A medium-energy electron-ion collider for Jefferson Lab

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Jefferson Lab, Newport News, VA

SESAPS, November 11–14, 2009; Atlanta, GA

Outline

1. EIC - the next generation QCD facility

- Background
- Collider Concepts

2. Some physics highlights

- The Nucleon Spin Puzzle
- Transverse Quark and Gluon Imaging

3. Activities at JLab and in the user community

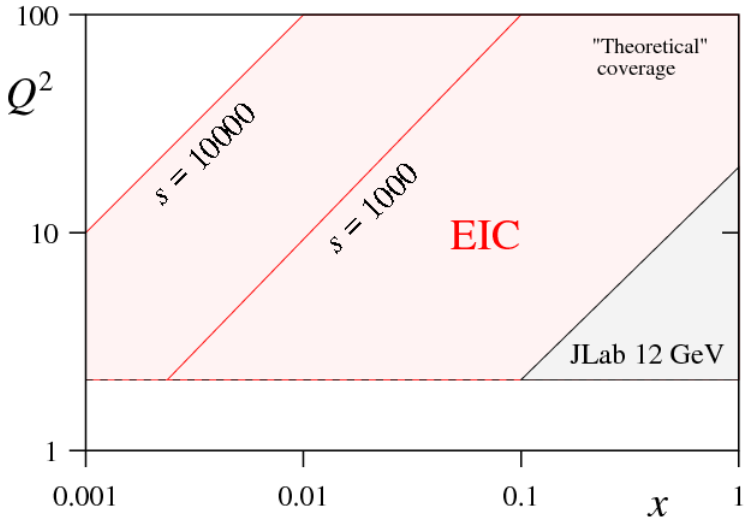
- Detector
- Working Groups and Workshops

Science Goals for the EIC

- Understanding gluons and sea quarks

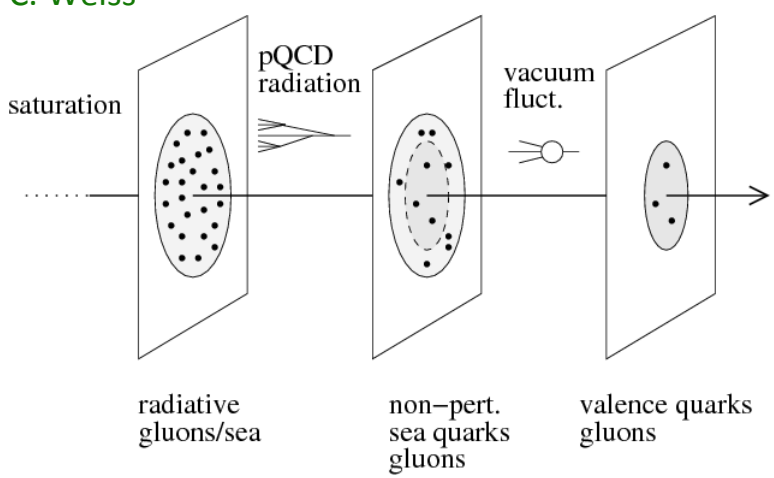
- What is the Internal Spin Landscape of the Nucleon?
  - Two spin decompositions
  - Benefits from both energy and luminosity
- What is the Spatial Landscape of the Nucleon?
  - Transverse imaging of gluons and sea quarks
  - Longitudinal $q\bar{q}$ correlations for $x' \neq x$ ($\xi \neq 0$)
  - Requires high luminosity
- What is the Role of Gluons in Nuclei?
  - Mapping gluons in nuclei
  - Gluon saturation
  - The latter requires high energy and “nuclear oomph”
- What is the Electroweak structure of the Nucleon?
- Add yours!

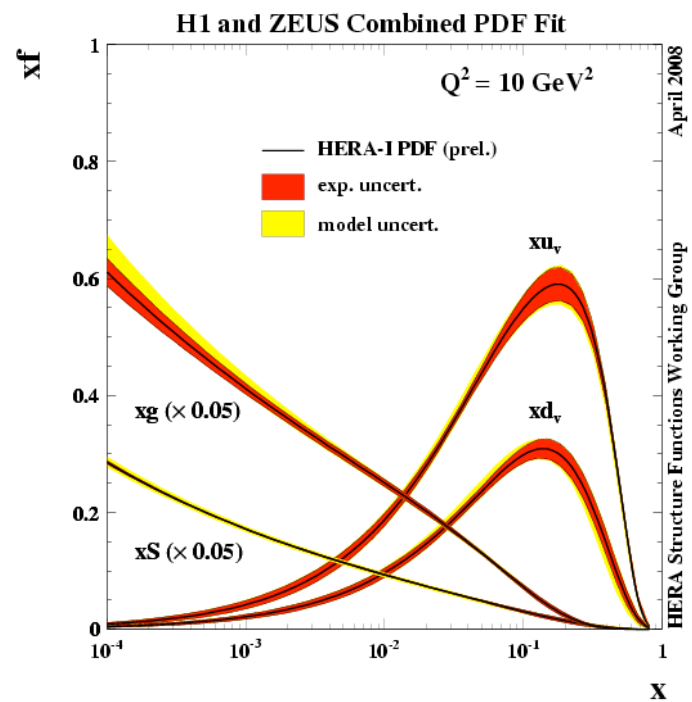
Nucleon structure beyond the valence region



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

C. Weiss

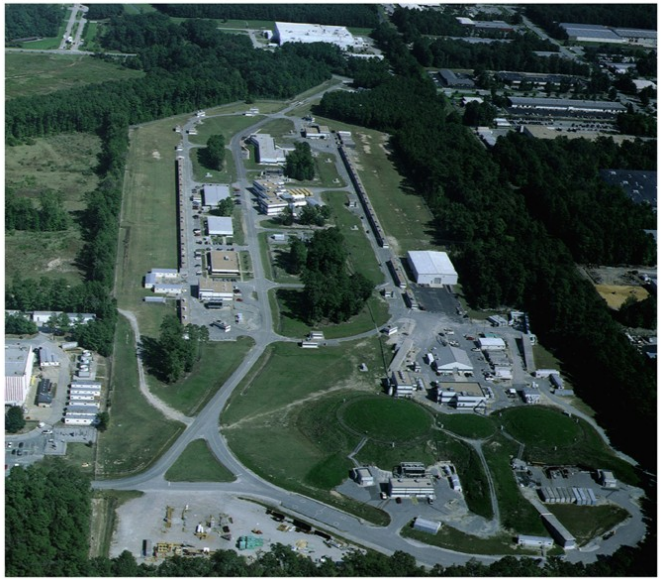




EIC – two communities come together

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

"We want a new HERA, but with polarization and heavy ions, to measure Δg and search for gluon saturation at low *x*."



JLab, Newport News
12 GeV e on fixed target, L = 1 x 10^{35}

"We like JLab 12 GeV, but want to increase the c.m. energy by a factor of 10-100 to probe gluons and sea quarks."

Despite a slightly different focus, there is a lot of common ground!

Why a Collider?

- Easier to reach high CM energies!
  - $E_{cm}^2 = s = 4E_eE_p$ for colliders, vs. $s = 2E_eM_p$ for fixed-target
    → 4 GeV e on 60 GeV p ~ 500 GeV e on fixed-target

- Longitudinal and Transverse Spin Physics!
  - 70+% polarization of beam and target **without dilution**
  - **transverse** polarization also **70%**!
  - no beam current limitations or target holding fields
  - lower backgrounds (also no Moller electrons from beam ions)

- Detection of fragments far easier in collider environment!
  - fixed-target experiments boosted to forward hemisphere
  - more symmetric kinematics improve resolution, PID, etc
  - no fixed-target material to stop target fragments
  - access to neutron structure w. deuteron beams (@ $p_m = 0$!)

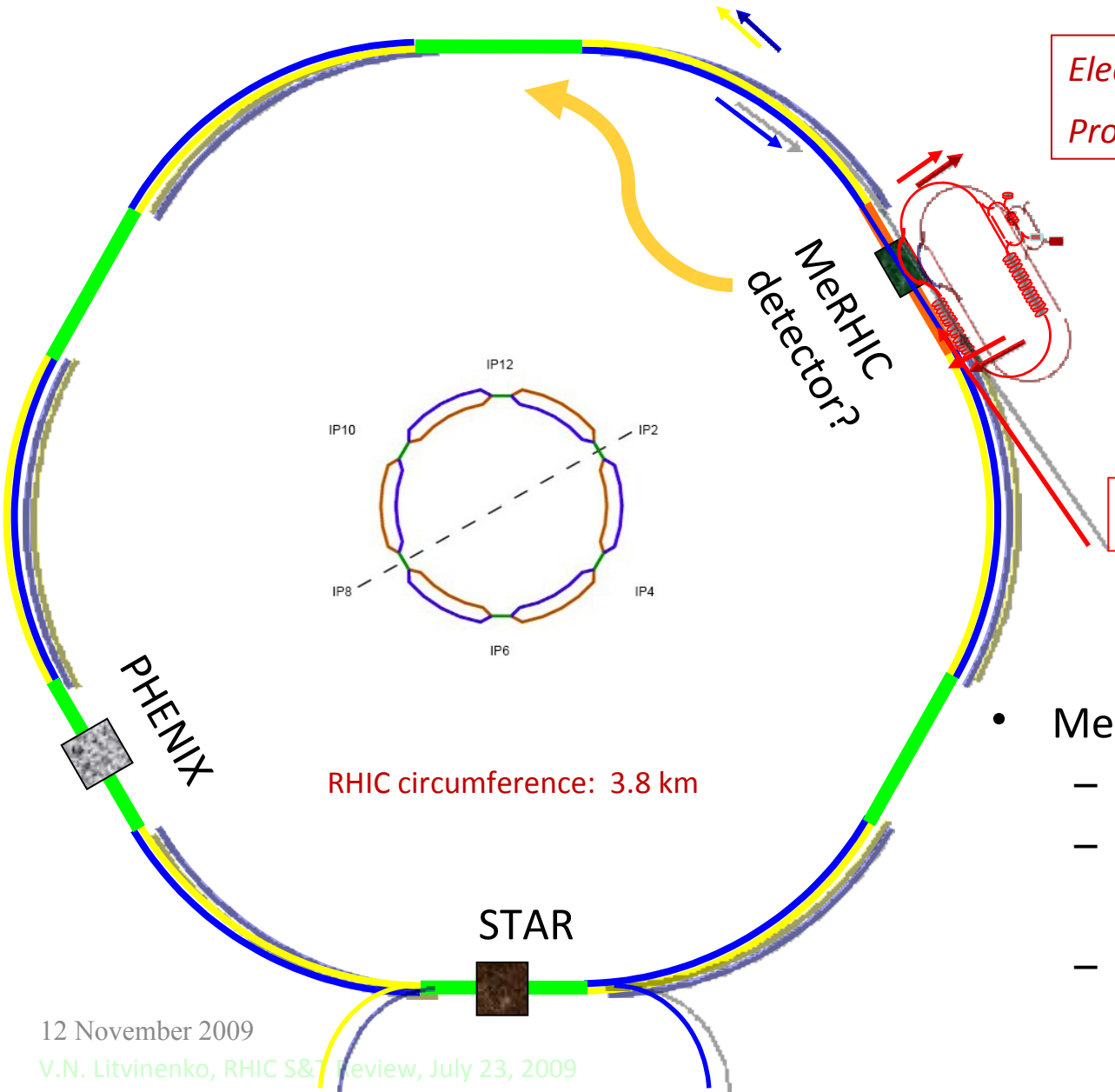
Current e-p/e-A Collider Ideas

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}
(M)EIC@JLab	11 x 60	150-2650	Few x 10^{34}
MeRHIC@BNL	4 x 250	(400-)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}

Present focus of interest (in the US) are the MEIC@JLab and Staged MeRHIC versions, with s up to 2650 and 4000, respectively, and polarizations for electrons and ions > 70%.

