Exploring Hadrons with Electromagnetic Probes:
Structure, Excitations, Interactions
2-3 November 2017, Newport News, VA

Deep Virtual Exclusive Scattering and Spectator Tagging at an Electron Ion Collider

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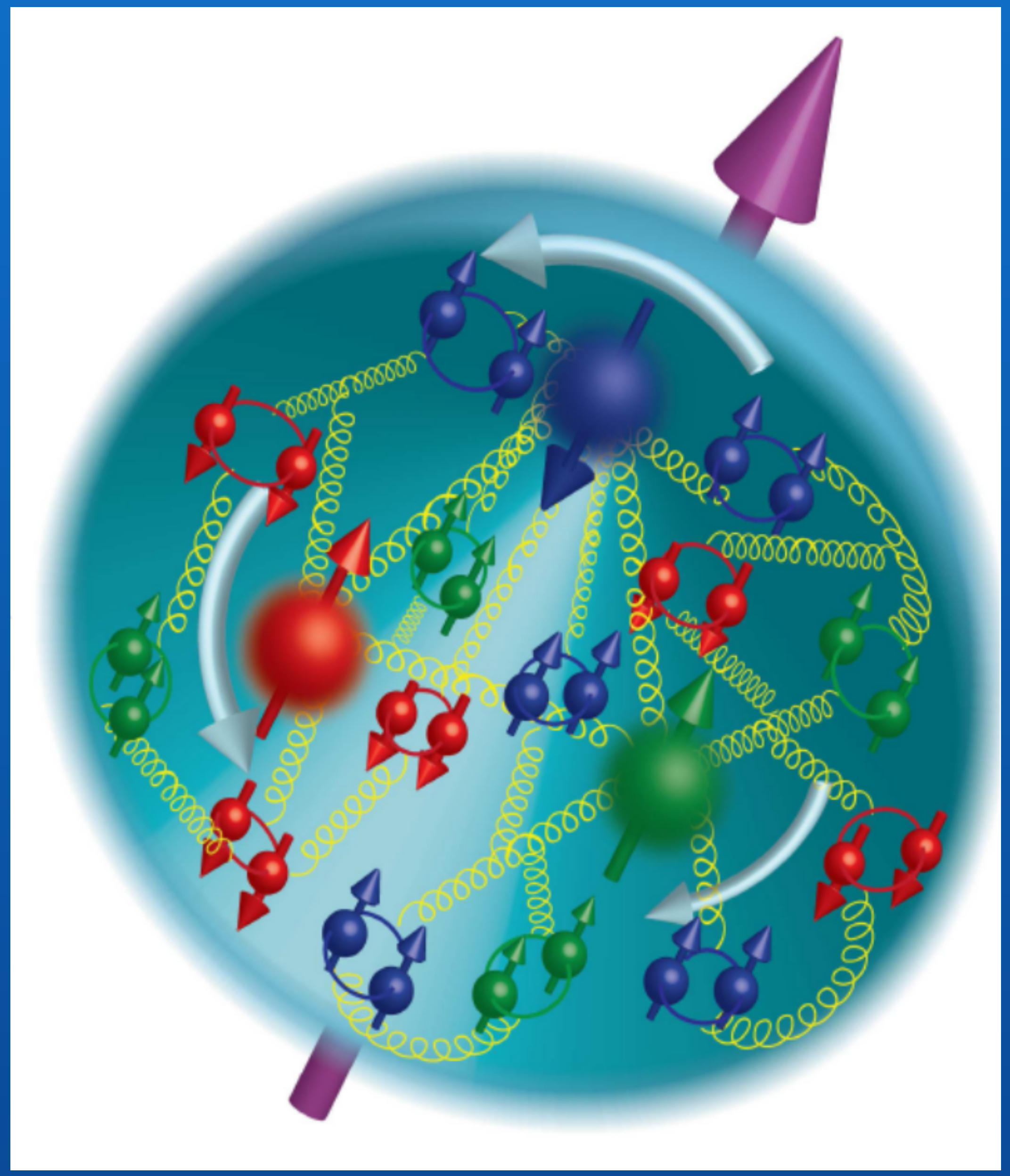


Why an EIC, and Why Now ?
I. Theory

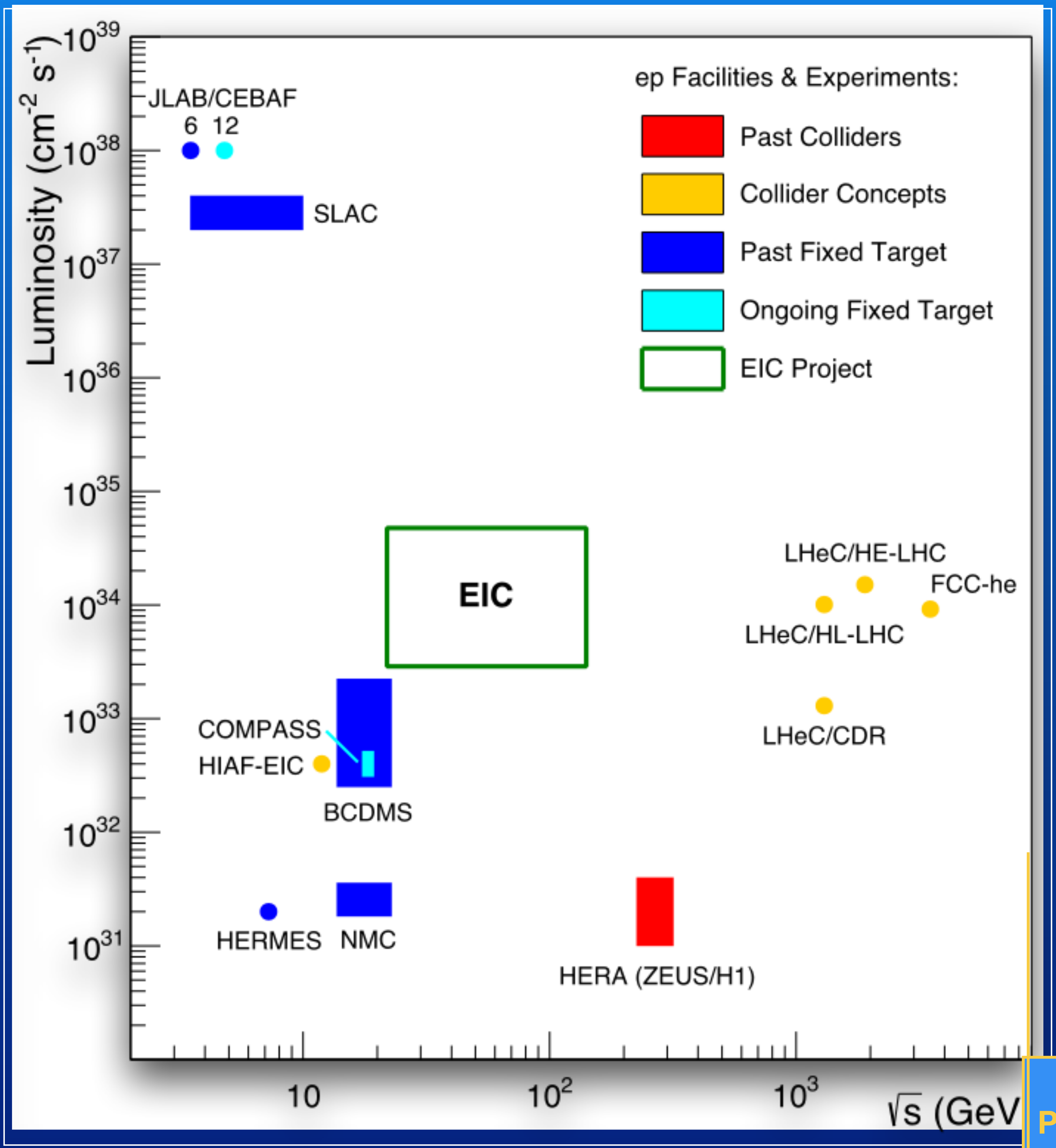
- We are on the cusp of revolutionary advances in our understanding of the QCD structure of matter
  - Lattice QCD
    - At the physical pion mass
    - Two- and Three-Body continuum
  - Effective Field Theory, in q-g and hadronic d.o.f.
  - Predictive Dyson Schwinger Equation calculations
  - New QCD concepts (light-cone matrix elements):
    - 3-dimension imaging (2-space$\otimes$momentum, 3-momentum)
    - Wigner functions (Diffractive di-jet production?)

Why an EIC, and Why Now ?
II. Experiment/Technology

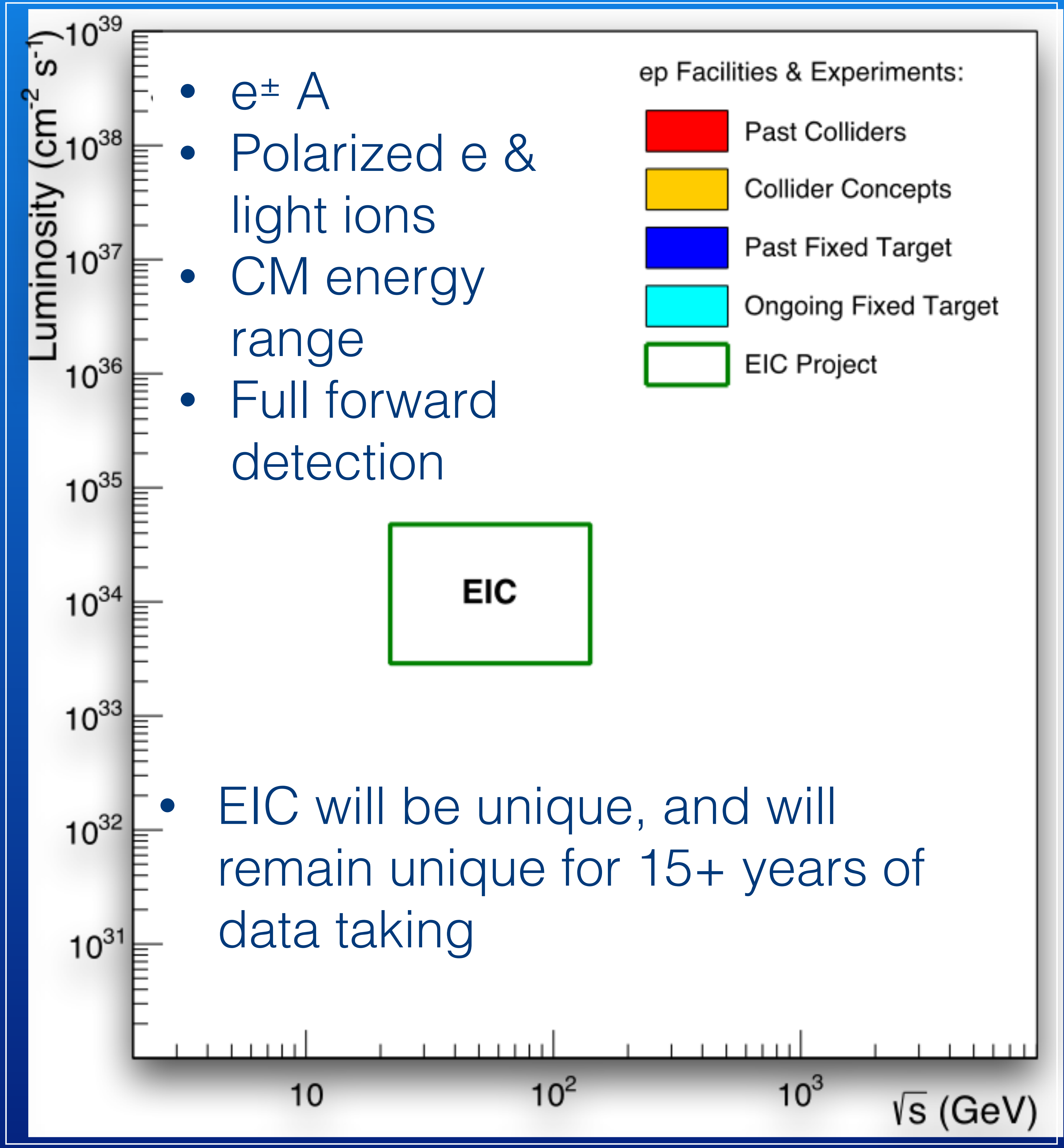
- The EIC will extend the QCD program of JLab, RHIC, COMPASS, LHC, PANDA, JPARC… with unprecedented capabilities:
  - Doubly polarized ep, eD*, e^3He, e^6Li*, e^7Li collisions (*JLEIC only)
    - No target dilution;
    - No transverse B-field to disrupt beams, or coils to block scattered particles
  - Ion species from D to U
  - Full reconstruction of Nuclear Final state
    - Integrate detector with accelerator lattice
    - Incident ion ^{A}Z has momentum per nucleon (ZP_0/A).
    - Fragment $^{A'}Z'$ has momentum per nucleon $\approx (A'/Z')\,(ZP_0/A)$

DIS Facilities: Past, Present, Future

EIC box includes different baseline and staging designs.



