RIKEN NiSHiNA CENTER

RIKEN Nishina Center for Accelerator-Based Science

November 11th, 2012

A Quick Tour of the EIC Physics Case

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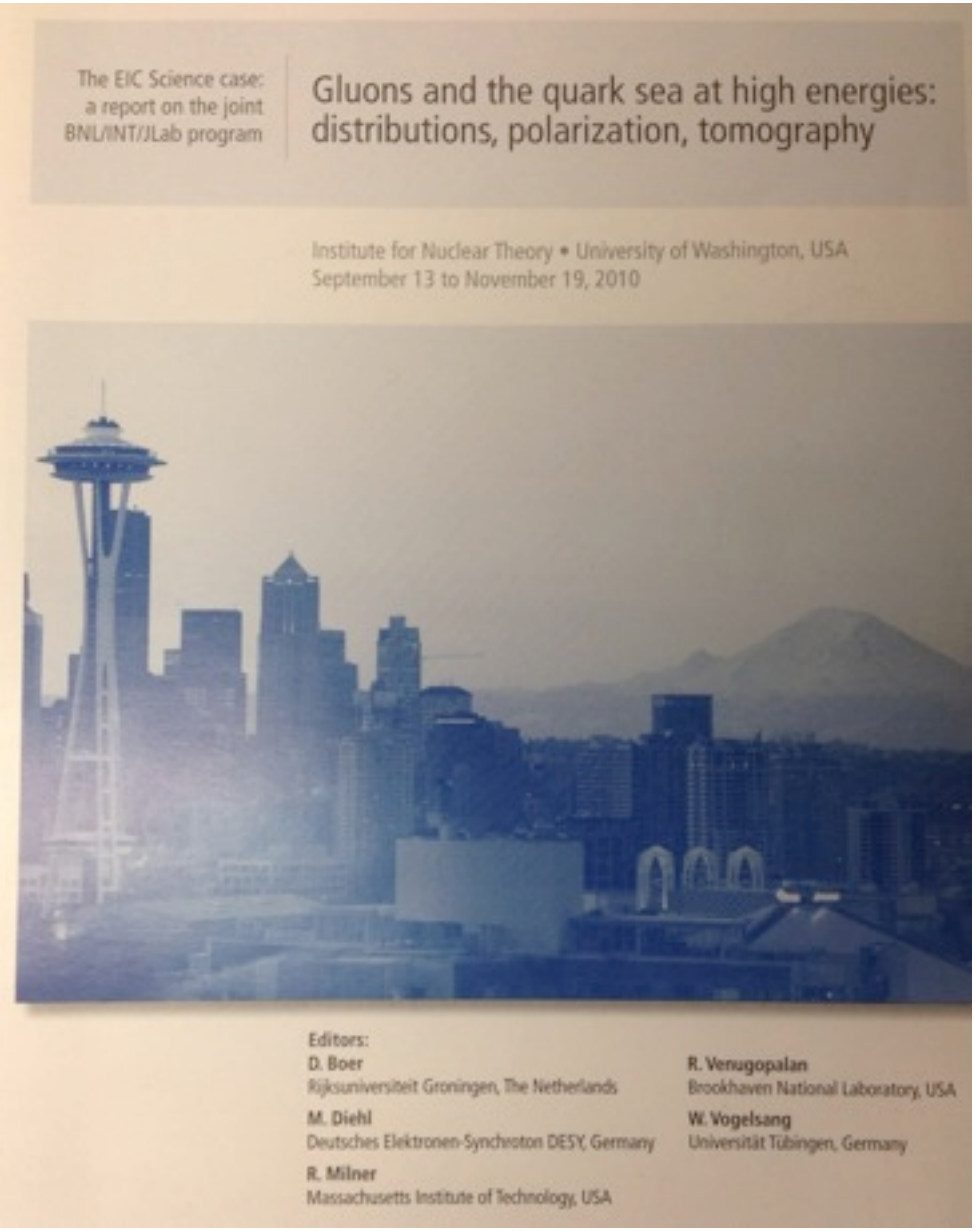
office of SCIENCE U.S. Department of Energy

this talk can only present some highlights of the EIC program



in the absence of the final EIC white paper,
I refer to the **500+ pages** INT report
arXiv:1108.1713

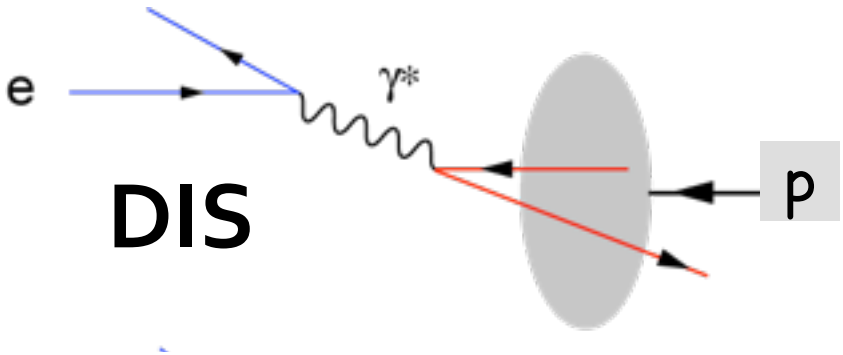
presented results are
mainly due to the efforts of
the EIC task force at BNL
and other supporters of an EIC

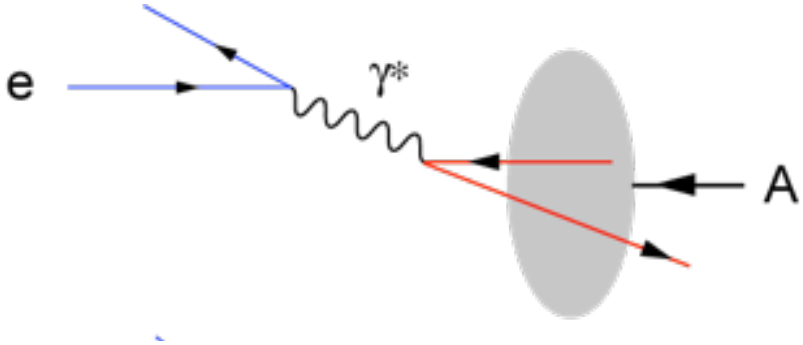
1

inclusive deep-inelastic scattering in ep and eA

what to measure

bread and butter probe at an electron-ion collider





need to measure only the **scattered electron** (its **energy** and **angle**)

- fully determines **two relevant kinematical variables**

  a 3rd variable (**inelasticity y**) is related to x,Q^2 through the available c.m.s. energy

Q^2 : virtuality of exchanged photon

x : momentum fraction of probed parton

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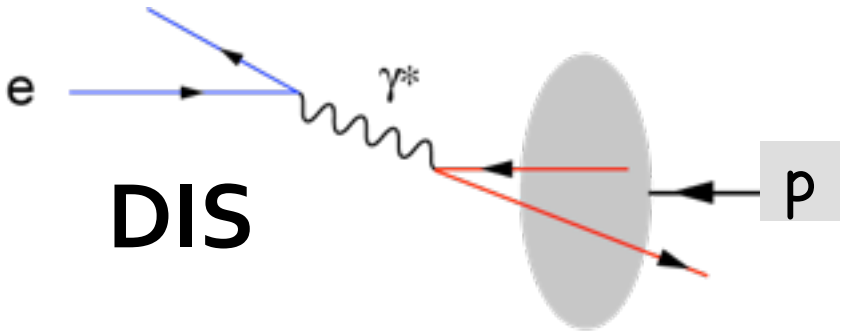

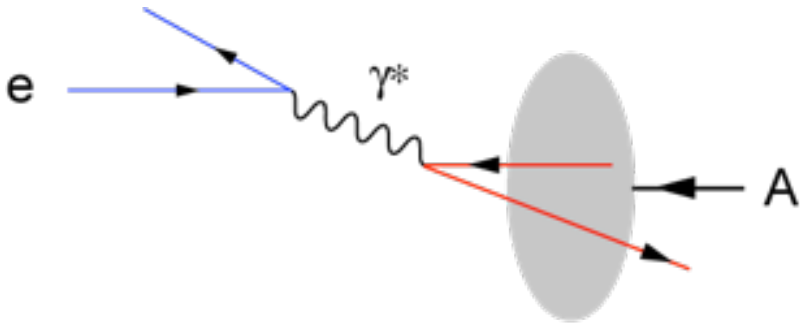

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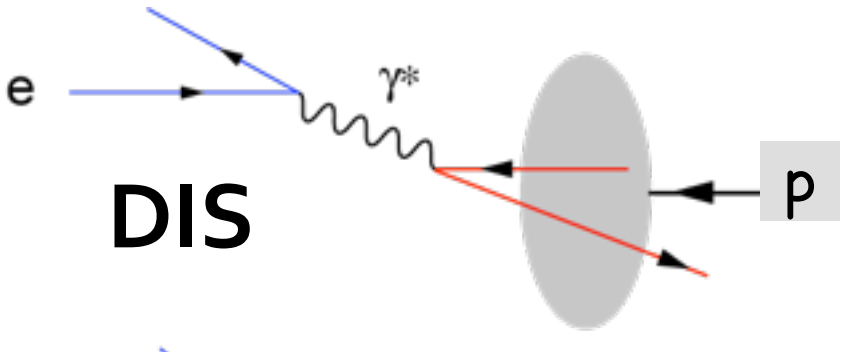

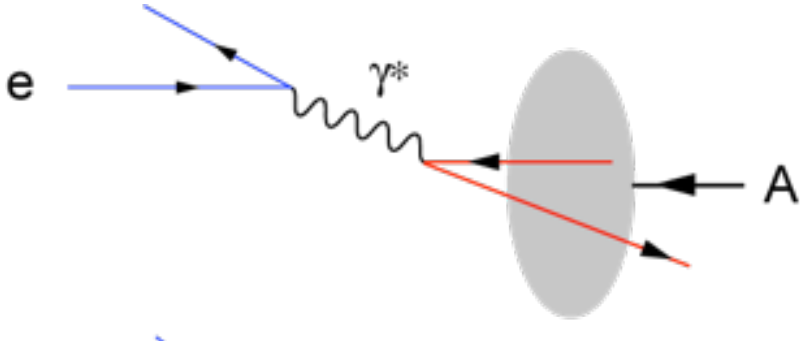

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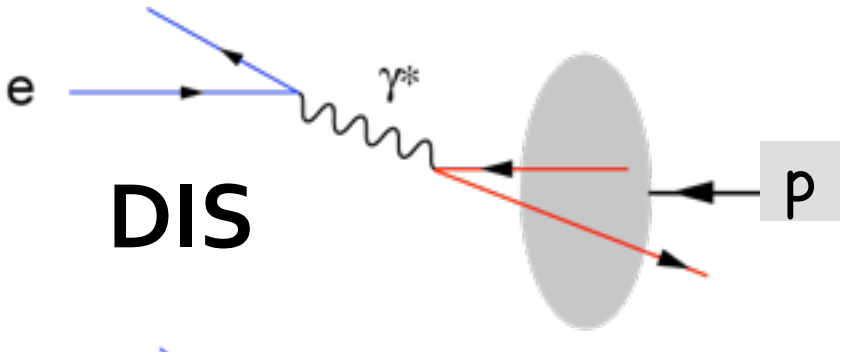

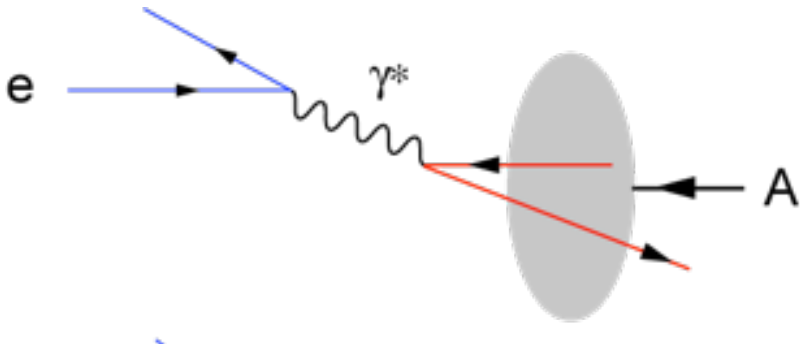

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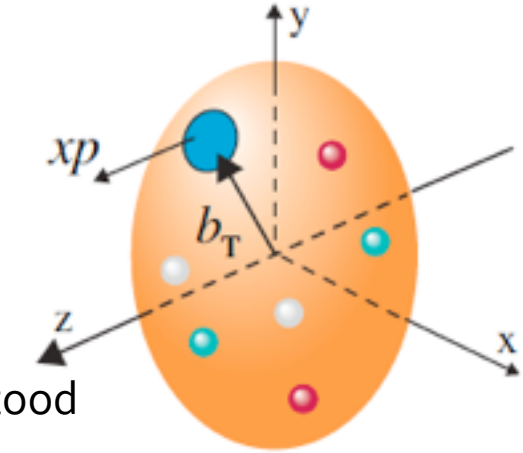
- ☐ need to measure also the polarization (and luminosity) very well

why is this interesting and what can we learn?

DIS measurements are *the* **classic tool** to study the partonic structure of nucleons (nuclei):



- ☑ distribution of partons in longitudinal momentum x
- ☑ **gluon density** from studying Q^2 dependence for fixed x
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- ☐ not so good for separation of quark flavors
- ☐ no information on spatial distribution of partons

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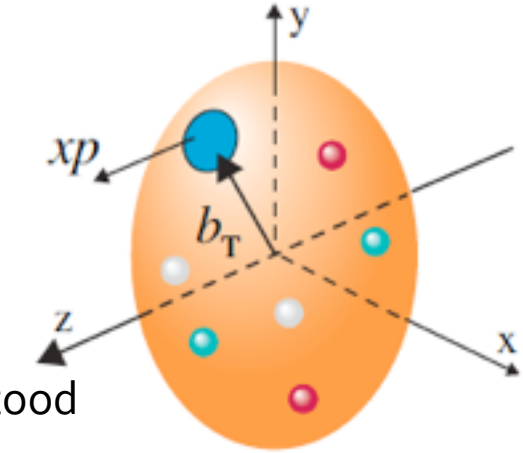

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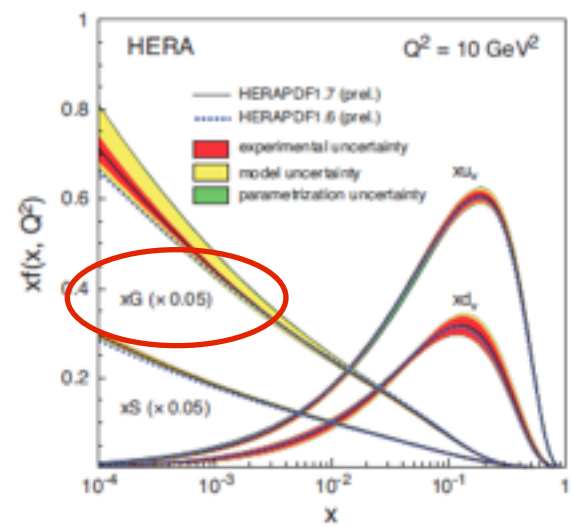

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  - discovered dramatic rise in gluon distribution
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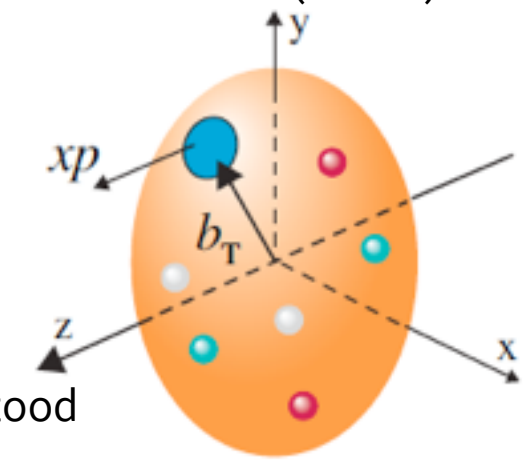

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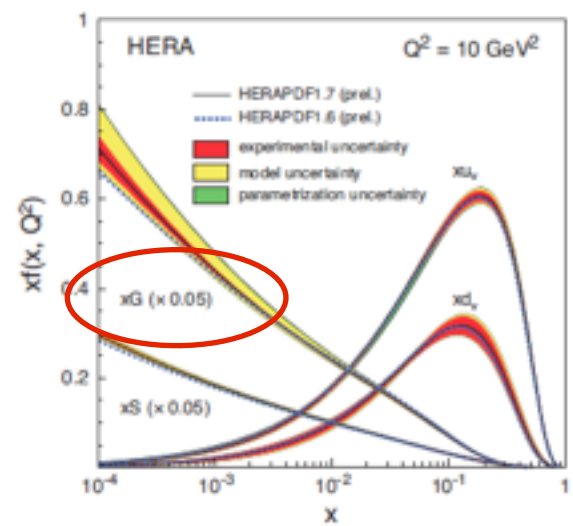

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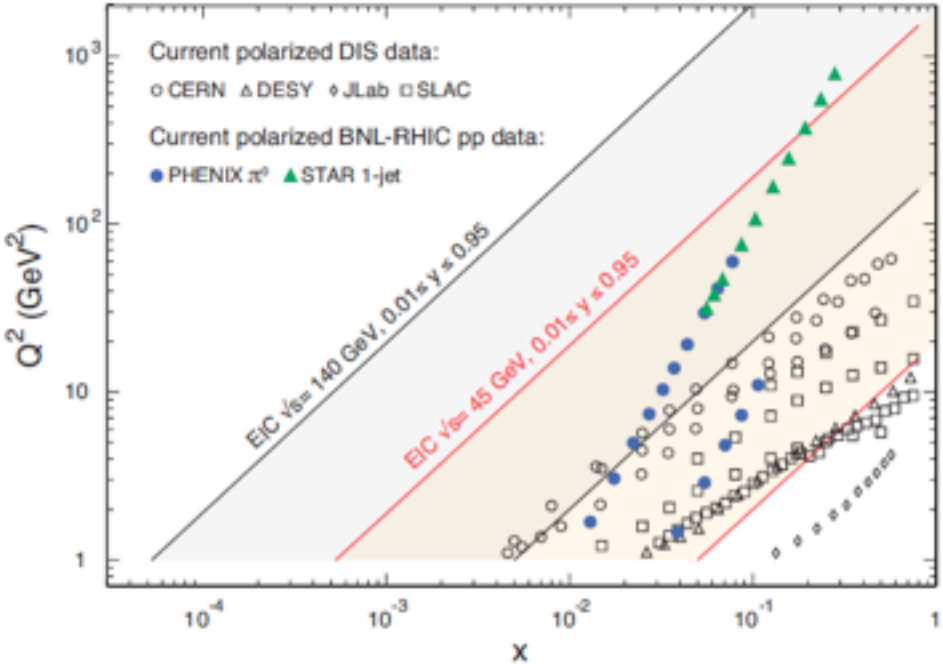
- current data for **polarized ep and eA DIS** cover only a very restricted x,Q^2 range (**no collider experiments so far**)

extension of x,Q^2 coverage with an EIC

polarized ep scattering



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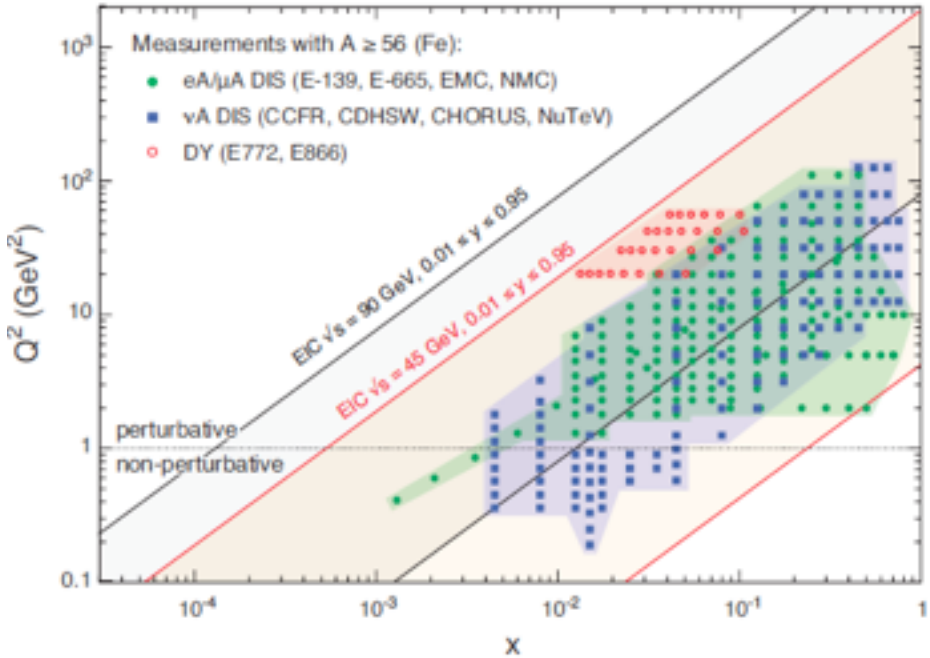

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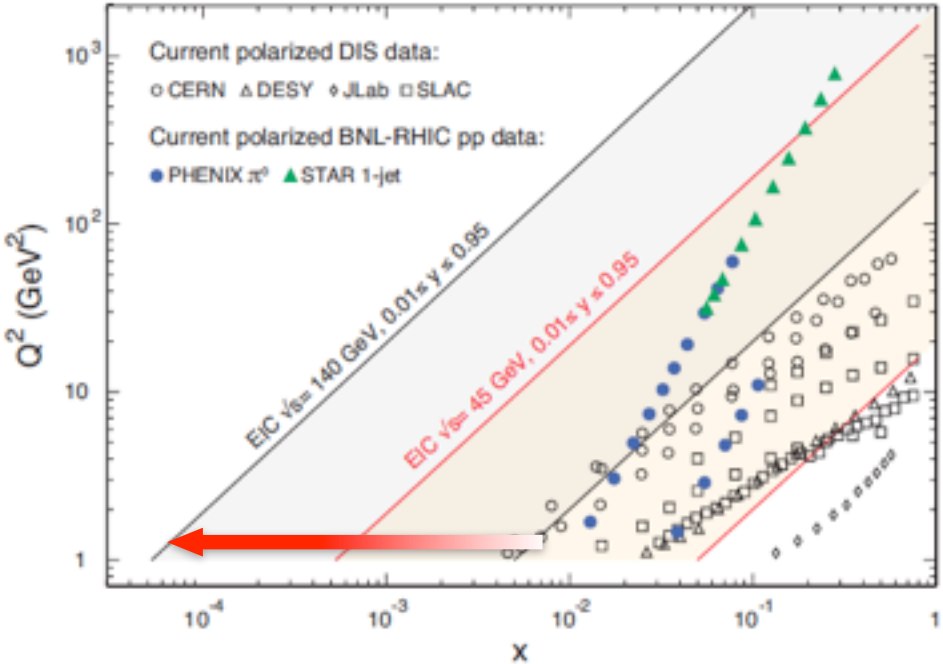

