(High-x) physics at an Electron-Ion Collider (EIC)

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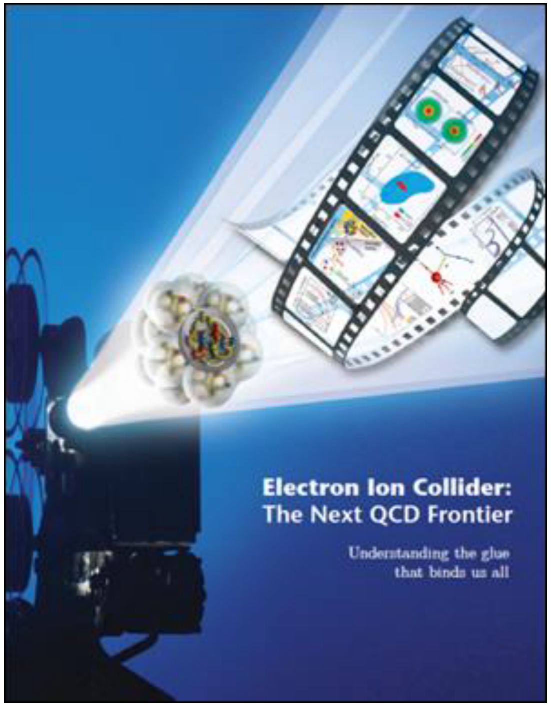
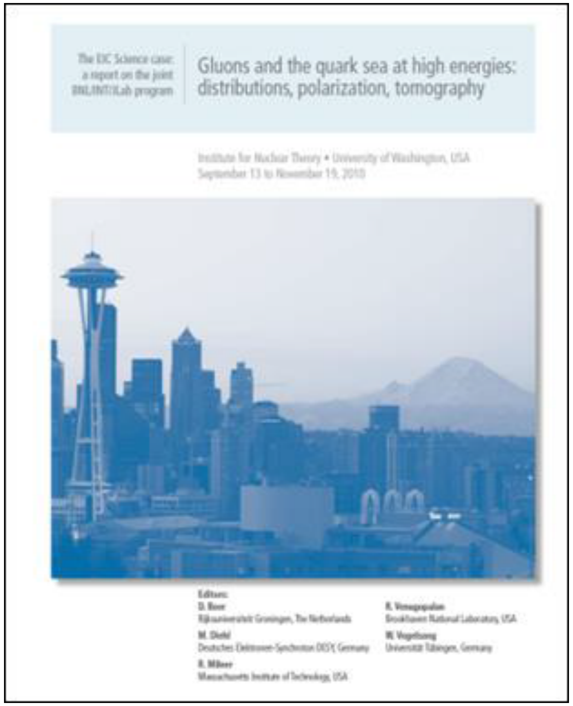
Jefferson Lab

4th International Workshop on Nucleon Structure at Large Bjorken x

Rome, Italy, November 17-21, 2014

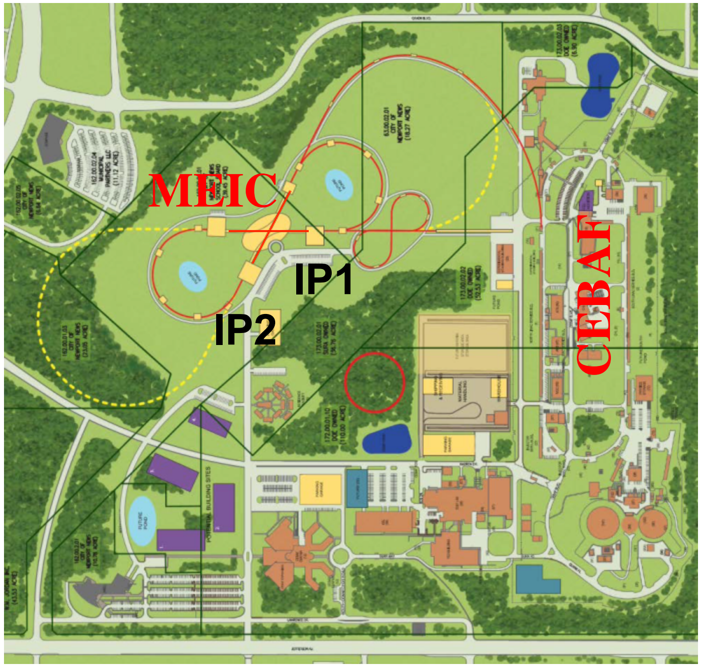
EIC physics program

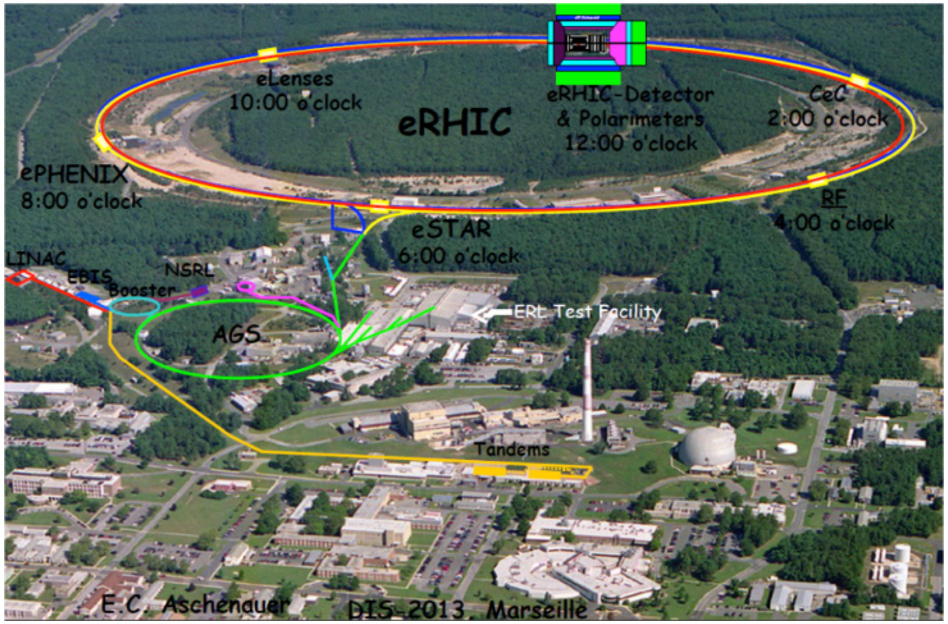




- A program for a generic EIC has been outlined in several documents
  - White paper, INT report, etc
- Both the proposed JLab and BNL implementations support the full generic program, although some unique capabilities are site-specific

EIC implementations at JLab and BNL



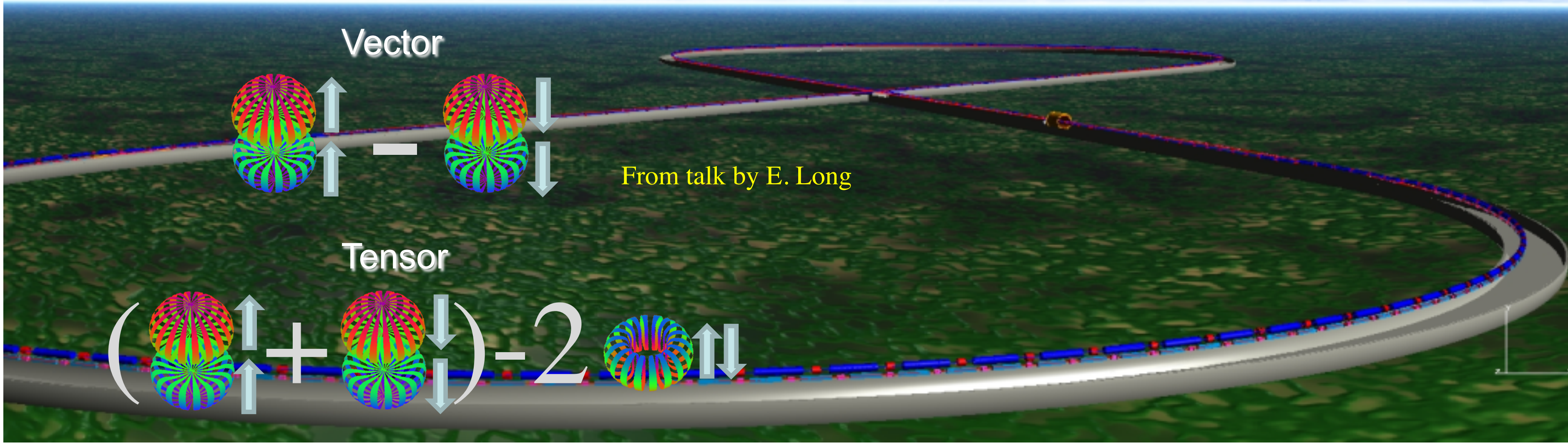


- The MEIC will add 2.2 km storage rings for ions and electrons to 12 GeV CEBAF (which is 1.4 km in circumference)
- The fixed-target capability will be retained during construction and operation
  - Interesting for for PVDIS, light meson spectroscopy, as well as high-x DIS

- eRHIC will replace one of the RHIC rings with a 3.8 km, recirculating, multi-pass linac with energy recovery
- The remaining ion ring will be changed to include all snakes in order to meet the EIC polarization goal of 70%.

Polarized light ions at an EIC

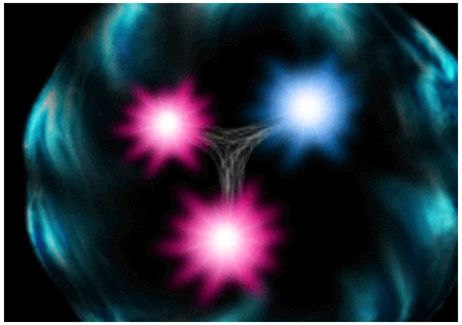
- The EIC will support a variety of light ions, including d, ^{3}He, Li, etc
  - Polarized ^{3}He beams are relatively straightforward
- The very small deuteron g-2 requires a figure-8 ring shape
  - Both vector- and tensor polarization possible



Some EIC physics highlights

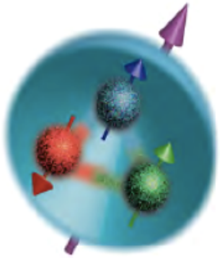
- 3D structure of nucleons

  How do gluons and quarks bind into 3D hadrons?



- Role of orbital motion and gluon dynamics in the proton spin

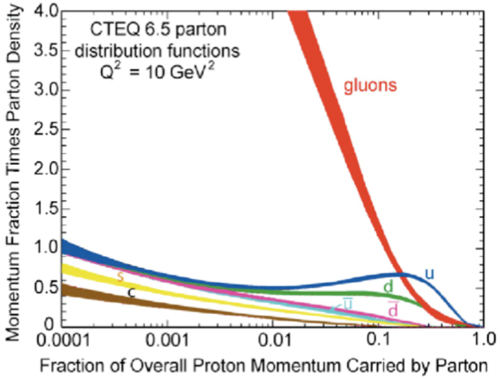
  Why do quarks contribute only ~30%?



- Gluons in nuclei (light and heavy)

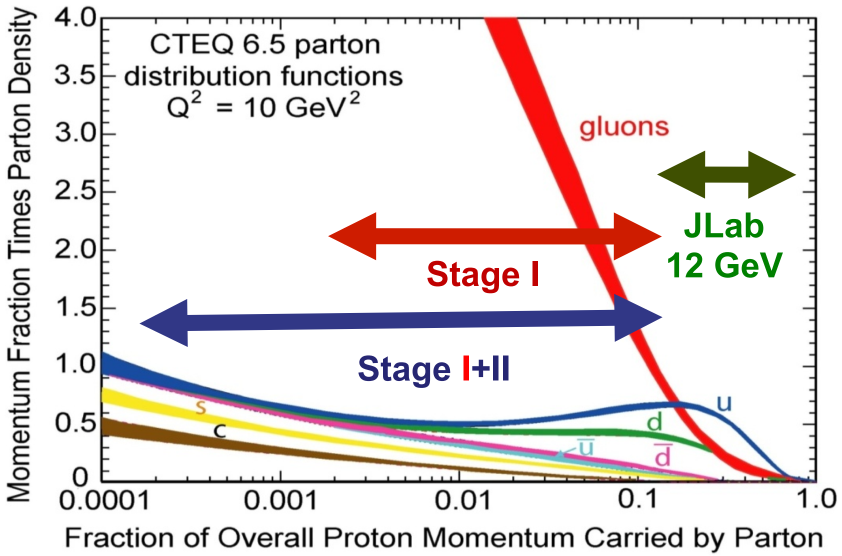
  Example: spectator tagging with light polarized nuclei

  Does the gluon density saturate at small x?

