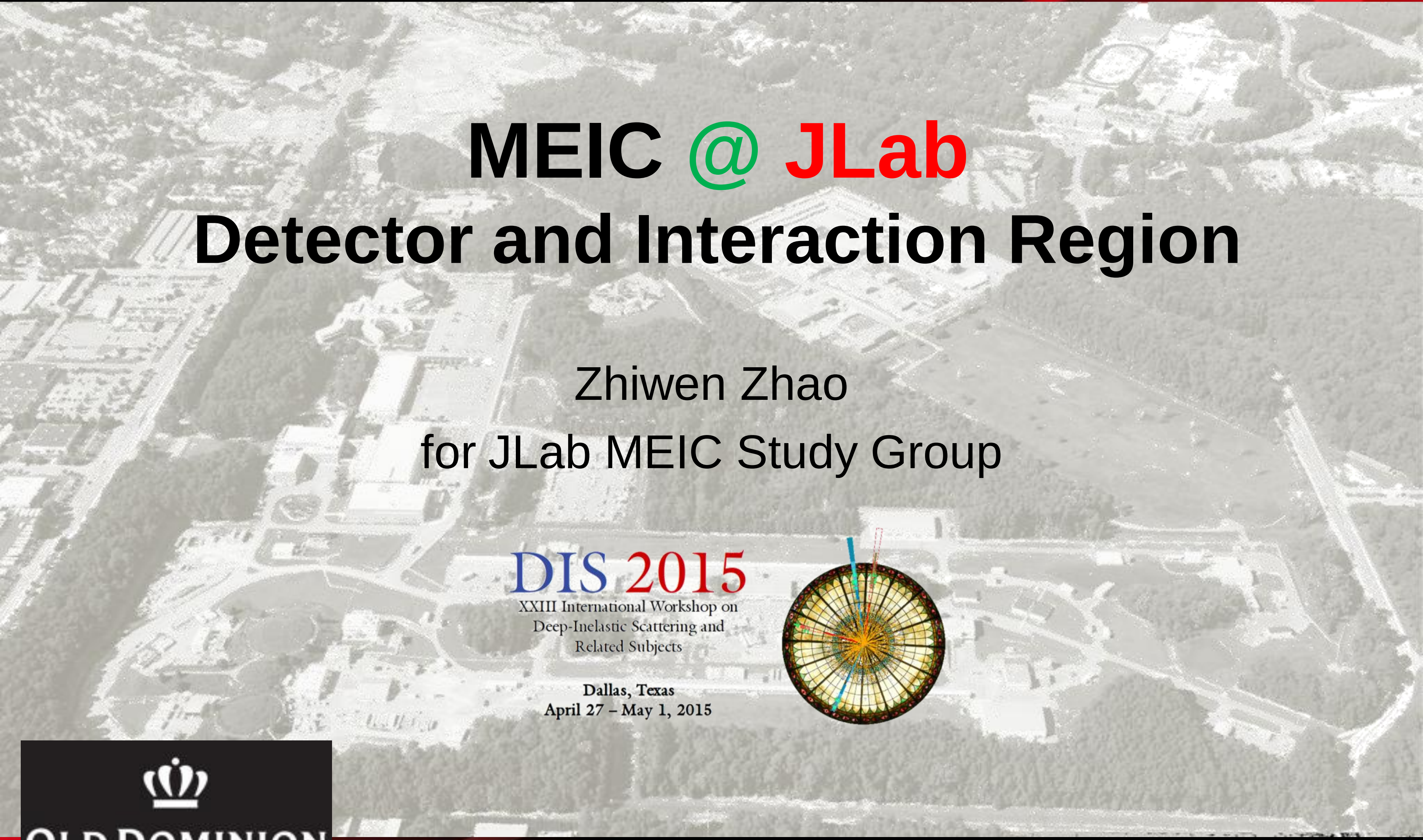


MEIC @ JLab
Detector and Interaction Region

Zhiwen Zhao

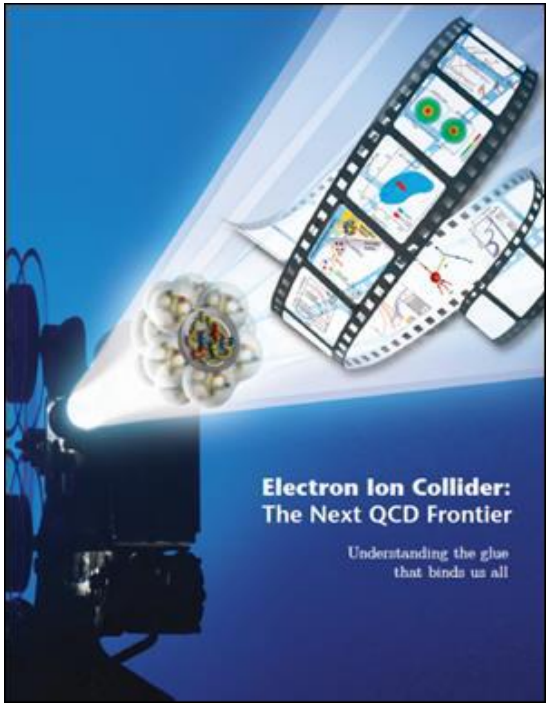
for JLab MEIC Study Group

DIS 2015

XXIII International Workshop on
Deep-Inelastic Scattering and
Related Subjects

Dallas, Texas
April 27 – May 1, 2015

EIC physics program



Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

- 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

- Highly polarized ($\sim 70\%$) electron and nucleon beams
- Ion beams from deuteron to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from ~ 20 – ~ 100 GeV, upgradable to ~ 150 GeV
- High collision luminosity $\sim 10^{33-34}$ cm^{-2}s^{-1}
- Possibilities of having more than one interaction region

MEIC design goals

Energy

Full coverage of $\sqrt{\mathbf{s}}$ from **15** to **65** GeV

Electrons **3-10** GeV, protons **20-100** GeV, ions **12-40** GeV/u

Ion species

Polarized light ions: **p**, **d**, **^{3}He**, and possibly **Li**

Un-polarized light to heavy ions up to A above 200 (Au, Pb)

Space for at least 2 detectors

Full acceptance is critical for the primary detector

High luminosity for the second detector

Luminosity

10^{33} to 10^{34}cm^{-2}s^{-1} per IP in a *broad* CM energy range

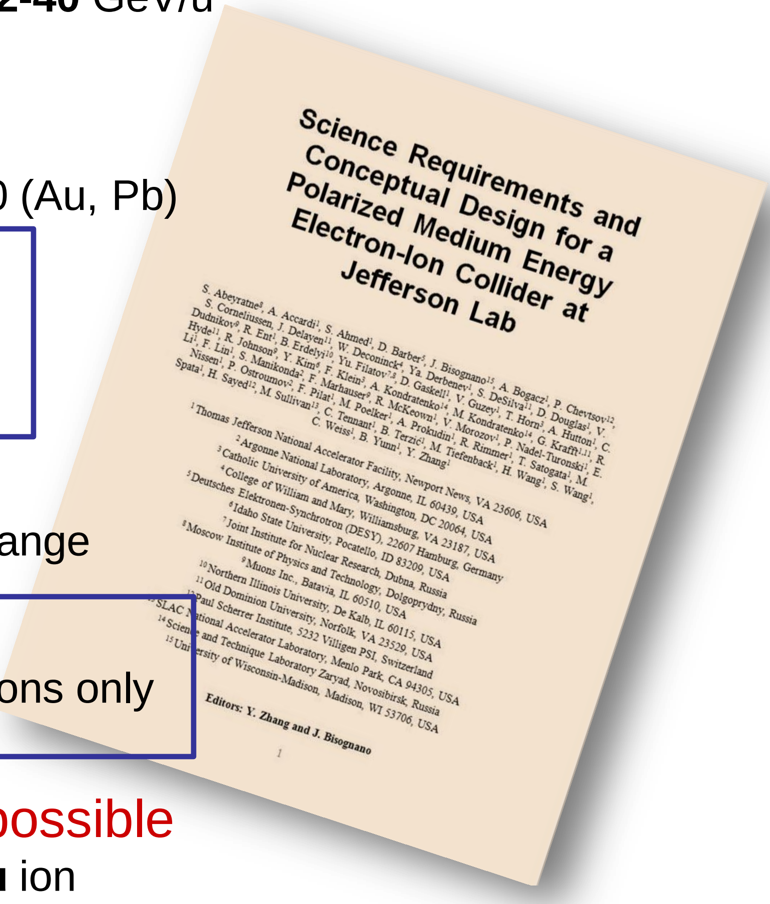
Polarization

At IP: longitudinal for both beams, transverse for ions only

All polarizations >70%

Upgrade to higher energies and luminosity possible

20 GeV electron, **250 GeV** proton, and **100 GeV/u** ion



Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

S. Abeyratne[8], A. Accardi[1], S. Ahmed[1], D. Barber[5], J. Bisognano[15], A. Bogacz[1], P. Chevtsov[12], S. Corneliussen, J. Delayen[11], W. Deconinck[4], Ya. Derbenev[1], S. DeSilva[11], D. Douglas[1], V. Dudnikov[9], R. Ent[1], B. Erdelyi[10], Yu. Filatov[7,8], D. Gaskell[1], V. Guzey[1], T. Horn[3], A. Hutton[1], C. Hyde[11], R. Johnson[9], Y. Kim[6], F. Klein[3], A. Kondratenko[14], M. Kondratenko[14], G. Krafft[1,11], R. Li[1], F. Lin[1], S. Manikonda[2], F. Marhauser[9], R. McKeown[1], V. Morozov[1], P. Nadel-Turonski[1], E. Nissen[1], P. Ostroumov[2], F. Pilat[1], M. Poelker[1], A. Prokudin[1], R. Rimmer[1], T. Satogata[1], M. Spata[1], H. Sayed[12], M. Sullivan[13], C. Tennant[1], B. Terzić[1], M. Tiefenback[1], H. Wang[1], S. Wang[1], C. Weiss[1], B. Yunn[1], Y. Zhang[1]

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[12] Paul Scherrer Institute, 5232 Villigen PSI, Switzerland
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[14] Science and Technique Laboratory Zaryad, Novosibirsk, Russia
[15] University of Wisconsin-Madison, Madison, WI 53706, USA

Editors: Y. Zhang and J. Bisognano

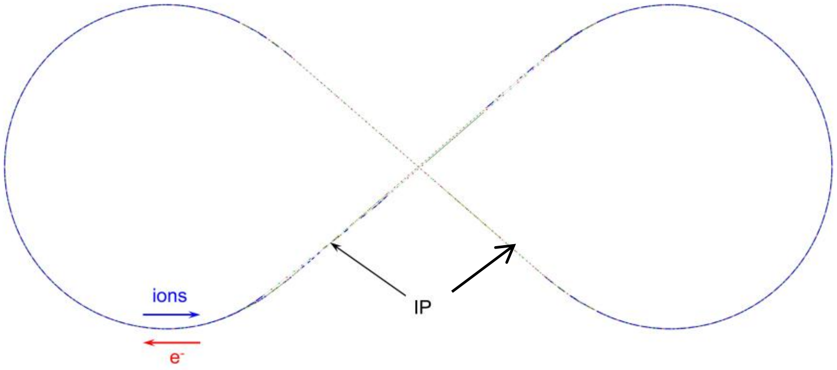
1

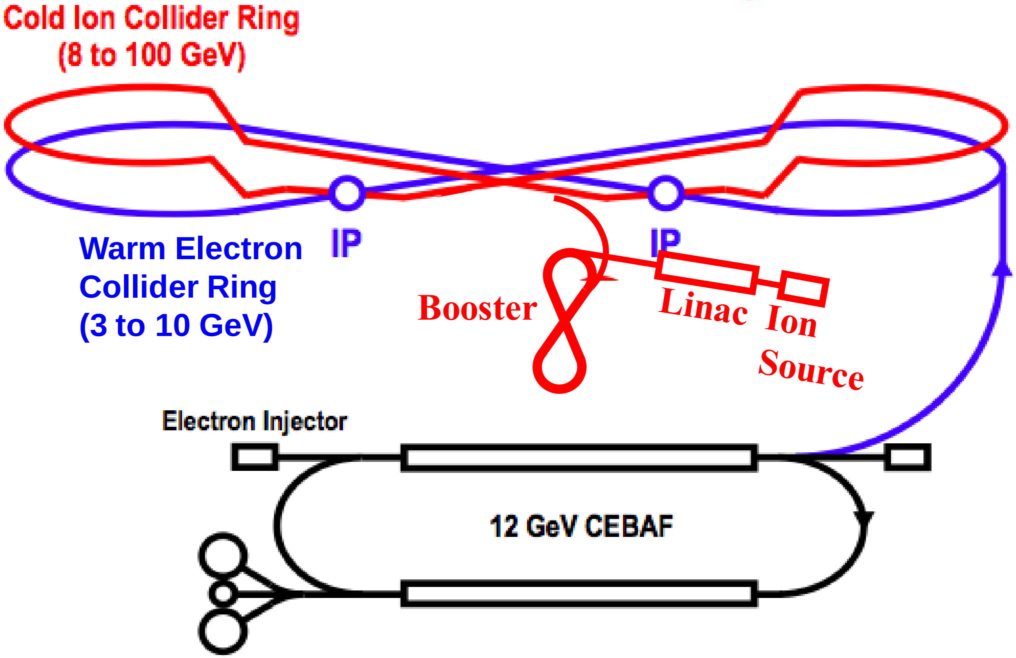
Design goals consistent with the White Paper requirements

