Physics for a Future US Facility for QCD

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Jefferson Lab, Newport News, VA

APS meeting, 14 February 2010, Washington, DC

Outline

1. Next generation colliders for QCD and nucleon structure

- Introduction

2. Some physics highlights

- Gluon Saturation and Gluons in Nuclei
- Nucleon Spin
- Transverse Quark and Gluon Imaging

3. The US Electron-Ion Collider (EIC) concepts

- Jefferson Lab
- Brookhaven

What I will not talk about

Hadronic facilities

- J-PARC (KEK, Japan)
- FAIR (GSI, Germany)

Fixed-target lepton-hadron facilities

- JLab 12 GeV (US)
- Upgraded COMPASS (CERN, Switzerland)

Sorry!

Science goals of an Electron-Ion Collider (EIC)

Overarching goal: Explore and understand QCD

- Important to directly probe the gluons and sea quarks (meson cloud)

Potential for electroweak physics?

- Very successful PVDIS fixed-target program at Jefferson Lab

NSAC 2007 Long Rangle Plan links the EIC to three questions

- What is the role of of gluons and gluon self-interactions in nucleons and nuclei?
- What is the internal (spin, flavor, spatial) landscape of the nucleons?
- What governs the transition of quarks and gluons into hadrons?

Why a collider?

Easier to reach high CM energies ($E_{cm}^2 = s$)

- $s = 4E_eE_p$ for colliders (*e.g.*, 4 x **8** x **60** = 1920 GeV^2)
- $s = 2E_eM_p$ for fixed target experiments (*e.g.*, 2 x **1000** x 0.938 = 1876 GeV^2)

Spin physics with high figure of merit

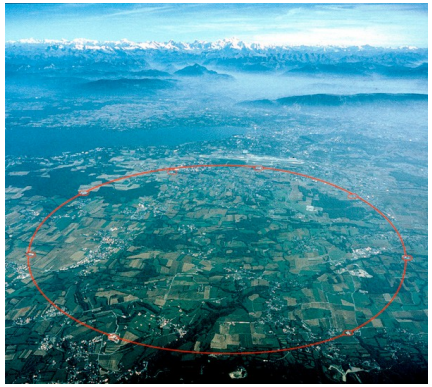
- >70% polarization for both beams – also transverse ion polarization!
- No dilution in polarized target
- No current limitations or holding fields
- No backgrounds from target (including Møller electrons)

Easier detection of reaction products

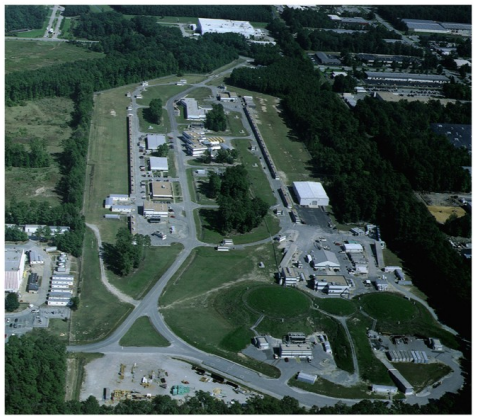
- Can optimize kinematics by adjusting beam energies
  - Laws of physics do not depend on frame, but measured uncertainties do!
- More symmetric kinematics improve acceptance, resolution, particle identification, etc
- Access to neutron structure with deuteron beams through spectator tagging ($p \neq 0$)

Past and future e-p and e-A colliders

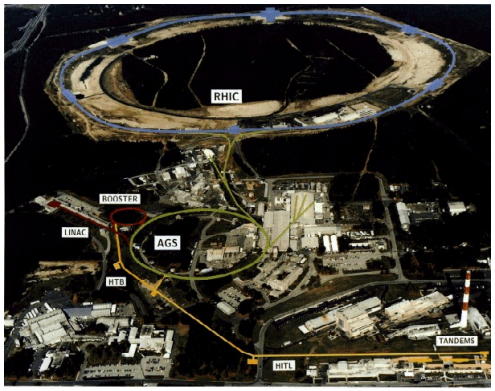
HERA, Hamburg, 1992-2007
27 GeV e on 920 GeV p, L = 5 x 10^{31}



LHeC, CERN, Geneva



EIC



Jefferson Lab, Newport News, VA

Brookhaven, Upton, NY

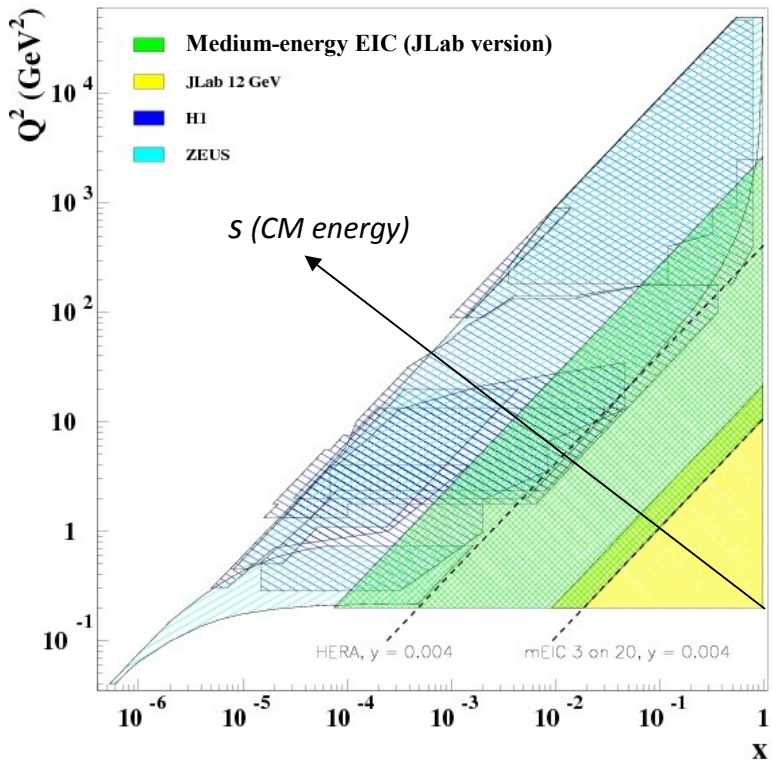
Summary of current e-p/e-A collider ideas

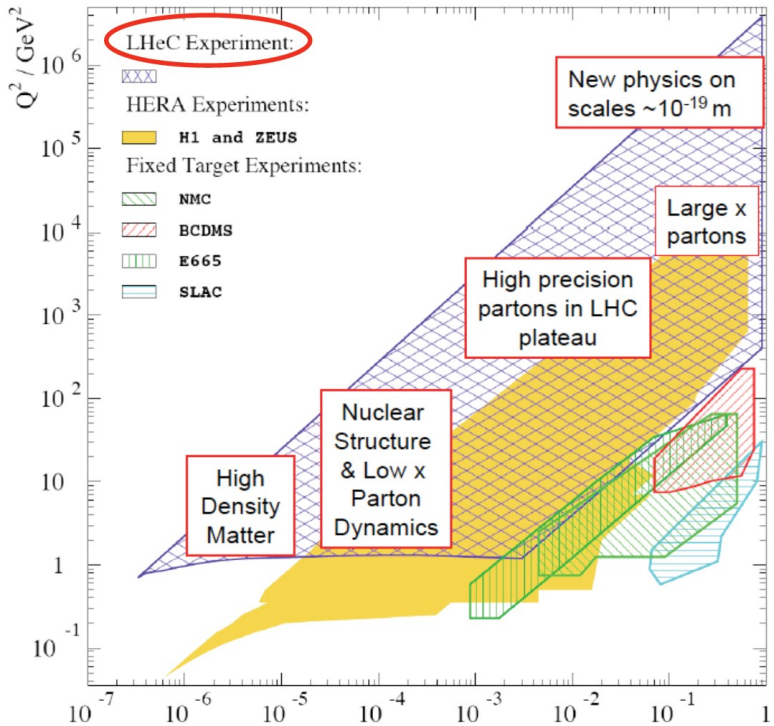
Design Goals for Colliders Under Consideration World-wide

	Max e/p Energies	s	Max Luminosity
ENC@GSI	3 x 15	180	Few x 10^{32}
MEIC@JLab	11 x 60	250-2650	Few x 10^{34}
MeRHIC@BNL	4 x 250	1200-4000	Close to 10^{33}
ELIC@JLab	11 x 250	11000	Close to 10^{35}
eRHIC@BNL	20 x 325	26000	Few x 10^{33}
LHeC@CERN	70 x 1000	280000	10^{33}

Kinematic coverage

$Q^2 \sim xys$

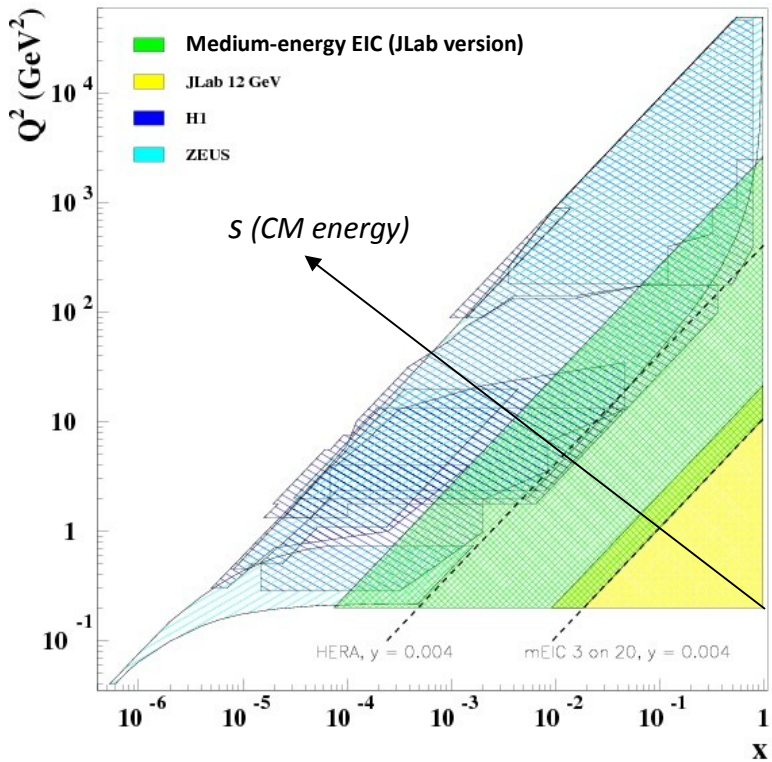


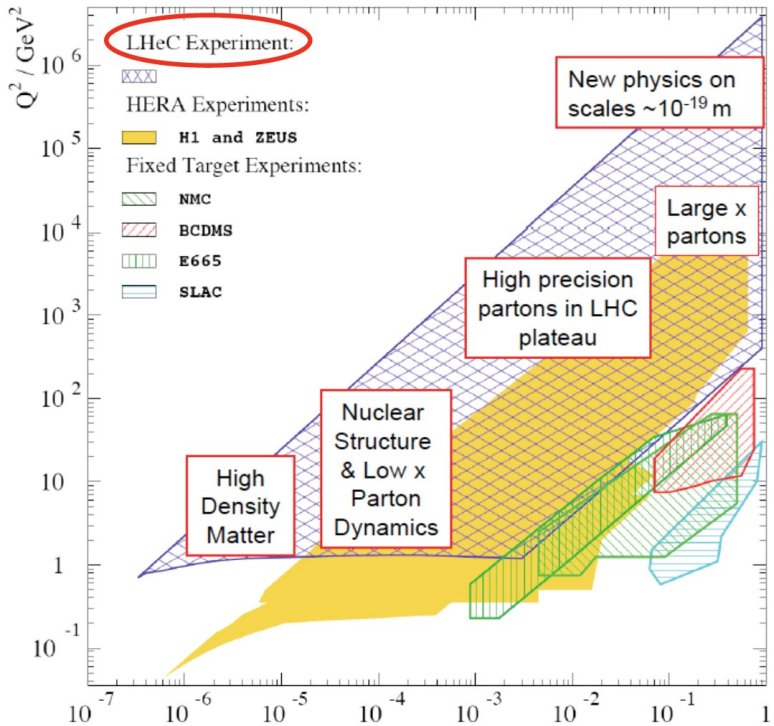


- Medium-energy EIC
  - Overlaps with and complements the LHeC (both versions)
  - Overlaps with JLab 12 GeV at corresponding luminosity (JLab version)
  - Provides high luminosity and excellent polarization for the range in between
    - Currently only low-statistics fixed-target data available in this region