LHC x
Plasma Wakefield e⁻
9 TeV x
$4 \cdot 10^{28}$ /cm²/s

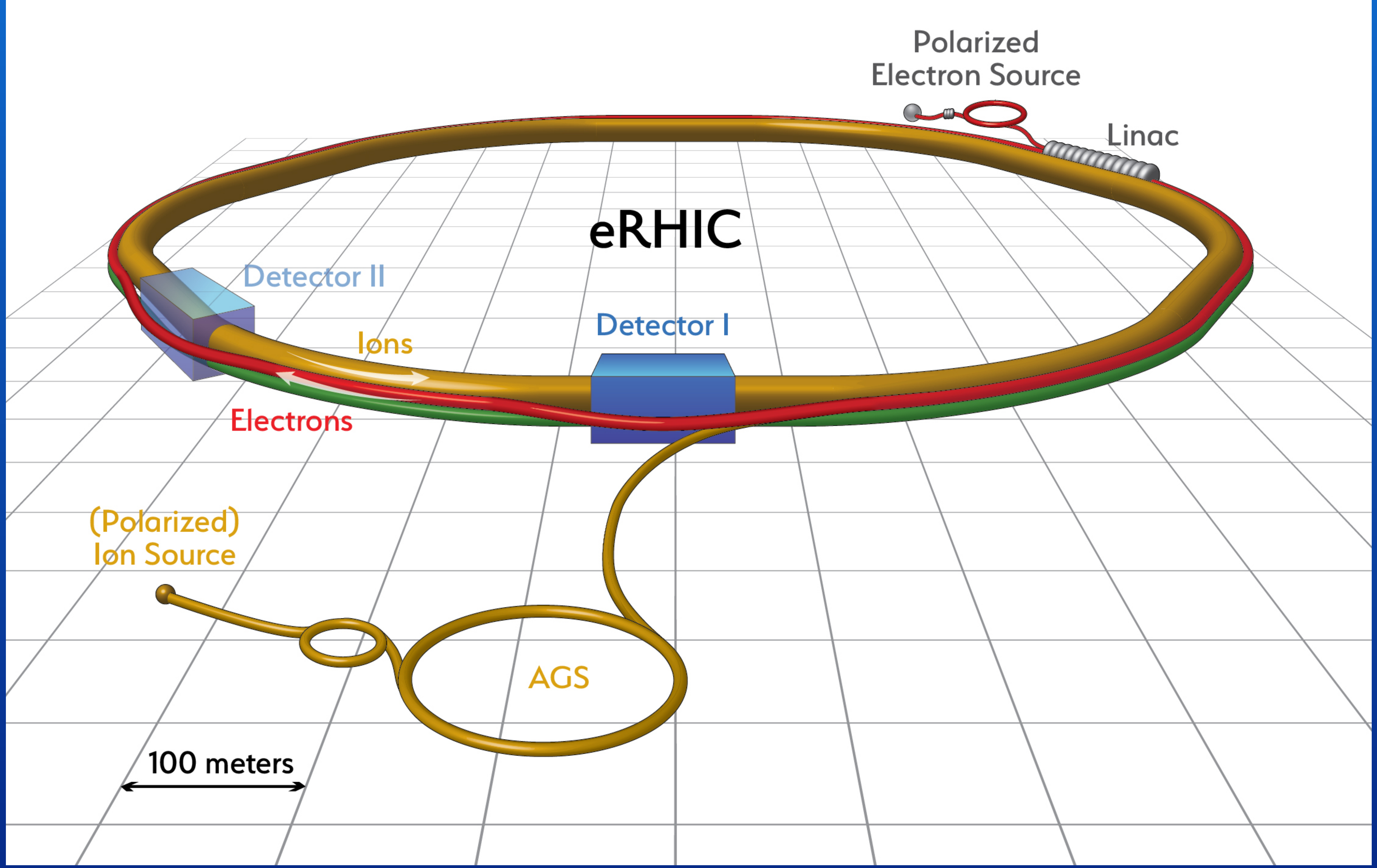


- $e^{\pm}$ A
- Polarized e & light ions
- CM energy range
- Full forward detection

- EIC will be unique, and will remain unique for 15+ years of data taking

eRHIC

RF Upgrades to RHIC
"Rapid cycling synchrotron"
injector to electron storage ring.

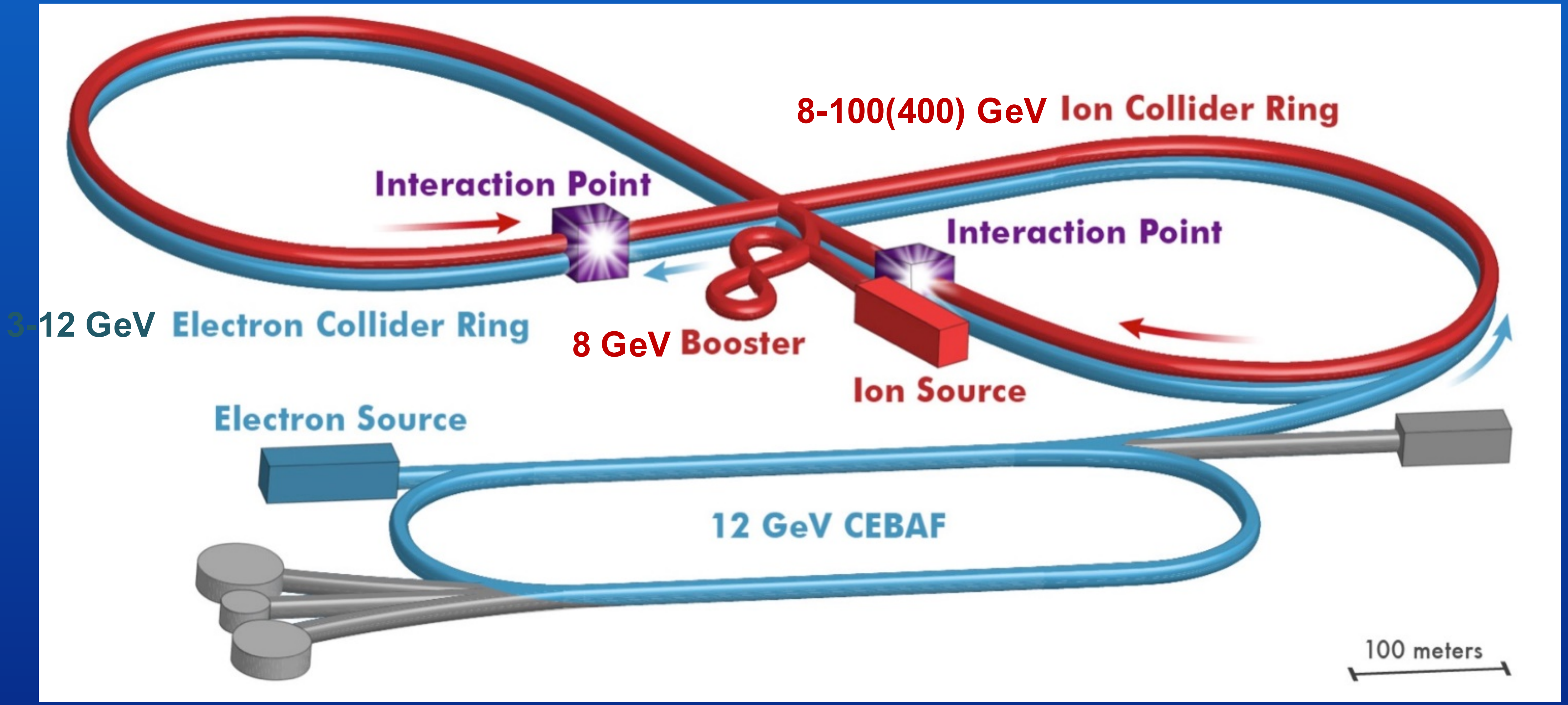


Parameters for maximal luminosity

Parameter	**units**	**No Ion cooling**	**Coherent Electron Cooling**
Momentum (Electron)	**GeV/c**	**15**	
Momentum (Proton, Ion)	GeV/c, GeV/c/ u	275(p), 137/u(N=Z), 110/u(N>Z)	
Crossing angle	mrad	22	
Collision *f*	MHz	29	110
Luminosity	$10^{33}/cm^2/s$	3	10

JLEIC

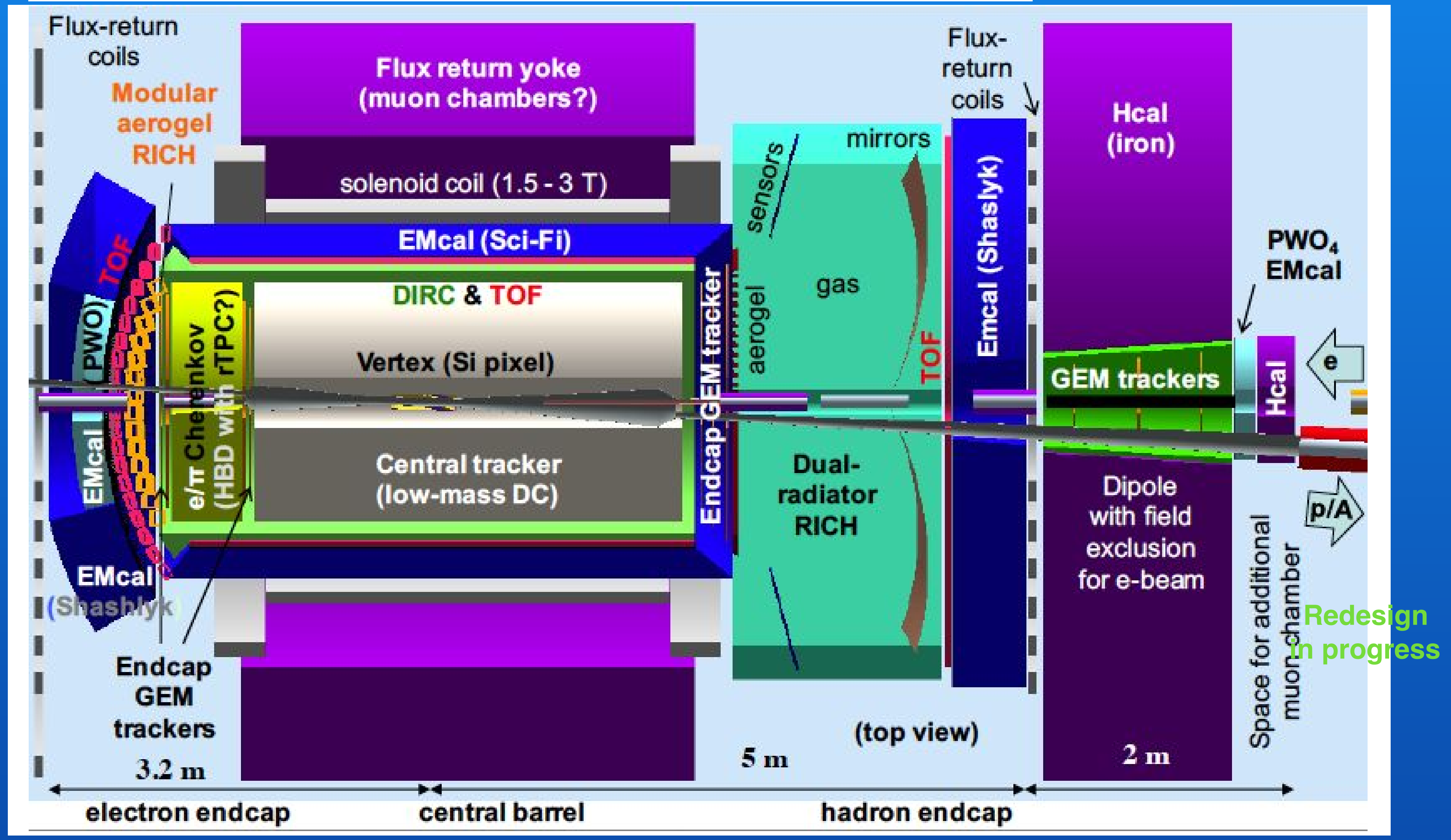
- Novel Figure-8 Ring for polarization control
  - Only solution allowing polarized deuterons (vector and tensor)
- CEBAF as full energy electron injector
  - Fixed target program can continue