MEIC baseline layout

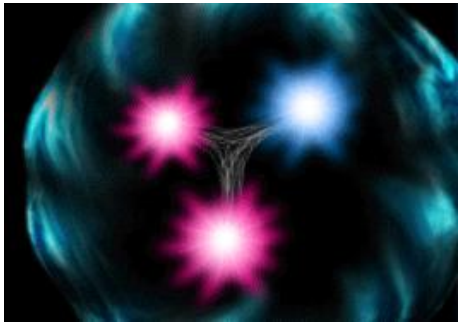
IP Considerations:

- Minimize synchrotron radiation
  - IP far from arc where electrons exit
  - Electron beam bending minimized in the straight before the IP
- Minimize hadronic background
  - IP close to arc where protons/ions exit





Some EIC physics highlights



- 3D structure of nucleons

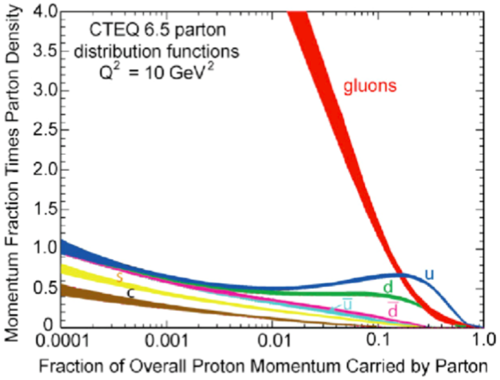
  How do gluons and quarks bind into 3D hadrons?

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

  Why do quarks contribute only ~30%?

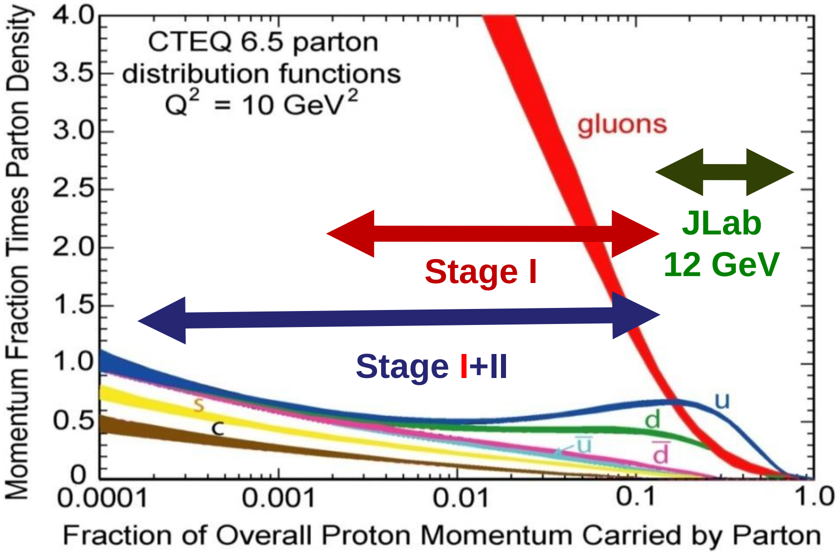
- Gluons in nucleon and nuclei (light and heavy)

  Does the gluon density saturate at small x?

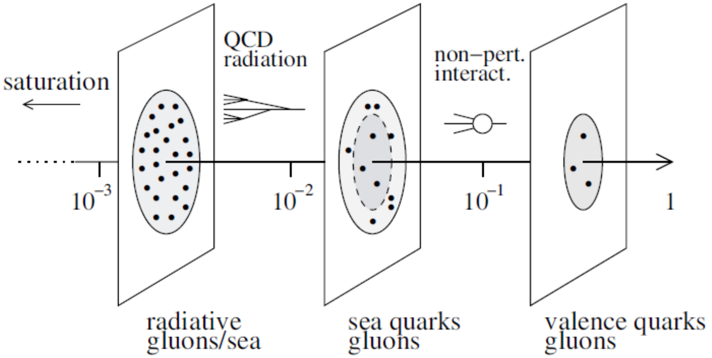


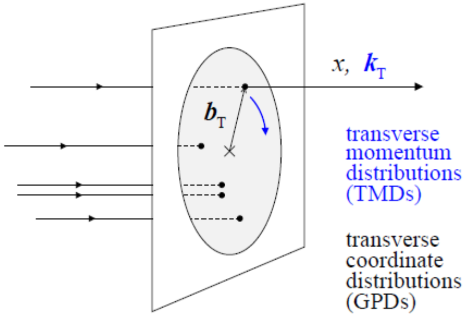
Kinematic coverage of an EIC

- JLab 12 GeV: valence quarks
- EIC stage I (MEIC): non-perturbative sea quarks and gluons
- EIC stage II: extends coverage into radiation-dominated region

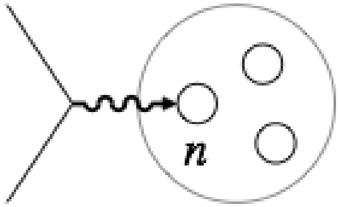


A stage I EIC (Jlab MEIC) covers the x and Q^2 range between JLab 12 GeV and HERA (or a future LHeC)



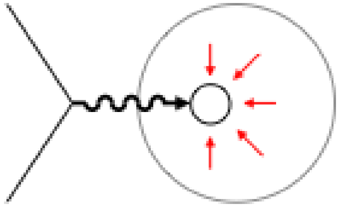


Physics opportunities with light ions



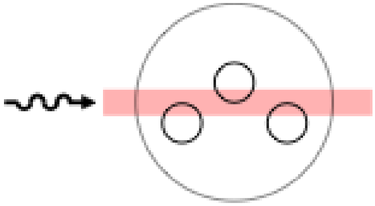
- Neutron structure
  - Flavor decomposition of quark spin, Δg, etc

    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., JLab LDRD-funded project

Experimental considerations

- Spectator tagging requires high-resolution forward hadron spectrometers
  - Large-acceptance magnets required for good p_T coverage (e.g., SRC)

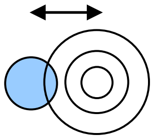
- Inclusive measurements at low x and Q^2 are systematics limited
  - Polarimetry and tagger is essential
  - Radiative corrections and detector coverage important at extreme values of y

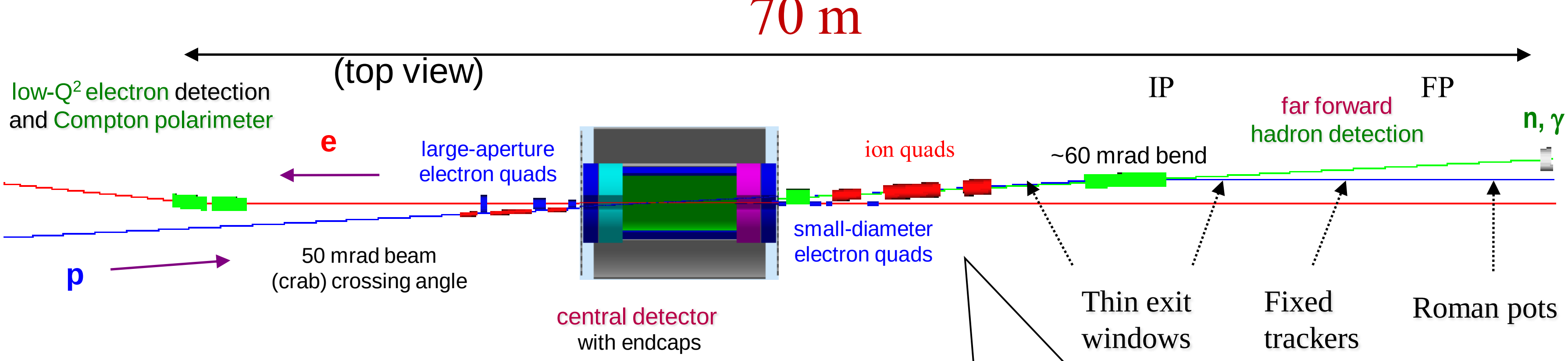
- Exclusive- and semi-inclusive reactions pose a wide range of challenges
  - Drive design of central detector
  - Spectator tagging equally important as for inclusive (e.g., DVCS on neutron)!

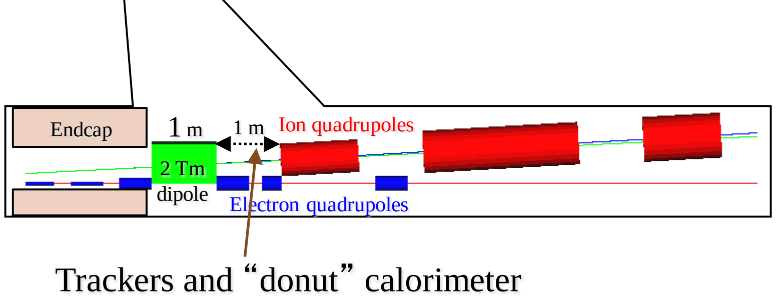
Interaction region

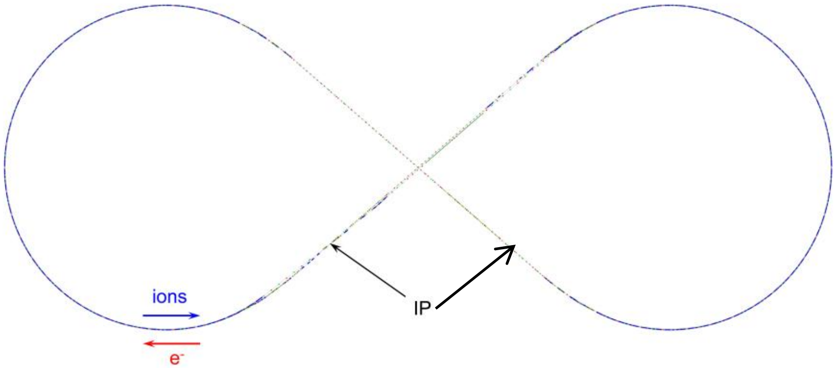
- Fully-integrated detector and interaction region satisfying
  - Detector requirements: full acceptance and high resolution
  - Beam dynamics requirements: consistent with non-linear dynamics requirements
  - Geometric constraints: matched collider ring footprints

