

# The EIC, Saturation, and the CGC

Henri Kowalski

Rockefeller U.

14th of May 2010

based on the talk by  
Thomas Ullrich (BNL)



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# EIC Science Case

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- How gluons are shaping the forms of matter
  - ▶ Study the Physics of Strong Color Fields
    - Saturation region
    - Momentum & space distributions of the glue, what is the role of the glue in nuclei?
    - Spin of gluons  $\Delta G(Q^2, x)$
    - precise study of the QCD evolution, what is the nature of color singlet excitations (Pomerons). Test and study the limits of universality (eA vs. pA)

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- What is the internal landscape of the nucleons

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  - ▶ What is the nature of the spin of the proton?
    - Spin of gluons  $\Delta G(Q^2, x)$
    - Polarization of the sea quarks
    - Transverse spin and momentum measurements and correlations
  - ▶ What is the Three-Dimensional Spatial Landscape of Nucleons?
    - Transverse imaging of quarks and gluons in nucleons
    - Transverse momentum dependent measurements and correlations

# EIC Science Case

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- What is the internal landscape of the nucleons

# EIC Science Case

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- What governs the transition of quarks and gluons into pions and nucleons?
  - ▶ How do fast probes interact with the gluonic medium?
    - Energy loss of quarks and gluons
  - ▶ Mechanism of fragmentation?
  - ▶ Parity Violating deep inelastic scattering (PVDIS)
    - Quark helicity distributions
    - Isovector EMC effect
    - Potential ultraprecise weak mixing angle measurements
  - ▶ Lepton Flavor and Number Violation
    - Electron-tau lepton conversion

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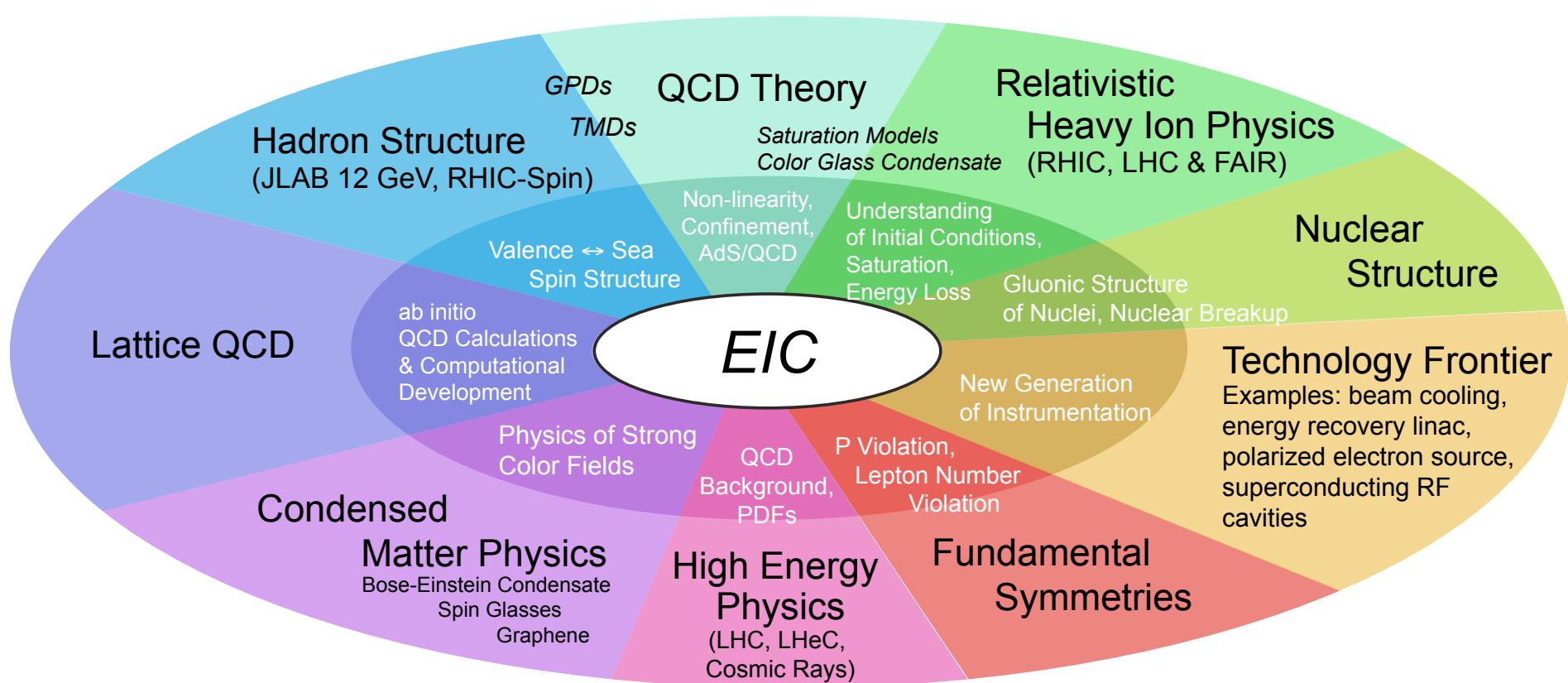
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- What governs the transition of quarks and gluons into pions and nucleons?

# EIC Science Case

How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?

The machine presents a unique opportunity for fundamental physics:



# Measurements & Techniques

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- Gluon Distribution  $G(x, Q^2)$

- ▶ Scaling violation in  $F_2$ :  $\delta F_2 / \delta \ln Q^2$
- ▶  $F_L \sim xG(x, Q^2)$
- ▶ 2+1 jet rates
- ▶ Diffractive vector meson production ( $[xG(x, Q^2)]^2$ )

- Space-Time Distribution

- ▶ Exclusive diffractive VM production ( $J/\psi, \phi, \rho$ )
- ▶ Deep Virtual Compton Scattering (nGPDs)
- ▶ Structure functions for various mass numbers A and its impact parameter dependence



Ongoing studies

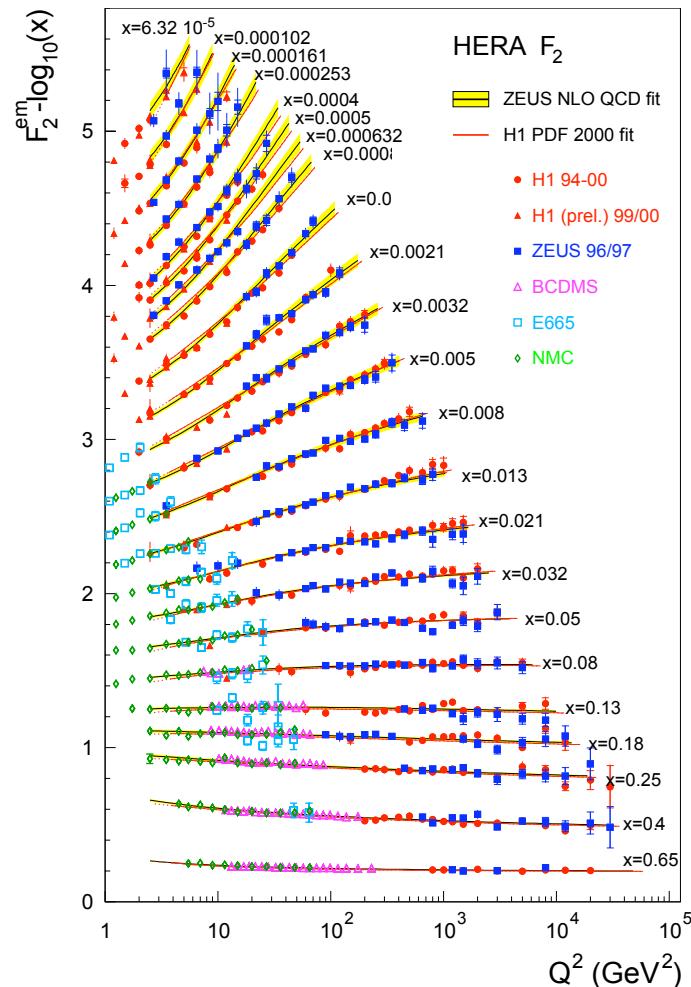
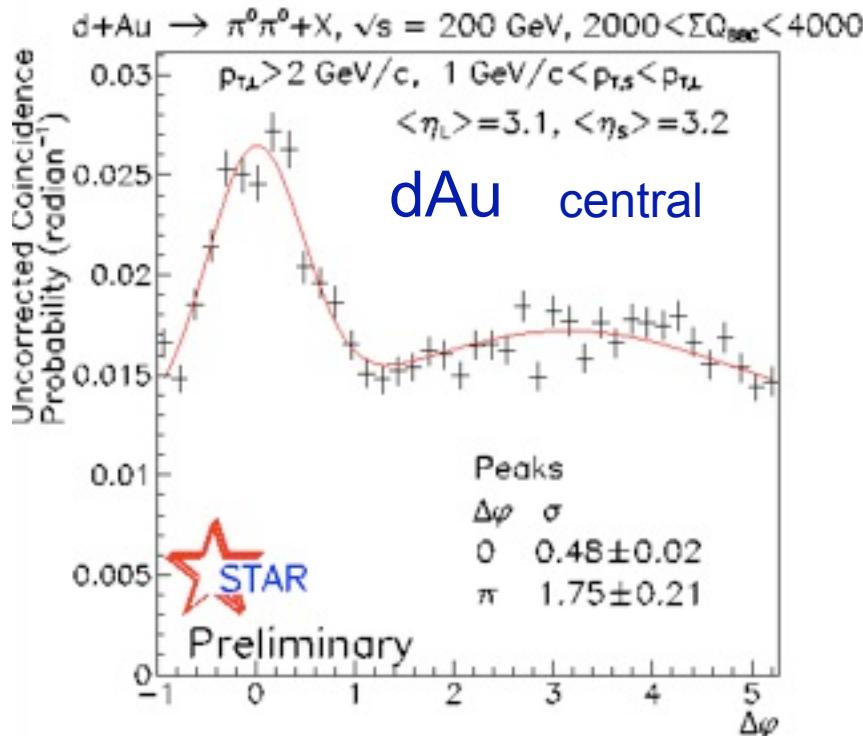


On To-Do List

# EIC - Reaching the Saturation Regime

Saturation:

- Au: Strong hints from RHIC at  $x \sim 10^{-3}$
- p: No (?) hints at Hera up to  $x=6.32 \cdot 10^{-5}$ ,  $Q^2 = 1-5 \text{ GeV}^2$



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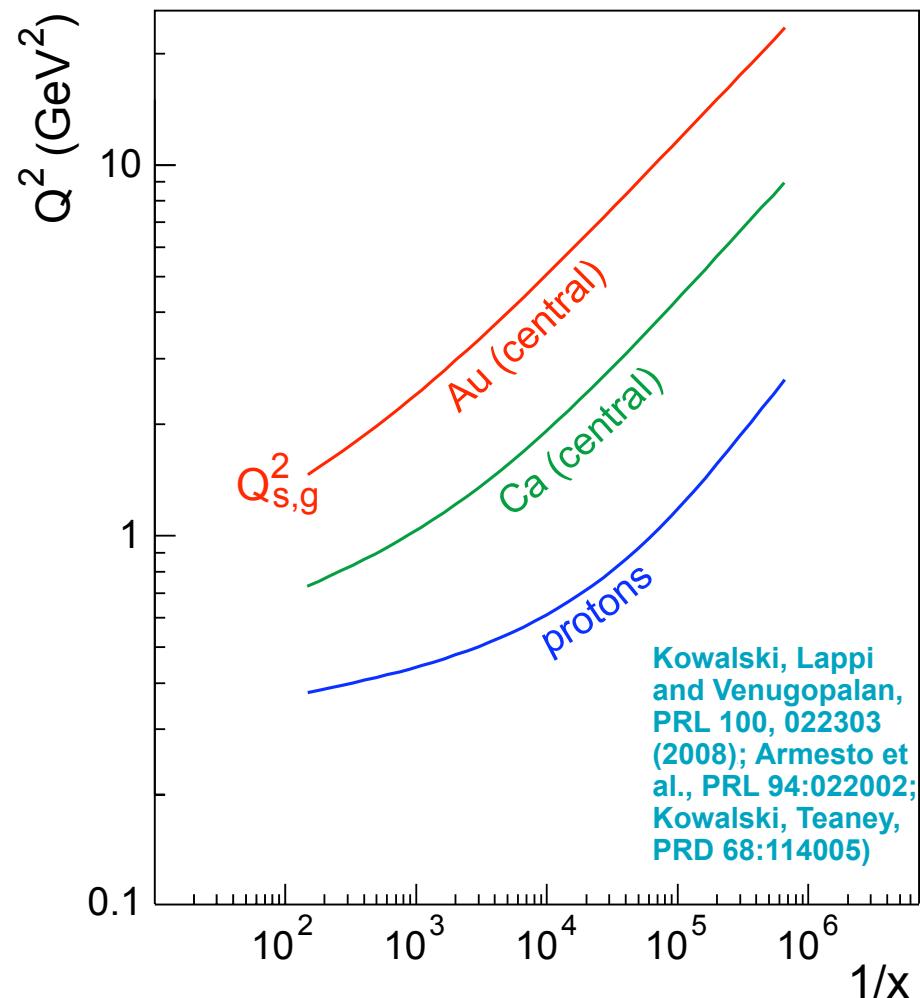
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Nuclear Enhancement:

$$(Q_s^A)^2 \approx c Q_0^2 \left( \frac{A}{x} \right)^{1/3}$$



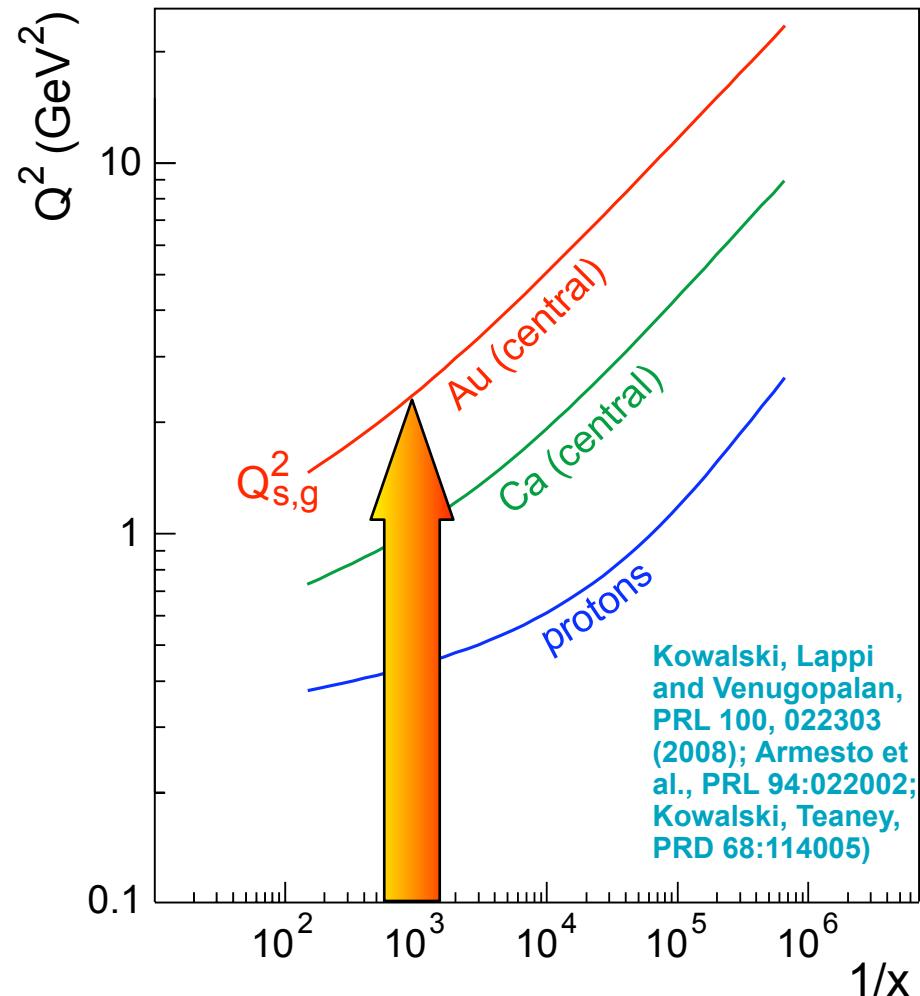
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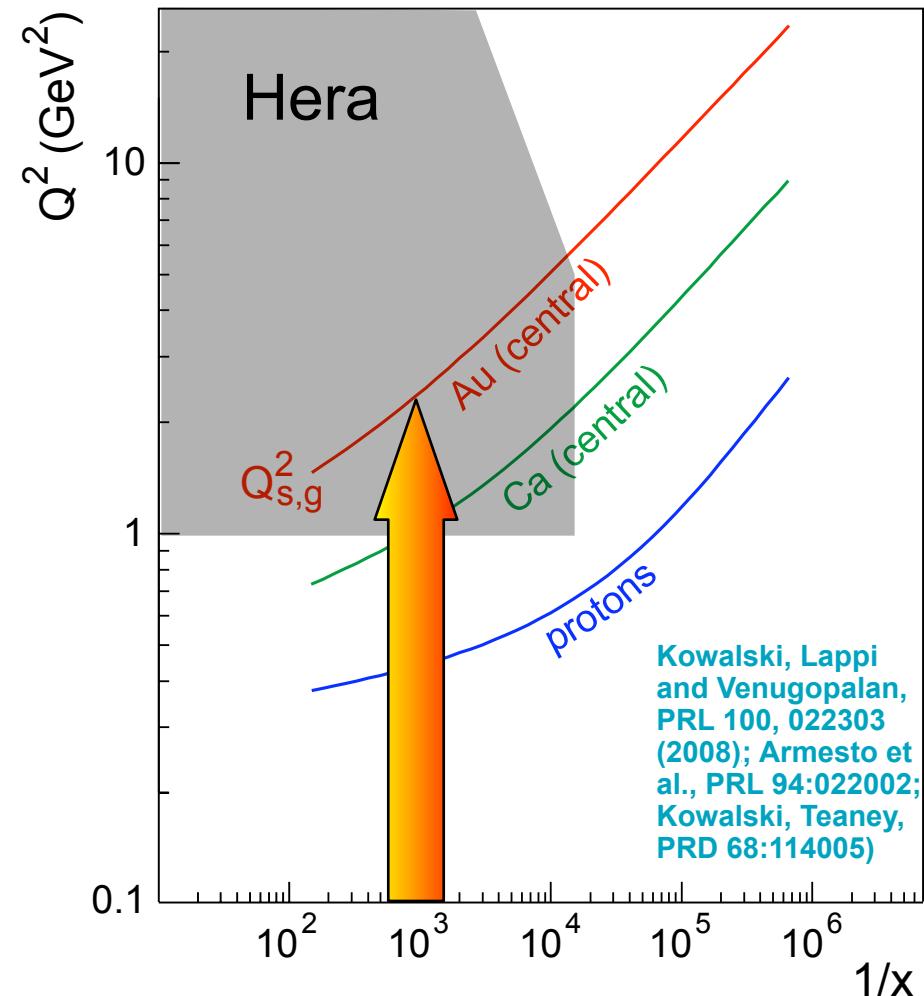
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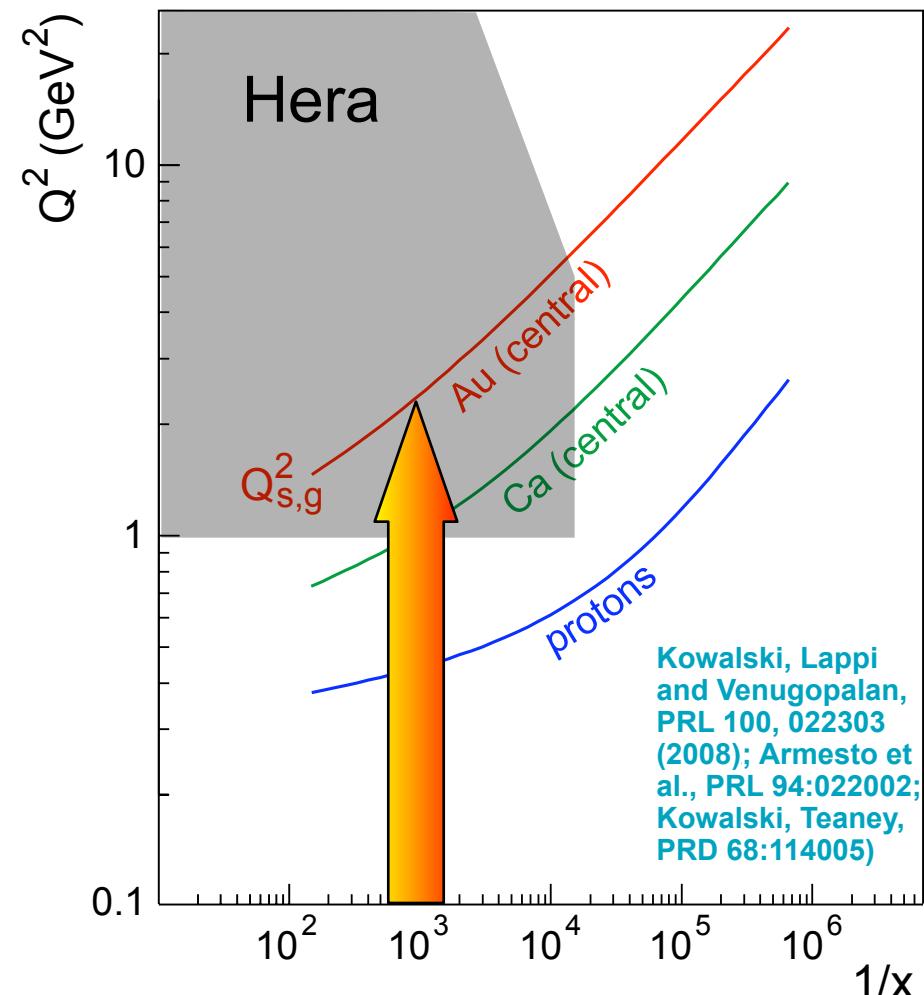
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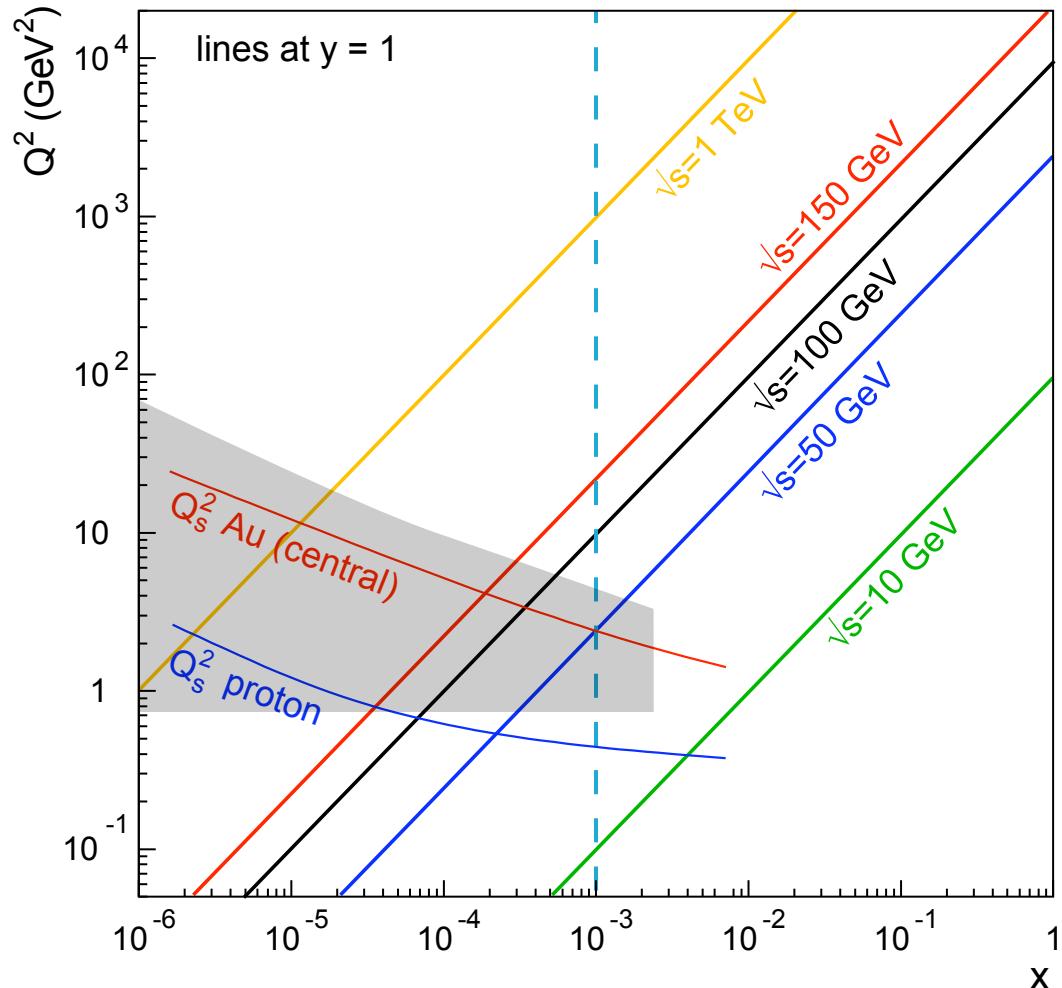
Nuclear Enhancement:

$$(Q_s^A)^2 \approx c Q_0^2 \left( \frac{A}{x} \right)^{1/3}$$

Finding RHIC and Hera  
&  $Q_s$  scalings consistent



# EIC - Energy Requirements

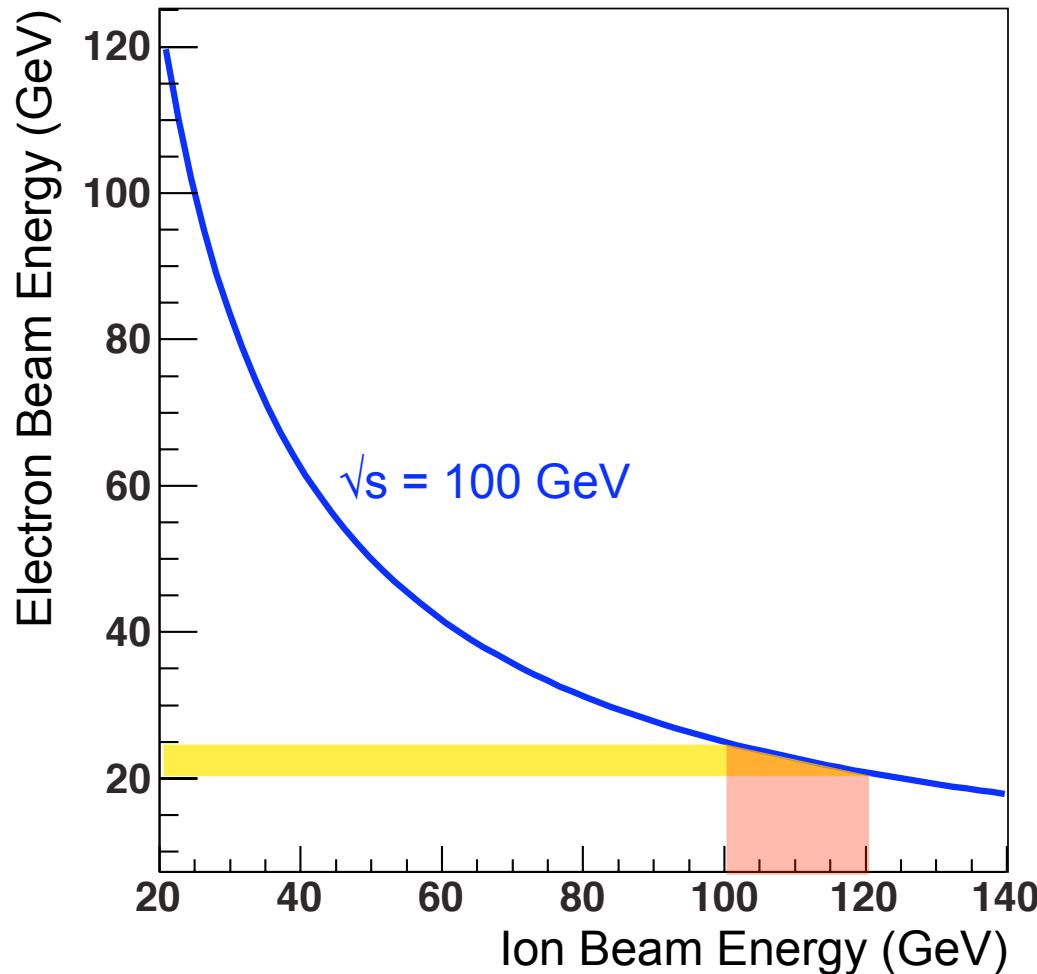


## Coverage

- Need lever arm in  $Q^2$  at fixed  $x$  to constrain models
- Need  $Q > Q_s$  to study onset of saturation

