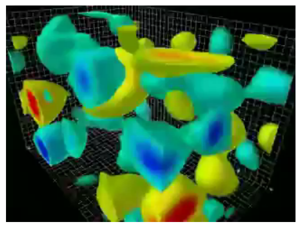
The US Electron Ion Collider: Why? How? When?

Precision study & understanding the role of glue in QCD



March 24, 2011
Lawrence Berkeley National Laboratory

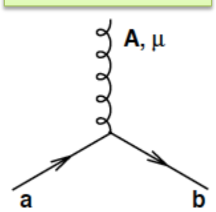
STONY BROOK STATE UNIVERSITY OF NEW YORK

Abhay Deshpande

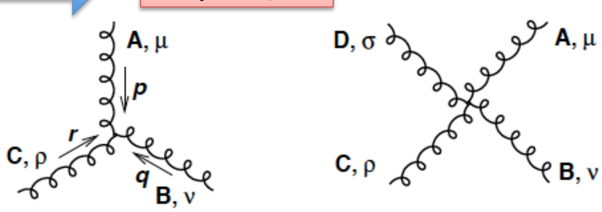
What distinguishes QCD from QED?

- QED is mediated by photons γ which are charge-less
- QCD is mediated by gluons g which *ARE* colored!

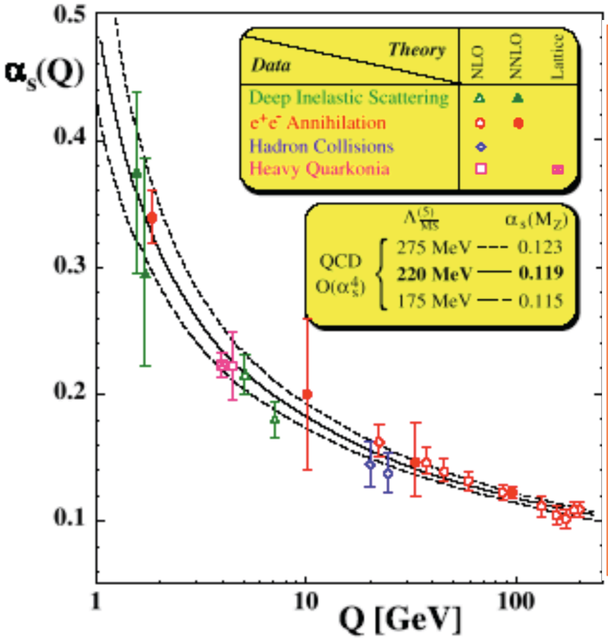
In QCD & g → γ in QED



Only in QCD



What distinguishes QCD from QED?



Asymptotic Freedom ⇔ antiscreening

$$\text{QCD: } \frac{\partial \alpha_s(Q^2)}{\partial \ln Q^2} = \beta(\alpha_s) < 0$$

Compare

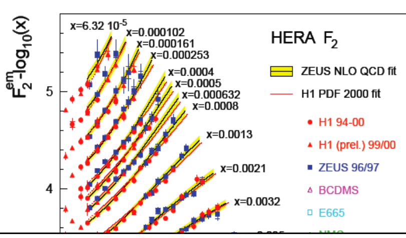
$$\text{QED: } \frac{\partial \alpha_{EM}(Q^2)}{\partial \ln Q^2} = \beta(\alpha_{EM}) > 0$$

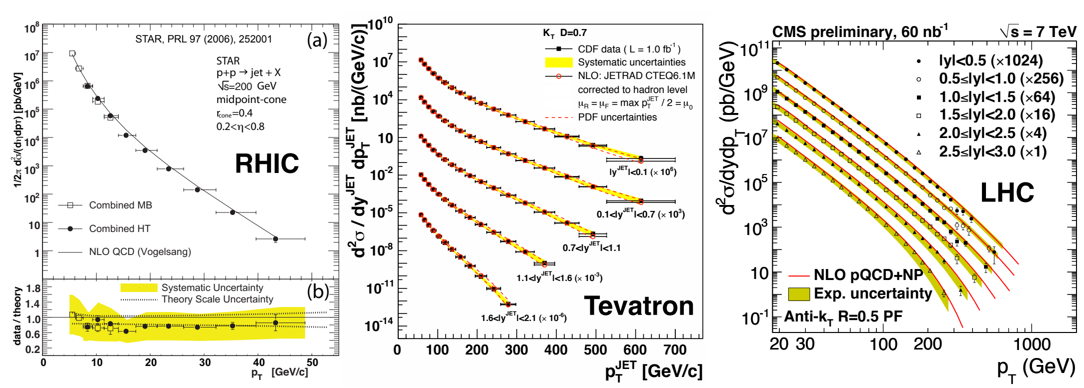
D.Gross, F.Willczek, Phys.Rev.Lett 30, (1973)
H.Politzer, Phys.Rev.Lett. 30, (1973)

2004 Nobel Prize in Physics

Success of pQCD at High Q: Jet Cross section

- Input:
  - $F_2(x,Q^2)$ RA
  - Next to I QCD





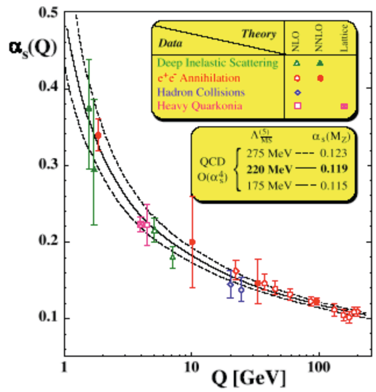
Compilation: J. Putschke

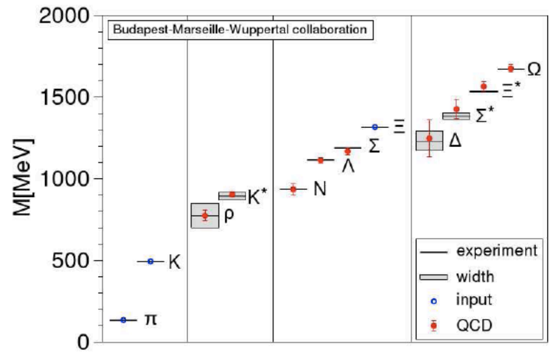
QCD definitely correct, but…

Lattice QCD

- Starting from QCD lagrangian → Static properties of hadrons: hadron mass spectrum

No guidance on partonic dynamics





Durr et al '08

- Perturbation theory ***assuming*** coupling is small
- Problematic at low Q fast rise of $\alpha_S(Q)$

QCD: The SM of Strong Interactions

"Folks, we need to stop "testing" QCD

and start understanding it"

Yuri Dokshitzer

1998, ICHEP Vancouver, BC , Conference Summary Talk

2004 For the discovery of asymptotic freedom in QCD

Do we really "understand" QCD?

While there is no reason to doubt QCD, our level of understanding of QCD remains extremely unsatisfactory: both at low & high energy

- Can we explain basic properties of hadrons such as mass and spin from the QCD degrees of freedom at low energy?
- What ***are*** the effective degrees of freedom at high energy?
- How do these degrees of freedom interact with each other and with other hard probes?
- What can we learn from them about confinement & universal features of the theory of QCD?

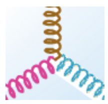
After ~20+ yrs of experimental & theoretical progress, we are only *beginning to understand* the many body dynamics of QCD

What is the role of gluons at high energy?

HOW WELL DO WE UNDERSTAND GLUONS?

Generation of Mass – Gluons in QCD

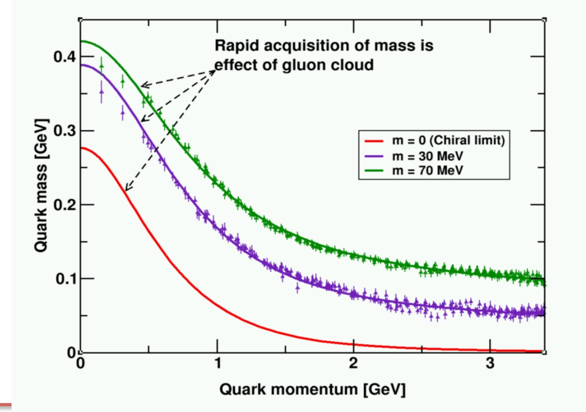
- Protons and neutrons form most of the mass of the **visible universe**
- 99% of the nucleon mass is due to **self generated gluon fields**
  - **Similarity** between p, n mass indicates that **gluon dynamics is identical** & overwhelmingly important

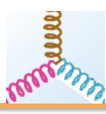


- Lattice QCD supports this

Higgs Mechanism, often credited with mass generation, is of no consequence

Bhagwat et al.





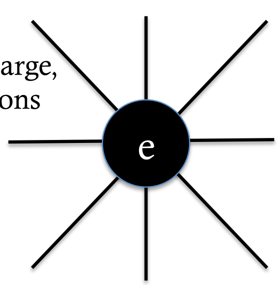
Gluon self-interaction in QCD

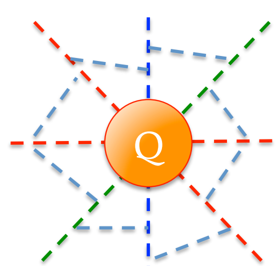
Dynamical generation & self-regulation of hadron masses

F. Wilczek in "Origin of Mass"

Its enhanced coupling to soft radiation… means that a 'bare" color charge, inserted in to empty space will start to surround itself with a cloud of virtual color gluons. These color gluon fields themselves carry color charge, so they are sources of additional soft radiation. The result is a self-catalyzing enhancement that leads to a ***runaway growth****. A small color charge, in isolation builds up a big color thundercloud….****theoretically the energy of the quark in isolation is infinite… having only a finite amount of energy to work with, nature always finds a way to short cut the ultimate thundercloud"***

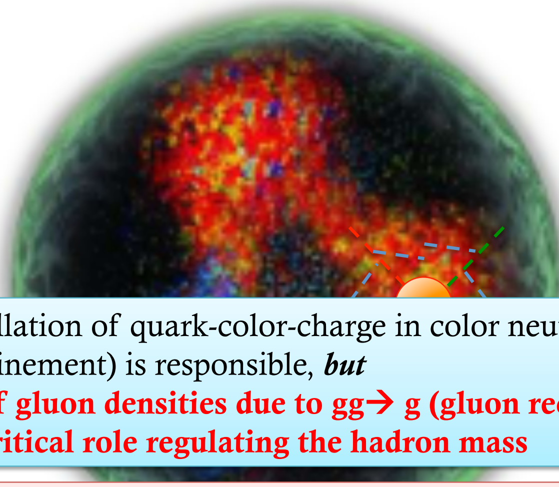
Electric charge, lines: photons





Color charge gluons

What limits the "thundercloud"?

