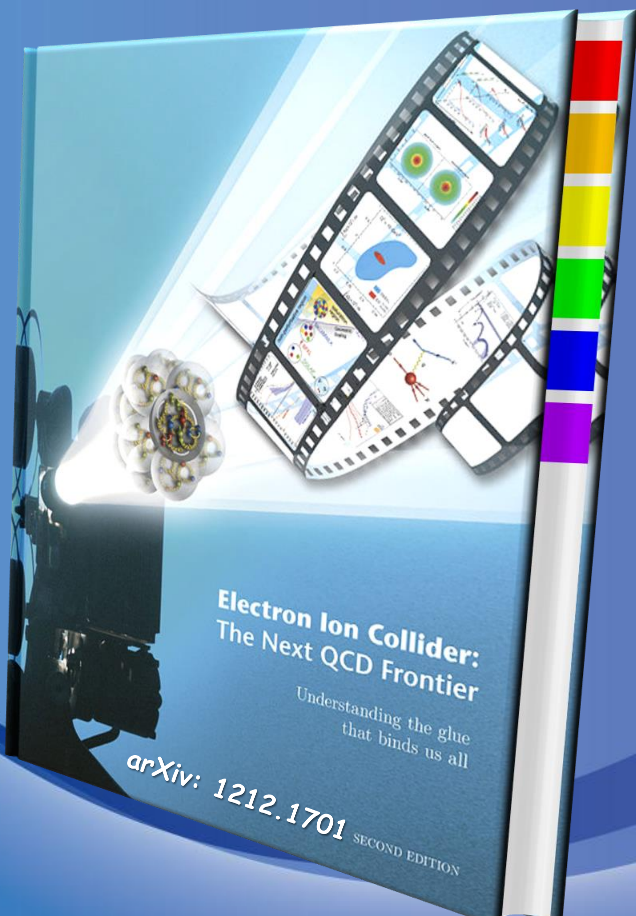
EIC PHYSICS AND CONNECTIONS TO UPC



Elke-Caroline Aschenauer

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

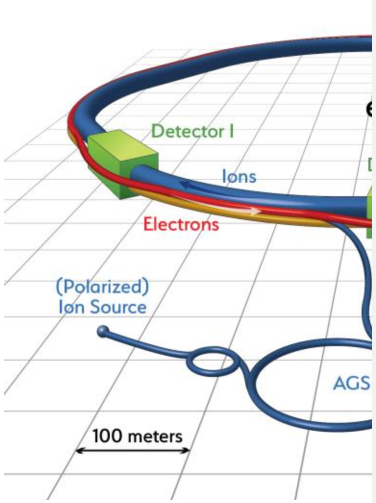
U.S. DEPARTMENT OF ENERGY | Office of Science

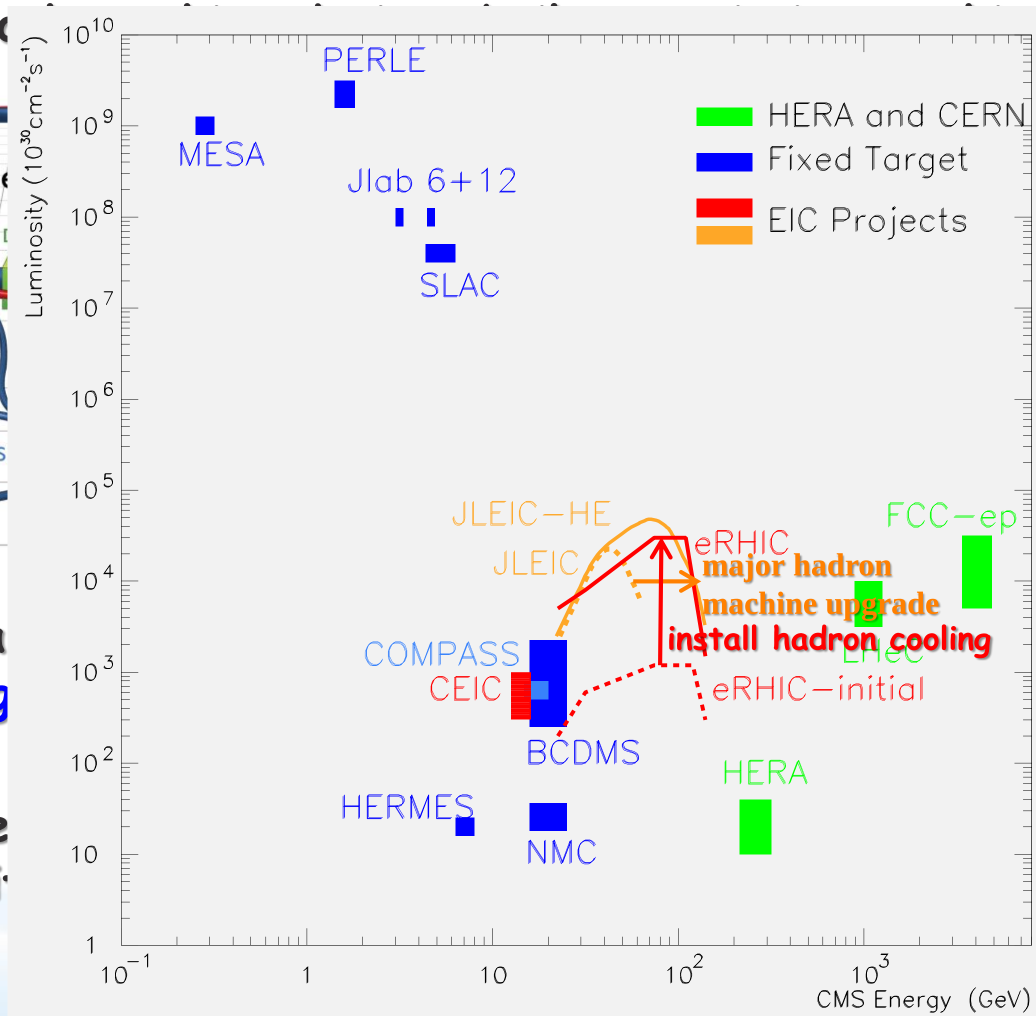
What is the EIC:

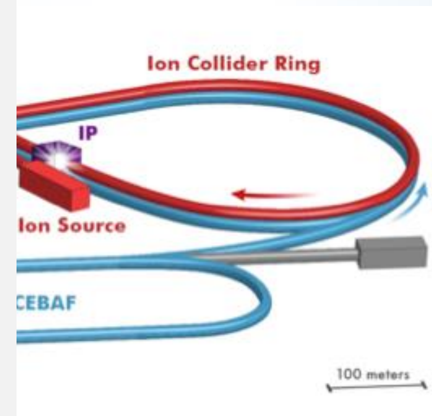
A high luminosity (10^{33} - 10^{34} $cm^{-2}s^{-1}$) polarized **e**lectron proton / **i**on **c**ollider with $\sqrt{s_{ep}}$ = 20 – 100 GeV upgradable to 140 GeV

eRHIC | JLEIC

Bo... es







full $\sqrt{s}$ range ava... to 10^{34} $cm^{-2}s^{-1}$

→ staging ... -of-mass energy

Both designs take ... nce for scattered protons from di... pectator tagging

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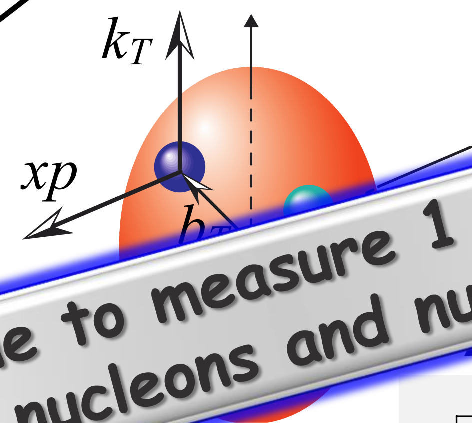
2+1 DIMENSIONAL IMAGING: QUARKS & GLUONS

Wigner function
$W(x, b_T, k_T)$

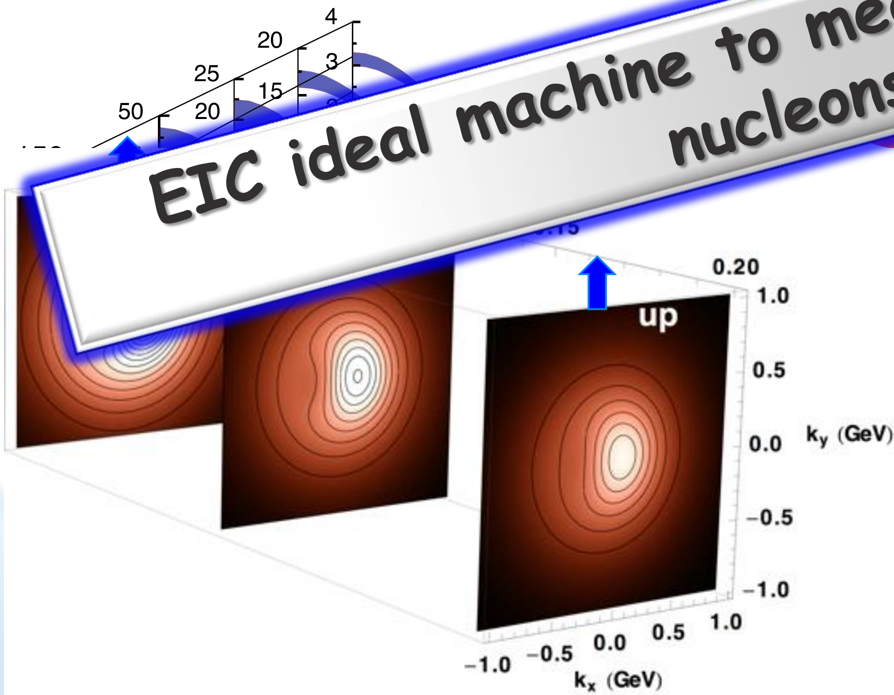
Momentum space $\int d^2 b_T$ $\int d^2 k_T$ *Coordinate space*

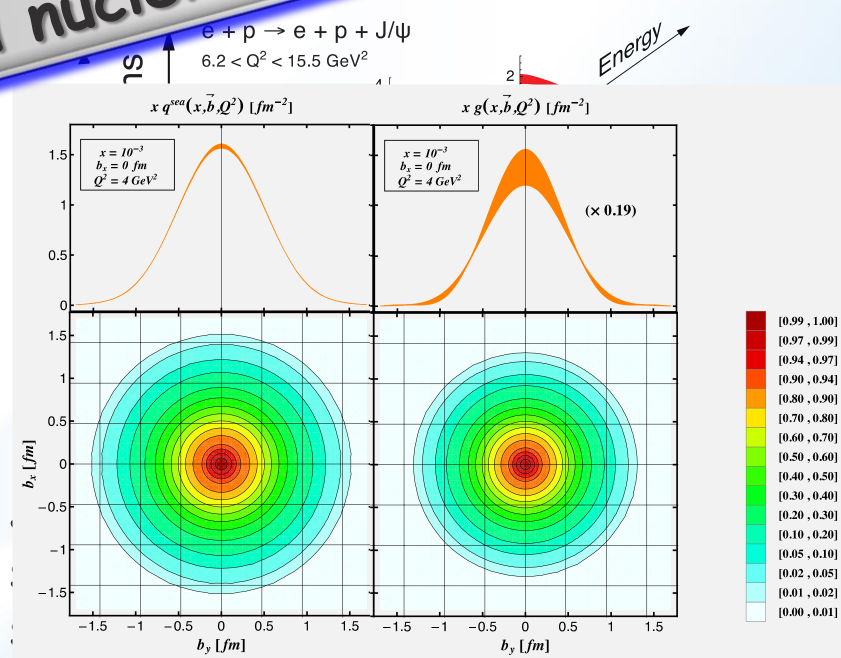
$f(x, k_T)$



Quarks **Gluons**

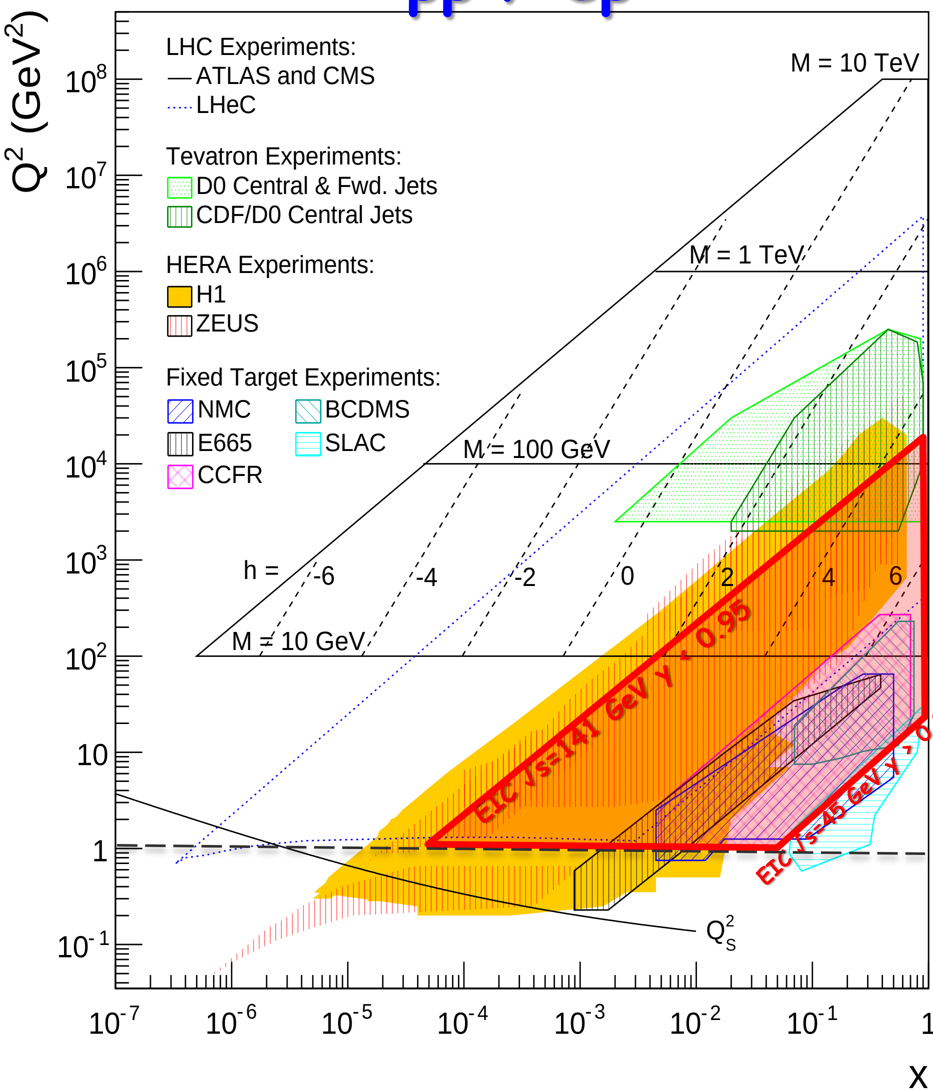
EIC ideal machine to measure 1 and 2d+1 PDFs for nucleons and nuclei



