Electron Ion Collider and Femtography Science

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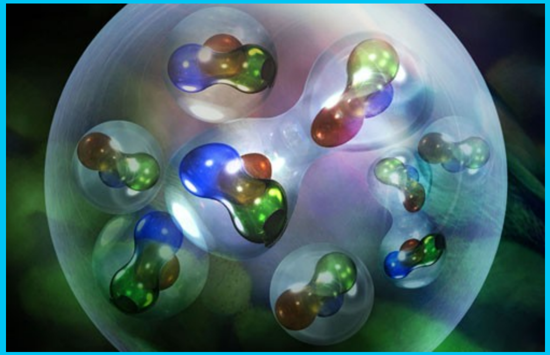
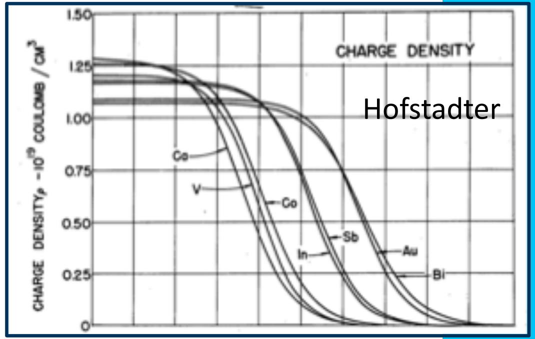


A Brief Pre-History of Femtography: I.

- 1911: Rutherford, Geiger, Marsden: Discovery of atomic nucleus
- 1920s Measurement of nuclear radii by (non-relativistic) α-scattering
  - Maximum radius for deviation from Coulomb Scattering: $R(A) \approx (1.4\ \text{fm})A^{1/3}$
- 1955: Hofstadter: Elastic scattering of relativistic electrons
  - Charge distributions of nuclei: $R(50\%) = (1.07\ \text{fm})A^{1/3}$
  - Proton *rms* radius (1955) = (0.78±0.24) fm
    - 2014 CODATA value 0.879(11) fm excluding 5σ μH 0.84169(66) fm
    - 2019 value *(ep* reanalysis) *:* 0.844(7) fm (JLab, MAMI)
- 1970s: Precision charge densities of nuclei
- 1990s: (JLab) Proton charge and magnetization densities unequal



A Brief Pre-History of Femtography: II.

- Folklore: Elastic electron scattering on proton, H*(e,e')p* measures 3-D Fourier transform of spatial charge density, with ill-defined relativistic corrections due to proton recoil :
  - initial state ≠ final state, Boosts do not commute with dynamics
  - Not a problem for nuclei heavier than He
- 1978: Gunion & Soper: Relativistic covariant analysis:
  - H*(e,e'p)* measures 2-D Fourier transform of charge density, after integrating over `longitudinal' coordinate.
  - Generally ignored.
- 1970s: 1-dimensional momentum distributions of quarks in proton
  - Deep Inelastic Scattering ➔ Parton (quark, gluon) Distribution Functions (PDFs)
- 1980s: European Muon Collaboration (EMC): PDF(Nuclei) ≠ PDF(nucleon)$\otimes$A

A Brief History of Femtography: I

- Light Cone variables: $P^{(t,x,y,z)} \rightarrow P^{(+,\perp,-)}$ $$P^{\pm} = \frac{1}{\sqrt{2}}(E \pm cP^{z}),$$ $\mathbf{P}_{\perp} = c(P^x, P^y)$
  - High energy reactions define a preferred longitudinal axis *z*.
  - Mixed coordinates: light cone momentum p^+, transverse spatial coordinates **b.**
- H(e,e')X → distribution of parton (quark, gluon) light cone momentum fraction
- 1994 Definition of Light-ray operators
  - Quantum amplitudes for a parton transition $[(x+\xi)P^+, \mathbf{b}] \rightarrow [(x-\xi)P^+, \mathbf{b}]$
- 1996:
  - Deep Virtual Exclusive Scattering: $ep \rightarrow ep\gamma$, as well as $ep \rightarrow ep$ hadron
  - At sufficiently large $(Q^2, q\cdot P)$, → Generalized Parton Distributions GPD$(x,\xi,t;Q^2)$: Variables $(\xi,t;Q^2)$ are kinematic, determined by experiment

Digression: $e\,p \rightarrow e\,p\,\gamma$
From Scattering to Femtography

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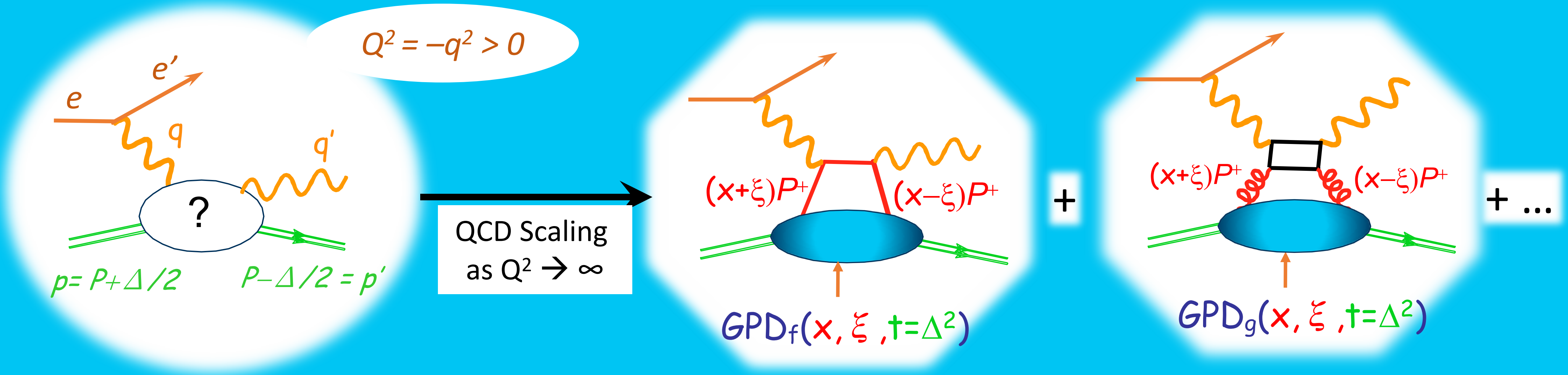


