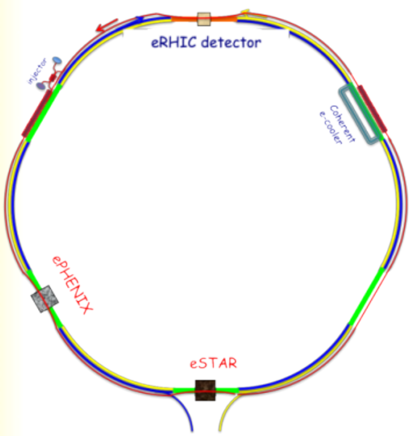
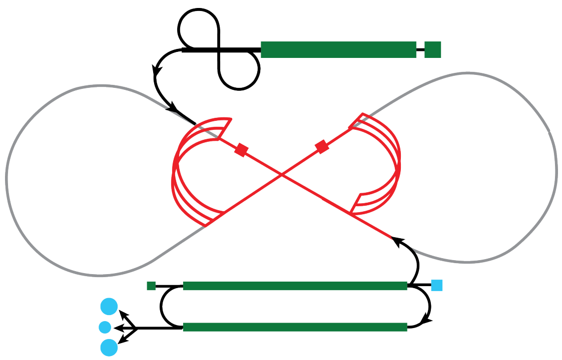
Exploring Hadron Structure with Tagged Structure Functions
16—18 January 2014
Jefferson Laboratory

Forward Tagging in an Electron-Ion Collider

Charles Hyde

Old Dominion University, Norfolk, VA





recent EIC white papers:
arXiv:1212.1701 arXiv:1209.0757

Why a Polarized Electron-Ion Collider?

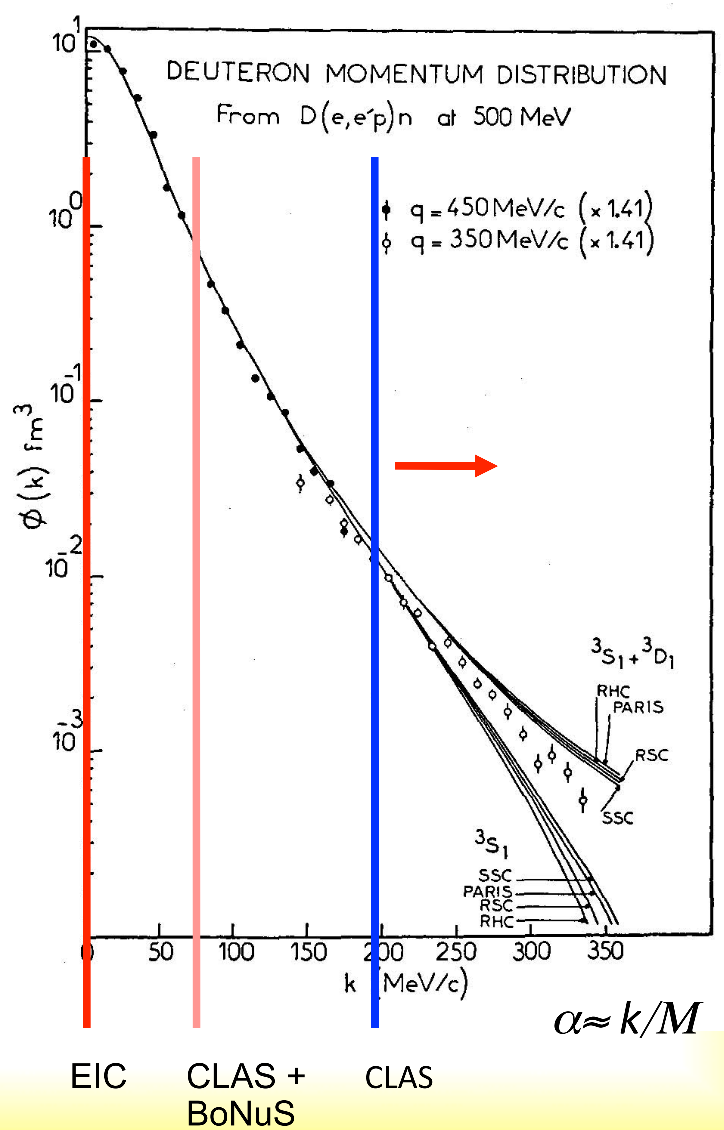
- Longitudinal & Transverse Ion polarization at IP
  - No intense transverse B-field at IP to disrupt electron beam
- Forward boost (incident ion species $P(A) = ZP_0$)
  - Target fragmentation region is boosted/easier to detect
    - Rapidity gap events can be identified
  - Spectator fragments are boosted forward
    - Incident ion species total momentum $P(A) = ZP_0$
    - Spectator fragment momenta $P(A') \approx A'(Z/A)P_0$
      - Spectator nucleon $p' = ZP_0/A$
    - Tag the initial momentum of the struck nucleon in DIS, SIDIS, DVES reactions on light nuclei.
    - Reconstruct the full nuclear final state in DIS on nuclei

JLab LDRD-2014 Project on Spectator Tagging in Polarized Light Ions

- JLab:
  - Ch. Weiss, D. Higinbotham, W. Melnitchouk, P. Nadel-Turonski,
- Old Dominion U.
  - Ch. Hyde, KJ Park, S. Kuhn
- Florida Int'l U.
  - M. Sargsian
- St. Petersburg State U.
  - V. Guzey
- Spectator Tagging on polarized D, ^{3}He
  - $D(e,e'N_S)X$
  - SIDIS $D(e,e'N_S\, h)\, X'$
  - DVES $D(e,e'N_S\, M\, N_{active})$

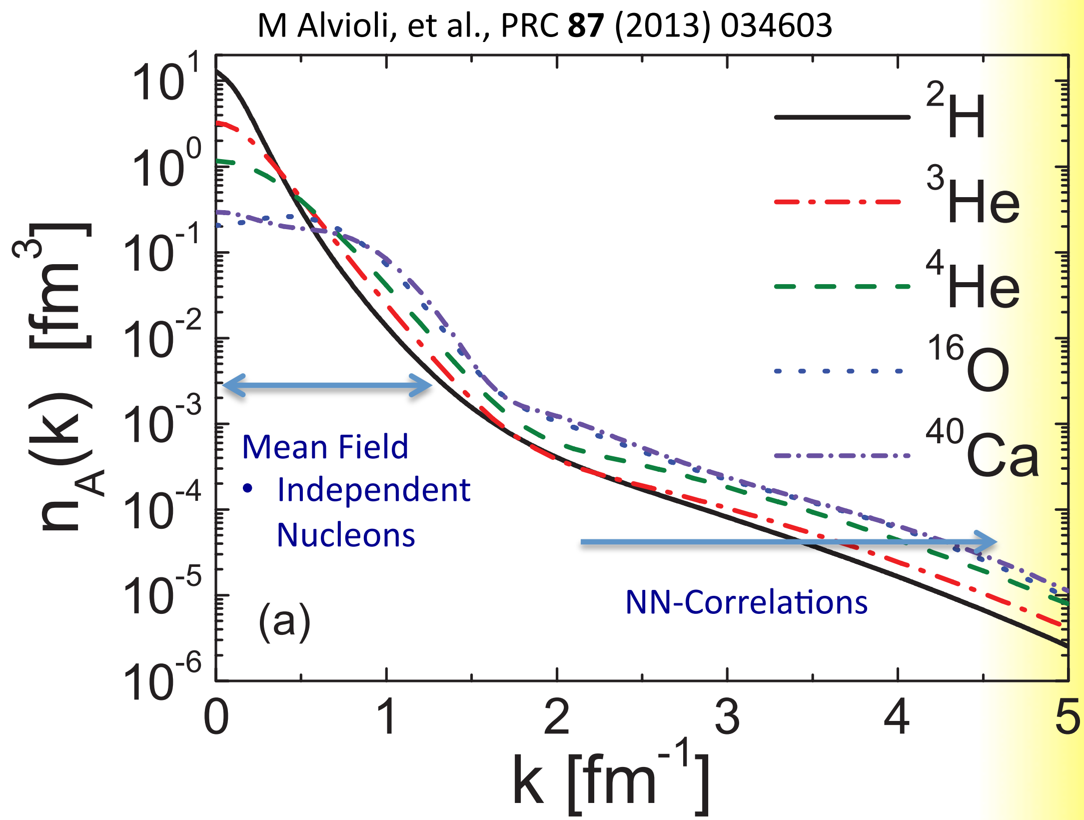
Neutron structure through spectator tagging

- Scattering on *bound neutrons*
  - Fermi motion,
  - NN correlations
  - Depolarization
- Solution is *Spectator Tagging*
  - *Fixed target:*
    - Low-momentum spectators
    - Thick Targets
  - Electron-Ion Collider
    - Spectator fragments are ultra-forward.
- The MEIC is designed from the outset to tag spectators, and other nuclear fragments.