Kinematic coverage

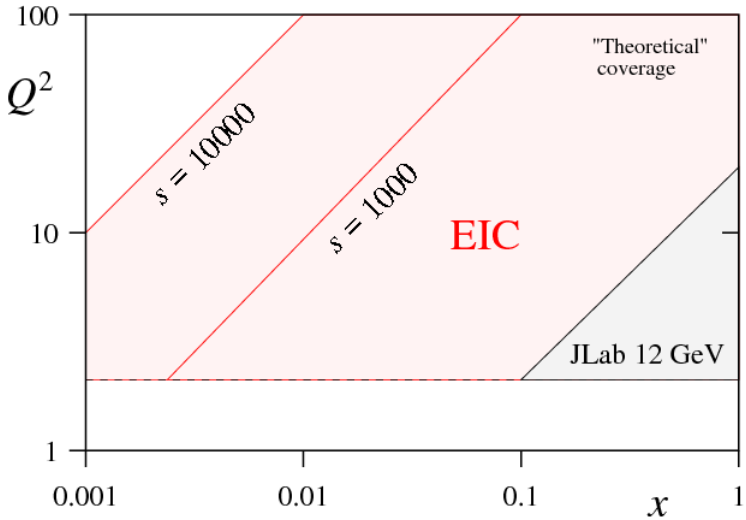
$Q^2 \sim xys$





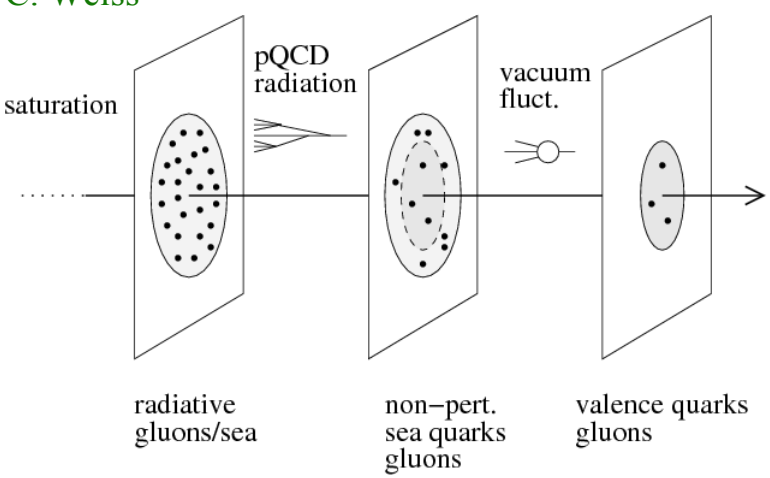
- High-energy EIC (not shown)
  - Will move higher into the region covered by HERA (and LHeC)
  - Will provide good polarization and heavy ions (which HERA did not have)
  - If LHeC is not build, may be only machine that can see gluon saturation in *e-A* collisions

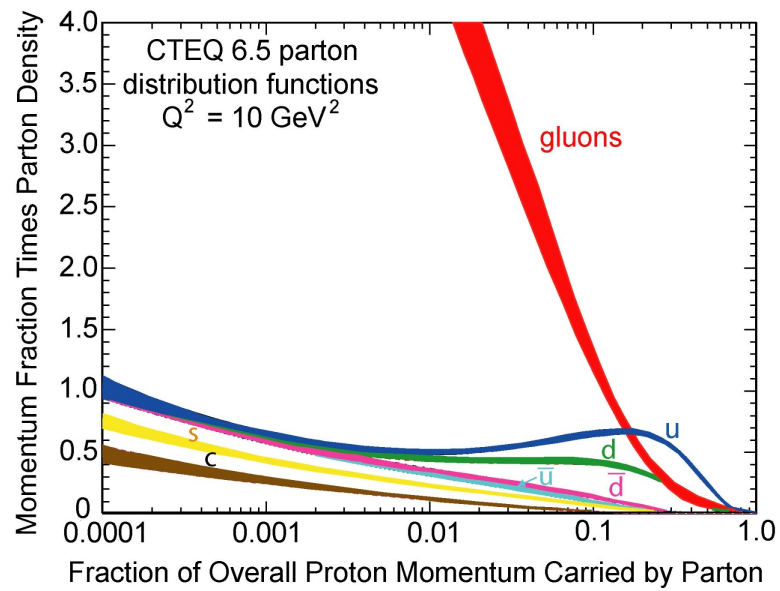
Nucleon structure beyond the valence region



- JLab 12 GeV: valence quarks
- EIC: gluons and sea quarks

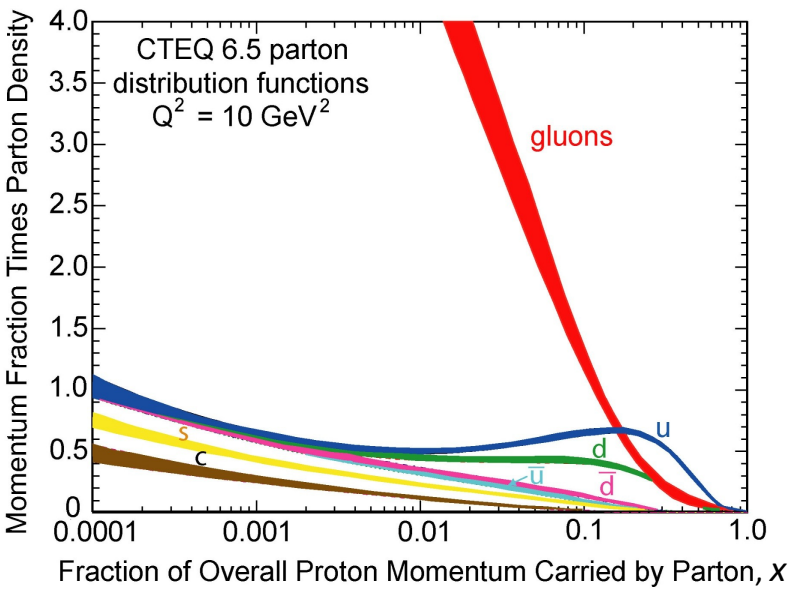
C. Weiss

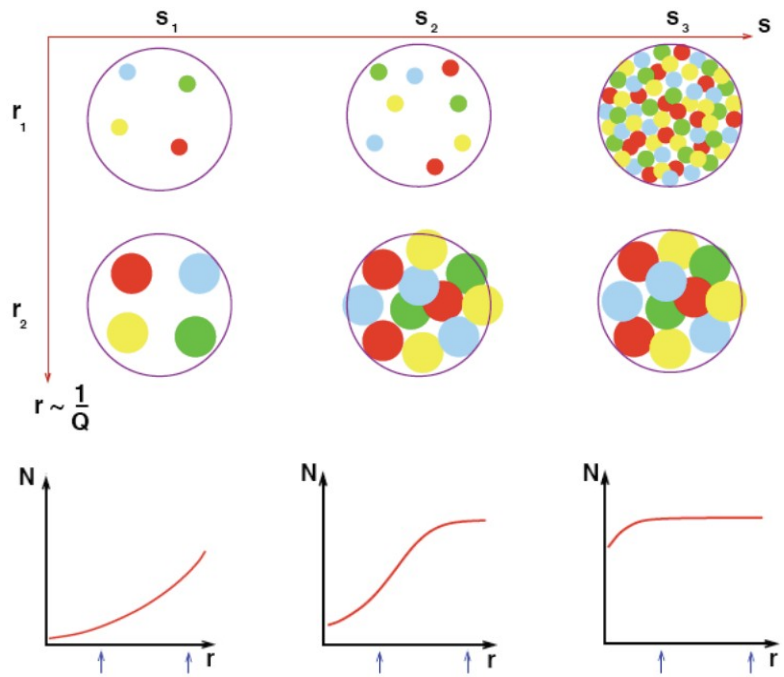




Gluon saturation

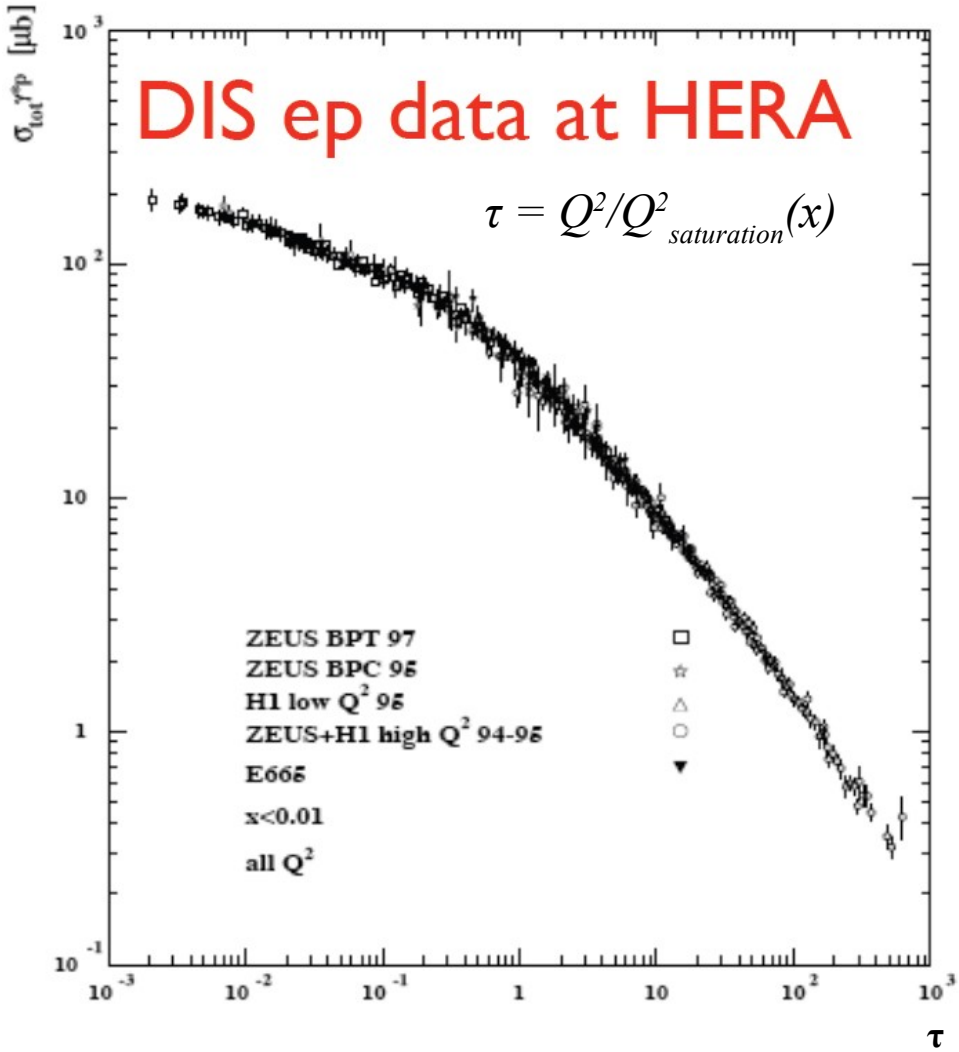
$Q^2 \sim xys$





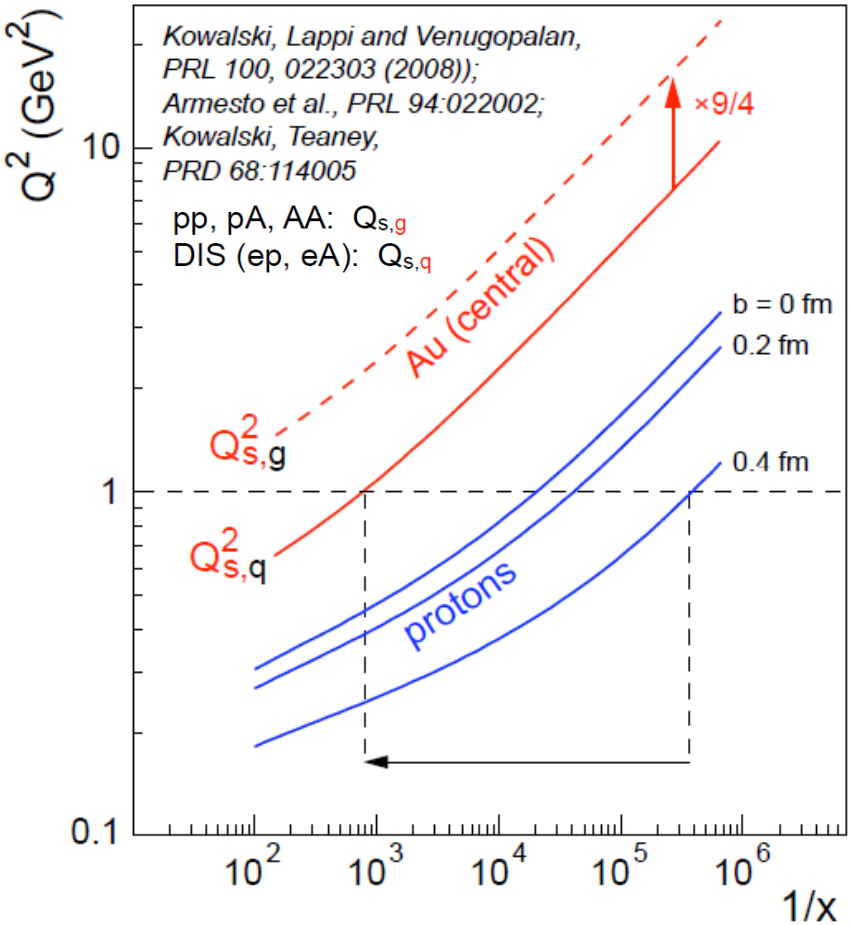
- At low virtuality (Q^2) photons are "large" probes
- One is more likely to find gluons carrying a small fraction of the total momentum (small x)
  - For a fixed Q^2 this corresponds to a rise in gluon density with collision energy (s)
- At some point (at low Q^2 and high s) the cross section (number of gluons) saturates
- Interesting for understanding QCD dynamics!