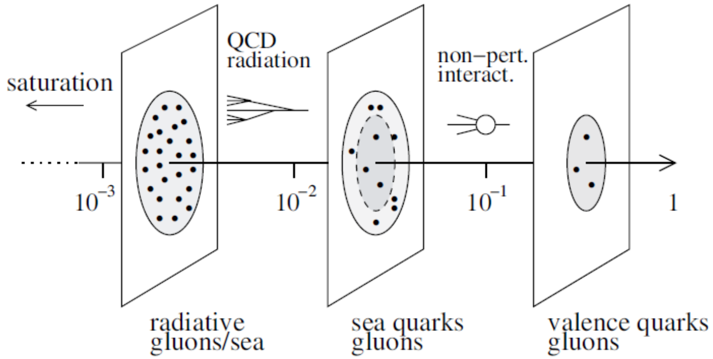


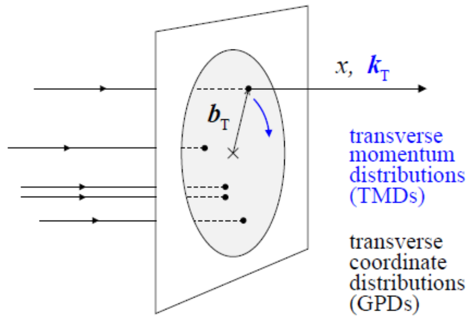
Kinematic coverage of an EIC

- JLab 12 GeV: valence quarks
- EIC stage I (MEIC): non-perturbabative sea quarks and gluons
  - **but also high *x* at high Q^2**: $x_{max} = Q^2 / (s_{min}\, y_{min})$, where $s = 4E_e E_p$
- EIC stage II: extends coverage into radiation-dominated region

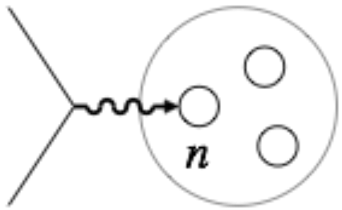


A stage I EIC (JLab MEIC) covers the x and Q^2 range between JLab 12 GeV and HERA (or a future LHeC)



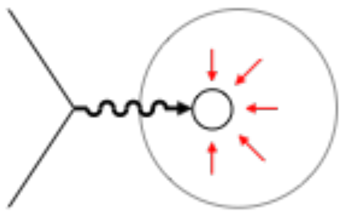


Physics opportunities with light ions



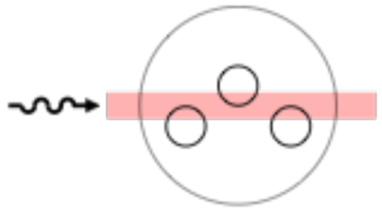
- Neutron structure
  - Flavor decomposition of quark spin, Δg, etc

    Binding, final-state interactions, polarization?



- Bound nucleon in QCD
  - Modification of quark/gluon structure by nuclear medium
  - QCD origin of nuclear forces

    Understand nuclear environment?



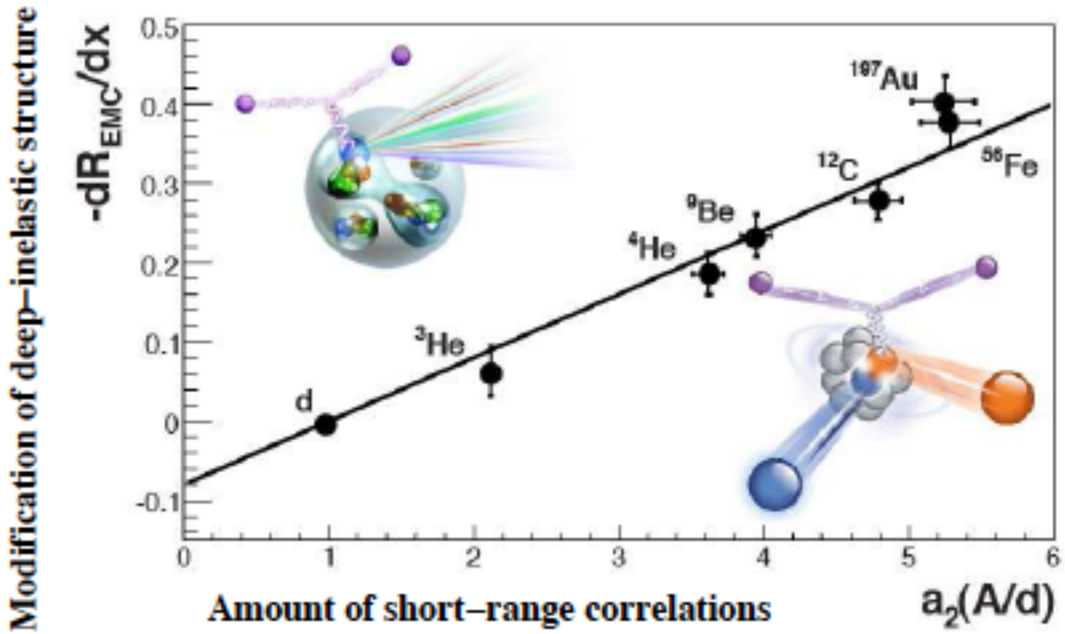
- Coherence and saturation
  - Interaction of high-energy probe with coherent quark-gluon fields

    Onset of coherence, signature of saturation?

[Nucleus rest frame view]

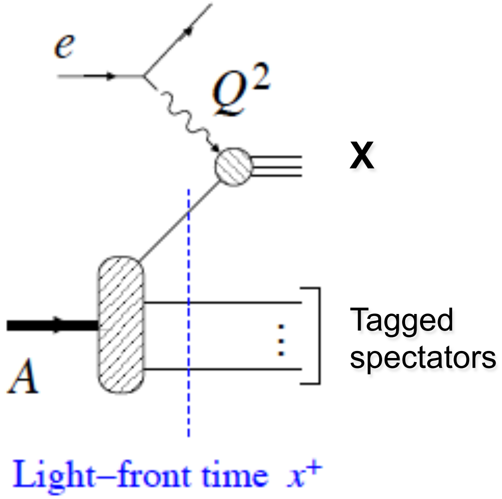
W. Cosyn, V. Guzey, D.W. Higinbotham, C. Hyde, S. Kuhn, W. Melnichouk, PNT, K. Park, M. Sargsian, M. Strikman, C. Weiss, JLab LDRD-funded project

In-medium nucleon

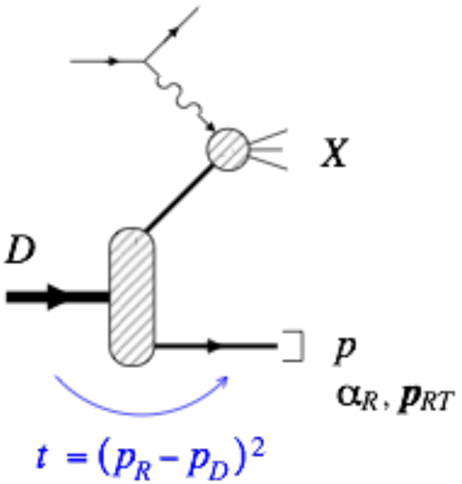


- EMC effect and Short-Range Correlations
- Measurements at JLab 6 and 12 GeV presented at this workshop
- At an EIC we can map out the recoil-momentum dependence in DIS on light nuclei
  - Large p_T acceptance for spectators (~ 0-2 GeV/c)

Measuring neutron structure



$$e + D \to e' + p + X$$



- High-resolution spectator tagging
- Polarized deuterium
  - Needs to be theoretically understood also for ^{3}He
  - Light-cone wave function simple and known
  - Limited possibilities for final-state interactions
  - Coherent effects at N=2

    Complementary to saturation in heavy nuclei
- Simplest case: tagged DIS on neutron
  - Recoil-proton light-cone momentum

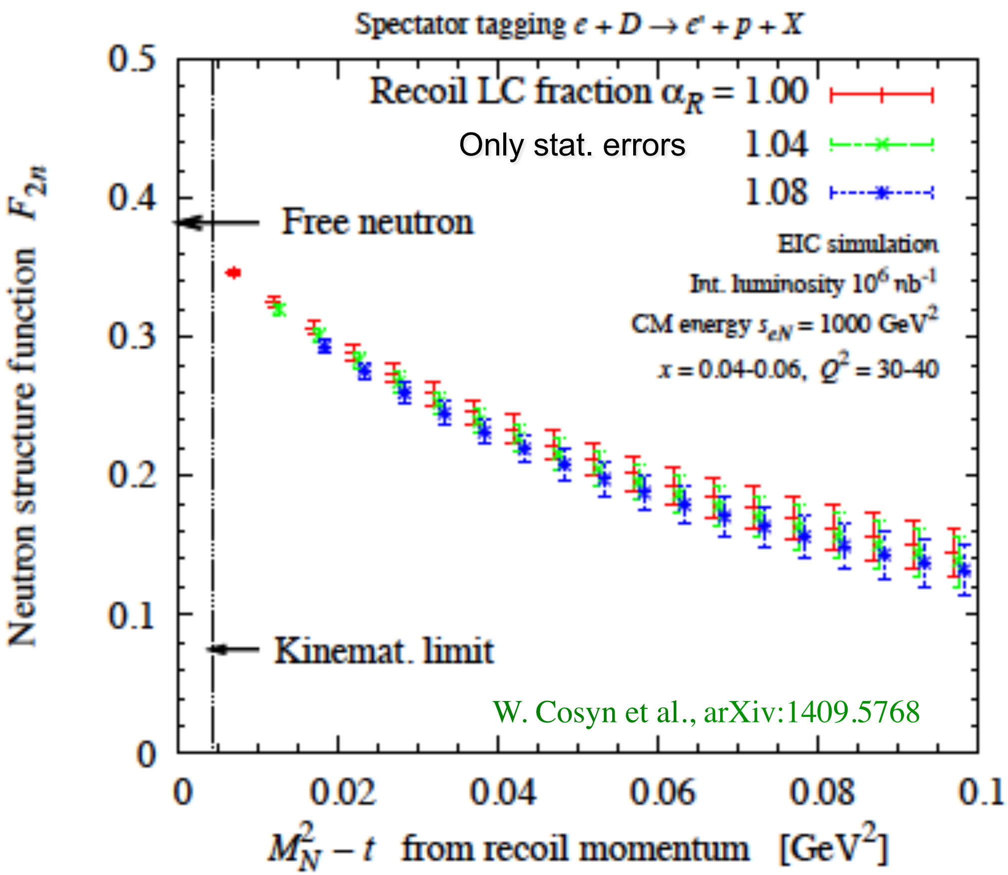
    $$\alpha_R = (E_R + p_{R||})/(E_D + p_{D||}) \text{ and } \mathbf{p}_{RT}$$
  - Cross section in impulse approximation

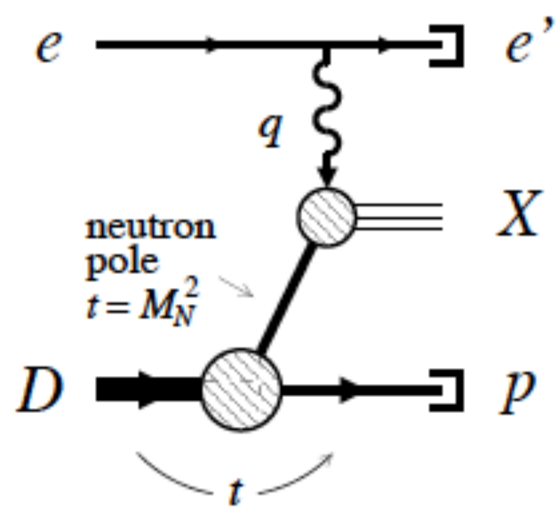
$$\frac{d\sigma}{dx\, dQ^2\, (d\alpha_R/\alpha_R)\, d^2p_{RT}} \propto |\psi_D^{LC}(\alpha_R, p_{RT})|^2 F_{2n}[x/(2-\alpha_R), Q^2]$$