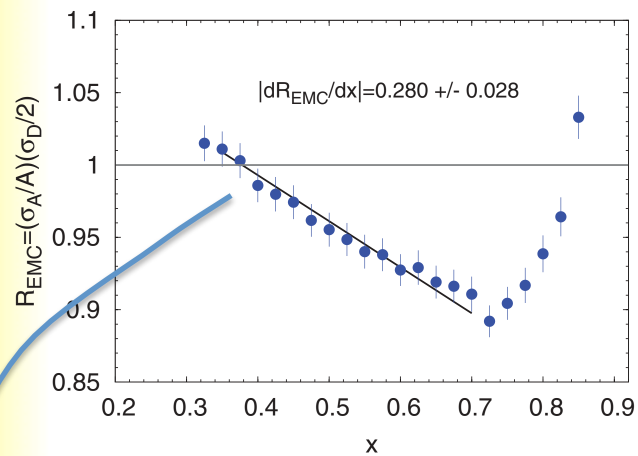
Nuclear Spectral Functions

- ^2H and ^3He
  - 'Neutron' targets
- Mean field ≈ 80%
- Correlations
  - EMC Effect
  - Modified quark-gluon structure

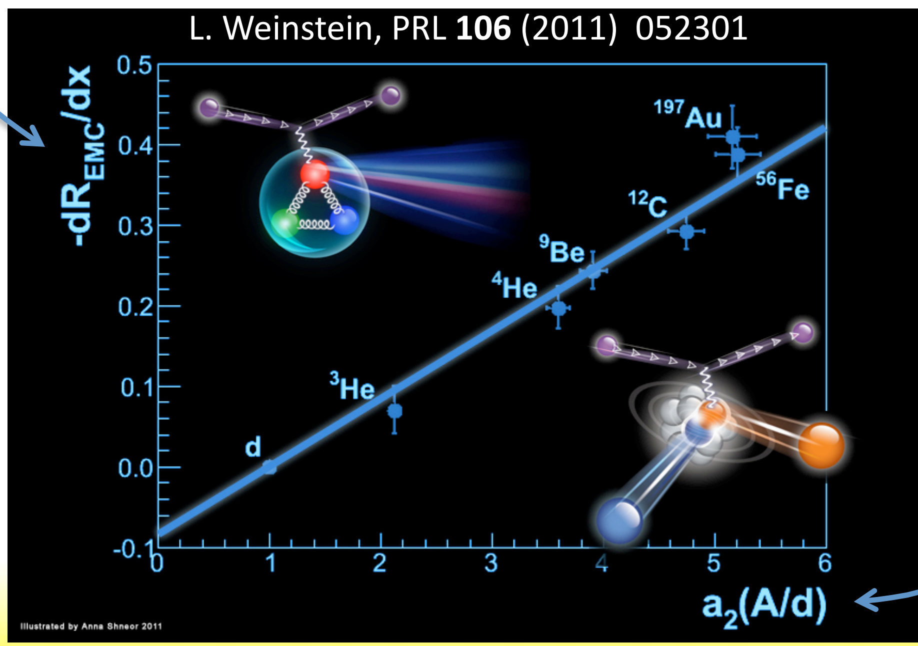


The EMC Effect and NN Correlations

EMC Effect:
J. Aubert et al., Phys. Lett. B 123, 275 (1983).



Recent ^{12}C JLab ‘EMC’ data
J. Seely PRL 103 (2009) 202301



N. Fomin et al, PRL **108** (2012) 092502

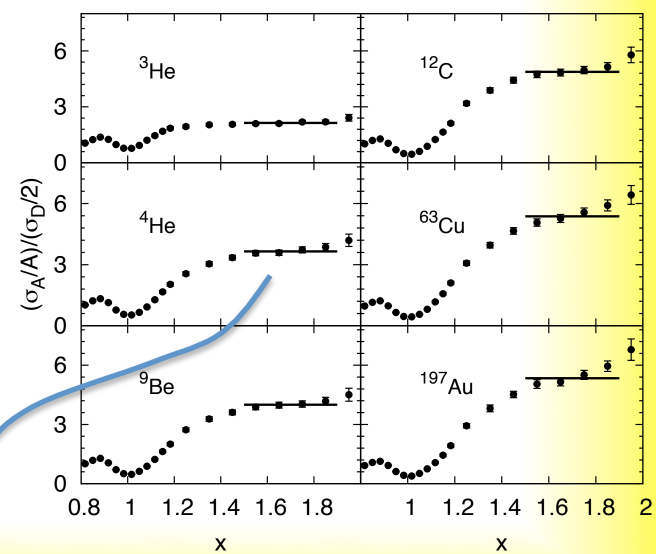
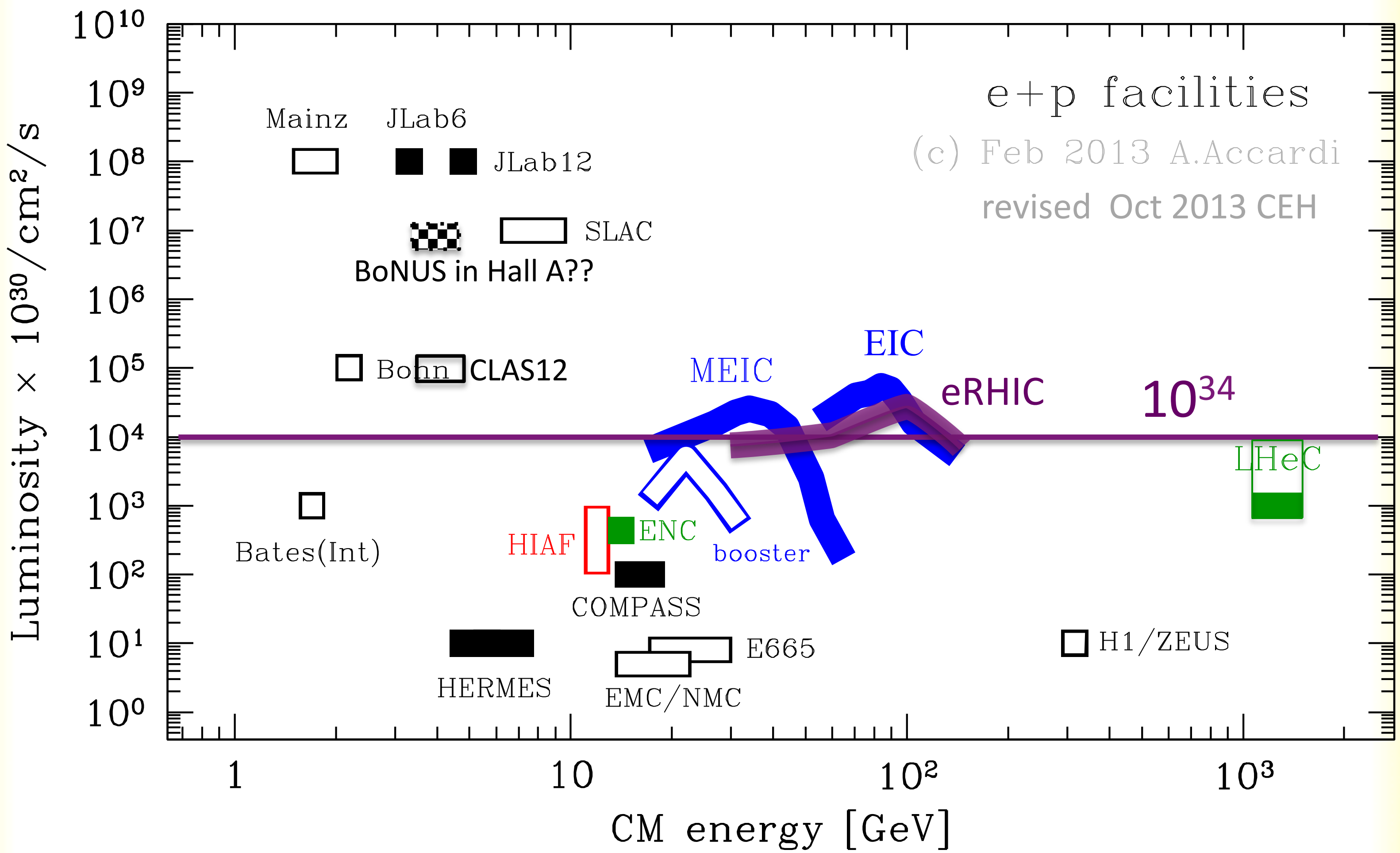


