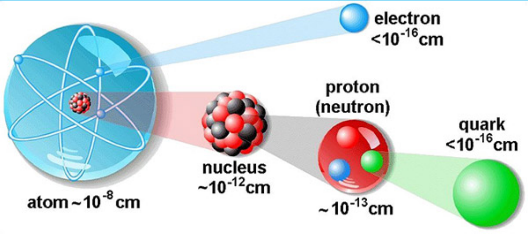
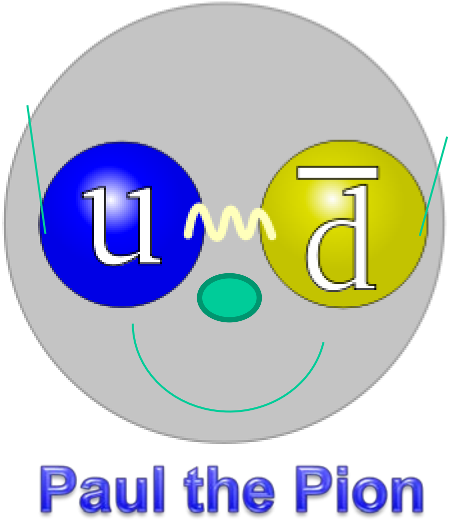
Nucleon Structure – 3D!

Tanja Horn





The Catholic University of America

HUGS Summer School

Jefferson National Laboratory

Lecture 6 of 6

Intro and Overview

- **Lecture 1 & 2: General Overview of QCD and imaging**
  - Introduction and importance of nucleon structure
  - From form factors to GPDs in electron scattering

- **Lecture 3 to Lecture 5: Valence quark imaging at JLab**
  - Jefferson Lab – the place to study nucleon structure
  - Comments on experimental techniques, e.g., Compton Scattering and Deeply Virtual Meson Production
  - Review of results and future prospects

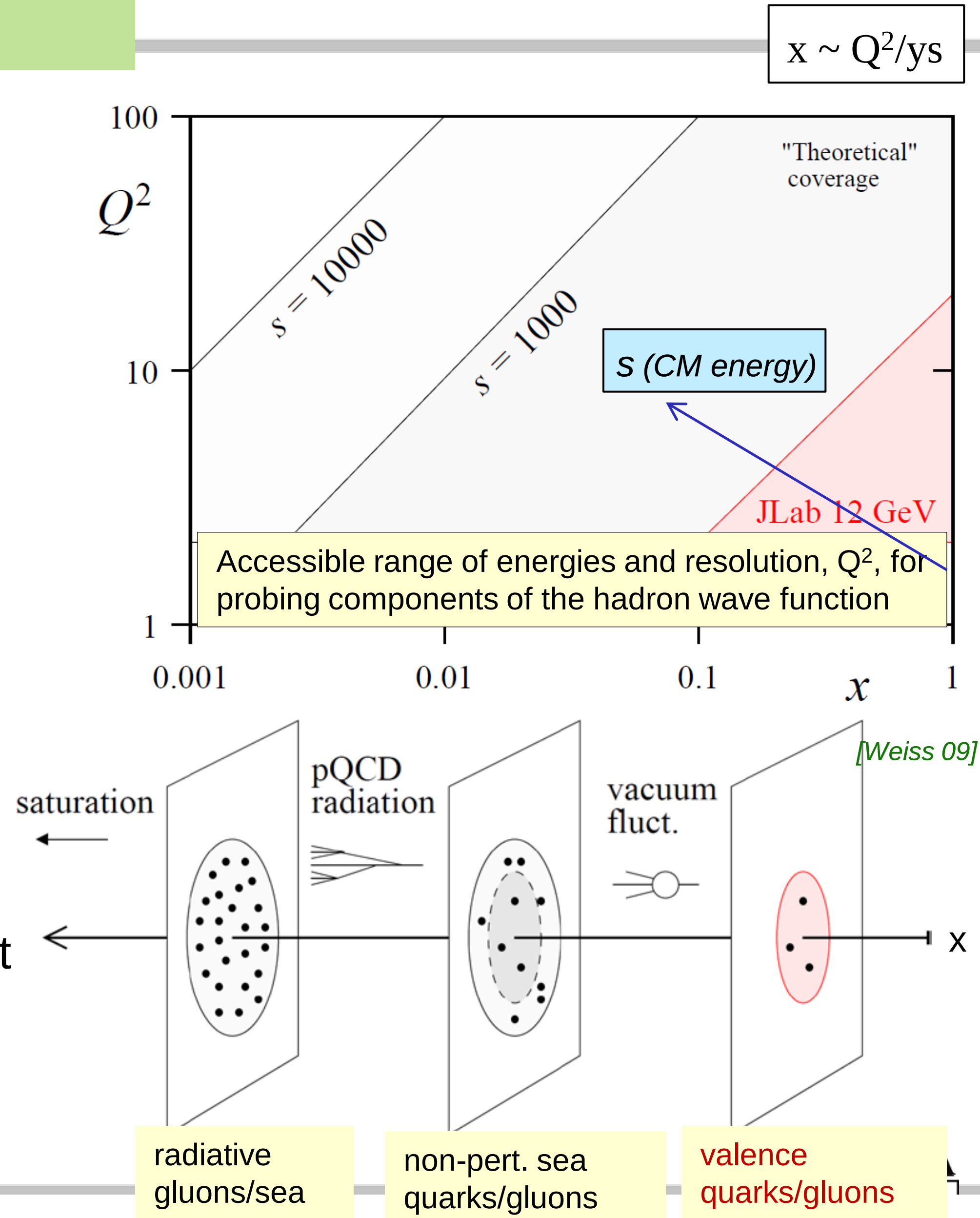
- **Lecture 6: Future of imaging studies** ←
  - Opportunities at Future Facilities

Internal Landscape of the Nucleon

- Hadrons in QCD are relativistic many-body systems
  - Hadron properties encoded in the wave function

- Probe the wave function by scattering a high resolution and high energy probe off of hadrons
  - Probe in electron scattering is virtual photon
  - Resolution scale is given by Q^2
  - Energy related to x

- Depending on x one probes different regimes of the wave function
  - JLab 12 GeV: valence region

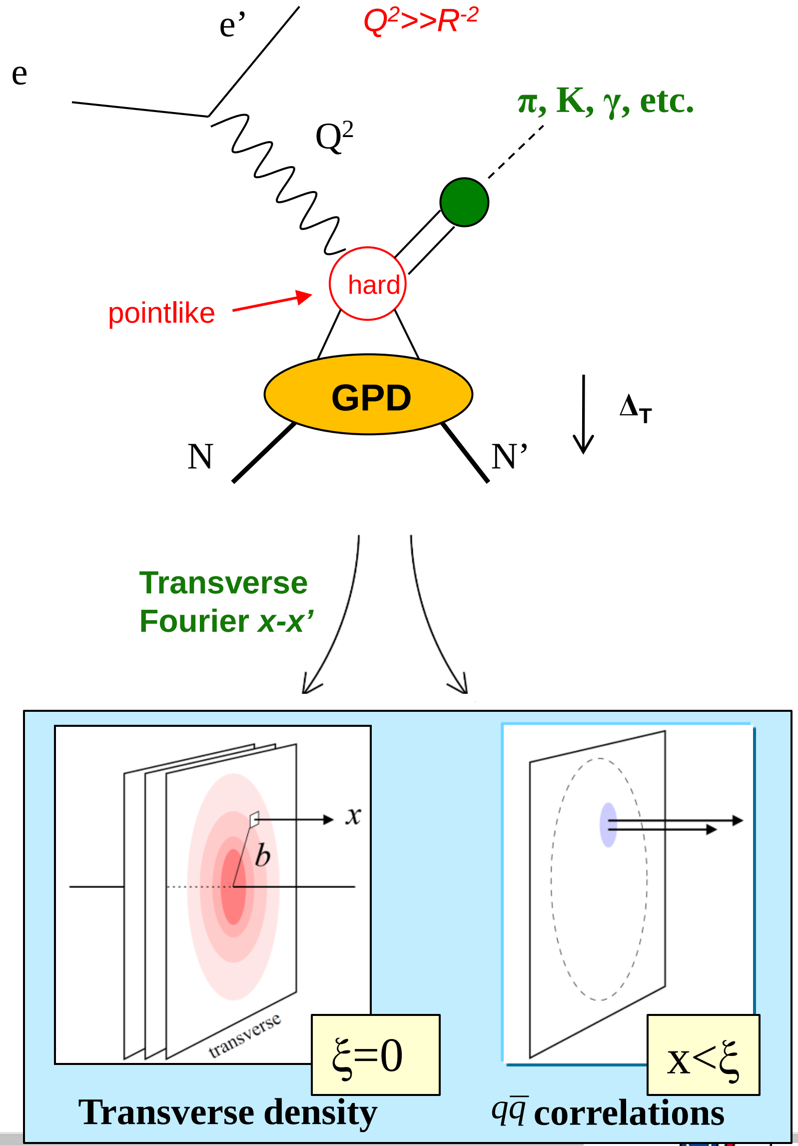


Nucleon Structure through Exclusive Processes

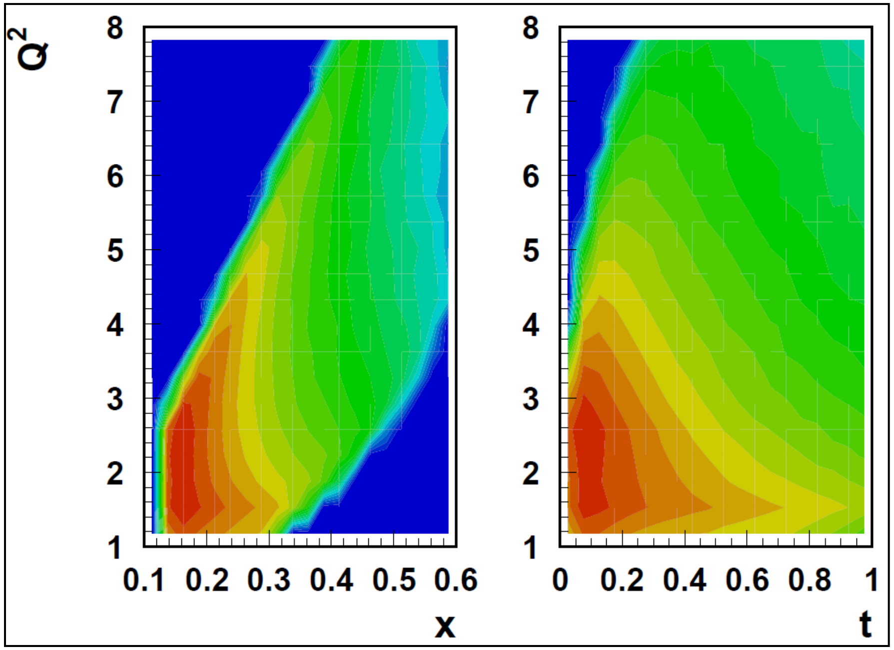
- Exclusive processes at sufficiently high Q^2 allow access to Generalized Parton Distributions (GPDs)
  - Factorization theorem: non-perturbative physics factorizes from perturbative QCD processes for longitudinal photons *[Collins , Frankfurt, Strikman 97]*

- GPDs are *a tool for transverse imaging of the nucleon*
  - **Encode information on correlations and distribution of partons in transverse space** *[Burkardt 00]*
  - Moments, Form factor of local twist-2 spin-n operators: EM tensor, angular momentum *[Ji 96, Polyakov 02]*

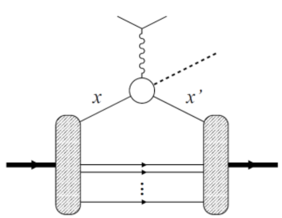
- Tests of reaction mechanism
  - Model-independent features of small-size regime
  - Finite-size corrections