Bjorken Variable

$$x_B = \frac{Q^2}{2q \cdot p}$$

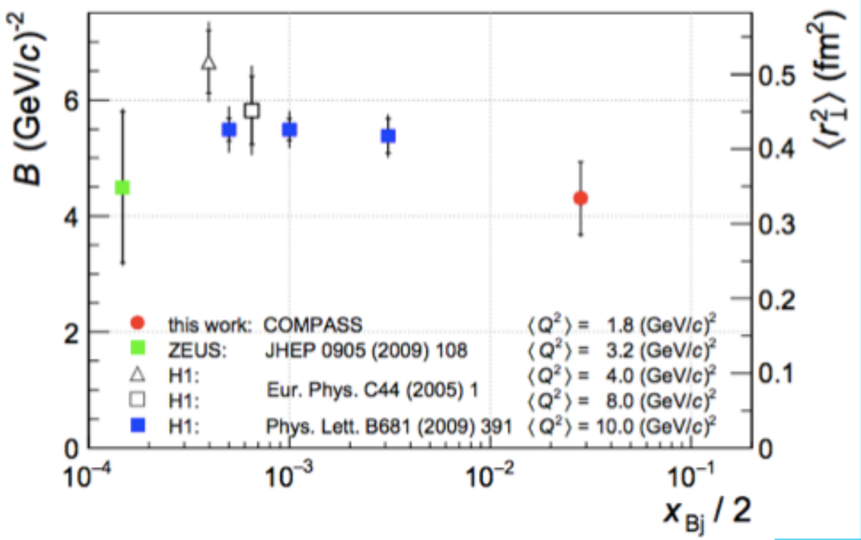
- Symmetrized Bjorken variable: $\xi = \dfrac{-(q+q')^2}{2(q+q')\cdot P} \xrightarrow[\Delta^2 << Q^2]{} \dfrac{x_B}{2-x_B}$
- $\Delta_\perp$ = **(q-q')$_\perp$** , Fourier conjugate to impact parameter **b**

Structure (Complications) of GPDs

- Two quark (Dirac) operators: $(\gamma^{+}, \gamma^{+}\gamma_{5}) \otimes$(proton helicity flip or non-flip)
  - Four GPDs (real functions): $[H, \widetilde{H}, E, \widetilde{E}](x, \xi, \Delta^{2}; Q^{2})$
  - Gluon and quark-flavor, *e.g.* $H \rightarrow H_g, H_u, H_d, H_s$ …
  - Q^2-dependence exactly described by perturbative QCD → mixes flavor⊗gluon
- Experiments measure Compton Form Factors (CFFs) not GPDs
  - $\mathcal{H}(x, t; Q^{2}) = \int_{-1}^{1} dx\, H(x, \xi, t; Q^{2}) \left[\frac{1}{x-\xi+i\epsilon} - \frac{1}{x+\xi+i\epsilon}\right]$
- For $Q^2 < 10$ GeV^2 important corrections to cross sections from more complicated quark-gluon correlation operators
  - Deep Virtual Meson Production: *electron + nucleon → electron + baryon + meson.* For $Q^2 < 20$ GeV^2 important corrections to cross sections from more complicated quark-gluon correlation operators