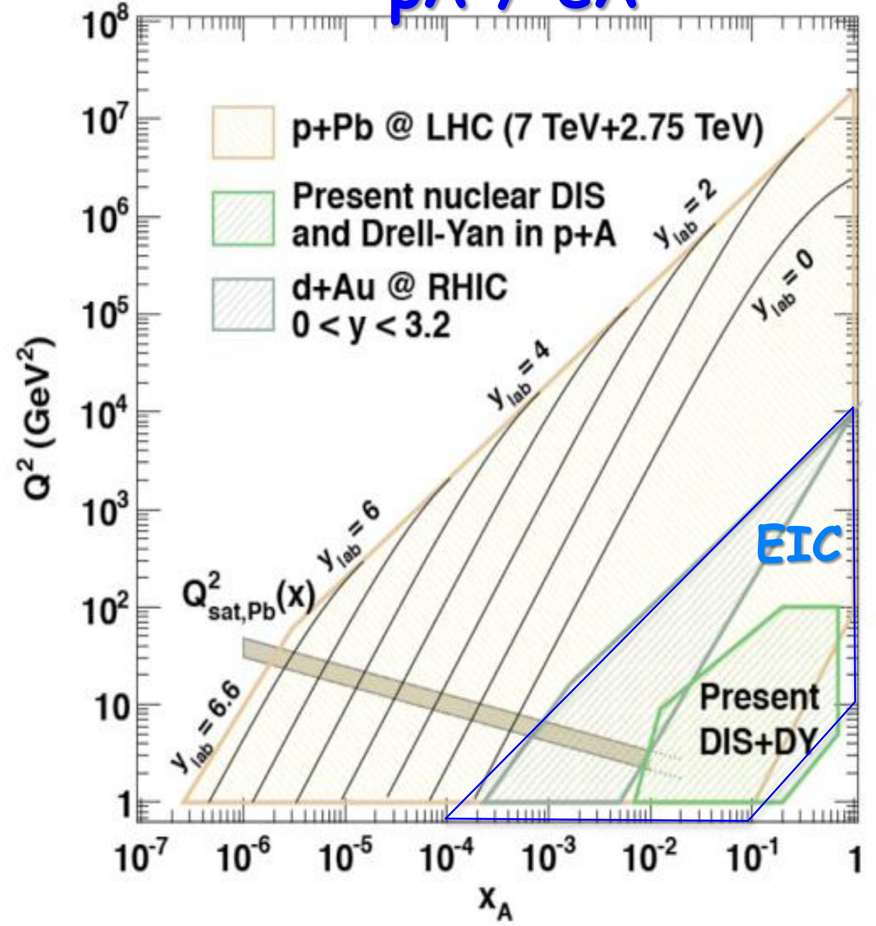


x-Q² COVERAGE FOR DIFFERENT FACILITIES

pp / ep

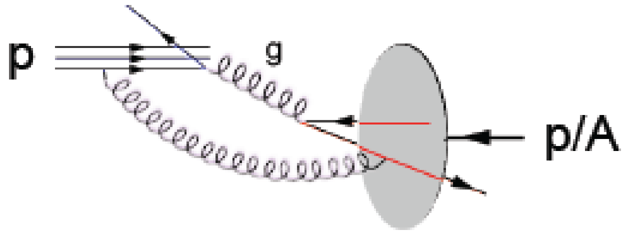


pA / eA



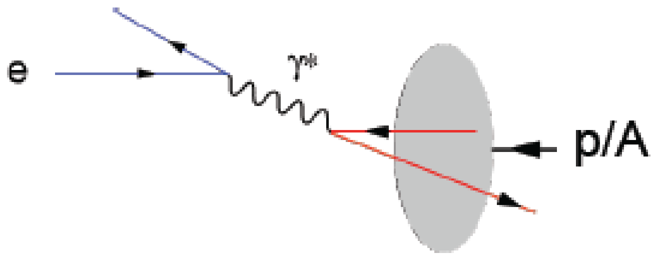
EIC'S PHYSICS IMPACT, COMPLEMENTARITY AND UNIQUENESS

Hadron-Hadron:



- probe has structure as complex as the "target"
- no clean access to parton kinematics
  $p_t \rightarrow x$; $p_t^2 \rightarrow Q^2 \rightarrow x\text{-}Q^2$ strongly correlated
  UPC: $M^2 \rightarrow Q^2$ can only be varied by VM
- limited access to spatial structure of nucleons and nuclei

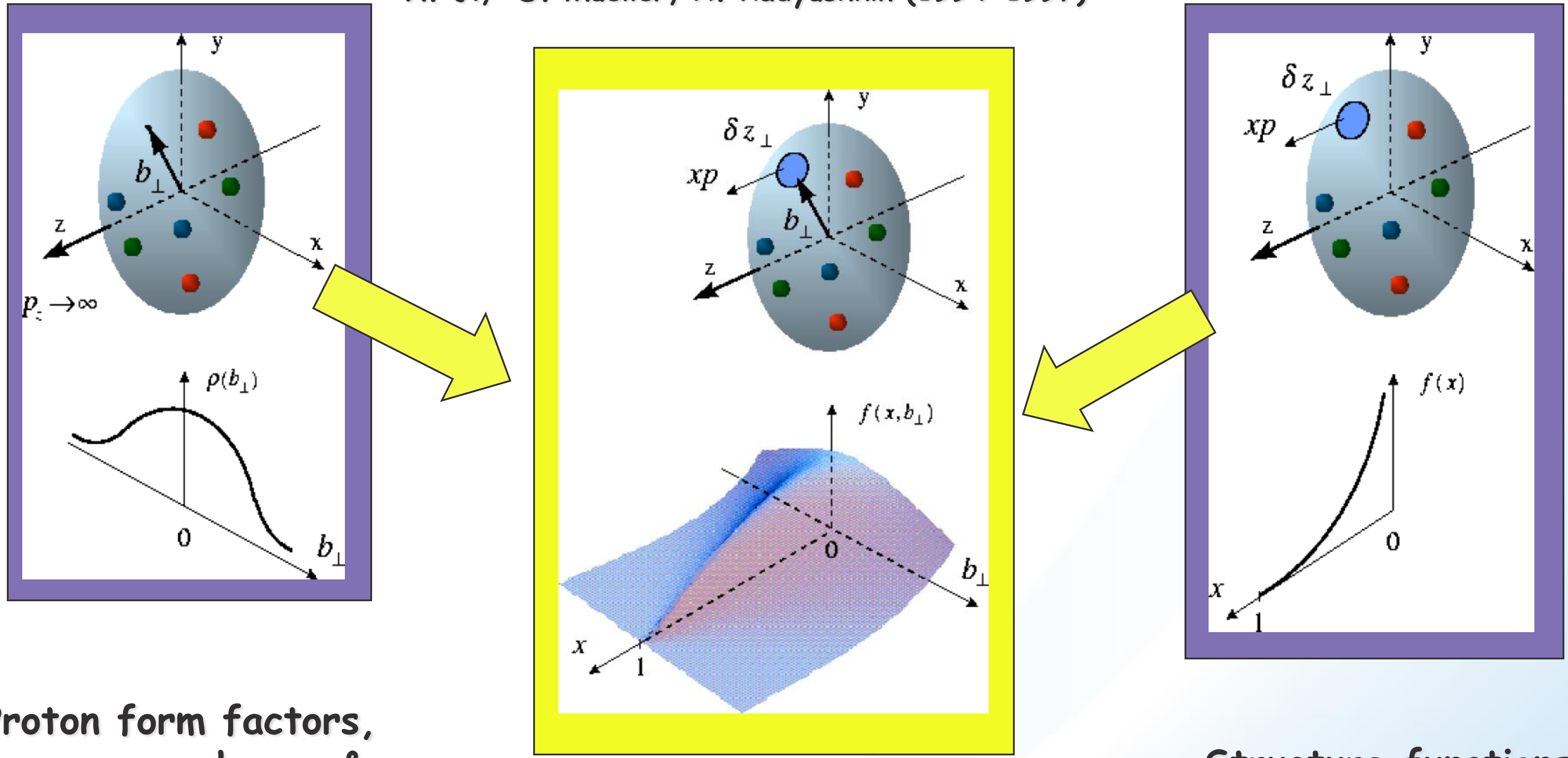
Electron-Hadron:



- Point-like probe → resolution
- High precision & access to partonic kinematics through scattered lepton → x, Q^2
- Interaction governed by colorless Photon
  → preserve the properties of partons in the nuclear wave function
- initial and final state effects can be cleanly disentangled

Generalized Parton Distributions

X. Ji, D. Mueller, A. Radyushkin (1994-1997)



Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

SMALL GPD PRIMER

the way to 3d imaging of the proton and access the orbital angular momentum L_q

Spin-Sum-Rule in PRF:

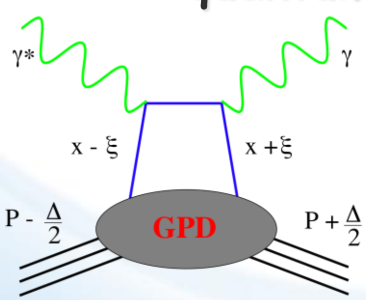
$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z \qquad J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^{q,g} + E^{q,g}\right)\right)_{t\to 0}$$

responsible for orbital angular momentum

How are GPDs characterized?

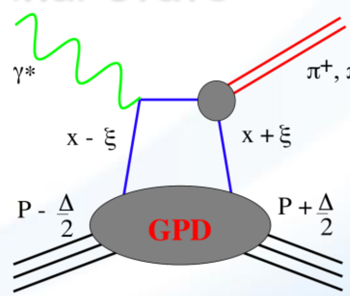
	unpolarized	polarized	
	$H^q(x,\xi,t)$	$\tilde{H}^q(x,\xi,t)$	conserve nucleon helicity $H^q(x,0,0) = q, \tilde{H}^q(x,0,0) = \Delta q$
	$E^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$	flip nucleon helicity not accessible in DIS

quantum numbers of final state $\Longrightarrow$ select different GPDs



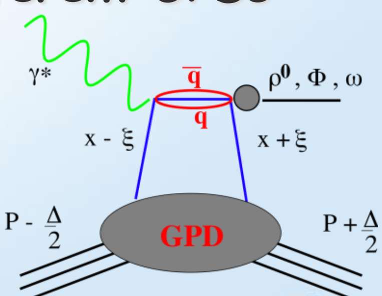
DVCS

$H^q \quad E^q \quad \tilde{H}^q \quad \tilde{E}^q$



pseudo-scaler mesons

$\tilde{H}^q, \tilde{E}^q$



vector mesons

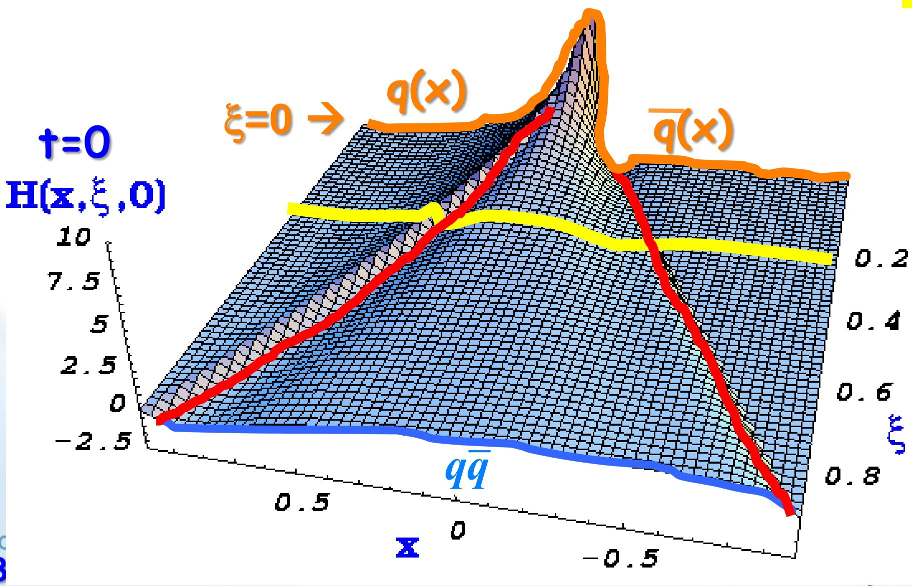
H^q, E^q

ACCESSING GPDS: SOME CAVEATS

$H(x,\xi,t)$ but only ξ and t accessible experimentally

- x is not accessible (integrated over):
  - apart from cross-over trajectory (x=ξ) GPDs not directly accessible: deconvolution needed ! (model dependent)
  - GPD moments cannot be directly revealed, extrapolations t → 0 are kind of model dependent