MeRHIC@BNL (ERL-Ring) – an overview



Electron energy: 2-4 GeV

Proton energy: up to 250 GeV

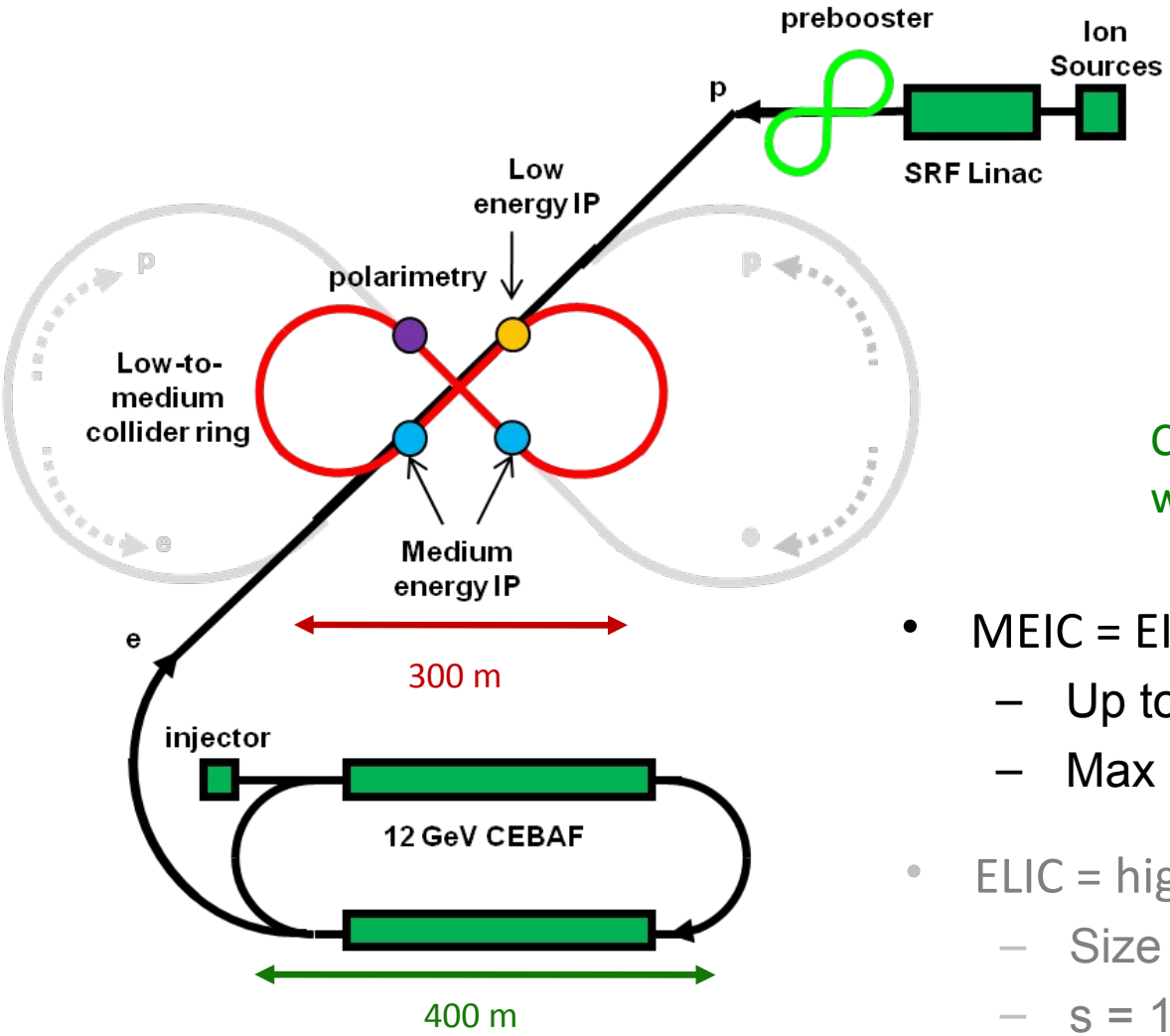
S = (400-) 4000 GeV^2

Cannot operate in parallel with A-A/p-p program

3 pass, 4 GeV ERL

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

MEIC@JLab (Ring-Ring) – an overview



Electron energy: 3-11 GeV

Proton energy: 12-60 GeV

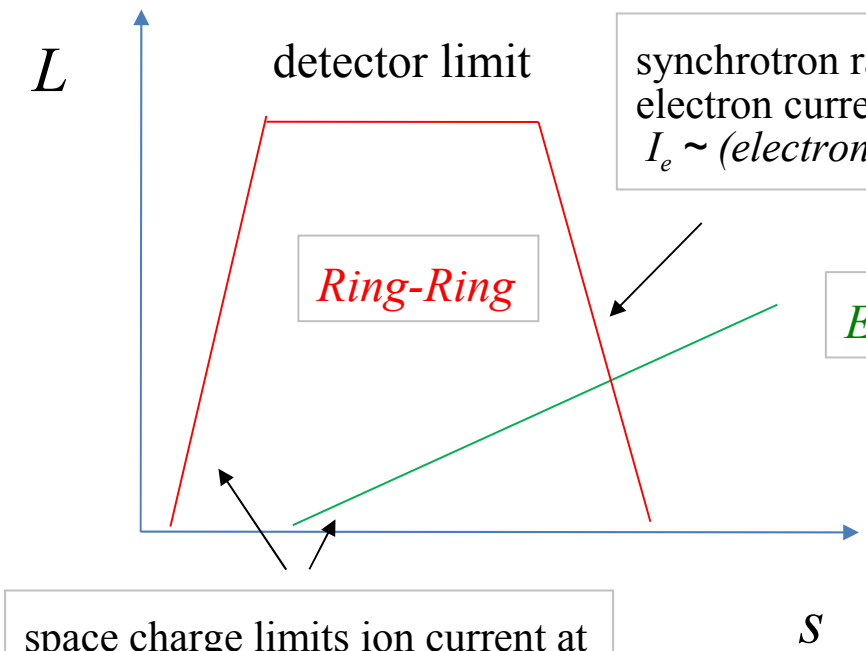
s = 150 - 2650 GeV^2

Can operate in parallel with fixed-target program

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

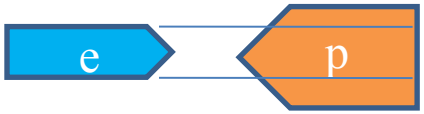
Luminosity – not just one number

$$\text{Luminosity} \propto I_e I_p \frac{p_p}{\varepsilon_p m_p}$$



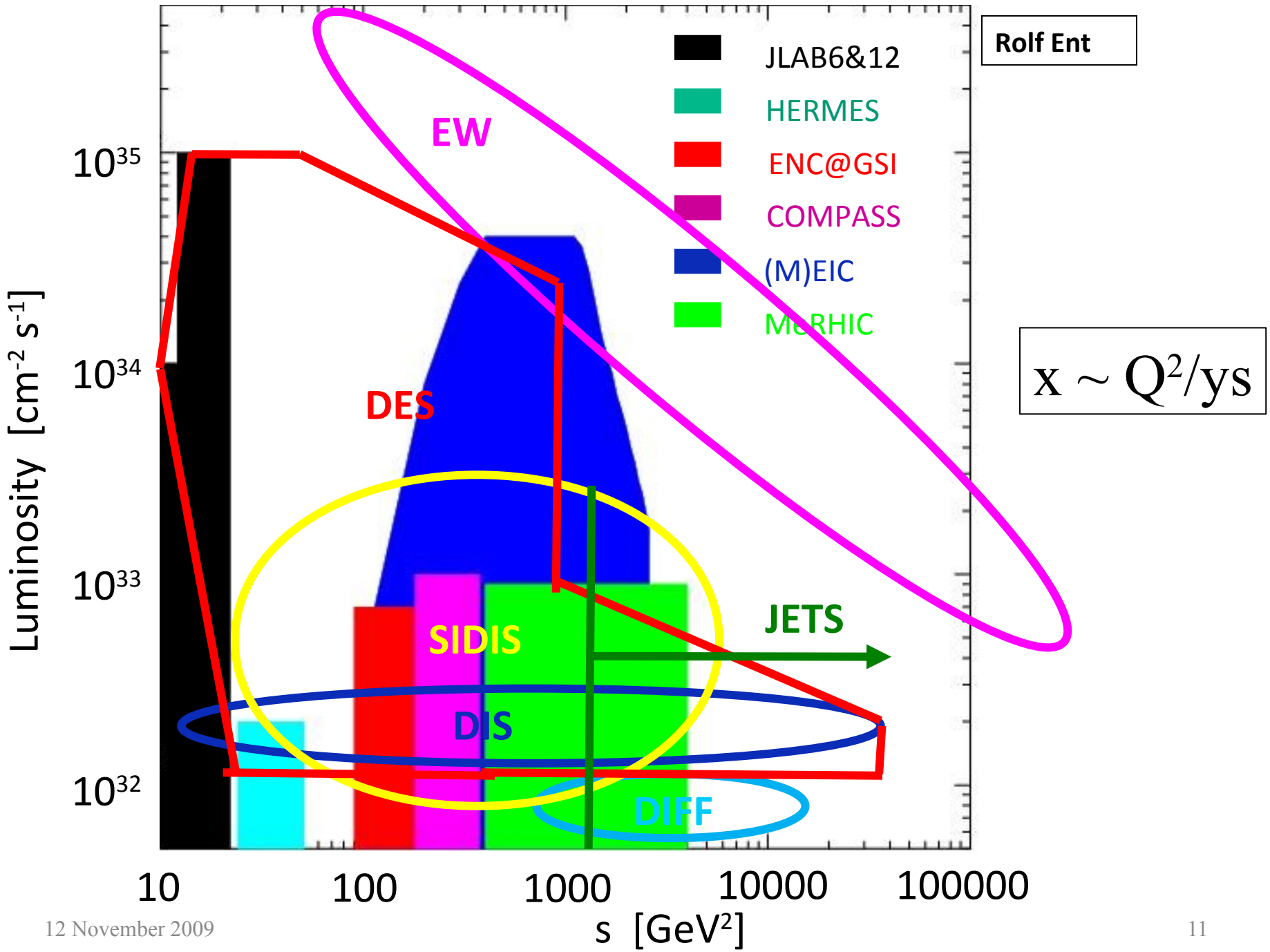
synchrotron radiation limits electron current:
$I_e \sim$ *(electron ring radius)*$/p_e^4$

Luminosity scales with ion momentum *if* cooling can shrink the ion beam (ε_p):
cooling efficiency ~ $1/p_p^2$

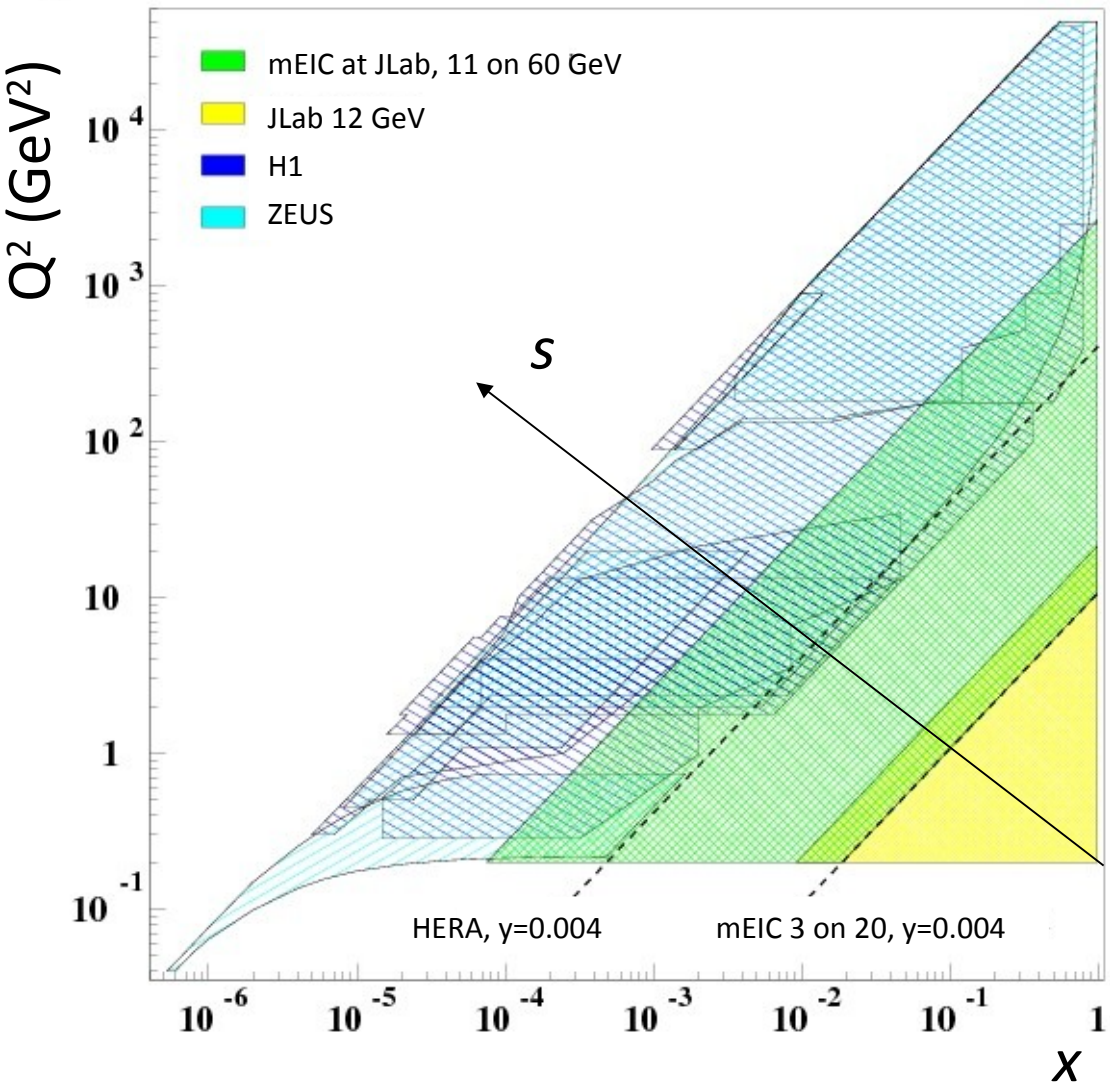


space charge limits ion current at low momentum:
$I_p \sim$ *1/(ion ring circumference)*

A medium-energy ring-ring collider provides a high luminosity over a range in *s, not only at the end point.*


Rolf Ent
JLAB6&12
HERMES
ENC@GSI
COMPASS
(M)EIC
MeRHIC
EW
DES
SIDIS
JETS
DIS
DIFF
$x \sim Q^2/ys$
Luminosity [cm^{-2} s^{-1}]
10^{35}
10^{34}
10^{33}
10^{32}
10
100
1000
10000
100000
s [GeV^2]

MEIC@JLab – Kinematic Coverage



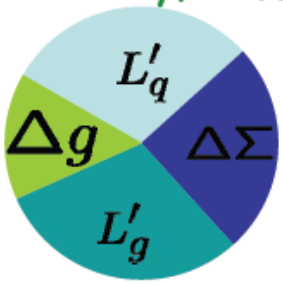
$$x \sim Q^2/ys$$

The MEIC@JLab will overlap with HERA and JLab 12 GeV at a comparable luminosity.