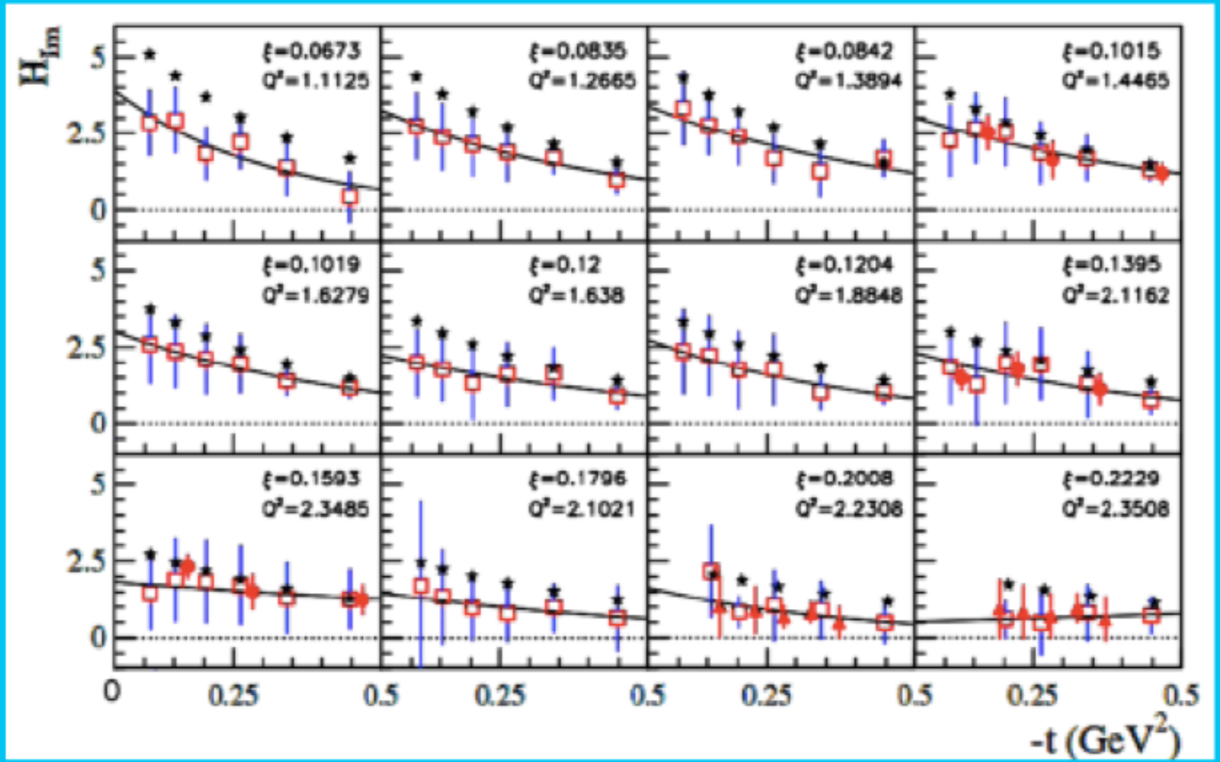
A Brief History of Femtography: II

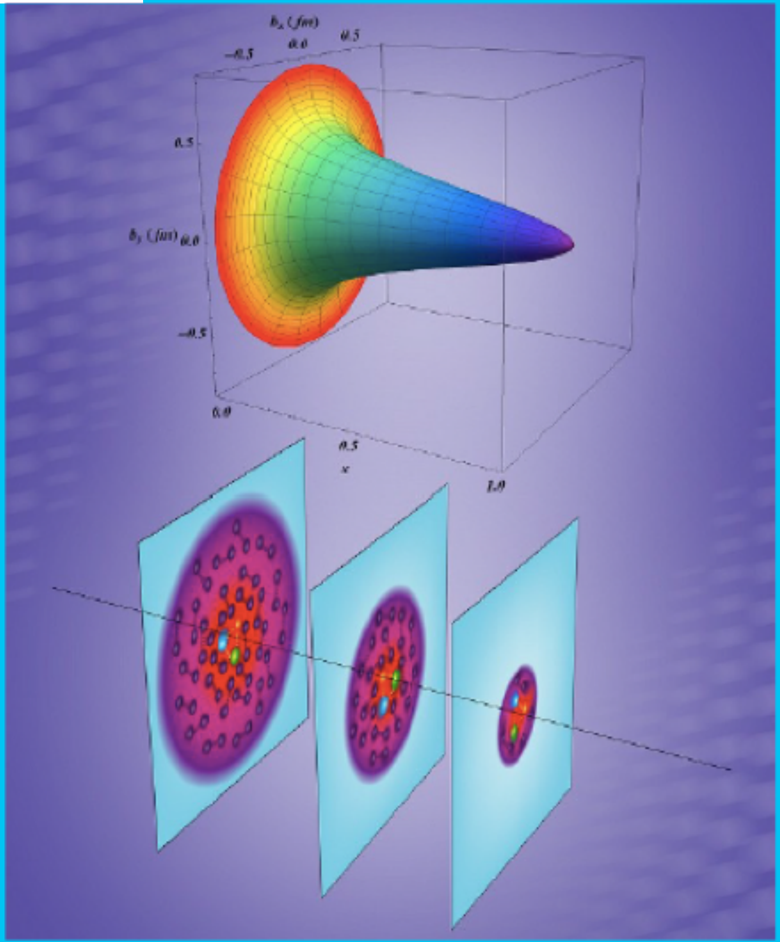
- 2001 First published data (polarized electrons)
  - HERA 27.5 GeV $e \otimes 920$ GeV p (shutdown 2007)
  - HERA-HERMES 27.5 GeV $e^{\pm} \otimes$ H, D-jet
  - JLab-CLAS



- 2012 COMPASS 160 GeV $\mu^{\pm} \otimes p$
- 2004 – 2012 JLab 6 GeV, long. pol. p,d
- 2014 Start of JLab 12 GeV: H(e,e'γ)p, H(e,e'π^0)p Hall A
- 2017 Start of CLAS12
  - H(e,e'γp), H(e,e'Vp): V = ρ,ϕ,J/Ψ
- 2021 CLAS12 Longitudinally polarized p, d targets

Tomography Results [Model-Dependent]

