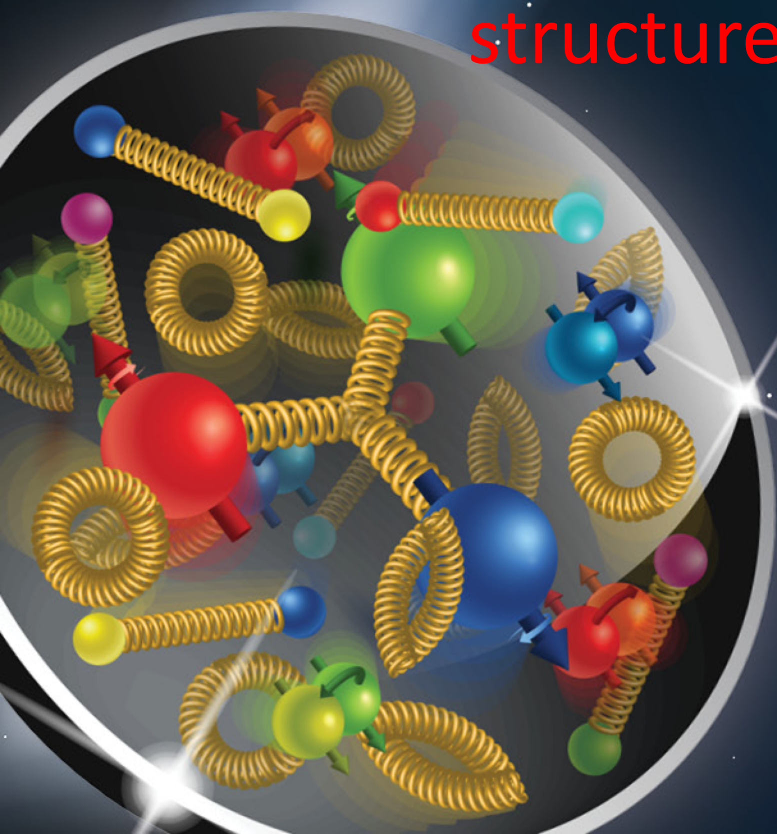
Multidimensional imaging of the partonic structure of hadrons with an Electron-Ion Collider



Salvatore Fazio

Brookhaven National Lab

Spin 2018

Ferrara, Italy

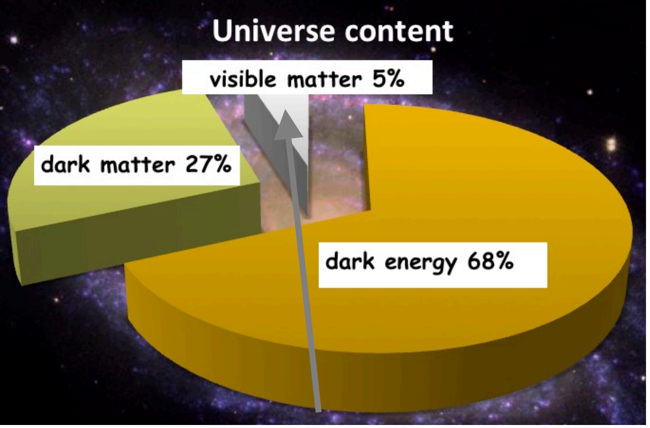
10-14 September 2018

BROOKHAVEN NATIONAL LABORATORY

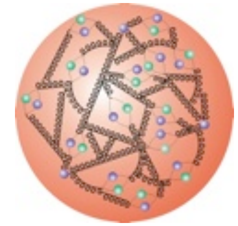
U.S. DEPARTMENT OF ENERGY | Office of Science

Plan of the talk

- Introduction to the Electron-Ion collider project
- Imaging with an EIC (the impact!)
  - GPDs
- Nuclei (imaging, saturation)
- Summary



What do we know?



This is us !!!

protons, neutrons, electrons

Proton
10^{-15}m

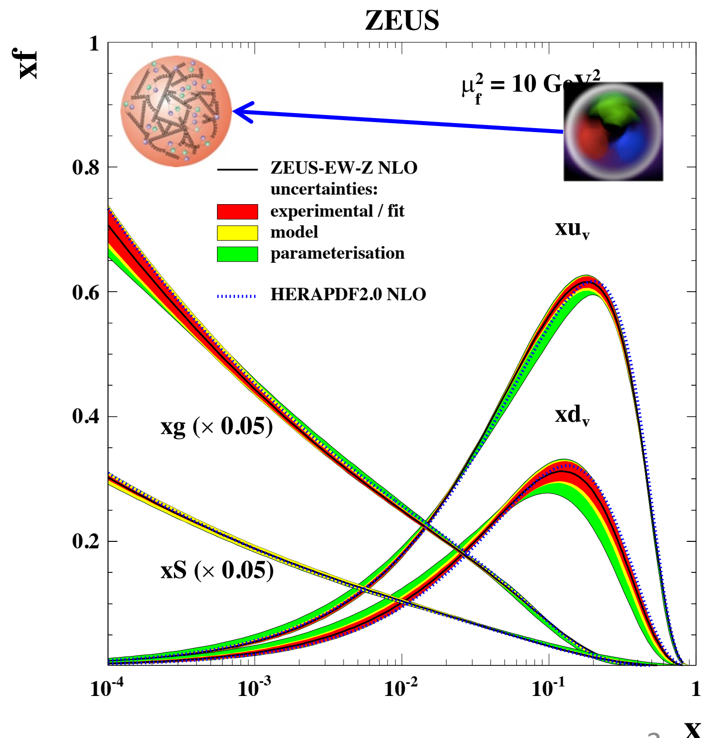
Quarks and Gluons
10^{-17}m

increase beam energy

To investigate the nucleon's partonic structure, the previous and only e+p collider, HERA, was built

The x (of Bjorken) variable: fraction of the nucleon's momentum carried by the interacting parton

HERA's discovery: Gluon density dominates at x<0.1



Proton:

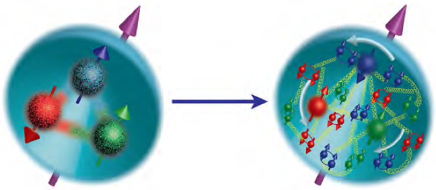
Quark-Masses: ~1% M_p

Mass of the "visible matter" is completely dominated by gluons, QCD dynamics

Most Compelling Physics Goals

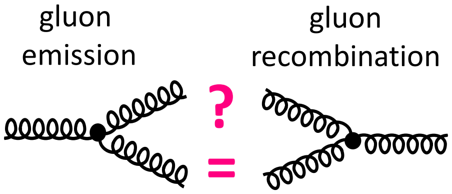
How are sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

- How do the nucleon properties emerge from them and their interactions?



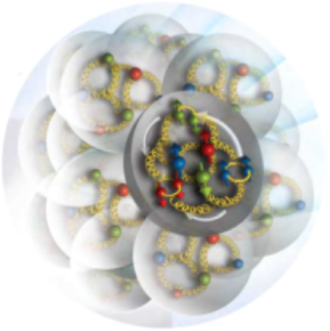
What happens to the gluon density in nuclei?

- Does it saturate at high energy?
- Does this saturation give rise to a gluonic matter with universal properties in all nuclei, even proton?



How does a dense nuclear environment affect the quarks and gluons, and their correlations and their interactions?

- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
- How do the confined hadronic states emerge from these quarks and gluons?
- How do the quark-gluon interactions create nuclear binding?



Ingredients for a High Resolution "Femtoscope"

Large center-of-mass coverage:

Access to wide kinematic range in x and Q^2

Polarized electron and hadron beams:

- access to spin structure of nucleons and nuclei
- Spin vehicle to access the 3D spatial and momentum structure of the nucleon
- Full specification of initial and final states to probe q-g structure of NN and NNN interaction in light nuclei

Nuclear beams:

- Accessing the highest gluon densities → amplification of saturation phenomena

High luminosity:

- Detailed mapping the 3D spatial and momentum structure of nucleons and nuclei
- Access to rare probes

All these requirement must be addressed by a future **Electron-Ion Collider**

The Electron Ion Collider

Two proposals for realization of the Science Case

For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Luminosity L_{ep} ~ 10^{34} $cm^{-2}sec^{-1}$
  100-1000 times HERA
- ✓ $\sqrt{s}$ = 20-100 (140) GeV Variable CoM

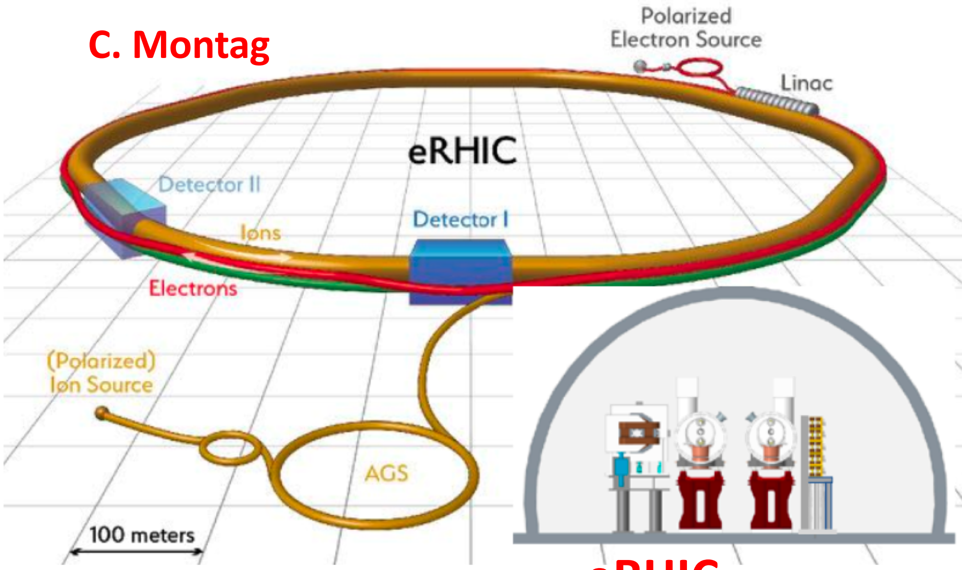
For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e+p
- ✓ Variable center of mass energy

World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

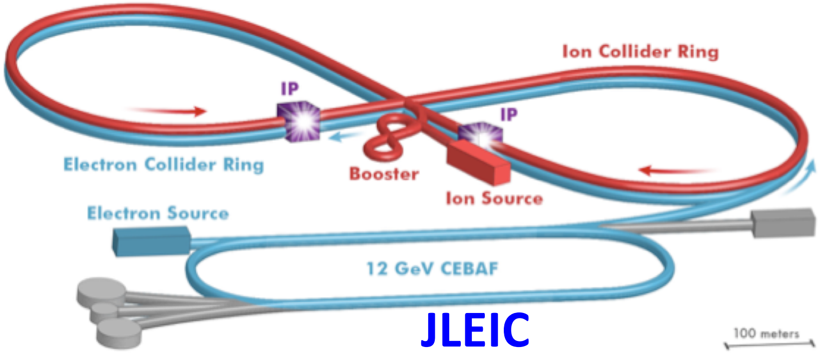
Both designs use DOE's significant investments in infrastructure

C. Montag



eRHIC
Brookhaven National Lab

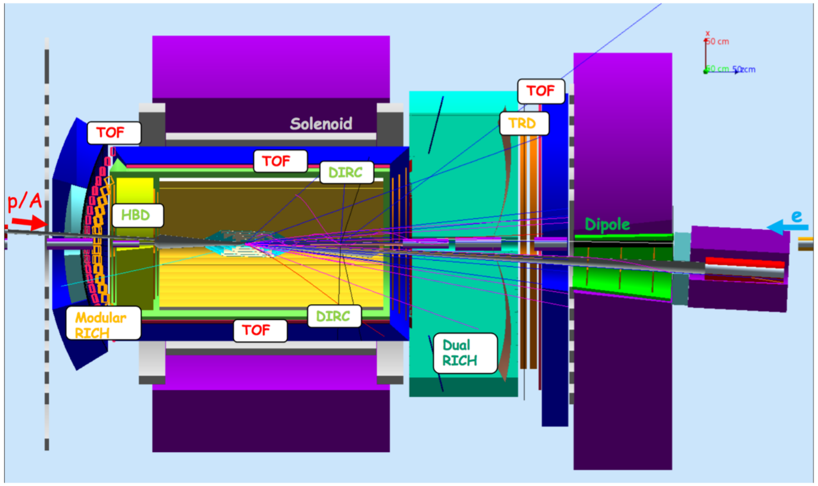
F. Lin

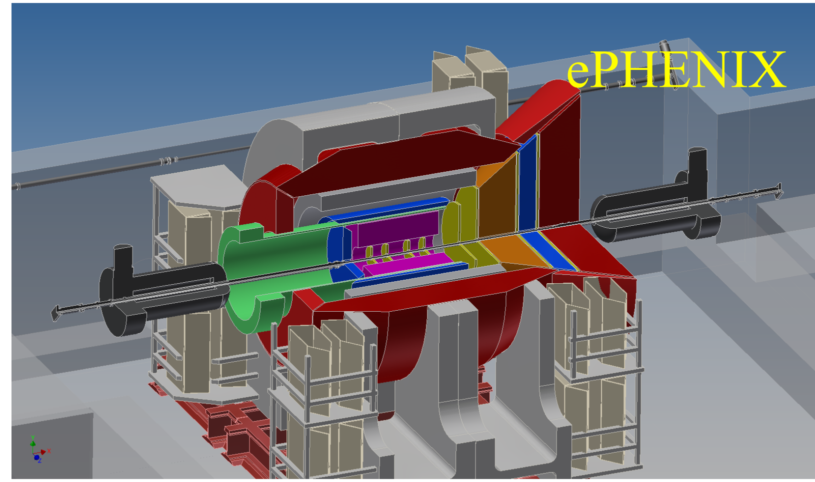


JLEIC
Thomas Jefferson National Lab

“General-porpose” detector general requirements

JLAB B. Sorrow **BNL**





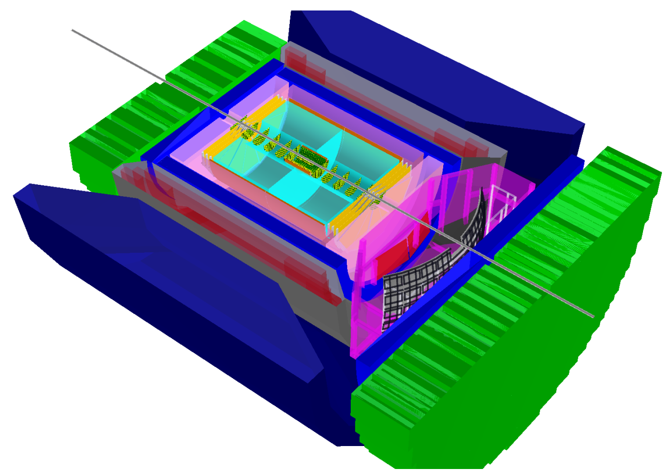
Overall detector requirements:

