Introduction to EIC/detector concept

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THE CATHOLIC UNIVERSITY of AMERICA

4th Workshop on Exclusive Reactions at High Momentum Transfer

Newport News, VA
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Why an electron-ion Collider?

- Easier to reach high Center of Mass energies ($E_{CM}^2 = s$)
  - $s = 4E_eE_p$ for colliders (e.g., 4 x 9 x 60=2160 GeV^2)
  - $s = 2E_eM_p$ 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, $\mathcal{L}$=5x10^{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

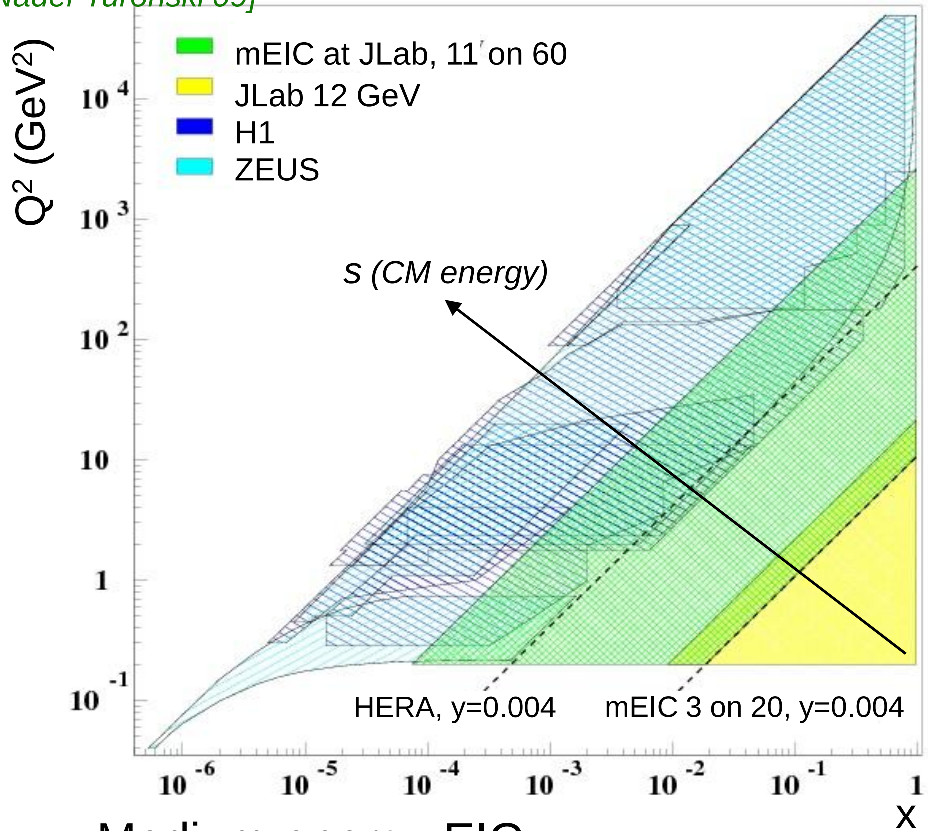
	Max e/p Energies	**s**	**Max Luminosity***
ENC@GSI	3 x 15	180	Few x 10^{32}
MEIC@JLab	11 x 70(100)	250-3080(4400)	10^{34}
MeRHIC@BNL	4 x 250	1200-4000	10^{32}
ELIC@JLab	11 x 250	11000	Close to 10^{35}
eRHIC@BNL	20 x 325	26000	Few x 10^{33}
LHeC@CERN	70 x 1000	280000	10^{33}

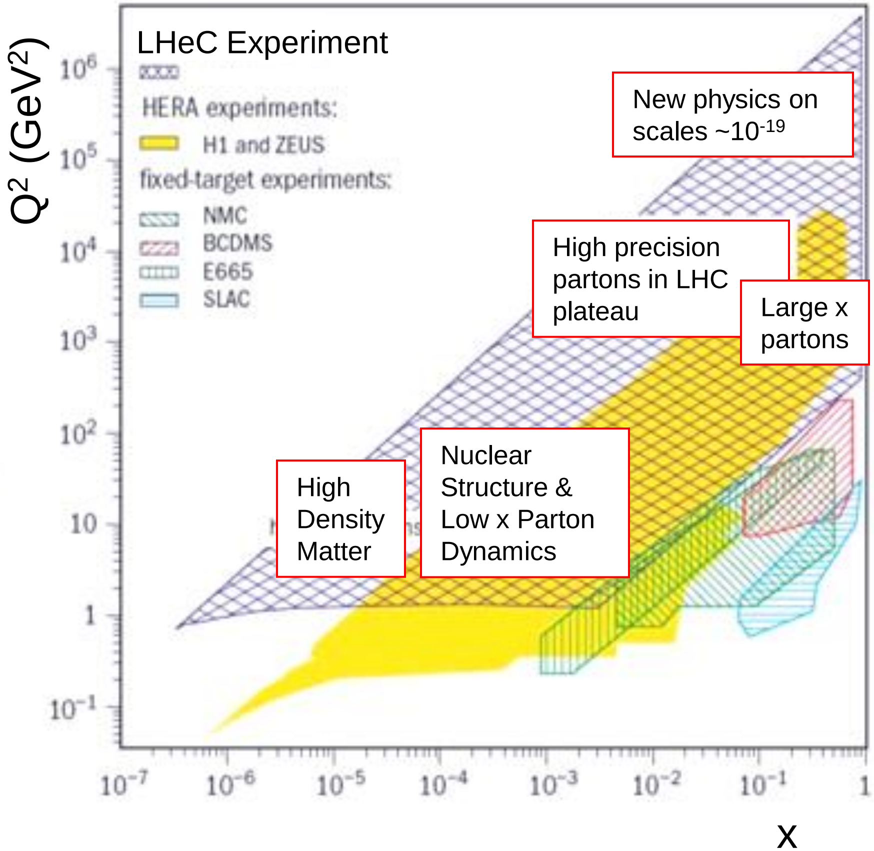
*without coherent electron cooling

Kinematic Coverage

$x \sim Q^2/ys$

[Nadel-Turonski 09]



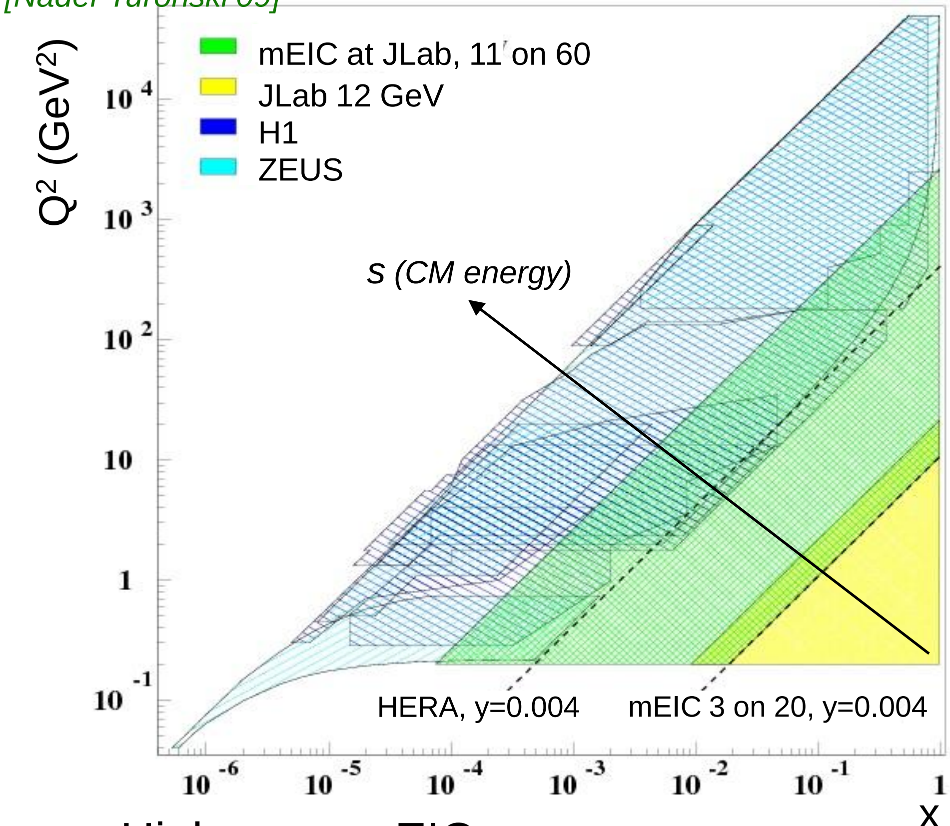


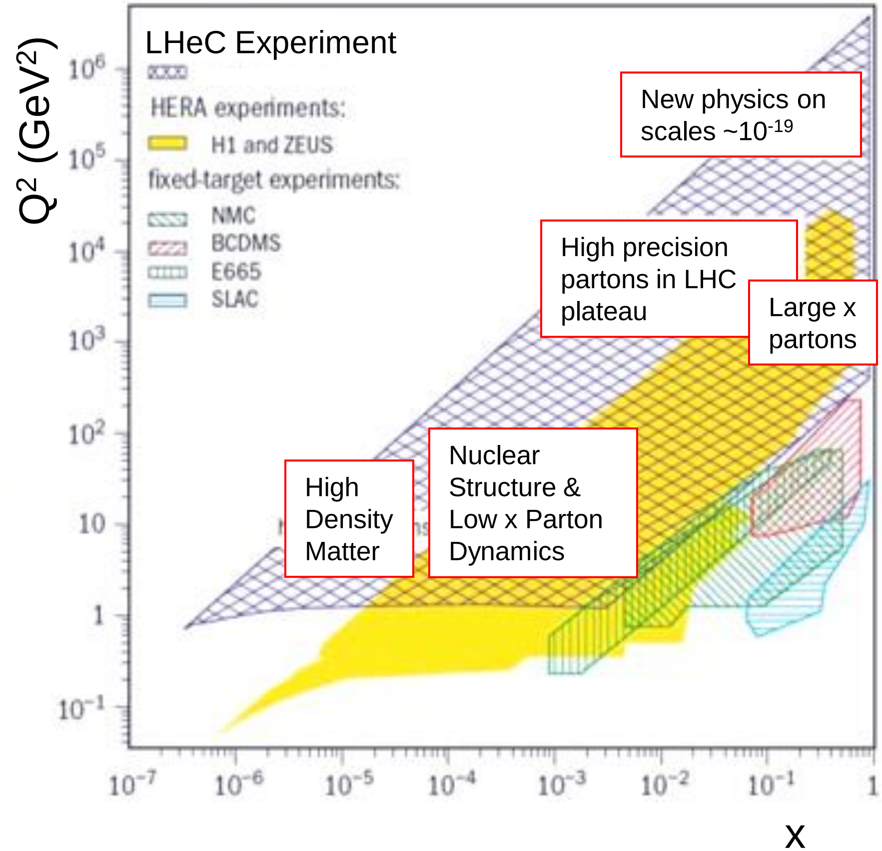
- Medium-energy EIC
  - Overlaps with and is complementary to the LHeC (both Jlab and BNL versions)
  - Overlaps with Jlab 12 GeV (Jlab version)
  - Provides high luminosity and excellent polarization for the range in between
    - Currently only low-statistics fixed-target data available in this region

Kinematic Coverage

$x \sim Q^2/ys$

[Nadel-Turonski 09]