Decomposition of Proton Spin

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)

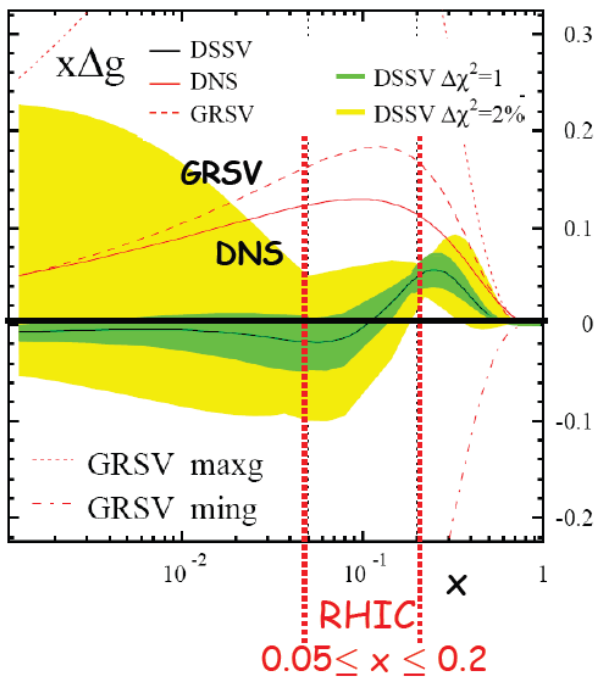
- lattice results for L_q are for Ji's sum rule and cannot be mixed with Δg
- num. difference between L_q and L_q' can be sizable

Burkardt, BC
arXiv:0812.1605

(From M. Stratmann, INT09-43W)

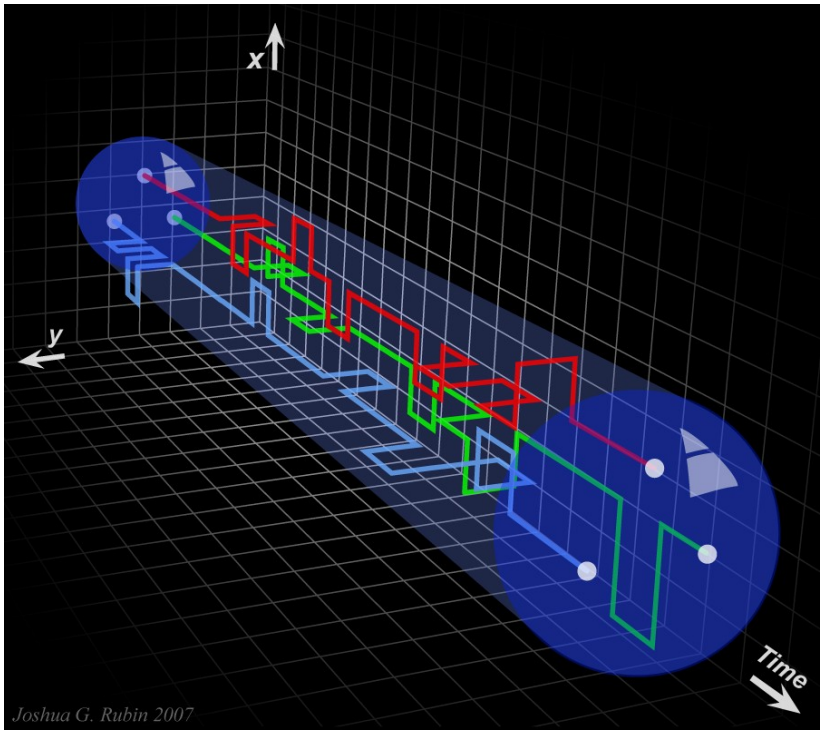
Proton spin – two complementary approaches

- Measure Δg over a sufficiently wide range in x (and Q^2)
  - How small x (high energy) is sufficient?
  - Global fits?
- Measure angular momentum through GPDs and TMDs
  - Connect with Lattice QCD
  - Requires high luminosity

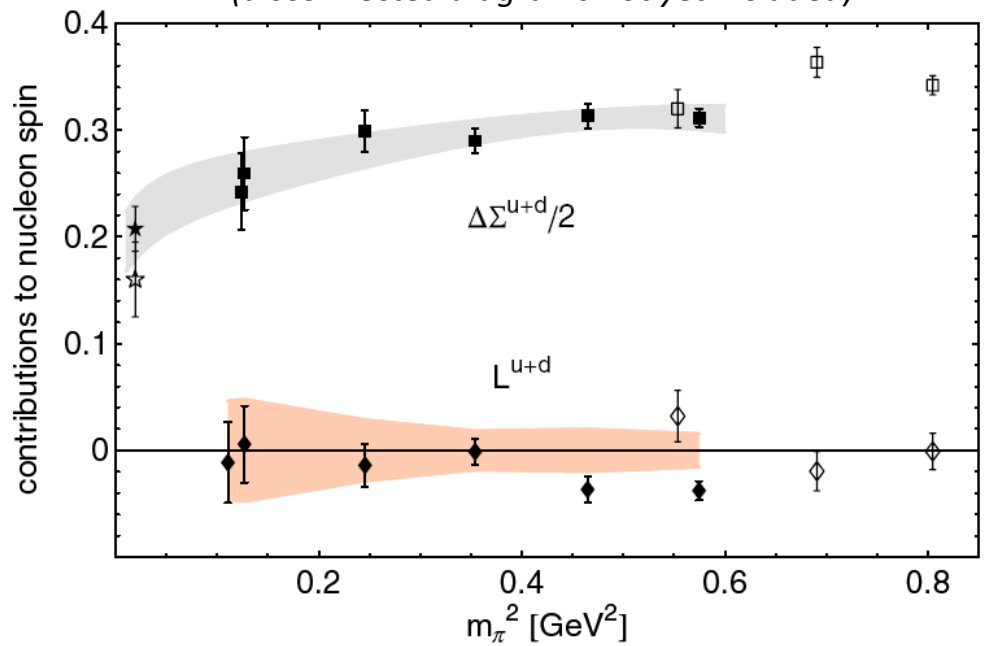


- RHIC spin measured Δg close to zero
- One could expect Δg to be small at small x, but uncertainties are large

Quark Spin and Angular Momentum from Lattice QCD



(disconnected diagrams not yet included)



LHPC Collaboration,
Phys. Rev. D77, 094502 (2008)

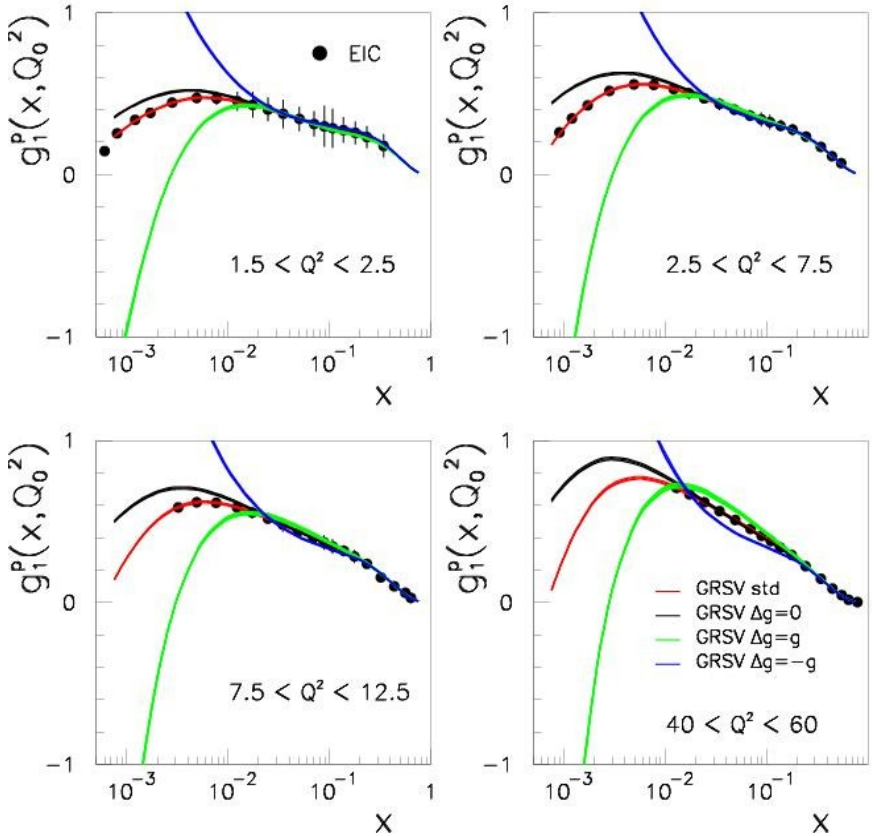
Input from Lattice QCD on GPD moments (also from deep exclusive scattering)

L_u and L_d separately quite substantial (~ 0.15), but cancel

Measuring Δg at an EIC

(Antje Bruell, Abhay Deshpande, Rolf Ent)

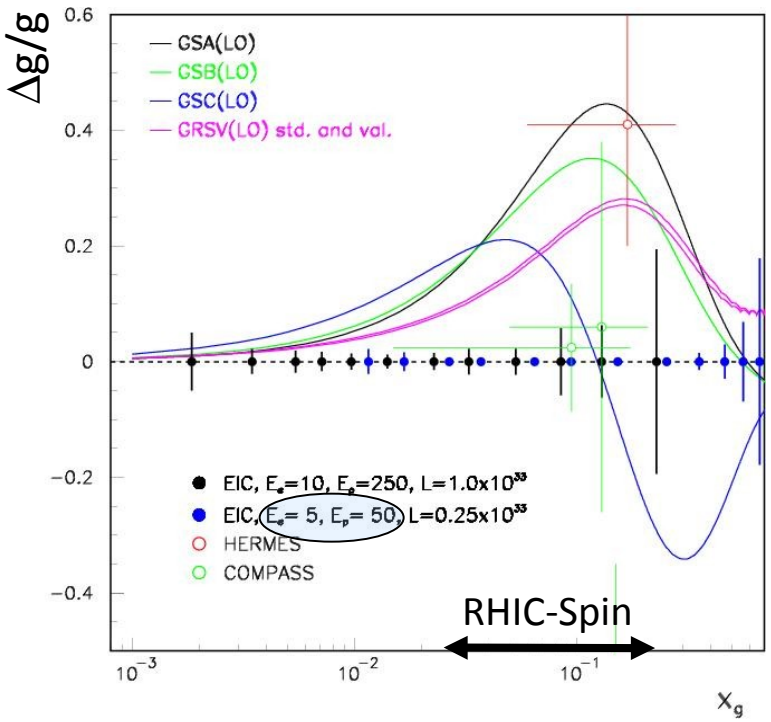
$$\frac{d\,g_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$



Simulation: example for s = 4200

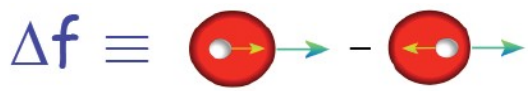
$\gamma + p \rightarrow D^0 + X$

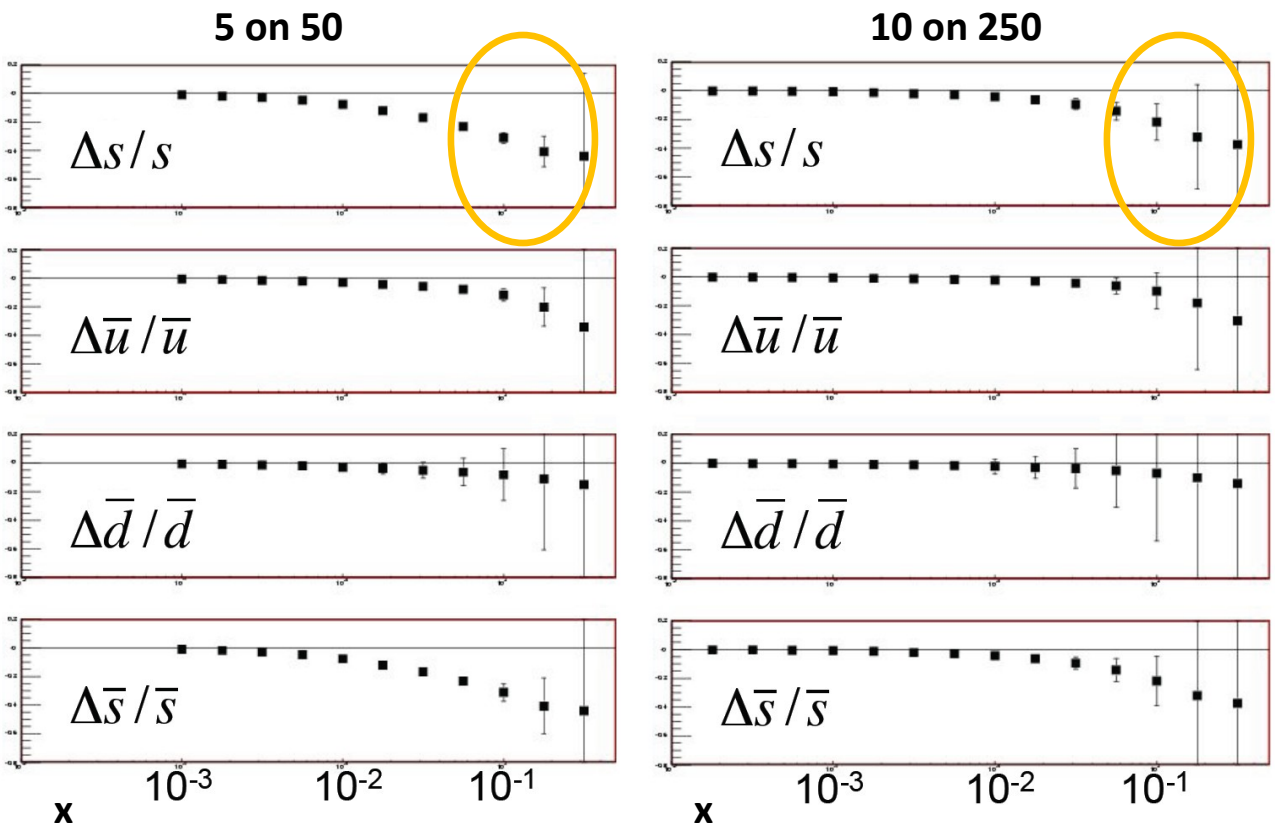
$\hookrightarrow K^- + \pi^+$



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

Flavor decomposition in SIDIS





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

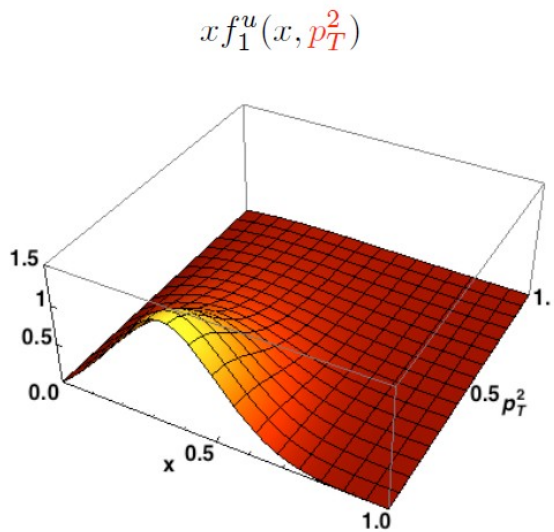
E. Kinney, J. Seele

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

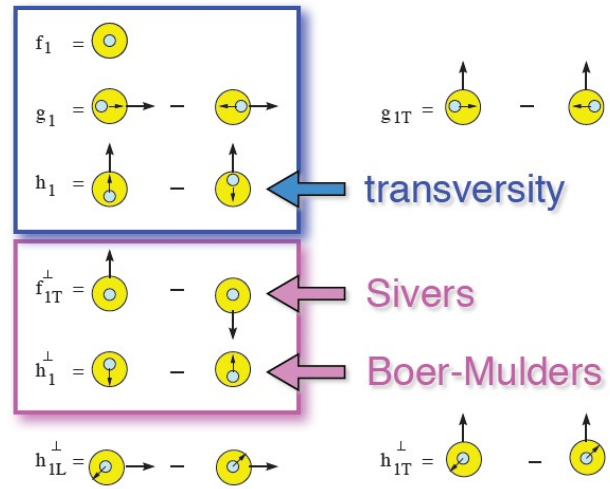
- Higher CM energies give
  - better coverage at small *x*
  - larger uncertainties at large *x* (>=0.1)
- Good particle ID range of E_h=1-10 GeV suited to relevant range of $z=E_h/\nu$