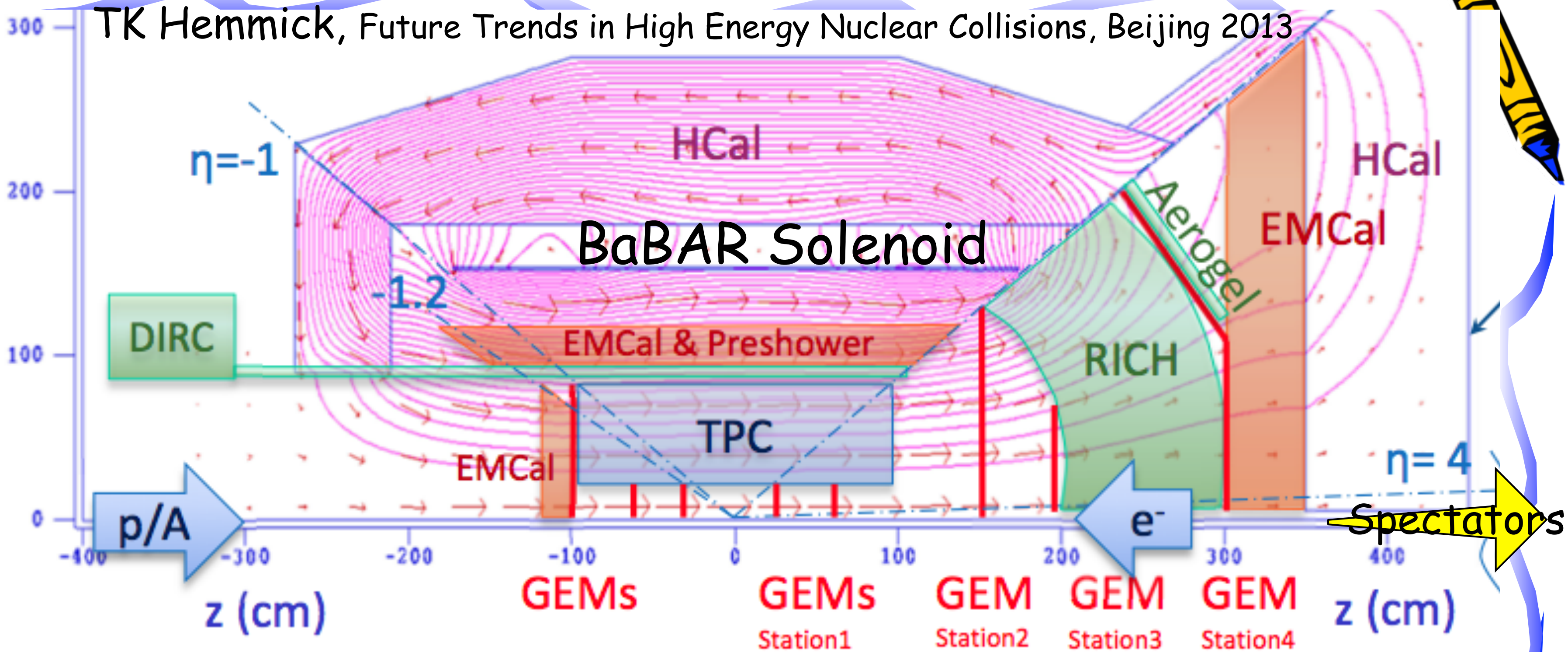
FIG. 2: Per-nucleon cross section ratios vs x at θ_e=18°.

MEIC-EIC(Jlab) and eRHIC Performance



ePHENIX (fsPHENIX) Detector Concept

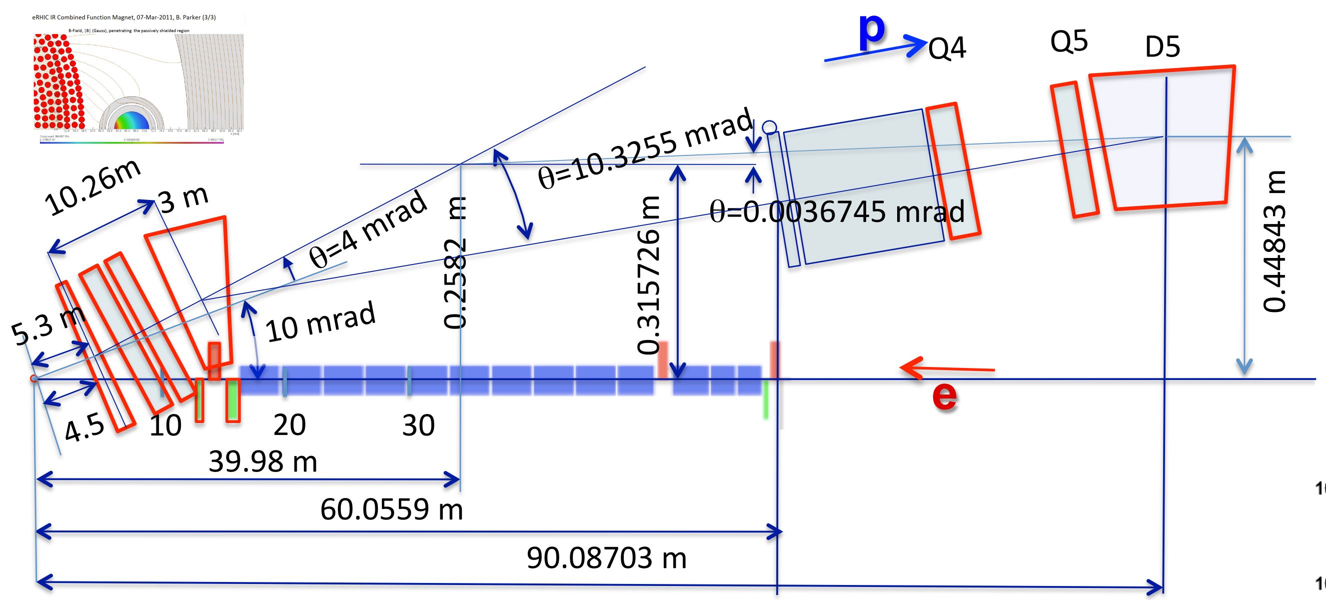
TK Hemmick, Future Trends in High Energy Nuclear Collisions, Beijing 2013

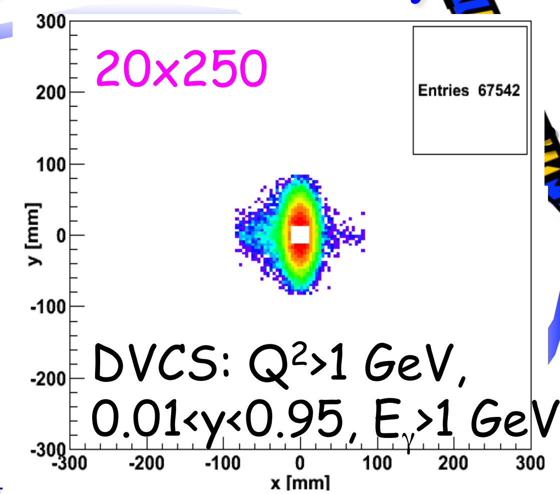


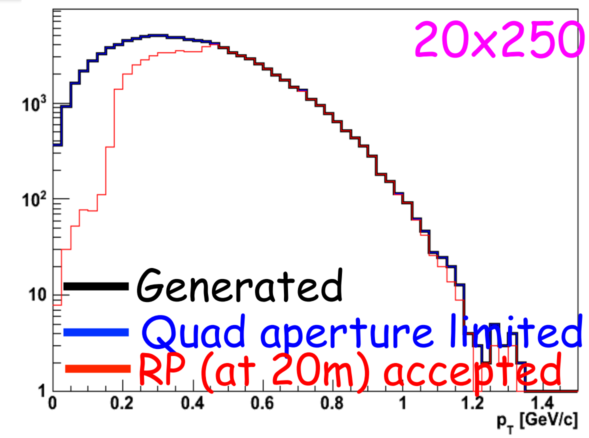
- fsPHENIX definition:
  - sPHENIX with hadron endcap
  - Adds GEM-tracking, RICH, Aerogel, addn'l ecal & hcal.
  - Leaves sPHENIX barrel unchanged.
- ePHENIX definition:
  - fsPHENIX with electron endcap
  - Removes silicon tracking
  - Adds crystal emcal, TPC, DIRC.

Discussing ePHENIX covers all of fsPHENIX

eRHIC: high-luminosity IR







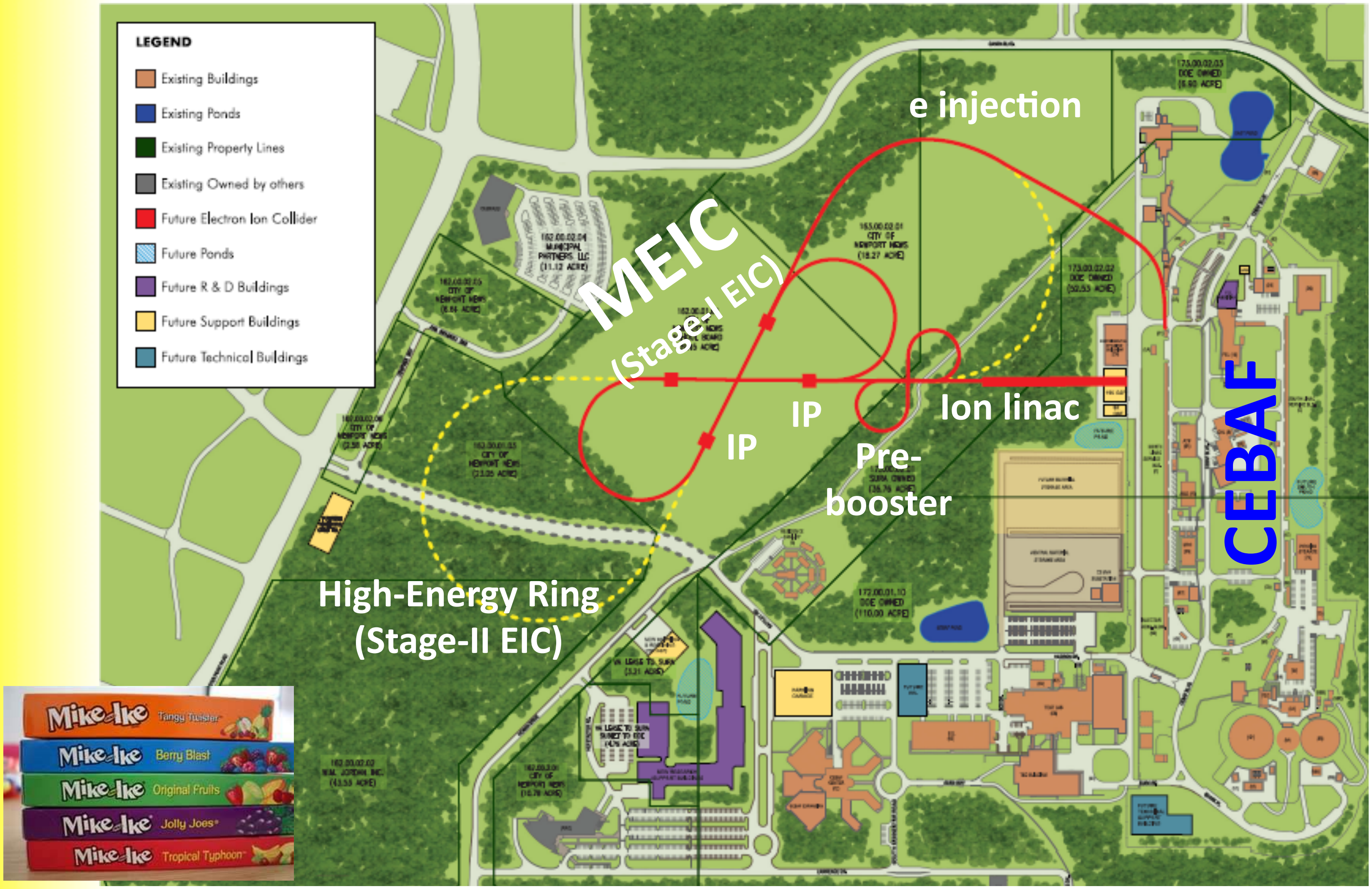
eRHIC - High-lumi IR with β*=5 cm, l*=4.5 m