- ep: even 1 TeV is on the low side
- eA:  $\sqrt{s} = 50$  GeV is marginal, around  $\sqrt{s} = 100$  GeV desirable

# EIC - Energy Requirements



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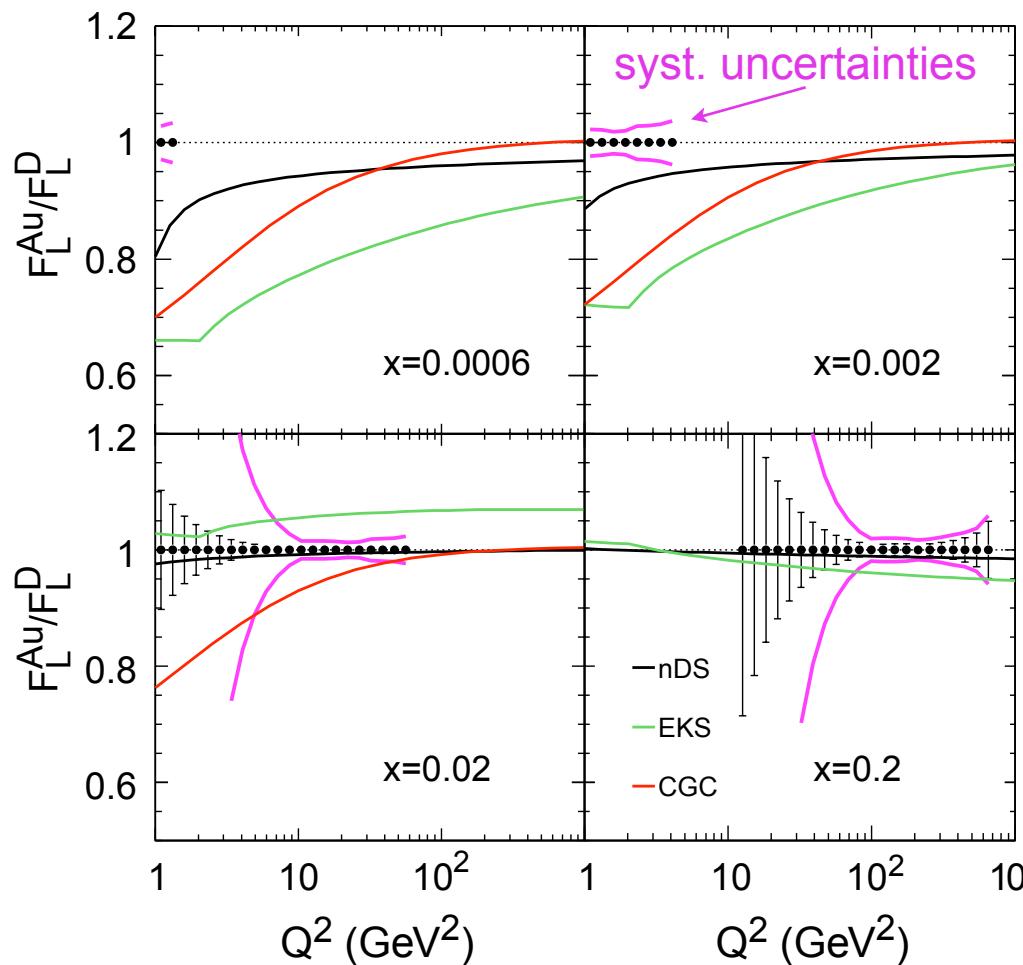
Current best estimate to study saturation:

Electron energy  $\sim 20 \text{ GeV} \times$  Ion Energy  $\sim 100 \text{ GeV}$

# EIC - What Luminosity is Needed?

Hera suffered from low luminosity:  $L = 1.6\text{-}3.8 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

EIC-Example  $F_L$ : *inclusive* measurements at different  $\sqrt{s}$ , assume 1% energy-to-energy normalization



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

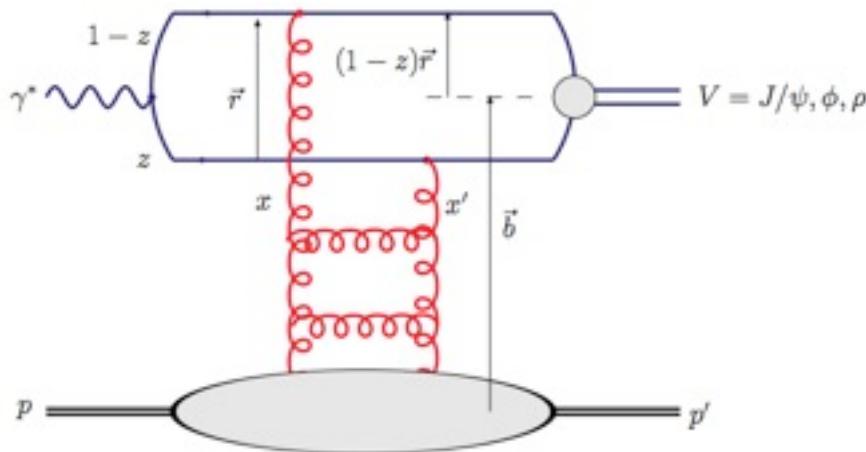
All together 10 weeks at  
 $L \sim 4 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  and 50% duty cycle  
(Note: 100x Hera L)

Conclusion from this study:

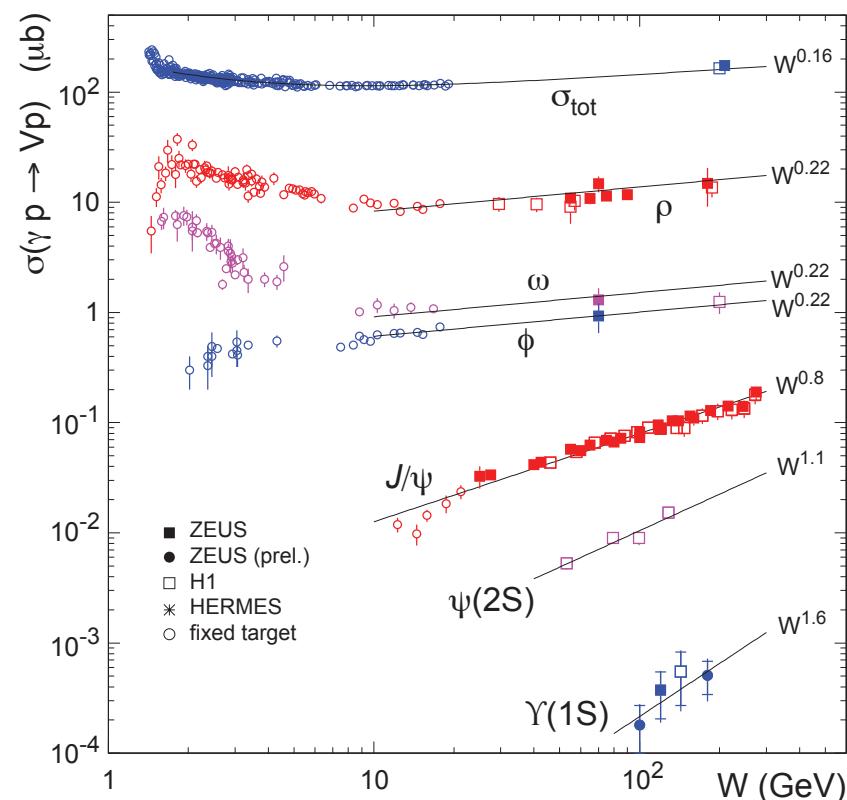
- Dominated by sys. uncertainties
- More statistics does not provide higher accuracy

# EIC - What Luminosity is Needed?

Key measurement: exclusive diffractive vector meson production:  $e A \rightarrow e' A' V$



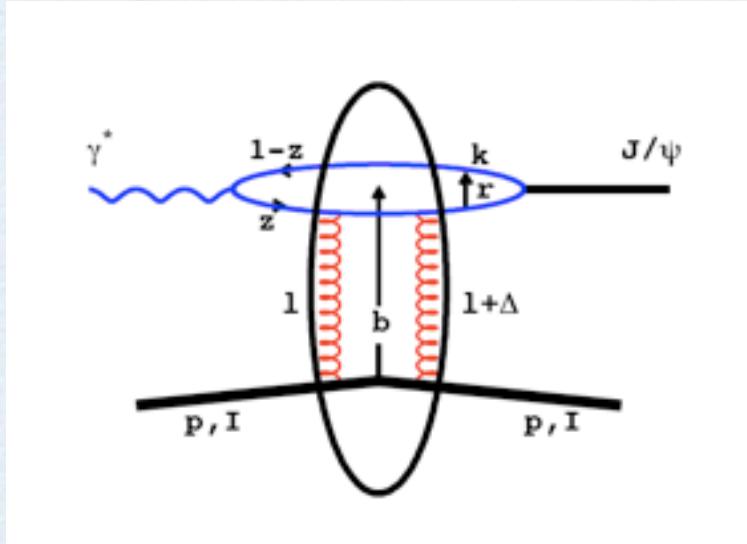
Sensitive means to probe  $G(x, Q^2)$  and saturation:  $\sigma \propto G(x, Q^2)^2$



$\sigma(x_{IP}, x, Q^2, t)$  double/triple differential & small  $\sigma$

⇒ high L required (statistical >> systematic errors),  
(DVCS even more L hungry → GPDs)

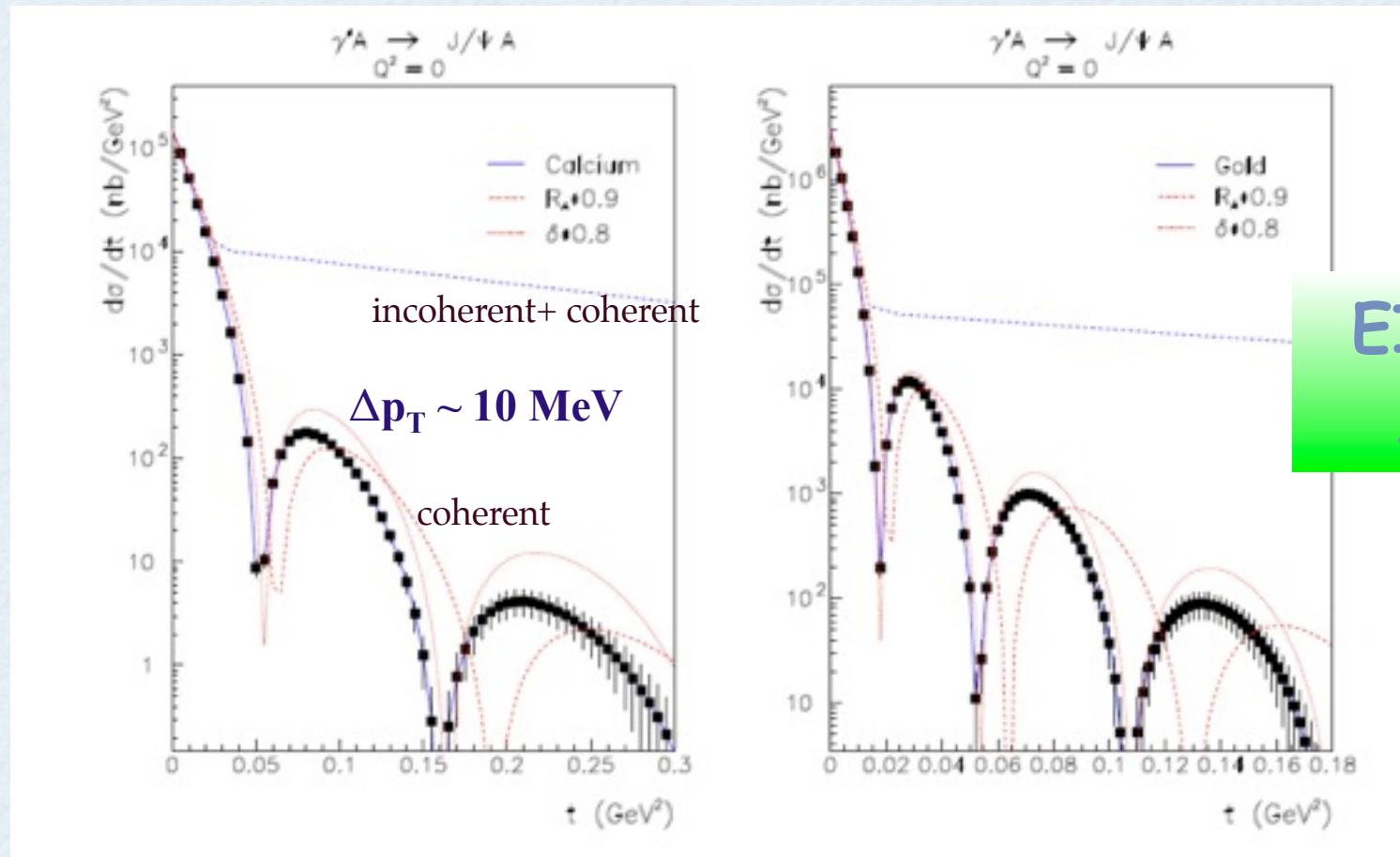
## J/ $\psi$ $p_T$ resolution at EIC or LHeC



In photoproduction, J/psi  $p_T$  is determined from  $p_T$  of ee or  $\mu\mu$  decay pair  
 $p_T$  resolution for J/psi -  $O(1)$  MeV for a TPC with 2m radius  
no measurement of a proton or ion momentum necessary  
beam electron  $p_T < 1$  MeV (0.2 with cooling MeV) for  $E_e < 5$  GeV  
scattered electron can be easily detected in the forward detector