Flavor decomposition in SIDIS: nucleon/nuclear structure studies favor medium-energy EIC

Transverse Momentum Distributions (TMDs)



TMD



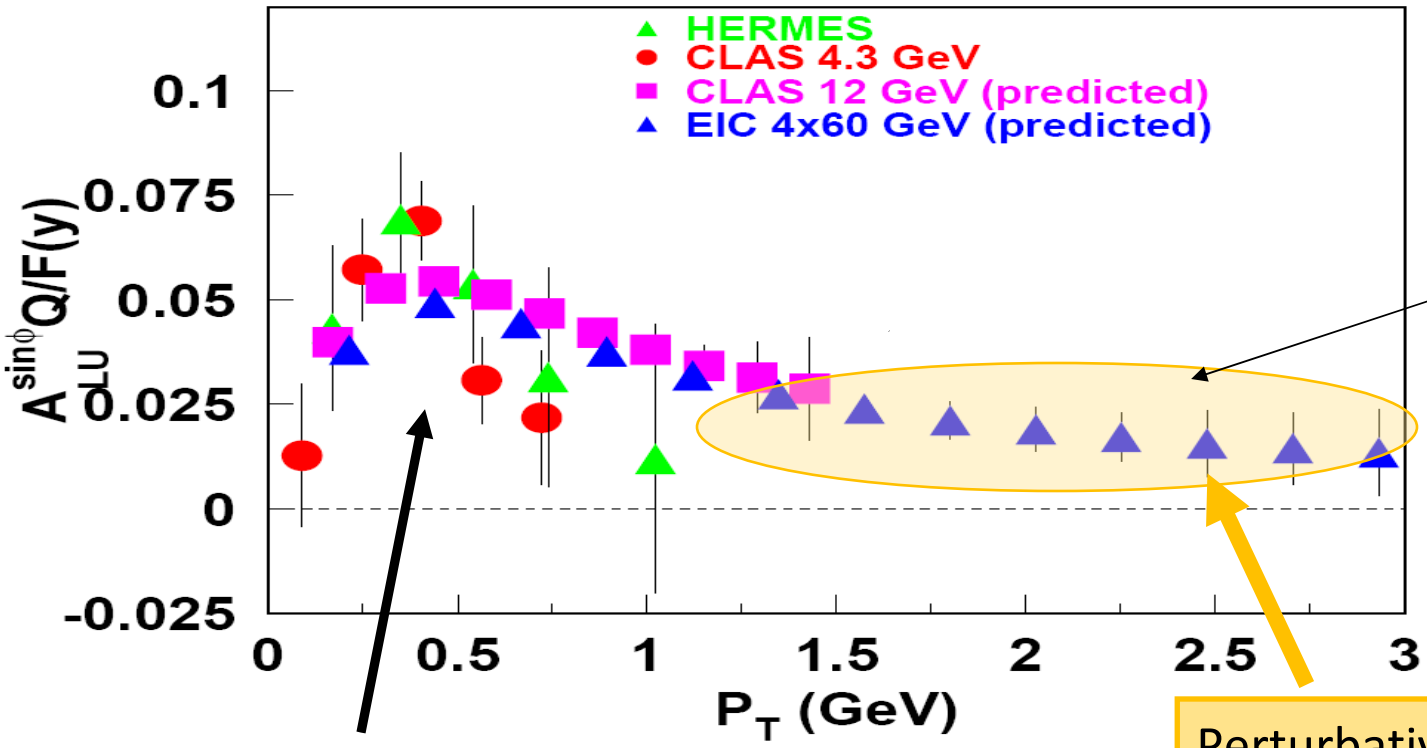
(A. Bacchetta)

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

- In SIDIS, parton distributions can remain unintegrated over transverse momentum
- parton and nucleon spins then give 18 structure functions
- These can be combined into TMDs, from which we can learn about orbital motion

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

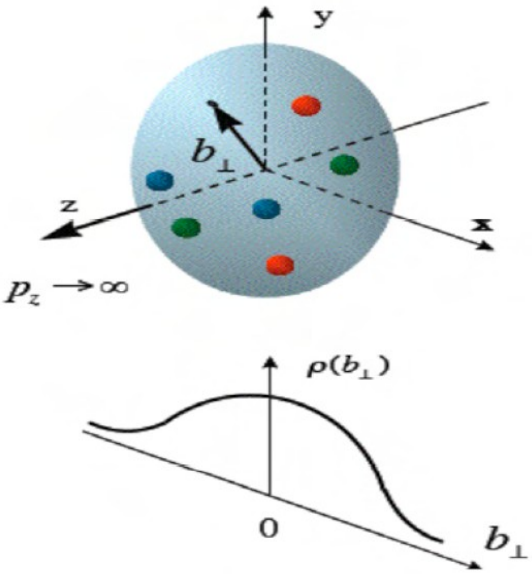
100 days at 10^{33} cm^{-2} s^{-1}

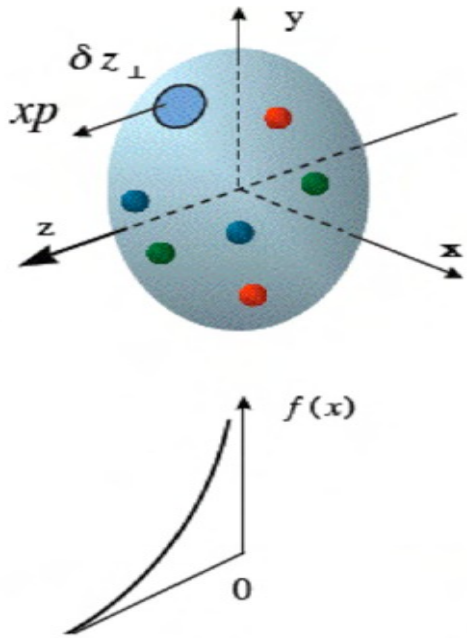
Nonperturbative TMD

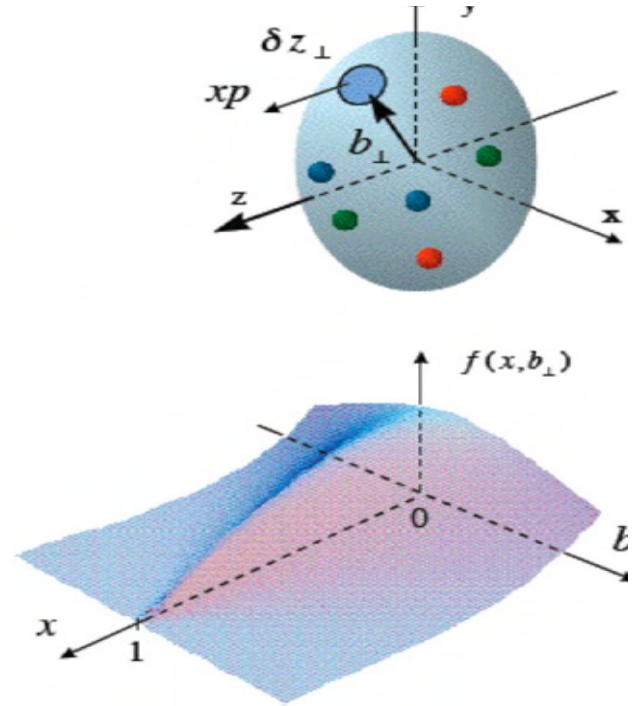
Perturbative region

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

Generalized Parton Distributions (GPDs)







Elastic Form Factors

charge and magnetization
[GPDs integrated over x]

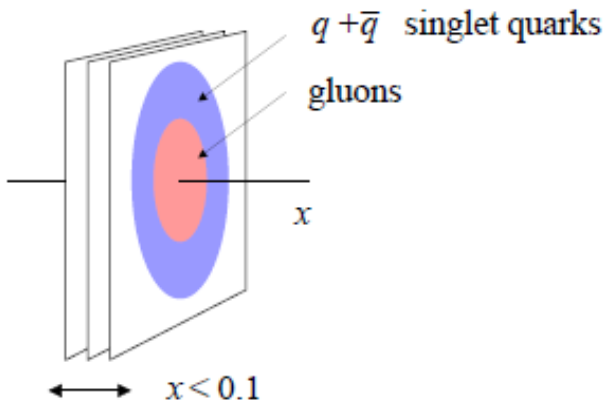
Parton Distribution Functions

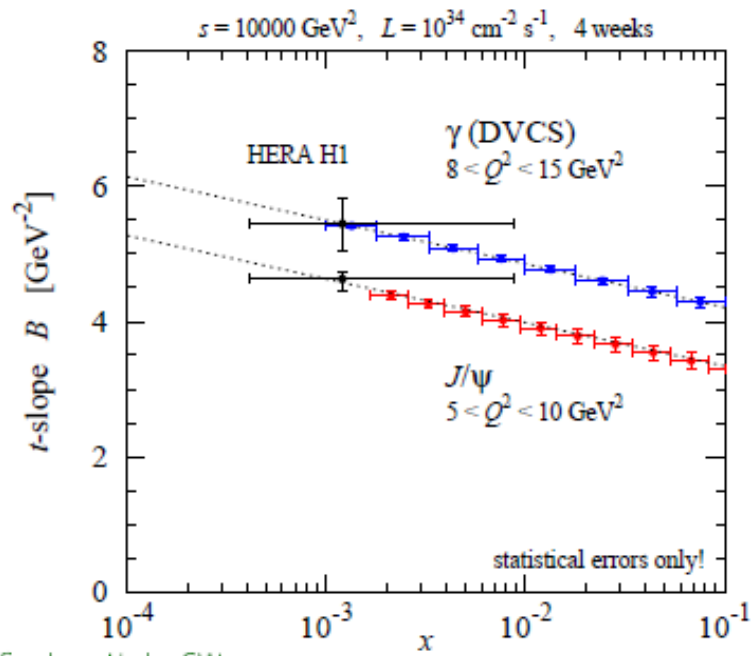
longitudinal momentum (DIS)

Generalized Parton Distributions

3-D imaging of the nucleon
(exclusive reactions)

Gluon imaging example: gluon vs. quark size





Sandacz, Hyde, CW

- Do singlet quarks and gluons have the same transverse distribution?

  Hints from HERA:
  Area$(q+\bar{q})$ > Area(g)

  Dynamical models predict difference:
  Pion cloud, constituent quark picture

  No difference assumed in present pp MC generators for LHC!

- EIC: Gluon size from J/ψ, singlet quark size from DVCS

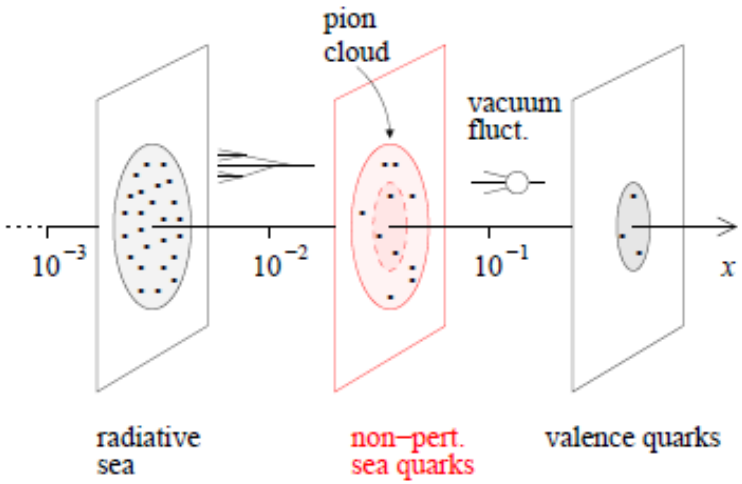
  x–dependence: Quark vs. gluon diffusion in wave function

  Detailed analysis: LO → NLO Müller et al.

Detailed differential images of nucleon's partonic structure

C. Weiss

Exclusive meson production



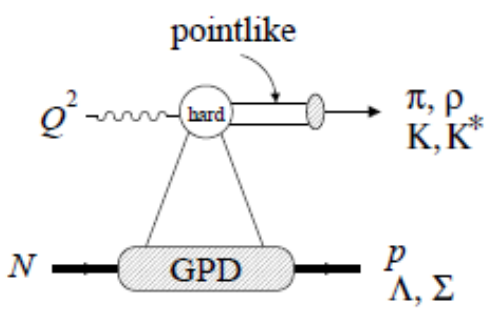
- Transverse distribution of non-perturbative sea quarks

  Flavor structure $\bar{u} \leftrightarrow \bar{d} \leftrightarrow s, \bar{s}$

  Longitudinal polarization $q_+ \leftrightarrow q_-$

  $\rightarrow$ QCD vacuum structure

  $\rightarrow$ Chiral dynamics, "pion cloud"



- Exclusive meson production $\gamma^* N \rightarrow M + B$

  Requires $Q^2 > 10\,\mathrm{GeV}^2$ for dominance of "pointlike" configurations $\rightarrow$ pQCD

  Meson quantum numbers select spin/flavor component of GPD

  Information about meson wave function: Size, flavor structure

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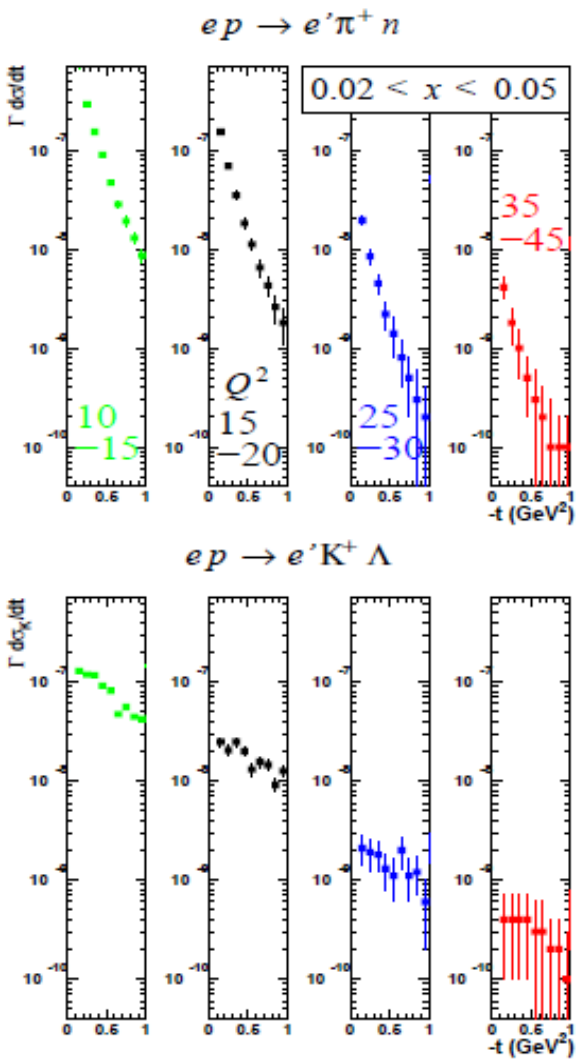
Transverse sea quark imaging example



T. Horn

- Do strange and non-strange sea quarks have the same spatial distribution?

