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

Understanding the role of gluons in QCD

Abhay Deshpande

Stony Brook University

QCD

"Folks, we need to stop "testing" QCD

and start <u>understanding</u> it"

Yuri Dokshitzer

1998, ICHEP Vancouver, CA in his Summary Talk

2004 For the discovery of asymptotic freedom in QCD





Do we understand QCD?

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

- We don't understand the basic properties of hadrons such as mass and spin from the QCD degrees of freedom
- We don't understand what the effective degrees of freedom at high energy are
- We don't understand how 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?

We are only beginning to explore the high energy many body dynamics of QCD

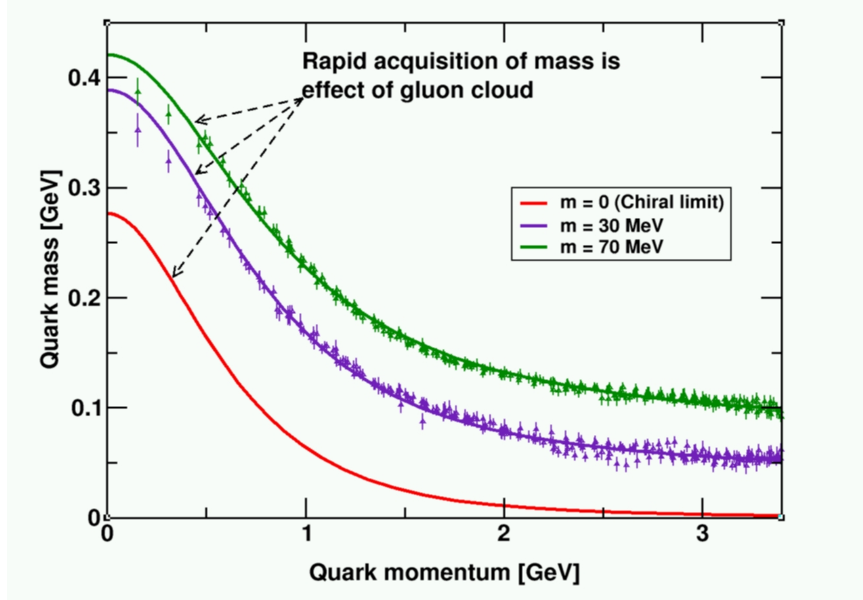
ORIGIN OF MASS….

Origin of Mass – Gluons in QCD

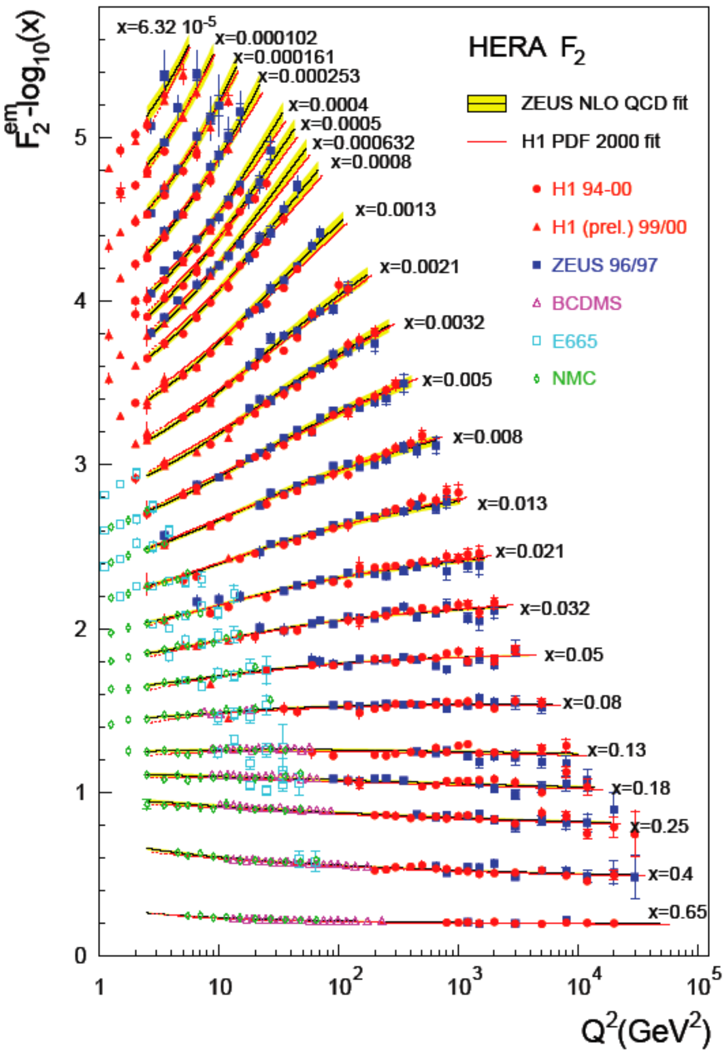
- Protons and neutrons form most of the mass of the **visible universe**
- 99% of the nucleon mass is due to **self generated gluon fields**
  - **Similarity** between p, n mass indicates that **gluon dynamics is identical** & overwhelmingly important
- Lattice QCD supports this

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

Bhagwat et al.



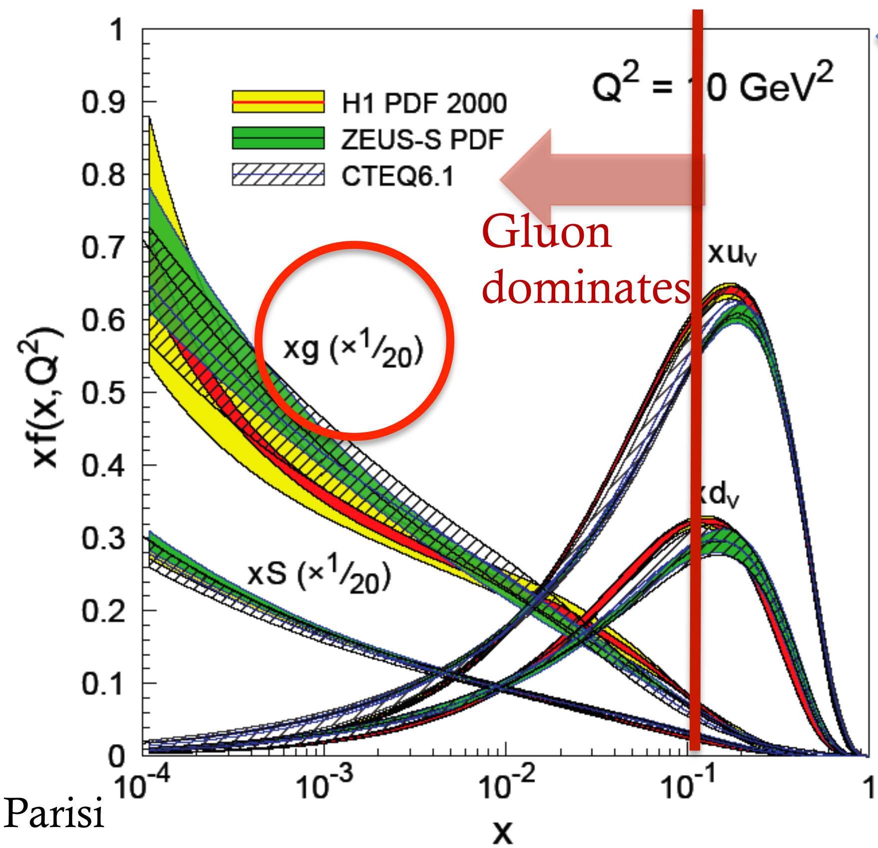
Measurement of Glue at HERA



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

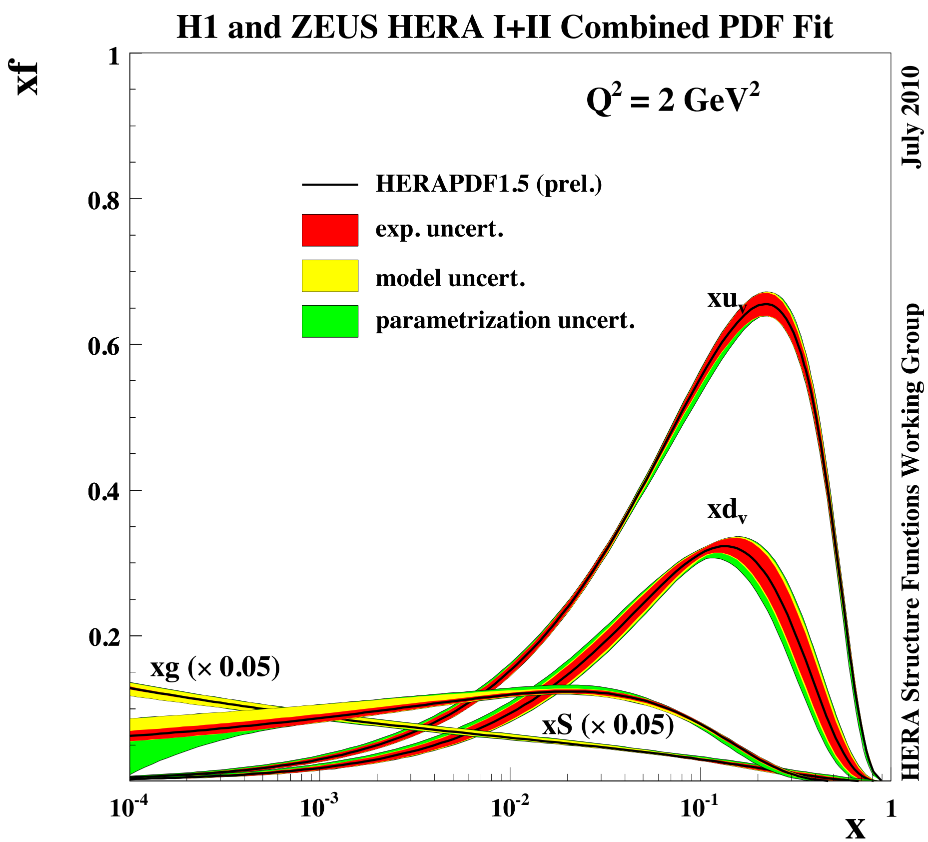
$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto G(x,Q^2)$$

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

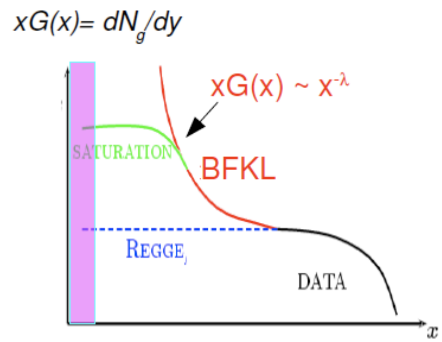


*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

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?

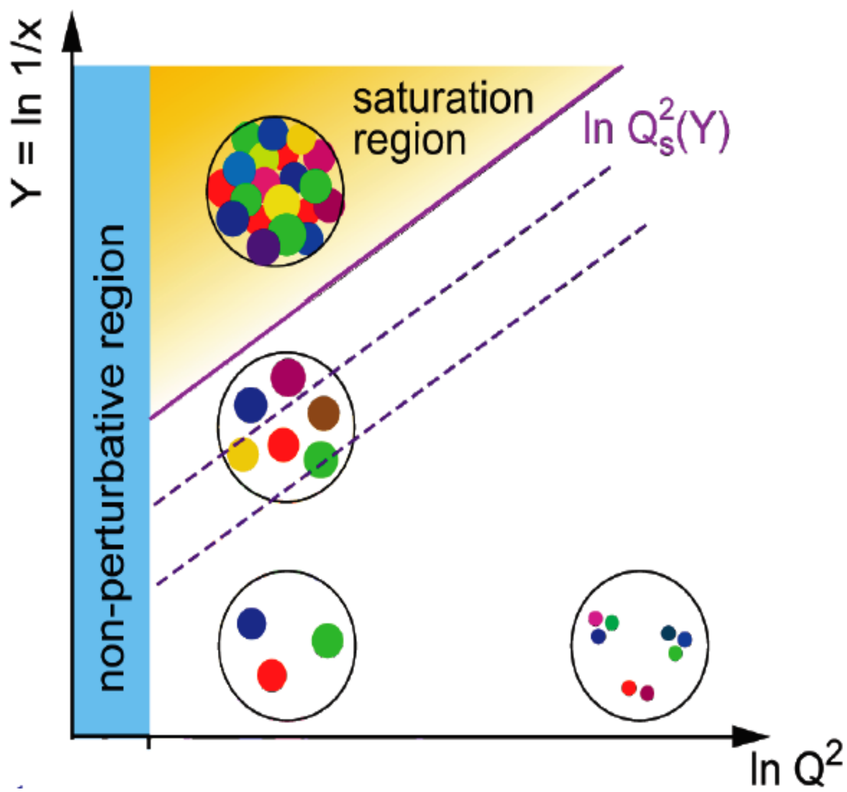


- How would we find out?

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

→ **Color Glass Condensate**

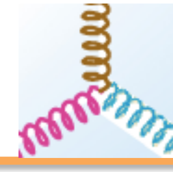
Saturation Scale **$Q_S(x,Q^2,A)$**

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

No unambiguous experimental evidence yet, but many smoking guns (HERA, RHIC & now LHC!)

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

Gluons in QCD



Dynamical generation & self-regulation of hadron masses

F. Wilczek in "Origin of Mass"

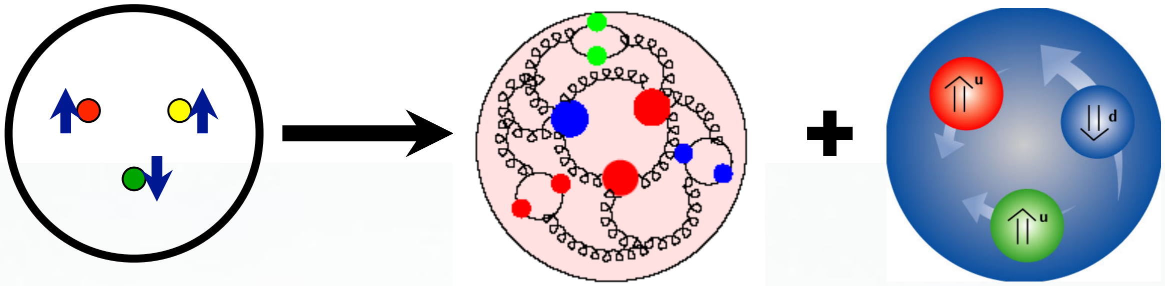
Its enhanced coupling to soft radiation… means that a 'bare" color charge, inserted in to empty space will start to surround itself with a cloud of virtual color gluons. These color gluon fields themselves carry color charge, so they are sources of additional soft radiation. The result is a self-catalyzing 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"***

- 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 non-linear QCD regions of extreme high gluon density

CONSTITUTION OF NUCLEON SPIN….

