THE PROTON AND NUCLEI IN 3D

BROOKHAVEN NATIONAL LABORATORY

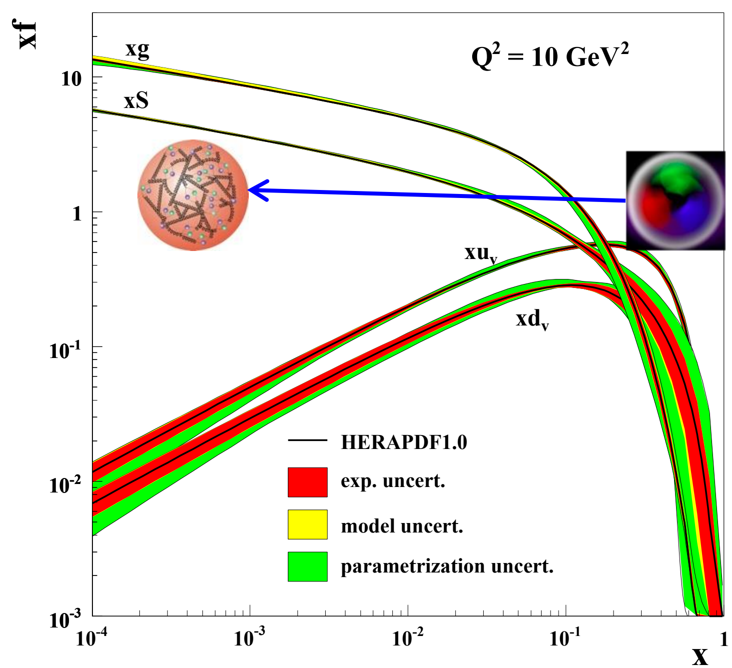
a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

WHAT DO WE KNOW

HERA's discovery:

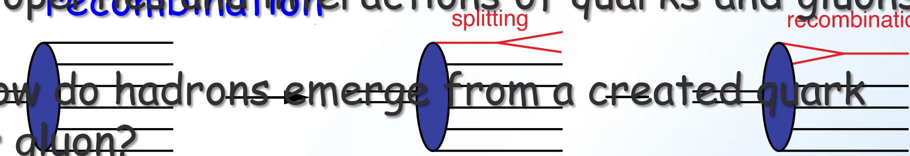
Gluon density dominates at x<0.1



WHAT WE DON'T KNOW

- Rapid rise in gluon density at x < 0.1
- This cannot continue forever –
  → non-linear pQCD evolution equations provide a natural way to tame this growth and lead to a saturation of gluons, characterized by the saturation scale $Q^2_s(x)$

QCD: Dynamical balance between radiation and recombination



- How does quark and gluon dynamics generate the proton spin?
  It is more than the number 1/2 !
  It is the 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

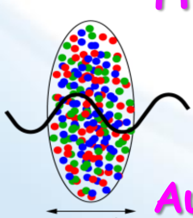
- 2+1D Structure of nucleons and nuclei
  How does the glue bind quarks and itself into nucleons and nuclei?

Color Confinement — 200 MeV (1 fm)

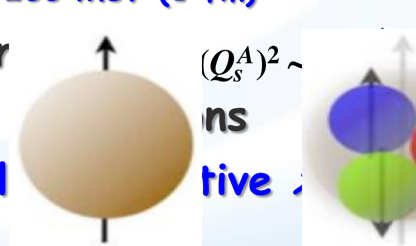
Asymptotic freedom — 2 GeV (1/10) fm

Q^2 GeV² Probing momentum

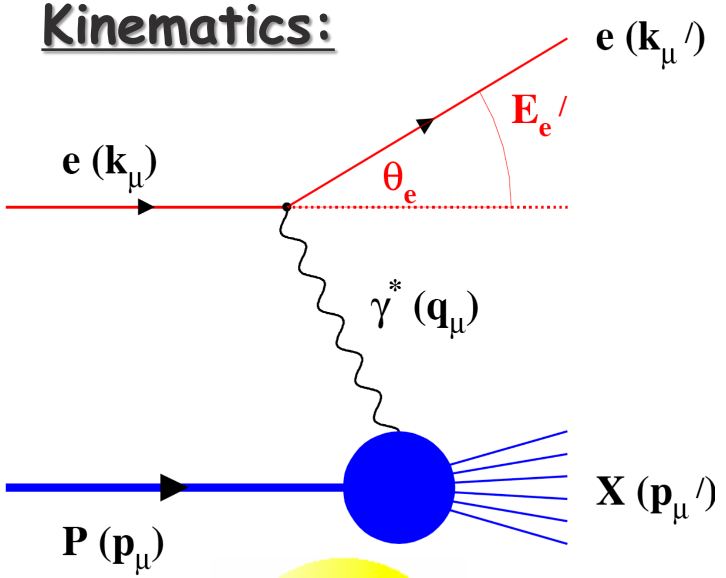
A new regime of QCD matter
→ Color Glass Condensate (CGC)
Hints from HERA, RHIC and LHC



eA: Probe ir…
coherently with …ns
Au: ~200 times smal…tive



Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k_\mu')^2$$

$$Q^2 = 2E_e E_e'(1-\cos\Theta_{e'})$$

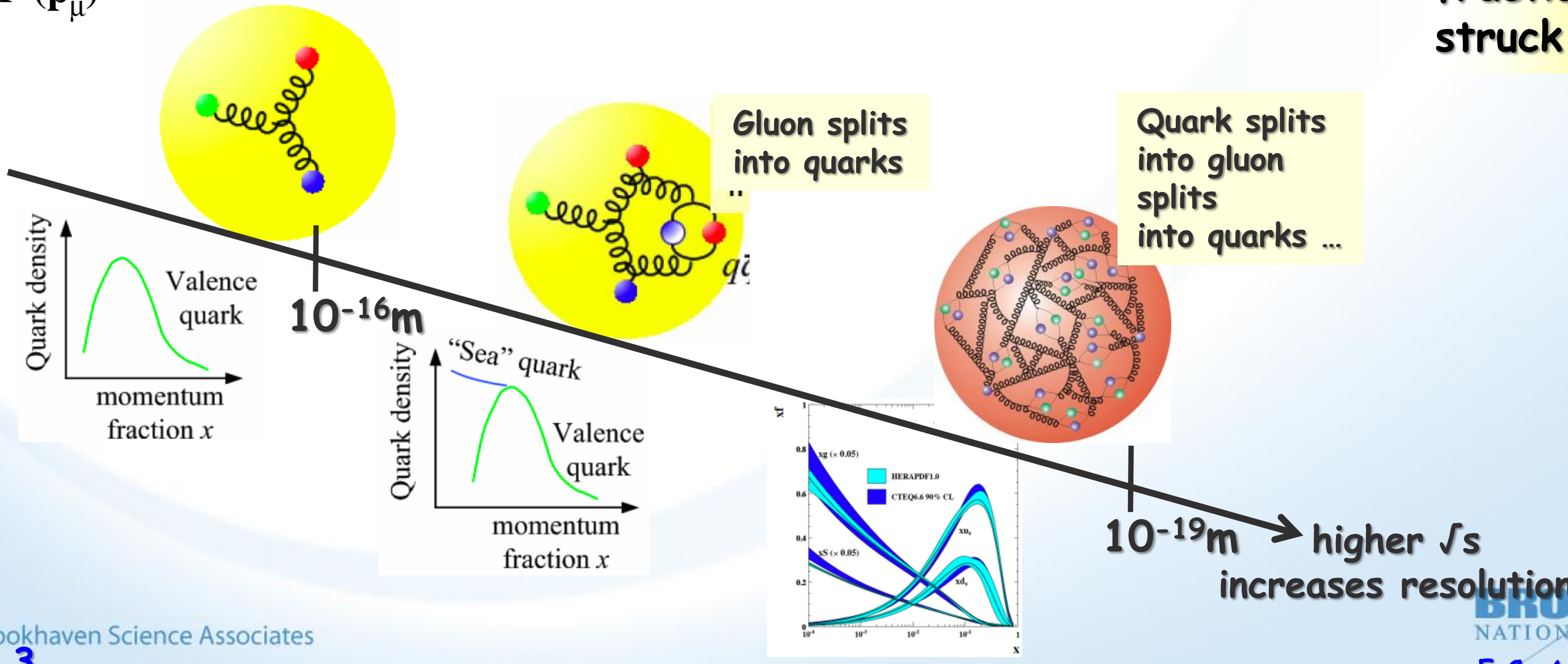
Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E_e'}{E_e}\cos^2\left(\frac{\theta_e'}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark



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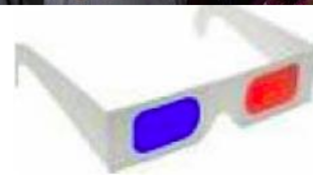
QUANTUM TOMOGRAPHY OF THE NUCLEONS & NUCLEI

Join the real
3D experience !!

TMDs

GPDs



2D+1 picture in momentum space

2D+1 picture in coordinate space

Spin as vehicle to do tomography of the nucleon

What is the dynamic structure of the proton and nuclei
2D+1 picture in momentum and coordinate space
Visualize color interactions in QCD
collective phenomena and correlations in fragmentation

→ New physics aspects due to confined motion

To separate interaction dependent phenomena from intrinsic properties
UNIVERSALITY
different complementary probes are needed
pp & pA <-> ep & eA

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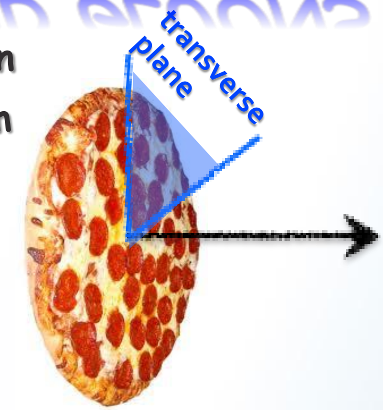
THE PATH TO IMAGING QUARKS AND GLUONS

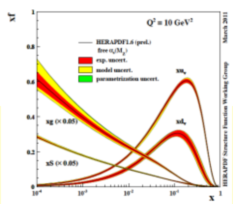
- std collinear PDFs do not resolve transverse momenta or positions in the nucleon
- fast moving nucleon turns into a `pizza' but transverse size remains about 1 fm

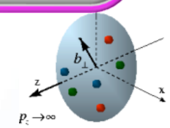


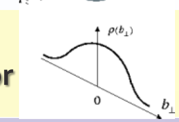
compelling questions

- how are quarks and gluons spatially distributed
- how do they move in the transverse plane
- do they orbit and do we have access to spin-orbit correlations

→ requires set of new measurements & theoretical concepts







1-D

$f(x)$ parton densities

$F(t)$ form factor

$\int d^2k_T$ $\int d^2b_T$ $\int dx$

2+1-D

$f(x, k_T)$ transv. mom. dep. PDF — *semi-inclusive DIS*

not related by Fourier transf.

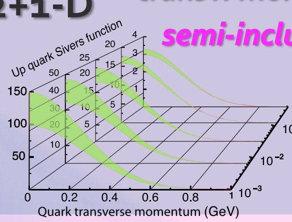
$f(x, b_T)$ impact par. dep. PDF

$b \leftrightarrow t$

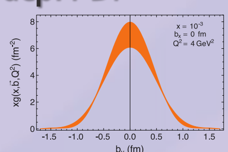
$H(x, 0, t)$

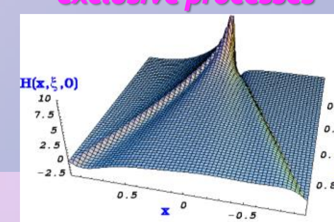
$\xi \to 0$

$H(x, \xi, t)$ generalized PDF — *exclusive processes*



$\int d^2b_T$ $\int d^2k_T$





4+1-D

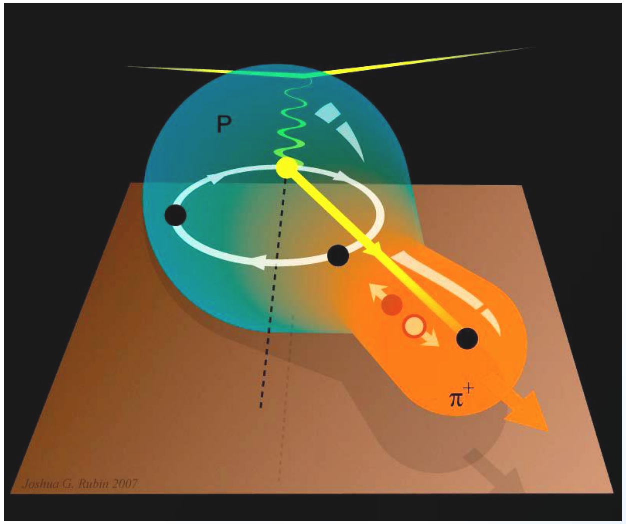
Wigner function

$W(x, k_T, b_T)$

high-level connection

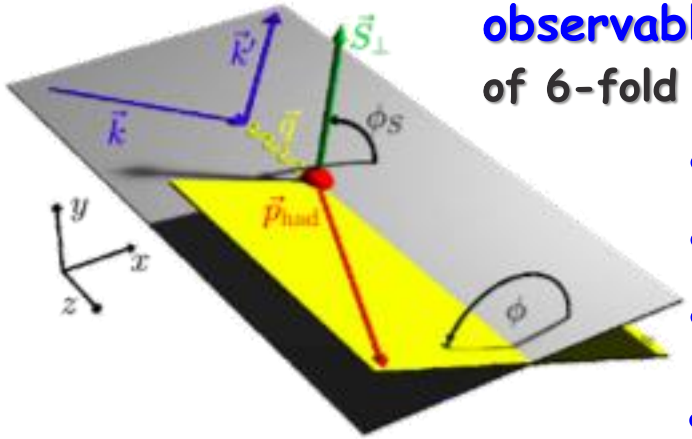
measurable ?

important in other branches of Physics



Transverse momentum dependent distributions (TMD)

TRANSVERSE MOMENTUM DEPENDENT PDFs & FFs

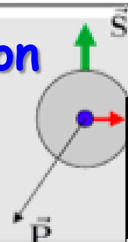


observable: azimuthal modulations of 6-fold differential SIDIS cross section $\frac{d\sigma}{dx dQ^2 dz d\phi_s d\phi_h dp_T^h}$

- theoretically interesting multi-scale problem: Q^2, p_T
- TMD framework/factorization applicable for $Q^2 >> p_T$
- so far if at all only valence quark TMDs extracted from fixed target data
- **very different evolution then collinear PDFs** pertubative & **non-pertubative** contributions
- slew of different TMDs can be defined

example: Sivers function correlation of nucleon's transverse spin with the k_T of an unpolarized quark

$\sin(\phi_h - \phi_s)$ modulation



Leading Twist TMDs — Nucleon Spin, Quark Spin

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 =		$h_1^\perp$ = − (Boer-Mulders)
L		g_{1L} = − (Helicity)	$h_{1L}^\perp$ = −
T	$f_{1T}^\perp$ = − (Sivers)	$g_{1T}^\perp$ = −	h_1 = − (Transversity); $h_{1T}^\perp$ = −

$$f_{q/P^\uparrow}(x, \mathbf{k}_\perp, S) = f_1(x, \mathbf{k}_\perp^2) - \frac{\mathbf{S}\cdot(\hat{\mathbf{P}}\times\mathbf{k}_\perp)}{M} f_{1T}^\perp(x, \mathbf{k}_\perp^2)$$

unpolarised TMD — Sivers function

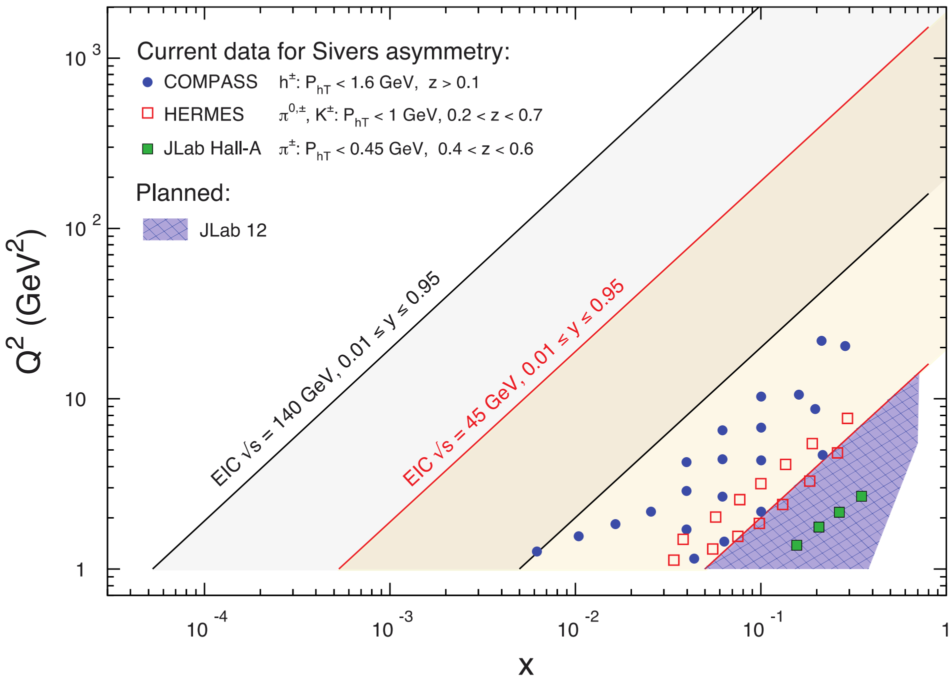
important link to physics of gluon saturation at small x for gluons