- **Large acceptance in pseudorapidity**: $-4.5 \lesssim \eta \lesssim 4.5$
- Equal coverage of tracking and EM-calorimetry
- High performance PID to separate p, K, π on track level
- High precision low mass tracking
- Forward instrumentation for protons and neutrons
- High control on systematic effects

A full silicon detector concept also proposed by Argonne

EIC Detector and R&D program

→ https://wiki.bnl.gov/conferences/index.php/EIC_R%25D



A model detector concept: BeAST (Brookhaven eA Solenoidal Tracker)

Partonic tomography of the nucleons

Wigner distribution **5D**

$$W(x, k_T, r_T)$$

TMDs d^2r_T

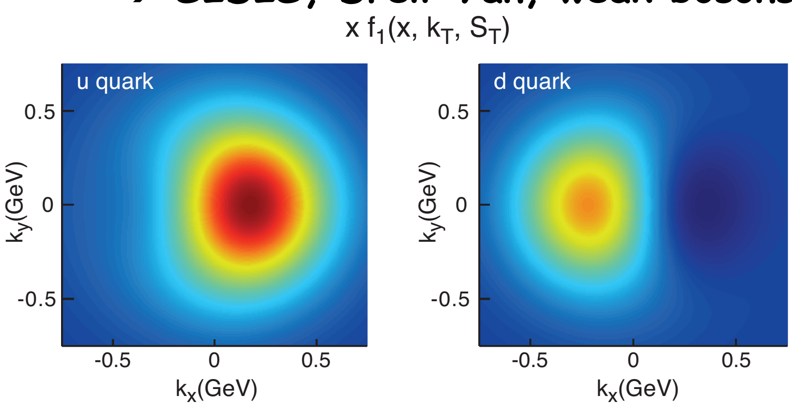
GPDs d^2k_T

R. Yoshida
H. Avagyan

3D

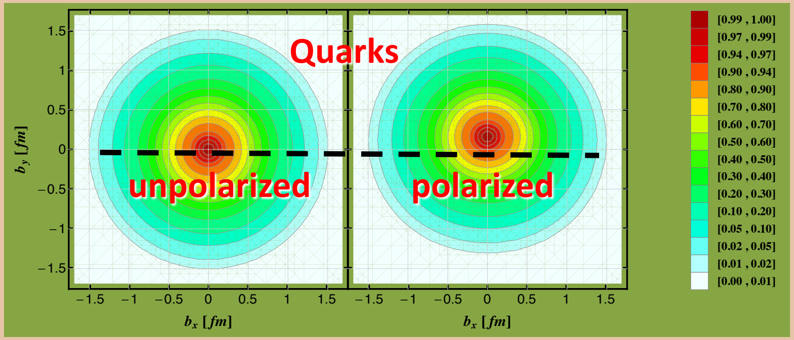
2D+1 picture in momentum space

transverse momentum dependent PDFs
→ SIDIS, Drell-Yan, weak bosons



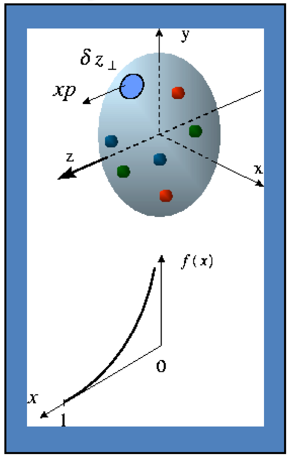
2D+1 picture in coordinate space

generalized parton distributions
→ exclusive reaction



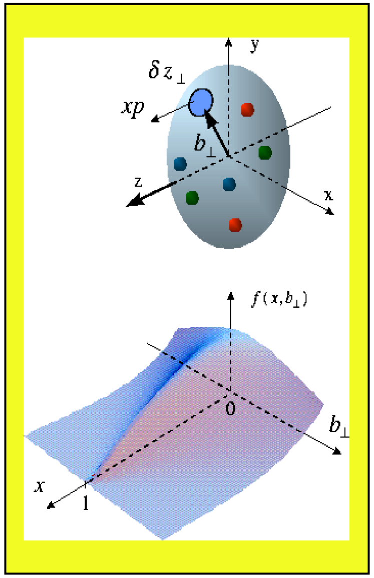
Generalized Parton Distributions

Longitudinal momentum & helicity distributions



$f(x)$

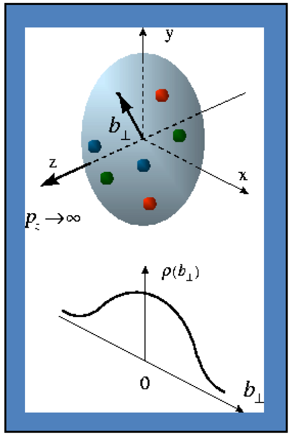
parton densities



$H(x,\xi,t)$

GPDs

transverse charge & current densities



$F_1(t)$

form factors

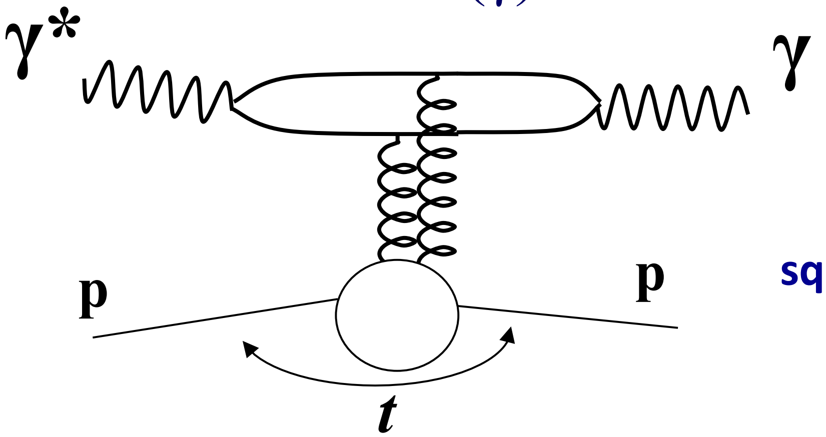
The nucleon (spin-1/2) has **four quark and gluon GPDs** (H, E and their polarized versions). Like usual PDFs, GPDs are non-perturbative functions **defined via the matrix elements of**

$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ix\bar{P}^+z^-} \langle p'|\bar{q}(-\frac{1}{2}z)\gamma^+ q(\frac{1}{2}z)|p\rangle|_{z^+=0,\mathbf{z}=0}$$

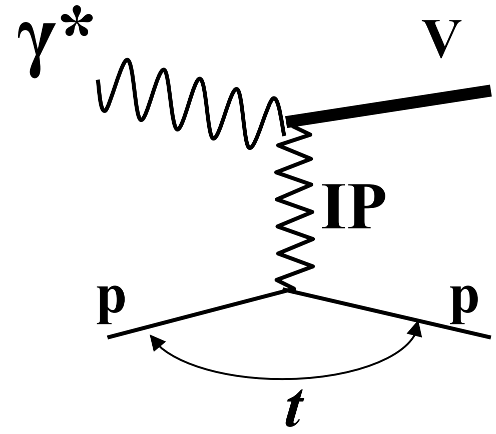
$$= \frac{1}{2\bar{P}^+}\left[H^q(x,\xi,t,\mu^2)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t,\mu^2)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_N}u(p)\right]$$

Exclusive Vector Meson and real photon production

DVCS (γ)



VM (ρ, ω, φ, J/ψ, Υ)



square 4-momentum at the *p* vertex:

$$t = (p' - p)^2$$

Scale: Q^2 ⟷ $Q^2 + M^2$

DVCS:

- Very clean experimental signature
- No VM wave-function uncertainty
- Hard scale provided by Q^2
- Sensitive to both quarks and gluons [via Q^2 dependence of xsec (scaling violation)

VMP:

- Uncertainty of wave function
- J/Psi → direct access to gluons, c+bar-c pair produced via quark(gluon)-gluon fusion
- Light VMs → quark-flavor separation

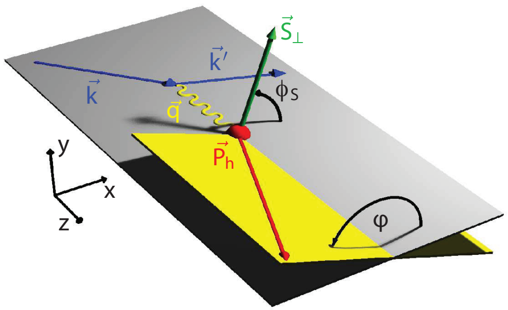
Alternative/complementary way to quark-flavor separation

DVCS on a real neutron target → polarized Deuterium or He^3

Accessing the GPDs in exclusive processes

$$\frac{d\sigma}{dt} \sim A_0 \left[|H|^2 (x,t,Q^2) - \frac{t}{4M_p^2} |E^2| (x,t,Q^2) \right]$$

Dominated by H
slightly dependent on E

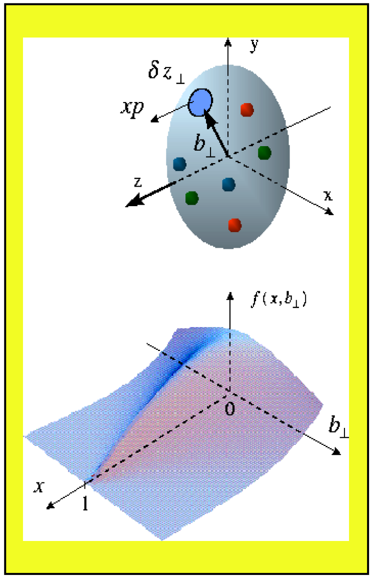


$$\varphi = \phi_h - \phi_l$$

Angle btw the production and scattering planes

$$\varphi_s = \Phi_T - \phi_h$$

Angle btw the scattering plane and the transverse pol. vector



$$A_C = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto Re(A)$$

Requires a positron beam
done @ HERA

$$A_{UT} \propto \sqrt{\frac{-t}{4M^2}} \left[F_2(t) H(\xi,\xi,t,Q^2) - F_1(t) E(\xi,\xi,t,Q^2) + \dots \right]$$

$\sin(\Phi_T - \phi_N)$
governed by E and H
Requires a polarized proton-target

Spin-Sum-Rule in PRF: **from g_1**

$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z$$

$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx \left(H^{q,g} + E^{q,q} \right) \right)_{t \to 0}$$

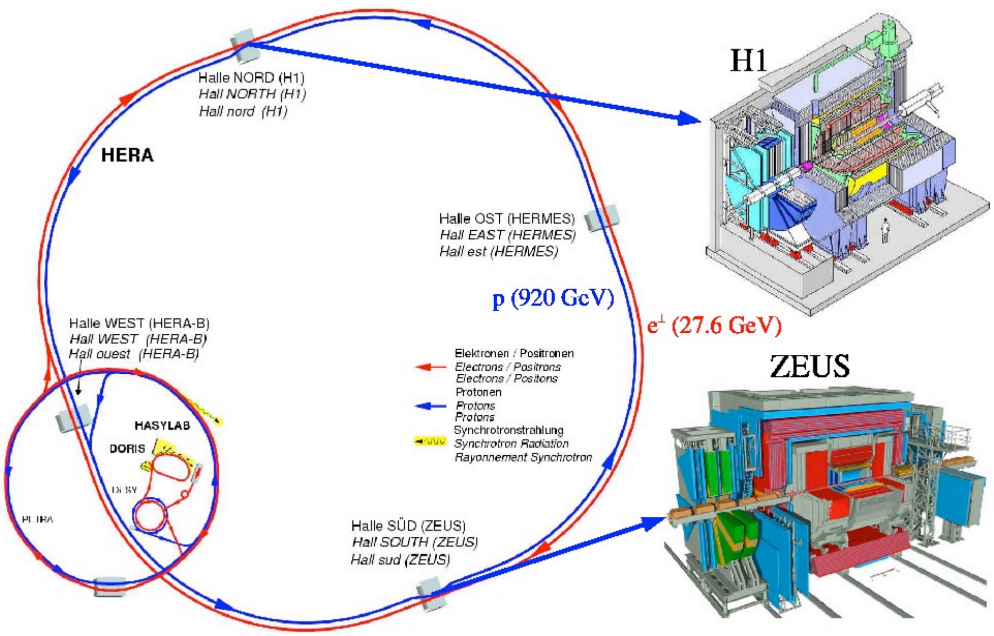
responsible for orbital angular momentum
a window to the SPIN physics

The HERA Collider and experiments

- 27.5 GeV electrons/positrons on 920 GeV protons →√s=318 GeV
- 2 collider experiments: **H1 and ZEUS**
- HERA I: 16 pb^{-1} e-p, 120 pb^{-1} e+p
  HERA II (after lumi upgrade): 500 pb^{-1}, polarisation of e+,e-

Closed July 2007, still lot of excellent data to analyse…

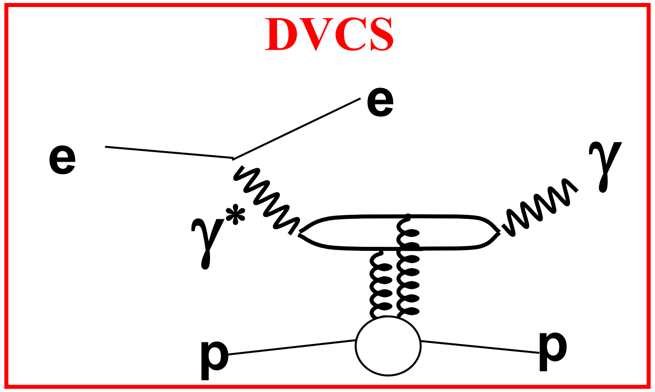
- **Fixed target experiment**
- **Intense program on DVCS!**

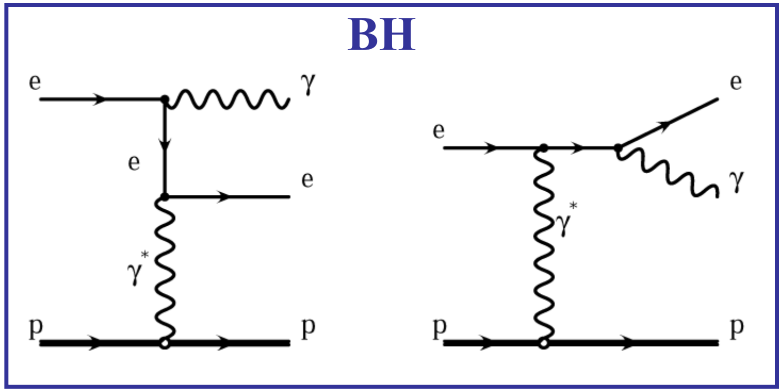


Detectors not originally designed for forward physics, but diffraction at HERA is great success story!