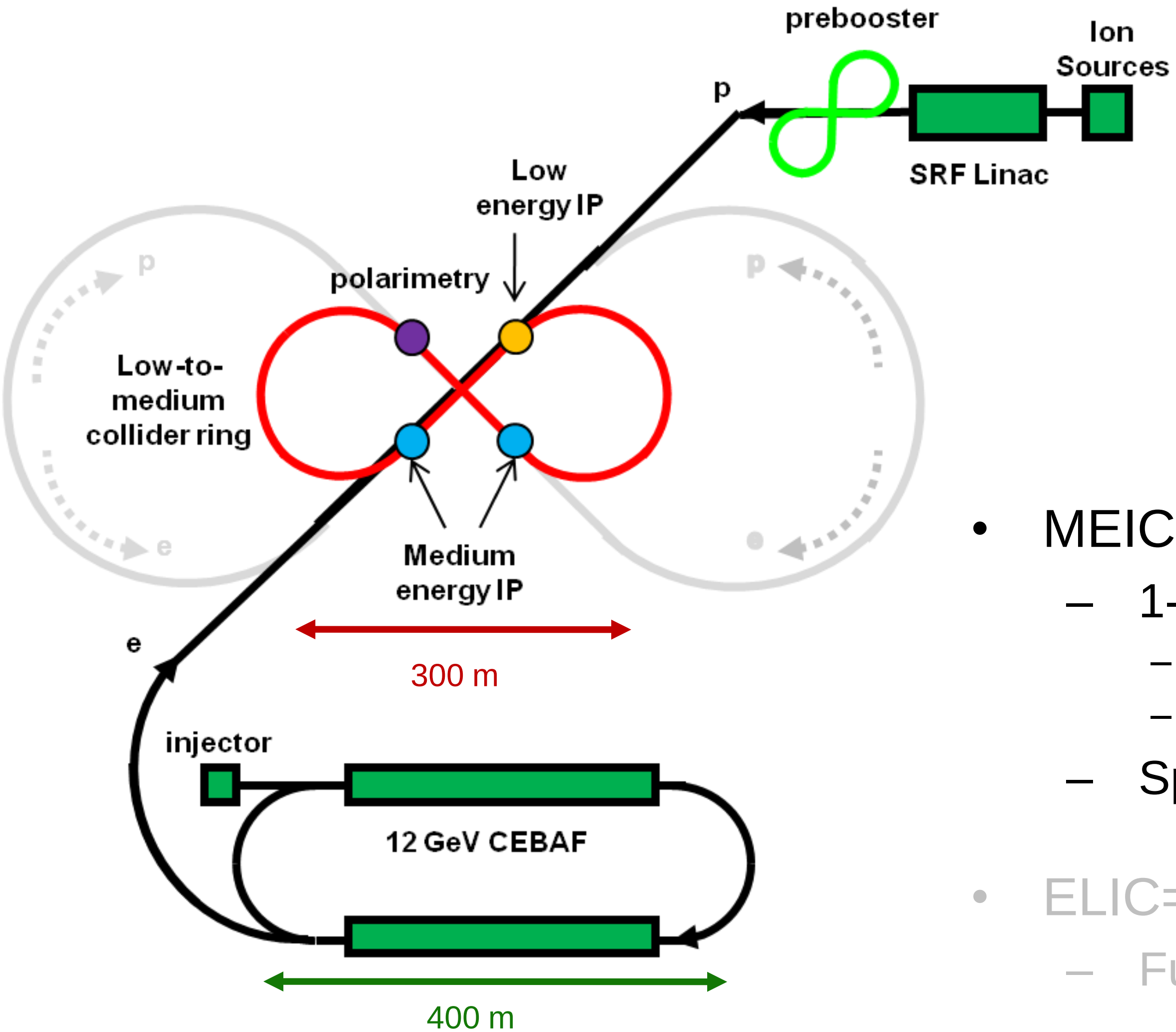


- High-energy EIC
  - Will move higher into the region covered by HERA (and LHeC)
  - Will provide good polarization and heavy ions (which HERA did not have)
  - If LHeC is not built, may be the only machine that can see gluon saturation in e-A collisions

A high-luminosity EIC at JLab

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

[Zhang 09]



Electron energy: 3-11 GeV

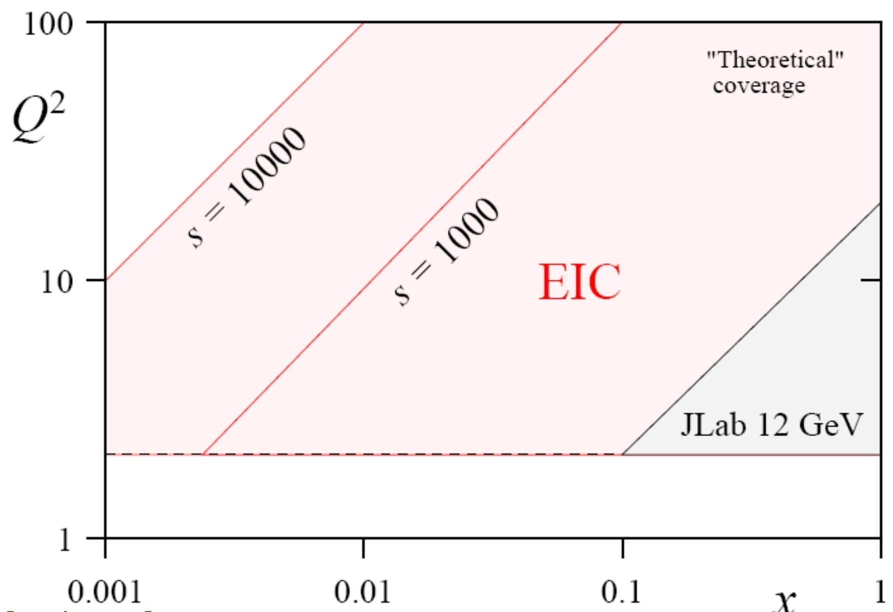
Ion energy: 20-70(100) GeV

$s=250\text{-}3080(4400)\ GeV^2$

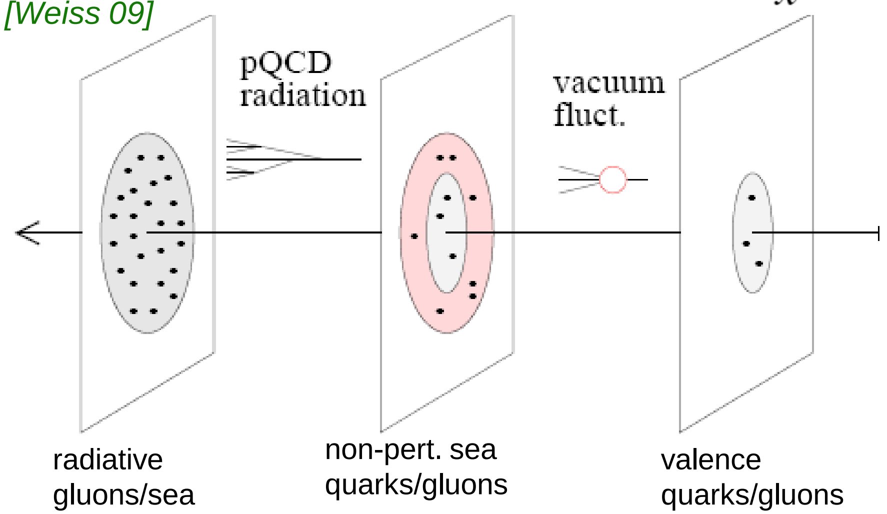
Can operate in parallel with fixed-target program

- 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?

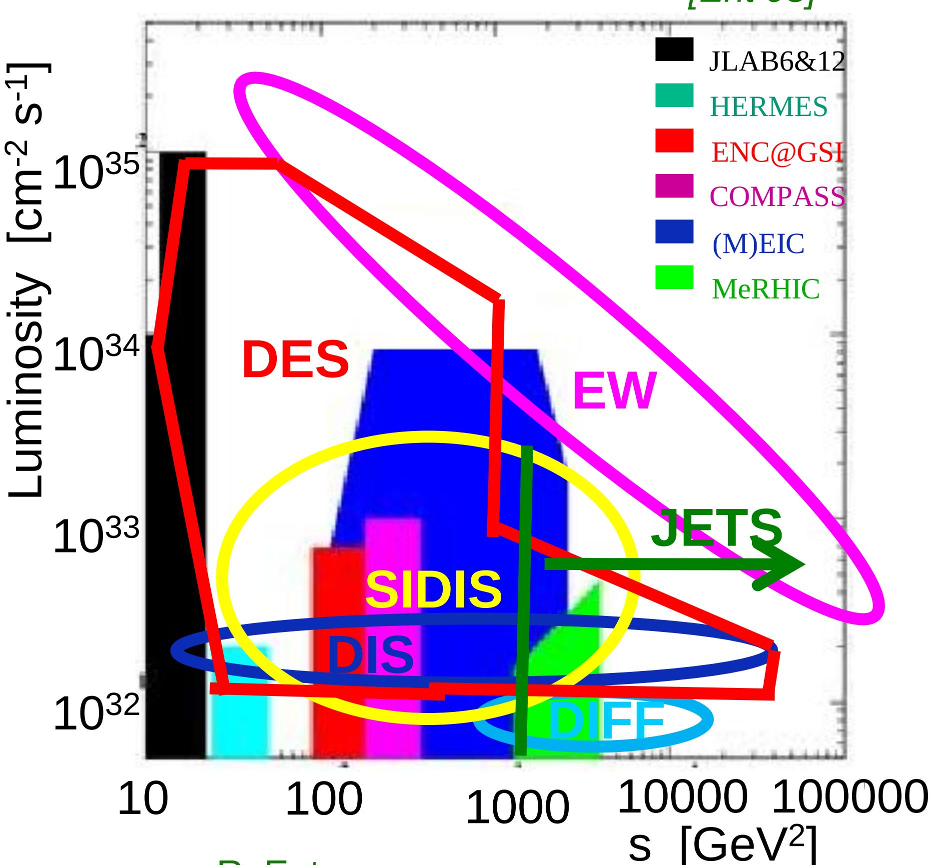
Physics, Kinematic Coverage, and Luminosity



[Weiss 09]



[Ent 08]



R. Ent

- 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

More detail in physics talks in this session:

- ***W. Cosyn, L. Gamberg, V. Guzey, N. Ivanov, S. Liuti, M. Strikman***

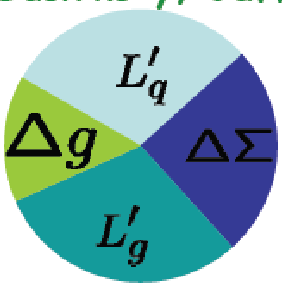
	Energies	s	Luminosity*
EIC@Jlab	Up to 11 x 70(100)	250-3080(4400)	10^{34}
Future option	Up to 11 x 250	11000	$>10^{34}$

*without coherent electron cooling

The spin of the proton

ambiguities arise when decomposing proton spin in gauge theories

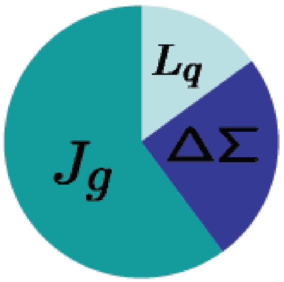
Jaffe, Manohar;
Bashinsky, Jaffe



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 → interpretation ?