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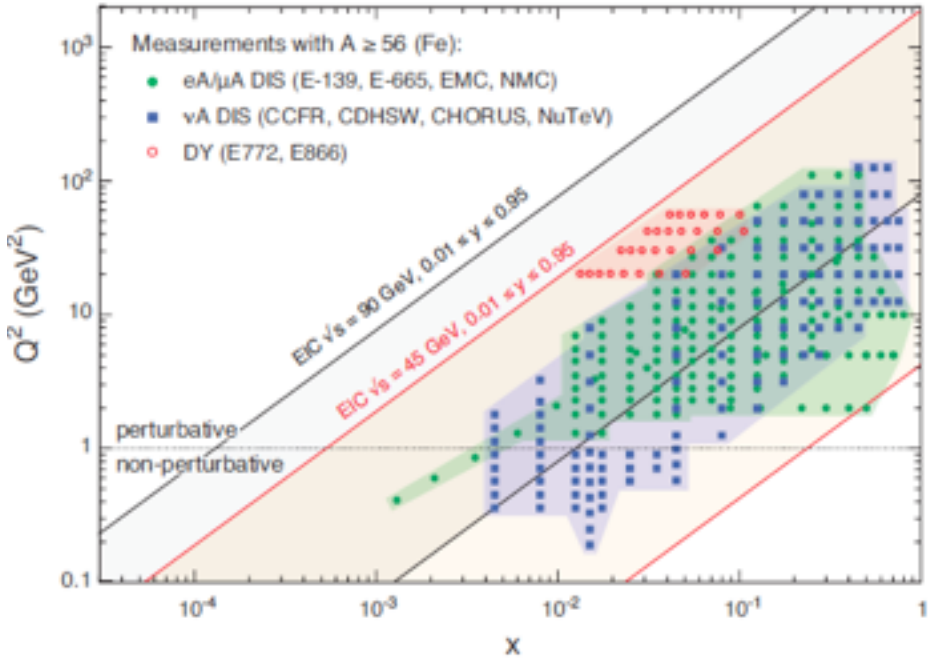

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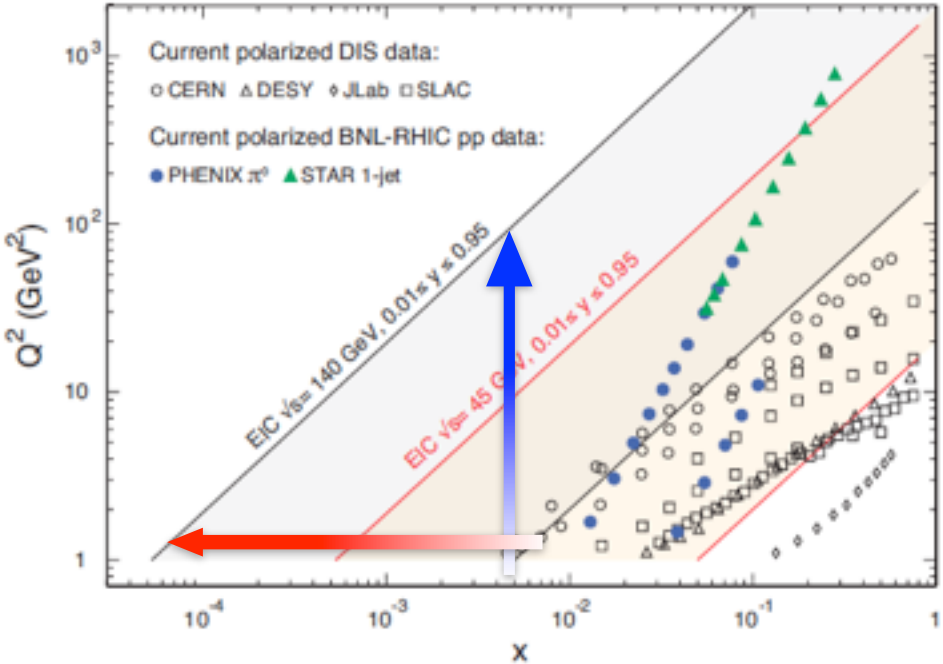

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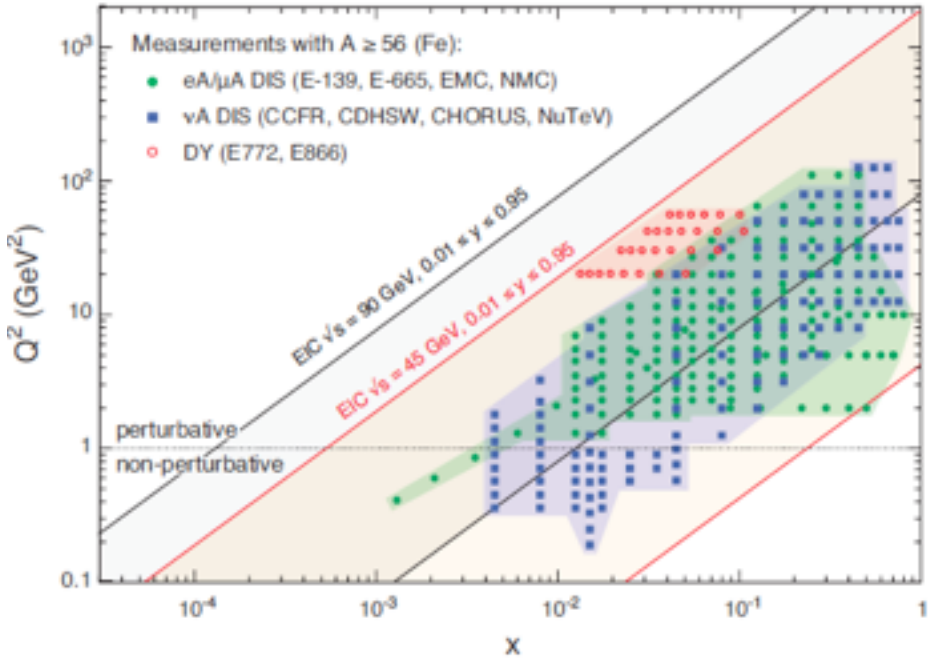

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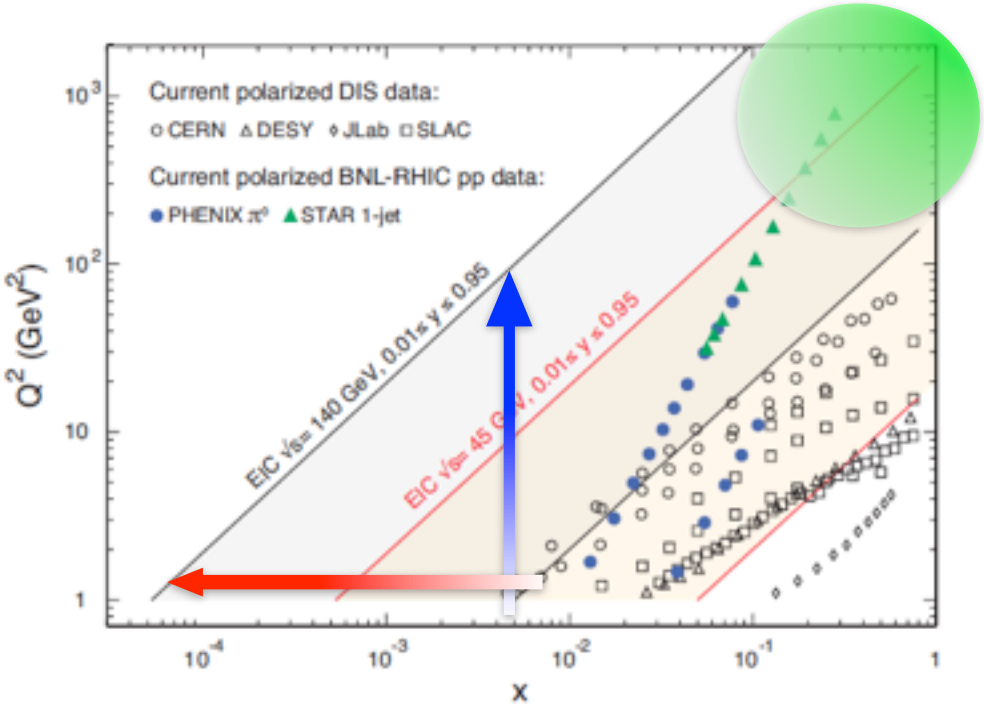

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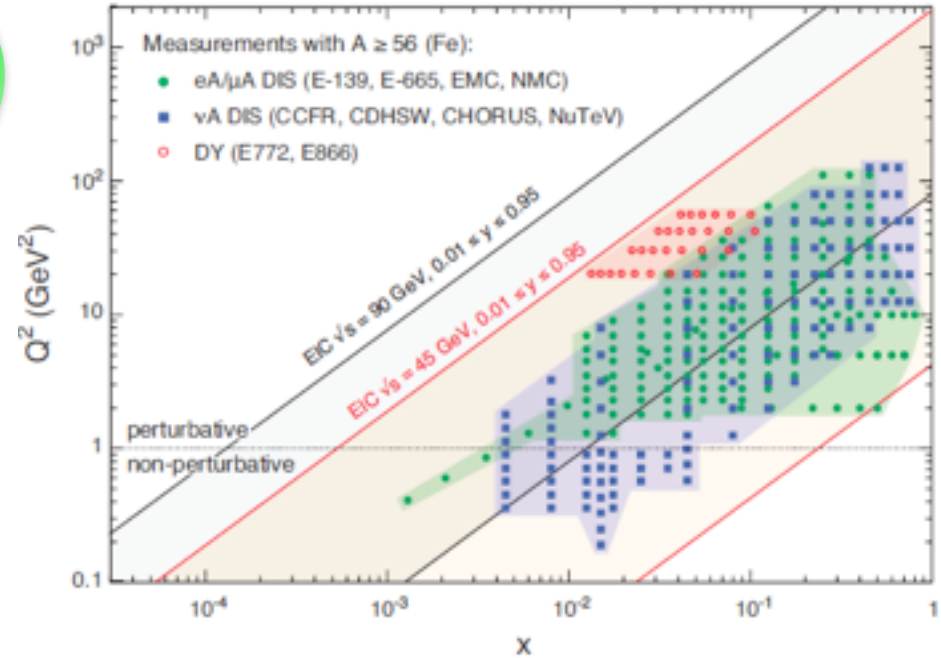

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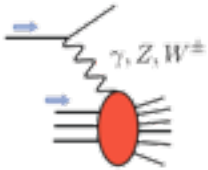
- **can reach large Q^2** (at medium-to-large x) -> access to electroweak effects



what can be achieved: spin structure

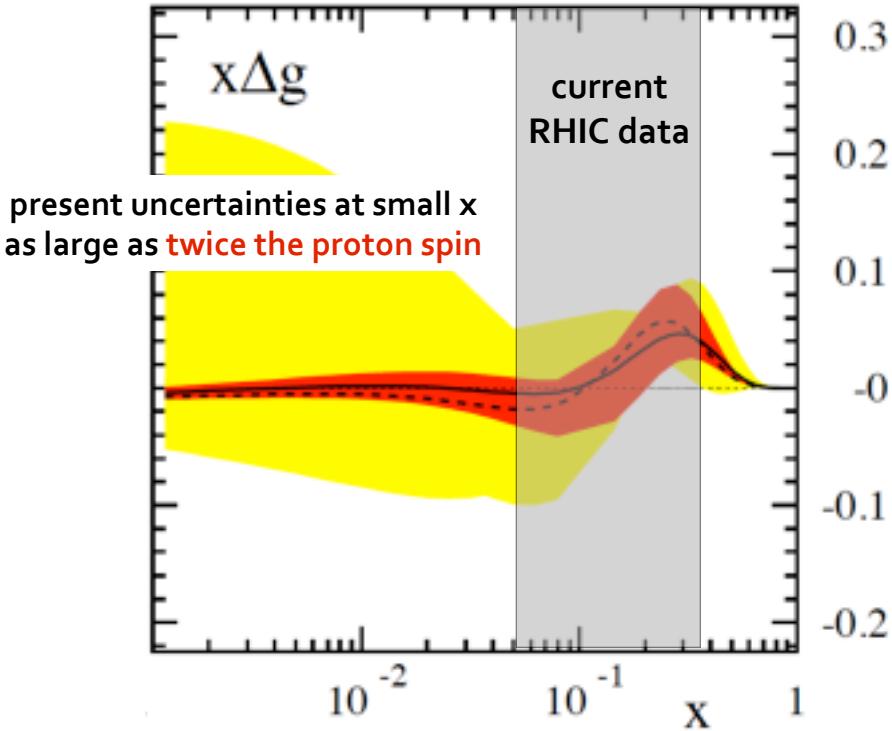
- RHIC will determine $\Delta g(x,Q^2)$ down to $x \simeq$ few $\times\ 10^{-2}$

  but need access down to few $\times\ 10^{-4}$ to close chapter on spin

- an EIC can do just that ...

recall:

$$\Delta f(x) \equiv f_{\rightarrow\rightarrow}(x) - f_{\leftarrow\rightarrow}(x)$$



present uncertainties at small x as large as twice the proton spin

based on global QCD analyses with and without realistic EIC pseudo data

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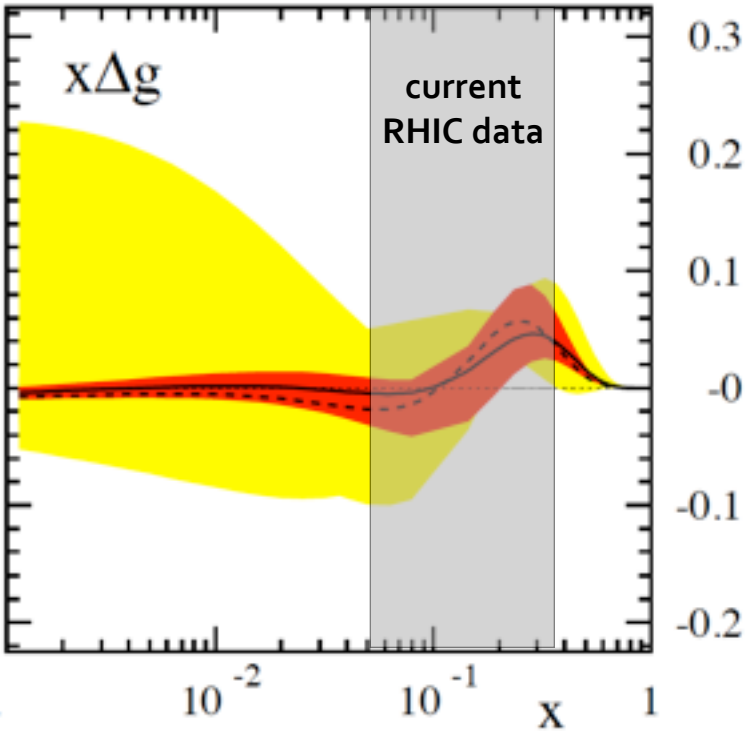

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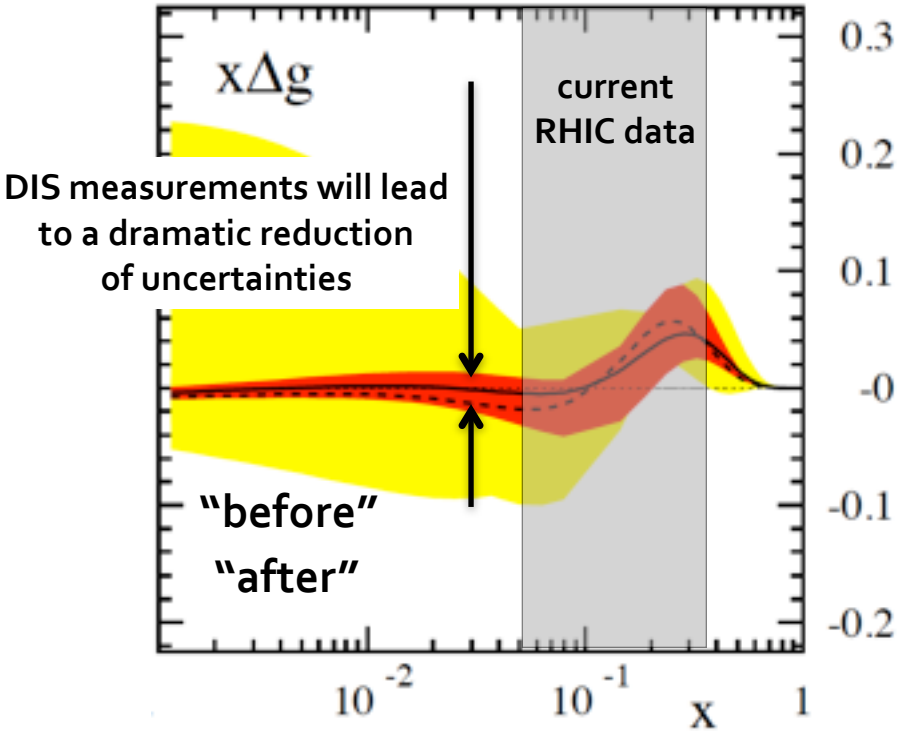

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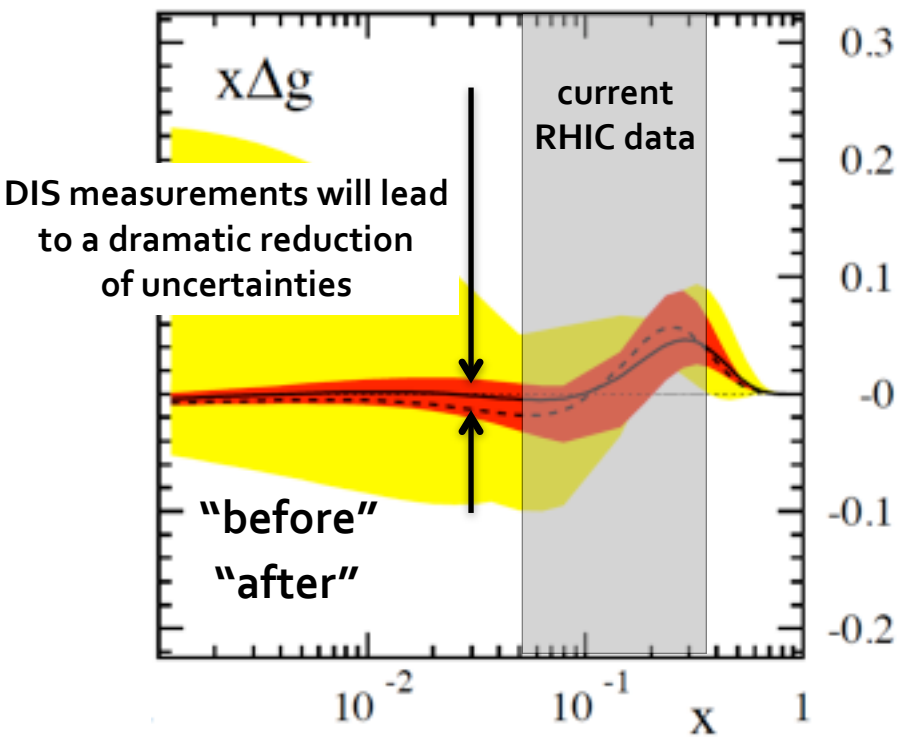

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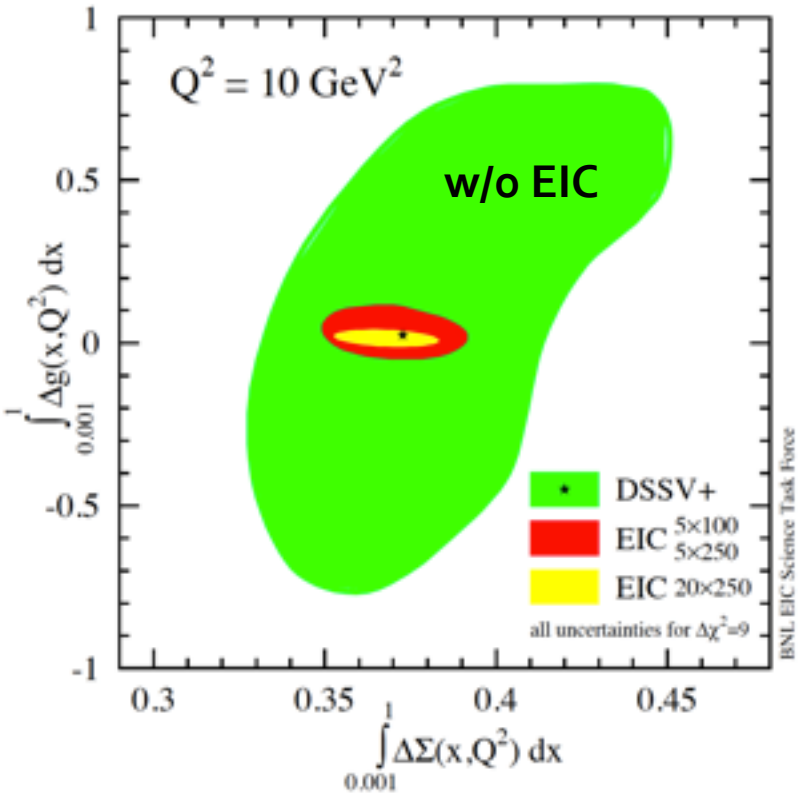
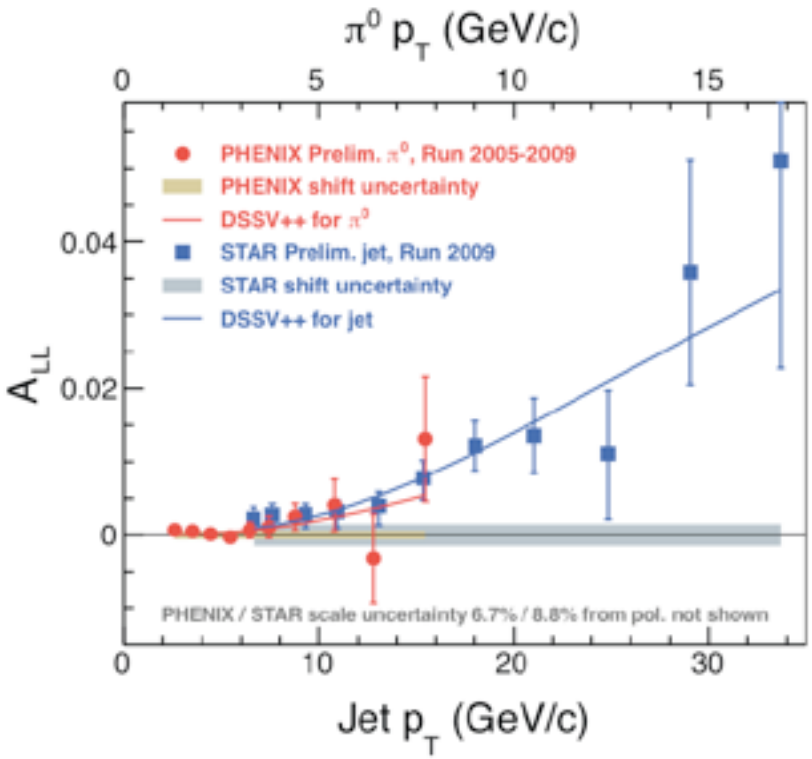