# Nuclear gluonic shapes

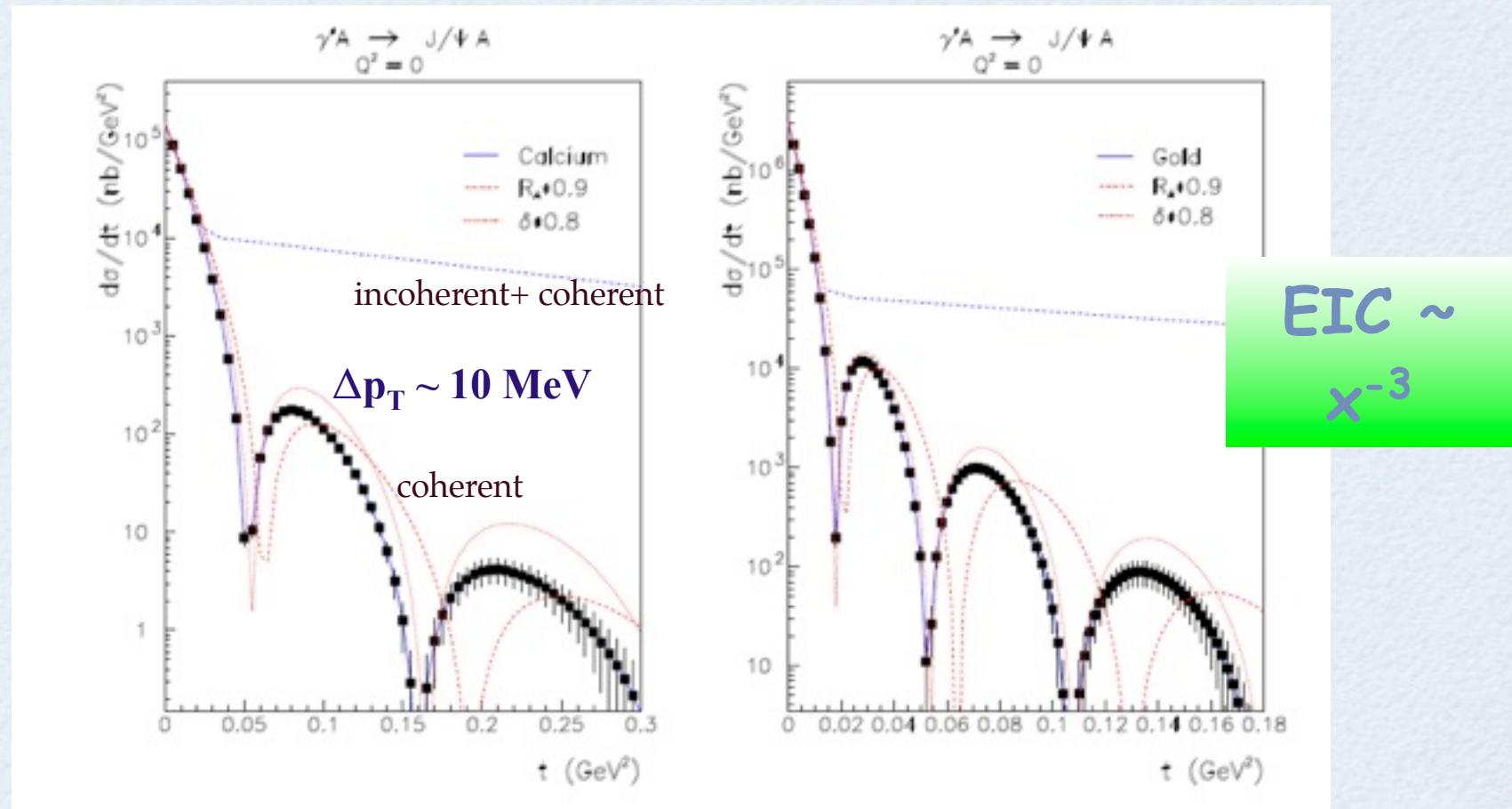
## Coherent and incoherernt $eA \rightarrow J/\psi A$ photoproduction



Coherent - nucleus remains in the ground state  
 incoherent - nucleus gets excited or breaks up,  
 no additional particles are produced

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Coherent - nucleus remains in the ground state  
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 no additional particles are produced

Forward em and  
 had detectors  
 required

# Measurement of momenta of J/ $\psi$ decay muons

Expected resolution of drift chambers:

$$(\sigma_{p_t}/p_t)_{meas} = \frac{p_t \sigma_{r\phi}}{0.3L^2B} \sqrt{\frac{720}{N+4}}$$

$$(\sigma_{p_t}/p_t)_{MS} = \frac{0.05}{LB\beta} \sqrt{1.43 \frac{L}{X_0} [1 + 0.038 \log(L/X_0)]}$$

## TPC parameters

1. outer radius R = 2 m
2. solenoidal field B = 3.5 T
3. gas density X<sub>0</sub> = 450 m
4. point resolution  $\sigma$  = 100  $\mu$ m
5. measurement N = 200 points.

*meas*

*MS*

$$\sigma_{p_t}/p_t = 0.005 \cdot p_t \oplus 0.045/\beta \%$$



$\Delta p_T < 1 \text{ MeV}$

# EIC - Requirements

Requirements depend on specific measurements

Measurement	$\sqrt{s}$	$L$ ( $\text{cm}^{-2} \text{ s}^{-1}$ )
Saturation (eA)	Inclusive F2, FL	High $\sqrt{s} > 50 \text{ GeV}$ preferred $\sqrt{s} \sim 100 \text{ GeV}$
	Diffractive VM & n-differential	high $\geq 10^{33}$
3D Imaging (ep and eA)	GPD, TMD n-differential	Moderate $\sqrt{s} > 50 \text{ GeV}$
Electroweak (ep)	PVDIS, W production, $\gamma$ -Z interference, Lepton number violation	Moderate to high
Spin structure of the nucleon (ep)	Inclusive: structure functions, g1, ... Semi-inclusive (tag quark)	High $\sqrt{s} > 50 \text{ GeV}$ preferred $\sqrt{s} \sim 100 \text{ GeV}$
Fragmentation, Energy loss (ep, eA)	Spectra: $v, p_T, Q^2$ flavor dependence (c, b)	Low - High $\sqrt{s} > 50 \text{ GeV}$ (heavy flavor)

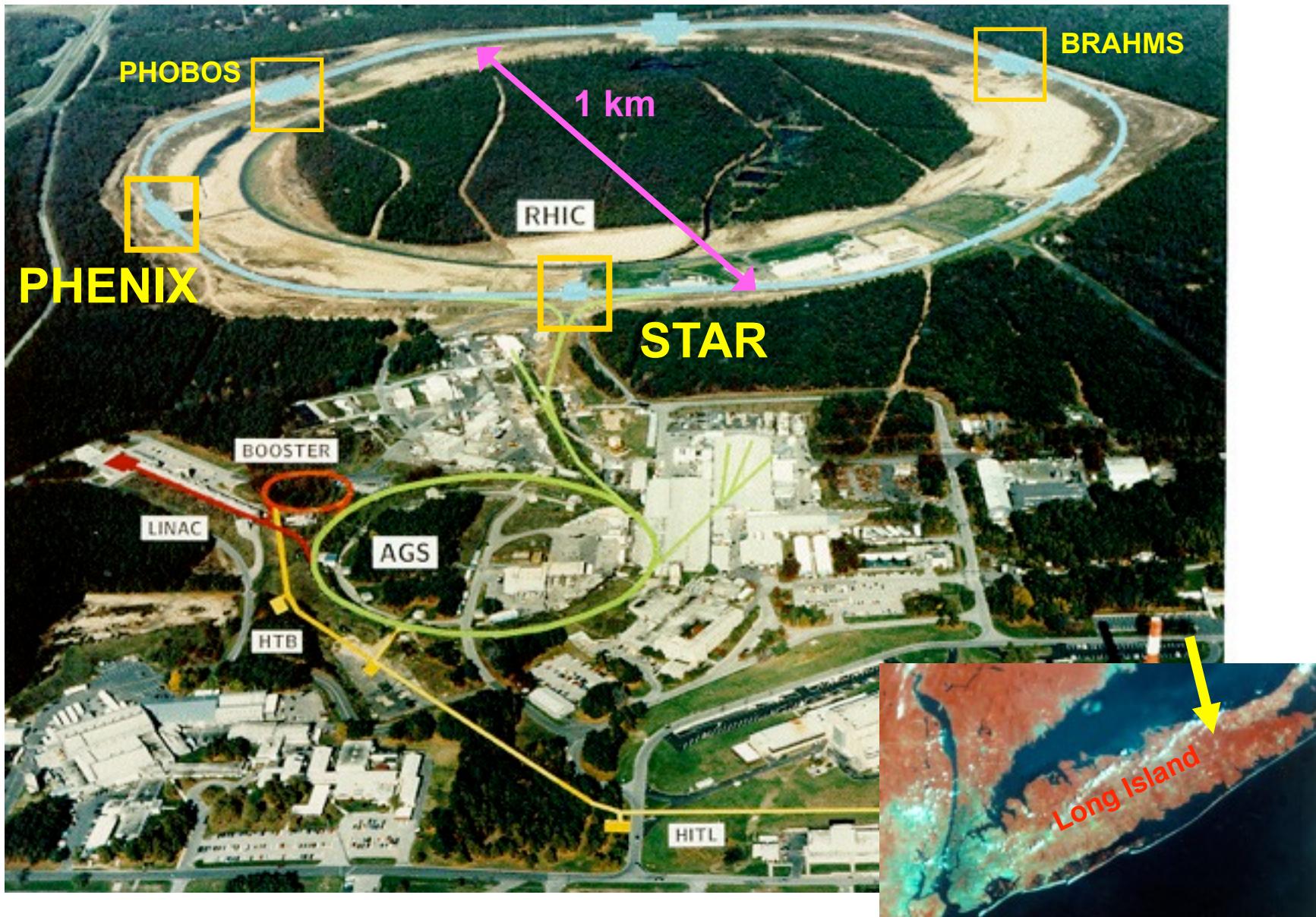
# EIC - Realization

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High  $\sqrt{s}$ , high L machine: costs too high to build in one step ⇒ **staged approach**

- **QCD Community:** JLAB & RHIC
  - ▶ BNL: EIC Task Force, eRHIC-CAD
  - ▶ JLAB: User Group
- **EIC Collaboration** (<http://web.mit.edu/eicc/>)
  - ▶ Collaboration Meetings, Working Groups
  - ▶ Steering Committee
- **International Advisory Committee**
  - ▶ Members from broad community, chair: W. Henning
- **EIC Concepts**
  - ▶ eRHIC (RHIC/BNL)
  - ▶ ELIC (CEBAF/JLAB)
- **Timeline:** ~2020 (vital: NSAC Long Range Plan 2012/13)