50mrad Crossing Angle



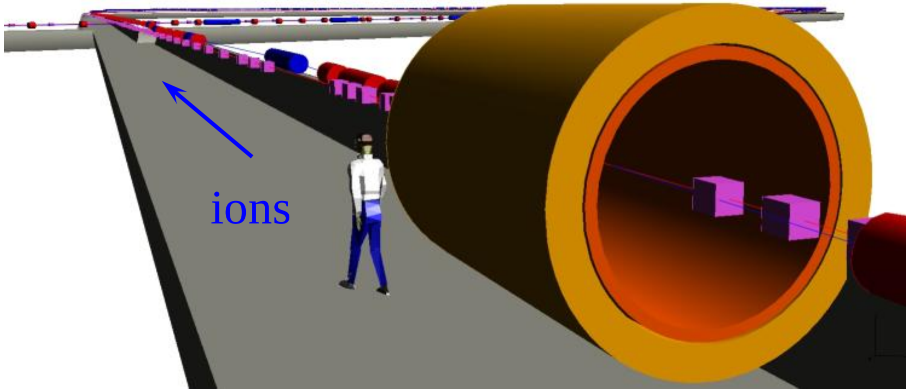


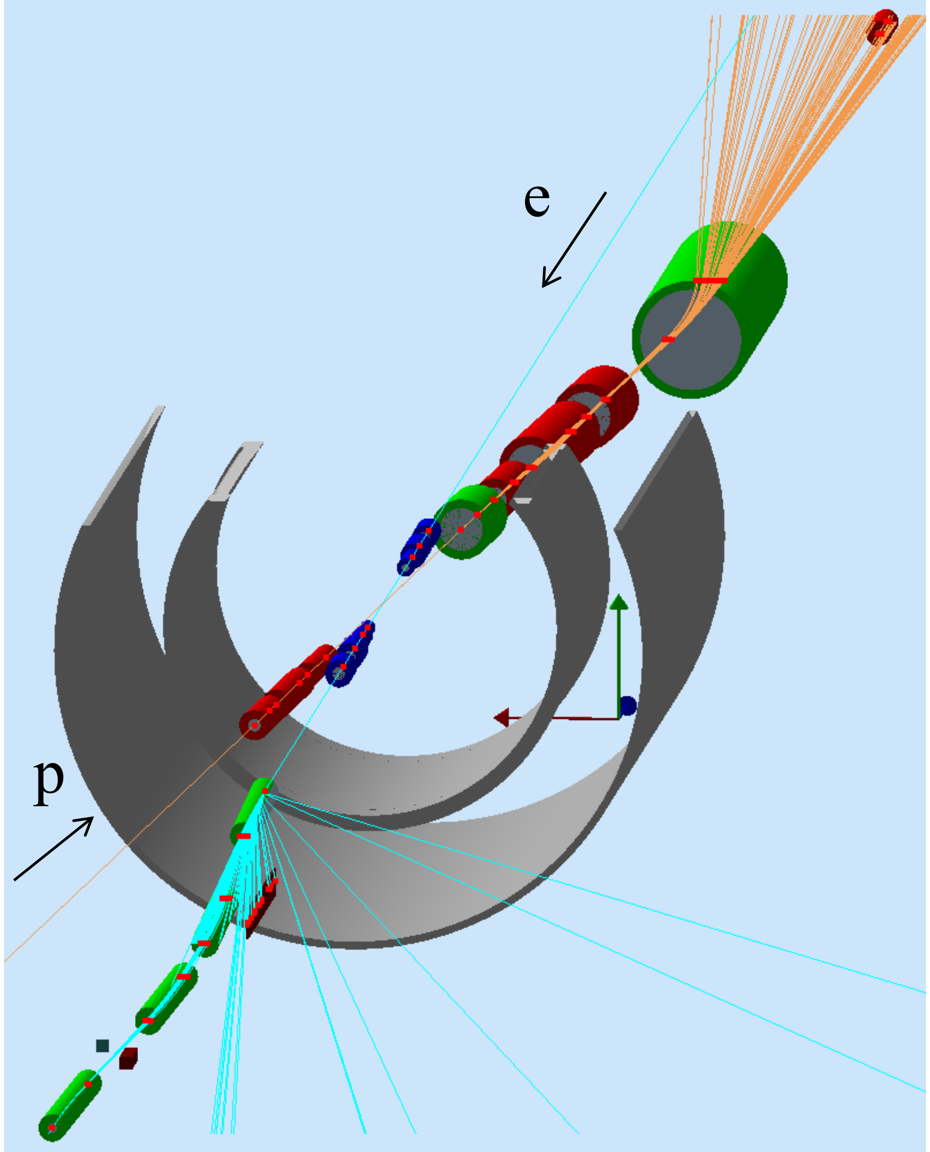




Interaction region

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

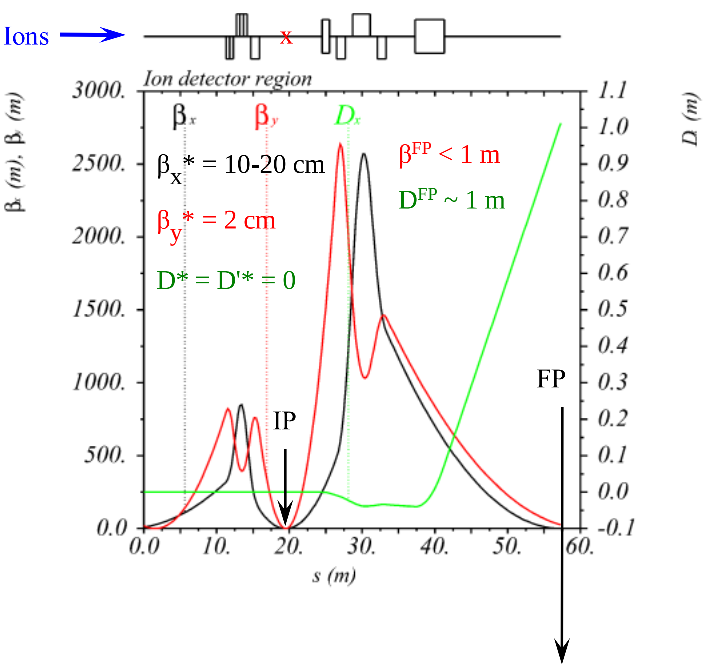


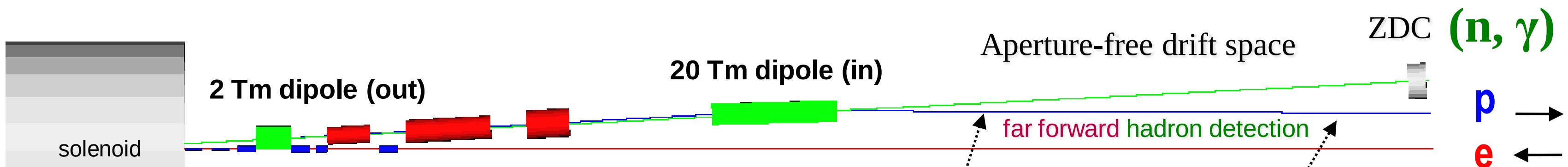


Far-Forward Hadron Detection

- Good acceptance for ion fragments
  - Large downstream magnet apertures/ small downstream magnet gradients
- Good acceptance for low-p_T recoil baryons
  - Small beam size at second focus
  - Large dispersion
- Good momentum and angular resolution
  - Large dispersion
  - No contribution from D′ to angular spread at IP
  - Long instrumented magnet-free drift space
- Sufficient separation between the beam lines

Asymmetric IR (minimizes chromaticity)





2 Tm dipole (out)

20 Tm dipole (in)

Aperture-free drift space

far forward hadron detection

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

Spectator protons (exit windows)

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

50 mrad crossing angle (Belle II: 83 mrad)

Spectator angle after dipole is 75 mrad with respect to beam

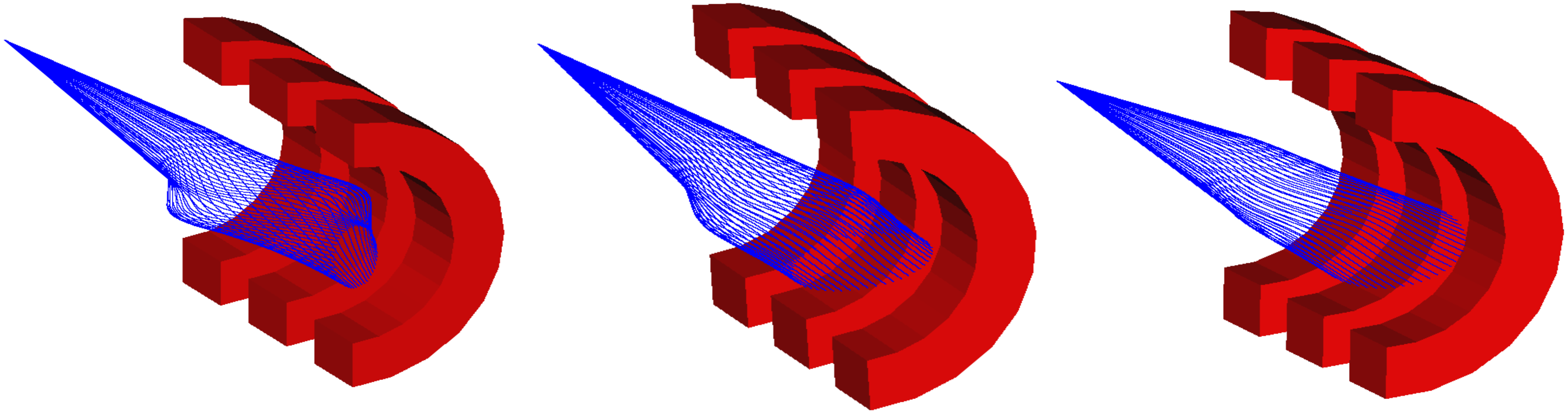
Far-Forward Hadron Detection

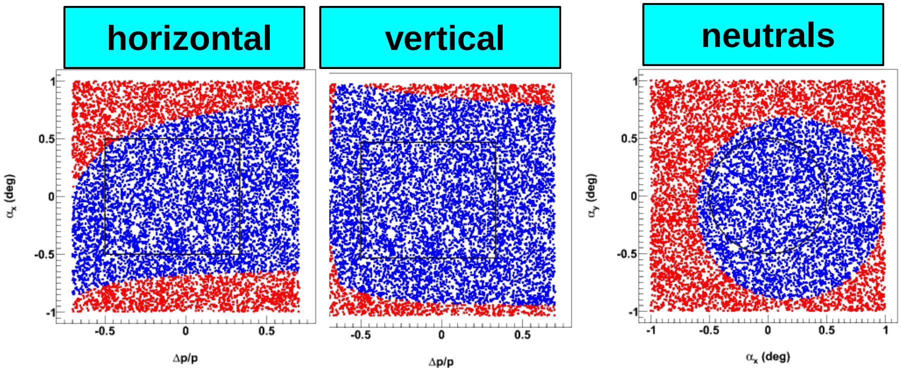
(proton rich fragments) ⟵ ⟶ (neutron rich fragments)

$\Delta p/p = -0.5$
(spectator protons from deuterium)

$\Delta p/p = 0.0$
(exclusive / diffractive recoil protons)

$\Delta p/p = 0.5$
(tritons from N=Z nuclei)