Evolution: Our Understanding of Nucleon Spin



1980s

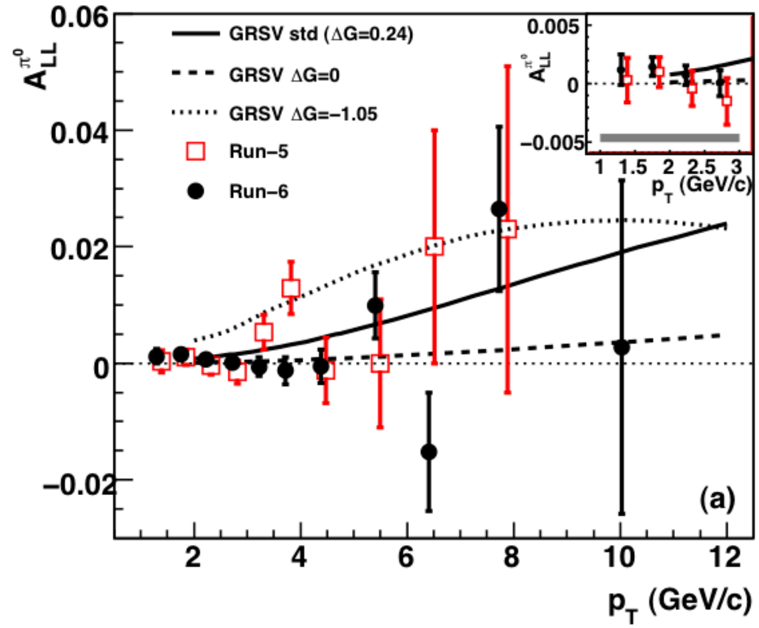
1990/2000s

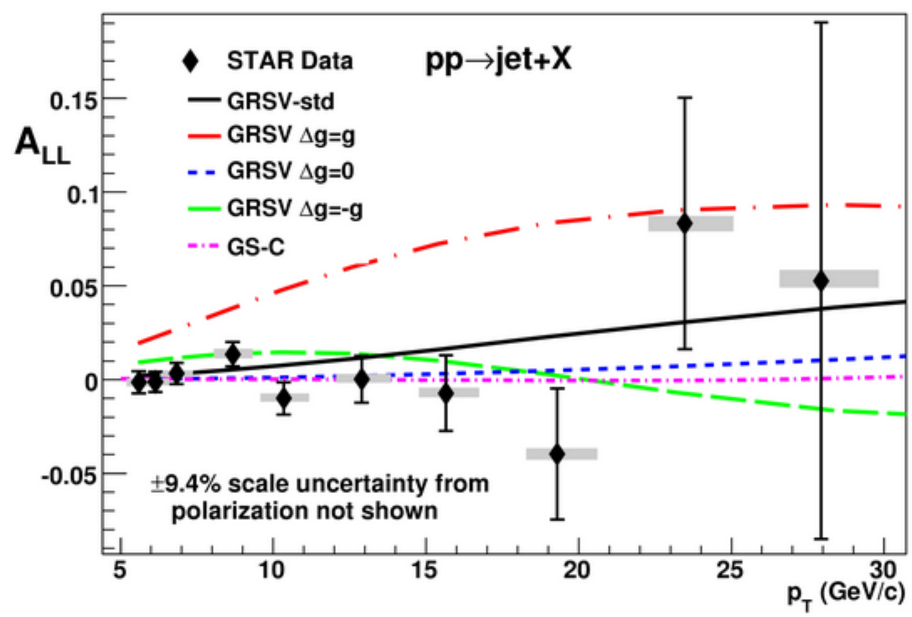
We have come a long way, but do we understand nucleon spin?

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

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_Q + \Delta G + L_G$$

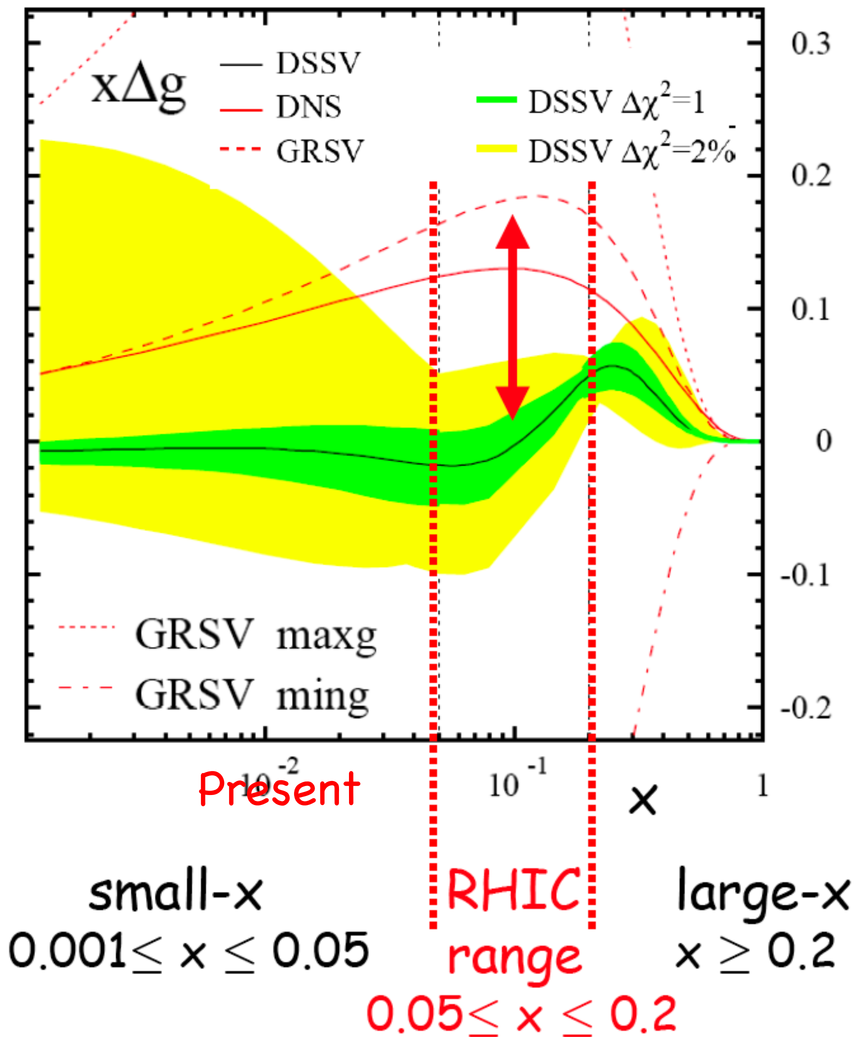
- We know how to measure ΔΣ and ΔG precisely using pQCD
  - ½ (ΔΣ) ~ 0.15 : From fixed target pol. DIS experiments
  - RHIC-Spin: ΔG *not large* as anticipated in the 1990s, but *measurements & precision needed at low & high x*





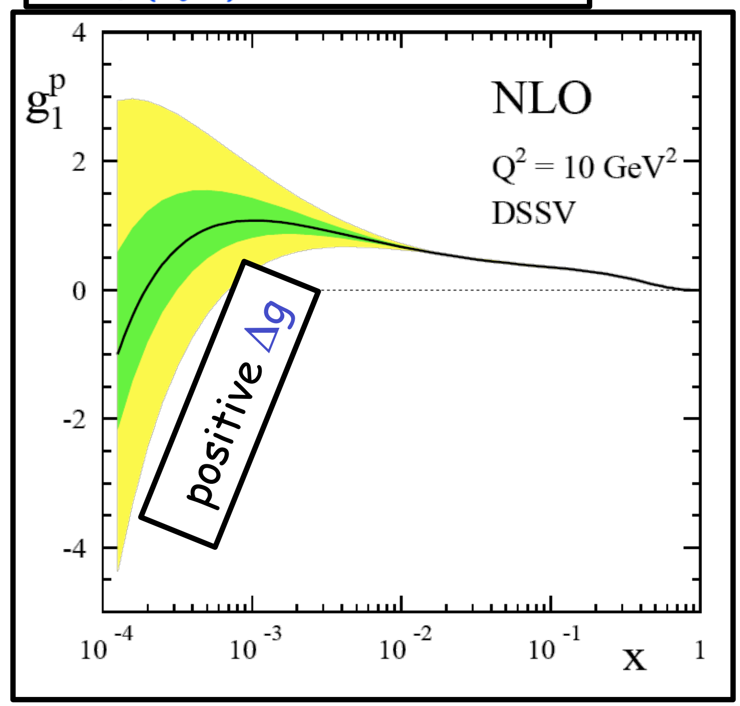
ΔG(x) @ Q^2=10 GeV^2

de Florian, Sassot, Stratmann & Vogelsang



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

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



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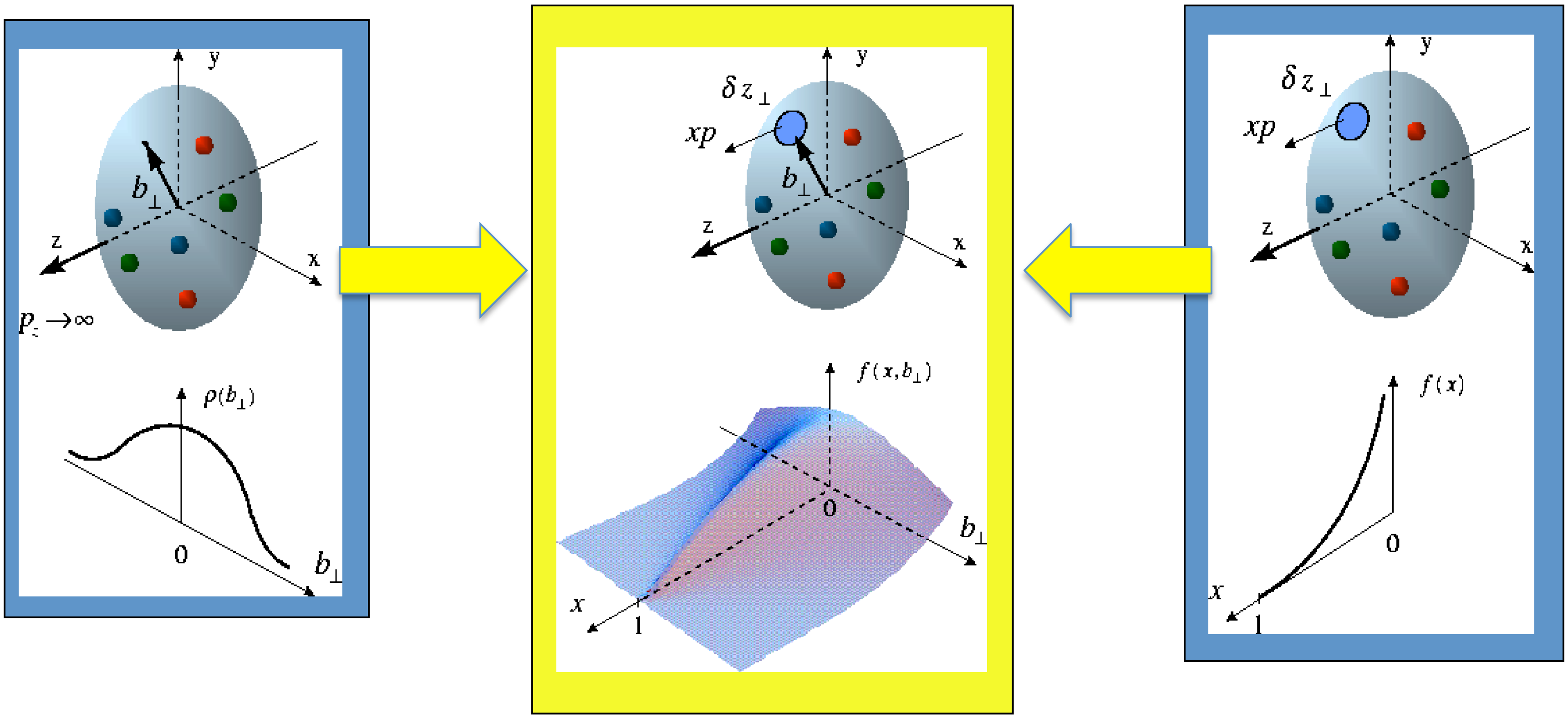
  - ½ (ΔΣ) ~ 0.15 : From fixed target pol. DIS experiments
  - RHIC-Spin: ΔG *not large* as anticipated in the 1990s, but *measurements & precision needed at low & high x*
- Orbital angular momenta: L_Q (L_G?)
  - Quark GPDs: 12GeV@JLab & COMPASS@CERN
  - Gluon GPDs: low x → J_G → will need the future 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)?**
  - TMDs, GPDs: 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

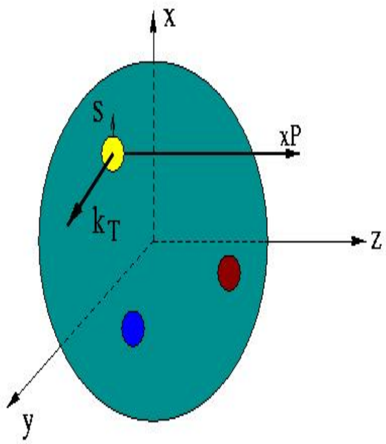
Structure functions, quark longitudinal momentum & helicity distributions

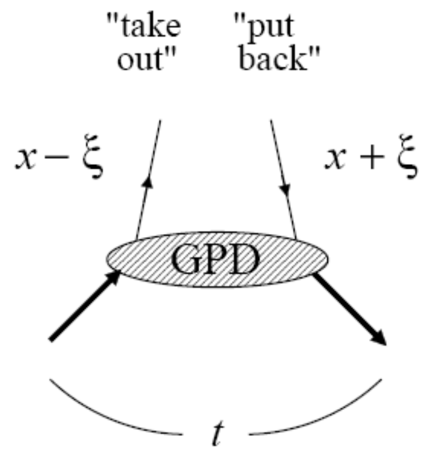
Unified View of Nucleon Structure

6D Dist.