Similar for gluons

- measures spin-orbit correlations
- link to parton orbital motion (through models)
- reveals non-trivial aspects of QCD color gauge invariance

MORE INSIGHTS TO THE PROTON: TMDs

eRHIC vs. world coverage

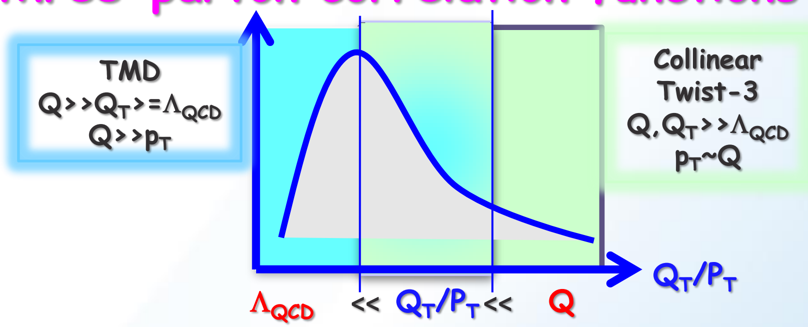


eRHIC:

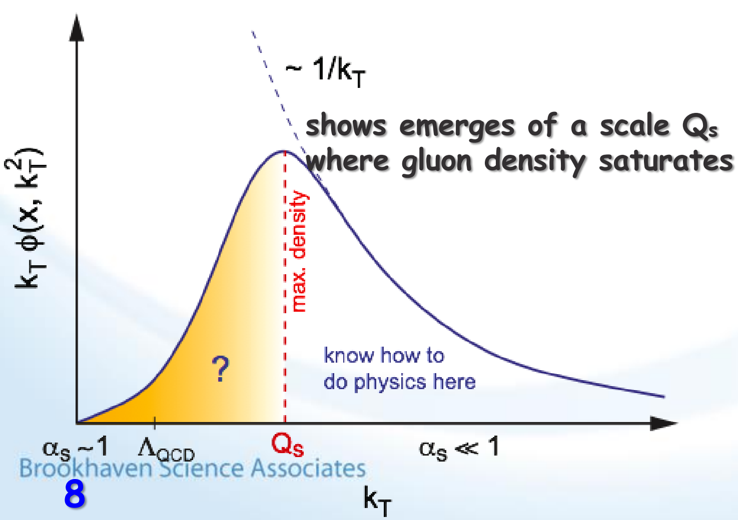
large x, Q^2, p_T and z coverage

→ only place to measure data to pin down TMD evolution

→ only place to test theoretical concepts of TMD to collinear TWIST-3 three-parton correlation functions



$$gT_{q,F}(x,x) = -\int d^2k_{\perp} \frac{|k_{\perp}|^2}{M} f_{1T}^{\perp q}(x,k_{\perp}^2)_{SIDIS}$$



- unintegrated gluon density $g(x,Q2,k_T)$ important for physics at small x
  → CGC
  → many applications at LHC

Important: eRHIC ideal machine to understand transition form low to high k_T

What are the best observables ?

VISUALIZE COLOR INTERACTIONS IN QCD

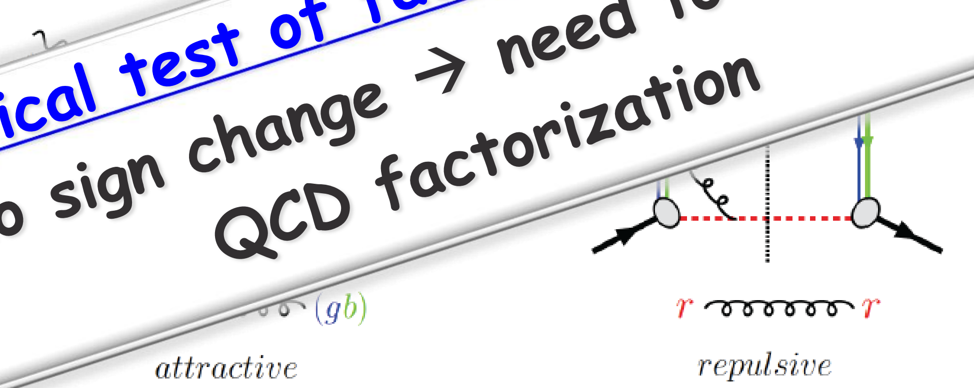
Measure non-universality of sivers-functi…

QCD:

DIS:
γq-scattering
attractive FS…

Critical test of factorization in QCD

no sign change → need to rethink QCD factorization



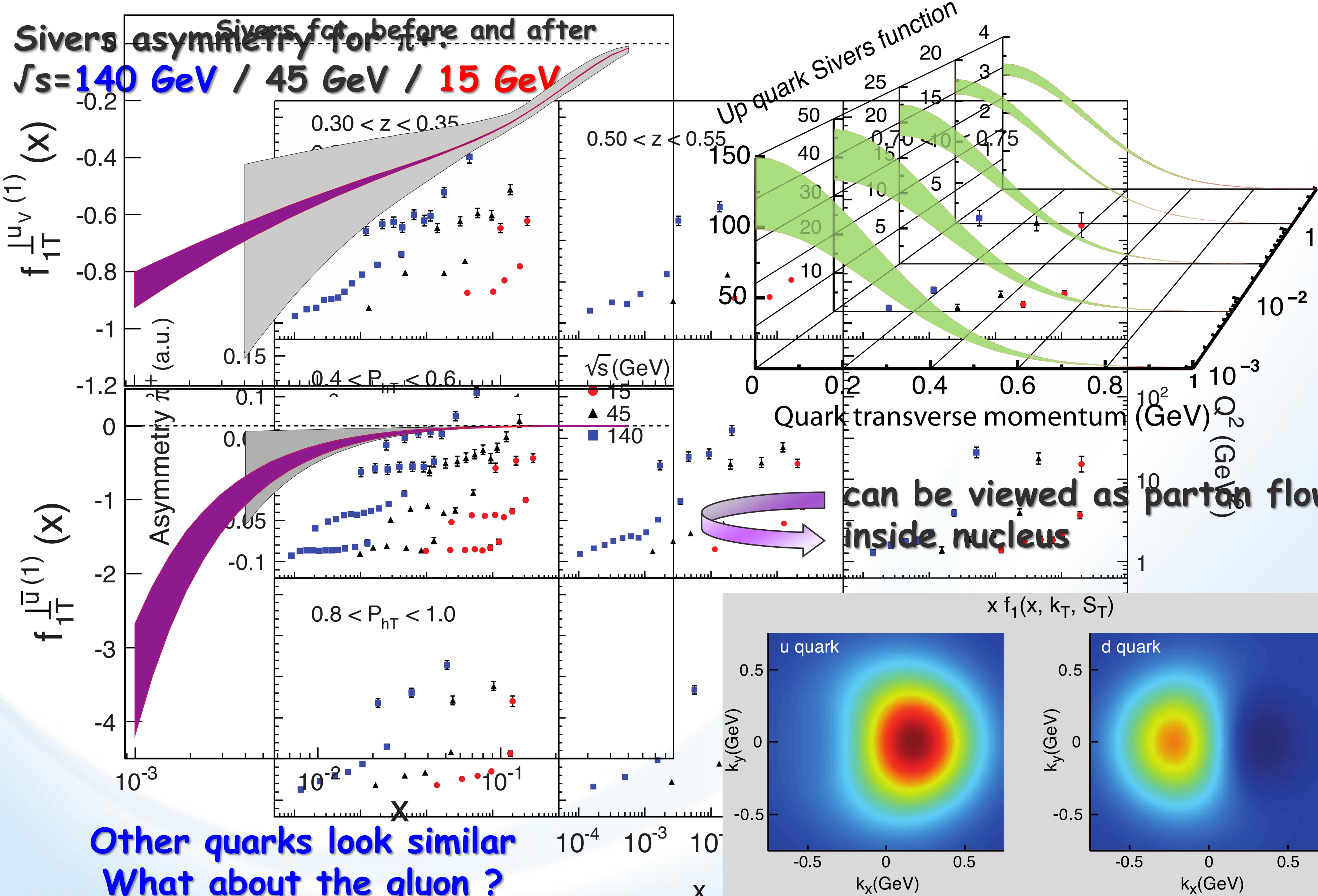
$Sivers_{DIS}$ = **−** $Sivers_{DY}$ or $Sivers_{W}$ or $Sivers_{Z0}$

A_N(direct photon) measures the sign change in the Twist-3 formalism

All three observables can be attacked at 500 GeV at RHIC

Sivers asymmetry for π^+:

$\sqrt{s}$=140 GeV / 45 GeV / 15 GeV

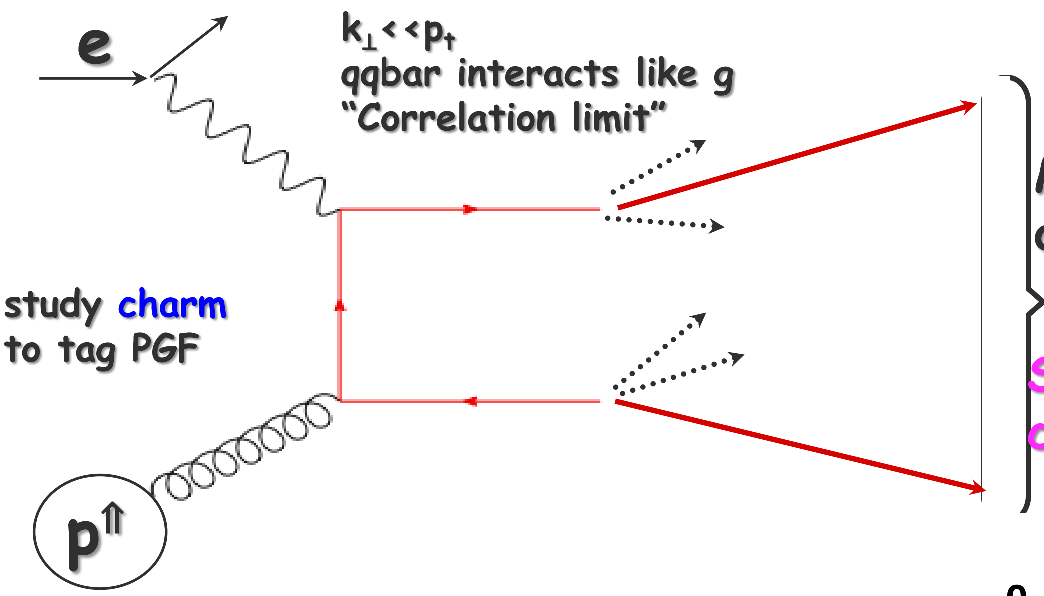


can be viewed as parton flow inside nucleus

Other quarks look similar

What about the gluon ?

The Gluon Sivers Function: $\gamma^* p^{\Uparrow} \rightarrow h+h+X$



Measure a pair of D mesons

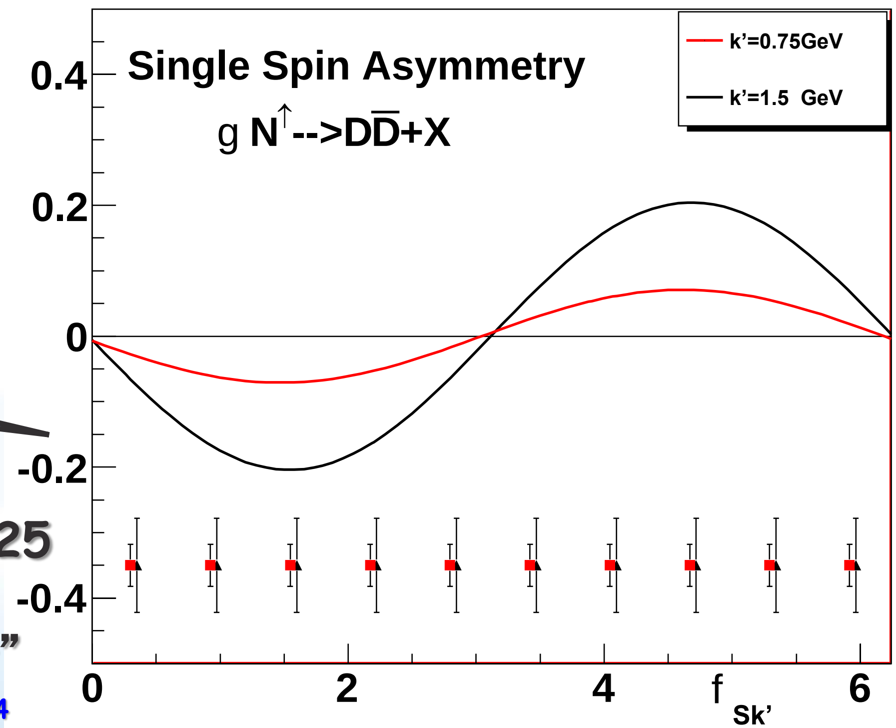
$k_\perp = |k_{1T} + k_{2T}|$

Statistically challenging

$P_T = (k_{1T} - k_{2T}) / 2$

$$A(k'_\perp, \phi_{Sk'}) = \frac{d\sigma(k'_\perp, \phi_{Sk'}) - d\sigma(k'_\perp, \phi_{Sk'} + \pi)}{d\sigma(k'_\perp, \phi_{Sk'}) + d\sigma(k'_\perp, \phi_{Sk'} + \pi)}$$

~8 months with 50% efficiency and $L = 10^{34} cm^2 s^{-1}$



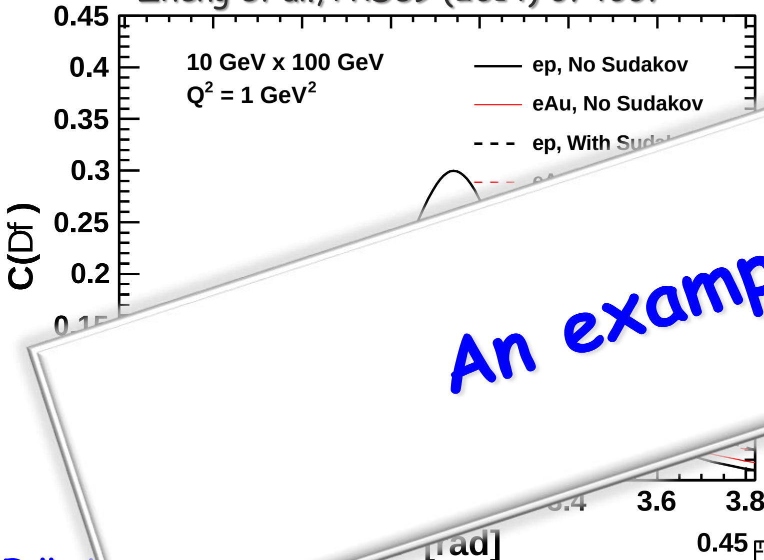
- Beam Energies: 20 GeV x 250 GeV
- Q^2: 1 – 10 GeV^2, y: 0.01 – 0.95, z>0.25
- no cut on $k_\perp$ and p_t, but on $k_\perp/p_t$ < 0.5 for "correlation limit"