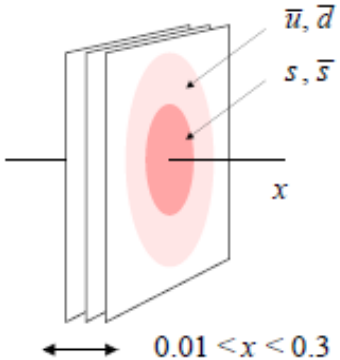
  → πN or $K\Lambda$ components in nucleon?
  → QCD vacuum fluctuations?

- EIC: Exclusive π and K production

  High luminosity for low rates, differential measurements in x, t, Q^2

  Kinematic reach in Q^2, x

  Recoil detection for exclusivity, t–distributions



Spatial structure of non-perturbative sea – many more examples!

C. Weiss

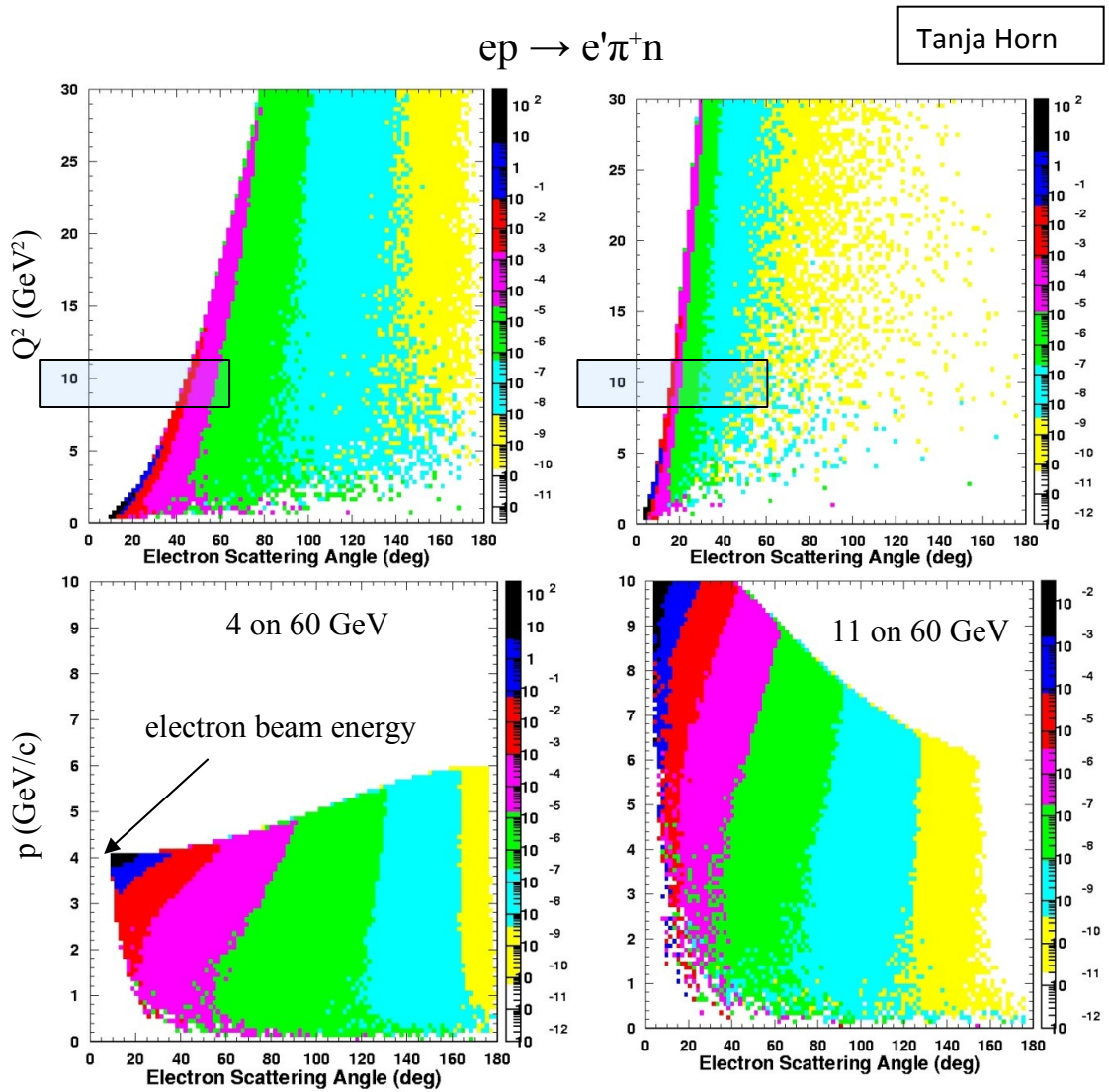
Examples of reactions to be measured

- Inclusive DIS
  - Polarized: ΔG and $\Delta q+\Delta q$ from global fits (+ RHIC-spin, COMPASS, JLab 12 GeV)
  - Unpolarized: EMC effect, neutron structure from spectator tagging in D(e,e'p)X
- Semi-inclusive DIS
  - Unpolarized: Flavor decomposition: $q \leftrightarrow \bar{q}$, $u \leftrightarrow d$, strangeness s, $\bar{s}$
  - Polarized: TMDs: spin-orbit interactions from azimuthal asymmetries, p_T dependence
  - Target fragmentation and fracture functions
- Charm as direct probe of gluons
  - J/ψ, exclusive: spatial distribution of gluons
  - D Λ_c, open charm (including quasi-real D^0 photoproduction for ΔG)
- Exclusive processes and GPDs
  - Non-diffractive: sea quarks from light mesons
  - Diffractive: gluons from DVCS and J/ψ; DVCS on nuclei

Experimental requirements

Deep Exclusive – electron kinematics

- symmetric kinematics: access to higher Q^2 at small scattering angles
  - Cerenkov coverage
  - PID in SIDIS
- asymmetric kinematics: lower momenta at small scattering angles
- A medium energy collider allows optimization of kinematics for each experiment.

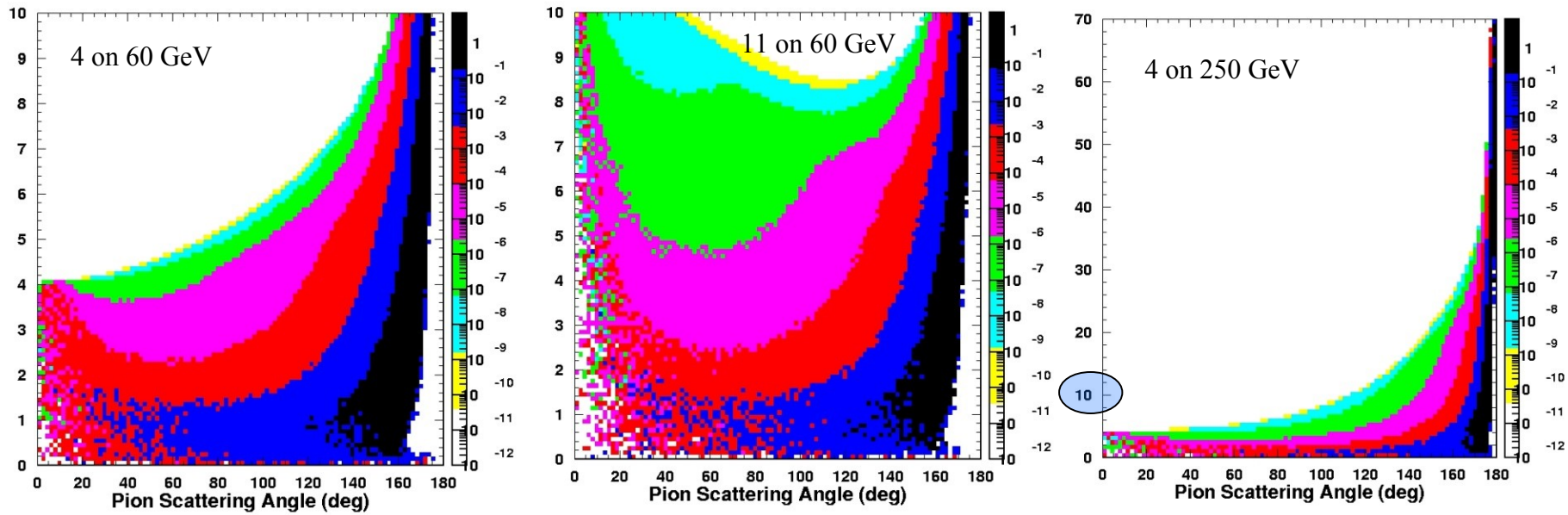


Deep Exclusive – meson kinematics

p (GeV/c)

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

Tanja Horn



- Large boost in asymmetric *e-p* collisions
  - hadrons produced in narrow cone with large lab momenta

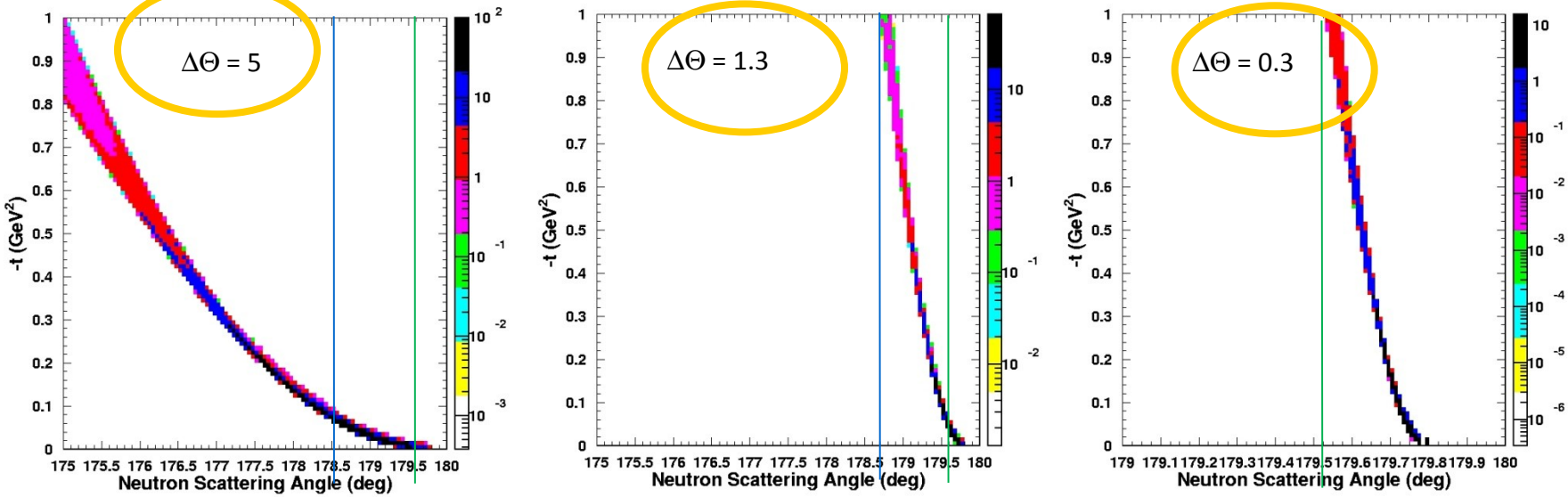
- More symmetric kinematics improve detector *acceptance (hermeticity)*, *particle identification*, and *resolution (momentum and angular)*.