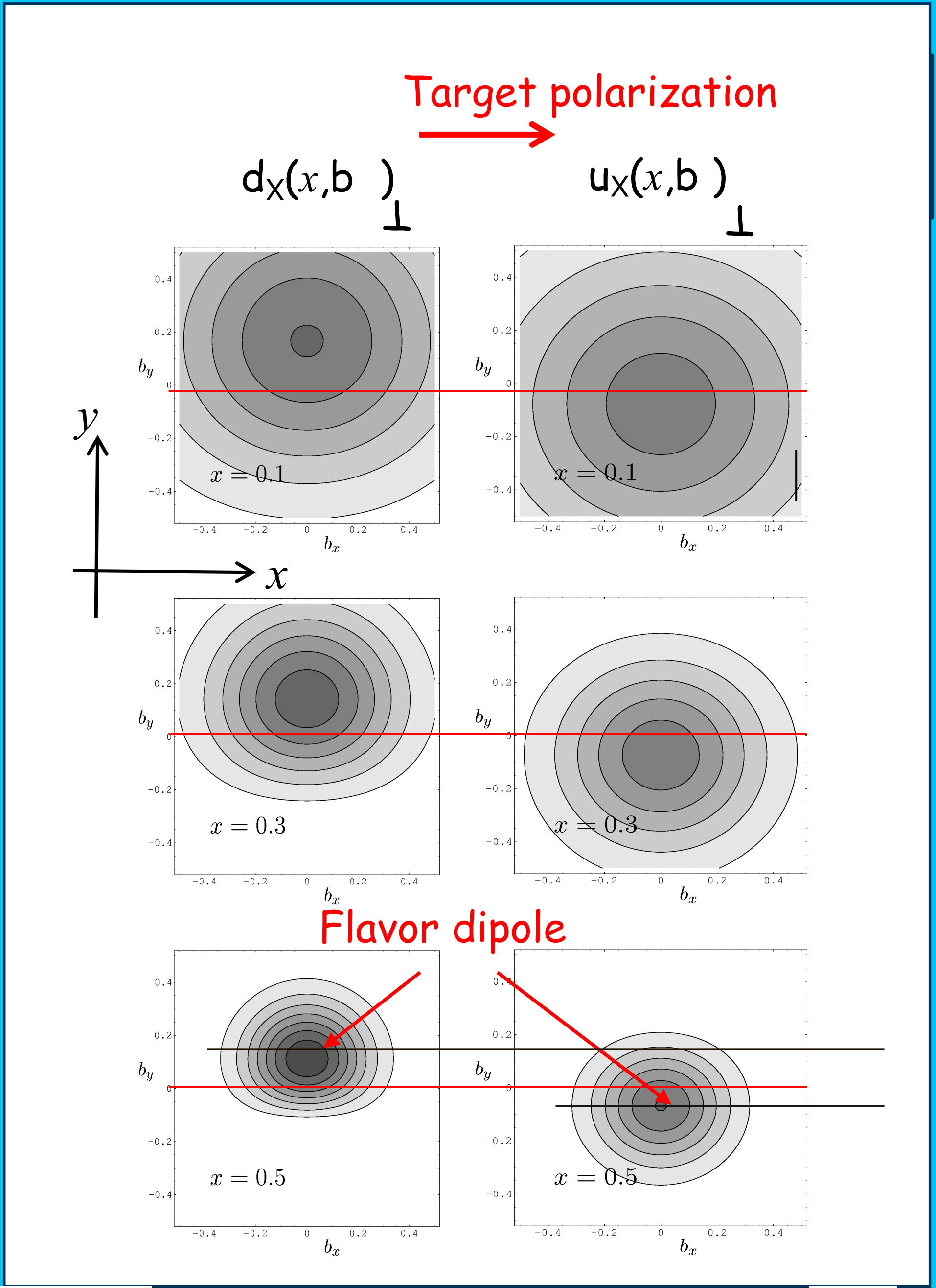




- t-slope → $\langle b^2 \rangle$

The Proton Isn't Round

- Proton spin **s** polarized (statistically) ⊥ to *light-cone* direction z
  - Up and down quarks separate in direction $\hat{s}\times\hat{z}$
  - Average separation dictated by anomalous magnetic moments of *p,n*
- Transverse *p* polarization
  - Difficult in fixed target
  - Natural in collider



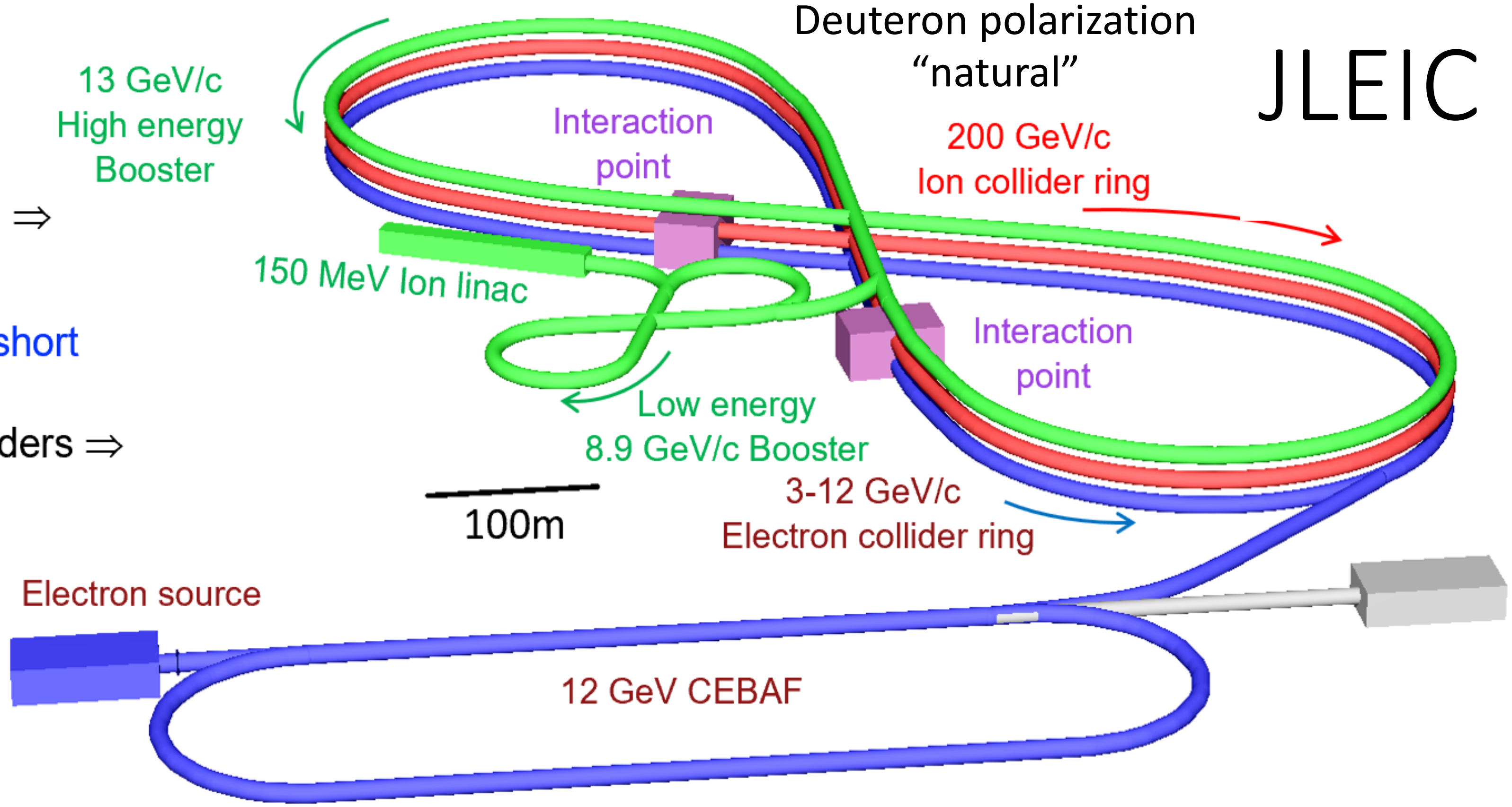
The Electron Ion Collider

- JLEIC or eRHIC
- Mission Need Statement from DOE expected by Oct 2019
  - `Other Project Costs’ requested in FY2020 budget
- T. Hallman (DOE Nuclear Physics) @ EIC Users Group Meeting, Paris France July 2019:
  - ”Implementation review” aka down-select process started, decision “soon” by Paul Dabber, Under-Secretary of Energy for Science
  - **“The EIC will be one of the most complex and sophisticated collider accelerators ever built”**

Why Another Collider?