# EIC Concept: RHIC → eRHIC @ BNL

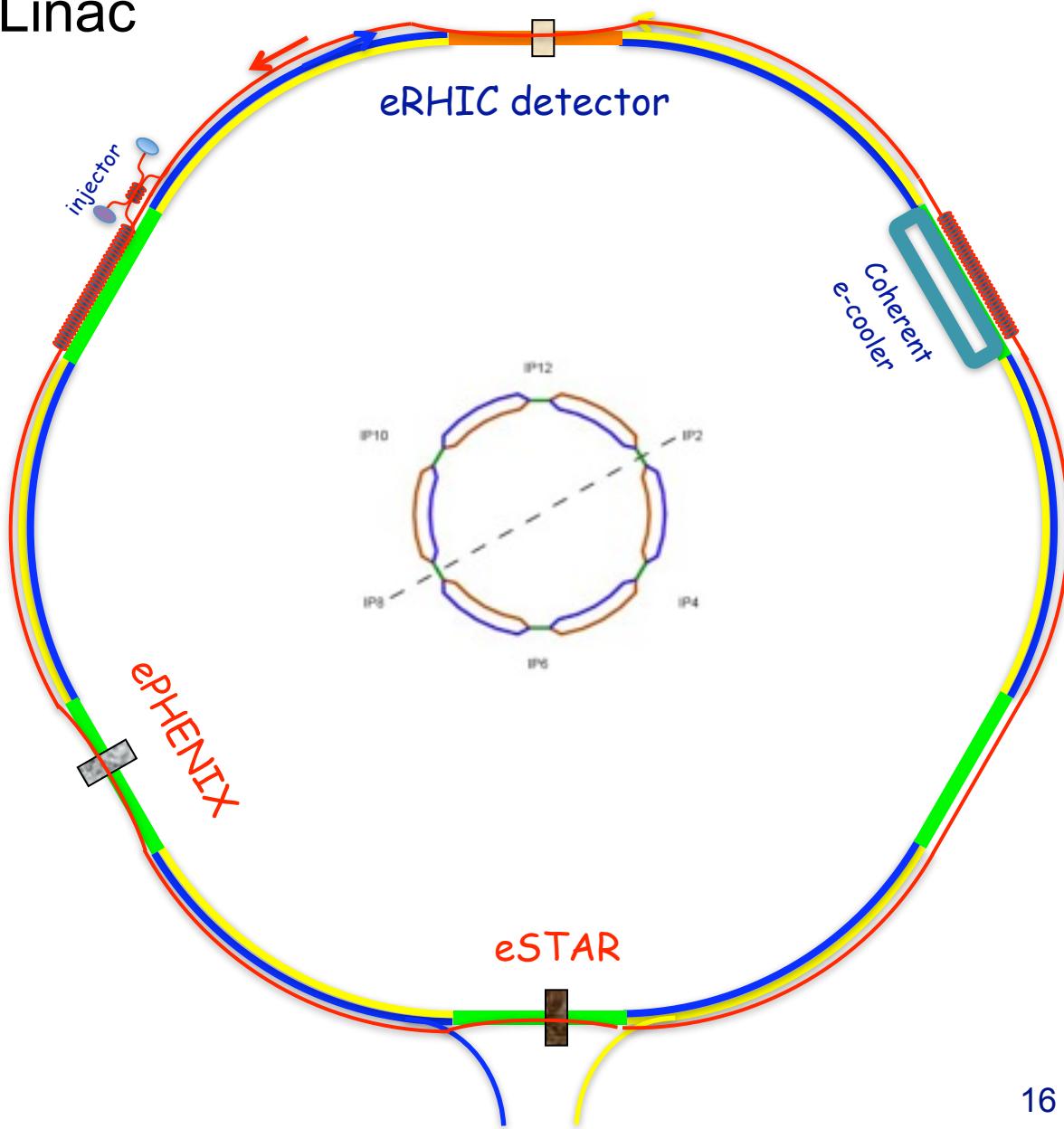


# EIC Concept: RHIC → eRHIC @ BNL

ERL: Energy Recovery Linac

1 - 5 GeV per pass

4 (6) passes

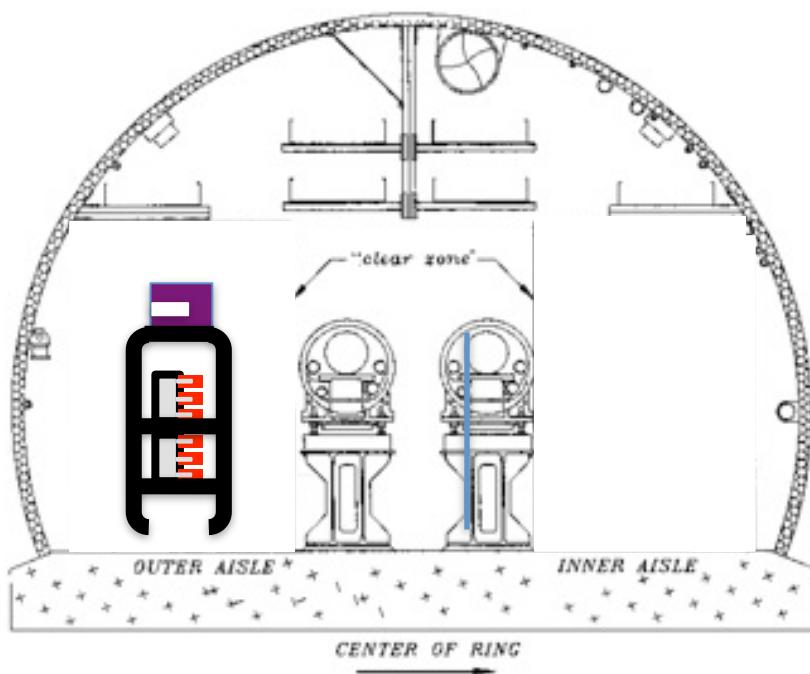
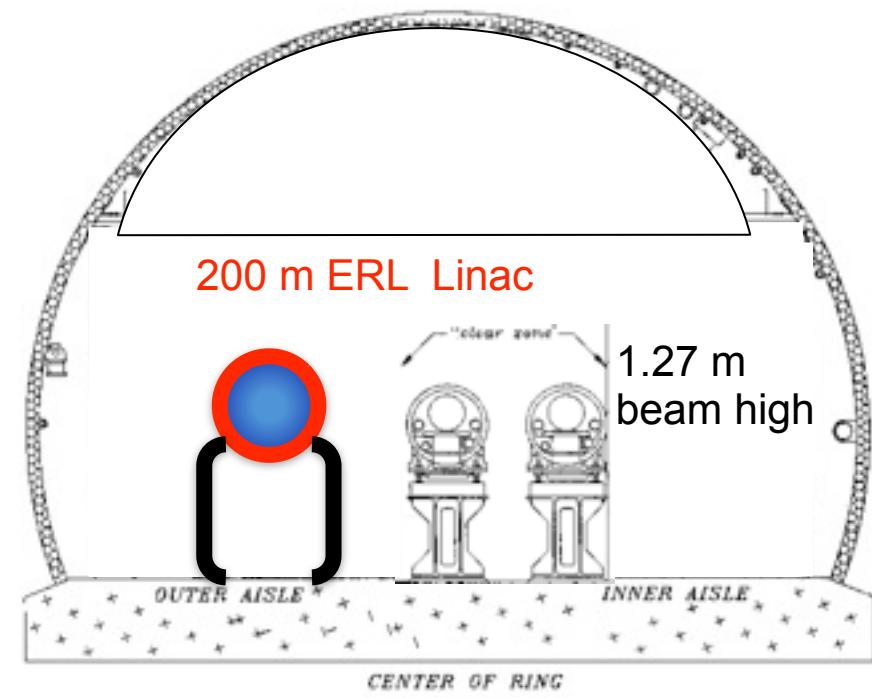


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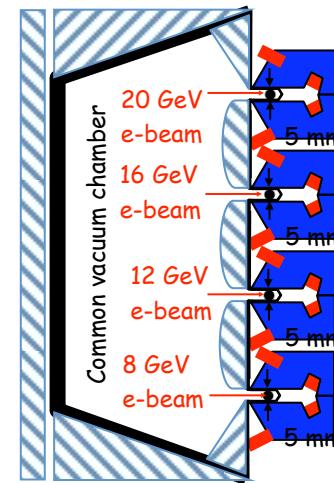
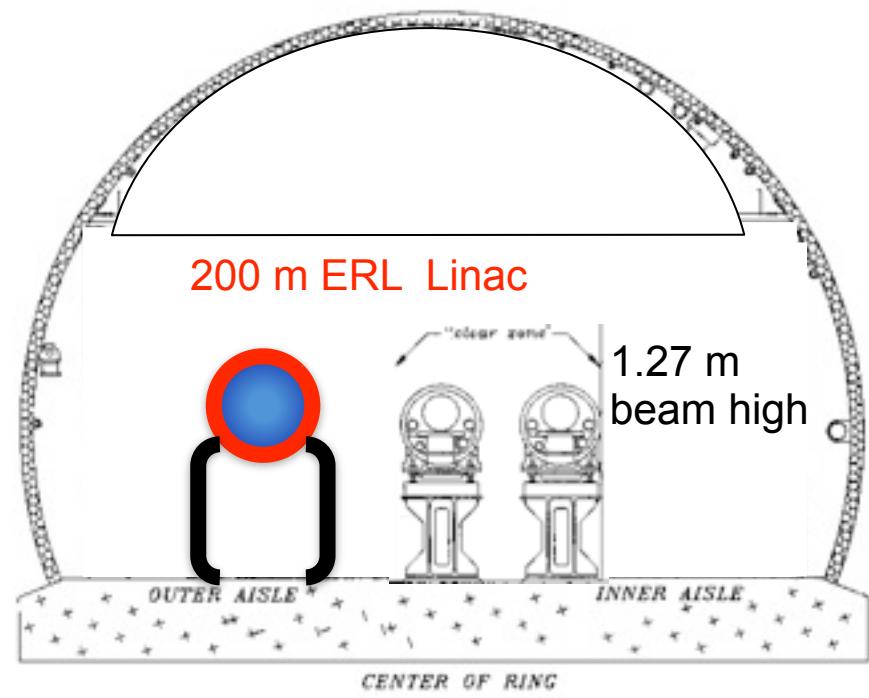
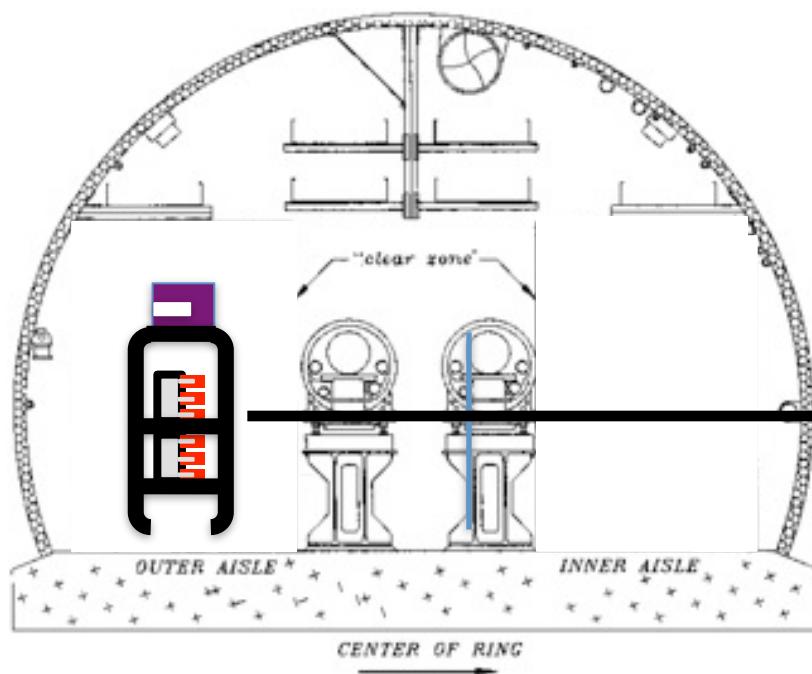


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# EIC Concept: RHIC → eRHIC @ BNL

## eRHIC (stage 1):

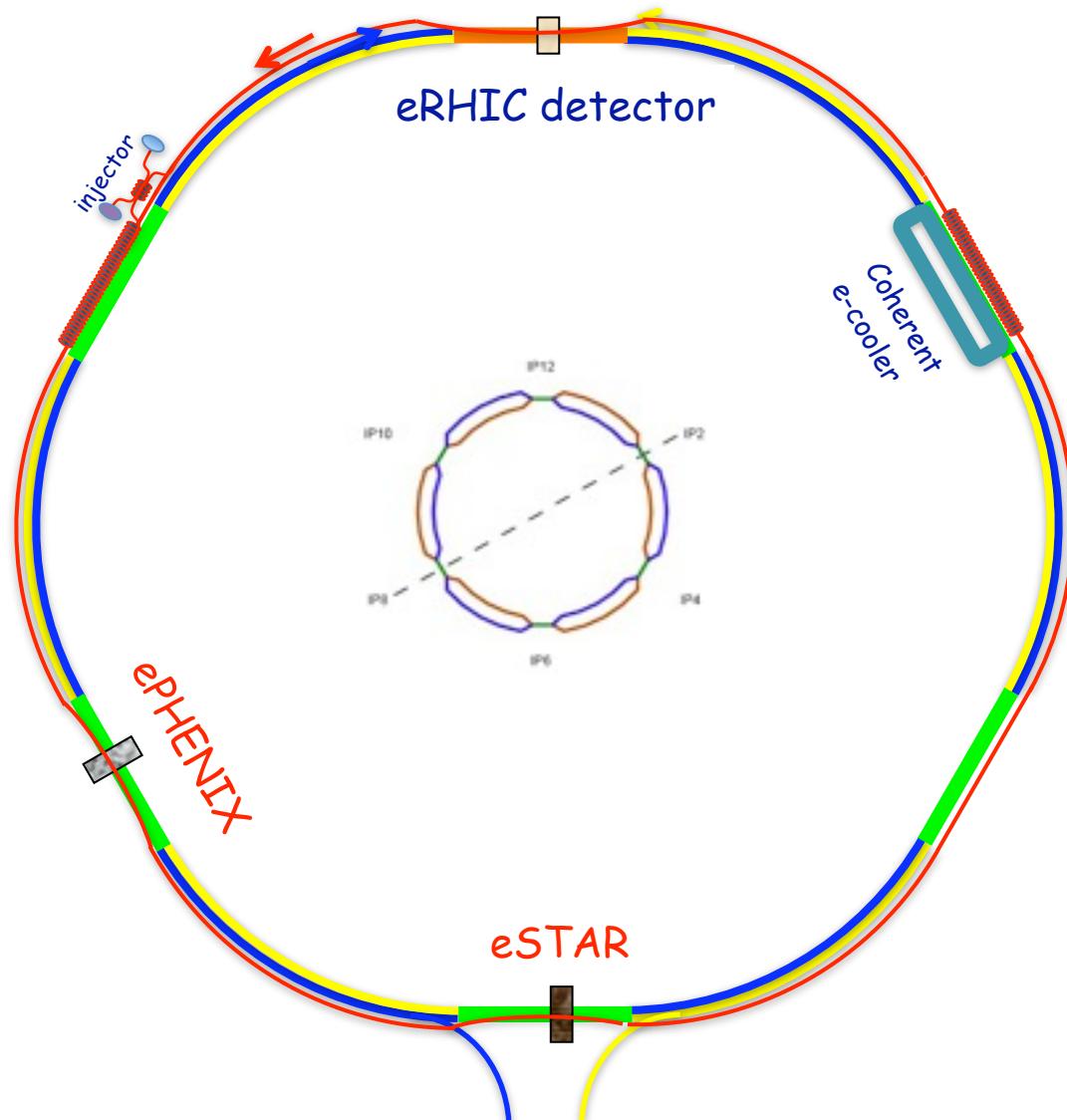
- 4 GeV e x 250 GeV p ( $\sqrt{s} = 63$  GeV)
- 4 GeV e- x 100 GeV/n Au ( $\sqrt{s} = 40$  GeV)
- $L \sim 10^{32}-10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

## eRHIC (stage 2):

- 20 GeV e x 325 GeV p ( $\sqrt{s} = 160$  GeV)
- 20 GeV e x 120 GeV/n Au ( $\sqrt{s} = 98$  GeV)
- $L \sim 10^{33}-10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

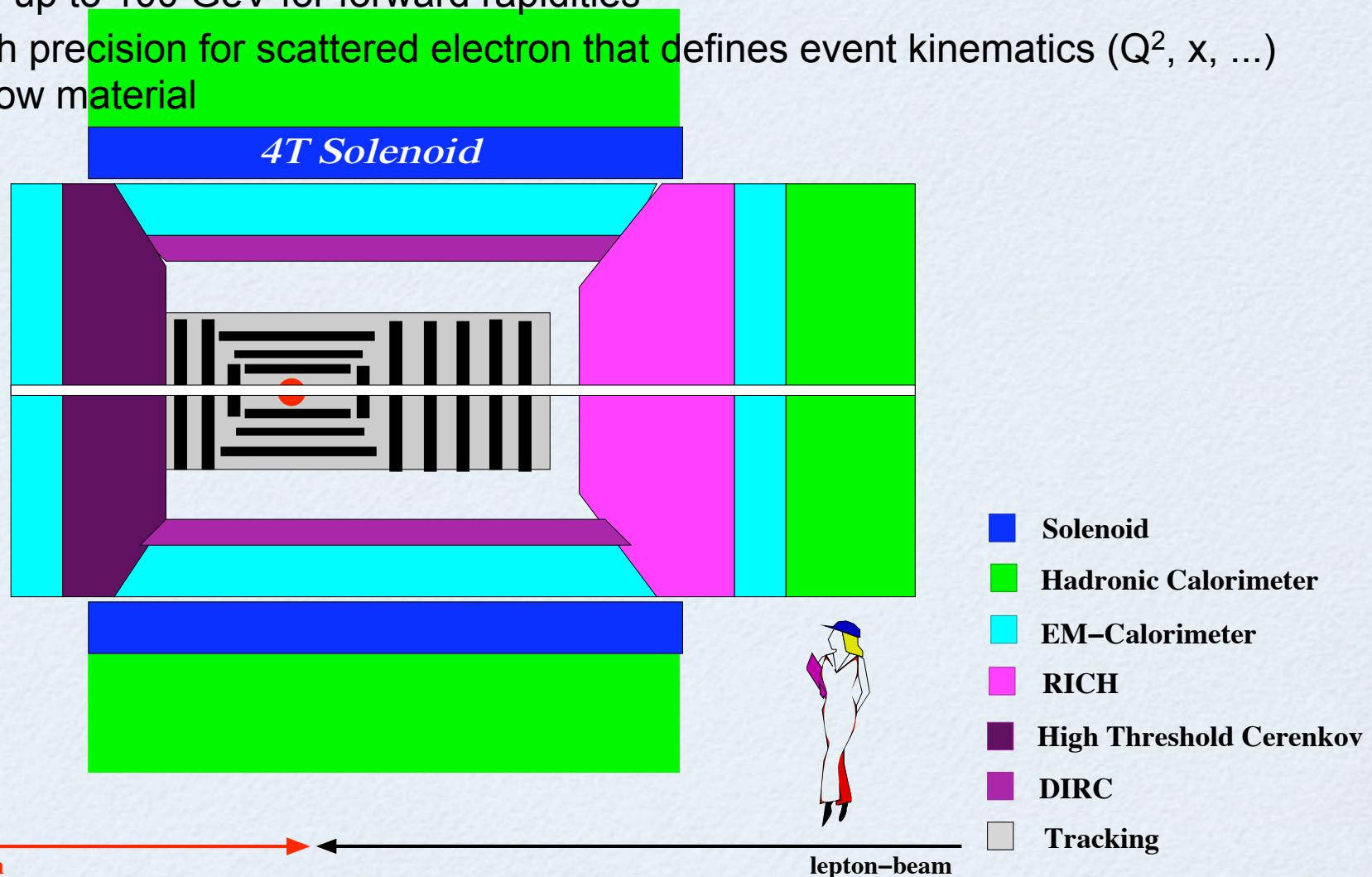
## eRHIC upgrades

- Higher luminosity
- Higher hadron energy



## Detector concept

- Hermeticity (diffraction  $\Leftrightarrow$  rapidity gap)
- Extreme forward angle  $\Leftrightarrow$  low-x physics
- PID < 4 GeV/c in central detector
- PID up to 100 GeV for forward rapidities
- High precision for scattered electron that defines event kinematics ( $Q^2$ ,  $x$ , ...)  
 $\Rightarrow$  low material