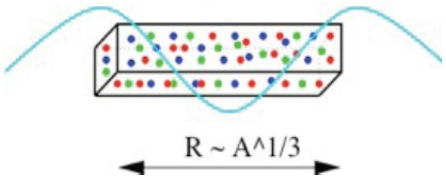
Gluon saturation in the nucleon



- HERA *e-p* data indicate that the cross section begins to saturate at small values of τ
- The saturation regime will be explored in ultraperipheral *p-p* collisions at the LHC
- Better measurements using *e-p* may be possible at the LHeC
- Gluon saturation in the proton will be outside the energy reach of the EIC
- EIC will study the transition to saturation in *e-p* collisions
  - Outside of LHeC reach
  - As important!

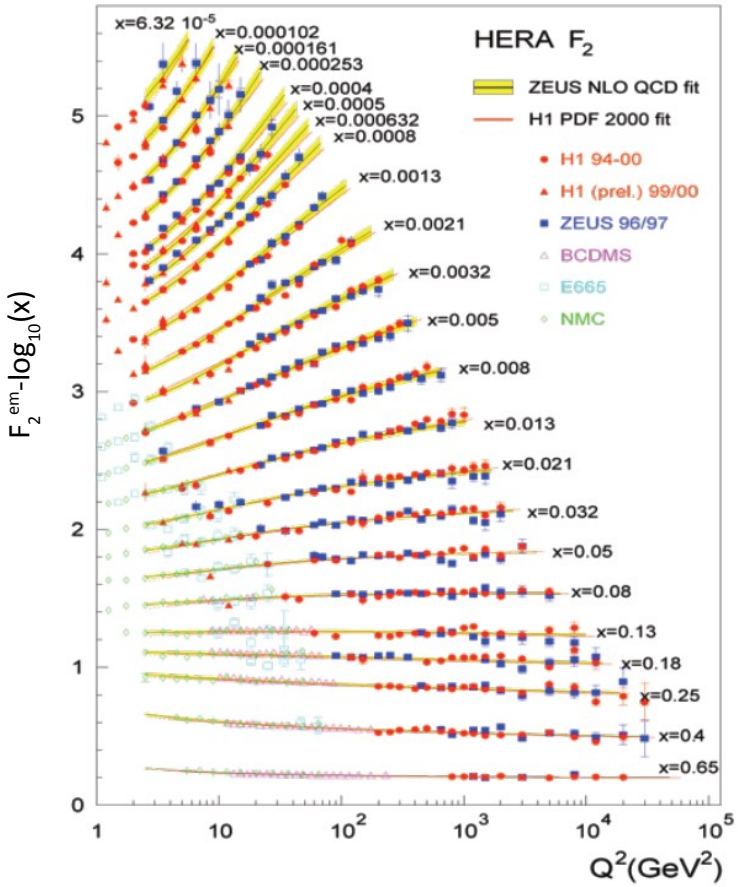
Gluon saturation in nuclei





- If the probe interacts coherently, there will be an enhancement, naively proportional to the radius.
- Nuclear beams make it possible to see the onset of saturation at lower collision energies.
- Results from *A-A* collisions at RHIC indicate that saturation models (Color Glass Condensate) may be applicable at unexpectedly low energies
- Saturation in *e-A* collisions may be within reach of an EIC

Gluons in nuclei



$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

Role of gluons in nuclei

- As important as saturation physics!

Longitudinal gluon distributions

- Measured at HERA for the nucleon (see figure)
  - DIS: $F_L \sim xG(x,Q^2)$, scaling violations in F_2
  - Diffractive vector meson production
  - 2+1 jet production
- EIC will provide the data on nuclei!

Multidimesional gluon distributions

- Coherent exclusive reactions
  - DVCS
  - Vector meson production (J/Ψ, φ, ρ)
- Generalized Parton Distributions
  - Will be discussed in the context of the nucleon

The spin of the proton

ambiguities arise when decomposing proton spin in gauge theories

Jaffe, Manohar;
Bashinsky, Jaffe

reshuffling of ang. momentum
between matter and gauge degrees
only $\Delta\Sigma$ unchanged

Ji

intuitive; partonic interpretation
Δg, $L'_{q,g}$ local only in $A^+ = 0$ gauge
how to determine $L'_{q,g}$ experimentally ?

manifest gauge invariant local operators
contain interactions $\rightarrow$ interpretation ?
$L_q + \Delta q/2$, $J_g \leftrightarrow$ GPDs (DVCS)

- lattice results for L_q are for Ji's sum rule and cannot be mixed with Δg
- num. difference between L_q and L_q' can be sizable

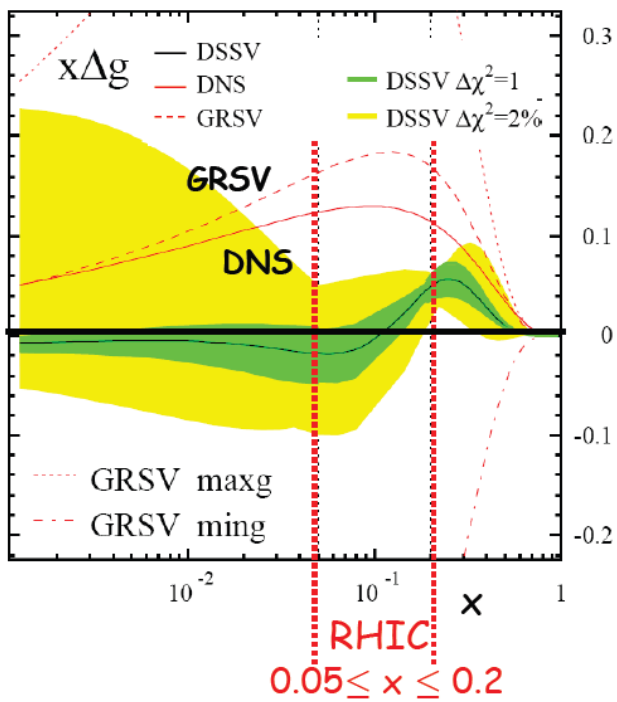
Burkardt, BC
arXiv:0812.1605

(From M. Stratmann, INT09-43W)

Proton spin – two complementary approaches

- Measure GPDs and TMDs to learn about angular momentum (Ji)
  - Connects with Lattice QCD
  - Exclusive measurements require high luminosity at lower energies

- Measure Δg (Jaffe *et al.*) over a sufficiently wide range in x



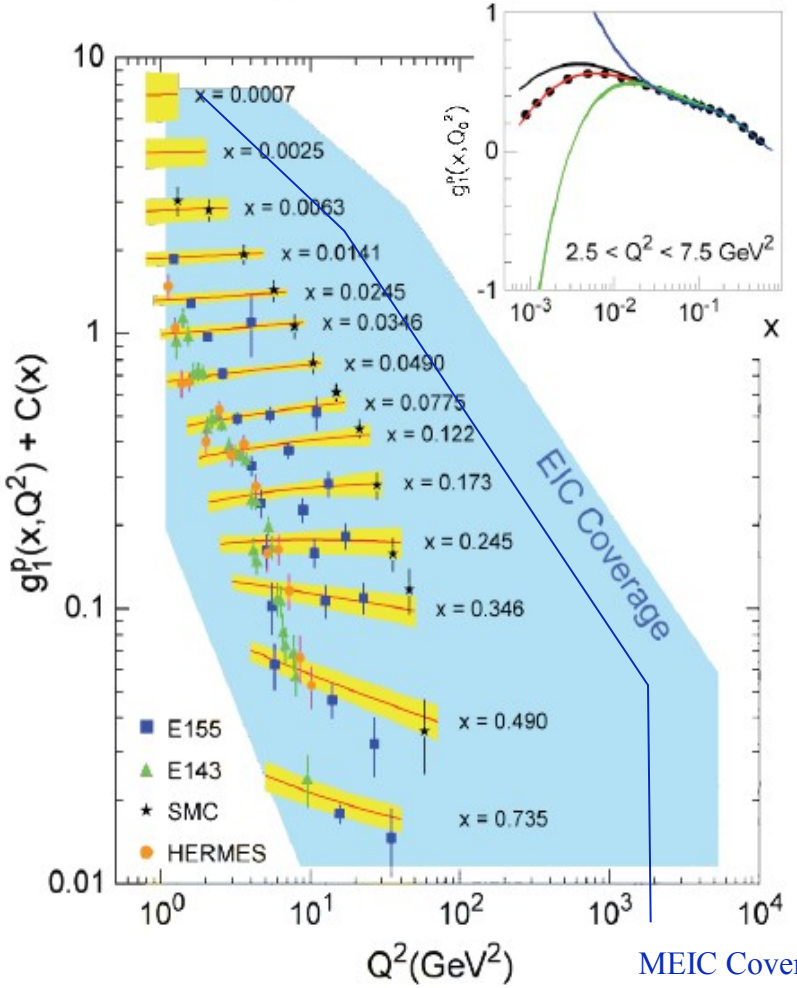
- At sufficiently small x, xΔg is expected to be small, but not clear what is sufficiently small (are we there yet?)

- The net contribution measured by RHIC spin is close to zero

- Since all values of x contribute to the final uncertainty, this will be large without data at small x

Measuring Δg (Jaffe *et al.*) at an EIC

$$\frac{d\,g_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$

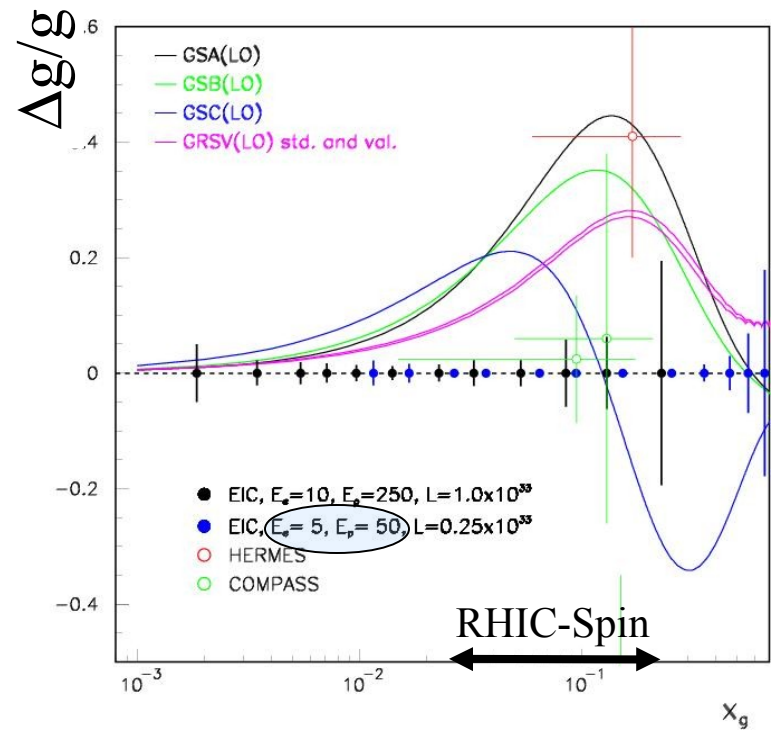


MEIC Coverage

(Antje Bruell, Abhay Deshpande, Rolf Ent)