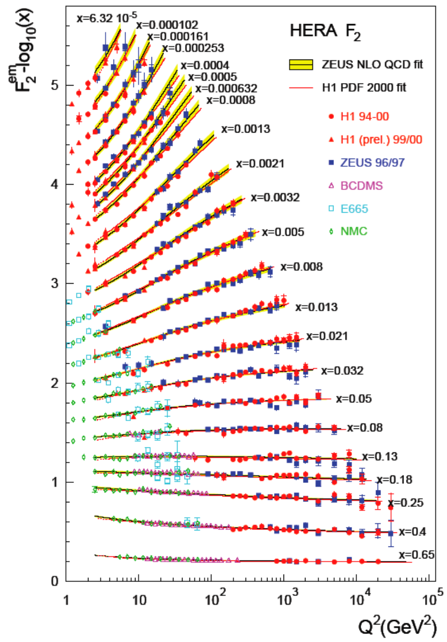


- Partial cancellation of quark-color-charge in color neutral finite size of the hadron (confinement) is responsible, ***but***
- **Saturation of gluon densities due to gg→ g (gluon recombination) must also play a critical role regulating the hadron mass**

Need to experimentally explore and study ***many body dynamics***
a) regions of ***quark-hadron transition*** and
b) non-linear QCD regions of extreme ***high gluon density***

HOW WELL DO WE KNOW GLUONS?

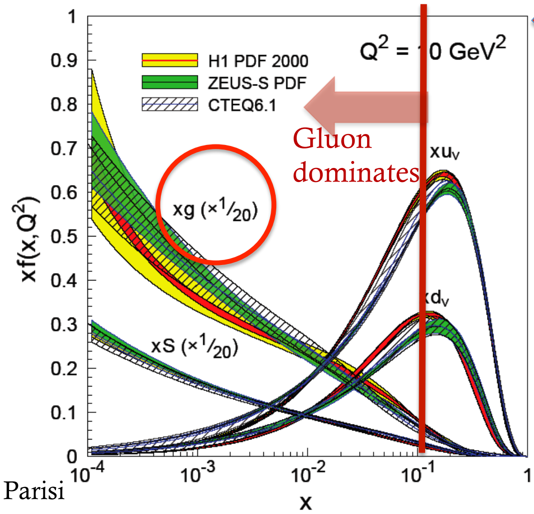
Measurement of Glue at HERA



- Scaling violations of $F_2(x,Q^2)$

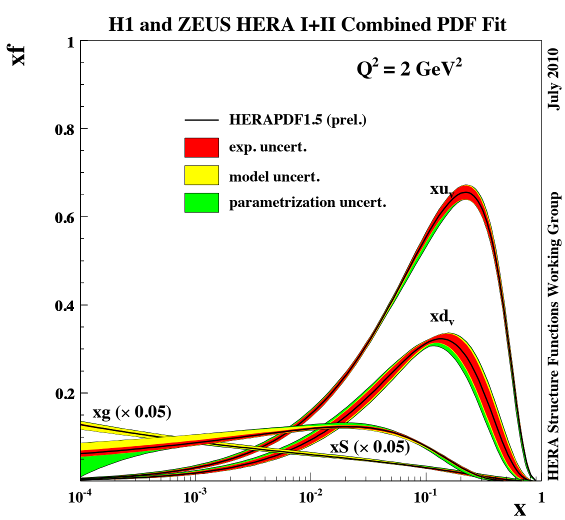
$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto G(x,Q^2)$$

- NLO pQCD analyses: fits with **linear** DGLAP* equations

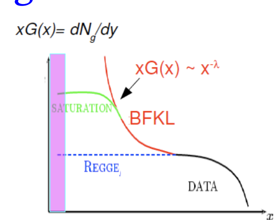


*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

Gluon distribution at low-x understood?



- Indefinite rise: Infinite high energy hadron cross section?
  - Could this be an **artifact** of using of **linear** DGLAP in gluon extraction?



- How would we find out?

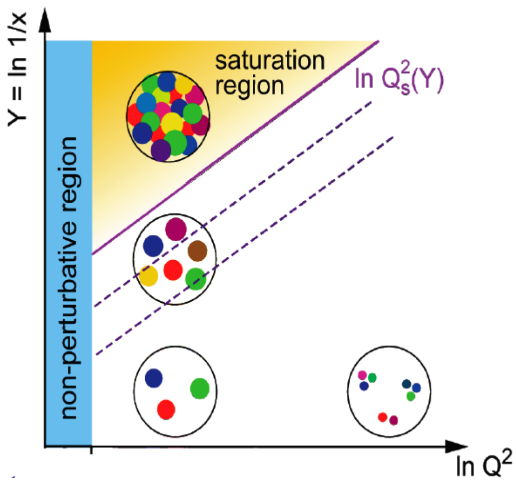
No higher energy e-p collider than HERA!

→ Nuclei, naturally enhance the densities of partonic matter

Why not use Nuclear DIS at high energy?

Low-x, higher twist & Color Glass Condensate

McLerran, Venugopalan… See Review: F. Gelis et al., , arXiv:1002.0333)



Method of including **non-linear** effects in DGLAP equation →

Small coupling, high gluon densities

→ Saturation Scale $\mathbf{Q_S(x,Q^2,A)}$

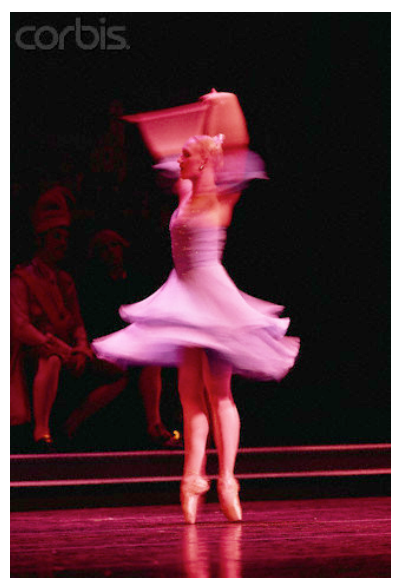
→ Some form of saturation, including Color Glass Condensate

$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

Kowalski
Teany
PRD 68:114005

No unambiguous experimental evidence yet, but many smoking … C!)

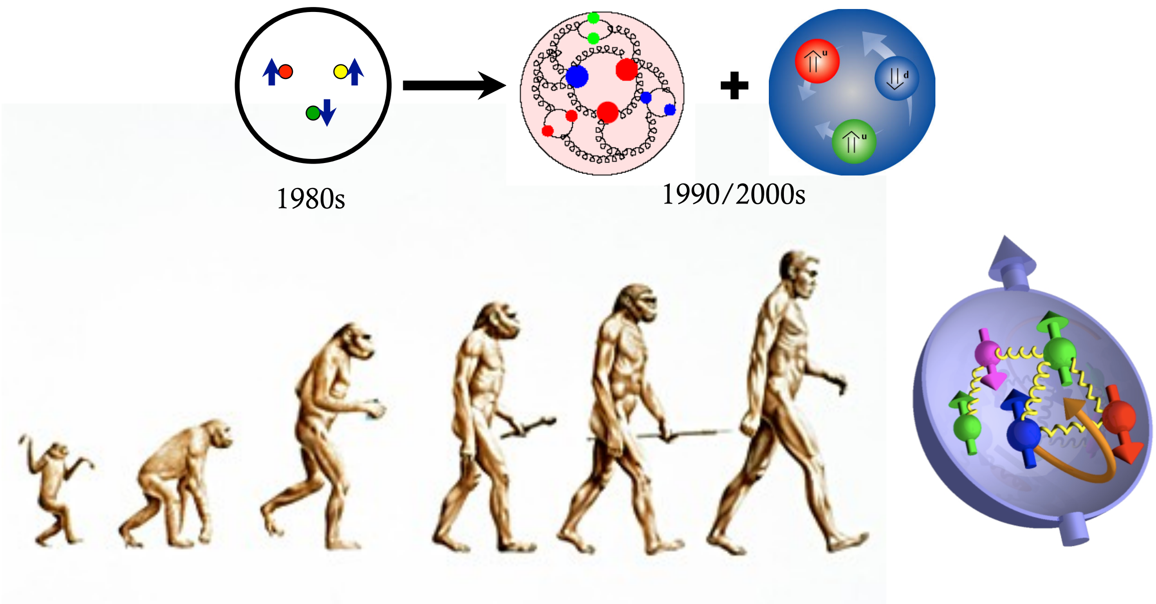
Could be explored cleanly in future with a high energy electron-Nucleus Collider



UNDERSTANDING NUCLEON SPIN:

WHAT ROLE DO GLUONS PLAY?

Evolution: Our Understanding of Nucleon Spin

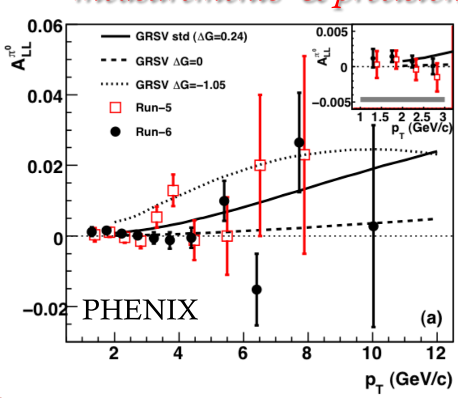


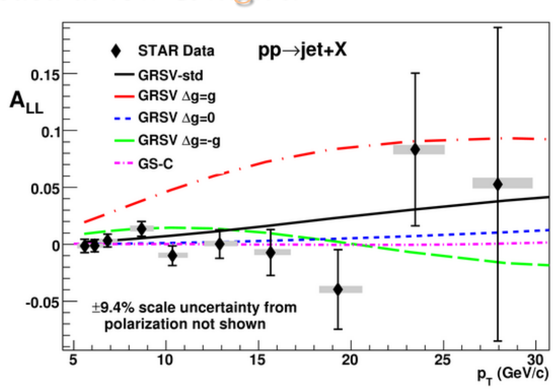
We have come a long way, but do we understand nucleon spin?