Deep Exclusive – recoil baryon kinematics

$$ep \longrightarrow e'\pi^{+}n$$

Tanja Horn

4 on 12 | 4 on 60 | 4 on 250

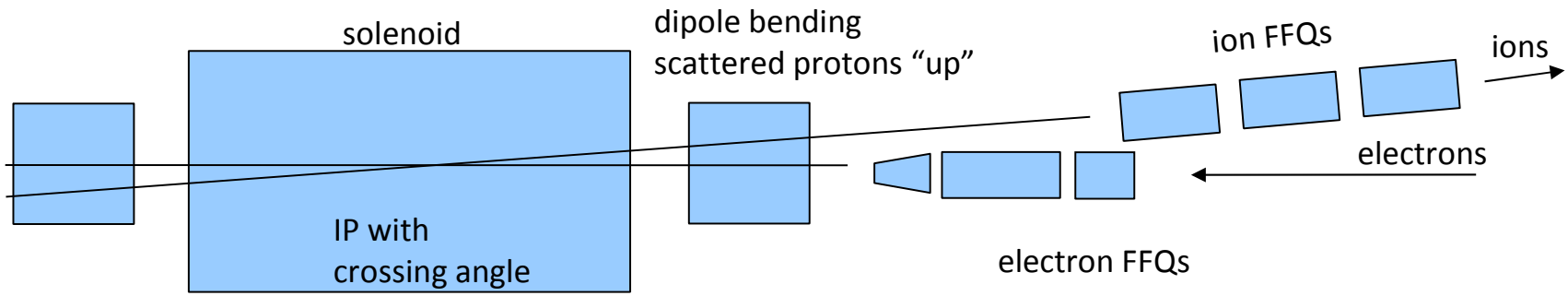


$-t \sim E_p^2(\theta\text{-}180^\circ)^2$

- Symmetric kinematics greatly improve acceptance (t-coverage)
- Forward detection needed to reach very low –t
  - Long magnet free space between IP and first beam quad
  - Spreader magnet for recoil protons
  - Calorimeter for recoil neutrons (angular information only)

$\delta t/t \sim t/E_p \rightarrow$ lower E_p better

EIC@JLab Detector/IR Layout



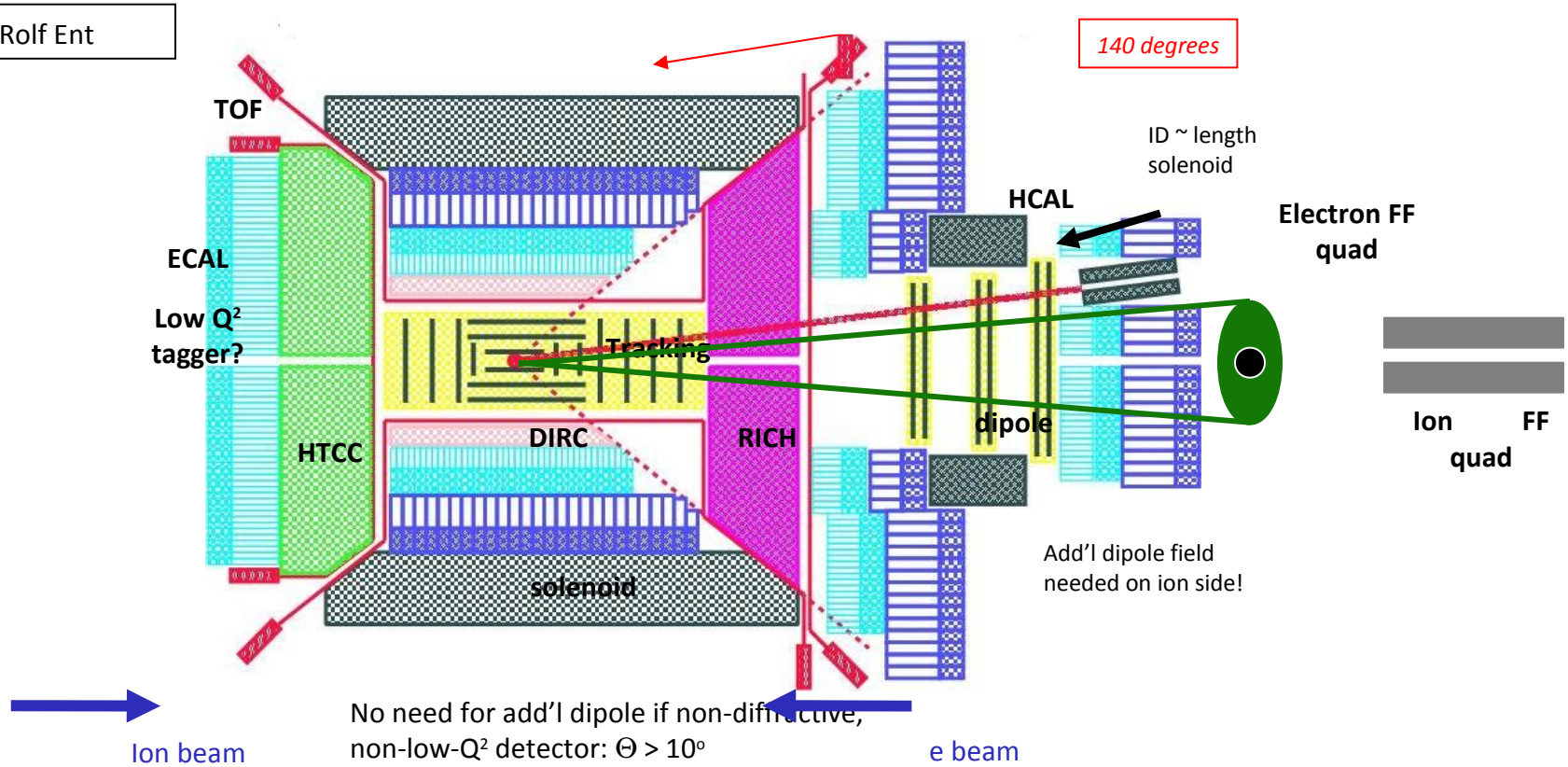
Distance from IP to electron FFQ: 6 m
to ion FFQ: 9m

Electron FF quad	Distance from IP	Length	Field strength	Beam size σ_x @ 3 GeV	Beam size σ_y @ 3 GeV
Quad 1	6.0 meter	50 cm	-1.14 kG/cm	5 mm	4 mm
Quad 2	6.75 meter	120 cm	0.71 kG/cm	8 mm	3 mm
Quad 3	8.7 meter	50 cm	-0.75 kG/cm	4 mm	4 mm

Modest electron final focusing quad field requirements → quads can be made small

EIC@JLab – detector cartoon

Rolf Ent



- Detector offers very good acceptance
- It is well suited to symmetric kinematics
- **Particular attention has been paid to baryon recoil detection**
- Low-Q^2 tagger can be easily implemented

EIC@JLab Simulation Working Group

- The main goal of the simulation working group is to provide
  - Event generators for various processes
  - Fast Monte Carlo to explore acceptance and resolution requirements
  - GEANT4 based Monte Carlo to study detector resolution and acceptance
  - Event Reconstruction for GEANT based MC

- GEANT4 MC will use the standard CLAS12 engine, GEMC.
  - Flexible design uses external, implementation independent field map and detector geometry servers.
  - Implementation of EIC detector into this framework will begin in November.
  - Support for digitizations, etc provides data that can be used for full event reconstruction.
  - Package will be maintained and developed together with CLAS12.

Workshops and Working Groups

- Working Group on Hadronic Physics (e-p):
  - SIDIS and TMD workshop at Duke: March 12-13, 2010 (H. Gao)
  - GPD workshop at Rutgers (R. Gilman)

- Working Group on Nuclear Physics (e-A):
  - Nuclear Chromo-Dynamics workshop at Argonne (K. Hafidi)

- Working Group on Electroweak Physics:
  - Electroweak workshop at UVA (K. Kumar)

- Working Group on Detector:
  - Detector workshop at JLab (C. Hyde)

Stay tuned for more details on workshops!

- wiki: eic.jlab.org/wiki
- mailing list: meic_np@jlab.org

Summary

- The EIC@JLab is well suited for taking JLab beyond 12 GeV
  - Excellent tool to access nucleon/nuclear structure
- A medium-energy collider is particularly appealing for measurements requiring *transverse targets,* good *resolution,* and good *particle id*.
- Matches *energy, luminosity,* and detector/IR for deep exclusive and SIDIS processes (GPDs, TMDs).
  - These processes also benefit excellent *polarization*, and more *symmetric* collision kinematics.
- Rapidly Expanding User Community

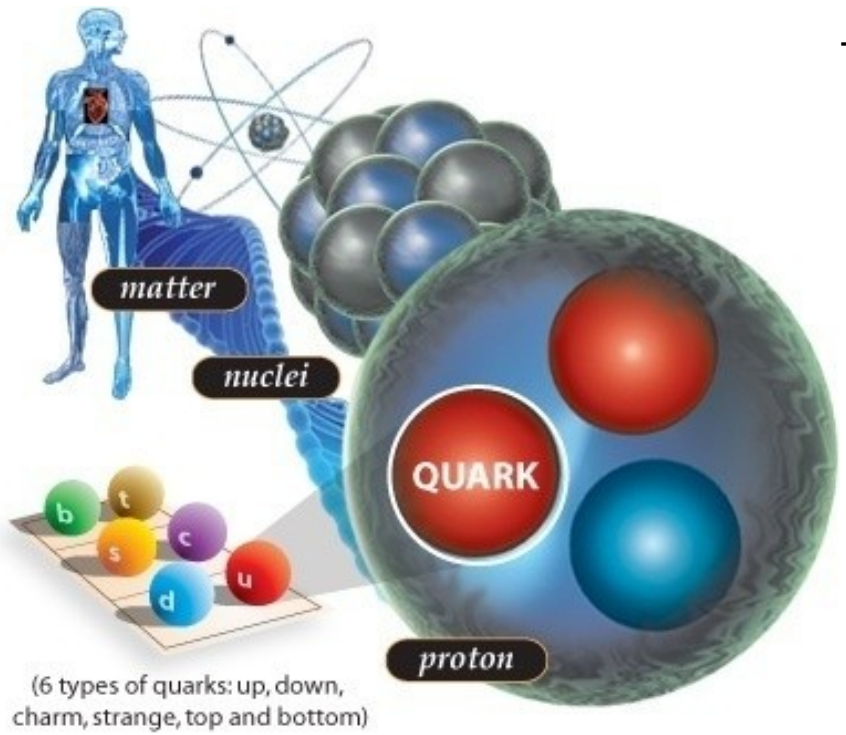
EIC@JLab – further info

- EIC@JLab webpage: http://eic.jlab.org
  - Overview and general information
- EIC@JLab wiki: https://eic.jlab.org/wiki
  - Ongoing project information
  - Working groups
- Weekly project meetings at JLab
  - Fridays at 9:30am in ARC724 or F324/25
- Next EIC Collaboration meeting: January 10-12, 2010 @ Stony Brook
- Series of topical workshops starting in 2010
- Next EIC Advisory Committee meeting: June 2010 at BNL

Backup

Exploring the strong force

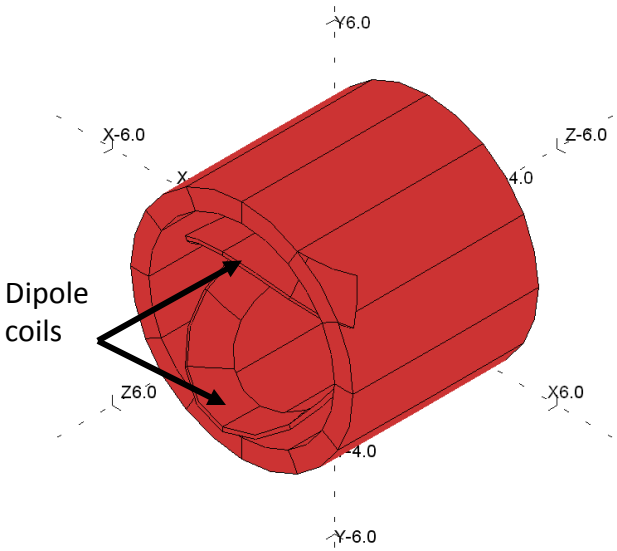
- Today there are two major nuclear physics labs exploring QCD in the US



- Brookhaven National Lab (BNL)
  - *RHIC:* colliding gold nuclei creates nuclear matter at very high temperatures (quark-gluon plasma), and polarized proton collisions study its spin.
- Jefferson Lab (JLab)
  - *CEBAF:* polarized electron scattering provides precision measurements of spatial distributions and orbital motion of quarks, nuclear effects, excited hadrons (glue), and *electroweak physics*.

Detector Magnetic Field

- Central 4T solenoid with 5 meter length and 4 meter ID
  - Need to add good particle identification detectors up to 40 degrees on ion side → drives large ID to keep this area "open"
  - 4T field renders O(1%) or better momentum resolution for particles with momentum < 10 GeV (and angles > 40 degrees)
- Optimize detector to detect particles down to (at least) one degrees
  - Add 2-3 Tm dipole field to improve momentum resolution at forward angles.
  - Two solutions: add dipole, or **add dipole to solenoid?**
  - Can in principle also have split dipole, with different polarity before/after IP, if this helps accelerator design.



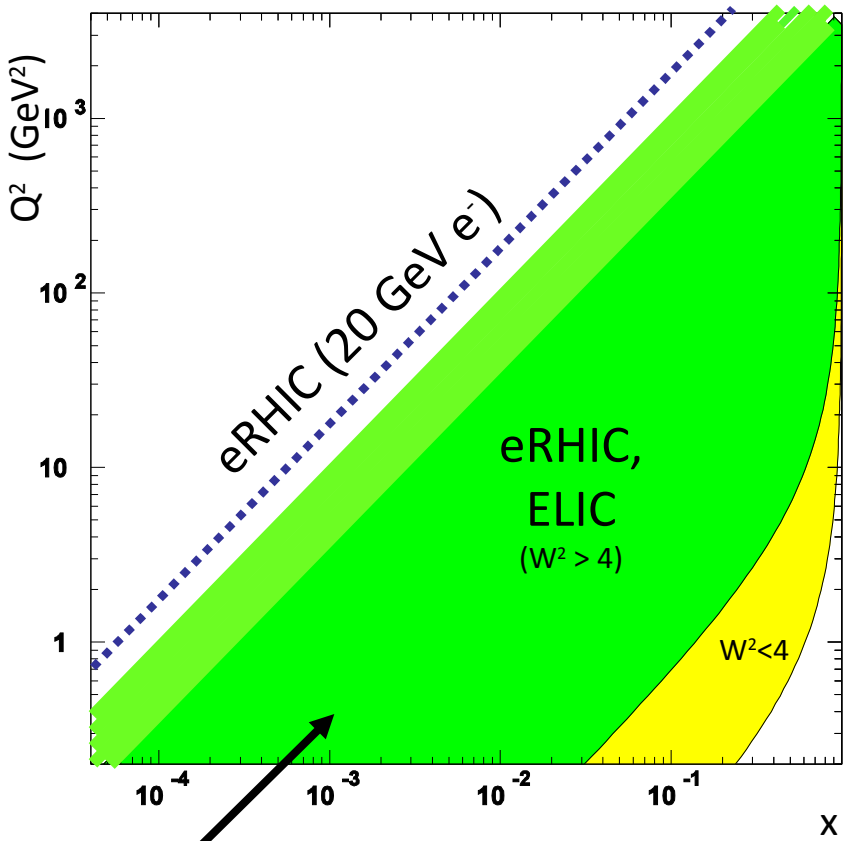
5T solenoid with 0.6T dipole winding:
Integrated transverse (B_y) field strength