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

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





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

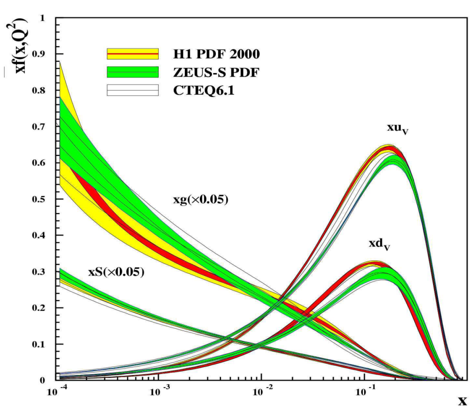
GPDs/IPDs

3D imaging

d^2k_T

d^2r_T

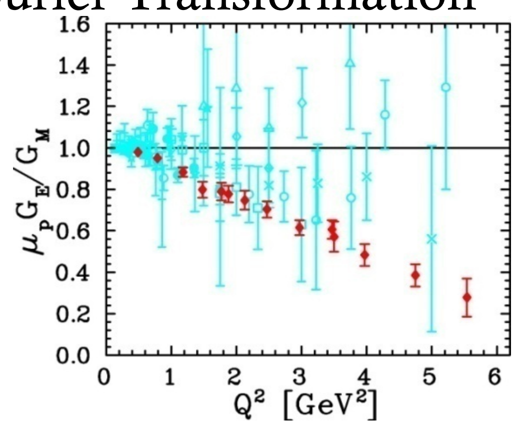
dx &
Fourier Transformation



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

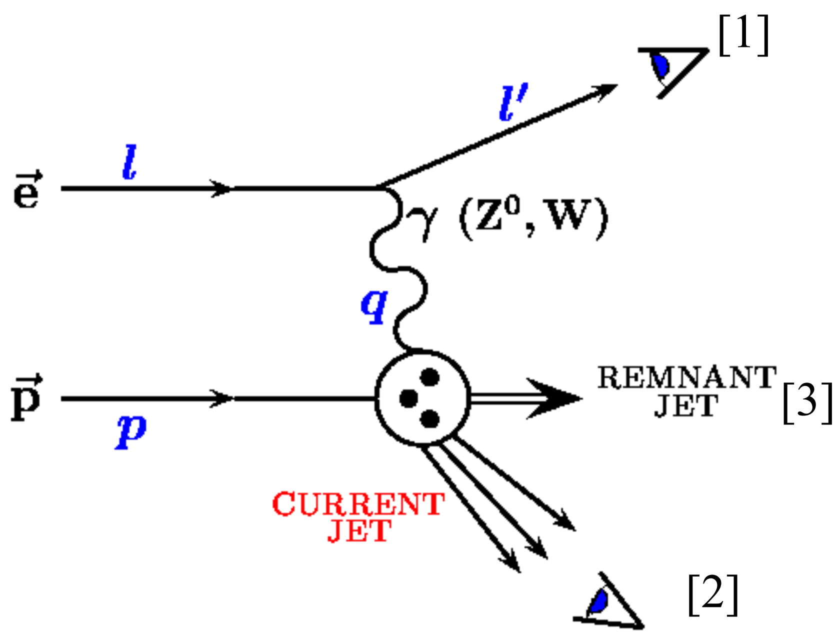
1D

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



The Proposal:

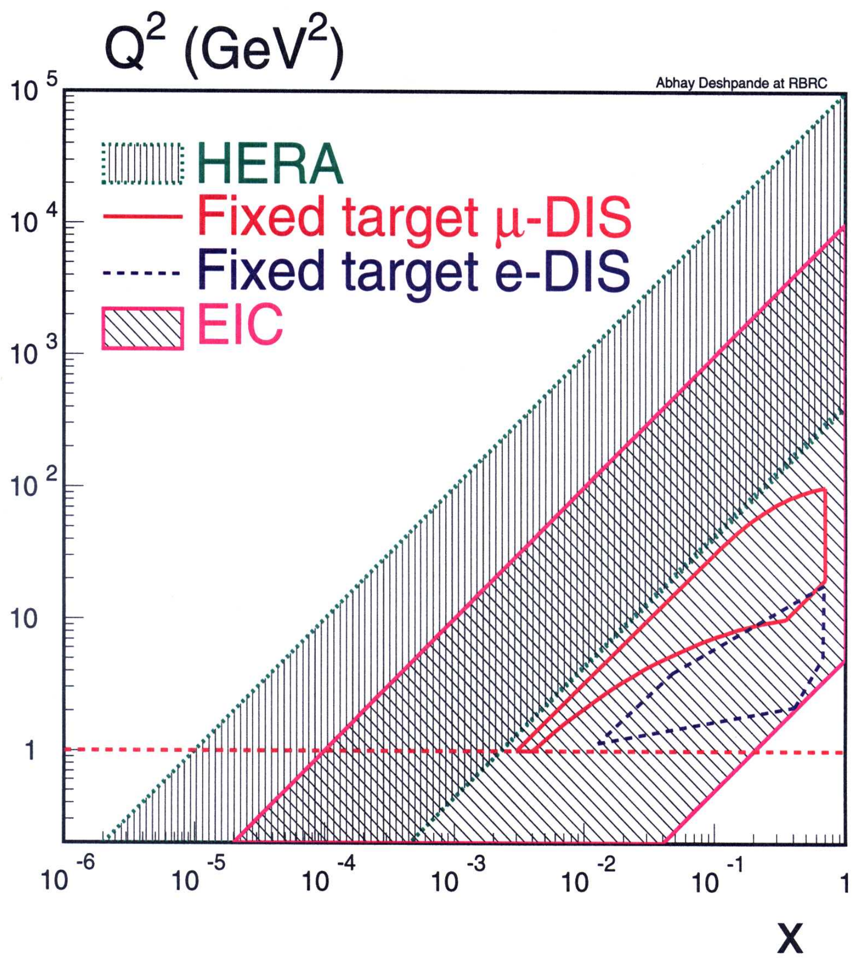
Future DIS experiment at an Electron Ion Collider: A high energy, high luminosity (polarized) *ep* and eA collider and a suitably designed detector



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 $L_{ep} = 10^{33\text{-}34}$ 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}**

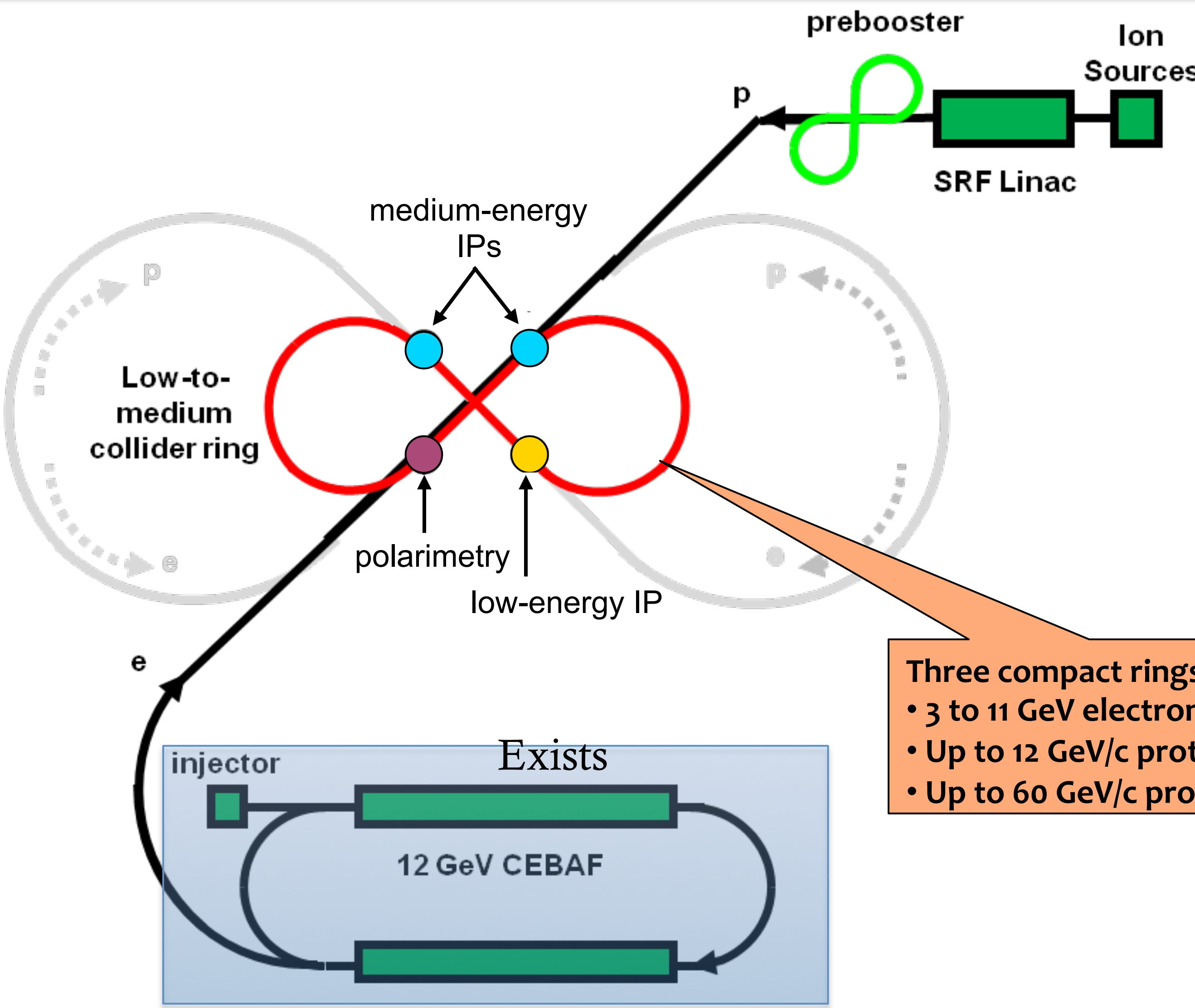
Machine Designs

eRHIC at Brookhaven National Laboratory
using the existing RHIC complex

ELIC at Jefferson Laboratory using the
Upgraded 12GeV CEBAF

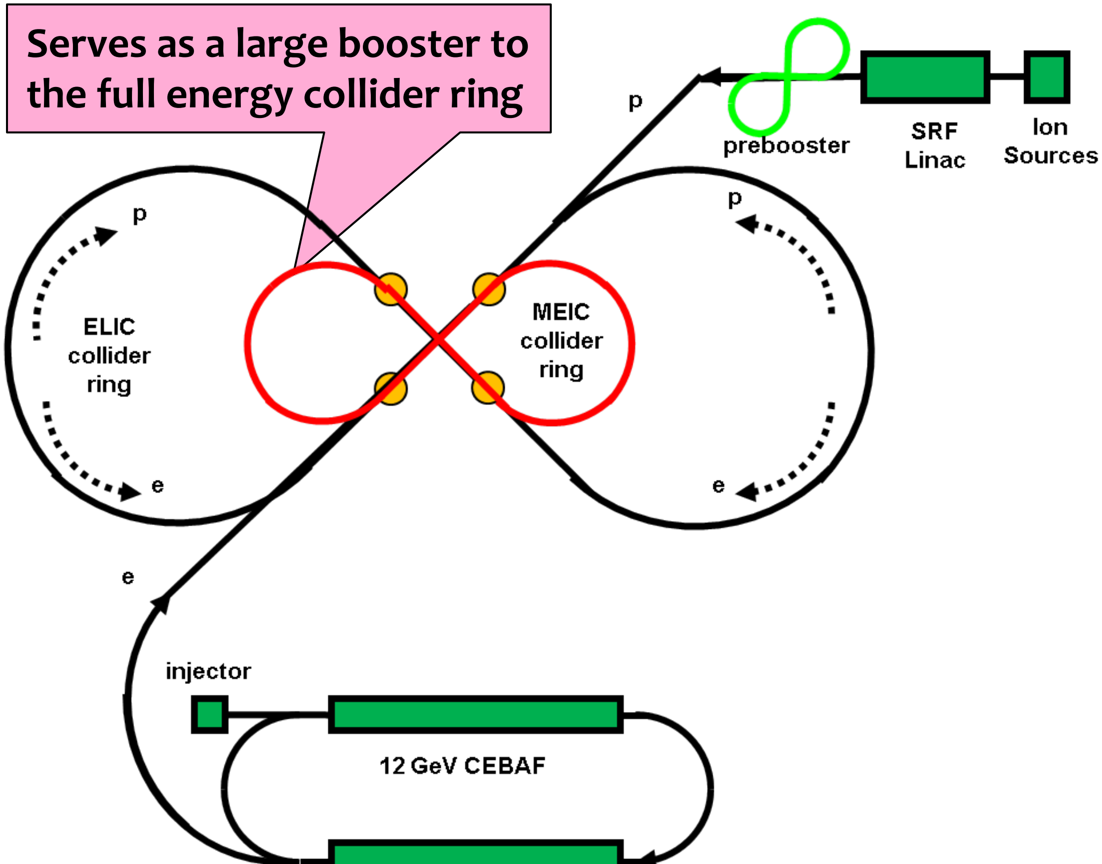
Both planned to be STAGED

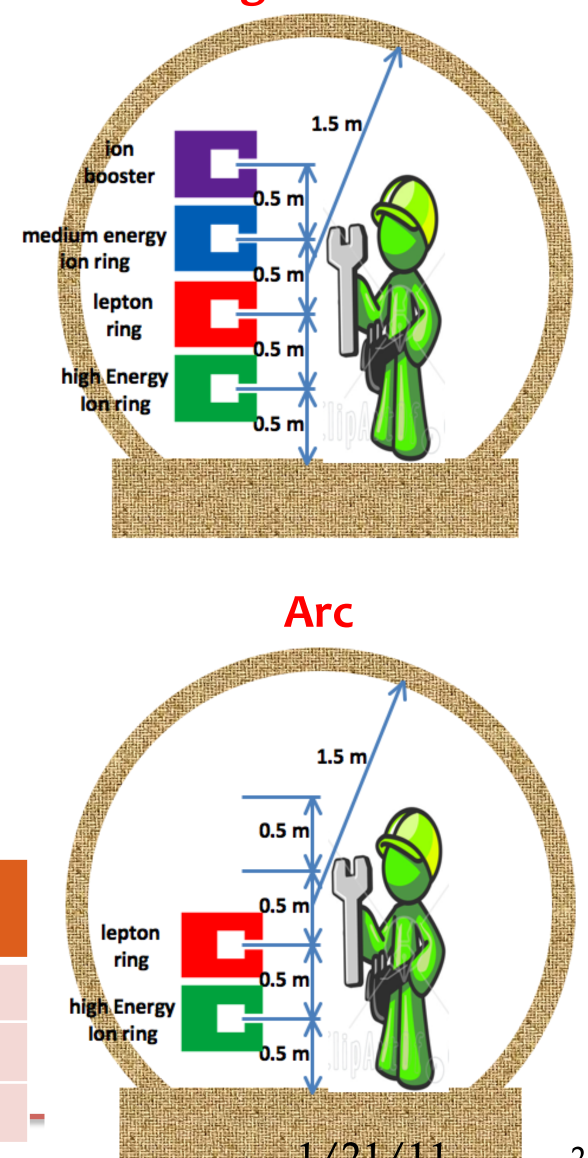
MEIC : Medium Energy EIC



Three compact rings:
- 3 to 11 GeV electron
- Up to 12 GeV/c proton (warm)
- Up to 60 GeV/c proton (cold)