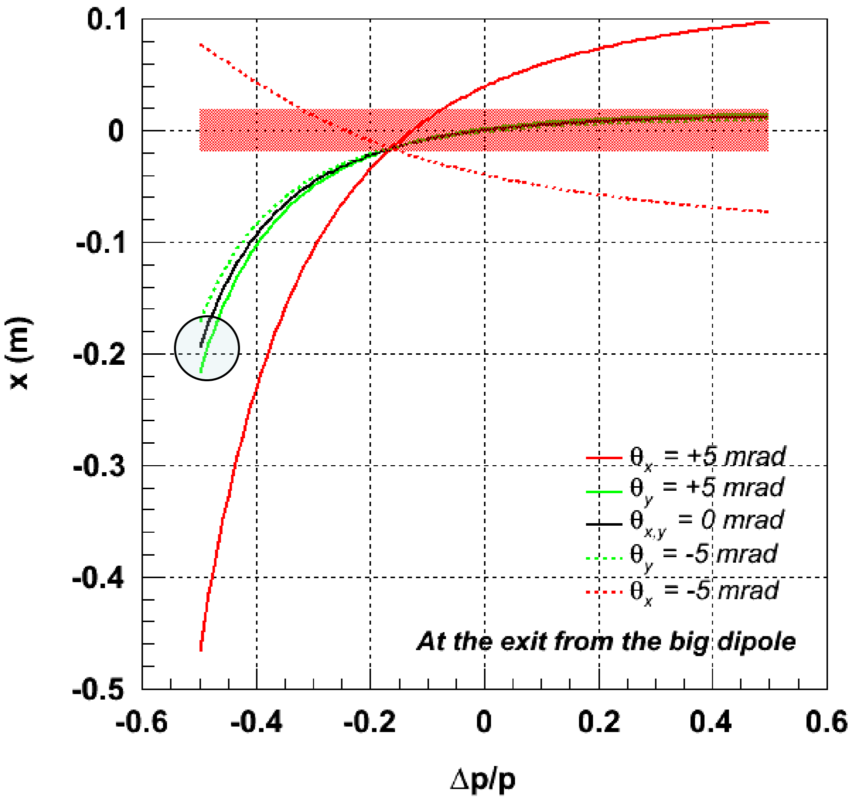


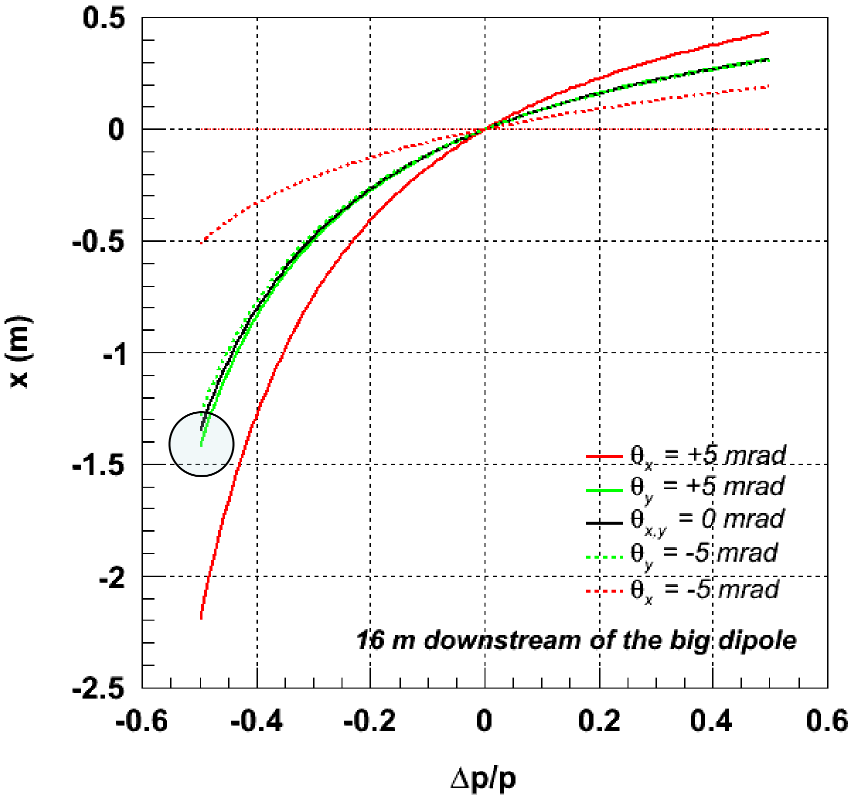
Red: detected *before* ion quadrupoles

Blue: detected *after* ion quadrupoles

Spectator protons from d: dp/p ~ -0.5

Spectator angles *after* dipole

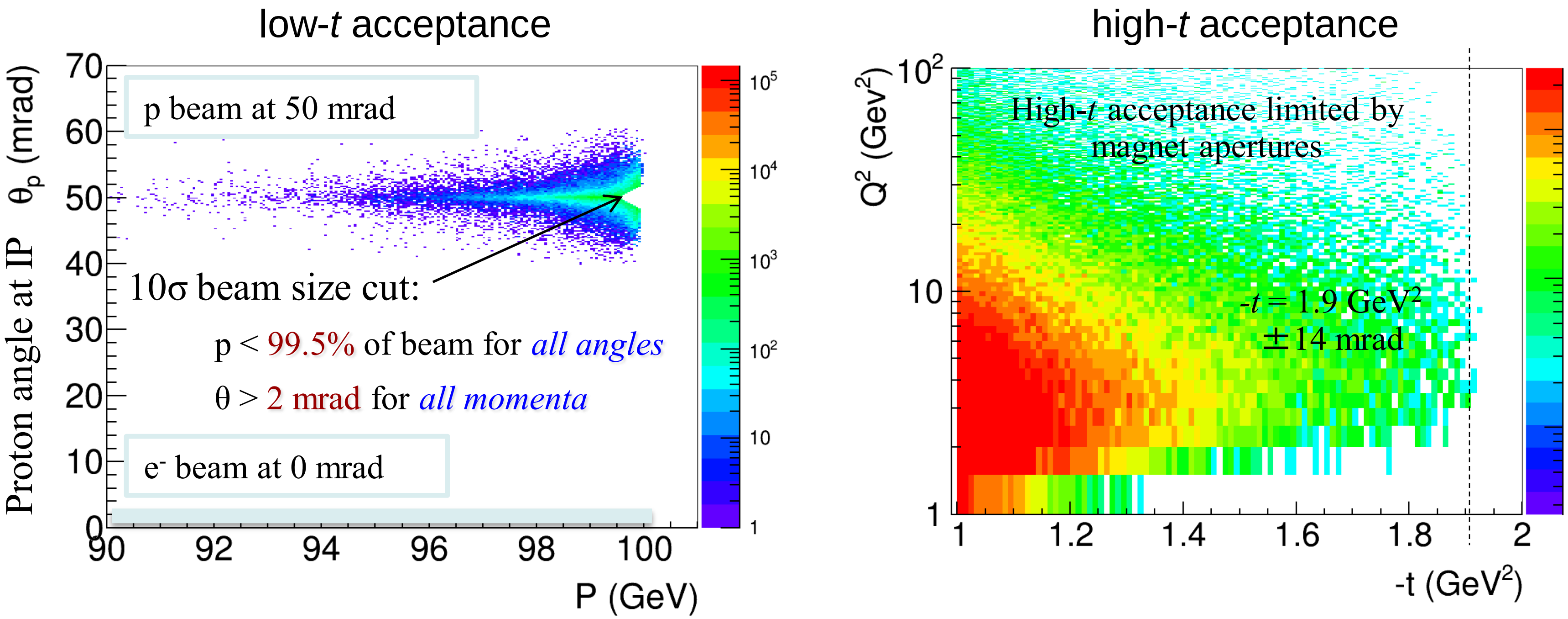




- True spectator fragments have very small scattering angles at the IP (black curve)
- Spectator protons from deuterium have $\Delta p/p = -0.5$
- After passing the large bending dipole, the spectator angle with respect to the ion beam is large
- The angle in the magnet-free drift section after the dipole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

DVCS recoil proton acceptance

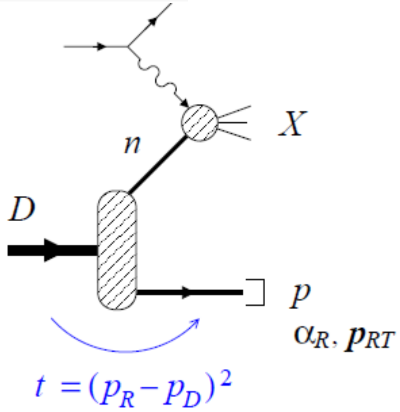
- **Kinematics:** 5 GeV e$^-$ on 100 GeV p at a crossing angle of 50 mrad.
  - Cuts: $Q^2 > 1$ GeV^2, $x < 0.1$, $E'_e > 1$ GeV, recoil proton 10σ outside of beam
- **DVCS generator:** MILOU (from HERA, courtesy of BNL)
- **GEANT4 simulation:** tracking through all magnets done using the JLab GEMC package


low-*t* acceptance

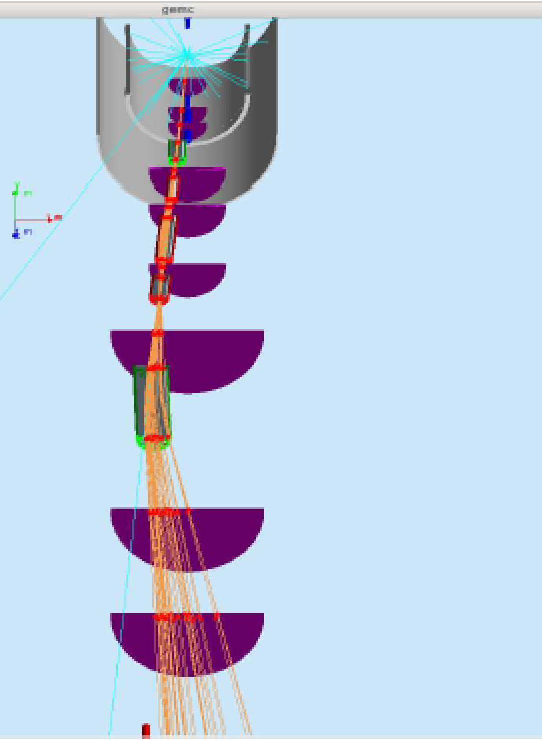
high-*t* acceptance

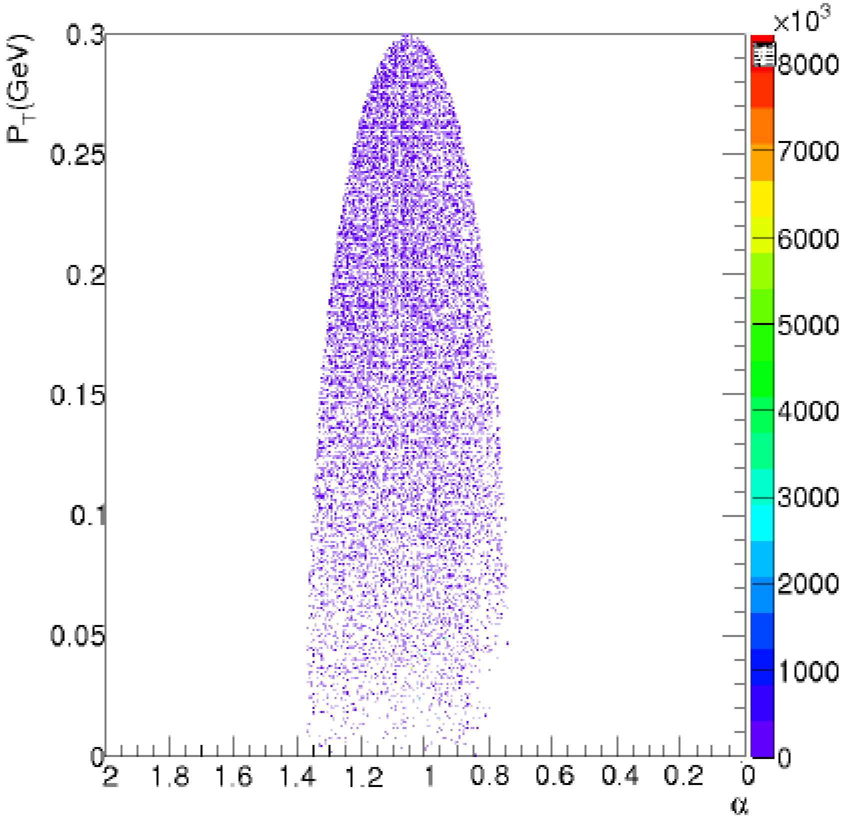
- Recoil proton angle is independent of electron beam energy: $\theta_p \approx p_T/E_p \approx \sqrt{(-t)}/E_p$
- A wider angular distribution at lower energies makes precise tracking easier