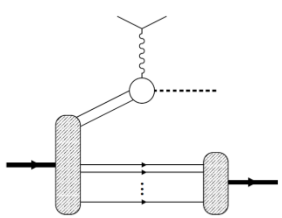
JLab 12 GeV: exclusive reactions



CLAS12 kinematic coverage $N(e,e'\gamma)N$



Scattering from q or $\bar{q}$



Knockout of $q\bar{q}$ pair

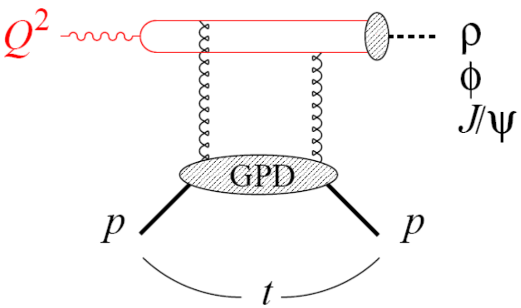
$s = 2E_e m_p$

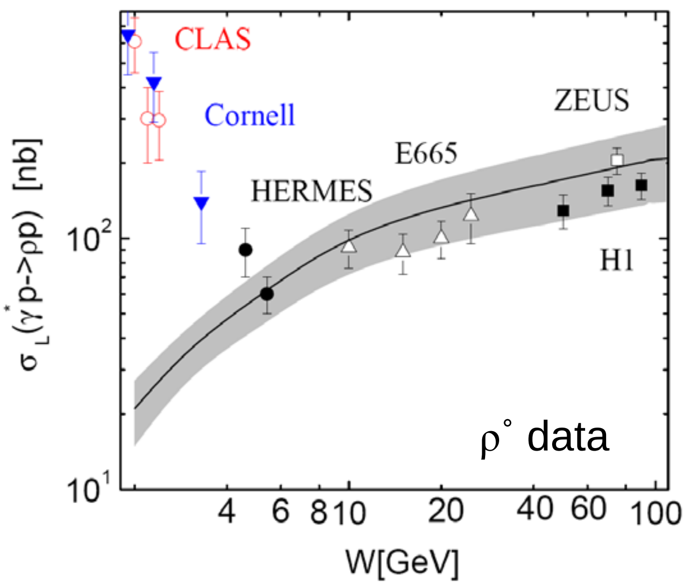
- Unique features:
  - Center of mass energy, s=20.6 GeV^2
  - Luminosity 10^{37} cm^{-2}s^{-1} (Hall A,C), 10^{35} (CLAS12) for valence region, differential measurements, spin asymmetries
  - CLAS12 and magnetic spectrometers in Hall A, C are complementary
- Transverse imaging in valence region:
  - GPDs from DVCS $\gamma^* N \to \gamma + N$
    [→Talks by *F-X Girod]*
  - Transverse charge densities from elastic form factors $\int dx\, \rho(x,b)$
  - **Transverse flavor/spin distributions from exclusive meson production**

    $$\gamma^* N \to N + \pi, K, \rho, K^*, \phi$$
- Limited kinematic coverage:
  - How to test the reaction mechanism?

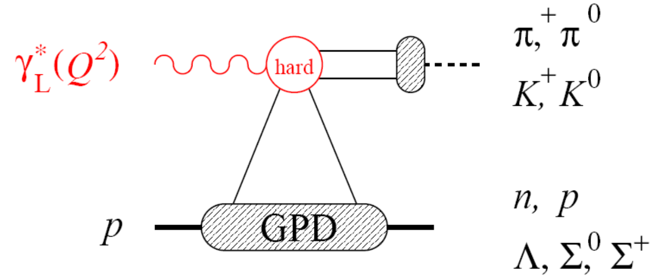
Meson Reaction Mechanism: JLab 12 GeV

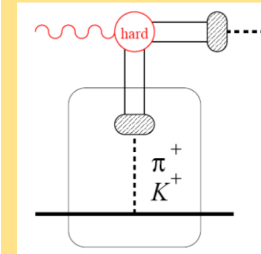
Vector Mesons



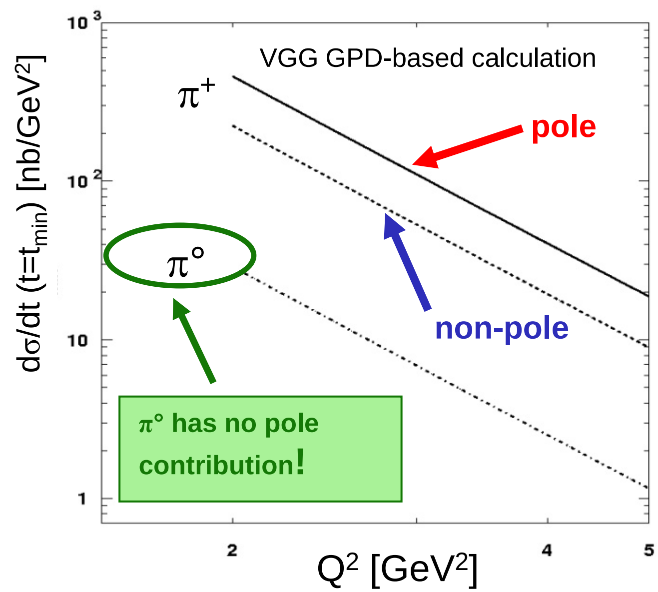


Pseudoscalar Mesons





"pole"

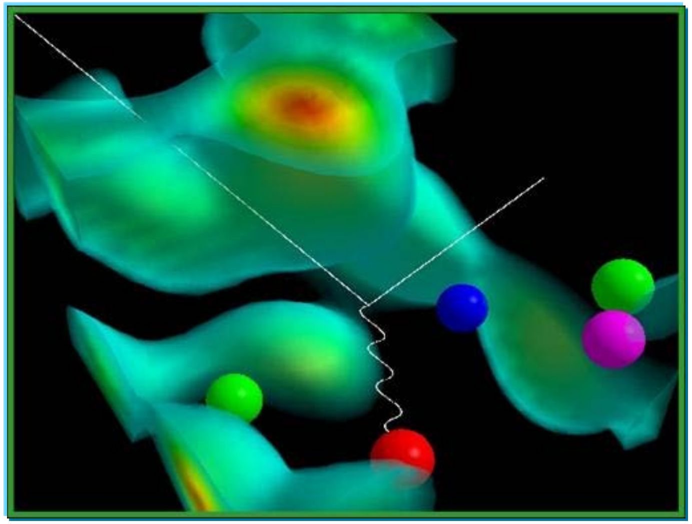


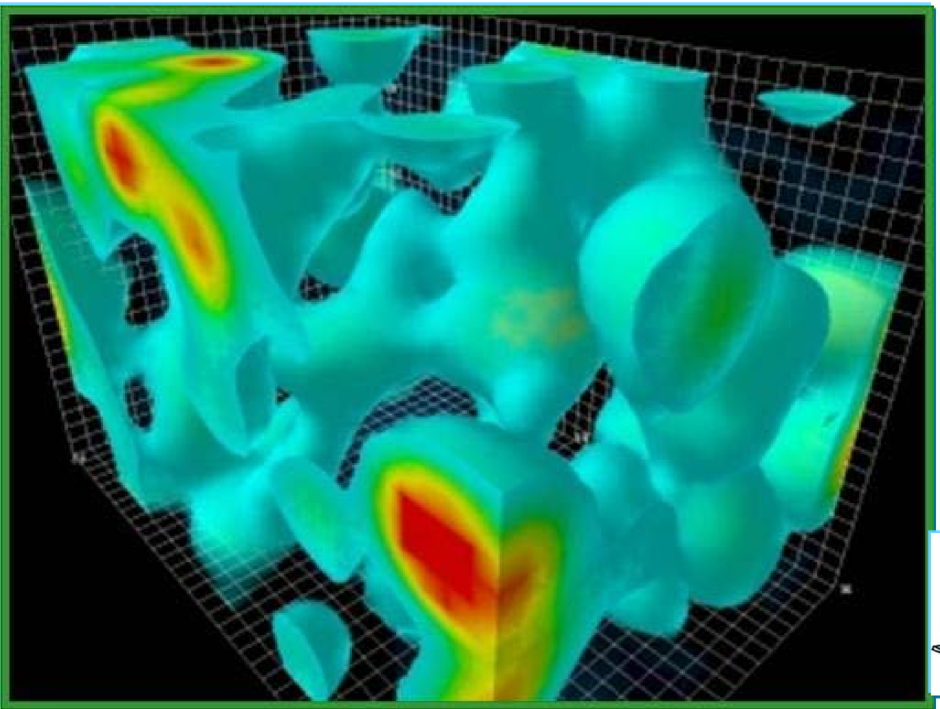
- Understanding of reaction mechanism
  - Role of qqbar pair knockout
  - Finite-size corrections

- Feature: *pole term* in GPD
- Understand relative importance of "pole and "non-pole" contributions

Imaging studies beyond JLab

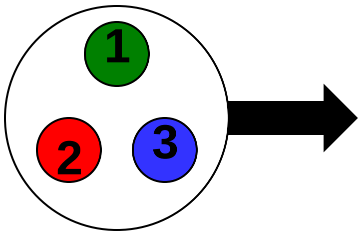
❖ At JLab we can learn about the three (valence) quarks that make up the nucleon, but the story does not end there….





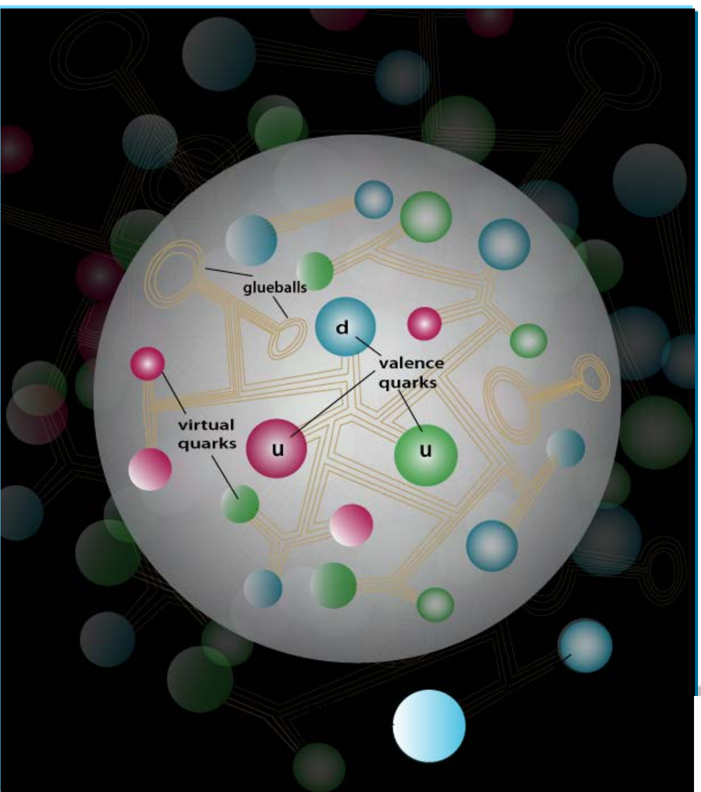
❖ At an Electron-Ion Collider (EIC) we can directly probe the *force carriers of QCD!*

Nucleon with some momentum



- May expect: $$\sum_x \left[xu(x) + xd(x) \right] = 1$$

- Might expect the 3 valence quarks to carry all of the momentum of the nucleon



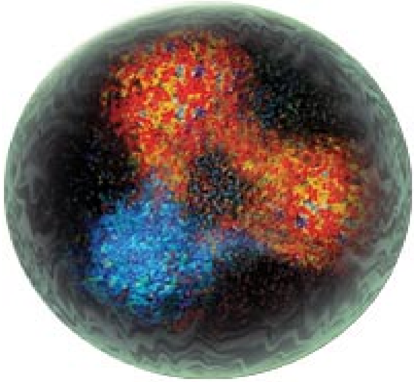
- Actually, one gets:

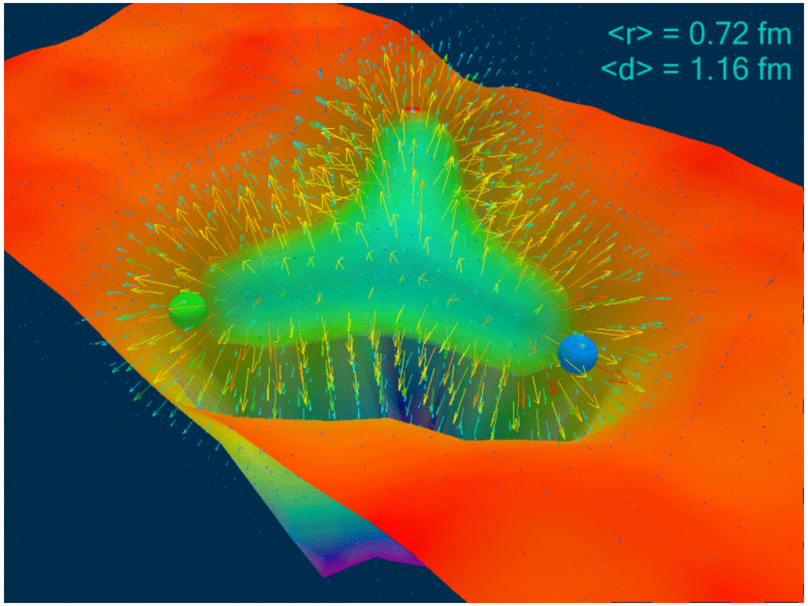
$$\sum_x \left[xu(x) + xd(x) \right] \approx 0.5$$

There is something else in the nucleon, which carries at least half of the nucleon's momentum!