ELIC: High Energy & Staging

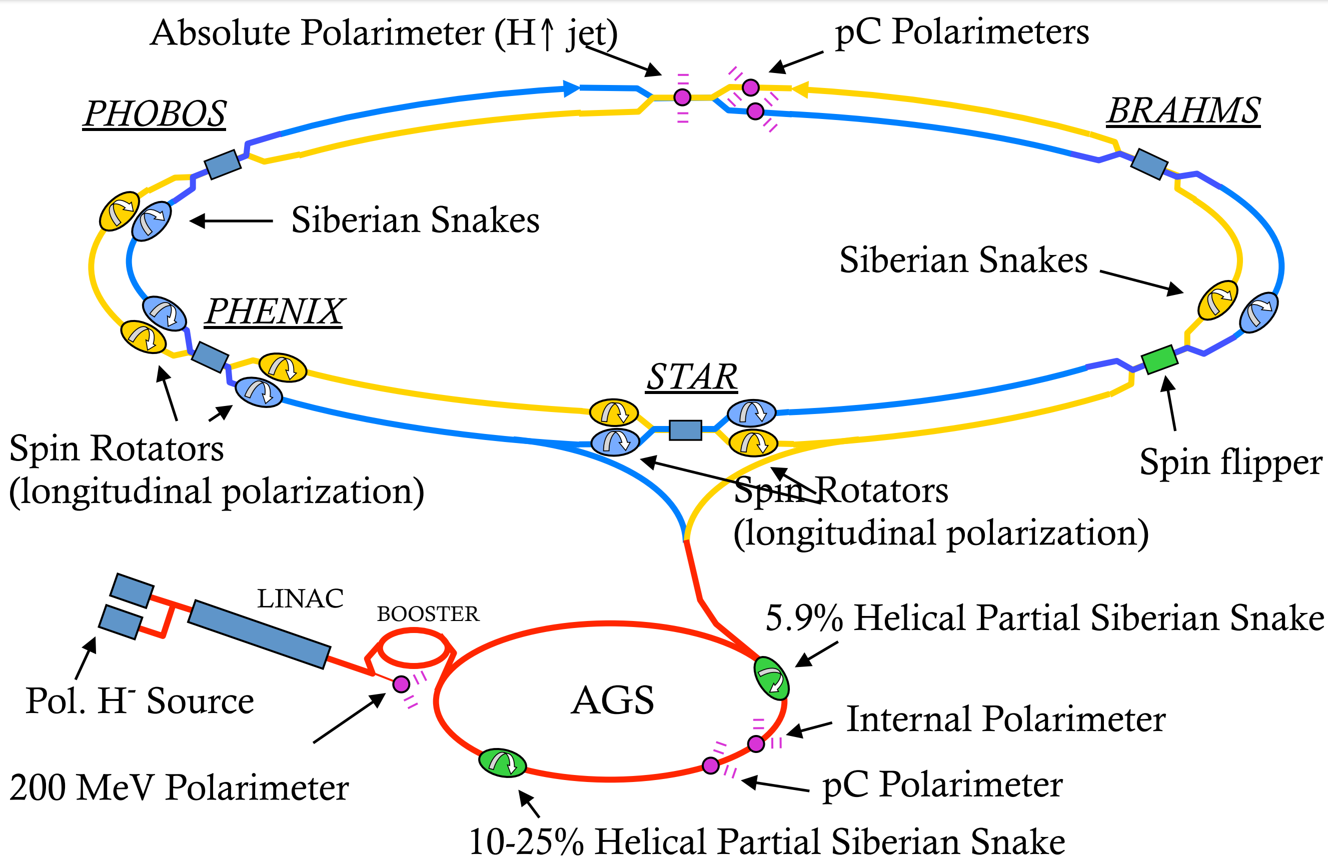




Stage	Max. Energy (GeV/c)		Ring Size (m)	Ring Type		IP #
	p	e		p	e	
Medium	96	11	1000	Cold	Warm	3
High	250	20	2500	Cold	Warm	4

RHIC as a Polarized Proton Collider

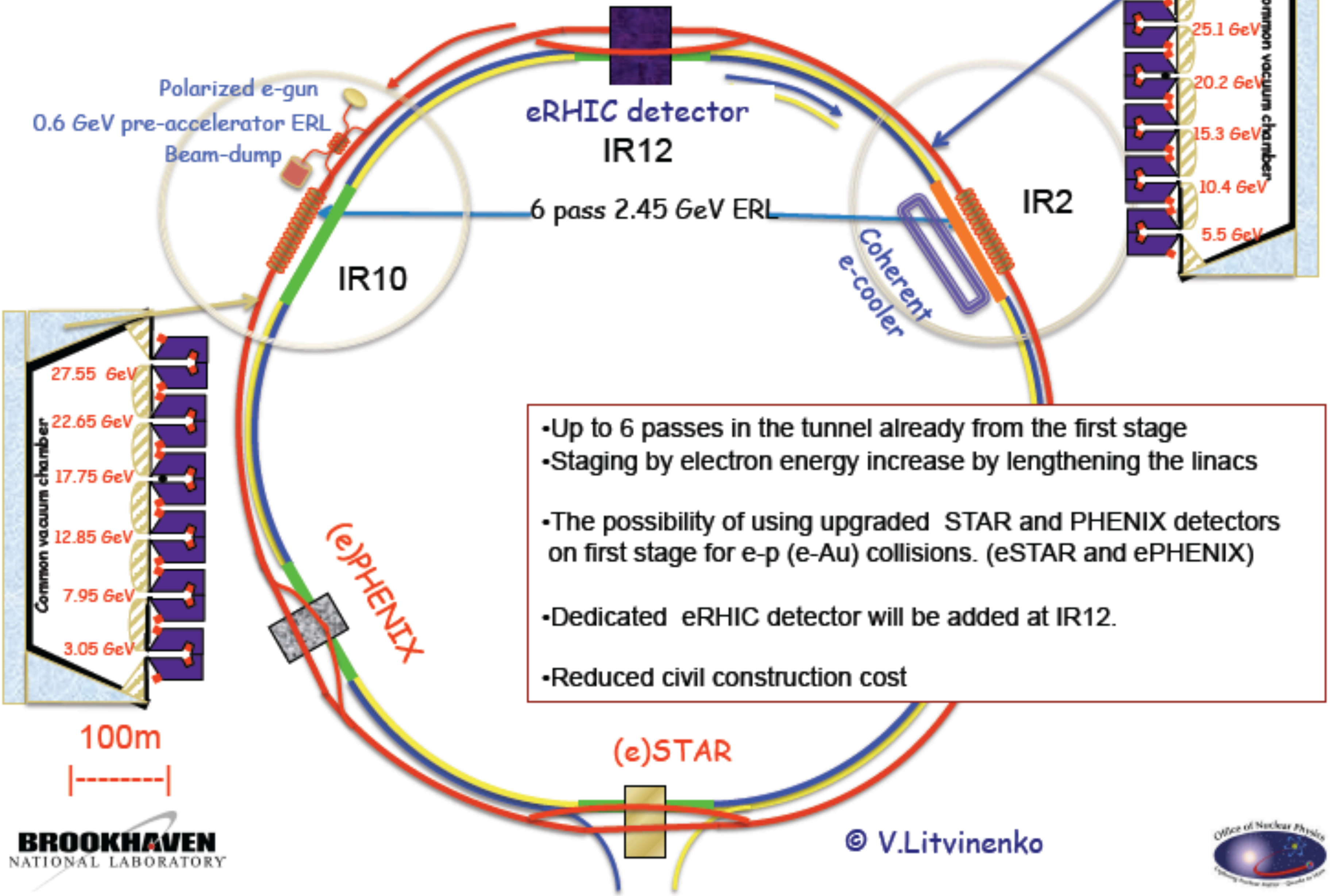
Exists!



Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79\ E/m \rightarrow \sim 1000$ 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

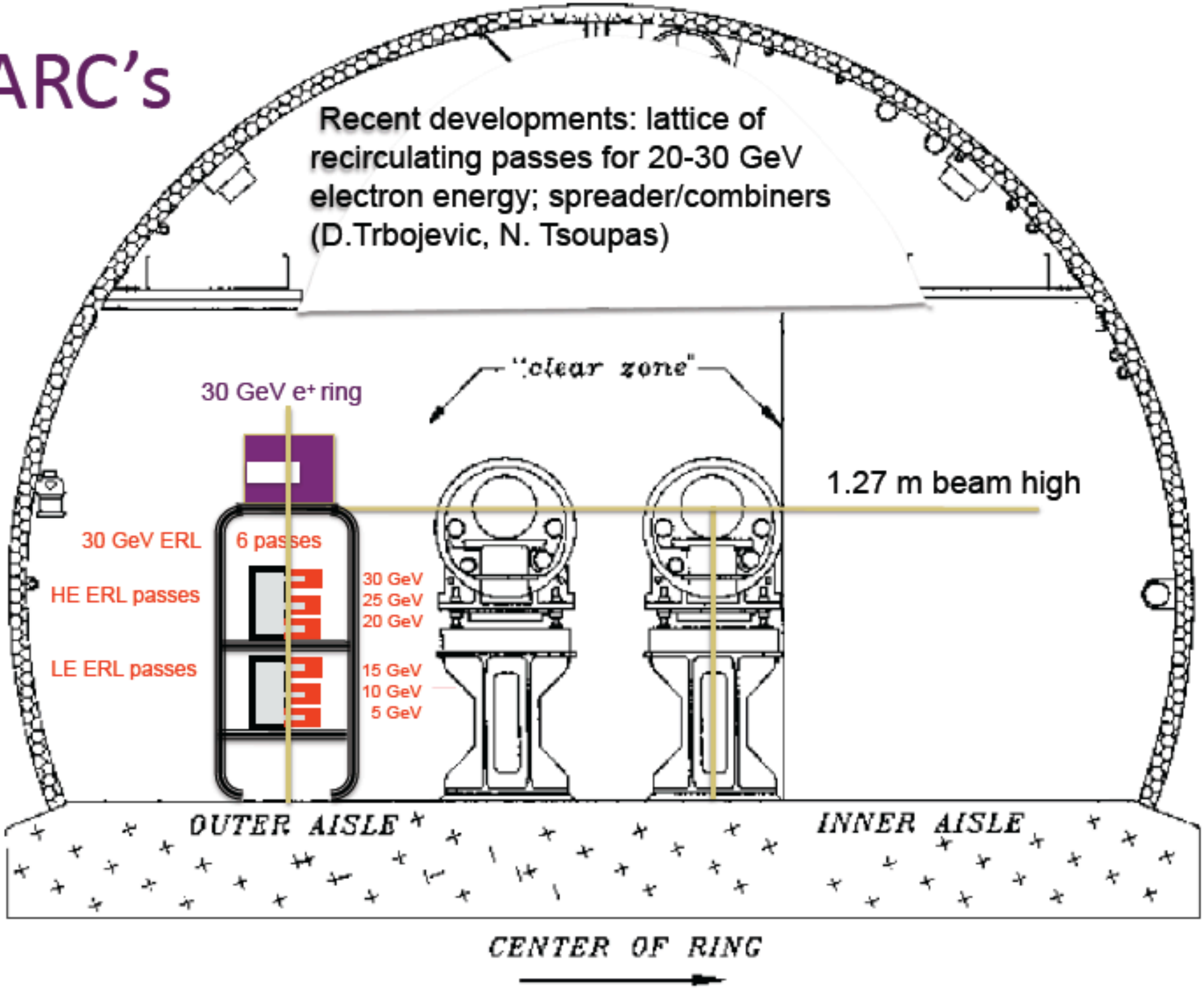
e-RHIC is a triple IP collider

5 to 30 GeV e⁻ x 325 GeV p - 130/u Au

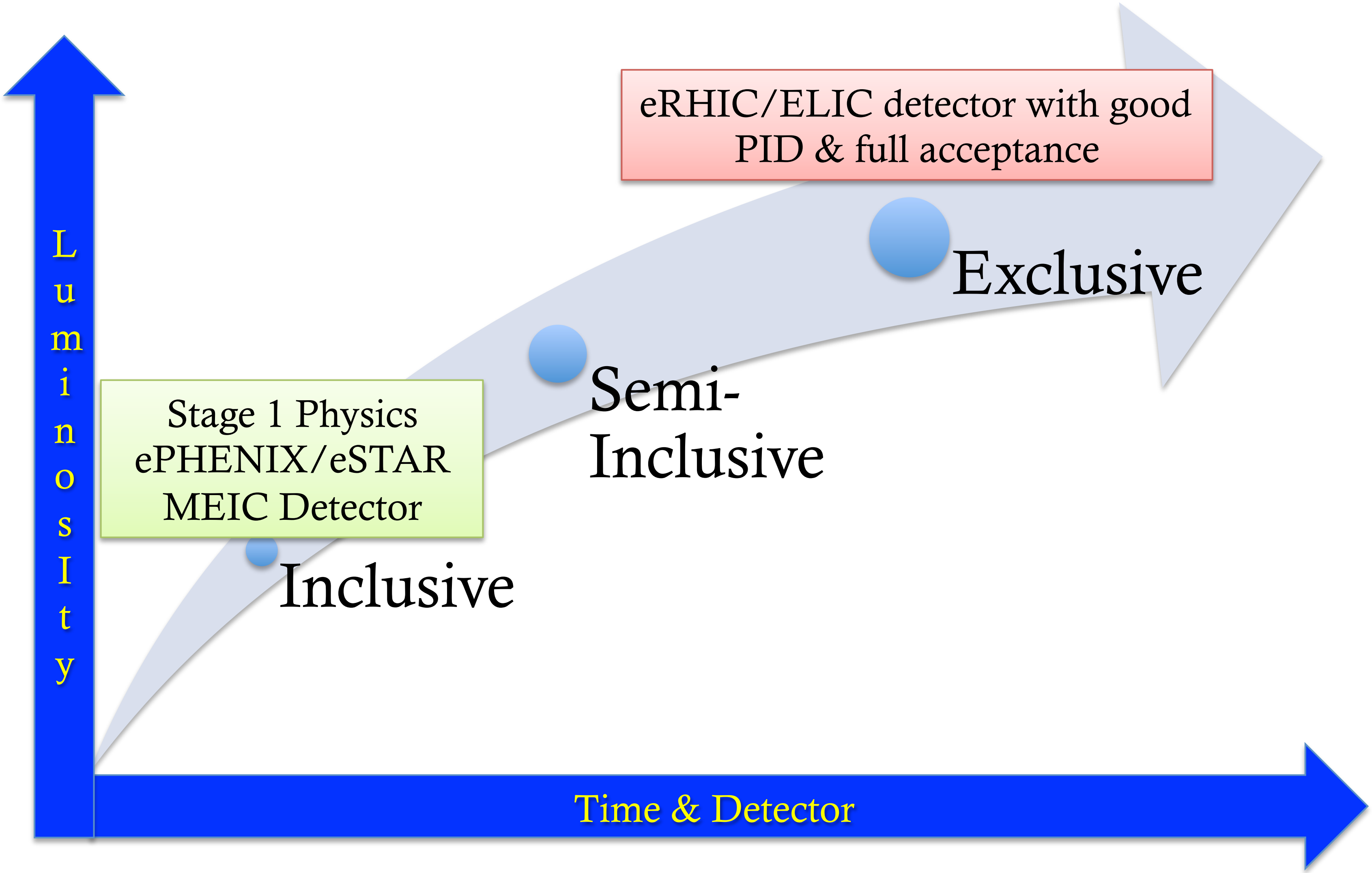


- Up to 6 passes in the tunnel already from the first stage
- Staging by electron energy increase by lengthening the linacs
- The possibility of using upgraded STAR and PHENIX detectors on first stage for e-p (e-Au) collisions. (eSTAR and ePHENIX)
- Dedicated eRHIC detector will be added at IR12.
- Reduced civil construction cost