Deuteron Spectator Tagging



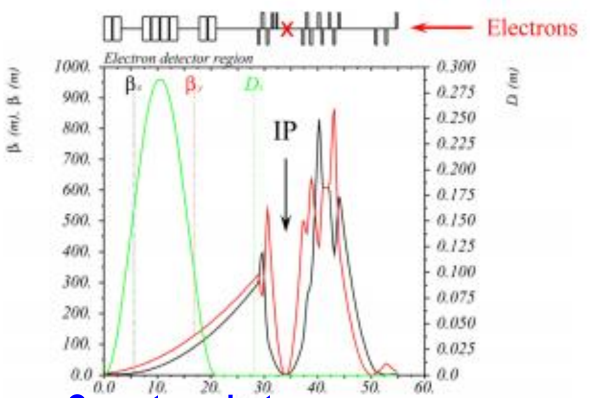
$$\alpha_R = 2\frac{E_R + p_R^z}{M_D}$$

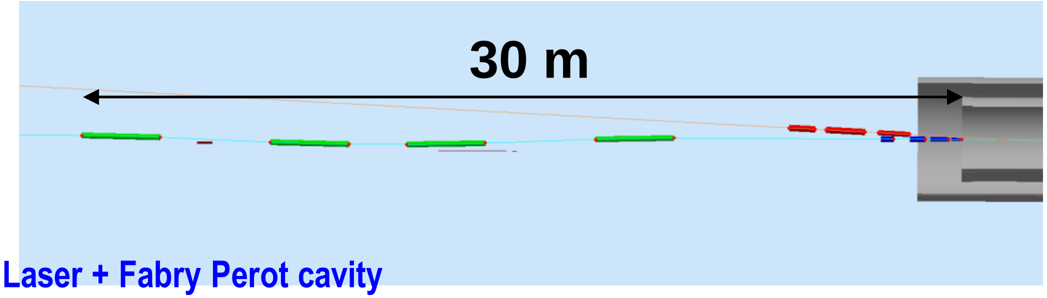


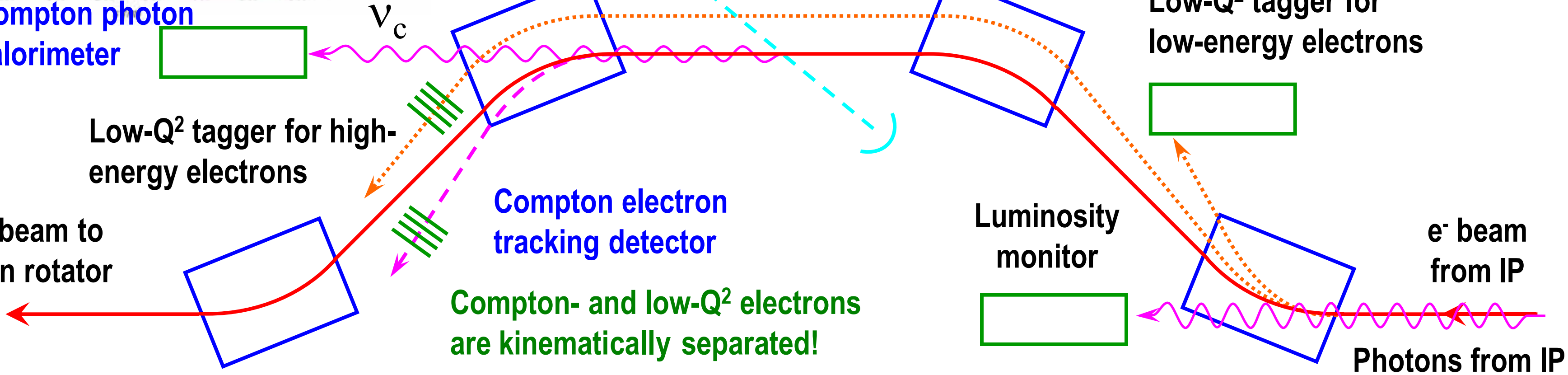


- Left: MEIC beam-line with spectator proton (red rays) and scattered electrons (blue rays), Right: Acceptance as function of p_T, α_R at the exit of the second dipole. Acceptance drops at smaller α_R and p_T due to the second dipole geometry. Note that α_R goes the same way with bending spectator proton at the second dipole.

Polarimeters and low-Q^2 tagger







Laser + Fabry Perot cavity

Compton photon calorimeter

Low-Q^2 tagger for low-energy electrons

Low-Q^2 tagger for high-energy electrons

e$^-$ beam to spin rotator

Compton electron tracking detector

Luminosity monitor

e$^-$ beam from IP

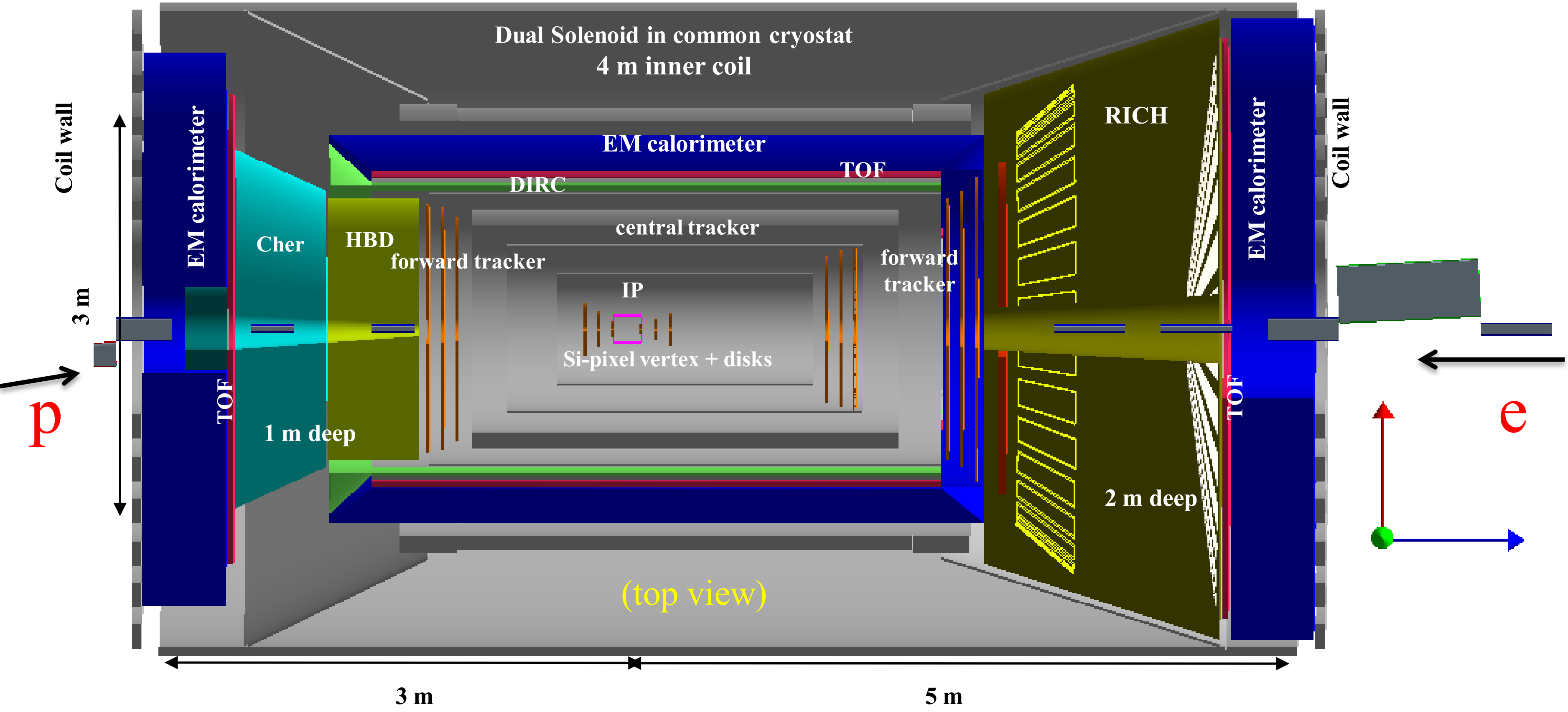
Compton- and low-Q^2 electrons are kinematically separated!

Photons from IP

- 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 0.5 -1 %

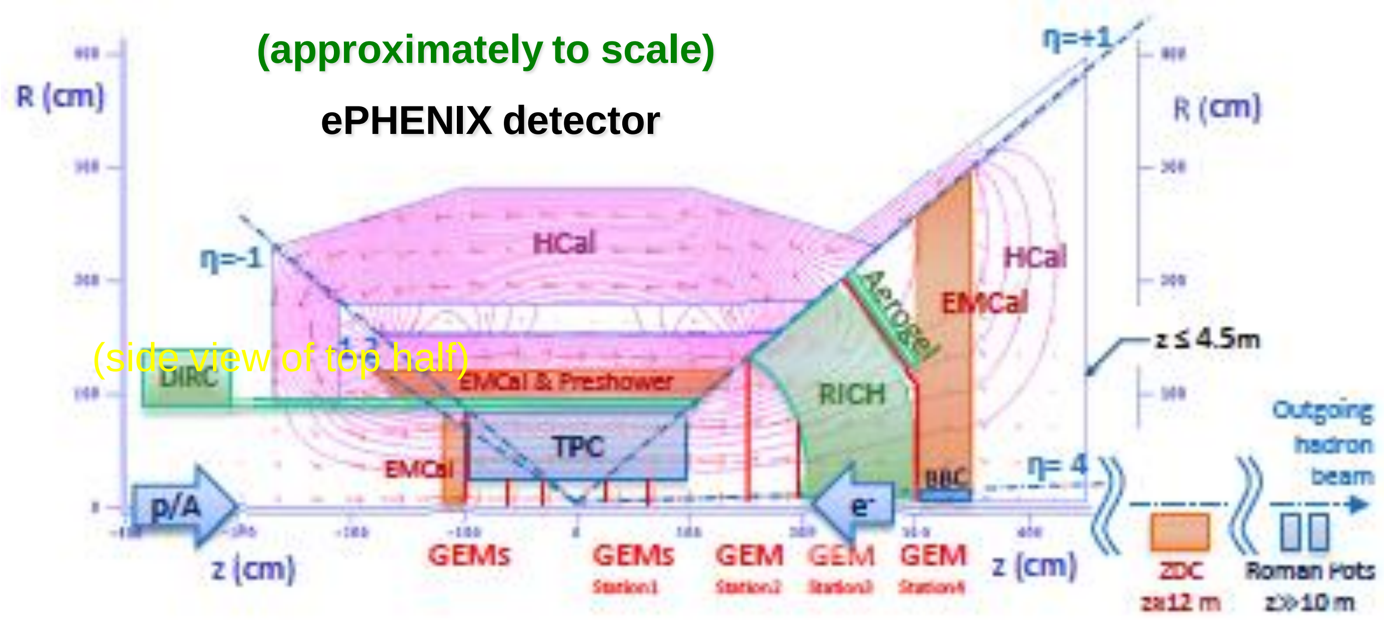
Full-acceptance Central Detector

- Dual Solenoid Magnet, inner size similar to CLEO/BaBar magnet
- Various detector concepts under development
- Possible to add hadron calorimeter outside



High luminosity central detector

- MEIC IP1 (full-acceptancen central detector)
  - Focus on exclusive processes and semi-inclusive DIS
  - Several solenoid options available
- ePHENIX
  - Focus on jet-physics
  - Possible to move ePHENIX to MEIC IP2 ?