crucial impact on our understanding of decomposition of proton spin

aside: latest news on Δg from RHIC

RHIC run-9 data for jets and π°



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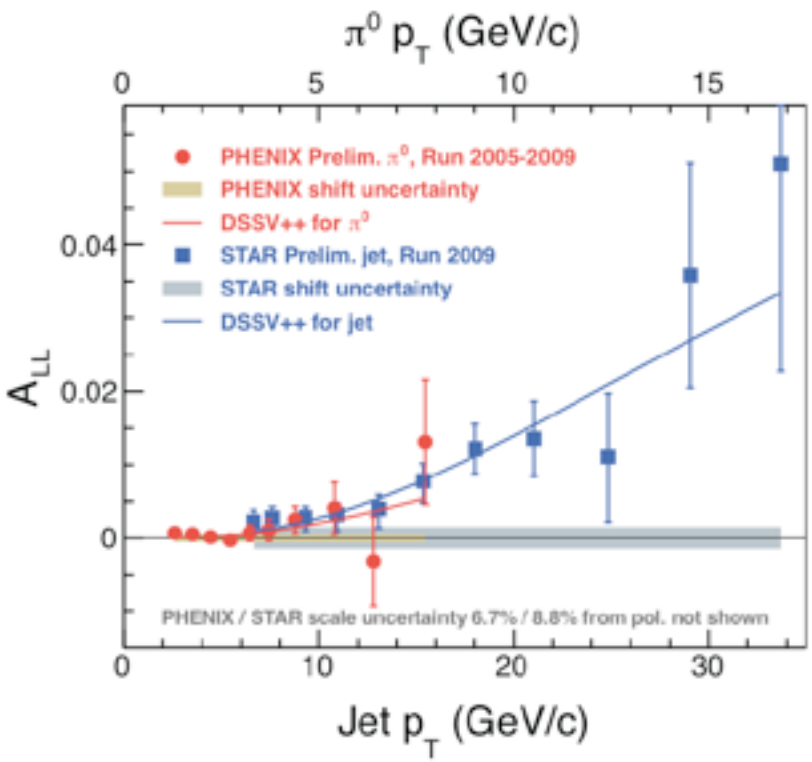
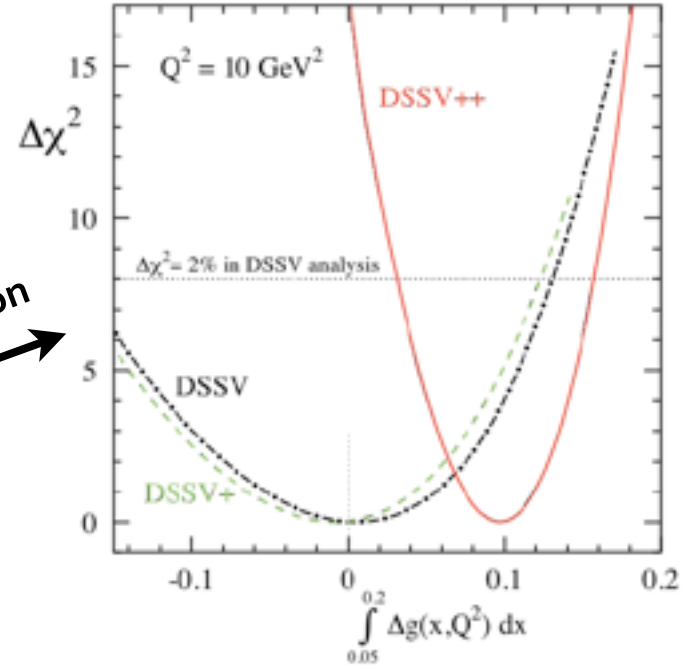


lead to non-zero Δg in RHIC region



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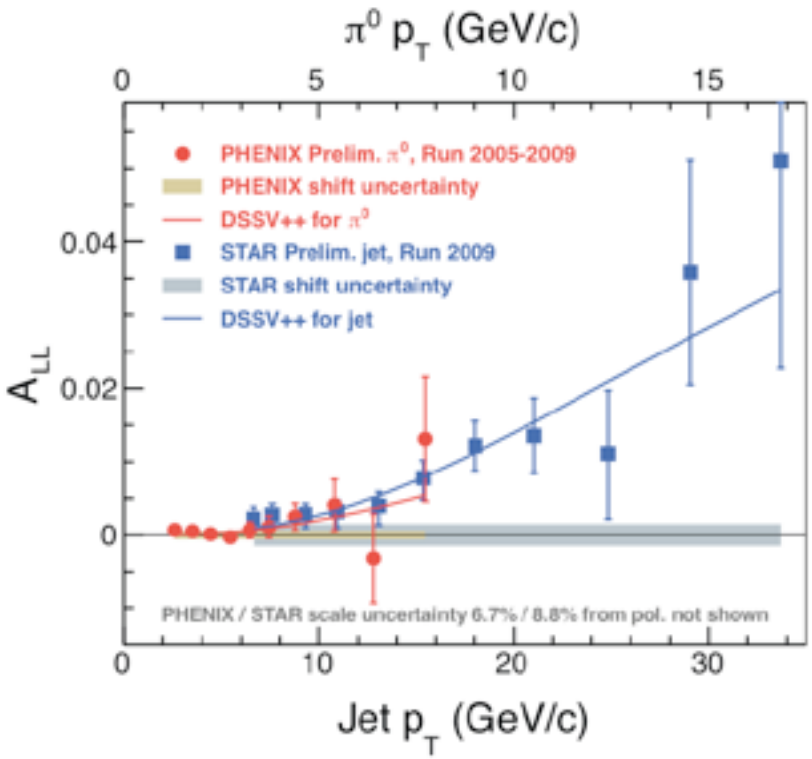

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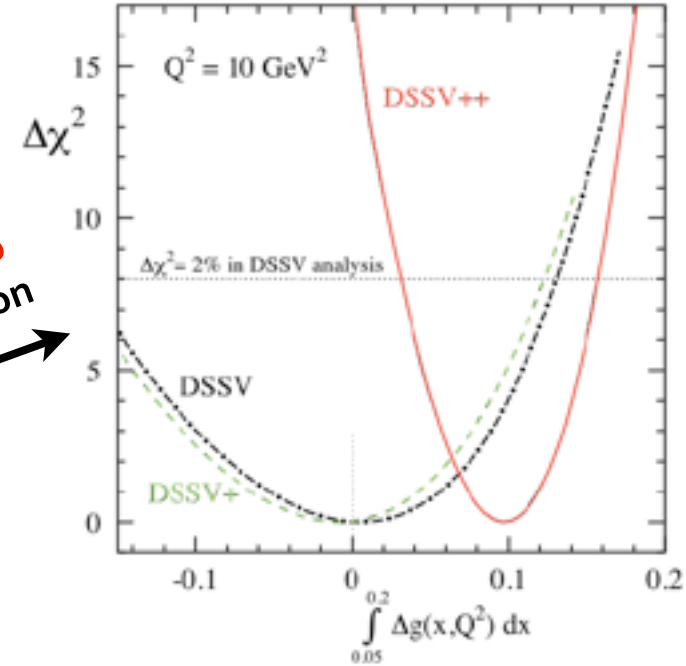

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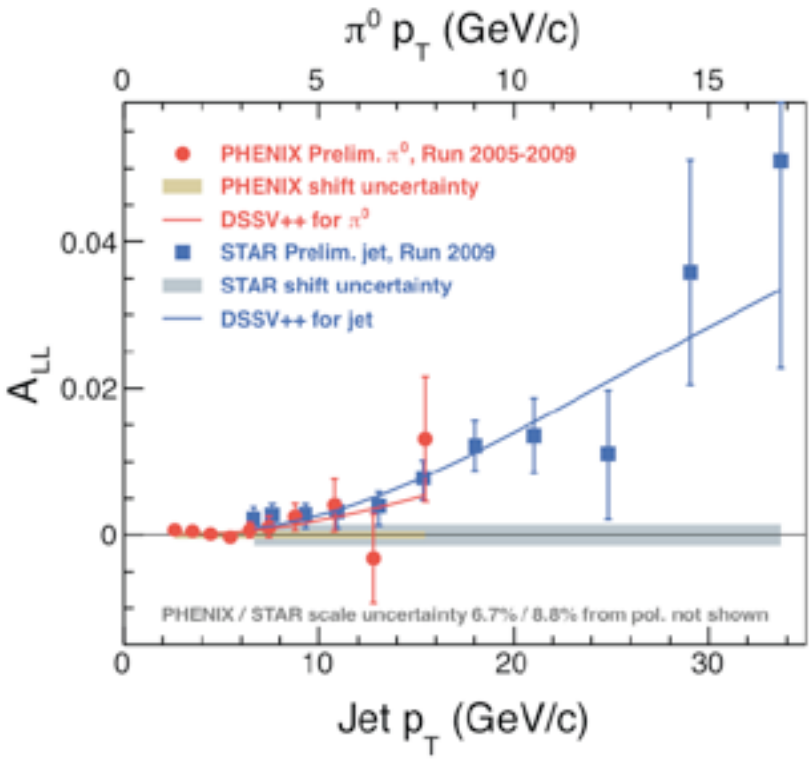

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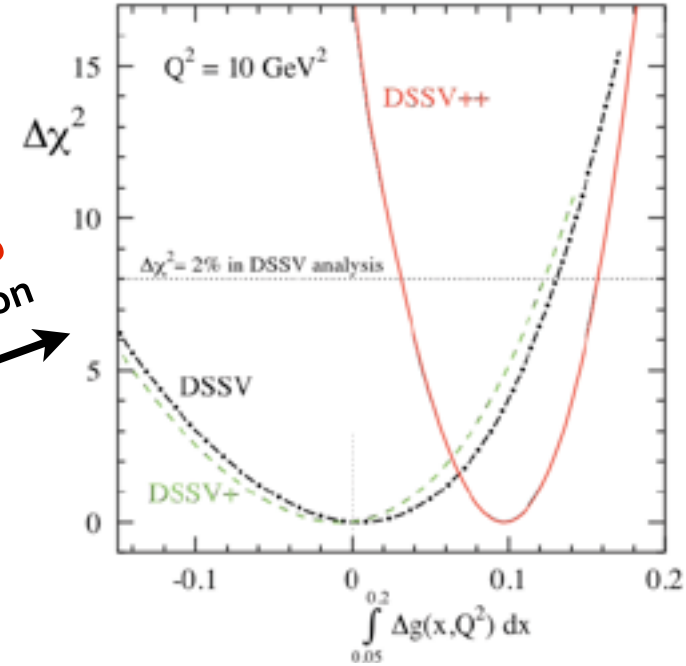
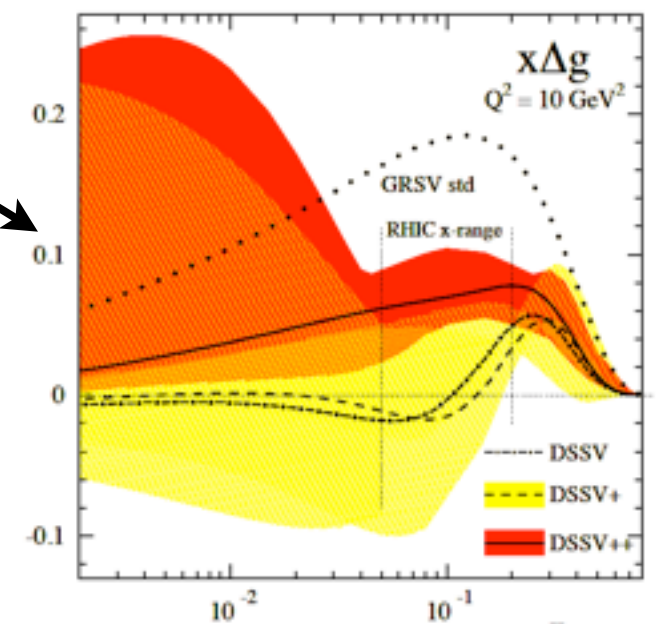


positive Δg in RHIC region



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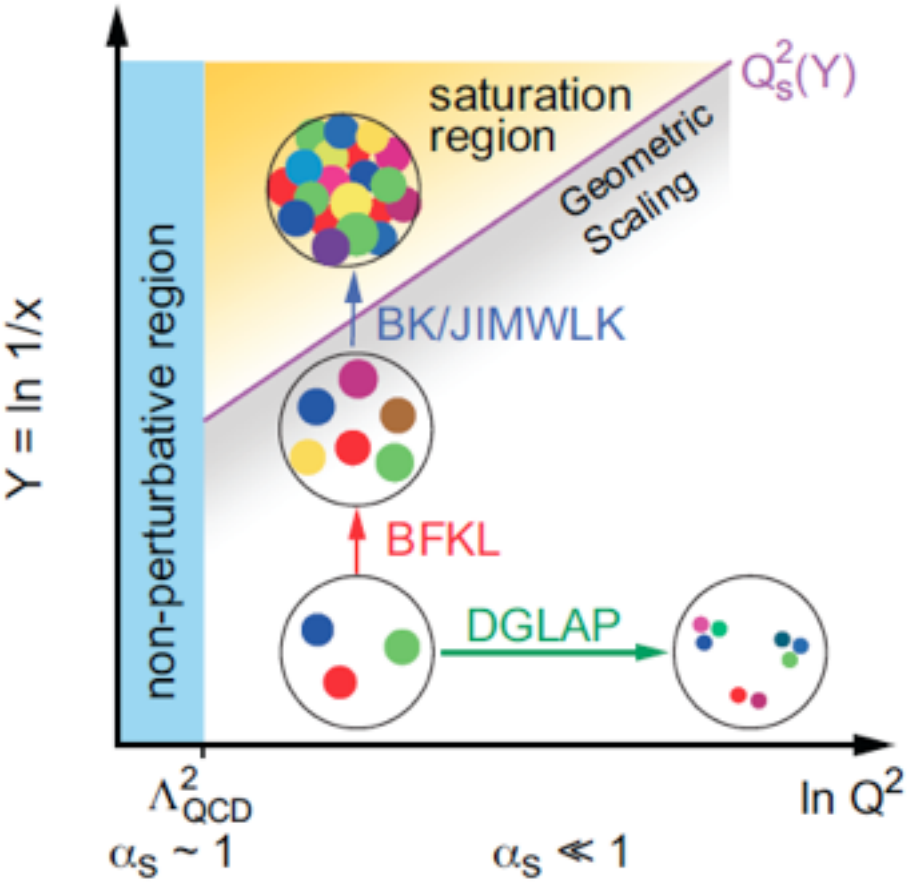
what can be achieved: nuclear PDFs

goals:

- map the momentum distribution of sea quarks and gluons down to small x
- gather unambiguous evidence for non-linear QCD dynamics (aka **saturation**)



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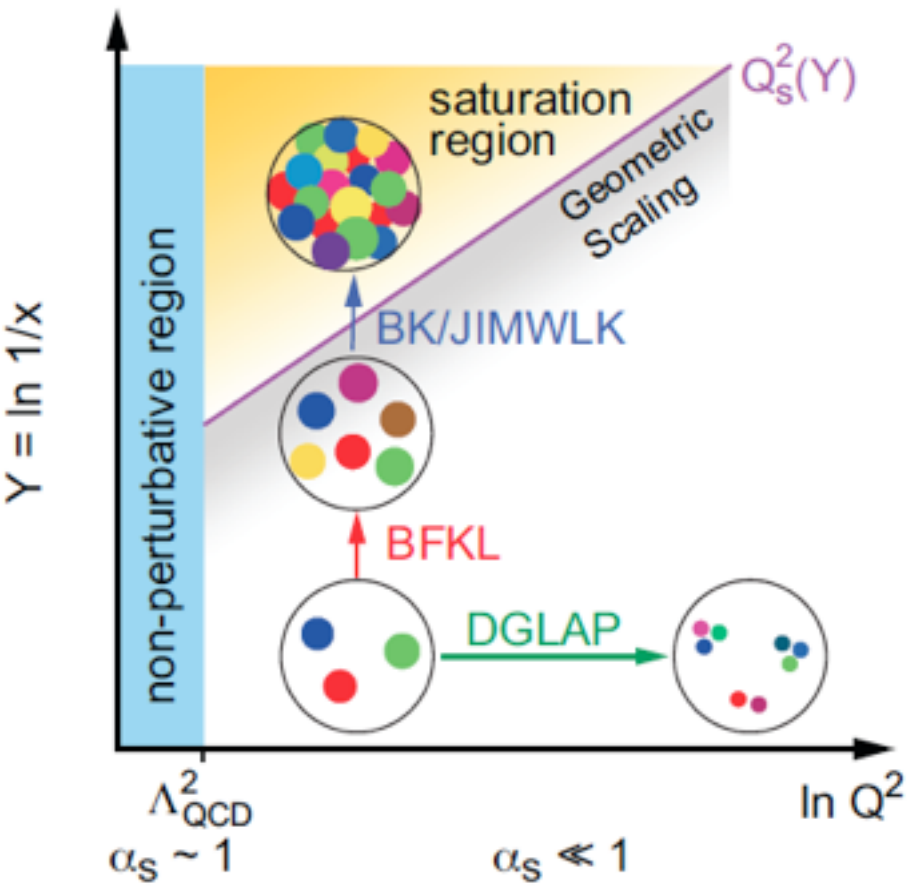

key advantage of eA DIS over ep DIS

amplification of non-linear effects by nuclear "oomph factor"

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

expect to see saturation in eA at 100-200 × higher values of x than in ep

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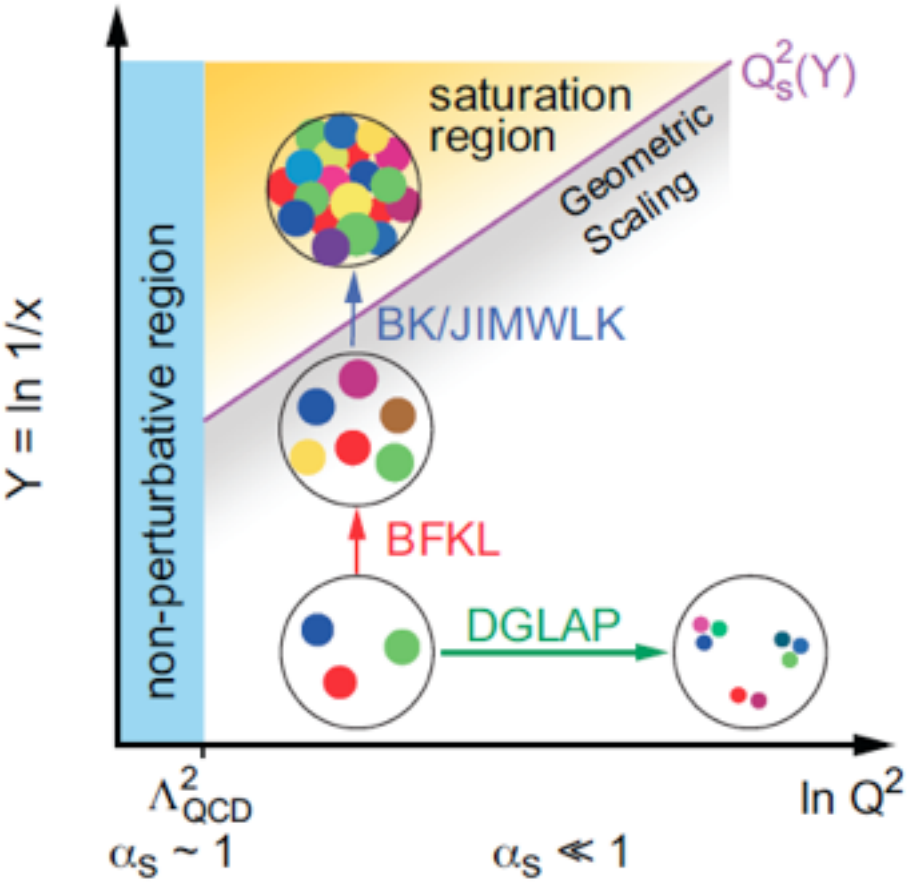

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- presence of (large enough) **saturation scale Q_s** allows one to perform quant. calculations in well-defined framework ("CGC")

- expect **"physics at high gluon density"** to be universal; can verify this at an EIC !

what can be achieved: nuclear PDFs

particularly suited inclusive observable: DIS structure function $F_L(x,Q^2)$ unmeasured so far

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  measurements at fixed x,Q^2 for different y (i.e., S)

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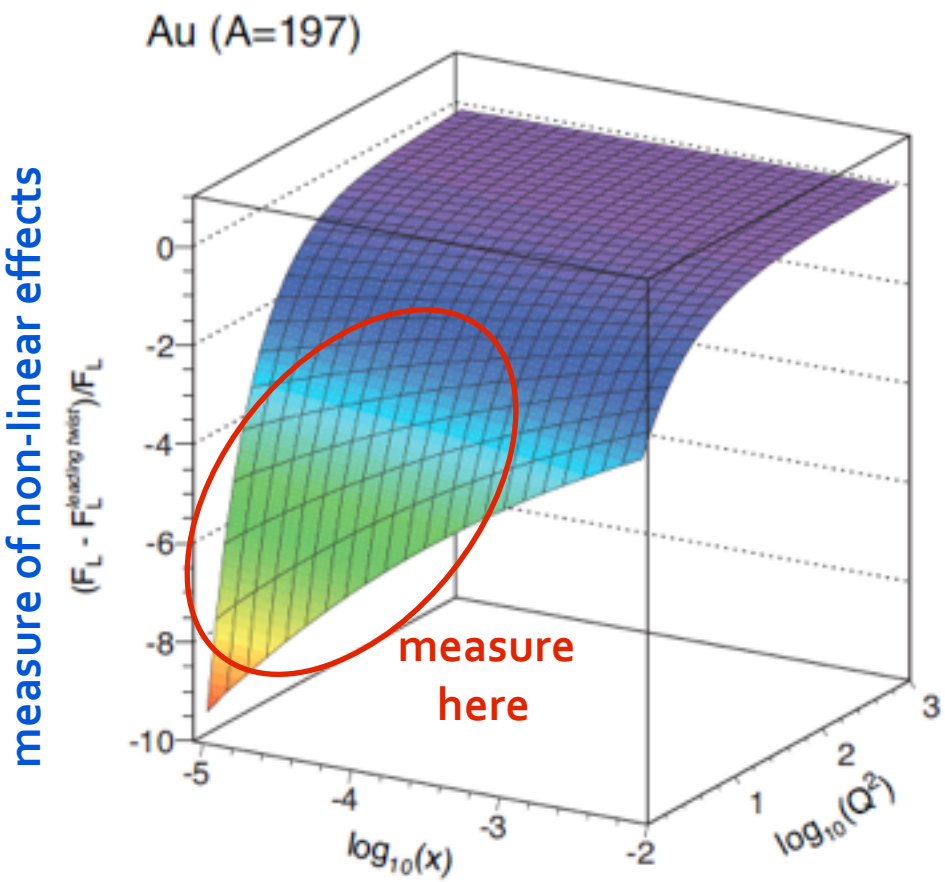