Status of "Nucleon Spin ~~Crisis~~ Puzzle"

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta g + L_g$$

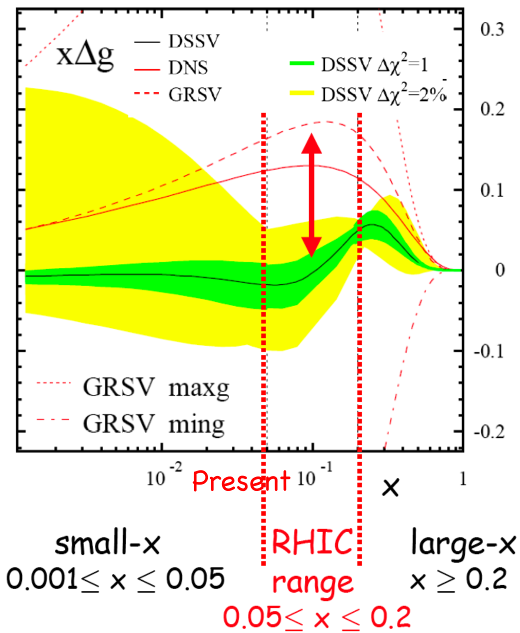
- We know how to determine ΔΣ and Δg precisely: data+pQCD
  - ½ (ΔΣ) ~ 0.15 : From fixed target pol. DIS experiments
  - RHIC-Spin: Δg *not large* as anticipated in the 1990s, but *measurements & precision needed at low & high x*





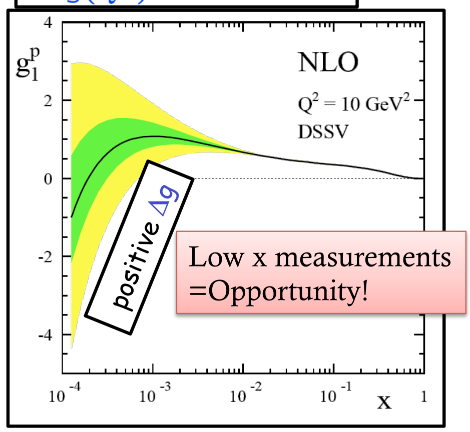
$\Delta g(x)$ @ Q^2=10 GeV^2

de Florian, Sassot, Stratmann & Vogelsang



- **Global analysis: DIS, SIDIS, RHIC-Spin**
- **Uncertainty on ΔG large at low x**

$$\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$



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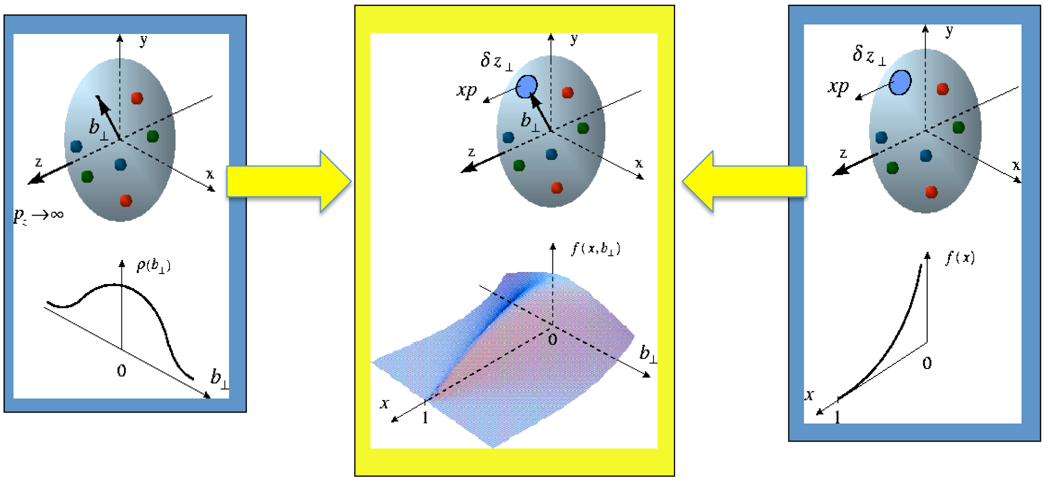
  - ½ (ΔΣ) ~ 0.15 : From fixed target pol. DIS experiments
  - RHIC-Spin: ΔG *not large* as anticipated in the 1990s, but *measurements & precision needed at low & high x*
- Orbital angular momenta: Generalized Parton Distributions (GPDs): H,E,E',H'
  - Quark GPDs: 12GeV@JLab & COMPASS@CERN
  - Gluons @ low x → J_G → will need the future EIC!
- **Would it not be great to have a (2+1)D tomographic image of the proton…. (2: x,y position and +1:momentum in z direction)?**
  - Transverse Momentum Distributions, GPDs of Quarks & Gluons… full understanding of transverse and longitudinal hadron structure including spin!

Beyond form factors and quark distributions

Generalized Parton Distributions

X. Ji, D. Mueller, A. Radyushkin (1994-1997)



Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Unified View of Nucleon Structure

6D Dist.

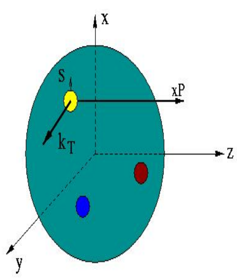
$W_p^u(x,k_T,\boldsymbol{r})$ Wigner distributions

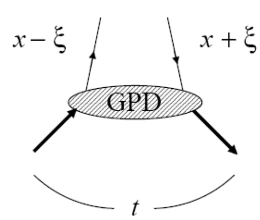
$d^3\boldsymbol{r}$ $d^2k_T\, dr_z$

TMD PDFs $f_1^u(x,k_T)$, .. $h_1^u(x,k_T)$

GPDs/IPDs

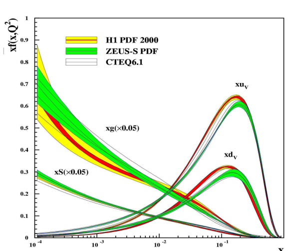
3D imaging





d^2k_T d^2r_T

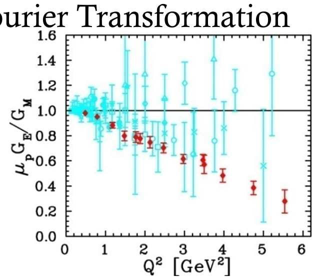
dx & Fourier Transformation



PDFs $f_1^u(x)$, .. $h_1^u(x)$

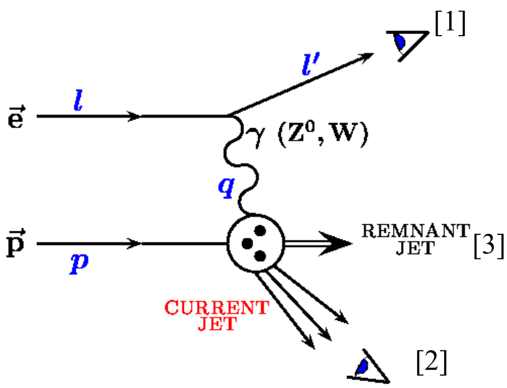
1D

Form Factors $G_E(Q^2)$, $G_M(Q^2)$



The Proposal:

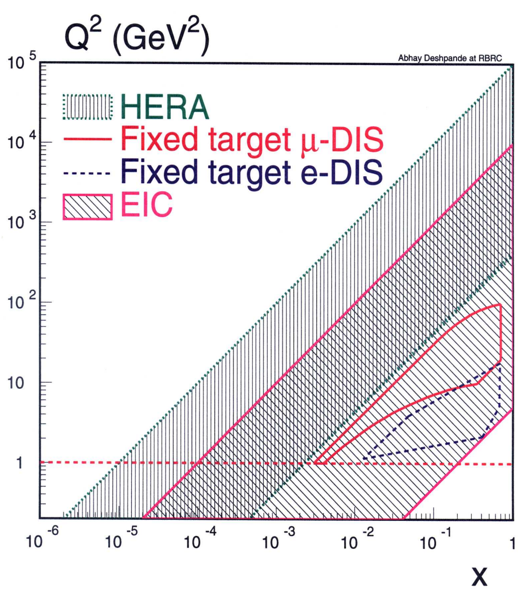
Future DIS experiment at an Electron Ion Collider: A high energy, high luminosity (polarized) *ep* and eA collider and a suitably designed detector



Measurements:
[1] → Inclusive
[1] and [2] **or** [3] →Semi-Inclusiv
[1] and [2] **and** [3] →Exclusive

Inclusive → Exclusive
Low → High Luminosity
Demanding Detector capabilities

EIC : Basic Parameters



- E_e=10 GeV (5-30 GeV variable)
- E_p=250 GeV (50-325 GeV Variable)
- Sqrt(S_{ep}) = 100 (30-200) GeV
- $X_{min} = 10^{-4}$; $Q^2_{max} = 10^4$ GeV
- Beam polarization ~ 70% for e,p
- Luminosity $L_{ep} = 10^{33-34}\ cm^{-2}s^{-1}$
- Minimum Integrated luminosity:
  - 50 fb^{-1} in 10 yrs (100 x HERA)
  - Possible with $10^{33}\ cm^{-2}s^{-1}$
  - Recent projections *much higher*

Nuclei:

- **p->U; E_A=20-100 (140) GeV/N**
- **Sqrt(S_{eA}) = 12-63 (75) GeV**
- **$L_{eA}/N = 10^{33}\ cm^{-2}s^{-1}$**