Gluons

- ✓ Gluons carry a significant fraction of the nucleon's momentum
- ✓ Gluons are essential components of protons and nucleons
- ✓ Gluons provide the "glue", which keeps the quarks inside the nucleon
  - They are the carriers of the strong force





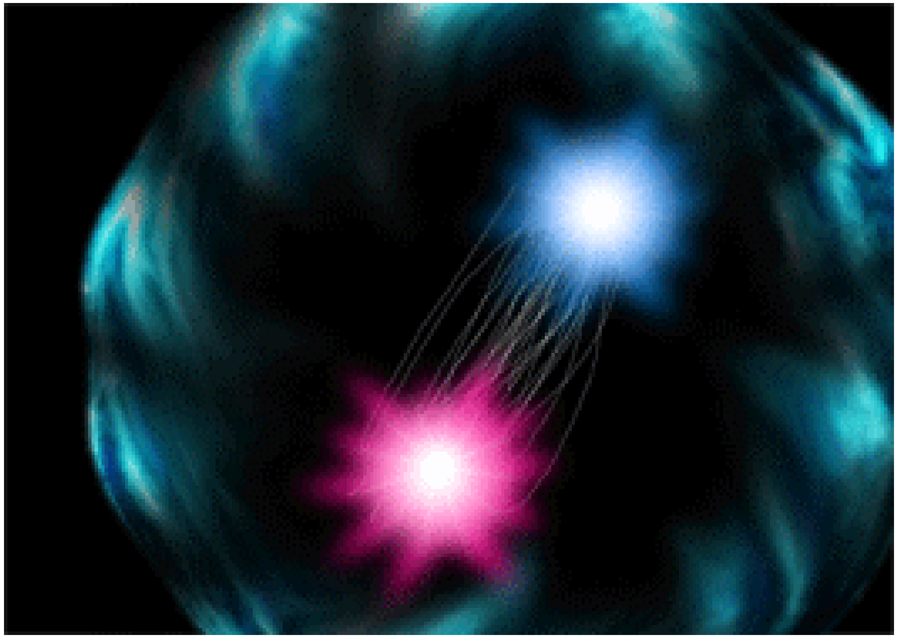
Sea quarks

- The pion cloud around the nucleon from which we knocked out the virtual pion is really part of the nucleon itself

- In fact, the three valence quarks move in a sea of virtual quarks and gluons.

- These virtual quark-antiquark pairs carry the rest of the nucleons momentum

- As with all virtual particles, they exist only long enough such that the Heisenberg principle is not violated

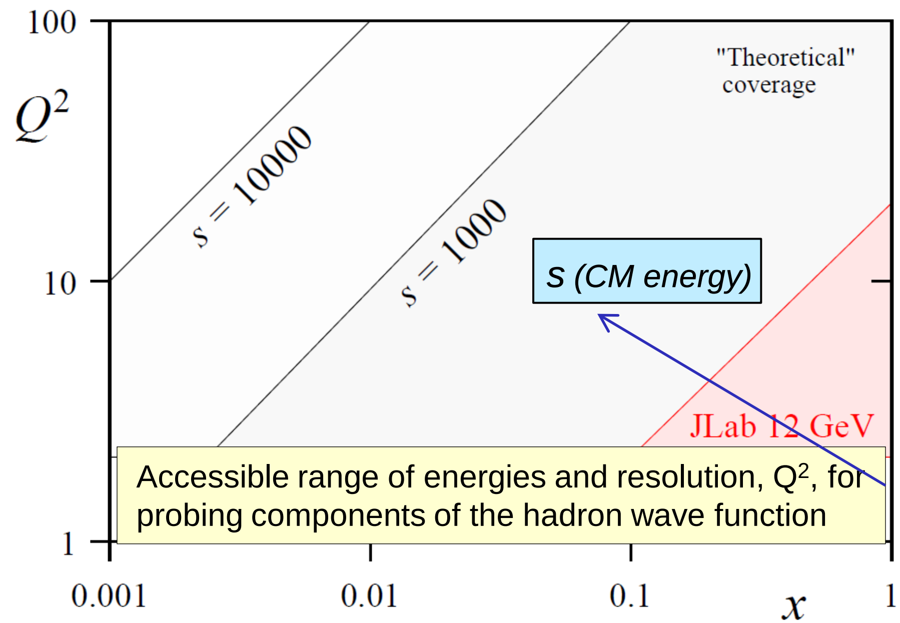


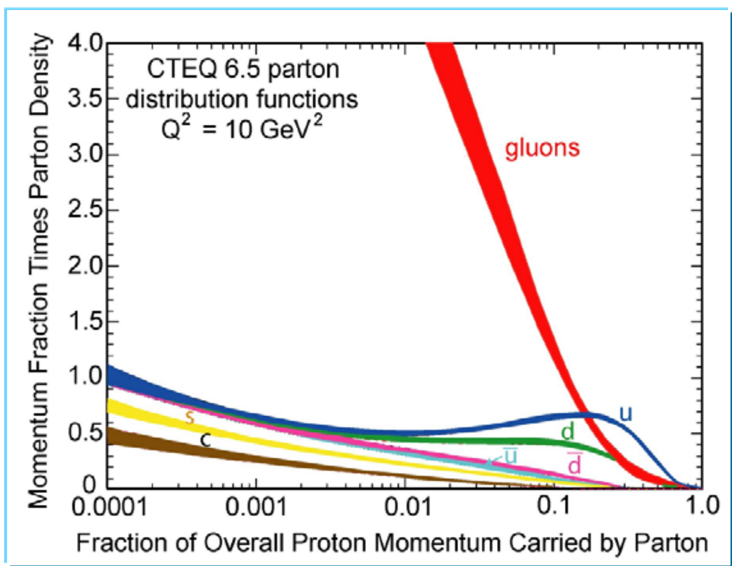
Quark Momentum Distributions

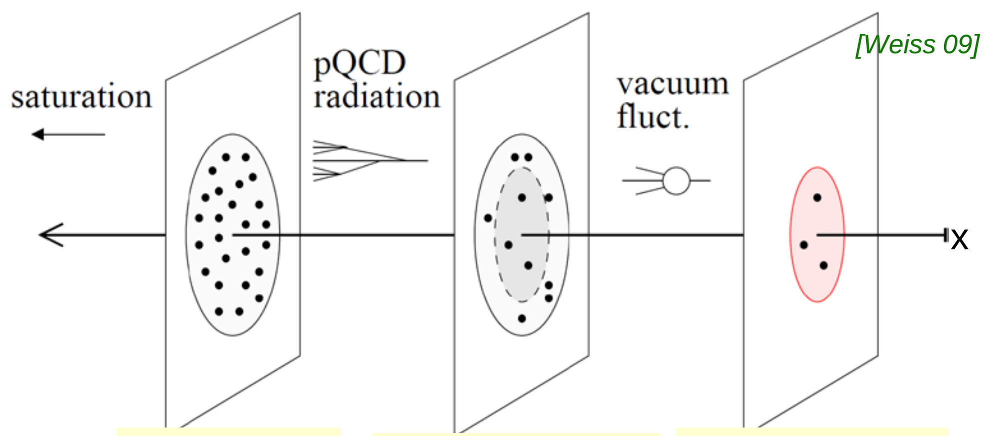
$x \sim Q^2/ys$

- Where do we look for gluons in the nucleon? – *at low x*

- This is also the place to look for strange sea quarks







Electron Ion Collider (EIC)

- A next-generation facility aimed at providing unprecedented access to gluon imaging in nucleons and nuclei

We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron-Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton. [NSAC Long Range Plan 2007]

- Two possible physics goals:
  - QCD at high gluon densities
  - Precision imaging of sea-quarks and gluons to determine spin, flavor, and spatial structure of the nucleon

- Candidates for the EIC are BNL and JLab

Why an electron-ion Collider?

- **Easier to reach high Center of Mass energies ($E_{CM}^2 = s$)**
  - $s = 4E_e E_p$ for colliders (e.g., 4 x 9 x 60=2160 GeV^2)
  - $s = 2E_e M_p$ for fixed target experiments (e.g., 2 x 11 x 0.938)=20 GeV^2)

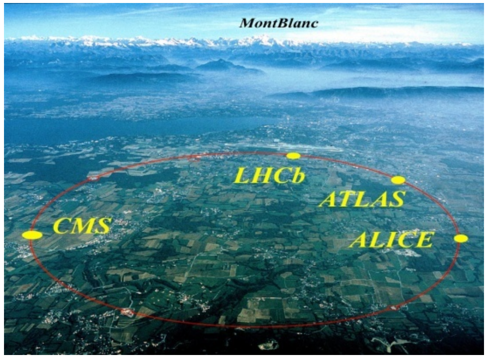
- **Spin physics with high figure of merit**
  - Unpolarized FOM = **Rate = Luminosity x Cross Section x Acceptance**
  - Polarized **FOM = Rate x (Target Polarization)^2 x (Target Dilution)^2**
  - No *dilution* and high ion polarization (also *transverse*)
  - No current (*luminosity*) limitations, no holding fields (*acceptance*)
  - No *backgrounds* from target (Moller electrons)

- **Easier detection of reaction products**
  - Can optimize kinematics by adjusting beam energies
  - More symmetric kinematics improve acceptance, resolution, particle ID, etc.
  - Access to neutron structure with deuteron beams ($p_p \neq 0$)

Target	$f_{dilution, fixed\_target}$	P_{fixed_target}	$f^2P^2_{fixed\_target}$	$f^2P^2_{EIC}$
p	0.2	0.8	0.03	0.5
d	0.4	0.5	0.04	0.5