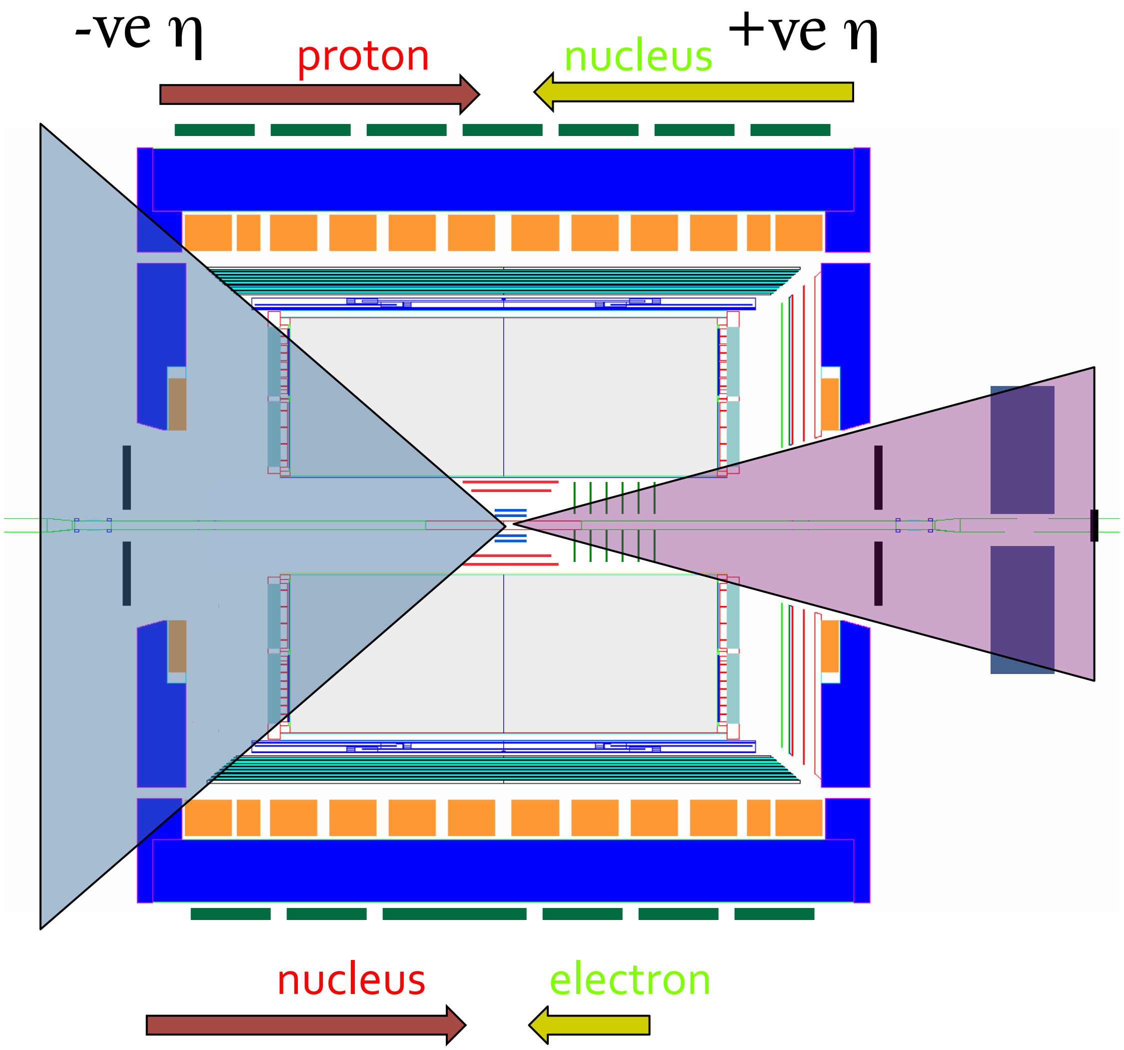
ARC's


Recent developments: lattice of recirculating passes for 20-30 GeV electron energy; spreader/combiners (D.Trbojevic, N. Tsoupas)
"clear zone"
30 GeV e+ ring
1.27 m beam high
30 GeV ERL
6 passes
HE ERL passes
LE ERL passes
30 GeV
25 GeV
20 GeV
15 GeV
10 GeV
5 GeV
OUTER AISLE
INNER AISLE
CENTER OF RING

EIC Luminosity vs. Time (Detector)



STAR → eSTAR for eRHIC-Stage-1



Positive η: Drell-Yan

2013-2018 will need

High precision tracking

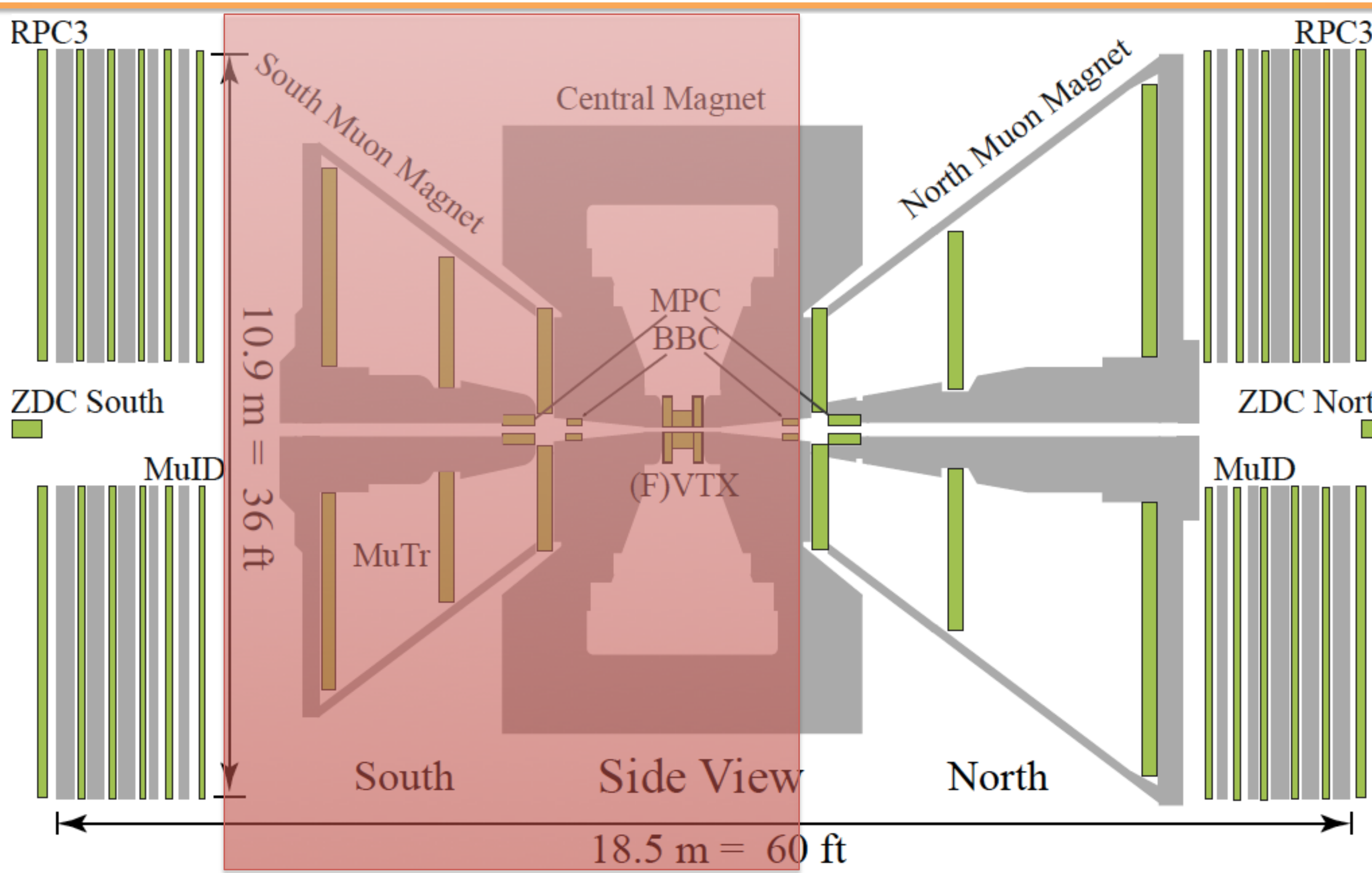
Negative η: eRHIC

Optimized for low energy scattered electrons (1 GeV)

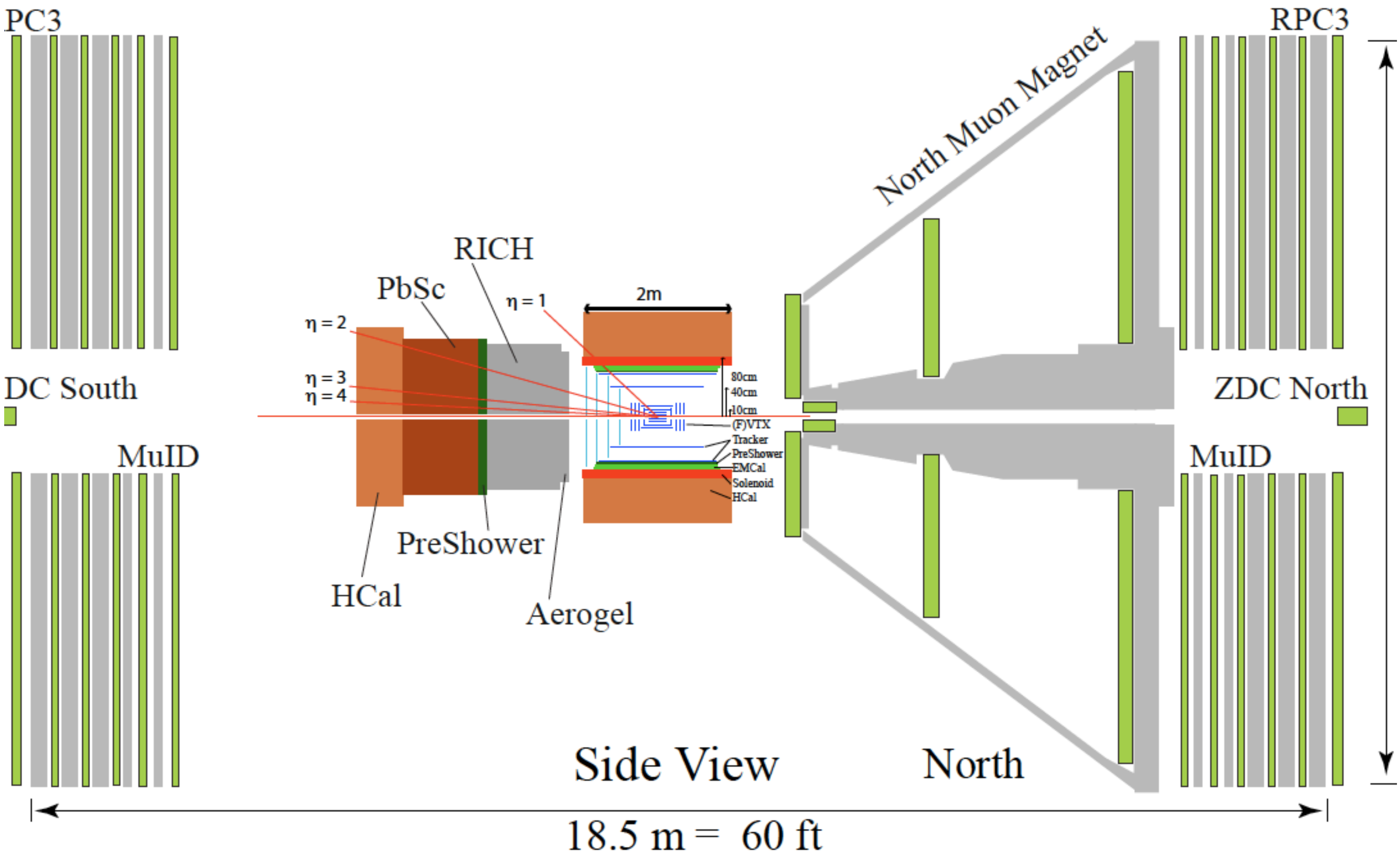
Tracking, triggering and PID

R&D needed for optimization

PHENIX "today"