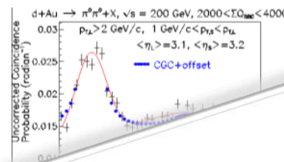
DI-HADRON CORRELATIONS IN eP AND eA

"Simple" measurement giving access to multi-parton correlations
→ saturation

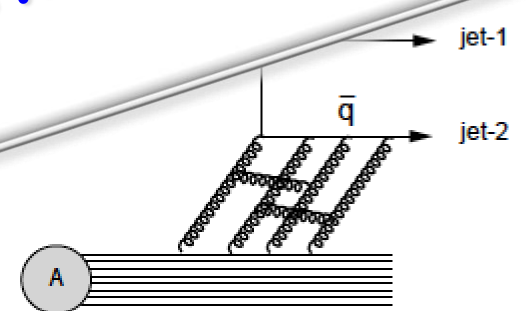
Same observable as in dA @ RHIC

Zheng et al., PRD89 (2014) 074037

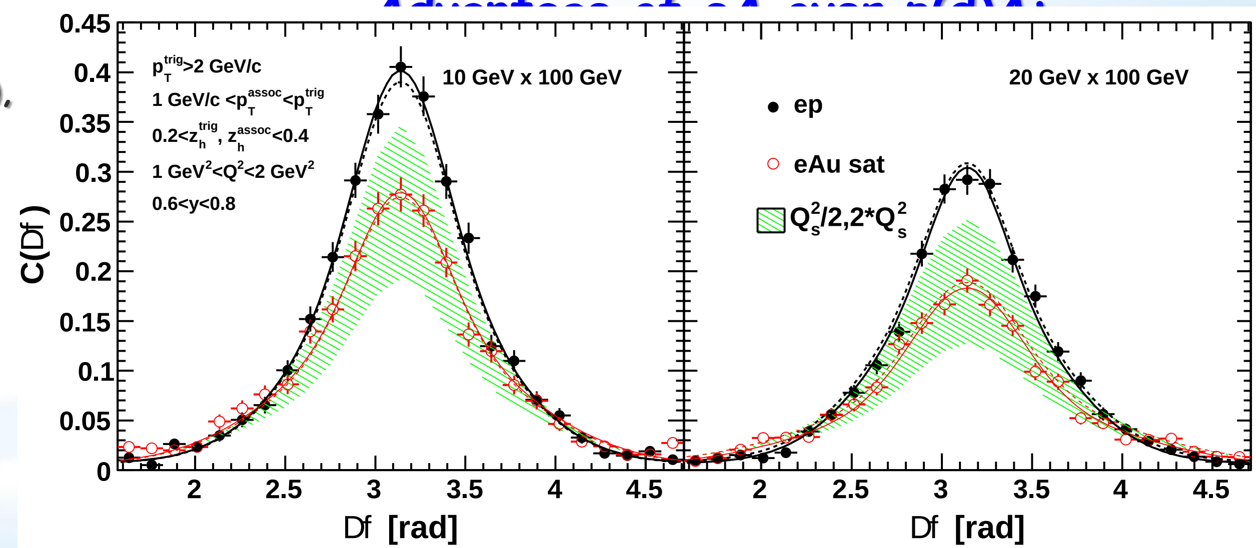




An example for TMDs in eA

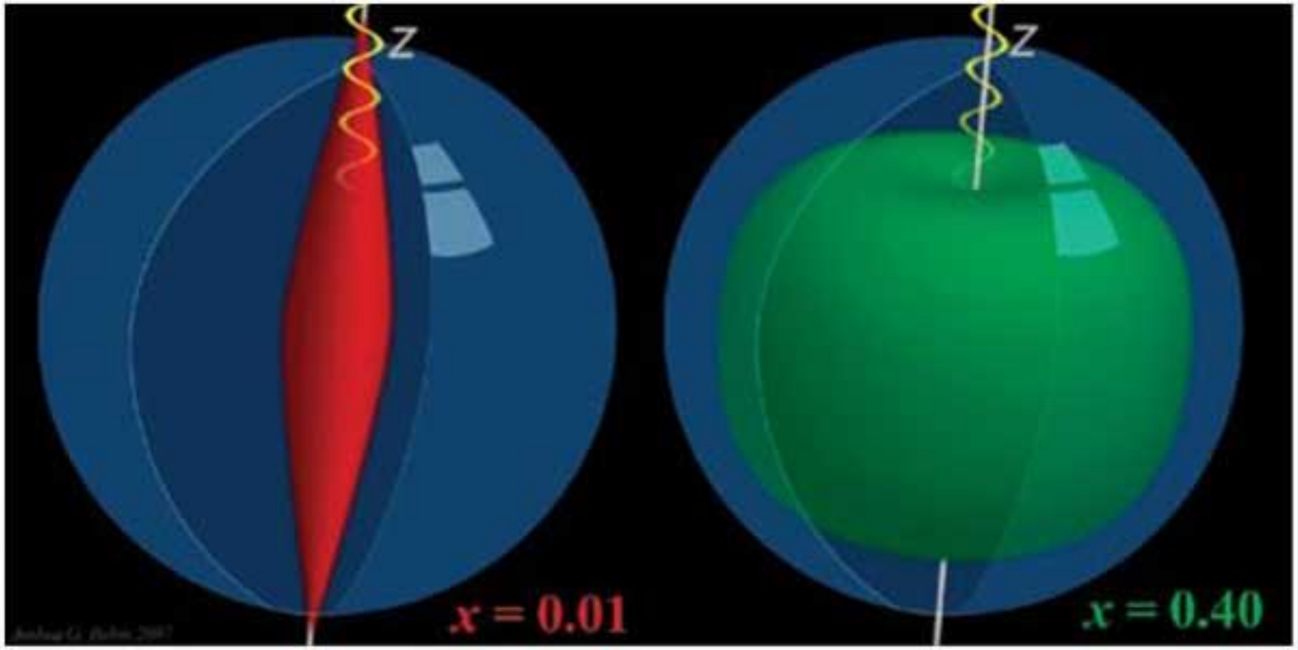


Fully b...
Doming... al. PRD83, 105005 (2011),
PRL 106, 022301 (2011)



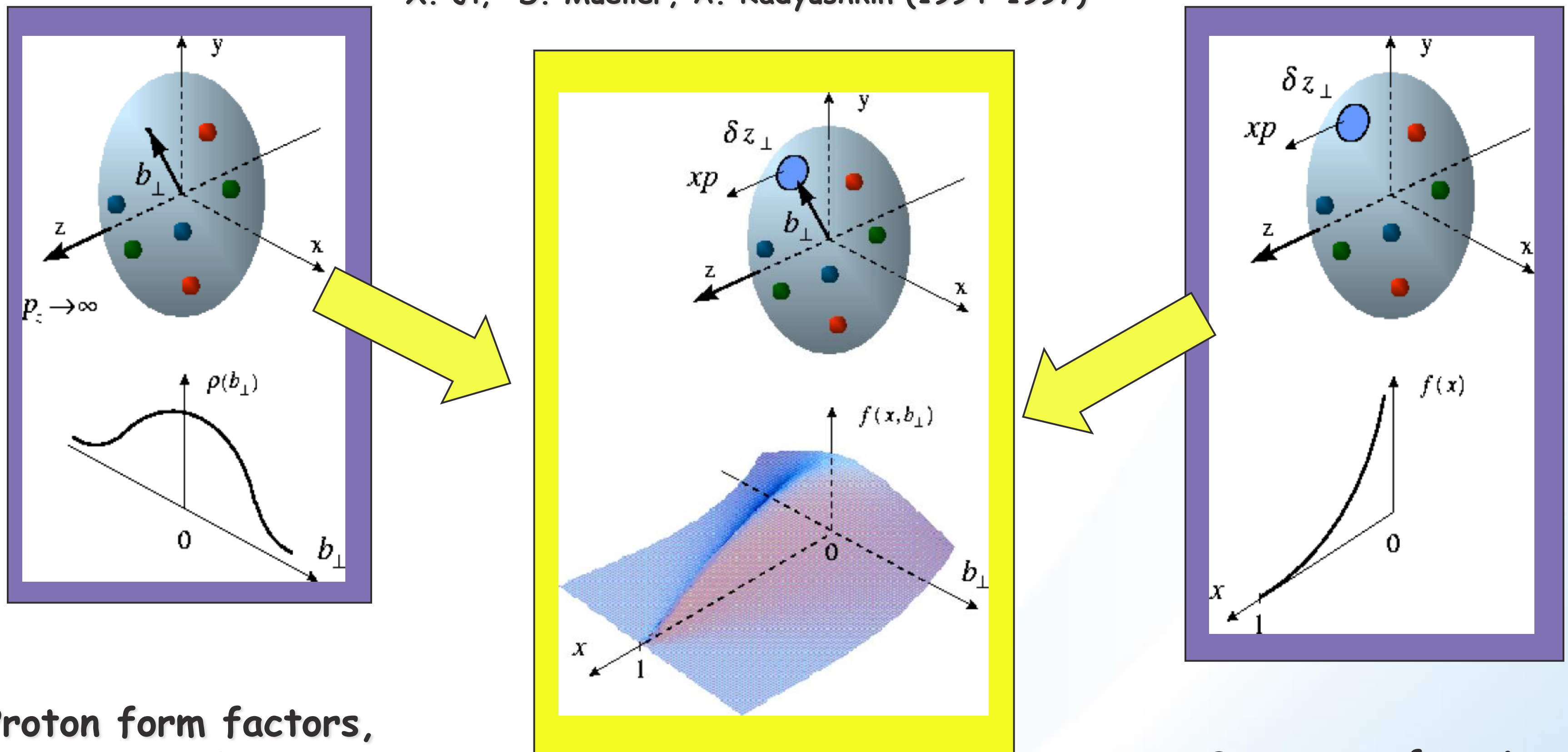
GENERALIZED PARTON DISTRIBUTIONS (GPDs)

or



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

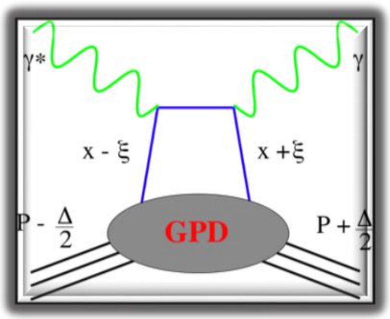
the way to 3d imaging of the proton and the orbital angular momentum L_q & L_g

Constrained through exclusive reactions

How are GPDs characterized?

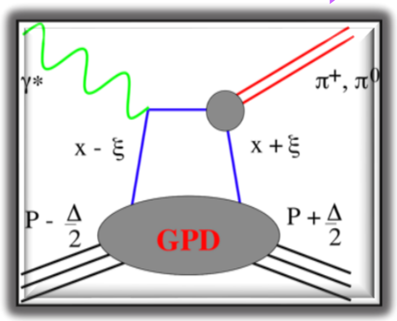
unpolarized	polarized	
$H^q(x,\xi,t)$	$\tilde{H}^q(x,\xi,t)$	conserve nucleon helicity $H^q(x,0,0)=q,\ \tilde{H}^q(x,0,0)=\Delta q$
$E^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$	flip nucleon helicity not accessible in (SI)DIS

quantum numbers of final state
cross sections, SSA, DSA ⇒ select different GPDs



DVCS

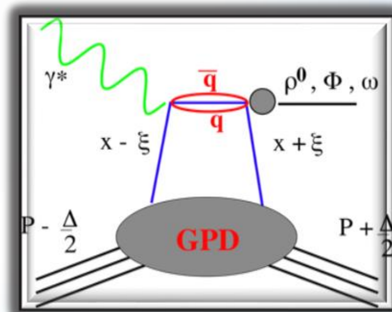
$H^q\quad E^q\quad \tilde{H}^q\quad \tilde{E}^q$



pseudo-scaler mesons

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

π^0	2Δu+Δd
η	2Δu–Δd



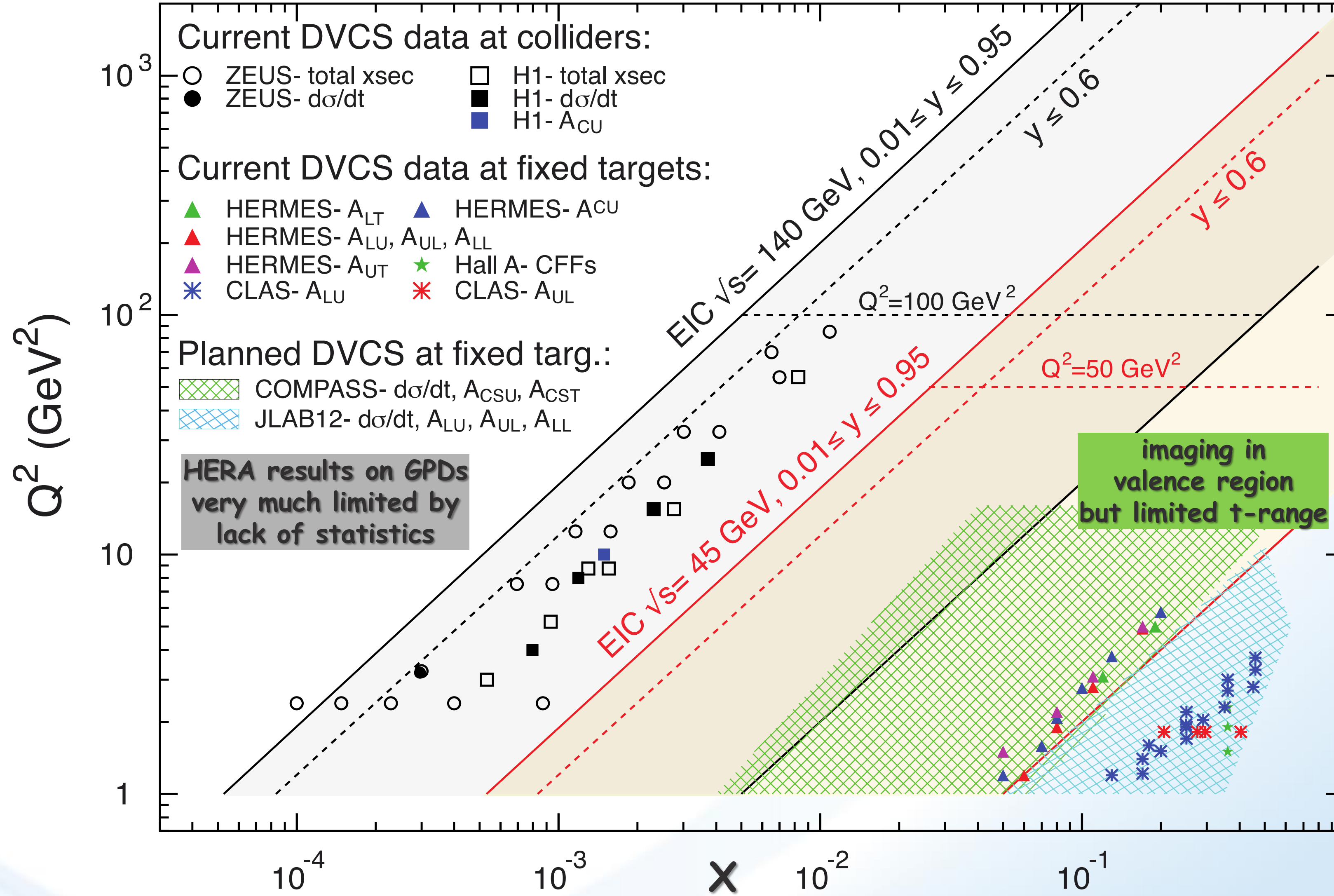
vector mesons

H^q, E^q

ρ^0	2u+d, 9g/4
ω	2u-d, 3g/4
ϕ	s, g
ρ^+	u-d
J/ψ	g

- $x+\xi$, $x-\xi$ long. mom. fract.
- $t = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$

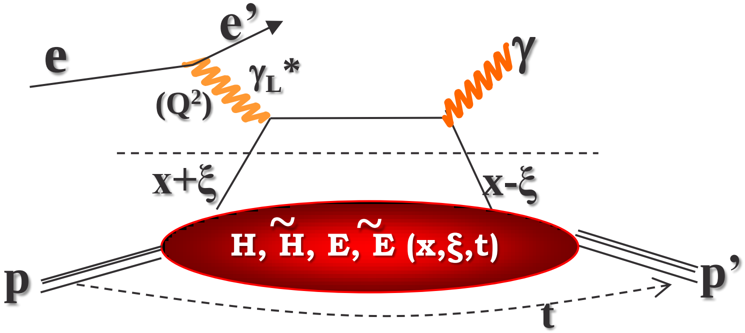
THE DVCS PHASE SPACE



quantum numbers of final state → selects different GPD

DVCS: wide range of observables (σ, A_{UT}, A_{LU}, A_{UL}, A_C) to disentangle GPDs

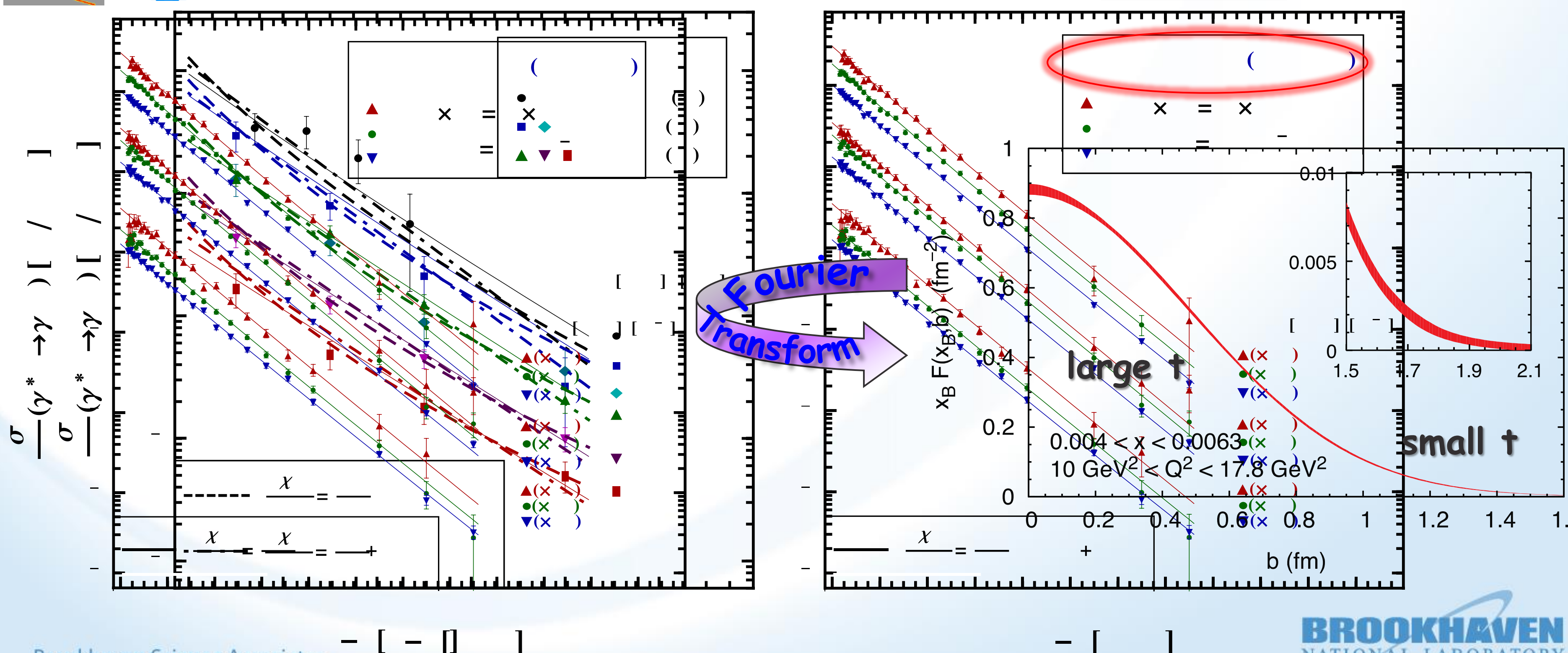
DVCS AT eRHIC



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

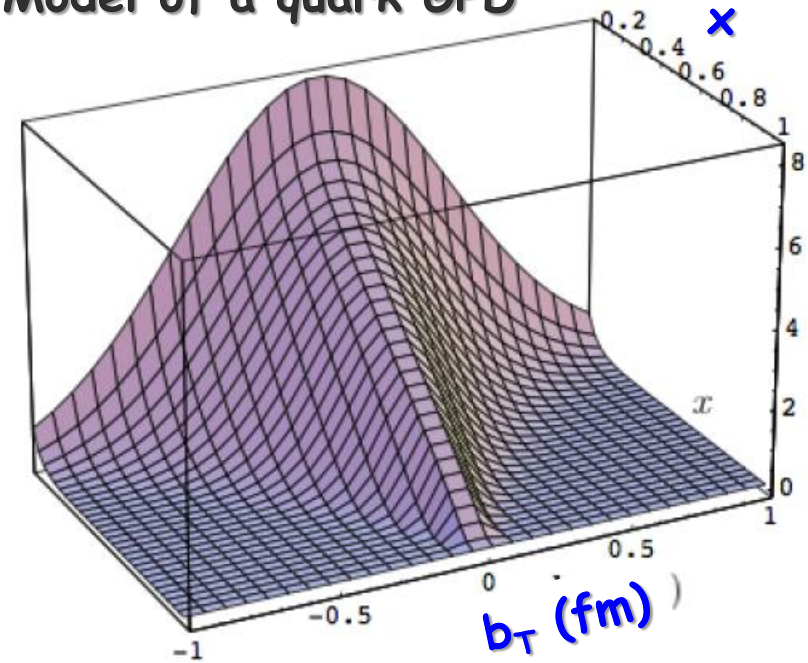
DVCS data at end of HERA

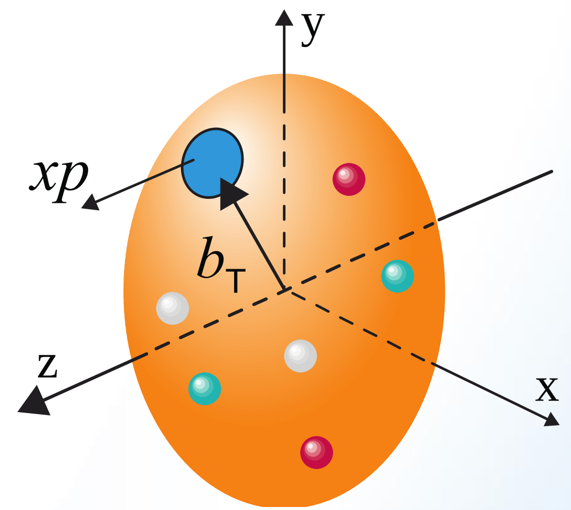
D. Mueller, K. Kumericki
S. Fazio, and ECA
arXiv:1304.0077