→ 10^{34} cm^{-2} s^{-1}

- 10 mrad crossing angle and crab-crossing
- High gradient (200 T/m) large aperture Nb_3Sn focusing magnets
- Arranged free-field electron pass through the hadron quad-triplet
- Integration with the detector: efficient separation and registration of low angle collision products

© D.Trbojevic, B.Parker, S. Tepikian, J. Beebe-Wang

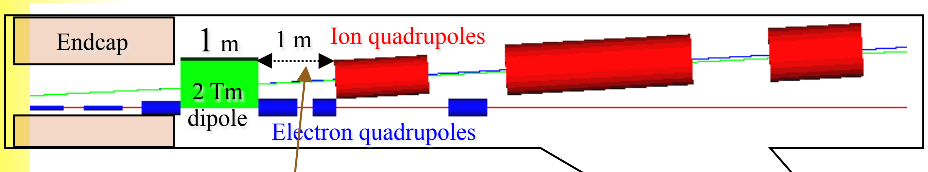
EIC – accelerator layout at JLab



- The MEIC has the same circumference as CEBAF or about 1/3 of RHIC

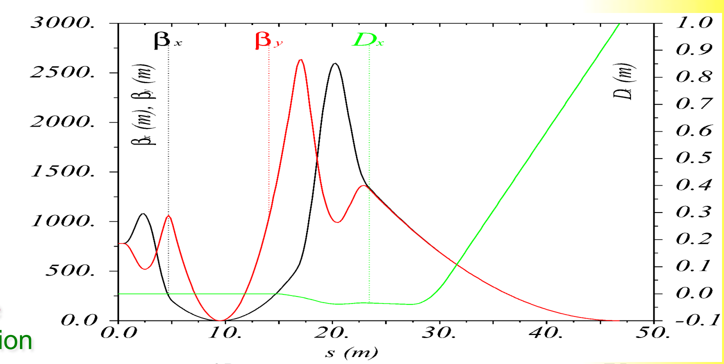
The full-acceptance detector concept

(G4BeamLine)



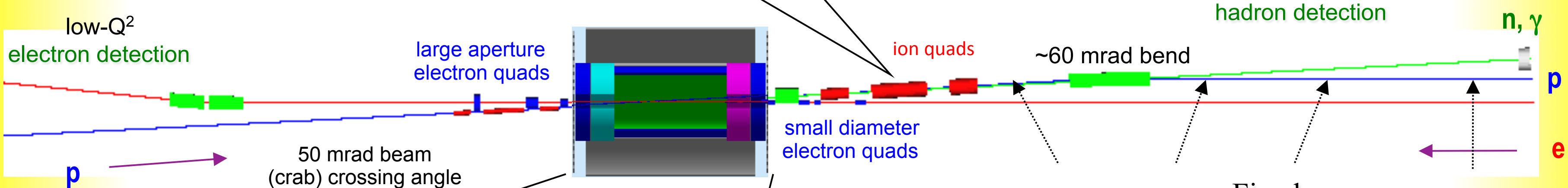
'Forward' Trackers (~1% δp/p)
and "donut" calorimeter

No other magnets or apertures between IP and FP!



small angle
hadron detection

Far-Forward
hadron detection



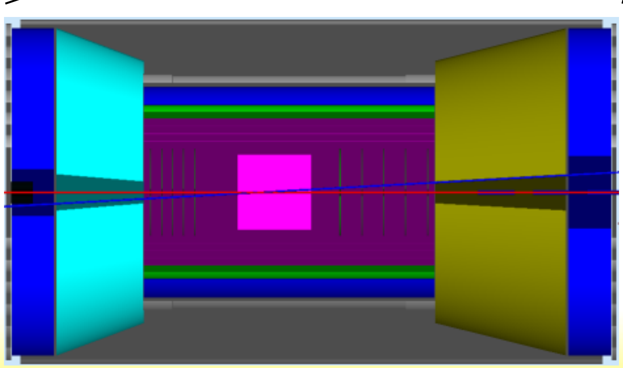
Thin exit windows

Fixed trackers in vacuum?

Roman pots

central detector
with endcaps

(GEANT4)



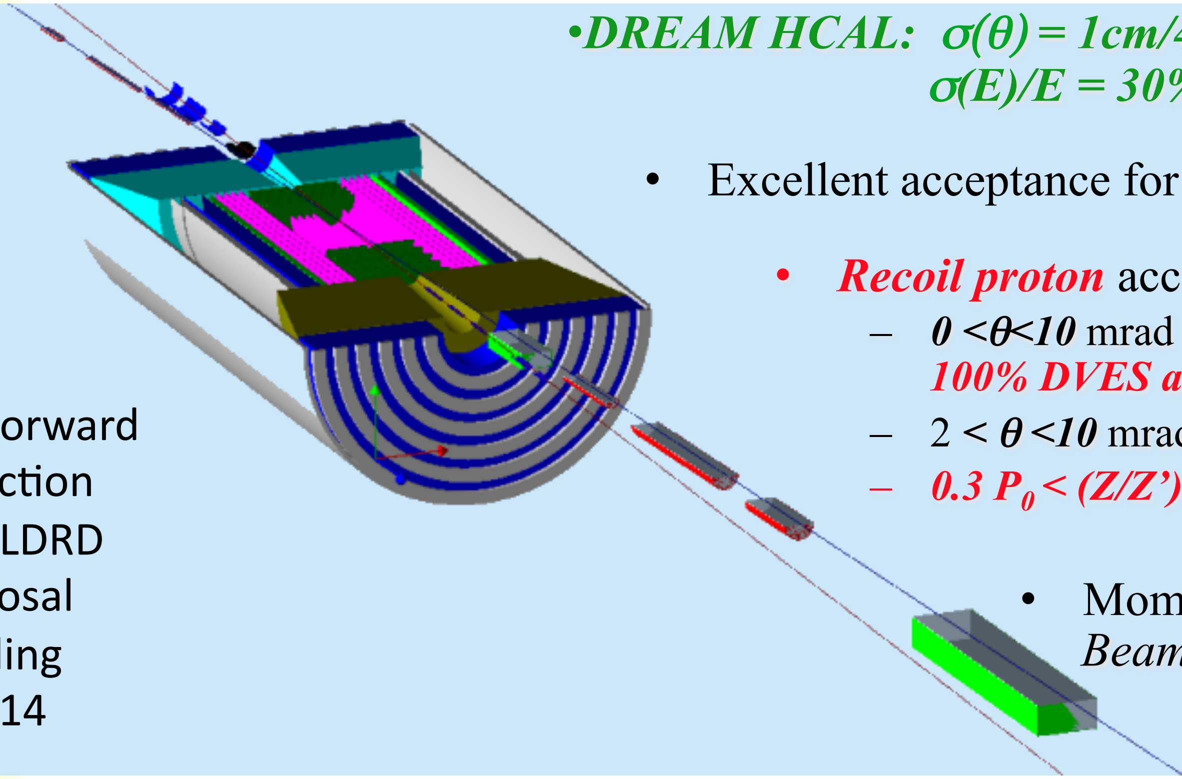
Forward hadron detection in three stages:

1. Endcap with 50 mrad crossing angle
2. Forward 2 T•m dipole covering angles up to a few degrees
3. Far-forward, up to 1° (neutrals) and 0.5° charged particles