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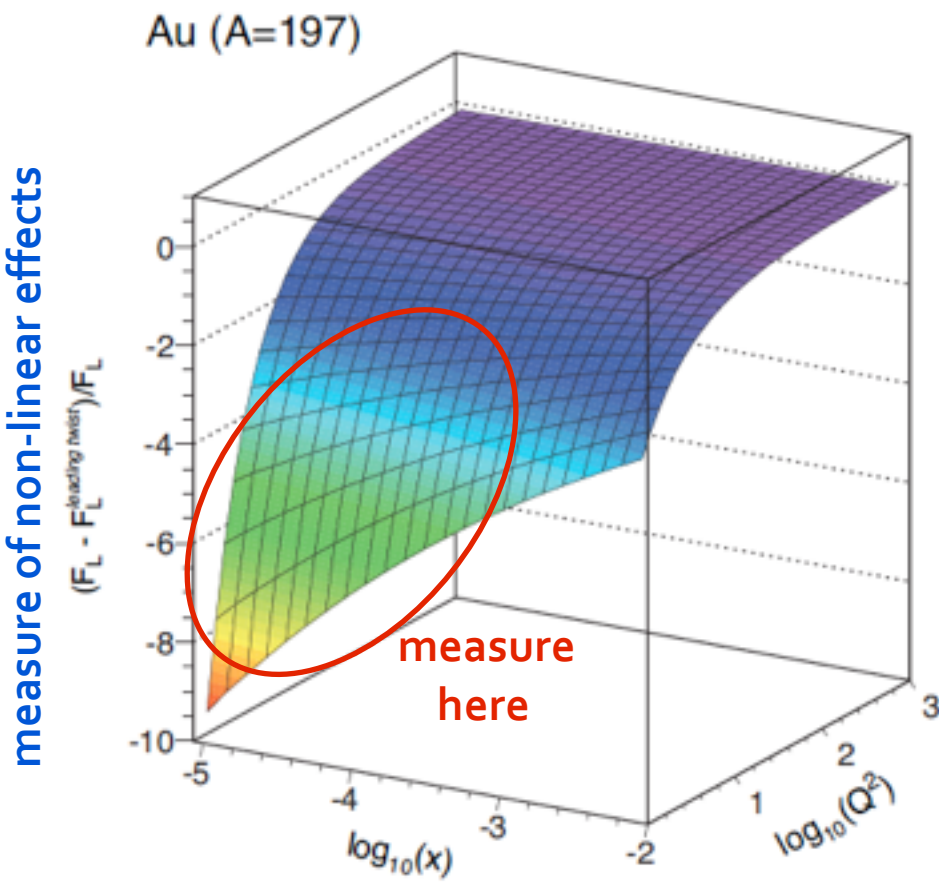

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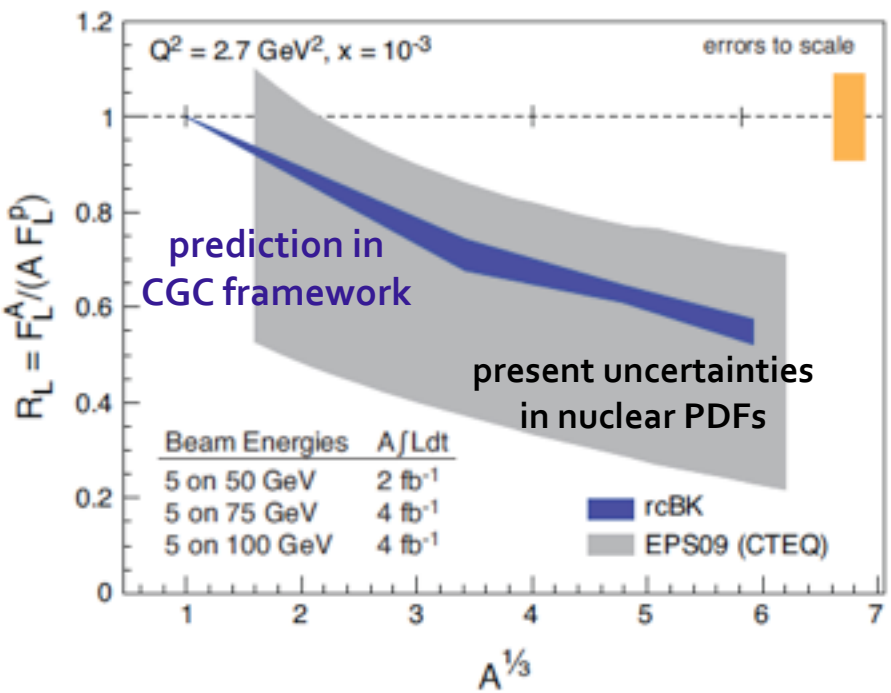
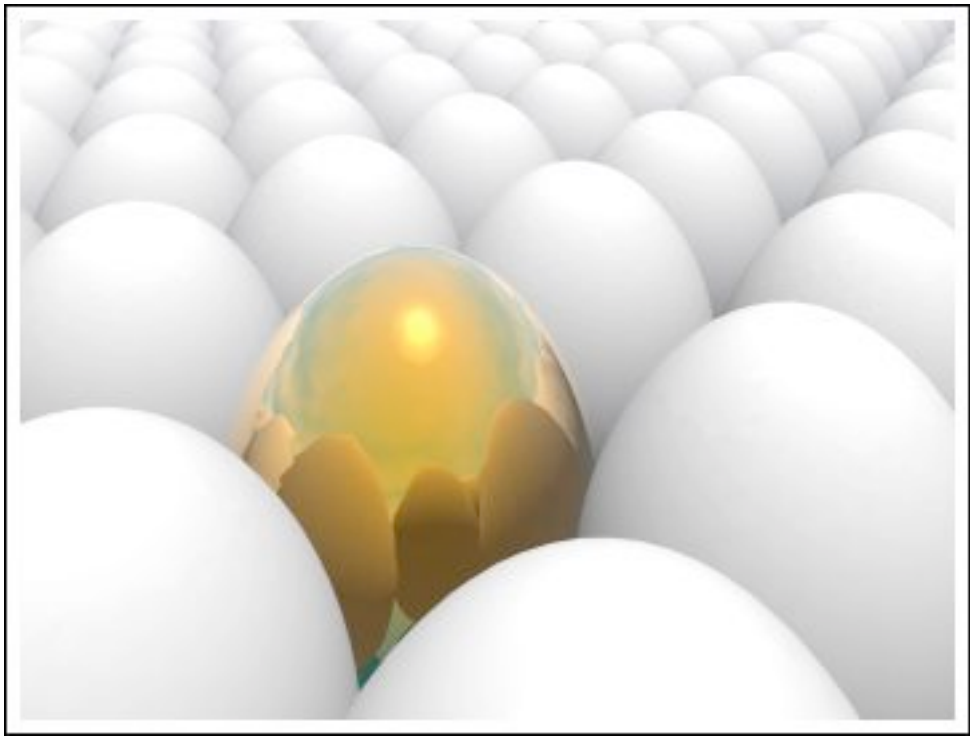


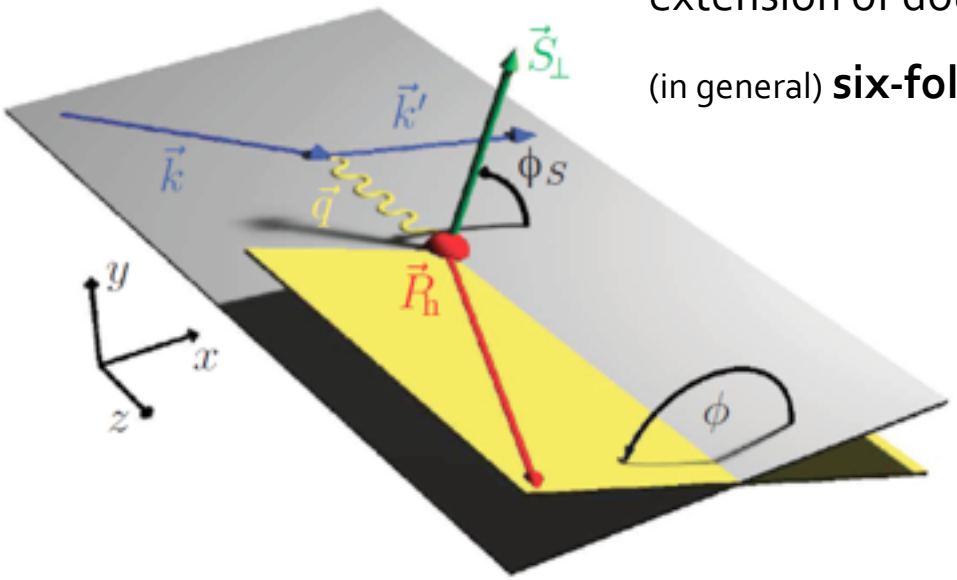
combined analysis with other observables can reveal presence of non-linear effects



2

semi-inclusive probes in ep and eA

what to measure and why



extension of double-differential DIS cross section to a

(in general) **six-fold diff. cross section** $\dfrac{d\sigma}{dx\, dQ^2\, dz\, d\phi_S\, d\phi_h\, dp_T^h}$

z : energy fraction of observed hadron

p_T^h: its transverse momentum

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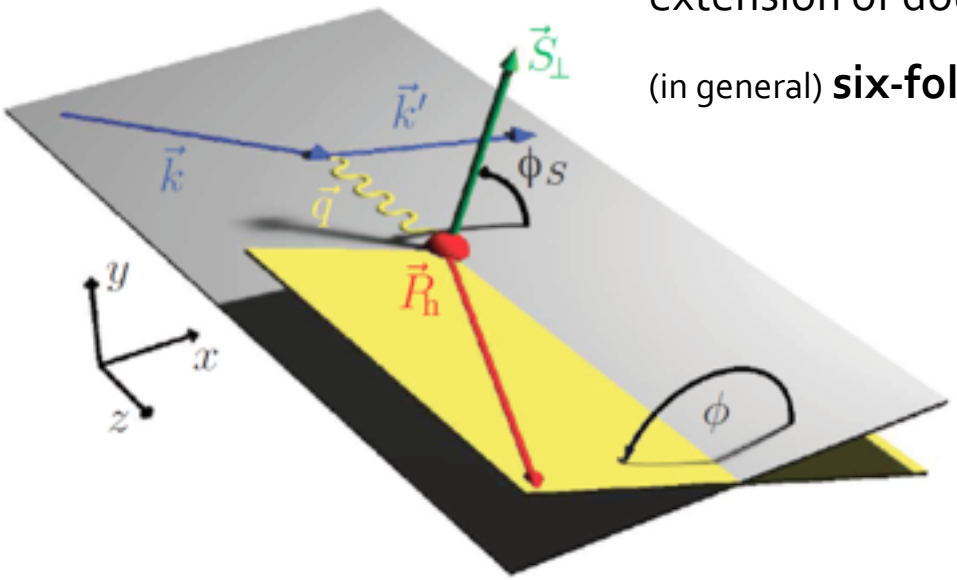

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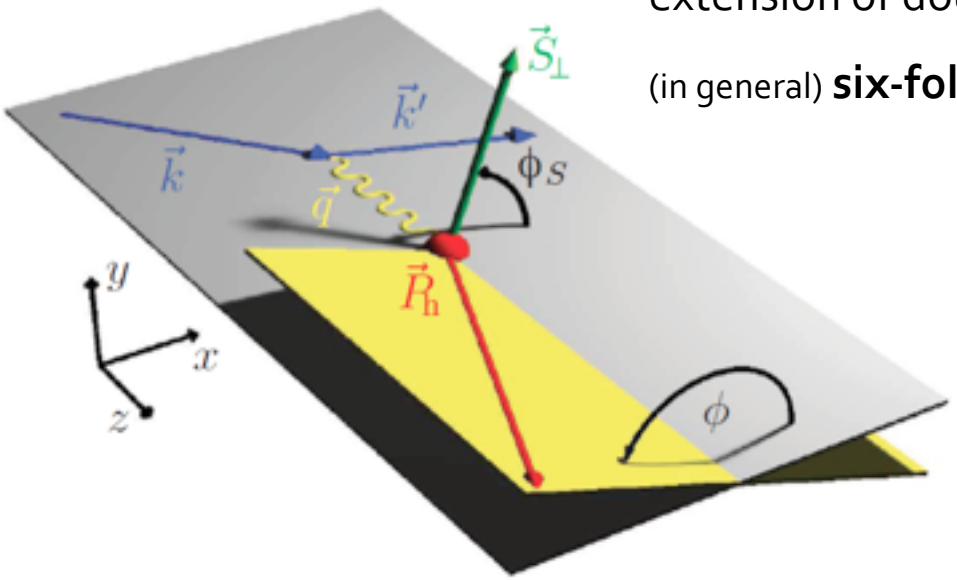

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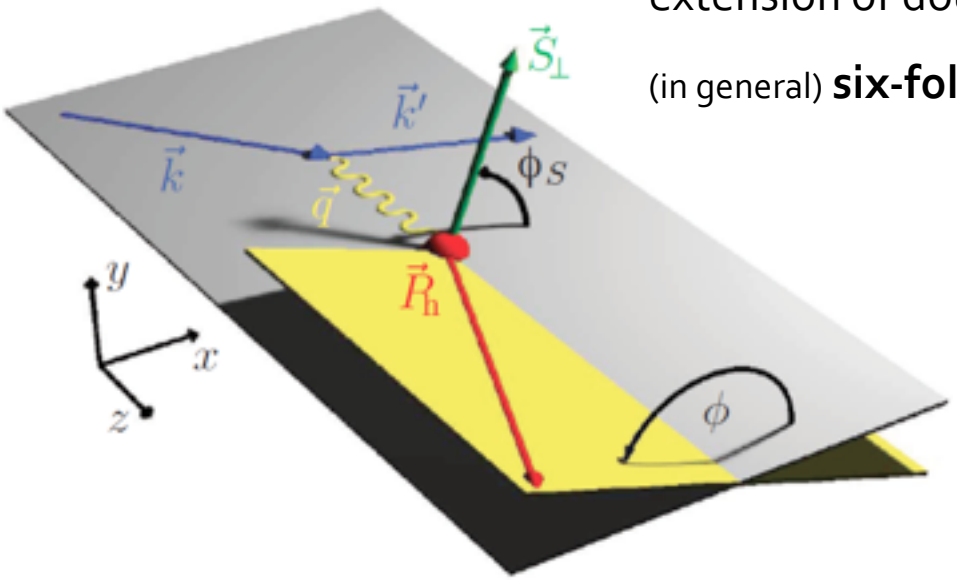

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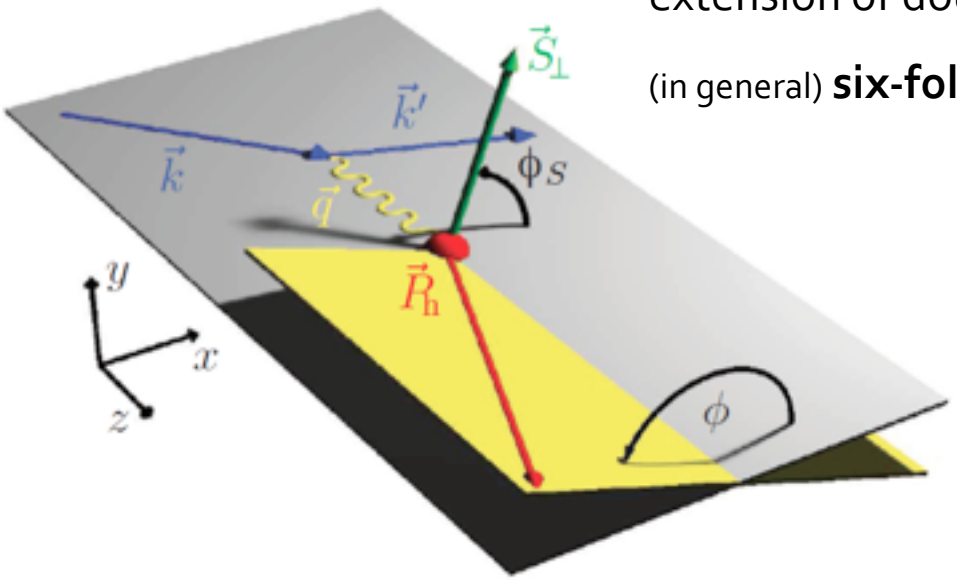

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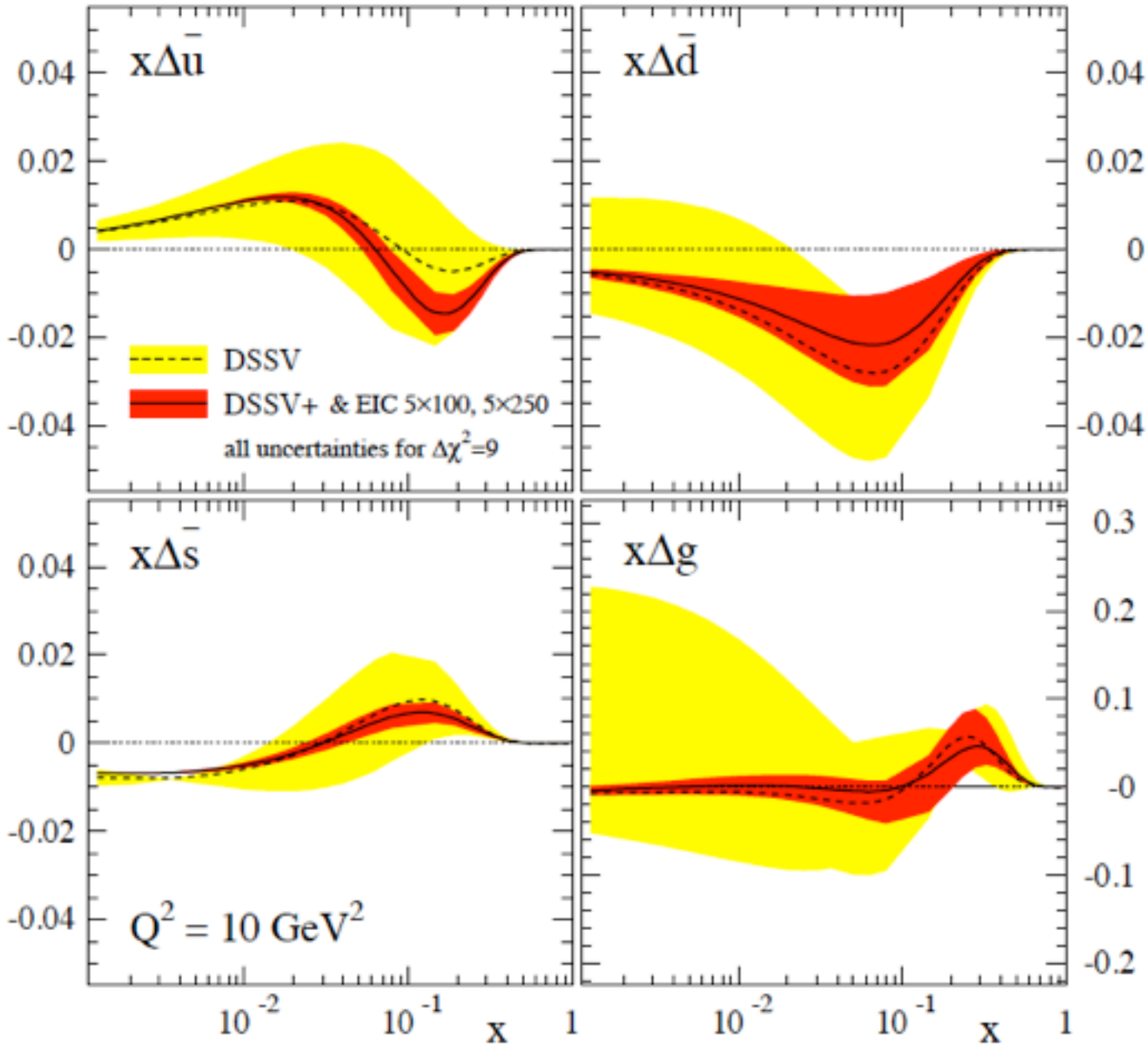
all SIDIS measurements require good particle ID in broad kinematic regime