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim \boxed{P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx} - \boxed{i\pi H(\pm\xi,\xi,t)} + \ldots$$

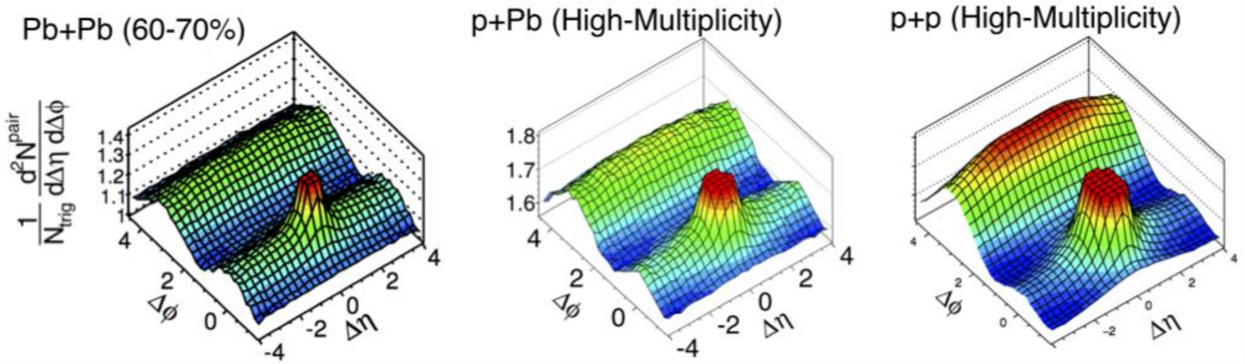


cross sections & beam-charge asymmetry ~ Re(T ^{DVCS})

beam or target-spin asymmetries ~ Im(T ^{DVCS})

PROTON STRUCTURE IMPORTANT FOR QGP IN SMALL SYSTEMS

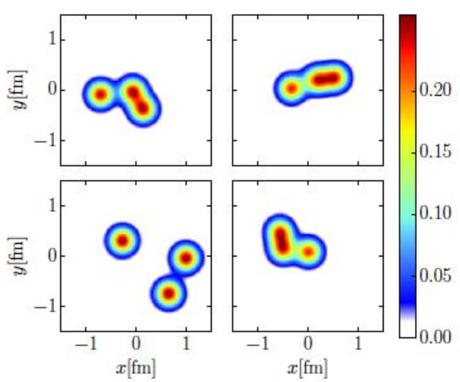
Collective phenomena seen in pA collisions, i.e. ATLAS 1409.792



H. Mäntysaari & B. Schenke
arXiv:1607.01711

In a hydro-picture (used in AA) fluctuations in the proton are crucial to understand the seen pA@LHC behaviors

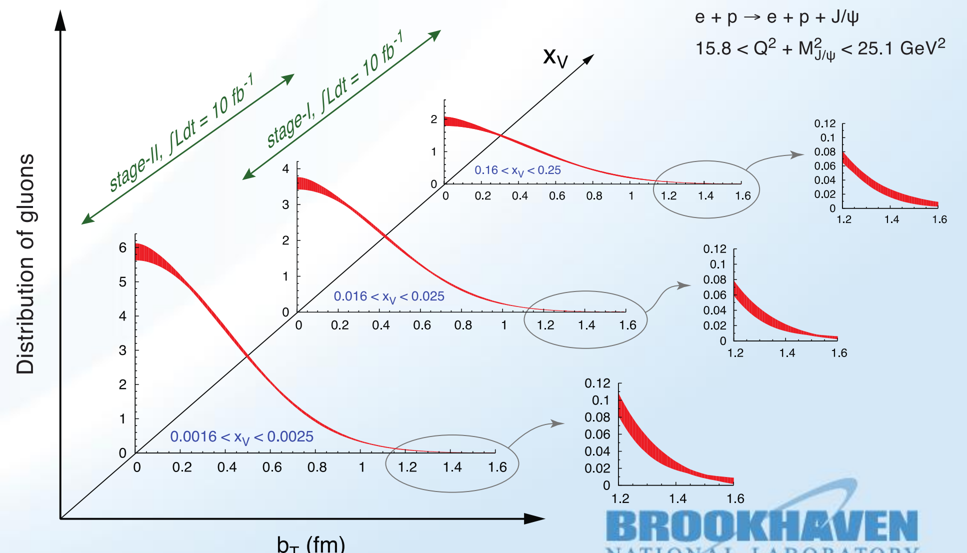
Examples of proton density profiles at x ~ 10^{-3}



(a) $B_{qc} = 3.3\ \mathrm{GeV}^{-2}, B_q = 0.7\ \mathrm{GeV}^{-2}$

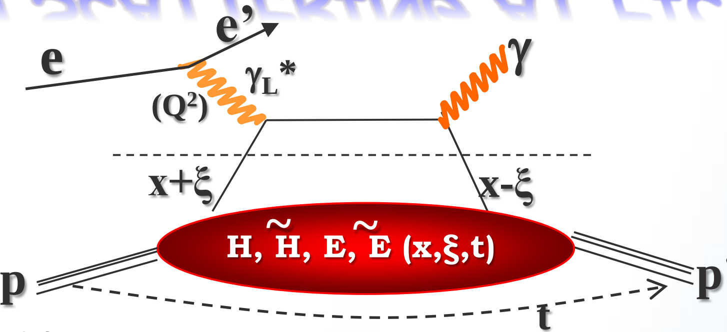
Study coherent and incoherent J/Ψ prod.

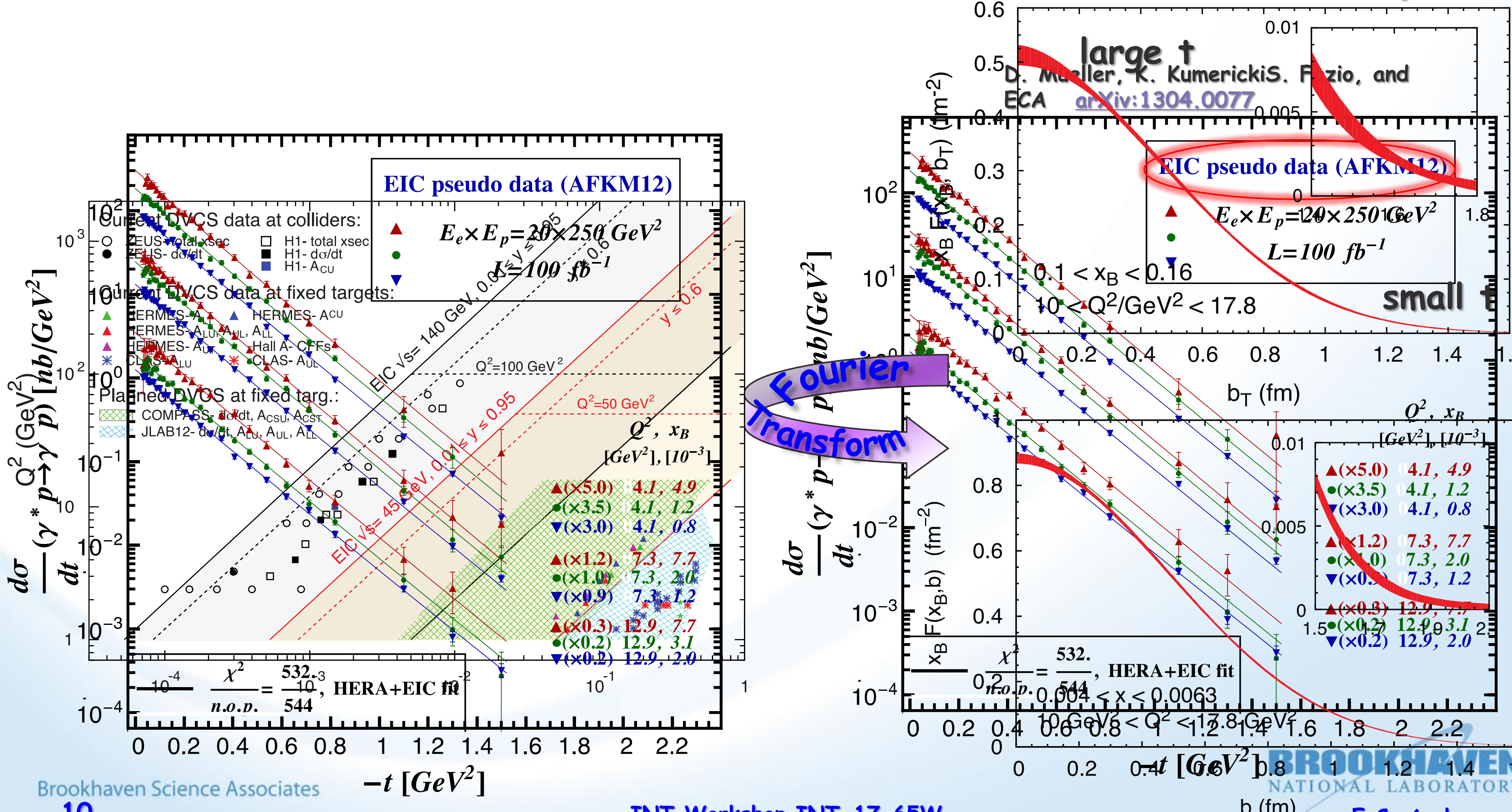
Only EIC can map out the spatial quark and gluon structure of the proton in x and Q^2



DEEPLY VIRTUAL COMPTON SCATTERING AT EIC

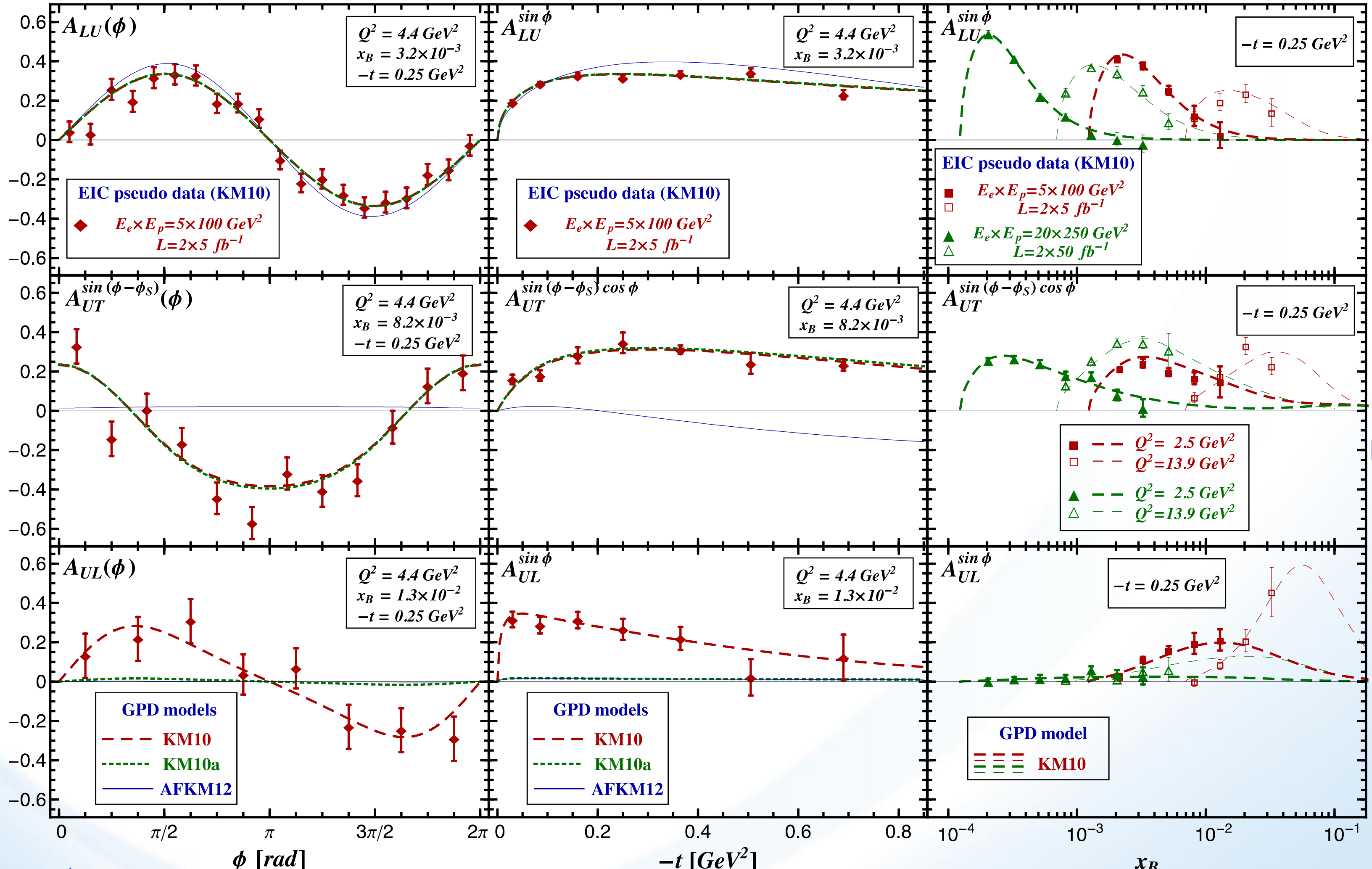
DVCS: Golden channel → theoretically clean
wide range of observables
(σ, A_{UT}, A_{LU}, A_{UL}, A_C)
to disentangle different GPDs