Deuteron LCWF   Neutron SF

Frankfurt, Strikman 1981

On-shell extrapolation t ➔ M_N





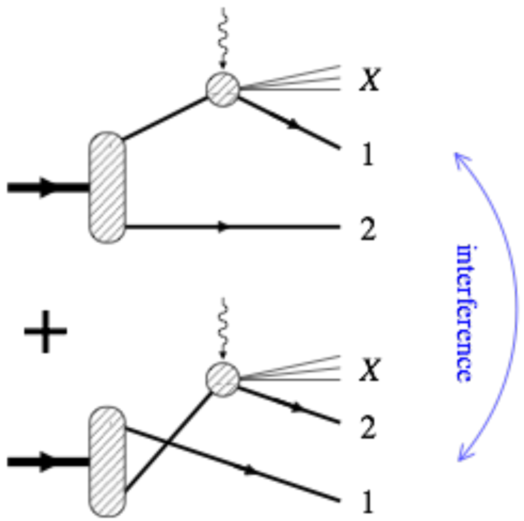
- Free neutron at pole
  - Pole value not affected by final-state interactions

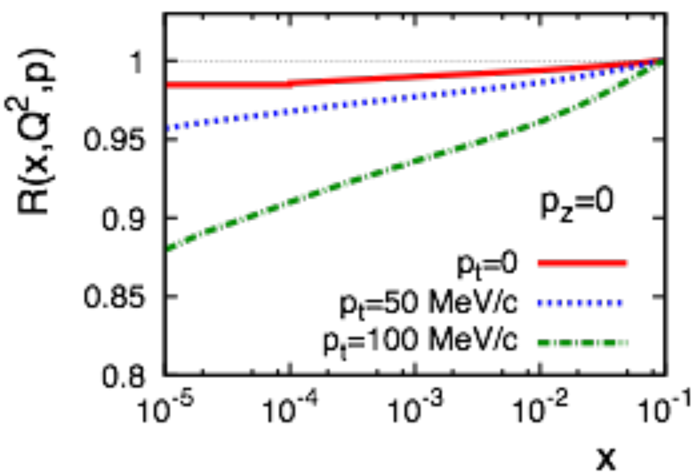
Sargsian, Strikman 2005: no-loop theorem

➔ Talk by Vim Cosyn

- As Chew-Low extrapolation in πN, NN
  - Model-independent method
  - Also applicable to other observables and channels

Shadowing





- Shadowing at small x
  - Interference between diffractive scattering on nucleons 1 and 2
  - Nuclear effect calculable in terms of nucleon diffractive structure

    Gribov 70's, Frankfurt, Strikman '98, Frankfurt, Guzey, Strikman '02+

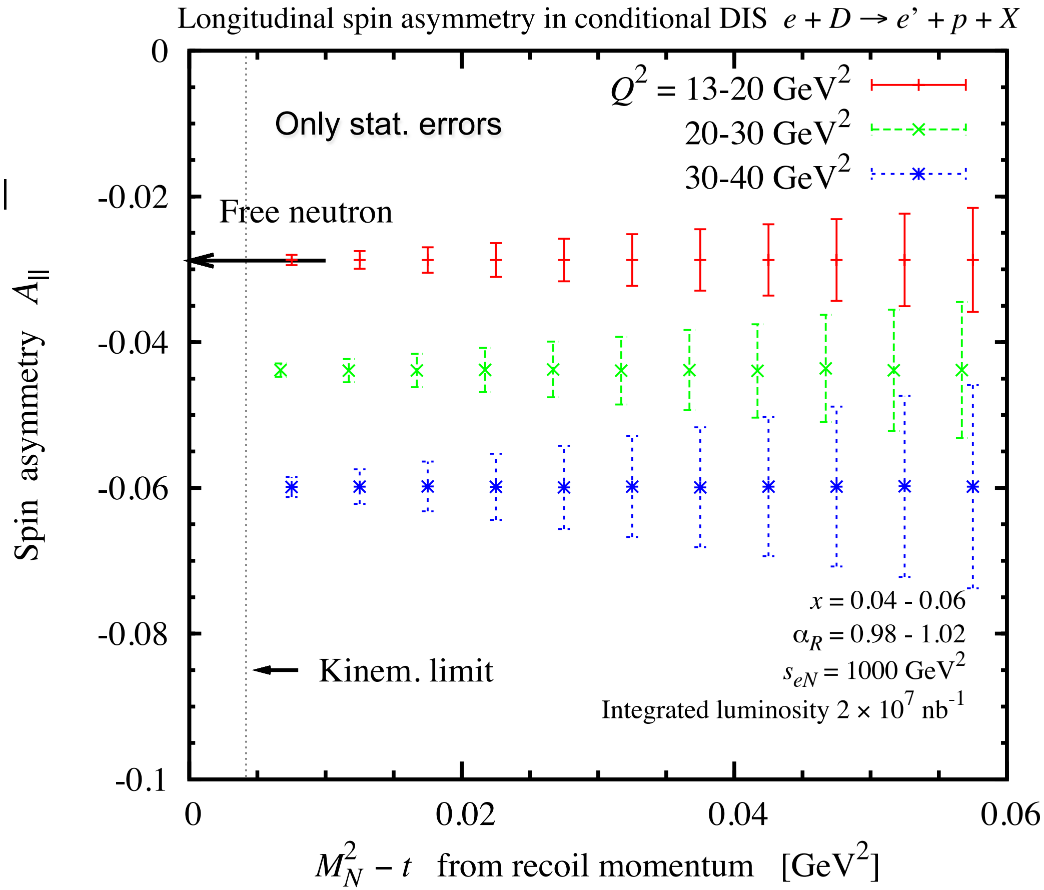
  - Determines approach to saturation in heavy nuclei

- Shadowing in tagged DIS
  - Strong p_T dependence
  - Clean coherent effect with N=2

    Frankfurt, Guzey, Strikman 2011

Polarized structure functions

- As with unpolarized structure functions, on-shell extrapolation can also be performed in the polarized case
- g_1^n accessible through longitudinal spin asymmetry $A_{||}$
- On-shell extrapolation of $A_{||}$ is easier than for F_2^n
  - Effects of FSI, etc, at higher values of $M^2 - t$ are not included here
- Note that $A_{||}$ increases with Q^2 at fixed x



W. Cosyn et al., arXiv:1409.5768

CM-energy dependence of $A_{||}$

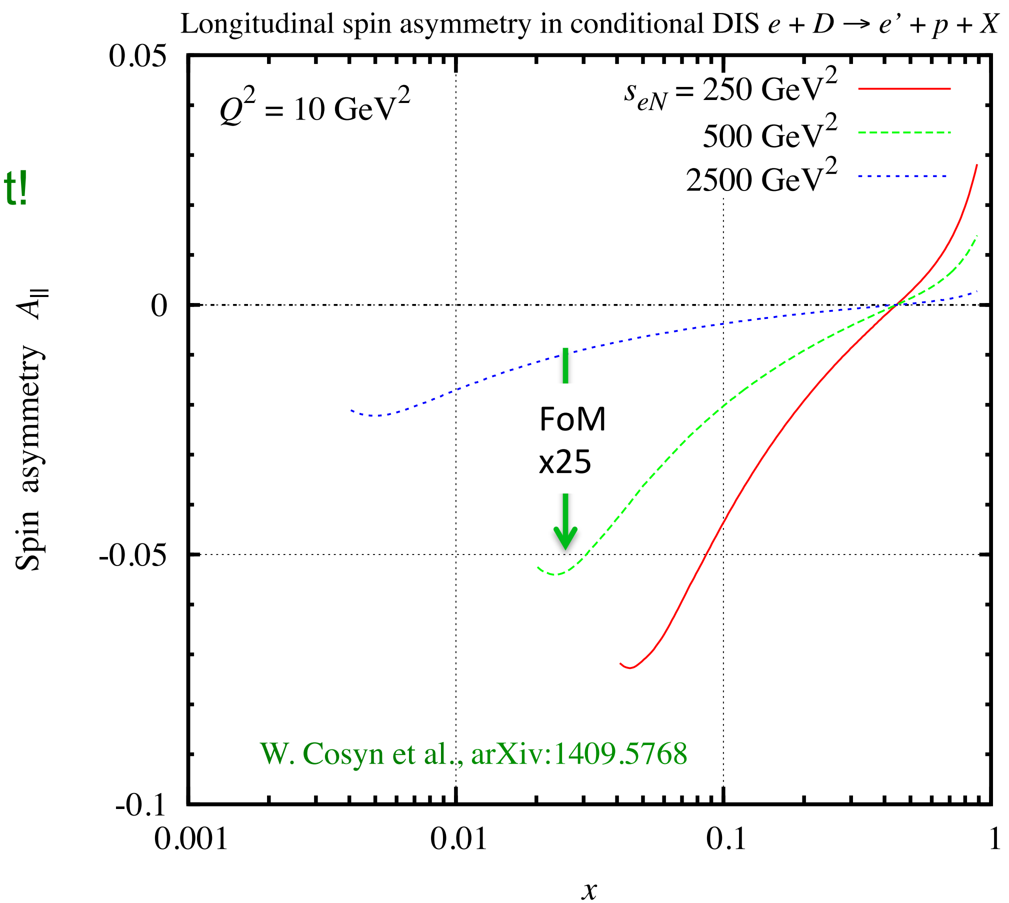
- At fixed x and Q^2, a lower cm-energy *s* increases the asymmetry
  - $A_{||}$ can be large compared with systematic uncertainties from polarimetry
- FoM ~ event rate x $(P_e P_D A_{||})^2$
- Good low-*s* performance important!

$$A_{||} = \frac{d\sigma(++) + d\sigma(--) - d\sigma(+-) - d\sigma(-+)}{d\sigma(++) + d\sigma(--) + d\sigma(+-) + d\sigma(-+)}$$

$$= D\frac{g_{1n}}{F_{2n}} + \ldots$$

$$D = \frac{y(2-y)}{2-2y+y^2}$$ Depolarization factor

$$y = \frac{Q^2}{x_{Bj}\left(s_{eN} - M^2\right)} \approx \frac{Q^2}{x_{Bj} s_{eN}}$$



Experimental considerations

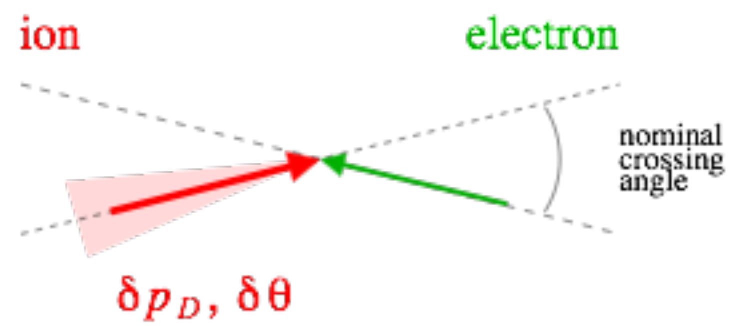
- Spectator tagging requires high-resolution forward hadron spectrometers
  - Large-acceptance magnets required for good p_T coverage (e.g., SRC)
- Inclusive measurements at low x and Q^2 are systematics limited
  - Polarimetry is essential
  - Radiative corrections and detector coverage important at extreme values of y
- Exclusive- and semi-inclusive reactions pose a wide range of challenges
  - Drive design of central detector
  - Spectator tagging equally important as for inclusive (e.g., DVCS on neutron)!
- High-x measurements possible at high Q^2 - extension of JLab 12 GeV
  - Good performance at low *s* is essential
  - At x = 0.7, and s_{eN} = 600 GeV^2 (e.g., 3 GeV e^- on 50 GeV/A N):