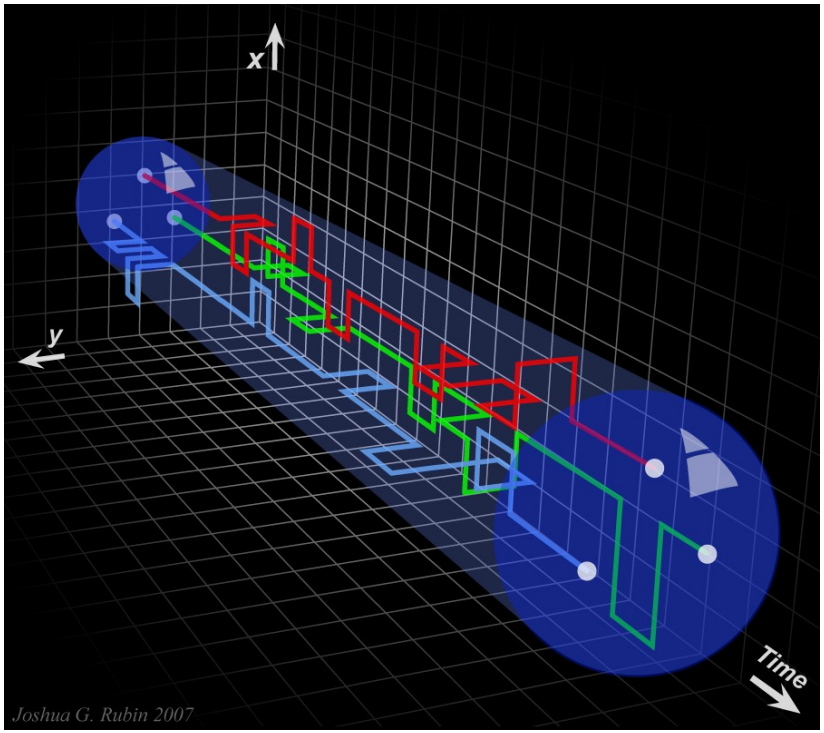
$\gamma + p \rightarrow D^0 + X$

$\hookrightarrow K^- + \pi^+$



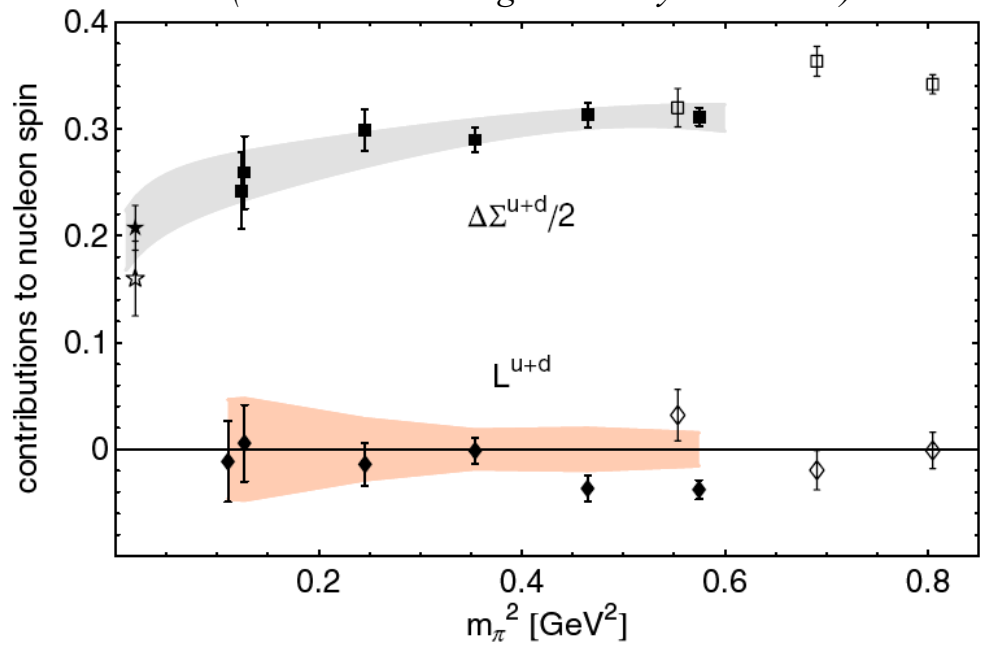
- Uncertainties in xΔg smaller than 0.01
- Measures ΔG @ $Q^2 = 10\ GeV^2$

$\Delta\Sigma$ and L_q (Ji) from Lattice QCD



LHPC Collaboration, PRD77, 094502 (2008)

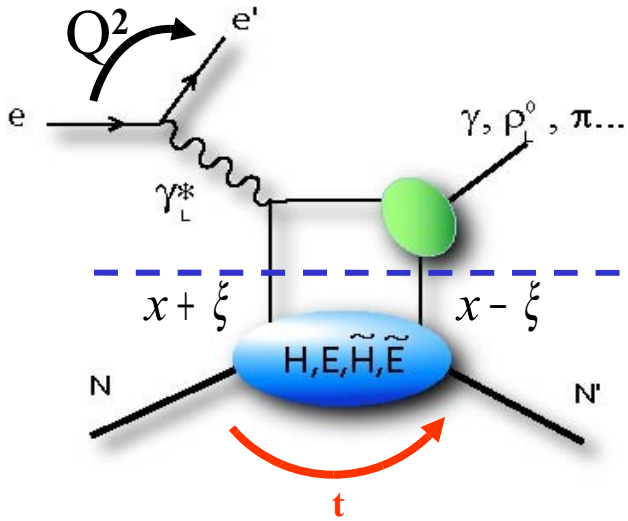
(disconnected diagrams not yet included)

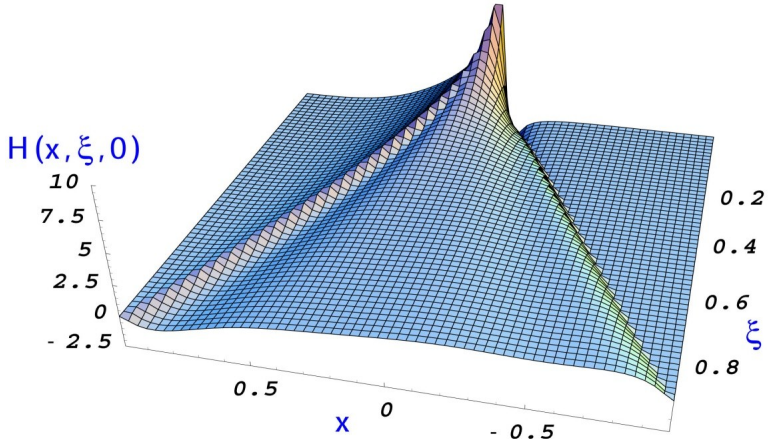


- Lattice QCD allows calculations in the non-perturbative regime
- Gives access to moments of GPDs, experimentally extracted from deep exclusive scattering data

- Orbital angular momentum of quarks
  - L^u and L^d are both ~ 0.15, but cancel
- Quark spin $\Delta\Sigma$ as expected
- Implications for gluon angular momentum J^g

Generalized Parton Distributions (GPDs)





Elastic Form Factors

$$\int_{-1}^{+1} dx\, H^q(x,\xi,t) = F_1^q(t) \qquad \int_{-1}^{+1} dx\, \tilde{H}^q(x,\xi,t) = g_A^q(t)$$

$$\int_{-1}^{+1} dx\, E^q(x,\xi,t) = F_2^q(t) \qquad \int_{-1}^{+1} dx\, \tilde{E}^q(x,\xi,t) = h_A^q(t)$$

Parton Distribution Functions (PDFs)

$$H^{q,g}(x,\xi = 0, t = 0) = q(x)$$

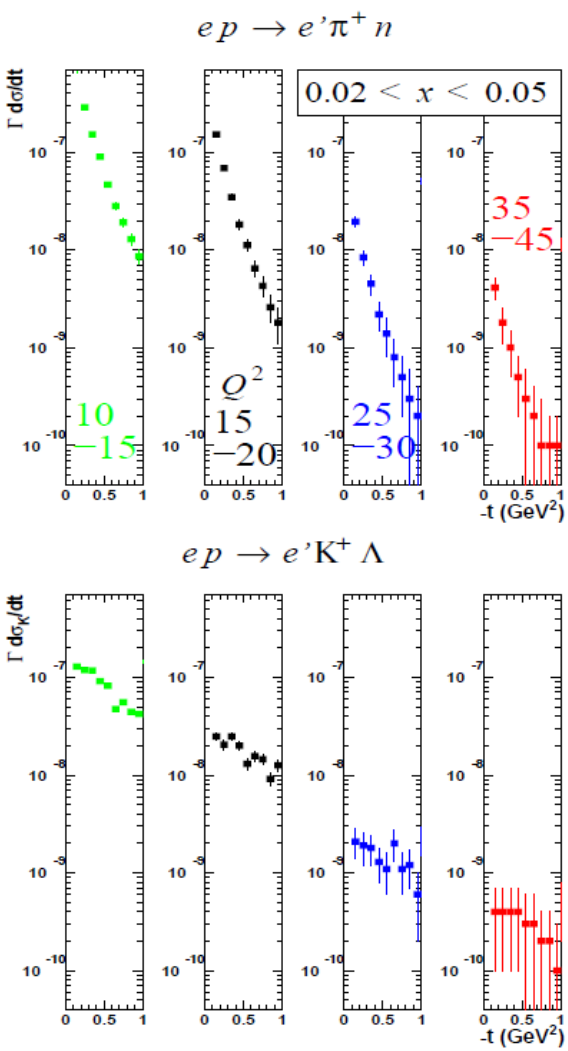
$$\tilde{H}^{q,g}(x,\xi = 0, t = 0) = \Delta q(x)$$

$E, \tilde{E}$ don't appear in DIS (*nucleon helicity flip)*

Generalized Parton Distributions

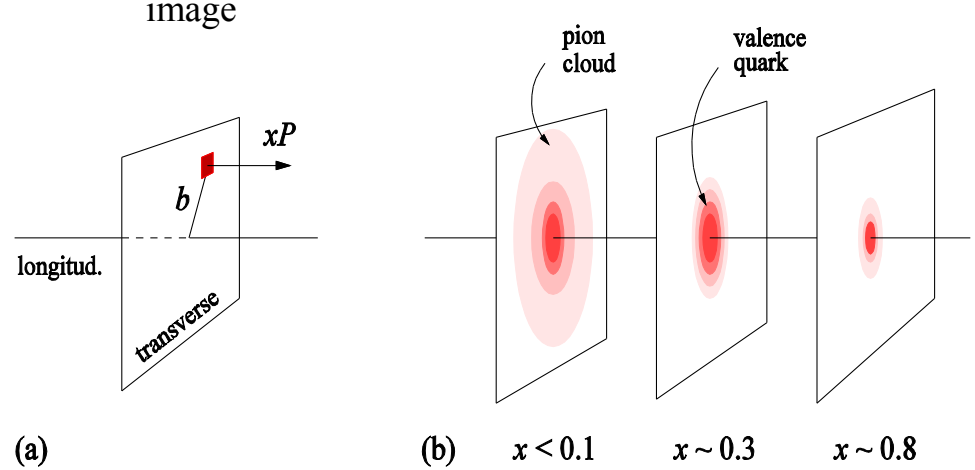
- The GPD framework contains FFs and PDFs
  - Transverse spatial information
  - Longitudinal momentum information
- Skewness (ξ) can provide information on longitudinal $q\bar{q}$ correlations

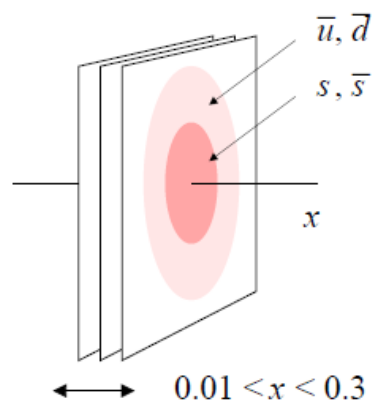
Transverse (sea) quark imaging



Tanja Horn

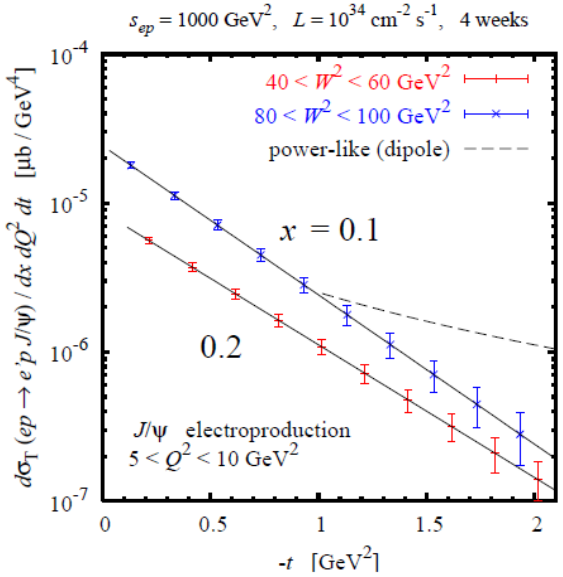
- GPDs as "x-dependent form factors"
  - Fourier transform of t-distribution provides transverse image

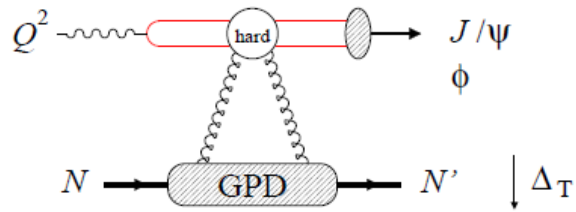




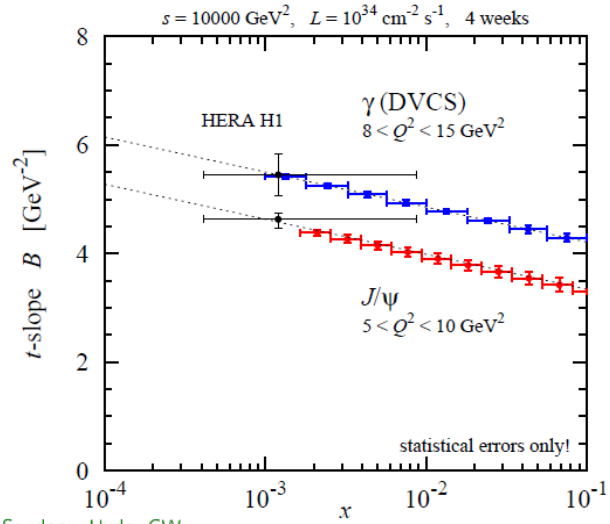
- Do strange and non-strange sea quark distributions have the same radius?
- πN or KΛ components in nucleon?