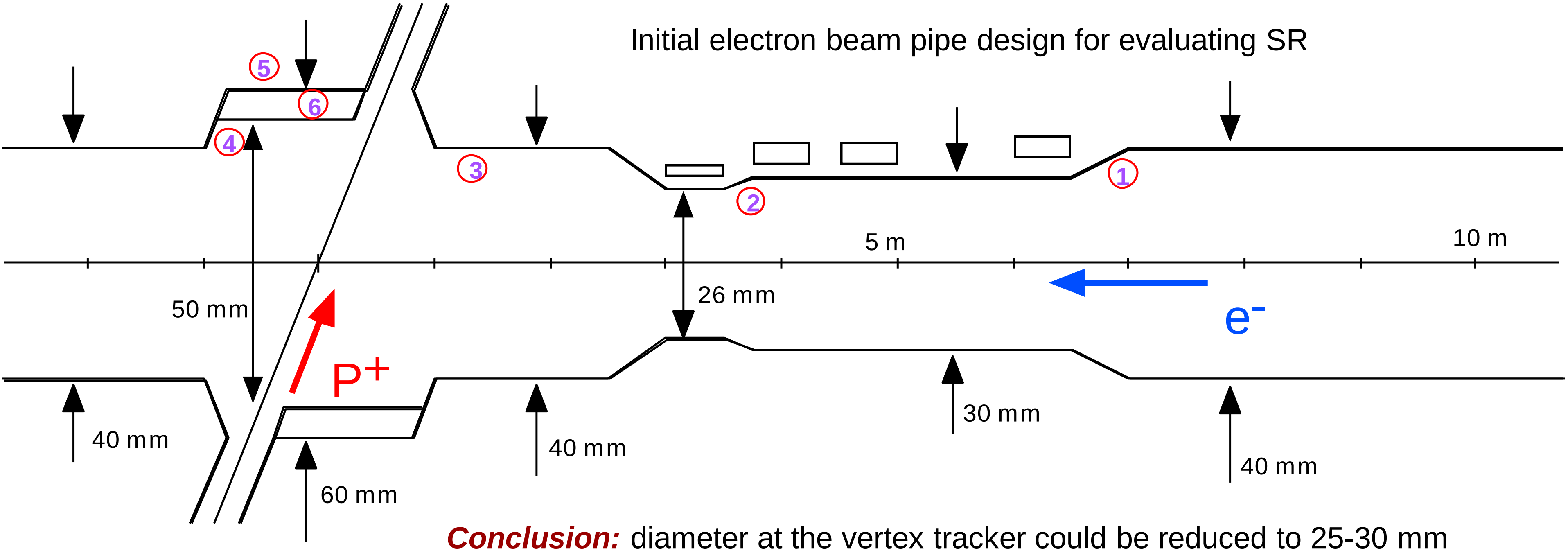


(approximately to scale)

ePHENIX detector

(side view of top half)

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 ^{2}H) 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 σ(100 GeV) / σ(920 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}

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
  - The bunch spacing of MEIC ~2ns (476MHz),close to CEBAF and similar to most e^+e^- colliders
  - 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)

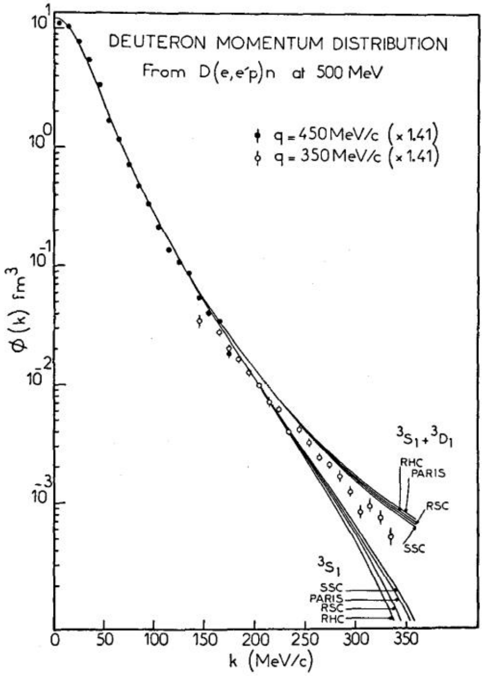
Summary

- EIC is the next-generation US QCD facility
- MEIC baseline design fulfills the white paper requirements
- MEIC detector and interaction region are in a coherent design
- MEIC detectors offer wide opportunities for various inclusive, semi-inclusive and exclusive measurements to fulfill physics goals of EIC
- R&D continues with increasing effort.

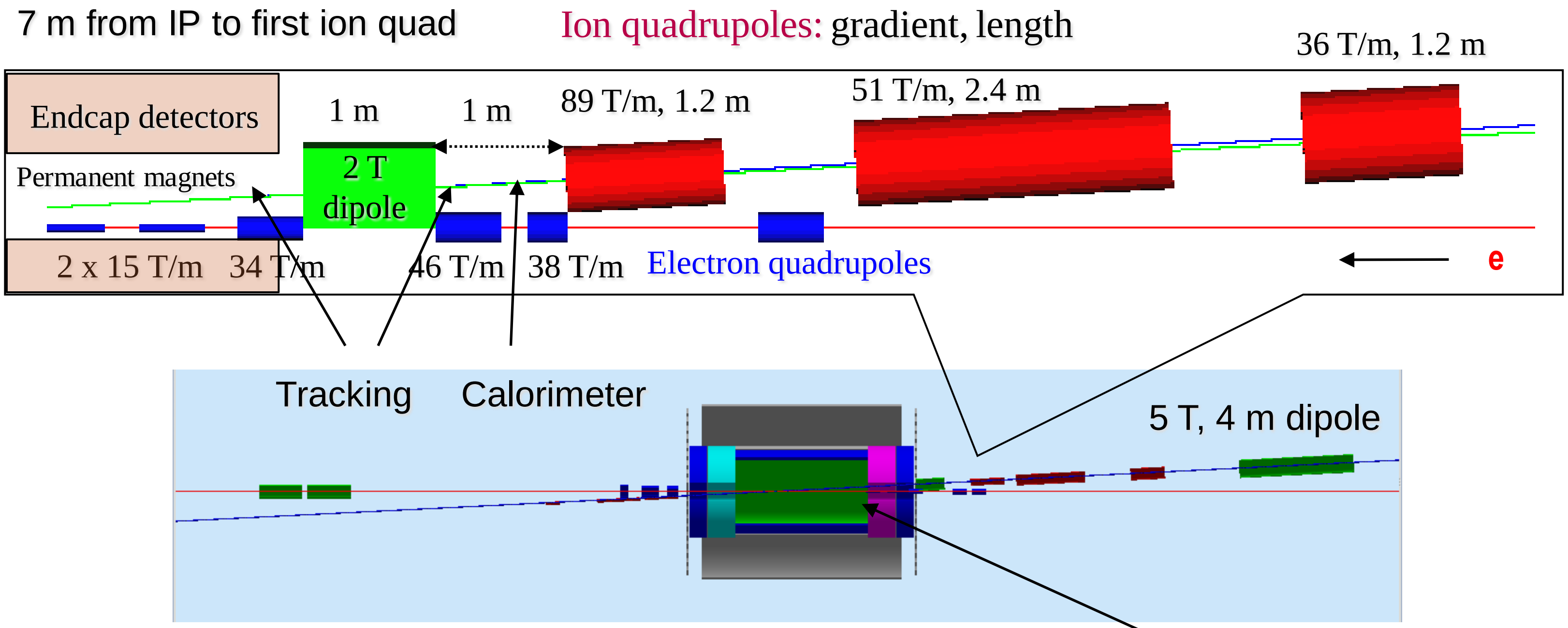
Backup

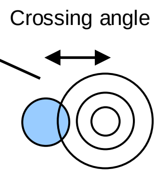
Forward detection – processes

- 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)



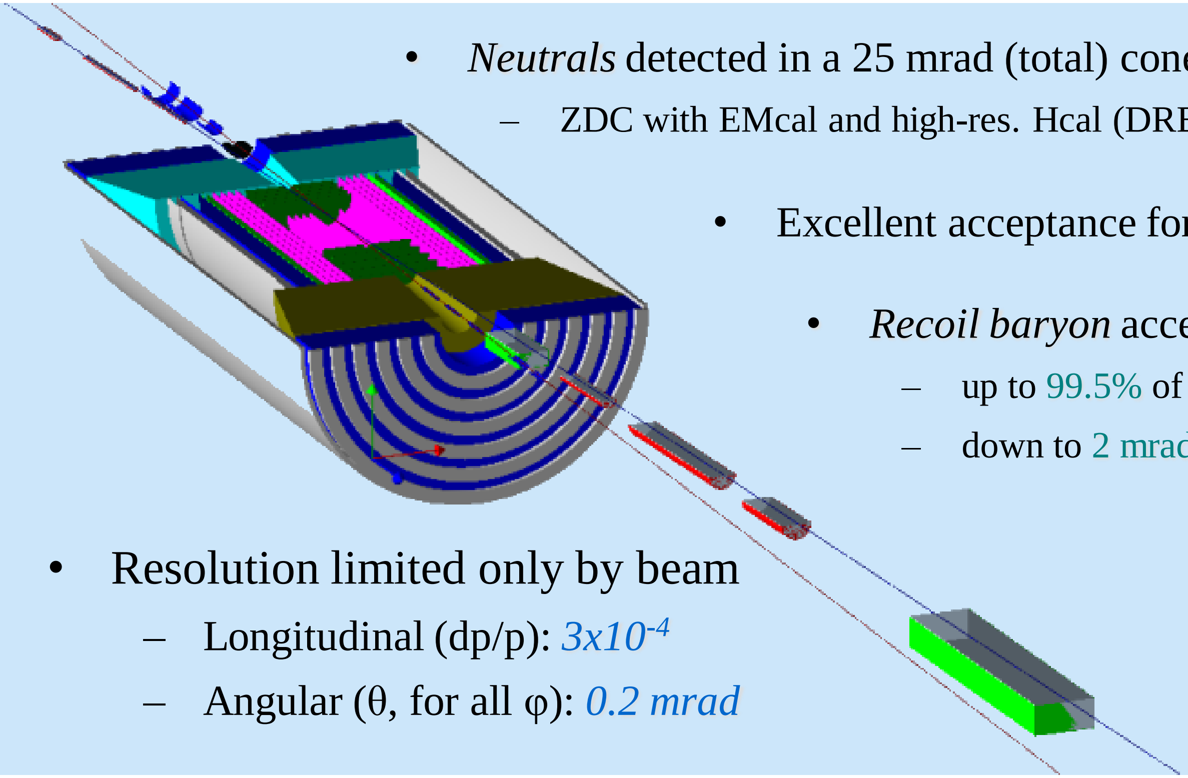
Forward detection *before* ion quads



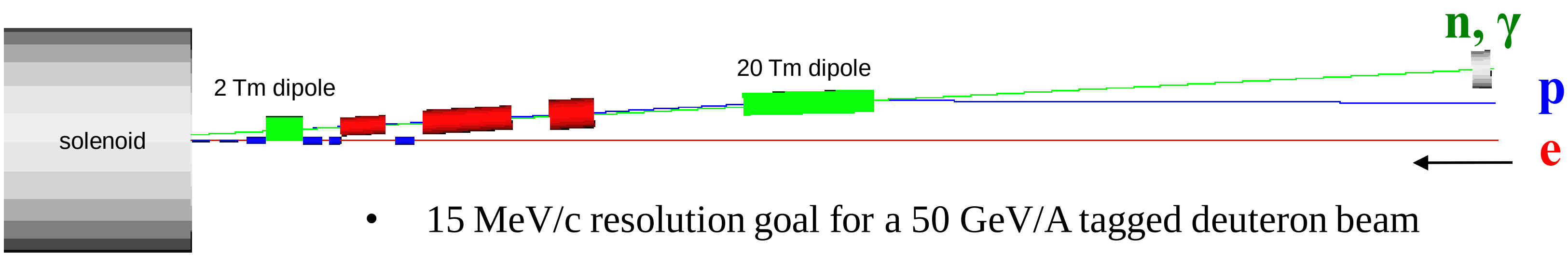


- 50 mrad crossing angle
  - Moves spot of poor resolution along solenoid axis into the periphery
  - Minimizes shadow from electron FFQs
- Dipole before quadrupoles further improves resolution in the few-degree range
- Low-gradient quadrupoles allow large apertures for detection of *all* ion fragments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