    Q^2 = 378 GeV^2 for y = 0.9

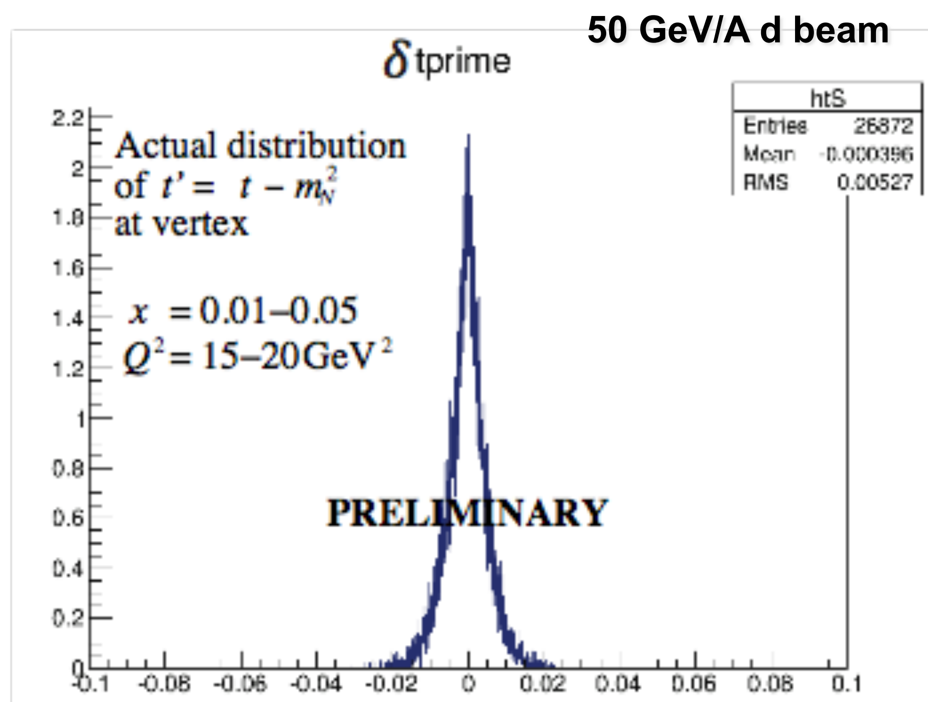
    Q^2 = 21 GeV^2 for y = 0.05
  - These are deuteron kinematics for which the MEIC reaches its full luminosity

Uncertainty in spectator momentum

- Two contributions to uncertainty in measured spectator momentum
  - Resolution of detector
    Final-state resolution
  - Momentum spread in the beam
    Initial-state resolution



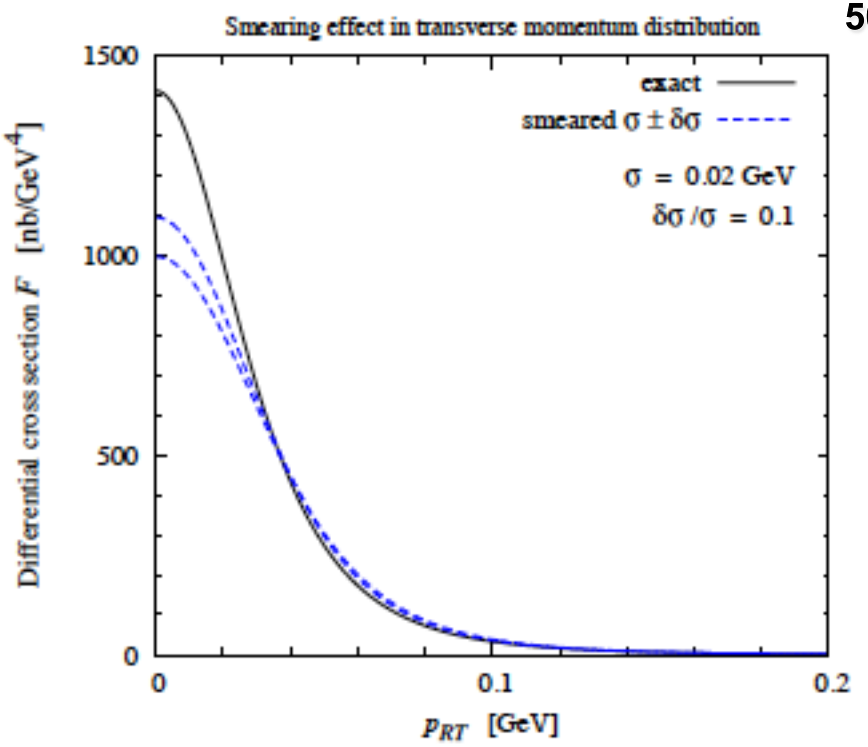
- Ideal detector gives negligible contribution to uncertainty
  - Can be achieved !
  - Uncertainty entirely due to beam
    few x 10^{-4} longitudinal (dp/p)
    few x 10^{-4} rad angular ($d\theta/\theta$)

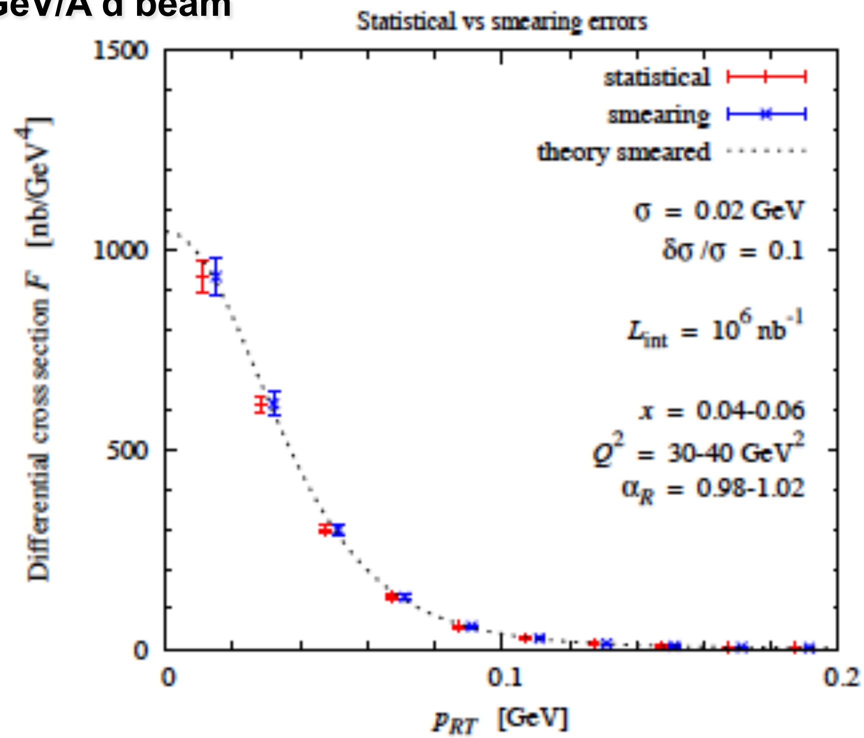


- Simulation shows effect on resolution (binning) in t'
  - Uncertainty increases with the ion beam energy

Systematic uncertainty on p_T

50 GeV/A d beam

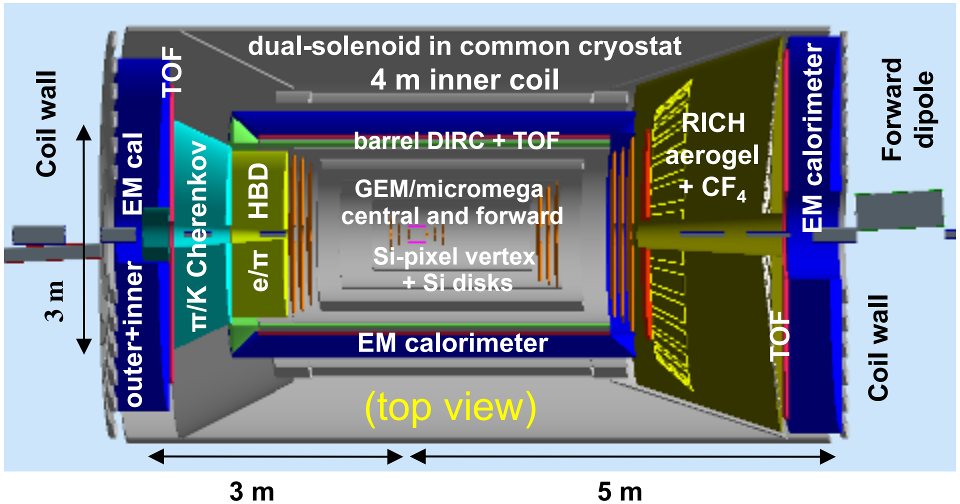




- Smearing in p_T (left) gives systematic affecting on-shell extrapolation (right)
- The resolution σ ~ 0.02 GeV/c for a 50 GeV/A beam, is known to 10%
- Can achieve systematic uncertainties for on-shell extrapolation comparable with the statistical uncertainties

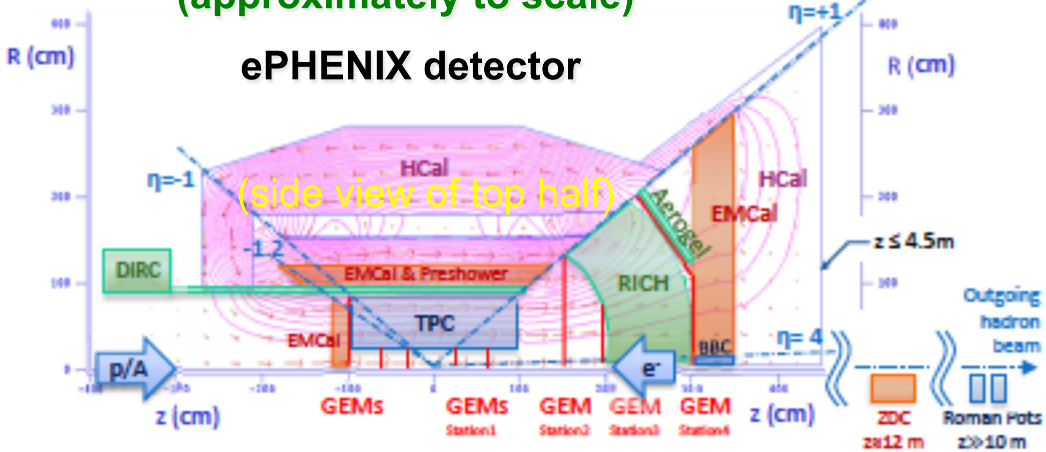
EIC central detectors

MEIC IP1 detector



(approximately to scale)

ePHENIX detector

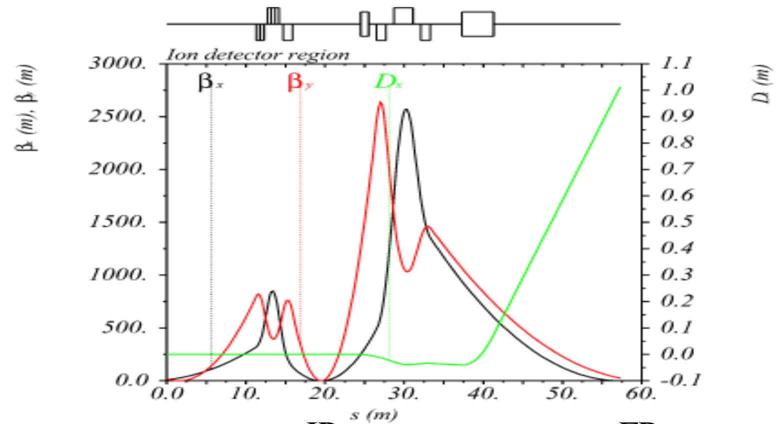


- The central detector concepts developed at JLab and BNL, exemplified by MEIC-IP1 and ePHENIX, are different in many details, but the impact on inclusive structure functions is limited
- MEIC IP1
  - Focus on exclusive processes and semi-inclusive DIS
  - Several solenoid options available (CLEO or dual)
- ePHENIX
  - Focus on jet-physics
  - Possible to move sPHENIX to MEIC IP2