- 100→ 1000 higher luminosity than HERA
- First ever *eA* with nuclei > proton
- First ever with polarized p, d, ^{3}He… beams
  - Longitudinal and transverse
- First ever with nearly-hermetic forward-detection (electron and ion) designed into Machine-Detector-Interface (MDI)
  - `Detector' is 100 m long
  - Tag spectator & active nucleon(s) for femtography on nearly free neutron in d, ^{3}He

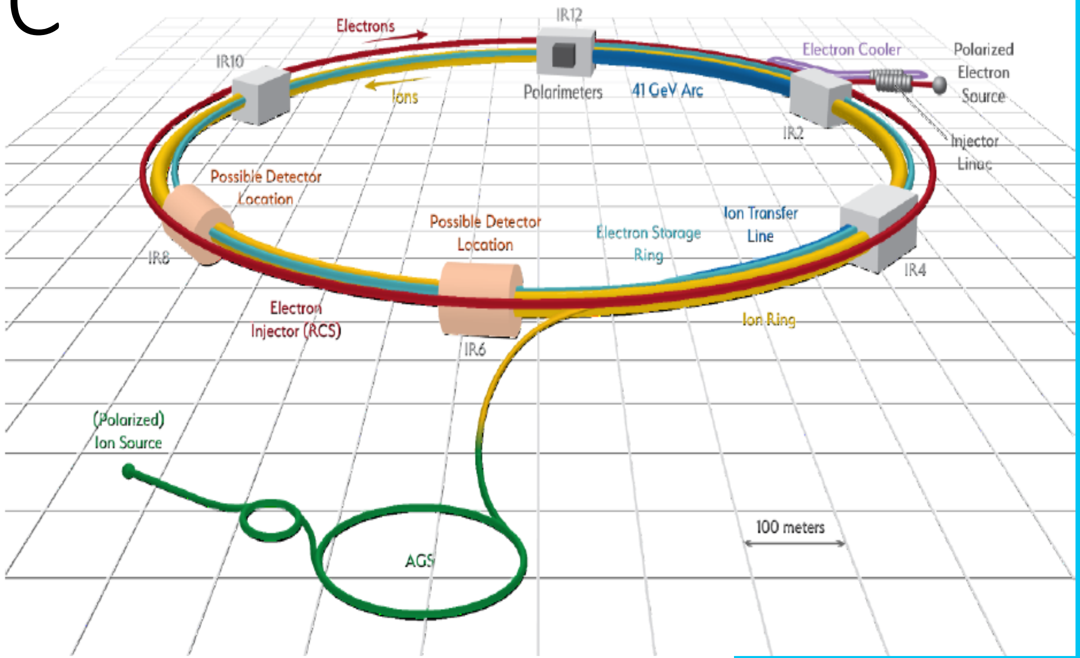
- Full-energy top-up injection of highly polarized electrons from CEBAF ⇒
  High electron current and polarization
- Full-size high-energy booster ⇒
  Quick replacement of colliding ion beam ⇒
  High average luminosity
- High-rate collisions of strongly-focused short low-charge low-emittance bunches similarly to record-luminosity lepton colliders ⇒
  High luminosity
- Multi-stage electron cooling using demonstrated magnetized cooling mechanism ⇒
  Small ion emittance ⇒
  High luminosity



Courtesy A.Seryi, V.Morozov

- Figure-8 ring design ⇒
  High electron and ion polarizations, polarization manipulation and spin flip
- Integrated full acceptance detector with far-forward detection sections being parts of both machine and detector
- Upgradable to 140 GeV CM by replacing the ion collider bending dipoles only with 12 T magnets

eRHIC



- **Hadrons up to 275 GeV**

- eRHIC will use the existing RHIC complex: Storage ring (Yellow Ring), injectors, ion sources, infrastructure,
- Need only few modifications for eRHIC
- Todays RHIC beam parameters are close to what is required for eRHIC

- **Electrons up to 18 GeV**

- Electron storage ring with up to 18GeV installed in RHIC tunnel. ➔ E_{cm} = 20 GeV -141 GeV. Electron beam current limited by the choice of installed RF power 10 MW.
- Electron beams with a variable spin pattern accelerated in the on-energy, spin transparent injector: Rapid Cycling Synchrotron with 1-2 Hz cycle frequency in the RHIC tunnel
- Polarized electron source and 400 MeV s-band injector linac in existing tunnel
- Design meets the high luminosity goal of **$L = 10^{34} cm^{-2} s^{-1}$**