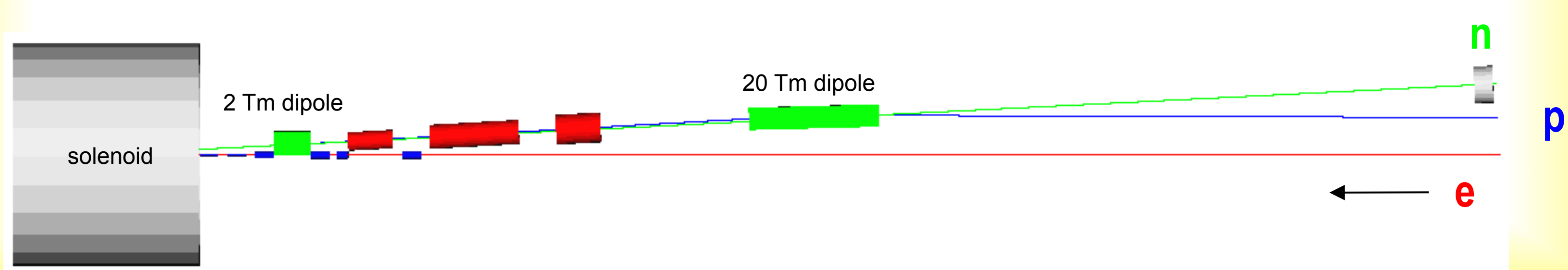
Far-Forward hadron detection

G4BeamLine → GEANT4

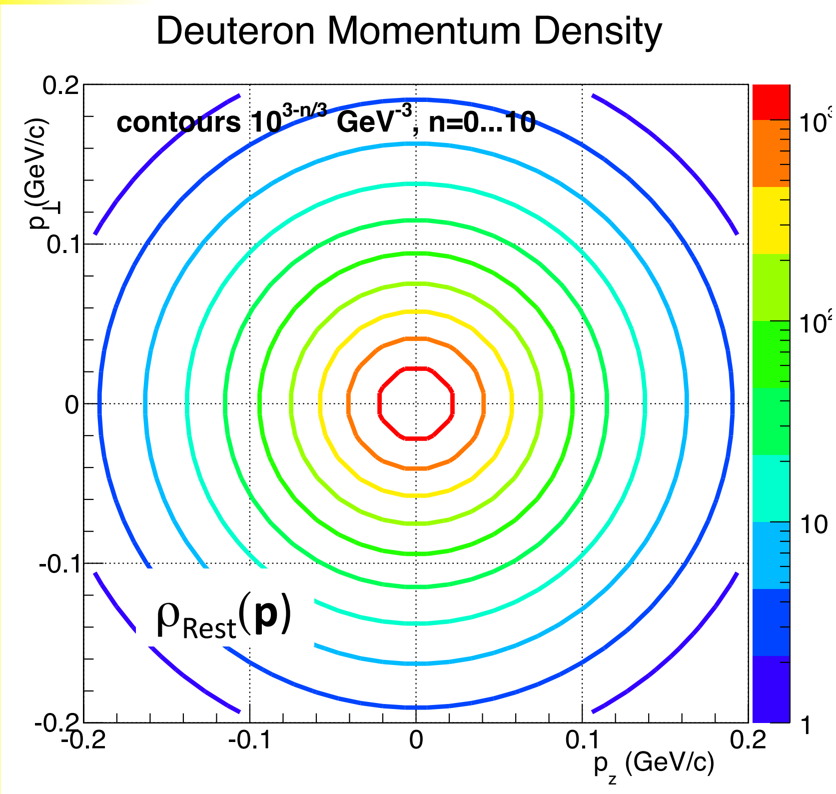
- ***Neutron*** detection in a 20 mrad cone ***down to 0°***
  - ***•DREAM HCAL:*** $\sigma(\theta) = 1cm/40m = 2.5 \cdot 10^{-4}$ *rad*
    $\sigma(E)/E = 30\%(1GeV/E)^{1/2}$
- Excellent acceptance for ***all ion fragments***
  - ***Recoil proton*** acceptance:
    - $0 < \theta < 10$ mrad for $|P' - P_0| > (0.05\%)\ P_0$
      100% DVES acceptance for $x_B > 0.005$
    - $2 < \theta < 10$ mrad for ***all P'***
    - $0.3\ P_0 < (Z/Z')\ P_0 < \infty$
- Momentum resolution < $3 \cdot 10^{-4}$
  Beam energy spread