ZEUS forward instrumentation no longer available in HERA II

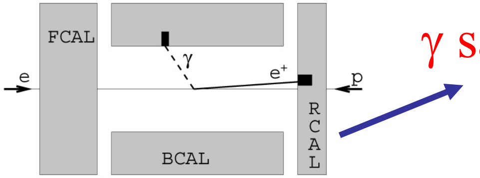
DVCS @ ZEUS - Strategy



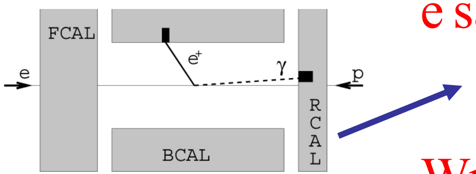


two electromagnetic candidates (ordered in energy) and up to one track

BH must be removed [**uncertainty on BH xsec ~ 3%**]



γ sample: no tracks matching to the second candidate — **Signal sample (DVCS+BH)**



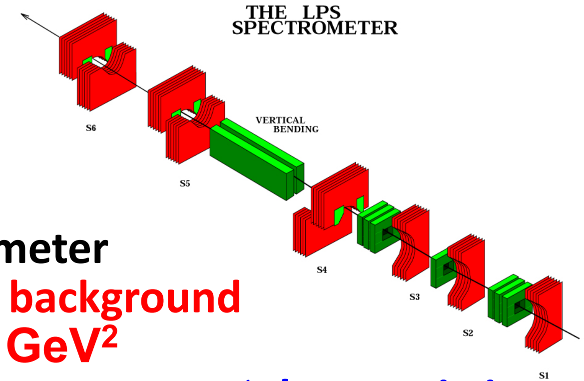
e sample: a track match to the second candidate — **Control sample (BH+ dilepton + J/ψ)**

Wrong-sign sample: a negative track match to the second candidate — **Control sample (dilepton + J/□)**

Kinematic region:
$1.5 < Q^2 < 100$ GeV^2
$40 < W < 170$ GeV

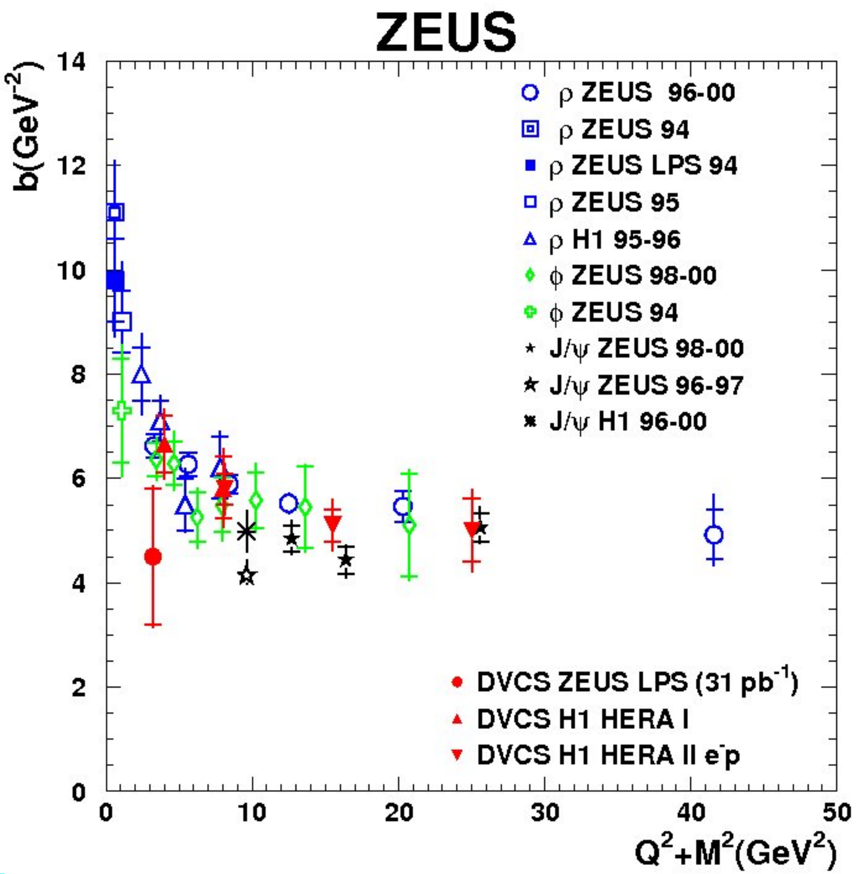
Details on the event selection in the back up slides

DVCS: *t* dependence – RPs

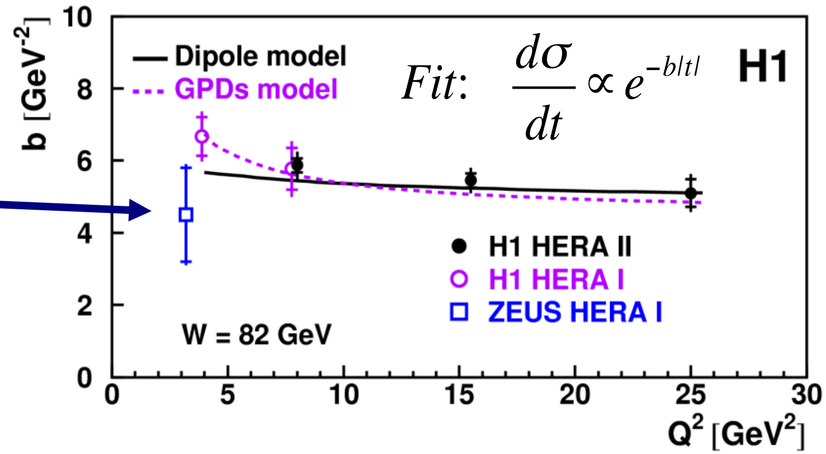


Roman Pots spectrometer
- No p-dissociation background
- $0.08 < |t| < 0.53$ GeV^2
- Low geometrical acceptance → low statistics

This detector was removed after the HERA II upgrade → $\mathcal{L}$ = 31 pb^{-1}

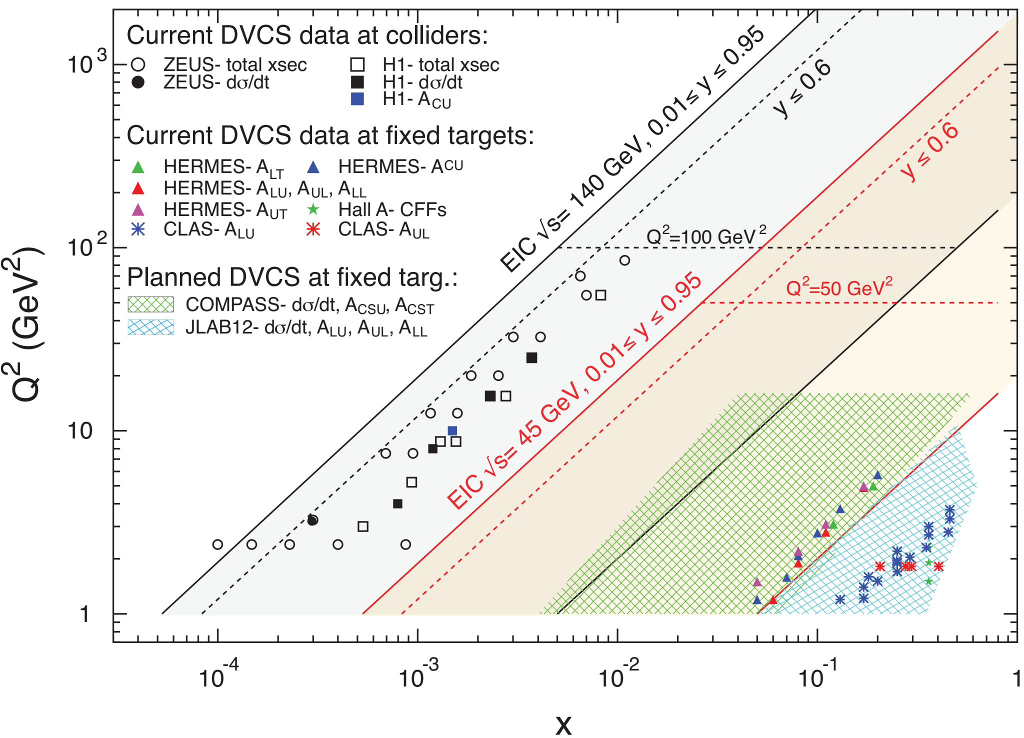


direct measurement of the outgoing proton 4-momentum using the Leading Proton Spectrometer (roman pots)



The ZEUS result still statistically compatible with H1, but hints for a flatter trend

DVCS at an EIC

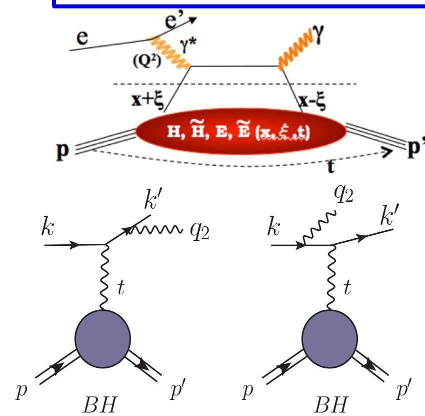


HERA results limited by lack of statistics

EIC: the first machine to measure cross sections and asymmetries

- ✧ **EIC will provide sufficient luminosity to bin in multi-dimensions**
- ✧ **Wide x and Q^2 range needed to extract GPDs**

E.C. Aschenauer, S. F., K. Kumerički, D. Müller
JHEP09(2013)093



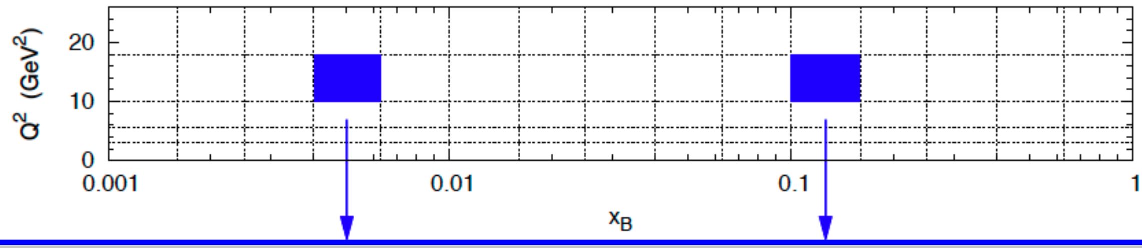
DVCS signal

Bethe-Heitler QED bkgd.

Comprehensive EIC studies

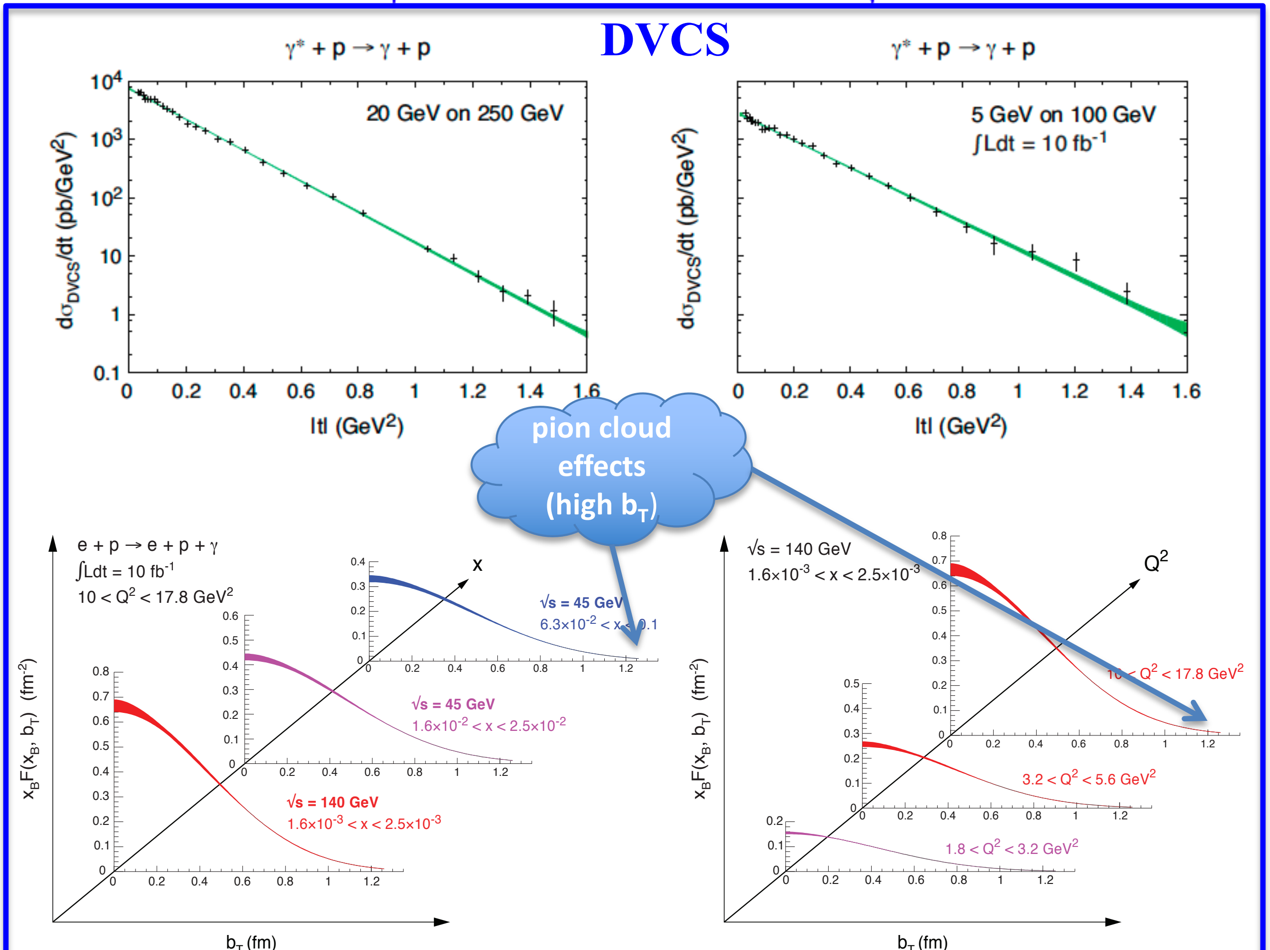
- **Signal extraction "a la HERA"**
- **xSec meas.: Specific requirements to suppress BH (*see backup*)**
  → keep BH/sample below 60% at high energies
- **Radiative Corrections evaluated (*bkup*)**
- **detector acceptance & smearing**
- **t-slope: b=5.6 compatible with H1 data**
- **|t|-binning is (3*resolution)**
- **5% systematic uncertainties**