Past and Future e-p and e-A Colliders

HERA, Hamburg, 1992-2007
27 GeV e on 920 GeV p, $\mathcal{L}=5\times10^{31}$



LHeC, CERN, Geneva

Jefferson Lab, Newport News, VA

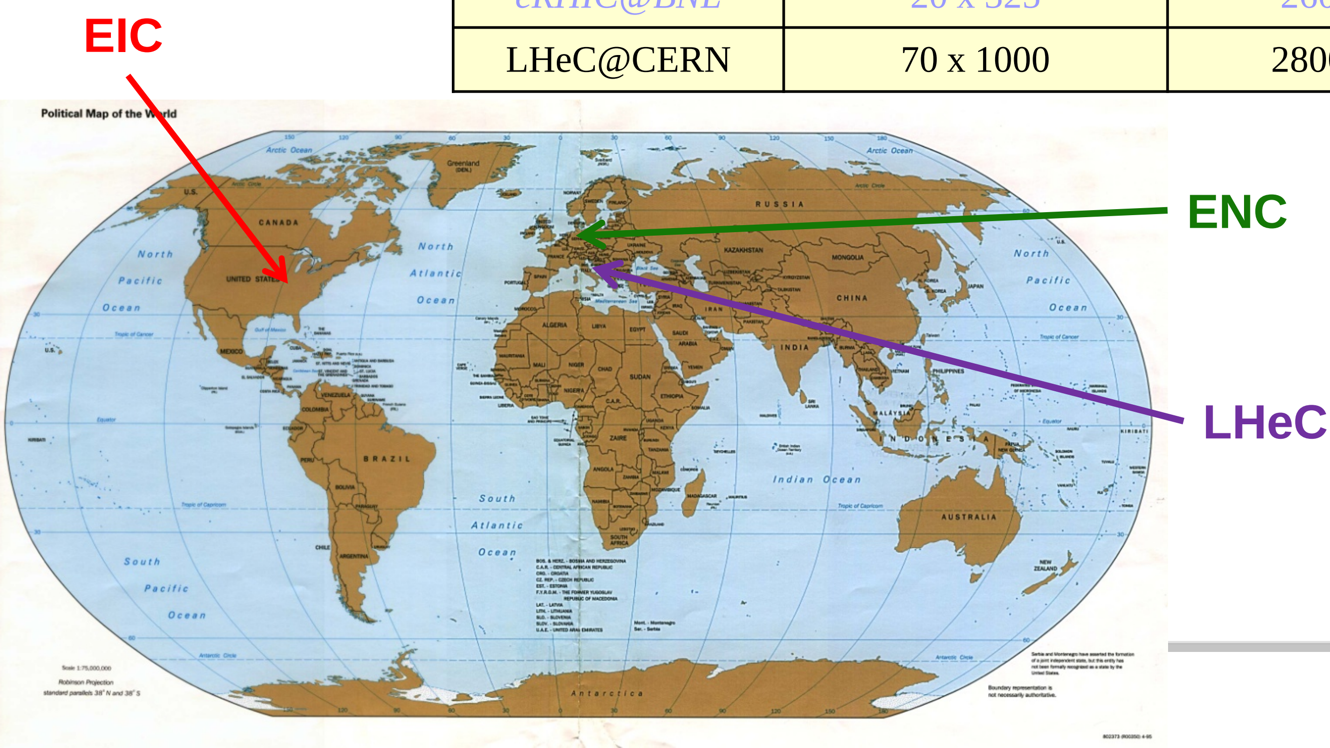
EIC ⟷

BNL, Upton, NY

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

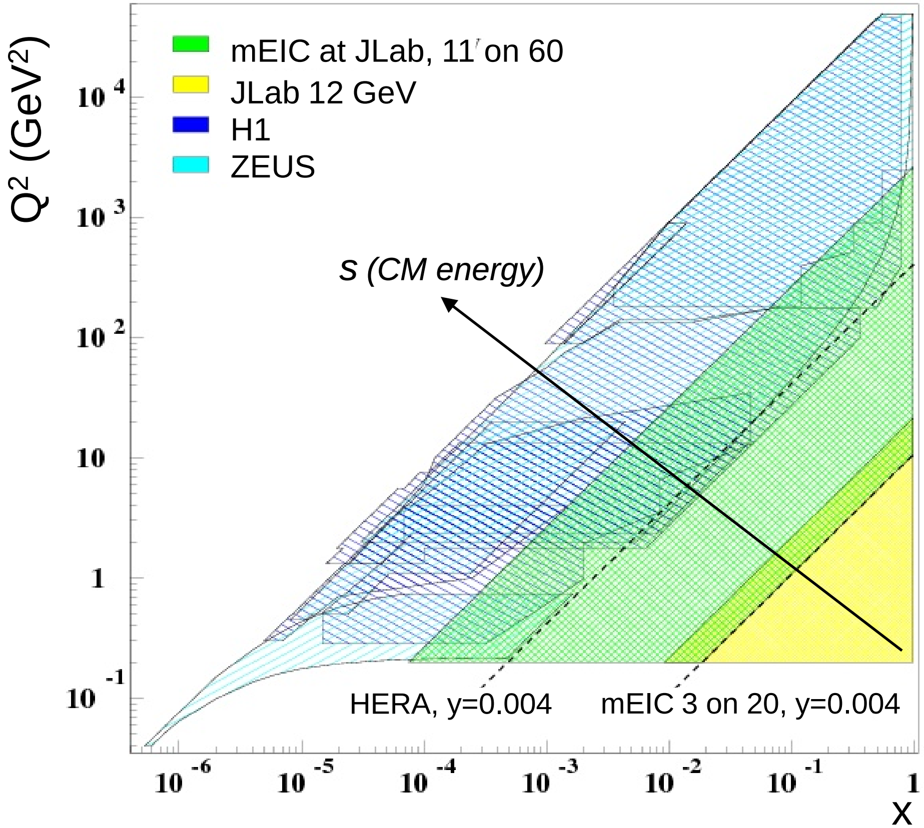
Design Goals for Colliders Under Consideration World-wide

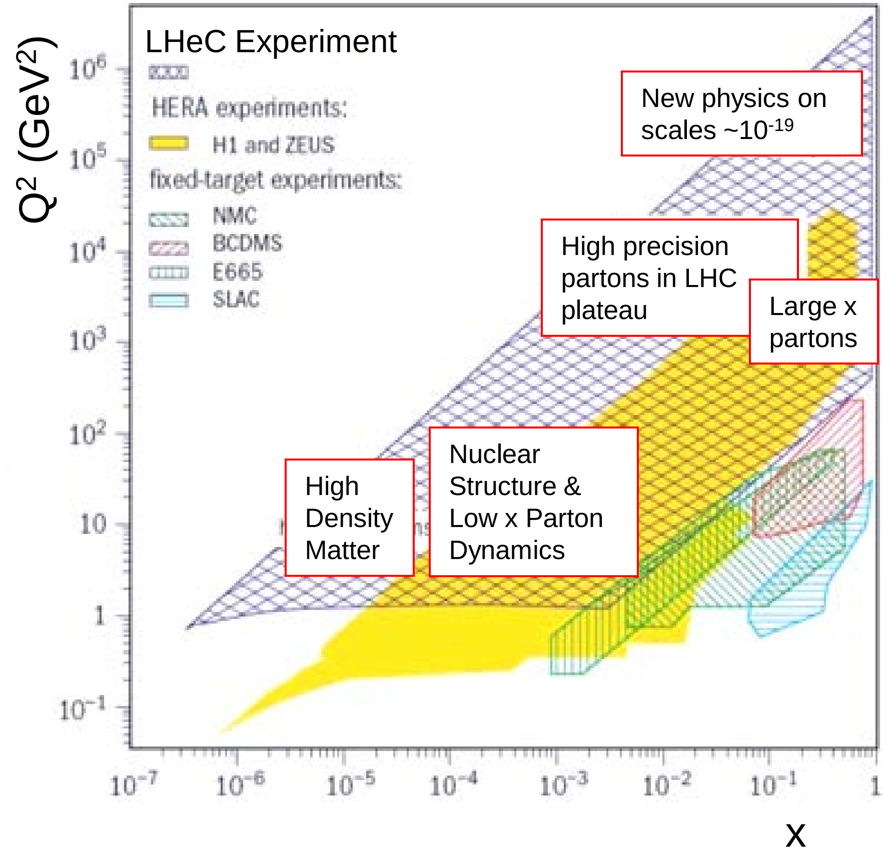
	Max e/p Energies	s	Max Luminosity*
ENC@GSI	3 x 15	180	Few x 10^{32}
MEIC@JLab	11 x 70(100)	250-3080(4400)	10^{34}
MeRHIC@BNL	4 x 250	1200-4000	10^{32}
ELIC@JLab	11 x 250	11000	Close to 10^{35}
eRHIC@BNL	20 x 325	26000	Few x 10^{33}
LHeC@CERN	70 x 1000	280000	10^{33}



Kinematic Coverage

$x \sim Q^2/ys$

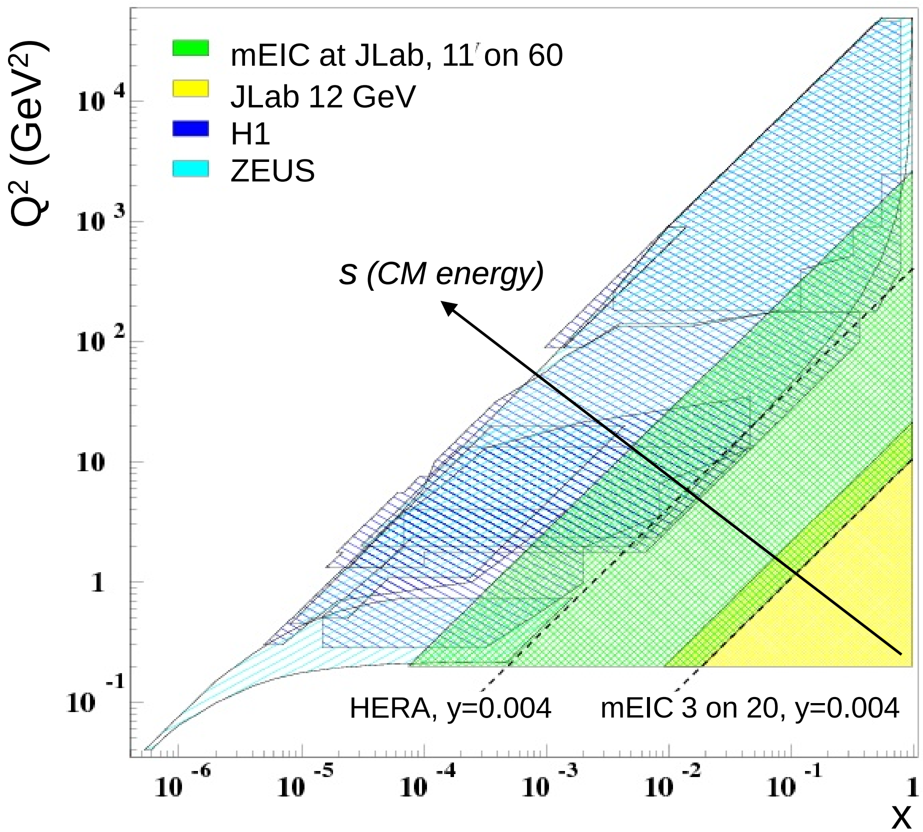


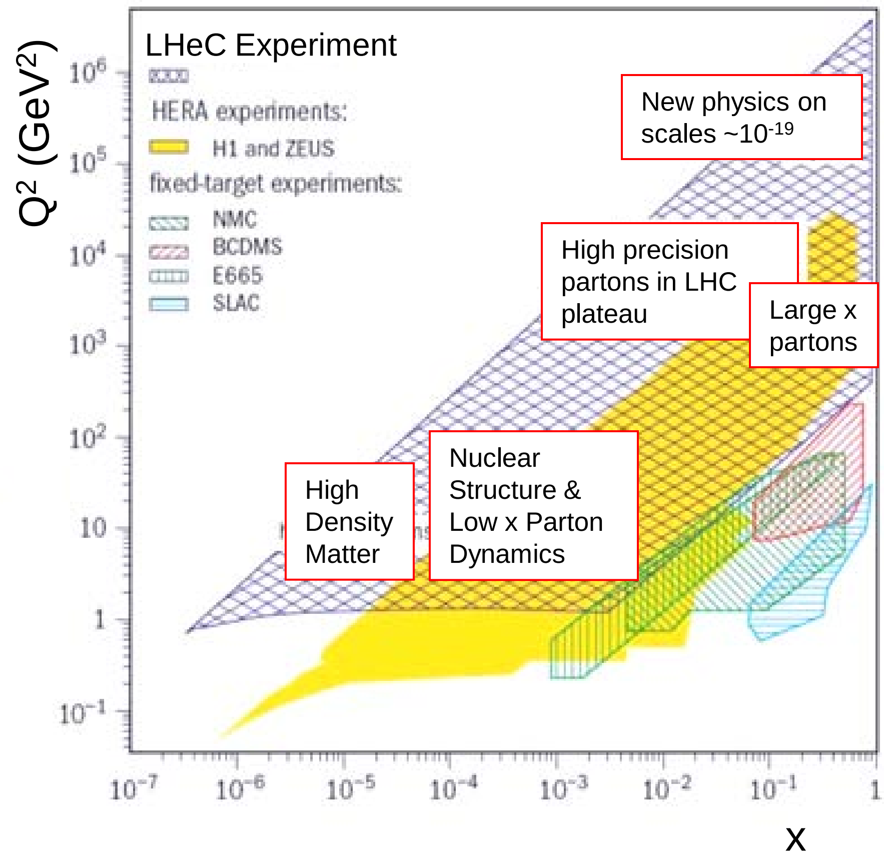


- Medium-energy EIC
  - Overlaps with and is complementary to the LHeC (both Jlab and BNL versions)
  - Overlaps with Jlab 12 GeV (Jlab version)
  - Provides high luminosity and excellent polarization for the range in between
    - Currently only low-statistics fixed-target data available in this region