Far-Forward Detection JLab LDRD proposal pending FY2014

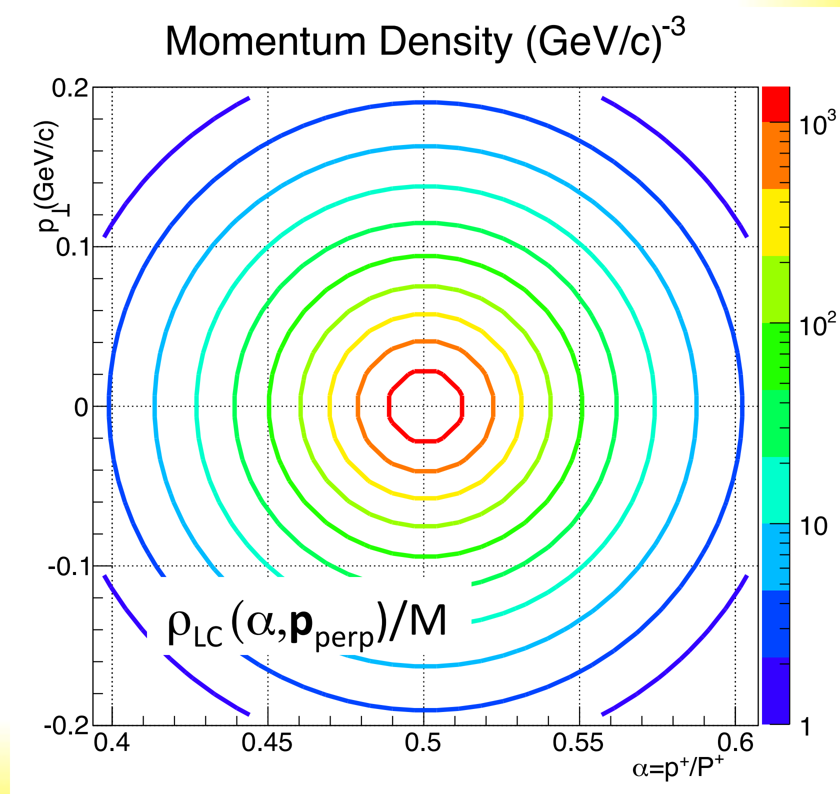


The Deuteron



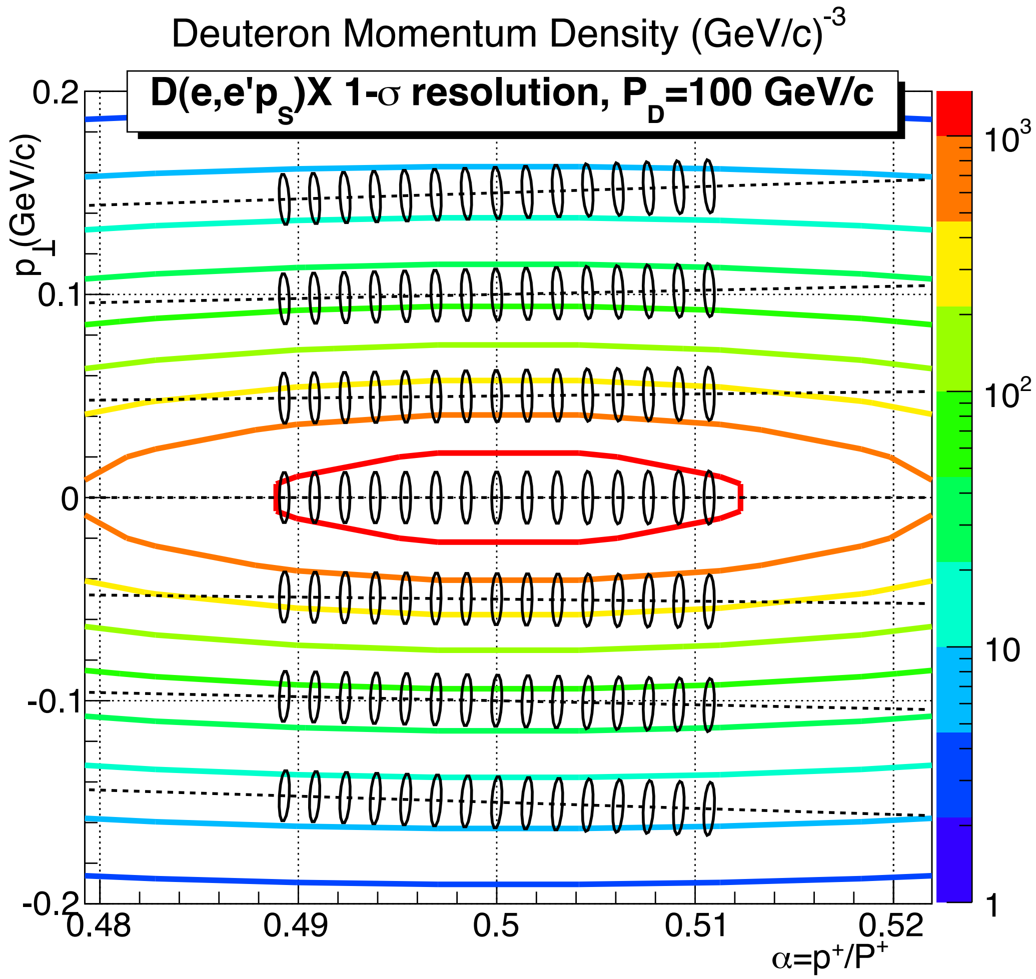
Rest Frame

Lightcone: $p_{\perp}$, $\alpha = \dfrac{E_N + p_N}{E_D + P_D}$



Proton Spectator Tagging in the Deuteron

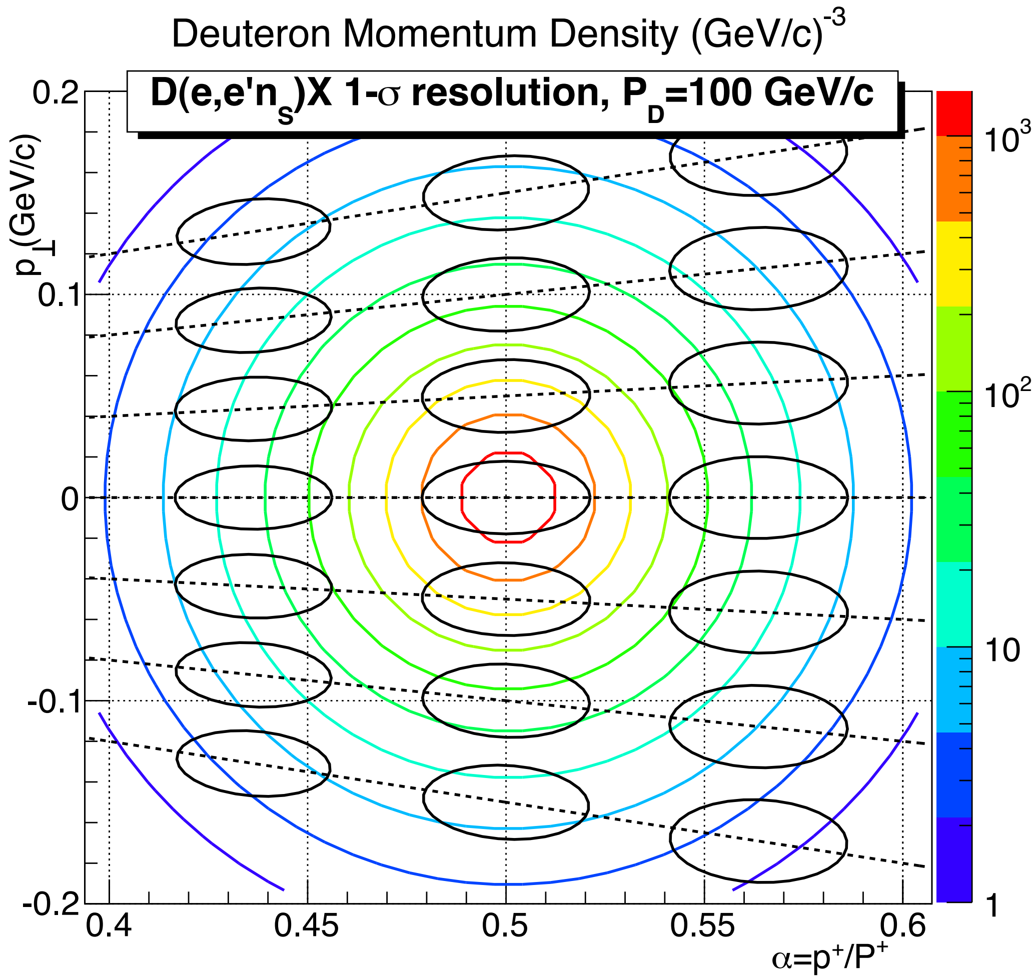
- **MEIC:** Polarized DIS, SIDIS, DVES… on bound **Neutron**
  - Each contour is $\sqrt[3]{10}$
- **eRHIC:** Unpolarized



MEIC Resolution

Neutron Spectator Tagging in the Deuteron

- **MEIC** Polarized DIS, SIDIS, DVES… on bound **proton**
- **eRHIC** unpolarized



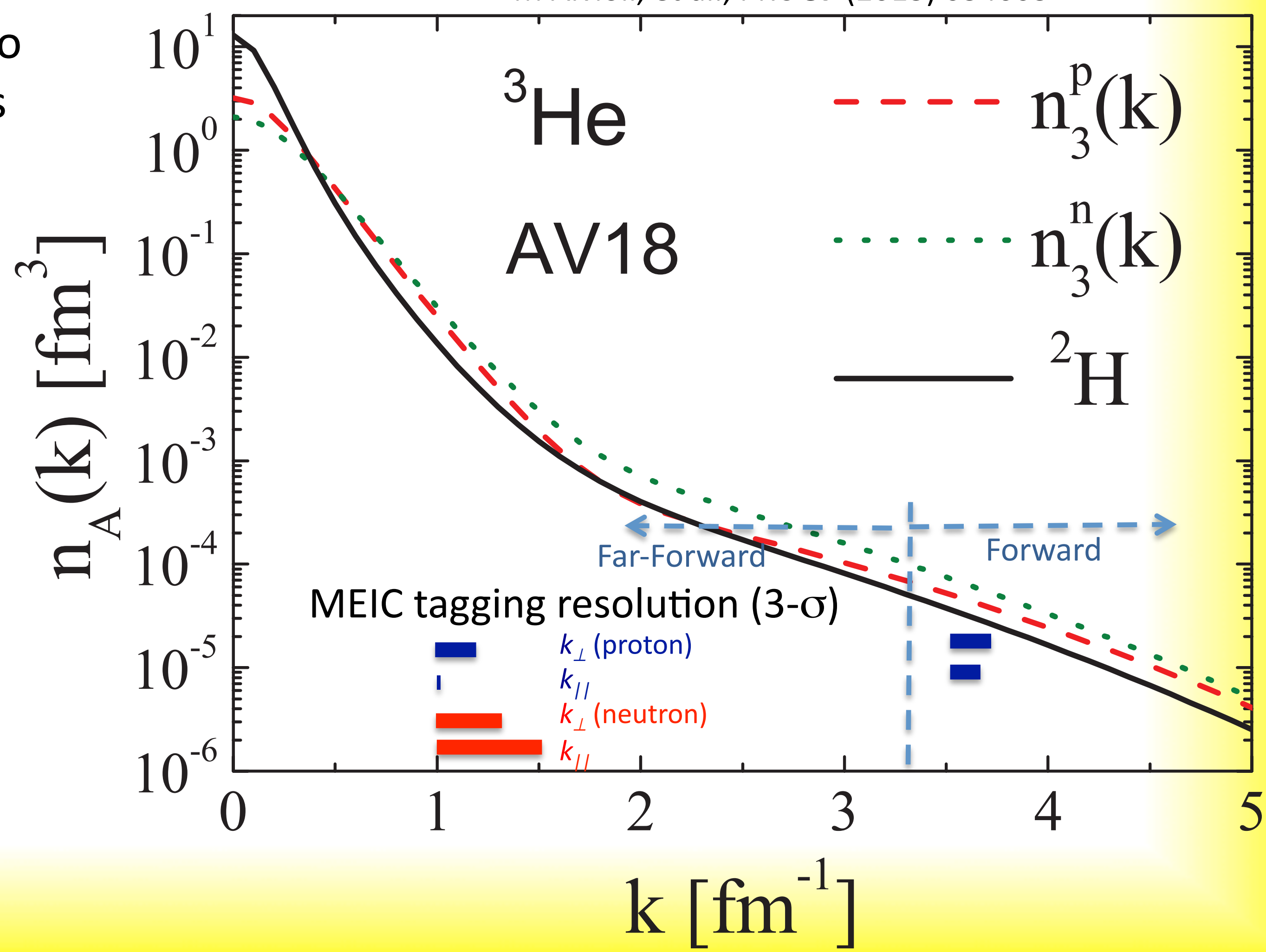
MEIC Resolution

$^3He(e,e'N_SN_S)X$

PWIA `measurement' of active nucleon momentum:

- Active Neutron ➔
  - Tagging of the two spectator protons
- Active Proton ➔
  - Tagging of spectator proton and neutron.
  - Tag spectator deuteron
- Polarized ^3He: Neutron: +86% polarized. Each Proton: –2.8% polarized.

M Alvioli, et al., PRC **87** (2013) 034603

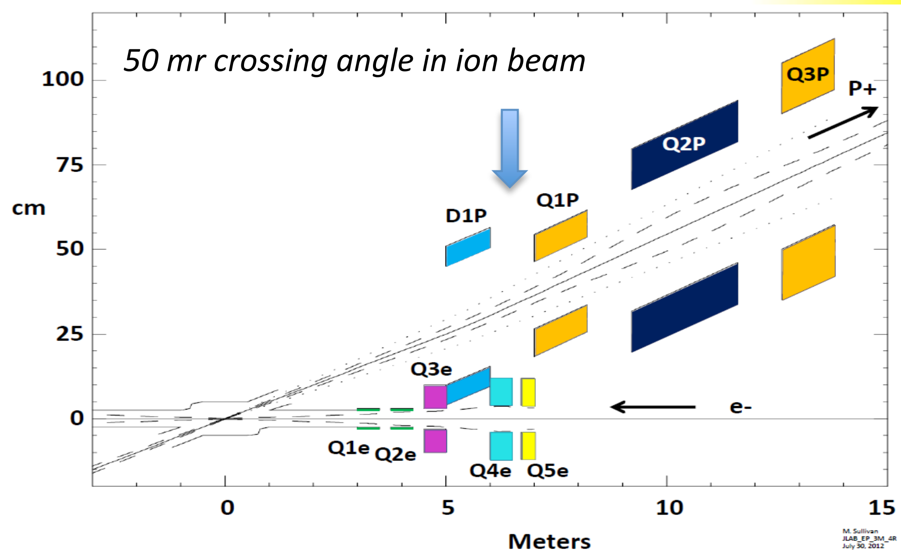


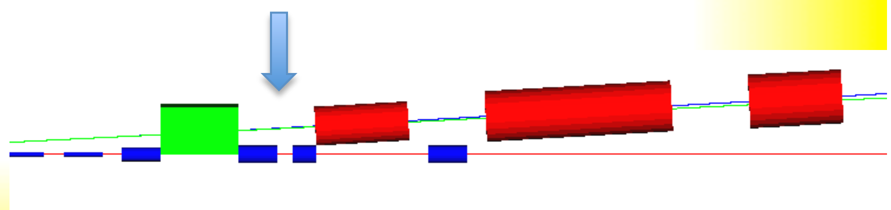
Nuclear Tagging

- A hot nucleus decays by emitting neutrons, protons of ~10 MeV, or $p_{perp} \leq$ 140 MeV/c
- Incident nucleus P_A = Z•100 GeV/c
  - per nucleon p = (Z/A)•100 GeV/c→50—40 GeV/c
  - Evaporation neutrons θ~ 0.14/40 = 3.5 mr
- Forward baryon multiplicity as a tag on centrality in DIS?