DISENTANGLE DIFFERENT GPDs

Vary electron and proton beam spin directions:



electron beam longitudinal polarised → H

proton beam transverse polarised → H,E

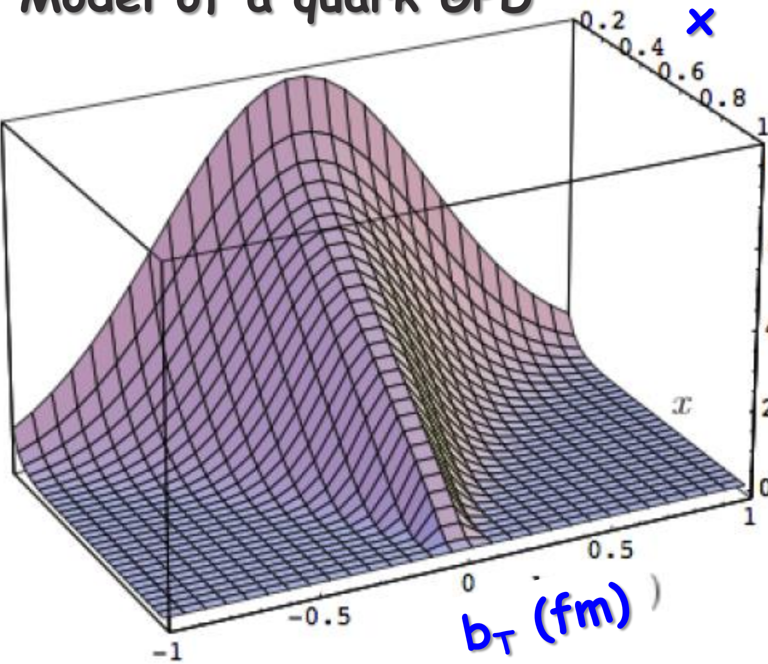
proton beam longitudinal polarised → $\tilde{H}$

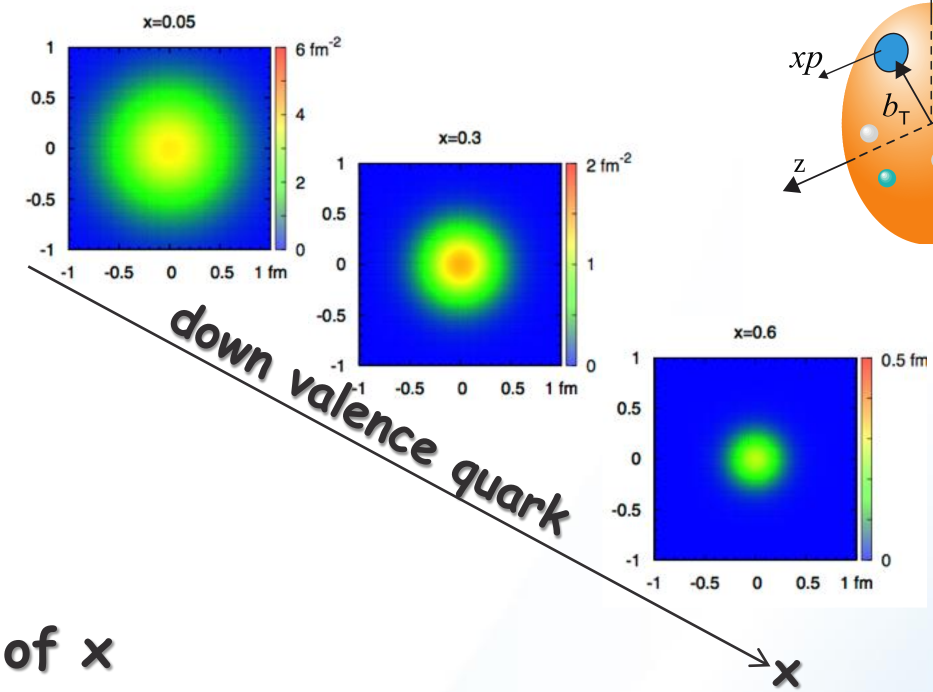
$\Delta\sigma_{UT}$

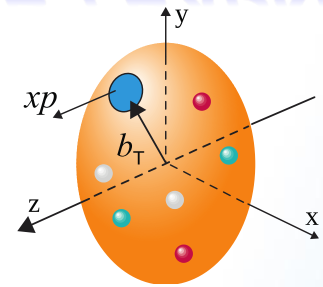
beam target

WHAT CAN WE LEARN

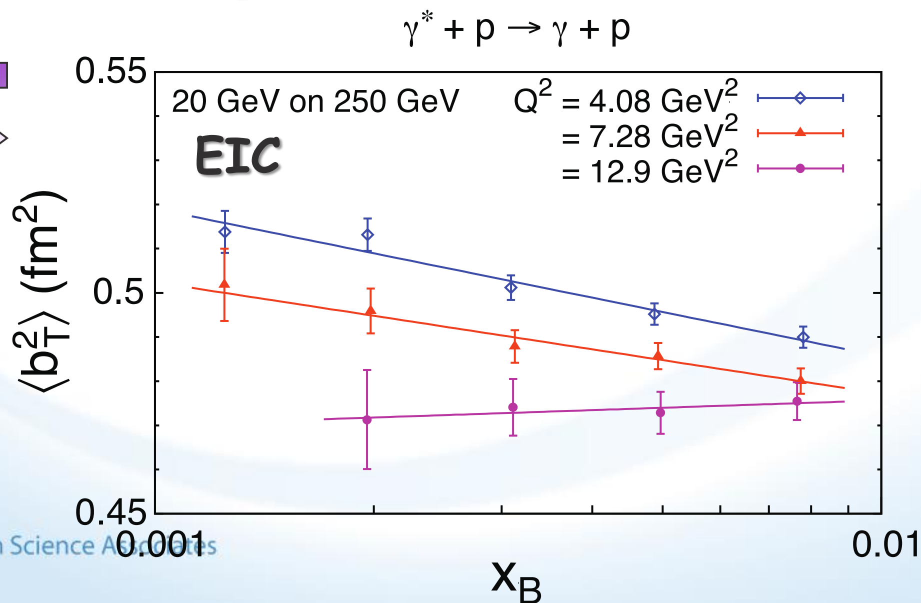
Model of a quark GPD







b_T decreasing as a function of x



Valence (high x) quarks at the center → small b_T

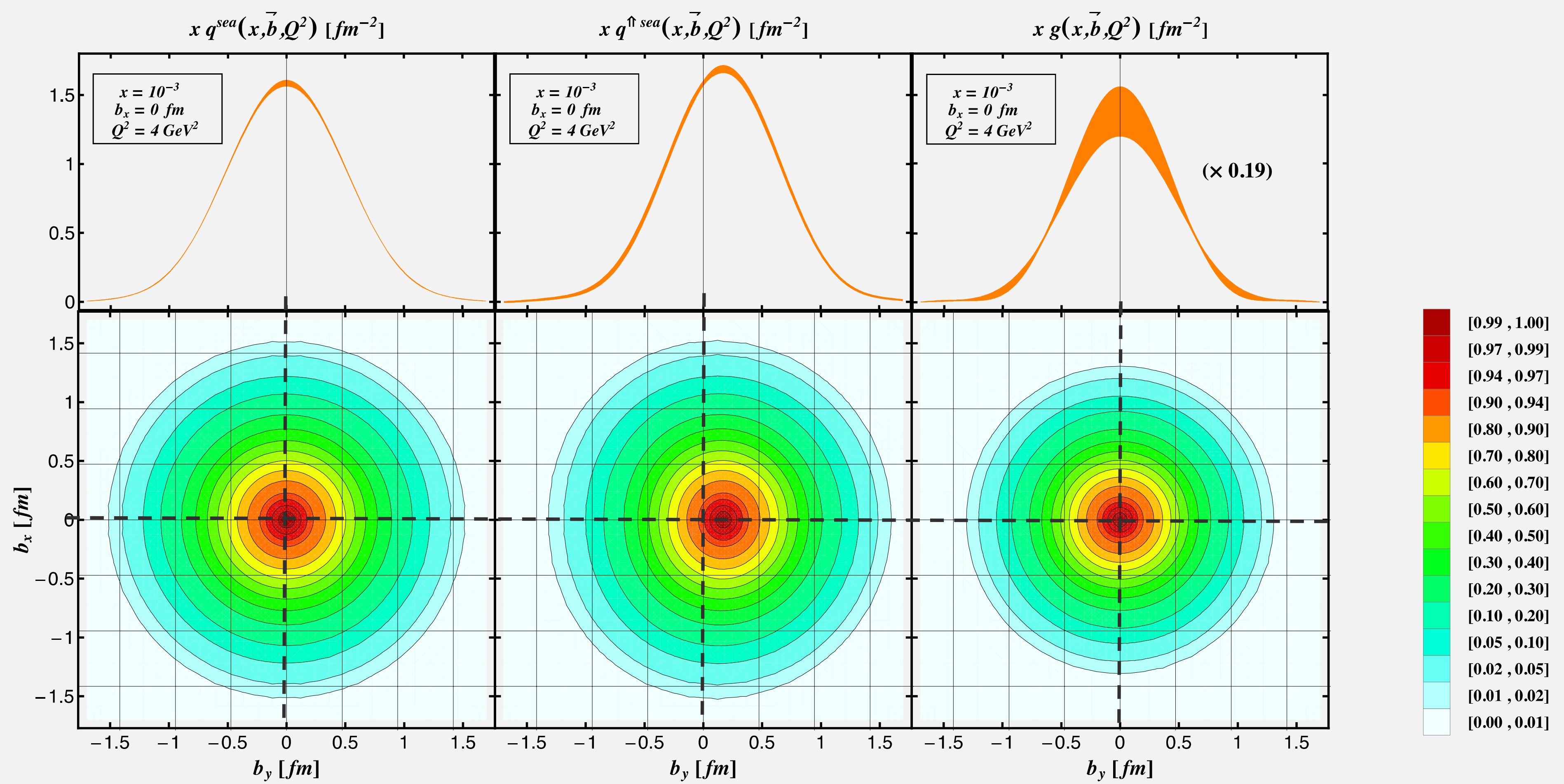
Sea (small x) quarks at the périphérie → high b_T ?

GLUONS ???

WHAT WILL WE LEARN ABOUT 2D+1 STRUCTURE OF THE PROTON

GPD H and E as function of t, x and Q^2 2d+1

arXiv:1304.0077

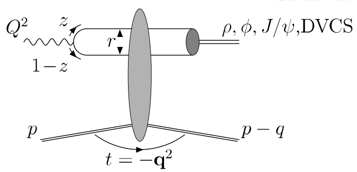


$-t$ [GeV^2]

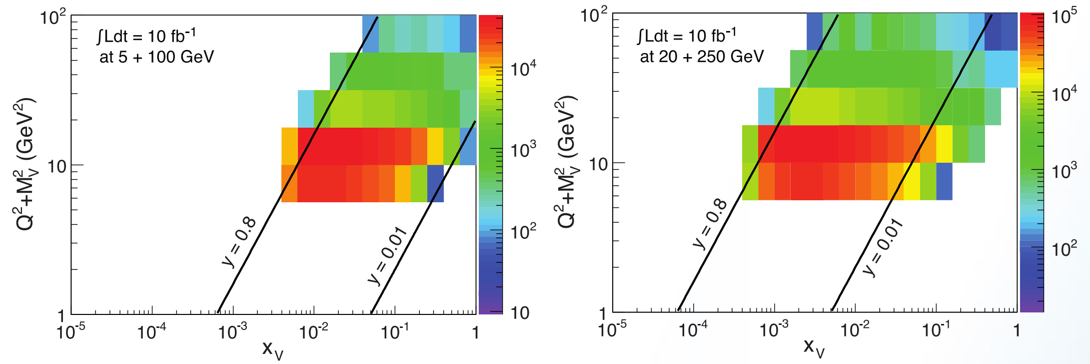
GPD H and E 2d+1 structure for sea-quarks and gluons

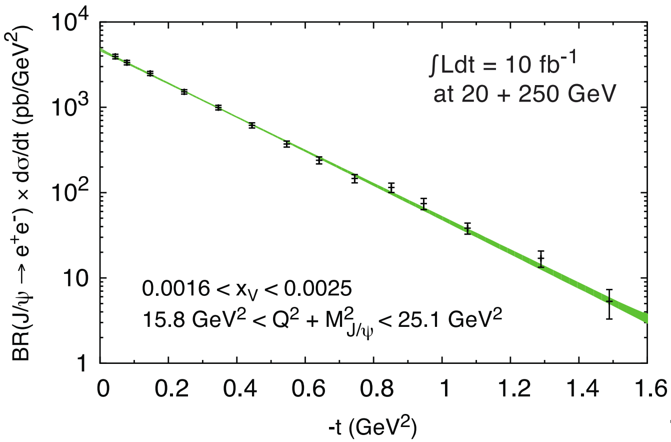
- Excellent reconstruction of H^{sea}, H^{sea} and good reconstruction of H^g (from $d\sigma/dt$)

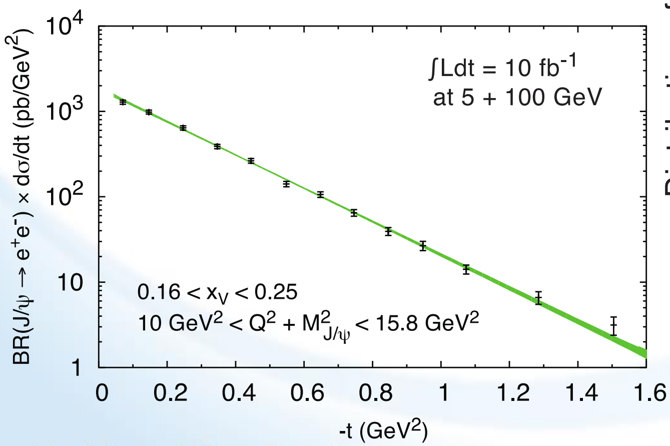
To improve imaging on gluons add J/ψ observables