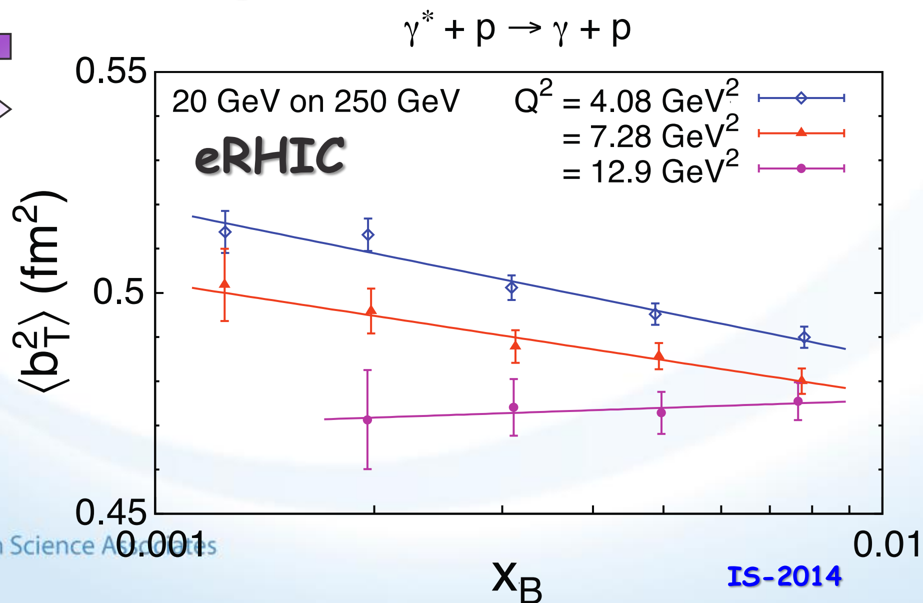
WHAT CAN WE LEARN

Model of a quark GPD





b_T decreasing as a function of x



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

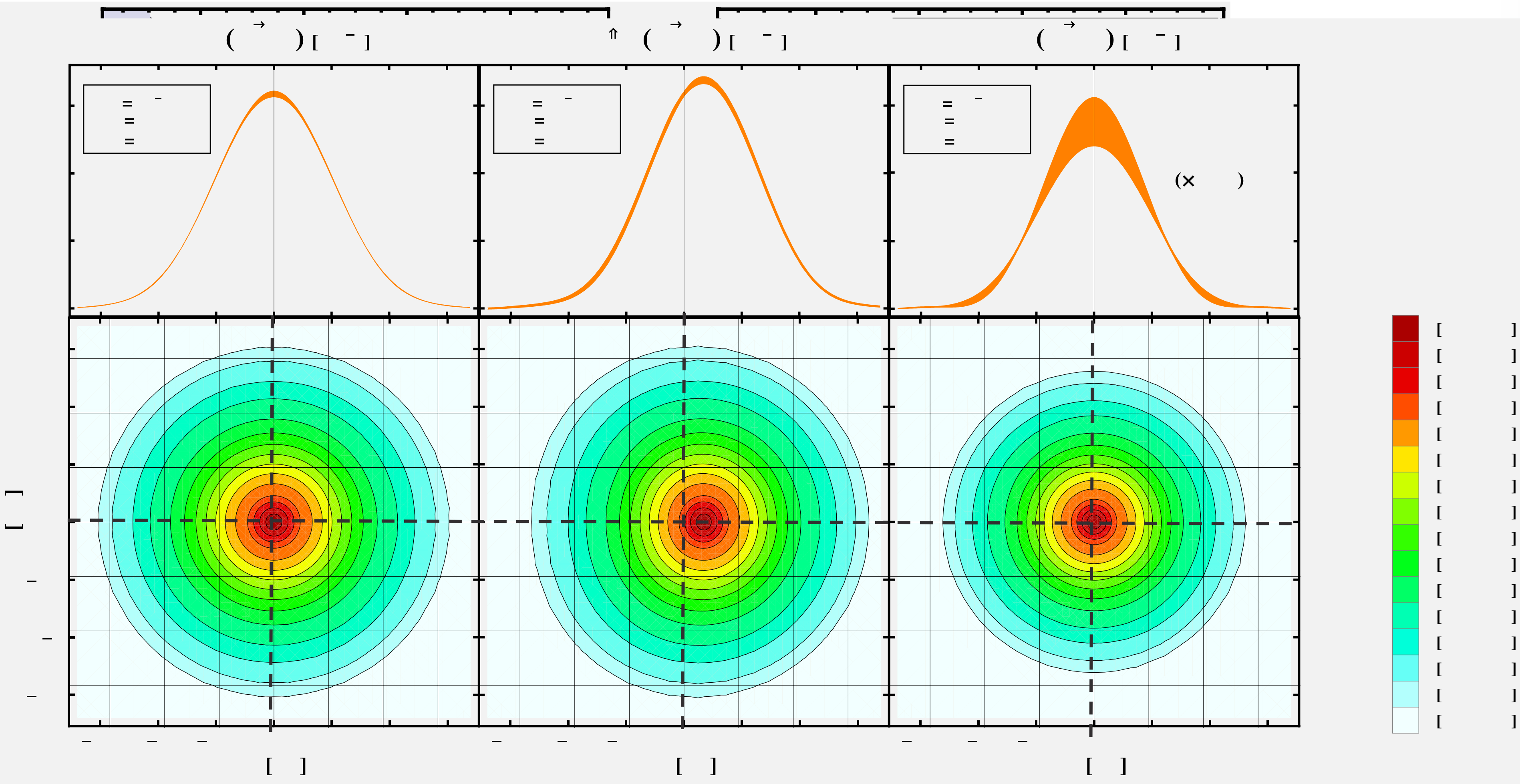
Sea (small x) quarks at the perifery → high b_T

GLUONS ???

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

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

arXiv:1304.0077

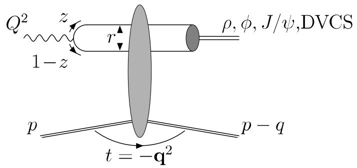


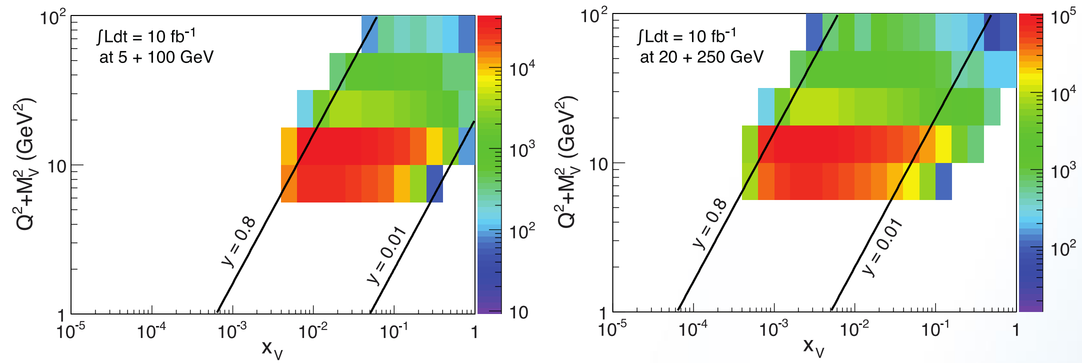
GPD H and E 2d+1 structure for sea-quarks and gluons

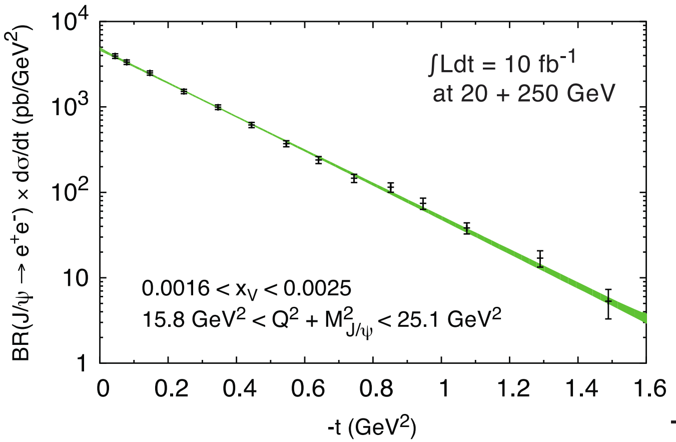
- Excellent reconstruction of H^{sea}, H^{val} and good reconstruction of H^g (from $d\sigma/dt$)

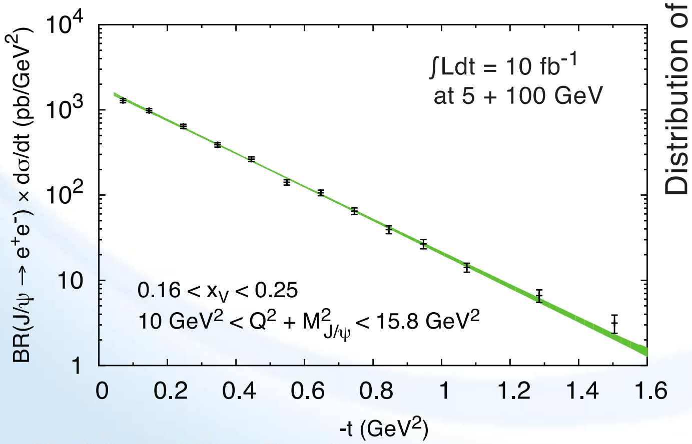
To improve imaging on gluons add J/ψ observables

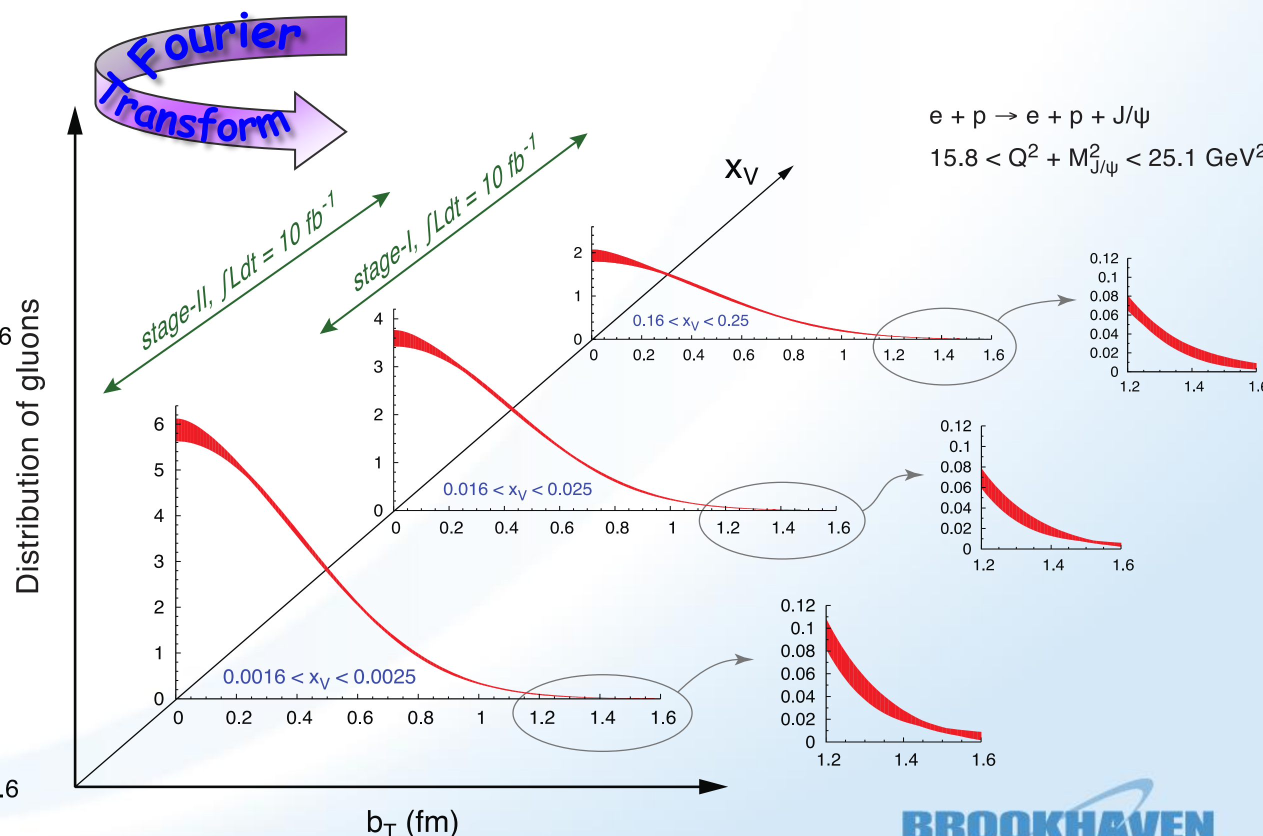
- ❑ cross section
- ❑ A_{UT}
- ❑ …..