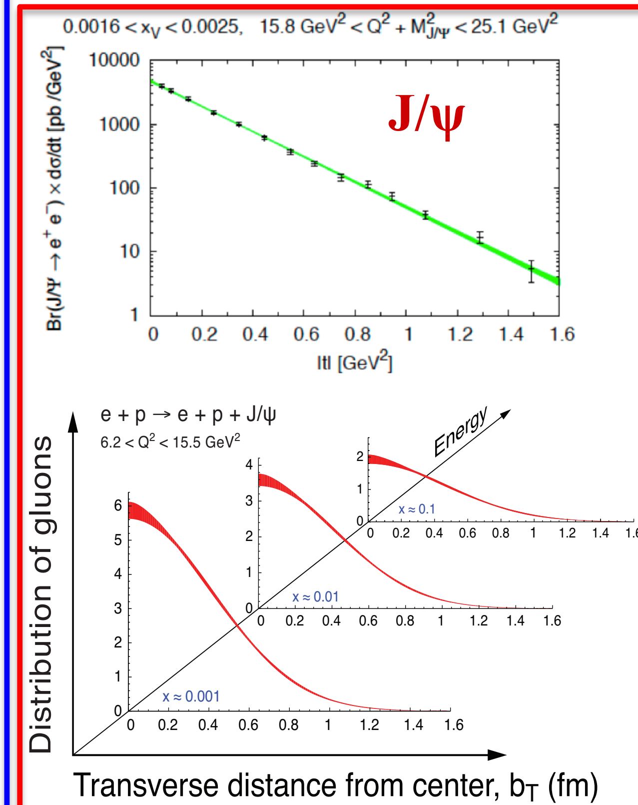
DVCS & J/ψ differential cross section



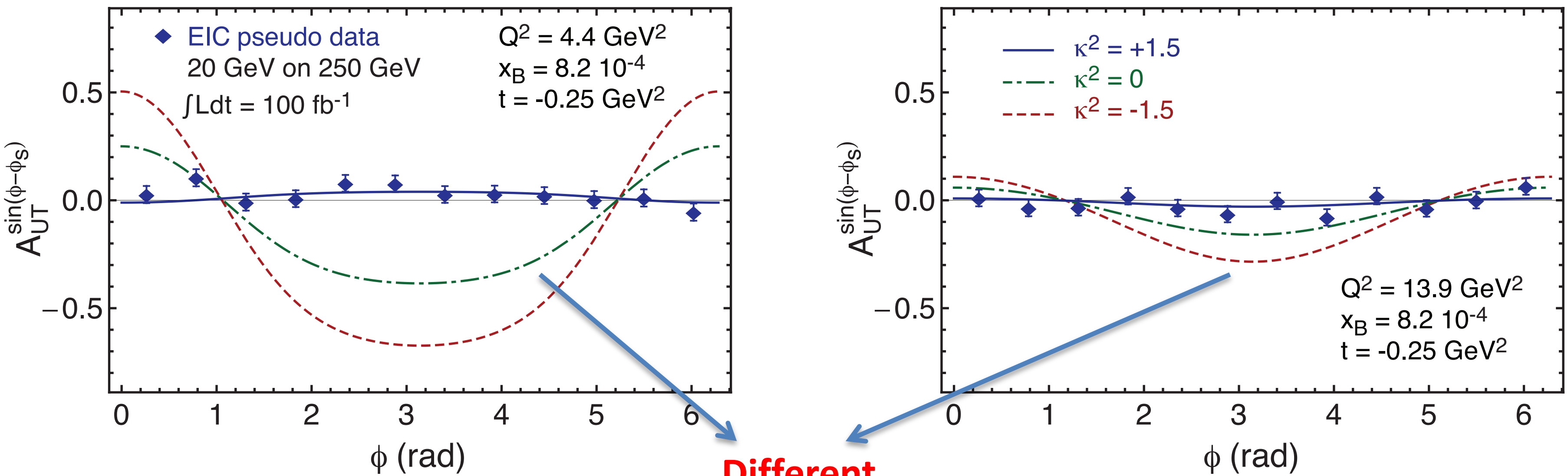
Luminosity: 10 fb^{-1}

- Measurement dominated by systematics
- Fourier transf. of dσ/dt → partonic profiles





Transverse target-spin asymmetry



Different assumptions for E

$$A_{UT} \propto \sqrt{\frac{-t}{4M^2}}\left[F_2(t)H\left(\xi,\xi,t,Q^2\right) - F_1(t)E\left(\xi,\xi,t,Q^2\right) + \ldots\right]$$

sin(Φ$_T$–φ$_N$)
governed by E and H

Spin-Sum-Rule in PRF: **from g_1**

$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z$$

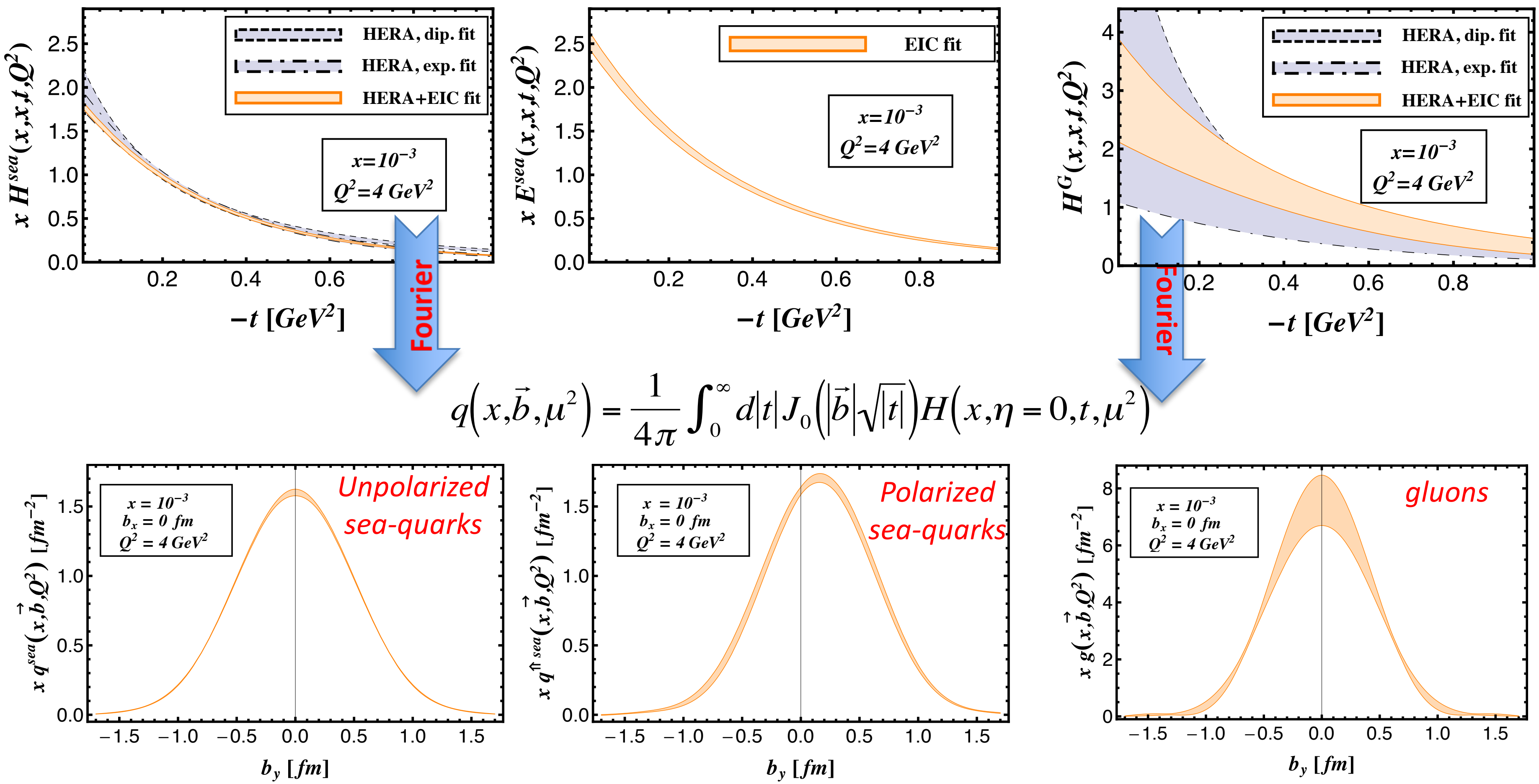
$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^{q,g} + E^{q,q}\right)\right)_{t\to 0}$$

Gives access to GPD E

E.C. Aschenauer, S. F., K. Kumerički, D. Müller
JHEP09(2013)093

DVCS-based imaging

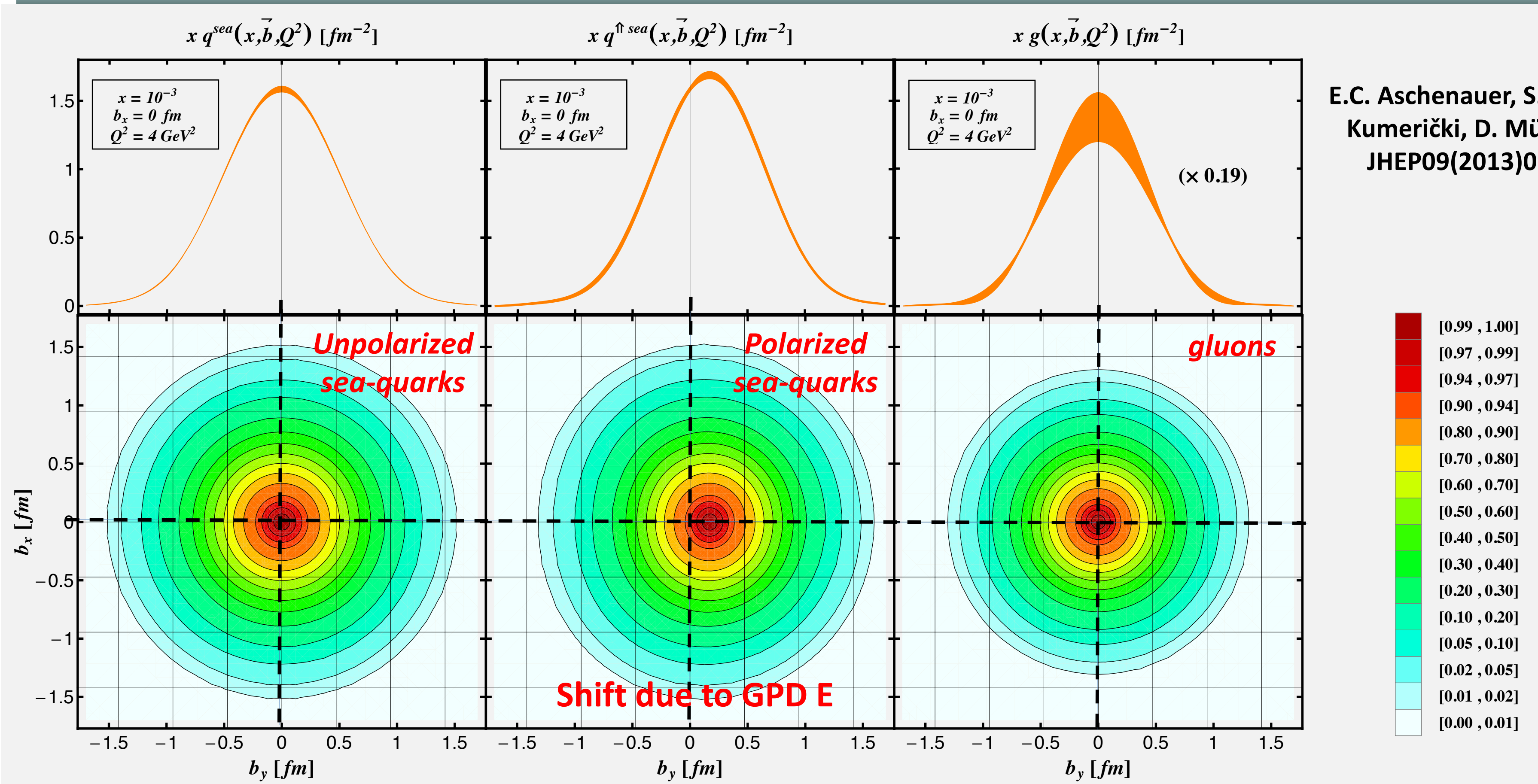
- A global fit over all mock data was done, based on: [Nuclear Physics B 794 (2008) 244–323]
- Known values *q(x)*, *g(x)* are assumed for H^q, H^g (at t=0 forward limits E^q, E^g are unknown)



$$q\left(x,\vec{b},\mu^2\right) = \frac{1}{4\pi}\int_0^\infty d|t|\, J_0\left(|\vec{b}|\sqrt{|t|}\right) H\left(x,\eta=0,t,\mu^2\right)$$

E.C. Aschenauer, S. F., K. Kumerički, D. Müller, JHEP09(2013)093

Spatial Imaging – as in the EIC White Paper



E.C. Aschenauer, S. F., K. Kumerički, D. Müller, JHEP09(2013)093

Impact of EIC (based on DVCS only):

- ✓ Excellent reconstruction of H^{sea}, and H^{g} (from $d\sigma/dt$)
- ✓ Reconstruction of sea-quarks GPD E

Other capabilities still to be evaluated?