Kinematic Coverage

$x \sim Q^2/ys$

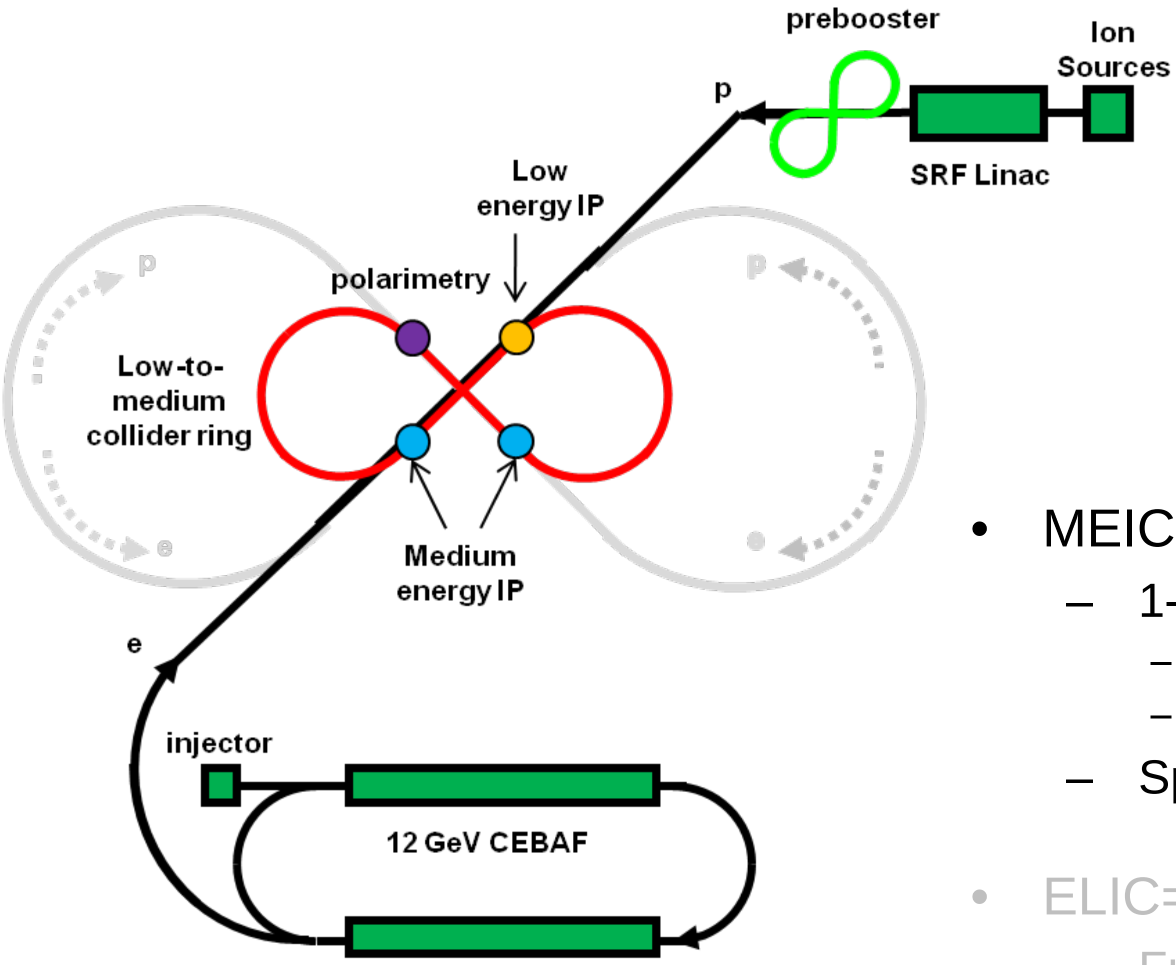




- High-energy EIC
  - Will move higher into the region covered by HERA (and LHeC)
  - Will provide good polarization and heavy ions (which HERA did not have)
  - If LHeC is not built, may be the only machine that can see gluon saturation in e-A collisions

A high-luminosity EIC at JLab

Use CEBAF "as-is" after the 12-GeV Upgrade



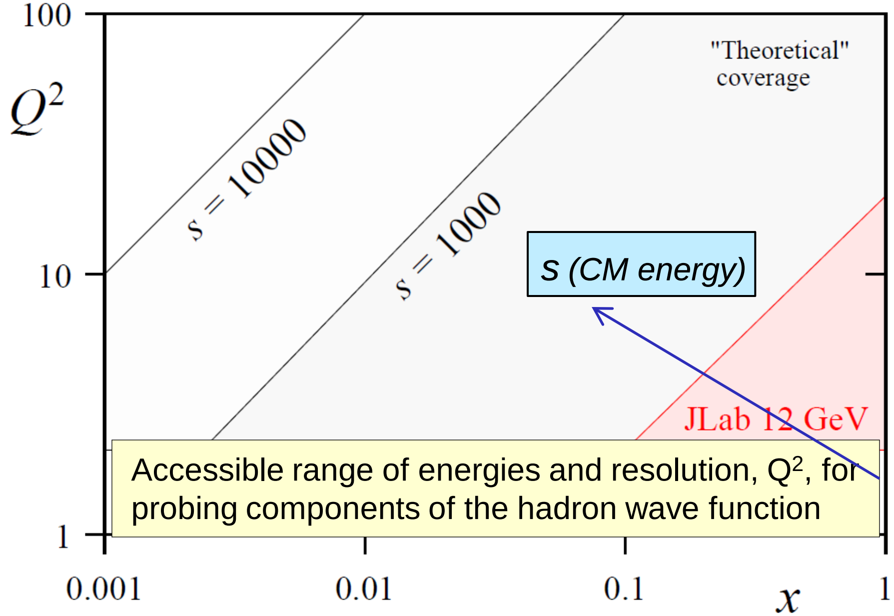
Electron energy: 3-11 GeV
Ion energy: 20-70(100) GeV

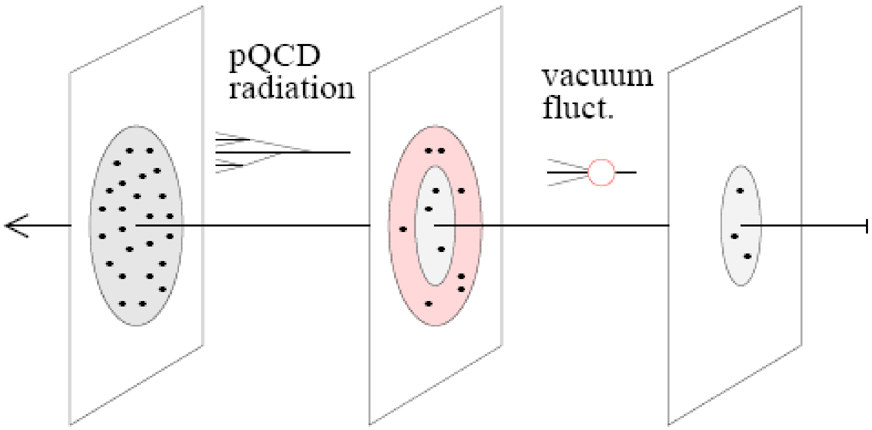
s=250-3080(4400) GeV^2

Can operate in parallel with fixed-target program

- MEIC=EIC@JLAB
  - 1-2 high-luminosity detectors
    - Luminosity ~10^{34} $cm^{-2}s^{-1}$
    - Low backgrounds
  - Special detector
- ELIC=high-energy EIC@JLab
  - Future Upgrade?

Physics, Kinematic Coverage, and Luminosity





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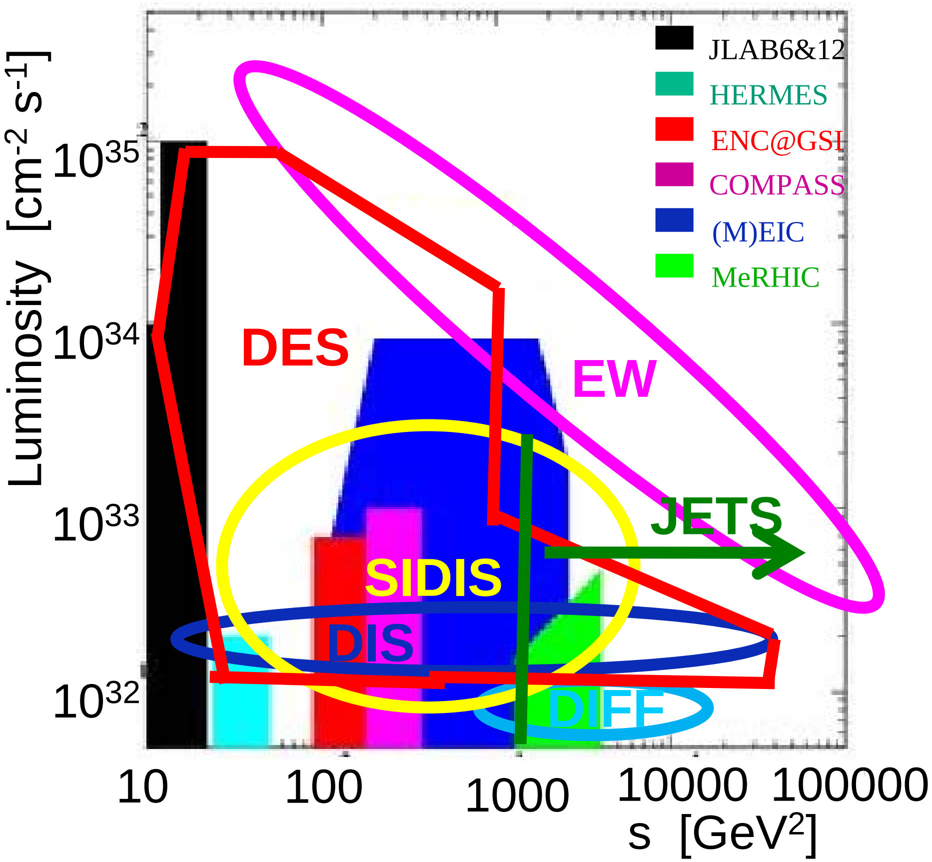


Right plot (L vs. s) is a projection on the diagonal of the left one (Q^2 vs. x)

EIC@JLab Science Summary

- ✓ Gluon and sea quark (transverse) imaging of the nucleon
- ✓ Nucleon Spin (ΔG vs. $\ln(Q^2)$, transverse momentum)
- ✓ Nuclei in QCD (gluons in nuclei, quark/gluon energy loss)
- ✓ QCD Vacuum and Hadron Structure and Creation
- ✓ Electroweak Physics

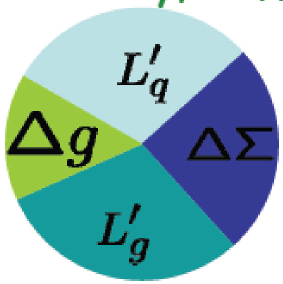
	Energies	s	Luminosity*
EIC@Jlab	Up to 11 x 70(100)	250-3080(4400)	10^{34}
Future option	Up to 11 x 250	11000	$>10^{34}$

*without coherent electron cooling

The spin of the proton

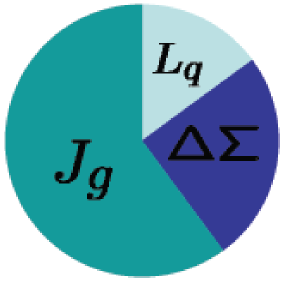
ambiguities arise when decomposing proton spin in gauge theories