$L_q + \Delta q/2$, J_g ↔ GPDs (DVCS)

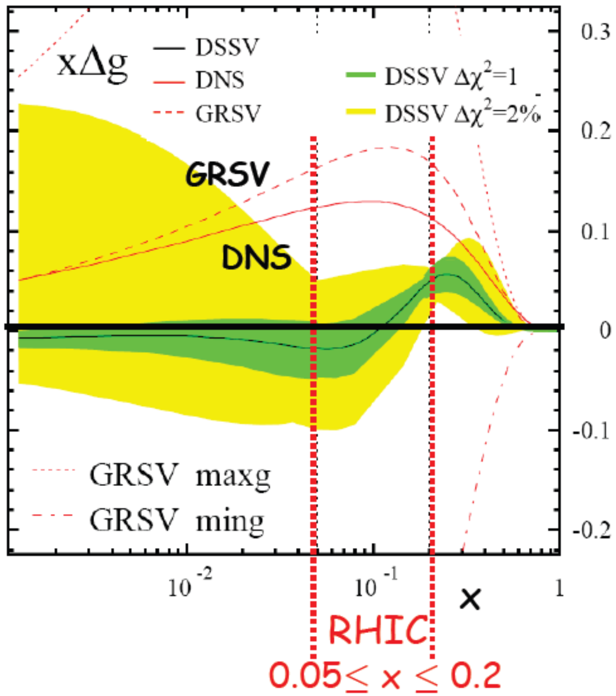
- lattice results for L_q are for Ji's sum rule and cannot be mixed with Δg
- num. difference between L_q and L_q' can be sizable

Burkardt, BC
arXiv:0812.1605

[From M. Stratmann, INT09-43W]

Proton Spin: two complementary approaches

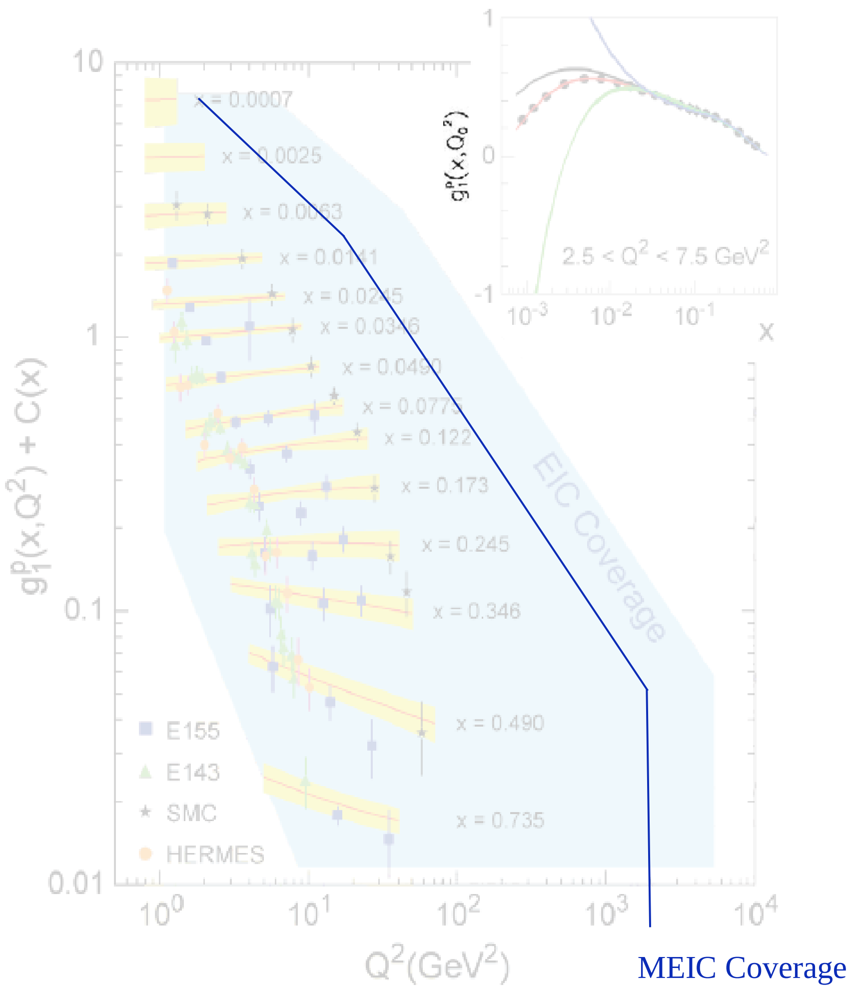
- Measure GPDs and TMDs to learn about angular momentum (Ji)
  - Connected to Lattice QCD
  - Exclusive measurements require high luminosity at lower energies
- Measure Δg (Jaffe *et al.*) over a sufficiently wide range in x



- At sufficiently small x, $x\Delta g$ 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

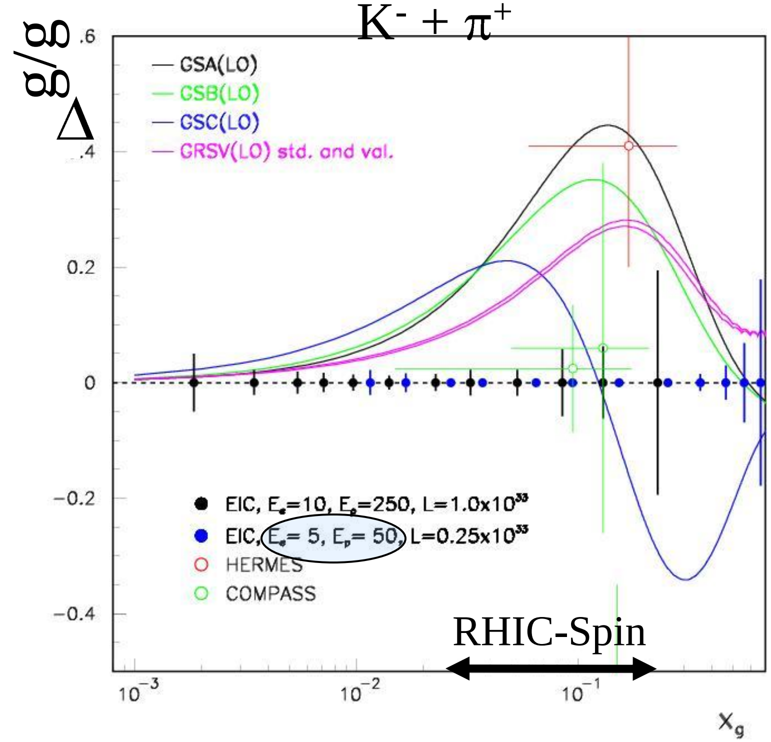
$$\frac{d\,g_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$



[Antje Bruell, Abhay Deshpande, Rolf Ent]

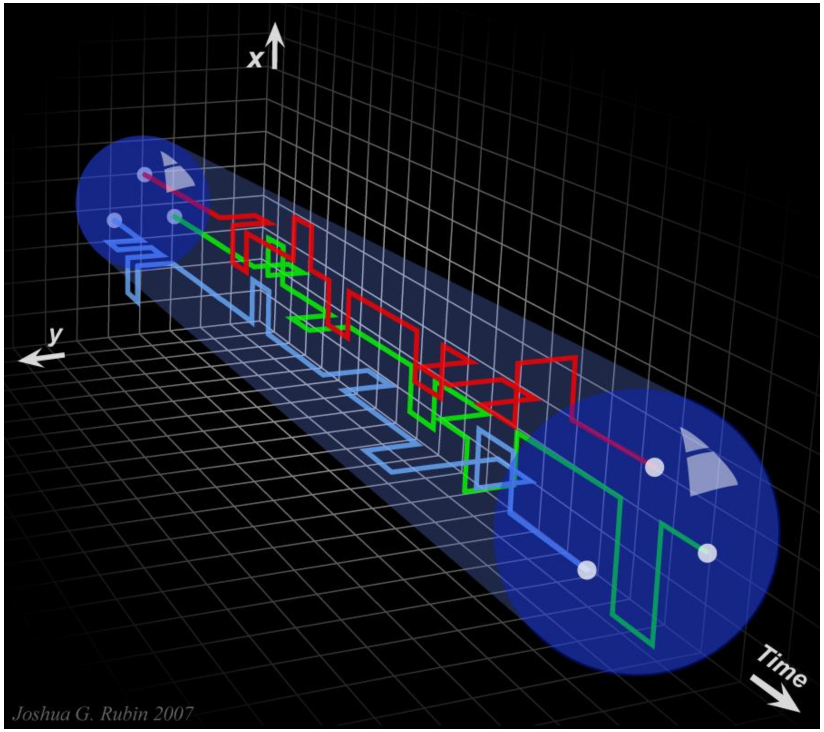
$\gamma + p \rightarrow D^0 + X$

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



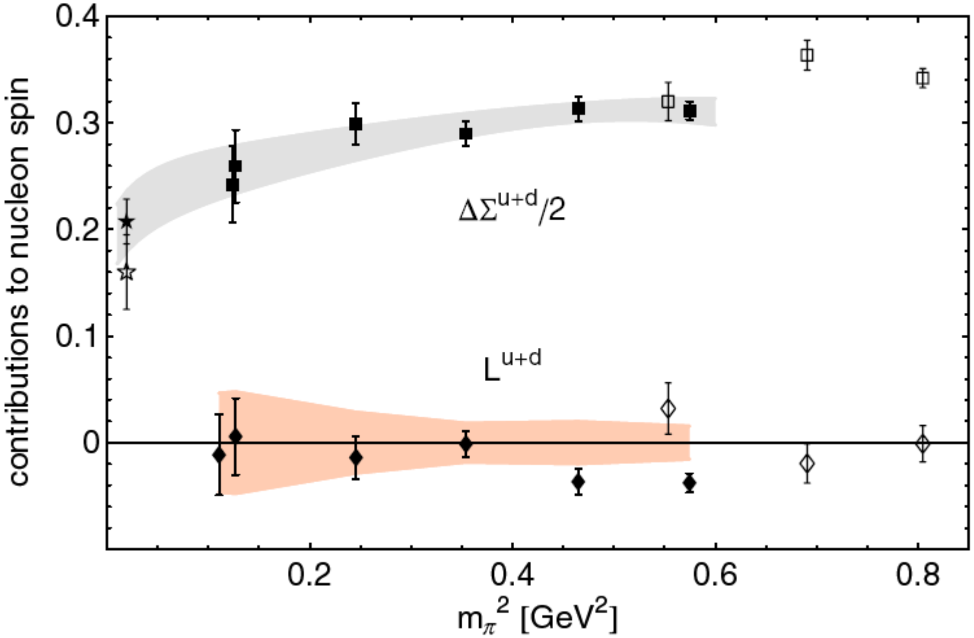
- Uncertainties in $x\Delta g$ smaller than 0.01
- Measures ΔG @ $Q^2 = 10$ GeV^2

$\Delta\Sigma$ 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

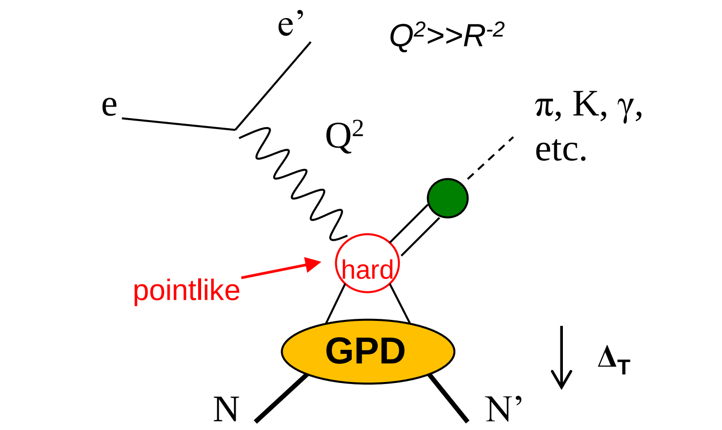
- Orbital angular momentum of quarks
  - L^u and L^d are both ~ 0.15, but cancel
- Quark spin $\Delta\Sigma$ as expected
- Implications for gluon angular momentum J^g

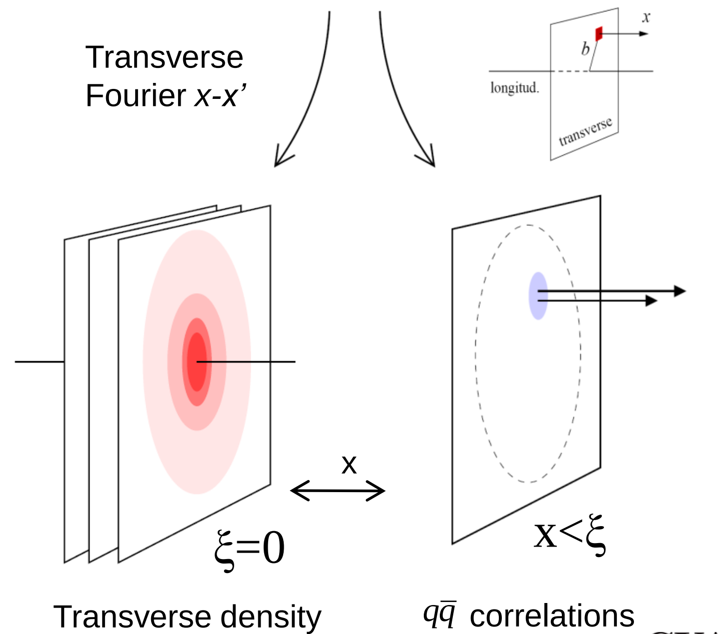
GPDs and Transverse Imaging

- Exclusive processes at sufficiently high Q^2 should be understandable in terms of the "handbag" diagram
  - The non-perturbative (soft) physics is represented by the GPDs
    - Shown to factorize from QCD perturbative processes for longitudinal photons *[Collins, Frankfurt, Strikman 97]*