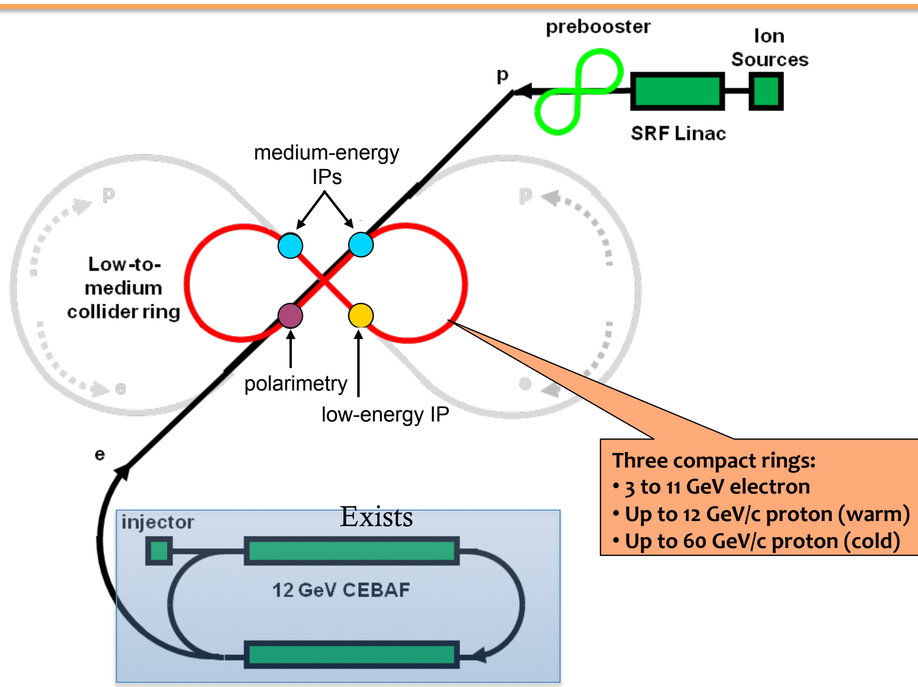
Machine Designs

eRHIC at Brookhaven National Laboratory
using the existing RHIC complex

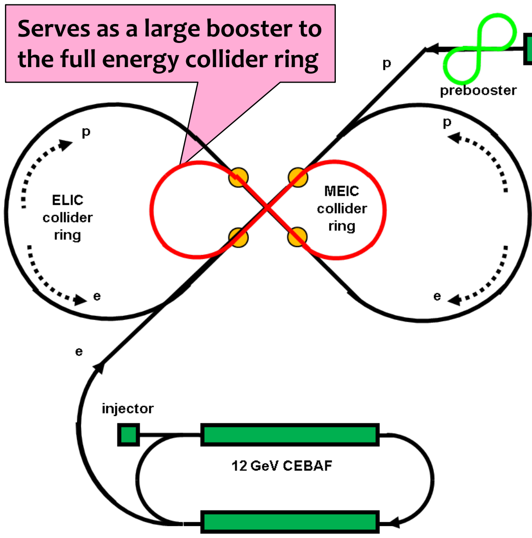
ELIC at Jefferson Laboratory using the
Upgraded 12GeV CEBAF

Both planned to be STAGED

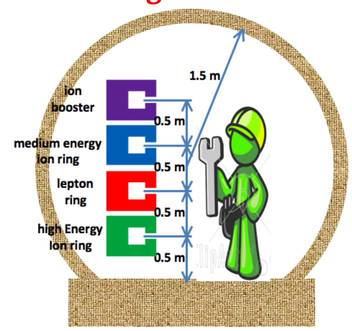
MEIC : Medium Energy EIC



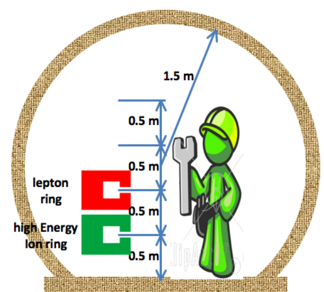
ELIC: High Energy & Staging



Straight section



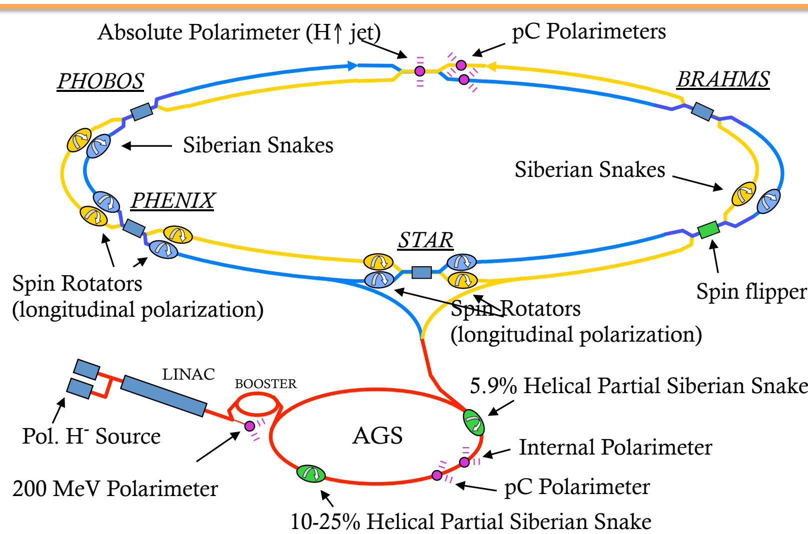
Arc



Stage	Max. Energy (GeV/c)		Ring Size (m)	Ring Type		IP #
	p	e		p	e	
Medium	96	11	1000	Cold	Warm	3
High	250	20	2500	Cold	Warm	4

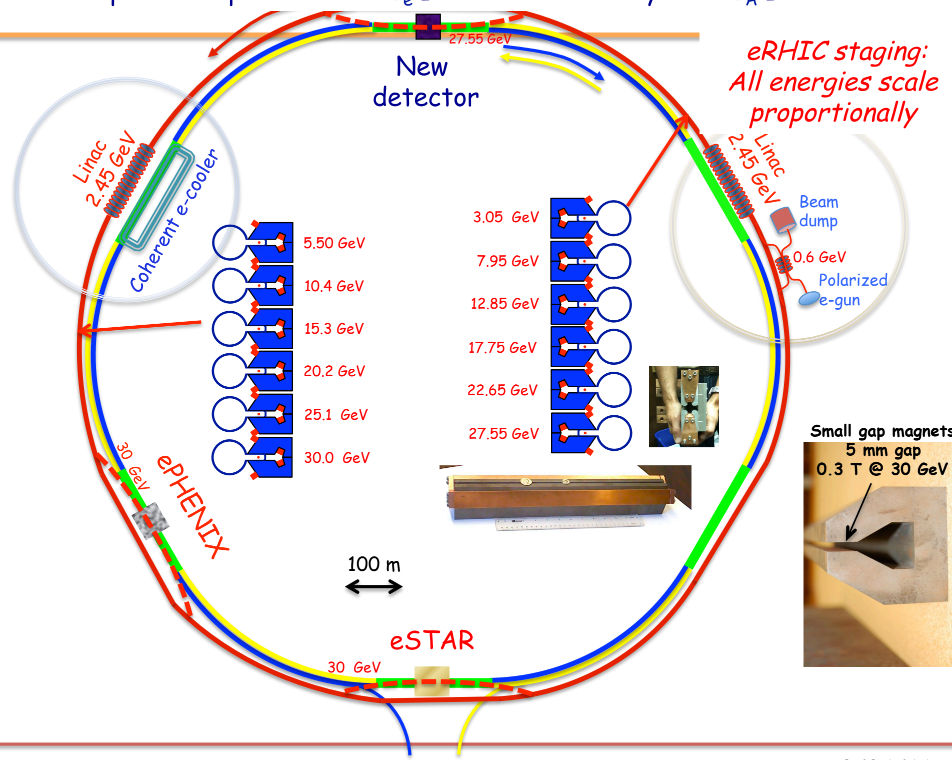
RHIC as a Polarized Proton Collider

Exists!

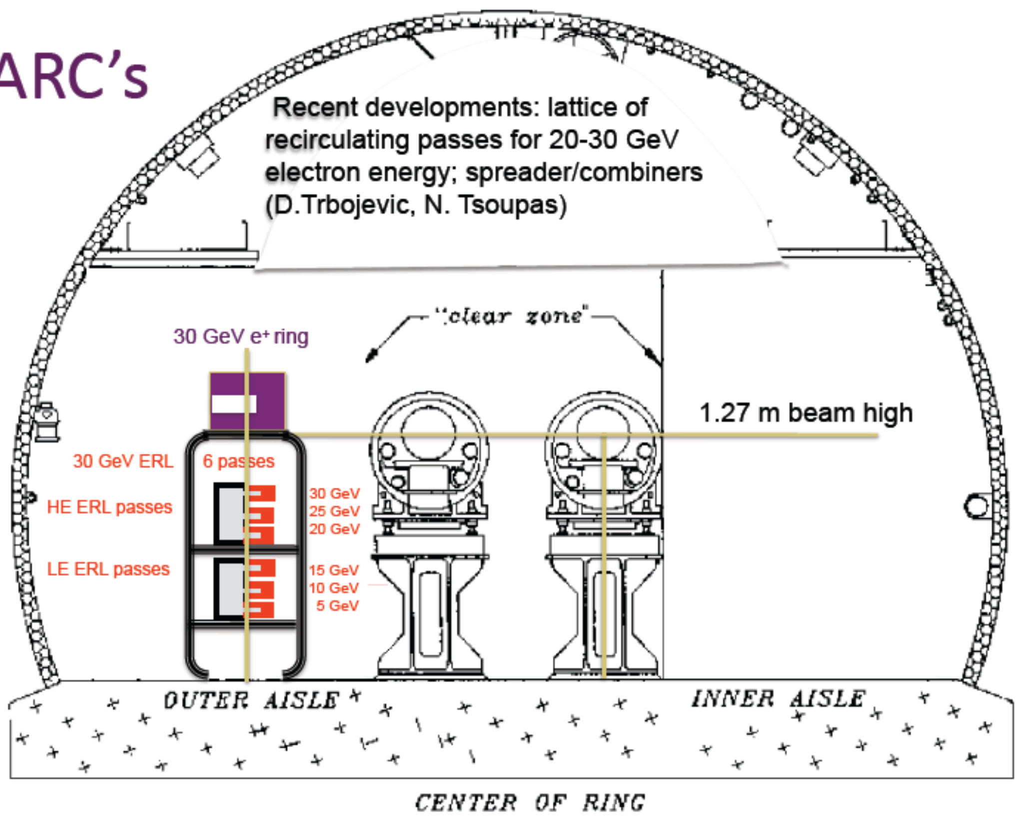


Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79\ E/m \rightarrow$ ~1000 depolarizing resonances
With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½ \rightarrow$ no first order resonance
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