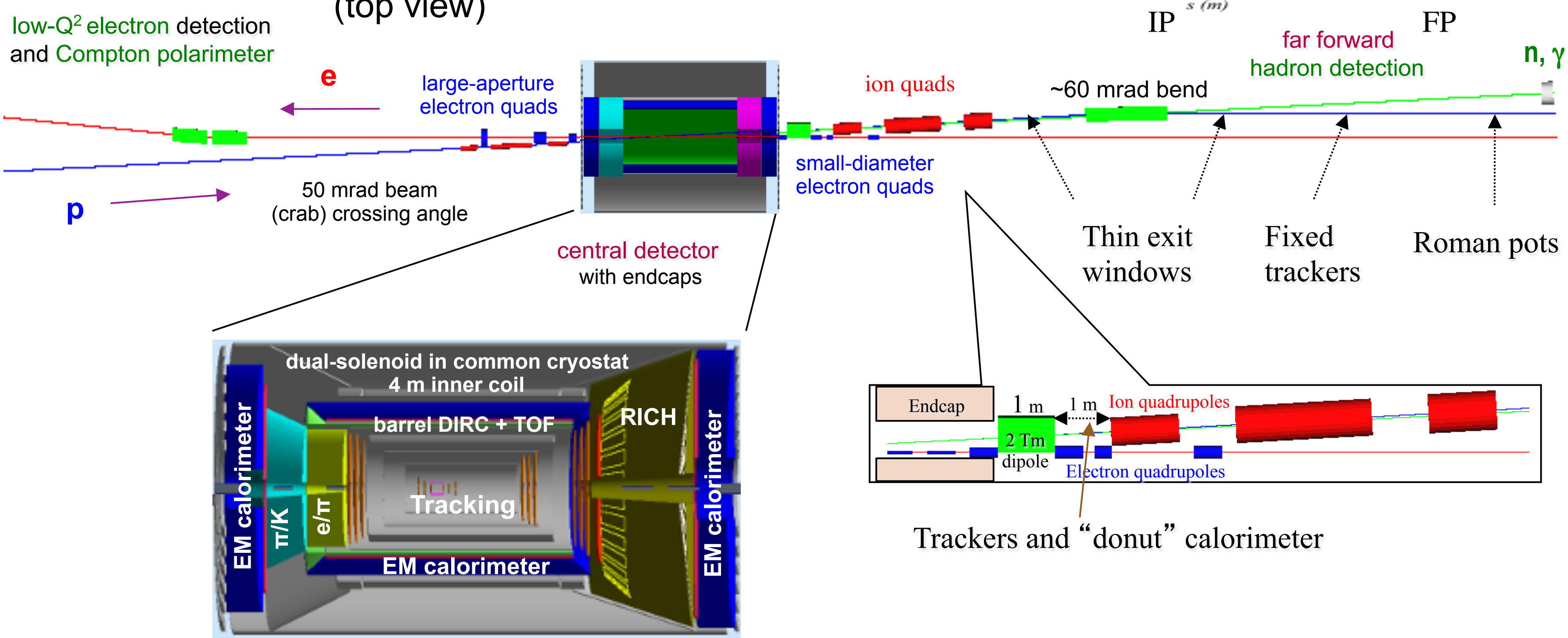
The MEIC *full-acceptance* detector

Design goals:

1. **Detection/identification of complete final state**
2. **Spectator p_T resolution << Fermi momentum**
3. **Low-Q^2 electron tagger for photoproduction**
4. **Compton polarimeter with e^- and γ detection**



(top view)

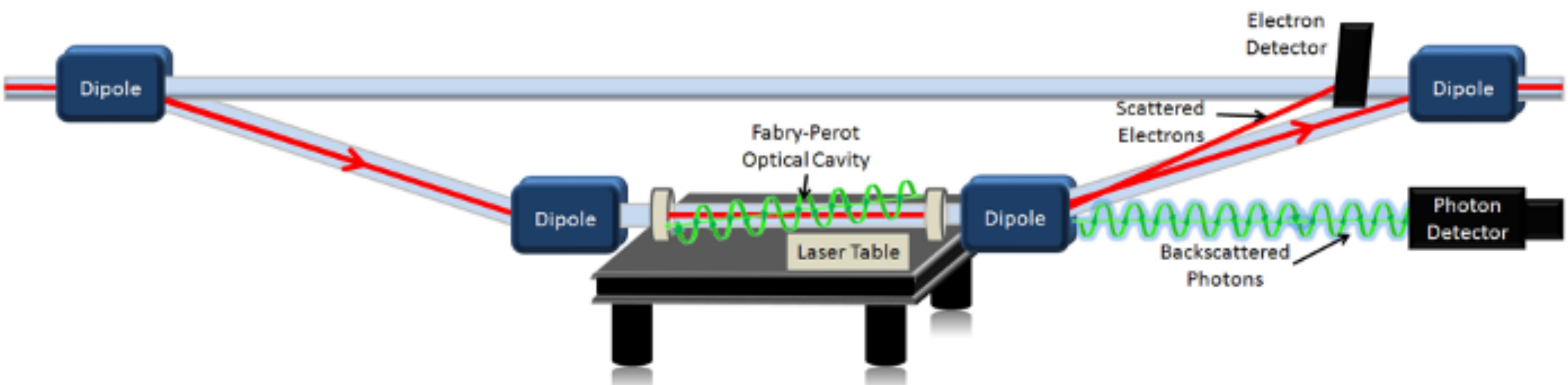


Compton polarimetry

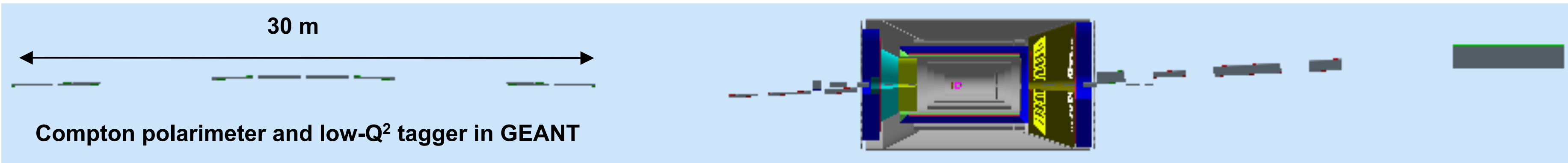
- Experience from HERA: uncertainty > 1%
  - Limited to detection of Compton photon only
  - Accelerator limitations (non-colliding bunches)

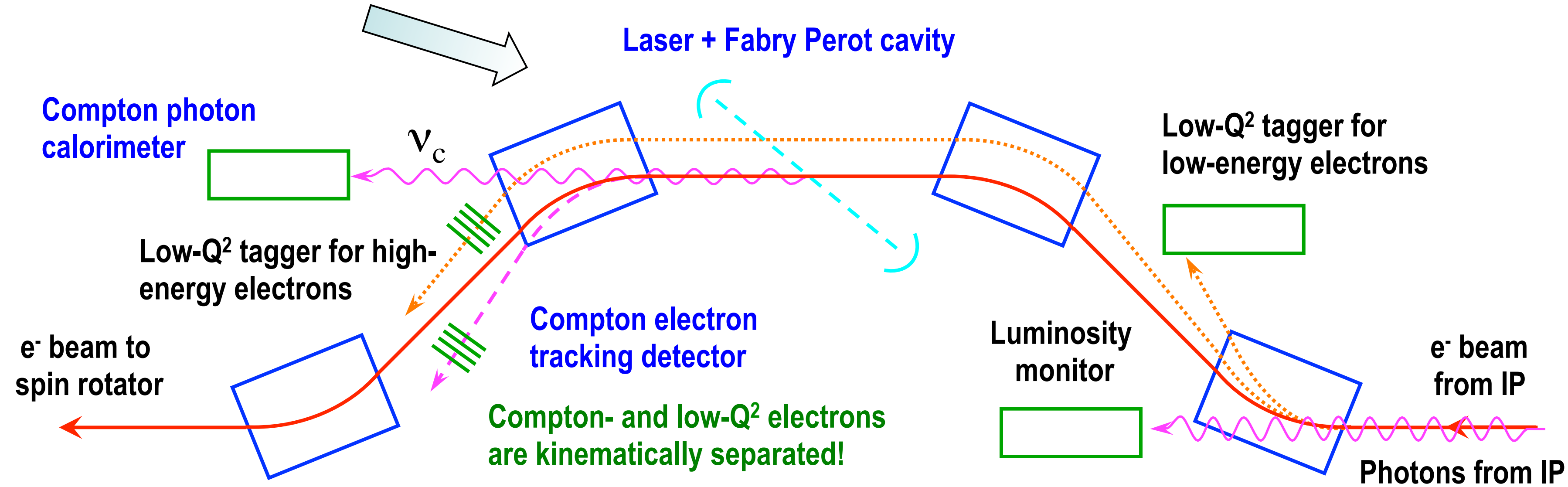
- Experience from JLab and SLAC
  - SLD at SLAC reached 0.5% detecting the Compton electron
  - Compton polarimeters in Halls A and C at JLab reach ~1% detecting both the photon *and* the electron for cross check

    Laser at Chicane center ensures that polarization is identical to IP



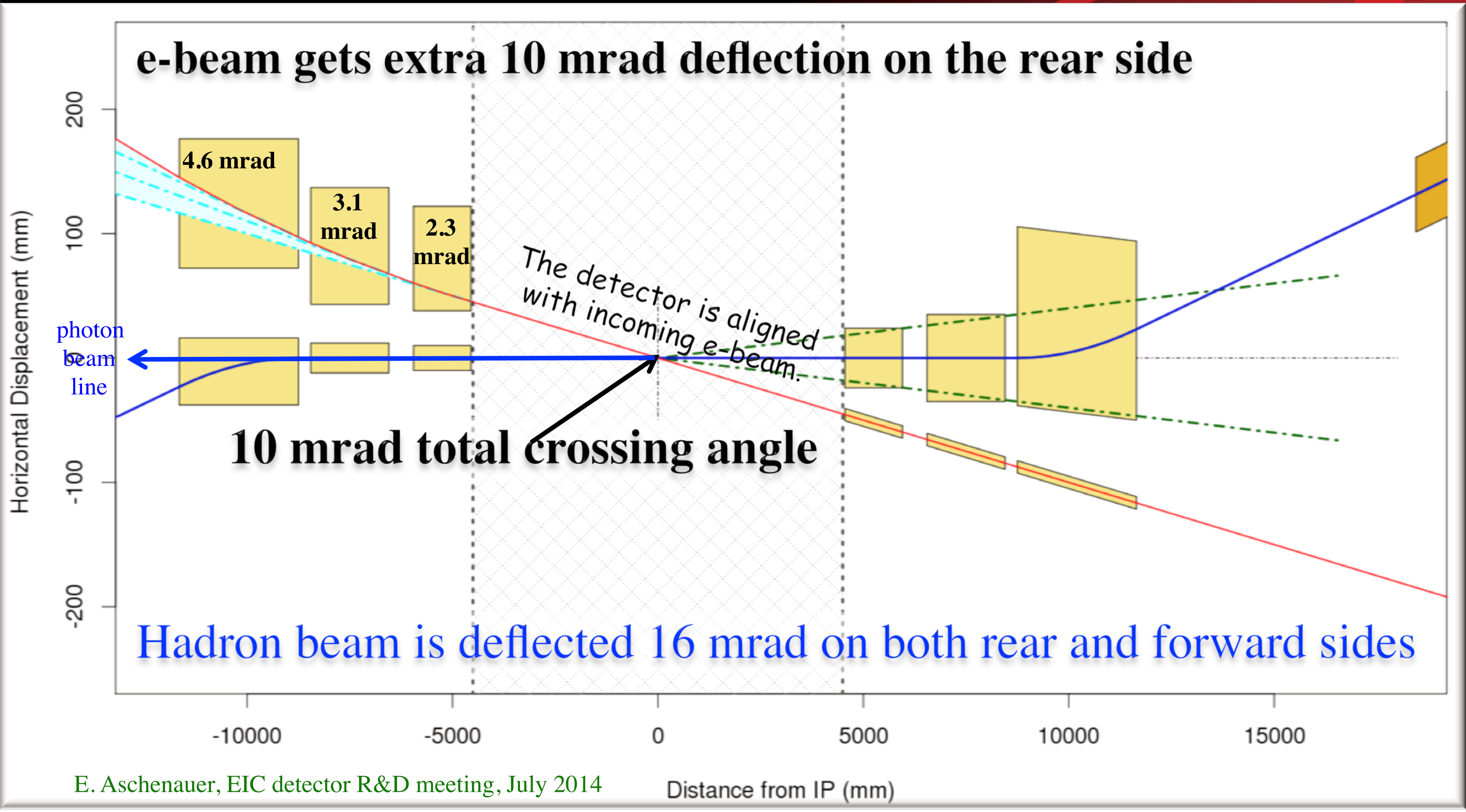
MEIC polarimeters and low-Q^2 tagger





- One IP will have much larger version of the JLab Compton chicane
  - Detection of both electron and photon, the latter with low synchrotron background
- Second IP will have a similar chicane optimized for electron detection
  - Goal is to push the uncertainty of the polarimeter towards what SLAC achieved

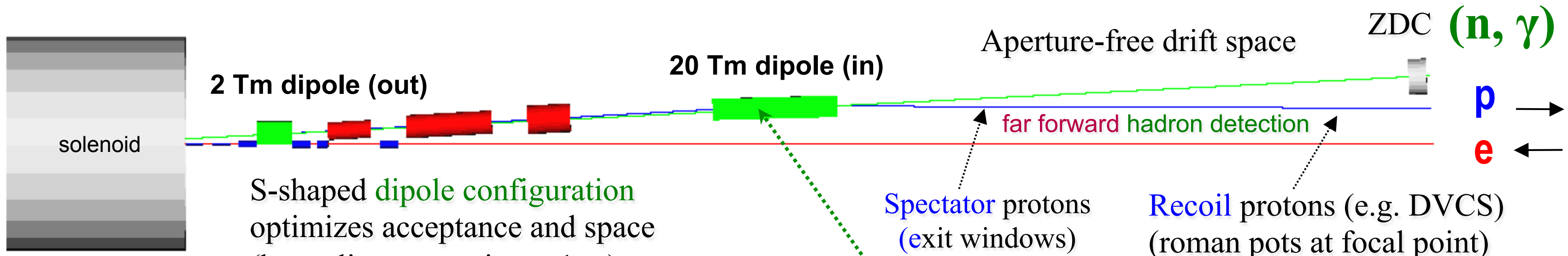
eRHIC: small-angle electron detection



E. Aschenauer, EIC detector R&D meeting, July 2014

- The design of a Compton polarimeter and a low-Q^2 tagger for eRHIC is funded by the Generic detector R&D for an EIC program.