Intrinsic Charm

- $\gamma^{*}+p \rightarrow X+\Lambda_C$ ‘Spectator Λ_C’
  - $\Lambda_C \rightarrow pK^0$ 2.3%
- For 100 GeV/c incident protons
  - Spectator Λ_C momentum ~60 GeV/c
  - 50% of Λ_C decay protons are ≤ 1.5°
  - 75% of Λ_C decay protons are ≤ 2.4°
    - Tagging in Forward region after small (6 mr bend) dipole





A high-luminosity Electron-Ion Collider

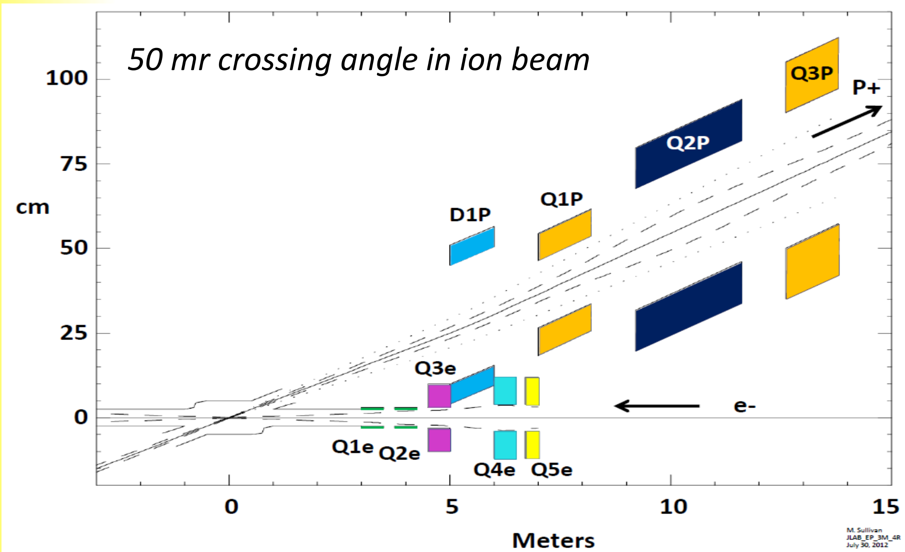
- Unprecedented capabilities to study the QCD structure of matter
- Polarized Light Ions:
  - Precision study of neutron structure
    - Spectator proton tagging
  - Quark-gluon structure of nuclear binding
    - Bound proton structure via neutron tagging
    - DIS, SIDIS, DVES processes identified in mean-field and NN-correlations regions
- Target fragmentation region
  - Heavy Quarks
- Heavy Nuclei
  - Tag the full nuclear final state → DIS vertex tagging?

Back-up Slides

How to Tell the Spectator Nucleons from the Active Nucleon?

- DIS, SIDIS
  - Target fragmentation produces a forward nucleon
  - Fragmentation increases $p_\perp$, decreases $p_{//}$
- DVES:
  - $p_z' \approx p_z(1–x_B) \Rightarrow p'^+/P^+ \approx \alpha - x_B$
  - $–t = –\Delta^2 \approx (x_B{}^2M^2+ \Delta_\perp{}^2)/(1-x_B)$
  - D, ^{3}He, Momentum densities fall by ~1/1000 for
    $x_B > 0.1$, **or**
    $\Delta_\perp = p_\perp' > 300$ *MeV/c* $\Rightarrow –t>0.1$ *GeV*^{2}
    Antisymmetrization < 3%
  - At smaller x_B **and** smaller $p_\perp'$, sum over all nucleons as active or spectator, w/ anti-symmetrization