@ 90 degrees 10.9 Tm
@ 40 degrees 15.3 Tm
@ 1 degree 1.4 Tm

→May present alternate solution if space is at a premium & 1.4 Tm sufficient field strength at 1°.
→ Note: all configurations iron free at moment

Luminosity Considerations for EIC

eRHIC: x = 10^{-4} @ $Q^2 = 1$
ELIC : x = 10^{-4} @ $Q^2 = 1$
12 GeV: x = 4.5×10^{-2} @ $Q^2 = 1$



Include low-Q^2 region

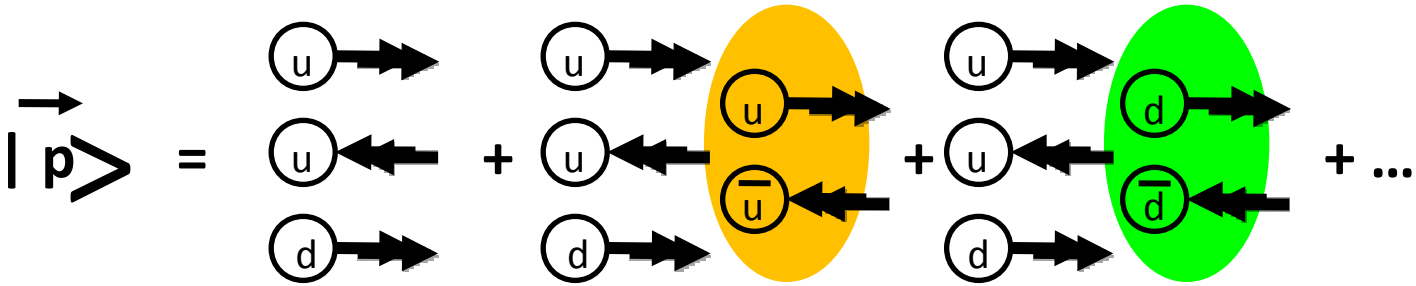
- Luminosity of 1×10^{33} cm^{-2} sec^{-1}
  - One day → 50 events/pb
  - Supports Precision Experiments

Lower value of x scales as s^{-1}

- DIS Limit for $Q^2 > 1$ GeV^2 implies x down to 1.0 times 10^{-4}
  - Significant results for 200 events/pb for inclusive scattering
- If $Q^2 > 10$ GeV^2 required for Deep Exclusive Processes can reach x down to 1.0 times 10^{-3}
  - Typical cross sections factor 100-1,000 smaller than inclusive scattering
  - Significant results for 20,000-200,000 events/pb → high luminosity essential

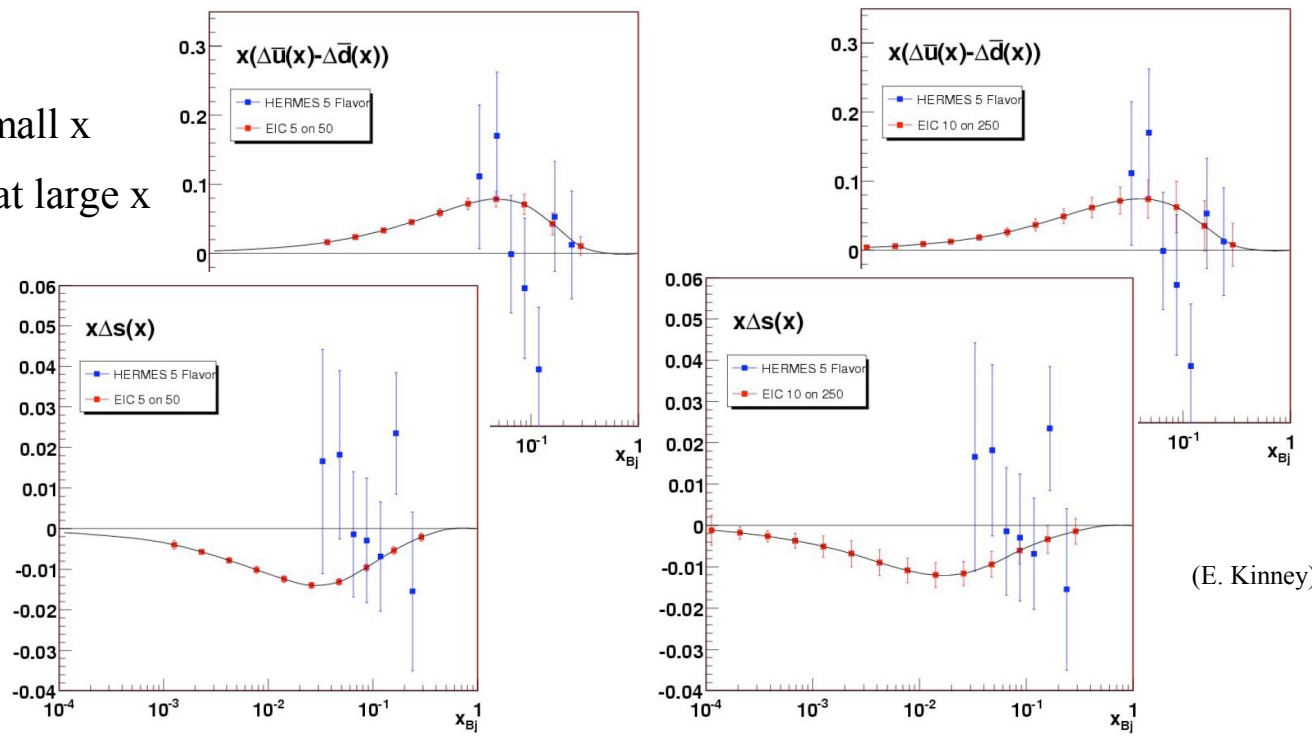
Staging example: s ~ 1000 → x = 1.0×10^{-3}@Q^2=1

SIDIS – flavor decomposition



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

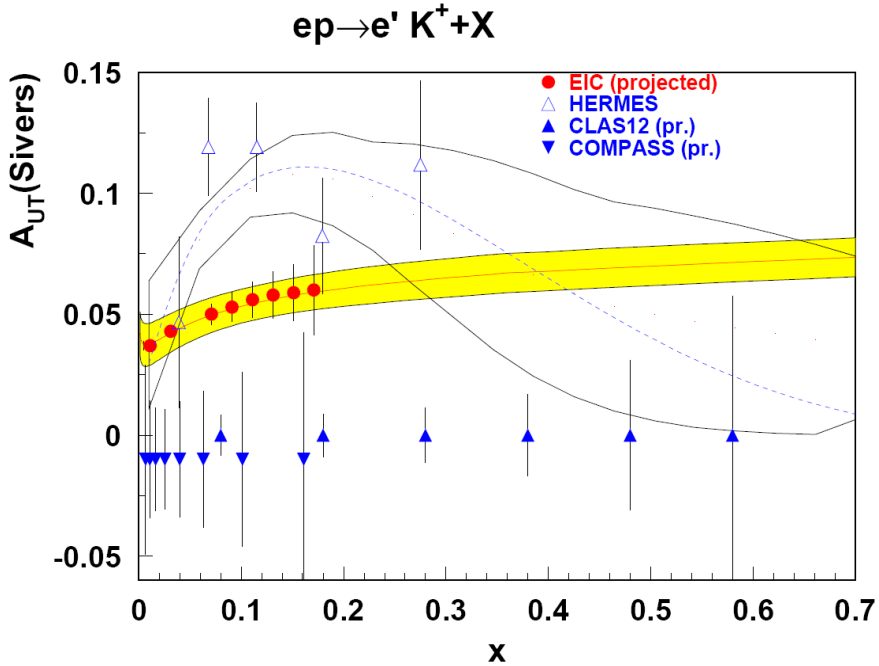
- Also interesting are spatial correlations in the vacuum (nucleon sea). *See previous talk.*



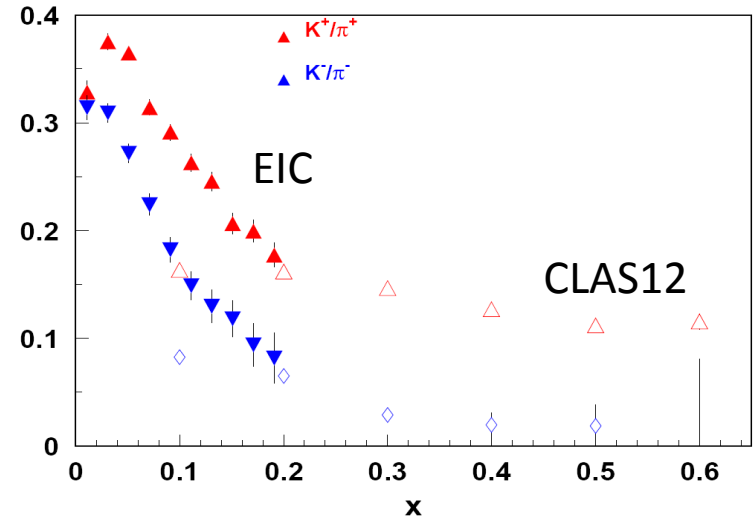
(E. Kinney)

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

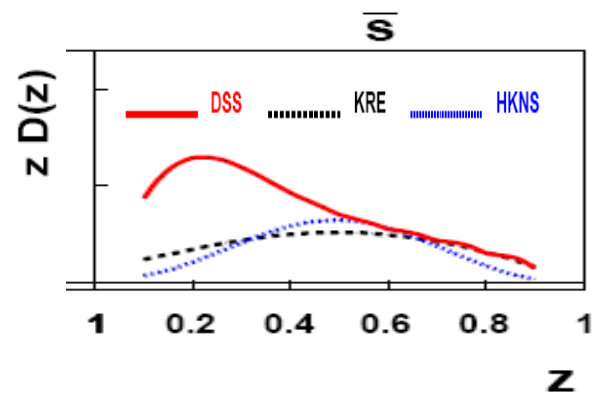
TMDs – simulations



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



H. Avakian



Ideal place to study Sivers asymmetry for kaons is x~0.1 where relative rates are higher.

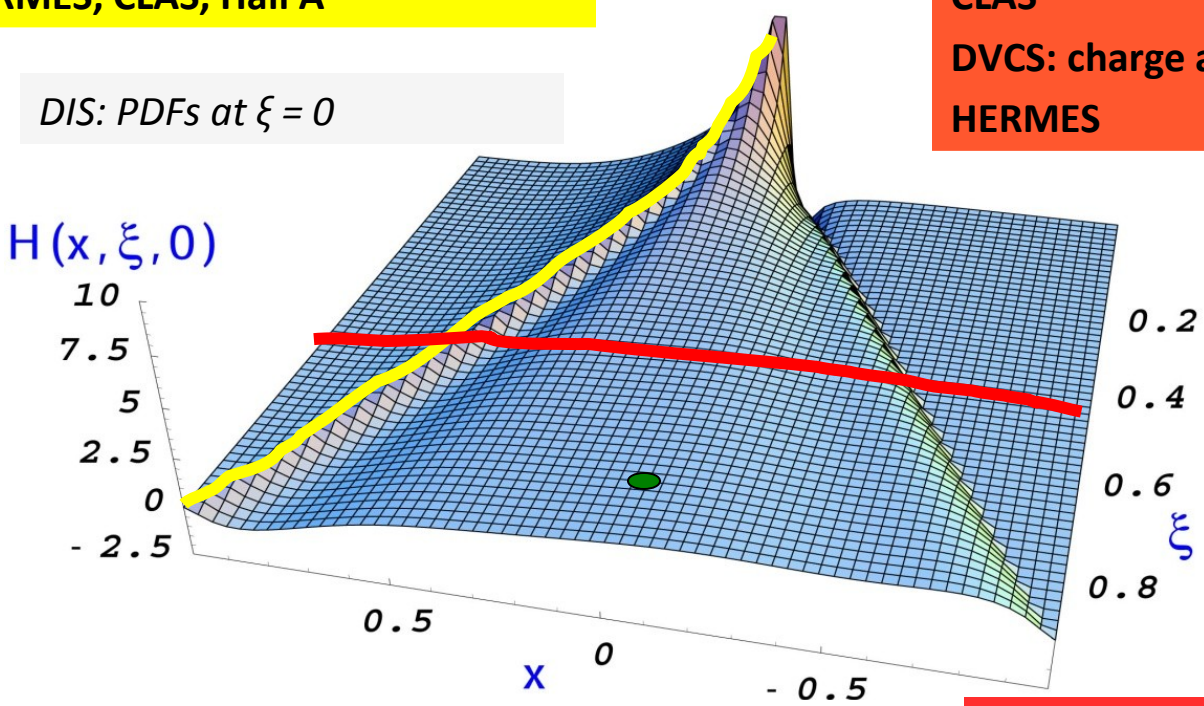
Combination with CLAS12 data will provide almost complete x coverage.

Probing GPDs

(Im, x=ξ)
DVCS: spin asymmetries
HERMES, CLAS, Hall A

(|Re|)
TCS: azimuthal asymmetry
CLAS
DVCS: charge asymmetry
HERMES

DIS: PDFs at ξ = 0



(Im, x ≠ ξ, x < |ξ|)
DDVCS, CLAS12 ?