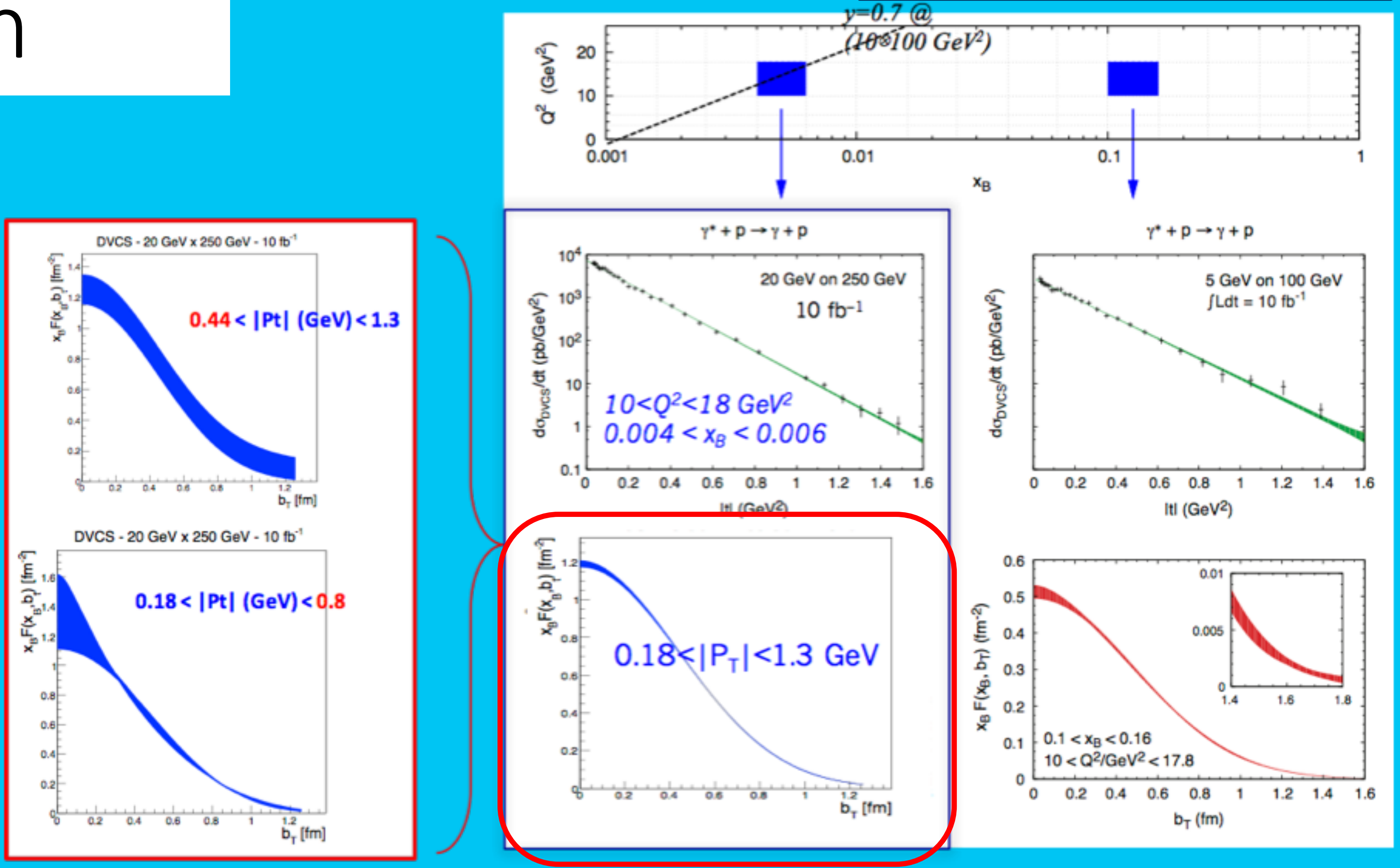
Courtesy F. Willeke

Deuteron Polarization difficult.
Not impossible

Femtograpy @ EIC: DVCS on proton

- Tagging the recoil protons over the full momentum range is essential for precision imaging
- Repeat with L & T polarized beam
- Repeat with polarized D(e,e'$p_S\gamma$n)

eRHIC Simulations
(within JLEIC acceptance)



Other Spatial Femtography topics at JLab & EIC

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- $eN \to eN\ \phi$, $eN \to eN\ J/\Psi$: Gluon Densities
- Nuclei: Longstanding questions about neutron *vs* proton radii of nuclei with *A>2Z*
  - Relevant to structure of Neutron Stars
  - Equivalent to questions of up-quark vs down-quark radii
- Tomography of excited states of the nucleon
- Strange quarks: $ep \to eK^+\Lambda$

Femtography topics I have ignored: Transverse Momentum Densities

- Semi-Inclusive Deep Inelastic Scattering (SIDIS)
  - $ep \to e \genfrac{}{}{0pt}{}{\pi}{K} X$
  - TMD(x,$\mathbf{p}_\perp$): Unfold intrinsic transverse momentum of quark in nucleon from measurement of perpendicular component of momentum of final state meson. Q^2 , $q \bullet P$, M_X^2 all large
  - Easier to measure than GPDs.
  - Harder to interpret than GPDs

Femtography topics I have ignored: Quark-Gluon Wigner Functions

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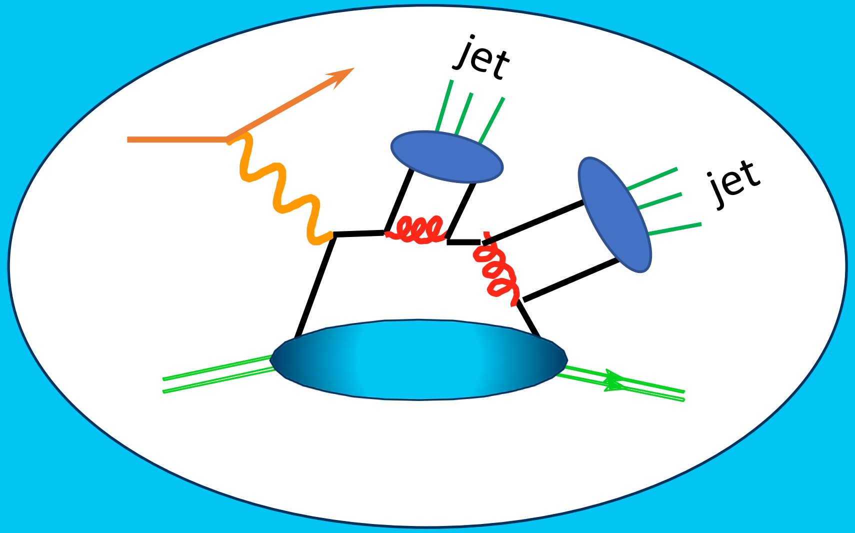
- $W_{f,g}(x,\mathbf{b},\mathbf{p}_\perp)$
- Complete Phase space distribution of single quarks and gluons
- Theory in infancy
- Experiment in pre-infancy
  - $e + p \rightarrow e + p +$ di-jet



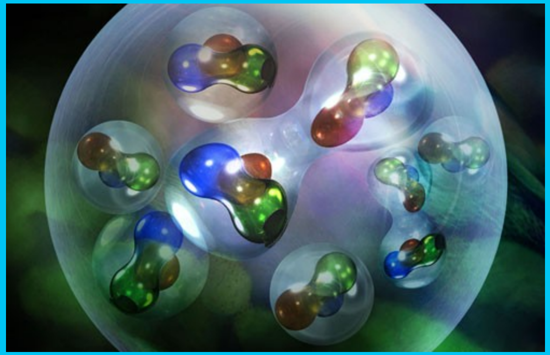
Extremely schematic

Conclusions

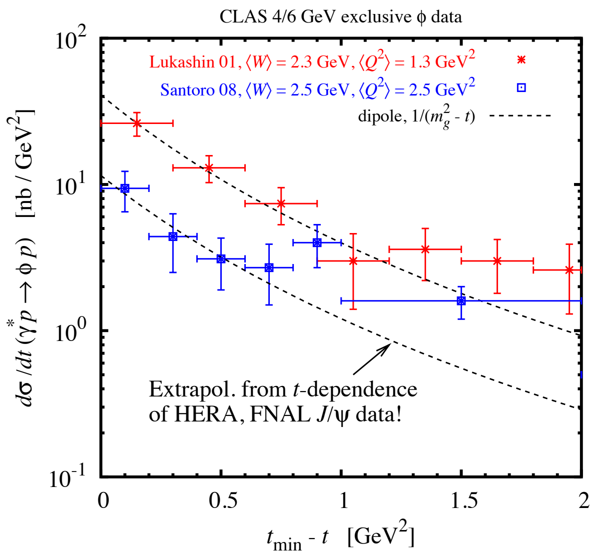
- We (nuclear + accelerator physicists) have a lot of work to do.
- We need your (data science, machine learning, A.I. scientists) help.
- Some examples:
  - Femtography with sparse data, inversion ill-defined
  - Particle track reconstruction in noisy, sometimes ambiguous data
  - Particle Identification
    - Convert raw signals into decisions:
      this was an electron, a pion, a kaon, a proton, a gamma-ray, or a neutron.
- The time is now.
  - Detectors designs must be complete in 4 years
  - Data will start in 10 years