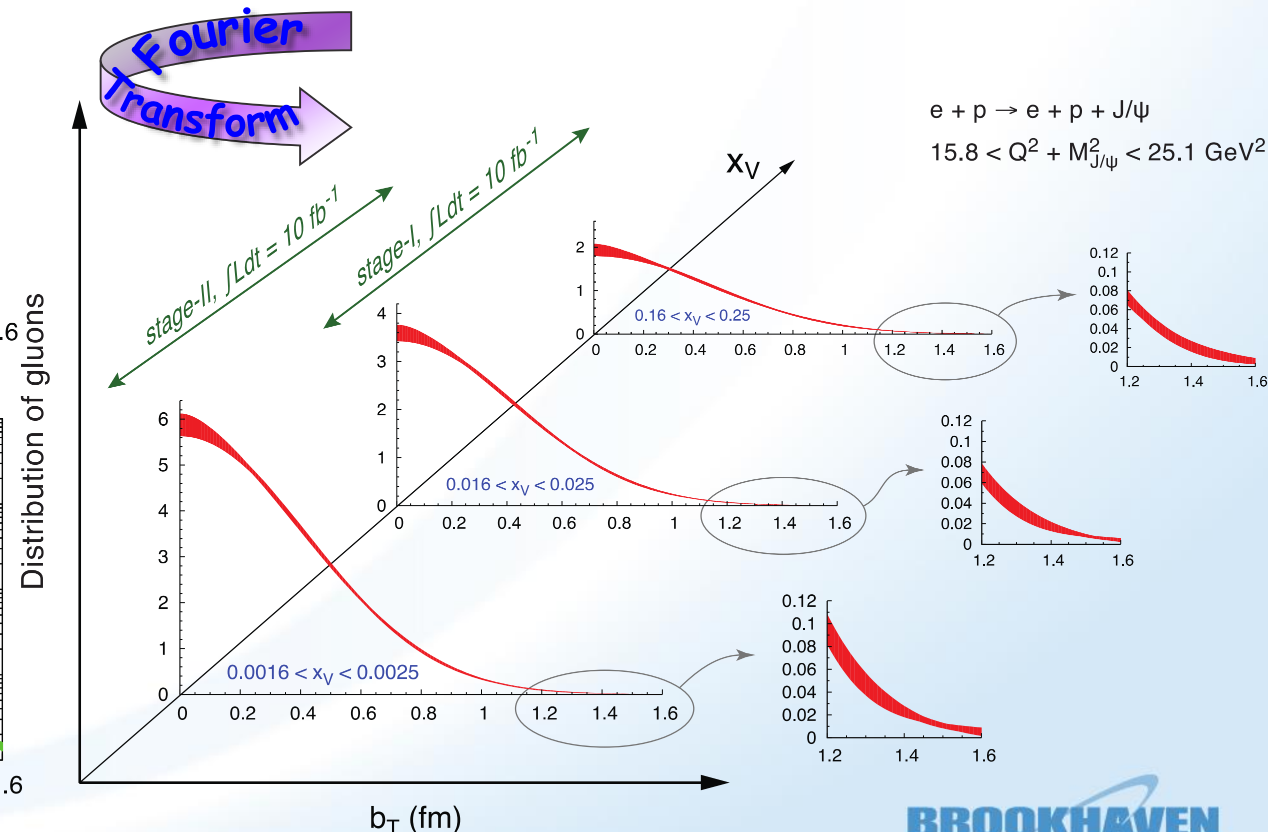


- cross section
- A_{UT}
- ….









GET A FIRST LOOK ON E^G

Remember:

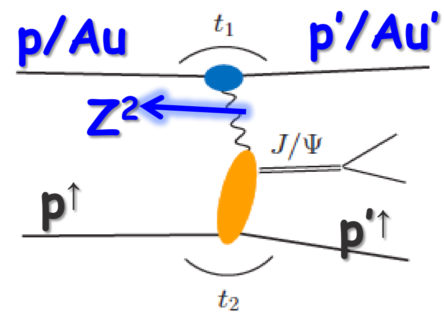
Spin-Sum-Rule in PRF:

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

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

responsible for orbital angular momentum

J/Ψ production in transversely polarized p↑Au / p↑p UPC
→ world wide only access to gluon GPD E



$$A_{UT}(t',t) \sim \frac{\sqrt{t_0 - t}}{m_p}\,\frac{\mathrm{Im}(E^* H)}{|H|} \qquad t = \frac{M^2_{J/\Psi}}{s}$$

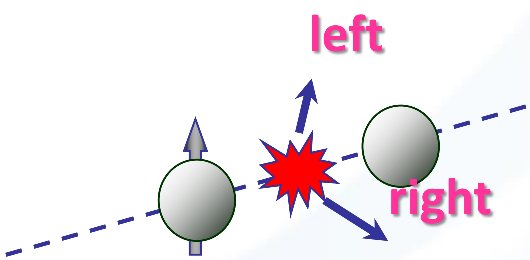
What is measured:

Single-spin transverse asym.

$$A_N \equiv \frac{1}{P_1}\,\frac{N_\uparrow/\mathcal{L}_\uparrow - N_\downarrow/\mathcal{L}_\downarrow}{N_\uparrow/\mathcal{L}_\uparrow + N_\downarrow/\mathcal{L}_\downarrow}$$

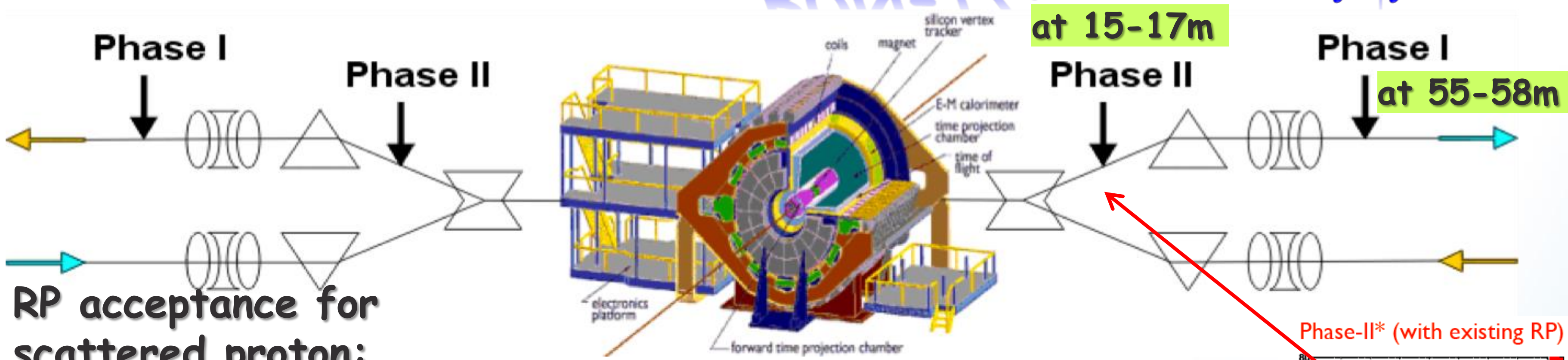
where ↑ (↓) are defined with respect to reaction plane

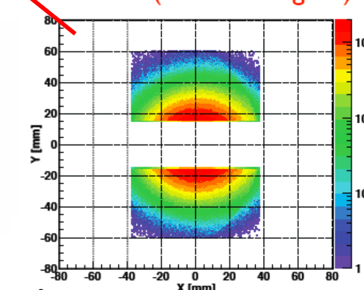
Stat. Unc. ~ $1/(P_1\sqrt{N})$



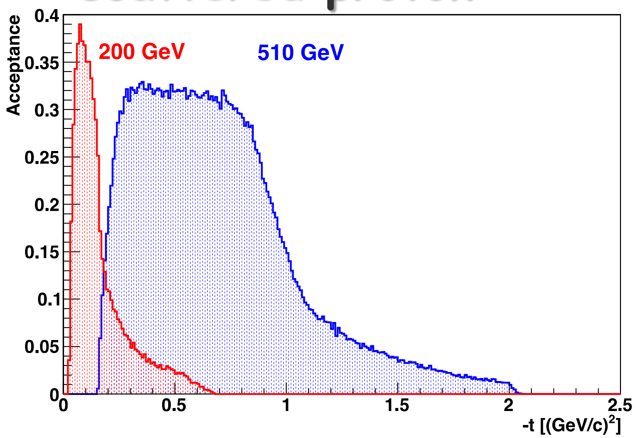
Run-15 p↑Au: 7000 J/Ψ
- photon emitted by Au
- trigger on e+e- in Barrel-ECal
- no requirement on n in ZDC

RUN-17: J/ψ IN p↑p UPC

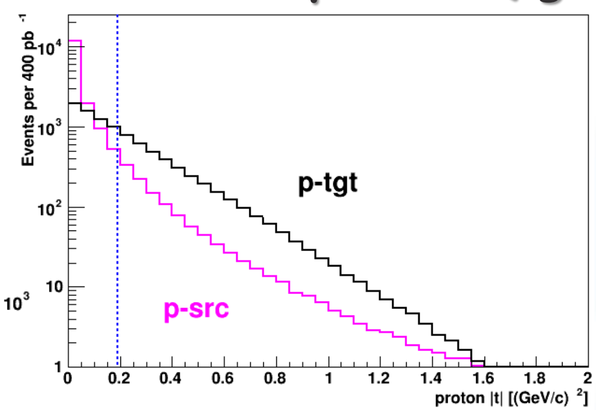




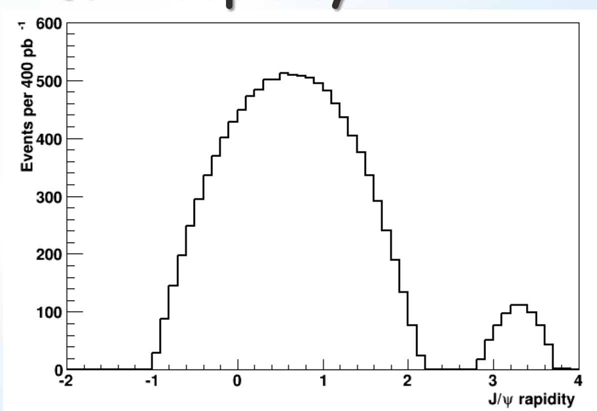
RP acceptance for scattered proton:

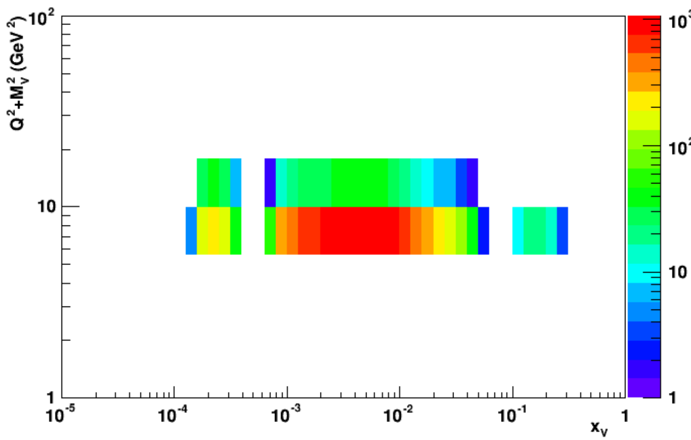


t-dist for protons (tgt & γ-src):



J/Ψ-rapidity





Required:

2017 p↑+p 400 nb-1
→ 11k J/Ψs
→ δA_{UT}: +/-0.04 in 3 t-bins

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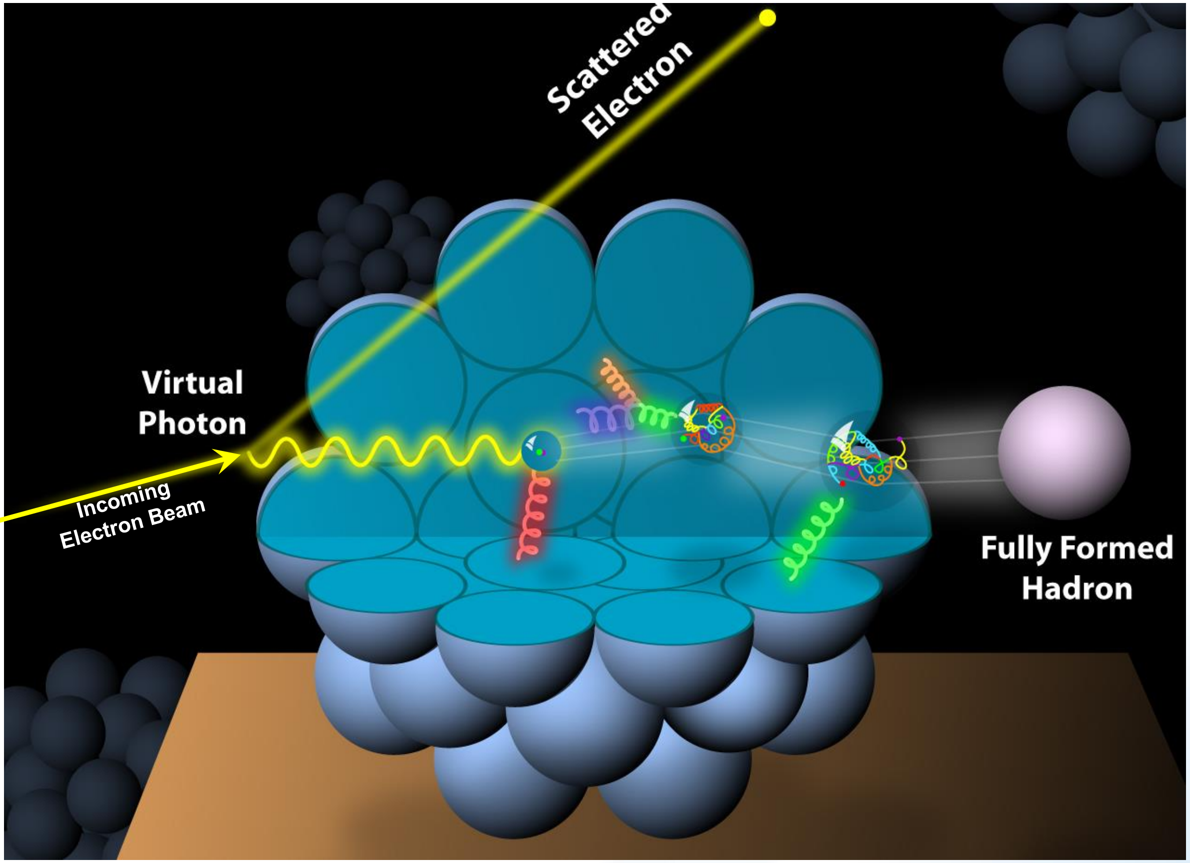
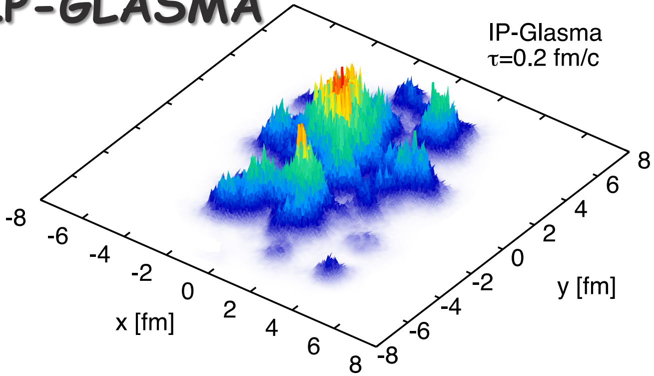
WHAT ABOUT NUCLEI?