1st example: flavor separation for helicity PDFs



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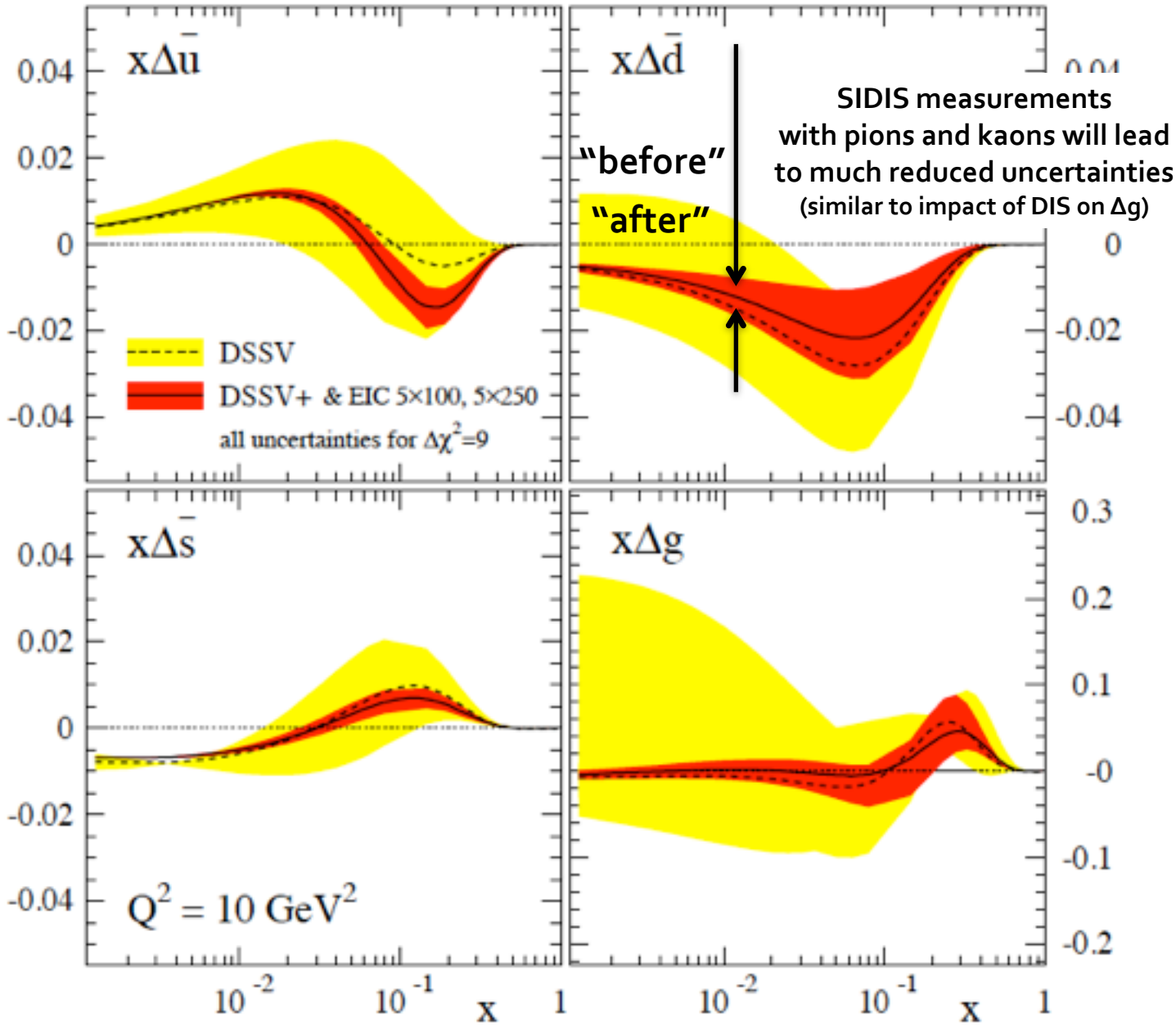
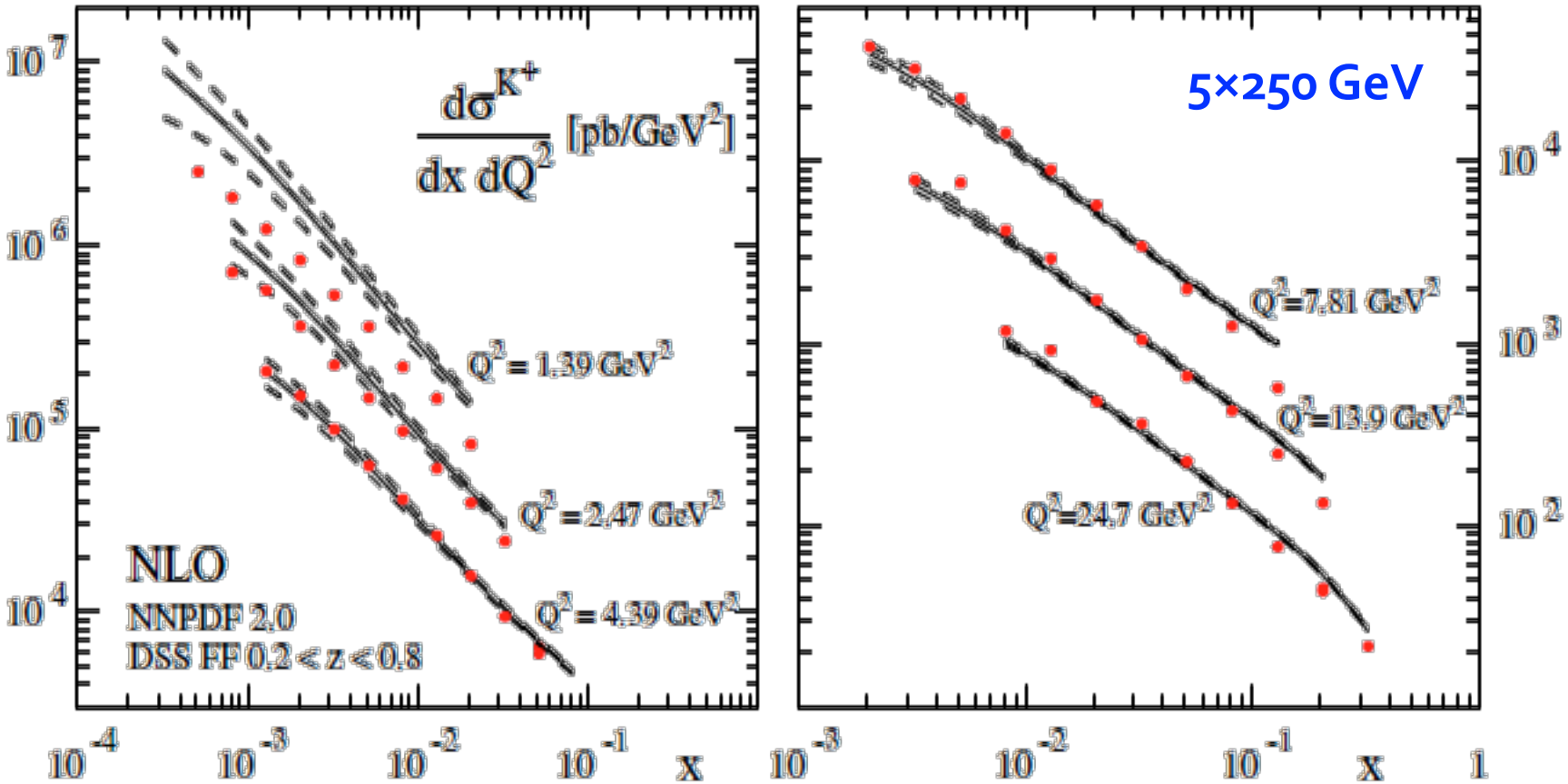


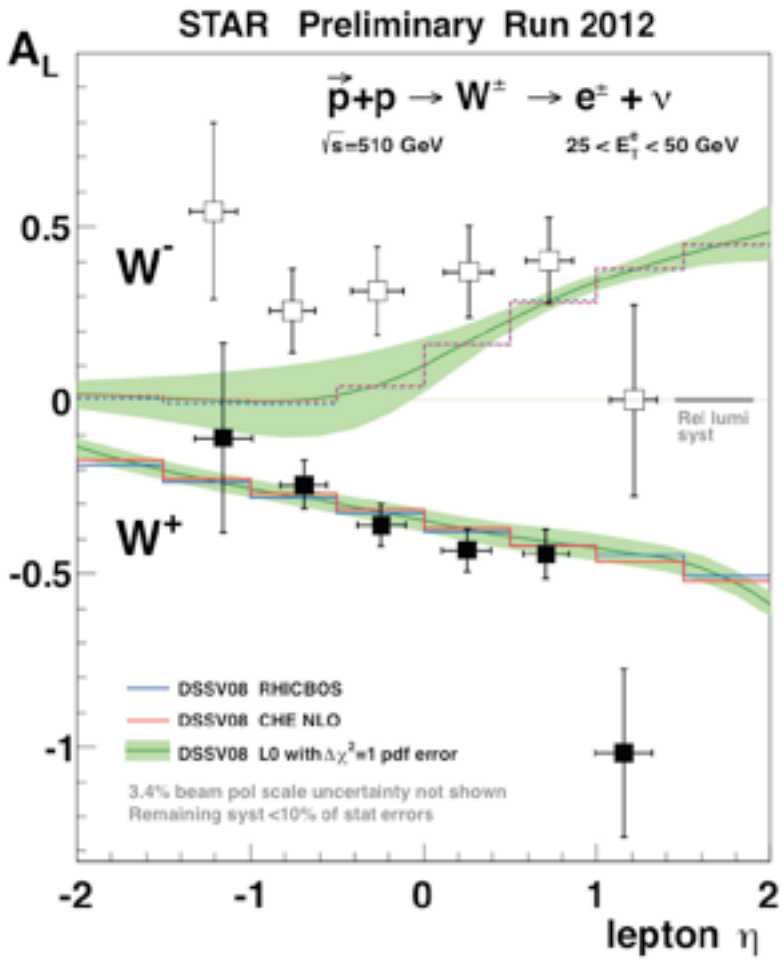
kaon production in SIDIS

- compute K^+ yields at NLO with 100 NNPDF replicas (**sensitivity to s(x) PDF**)
- z integrated to minimize FF uncertainties (z binning can be used to **determine FFs**)



NLO agrees well with PYTHIA simulation (•) despite very different hadronization

aside: impact of latest RHIC W data



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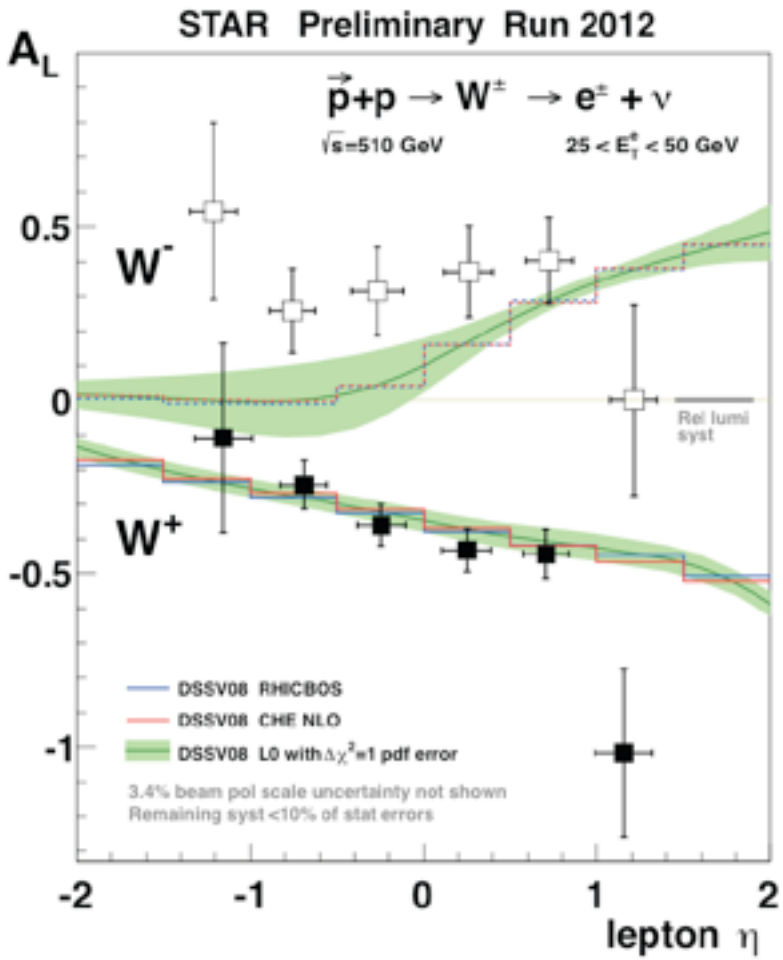

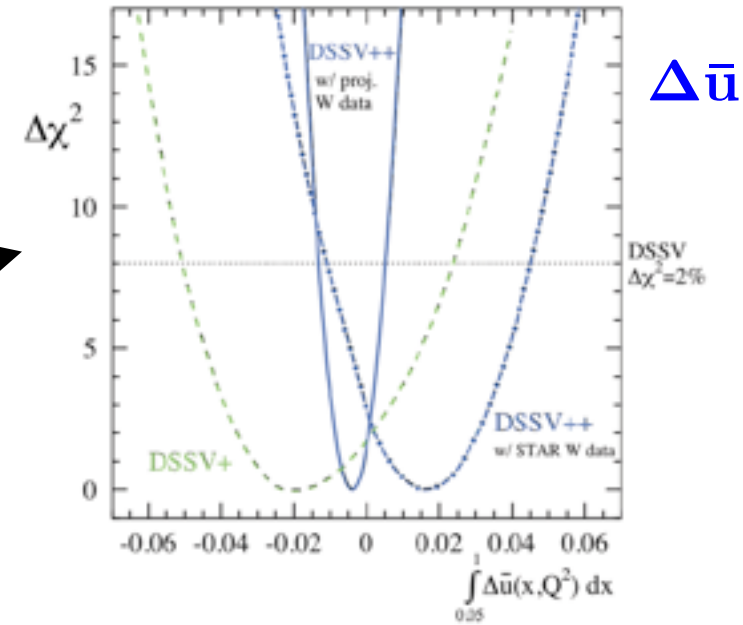

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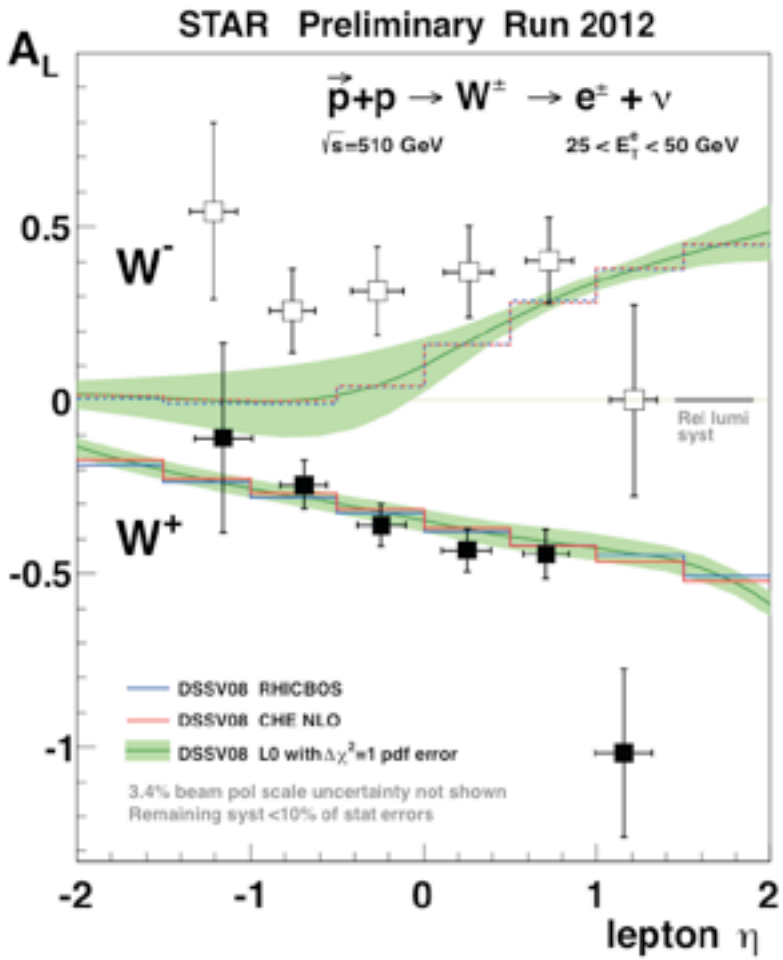

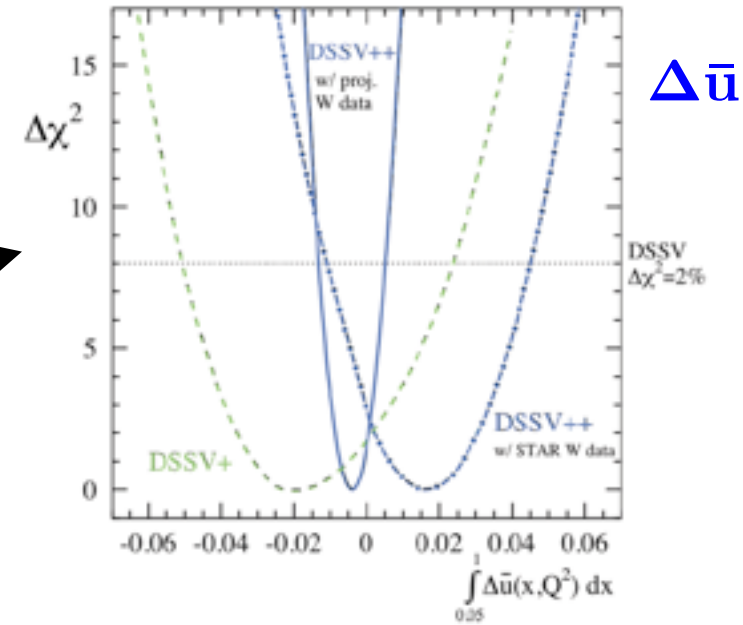

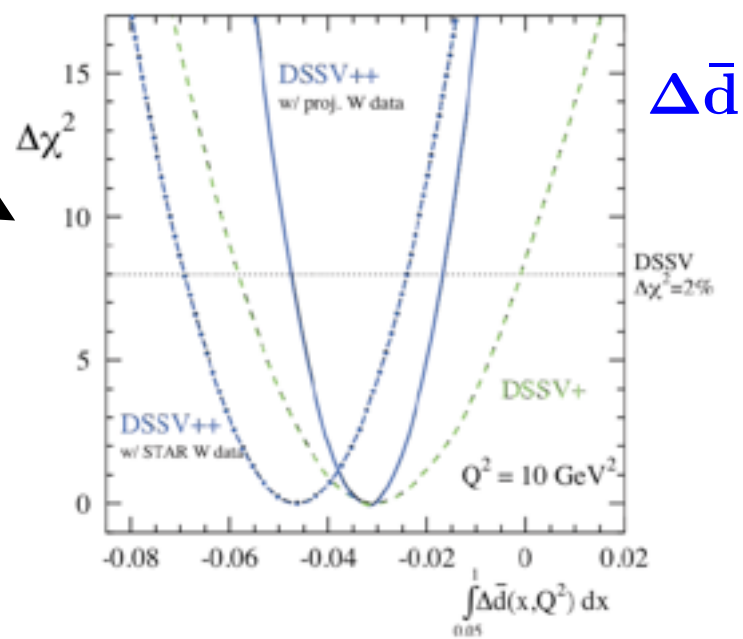

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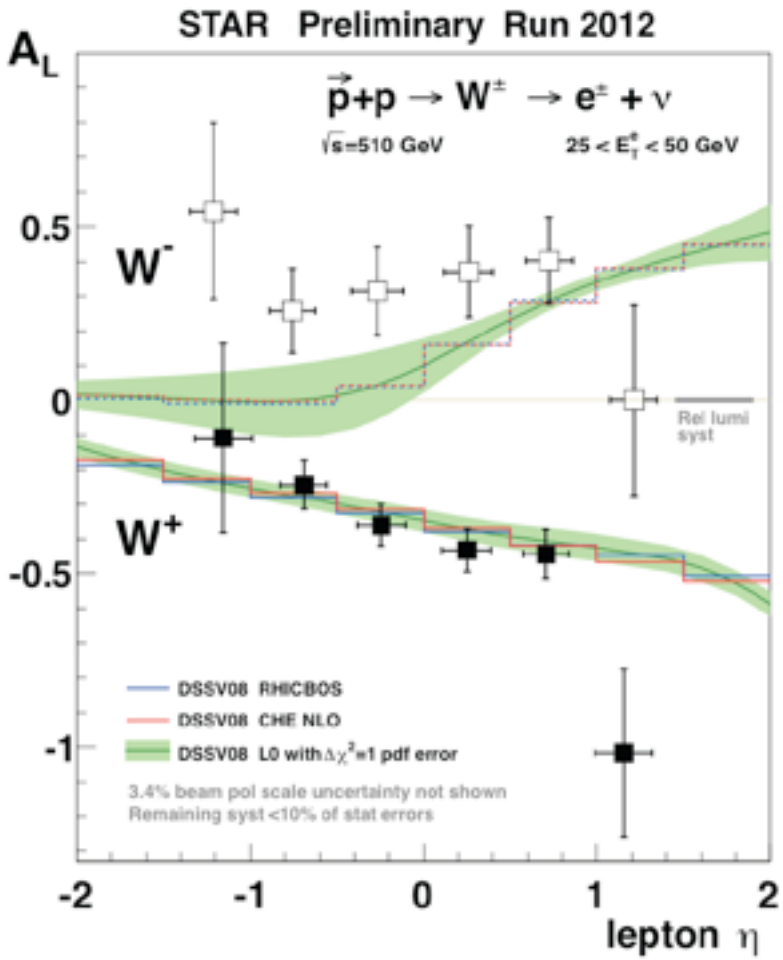
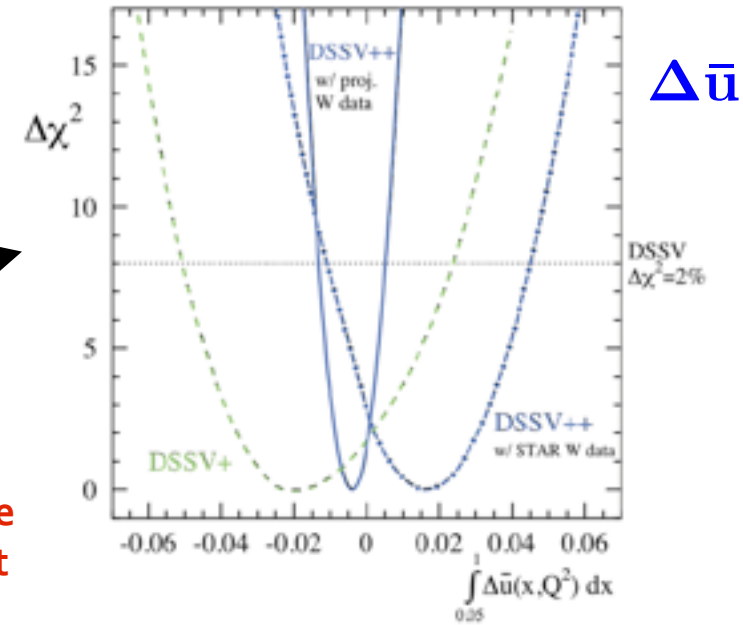
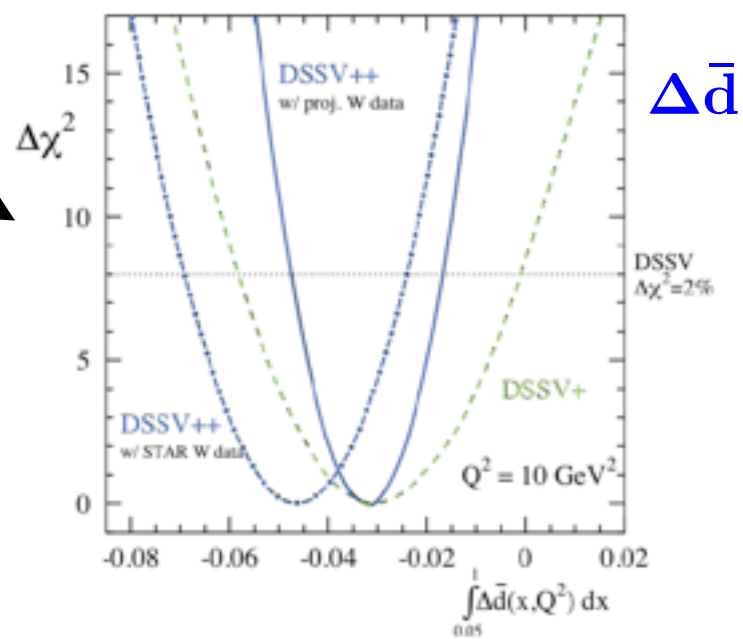


run 12 data already have a significant impact





much more to come from the next RHIC run

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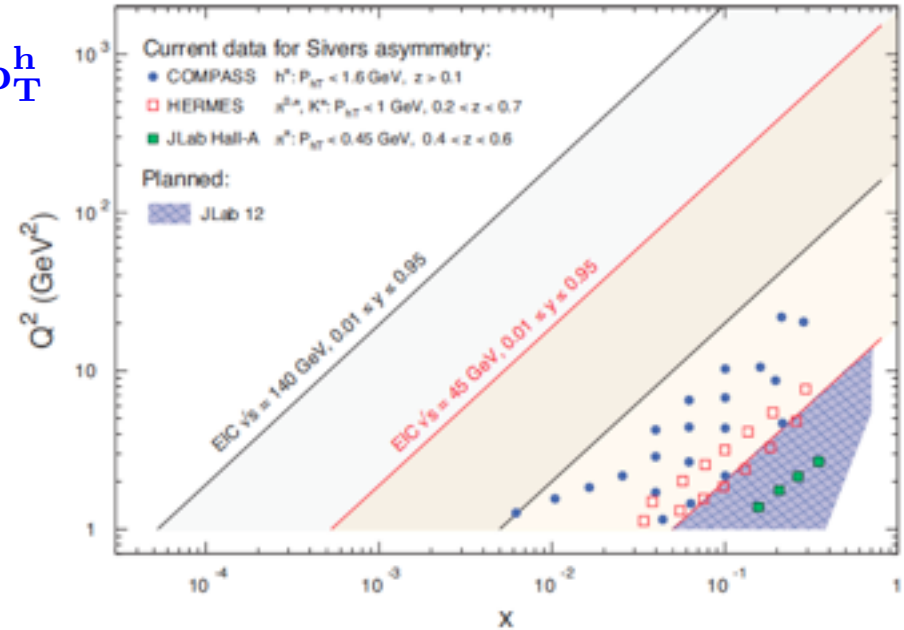
- theoretically interesting multi-scale problem: $\mathbf{Q^2, p_T^h}$
- TMD framework applicable for $\mathbf{Q^2 \gg p_T^h}$
- studied only in fixed target regime
  nothing known yet about sea quarks and gluons