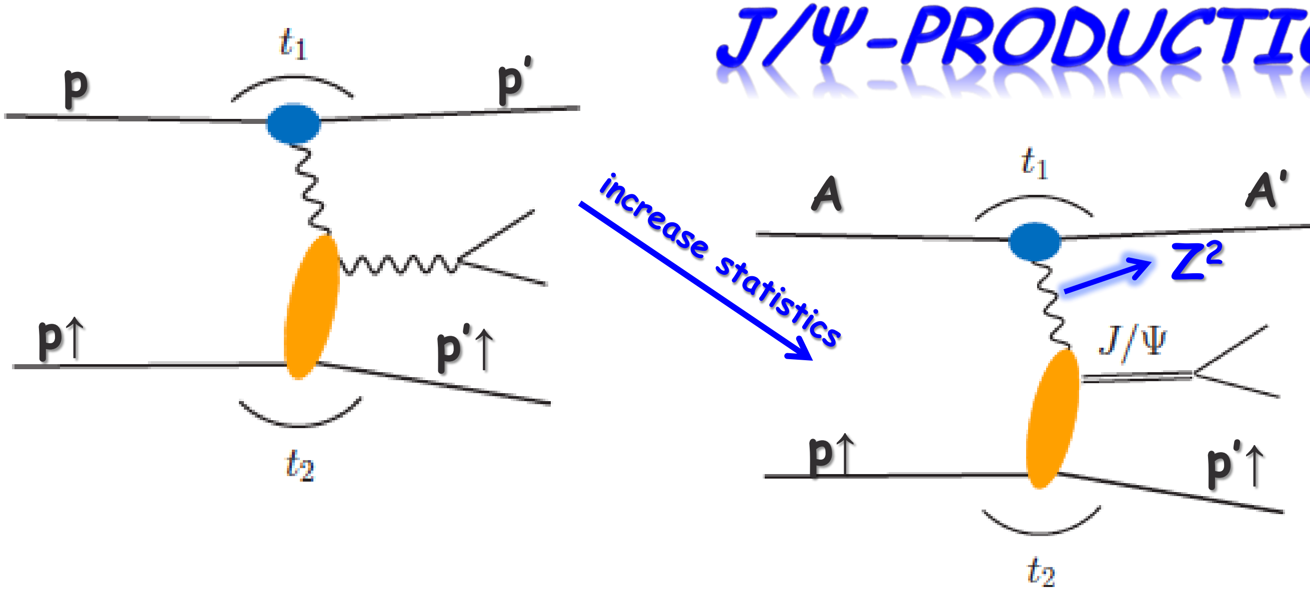








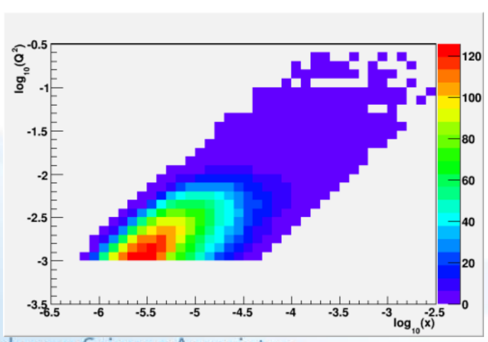
J/Ψ-PRODUCTION: UPC IN pA

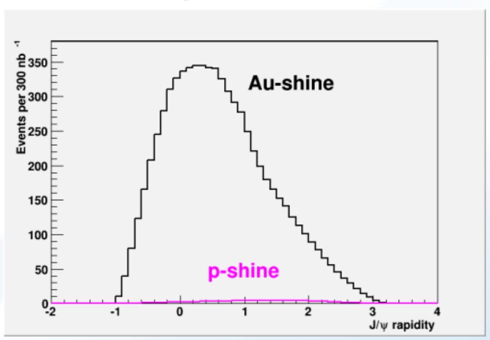


- transverse target spin asymmetry → calculable with GPDs

$$A_{UT}(t,\tau) \sim \frac{\sqrt{t_0 - t}}{m_p} \frac{\mathrm{Im}(E^* H)}{|H|} \qquad \tau = \frac{M^2_{J/\Psi}}{s}$$

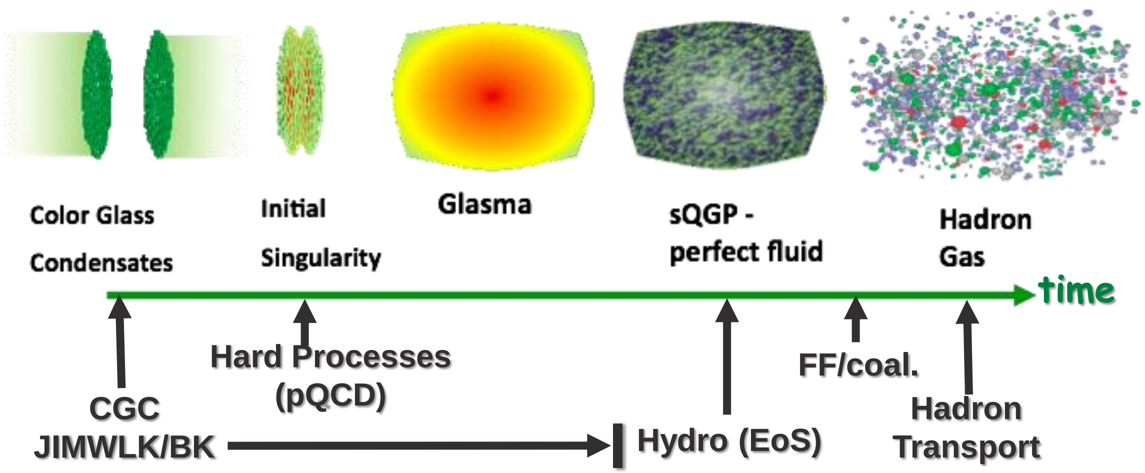
- information on helicity-flip GPD **E** for gluons
  golden measurement for eRHIC
- Estimates for J/ψ (hep-ph/0310223)

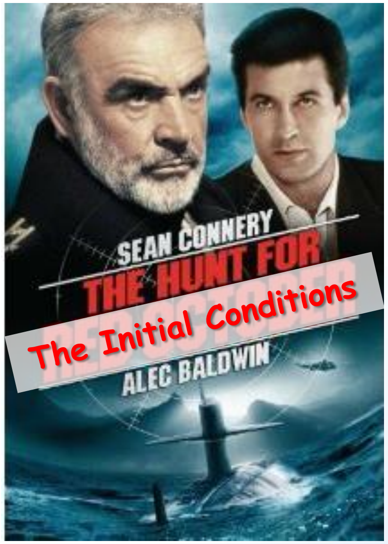




Required:
2015 p+A 300 nb^{-1}
RP-Phase II*
→ 7k J/ψ

SPATIAL IMAGING OF NUCLEI





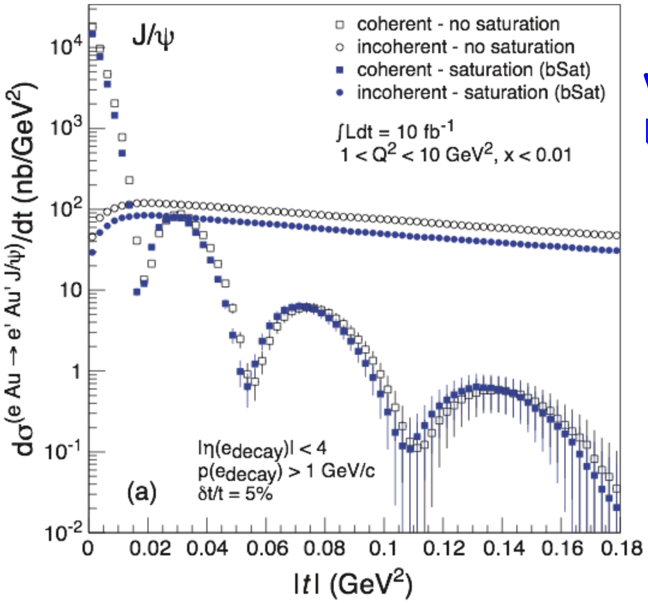
Our understanding of some **fundamental** properties of the Glasma, sQGP and Hadron Gas depend **strongly** on our knowledge of the initial state!

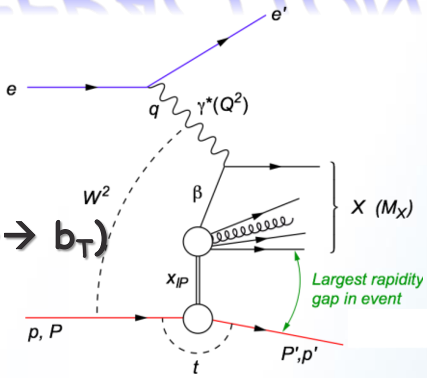
3 conundrums of the initial state:

1. What is the spatial transverse distributions of nucleons and gluons?
2. How much does the spatial distribution fluctuate? Lumpiness, hot-spots etc.
3. How saturated is the initial state of the nucleus?
   → unambiguously see saturation

IMAGING IN eA: DIFFRACTION

- Hard diffraction at small x





Why is diffraction so important

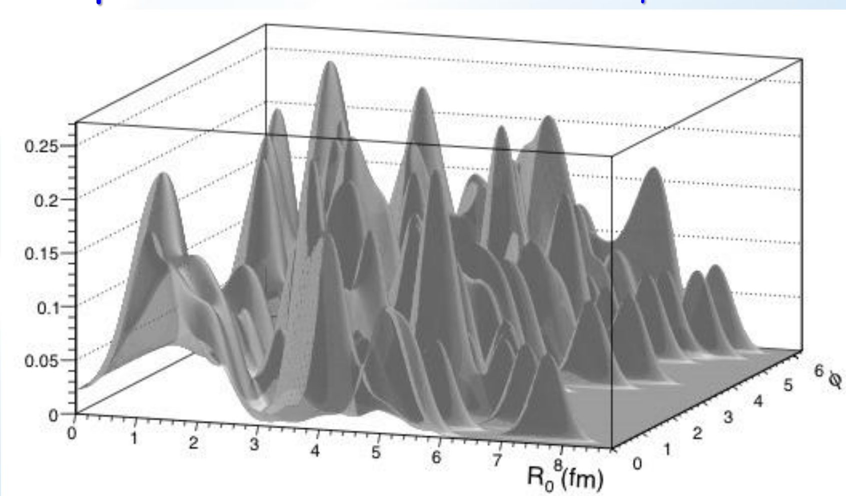
- Sensitive to spatial gluon distribution ($t \leftrightarrow b_T$)

$$F(b) \sim \frac{1}{2\pi}\int_0^\infty d\Delta \Delta J_o(\Delta b)\sqrt{\frac{d\sigma}{dt}}$$

$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)

  - 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 (fluctuations, hot spots, ...)
- VM: Sensitive to gluon momentum distributions
  - $\sigma \sim g(x,Q^2)^2$

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



- Diffraction in e+A:
  - coherent diffraction (nuclei intact)
  - incoherent diffraction breakup into nucleons (nucleons intact)

Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%

HERA: 15% of all events are hard diffractive

TAKE AWAY MESSAGE

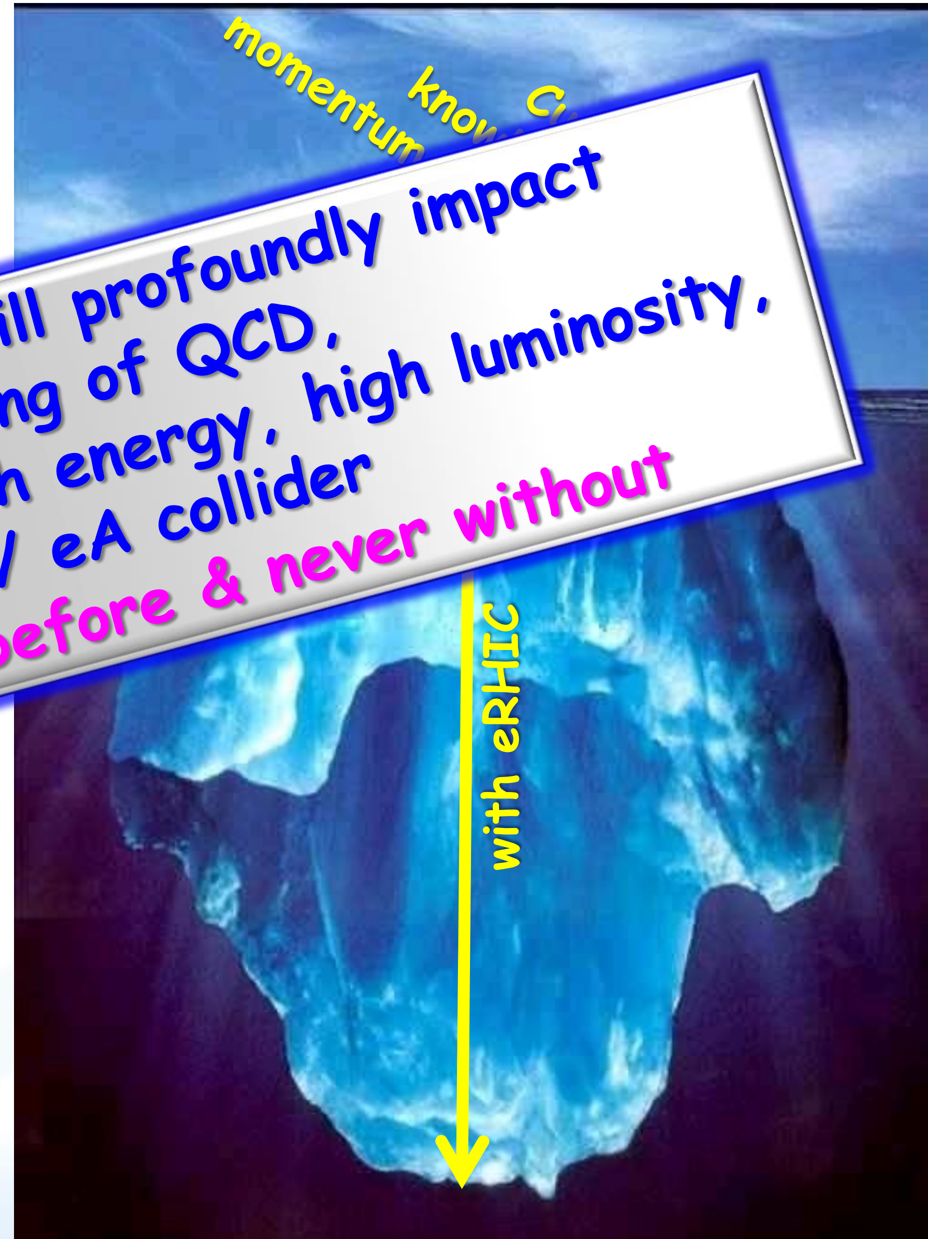
The eRHIC will profoundly impact our understanding of QCD with its high energy, high luminosity eA and polarized ep collisions

"all stars align":

- th…
- c…
  h… …larized
  ep…
- de… …nologies allow for a col…er detector with high resolution, wide acceptance and particle ID in the entire η range

eRHIC science program will profoundly impact our understanding of QCD, uniquely tied to a future high energy, high luminosity, polarized ep / eA collider

never been measured before & never without

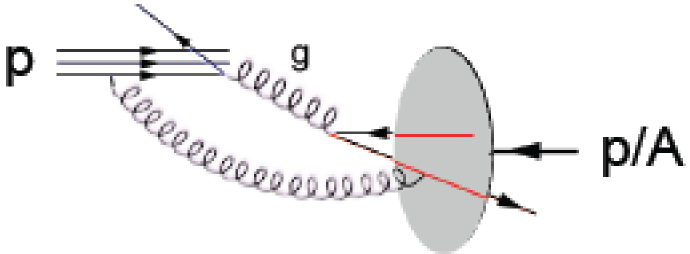


Additional material:
https://wiki.bnl.gov/eic/index.php/Publications_and_presentations#Publications

ADDITIONAL MATERIAL

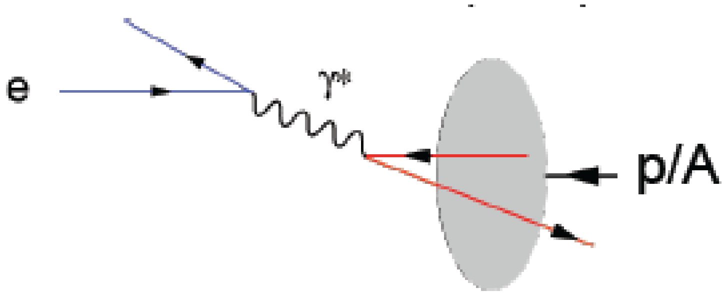
p+A COMPARED TO e+A

Hadron-Hadron:



- probe has structure as complex as the "target"
- More direct information/access on the response of a nuclear medium to gluon probe
- Soft color interactions before the collision can alter the nuclear wave fct. and destroy universality of parton properties (break factorization)
- no direct access to parton kinematics

Electron-Hadron:

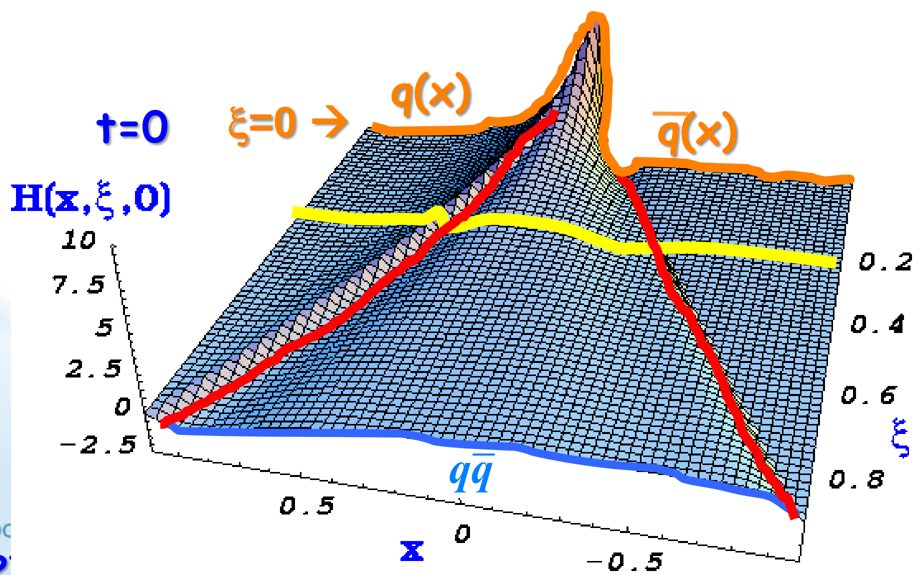


- Point-like probe
- High precision & access to partonic kinematics through scattered lepton (x, Q^2)
- Dominated by single photon exchange
  → no direct color interaction
  → preserve the properties of partons in the nuclear wave function
- Nuclei always "cold" nuclear matter
- eA experimentally much cleaner
  - no "spectator" background to subtract
- initial and final state effects can be disentangled cleanly
- Saturation:
  - no alternative explanations,
  - i.e. no hydro in eA

ACCESSING GPDS: SOME CHALLENGES

- $H(x,\xi,t)$ but only ξ and t accessible experimentally
  x is not accessible → integrated over
- apart from the cross-over trajectory (x=ξ) GPDs are not directly accessible
  de-convolution needed
  outer regions: govern the evolution at the cross-over trajectory
- **GPD moments cannot be fully directly revealed,**
  extrapolations t → 0 are model dependent