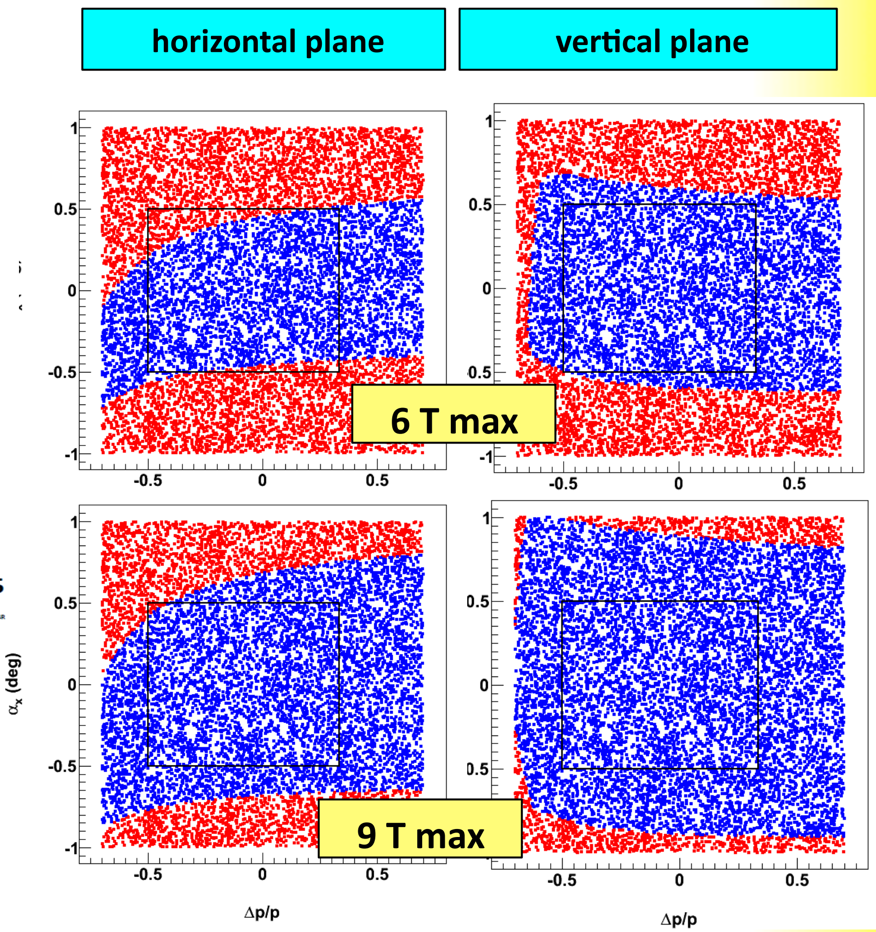
Ultra-forward charged-hadron acceptance



Red: Detection before ion quadrupoles

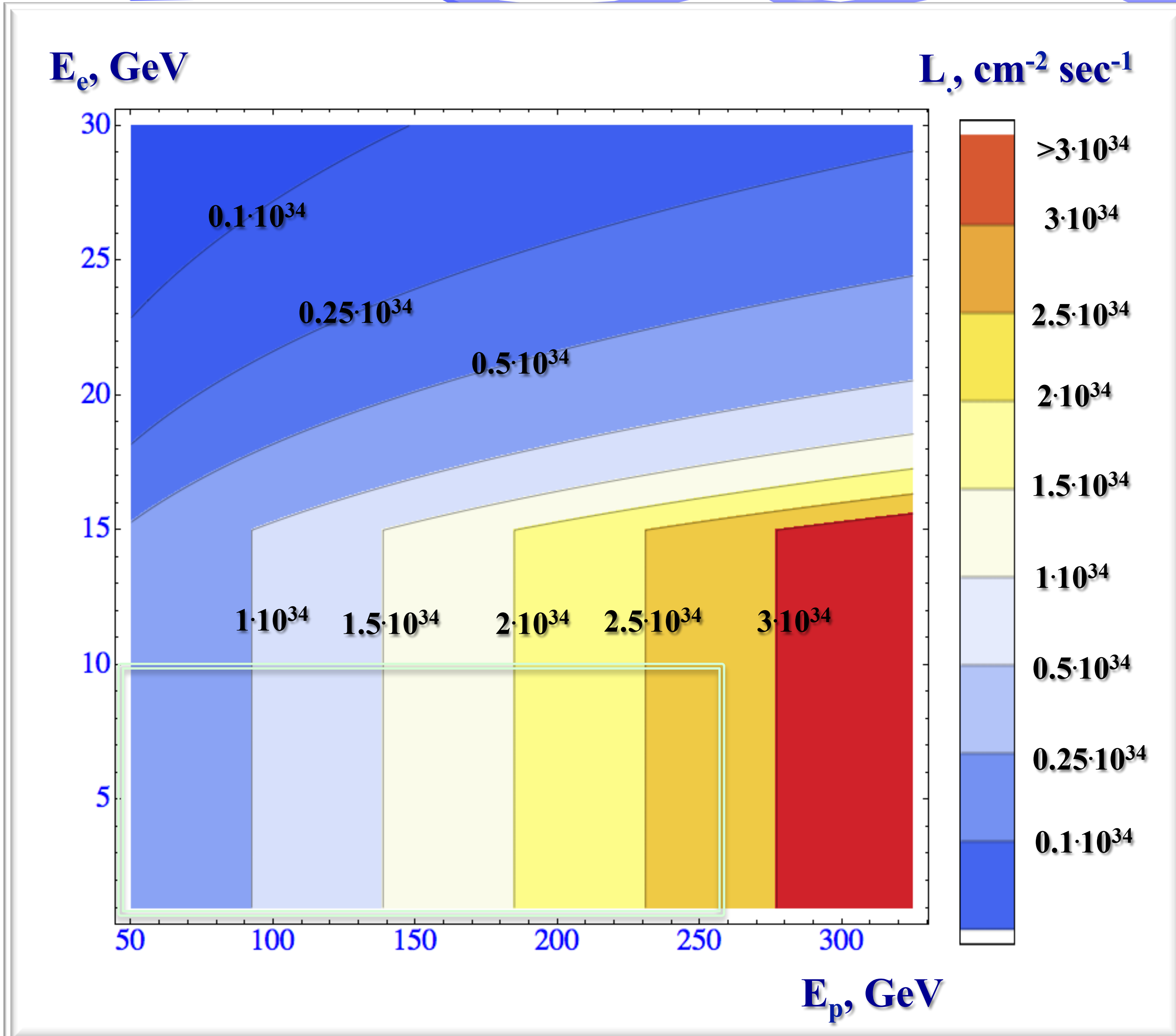
Blue: Detection after ion quadrupoles

Forward acceptance vs.magnetic rigidity



Tagged d beam: dp/p = -0.5
Tagged ^{3}He beam: dp/p = +0.33

eRHIC: design luminosity



eRHIC: design luminosity

	e	p	$^{2}He^{3}$	$^{79}Au^{197}$	$^{92}U^{238}$
Energy, GeV	20	250	167	100	100
CM energy, GeV		100	82	63	63
Number of bunches/distance between bunches	107 nsec	111	111	111	111
Bunch intensity (nucleons) ,10^{11}	0.36	4	6	6	6
Bunch charge, nC	5.8	64	60	39	40
Beam current, mA	50	556	556	335	338
Normalized emittance of hadrons , 95% , mm mrad		1.2	1.2	1.2	1.2
Normalized emittance of electrons, rms, mm mrad		16	24	40	40
Polarization, %	80	70	70	none	none
rms bunch length, cm	0.2	5	5	5	5
β*, cm	5	5	5	5	5
Luminosity per nucleon, $\times 10^{34}$ $cm^{-2}s^{-1}$		2.7	2.7	1.6	1.7

Hourglass the pinch effects are included. Space charge effects are compensated.

Energy of electrons can be selected at any desirable value at or below 30 GeV

The luminosity does not depend on the electron beam energy below or at 20 GeV

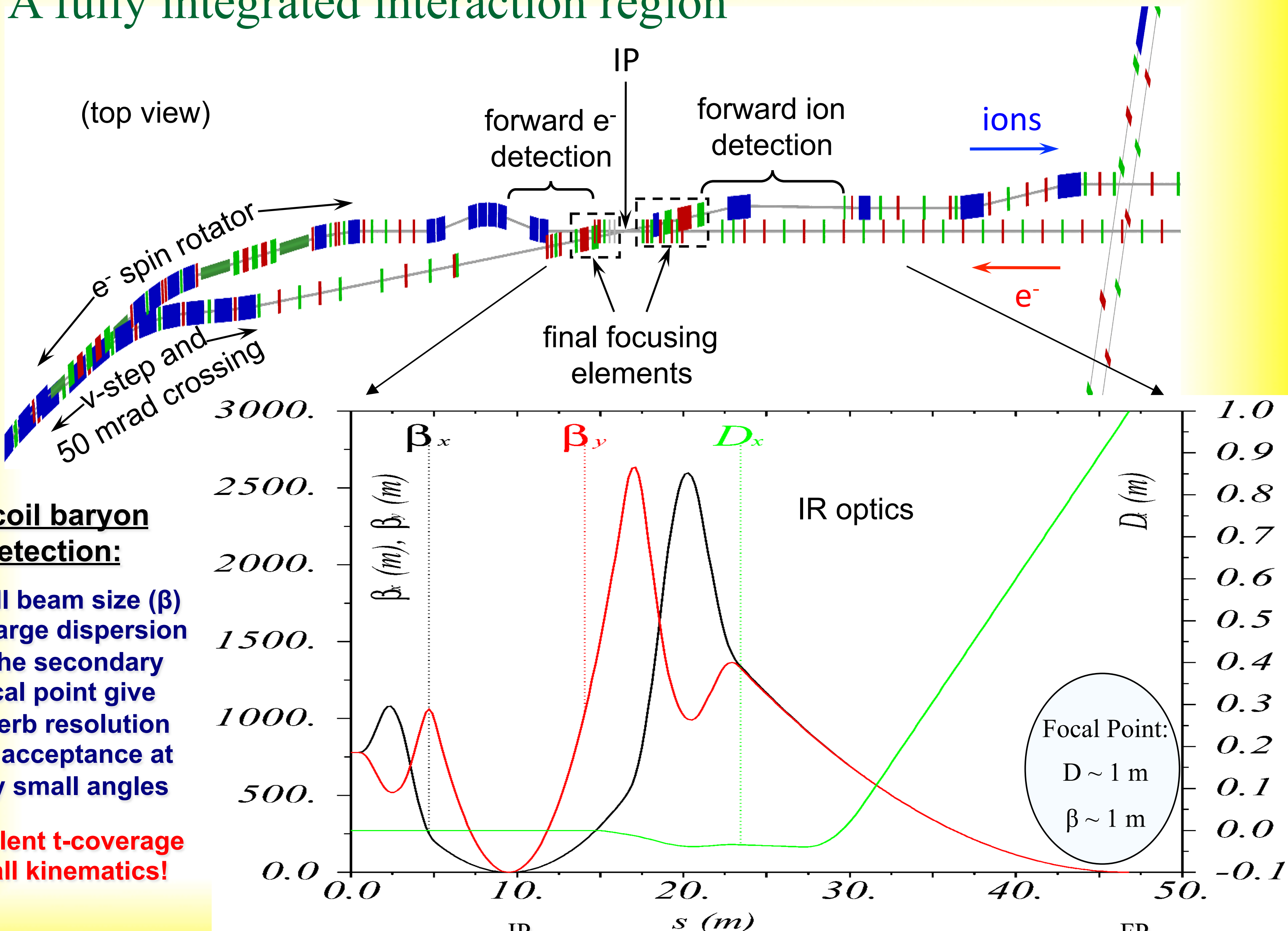
The luminosity falls as E_e^{-4} at energies above 20 GeV

The luminosity is proportional to the hadron beam energy: $L \sim E_h/E_{top}$

Parameters for ***Full Acceptance*** Interaction Point

		Proton	Electron
Beam energy	GeV	60	5
Collision frequency	MHz	750	750
Particles per bunch	10^{10}	0.416	2.5
Beam Current	A	0.5	3
Polarization	%	> 70	~ 80
Energy spread	10^{-4}	~ 3	7.1
RMS bunch length	mm	10	7.5
Horizontal emittance, normalized	µm rad	0.35	54
Vertical emittance, normalized	µm rad	0.07	11
Horizontal β*	cm	10	10
Vertical β*	cm	2	2
Vertical beam-beam tune shift		0.014	0.03
Laslett tune shift		0.06	Very small
Distance from IP to 1st FF quad	m	7	3
Luminosity per IP, 10^{33}	$cm^{-2}s^{-1}$	5.6	

A fully integrated interaction region



Recoil baryon detection:

Small beam size (β) and large dispersion at the secondary focal point give superb resolution and acceptance at very small angles

Excellent t-coverage for all kinematics!

Spectator tagging in a collider

- $P_D = 100\ GeV/c$ deuteron
  - $p_p \approx (P_D/2)(1+\alpha) + p_\perp$ f
    - α < 50 MeV/1GeV, $\theta_S = p_\perp/(P_D/2) \leq 1\ mrad$
  - $p_n \approx (P_D/2)(1-\alpha) - p_\perp$
    - Measure $\theta_n \approx p_\perp/(P_D/2)$ accurately in Forward Hadronic Calorimeter (integrate over α).
      $\delta\theta_n \approx (1\ cm)/(40\ m) = 0.25\ mrad$
- $P(^4He) = 200\ GeV/c = ZP_0$
  - *Magnetic rigidity* $K(^4He) = P/(ZB) = (100\ GeV/c)/B = K_0$
  - P(Spectator $^3He) \approx (3/4)P(^3He)$ ➔ $K(^3He) = (3/4)\ K_0$
  - P(Spectator $^3H) \approx (3/4)P(^3H)$ ➔ $K(^3H) = (3/2)\ K_0 > K_0$

Nuclear Spectral Functions

- C. Ciofi degli Atti, S. Simula PRC **53** (1996)