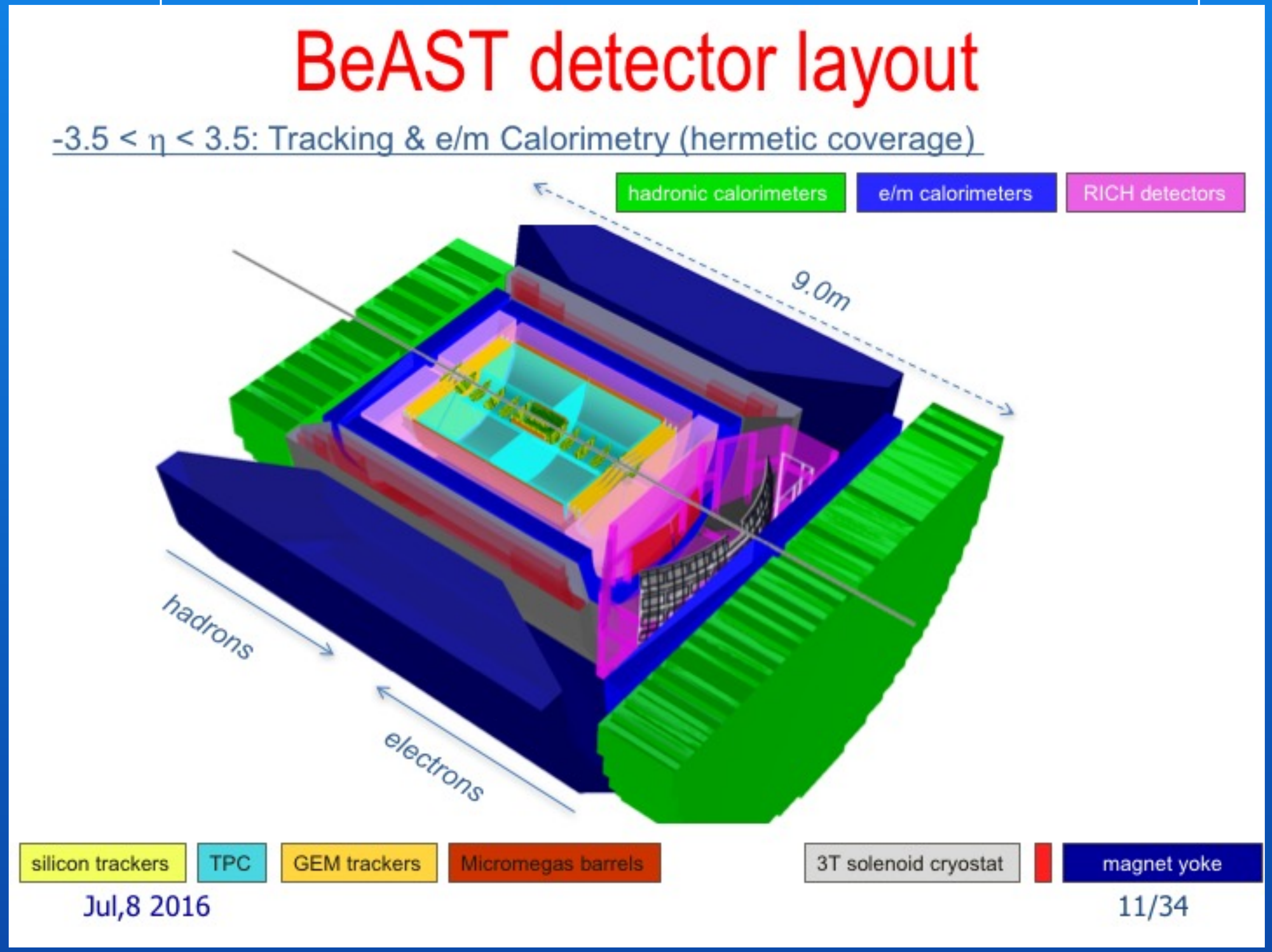
Parameter	units	maximal Lumi	maximal energy
Momentum (Electron)	GeV/c	5	10
Momentum (Proton, Ion)	GeV/c, (GeV/c)/ u	100(p), 50/u(N=Z), 40/u(N>Z)	
Crossing angle	mrad	50	
Collision *f*	MHz	497	110
Luminosity	$10^{33}/cm^2/s$	20	6