- GPD H-Gluon is nice but can be much better by including J/ψ
- Access to GPD E-gluon → orbital momentum (Ji sum rule)
- Flavor Separation of GPDs (VMP and/or DVCS on deuteron)
- Nuclear imaging (modification of GPDs in p+A collisions)

Next-generation GPD studies with exclusive meson production at EIC

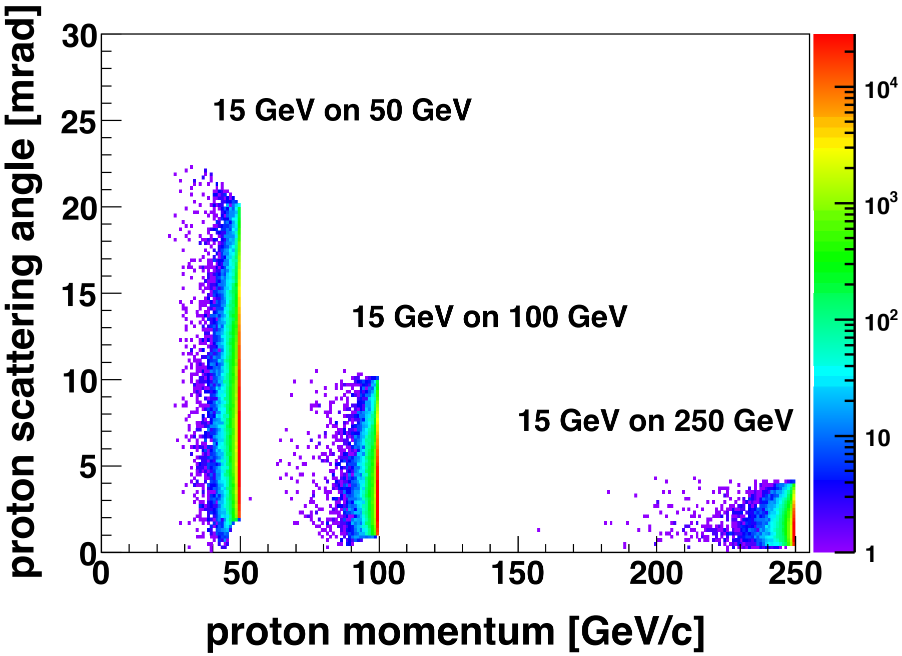
Center for Frontiers in Nuclear Science

Topical Workshop, CFNS, Stony Brook U., 4-6 June 2018
Organizers: Marie Boer, S. F., Lech Szymanowski, Christian Weiss
35 participants, 3 days of presentations and discussions
INDICO page: https://indico.bnl.gov/event/4346/

Objective: Assess potential of hard exclusive meson production and related processes for GPD studies and plan EIC simulations

- Concepts and interpretation: Quark/gluon imaging, energy-momentum tensor
- Reaction theory: QCD factorization, finite-size effects
- Experimental results: HERA, JLab 6 & 12 GeV, COMPASS; LHC UPC pA, future RHIC UPC plans
- EIC machine and detector requirements
- Simulation tools: Physics models, PARTONS framework, detector models

Scattered Proton measurement



Remember:

Detector -4 to 4 in h

→ 35 mrad from beam line

→ so not seen in main detector

→ need different detection technology

p_T of proton critical for physics

$p_T = p' \sin(\Theta)$

$p'_L > 97\%$ of p_{Beam}

ZEUS Coll, JHEP 06 (2009) 074

Note:

high energy colliders (HERA, Tevatron, LHC, RHIC) use Roman Pots to detect these protons

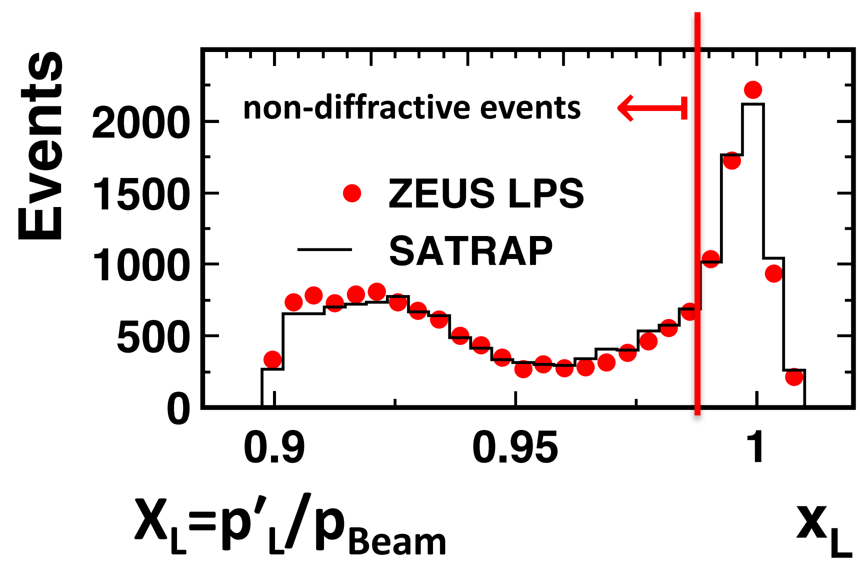
→ RPs are high resolution movable small tracking detectors (Si strips, Si pixels…), a crucial component

→ Θ < 10 mrad

→ impact on large p_T-acceptance

→ small p_T-acceptance limited by beam divergence and immittance

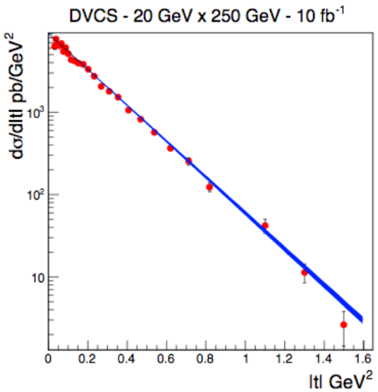
→ rule of thumb keep 10s between RP and beam



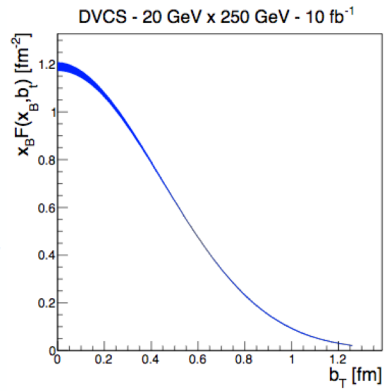
Impact of proton acceptance

Measurement

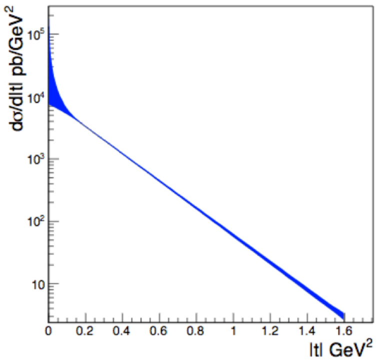
Physics observable (cross-section vs impact parameter)



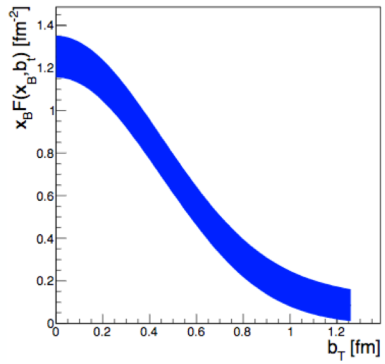
Plots from
EIC White Paper:



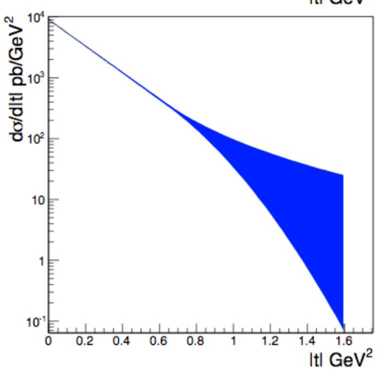
Requirement:
$\int L_{int}$=10fb^{-1}
$0.18 < p_t$ (GeV) < 1.3
$0.03 < |t|$ (GeV^2) < 1.6



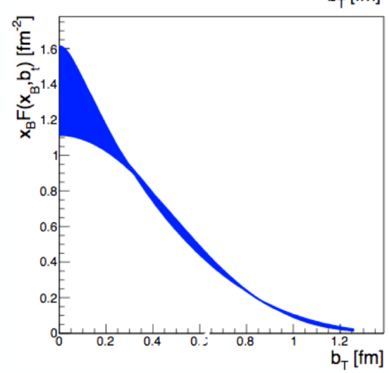
limited
lower
p_T-acceptance



$\int L_{int}$=10fb^{-1}
$0.44 < p_T$(GeV) < 1.3



limited
higher
p_T-acceptance

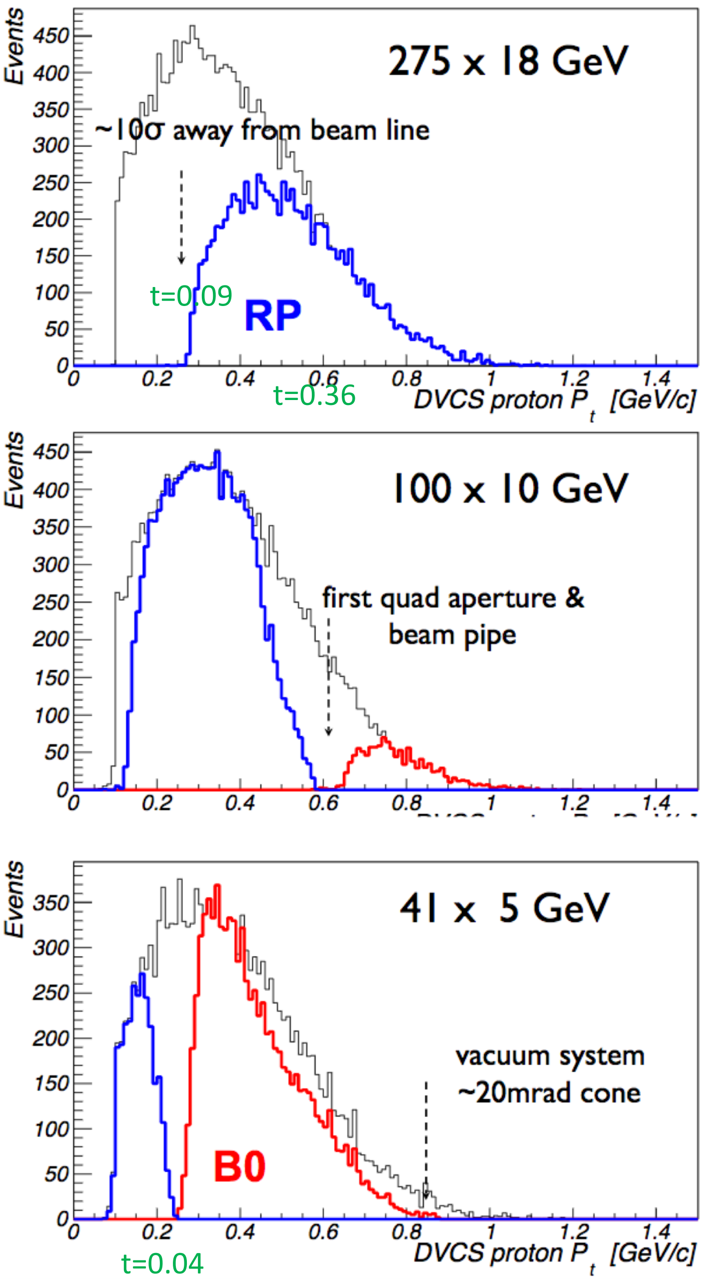


$\int L_{int}$=10fb^{-1}
$0.18 < p_T$ (GeV) < 0.8

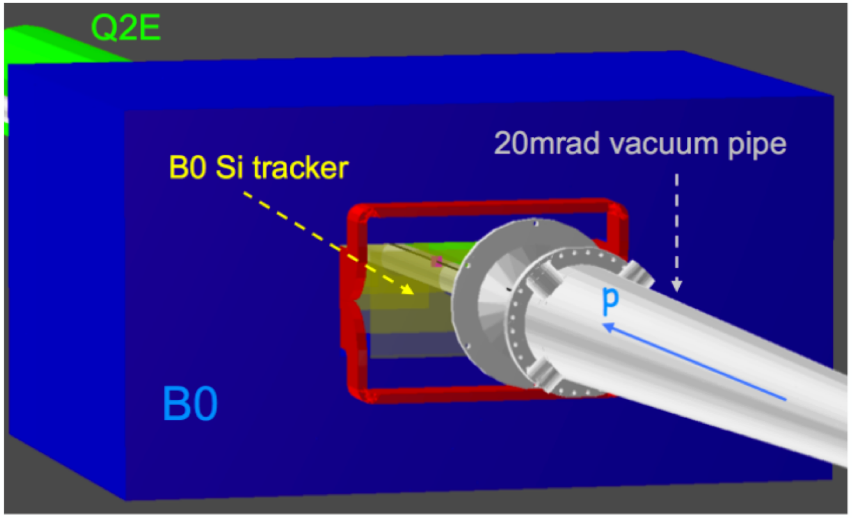
We need large acceptance Proton spectrometers!

Proton acceptance with eRHIC

J.H. Lee
EIC Users Meeting

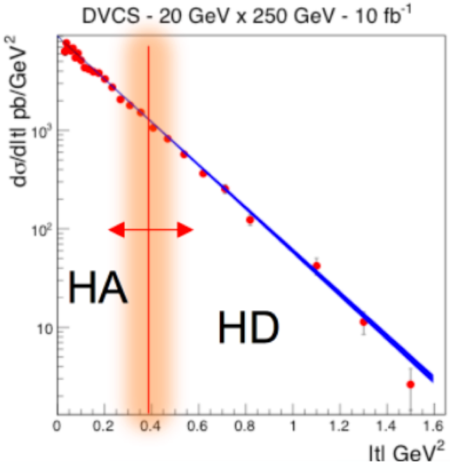


p_T acceptance for forward scattered protons from exclusive reactions



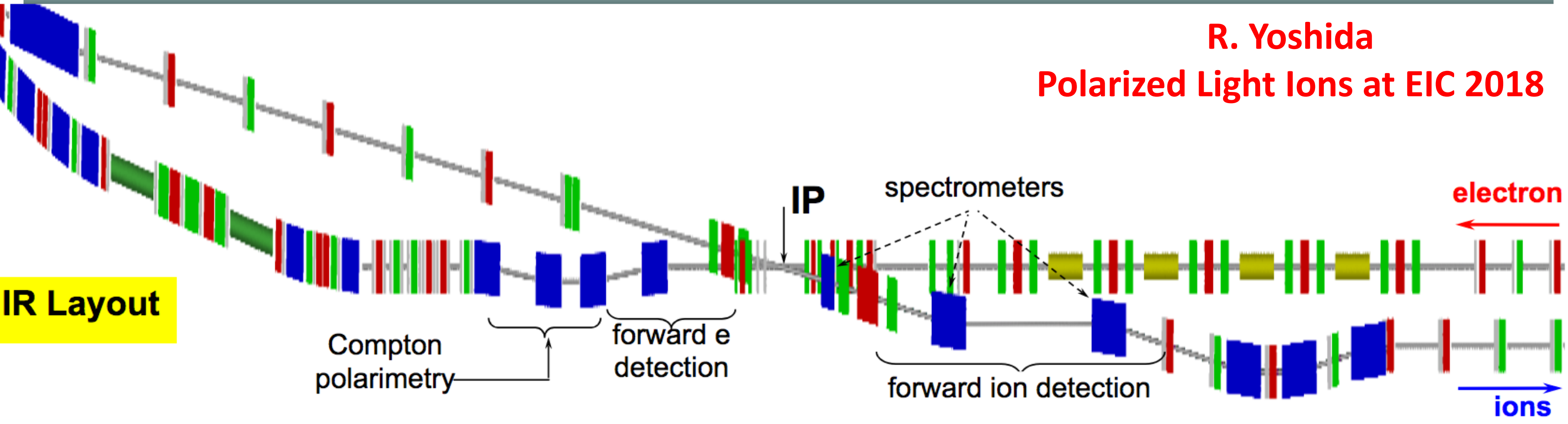
- Plots: HD (high divergence) mode
- Acceptance gap between RP and B0 will be further optimized