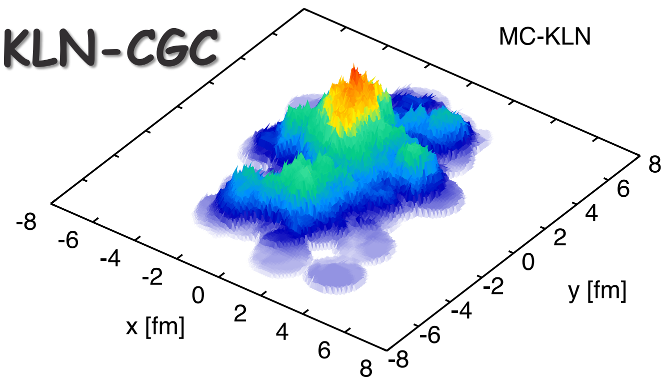


THE INFLUENCE OF THE INITIAL STATE IN AA

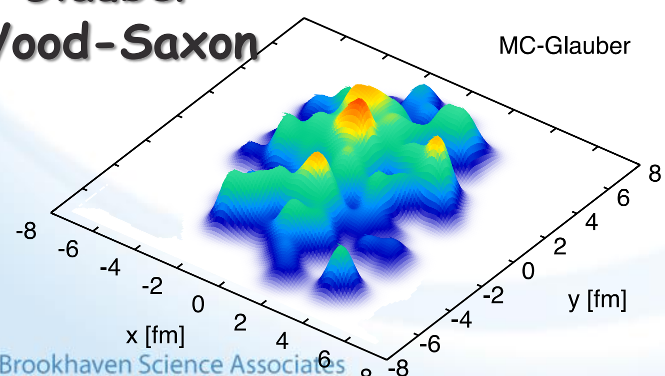
IP-GLASMA



KLN-CGC

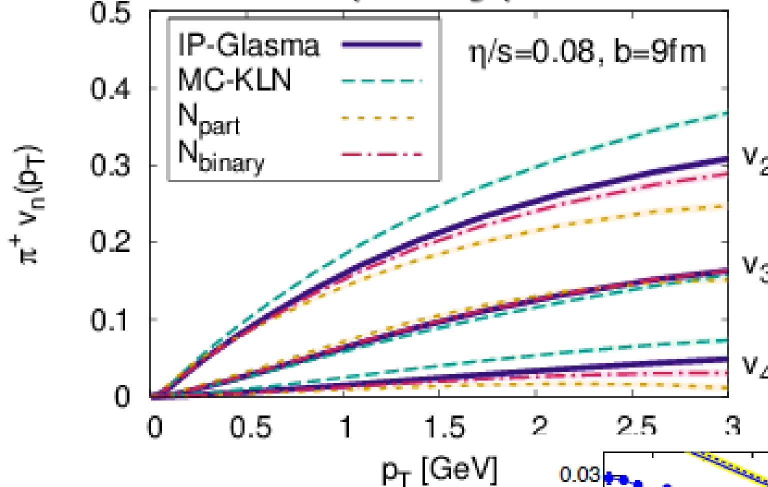


Glauber
Wood-Saxon

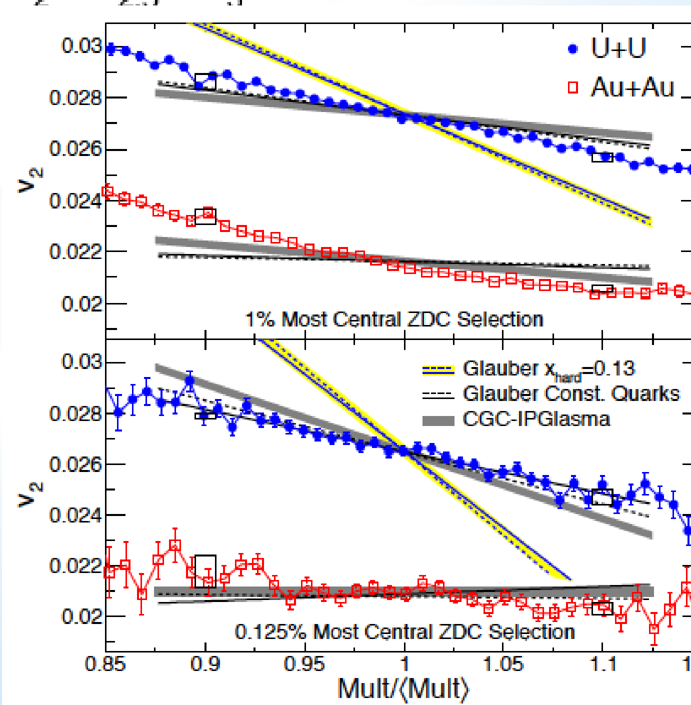


AdS/CFT predicts for a perfect fluid:
$\eta/s = 1/(4\pi) \sim 0.08$

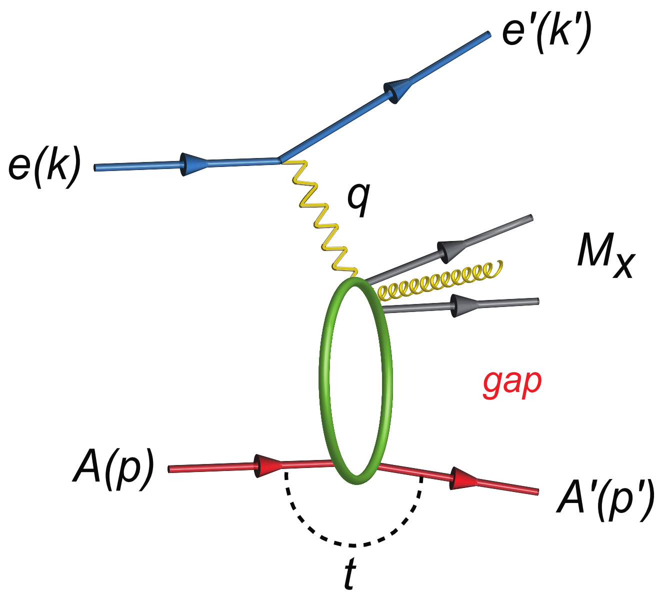
Schenke, Tribedy, Venugopalan arXiv:1202.6646



Different initial state → different fluctuation scales



Diffraction:



Diffractive events are indicative of a color neutral exchange between the virtual photon and the proton or nucleus over several units in rapidity.

M_X^2: Squared mass is the diffractive final state

x_{IP}: Momentum fraction of the "Pomeron" with respect to the hadron. The rapidity gap between produced particles and the proton or nucleus is $Y \sim \ln(1/x_{IP})$

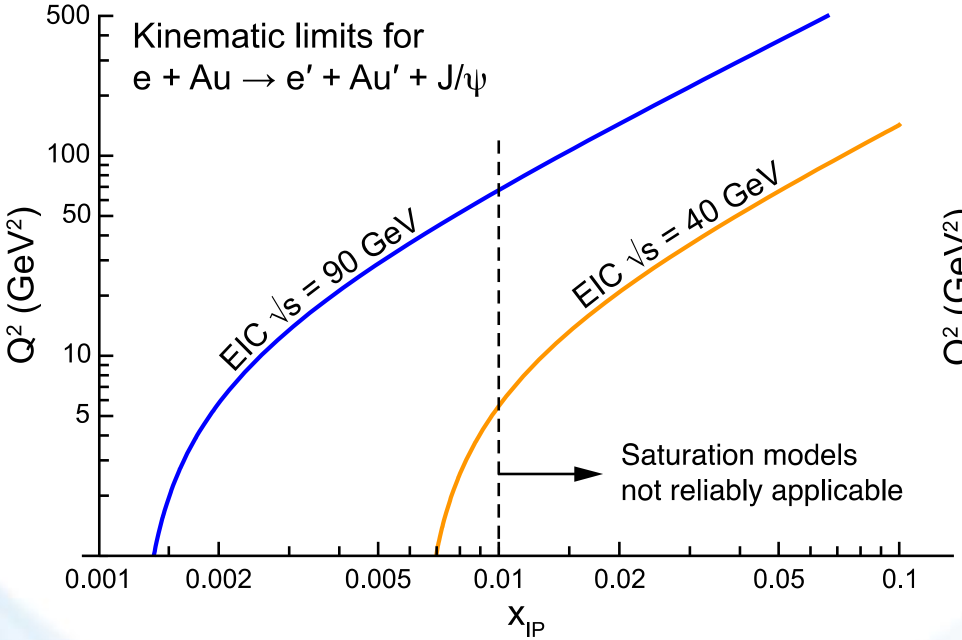
3D-IMAGING OF NUCLEI

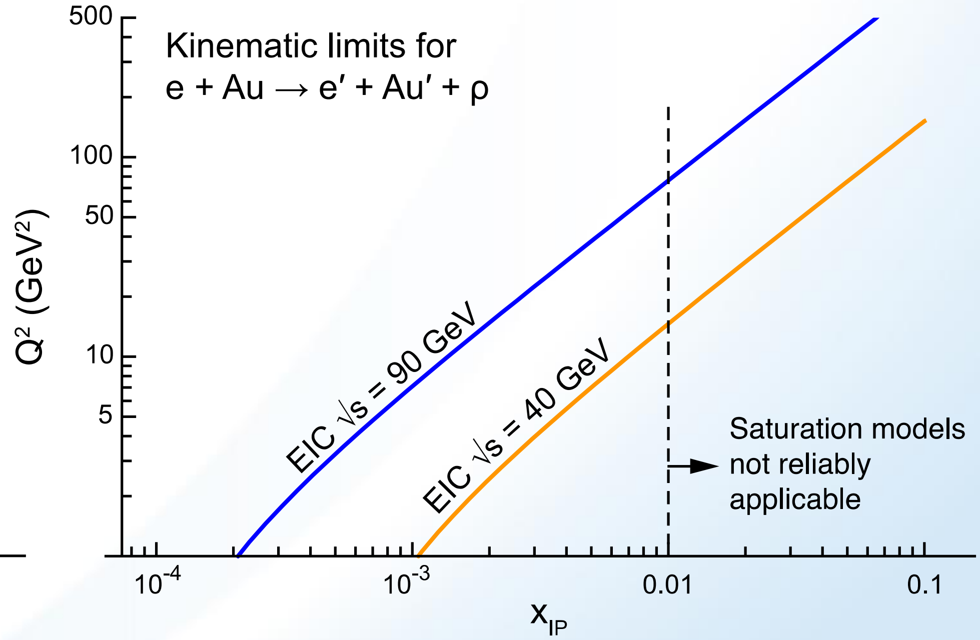
1950-60: Measurement of charge (proton) distribution in nuclei
Ongoing: Measurement of neutron distribution in nuclei
EIC ⇒ spatial gluon distribution in nuclei → Saturated or non-saturated ?