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

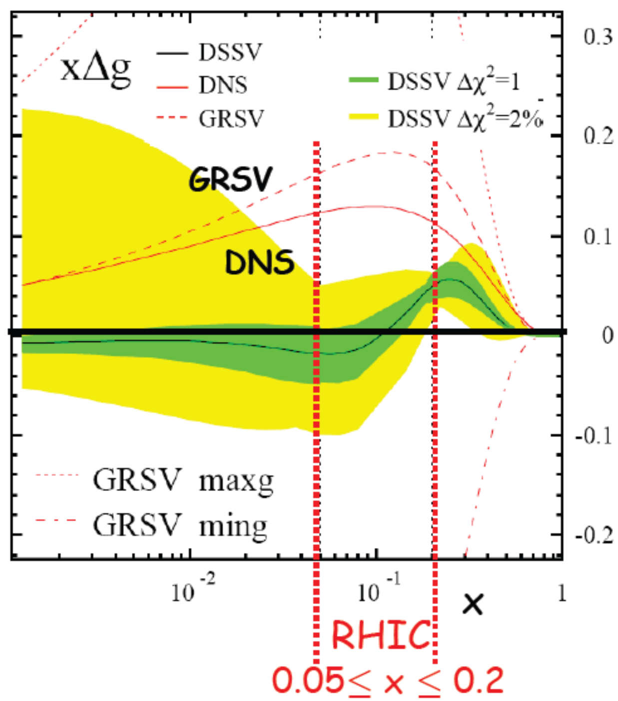
Burkardt, BC
arXiv:0812.1605

[From M. Stratmann, INT09-43W]

Proton Spin: two complementary approaches

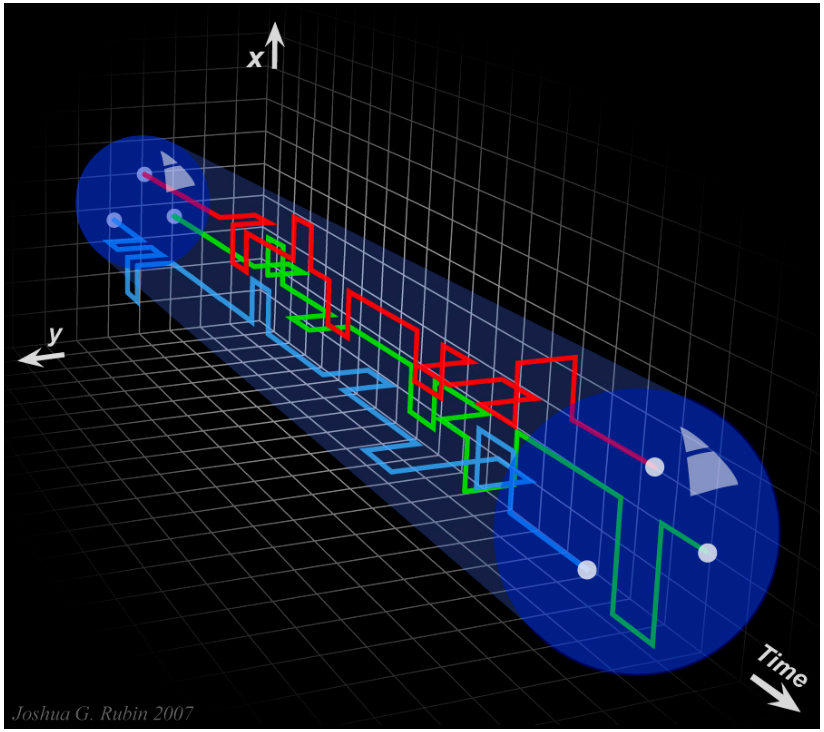
- Measure GPDs and TMDs to learn about angular momentum (Ji)
  - Connected to Lattice QCD
  - Exclusive measurements require high luminosity at lower energies

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



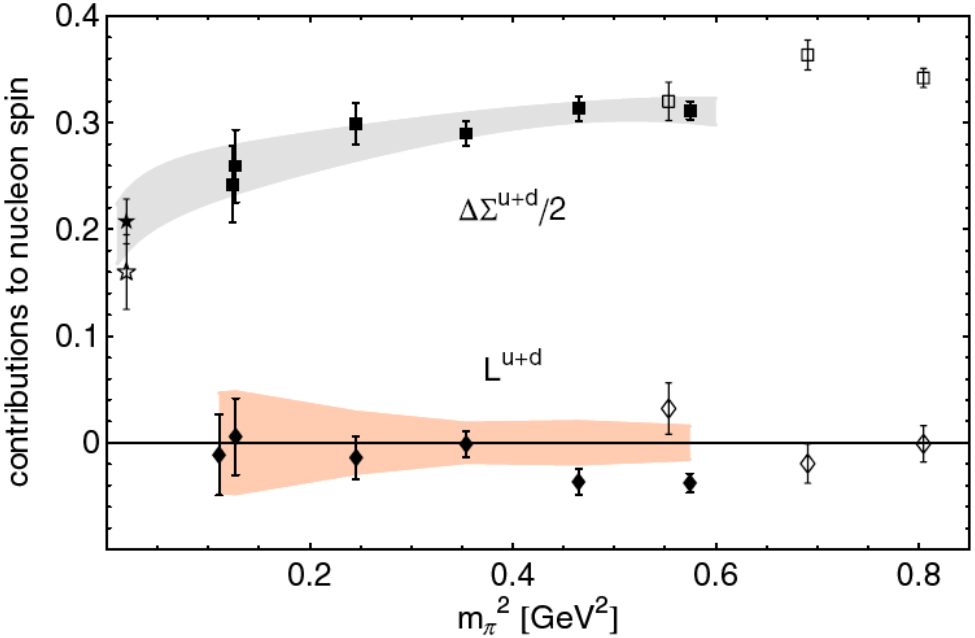
- ➢ At sufficiently small x, xΔg is expected to be small, but not clear what is sufficiently small (are we there yet?)
- ➢ The net contribution measured by RHIC spin is close to zero
- ➢ Since all values of x contribute to the final uncertainty, this will be large without data at small x

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



LHPC Collaboration, PRD77, 094502 (2008)

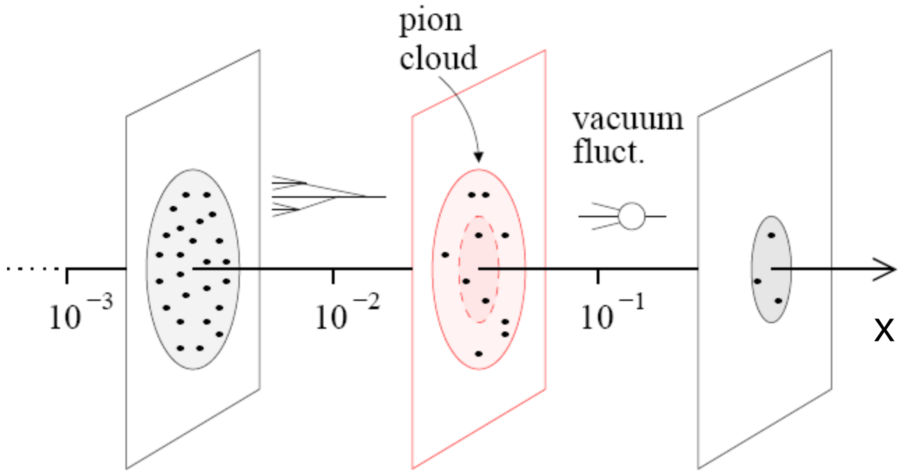
(disconnected diagrams not yet included)



- 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

Sea Quark Imaging at an Electron-Ion Collider

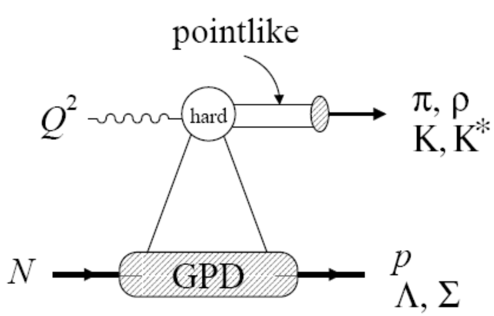


radiative sea

Non-perturbative sea quarks

valence quarks

[Jlab 12 GeV]

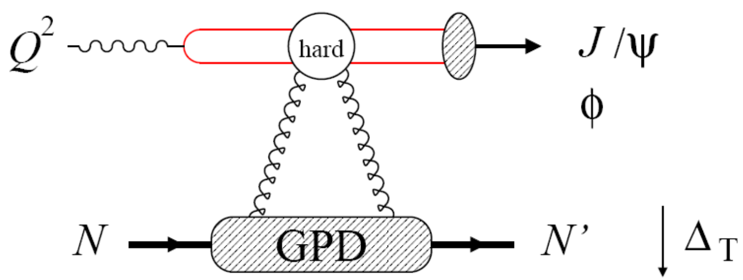


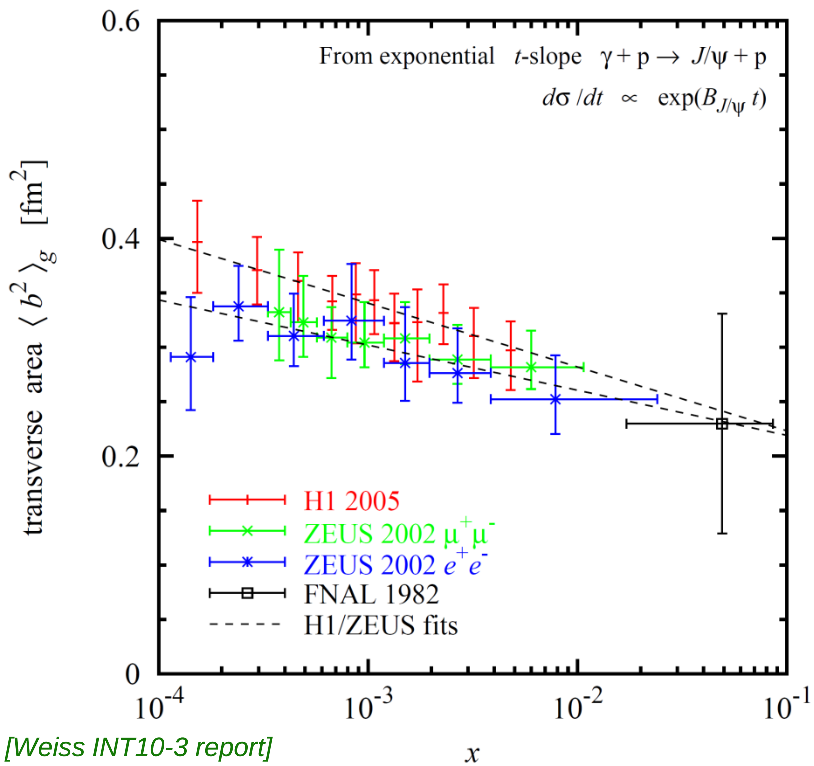
- Physics interest
  - Transverse imaging of non-perturbative sea quarks and gluons
  - Information about meson wave function: spin/flavor structure
- Mesons select definite charge, spin, flavor component of GPD

J/Ψ, φ	gluon
ρ^o, γ	gluon + singlet quark
ρ^+, K*	non-singlet q
π, K, η	non-singlet Δq

EIC enables a comprehensive program of transverse imaging of gluons and sea quarks