Accept 0.3 < p_T< 1.3 GeV and higher
→ Low p_T-part can be filled in with HA (high acceptance, smaller beam divergence) running mode



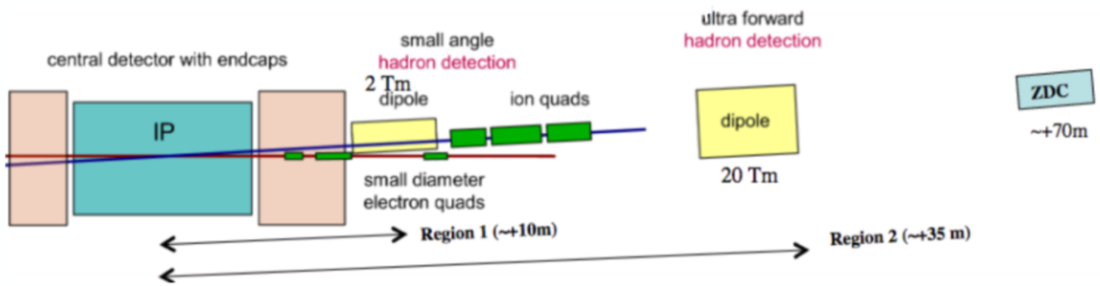
Proton acceptance with JLEIC

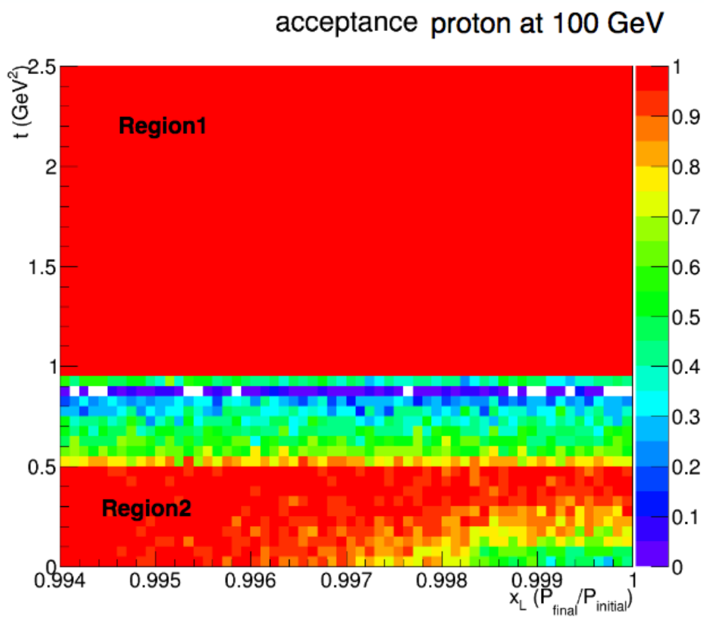
R. Yoshida
Polarized Light Ions at EIC 2018



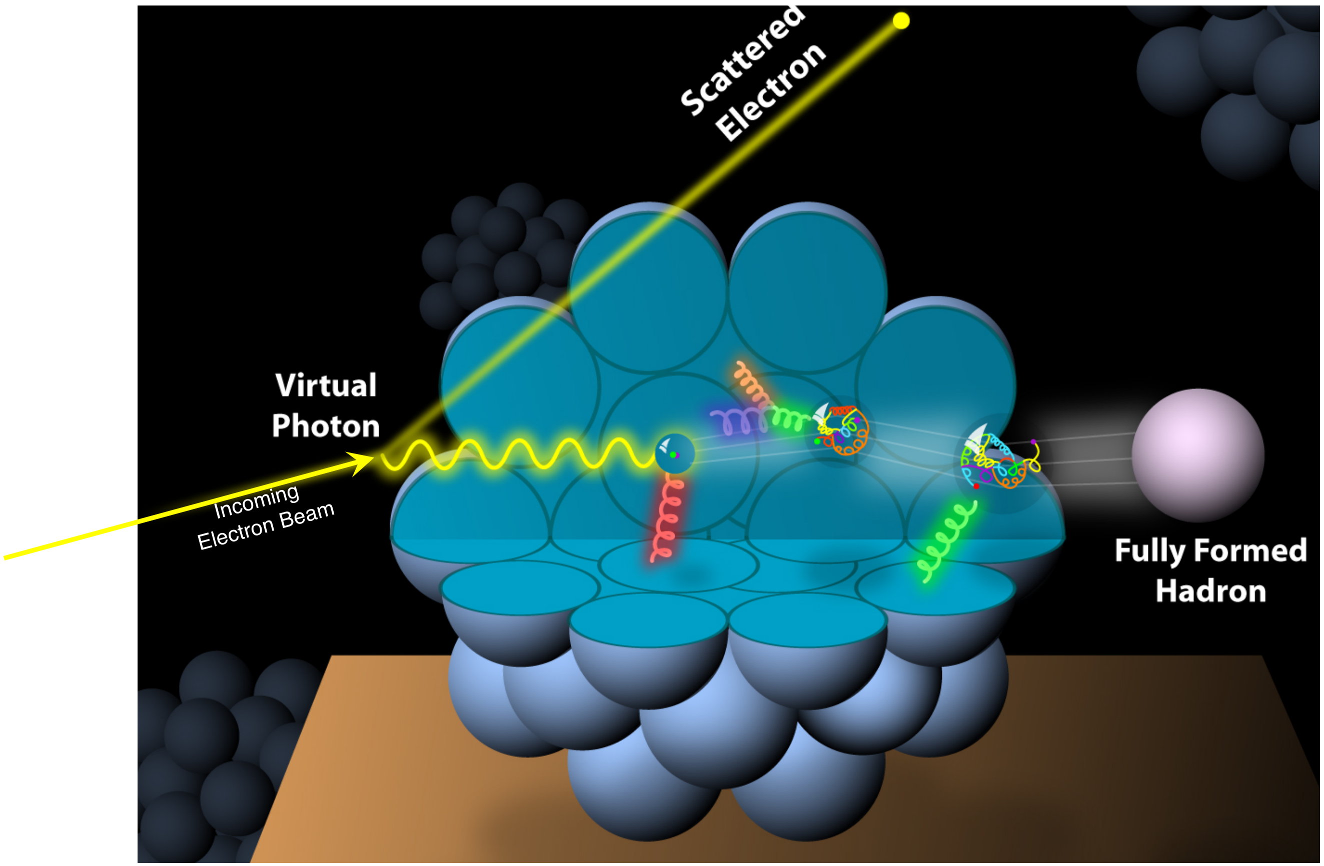
Two forward charged hadron detector regions:

- Region 1: Small dipole covering scattering angles from 0.5 up to a few degrees (before quads)
- Region 2: Far forward, up to one degree, for particles passing through (large aperture) accelerator quads. Use second dipole for precision measurement. (Hi Res)

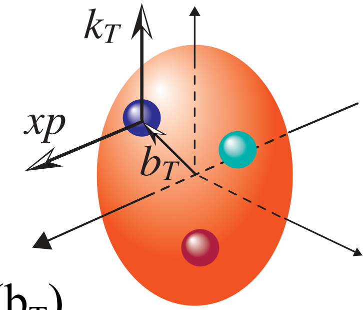




And What about nuclei?



Imaging the gluons in nuclei

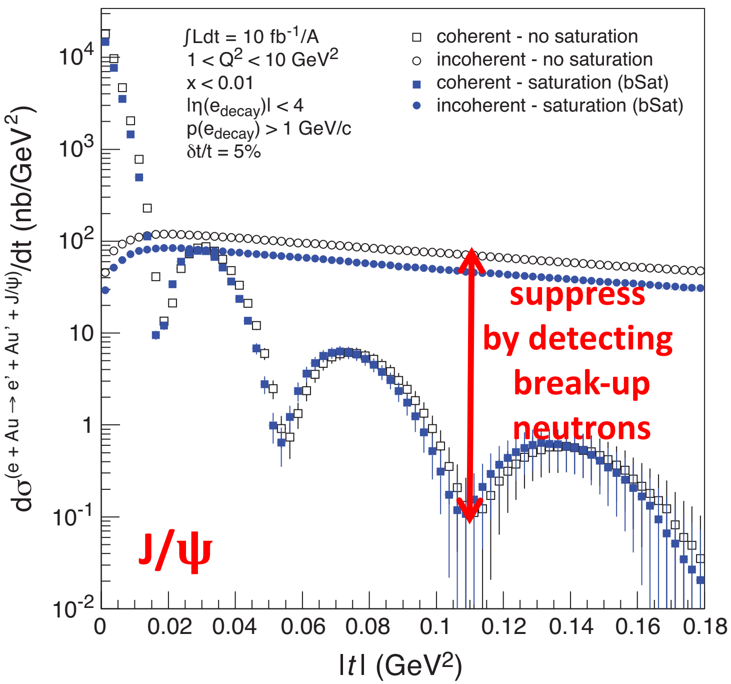


Diffractive physics in eA

→ Measure spatial gluon distribution in nuclei

→ Reaction: e + Au → e′ + Au′ + J/ψ, φ, ρ

→ Momentum transfer t = $|p_{Au} - p_{Au'}|^2$



Physics requires forward scattered nucleus needs to stay intact

→ Veto breakup through neutron detection

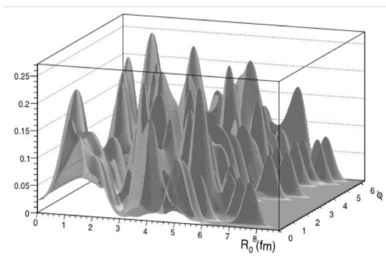
Hot topic:

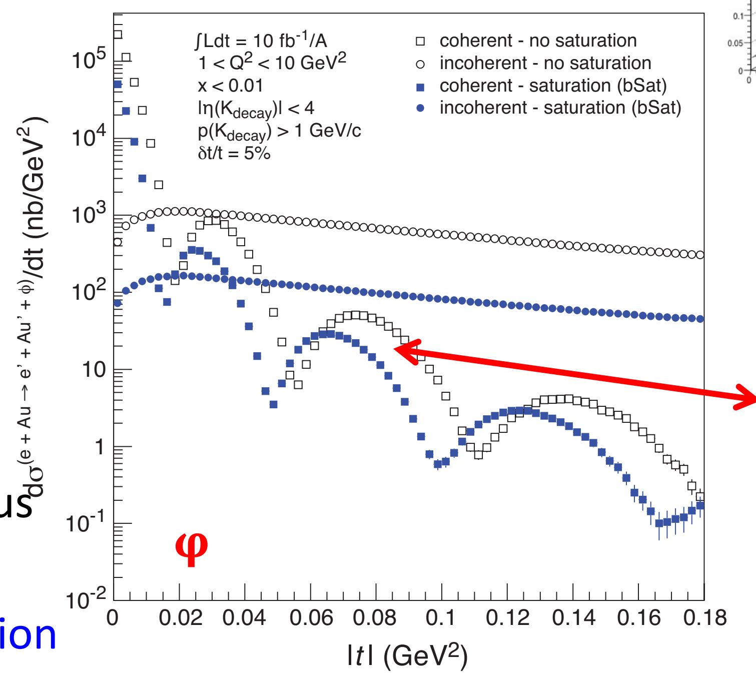
- ➤ Lumpiness of source?
- ➤ Just Wood-Saxon+nucleon g(b_T)

❑ coherent part probes "shape of black disc"

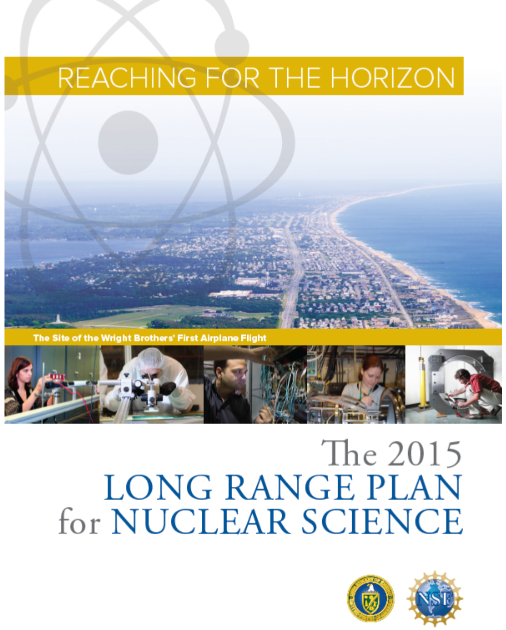
❑ incoherent part (large t) sensitive to "lumpiness" of the source [= proton] (fluctuations, hot spots, ...)

possible Source distribution with b_T^g = 2 GeV^{-2}





Sensitive to saturation effects!



The EIC project status

The EIC received in the 2015 Long Range Planning of the American National Science Advisory Committee (NSAC) the following recommendation

"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB"

http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

The National Academy of Science (& Engineering & Arts) in July 2018 unanimously concluded that an EIC will be: *"... a unique facility in the world that would answer science questions that are compelling, fundamental, and timely, and help maintain U.S. scientific leadership in nuclear physics*".

Following these recommendation we would expect DOE to launch its Critical Decision (CD) process...

- CD0 (possibly soon)
- CD1: site selection (possibly ~> a couple of years after CD0)
- CD3: start of construction (possibly within ~three years after CD1)

EIC is an International enterprise!

Currently ~807 members from 171 institutions, 30 countries, 7 world regions

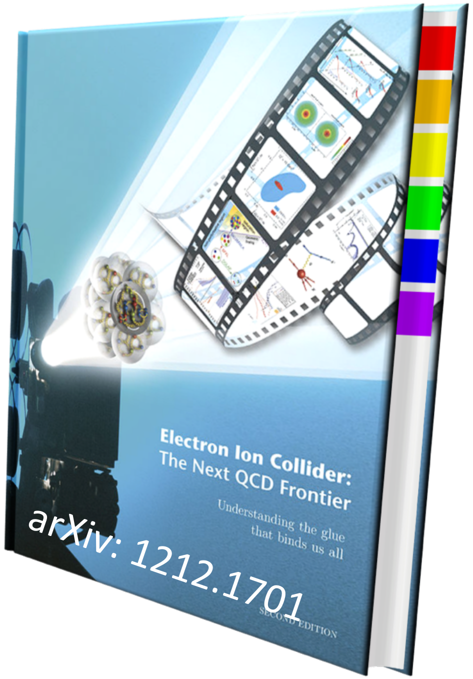
USA: 47% Europe: 28% Asia: 19% → continuously growing! (B. Sorrow's talk for details)

Summary

We studied and quantified the capability of an EIC to provide high precision and fine binned DVCS and VMP measurements of both cross sections and asymmetries over a large phase-space. This opens an unprecedented possibility for

- **Accurate 2+1D imaging of the polarized and unpolarized quarks and gluons inside the hadrons, and their correlations**
- **Investigate the proton-spin decomposition puzzle (orbital angular momentum)**
- **Study of GPDs in nuclei (and possible gluon saturation effects)**

EIC science program will profoundly impact our understanding of nucleon structure and the glue

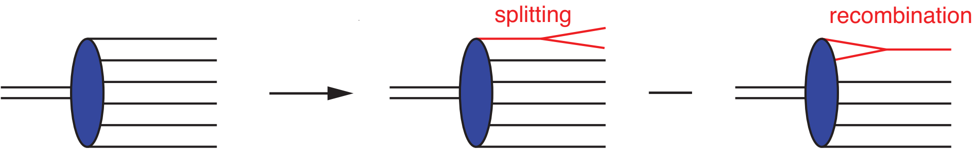


Back up

...and what we don't know!