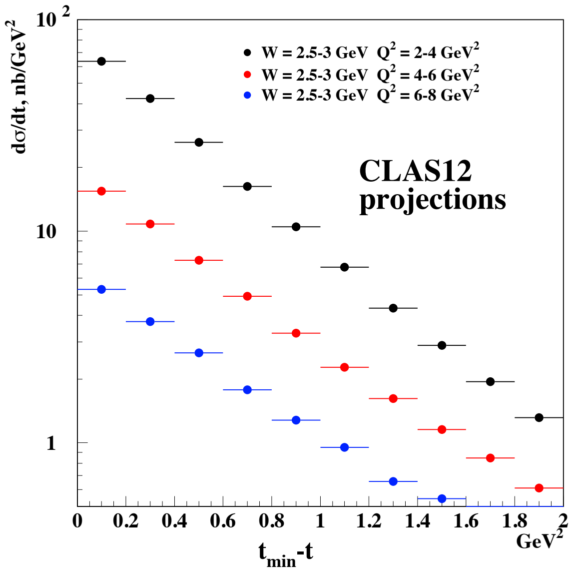
Backup

Commission the glass studio at the Chrysler Museun in Norfolk to make us a nucleus (or proton)



Exclusive ϕ: CLAS12 experiment





- t–dependence of 6 GeV ϕ data consistent with gluonic radius measured at high energies
  Extrapolation of HERA, FNAL J/ψ results

- CLAS12: Test reaction mechanism and harden GPD–based description

  When does t–slope become independent of Q^2?

  How does W–dependence change with Q^2?

  L/T ratio from vector meson decay and s–channel helicity conservation

- CLAS12: Extract t–dependence of gluon GPD at $x = 0.2 - 0.5$

  Obtained from relative t–dependence of $d\sigma_L/dt$

First accurate gluonic image of nucleon at large x!

Key EIC Machine Parameters

as required by the NSAC LRP & NAS

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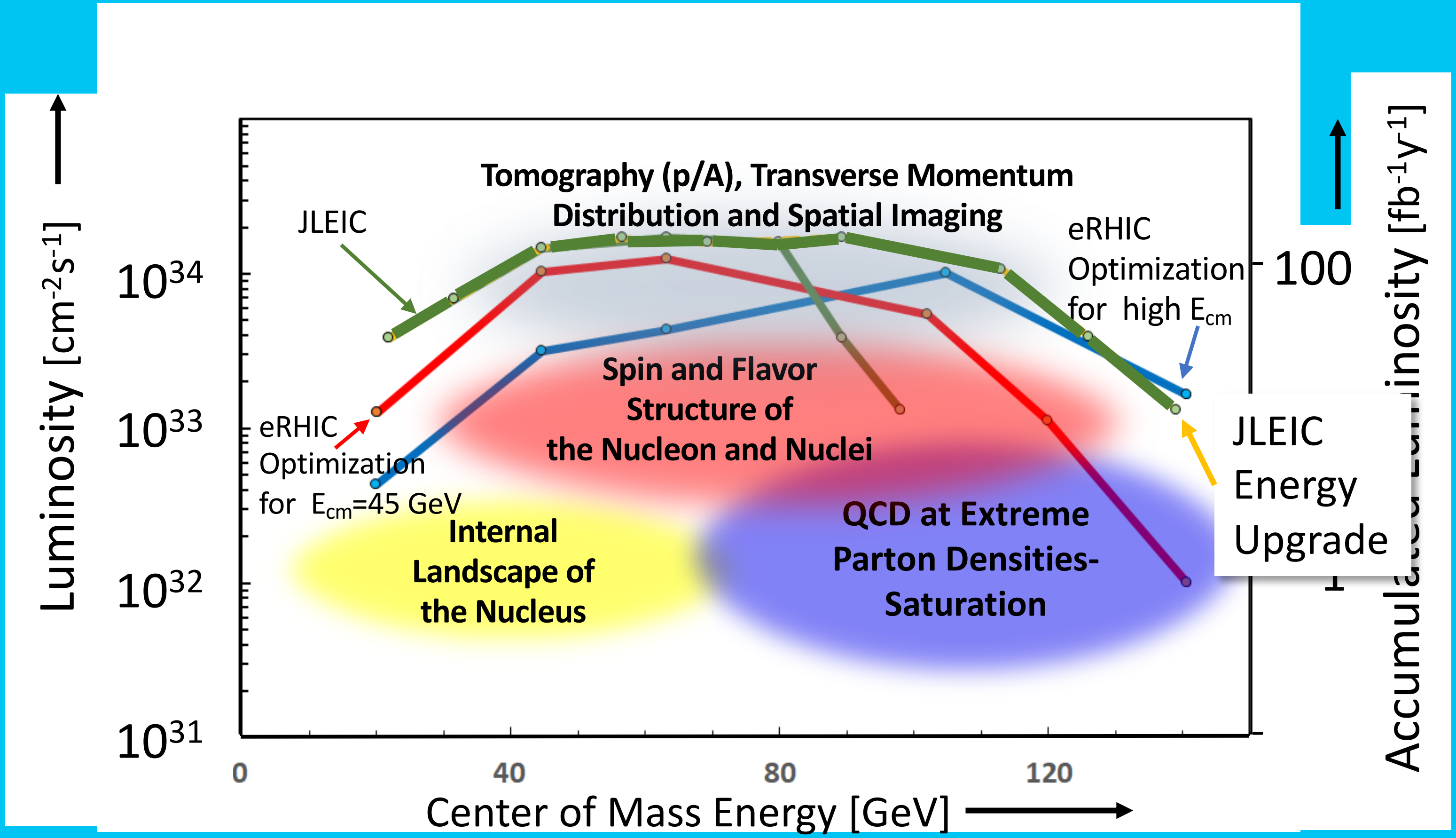
Parameter	Unit	JLEIC	eRHIC
Center of Mass Energies	[GeV]	20-100 a)	20-140
Ion Species		p to U	p to U
Number of Interaction Regions		2	2
Hadron Beam Polarization		85%	80%
Electron Beam Polarization		80%-85%	80%
Maximum Luminosity	$[10^{34} cm^{-2} s^{-1}]$	1.55	1.3