Method:

Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi, \varphi, \rho$

- Momentum transfer $t = |p_{Au} - p_{Au'}|^2$ conjugate to b_T





Only eRHIC has enough phase space to map out the 3d gluon distribution in the saturation regime

EIC: SPATIAL GLUON DISTRIBUTION FROM dσ/dt

1950-60: Measurement of charge (proton) distribution in nuclei

Ongoing: Measurement of neutron distribution in nuclei

EIC ⇒ Gluon distribution in nuclei

Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi$

Method:

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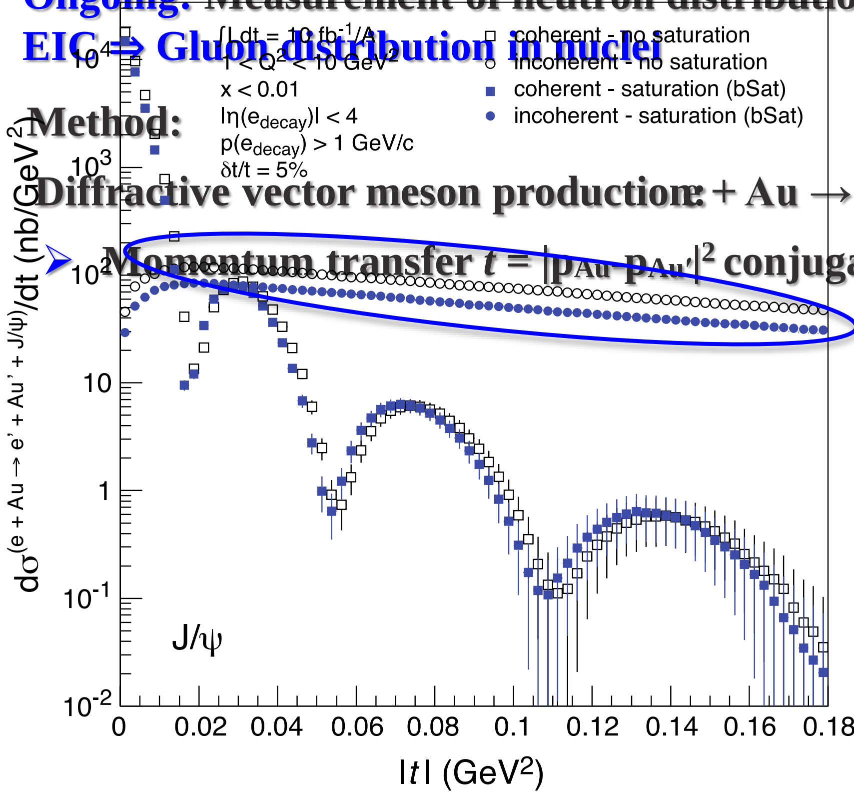
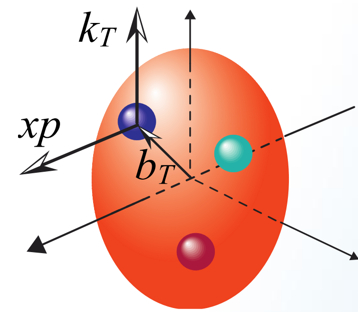
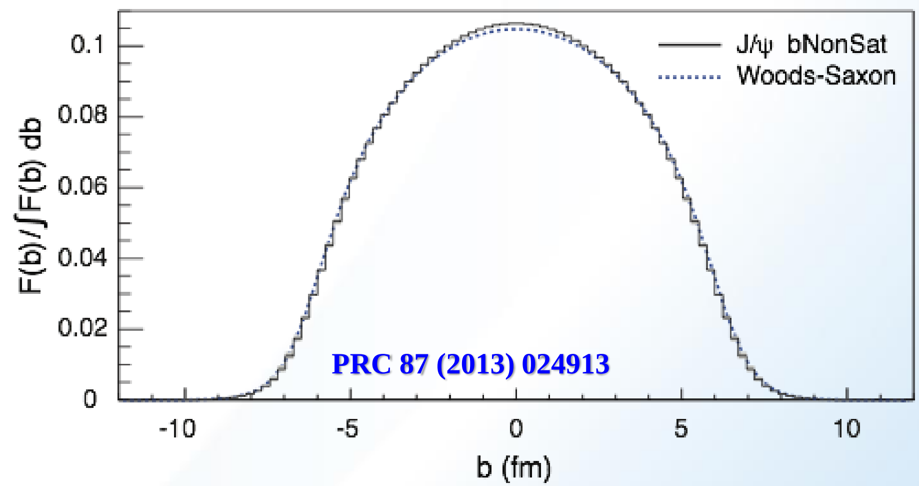
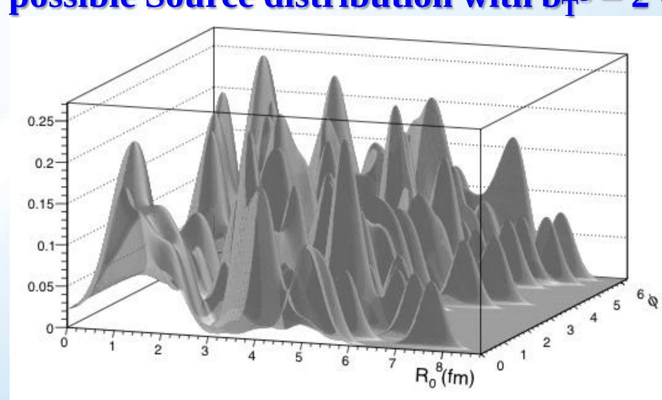


Fourier Transform





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



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, ...)

HOW TO ACCESS GLUONS IN DIS

Gluons manifest themselves through

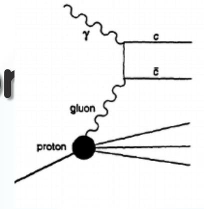
1. the scaling violation of the cross section as function of x and Q^2
   $dF_2(x,Q^2)/d\ln Q^2 \rightarrow G(x,Q^2)$

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

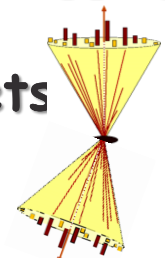
quark+anti-quark momentum distributions

gluon momentum distribution

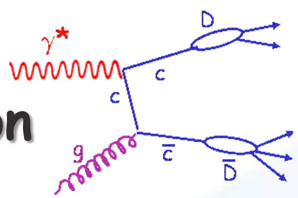
1. Directly through the measurement of F_L
1. Through tagging of the photon gluon fusion pr



   1. Di-jets

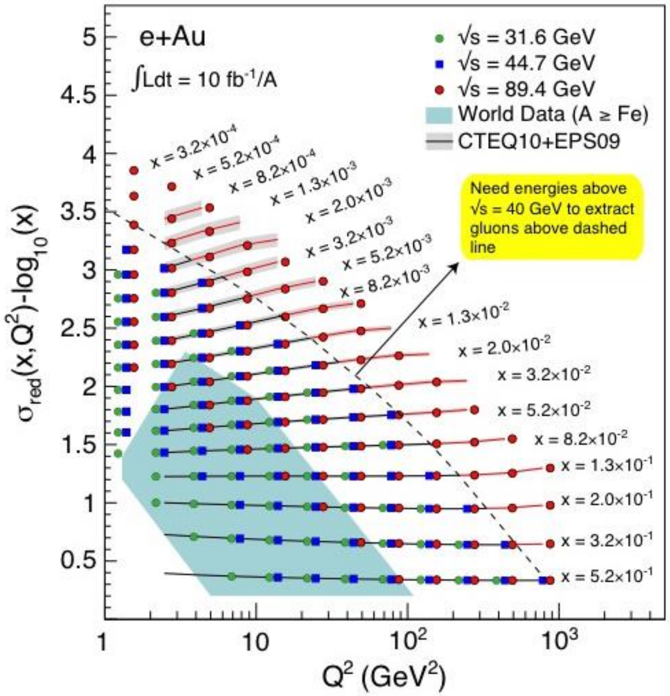


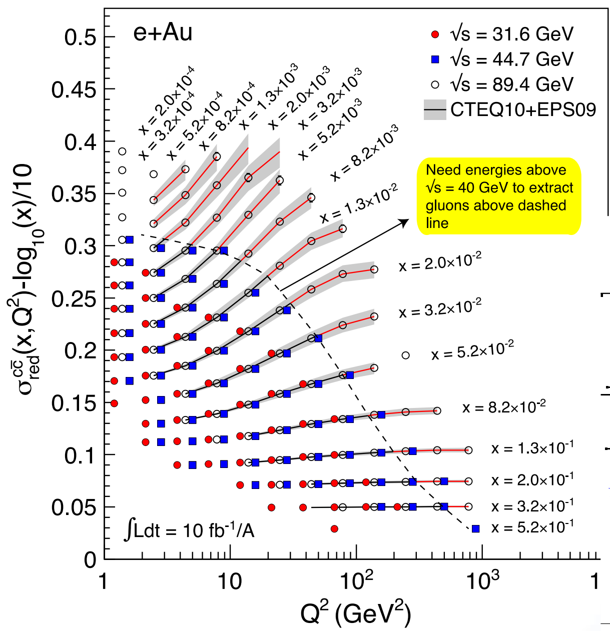
   1. charm production

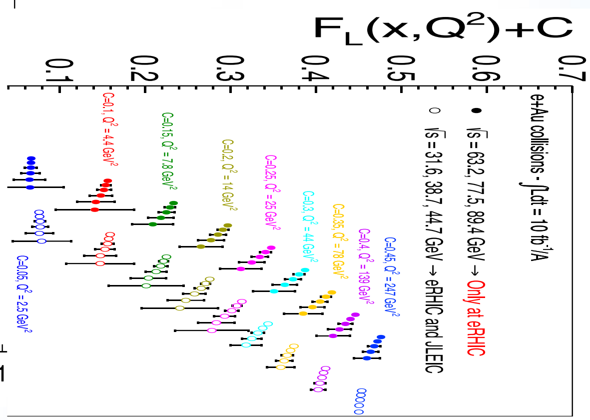


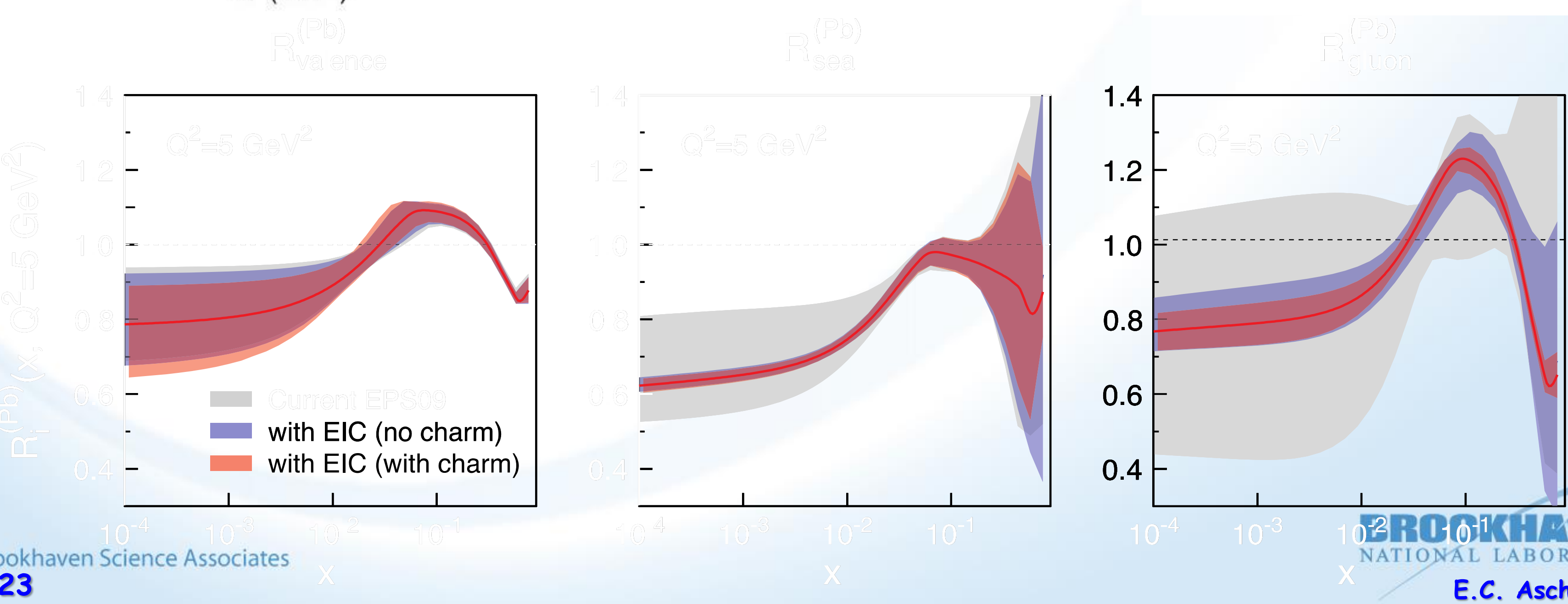
All these process need a wide coverage in x and Q^2

nPDFs BEFORE AND AFTER EIC



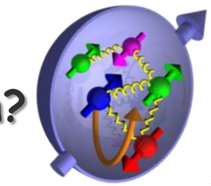


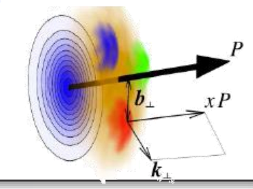




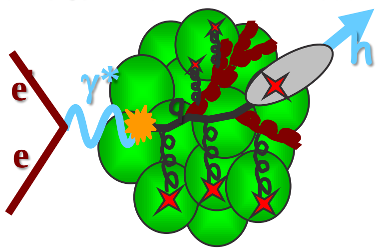
SUMMARY: EIC PHYSICS PROGRAM

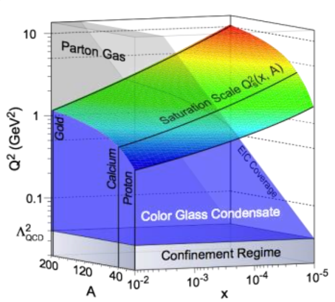
- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
- How do the nucleon properties emerge from these distributions?





- How does the nuclear environment affect the space and momentum distributions of quarks and gluons and their interactions?
- How do quarks and gluons form the hadronic final states and create nuclear binding?
- What does this dressing process tell us about the mechanisms by which quarks are normally confined inside nucleons?





- What happens to the gluon density in nuclei at high energy?
- Does it saturate, giving rise to a gluonic matter component with universal properties in all nuclei, even the proton?
- How does the nuclear environment affect quark and gluon distributions and interactions inside nuclei? Do the abundant low-momentum gluons remain confined within nucleons inside nuclei?