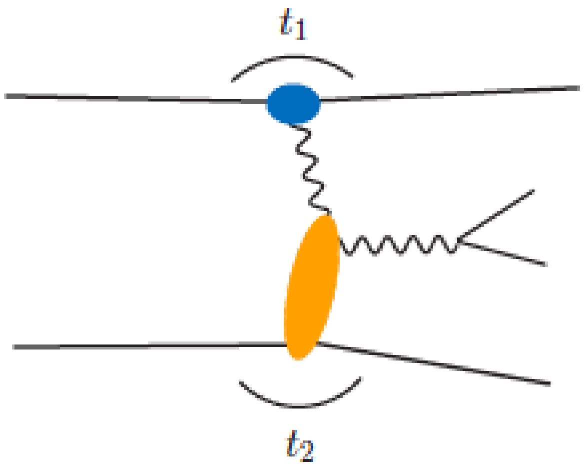
$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$



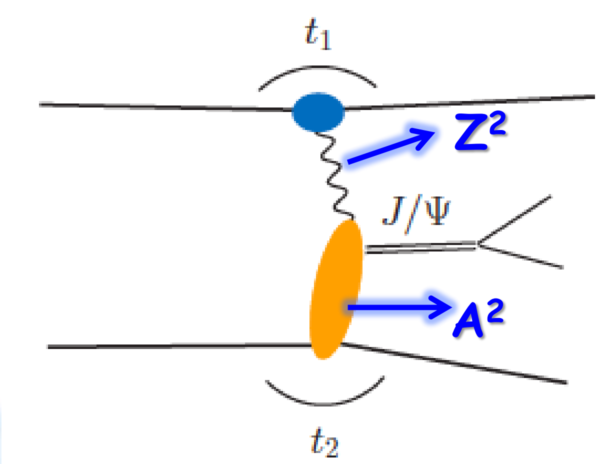
cross sections & beam-charge asymmetry ~ Re(T ^{DVCS})

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

FROM ep TO pp TO γ p/A



- Get quasi-real photon from one proton
- Ensure dominance of g from one identified proton
  by selecting **very** small t_1, while t_2 of "typical hadronic size"
  small t_1 ←→ large impact parameter b (UPC)
- Final state lepton pair ←→ timelike compton scattering
- timelike Compton scattering: detailed access to GPDs
  including $E^{q/g}$ if have transv. target pol.
- Challenging to suppress all backgrounds



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  - Done already in AuAu
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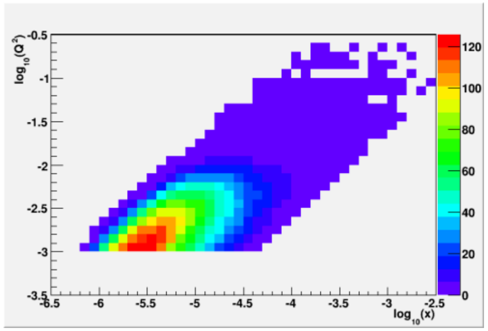
$$A_{UT}(t,t) \sim \frac{\sqrt{t_0 - t}}{m_p} \frac{\text{Im}(E^* H)}{|H|} \qquad t = \frac{M^2_{J/Y}}{s}$$

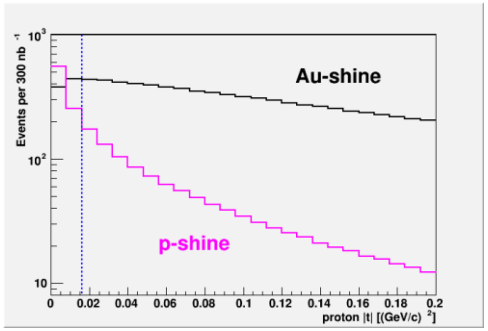
➤ information on helicity-flip distribution **E** for gluons
  golden measurement for eRHIC

Gain in statistics doing polarized p↑A

FROM ep TO pp TO γp/A

UPC in p+Au:





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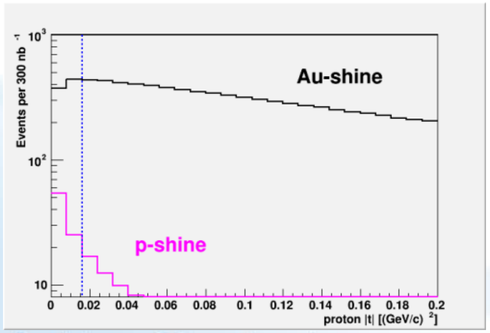
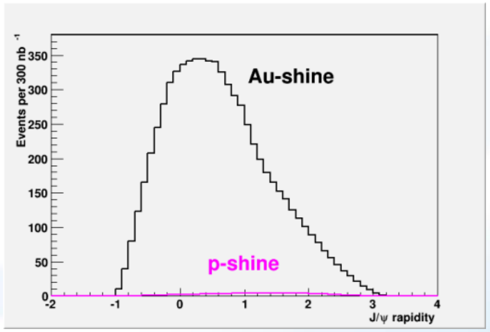
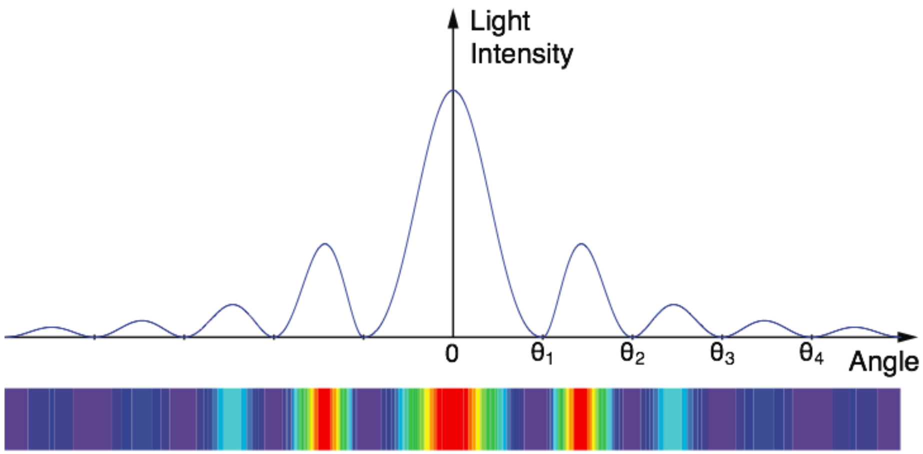


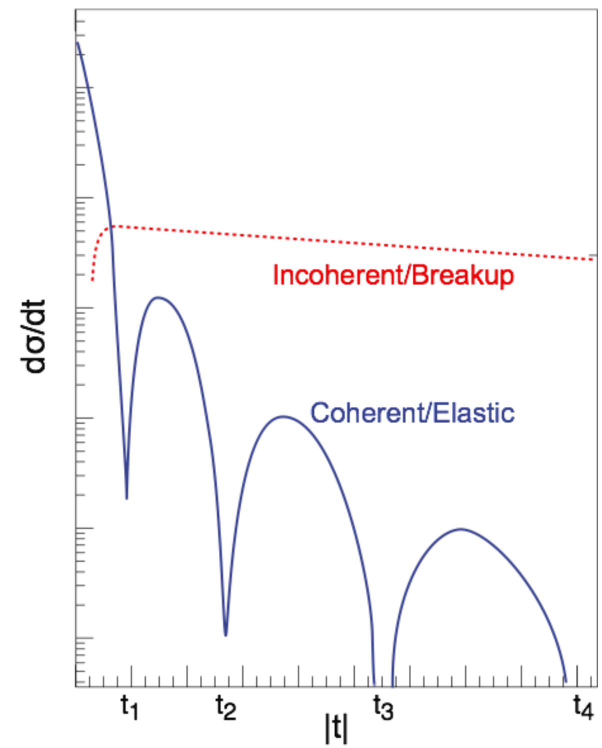


HARD DIFFRACTION IN DIS AT SMALL X

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

Diffraction Analogy: plane monochromatic wave incident on a circular screen of radius R



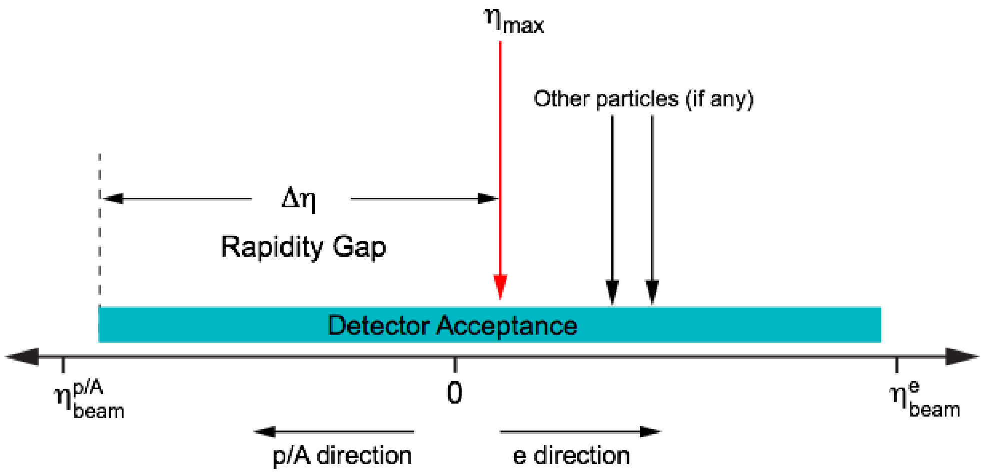


- coherent ⇔ p intact
- incoherent ⇔ breakup of p
- HERA: 15% of all events are hard diffractive

- breakup into nucleons (nucleons intact)
- incoherent diffraction
- Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%

LARGE RAPIDITY GAP METHOD (LRG)

- Identify **Most Forward Going Particle (MFP)**
  - Works at HERA but at higher √s
  - EIC smaller beam rapidities

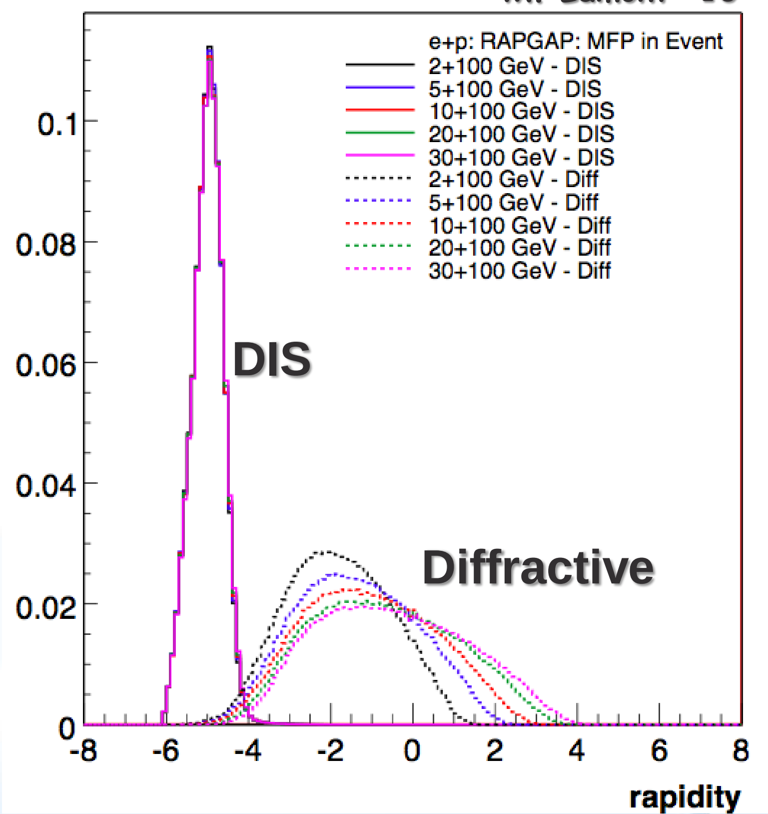


Hermeticity requirement:

- needs just to detector presence
- does not need momentum or PID
- simulations: √s not a show stopper for EIC (can achieve 1% contamination, 80% efficiency)

Diffractive ρ^0 production at EIC: η of MFP

M. Lamont '10



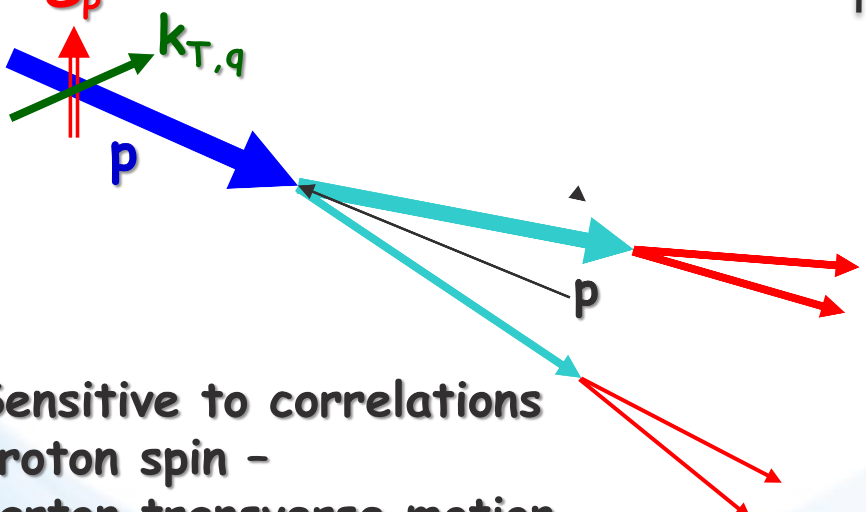
A_N: HOW TO GET TO THE UNDERLYING PHYSICS

measure less inclusive

Initial State	Final State

SIVERS/Twist-3

- A_N for jets, direct photons
- A_N for heavy flavour → gluon
- A_N for $W^{+/-}$, Z^0



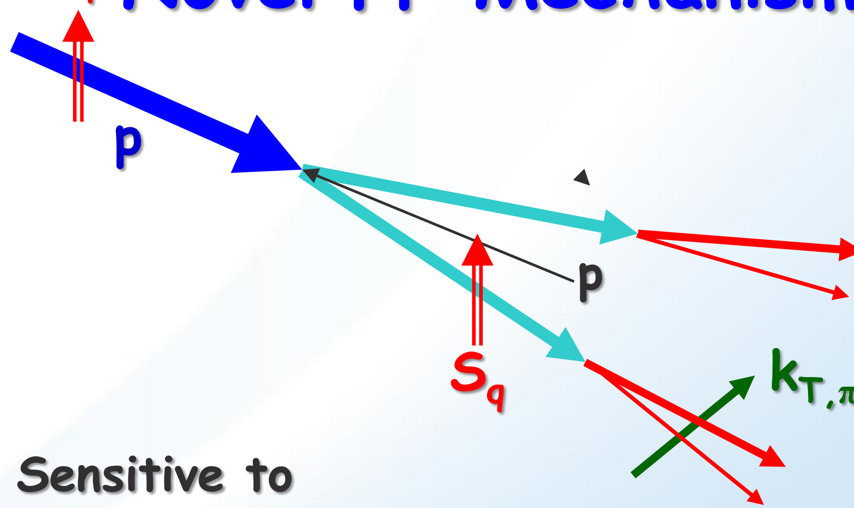
Sensitive to correlations
proton spin –
parton transverse motion

not universal between SIDIS & pp

Collins Mechanism

- asymmetry in jet fragmentation
  - $\pi^{+/-}\pi^0$ azimuthal distribution in jets
  - Interference fragmentation function

S_P Novel FF Mechanisms



Sensitive to
transversity x spin-dependent FF

universal between SIDIS & pp & e+e-

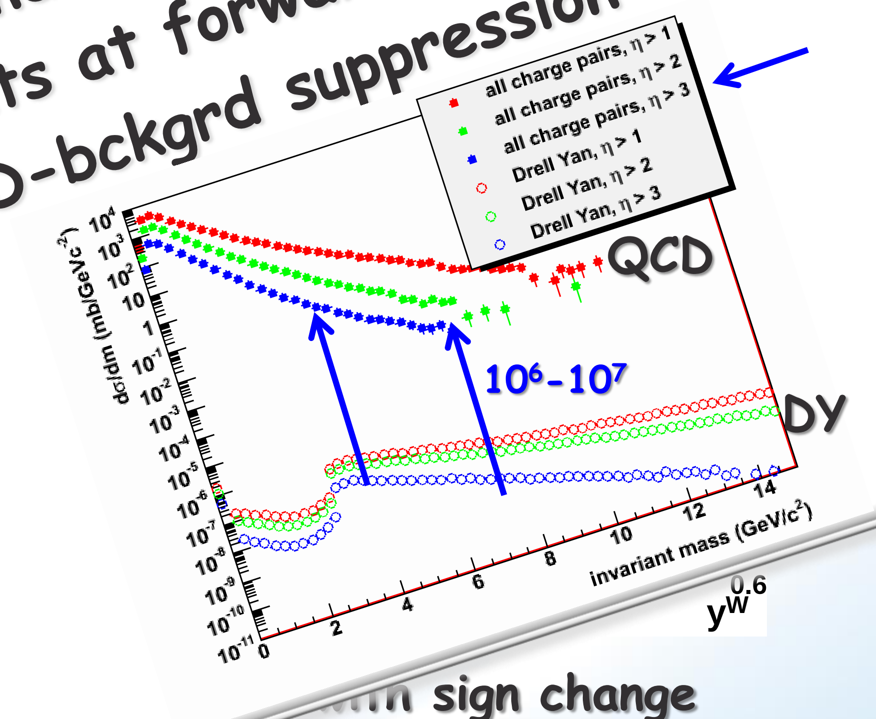
$A_N(W^{+/-}, Z^0)$ PROOF OF PRINCIPAL

S. Fazio
D. Smirnov
E.C. Aschenauer

Remember: Required fully reconstructed W … technique at RHIC

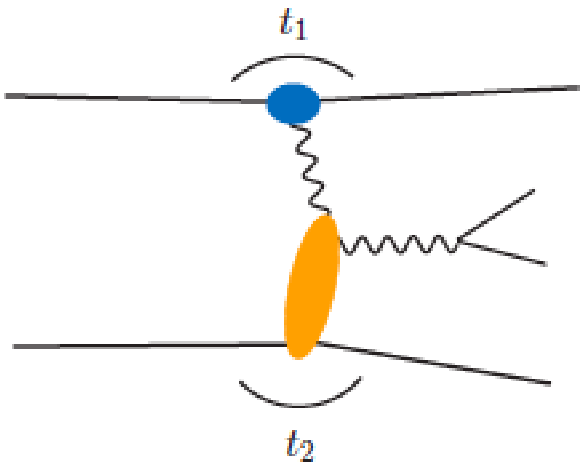
Measuring the sign change through DY

Both PHENIX and STAR are investigating in detail DY measurements at forward rapidities are possible needs QCD-bckgrd suppression of 10^6-10^7