MEIC small-angle hadron detection



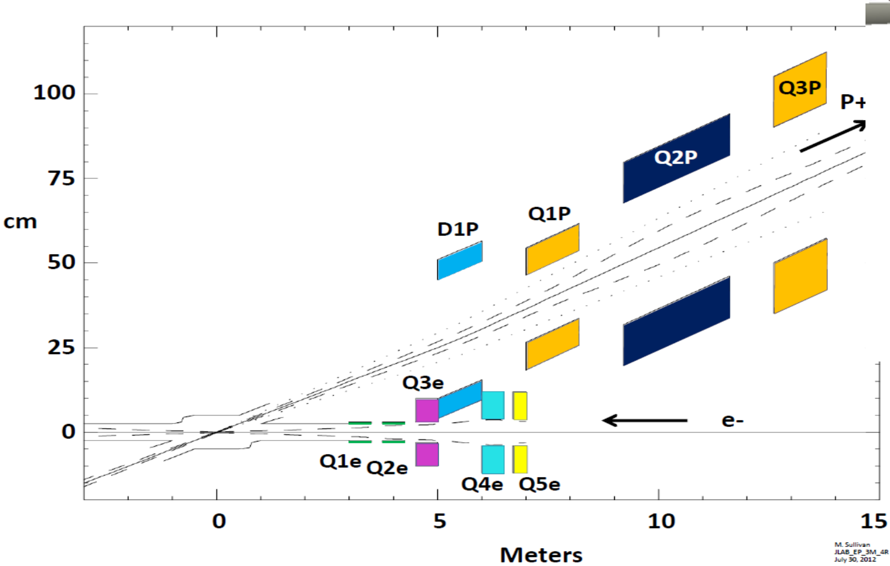
S-shaped dipole configuration optimizes acceptance and space (beam line separation > 1 m)

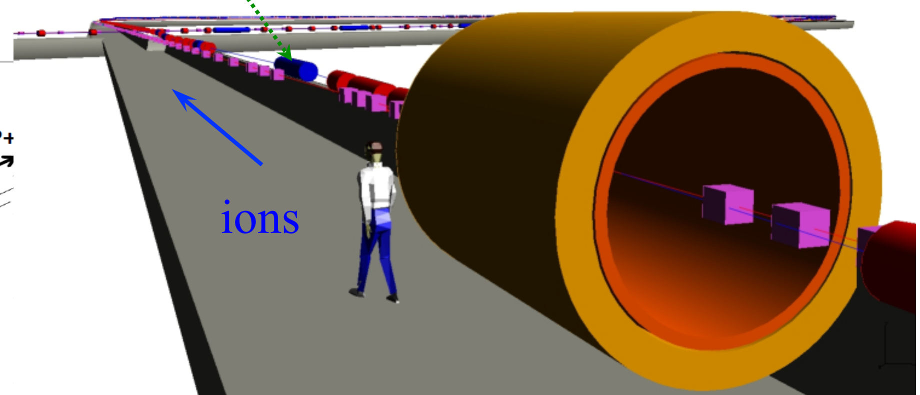
50 mrad crossing angle (Belle II: 83 mrad)

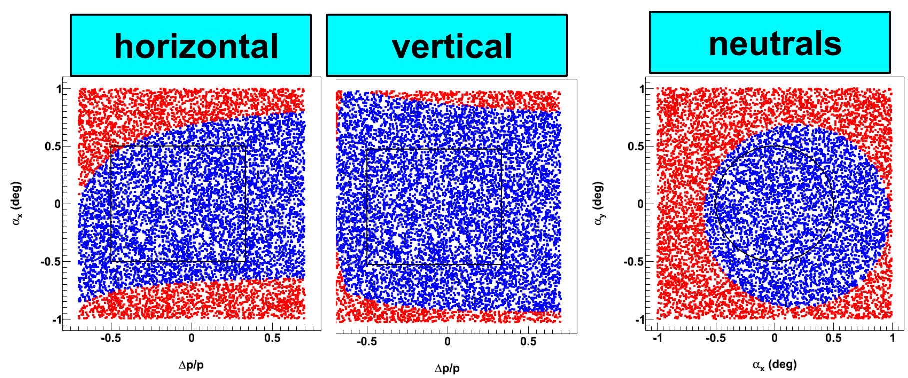
Spectator protons (exit windows)

Recoil protons (e.g. DVCS) (roman pots at focal point)

Spectator angle after dipole is 75 mrad with respect to beam







Red: detected *before* ion quadrupoles

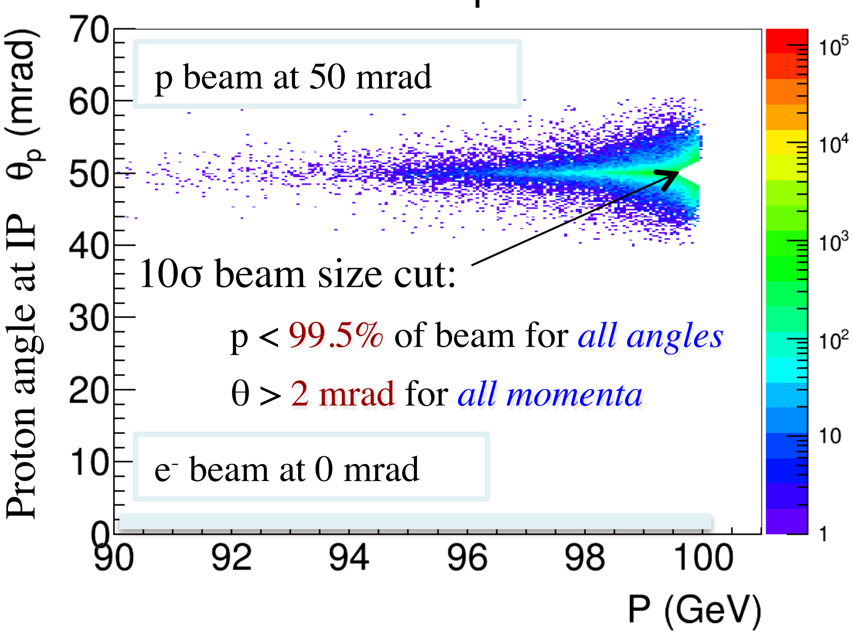
Blue: detected *after* ion quadrupoles

Spectator protons from d: dp/p ~ -0.5

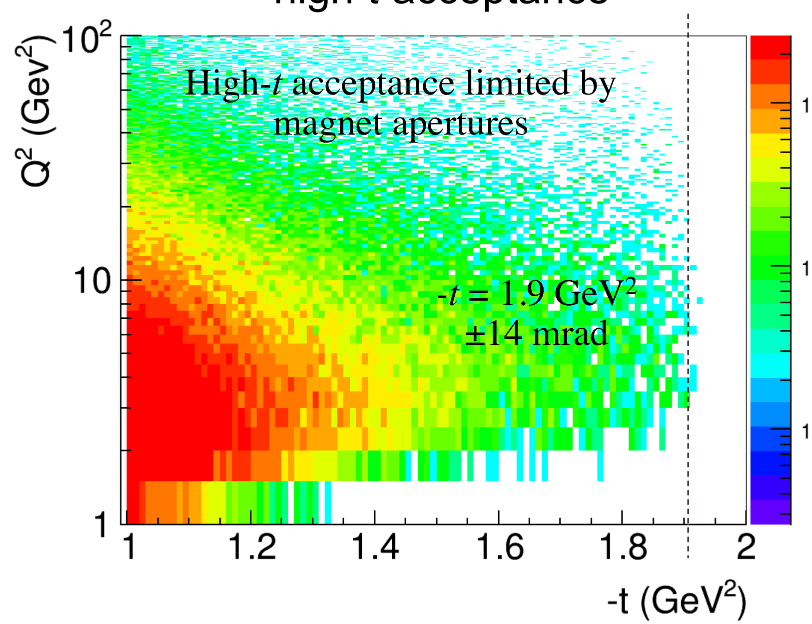
DVCS recoil proton acceptance

- **Kinematics:** 5 GeV e^- on 100 GeV p at a crossing angle of 50 mrad.
  - Cuts: $Q^2 > 1$ GeV^2, $x < 0.1$, $E'_e > 1$ GeV, recoil proton 10σ outside of beam
- **DVCS generator:** MILOU (from HERA, courtesy of BNL)
- **GEANT4 simulation:** tracking through all magnets done using the JLab GEMC package

low-*t* acceptance

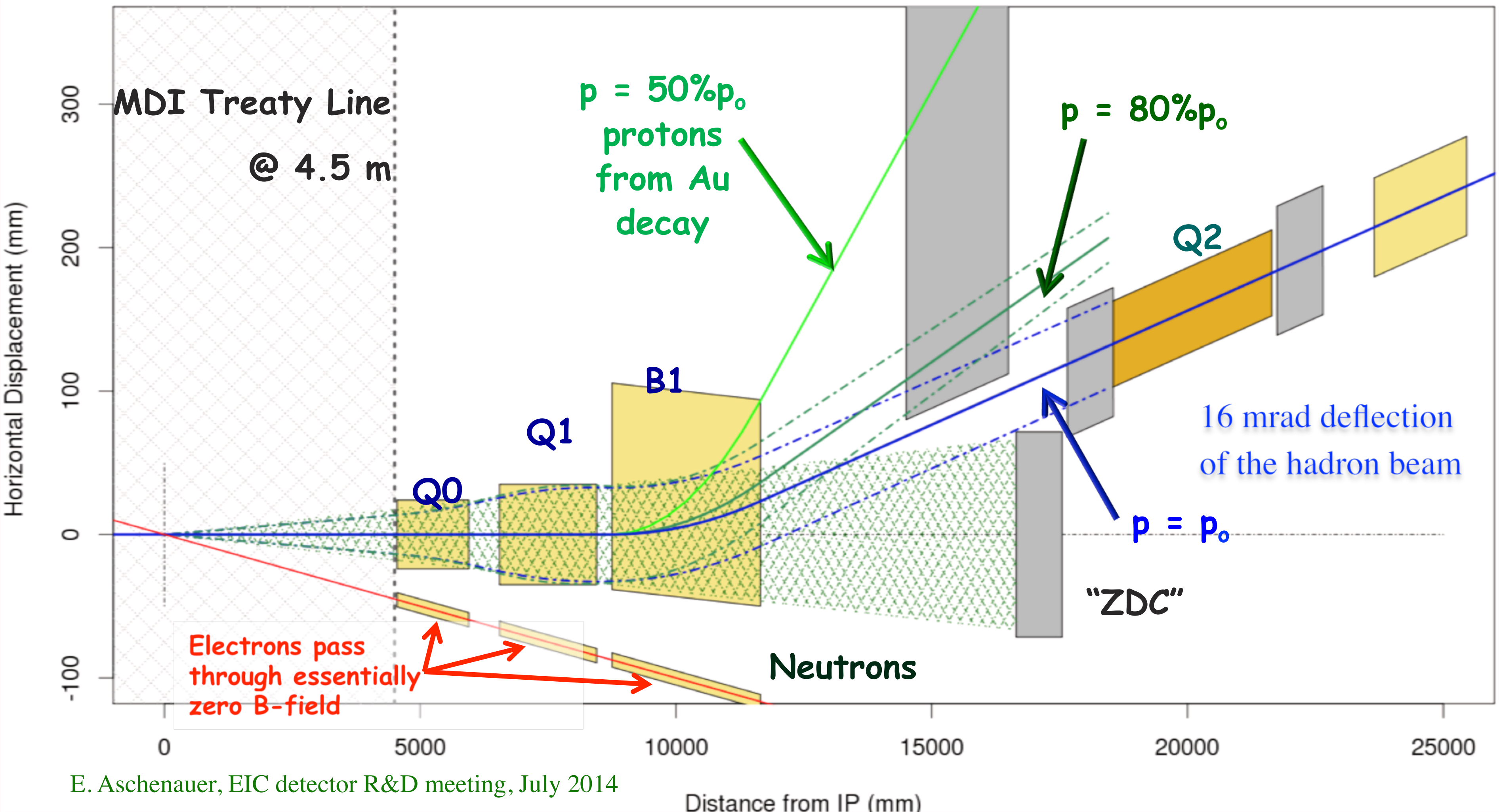


high-*t* acceptance



- Recoil proton angle is independent of electron beam energy: $\theta_p \approx p_T/E_p \approx \sqrt{(-t)}/E_p$
- A wider angular distribution at lower energies makes precise tracking easier