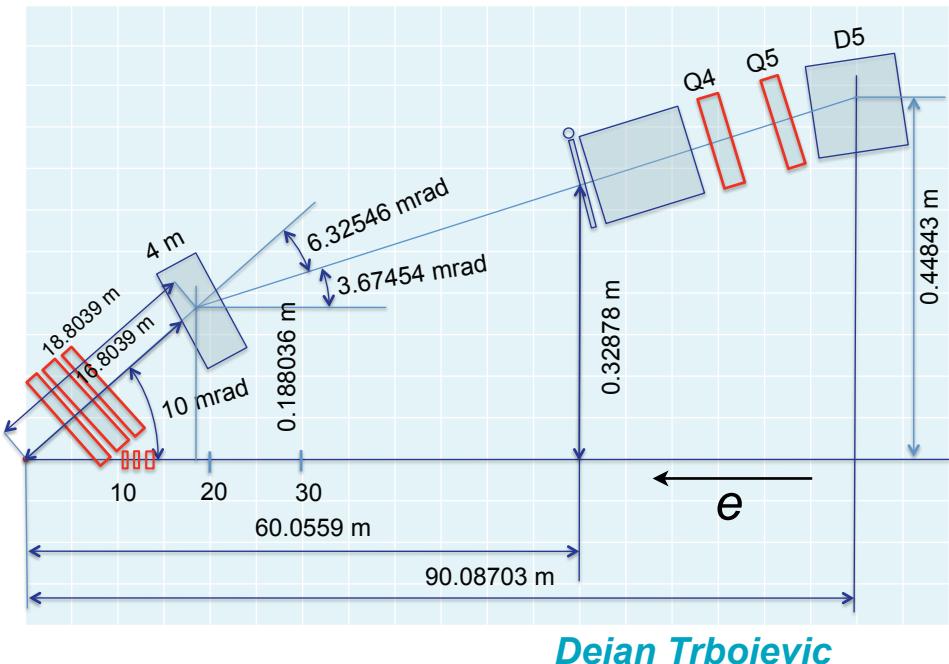


# eRHIC: Detector $\Leftrightarrow$ IR Design

## IR:

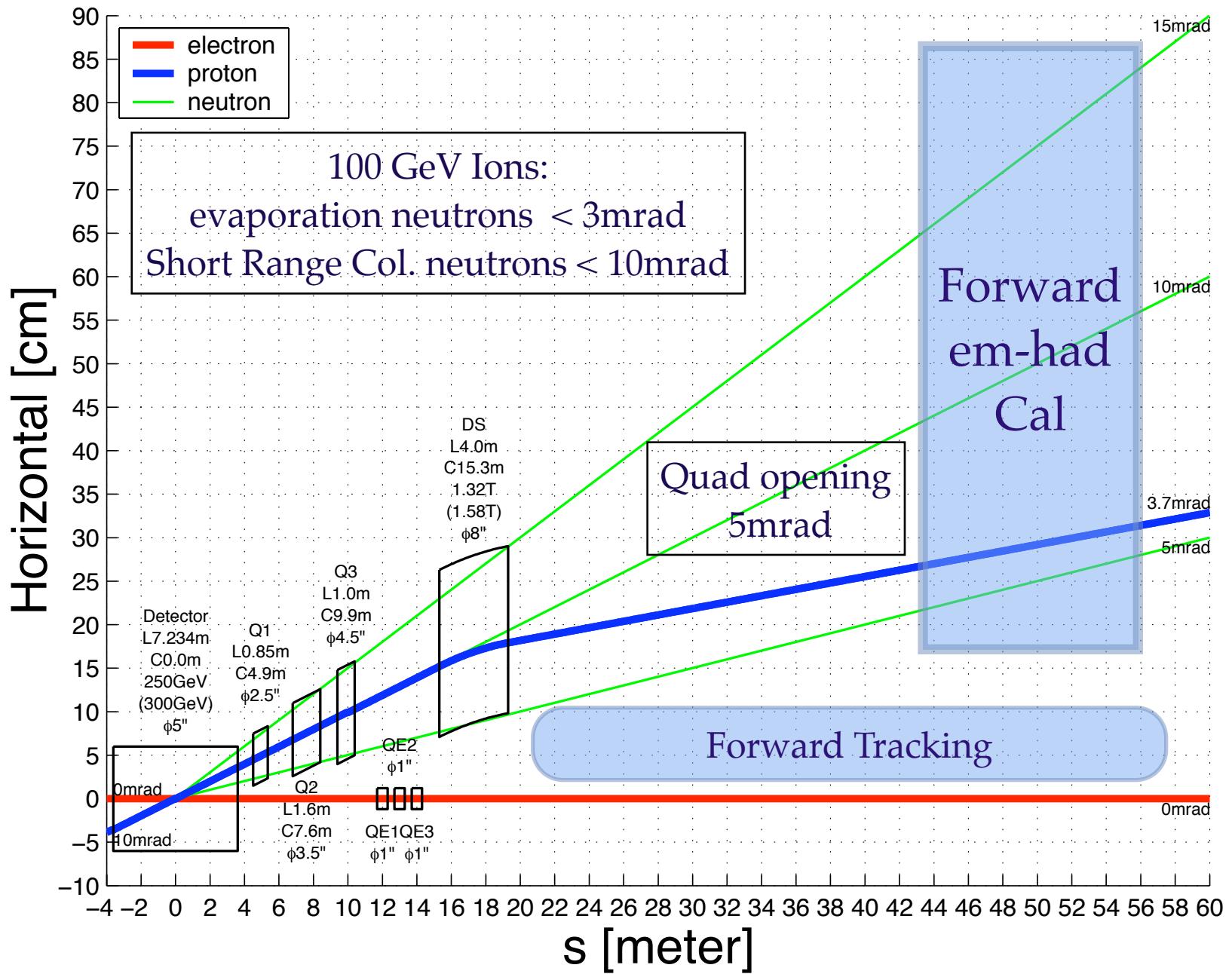
- minimize synchrotron radiation ( $P$  and  $\lambda$ )
- minimize  $\beta^* \Rightarrow L$
- First quads: maximize aperture for particles at extreme forward angle  $\Rightarrow$  detect n from breakup (diffraction)
- Design depends on presence/absence of pp/pA/AA ops

### *High Luminosity IR ( $\beta^* = 5$ cm)*

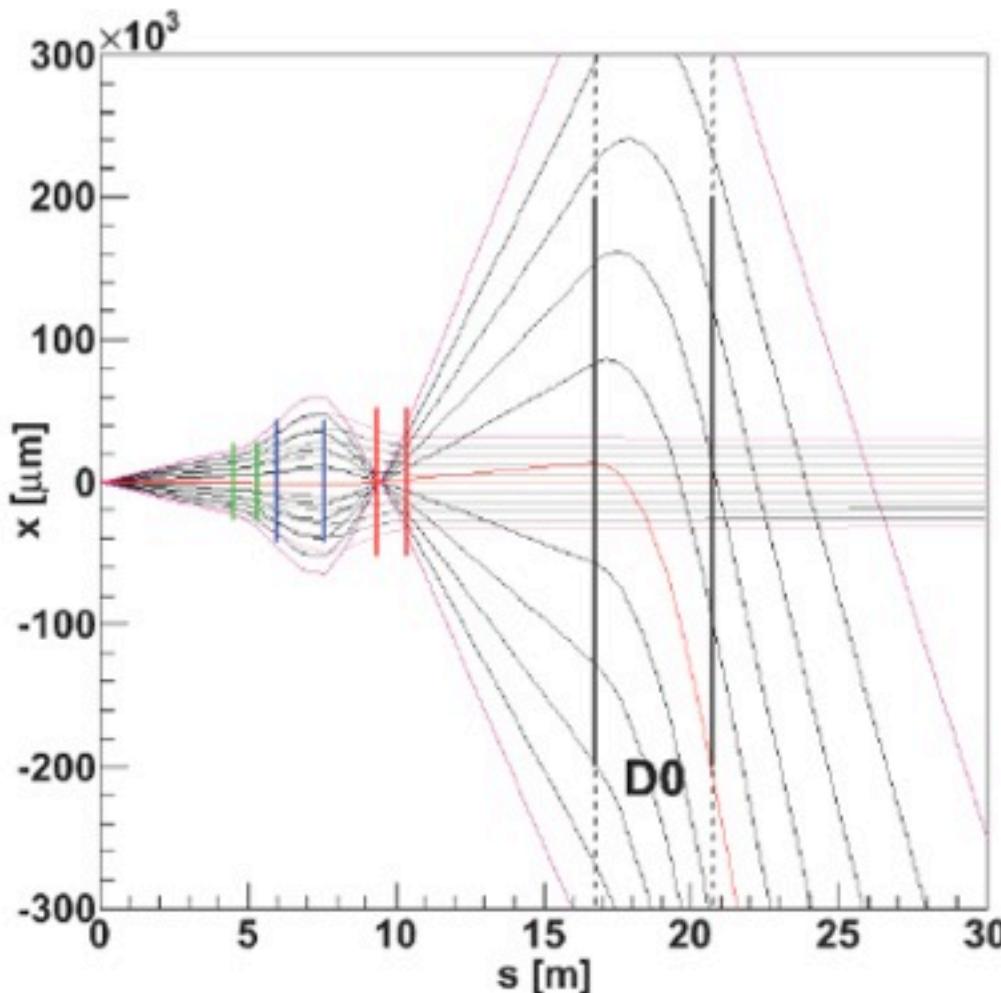


### Latest Design:

- ep(A) crossing angle of 10 mrad
- straight e beamline  $\Rightarrow$  almost no synchrotron radiation
- good separation of e/p beamlines
  - ▶ real estate for additional detectors
- need to fine tune for optimal instrumentation
- aperture of 1st quad:  $\pm 5$  mrad
  - ▶ important for breakup-neutron detection