… sign change

FROM ep TO pp TO γp/A



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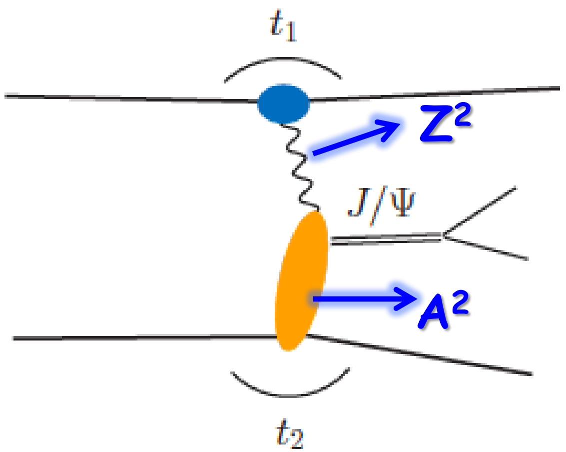

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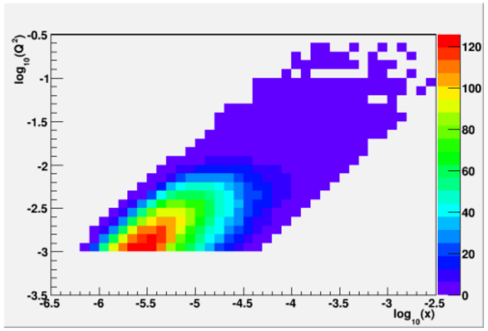
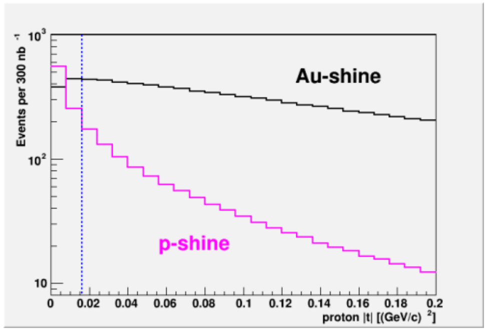
➢ information on helicity-flip distribution E for gluons
  golden measurement for eRHIC

Gain in statistics doing polarized p↑A

UPC in p+Au:





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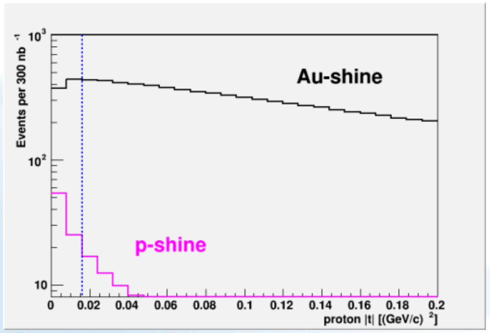
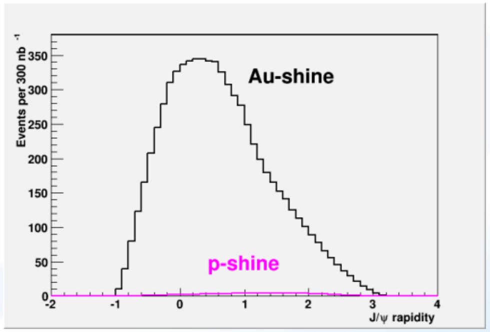
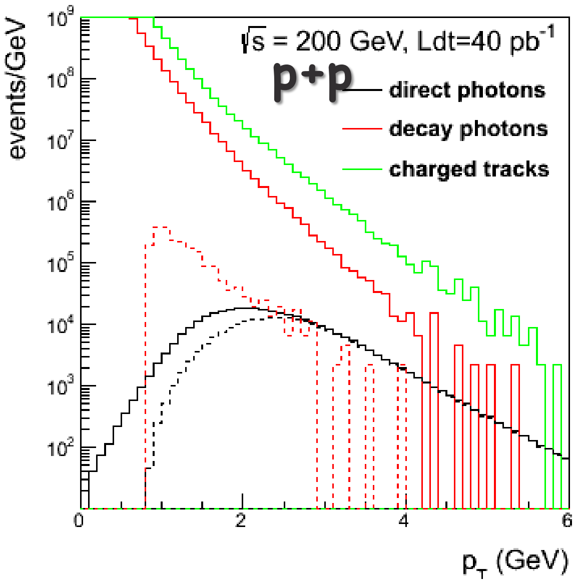
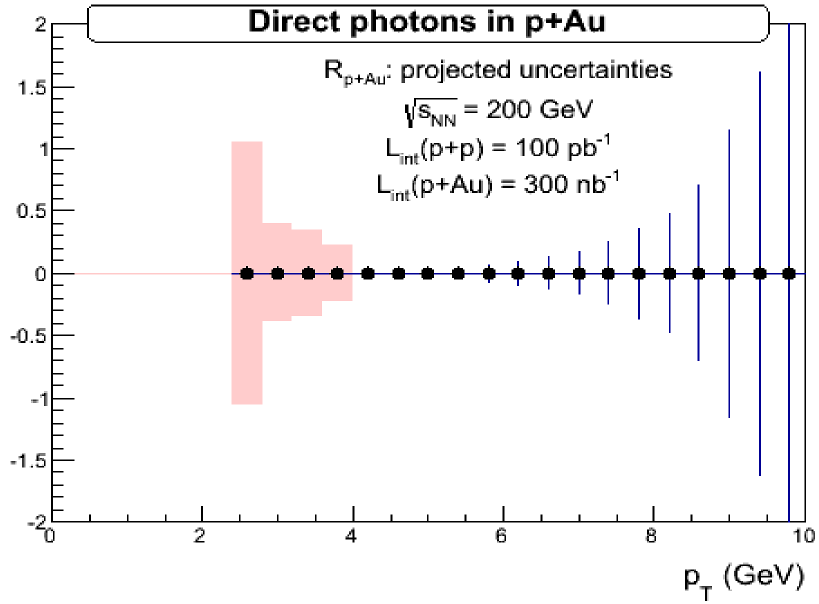




nuclear PDFs

Direct Photon R_{pAu}:

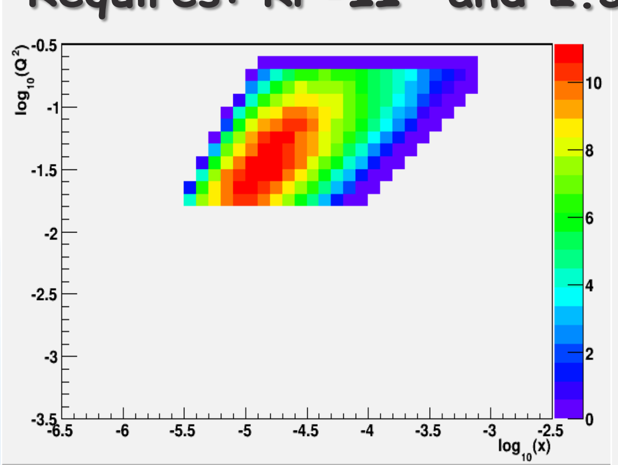


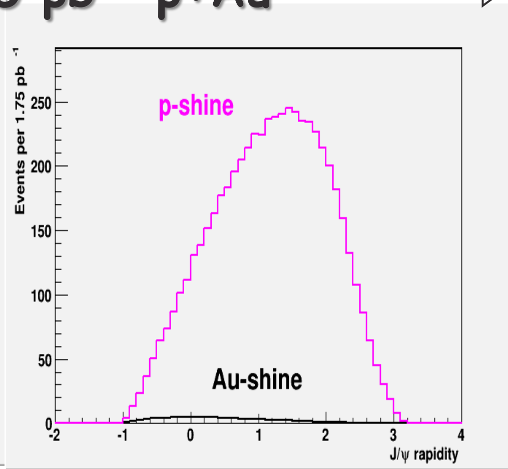


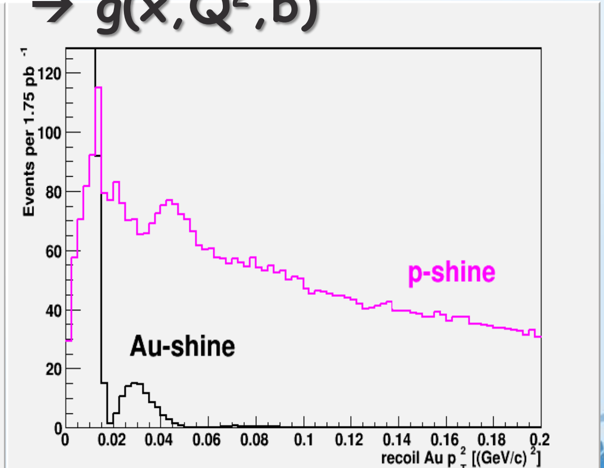
2015
required: FPS + FMS

2020+ UPC: "proton-shine"-case:
Requires: RP-II* and 2.5 pb^{-1} p+Au

Fourier transform of σ vs. t → $g(x,Q^2,b)$

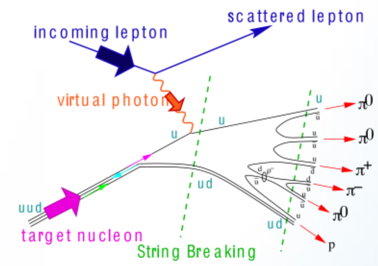


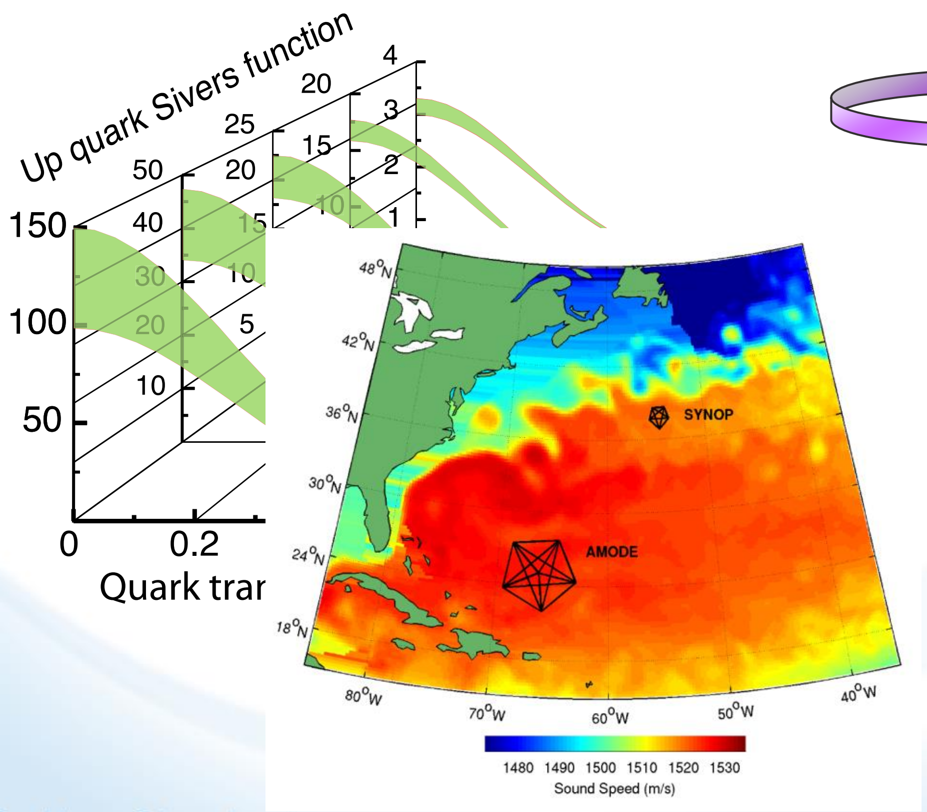




MULTI-PARTON CORRELATIONS IN p_t-SPACE

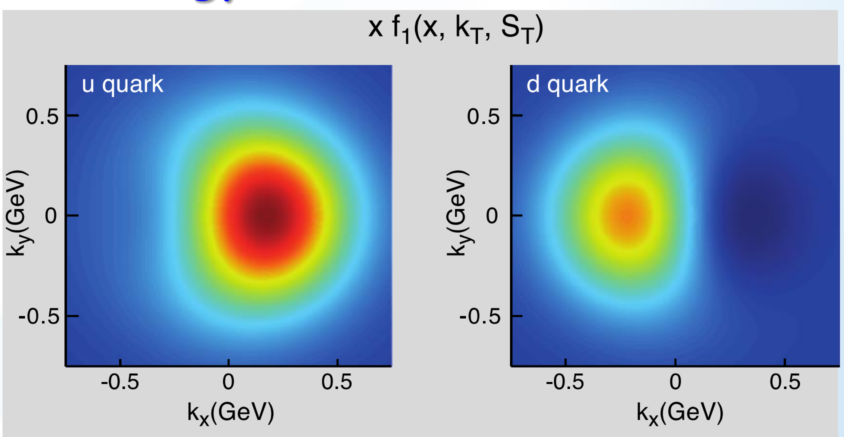
- Utilize the theoretical concepts of transverse momentum distributions (TMDs) and un-integrated PDFs, which encode correlations
  - spin-orbit correlations on parton level → hydrogen atom
  - teach us how colors charges in QCD interact
- **Observable:** azimuthal modulations of 6-fold differential cross section in semi-inclusive DIS $\frac{d\sigma}{dx\,dQ^2\,dz\,d\phi_s\,d\phi_h\,dp_T^h}$





can be viewed as parton flow inside nucleus

analogy: currents in oceans

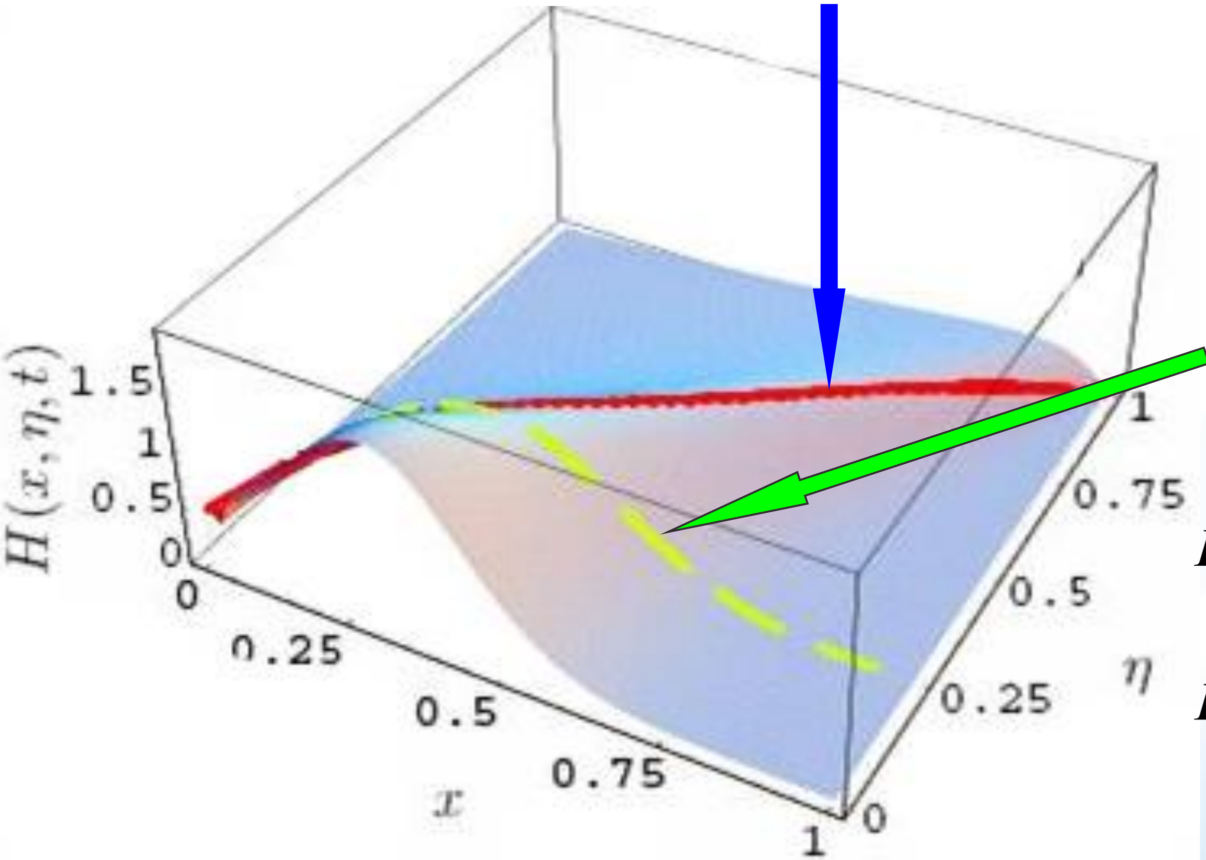


GPD MODELING AND EVOLUTION

outer region governs the evolution at the cross-over trajectory

$$\mu^2 \frac{d}{d\mu^2} H(x,x,t,\mu^2) = \int_x^1 \frac{dy}{x} V(1, x/y, \alpha_s(\mu)) H(x,y,\mu^2)$$

