurements
  - design + R&D of machines and experiments

Let's profit from the DIS 2011 enthusiasm to strengthen these efforts