Transverse gluon imaging

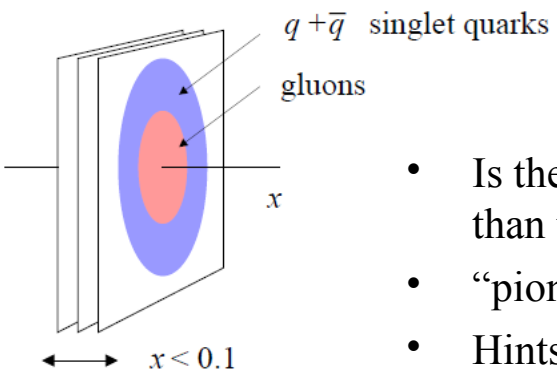




- Exclusive J/Ψ production a directly probe of gluons
- Hard scale given by mass, factorization ok even at low Q^2
- t-distribution powerlike for large -t?

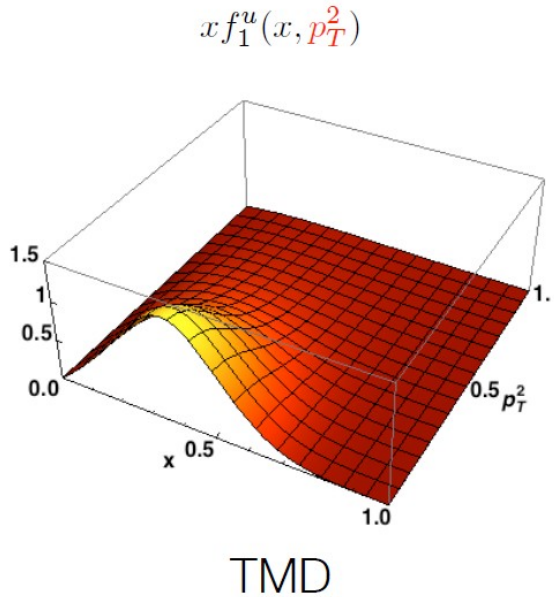


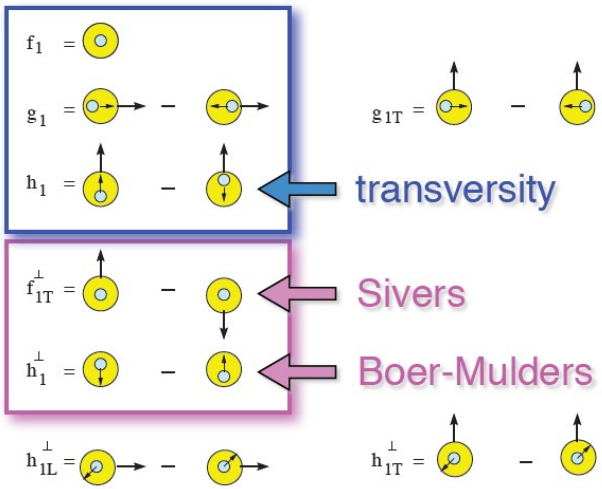
Sandacz, Hyde, CW



- Is the quark "radius" larger than the gluon radius?
- "pion cloud"
- Hints in HERA data

Transverse Momentum Distributions (TMDs)





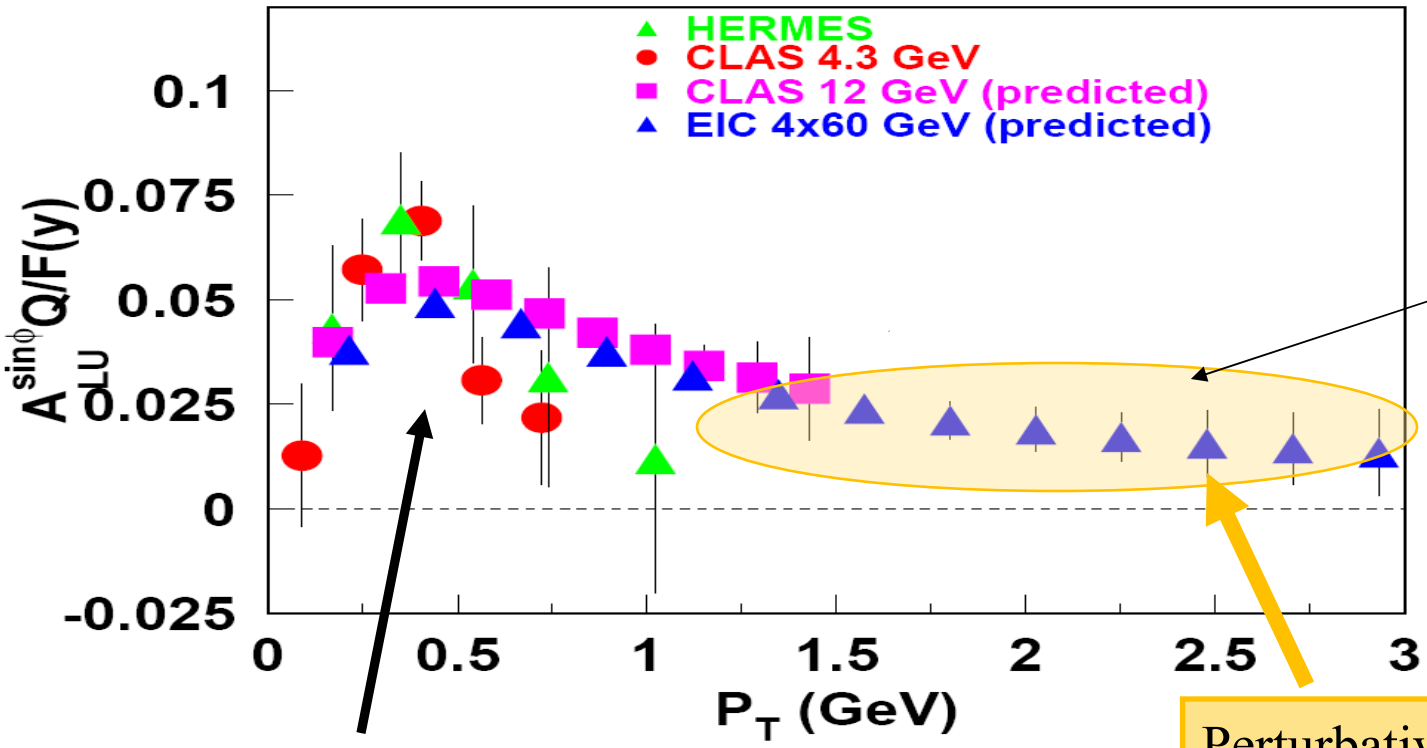
A. Bacchetta

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\quad + S_L\,\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad + S_T\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\quad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}
\end{aligned}
$$

- In SIDIS, PDFs can remain *unintegrated* over transverse momentum
- Parton and nucleon spins then give 18 structure functions
- Can be combined into TMDs, from which we can learn about *orbital angular momentum*

SIDIS: P_T-dependence

Transverse motion through, *e.g.*, spin-orbit interactions, "deformations"



H. Avakian

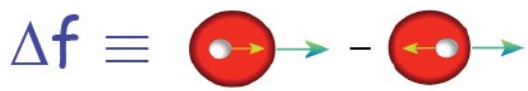
In the perturbative limit $1/P_T$ behavior is expected

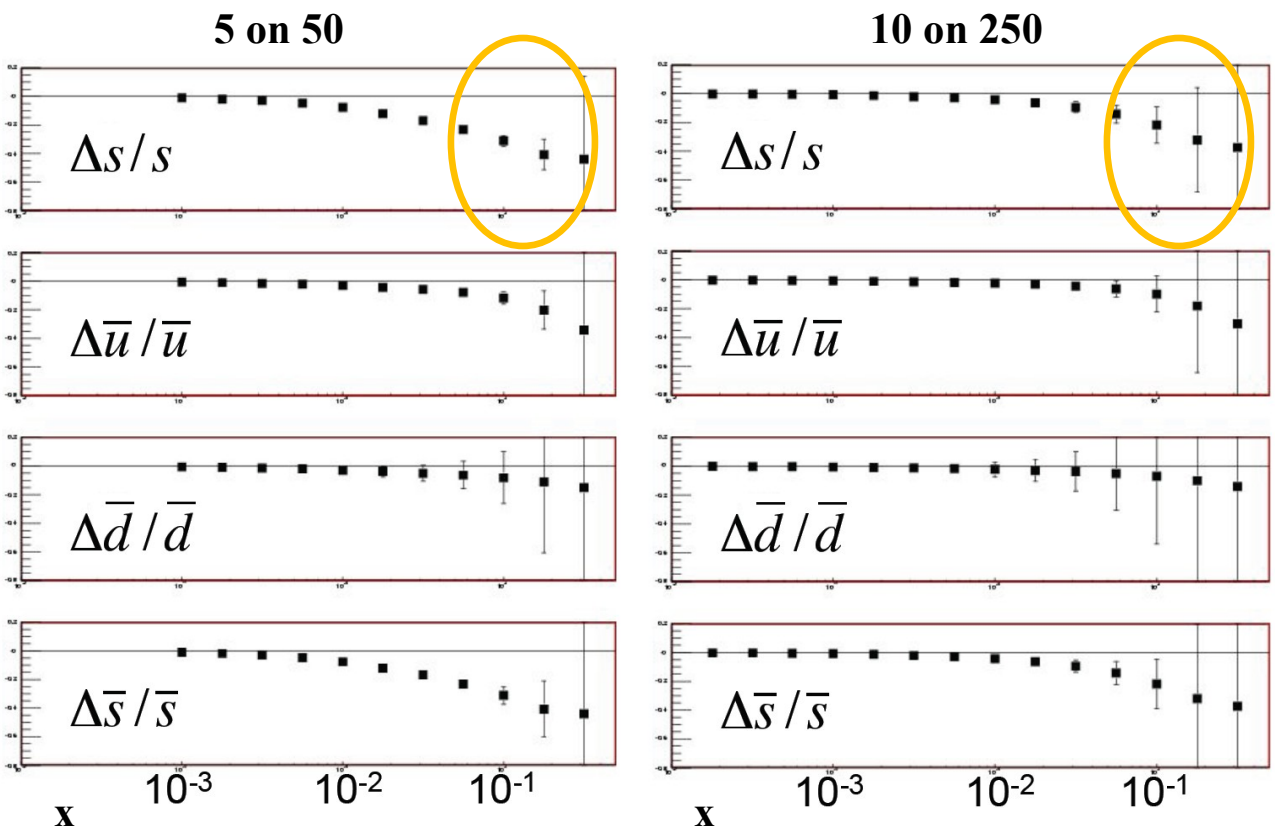
Nonperturbative TMD

Perturbative region

Study SSA in transition from non-perturbative to perturbative regime. EIC will significantly increase the P_T range.