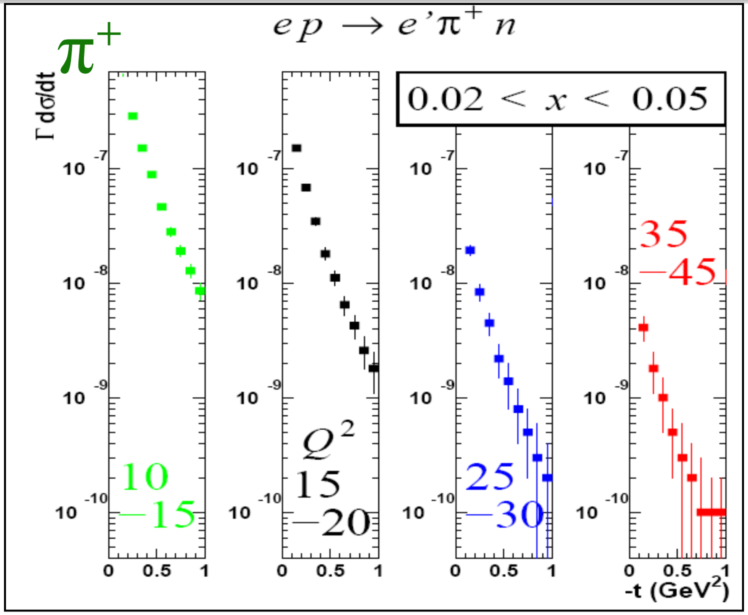
- Nucleon Structure from GPDs
  - **ξ=0 Transverse spatial distribution of partons with longitudinal momentum x** [Burkhardt 00]
  - $|x|<\xi$ $q\bar{q}$ correlations in the nucleon
  - Moment x^{n-1} Form factor of local twist-2 spin-n operator: EM tensor, angular momentum *[Ji 96, Polyakov 02]*

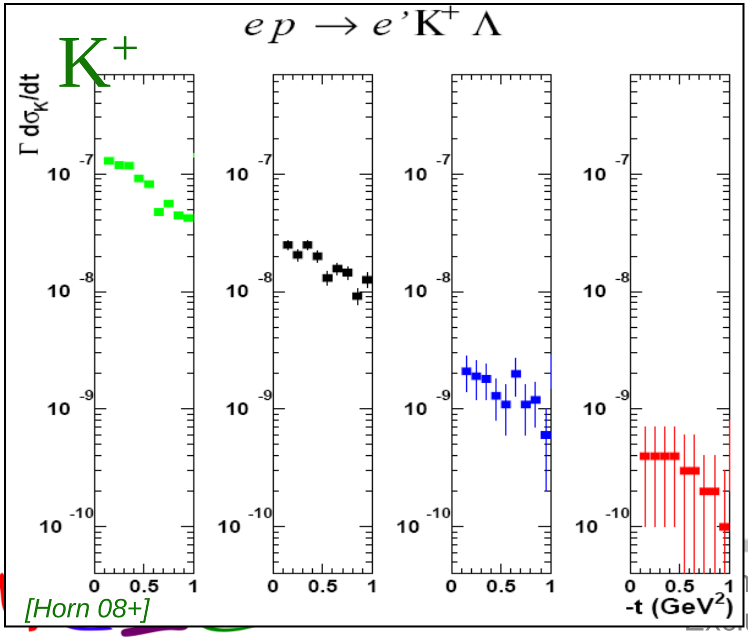
- Tests of reaction mechanism
  - Model-independent features of small-size regime? Finite-size corrections? [Frankfurt et al., Kroll, Goloskokov 05+]



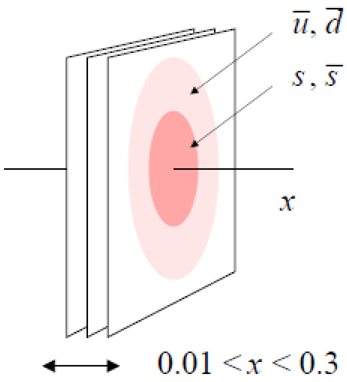


Transverse Sea Quark Imaging



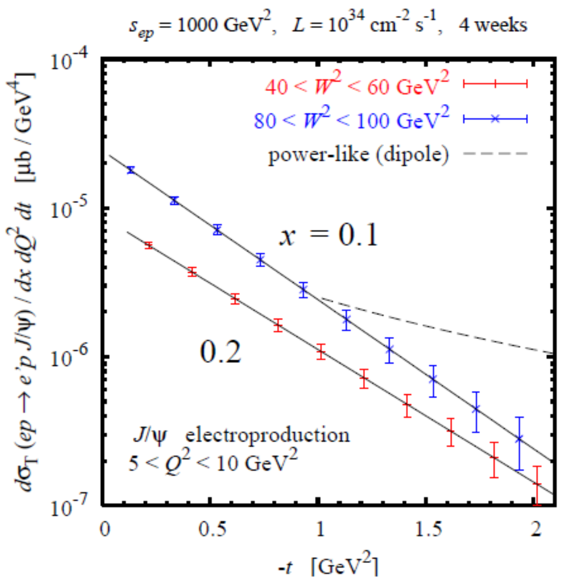


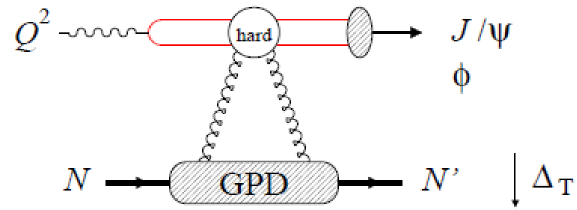
- Spatial structure of *non-perturbative sea*
  - Closely related to JLab 6/12 GeV
    - Quark spin/flavor separations
    - Nucleon/meson structure



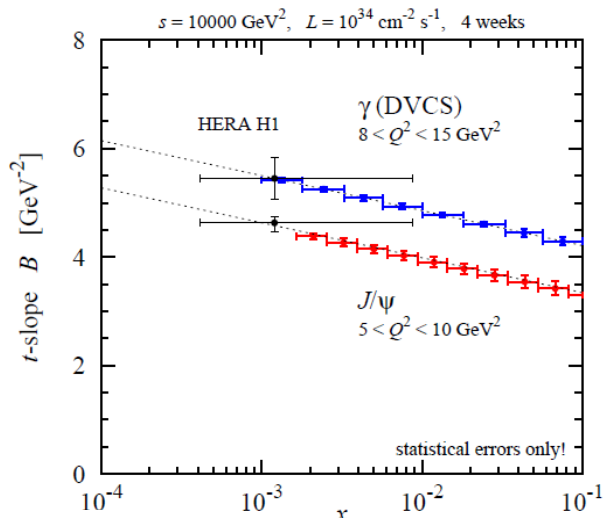
- Do strange and non-strange sea quarks have the same spatial distribution?
  - πN or $K\Lambda$ components in nucleon
  - QCD vacuum fluctuations
  - Nucleon/meson structure

Transverse Gluon Imaging

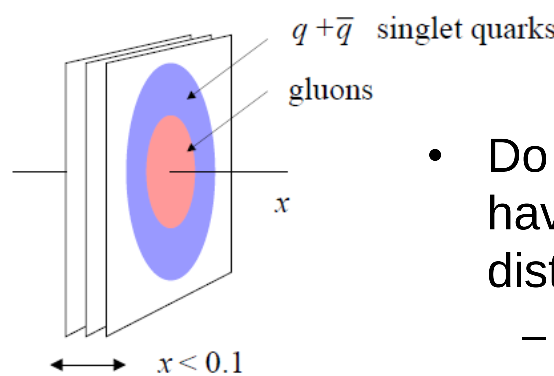




- Gluon size directly probed by J/Ψ and φ production (Q^2>10 GeV^2)
  - Require full t-distribution → Fourier
  - Powerlike at |t|>1GeV^2?



[Sandacz, Hyde, Weiss 09]



Gluon size from J/Ψ, singlet quark size from DVCS

- Do singlet quarks and gluons have the same transverse distribution?
  - Hints from HERA
  - Difference expected from chiral dynamics: pion cloud

Detector and IR Concepts

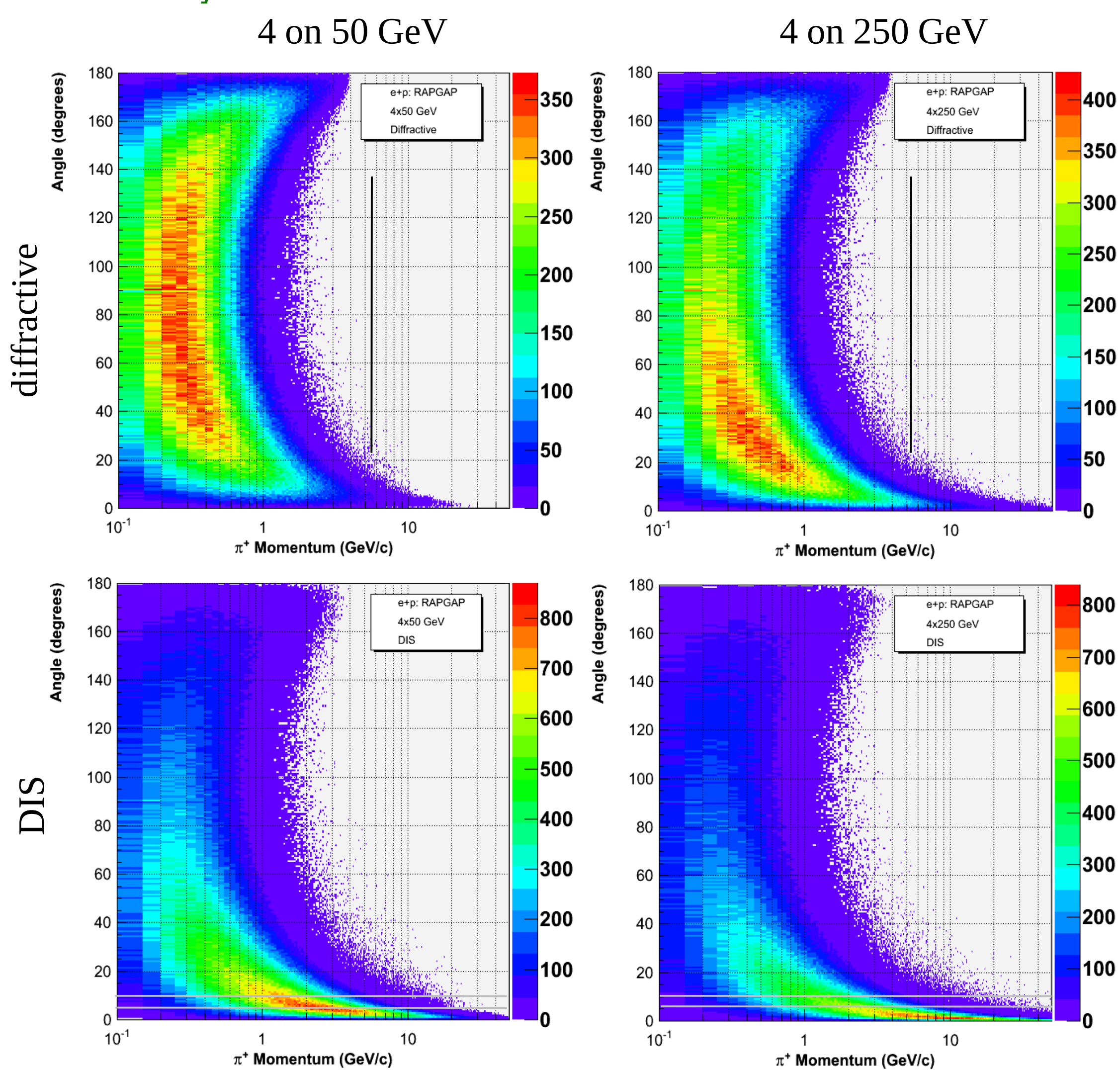
- Crossing angle and symmetric kinematics
  - Allows for a compact, hermetic forward ion detector
  - Can be used to eliminate synchrotron radiation
  - Produce electron and meson momenta comparable to CLAS

- Detector Challenges
  - Optimization of *forward ion detection*
  - PID at higher electron energies (5-10 GeV)
  - Beam divergence and transverse momentum spread