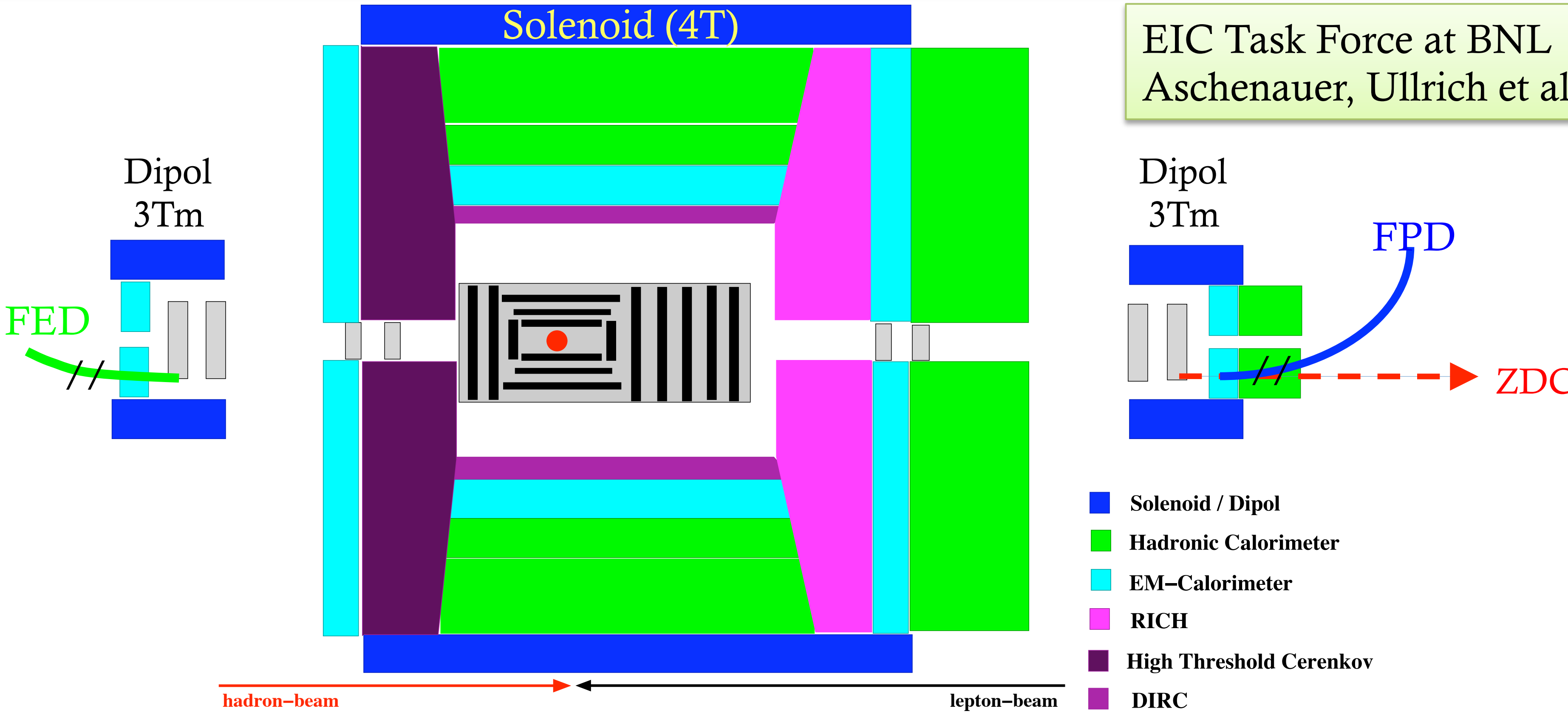
sPHENIX: ePHENIX for eRHIC-Stage-1



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

First ideas for a "eRHIC" detector

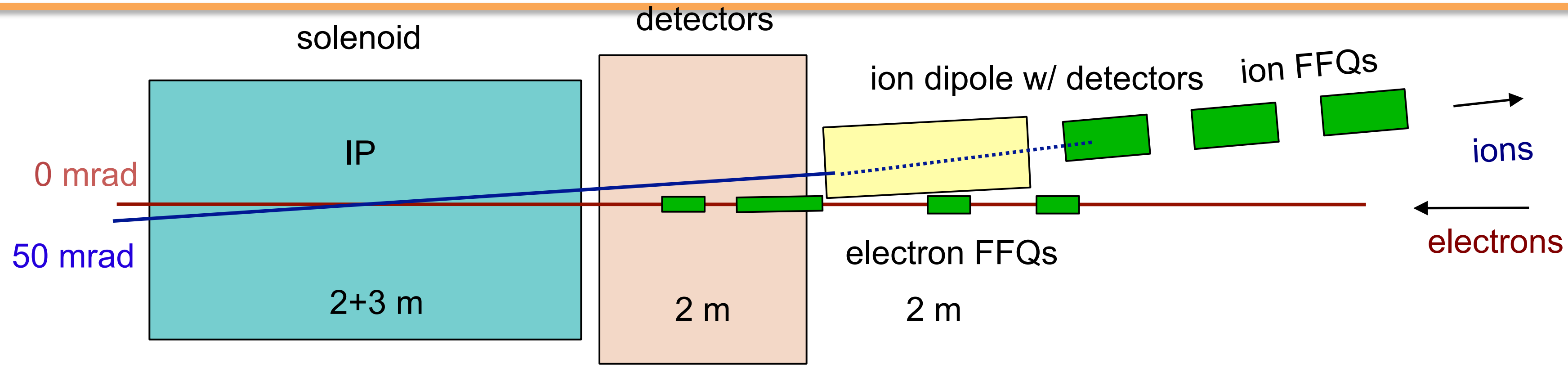
EIC Task Force at BNL
Aschenauer, Ullrich et al

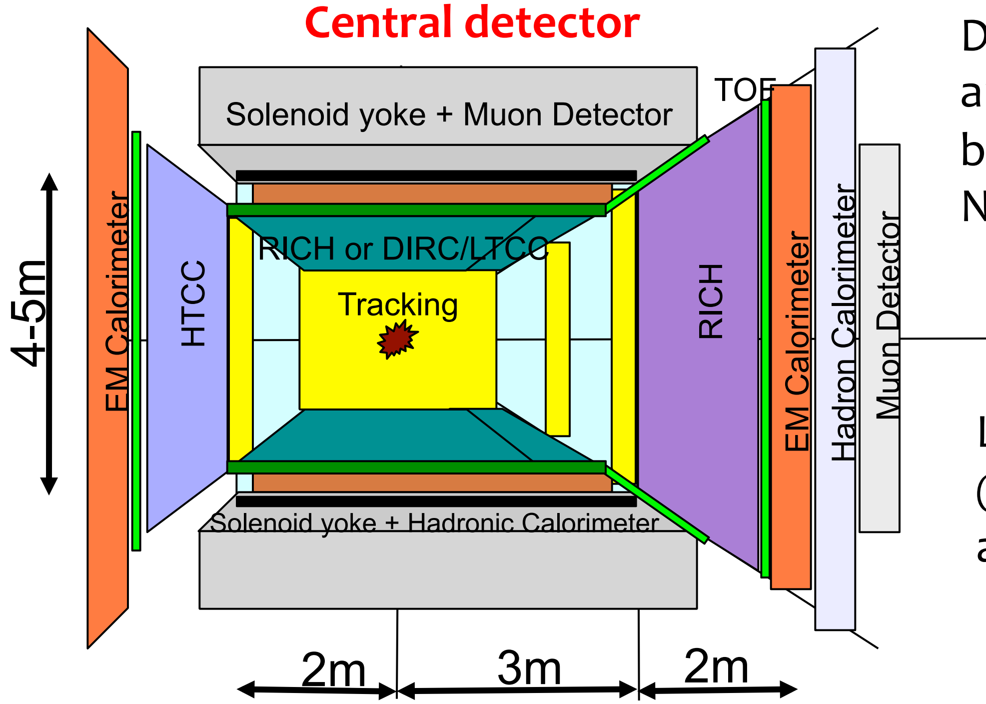


- ❑ Dipoles needed to have good forward momentum resolution
  - ➤ Solenoid no magnetic field @ r ~ 0
- ❑ DIRC, RICH hadron identification → π, K, p
- ❑ high-threshold Cerenkov → fast trigger for scattered lepton
- ❑ radiation length very critical → low lepton energies

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

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

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

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

Measurement of Gluons

- $F_2(x,Q^2)$ 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

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

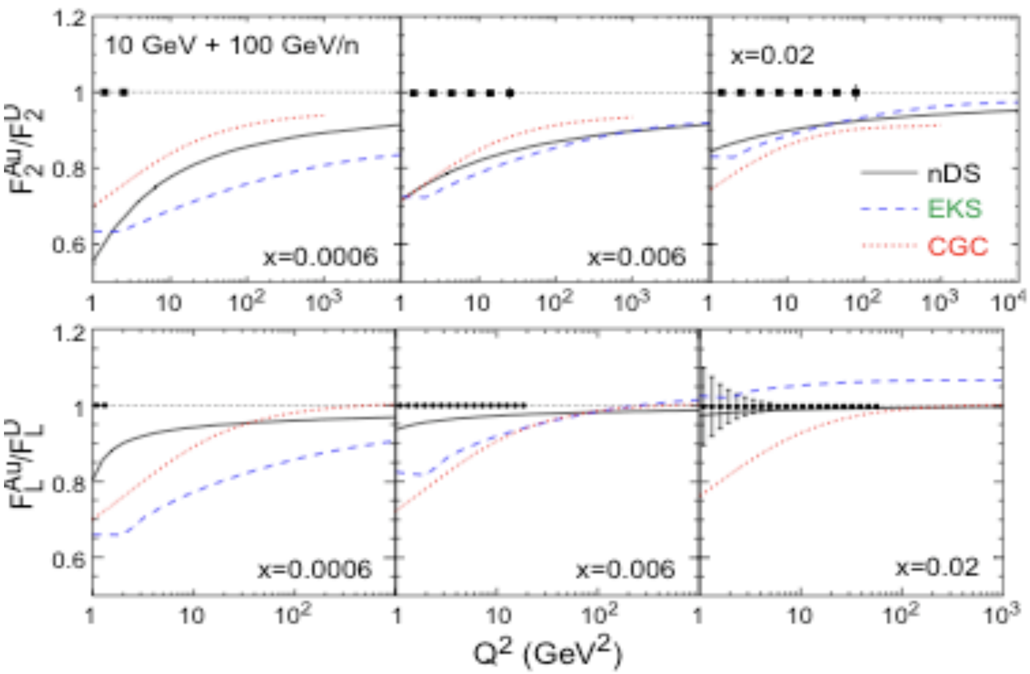
$$Q^2 = Sxy$$

Quarks and anti-quarks (F_2) — Gluon momentum distribution (F_L)

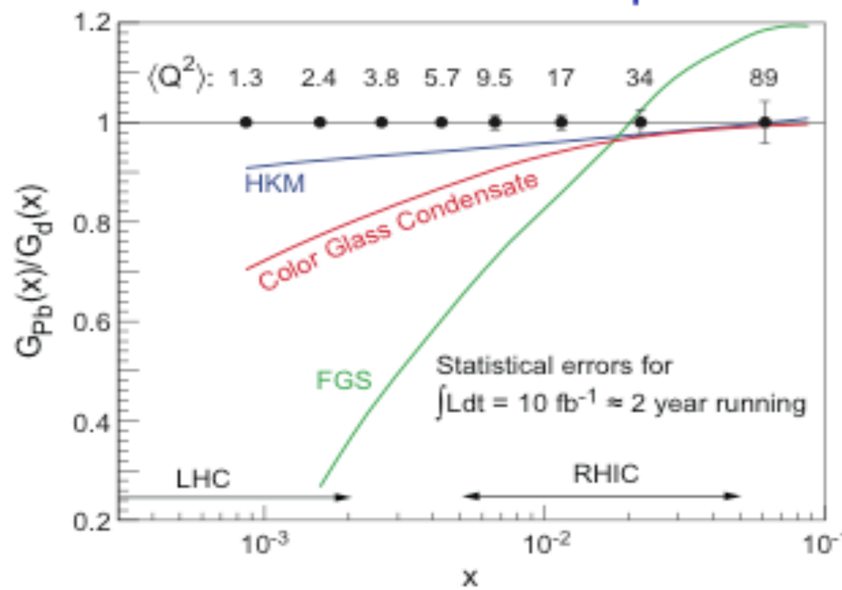
  - Needs **change of beam energies** to directly measure F_L

Preliminary e-A simulations

Simulations to demonstrate the quality of EIC measurements



Folded with EIC acceptance



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

Assume:

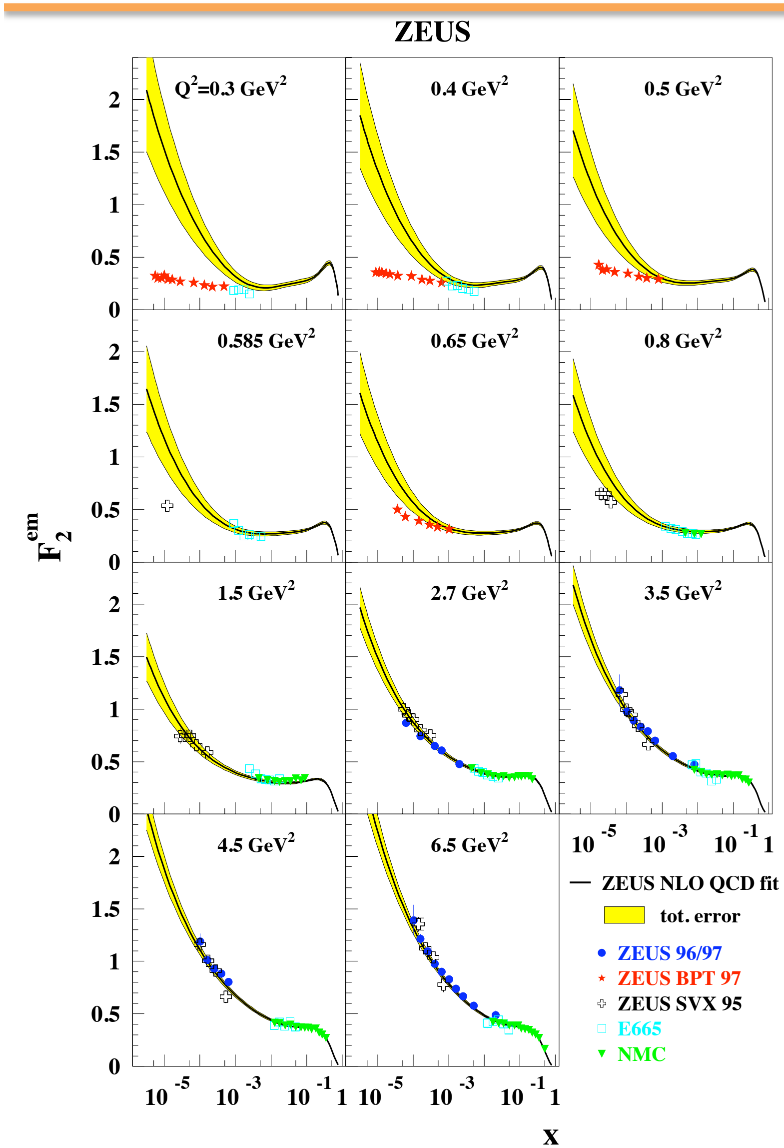
L = $3.8\ 10^{33}$ cm^{-2} s^{-1} (100x Hera)
T = 10 weeks
duty cycle: 50%
L ~ 1/A (approx)
$\int Ldt = 11$ fb^{-1}