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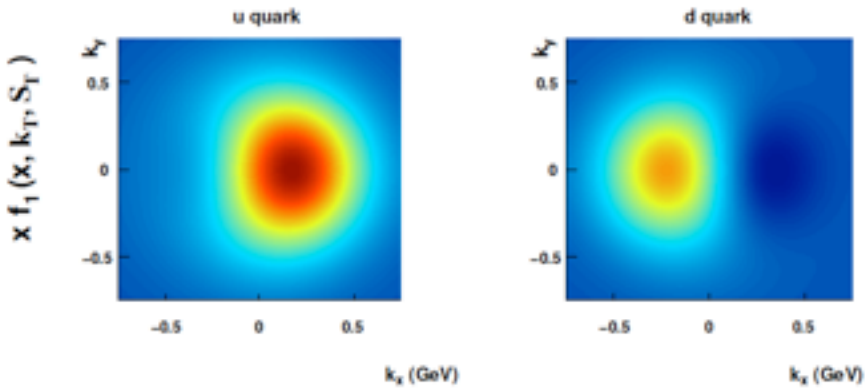

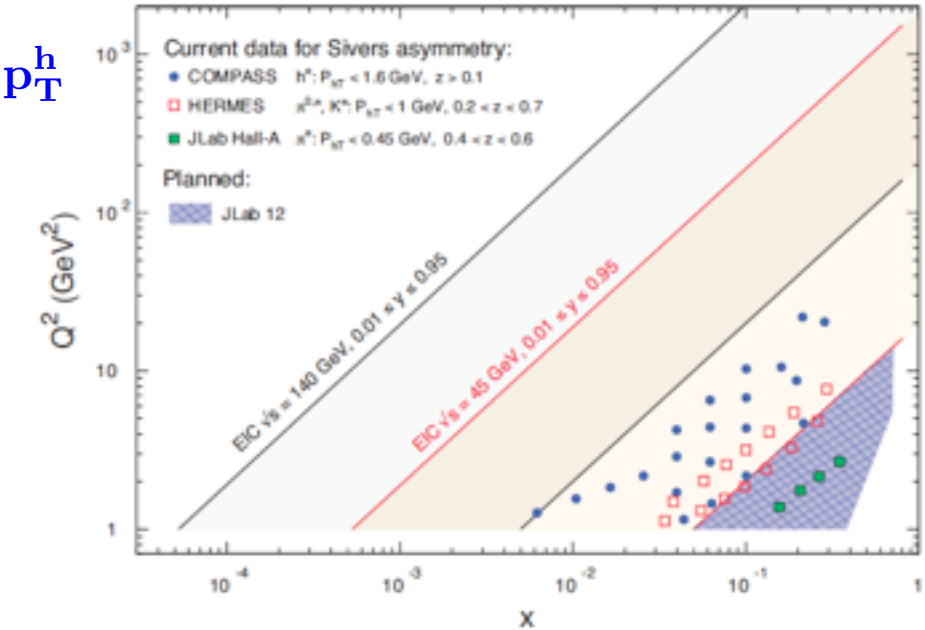

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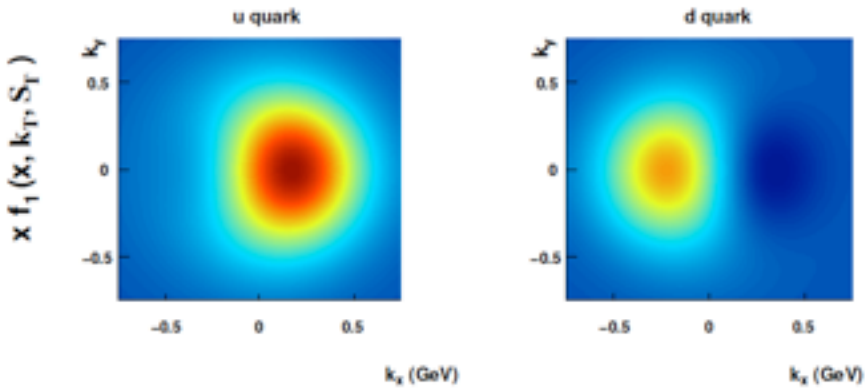

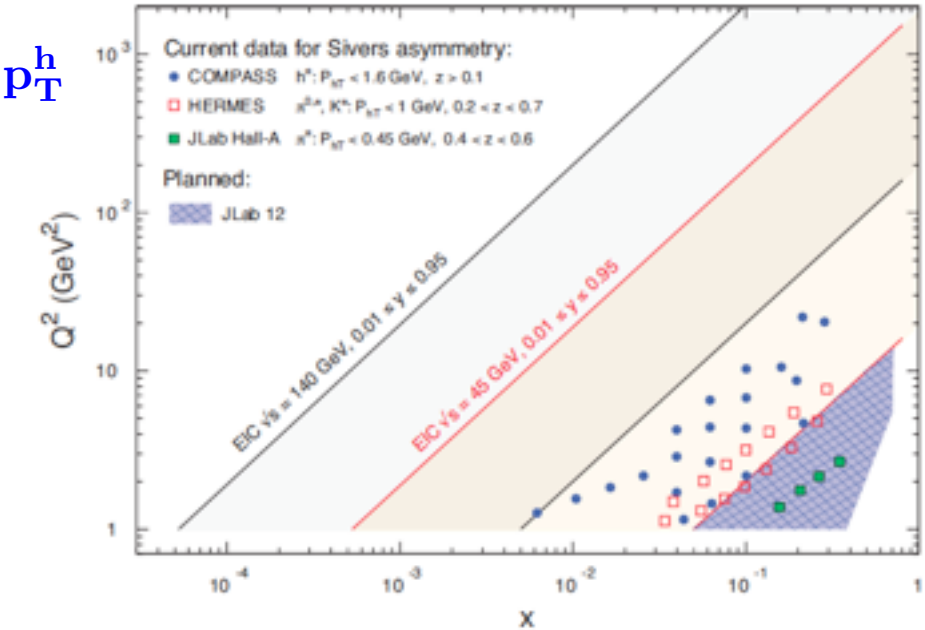

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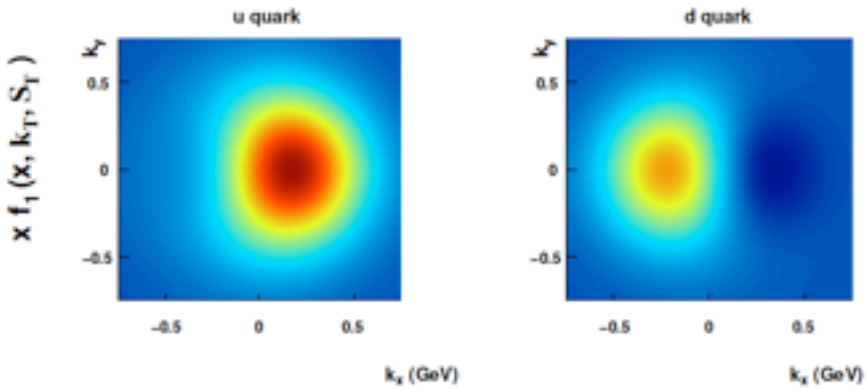

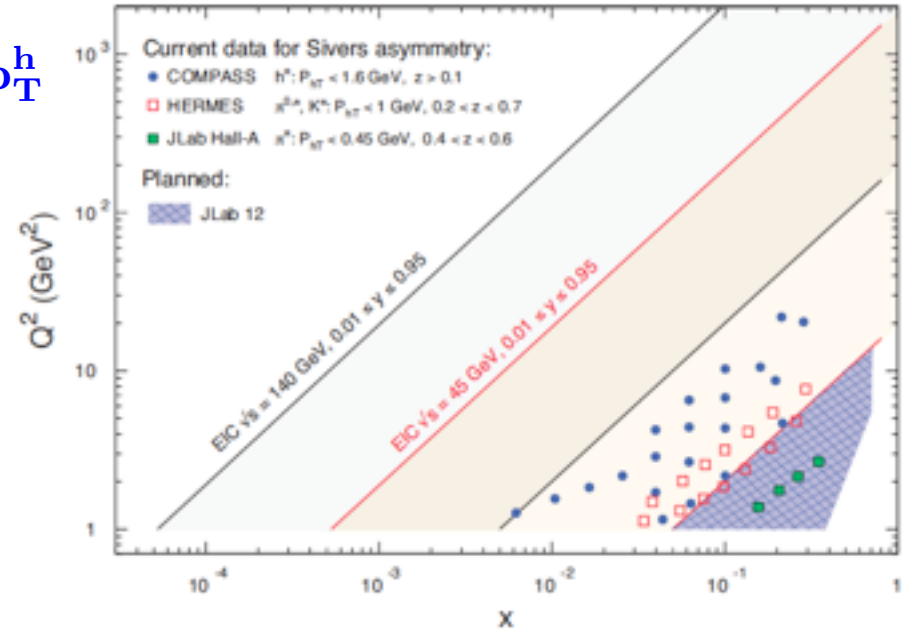

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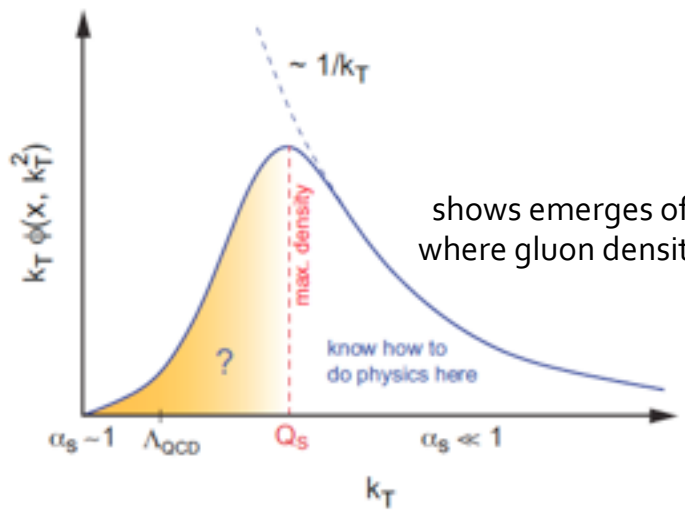
- origin of certain TMDs deeply linked with color gauge invariance of QCD
- unintegrated gluon density has **connection to CGC physics at small x**



shows emerges of a scale Q_s where gluon density saturates

specific example: Sivers function

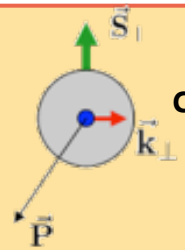
- slew of different TMDs can be measured by selecting certain ϕ modulations

example: **Sivers function**

measure

$\sin(\phi_{\mathbf{h}} - \phi_{\mathbf{S}})$

modulation



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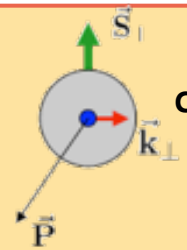

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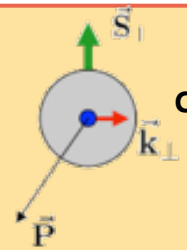

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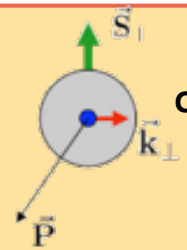

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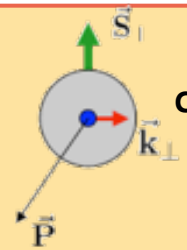

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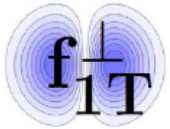

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Sivers asymmetry has been observed only in the valence quark regime

prospects for Sivers related measurements

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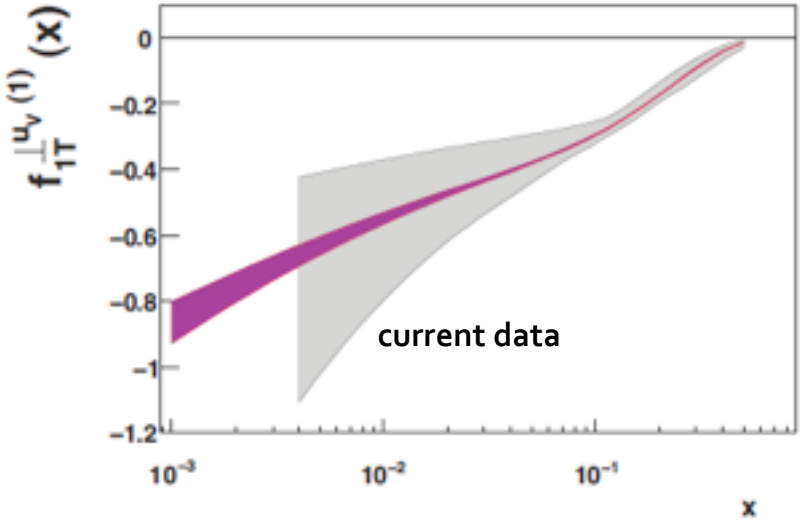

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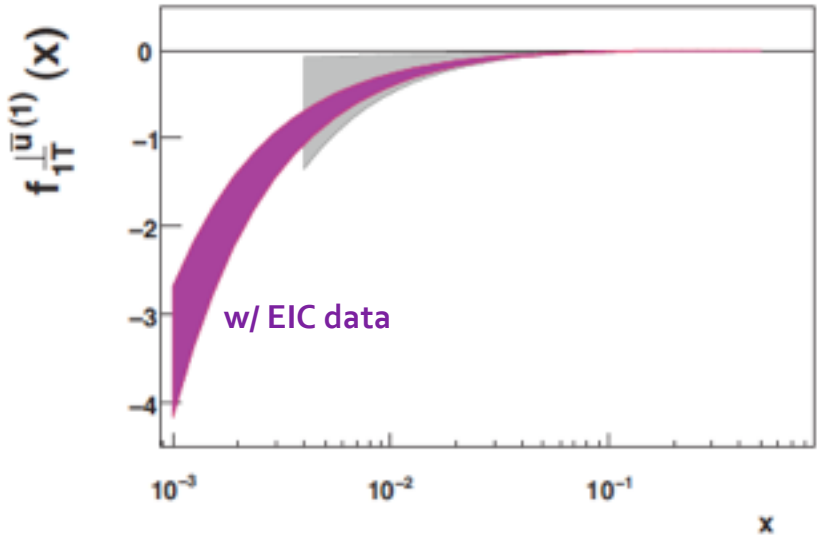

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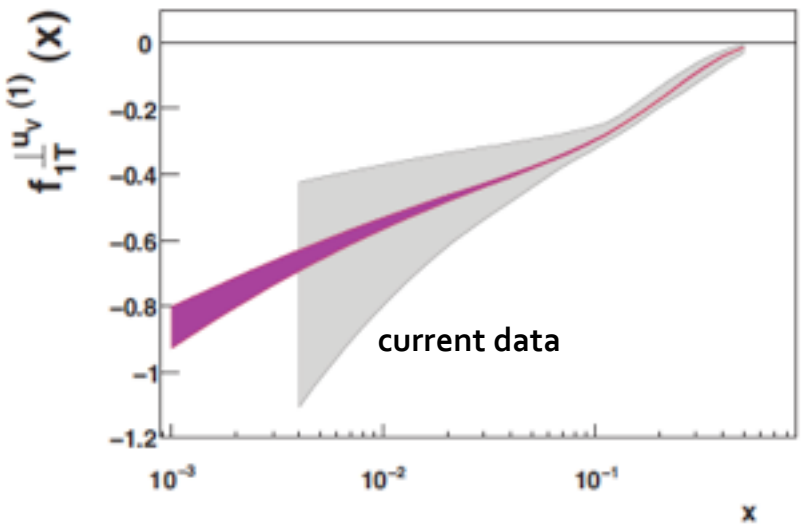

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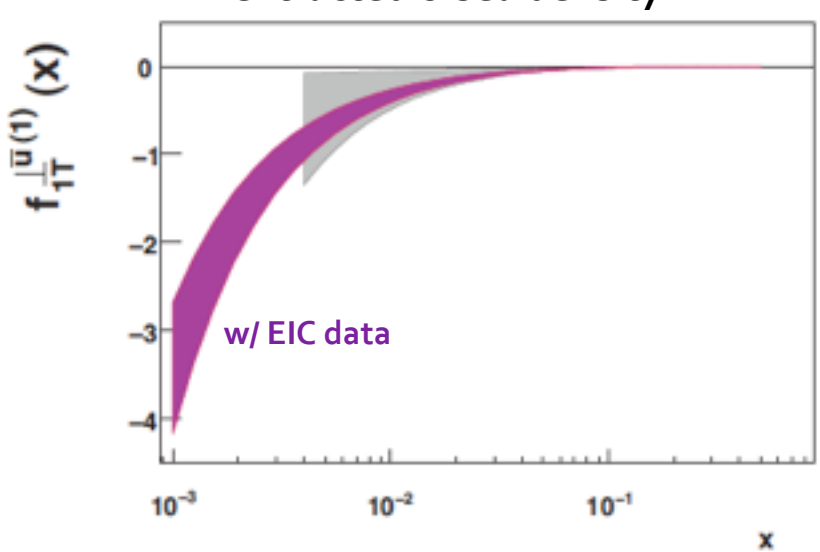
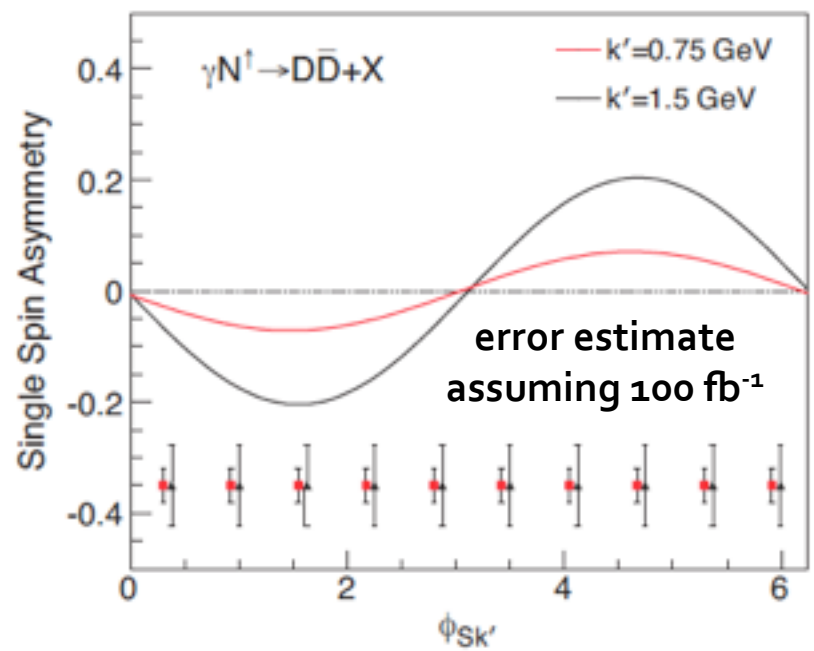


so far unmeasured **gluon Sivers fct** can be probed in D-meson correlations

observable: azimuthal asymmetry correlating the total k_T of the D-meson pair with transverse spin of the nucleon



angle between proton spin and k_T of D-meson pair

probing saturation with di-hadron correlations

- corresponding measurement in dAu at RHIC one of the best hints for saturation right now
- much cleaner probe in eA: no spectator background from electron side

tests universality of high gluon density framework between eA and pA

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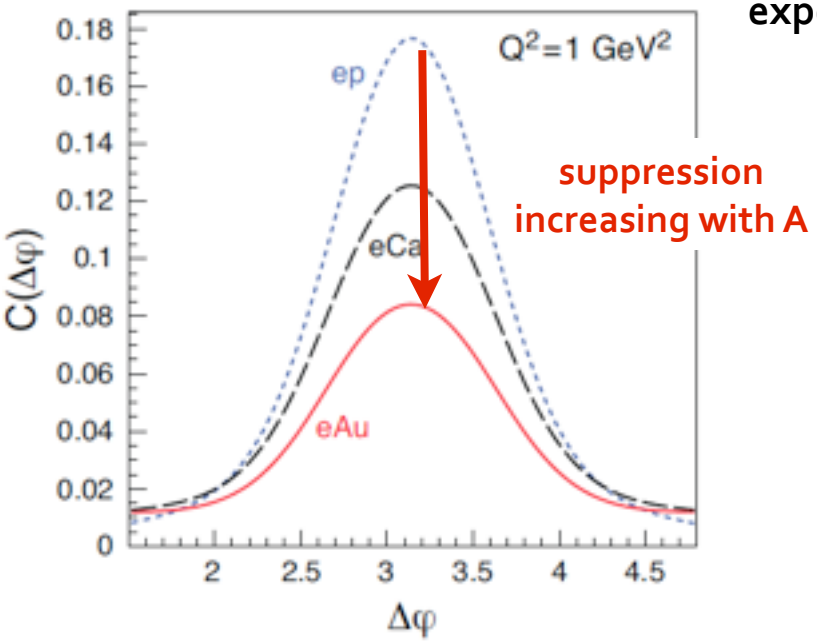
CGC expectation