Flavor decomposition in SIDIS





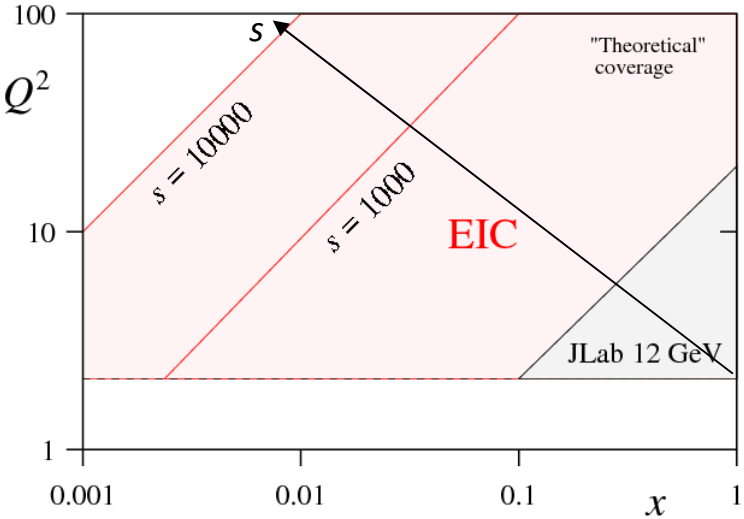
100 days at 10^{33} cm^{-2} s^{-1} shown

E. Kinney, J. Seele

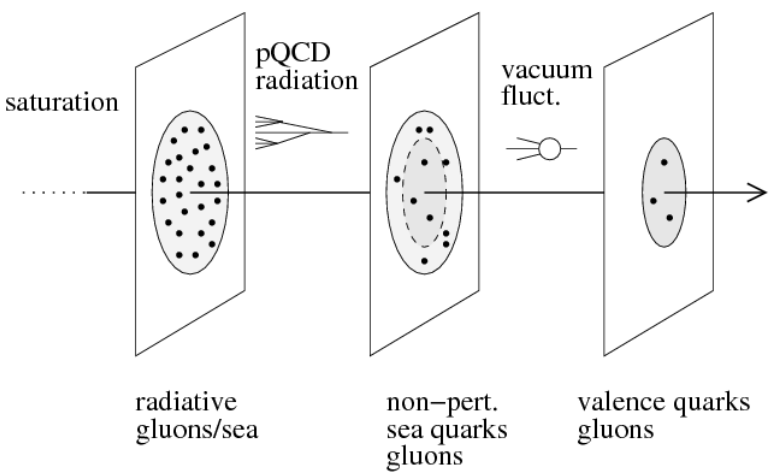
- Higher CM energies give
  - better coverage at small *x*
  - larger uncertainties at large *x* (> 0.1)

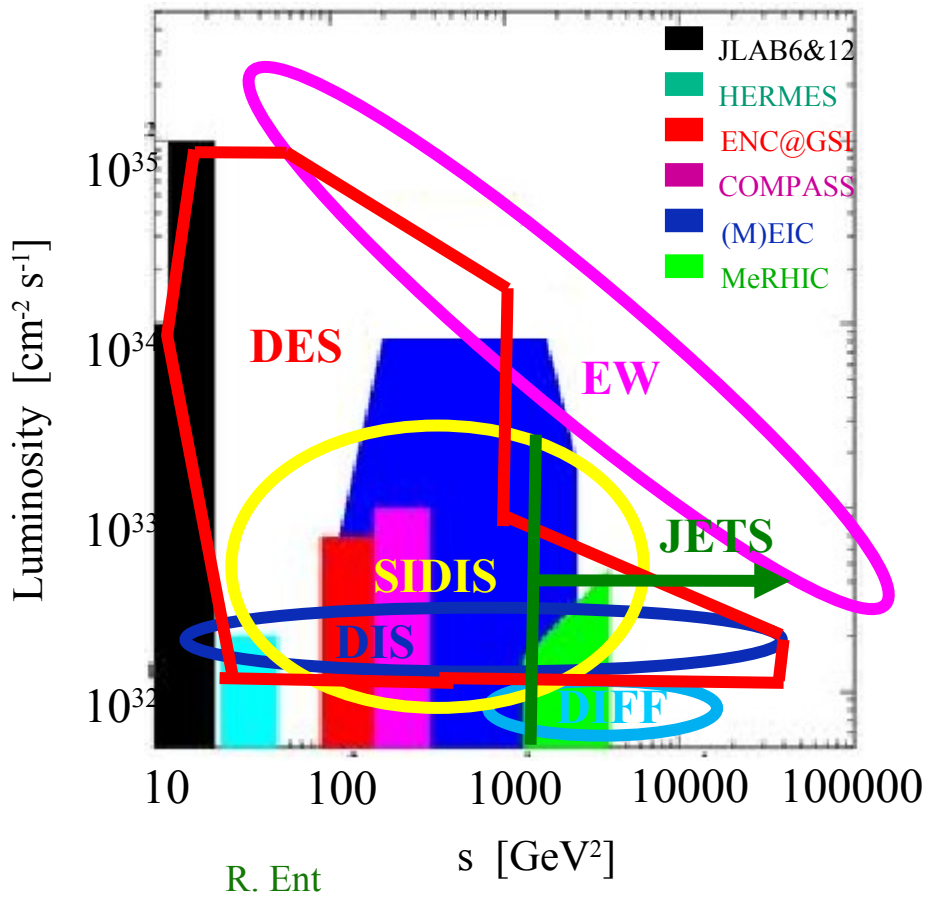
Note that inclusive DIS giv $\Delta q + \Delta\bar{q}$

Physics, kinematic coverage, and luminosity



C. Weiss

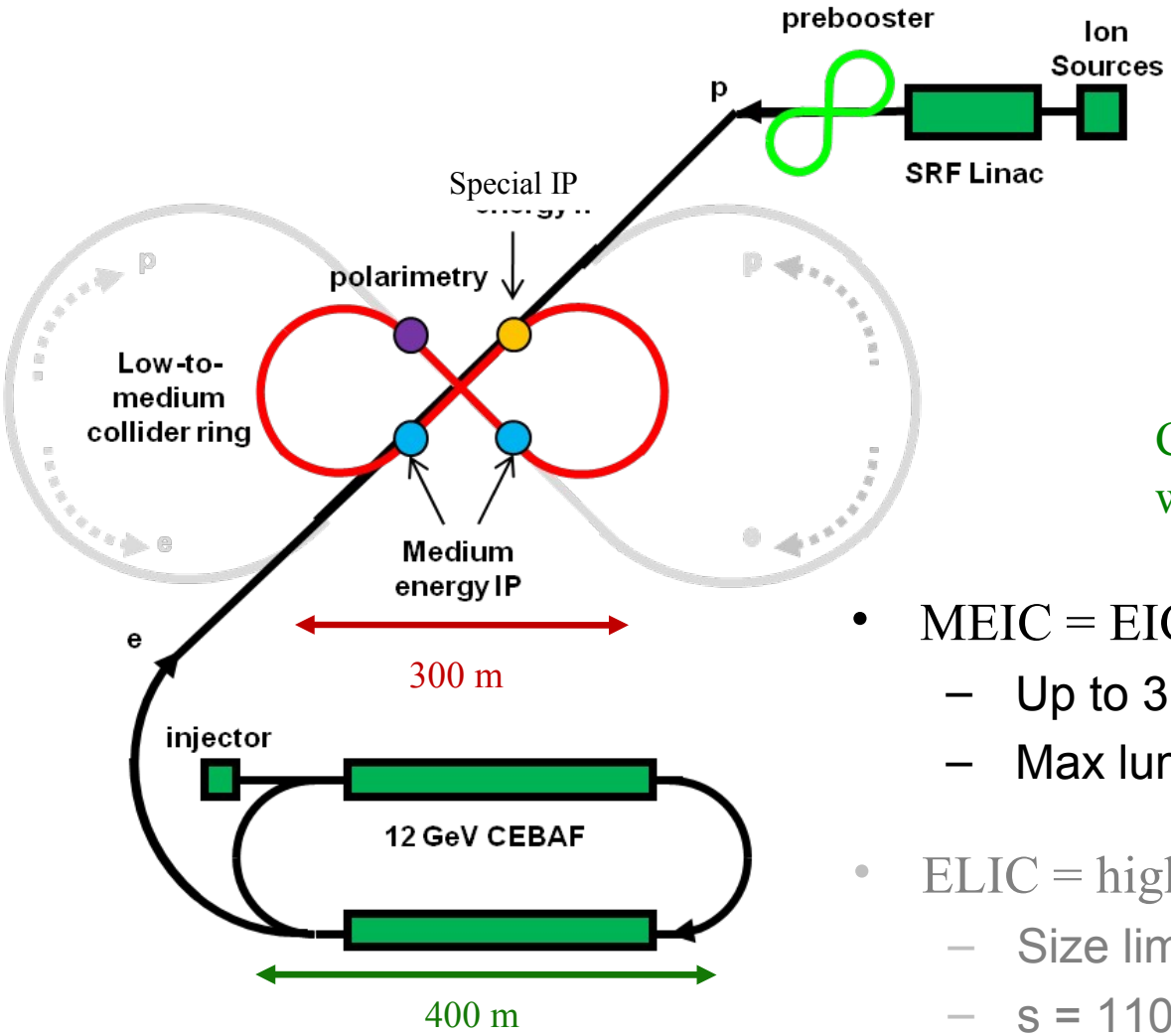




R. Ent

- Right plot (L vs. s) is a projection on the diagonal of the left one (Q^2 vs. x)

MEIC@JLab (Ring-Ring) – an overview



Electron energy: 3-11 GeV

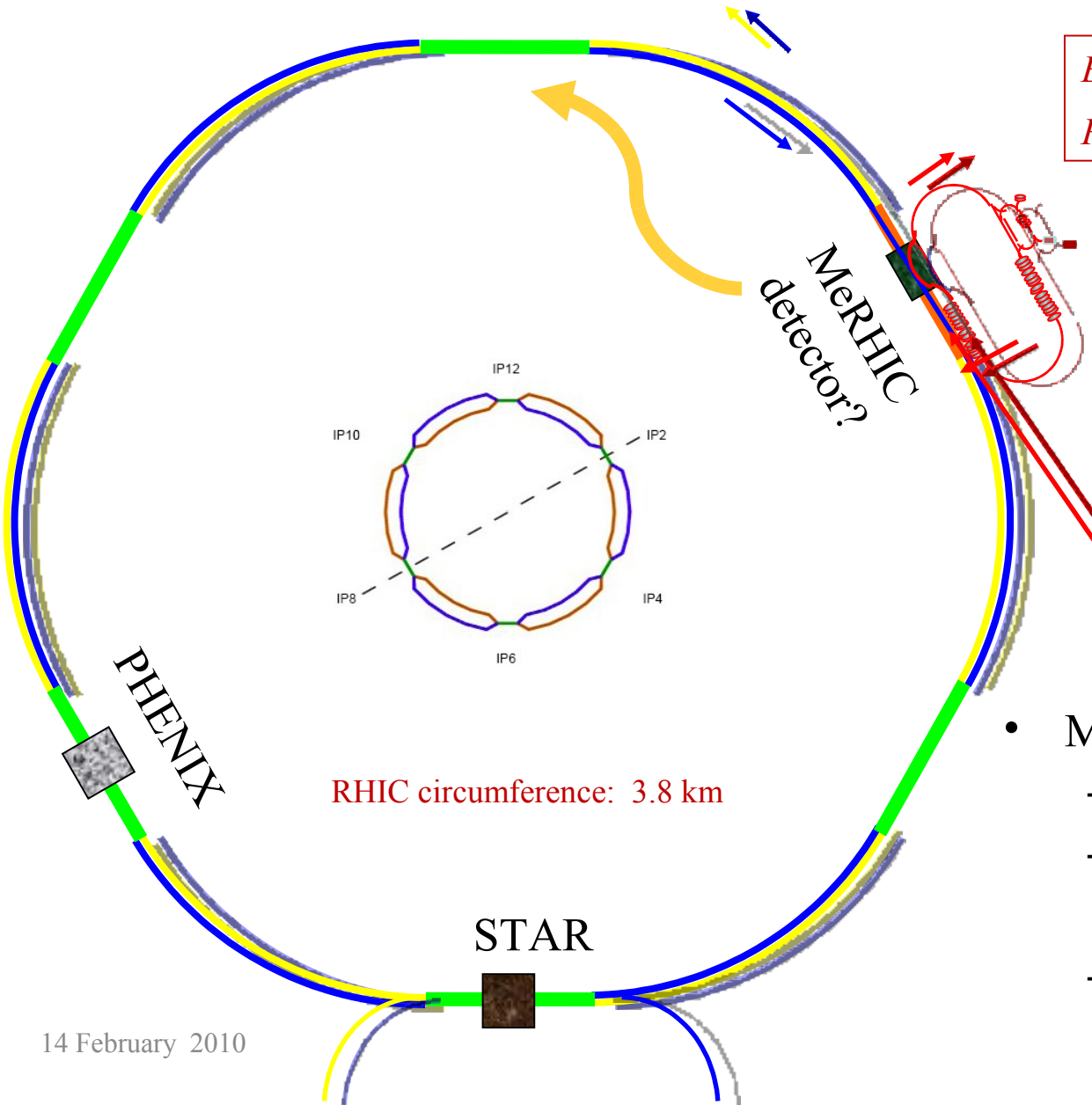
Proton energy: 12-60 GeV

s = 250 - 2650 GeV^2

Can operate in parallel with fixed-target program

- MEIC = EIC@JLAB
  - Up to 3 detectors
  - Max luminosity: above 10^{34} cm^{-2}s^{-1}
- ELIC = high-energy EIC@JLab
  - Size limited by JLab site
  - s = 11000 GeV^2