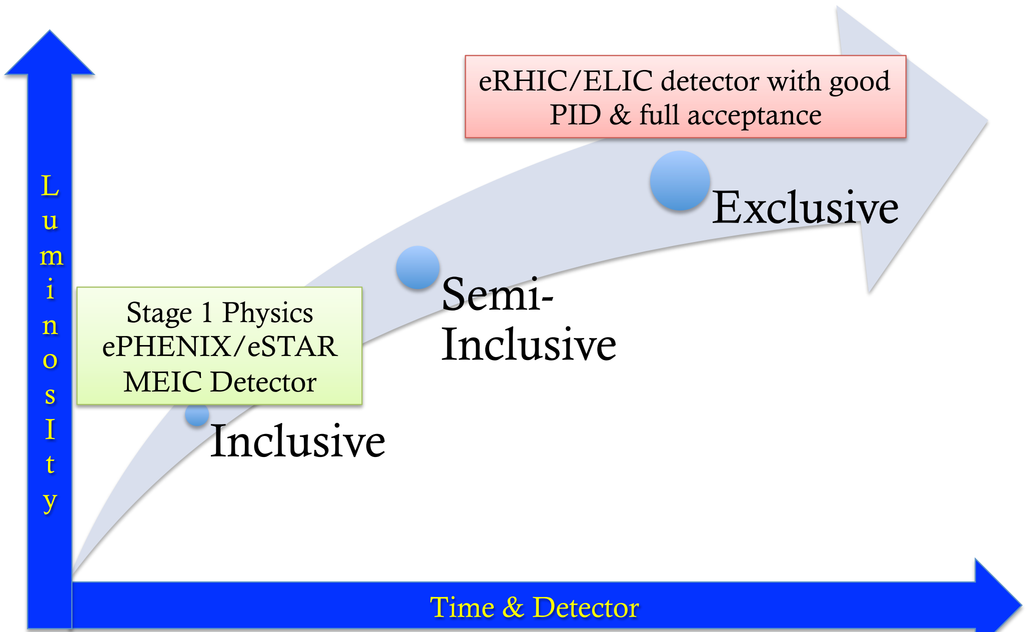
eRHIC: polarized electrons with $E_e \leq 30$ GeV will collide with either polarized protons with $E_e \leq 325$ GeV or heavy ions $E_A \leq 130$ GeV/u



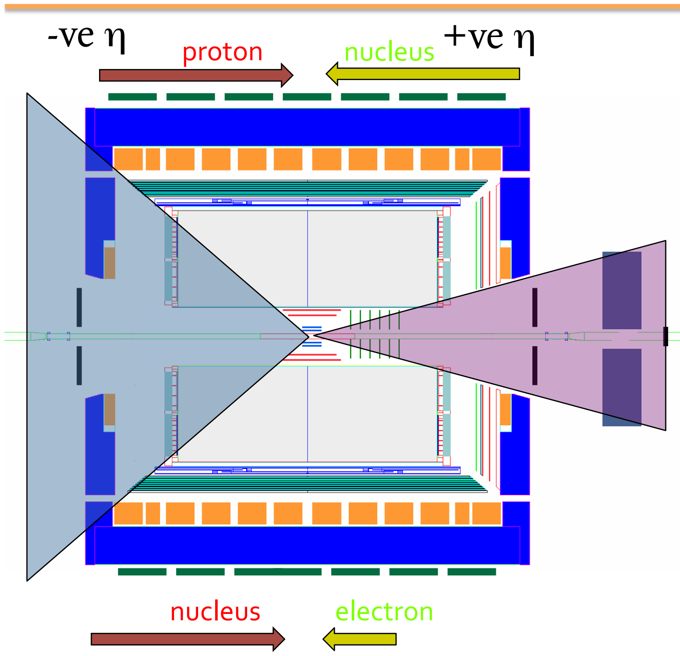
ARC's



EIC Luminosity vs. Time (Detector)



STAR → eSTAR for eRHIC-Stage-1



Positive η: Drell-Yan

2013-2018 will need

High precision tracking

Negative η: eRHIC

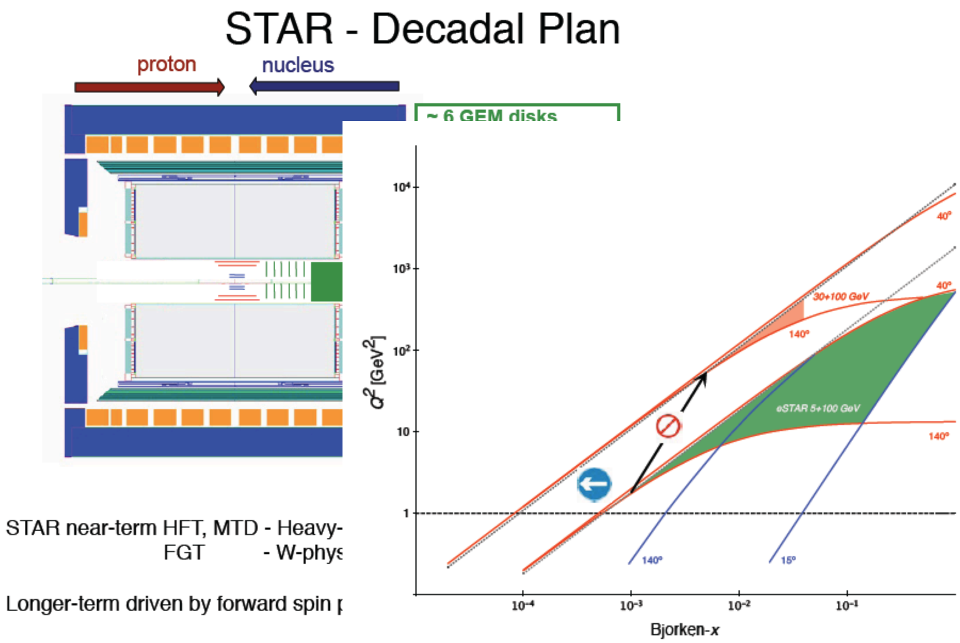
Optimized for low energy scattered electrons (1 GeV)

Tracking, triggering and PID

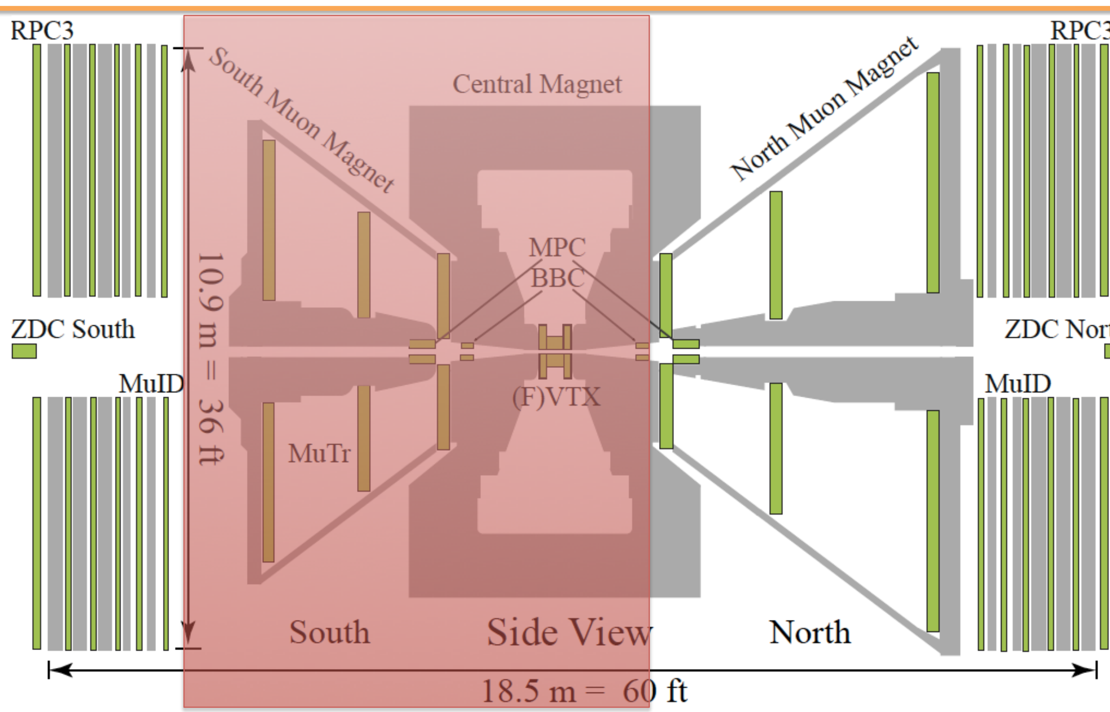
R&D needed for optimization

eSTAR: Stage 1 eRHIC detector

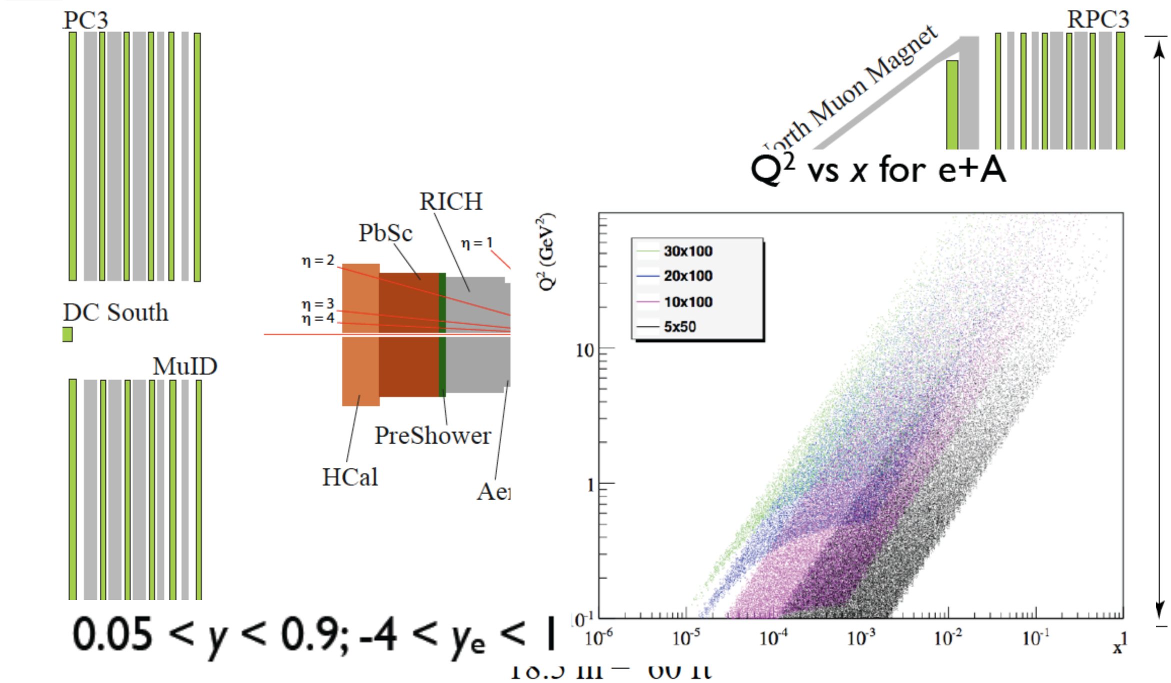
E. Sichtermann



PHENIX "today"