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

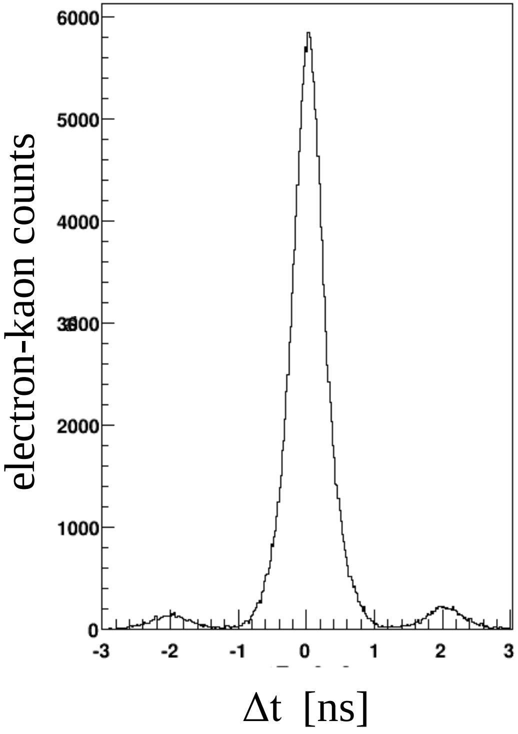
- Detectors (CLAS, BaBar, etc) at machines with high bunch crossing rates have not had problems in associating particle tracks with a specific bunch.
  - Having more bunches lowers the average number of collisions per crossing

- 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

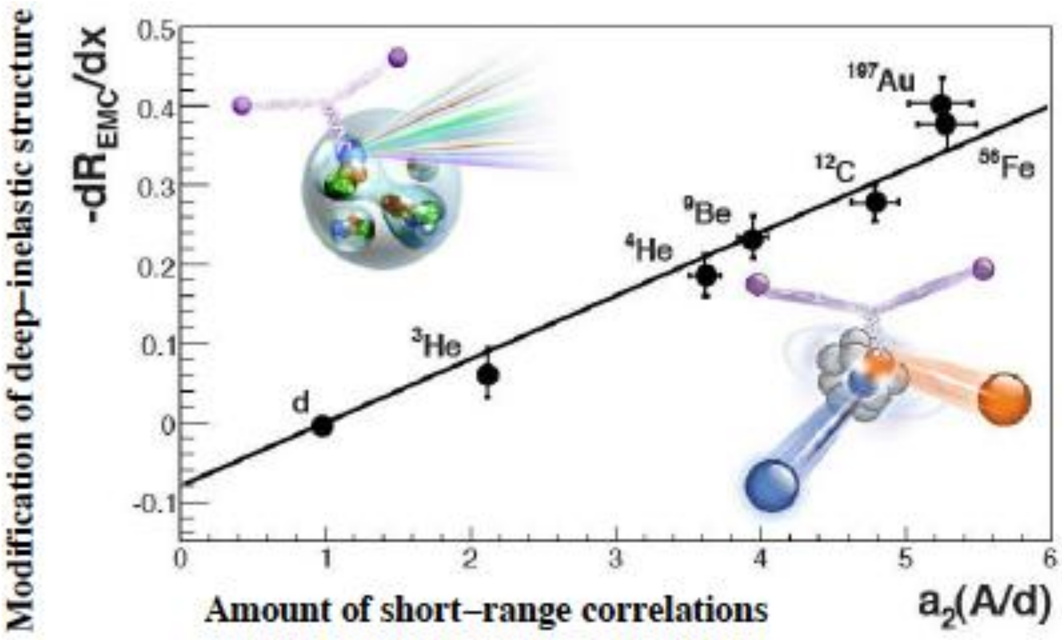
    The 2 ns bunch structure is clearly resolved
  - CLAS12 aims at a TOF resolution of 80 ps

- 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



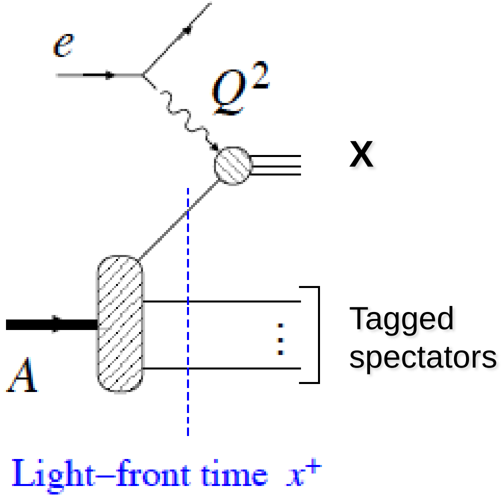
In-medium nucleon



- EMC effect and Short-Range Correlations

- 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)

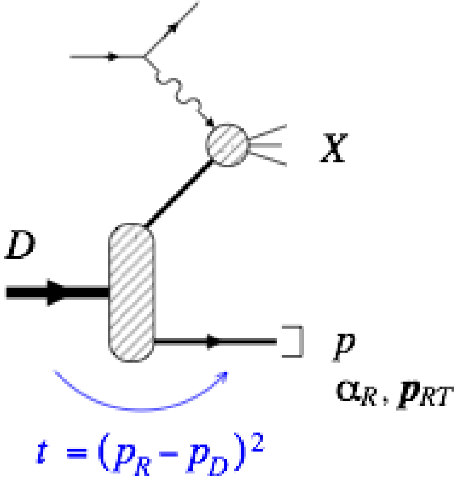
Measuring neutron structure



- 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

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



- Simplest case: tagged DIS on neutron
  - Recoil-proton light-cone momentum

$$\alpha_R = (E_R + p_{R||})/(E_D + p_{D||}) \text{ and } \mathbf{p}_{RT}$$

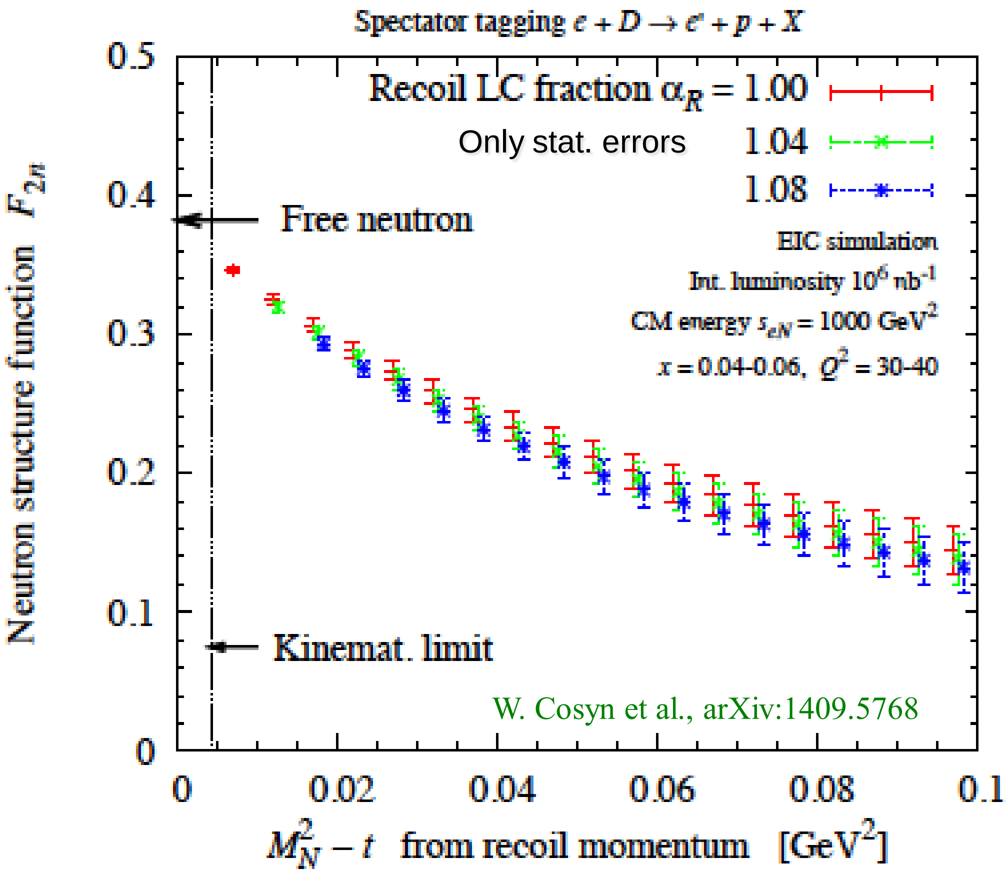
  - Cross section in impulse approximation

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

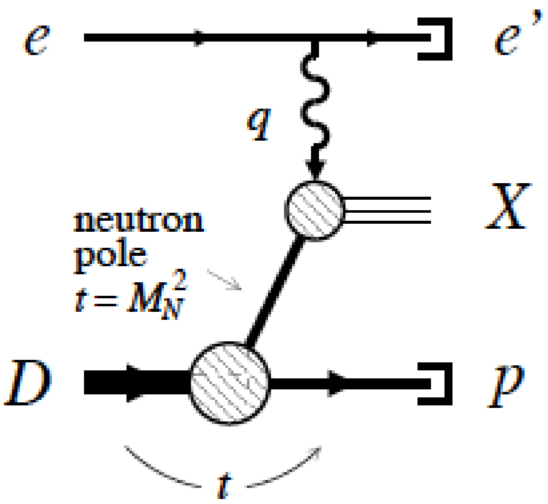
Deuteron LCWF Neutron SF

Frankfurt, Strikman 1981

On-shell extrapolation t ➔ M_N



W. Cosyn et al., arXiv:1409.5768



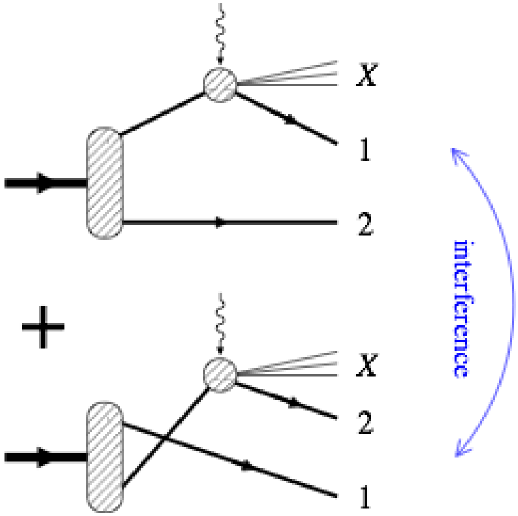
- Free neutron at pole
  - Pole value not affected by final-state interactions

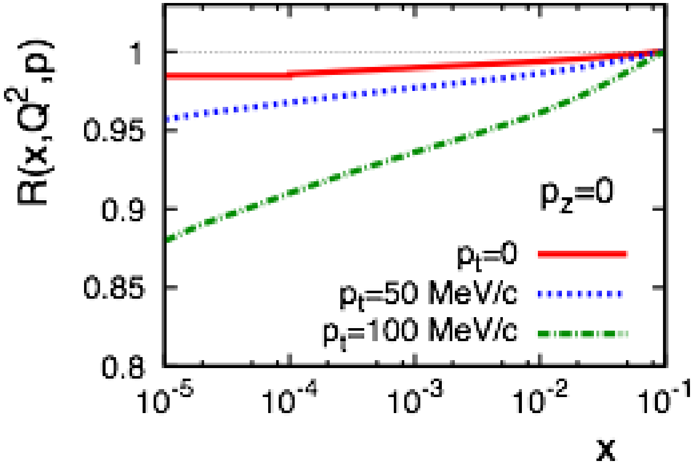
Sargsian, Strikman 2005: no-loop theorem