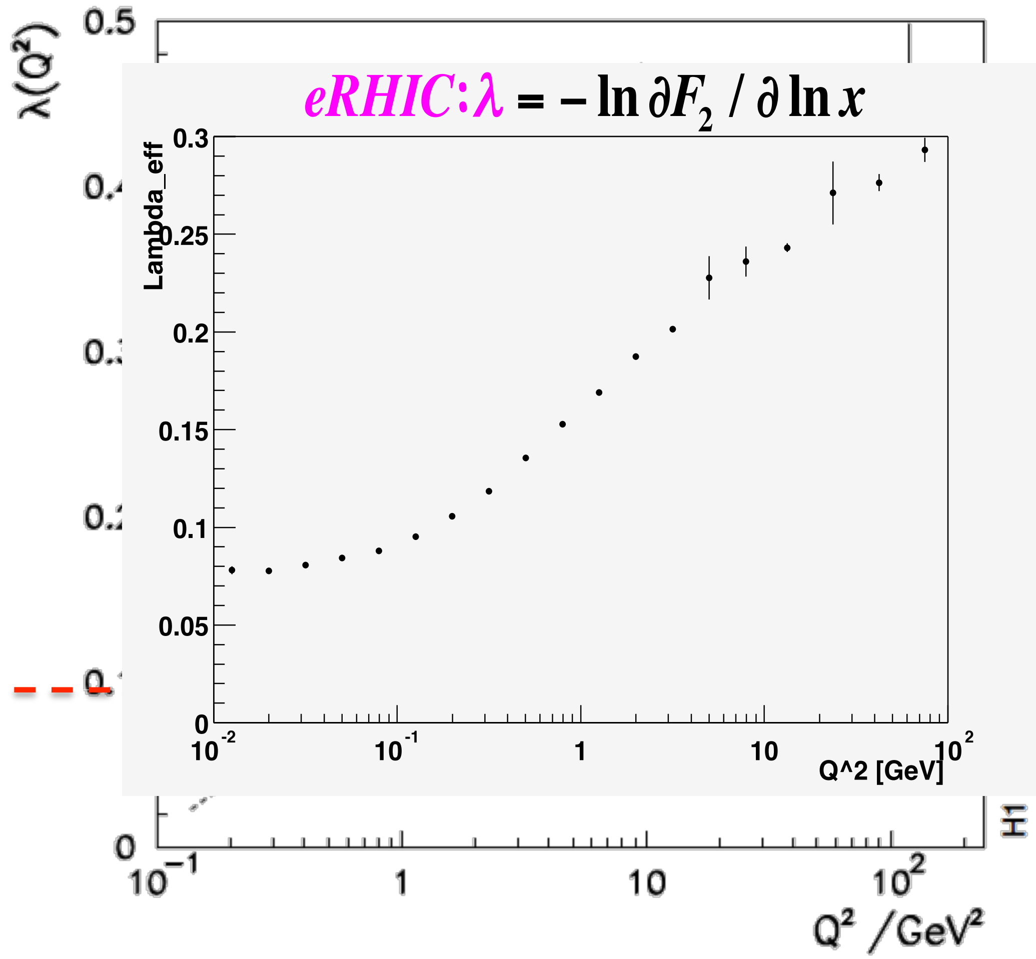
Plots above:

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

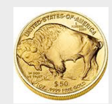
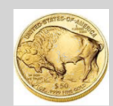
statistical error only

Transition from hadrons to partons?



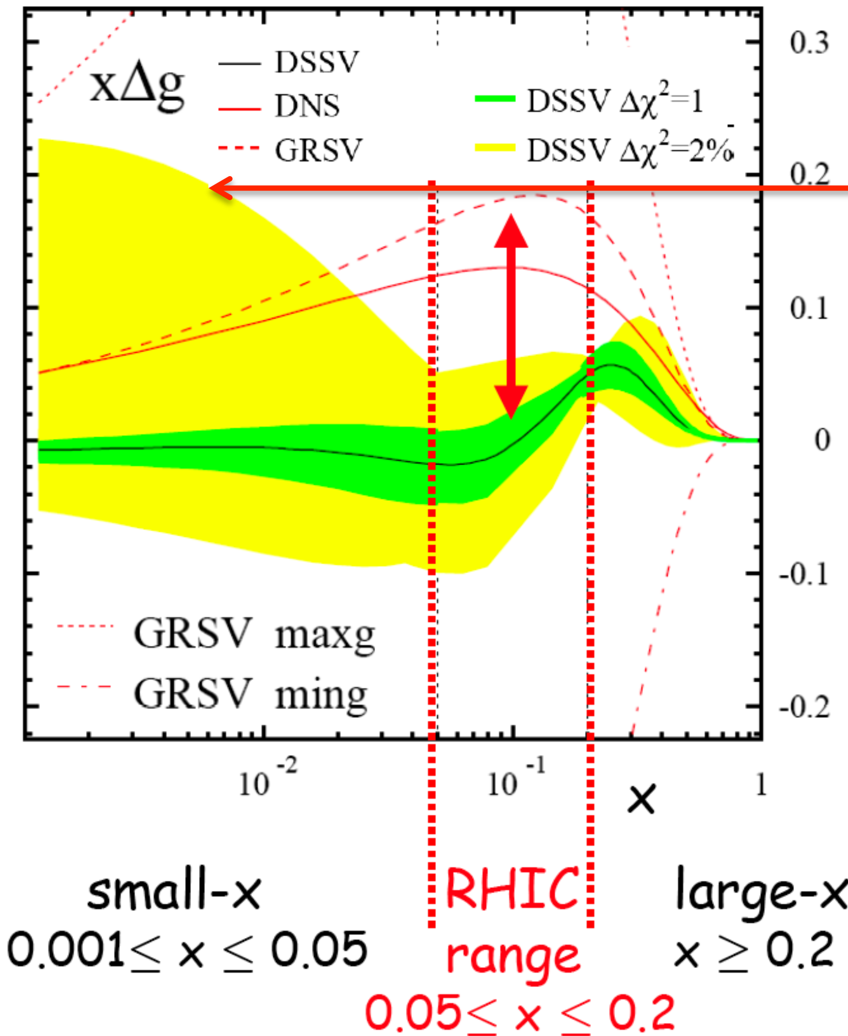


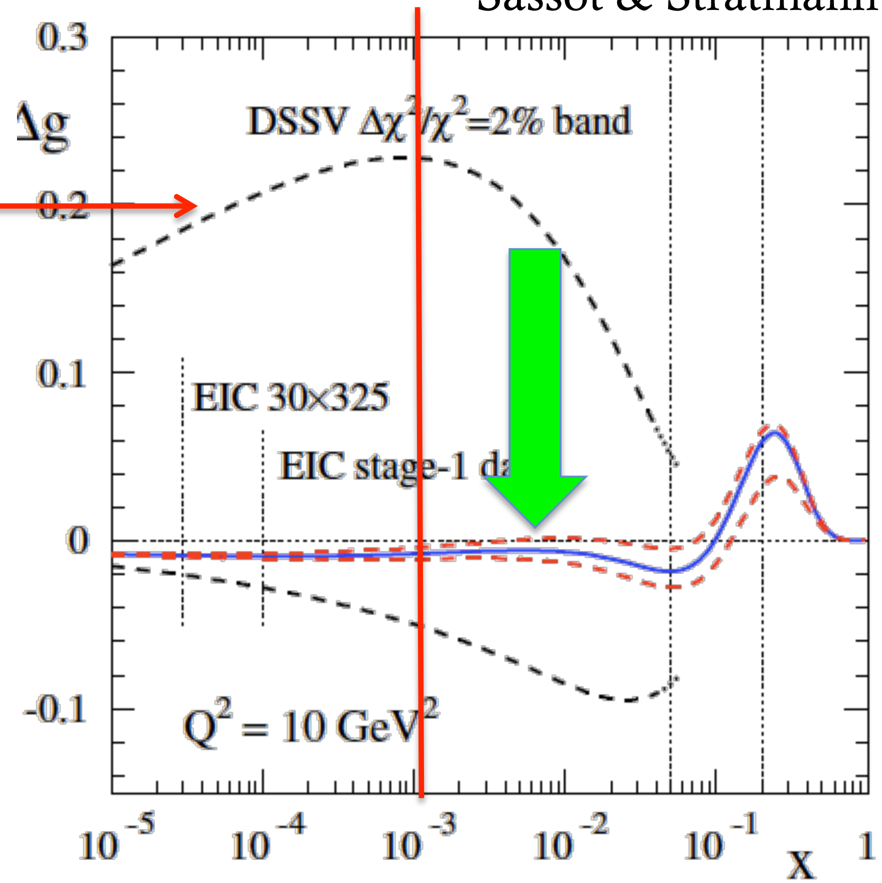
- Does the change in slope λ have something to do with "confinement"?

Science Deliverable	Basic Measurement	Uniqueness and Feasibility	Requirements
spin structure at small x contribution of Δg, $\Delta\Sigma$ 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

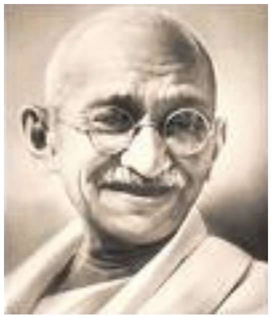
Sassot & Stratmann

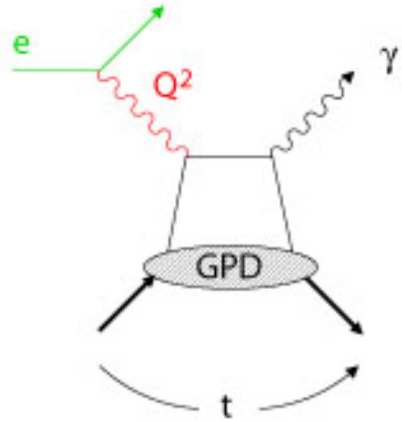




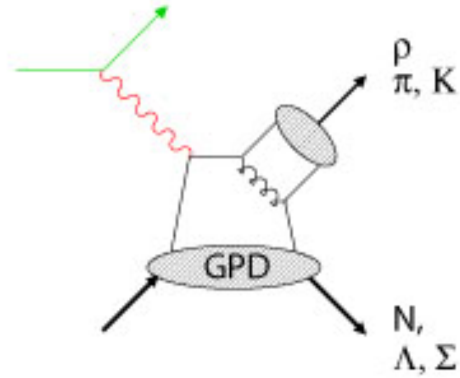
Yellow band (left) reduces to the band shown with **red dashed line** (right)

Towards 3D imaging of the proton….





Deeply virtual
Compton scattering



Deeply virtual
meson production

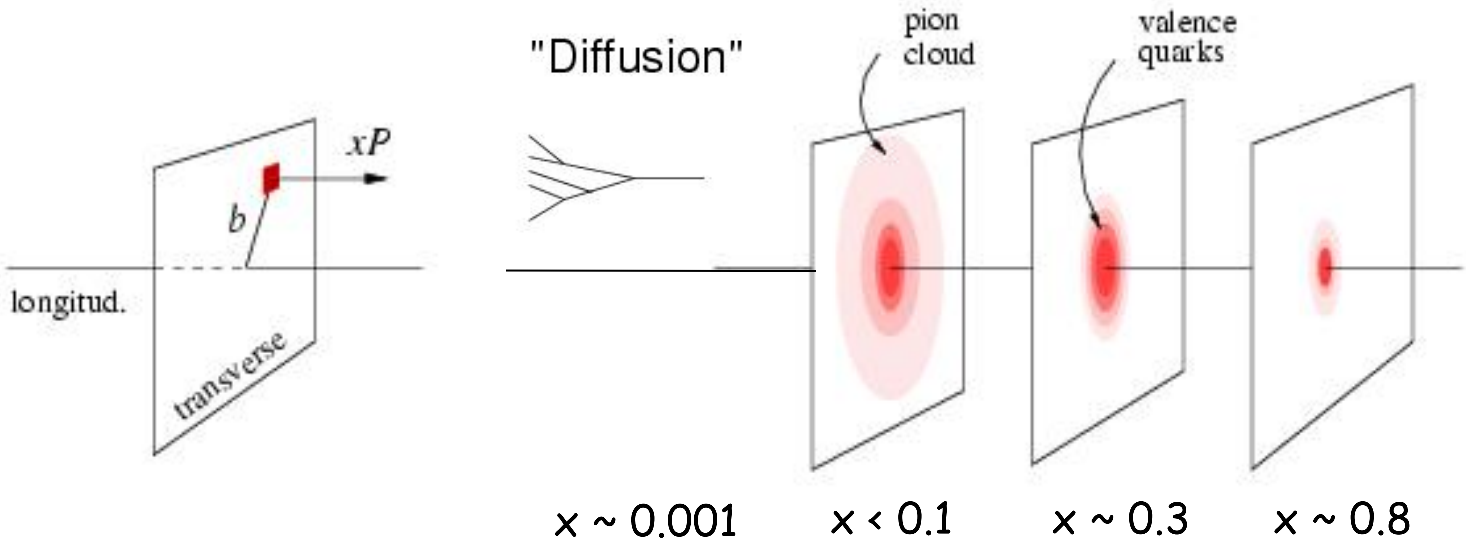
- Need ***non-violent*** collisions ……….
- The proton should remain intact even after the collisions and yet, we should have the ability to probe the partons and their dynamics inside….. 2 position and 1 momentum distributions

  Deeply Virtual Compton Scattering → $J_{quarks} = L_{quark} + \Delta\Sigma$

  Deeply Virtual Vector Meson Production → J_{gluon} – Gluon's total angular momentum requires EIC

GPDs and transverse parton imaging

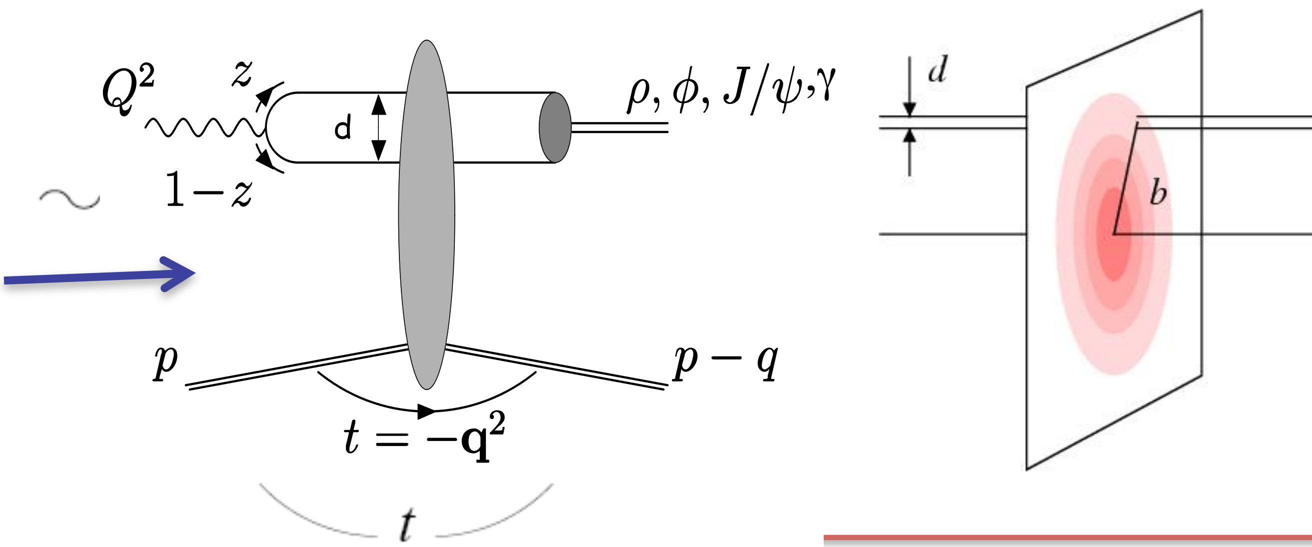
Fourier transform in momentum transfer



EIC:

1) x < 0.1: gluons!