GPD at η = x is `measurable' (LO)



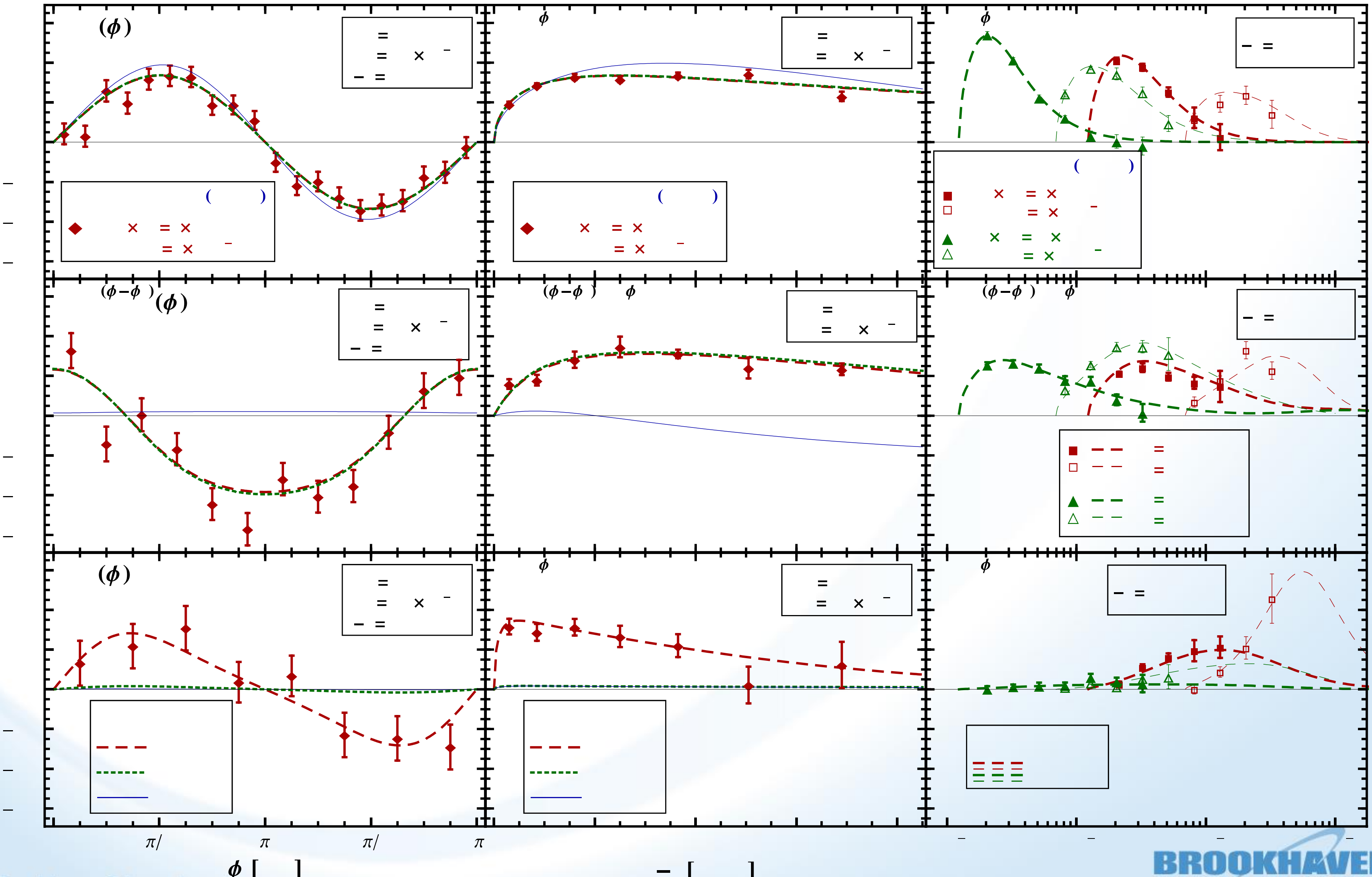
net contribution of outer + central region is governed by a sum rule:

$$PV \int_0^1 dx \frac{2x}{\eta^2 - x^2} H^-(x,\eta,t) =$$

$$PV \int_0^1 dx \frac{2x}{\eta^2 - x^2} H^-(x,x,t) + C(t)$$

DIFFERENT DVCS ASYMMETRIES

arXiv:1304.0077

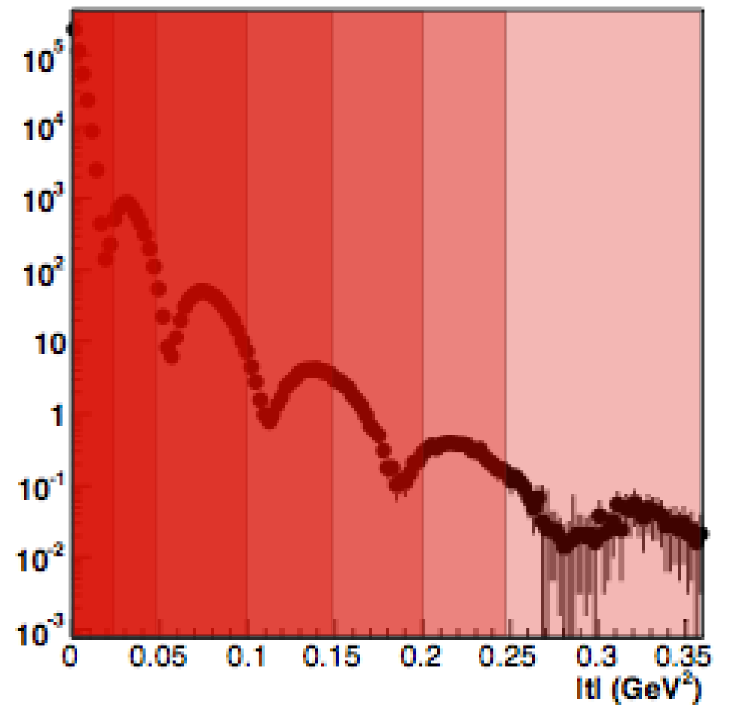


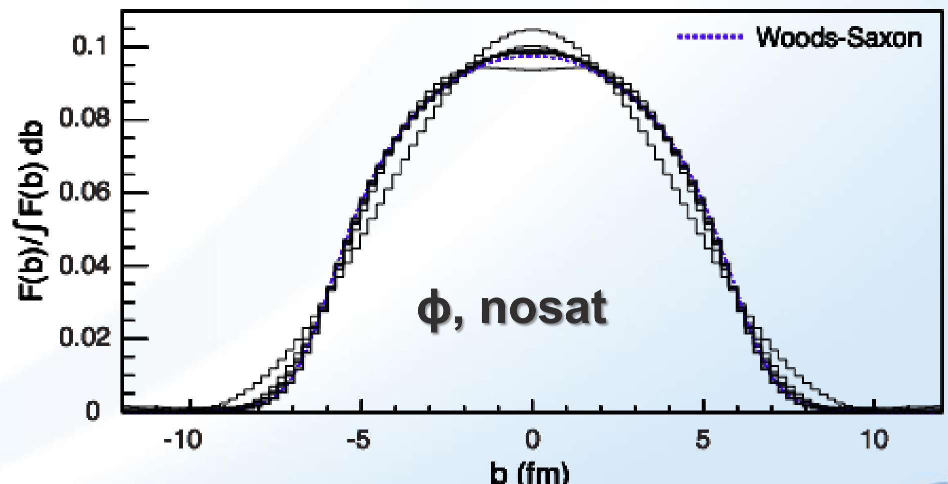
SPATIAL GLUON DISTRIBUTION THROUGH DIFFRACTION

- Idea: momentum transfer t conjugate to transverse position (b_T)
  - coherent part probes "shape of black disc"
  - incoherent part (dominant at large t) sensitive to "lumpiness" of the source (fluctuations, hot spots, ...)

Spatial source distribution: $$F(b) \sim \frac{1}{2\pi}\int_0^\infty d\Delta \Delta J_o(\Delta b)\sqrt{\frac{d\sigma}{dt}}$$

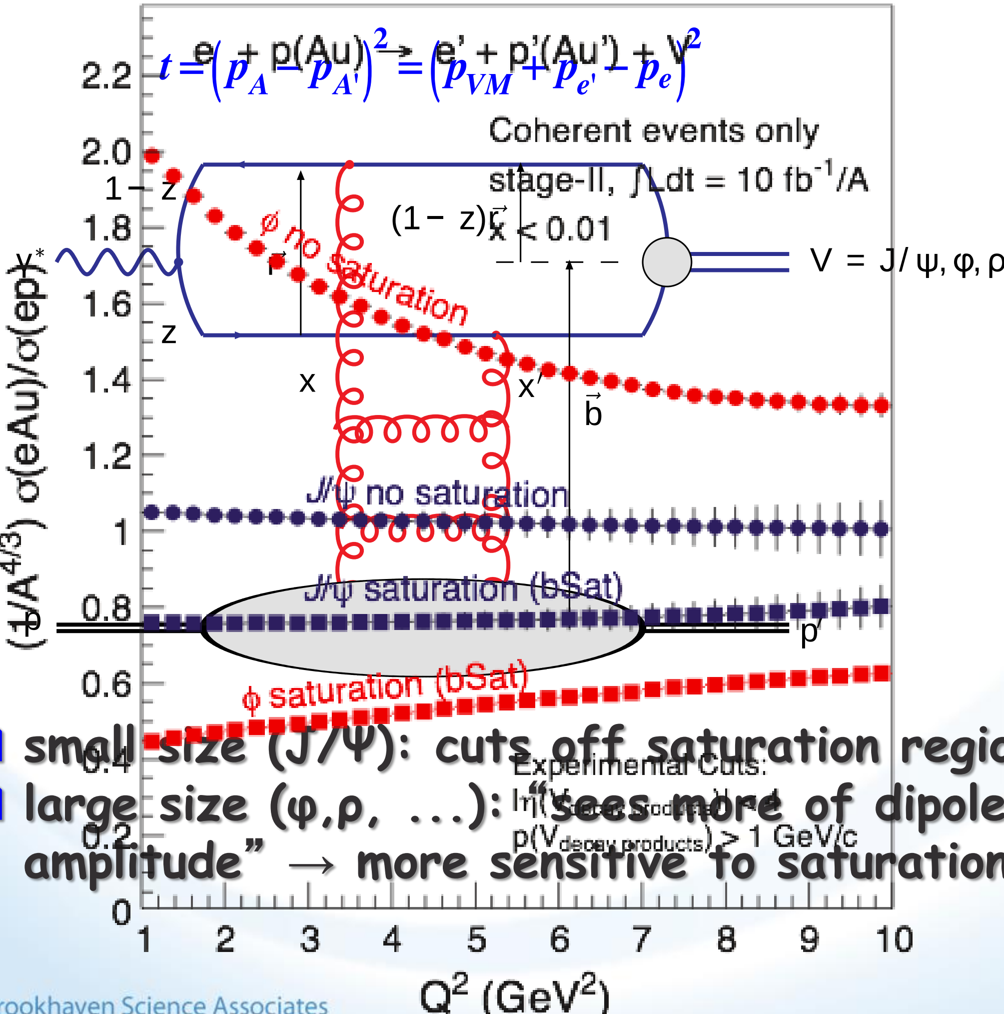
$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)





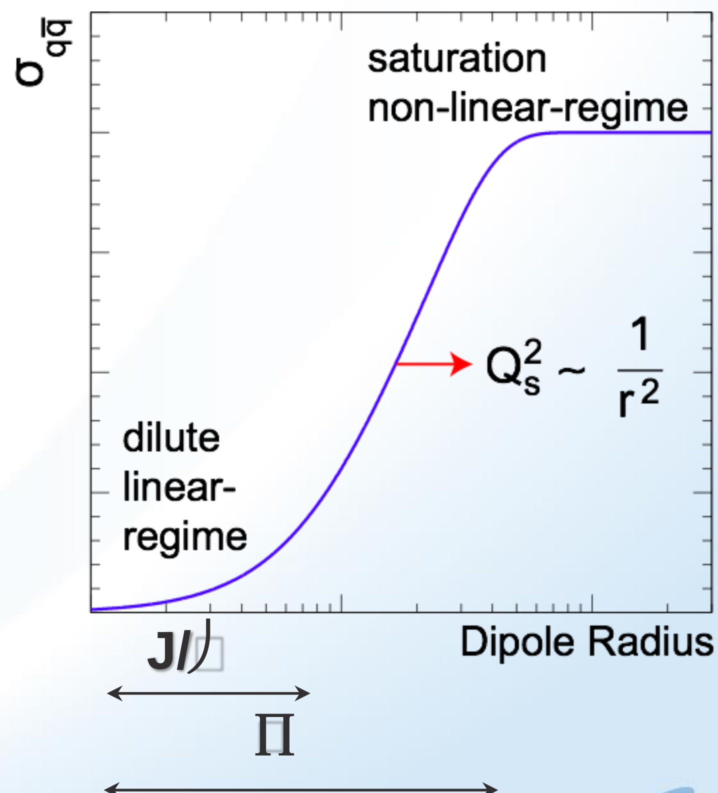
EXCLUSIVE VECTOR MESON PRODUCTION

- Unique probe - allows to measure momentum transfer t in eA diffraction
  - → in general, one cannot detect the outgoing nucleus and its momentum

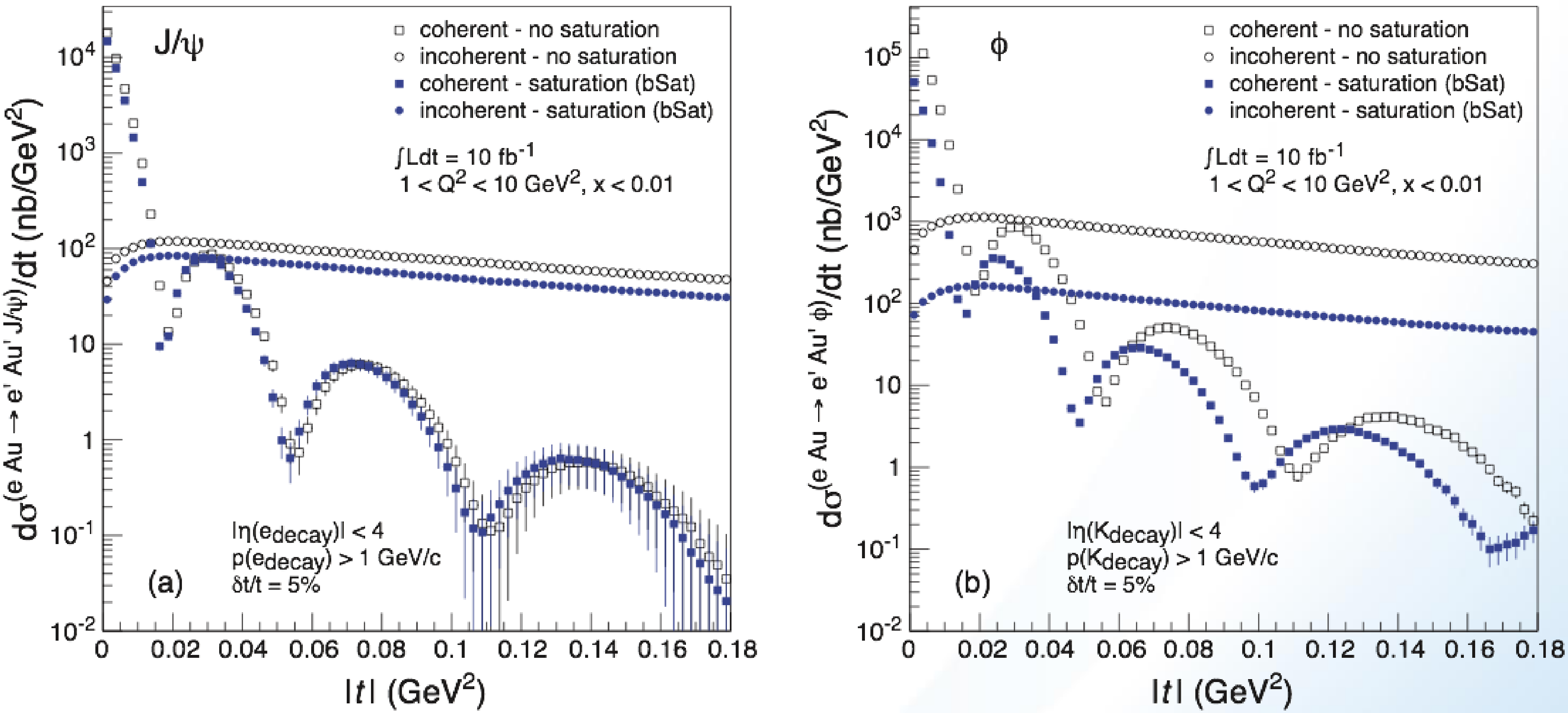


- small size (J/Ψ): cuts off saturation region
- large size (φ,ρ, ...): "sees more of dipole amplitude" → more sensitive to saturation

Dipole Cross-Section:



SPATIAL GLUON DISTRIBUTION THROUGH DIFFRACTION



- Goal: going after the source distribution of gluons through Fourier transform of $d\sigma/dt$
- Find: Typical diffractive pattern for coherent (non-breakup) part
- As expected: J/Ψ less sensitive to saturation effects than larger Φ–meson