Gluon Imaging with J/Ψ



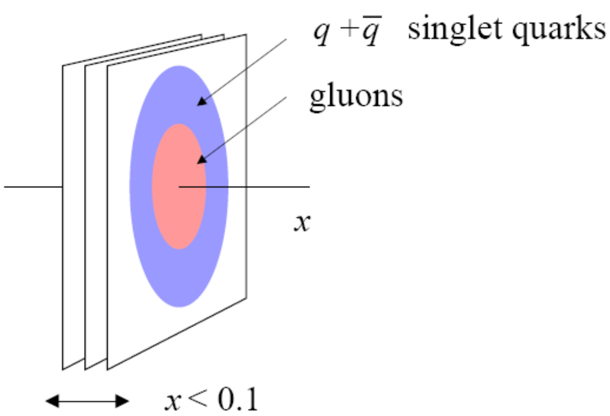


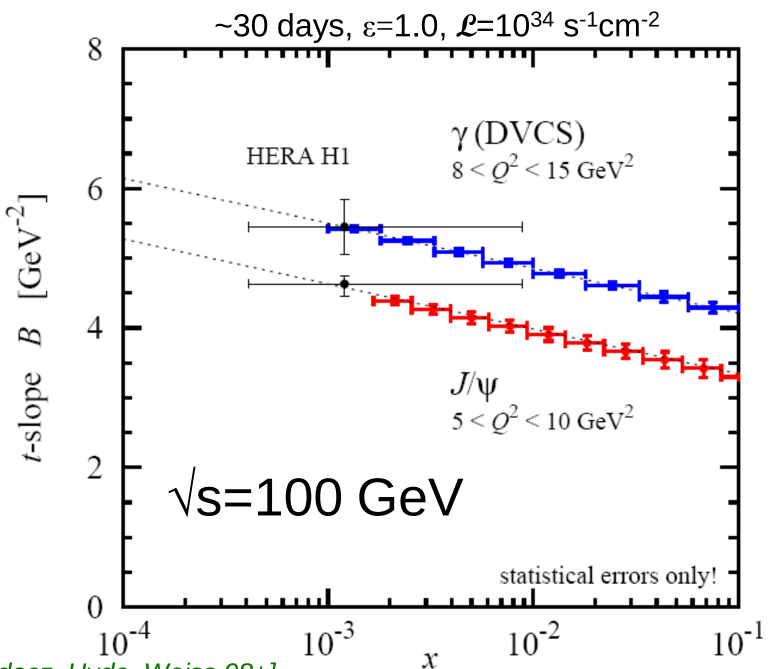
[Weiss INT10-3 report]

- Transverse spatial distributions from exclusive J/ψ, and φ at Q^2>10 GeV^2
  - Transverse distribution *directly* from Δ_T dependence
  - Reaction mechanism, QCD description studied at HERA [H1, ZEUS]
- Physics interest
  - Valence gluons, dynamical origin
  - Chiral dynamics at *b~1/M$_\pi$*
    [Strikman, Weiss 03/09, Miller 07]
  - Diffusion in QCD radiation
- Existing data
  - Transverse area x<0.01 *[HERA]*
  - Larger x poorly known *[FNAL]*

First gluon images of the nucleon at large x!

Gluon vs.singlet quark size





[Sandacz, Hyde, Weiss 08+]

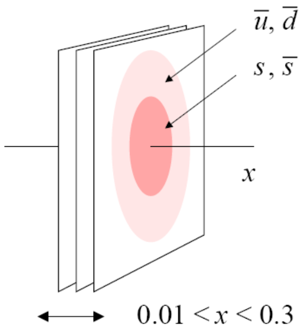
- Do singlet quarks and gluons have the same transverse distribution?
  - Hints from HERA: $Area(q+\bar{q}) > Area(g)$
  - Dynamical models predict difference: pion cloud, constituent quark picture *[Strikman, Weiss 09]*
  - No difference assumed in present pp MC generators for LHC!

- EIC: gluon size from J/ψ, singlet quark size from DVCS
  - x-dependence: quark vs. gluon diffusion in wave function
  - Detailed analysis: LO → NLO *[Mueller et al.]*

Detailed differential image of nucleon's partonic structure

Imaging of non-singlet sea quarks

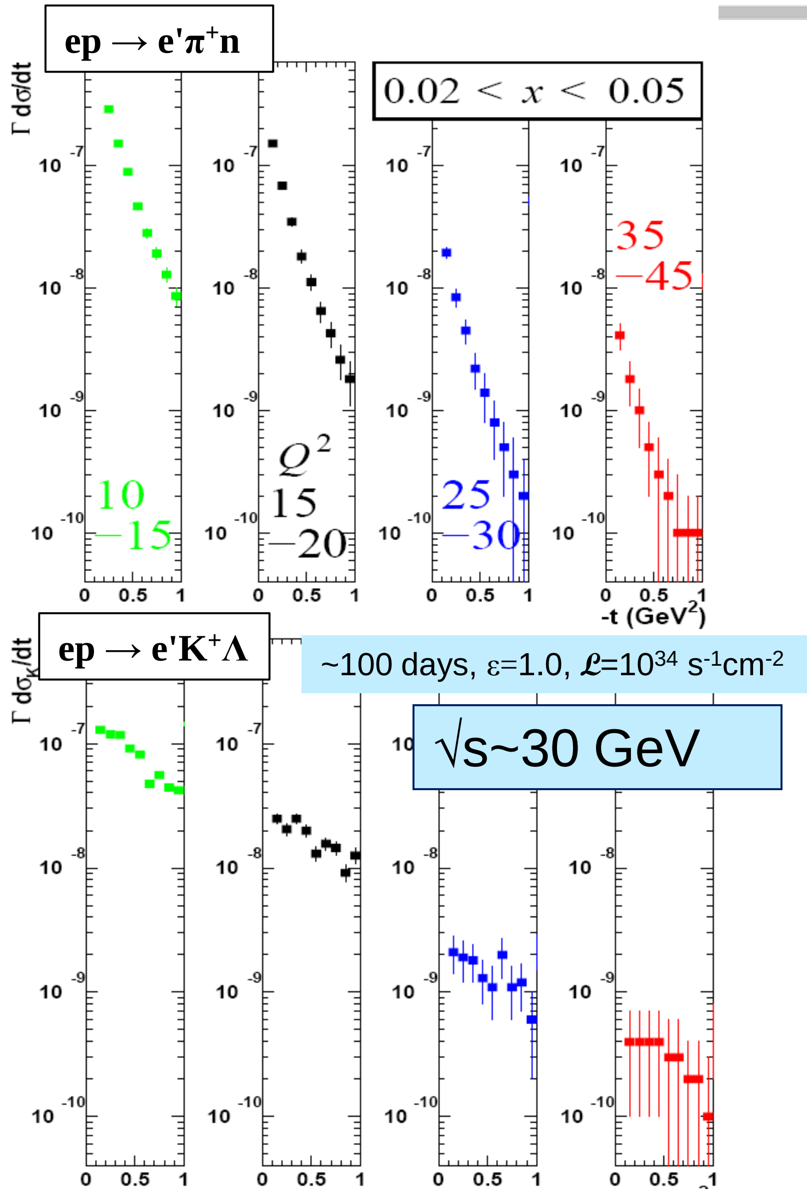
- New territory for collider!



- Do strange and non-strange sea quarks have the same spatial distribution?
  - πN or $K\Lambda$ components in nucleon
  - QCD vacuum fluctuations
  - Nucleon/meson structure

- Lower and more symmetric energies essential to ensure exclusivity
  - *t*-distributions, Fourier transform

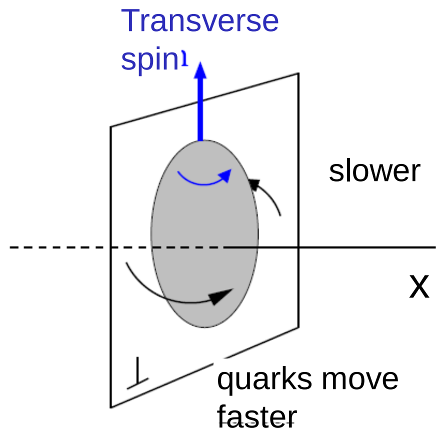
Imaging of *strange* sea quarks!

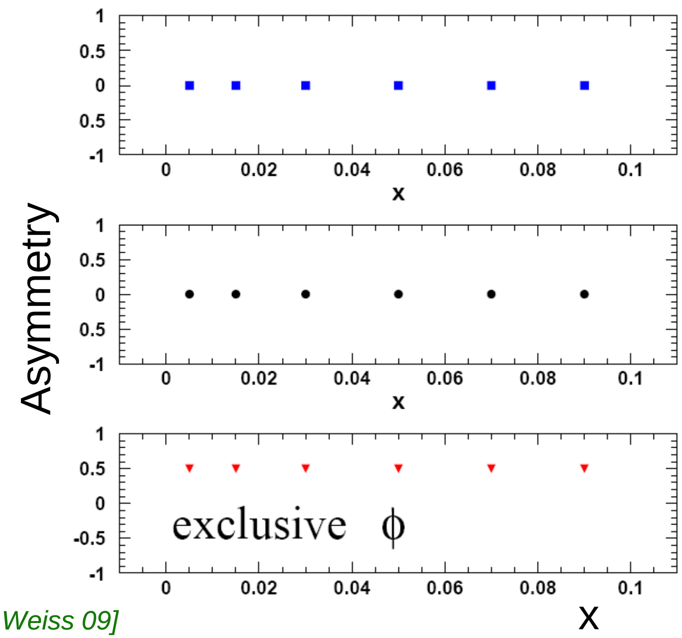


~100 days, ε=1.0, $\mathcal{L}$=10^{34} $s^{-1}cm^{-2}$

√s~30 GeV

Transverse polarization example





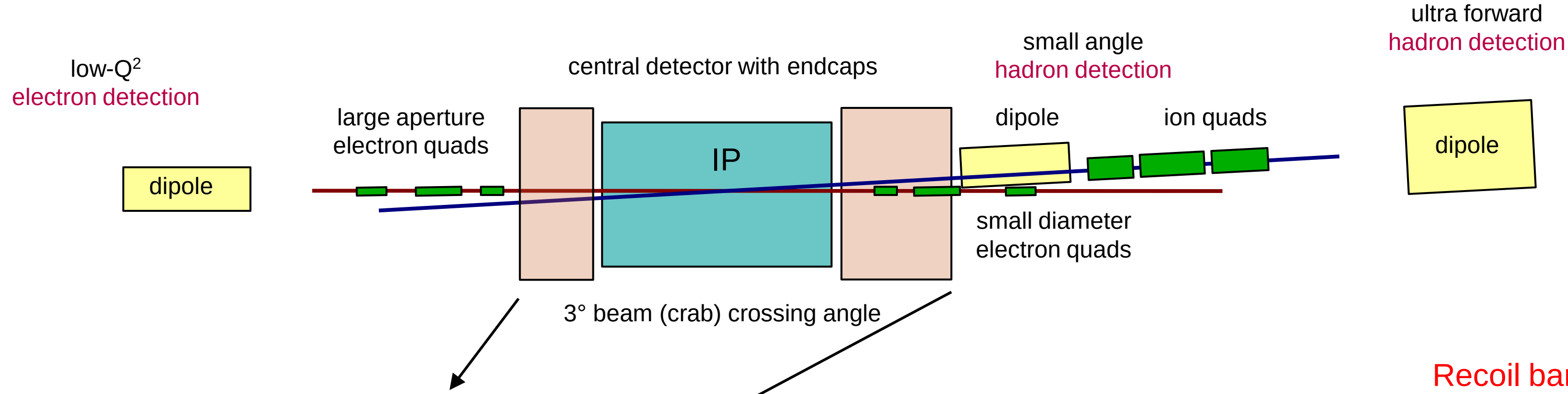
[Horn, Weiss 09]

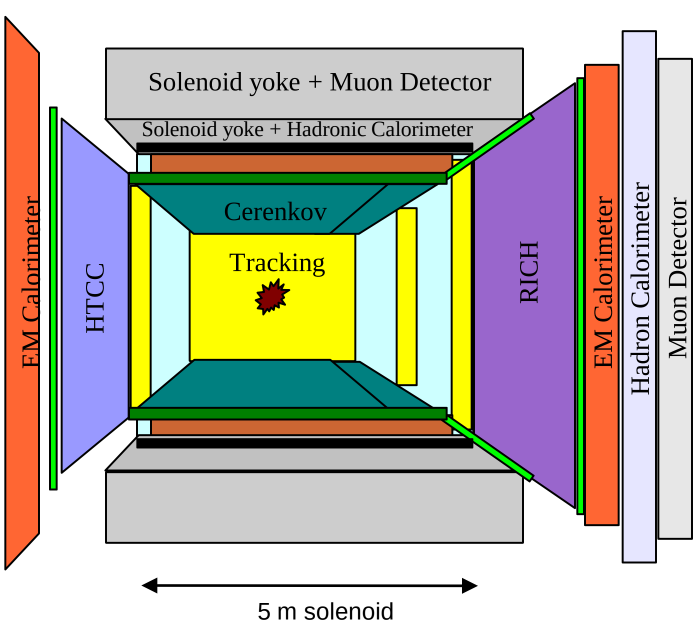
- Deformation of transverse distribution by transverse polarization of nucleon
  - Helicity flip GPD *E,* cf. Pauli ff
    [M. Burkardt]

- EIC: exclusive ρ and φ production with transversely polarized beam
  - Excellent statistics at Q^2>10 GeV^2
  - Transverse polarization natural for collider

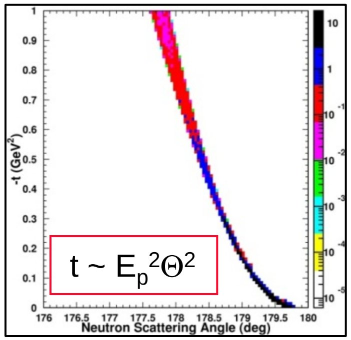
$$\frac{\sigma\uparrow - \sigma\downarrow}{\sigma\uparrow + \sigma\downarrow} \propto \frac{\mathrm{Im}(\mathcal{H}\mathcal{E}^*)}{|\mathcal{H}|^2 + \mathrm{corr.}}$$

How to detect the particles?