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kinematics:

$$\mathbf{p_T^{trig}} > \mathbf{2}\,\mathrm{GeV}$$

$$\mathbf{1}\,\mathrm{GeV} \leq \mathbf{p_T^{assoc}} \leq \mathbf{p_T^{trig}}$$

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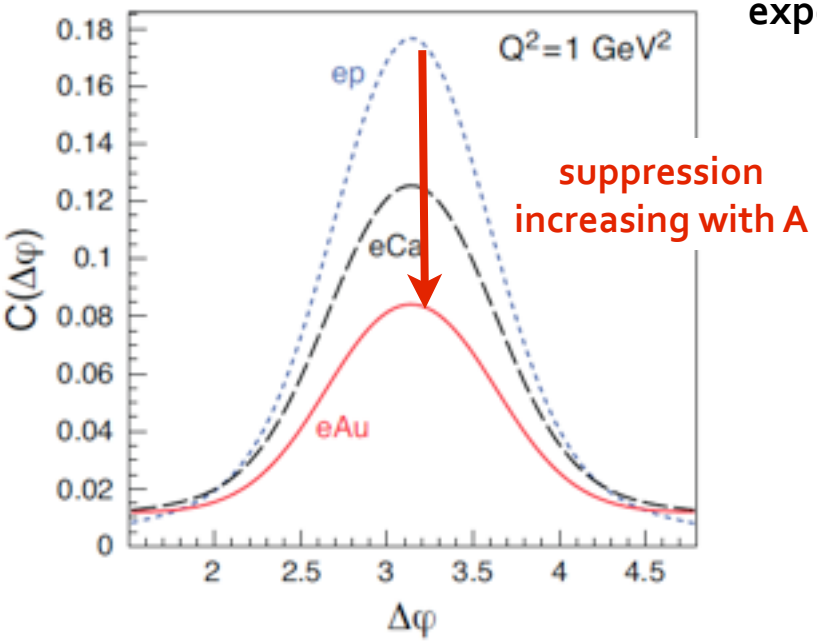

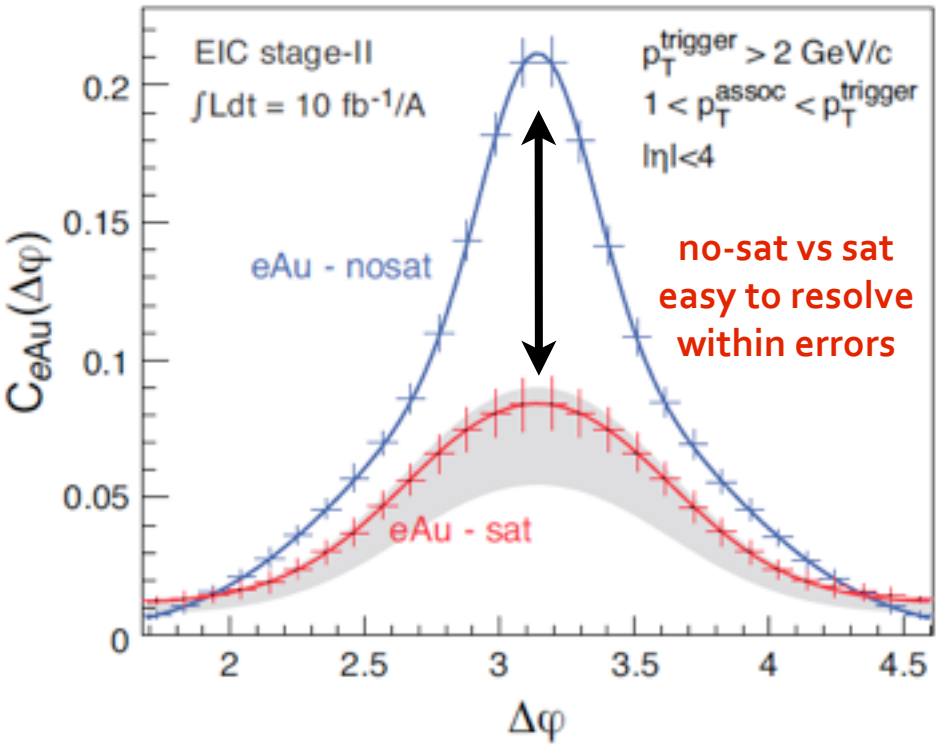

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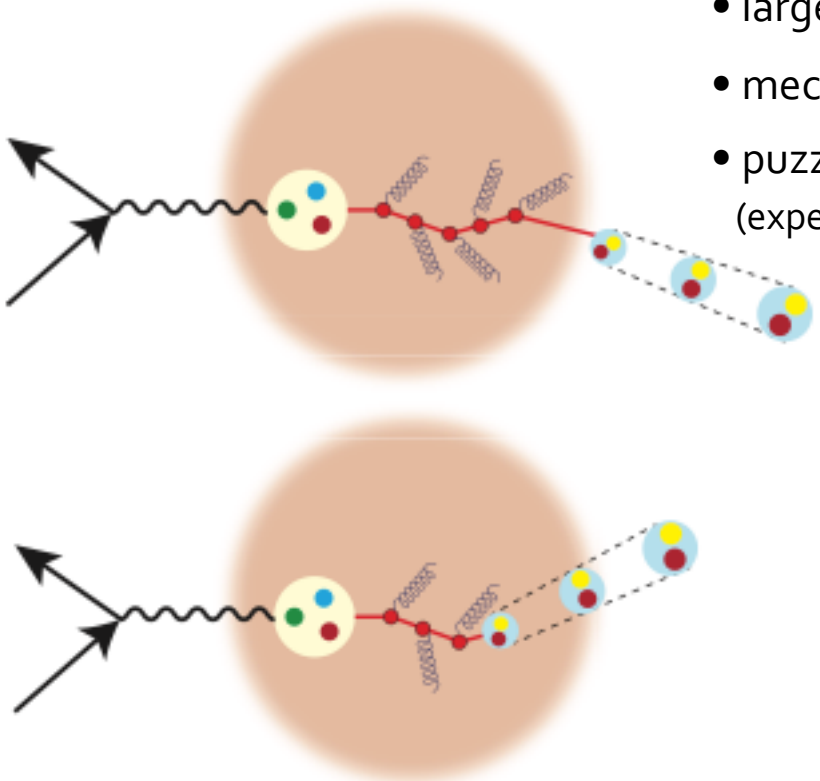
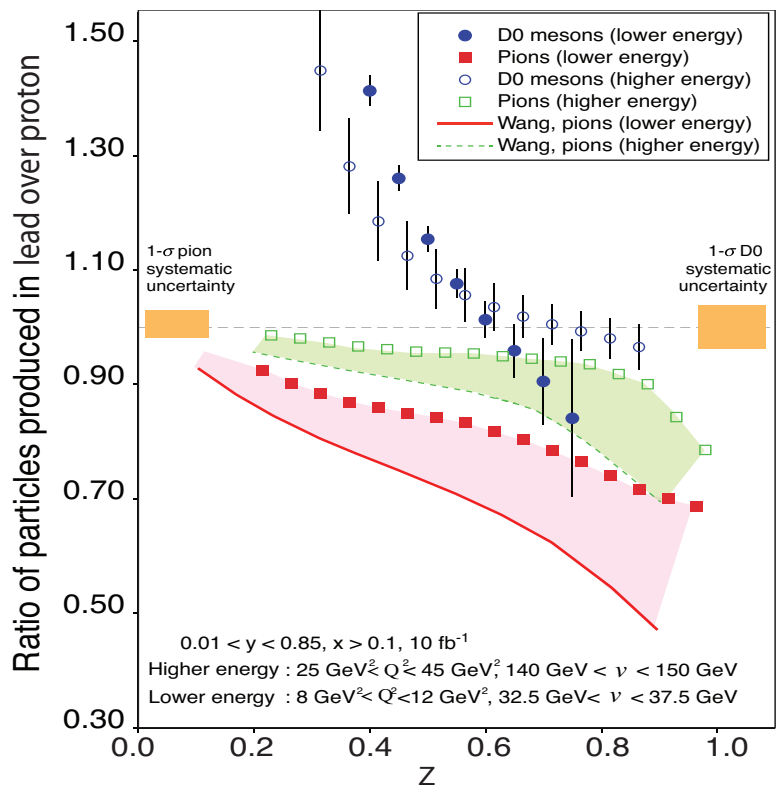
hadronization in a nuclear medium

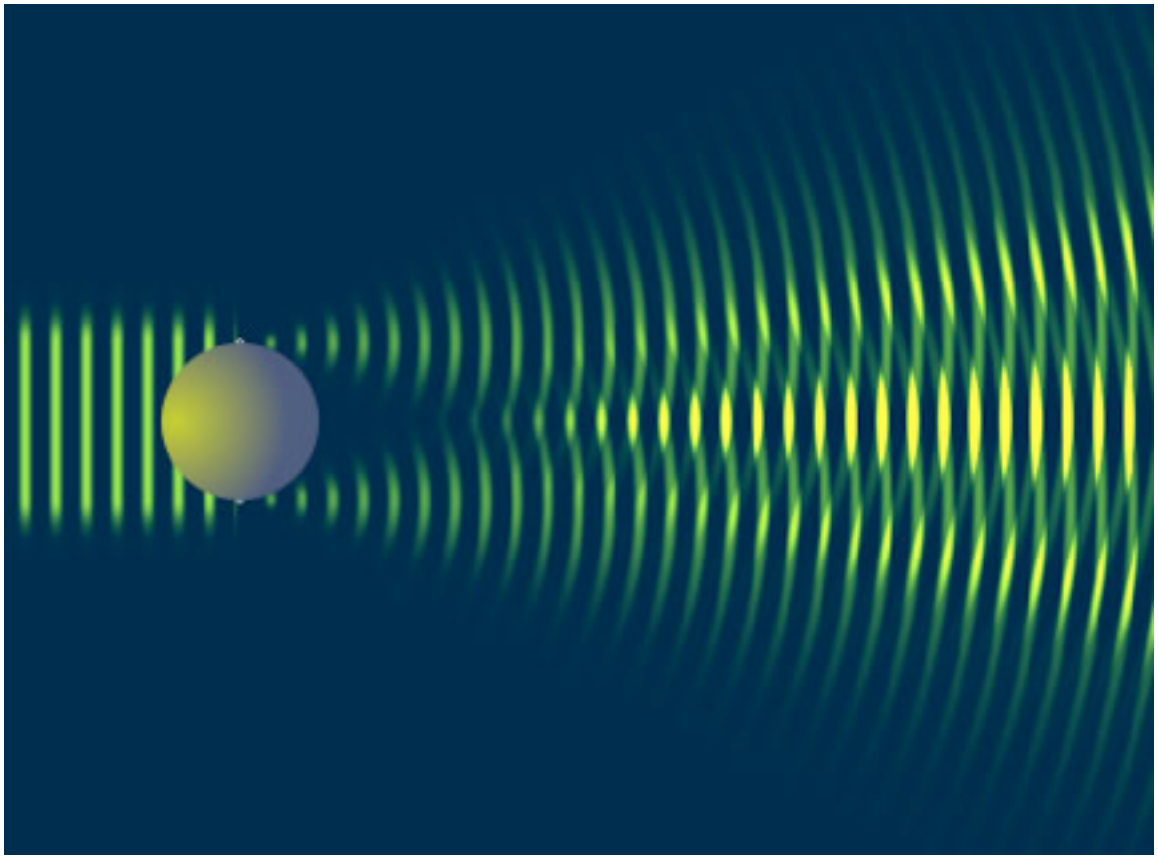
objective: precision study of propagation of a color charge through QCD matter



- large hadron attenuation observed at small ν (HERMES)
- mechanism for energy loss of partons?
- puzzle: c/b quarks suppression similar to light quarks (expect less due to "dead cone" for gluon radiation)



- much extended ν range compared to HERMES control "propagation length" before hadronization
- 1st study of D/B meson production in eA vs ep

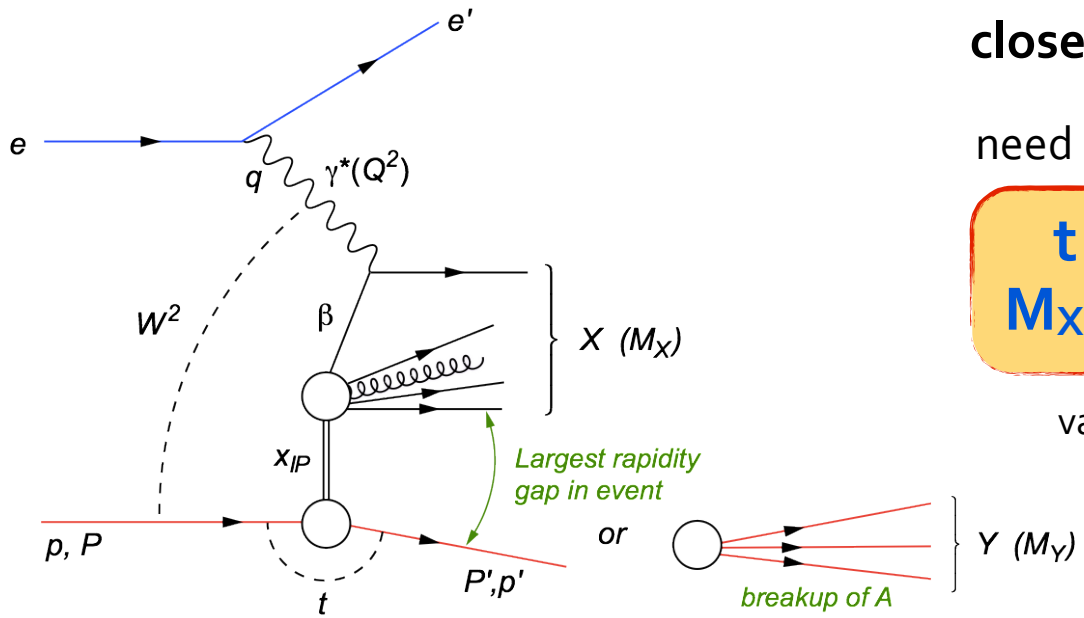


3

diffractive / exclusive processes

what to measure

- one of the surprises at HERA: large fraction of diffractive events (15% of total DIS rate)



close relative of DIS

need in addition

t : momentum transfer squared

M_X : mass of diffractive final-state

variables can be traded for β and x_P
where $x_{Bj} = \beta\, x_P$

diffractive event characterized by large **rapidity gap** (angular region w/o particle flow)
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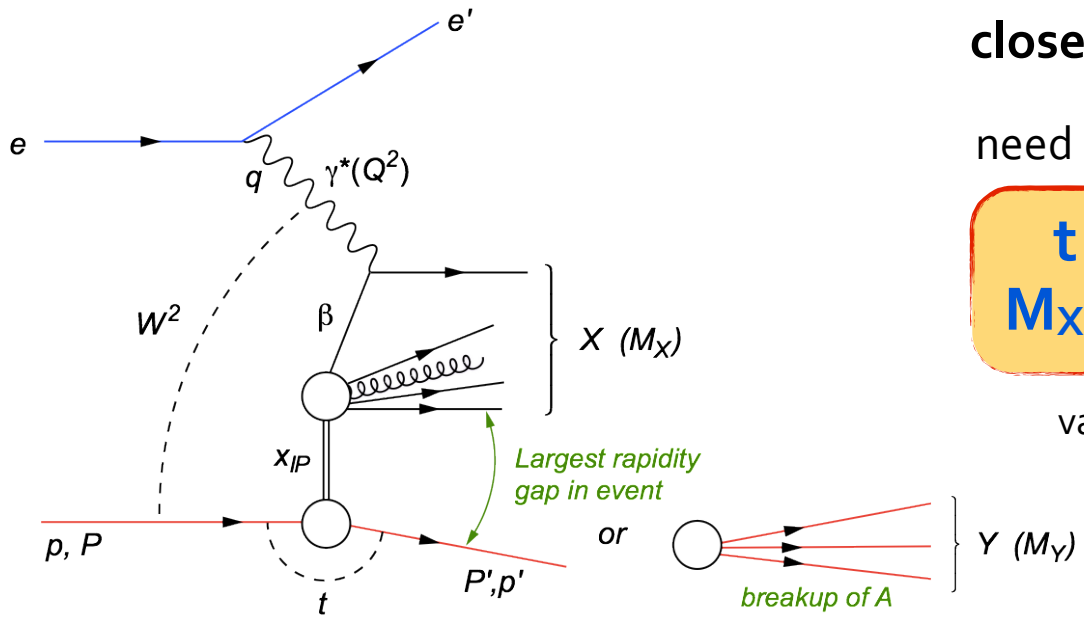

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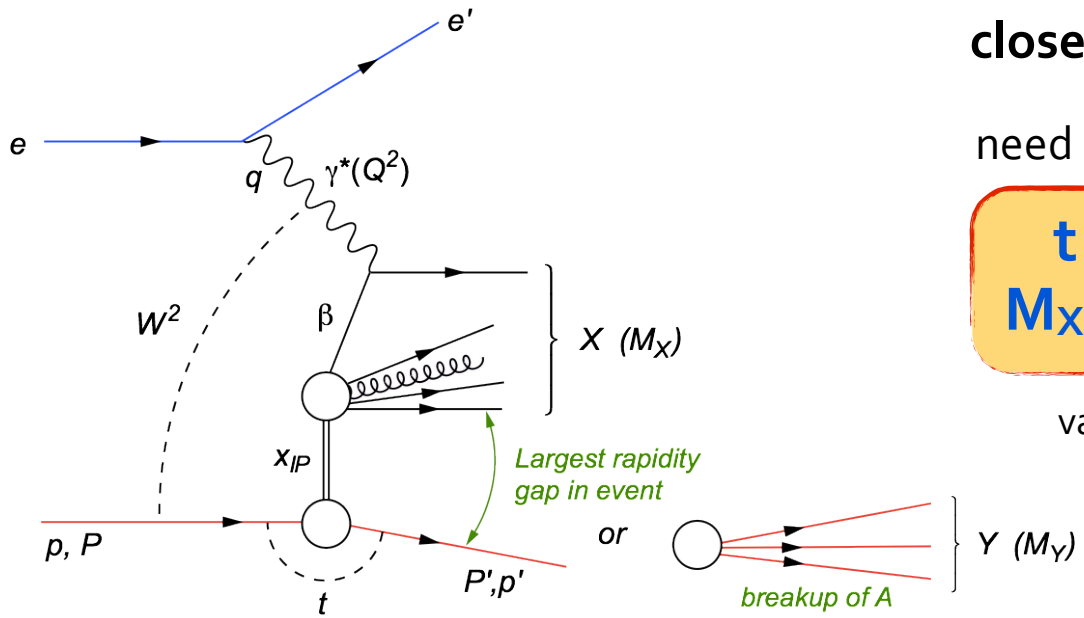

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- ep: detect intact protons in forward detectors

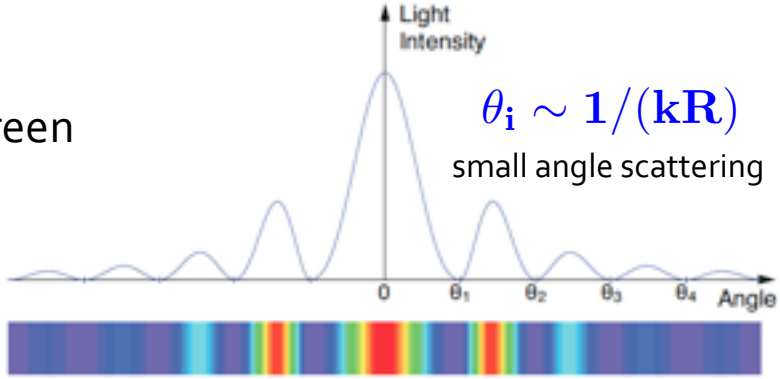
critical: IR design

- eA: need to tag on emitted neutrons from nuclear breakup (shown to be possible with near 100% efficiency)

diffractive physics - why relevant?

recall: diffractive pattern in optics

position of minima θ_i related to size R of screen



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small angle scattering

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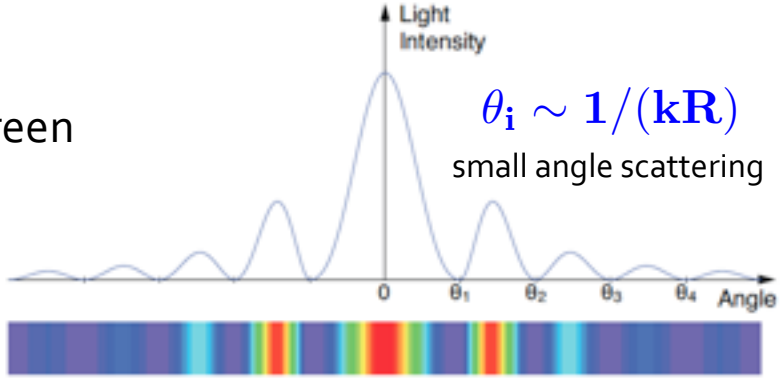

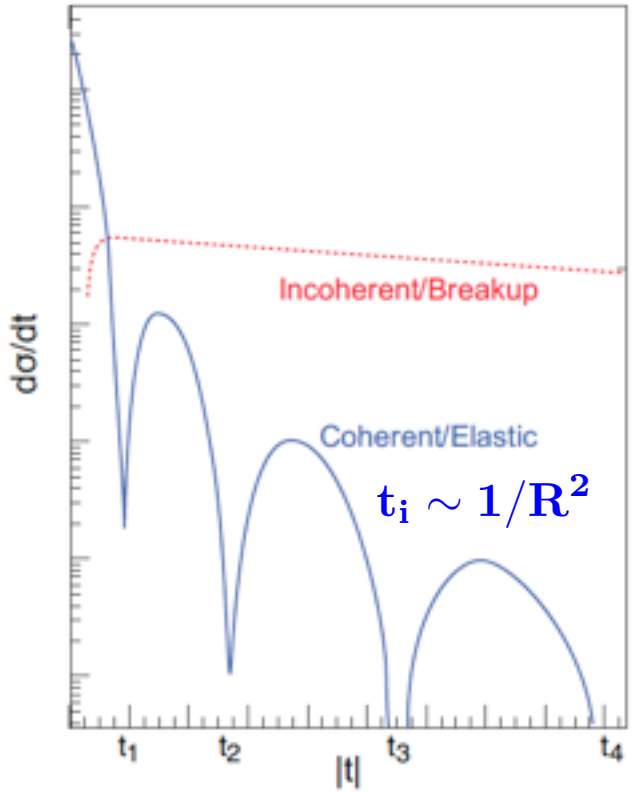

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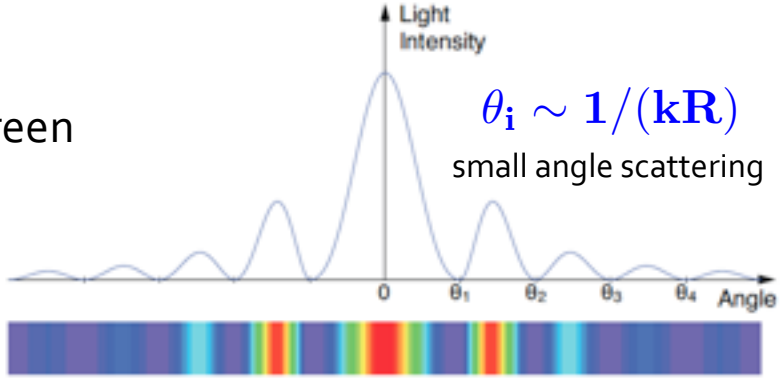