Four EIC Detector Concepts

JLEIC Full Acceptance Detector

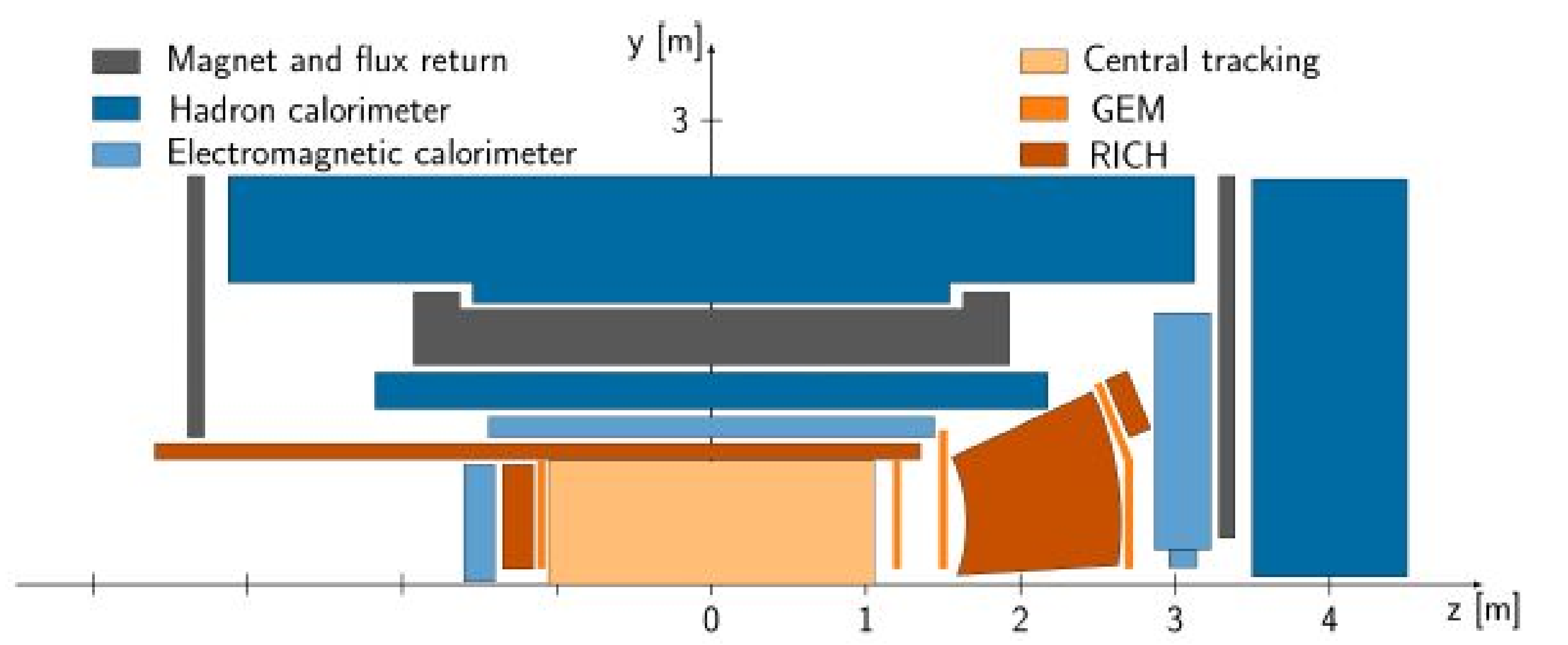


Brookhaven ***eA*** **S**olenoidal **T**racker

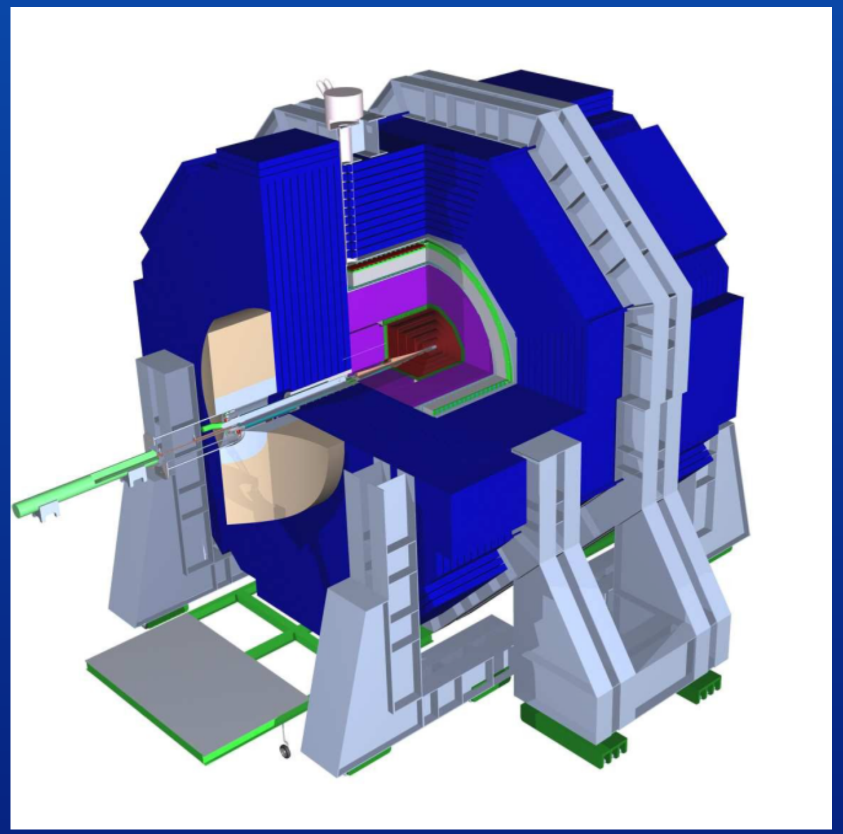


+eSTAR

ePHENIX, based on BaBAR Solenoid



ANL SiEIC Particle FLow HCal

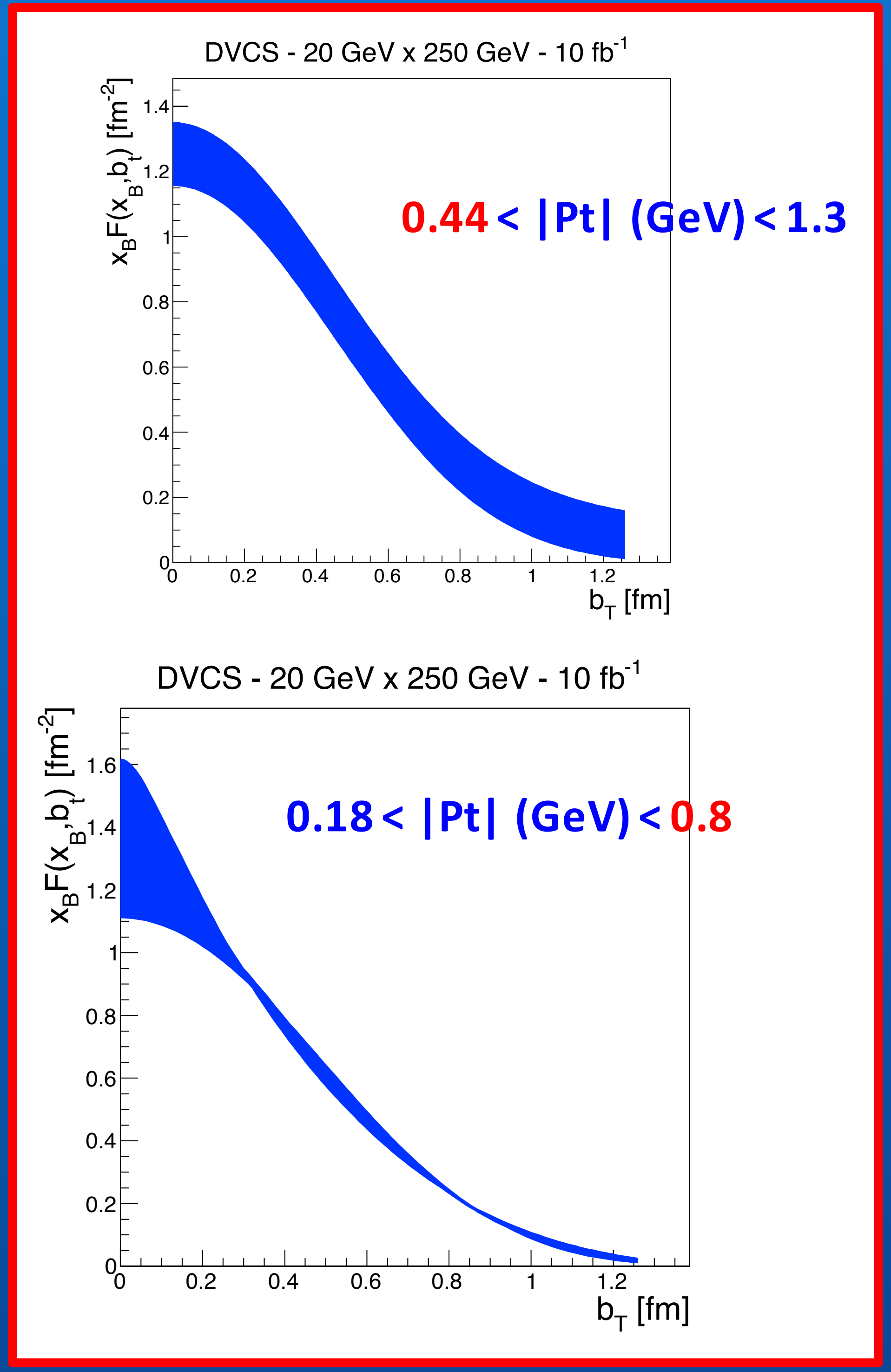


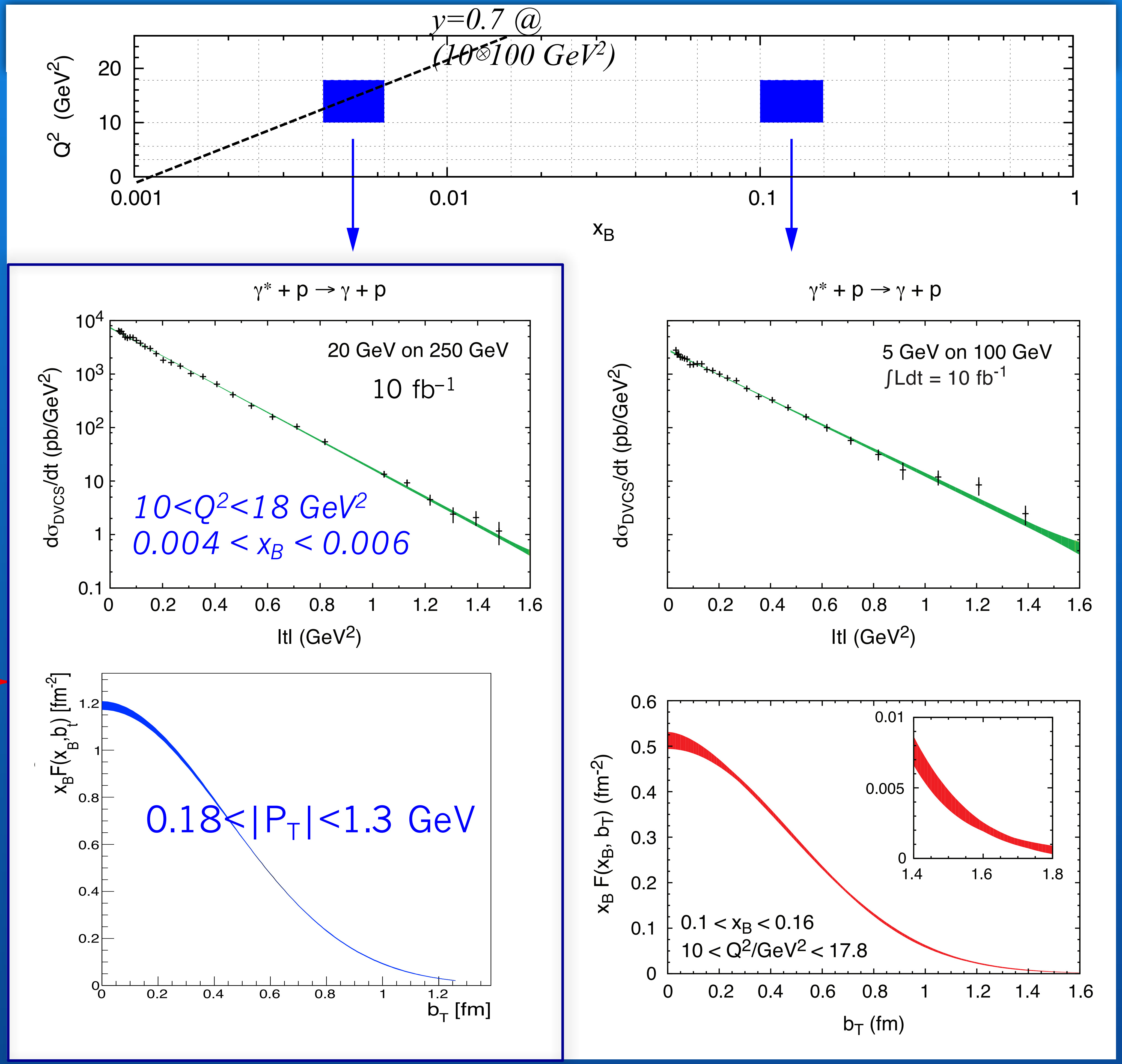
Imaging Quarks & Gluons in the Nucleon and in Nuclei

- DVCS: ep—> epγ: e_f^2, gluons
- Deep Virtual ϕ:
  - Gluons dominate with 10-20% s-quark interference at modest x
  - Strong Sudakov corrections for $Q^2 < 10$ GeV^2 (Goloskokov & Kroll)
- J/Psi: Gluons (intrinsic charm at high-x?)
- Pseudo Scaler mesons: Higher twist DA (instanton effects) and Nucleon transversity for $Q^2 < 10$ GeV^2 (new data from Hall A, B)
- $\boldsymbol{\rho}$, ω-meson, flavor sensitivity, mechanism unclear at modest Q^2
  - strong violation of SCHC in JLab, HERMES data.
  - $\sigma_T/\sigma_L \gtrsim 10\%$ in HERA data for $Q^2 \leq 20$ GeV^2

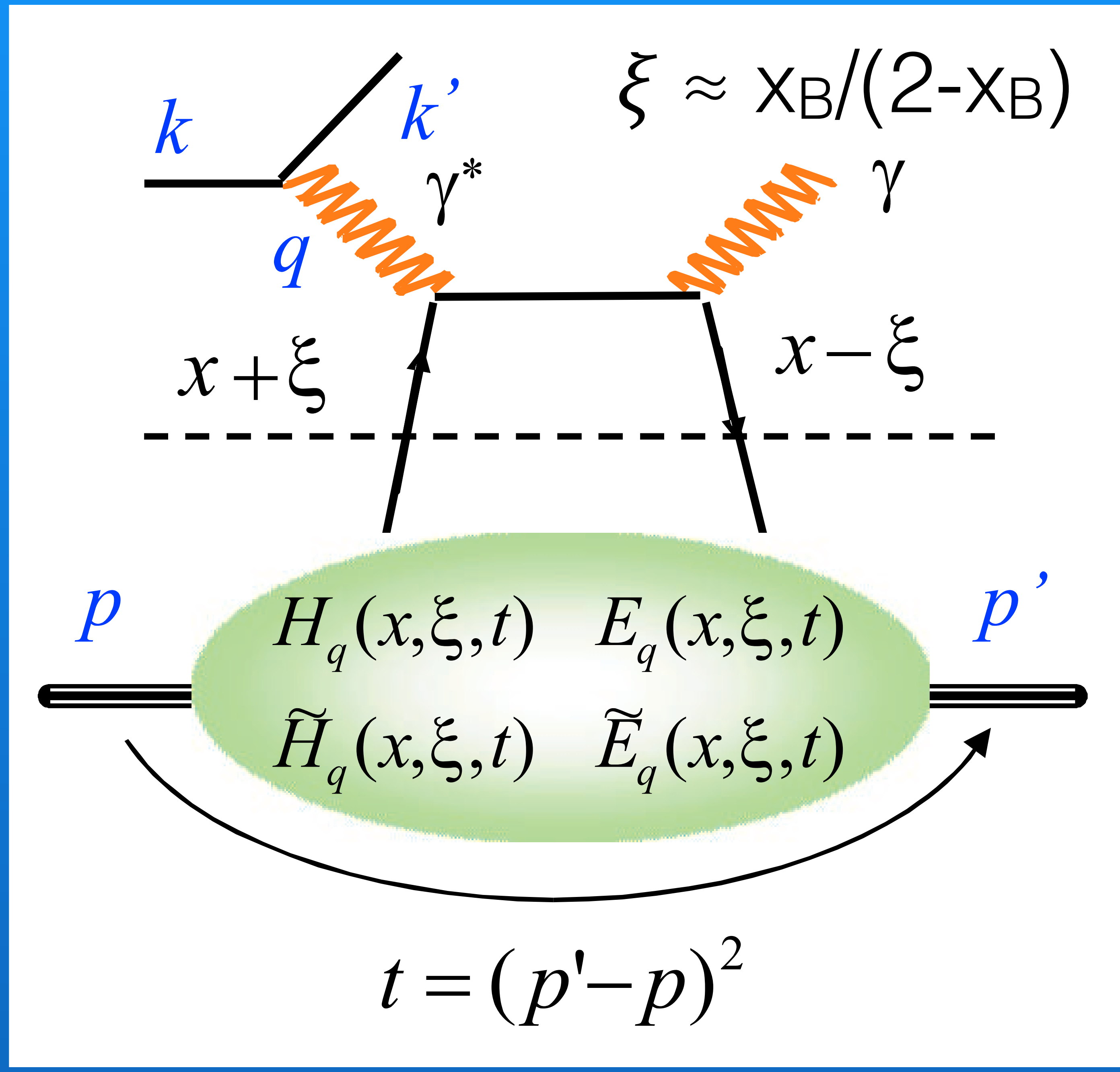
Deeply Virtual Compton Scattering on the Proton: Transverse Imaging vs x_B

- Tagging the recoil protons over the full momentum range is essential for precision imaging
- Repeat with longitudinally and transversely polarized beam

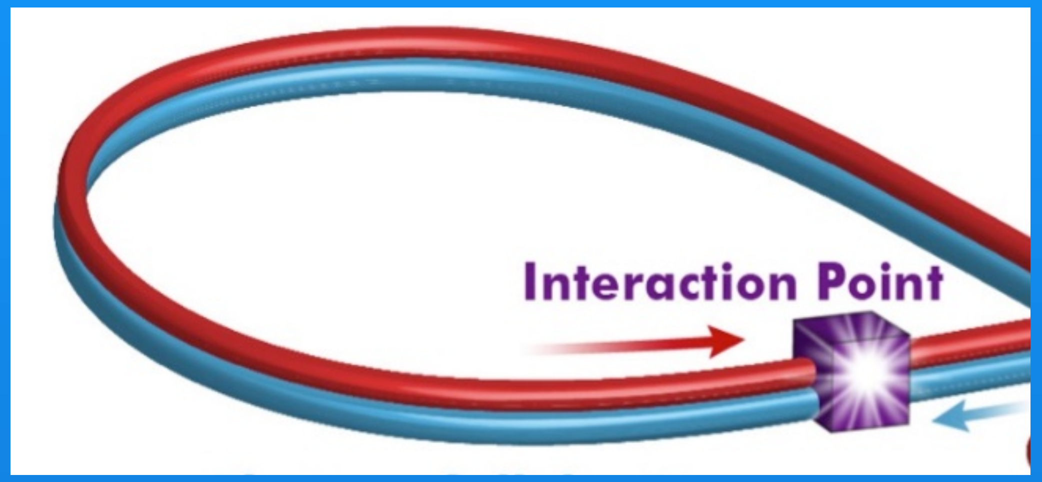




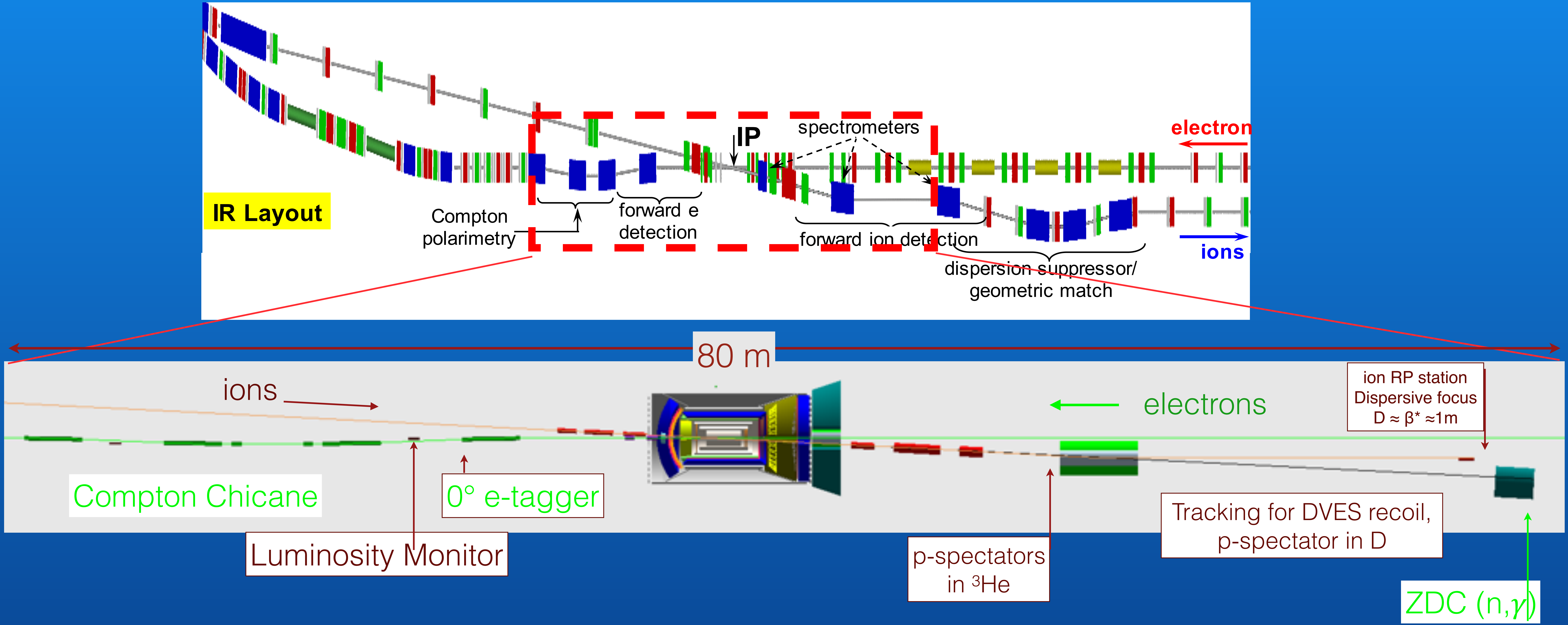
Detector Requirements: DVCS on the Proton(also π^0 and η)