- gluons distribution cannot rise forever
  → non-linear pQCD effects provide a natural way to tame this growth
  → characterized by the saturation scale $Q^2_s(x)$

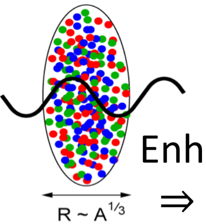
QCD: Dynamical balance between splitting and recombination



A new regime of QCD matter
→ Color Glass Condensate (CGC)

Hints from HERA, RHIC and LHC

need to test it unambiguously!



$$(Q_s^A)^2 \sim cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$

Enhancement of Q_S with A
⇒ saturation regime reached at significantly lower √s in nuclei

Au: ~200 times smaller effective *x* !

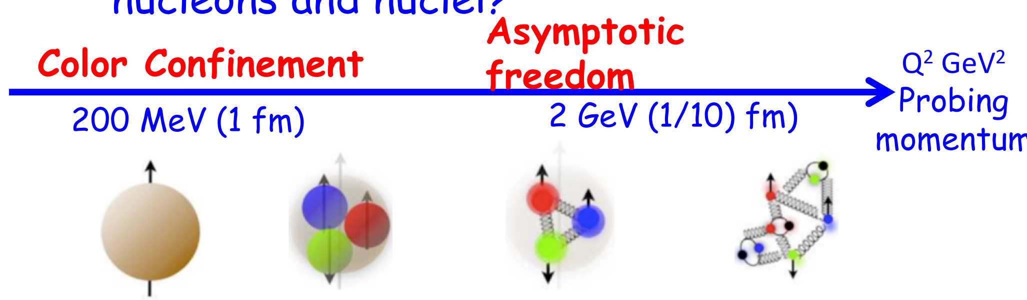
- Which correlations constitute the dynamics of the multi body system at low x

- How does quark and gluon dynamics generate the proton spin?

  It is more than the number $1/2\ \hbar$!
  → crucial interplay between the intrinsic properties and interactions of quarks and gluons

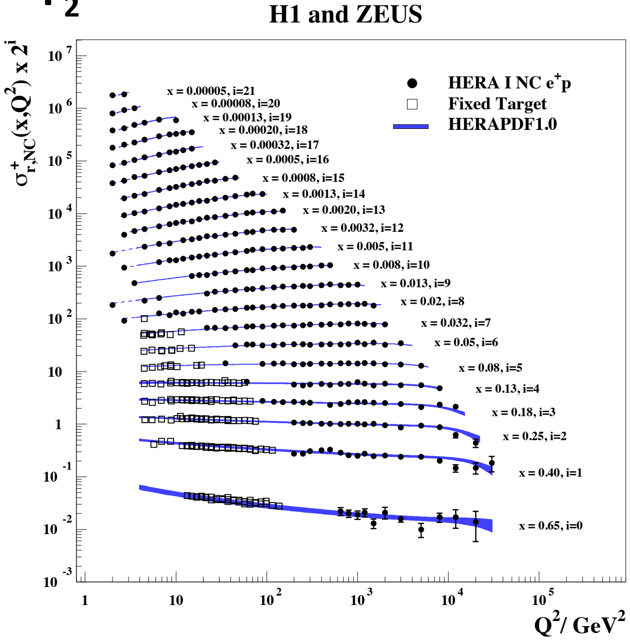
- How do hadrons emerge from a created quark or gluon?
  Neutralization of color - hadronization

- 2+1D Structure of nucleons and nuclei
  How does the glue bind quarks and itself into nucleons and nuclei?



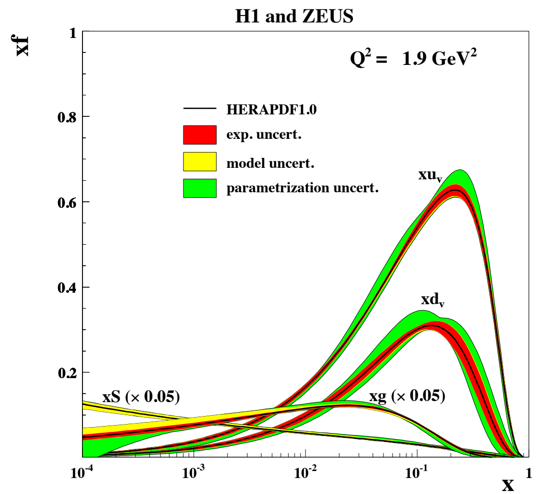
Structure functions

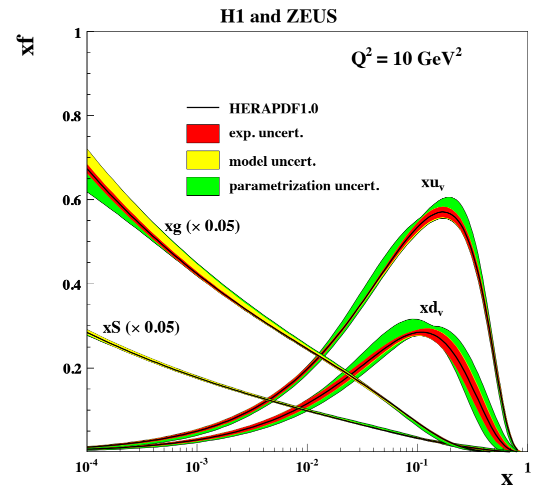
~F_2

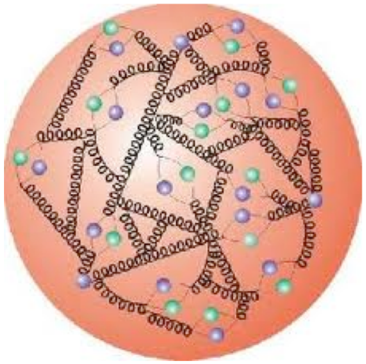


What we Know:

- ✓ Extensive program carried at HERA
- ✓ F_2 precisely measured in a large x range
- ✓ At low-x gluons dominate





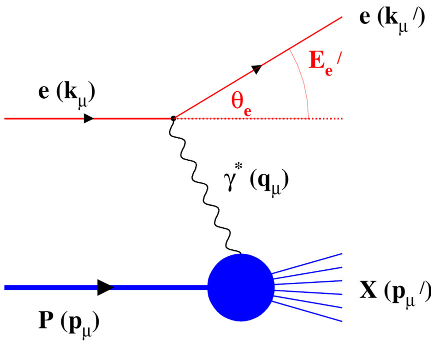


Differential cross section: $$\frac{d\sigma^{e^{\pm}p}}{dxdQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\sigma_r\left(x,Q^2\right)$$

Reduced cross section: $$\sigma_r\left(x,Q^2\right) = F_2\left(x,Q^2\right) - \frac{y^2}{Y^+}F_L\left(x,Q^2\right)$$

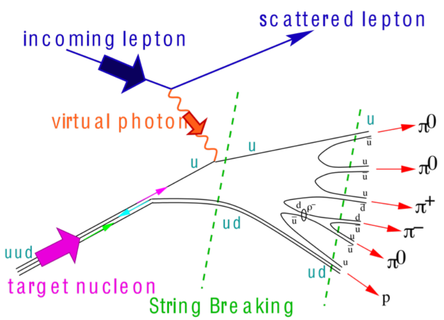
Summary of Detector Requirements

Detector requirements coming directly from the physics case!



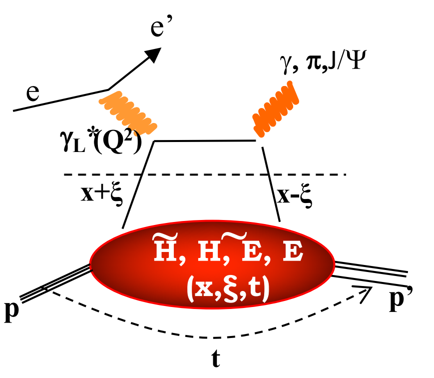
Inclusive Reactions in ep/eA:

- Physics: Structure Functions: g_1, F_2, F_L
- → Very good scattered electron ID
- → High energy and angular resolution of e' (defines kinematics $\{x,Q^2\}$)



Semi-inclusive Reactions in ep/eA:

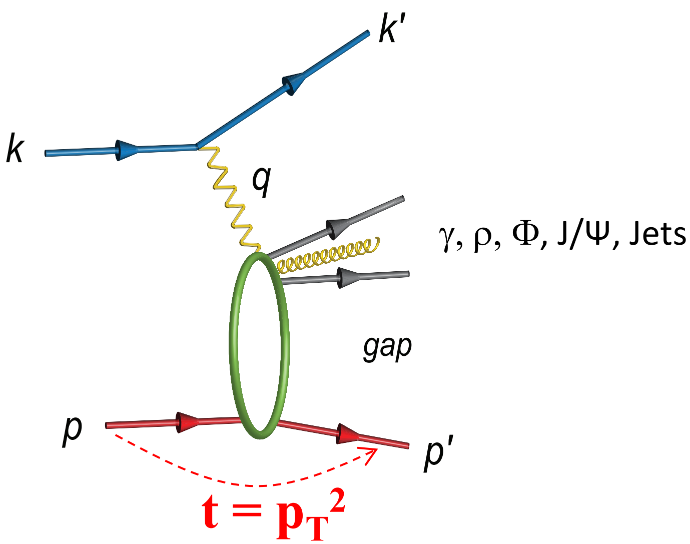
- Physics: TMDs, Helicity PDFs, FFs (with flavor separation); di-hadron correlations; Kaon asymmetries, cross sections; etc
- → Excellent hadron ID: $p^{\pm}$,$K^{\pm}$,$\pi^{\pm}$ separation over a wide $\{p, \eta\}$ range
- → Full Φ-coverage around γ^*, wide p_T coverage (TMDs)
- → Excellent vertex resolution (Charm, Bottom separation)



Exclusive Reactions in ep/eA:

- Physics: DVCS, exclusive VM production (GPDs; parton imaging in b_T)
- → Exclusivity (large rapidity coverage; reconstruction of all particles in a given event)
- → High resolution, ~100% acceptance, wide coverage in *t* → Roman pots
- → (eA): veto nucleus breakup, determine impact parameter of collision
  → Sufficient acceptance for neutrons in ZDC

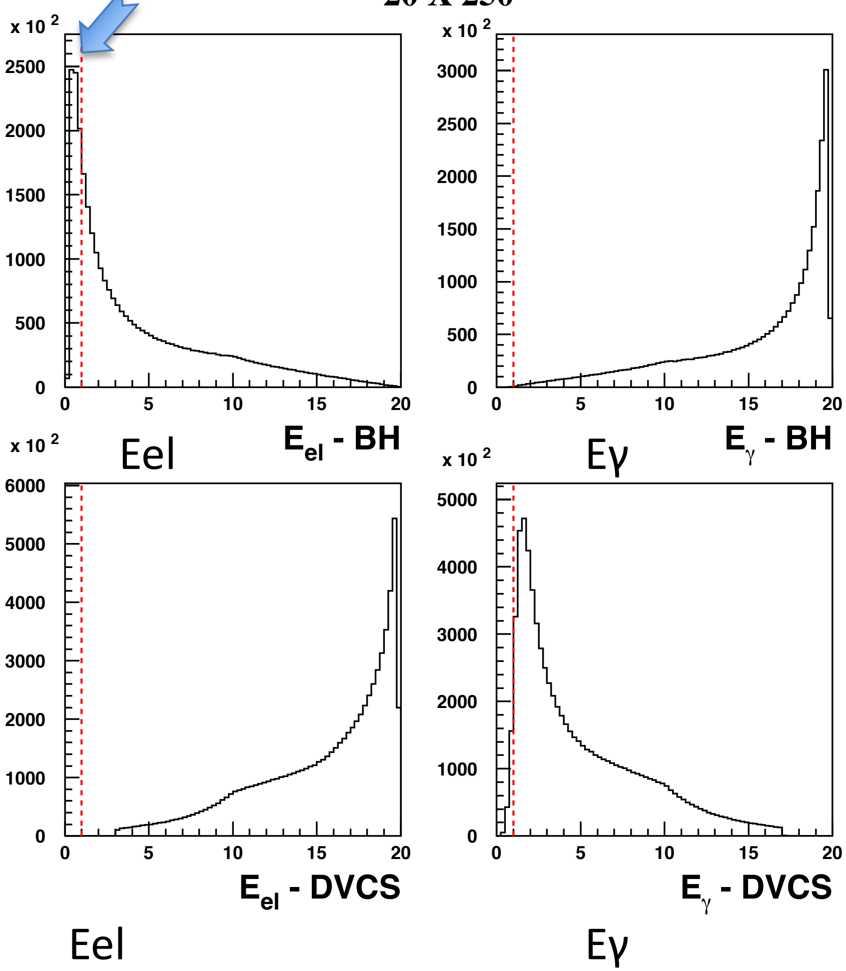
Detector Requirements for Exclusive Reactions in ep/eA



- Exclusivity criteria:
  - eA: large rapidity coverage → rapidity gap events
    - HCal for $1<\eta<4.5$ (ballpark ~50%/√E)
  - ep: reconstruction of all particles in event
    - wide coverage in t ($=p_T^2$) → Roman pots
- eA: large acceptance for neutrons from nucleus break-up
  - Zero Degree Calorimeter
    - veto nucleus breakup
    - determine impact parameter of collision