eRHIC: small-angle hadron detection



E. Aschenauer, EIC detector R&D meeting, July 2014

- New version of the eRHIC forward hadron detection has some similarities to the MEIC, but is smaller (16 vs 56 mrad bending angle, less drift space, no second focus on roman pot, no dipole before quads)

Summary

- The EIC is the next-generation US QCD facility

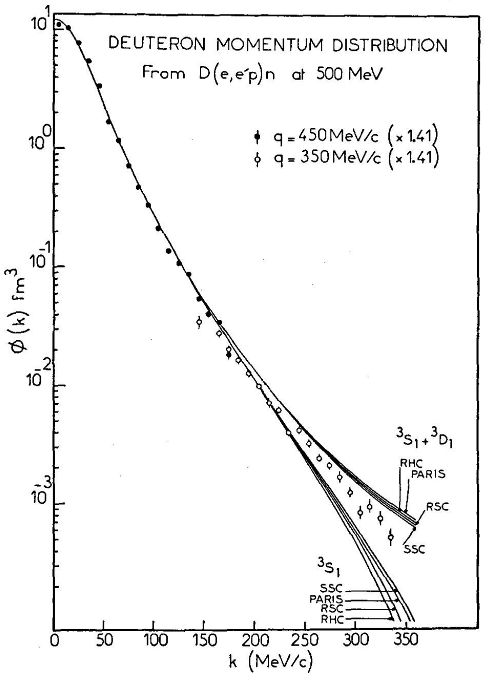
- Spectator tagging with polarized light ions offers many interesting opportunities

- High-x physics is possible also at an EIC !

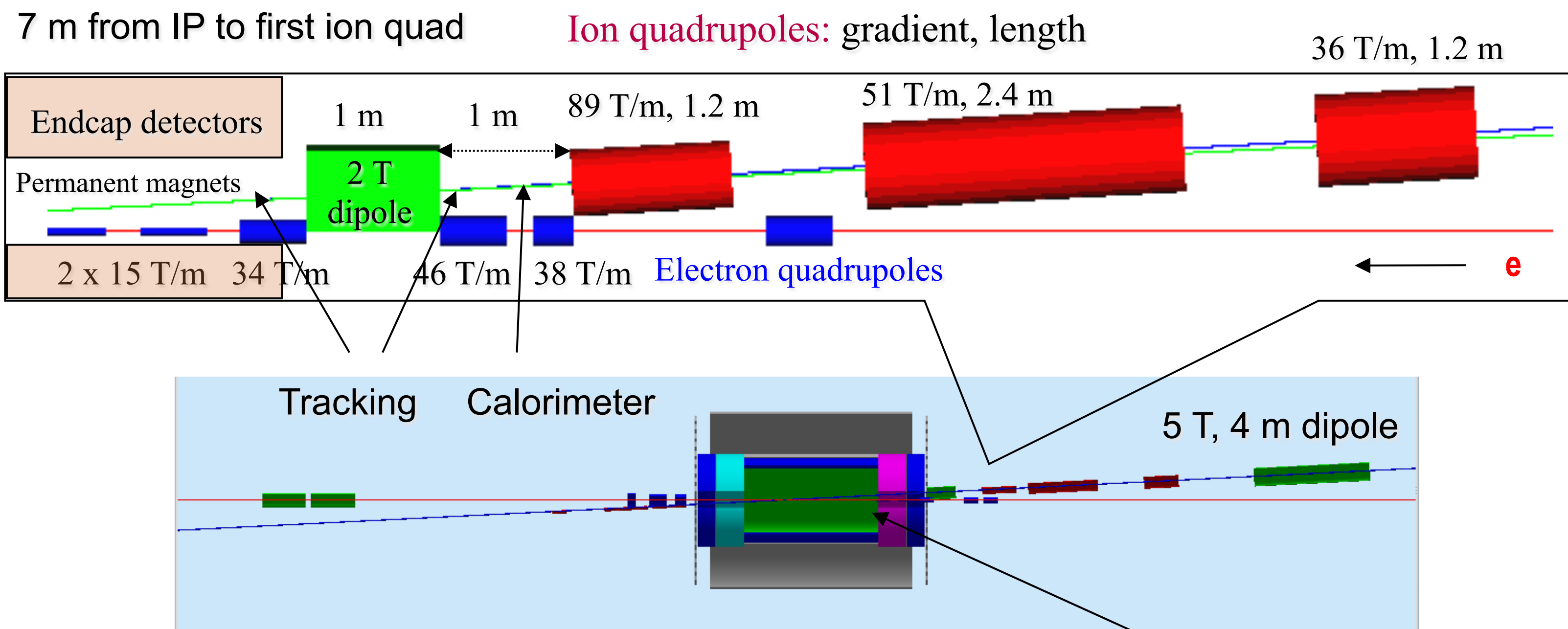
Backup

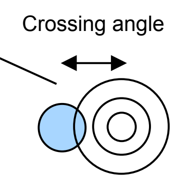
Forward detection – processes

- Recoils in exclusive (diffractive) processes
  - Recoil baryons
    - *Large t (p_T) range and good resolution desirable*
  - Coherent nuclear processes
    - *Good small-p_T acceptance extends detectable mass range*
    - *Suppression of incoherent background for heaviest nuclei through detection of all fragments and photons*
- Partonic fragmentation in SIDIS
  - Correlations of current and target jets
  - Decays of strange and charmed baryons
- Nuclear spectators and fragments
  - Spectator tagging with polarized light ions
    - *p_T resolution < Fermi momentum*
  - Final state in heavy-ion reactions
    - *Centrality of collision (hadronization, shadowing, saturation, etc)*
- Heavy flavor photoproduction (low-Q^2 electron tagging)