2) ξ ~ 0 → the "take out" and "put back" gluons act coherently.



Some measurements considered so far for the EIC:

- Push the luminosity requirements ~ 10^{34} $cm^{-2}s^{-1}$
  - Recall that although lower in luminosity than fixed target experiments, the collider is at (high) 100 GeV in CM Energy
- Push the polarimetry and beam quality requirements to the extreme:
  - (dPol/Pol) ~ 1%
  - Ultra low beam divergence for DVCS/Diffraction…

Why not consider using this machine for precision EW-Physics measurements?

Topics presently under consideration:

- High energy collisions of polarized electrons and protons and nuclei afford a unique opportunity to study electro-weak deep inelastic scattering
  - **Electroweak structure functions (including spin)**
  - Significant contributions from W and Z bosons which have different couplings with ***quarks and anti-quarks***

- **Parity violating DIS**: a probe of beyond TeV scale physics
  - Measurements at higher Q^2 than the PV DIS 12 GeV at Jlab
  - Precision measurement of $Sin^2\Theta_W$

- **New window for physics beyond SM?**
  - Lepton flavor violation search $e^- + p \rightarrow \tau^- + X$

arXiv: 006.5063v1 [hep-ph]
M. Gonderinger et al.

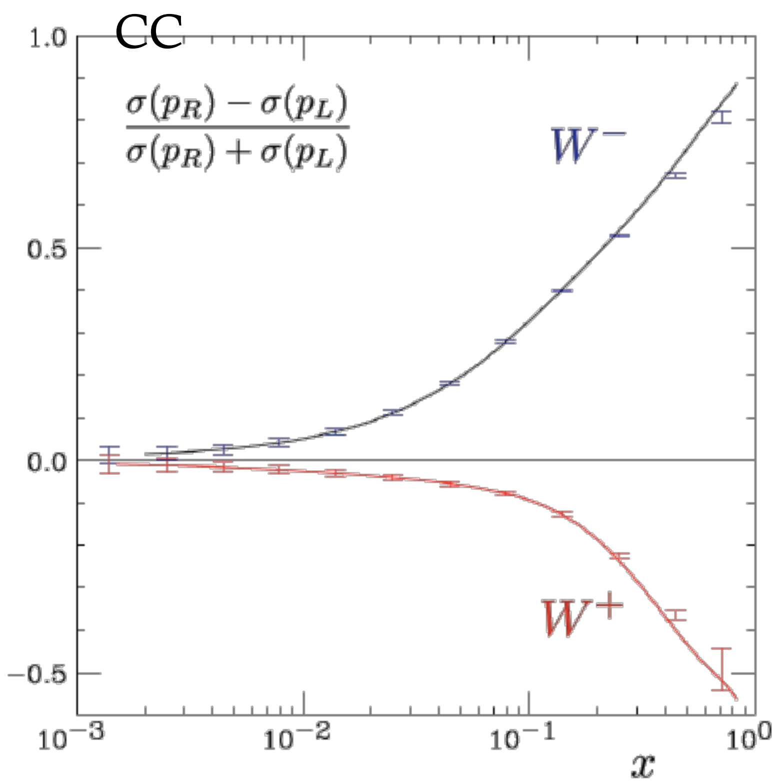
Charged & Neutral Currents…

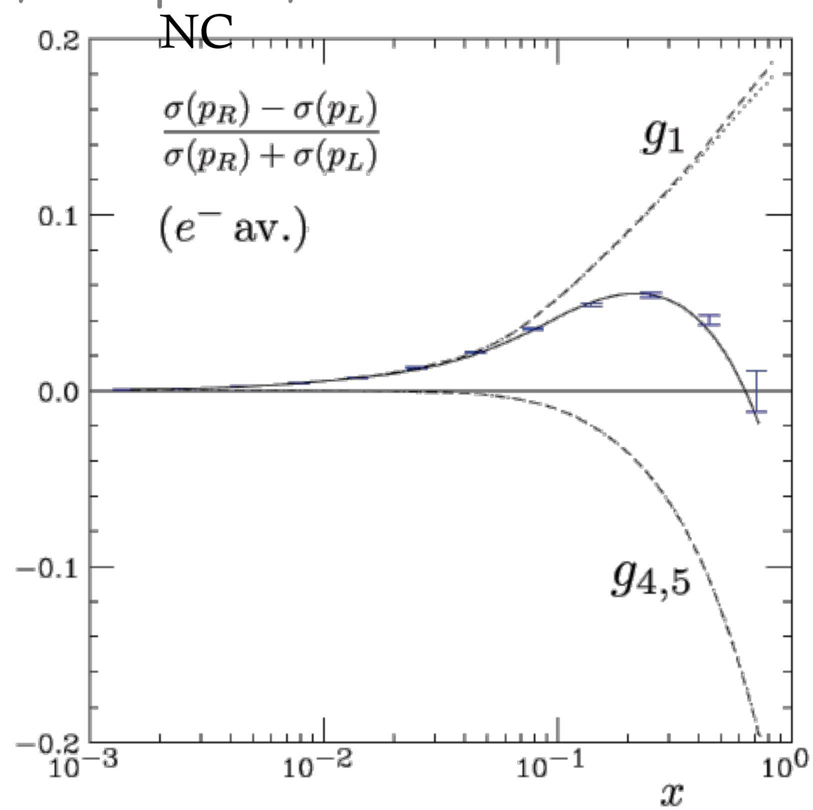
20 × 250 GeV, $Q^2 > 1$ GeV^2, $0.1 < y < 0.9$, **10 fb^{-1}**, DSSV PDFs

(Could begin the program with 5x250 GeV)

Two studies: (1) Ringer & Wogelsang (these figures),

(2) Taneja, Riordin, Deshpande, Kumar & Paschke



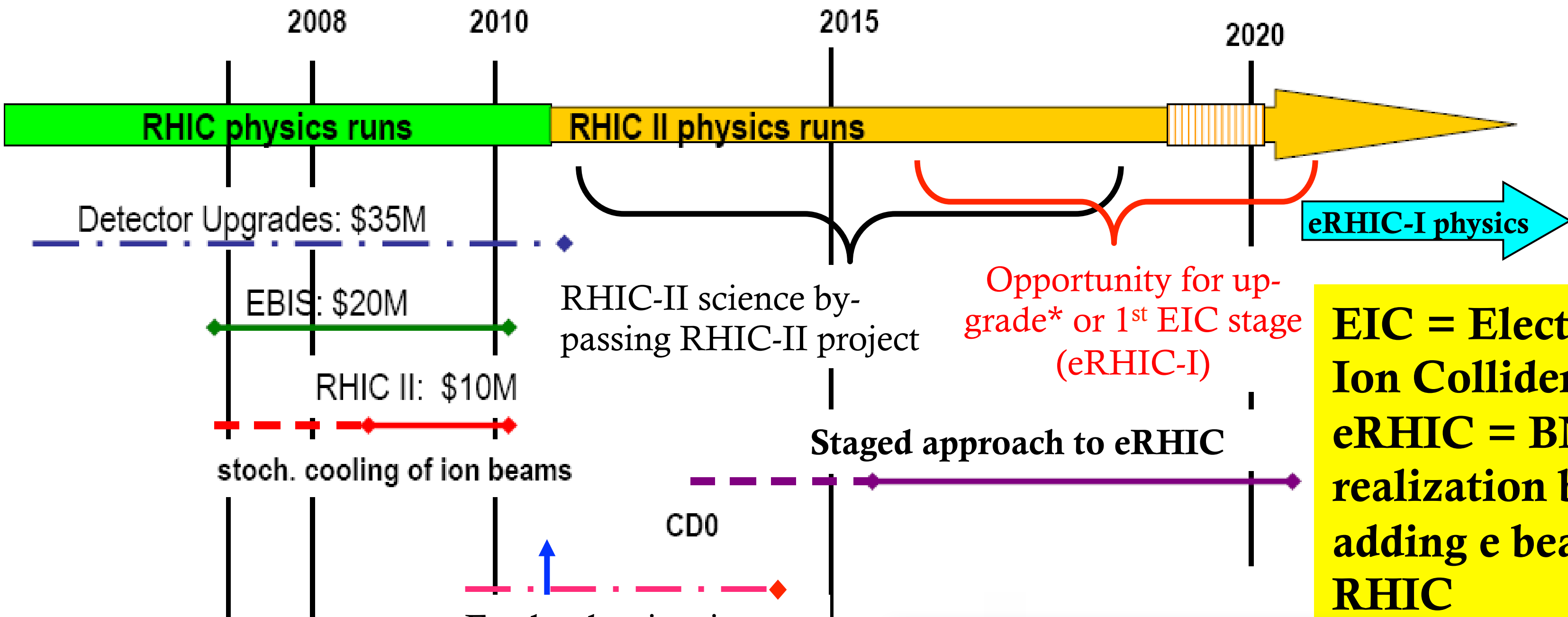


EIC Project status and plans

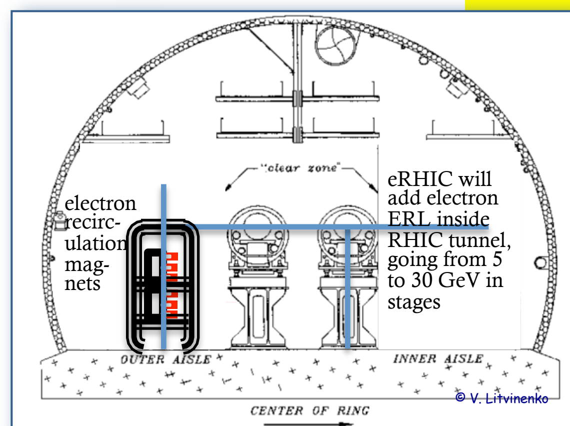
- A "collaboration" of highly motivated people/groups intends to take this project to realization:
  - EIC Collaboration **Web Page: http://web.mit.edu/eicc/**
  - 100+ dedicated physicists from 20+ institutes
  - Details of many recent studies: Recent Workshop @ INT at U. of Washington**: http://www.int.washington.edu**
  - Working groups/ Task Forces at BNL and at Jefferson Laboratory
  - Steering Group, co-chairs/contact persons: R. Milner (MIT) & AD
- International Advisory Committee (Chair: Walter Henning, ANL) formed by the BNL & Jlab Management to steer this project to realization
- 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



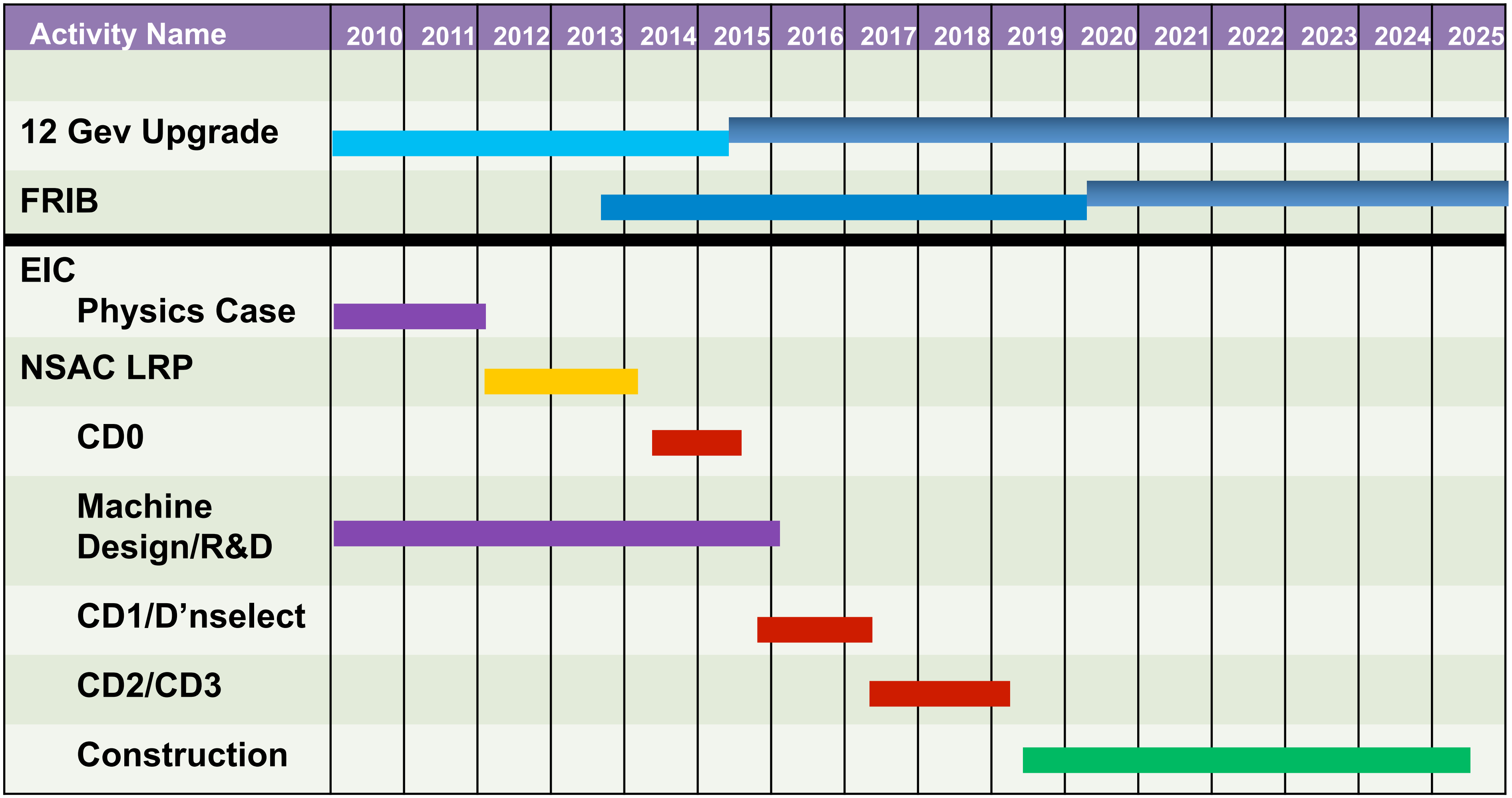
EIC = Electron-Ion Collider; eRHIC = BNL realization by adding e beam to RHIC



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

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"

Will enable us to understanding the nucleon & nuclei at high energy & *(icing on the cake)* studies of precision SM studies & possibly beyond

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 contribute directly to the understanding of QCD in the next decade!

Thank You!