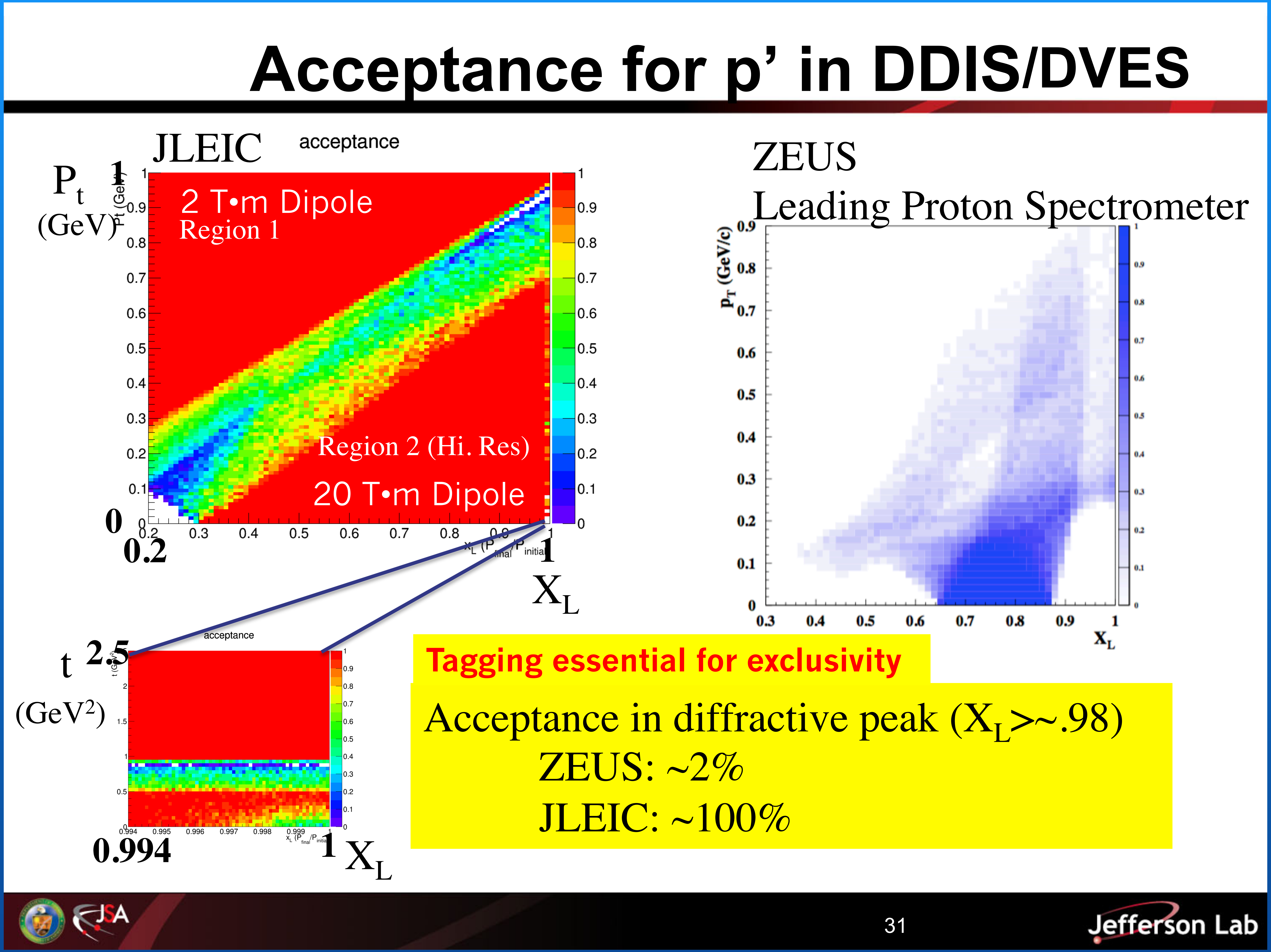
- Exclusivity:
  p(e,e'γp) triple coincidence (or N* → Nπ veto)
  veto neutron in ZDC or proton with $p/p_0 \lesssim M/M^*$
- Imaging:
  - $t = \Delta^2$ resolution requires dispersive focus at Roman Pots.
    Measure Δ=(p'-p) [better resolution than Δ=(k-k'-q')].
- Full proton detection acceptance to "Beam-Stay-Clear (BSC)" limit of ~10× beam rms emittance:
  - JLEIC: $\theta_p > 3$ mrad OR $|\Delta p_L/p_0| \approx x_{Bj} > 0.003$



JLEIC Full Acceptance Detector



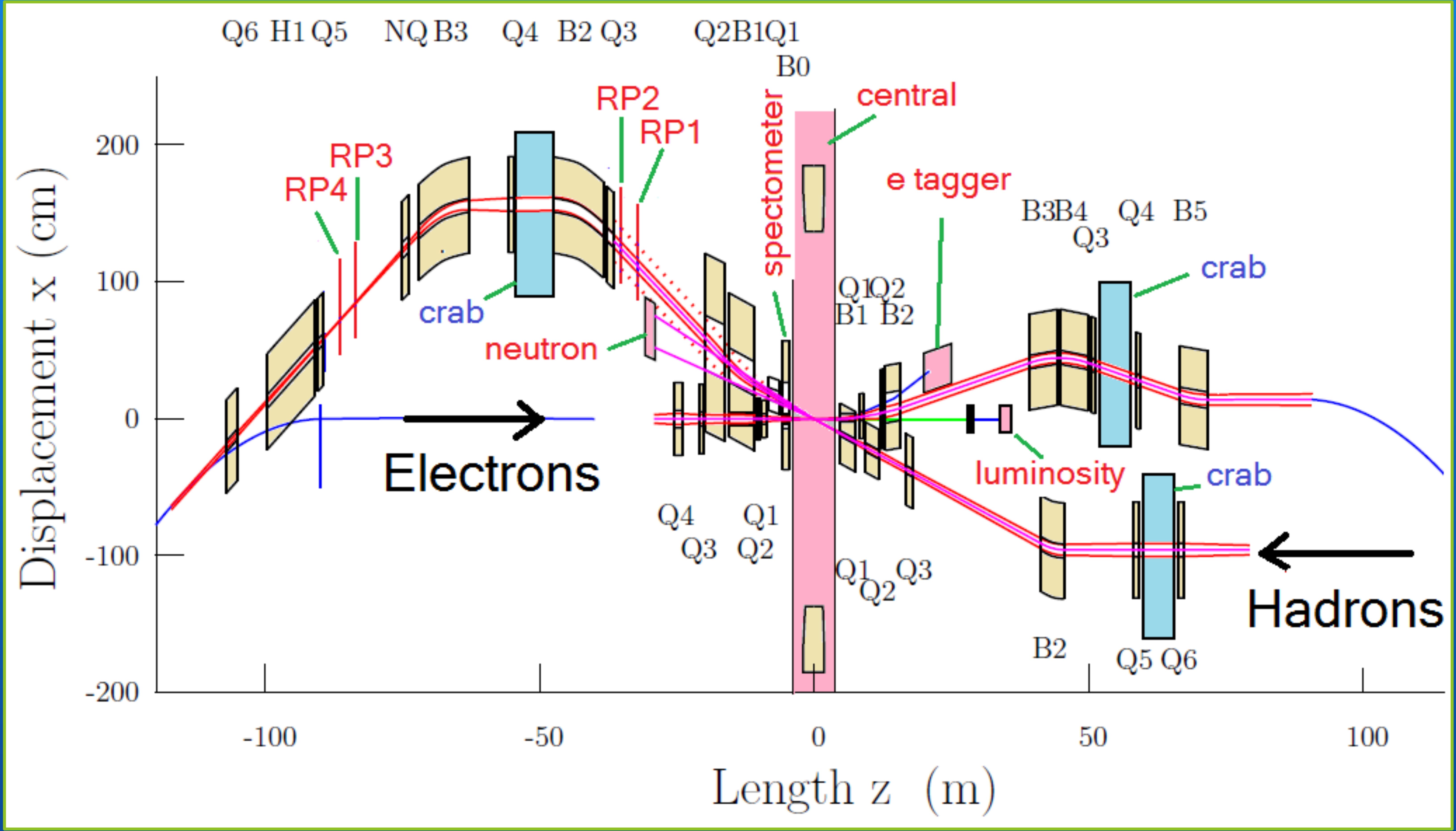
- no



Acceptance for p' in DDIS/DVES
JLEIC
acceptance
2 T•m Dipole
Region 1
Region 2 (Hi. Res)
20 T•m Dipole
Pt (GeV)
XL
t (GeV2)
ZEUS
Leading Proton Spectrometer
pT (GeV/c)
xL
Tagging essential for exclusivity
Acceptance in diffractive peak (XL>~.98)
ZEUS: ~2%
JLEIC: ~100%
31
Jefferson Lab

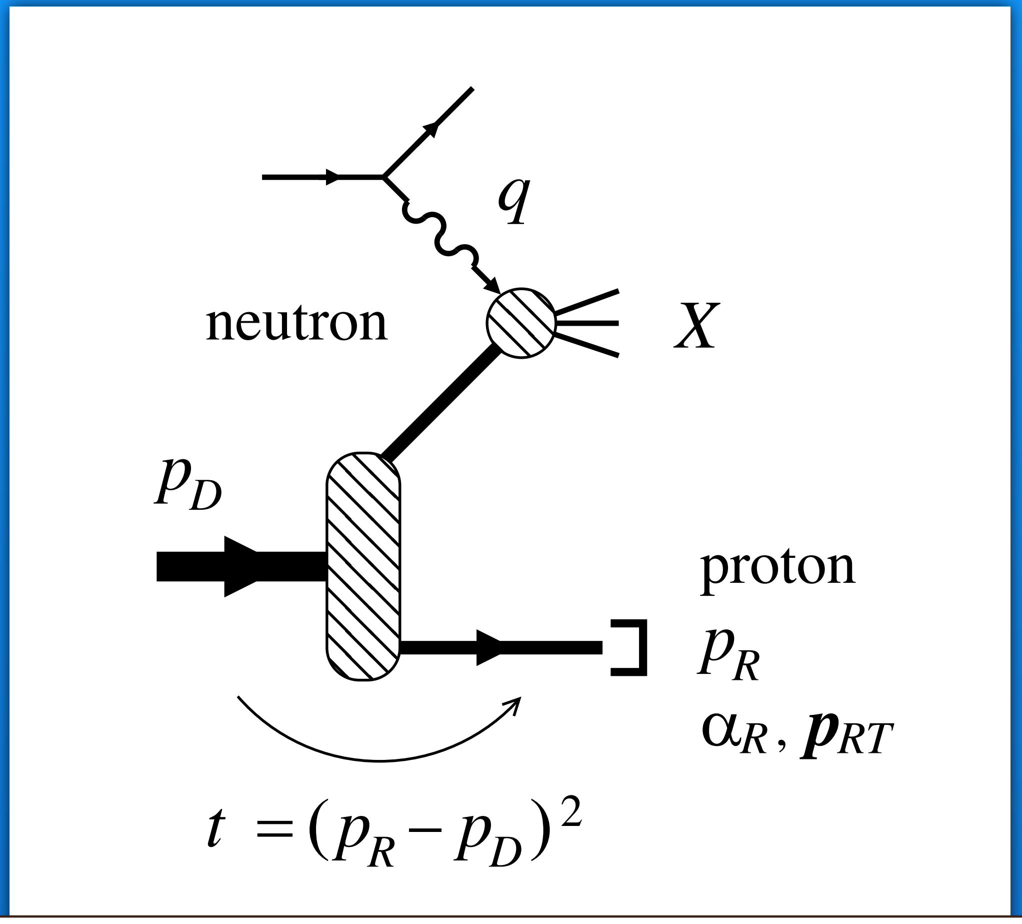
eRHIC Interaction Region Optics

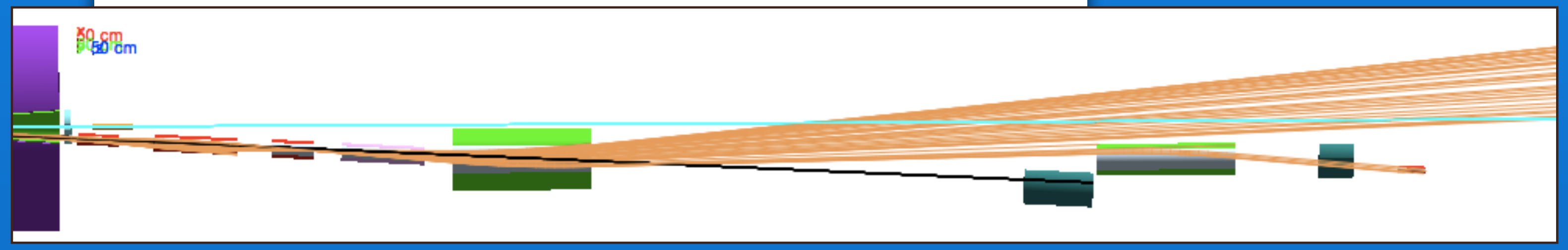
- Spectator protons in RP1,2
- DVCS Recoil protons in RP3,4



Deep Virtual Vector Meson Production

- p(e,e'V)X:
  - Reconstruct $t=\Delta^2 = (k-k'-p^+-p^-)^2$ from charged particle final states: $\rho \to \pi^+\pi^-$, $\phi \to K^+K^-$
  - $\omega \to \pi^+\pi^-\pi^0$ constraint on ω mass refines ω momentum resolution.
- Tagging/Veto required for exclusivity