MeRHIC@BNL (ERL-Ring) – an overview



Electron energy: 2-4 GeV

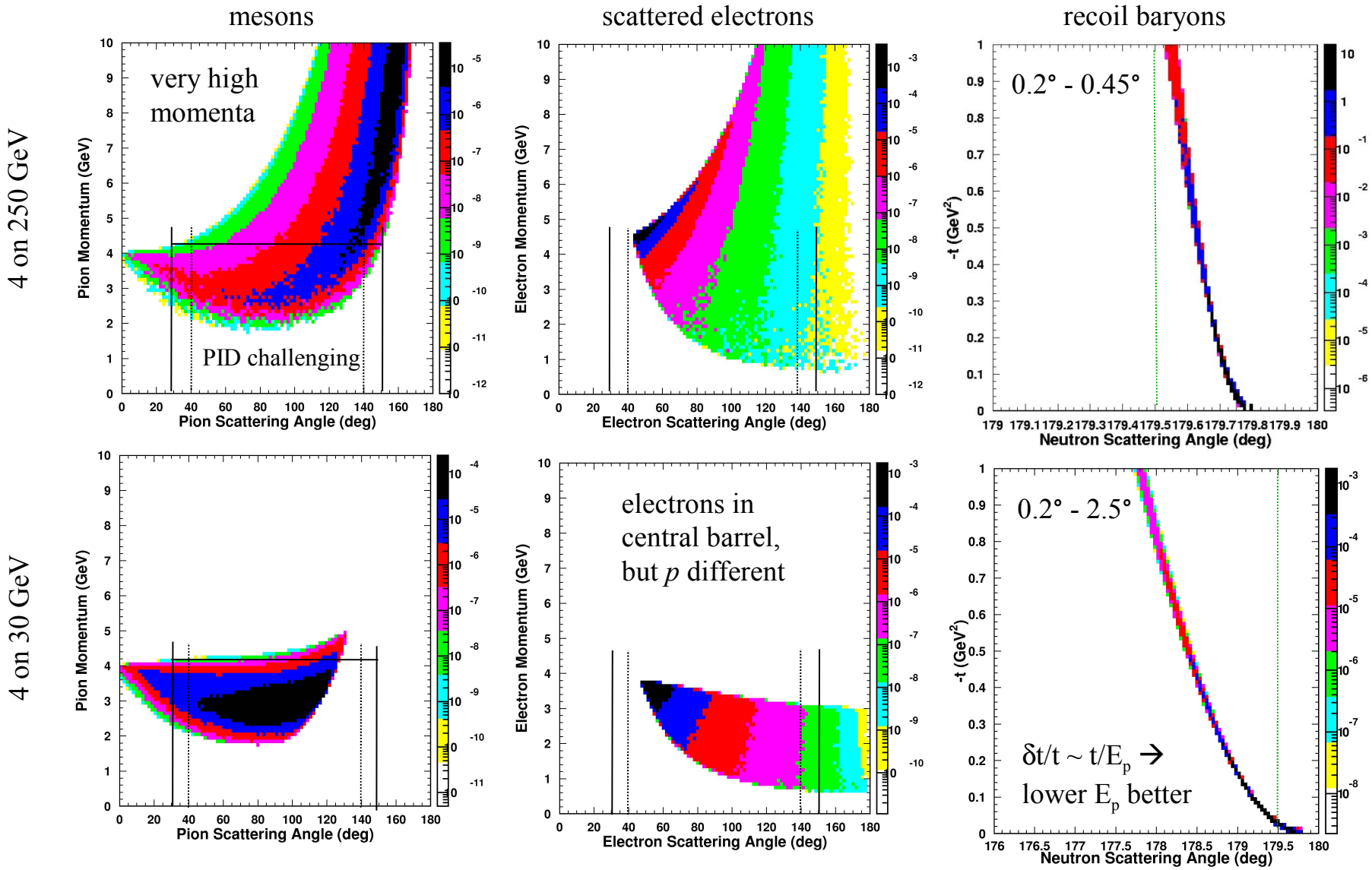
Proton energy: up to 250 GeV

$s = 1200 - 4000\ GeV^2$

3 pass, 4 GeV ERL

- MeRHIC
  - 1 (2 ?) detector(s)
  - Max Luminosity: 10^{32}-10^{33} $cm^{-2}s^{-1}$
  - 90% of hardware can be reused for eRHIC.

Exclusive light meson kinematics ($Q^2 > 10$ GeV^2)