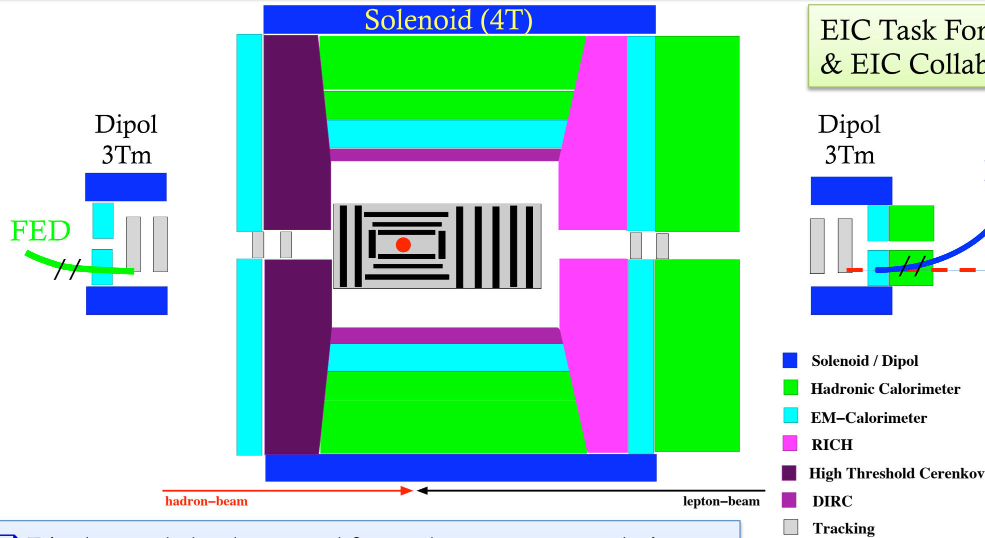
sPHENIX: ePHENIX for eRHIC-Stage-1



FINALLY…. THE eRHIC DETECTOR …. (stage 2?)

First ideas for a "eRHIC" detector

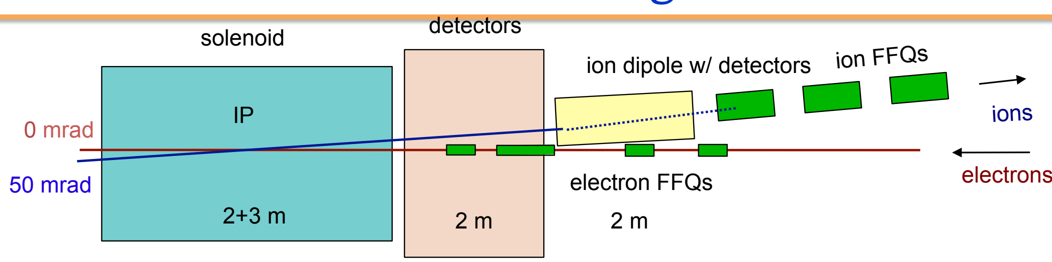
EIC Task Force at BNL & EIC Collaboration

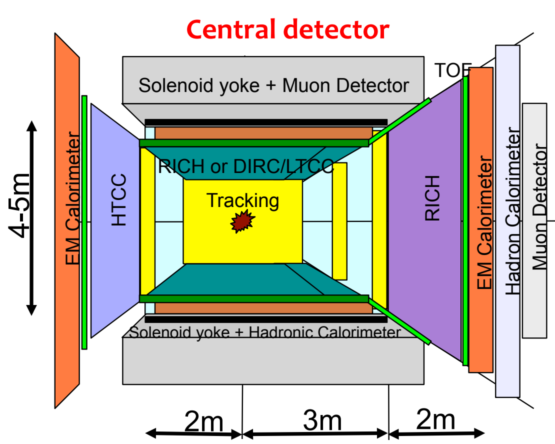


- ❑ Dipoles needed to have good forward momentum resolution
  - ➢ Solenoid no magnetic field @ r ~ 0
- ❑ DIRC, RICH hadron identification → π, K, p
- ❑ high-threshold Cerenkov → fast trigger for scattered lepton
- ❑ radiation length very critical → low lepton energies

Detector Location IP12

Detector & IR Design: ELIC





Detect particles with angles down to 0.5° before ion FFQs. Need 1-2 Tm dipole.

Detect particles with angles below 0.5° beyond ion FFQs and in arcs.

Very-forward detector

Large dipole bend @ 20 meter from IP (to correct the 50 mr ion horizontal crossing angle) allows for **very-small angle detection (<0.3°)**

Nadel-Turonski, Horn, Ent And EIC Collaboration

Institute of Nuclear Theory (INT) at U. of Washington Workshop: September – December 2010, organized by:

D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang

Some "golden" Measurements (simulations) & Impact of EIC….

Measurement of Gluons at Low x

- $F_2(x,Q^2)$ and its **scaling violations** of Nucleons & Nuclei
- **Diffractive cross section**
  - HERA surprise: 10-14% of total cross section diffractive
  - CGC suggests in e-A one would find 30-40% diffractive
- Structure function F_L

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

$$Q^2 = Sxy$$

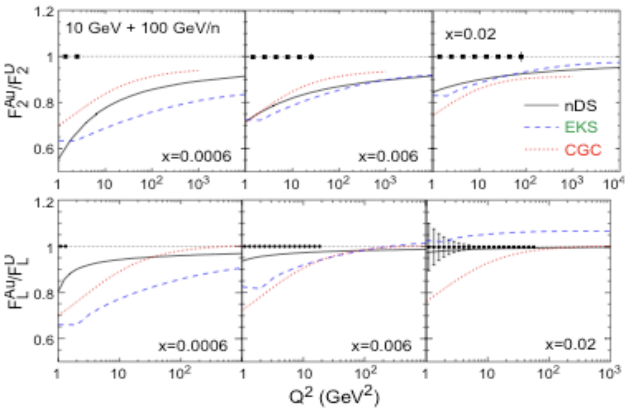
Quarks and anti-quarks

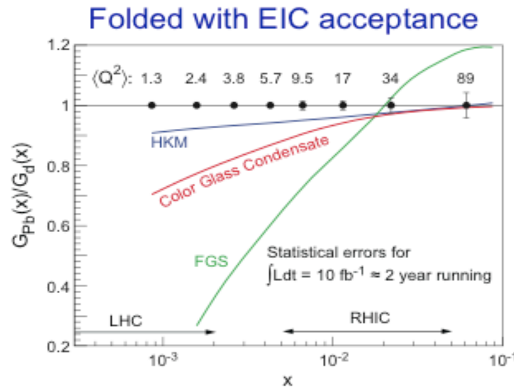
Gluon momentum distribution

  - Needs **change of beam energies** to directly measure F_L

Preliminary e-A simulations

Simulations to demonstrate the quality of EIC measurements



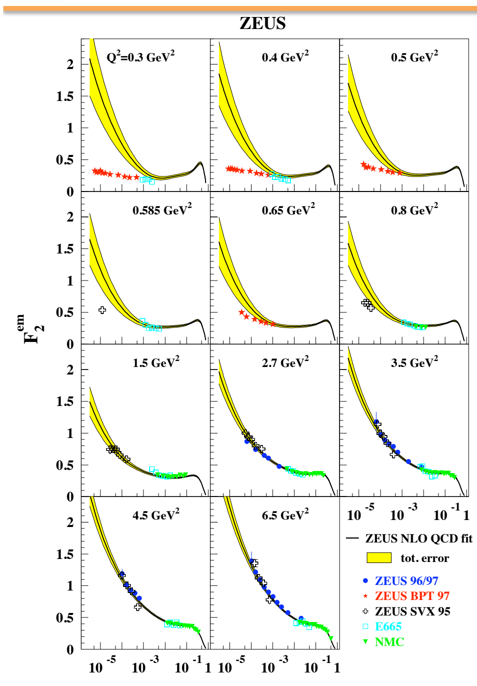


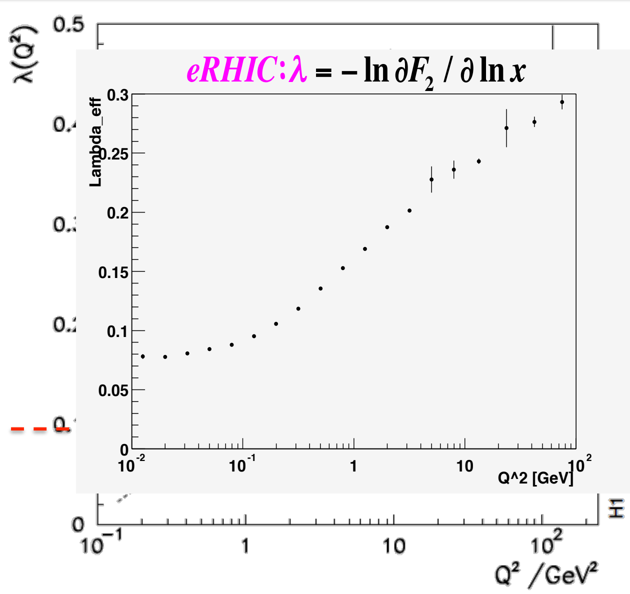
$F_L \sim \alpha_s\, G(x,Q^2)$ requires $\sqrt{s}$ scan, $Q^2/xs = y$

Assume:
$L = 3.8\ 10^{33}\ cm^{-2}\ s^{-1}$ (100x Hera)
T = 10 weeks
duty cycle: 50%
L ~ 1/A (approx)
$\int Ldt = 11\ fb^{-1}$

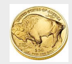
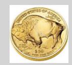
Plots above:
$\int \mathcal{L}dt$ = 4/A fb^{-1} (10+100) GeV
= 4/A fb^{-1} (10+50) GeV
= 2/A fb^{-1} (5+50) GeV
statistical error only

Transition from hadrons to partons?