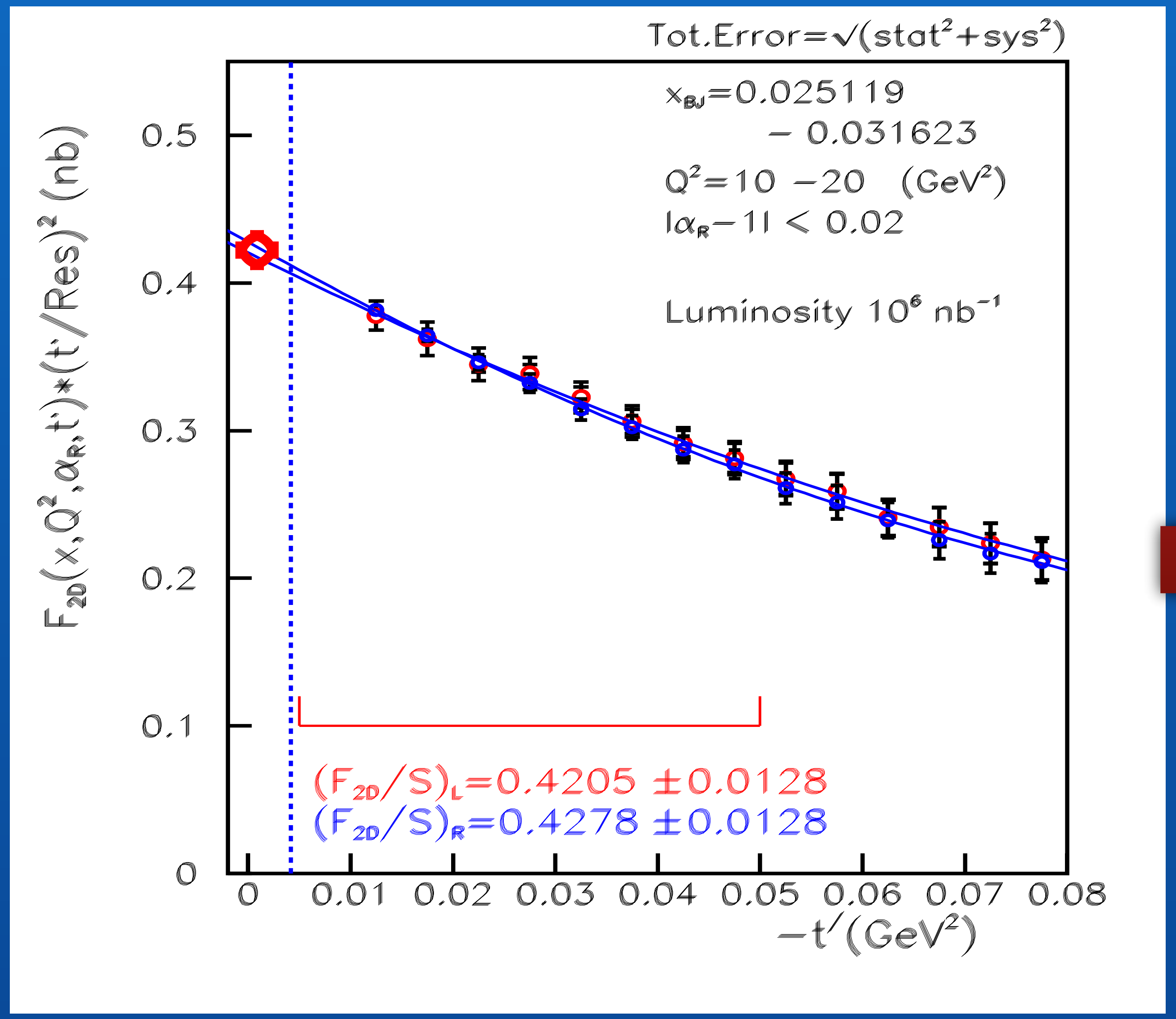
DIS, DVES with Neutrons

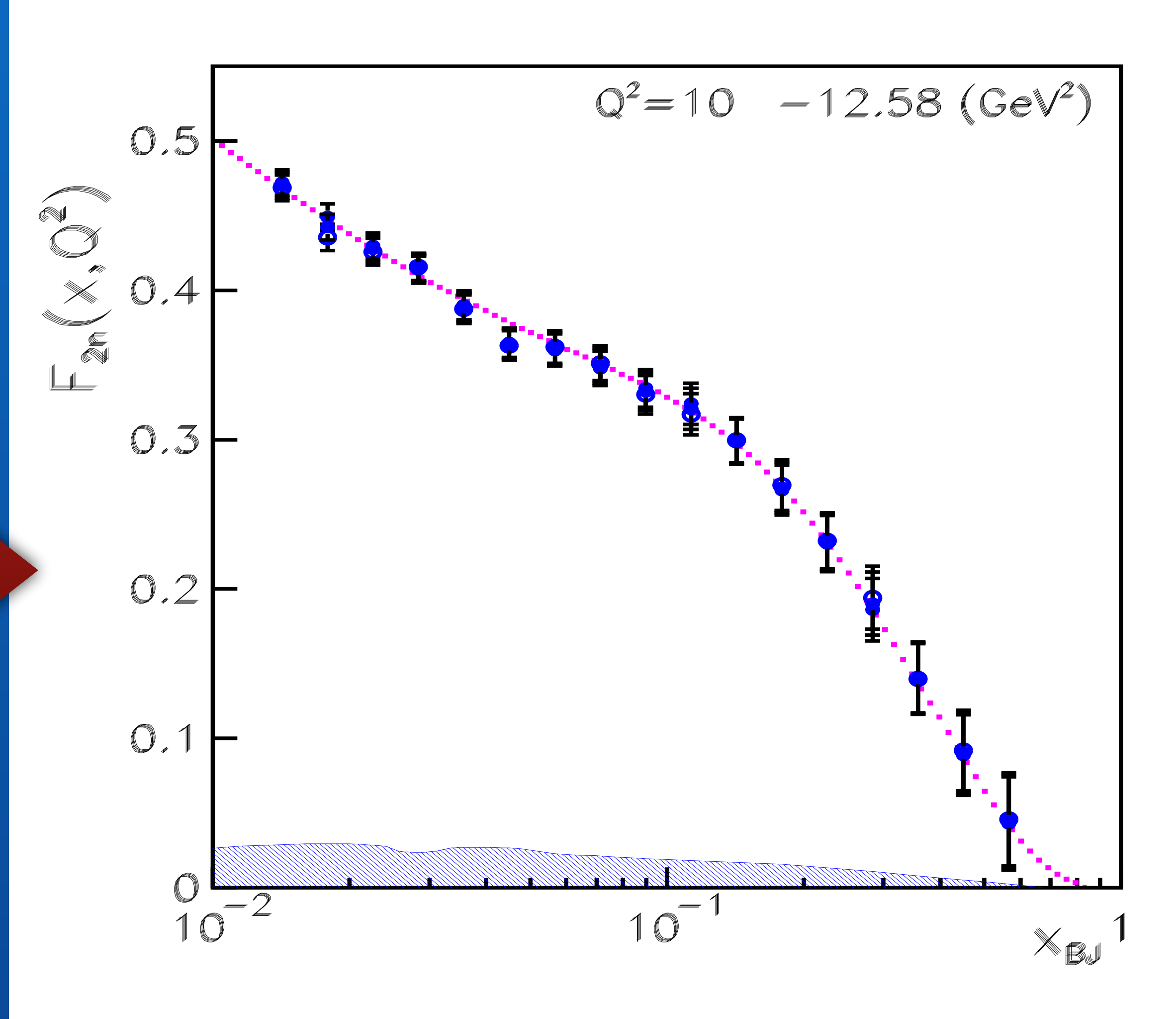
JLab LDRD, C.Weiss, et al.

- $P_R = 0$ spectator proton (D rest frame)
  ➩ $P_R = P_0/2$ forward proton in collider frame

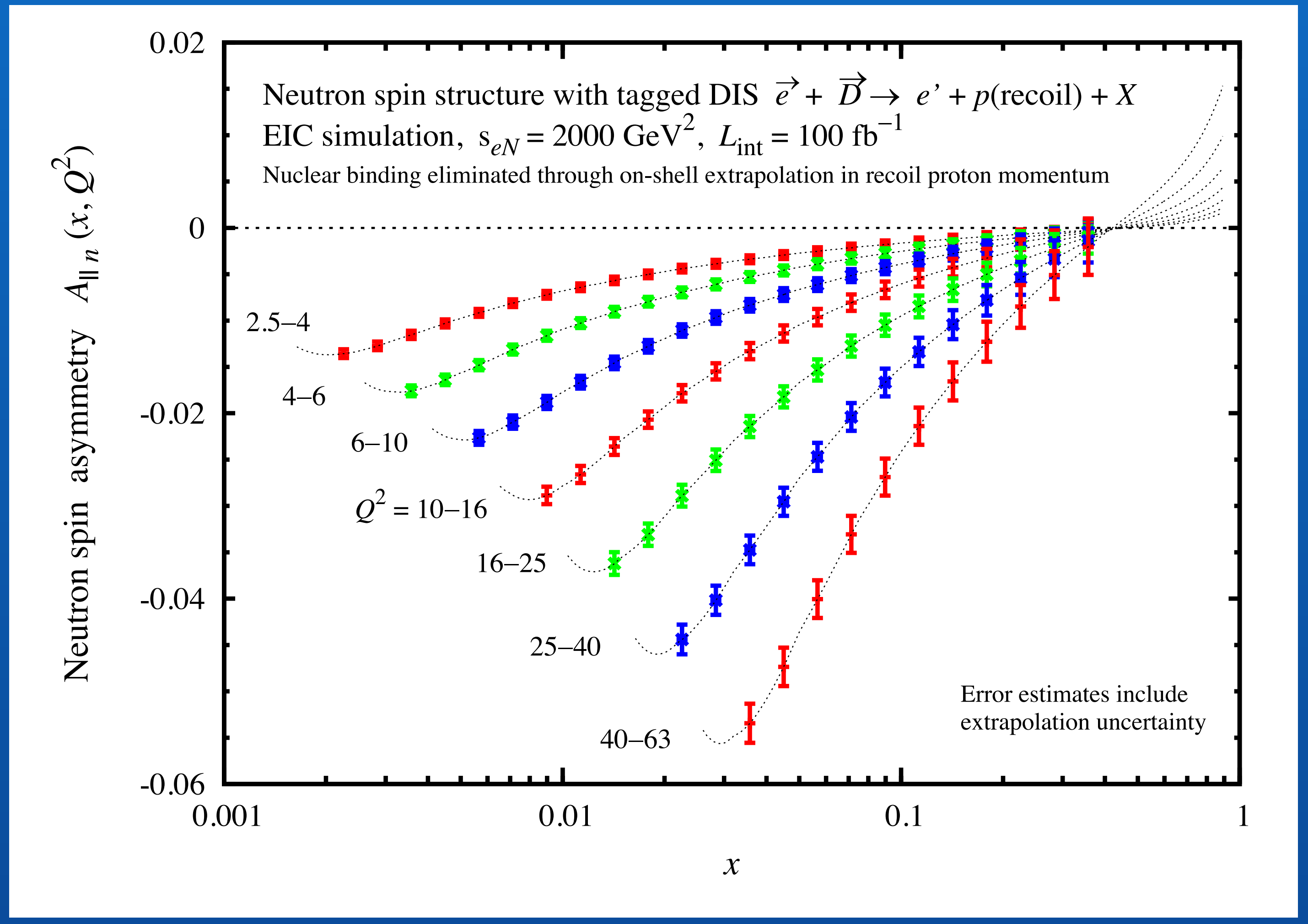
- Deuteron Momentum Distribution
  ➩ $P_S = [M(\alpha-1)/2, \boldsymbol{p}_T]$ D rest frame
  ➩ $P_S = [M(\alpha-1)/2, \boldsymbol{p}_T]$ Collider frame
- $-t' = M_N^2 - (P_D - P_R)^2 \geq 0$