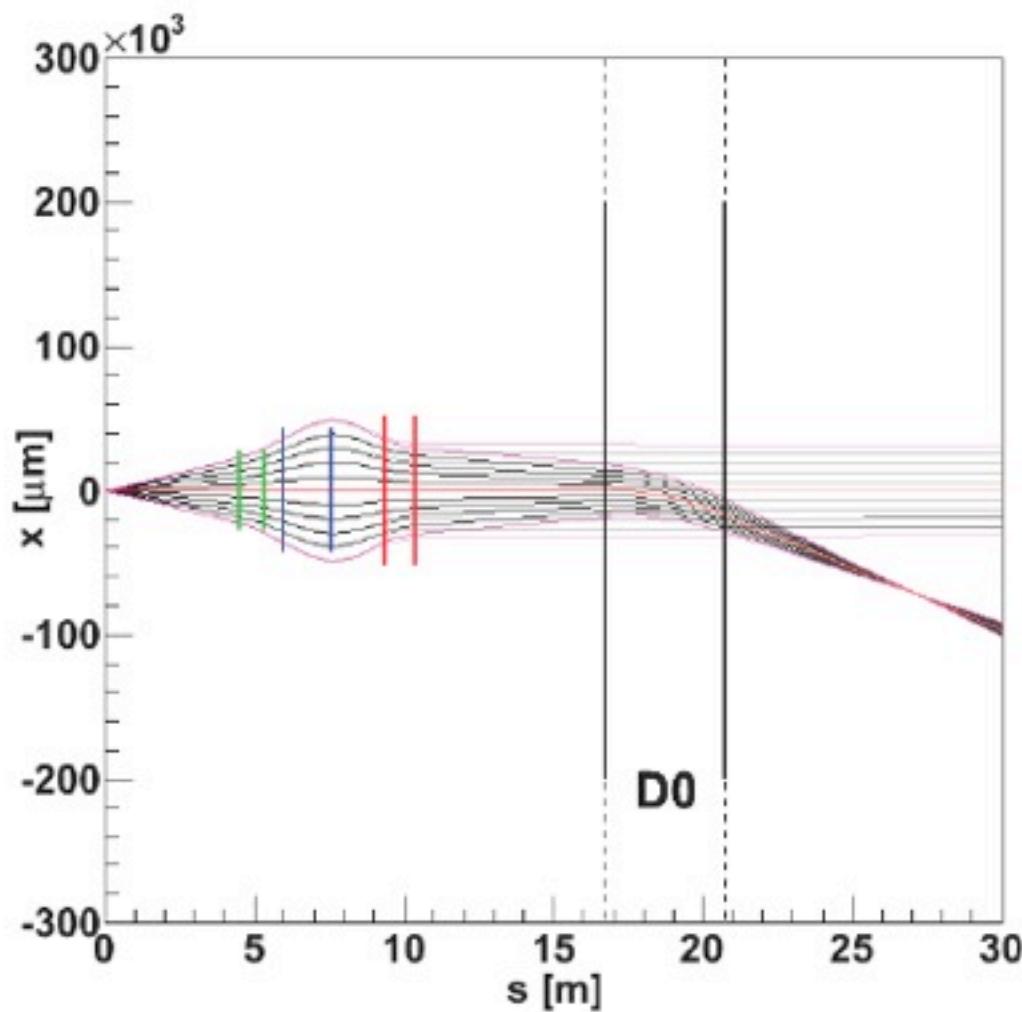


# proton track with $\Delta p = 40\%$ (-5mrad - +5mrad)

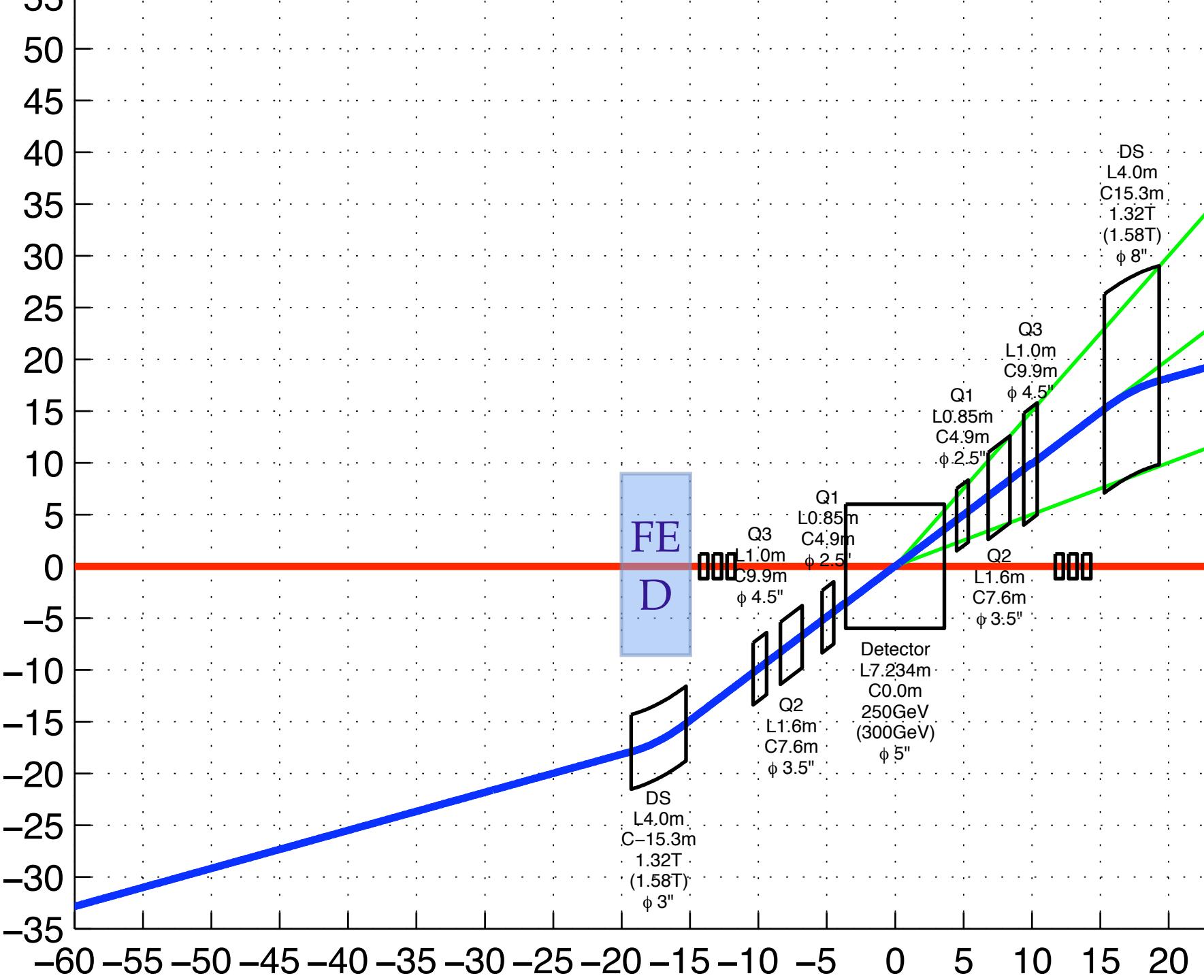


- $\Delta p = 40\%$ : Equivalent of fragmenting proton from Au in Au optics (79/197)

proton track with  $\Delta p = 10\% \text{ (-5mrad - +5mrad)}$



Horizontal [cm]

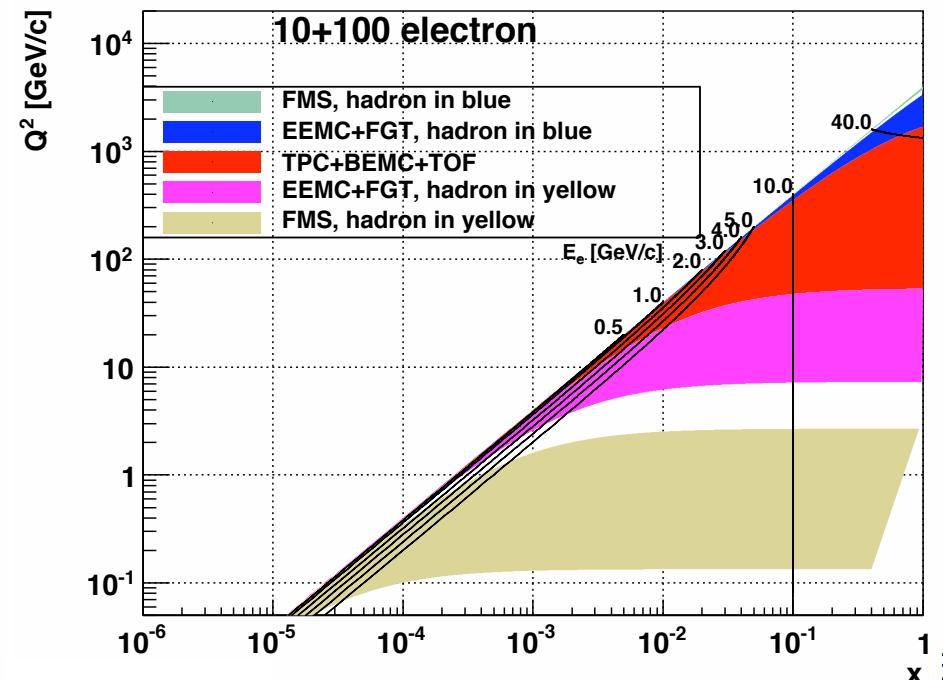
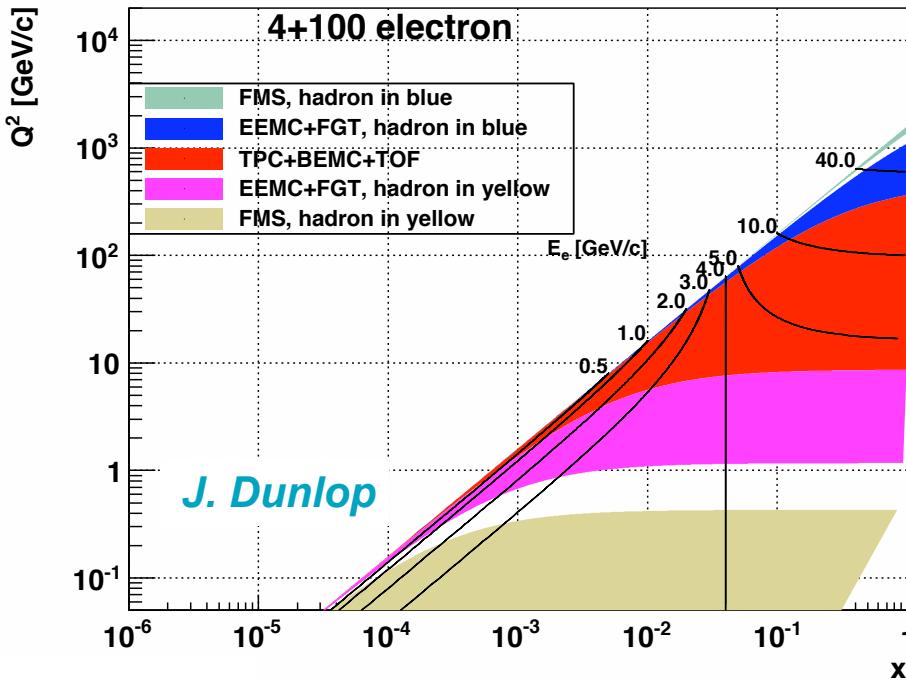


# Heavy Ion Experiments and ep/eA?

## eRHIC & staged eRHIC:

- Electron beam around RHIC tunnel
- Requires scheme for getting electron beamline **through** or **around** PHENIX and STAR
- Can STAR/PHENIX make use of the e-p and e-A collisions?
  - ▶ **RHIC decadal planing: experiments are looking into it**

*Example: STAR*



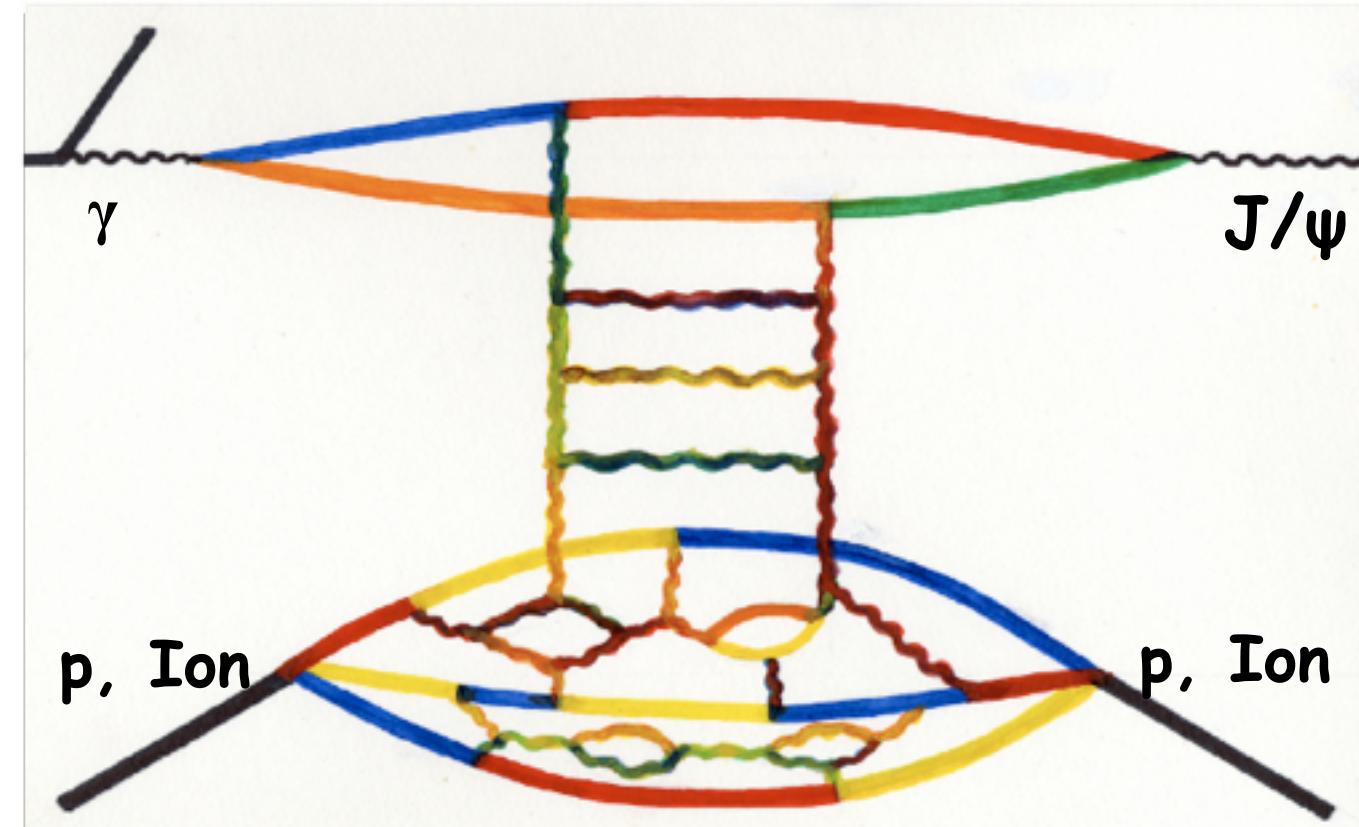
# Outlook

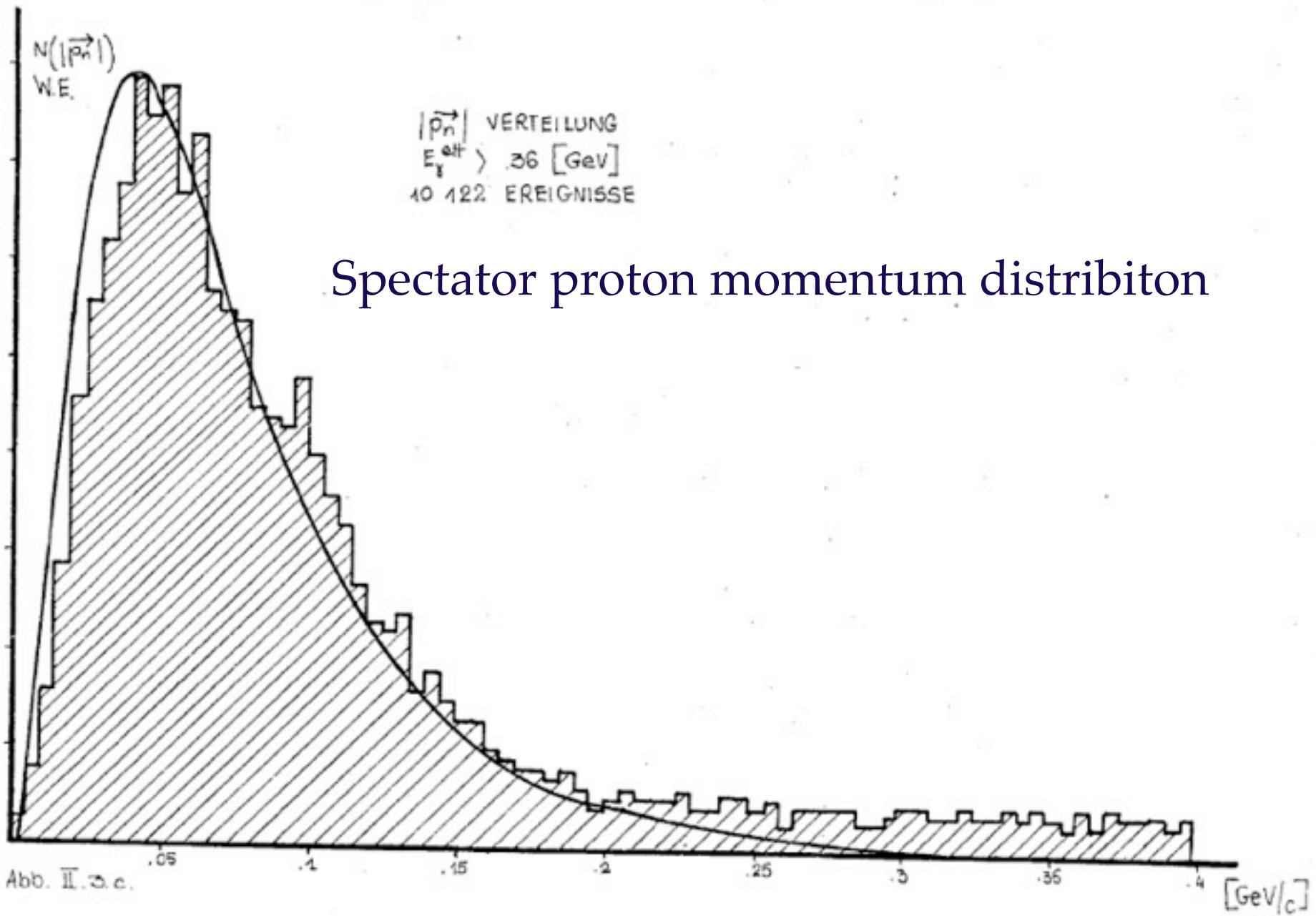
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- Increasing efforts at BNL & JLAB
- Concepts of eRHIC and ELIC are taking shape
  - ▶ substantial progress in machine & IR design
- Staged approach most promising path
  - ▶ Much can be done already at lower energy (e.g.  $F_L$ )
  - ▶ **Saturation** physics will require **full ELIC/eRHIC**
- At minimum one large multi-purpose detector
- ePHENIX/eSTAR under evaluation