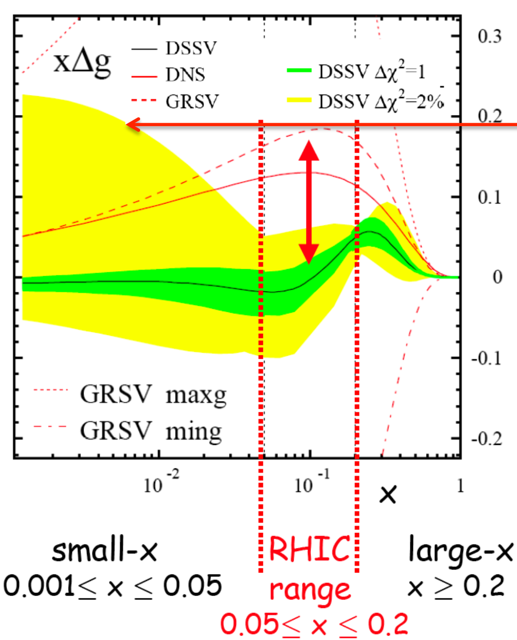


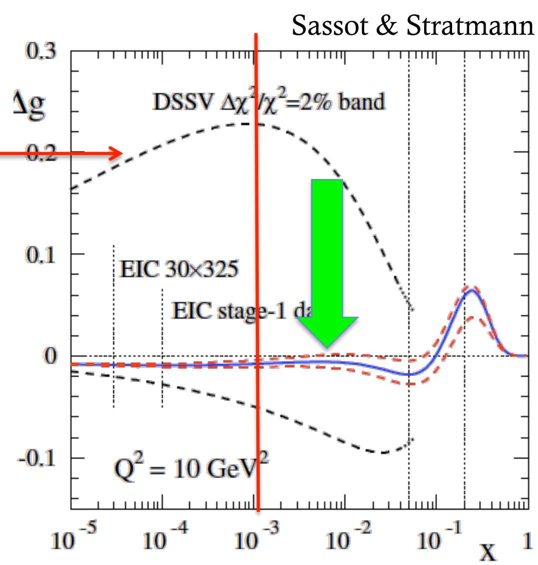


- Does the change in slope λ have something to do with "confinement"?

Science Deliverable	Basic Measurement	Uniqueness and Feasibility	Requirements
spin structure at small x contribution of Δg, ΔΣ to spin sum rule	inclusive DIS	✔ 	minimal large x,Q^2 coverage about 10fb^{-1}
full flavor separation in large x,Q^2 range strangeness, $s(x)$-$\bar{s}(x)$	semi-inclusive DIS	✔ 	very similar to DIS particle ID improved FFs (Belle,LHC)
electroweak probes of proton structure flavor separation electroweak parameters	inclusive DIS at high Q^2	✔  some unp. results from HERA	20x250 to 30x325 positron beam polarized ^{3}He beam
treatment of heavy flavors in pQCD	DIS (g_1, F_2, and F_L) with tagged charm	✔  some results from HERA	large x,Q^2 coverage charm tag
(un)polarized γ PDFs relevant for γγ physics at an ILC	photoproduction of inclusive hadrons, charm, jets	✔  unp. not completely unknown	tag low Q^2 events about 10 fb^{-1}

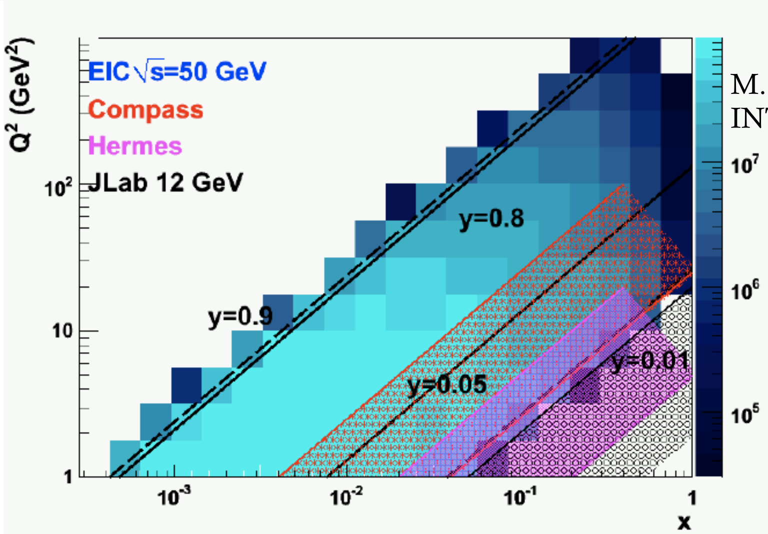
Nucleon Spin: Precision measurement of ΔG





Yellow band (left) reduces to the band shown with **red dashed line** (right)

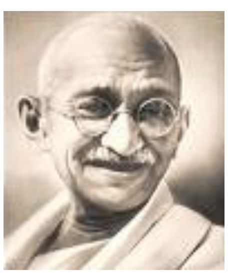
TMD Measurements @ EIC



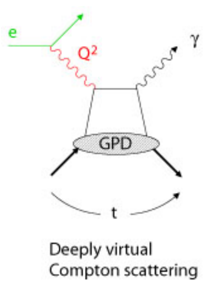
M. Anselmino et al
INT'10 proceedings

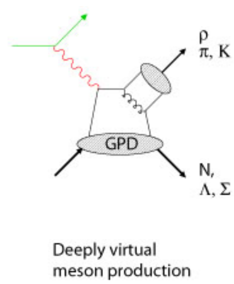
Figure 6: Colour online. Kinematic coverage in x and Q^2 for the EIC for an energy setting of $\sqrt{s} = 50$ GeV compared to the coverage of COMPASS, HERMES and future JLab12 experiments represented by the red, purple and black hatched areas, respectively.

Proton Tomography: GPDs
Orbital Angular Momenta?



Nonviolent collisions:





$$\text{Nucleon Spin} = \frac{1}{2} = J_{\text{quark}} + J_{\text{gluons}}$$

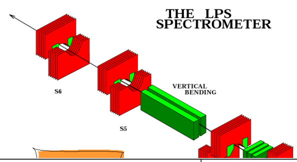
$$J_q = \frac{1}{2}\Delta\Sigma + L_q \qquad GPDs: H, E, \tilde{H}, \tilde{E}$$

$$J_q = \frac{1}{2}\int_0^1 xdx\,[H(x,t,\zeta) + E(x,t,\zeta)]$$

Similar expression for gluon J_g total spin contribution through DVVM
Needs measurements over a wide range in each of the variables

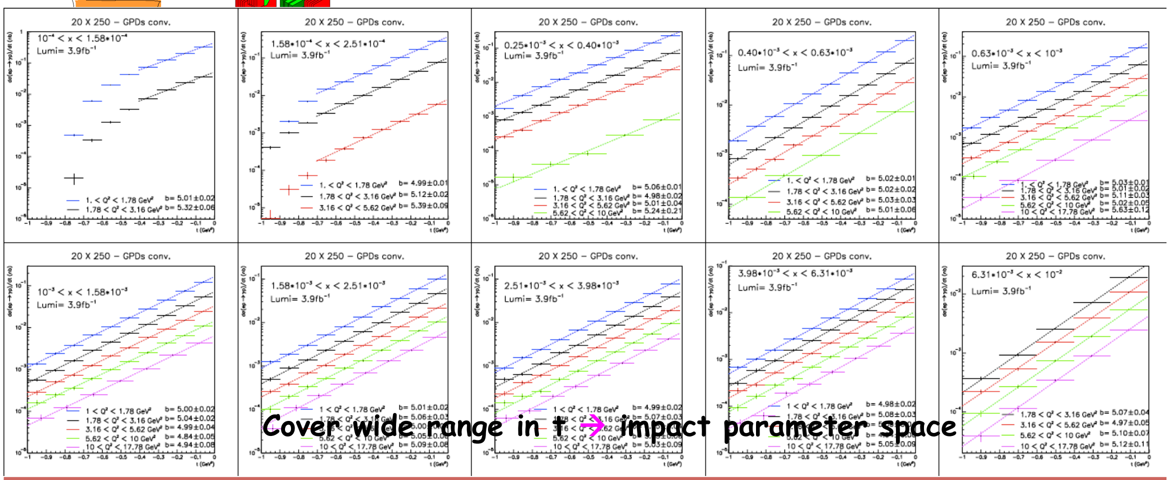
DVCS at EIC/eRHIC

Goal: measure t over a wide range
We'll get roman pots in the forward region at EIC!



Silicon micro-strips resolution:
0.5% for P_L
5 MeV for P_T

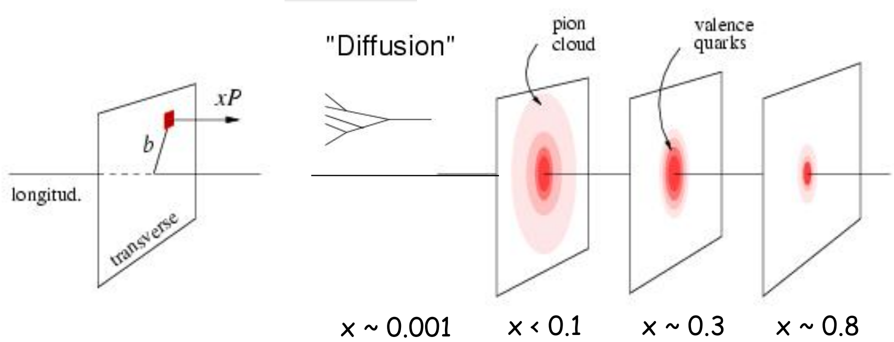
EIC/eRHIC with 4 fb^{-1} in a week could get:



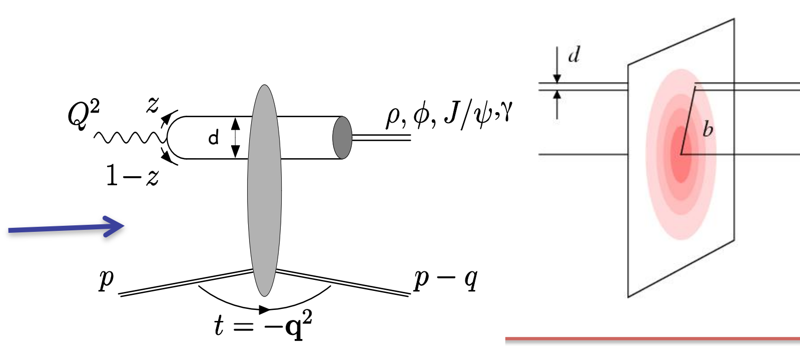
Cover wide range in t → impact parameter space

GPDs and transverse parton imaging

Fourier transform in momentum transfer



EIC:
1) x < 0.1: gluons!
2) ξ ~ 0 → the "take out" and "put back" gluons act coherently.