- Interaction region challenges
  - Quadrupole gradients and apertures
  - Chromatic corrections (~f/β*) limit β_{max} to ~2.5 km

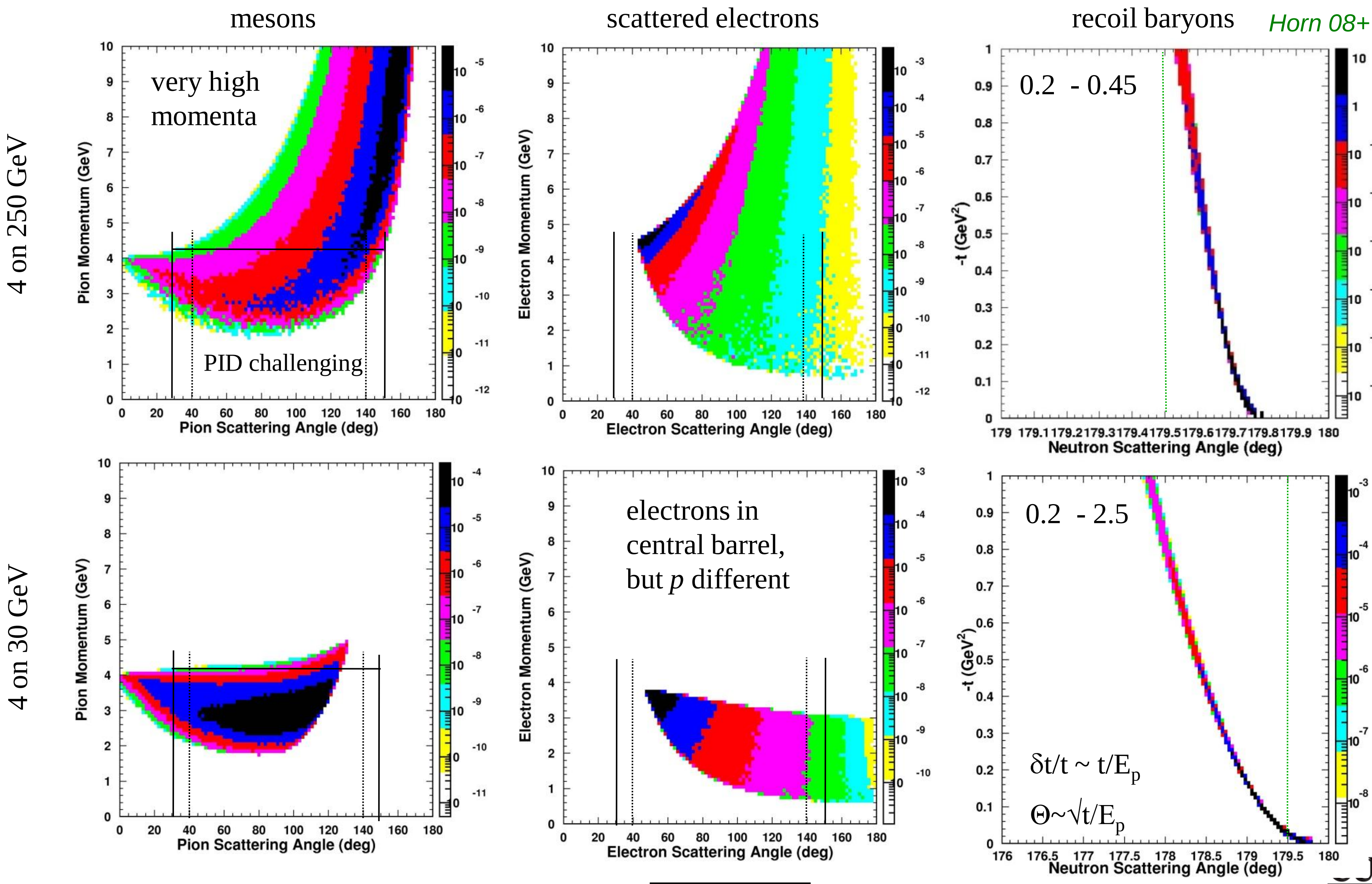
Diffractive and SIDIS (TMDs)

[W. Foreman 09]



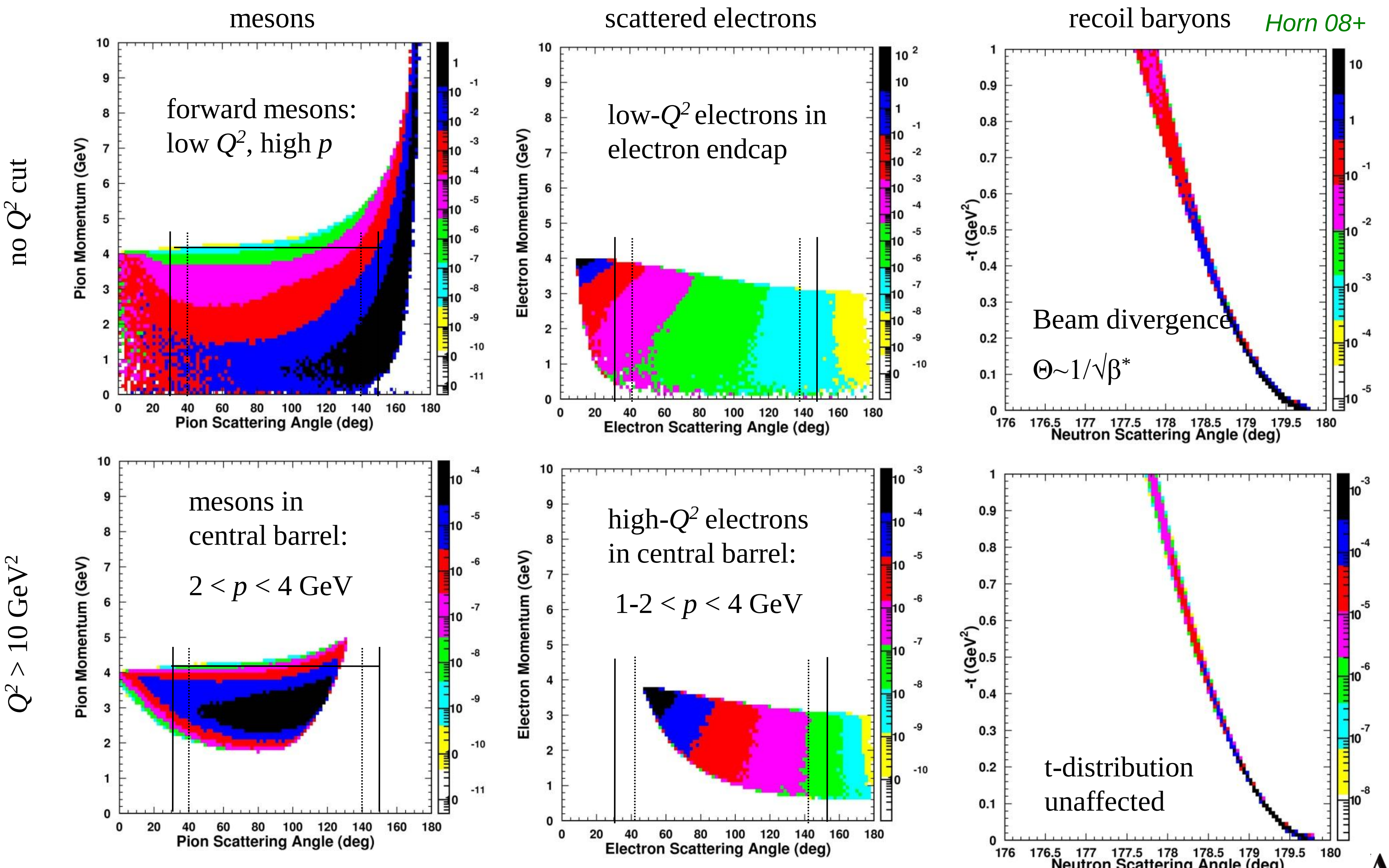
- Both processes produce high-momentum mesons at small angles
- For exclusive reactions, this constitutes our background