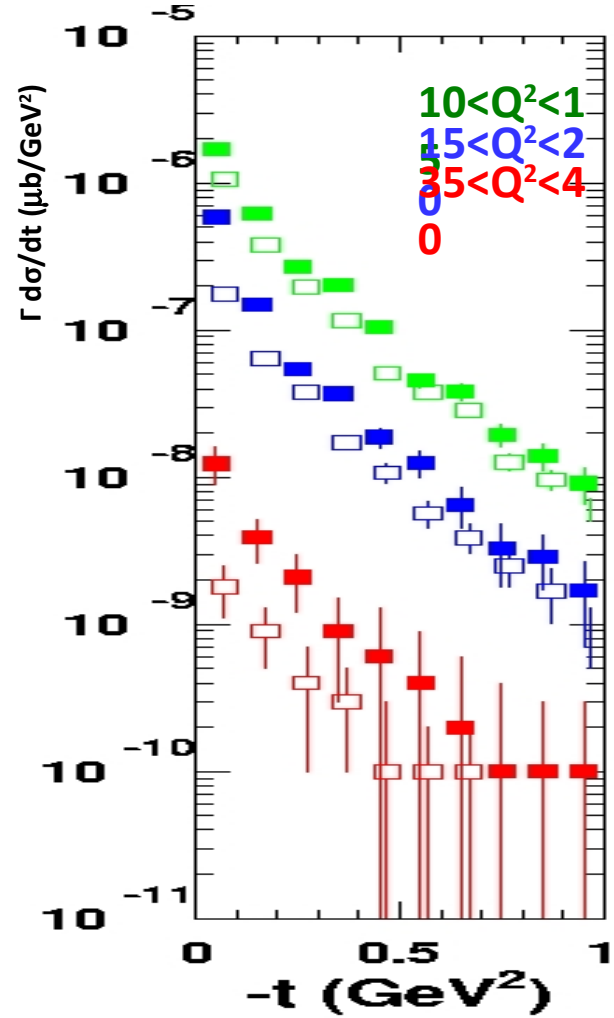
(|Re|²)
DVCS: cross sections
H1, Hall A

Non-diffractive: extension to quark imaging

- Much more demanding in luminosity
- Physics closely related to JLab 6/12 GeV
  - Quark spin/flavor separations
  - Nucleon/meson structure
- Simulation for π^+ production assuming 100 days at a luminosity of 10^{34} with 5 on 50 GeV (s=1000)
  - V. Guzey, C. Weiss: Regge model
  - T. Horn: empirical π^+ parameterization

Pushes for lower and more symmetric energies (to obtain sufficient ΔM_x)

→ Tanja Horn, EICC meeting, Berkeley Dec. 2008



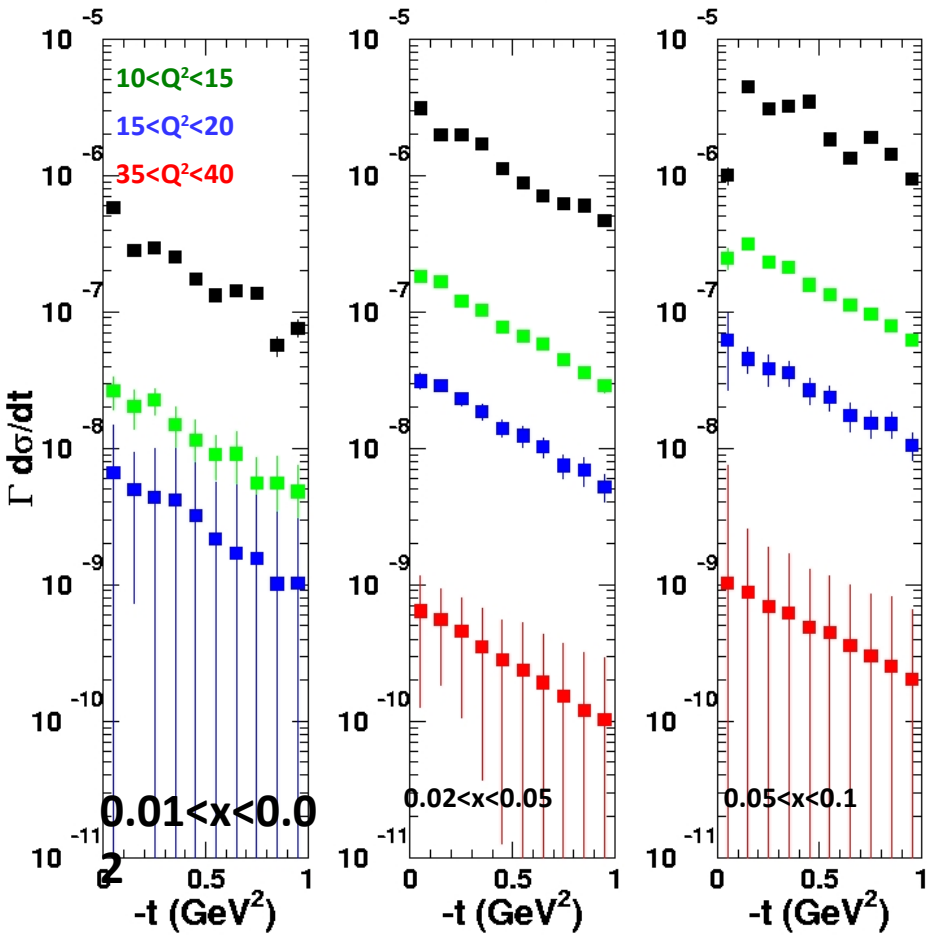
Tanja Horn, Antje Bruell, Christian Weiss

Non-diffractive: extension to quark imaging

Rate estimate for KΛ

Using an empirical fit to kaon electroproduction data from DESY and JLab assuming 100 days at a luminosity of 10^{34}, with 5 on 50 GeV (s = 1000)

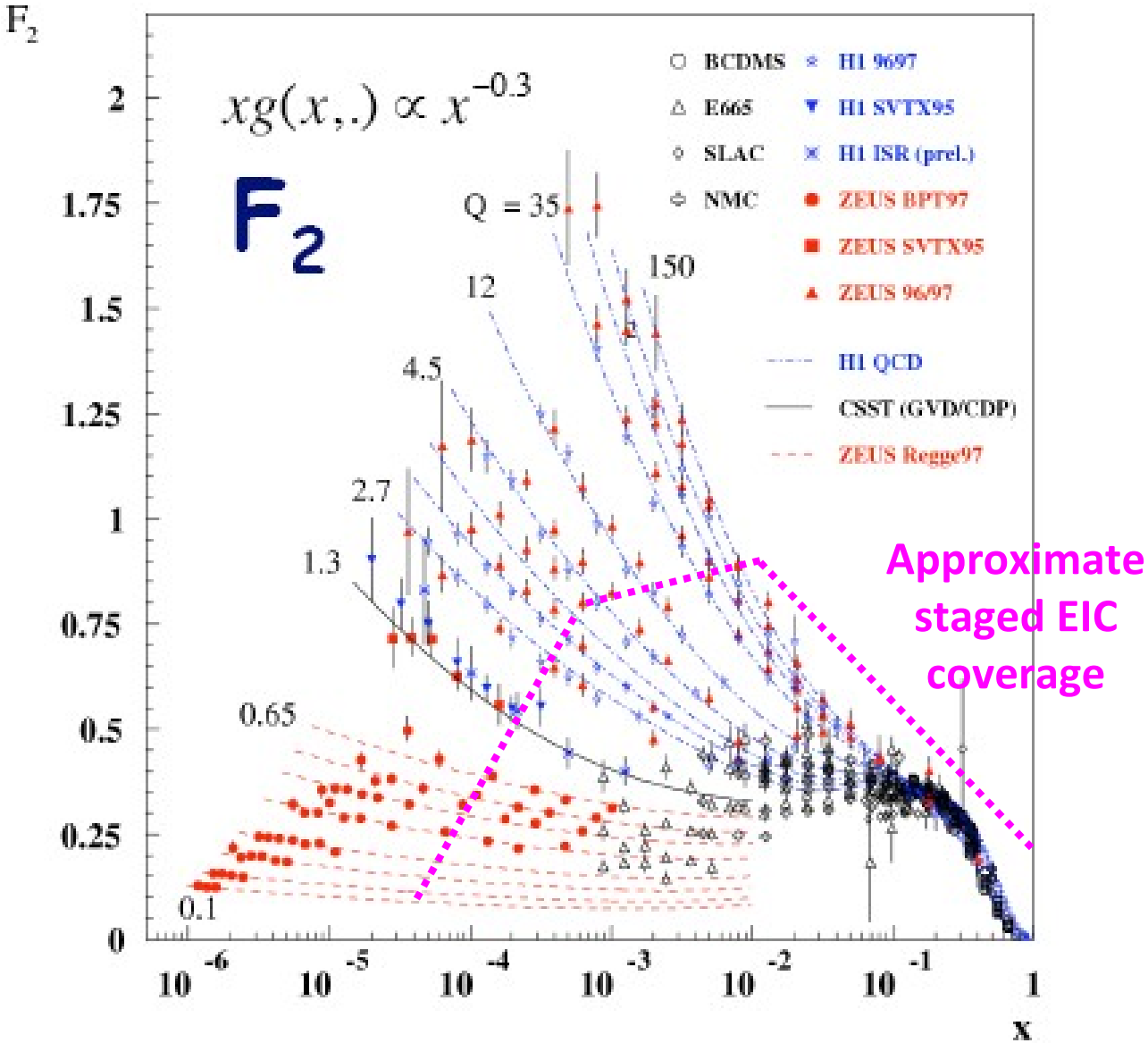
Pushes for lower and more symmetric energies (to obtain sufficient ΔM_x) **and luminosity > 10^{34}**

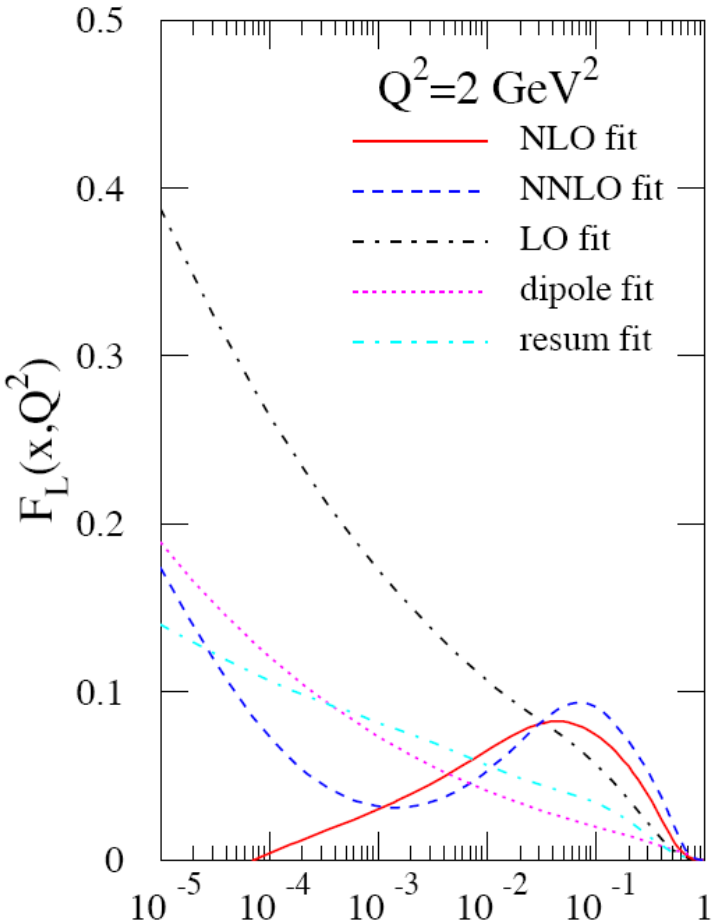
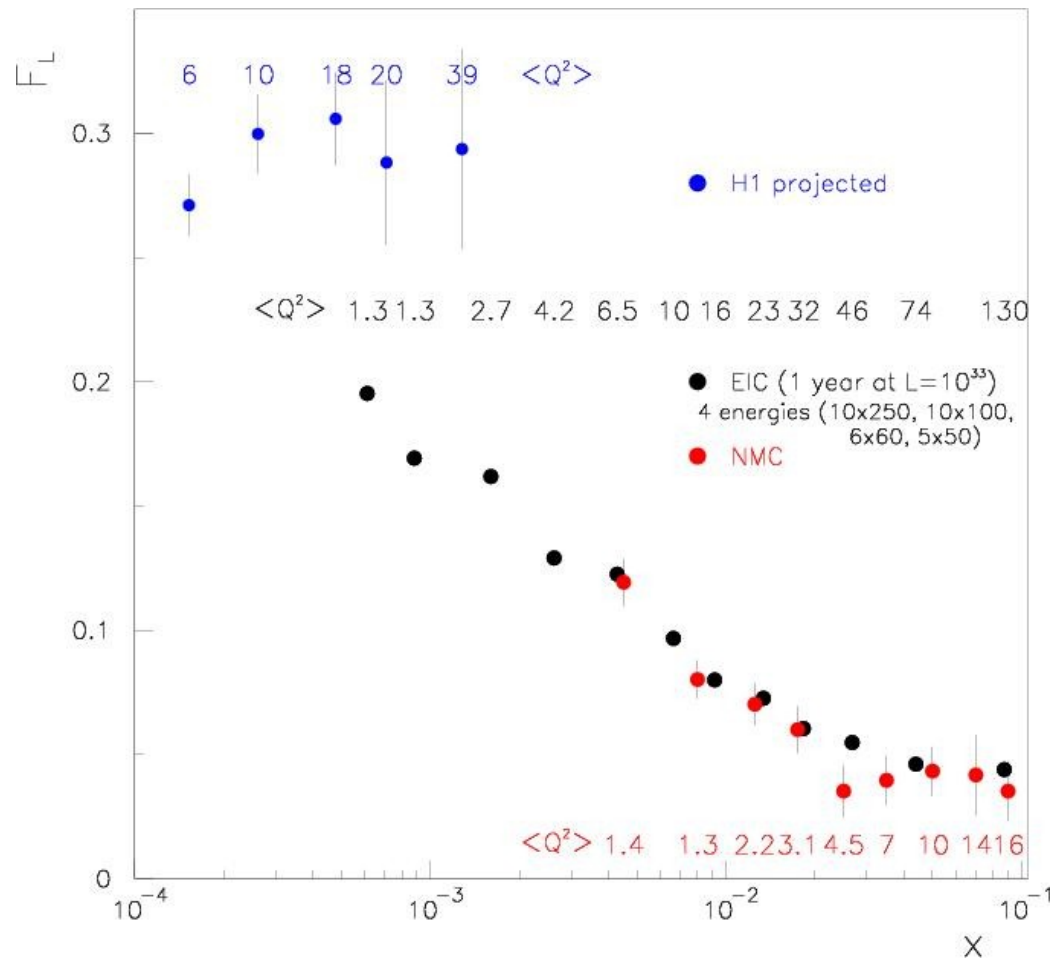


Tanja Horn, David Cooper

Consistent with back-of-the-envelope scaling arguments

s ~ 2500 sufficient to transcend into region of large rise of gluon density



Gluons in the Nucleon – Low x and Q^2

$$F_L \propto \frac{\alpha_s}{2\pi} x \int_x^1 \frac{d\xi}{\xi} \xi(1-\xi)\, g\left(\frac{x}{\xi}, Q^2\right) + \ldots$$