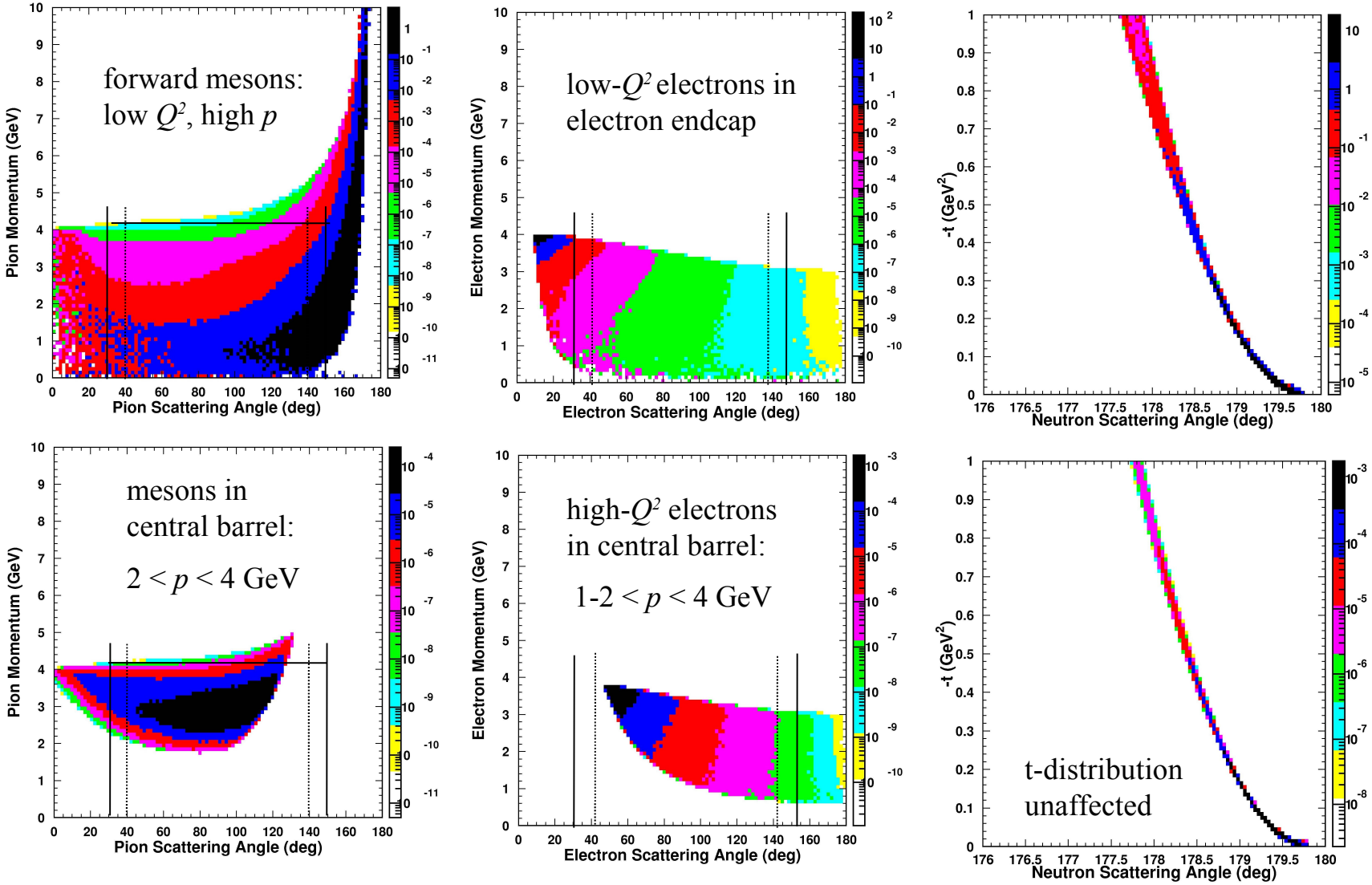
$ep \rightarrow e'\pi^+ n$

Low (J/Ψ) vs high Q^2 (light mesons) – 4 on 30 GeV

mesons | scattered electrons | recoil baryons

no Q^2 cut

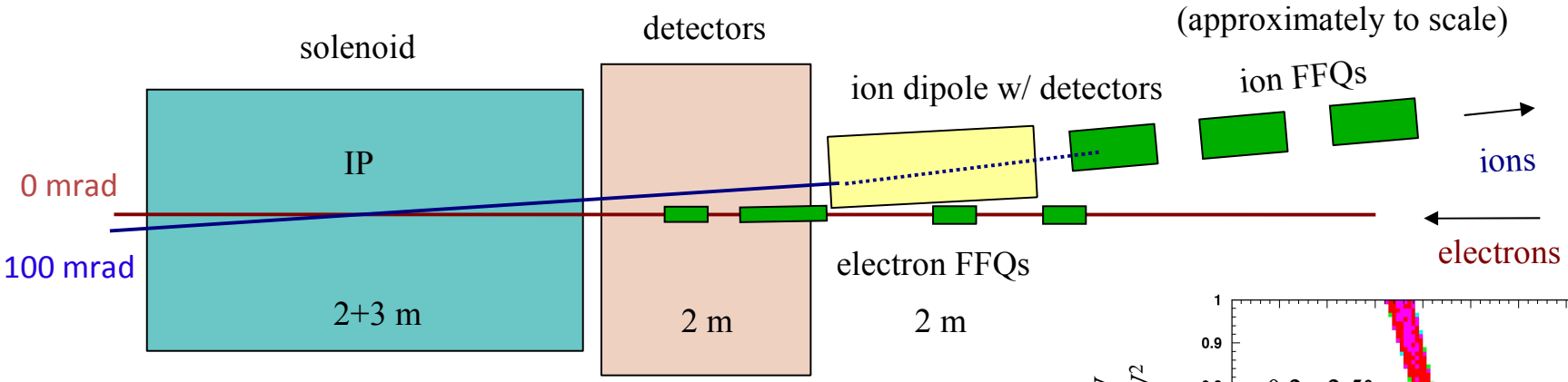
$Q^2 > 10$ GeV^2



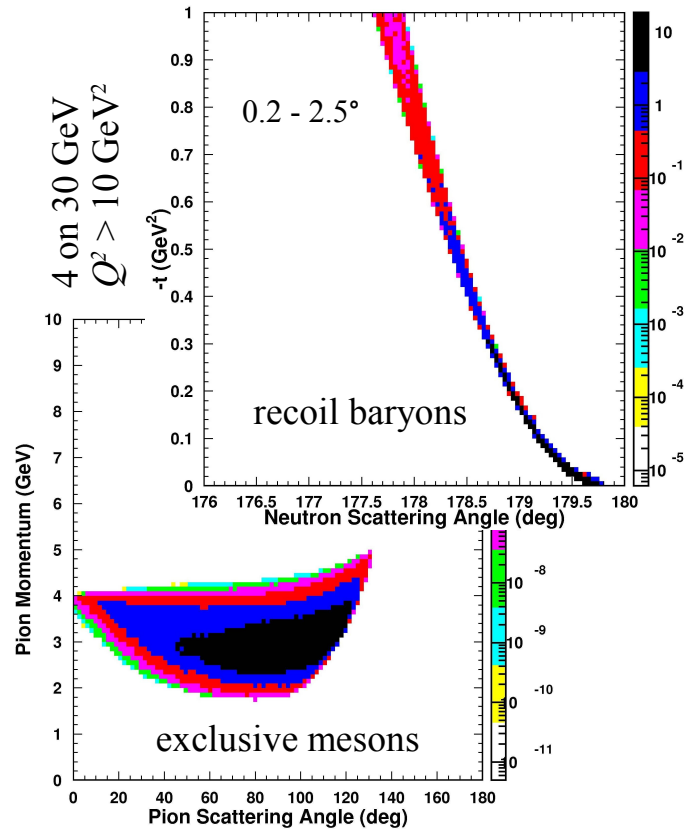
$ep \rightarrow e'\pi^+ n$

Tanja Horn

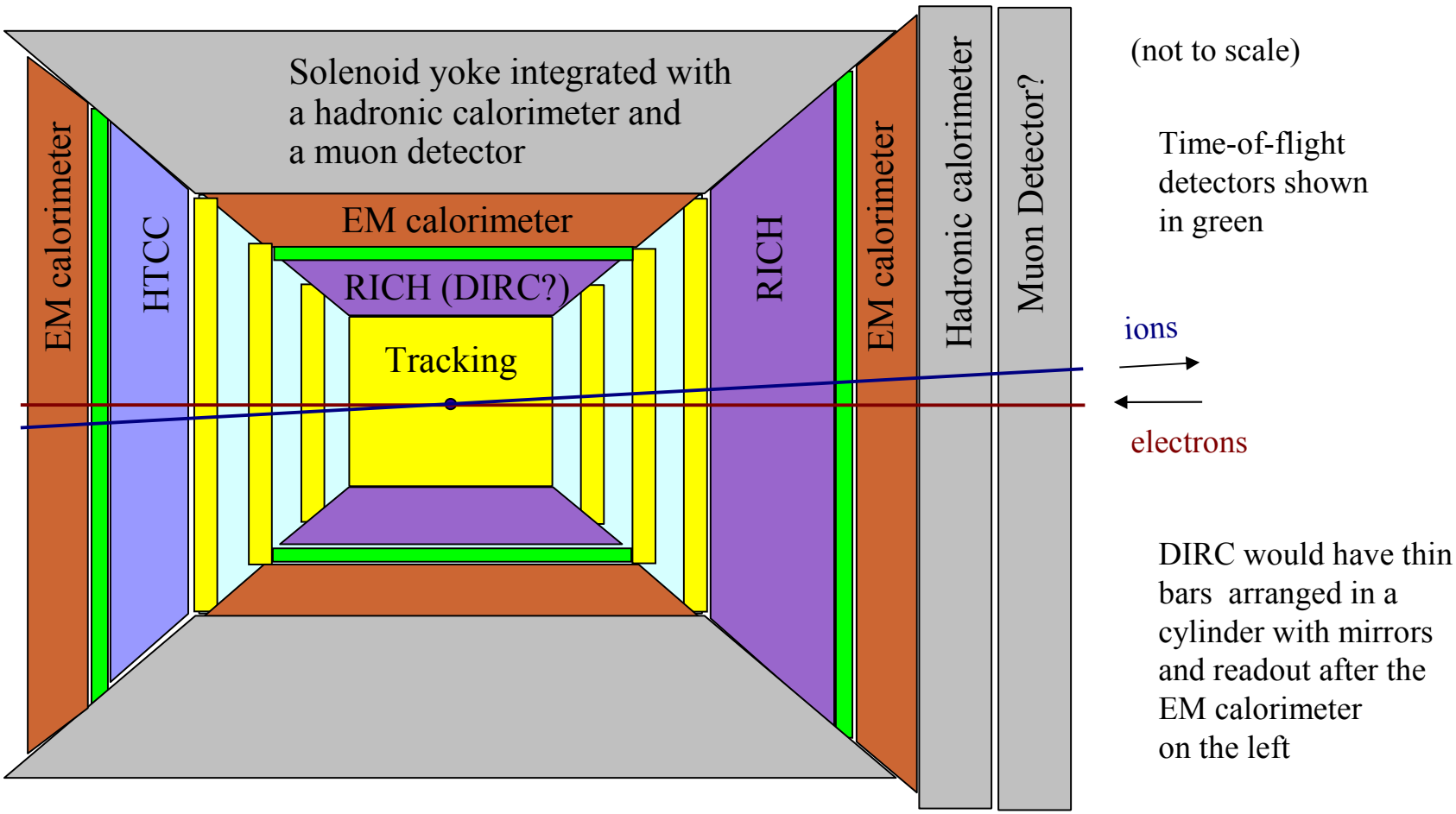
Forward detection with crossing angle



- Downstream dipole on ion beam line has several advantages
  - No synchrotron radiation
  - Electron quads can be placed close to IP
  - Dipole field not set by electron energy
  - Positive particles are bent *away* from the electron beam
  - Long recoil baryon flight path gives access to low *-t*
  - Dipole does not interfere with RICH and forward calorimeters
    - Excellent acceptance (hermeticity)



Sketch of central detector layout



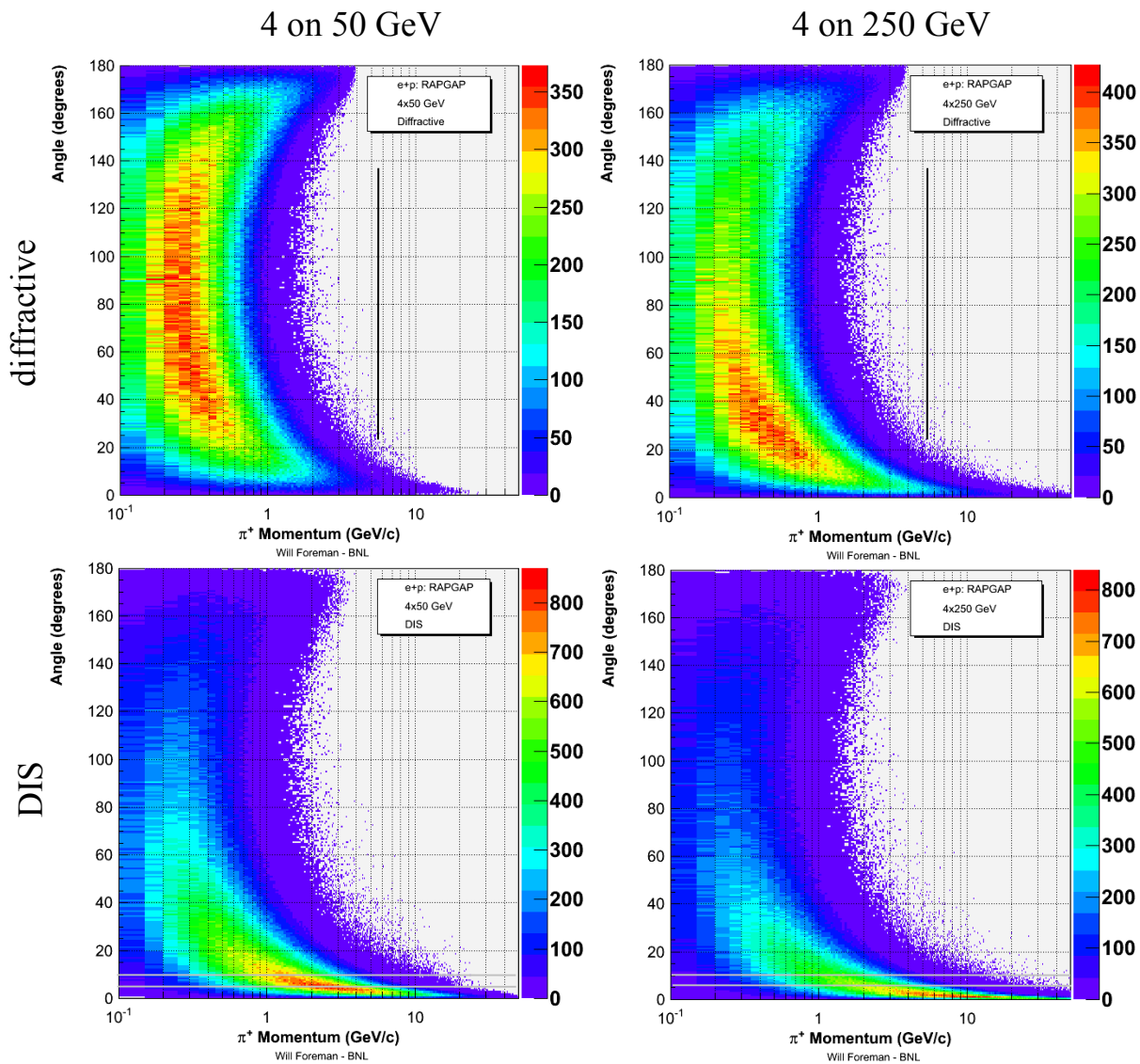
- IP is shown at the center, but can be shifted left
  - Determined by desired bore angle and forward tracking resolution

Summary

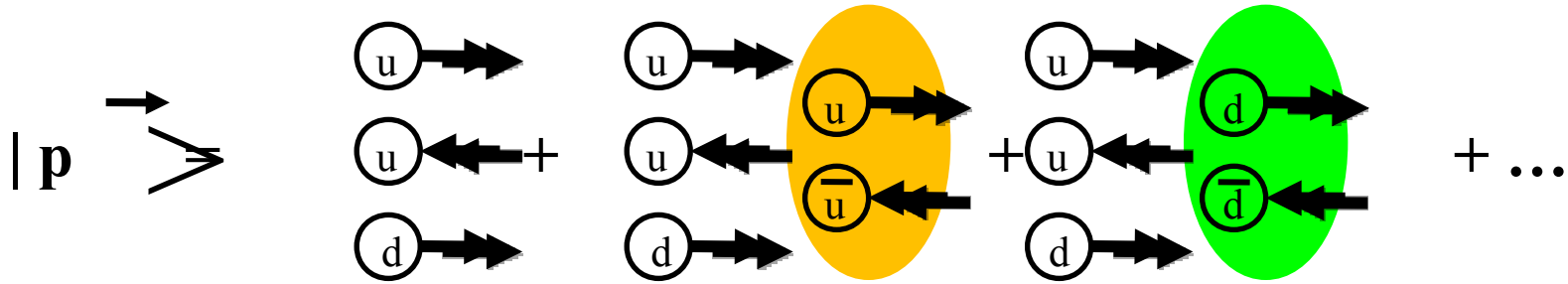
- The next generation QCD facility will focus on gluons and sea quarks
- Both Jefferson Lab and Brookhaven are actively working on implementation options, guided by an international advisory committee.
- The current focus for both labs is a medium-energy Electron-Ion Collider (EIC), with an option for a high-energy upgrade.
- The user community and its involvement is rapidly expanding

Backup

Diffractive and SIDIS (TMDs)

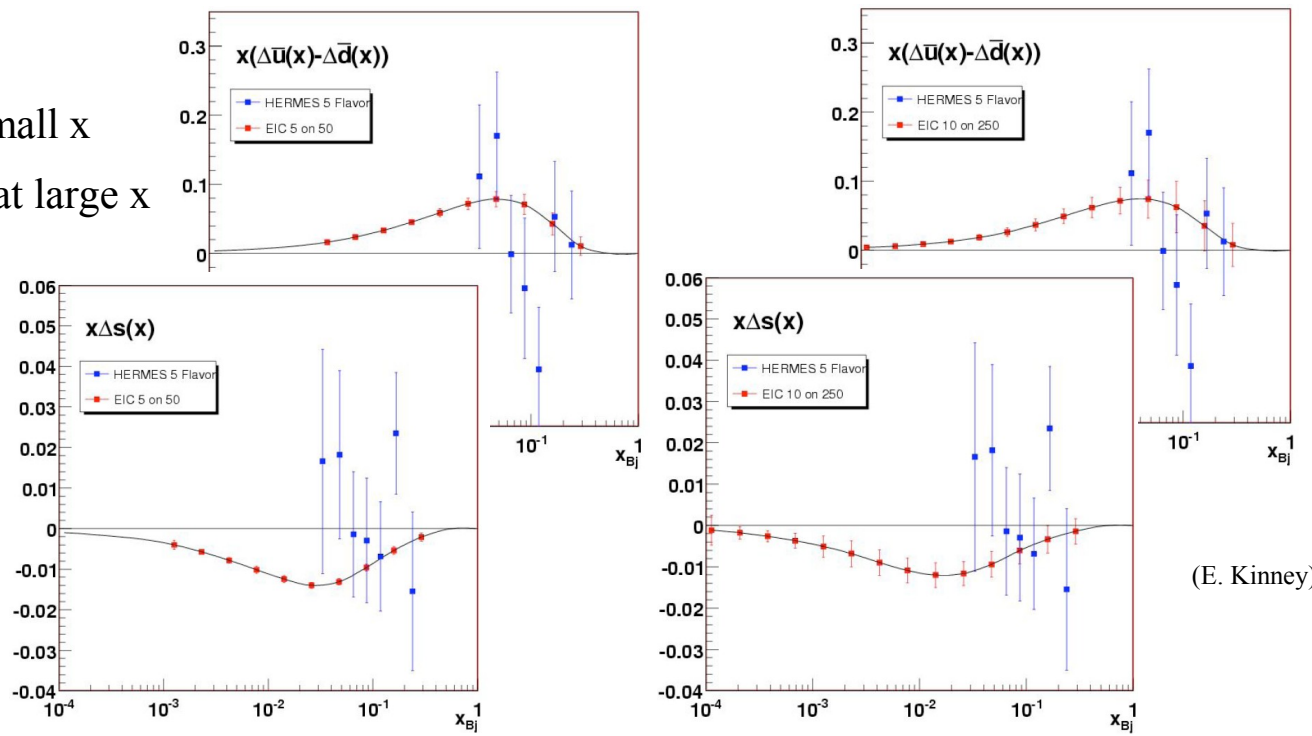


SIDIS – flavor decomposition



- Higher cm energies give
  - better coverage at small x
  - larger uncertainties at large x

- Also interesting are spatial correlations in the vacuum (nucleon sea).



(E. Kinney)

100 days at 10^{33} cm^{-2} s^{-1} shown, curves are GRSV