Exclusive light meson kinematics



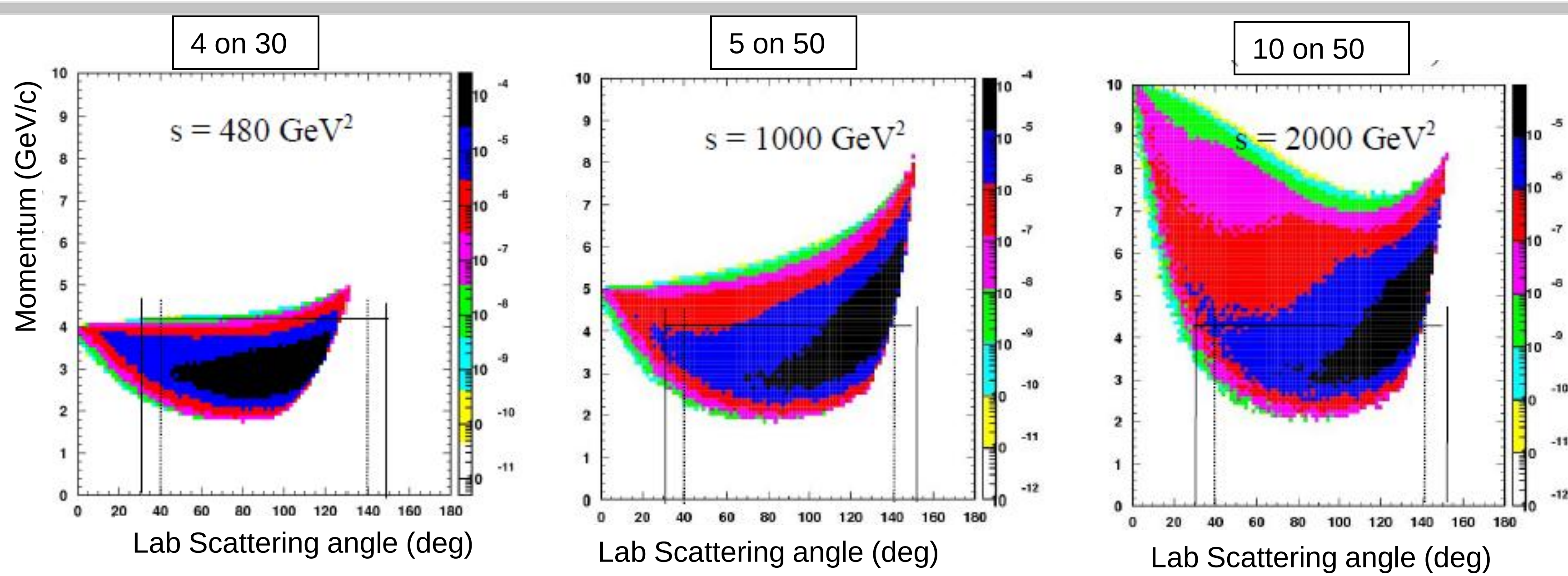
$ep \rightarrow e'\pi^{+}n$

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



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

DES at higher electron energies



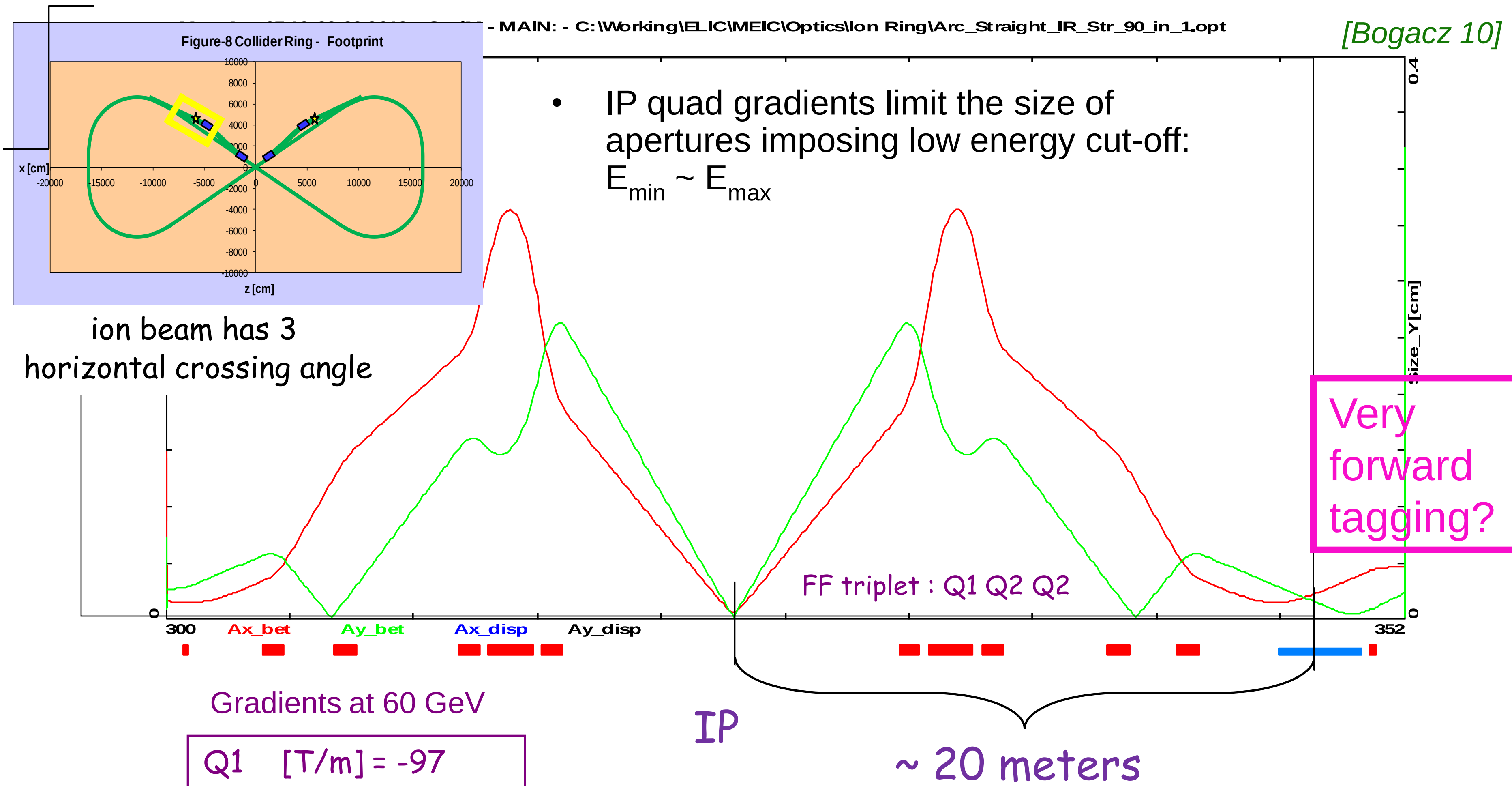
- With 12 GeV CEBAF, EIC@JLab has the option of using higher electron energies
  - DIRC no longer sufficient for π/K separation

- DIRC needs to be complemented by gas Cherenkov or replaced by dual radiator RICH to push the limit above 4 GeV

Interaction Region

[Bogacz 10]

- IP quad gradients limit the size of apertures imposing low energy cut-off: $E_{min} \sim E_{max}$



ion beam has 3 horizontal crossing angle

Very forward tagging?

Gradients at 60 GeV

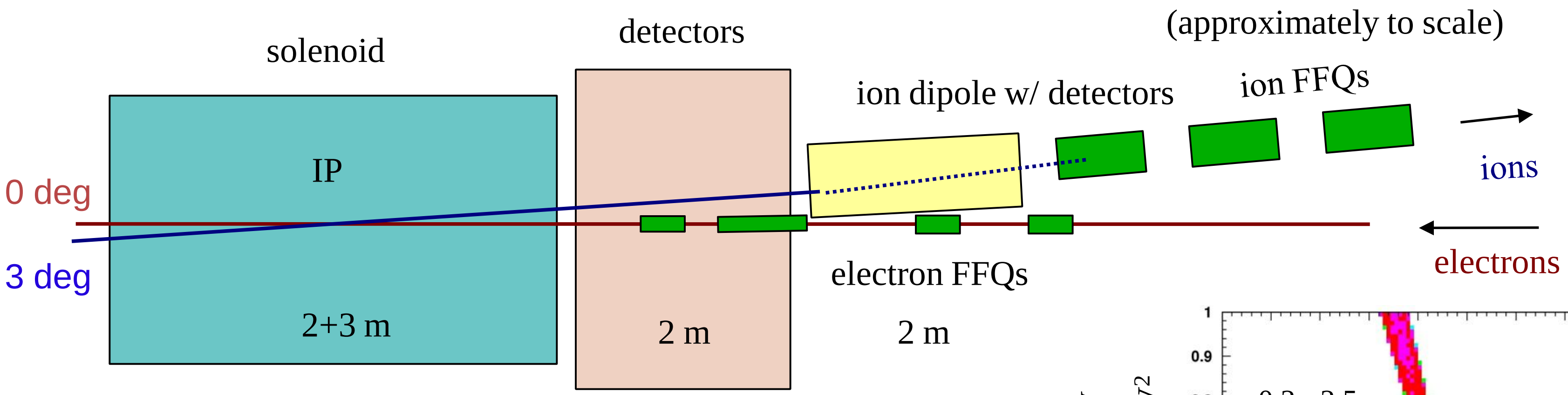
Q1	[T/m] = -97
Q2	[T/m] = +67
Q3	[T/m] = -63

- Q3 aperture 10 cm @12 m → 7 T peak field
  - Particles < 0.5 go though FF quads

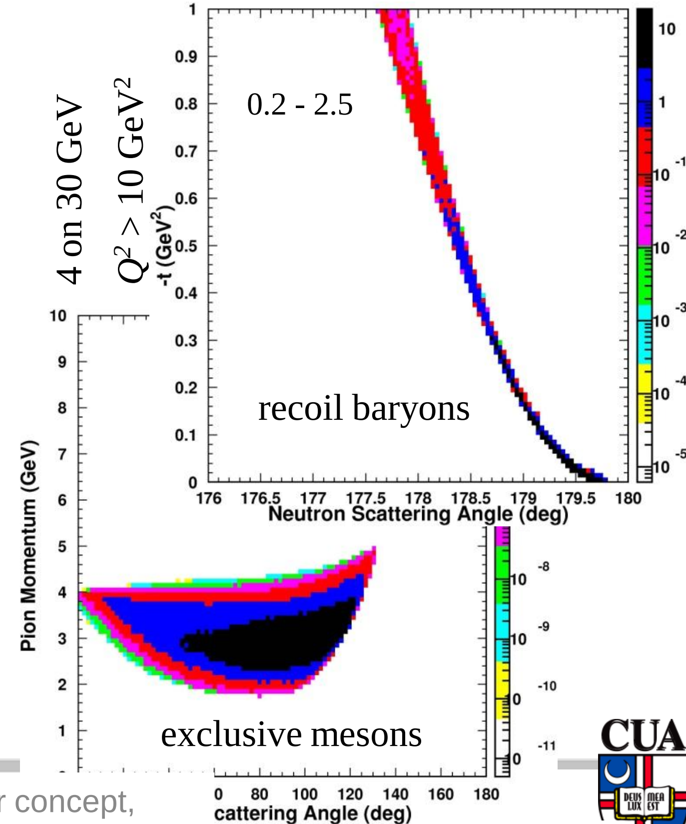
MEIC

CUA

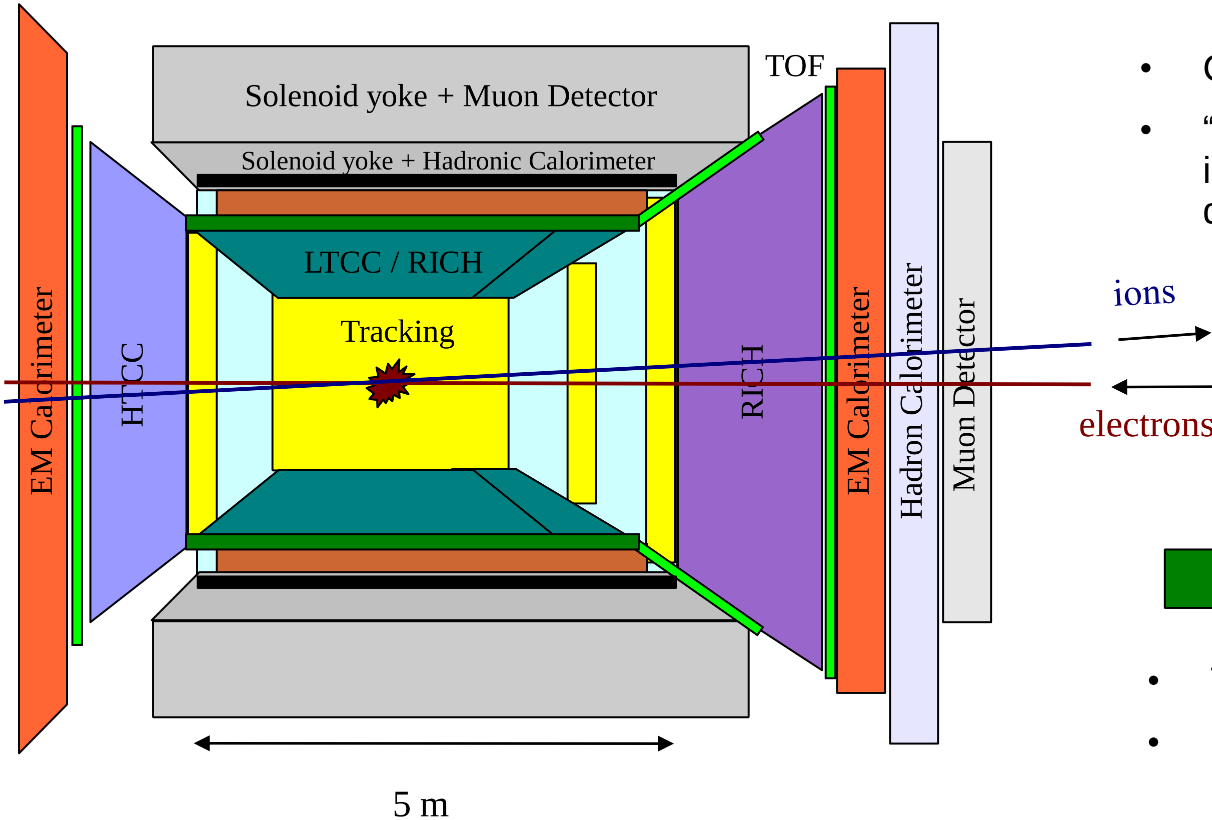
Forward detection with crossing angle



- 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)



Central detector layout

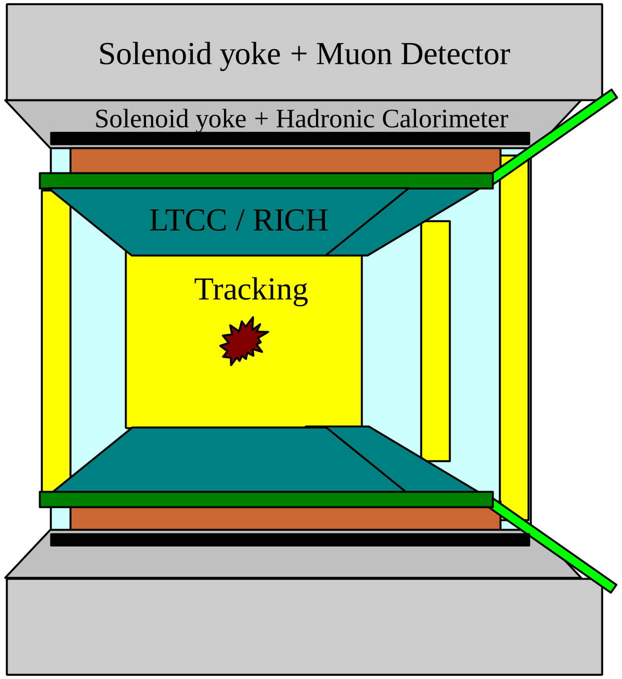


- Crossing angle: 3
- "Holes" for small-angle ion and electron detection not shown

- TOF (5-10 cm)
- DIRC (10 cm) ?