➔ 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, Guzery, Strikman 2011

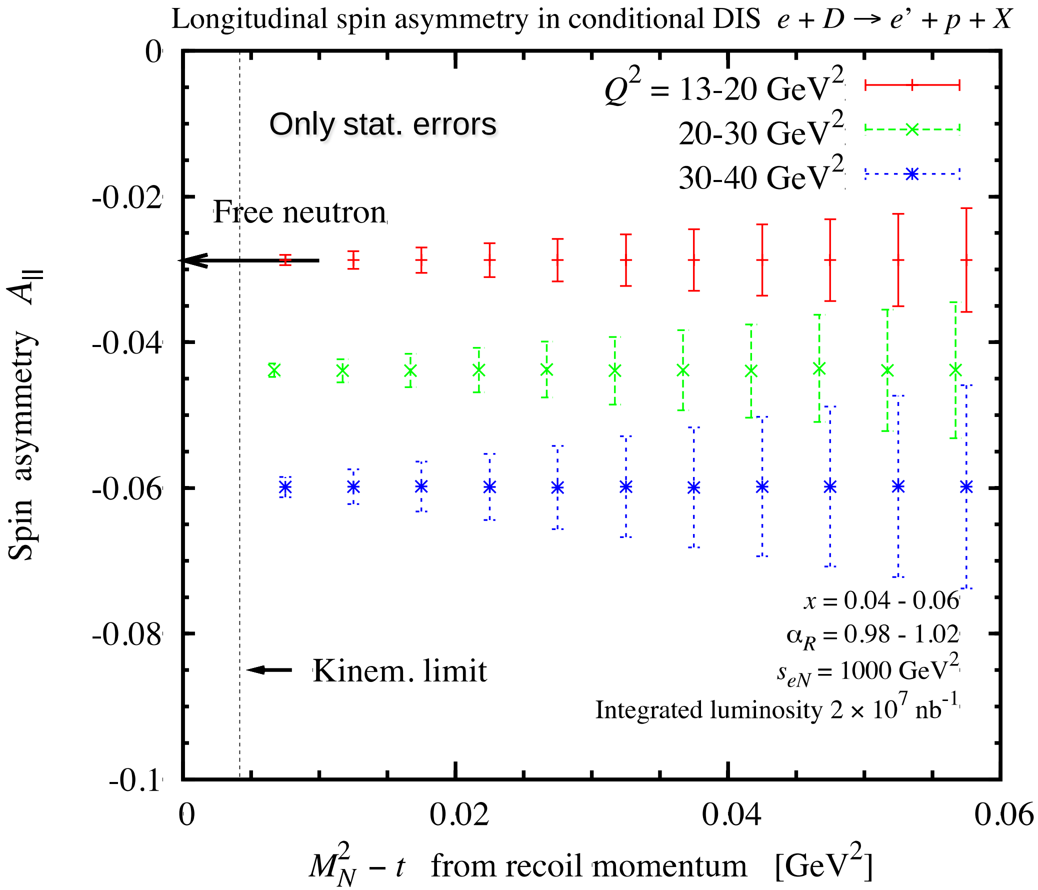
Polarized structure functions

- 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 $A_{||}$

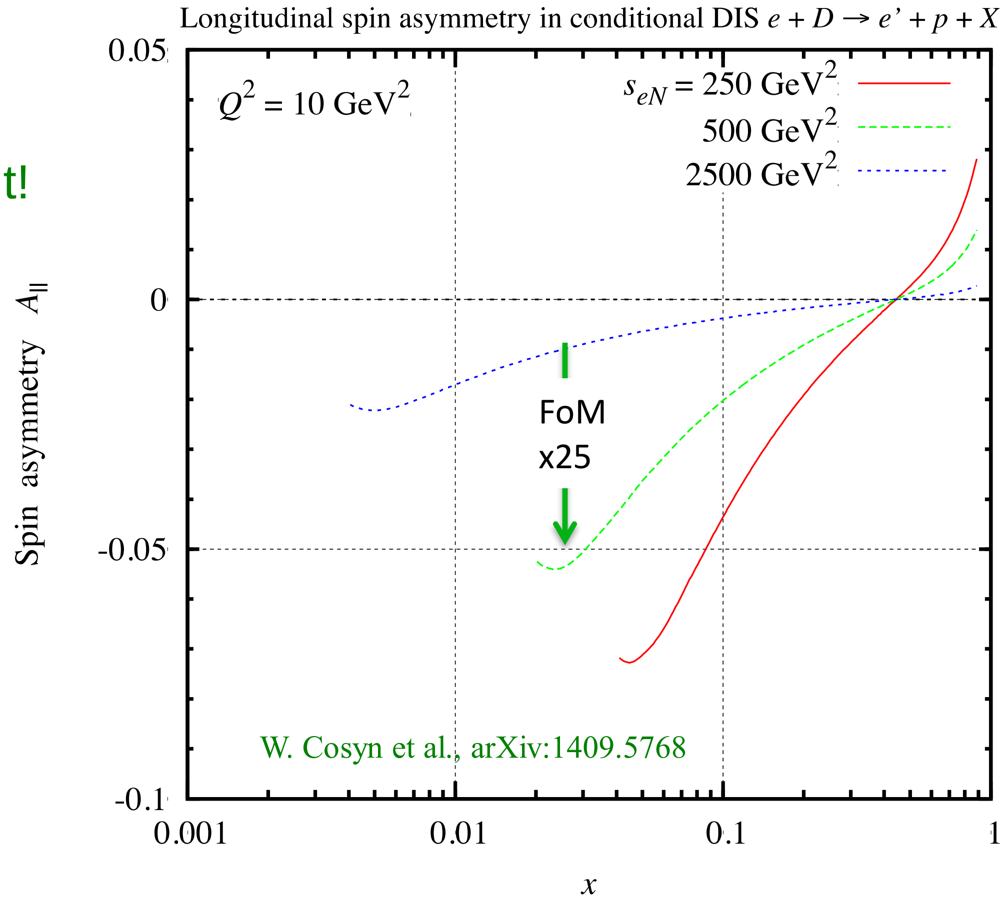
- At fixed x and Q^2, a lower cm-energy *s* increases the asymmetry
  - $A_{||}$ can be large compared with systematic uncertainties from polarimetry
- FoM ~ event rate x $(P_e P_D A_{||})^2$
- Good low-*s* performance important!

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

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

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

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

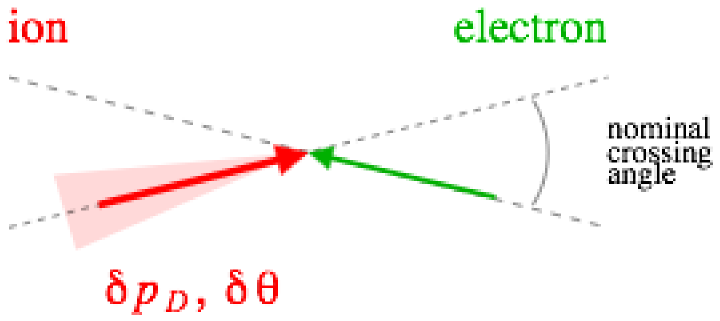


FoM x25

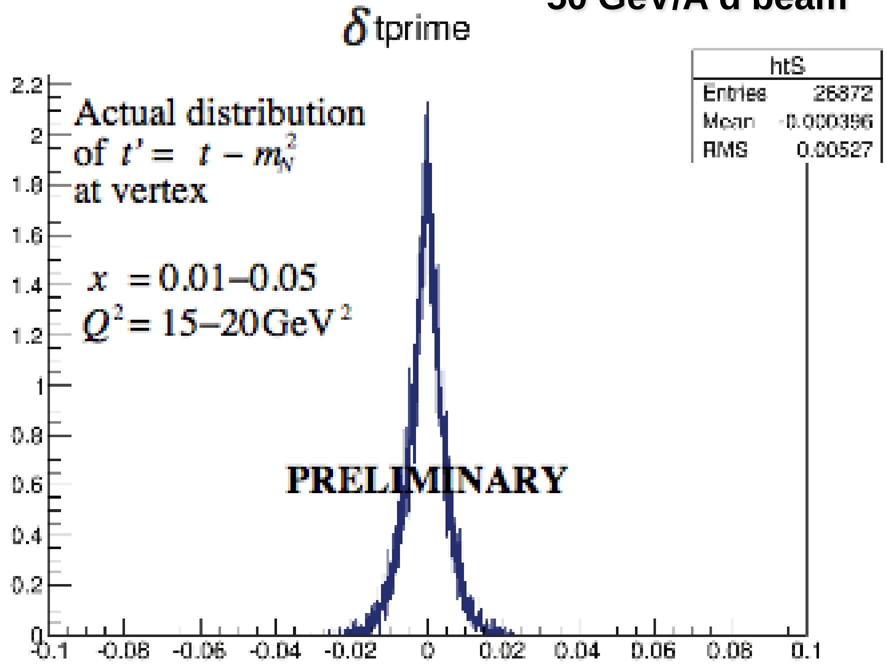
W. Cosyn et al., arXiv:1409.5768

Uncertainty in spectator momentum

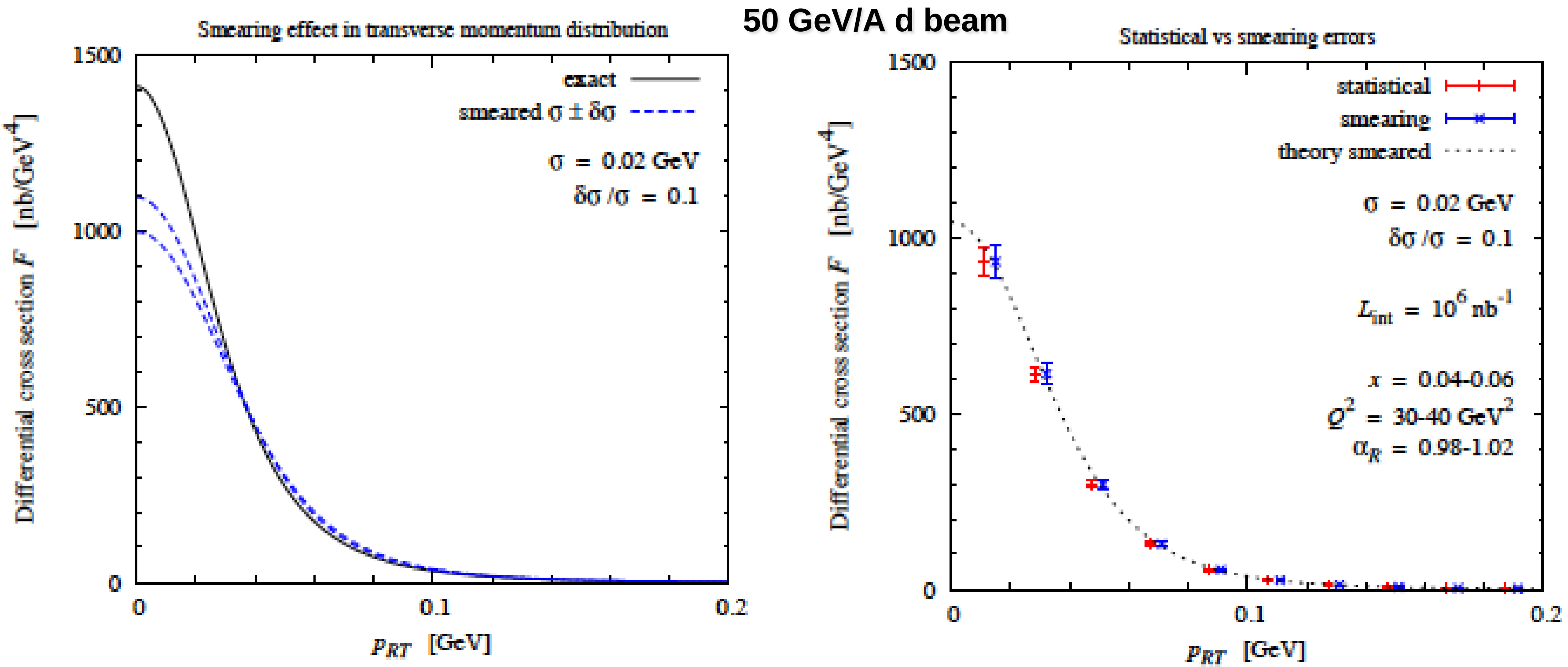
- Two contributions to uncertainty in measured spectator momentum
  - Resolution of detector
    Final-state resolution
  - Momentum spread in the beam
    Initial-state resolution
- Ideal detector gives negligible contribution to uncertainty
  - Can be achieved !
  - Uncertainty entirely due to beam
    few x 10^{-4} longitudinal (dp/p)
    few x 10^{-4} rad angular (dθ/θ)
- Simulation shows effect on resolution (binning) in t’
  - Uncertainty increases with the ion beam energy



50 GeV/A d beam



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