## Key Events:

- INT Workshop: Gluons and the Quark Sea at High Energies: Sep-Nov, 2010 ⇒ Science Case for EIC
- LRP 2012: Town meetings and LRP







# EIC Concept: CEBAF → ELIC @ JLAB

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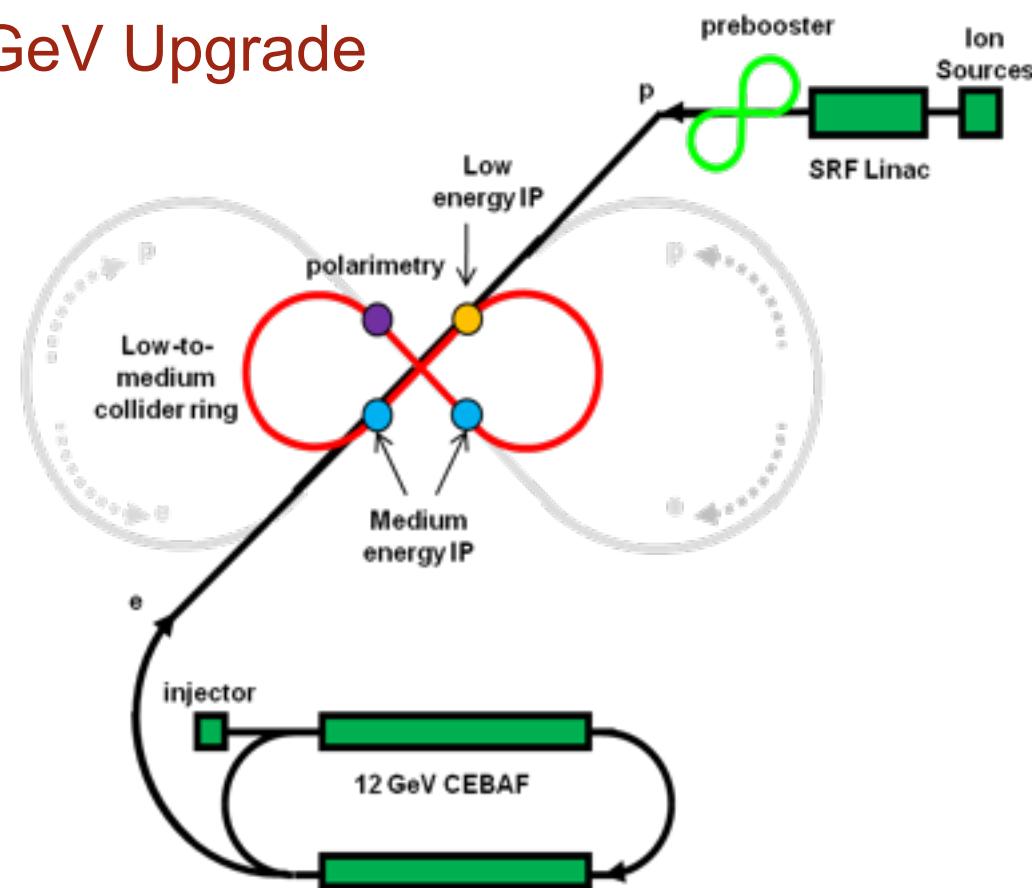


# EIC Concept: CEBAF → ELIC @ JLAB

Use CEBAF “as-is” after 12-GeV Upgrade

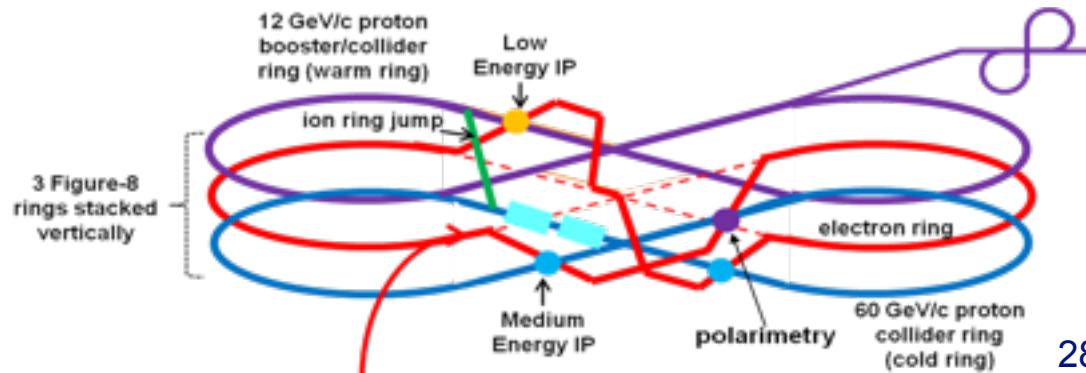
## MEIC:

- 3-11 GeV e
- 60 GeV p ( $\sqrt{s} = 51$  GeV)
- 24 GeV/n ion ( $\sqrt{s} = 33$  GeV)
- $L \sim 1 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  @ 5+60 GeV
- $L \sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  otherwise
- Up to heavy ion  $A = 208$



## ELIC: upgrades

- 250 GeV p ( $\sqrt{s} = 105$  GeV)
- 100 GeV ion ( $\sqrt{s} = 66$  GeV)
- $L$  up to  $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$



## ELIC: upgrades

- Increase  $E_e$

# Measurement of momenta of J/ $\psi$ decay muons

Expected resolution of drift chambers:

$$(\sigma_{p_t}/p_t)_{meas} = \frac{p_t \sigma_{r\phi}}{0.3L^2B} \sqrt{\frac{720}{N+4}}$$

$$(\sigma_{p_t}/p_t)_{MS} = \frac{0.05}{LB\beta} \sqrt{1.43 \frac{L}{X_0}} [1 + 0.038 \log(L/X_0)]$$

$$\sigma_{p_t}/p_t = (\sigma_{p_t}/p_t)_{meas} \oplus (\sigma_{p_t}/p_t)_{MS}.$$

1. outer radius  $R = 2$  m
2. solenoidal field  $B = 3.5$  T
3. gas density  $X_0 = 450$  m
4. point resolution  $\sigma = 100$   $\mu\text{m}$
5. measurement  $N = 200$  points.

$\Leftarrow$  TPC parameters  $\Downarrow$

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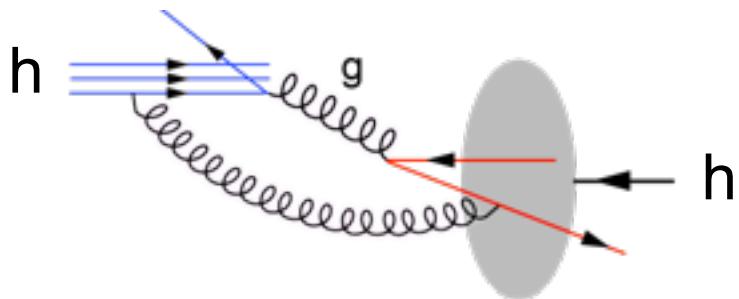
$\Downarrow$

$\Delta p_T < 1$  MeV

# Why Electrons ?

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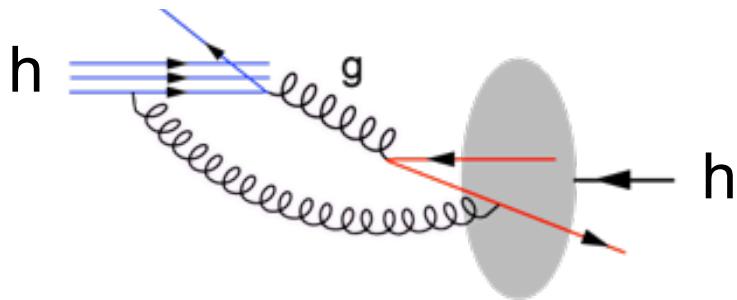
## Hadron-Hadron



- Probe/Target interaction directly via gluons
- lacks the direct access to parton kinematics
- probe has complex structure

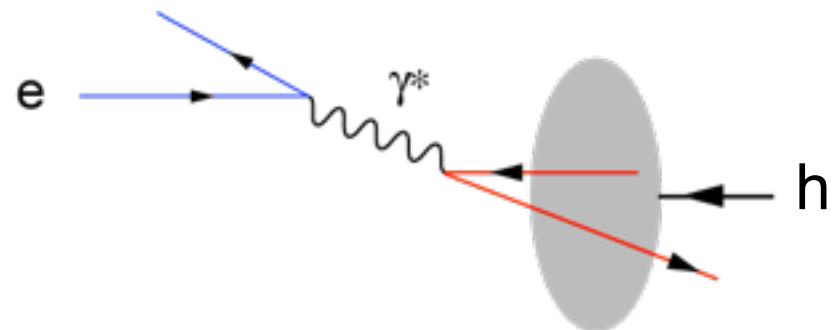
# Why Electrons ?

## Hadron-Hadron



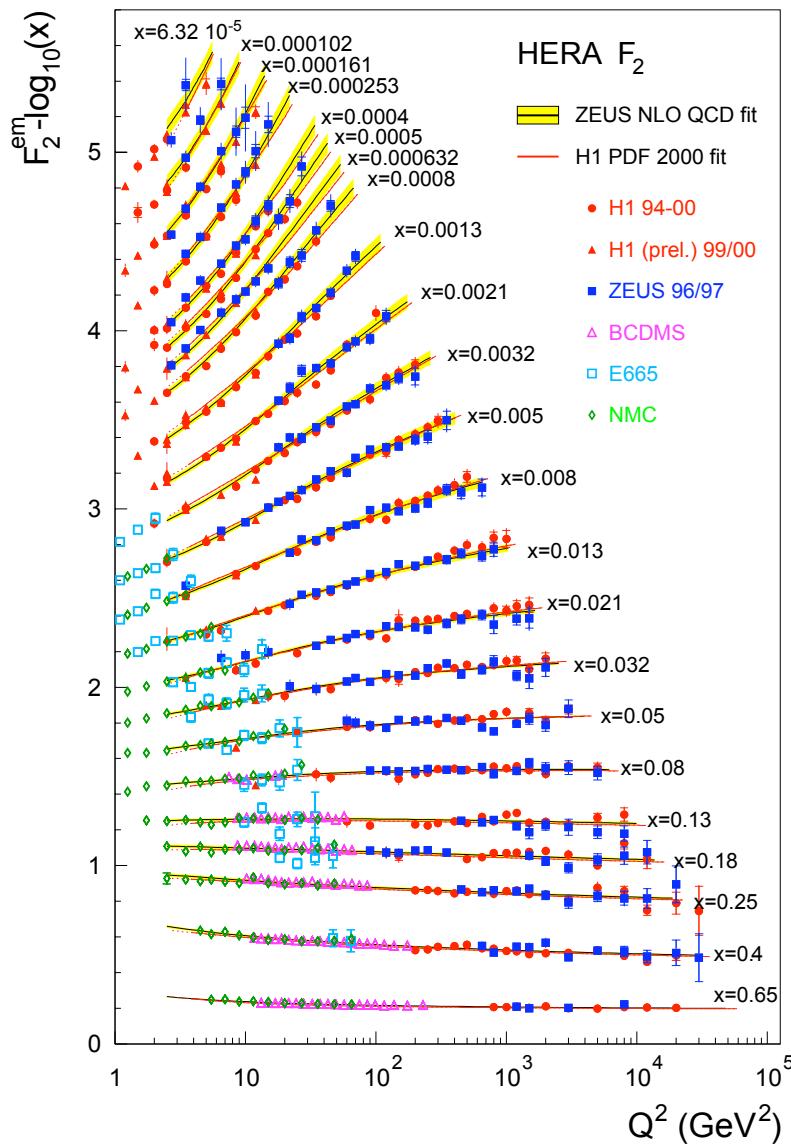
- Probe/Target interaction directly via gluons
- lacks the direct access to parton kinematics
- probe has complex structure

## Electron-Hadron (DIS)

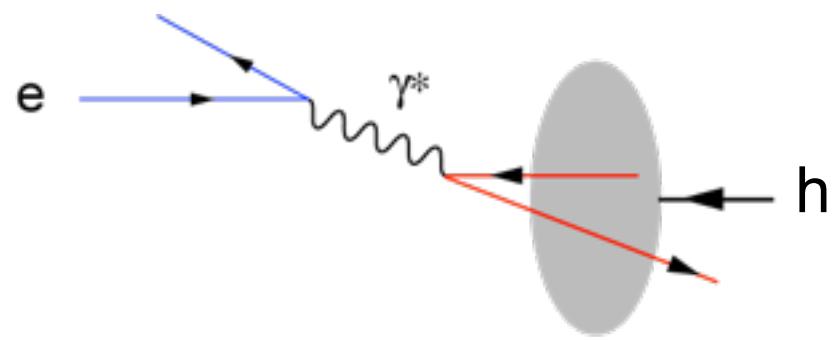


- Explore QCD & Hadron Structure
- Indirect access to glue
- High precision & access to partonic kinematics
- probe point-like

# Why Electrons ?



## Electron-Hadron (DIS)



- Explore QCD & Hadron Structure
- Indirect access to glue
- High precision & access to partonic kinematics
- probe point-like

Both are complementary but for precision  $\Rightarrow$  ep, eA