Summary: Science of EIC: Precise Investigations of the "Glue"

- Study of extreme high gluon densities via inclusive and sem-inclusive DIS off a wide range of nuclei and energies

Nucleon (spin) Structure:

- Precision measurements of Sea Quarks and Gluon's Spin via inclusive and semi-inclusive DIS including EW probes of the hadron structure → Spin puzzle
- Measurement of (gluon) GPDs & TMDs: via semi-inclusive and exclusive DIS → **wide range in x and Q^2**
  - 3D momentum and position (correlations) of the nucleon → Possibly leading to orbital angular momentum → Spin puzzle

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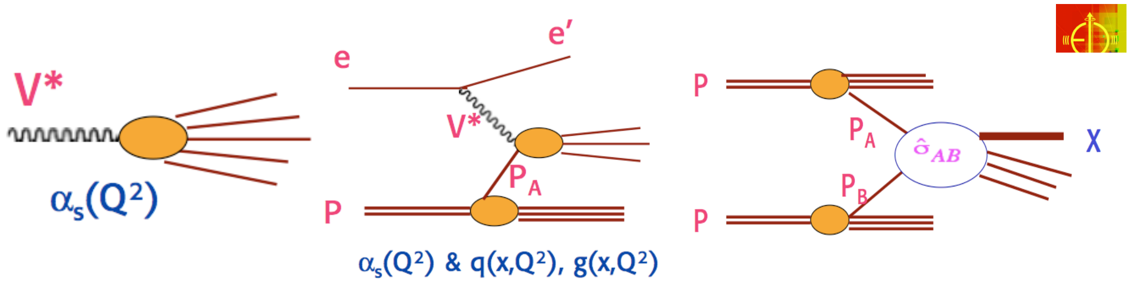
- High energy, beam polarization, and a full acceptance detector: why not explore precision electroweak physics and EW (spin) structure functions

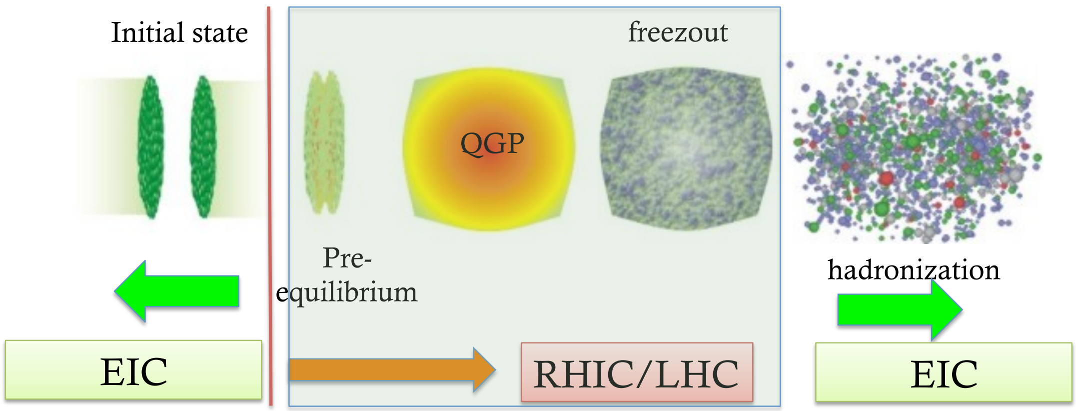


- Experimental tools of high energy physics:
  - e-e (ho hadron: LEP, BELLE, BaBar), e-p (one hadron: HERA), p-p (two hadrons: SppS, Tevatron… now at LHC)

Progress in physics needed continuous interplay amongst different techniques to take the full advantage of their complementarity

EIC will allow us to include nuclei in this game!

EIC and RHIC/LHC (Heavy Ion)



A decadal plan is being launched to characterize the "QGP"
To understand "QGP" fully, we need to understand:
The initial state i.e. the nucleus & hadronization
Deeper Connection: many body interactions of parton in QCD

An analogy….

- QED: understanding the interactions of electric & magnetic charges + including quantum mechanics + relativity
  - Condense Matter Physics is its natural outgrowth in to taking QED *of many body systems*
  - Complicated, but extremely important and rich!
  - Much learnt by collective phenomena, many Nobels!

- QCD: understanding the interactions of color charge leading to fundamental understanding of strong interactions….
  - *Heavy Ion Physics and the physics EIC are essential components for the next step: MANY BODY SYSTEMS IN QCD*
  - *"Condense Matter Physics equivalence of QCD"*

EIC Project status and plans

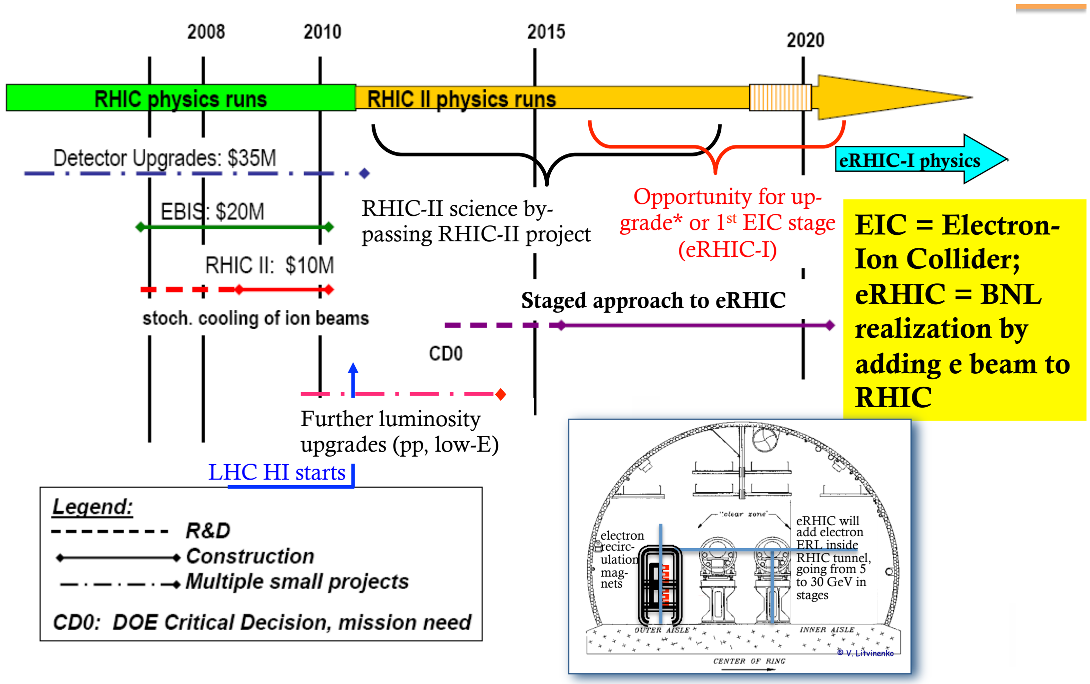
- A “collaboration” of highly motivated people/groups intends to take this project to realization:
  - EIC Collaboration **Web Page: http://web.mit.edu/eicc/**
  - 100+ dedicated physicists from 20+ institutes
  - Details of many recent studies: Recent Workshop @ INT at U. of Washington**: http://www.int.washington.edu**
  - Working groups/ Task Forces at BNL and at Jefferson Laboratory
  - Steering Group, co-chairs/contact: R. Milner (MIT) & AD (SBU)

- International Advisory Committee formed by the BNL & Jlab Management to steer this project to realization: *W. Henning (ANL, Chair), J. Bartels (DESY),A. Caldwell (MPI, Munich) A. De Roeck (CERN), D. Hetrzog (U of W), X. Ji (Maryland), R. Klanner (Hamburg), A. Mueller (Columbia), K. Oide (KEK), N. Saito (J-PARC), U. Wienands (SLAC)*

- Plan to go to the NSAC Long Range Plan (2012/13) with the science case & machine/detector designs (including costs & realization plans)

S. Vigdor, BNL Associate Director

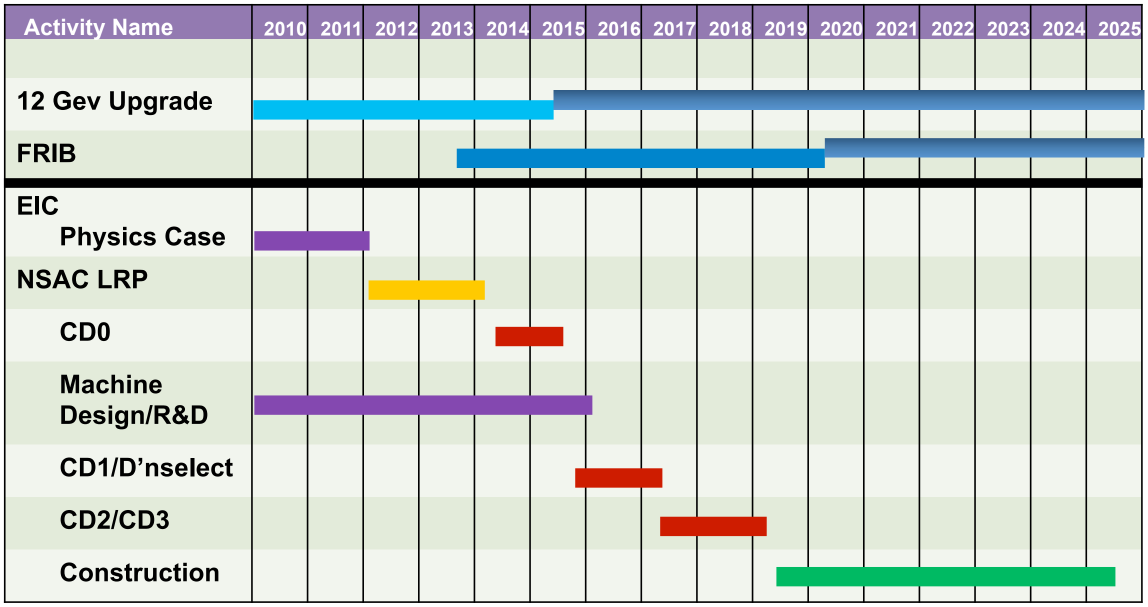
A Long Term (Evolving) Strategic View for RHIC



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

H. Montgomery, Jeff. Laboratory Director

EIC at JLab Realization Imagined



Summary

Science Case for EIC: → "Understand QCD" *a la* Dokshitzer

"Precision study of the role of gluons in QCD"

Many body dynamics in QCD is an essential part of this study

Will enable us to understanding the nucleon & nuclei at high energy including possibly (EW probes of hadron structure & beyond… *not mentioned today*)

The Collaboration & the BNL+Jlab managements are moving (*together*) towards realization: *NSAC approval 2013 → Next Milestone*

- Machine R&D, detector discussions, simulation studies towards making the final case including detailed detector design and cost considerations

INVITATION: Ample opportunities to get involved and influence the design of this machine according to your own physics interests and participate in the exciting quest for understanding of QCD!