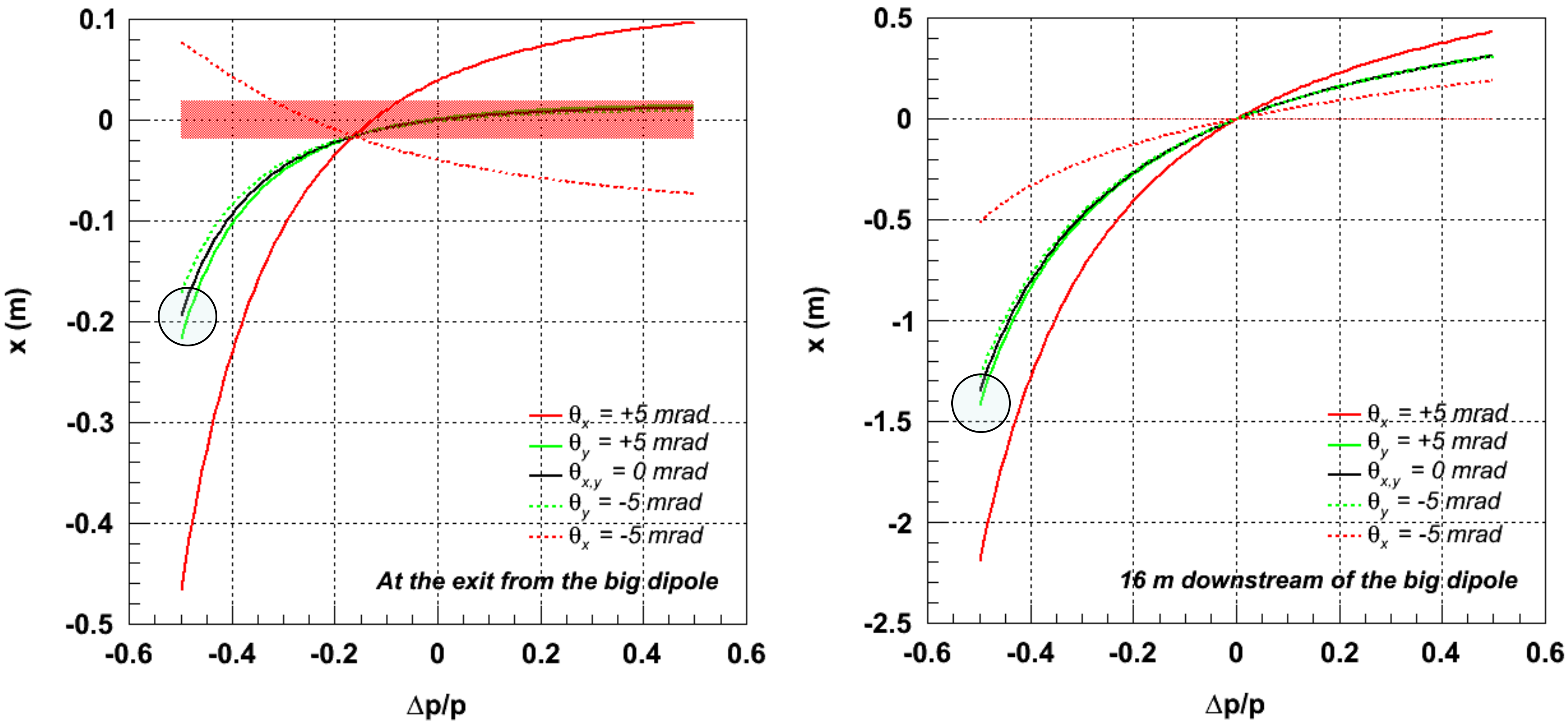
Forward detection *before* ion quads





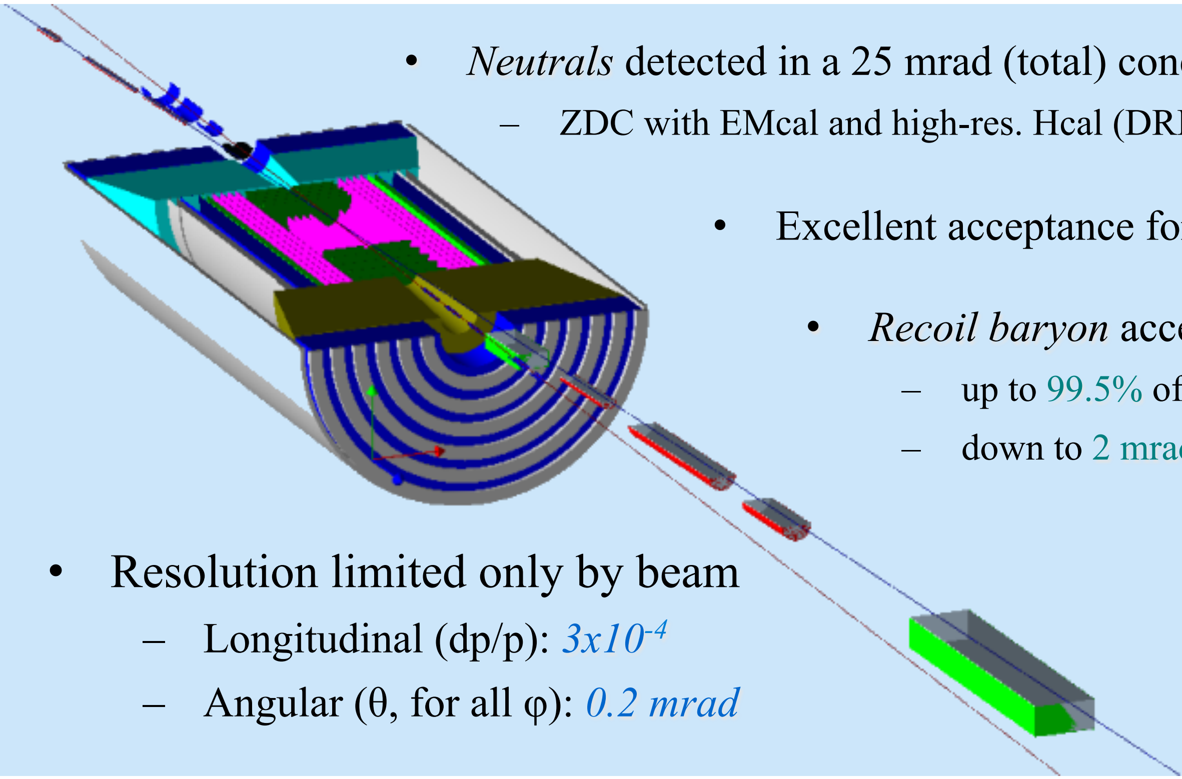
- 50 mrad crossing angle
  - Moves spot of poor resolution along solenoid axis into the periphery
  - Minimizes shadow from electron FFQs
- Dipole before quadrupoles further improves resolution in the few-degree range
- Low-gradient quadrupoles allow large apertures for detection of *all* ion fragments
  - **Peak field** = quad **gradient** x aperture **radius**

Spectator angles *after* dipole

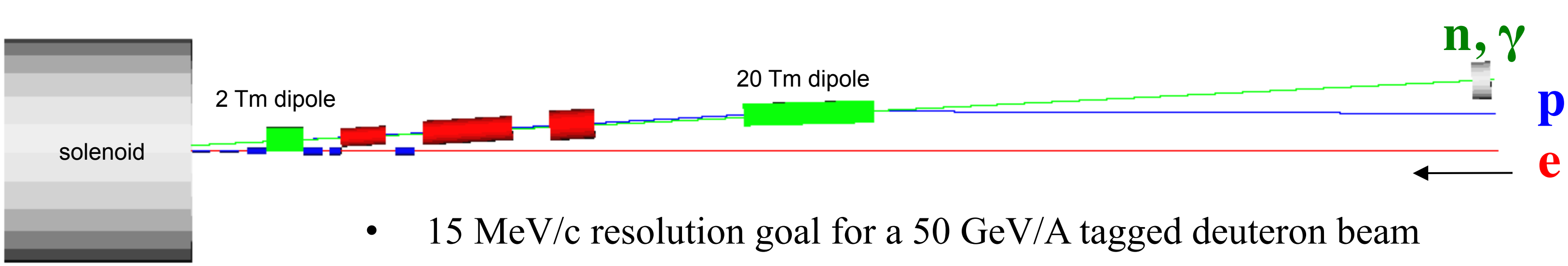


- True spectator fragments have very small scattering angles at the IP (black curve)
- Spectator protons from deuterium have Δp/p = -0.5
- After passing the large bending dipole, the spectator angle with respect to the ion beam is large
- The angle in the magnet-free drift section after the dipole can be calculated from the displacement at the dipole exit and a point 16 m further downstream:
  - θ = atan ((1.4- 0.2)/16) = 75 mrad (= 4.3°)

Far-forward detection summary



- *Neutrals* detected in a 25 mrad (total) cone *down to zero degrees*
  - ZDC with EMcal and high-res. Hcal (DREAM or particle flow).
- Excellent acceptance for *all ion fragments*
- *Recoil baryon* acceptance:
  - up to 99.5% of beam energy for *all angles*
  - down to 2 mrad for *all momenta*
- Resolution limited only by beam
  - Longitudinal (dp/p): $3x10^{-4}$
  - Angular (θ, for all φ): *0.2 mrad*



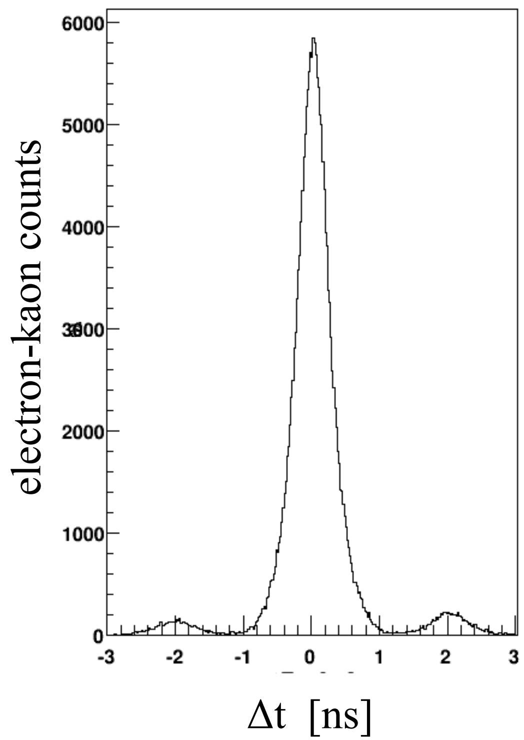
- 15 MeV/c resolution goal for a 50 GeV/A tagged deuteron beam

Bunch spacing and identification

- Detectors (CLAS, BaBar, etc) at machines with high bunch crossing rates have not had problems in associating particle tracks with a specific bunch.
  - Having more bunches lowers the average number of collisions per crossing
- Example: CLAS detector at JLab 6 GeV
  - 2 ns bunch spacing (500 MHz rep. rate)
  - 0.2 ns TOF resolution (0.5 ns FWHM)
  - The figure shows time matching of kaons in CLAS with electrons in the (low-Q^2) tagger, in turn matched to the accelerator RF signal

    The 2 ns bunch structure is clearly resolved
  - CLAS12 aims at a TOF resolution of 80 ps
- The bunch spacing in the MEIC is similar to CLAS and most e^+e^- colliders
  - PEP-II/BaBar, KEKB/Belle: **8 ns**
  - Super KEKB/Belle II: **4 ns** *(2 ns with all RF buckets full)*
  - MEIC: **1.3 ns** [750 MHz]
  - CERN Linear Collider (CLIC): **0.5 ns** [2 GHz]

K-e coincidence time in CLAS 6 GeV data

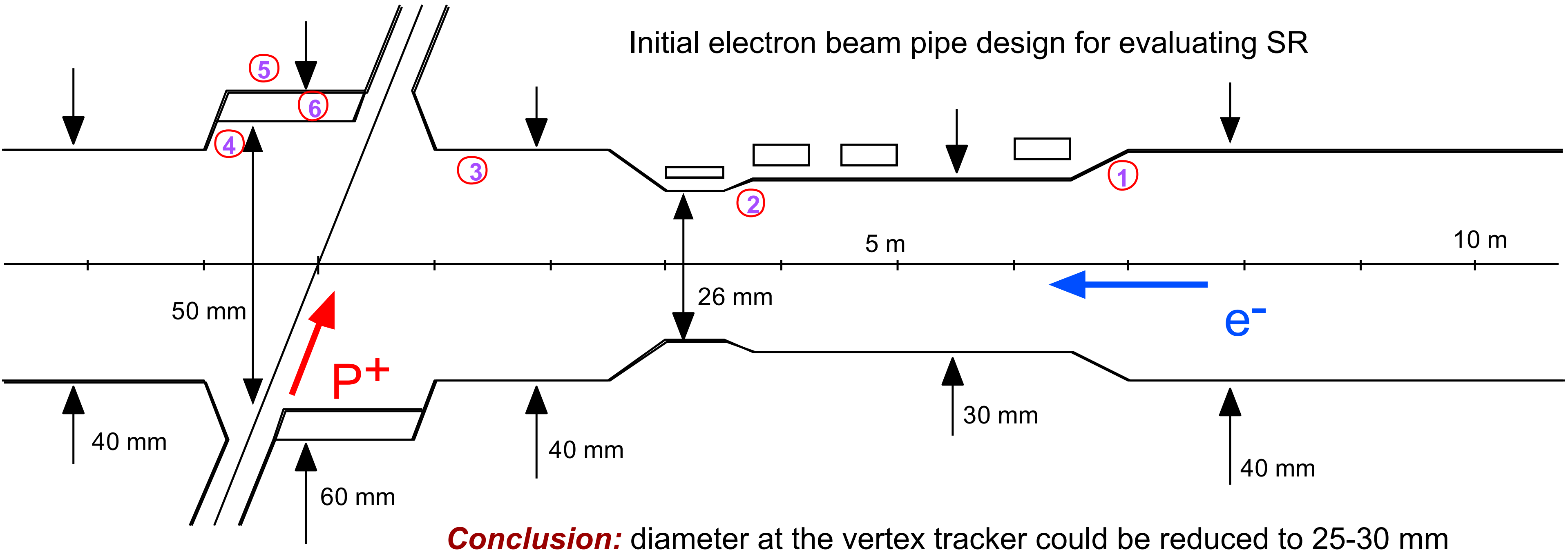


Asynchronous triggering

- The MEIC will use a “smart” asynchronous trigger and pipelined electronics
  - The MEIC L1 rate is expected to be comparable to GlueX (200 kHz)
    - *Low-Q^2 (photoproduction) events will be pre-scaled*
  - Simple tracking at L2 will suppress random background (not from vertex)
    - *Already planned for CLAS12*

- Data-driven, asynchronous triggers are well-established
  - If the number of collisions of interest per bunch crossing is << 1, synchronizing the trigger to each RF clock cycle becomes inefficient
  - Sampling rate requirements for the pipelined electronics depend on signal properties and backgrounds, not the bunch crossing frequency
    - *JLab 12 GeV uses flash ADCs with 250 MHz (4 ns) sampling*
  - When a trigger condition is fulfilled (*e.g.*, e^- found), memory buffers are written to disk or passed to L3 (at PANDA signals will go directly to L3)
  - Correlations with the RF are made offline
  - T0 is obtained from tracking high-β particles (*e.g.*, electrons in CLAS)

Synchrotron radiation background



Conclusion: diameter at the vertex tracker could be reduced to 25-30 mm

Surface:	1	2	3	4	5	6
Power (W) @ 5 GeV	3.0	5.7	0.2	0.8	-	0.03
γ >10 keV @ 5GeV	$5.6x10^5$	$3.4x10^5$	$1.4x10^4$	$5.8x10^4$	167	3,538
Power (W) @ 11 GeV	4.2	8.0	0.3	1.1	-	0.04
γ >10 keV @ 11 GeV	$5.6x10^5$	$2.8x10^5$	$9.0x10^4$	$3.8x10^5$	271	13,323

Photon numbers are per bunch

Simulation by M. Sullivan (SLAC)

Hadronic backgrounds

- Random hadronic background
  - Assumed to be dominated by scattering of beam ions on residual gas (mainly ^2H) in the beam pipe between the ion exit arc and the detector.
  - Correlated background from photoproduction events is discussed separately
- The conditions at the MEIC compare favorably with HERA
  - Typical values of *s* are 4,000 GeV^2 at the MEIC and 100,000 GeV^2 at HERA
  - Distance from arc to detector: 65 m / 120 m = 0.54
  - p-p cross section ratio $\sigma(100\ \text{GeV}) / \sigma(920\ \text{GeV}) < 0.8$
  - Average hadron multiplicity per collision $(4000 / 100000)^{1/4} = 0.45$
  - Proton beam current ratio: 0.5 A / 0.1 A= 5
  - At the *same vacuum* the MEIC background is 0.54 * 0.8 * 0.45 * 5 = 0.97 of HERA
  - But MEIC vacuum should be closer to PEP-II (10^{-9} torr) than HERA (10^{-7} torr)
- The signal-to-background ratio will be even better
  - HERA luminosity reached ~ 5 x 10^{31} cm^{-2}s^{-1}
  - The EIC (and the MEIC in particular) aims to be close to 10^{34} cm^{-2}s^{-1}