- If DIRC is used, configuration on left side may need adjustment to make space for readout

Central Detector



Solenoid Yoke, Hadron Calorimeter, Muons

- 3-4 T solenoid with about 4 m diameter
- Hadronic calorimeter and muon detector integrated with the return yoke (*c.f.* CMS)

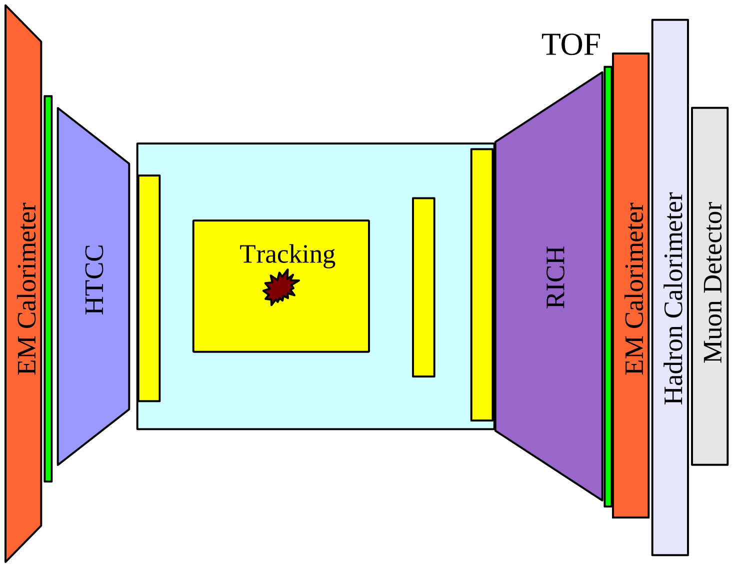
Particle Identification

- TOF for low momenta
- π/K separation options
  - DIRC + LTCC up to 9 GeV
  - dual radiator RICH up to 8 GeV
- e/π separation
  - LTCC (C_4F_8O RICH) up to 3 (5) GeV
  - EC: Tungsten powder / scintillating fiber?
    - Very compact, 6% resolution

Tracking

- vertex tracker (Si, microchannel?)
- barrel: (r, φ) chambers
  - Outer layer: z-tracker
- vertical caps: (x, y) trackers

Detector Endcaps



Tracking

- Forward / Backward
  - IP shifted to electron side (2+3 m)
  - Vertical planes in central tracker
  - Drift chambers on either side

Electron side (left)

- Bore angle: ~45   (line-of-sight from IP)
- High-Threshold Cerenkov
- Time-of-Flight Detectors
- Electromagnetic Calorimeter

Ion side (right)

- Bore angle: 30-40   (line-of-sight from IP)
- Ring-Imaging Cerenkov (RICH)
- Time-of-Flight Detectors
- Electromagnetic Calorimeter
- Hadronic Calorimeter
- Muon detector (at least at small angles)
  - Important for J/Ψ photoproduction

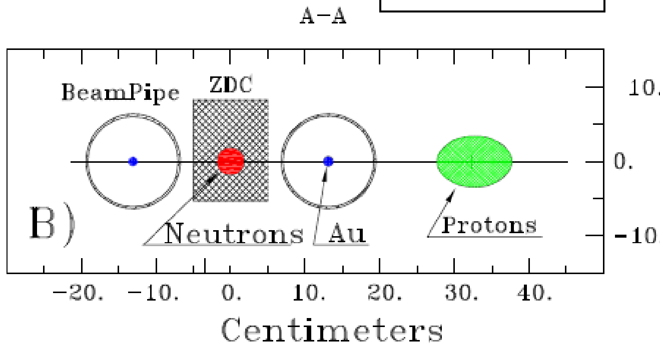
Forward Neutron Detection Thoughts – A Zero Degree Calorimeter

- EIC@JLab case: 20 Tm bend magnet at 20 meters from IP → very comparable to present RHIC case!
- 20 Tm bends 60 GeV protons with 2 times 3 degrees

→ deflection @ a distance of about 4 meters = 40 cm (protons)

→ no problem to insert Zero Degree Calorimeter in this design

RHIC ZDC



<2 mr at 18 meters from IP → neutron cone ~ 4 cm

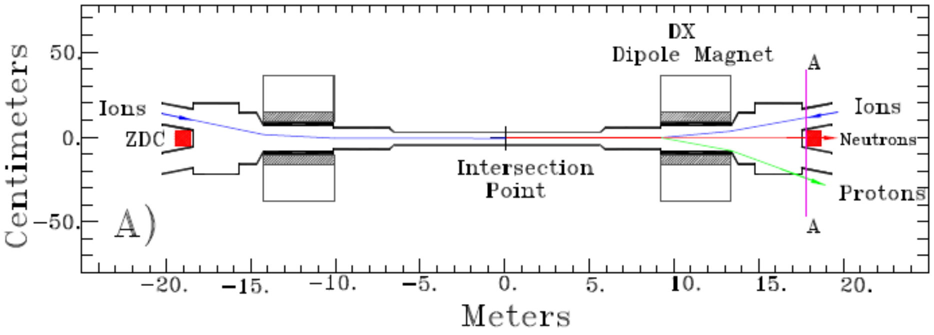
ZDC = 10 cm (horizontal) x 13 cm (vertical) (& 40 cm thick)

Zero Degree Calorimeter properties:

- Example: for 30 GeV neutrons get about 25% energy resolution *(large constant term due to unequal response to electrons and photons relative to hadrons)*

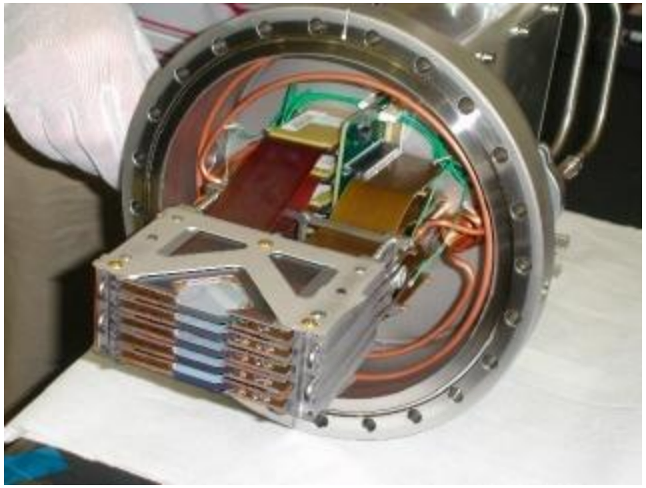
  → Should be studied more whether this is sufficient

- Timing resolution ~ 200 ps
- Very radiation hard (as measured at reactor)
- Angle and shower position resolution?



Very-Forward Ion Tagging

3 degree horizontal crossing angle for ion beam would require large 20Tm magnet at 20 meter from the IP. If so, can use this for spectator proton tagging.



Roman pots (photos at CDF (top) and LHC (bottom), …) ~ 1 mm from beam achieve proton detection with < 100m resolution

→ Need to use this for coherent processes like DVCS(p,4He) where recoil nucleus energy = beam energy minus a small t correction. *Work in progress.*

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* and/or good *resolution* and *particle id* (*e.g.*, TMDs, GPDs).
  - These processes benefit from high *luminosity*, excellent *polarization*, and more *symmetric* collision kinematics.
- Hermetic detector concept allows excellent coverage of all kinematics in exclusive reactions and SIDIS
- 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
- EIC Collaboration Meeting 29-31 July 2010 at CUA
  - http://web.mit.edu/eicc/CUA10/index.html
- INT Workshop at the University of Washington, Seattle:
  - http://www.int.washington.edu/PROGRAMS/10-3
- Weekly project meetings at JLab
  - Fridays at 9:30am in ARC724 or F324/25

Hadronic Background Comparison with HERA

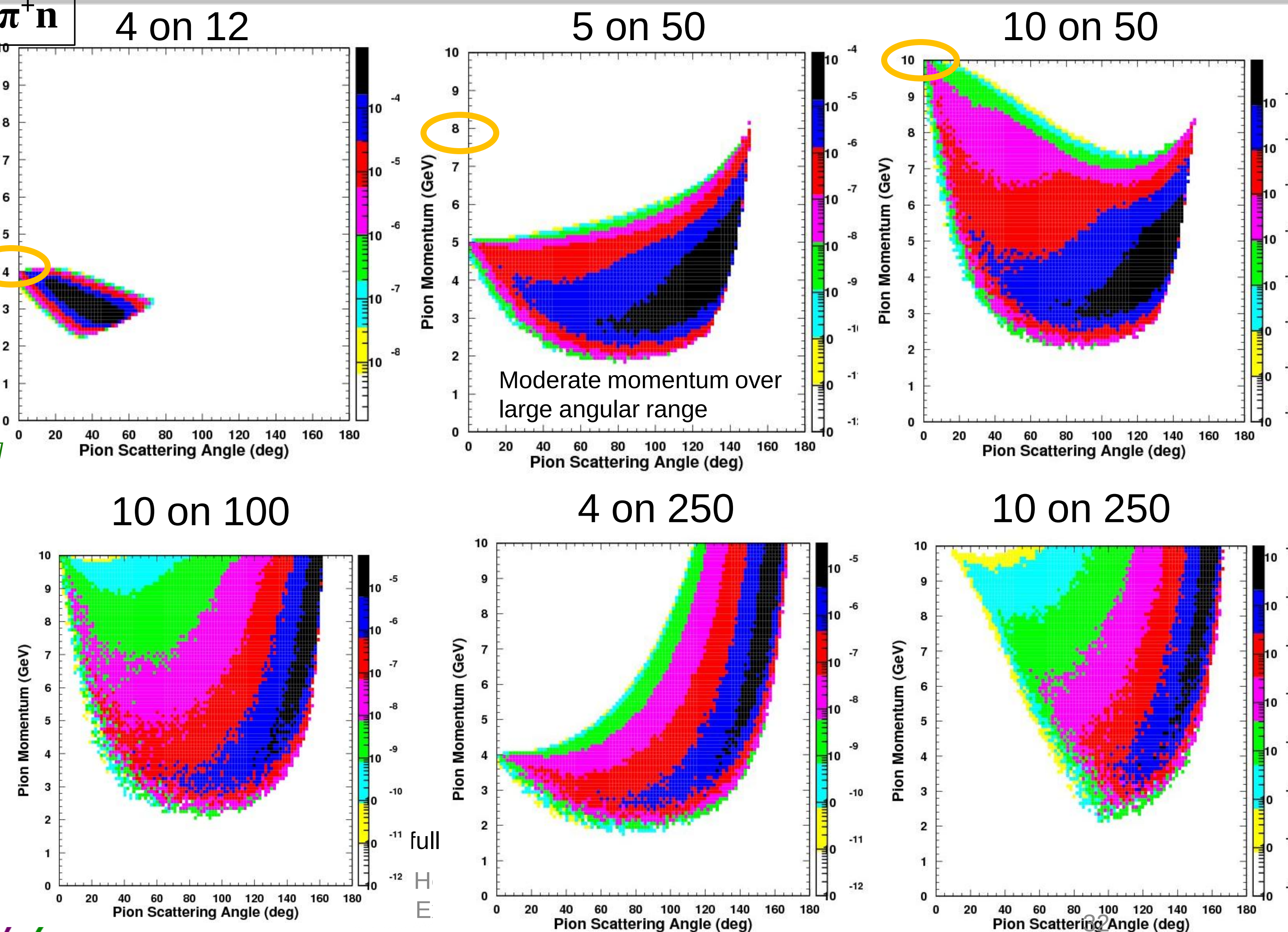
- Hadronic Random Background:
  - Dominated by interaction of beam ions with residual gas
  - Worst case at maximum energy
- Comparison of MEIC (11 on 60) and HERA (27 on 920)
  - Distance from ARC to IP: 30 m /120 m = 0.25
  - Average hadron multiplicity: $\sim(51\ \mathrm{GeV}/319\ \mathrm{GeV})^{1/2} = 0.4$
  - p-p cross section (fixed target): $\sigma(60\ \mathrm{GeV})/\sigma(920\ \mathrm{GeV})=0.7$
  - At the same current and vacuum, MEIC background is 7% of HERA
- Hadronic background is not a problem for the MEIC
  - At constant vacuum the MEIC can run 1.4 A with comparable background
  - Vacuum is much easier to maintain in a short section of a small ring
  - MEIC luminosity is more than 100 times higher (depending on kinematics)
  - Signal-to-background will be considerably better at the MEIC