BH suppression

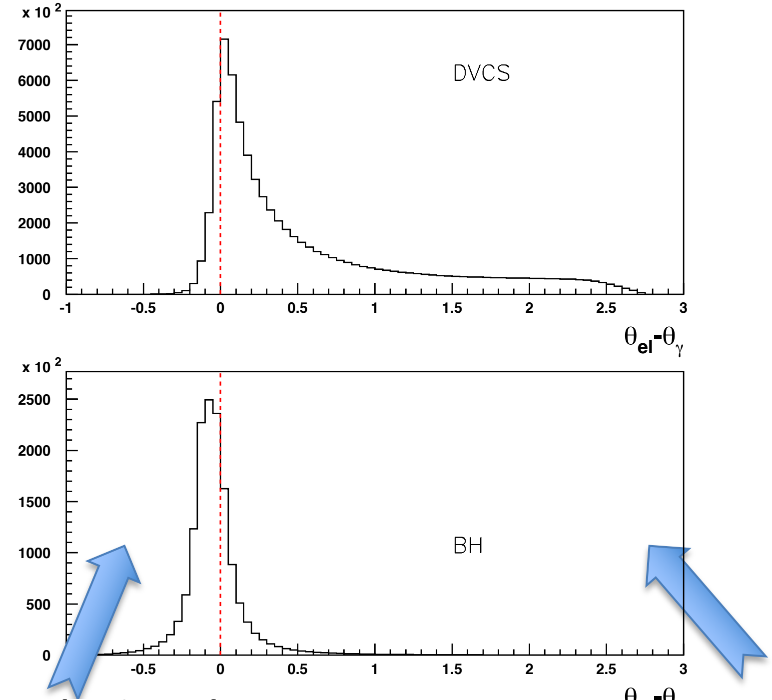
20 X 250



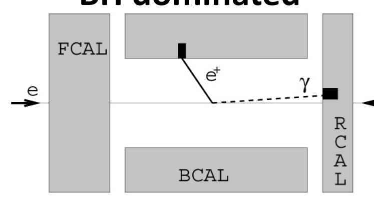
BH electron has very low energy (often below 1 GeV)

Important: em Cal must discriminate clusters above noise down to 1 GeV

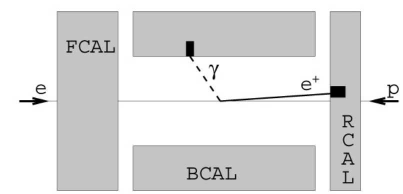
20 X 250



BH dominated



BH and DVCS

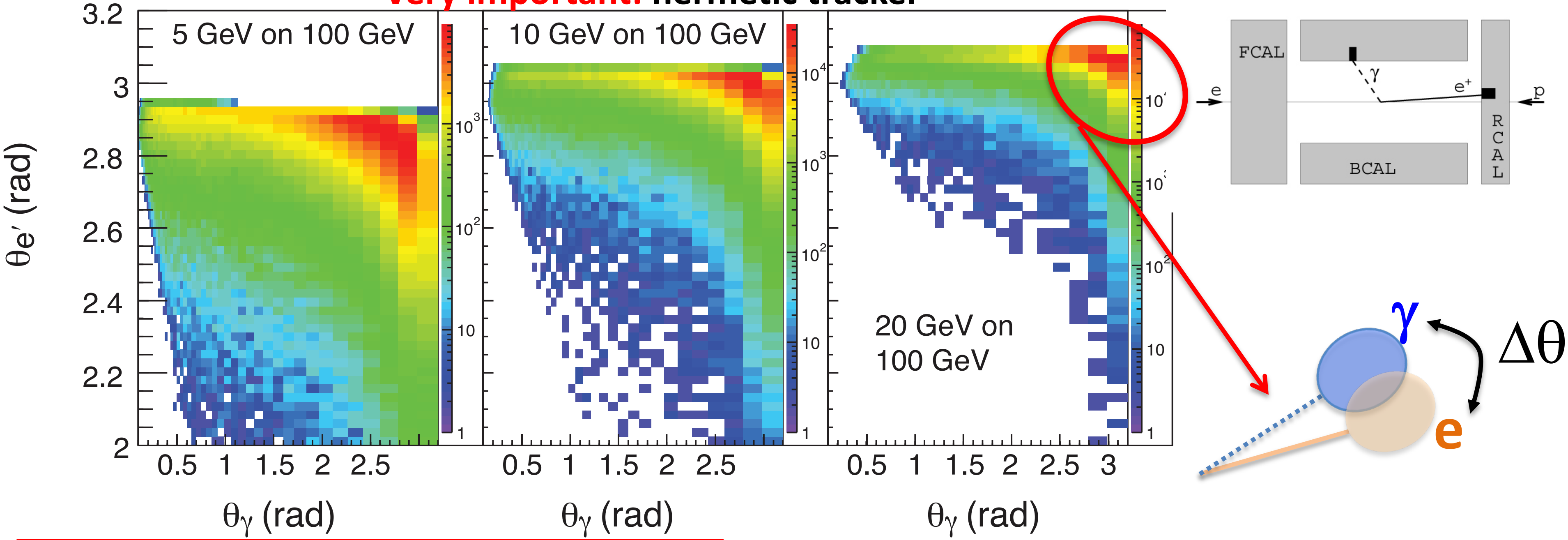


DVCS: most of the γ are less "rear" than e
(θel-θγ) > 0 → rejects most of the BH

cuts keep BH below 60% of the sample even at large y > 0.5 – at high energies

DVCS – clusters separation in rapidity

Very important: hermetic tracker



N.B. - Need for a emCAL with a very fine granularity, to distinguish clusters down to Δθ=1 deg

↓

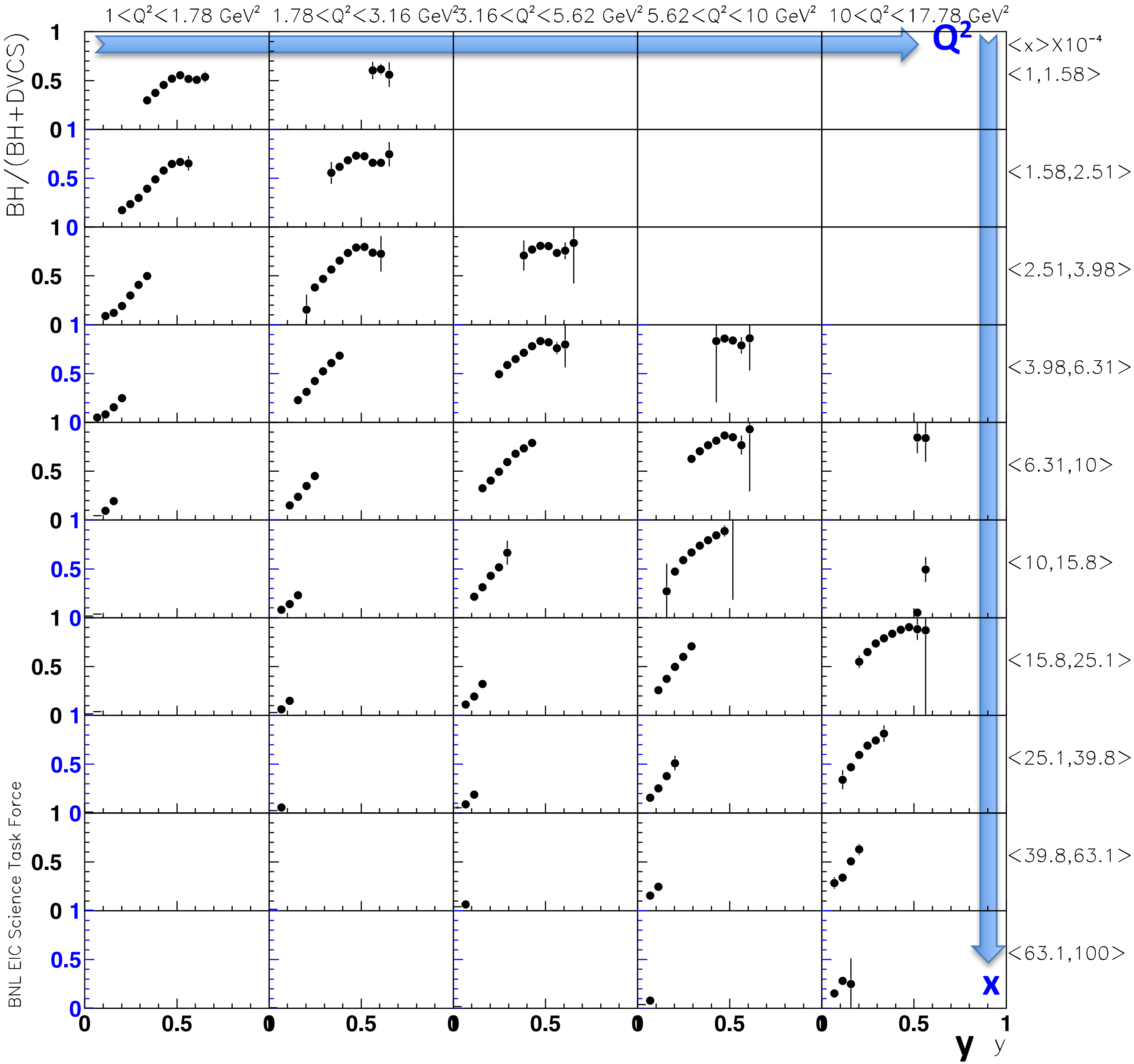
This is also important for Δϕ calculation in asymmetries measurement an for BH rejection in the xsec measurement

N.B. – when electron lies at a very small angle its track can be missing

↓

A pre-shower calorimeter needed to control background from $\pi^0 \rightarrow \gamma\gamma$

20 X 250



BH fraction

cuts keep BH below 60% of the sample at large y > 0.5

20 x 250 GeV^2

BH subtraction will be not an issue for y<0.6

BH subtraction will be relevant at lower energies and large y, in some of the x-Q^2 bin

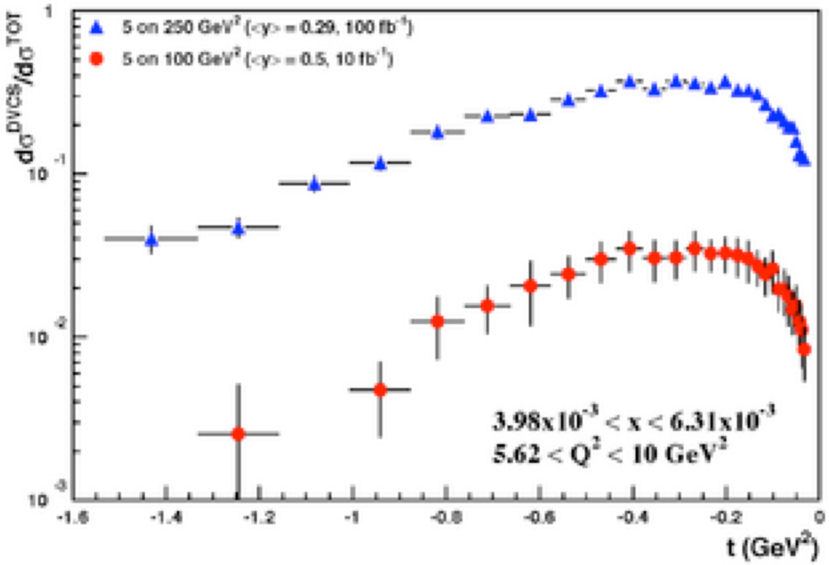
BUT…

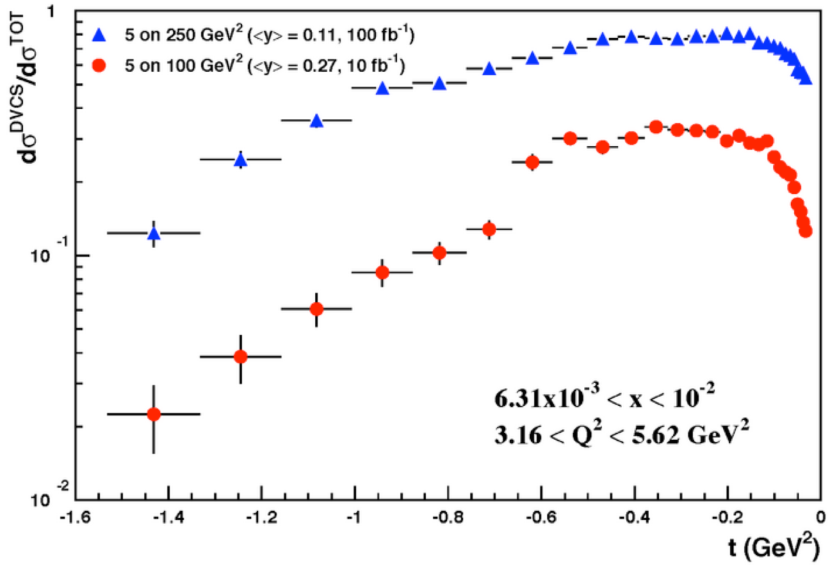
higher-lower √s kin. overlapping:
x-sec. measurements at a higher √s at low-y can cross-check the BH subtraction made at lower √s

Rosenbluth separation

$$d\sigma = \mathrm{d}\sigma_{DVCS} + \mathrm{d}\sigma_{BH} + \mathrm{d}\sigma_{INT}$$

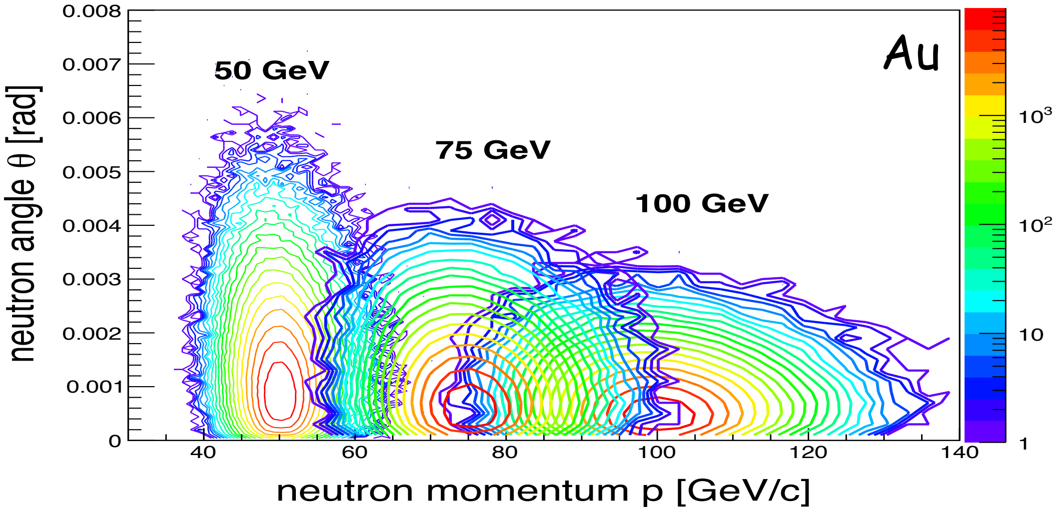
To separate DVCS from BH even at lower energies, we need a Rosenbluth separation of the electroproduction cross section into its parts





- The statistical uncertainties include all the selection criteria to suppress the BH
- exponential |t|-dependence assumed

Forward scattered neutrons



Requirements:

- Need at +/- 4 mrad beam element free cone before the zero degree calorimeter to detect the breakup neutrons
- Neutrons are also critical to reconstruct collisions geometry

L. Zheng, ECA, J-H. Lee arXiv:1407.8055

→ precision neutron energy reconstruction → transverse size of **ZDC**

E.C. Aschenauer