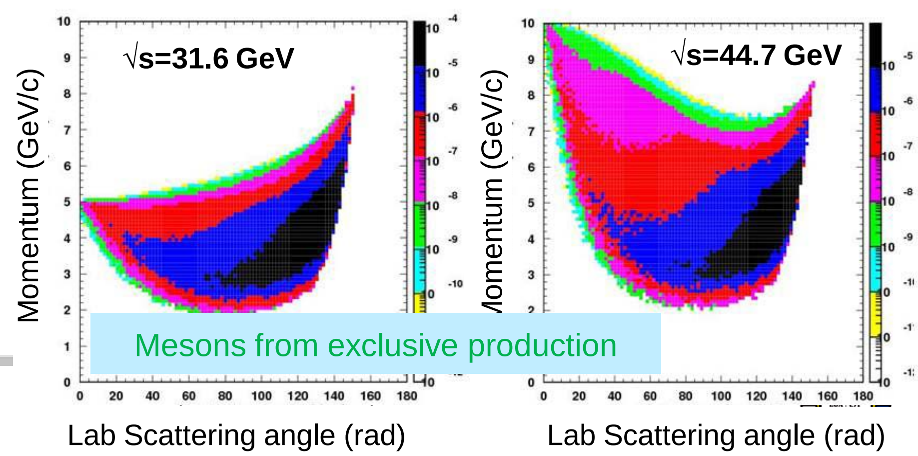




Recoil baryons

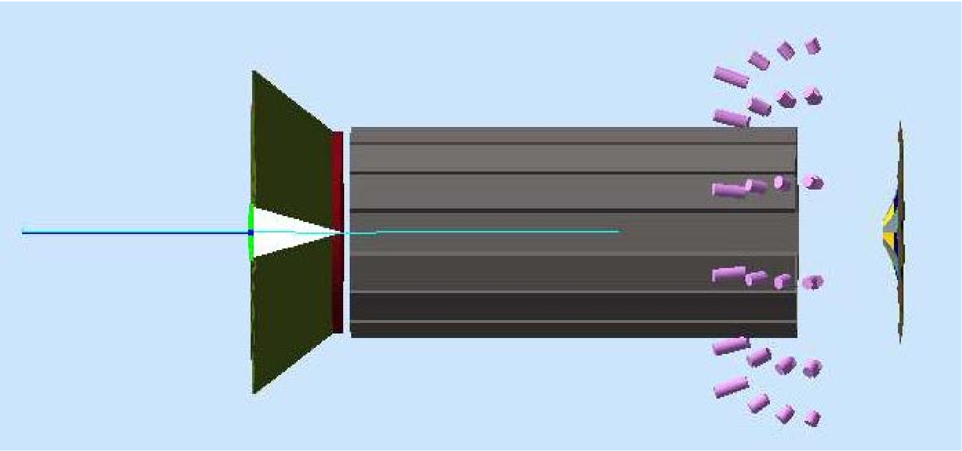


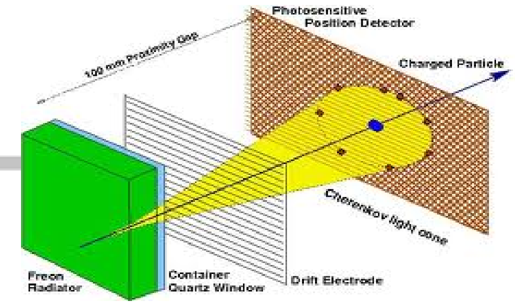
$ep \rightarrow e'\pi^+ n$

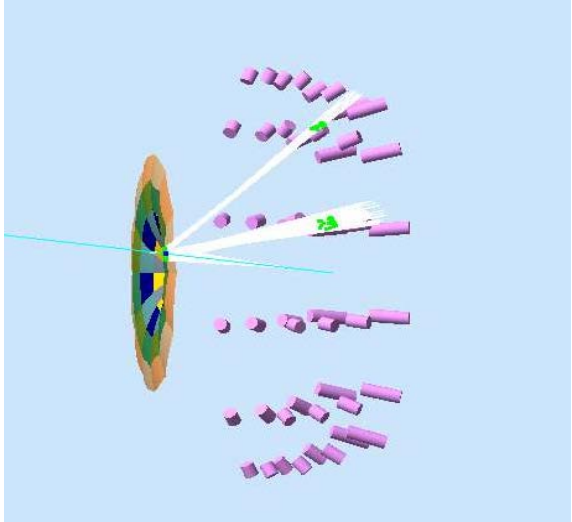


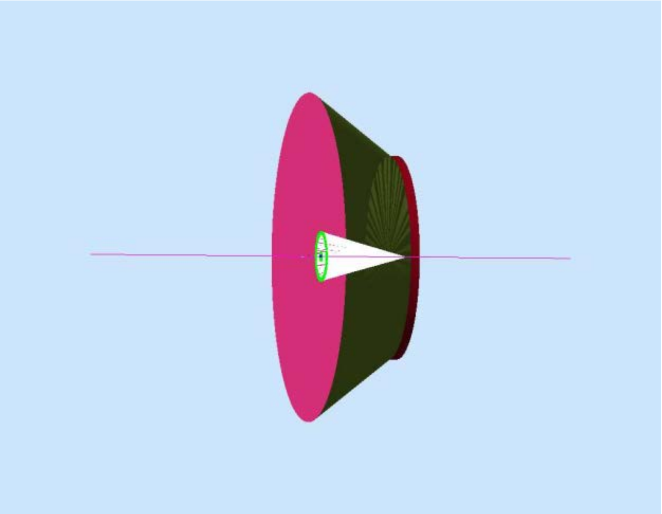
Mesons from exclusive production

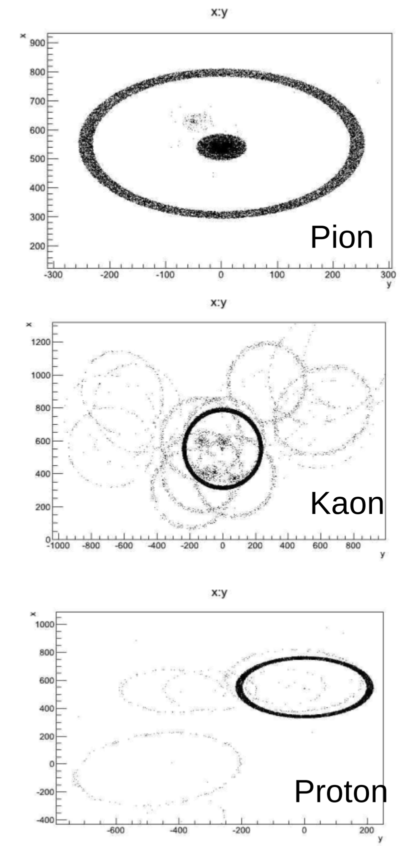
Cerenkov Detectors





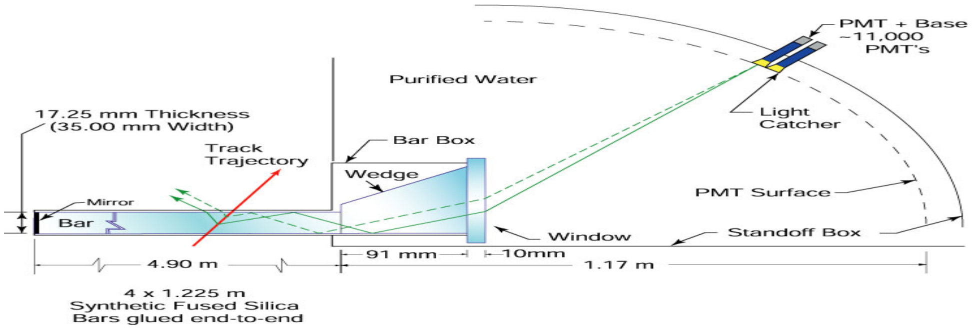


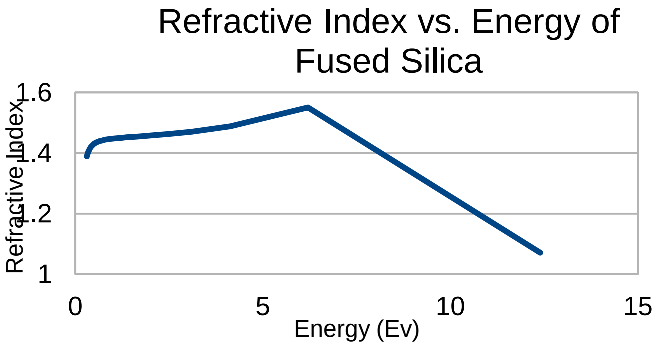


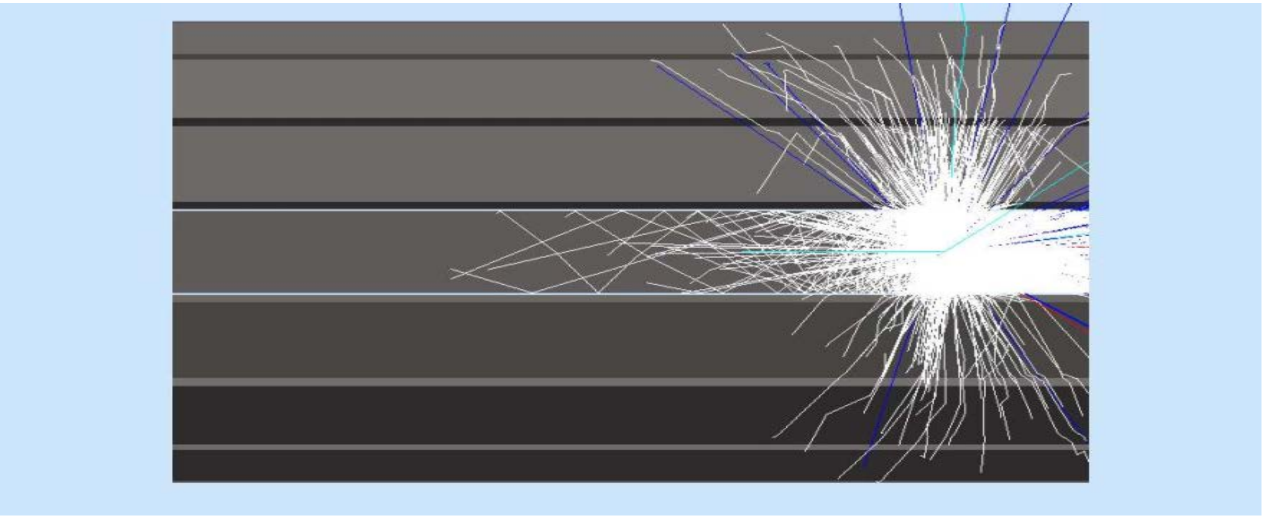


Summer Students (2011): Z. Burkley, J. Walker, N. Pomata

DIRC-based PID for the EIC Central Detector







EIC Generic R&D funds project

We are on a quest…

- The proton internal structure is complex
- We have come a long way learning about it
- New technologies and experimental facilities provide new perspectives and perhaps important information in this quest
- Lots of exciting new physics opportunities in the next few decades – perhaps you will be leading these efforts!

We want to understand the structure of matter
The proton's substructure, including the quarks inside a proton and the workings of the force that binds them.

Final Word(s)

And by the way….

All science is either physics or stamp collecting

Ernest Rutherford