BACK UP

eRHIC: SPATIAL GLUON DISTRIBUTION FROM dσ/dt

1950-60: Measurement of charge (proton) distribution in nuclei

Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi, \phi, \rho$

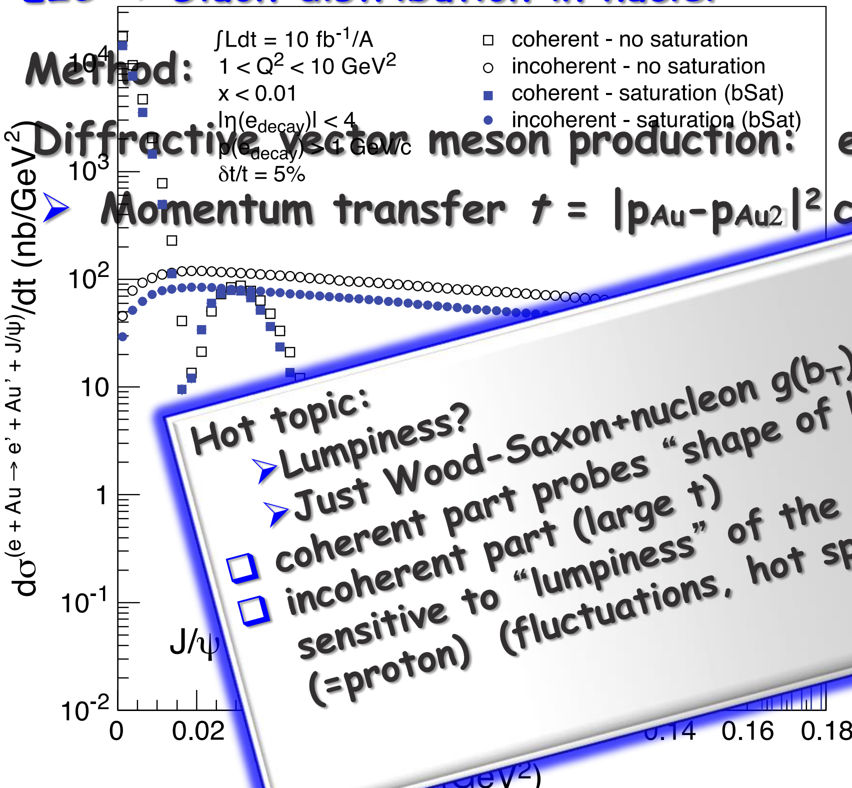
Ongoing: Measurement of neutron distribution in nuclei

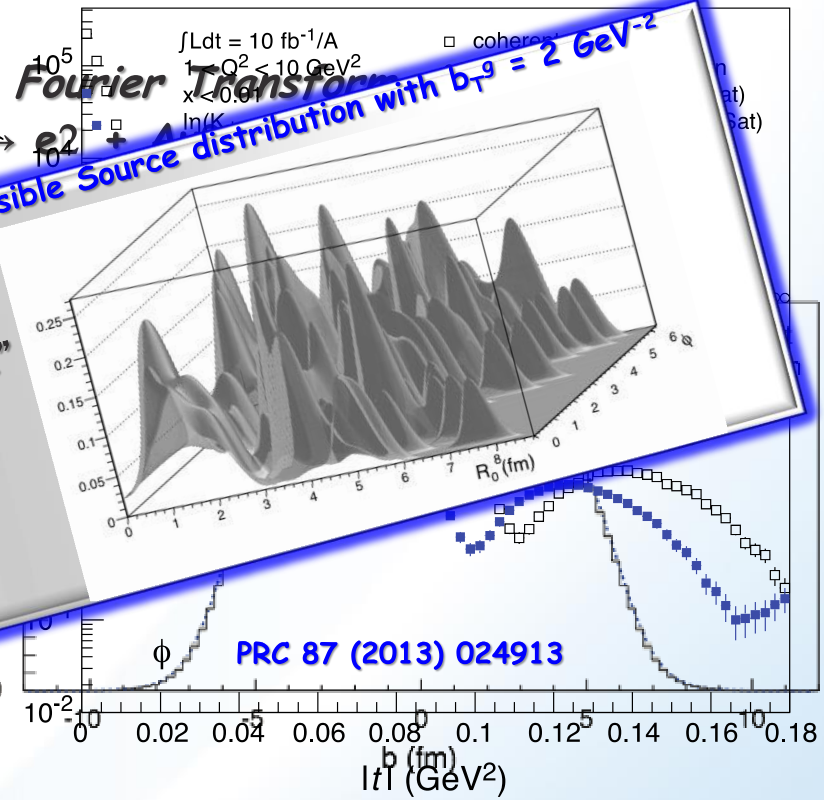
EIC ⇒ Gluon distribution in nuclei

Method: **Fourier Transform**

Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi, \phi, \rho$

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





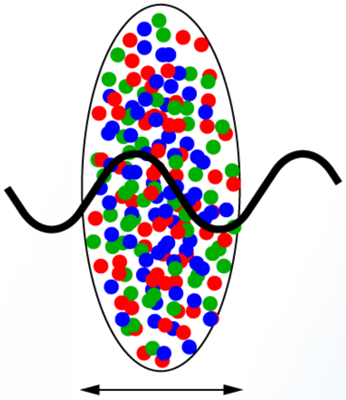
Hot topic:
- Lumpiness?
- Just Wood-Saxon+nucleon $g(b_T)$
- coherent part probes "shape of black disc"
- incoherent part (large t) sensitive to "lumpiness" of the source (=proton) (fluctuations, hot spots, …)

- Converges to input F(b) rapidly: $|t|$ < 0.1 almost enough
- **Recover accurately any input distribution used in model used to generate pseudo-data (here Wood-Saxon)**
- Systematic measurement requires $\int Ldt >> 1\ fb^{-1}/A$

- $d\sigma/dt$: diffractive pattern known from wave optics
- φ sensitive to saturation effects, smaller J/ψ shows no effect
- J/ψ perfectly suited to extract source distribution

Scattering of electrons off nuclei:

- Probes interact over distances $L \sim (2m_N x)^{-1}$
- For $L > 2 R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back of nucleon
- Probe interacts *coherently* with all nucleons



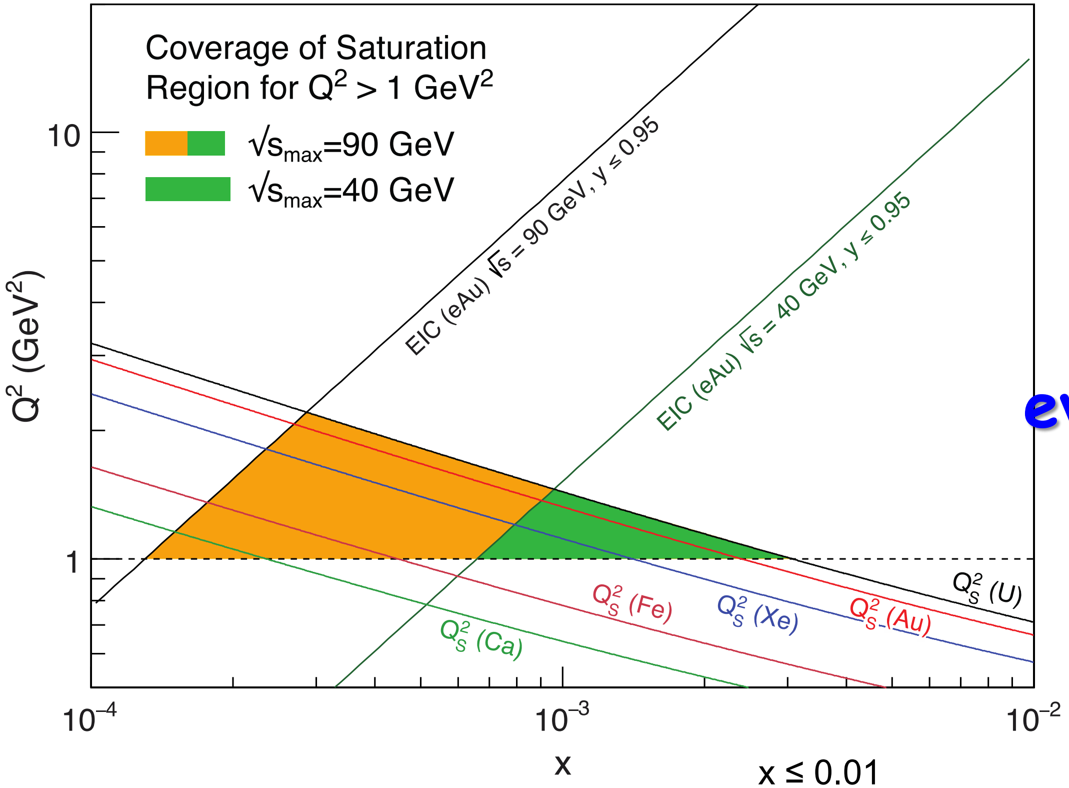
$$Q_s^2 \sim \frac{\alpha_s \, xG(x, Q_s^2)}{\pi R_A^2} \qquad \text{HERA}: \; xG \sim \frac{1}{x^{0.3}} \qquad \text{A dependence}: \; xG_A \sim A$$

Nuclear "Oomph" Factor Pocket Formula:

$$\boxed{(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}}$$

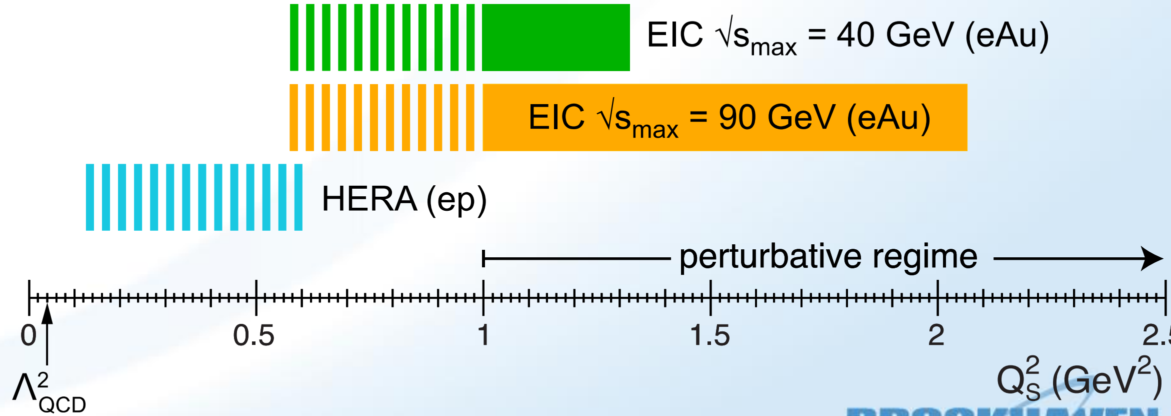
Enhancement of Q_S with A $\Rightarrow$ non-linear QCD regime reached at significantly lower energy in A than in proton

GLUONS AT LOW X IN NUCLEI



x ≤ 0.01

Only eRHIC allows to study the evolution of Q_s with x and A



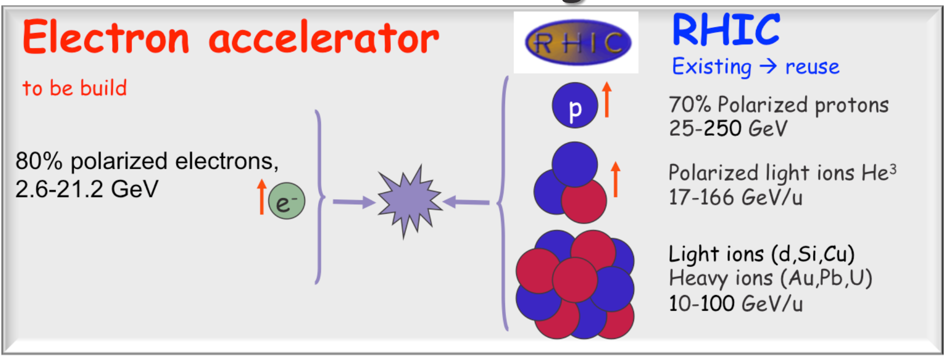
EIC MACHINE DESIGNS

eRHIC arXiv:1409.1633

JLEIC arXiv:1504.07961

Both machine designs built on existing machines

Linac - Ring



full √s range available from beginning

→ staging in luminosity

Ring- Ring

reuse Cebaf as full energy lepton injector
electron: 3-10 GeV
protons: 20-100 GeV
ions: 8-40 GeV/u for Pb
polarised ions: p, d, 3He, possibly Li
Polarisation for both beams: > 70%

Luminosity 10^{33} to 10^{34} cm^{-2}s^{-1}

→ staging center-of-mass energy

Both machines utilize crossing angles

10 mrad | 50 mrad

→ need for Crab cavities

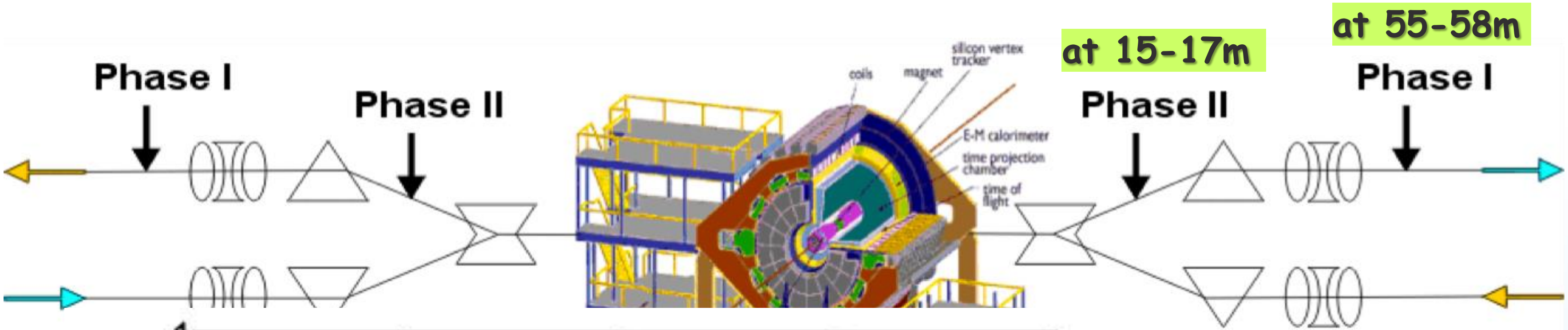
Bunch frequency: 9.4 MHz

Bunch frequency: 476 MHz
159 MHz@√s=63GeV

Both designs take great care to have maximal to full acceptance for scattered protons from diffractive reactions, breakup neutrons and spectator tagging

2 interaction regions

FORWARD PROTON TAGGING UPGRADE



Foll… pp2pp@STAR with
std. …ore

- shou…
- Stag…
  - …
  - …
  - → …
  - → … irection
  … ints
- Good…
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