K.Park, JLEIC
systematic & statistical errors



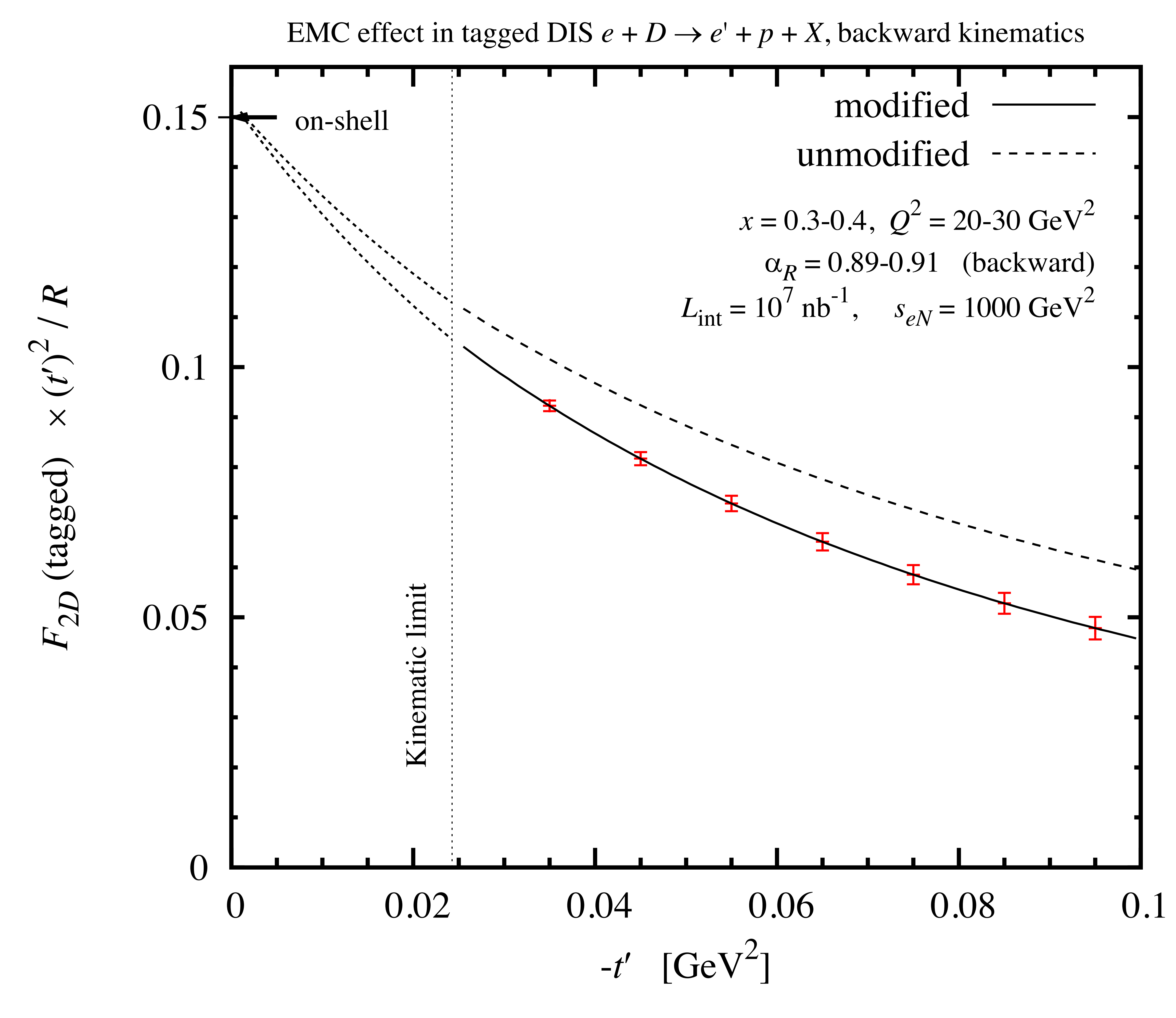


Polarized DIS

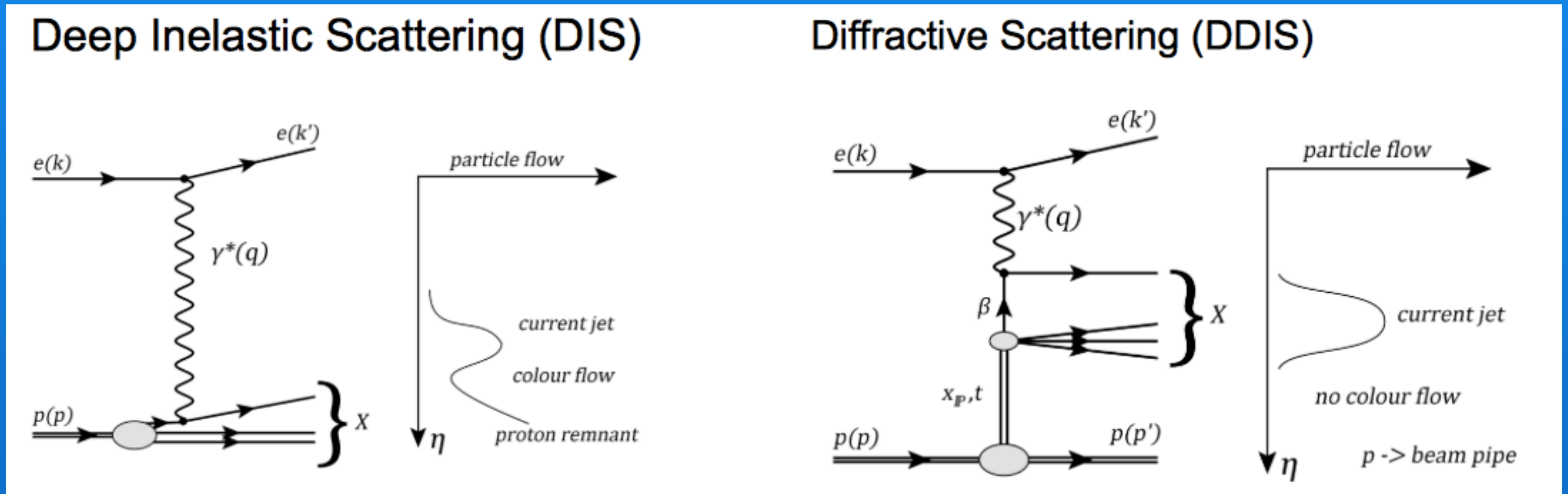


The EMC Effect in the Deuteron

- Measure on-shell neutron by extrapolation at small |α-1|
- Measure interacting neutron at large |α-1|

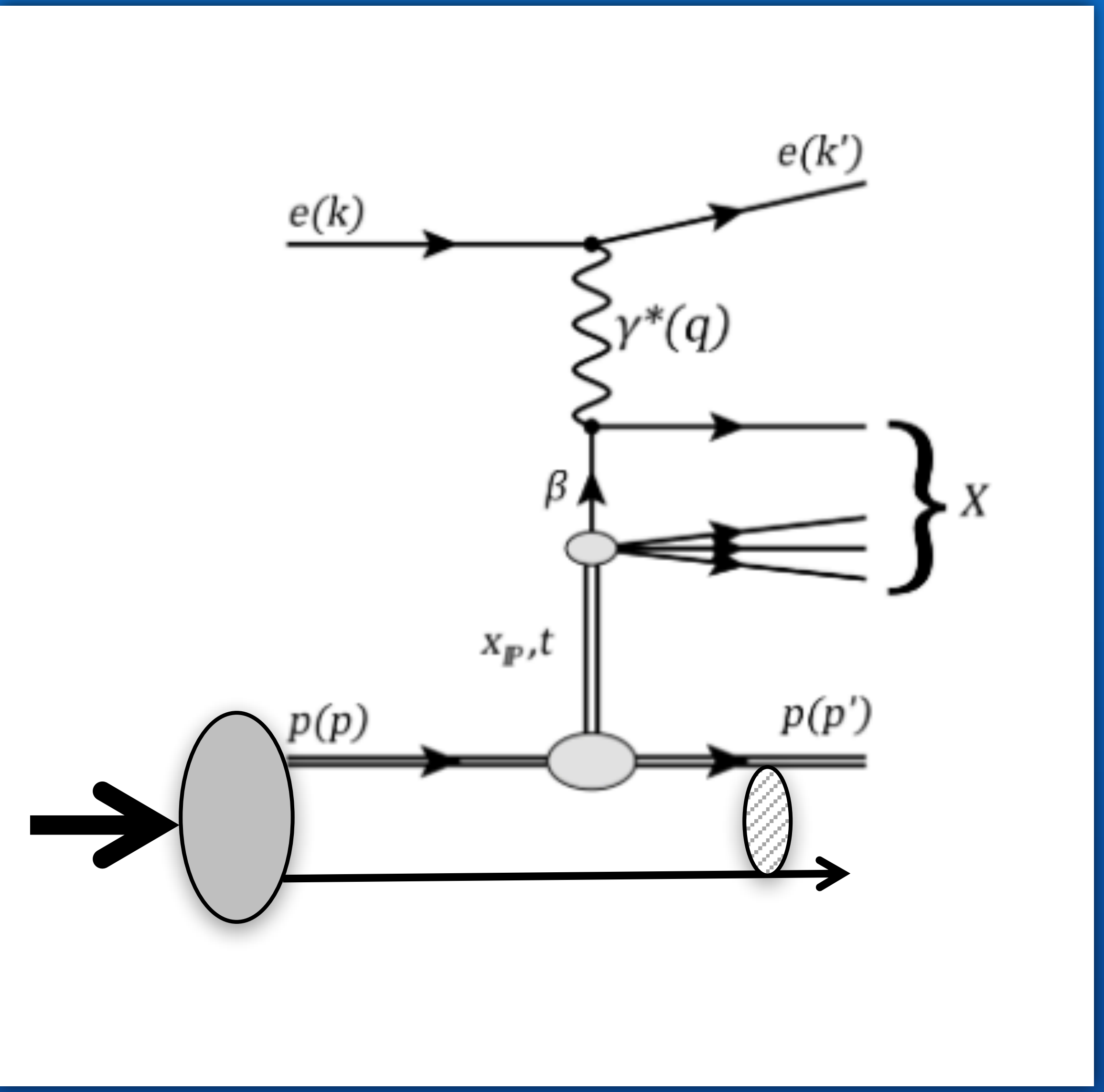


Diffraction & Shadowing



Incoherent Diffraction on D, ^{3}He,…

- A clean probe of QCD structure of multi-nucleon dynamics
  - Only low energy NN, NNN FSI
- Event-by-event measurement of relative momentum of *np* pair (from D) or *npp* from ^{3}He



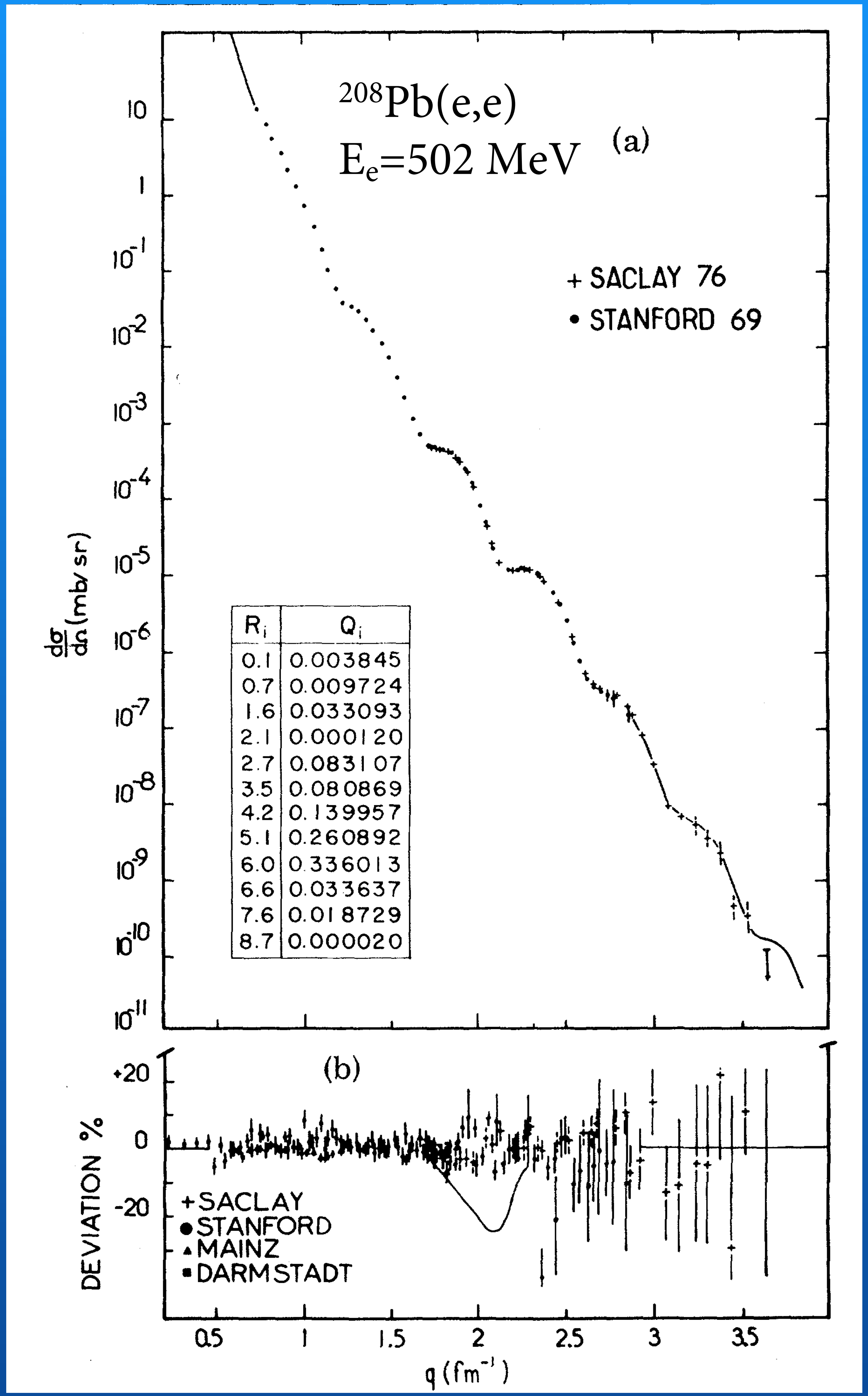
X: small color neutral system
No FSI with NN!