Deep Exclusive – meson kinematics

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

P (GeV/c)

$Q^2 > 10 GeV^2$



P (GeV/c)

[Tanja Horn]

full

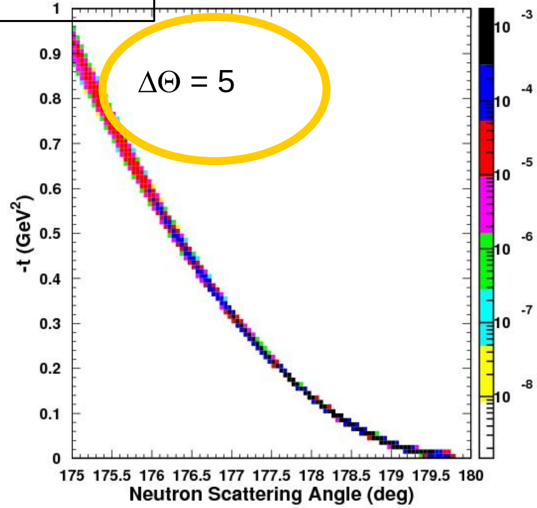
H

E

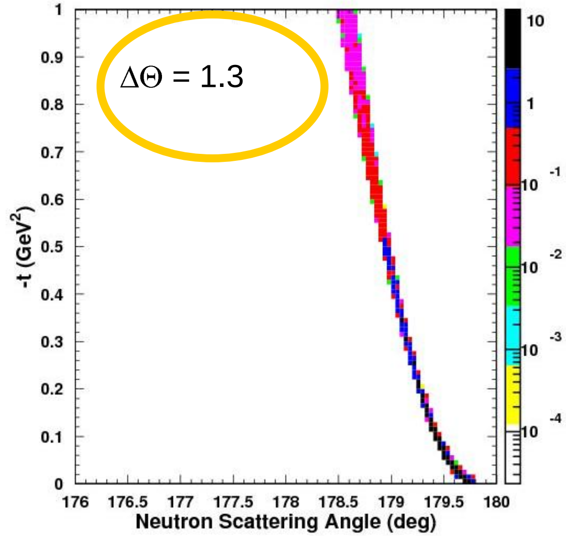
Deep Exclusive – recoil baryon kinematics

ep → e'π⁺n

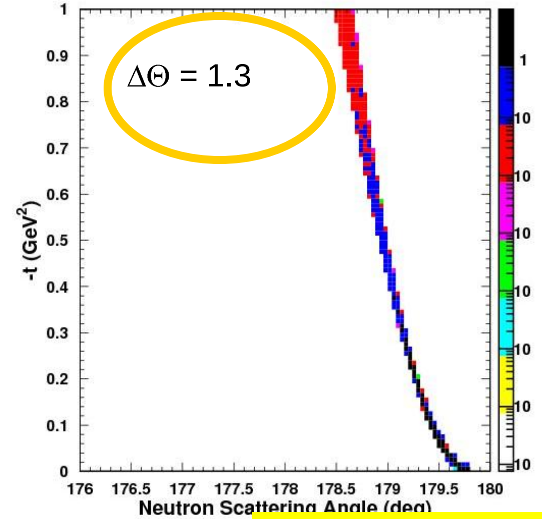
4 on 12



5 on 50



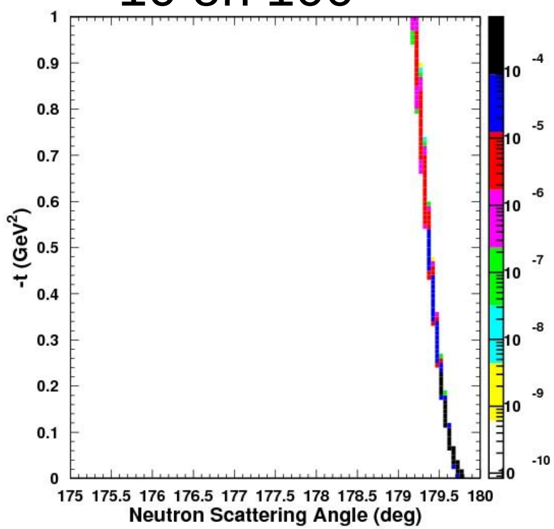
10 on 50



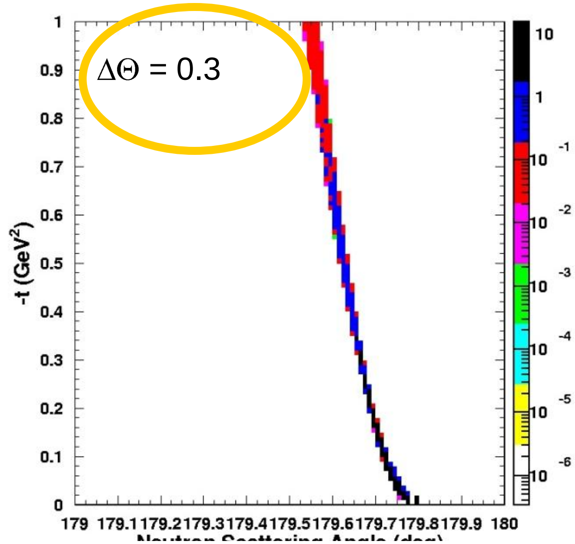
Want 0 < t < 1 Gev

$\delta t/t \sim t/E_p$

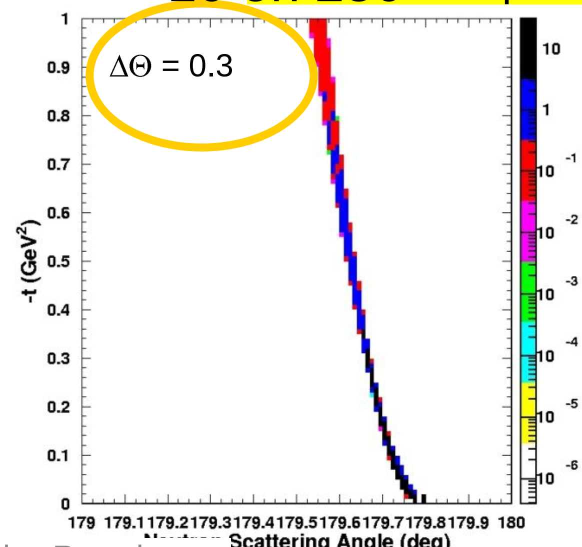
10 on 100



4 on 250

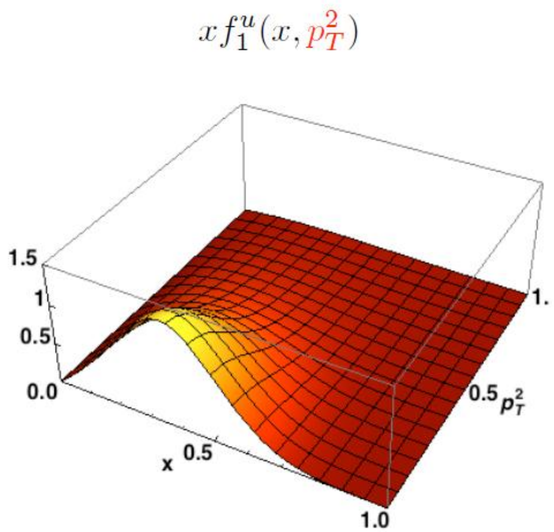


10 on 250



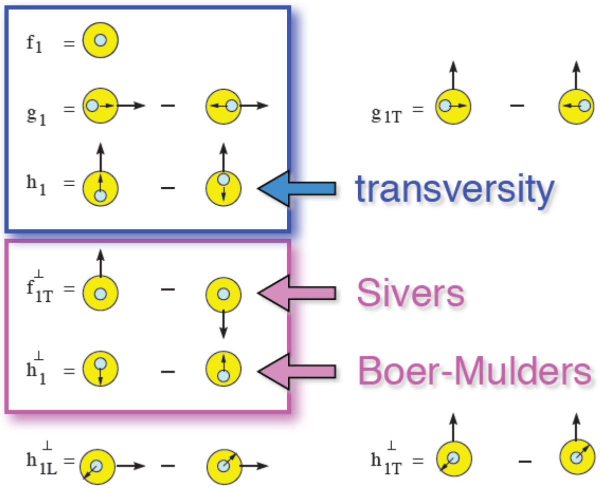
[Tanja

Transverse Momentum Distributions (TMDs)



TMD

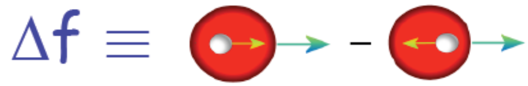
[A. Bacchetta]

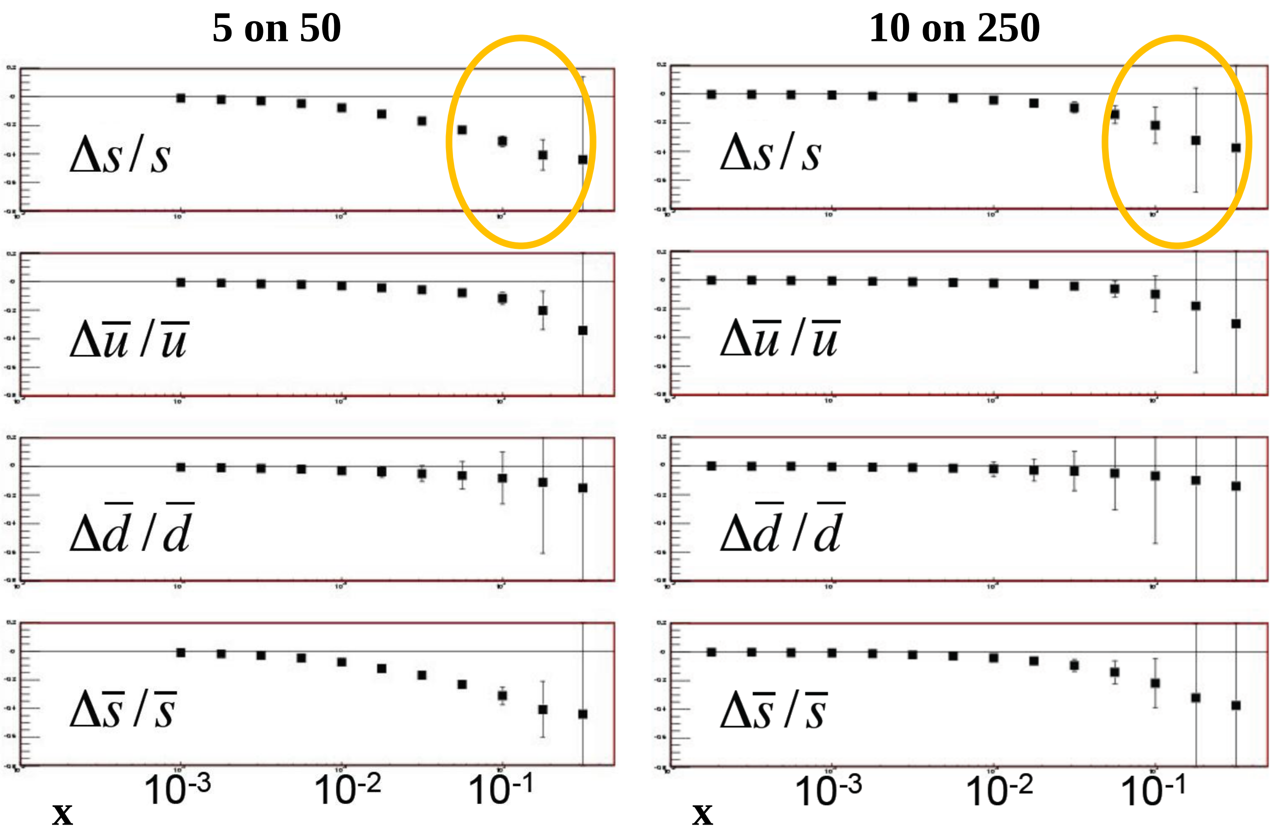


$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\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

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

Flavor Decomposition in SIDIS





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

[E. Kinney, J. Seele 08]

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

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