a) upgradable to 140 GeV

Electron Ion Collider

EIC Luminosity

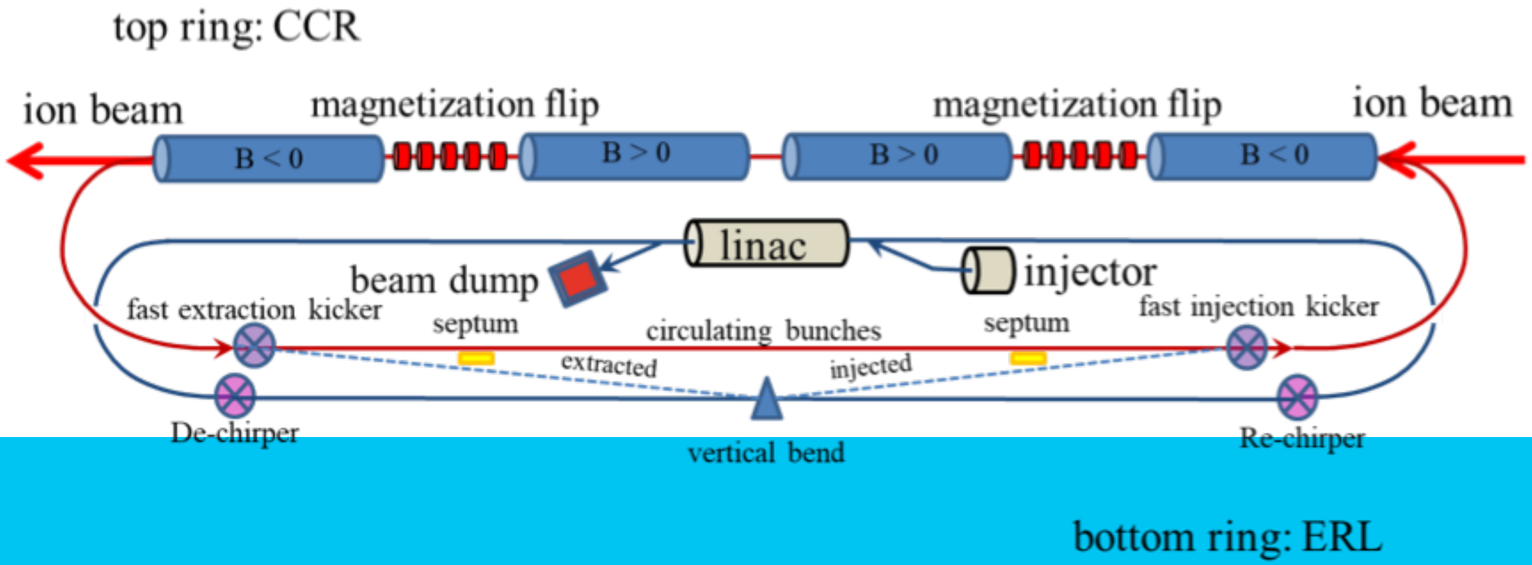


Note: For electron ion collisions, the E_{cm} scale needs to be reduced by a factor $(Z/A)^{1/2}$

Strong Hadron Cooling Scheme for JLEIC

FEMTOGRAPHY

- Magnetized electron beam for higher cooling efficiency
- Cooling electron beam is energy-recovered to minimize power consumption
- 11-turn circulator ring with 1 amp of beam current relaxes electron source requirements
- Fast harmonic kicker to kick electrons in and out of the circulator ring
- Pre-cooling a low energy is essential to achieve the anticipated performance



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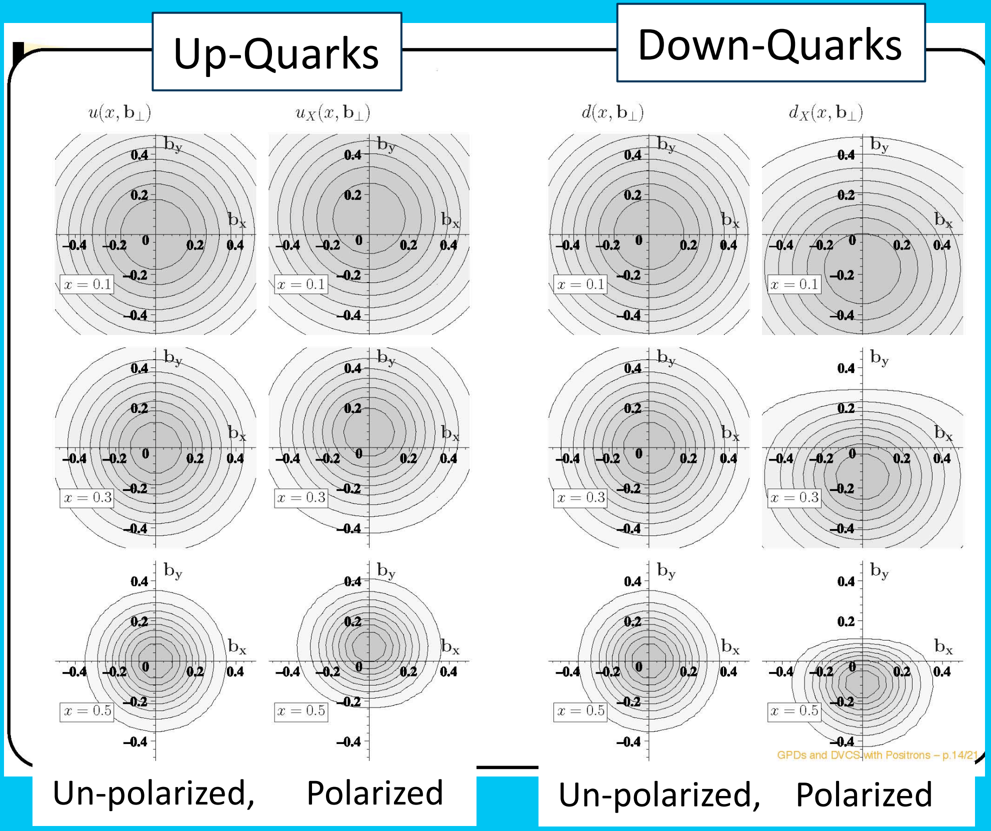

quark wave-length