DVES on Nuclei

- Precision charge densities measured in 1970s ☛

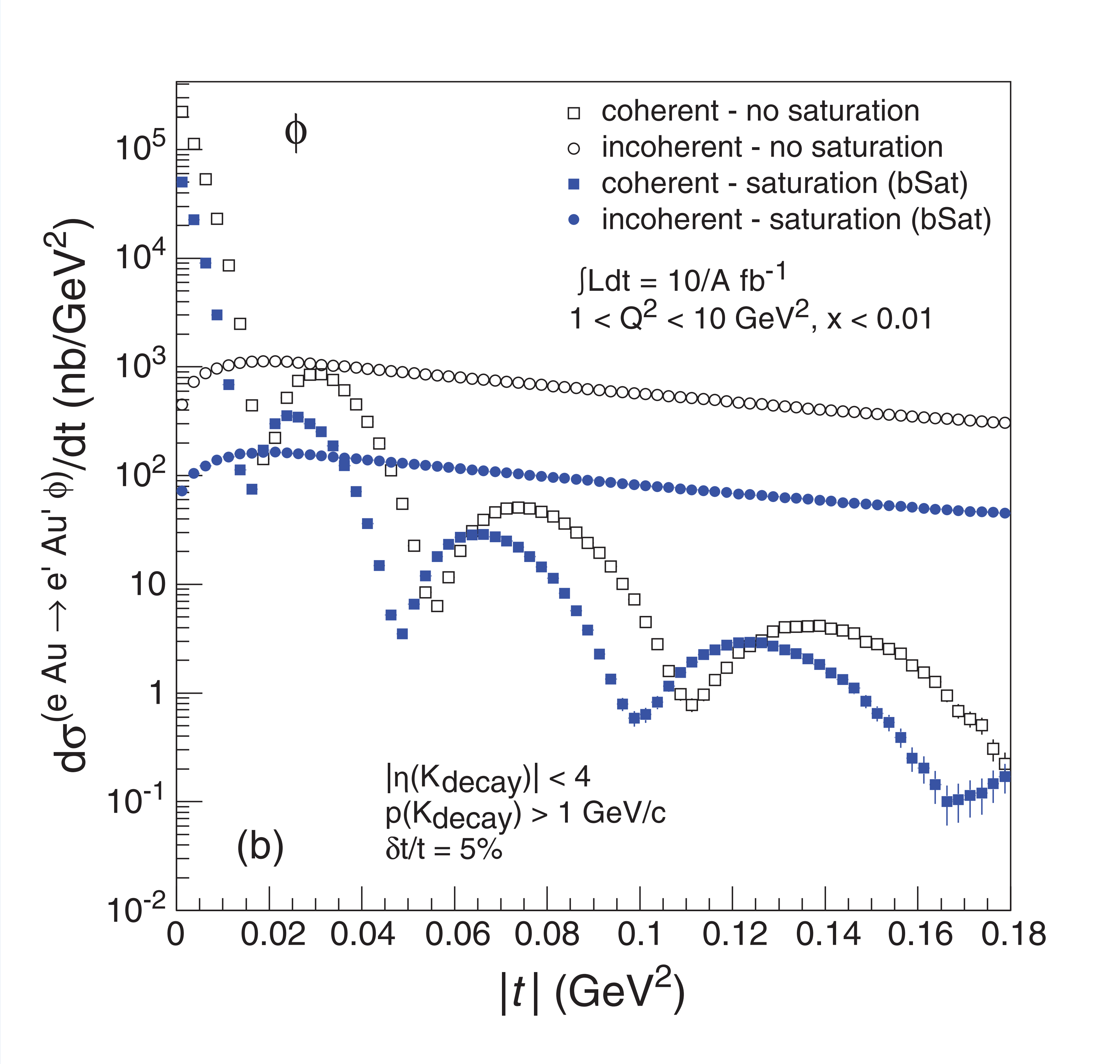
- “Neutron Skin” of heavy nuclei has implications for nuclear equation of state & neutron star structure.
  - p/n ≅ u-quark / d-quark
  - ρ,ω: DVES amplitude has charge weight $e_u \mp e_d$.
    - q + q-bar

- Gluon profiles of nuclei from J/Ψ and ϕ



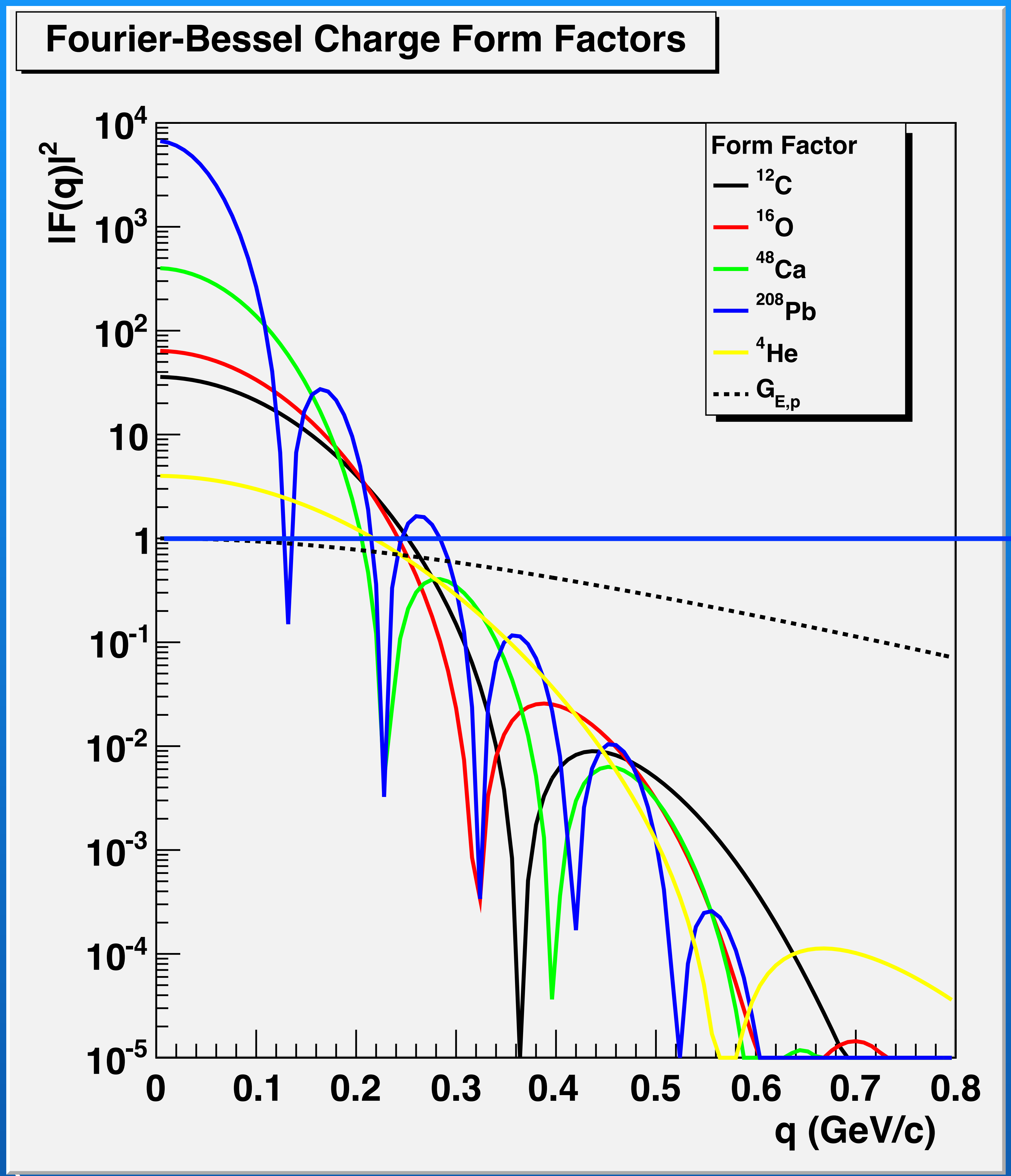
Deeply Virtual Vector Meson Production on Nuclei

- High resolution reconstruction of $|t|$ from e.g. *(e,e' K^+K^-)* kinematics.
    - Coherent nuclear recoil is unresolvable: lost in 10σ-BSC.
    - Dedicated 10% of run at large β* (small beam $\mathbf{P}_\perp$)
- Excitation of bound-states will wash out minima of coherent scattering.
    - Doubly-magic nuclei, γ-decay energies are large



^{208}Pb(e,e') & DVES

- If bound-excited states are not resolved, they smooth out the diffraction pattern. 3^-(2.6MeV), 5^-(3.2 MeV), 2^+(4.1MeV), 4^+(4.3MeV)
- In DVES@EIC, γ-cascade boosted ($\times 40$ JLEIC, $\times 100$ eRHIC)
- High Resolution ($PbWO_4$) forward EMCal can veto (~50% acceptance) $E_\gamma > 100$ MeV.
  - Backgrounds?



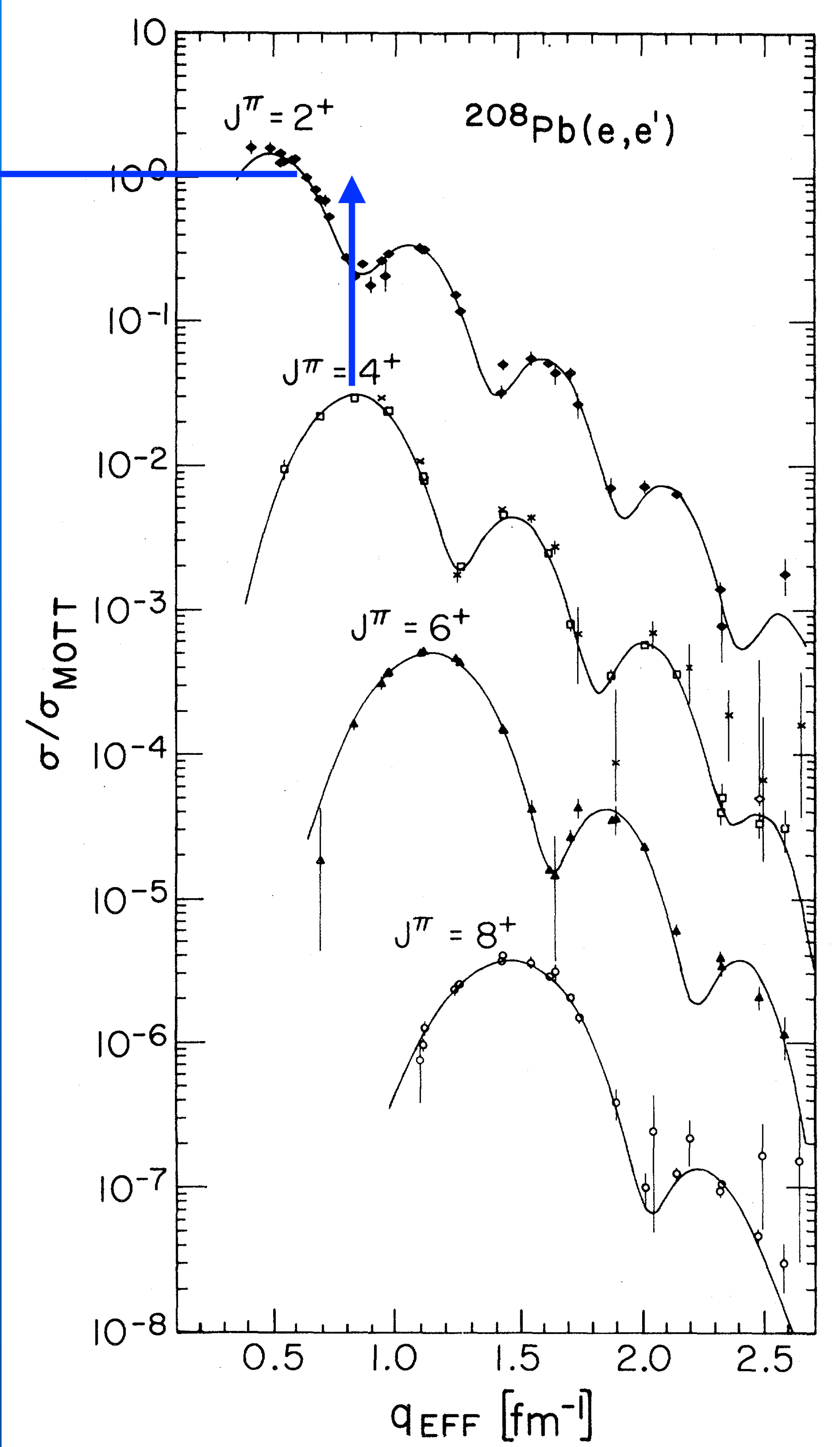


FIG. 3. Cross section for the even spin natural parity states in ^{208}Pb divided by (the cross section for a unit-point charge). Data and best fit for the 4^+ level are scaled down a factor of 0.03, for the 6^+ level a factor of 0.001, and for the 8^+ level a factor of 0.00003.

EICUG.org

- 165 Institutions
- 719 Members
- Join us!
  Theorists,
  Accelerator Physics
  welcome!

Concluding Comment:

An arbitrary JLEIC Run-Plan (similar for eRHIC)

- **Neither time- nor priority-ordered.**
- **2 run periods per year**
- **15 years for 'base program'**

Luminosity is important, even for "low luminosity physics"

Species	e/A Energy/u	Ion Pol	Run Periods
ep	10 x 100	L & T	2
	5 x 100	L & T	4
	10 x 40		1
e d	10 x 50	L & T	4
e ^{3}He	10 x 75?	L & T	3
e ^{4}He	10 x 50		1
e ^{9}Be	10 x 40		1
e ^{12}C	10 x 50		1
e ^{40}Ca	10 x 50		1
e ^{48}Ca	10 x 40		1
e ^{120}Sn	10 x 40		1
e ^{208}Pb	10 x 40		1
e ^{238}U	10 x 40		1
Positrons			8
Total			**30**