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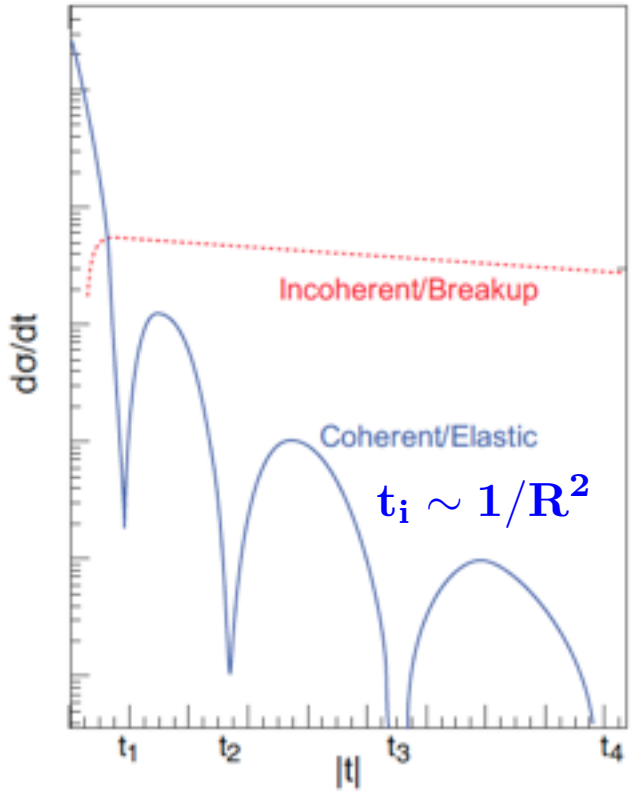

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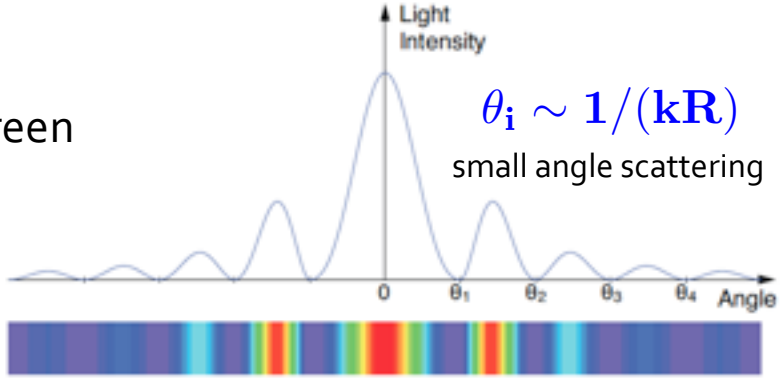

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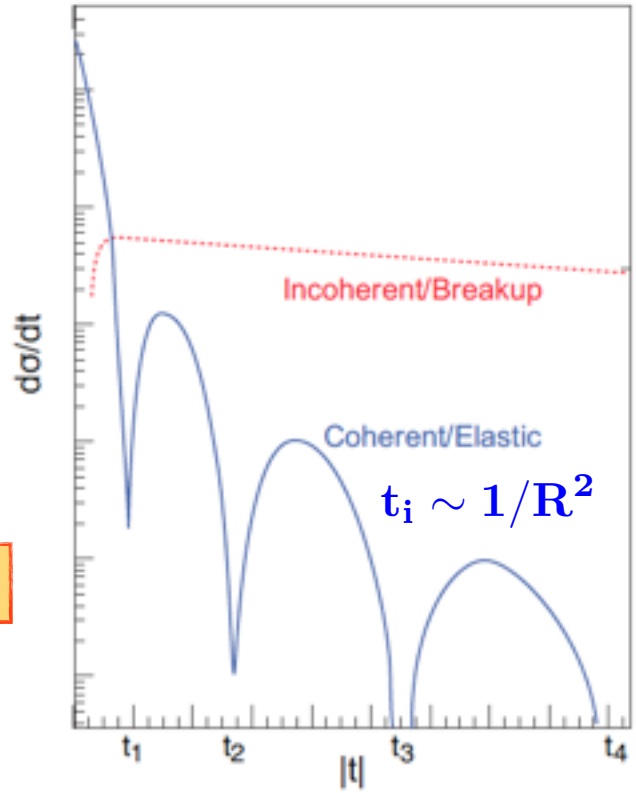

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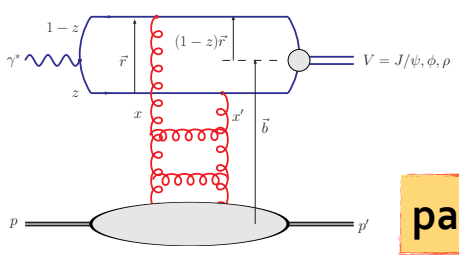

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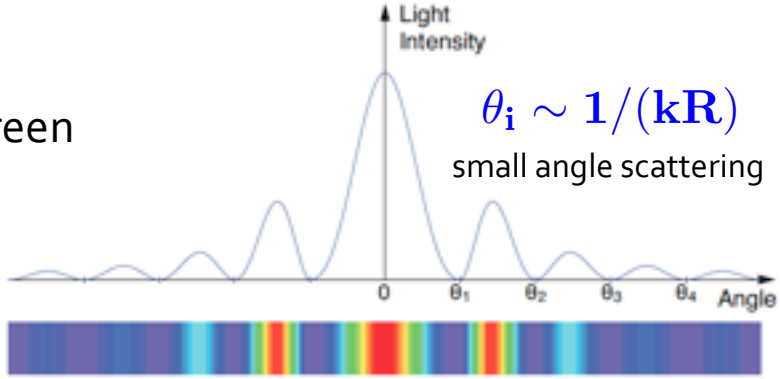

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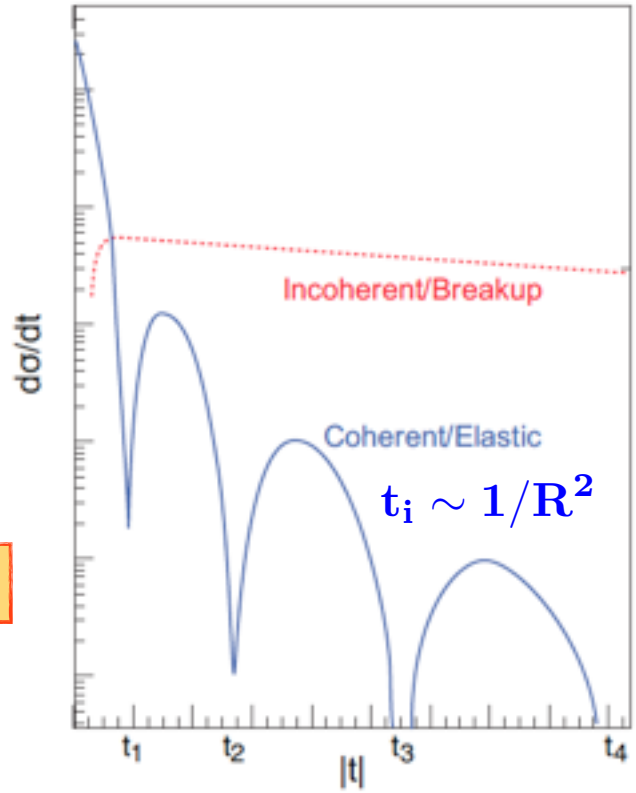

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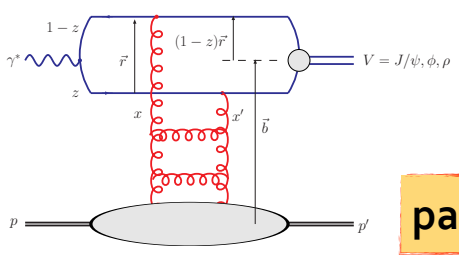

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bonus: $\frac{d\sigma}{dt}$ $\xleftrightarrow[\text{transform}]{\text{Fourier}}$ **spatial distribution of gluons**

ratio of diffractive to total cross section

- black disc limit characterized by $\sigma_{\mathrm{diff}}/\sigma_{\mathrm{tot}} = 1/2$ (recall: HERA sees ≈1/7 in ep)

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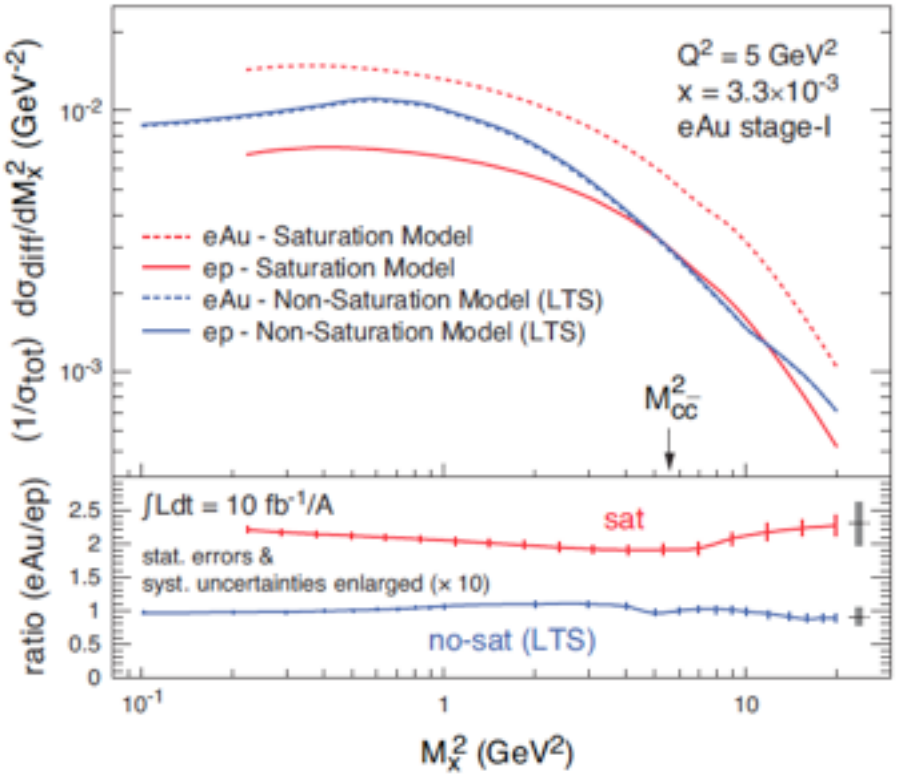
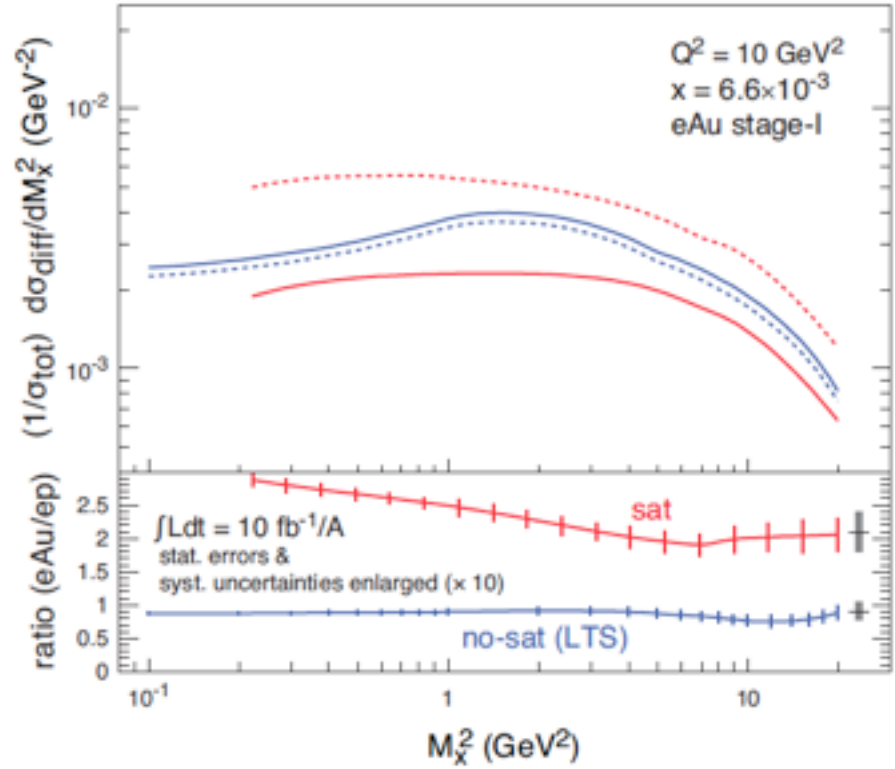
estimates for fraction of low-mass coherent diffraction in ep and eA at EIC kinematics:





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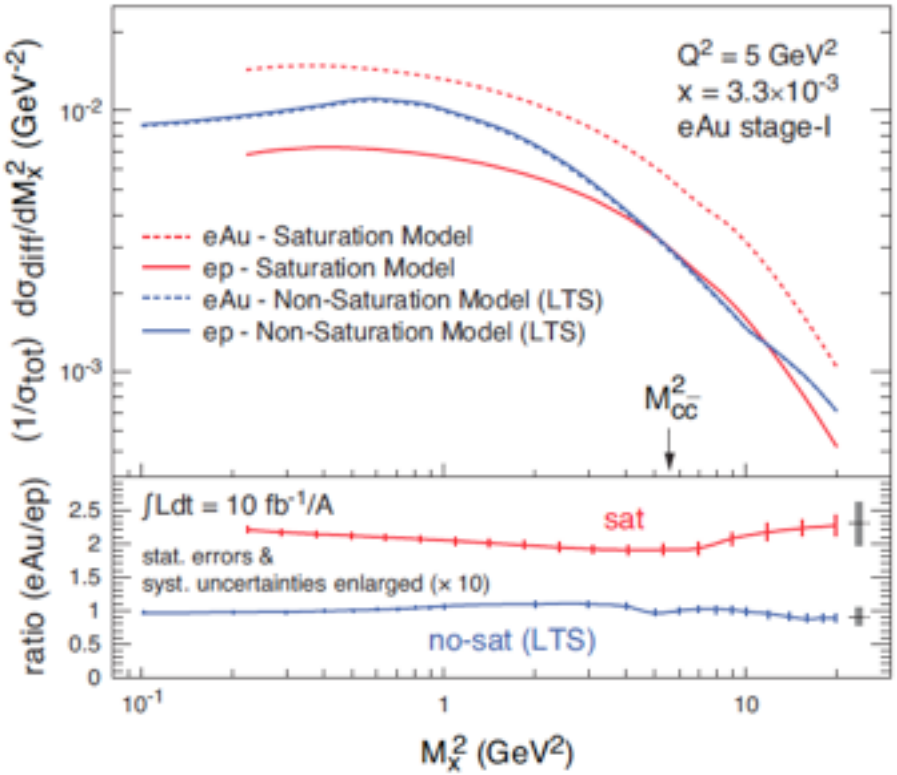

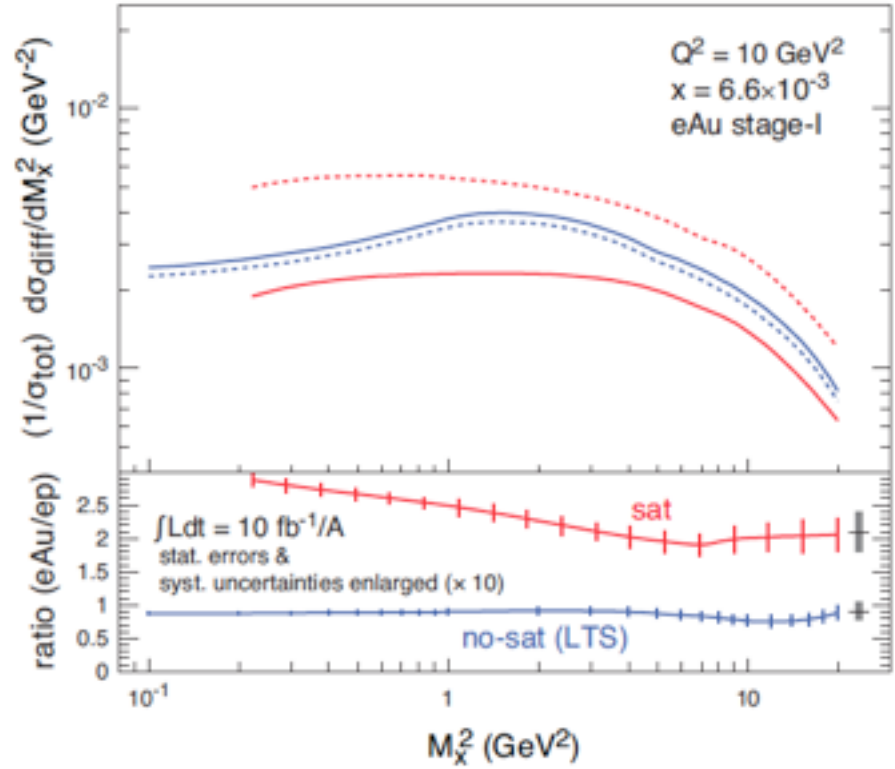

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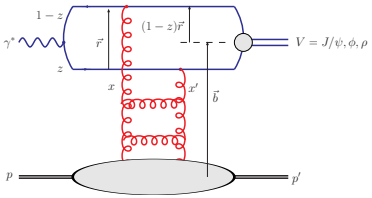
in general, one cannot detect the outgoing nucleus and its momentum



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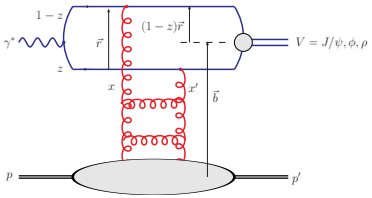

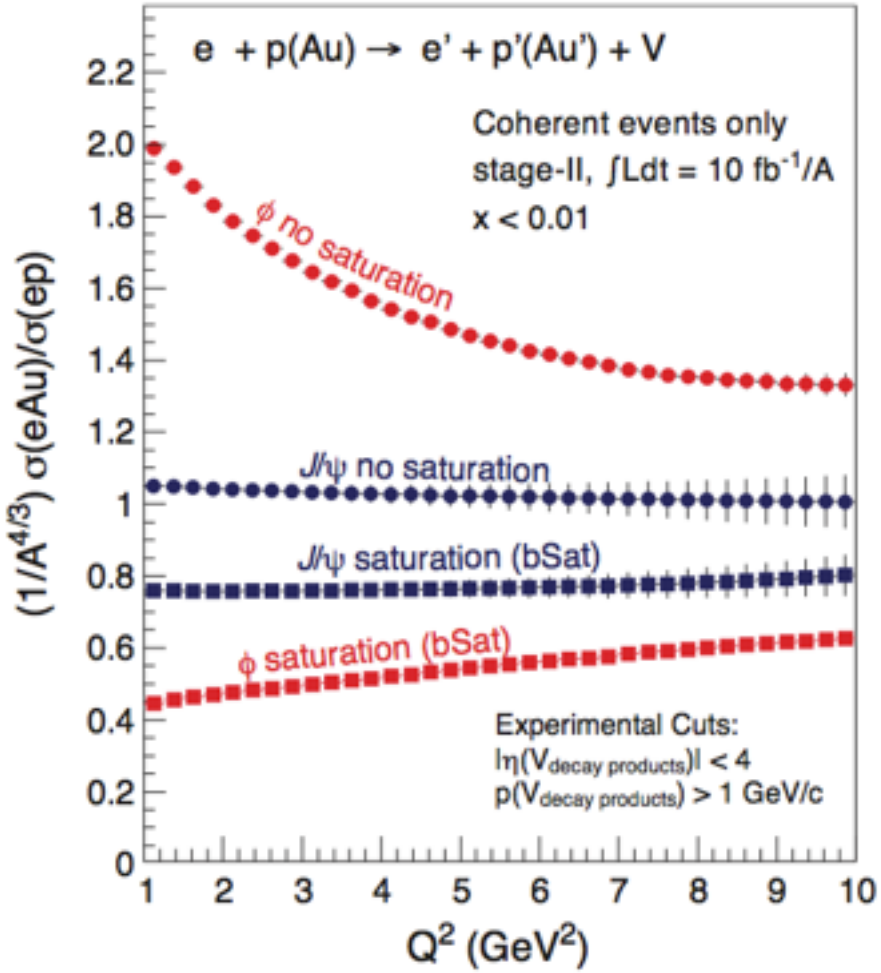

cross section strongly depends on overlap with VM wave function

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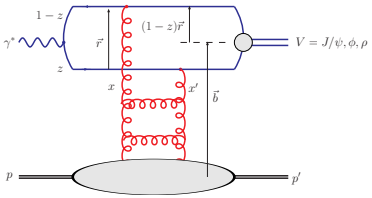

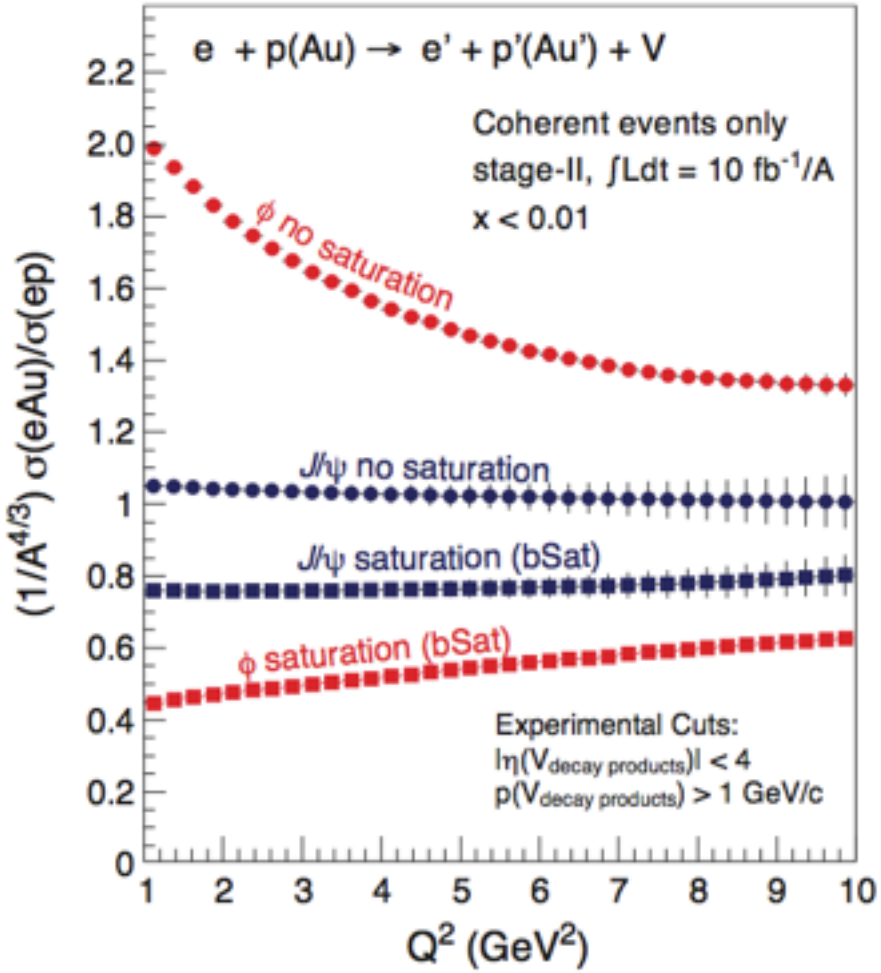

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Q^2 variation controls size of probe
→ go in (small Q^2) and out (large Q^2) of saturation region

spatial distribution of gluons through diffraction

goal: going after the source distribution of gluons through **Fourier transform of dσ/dt**

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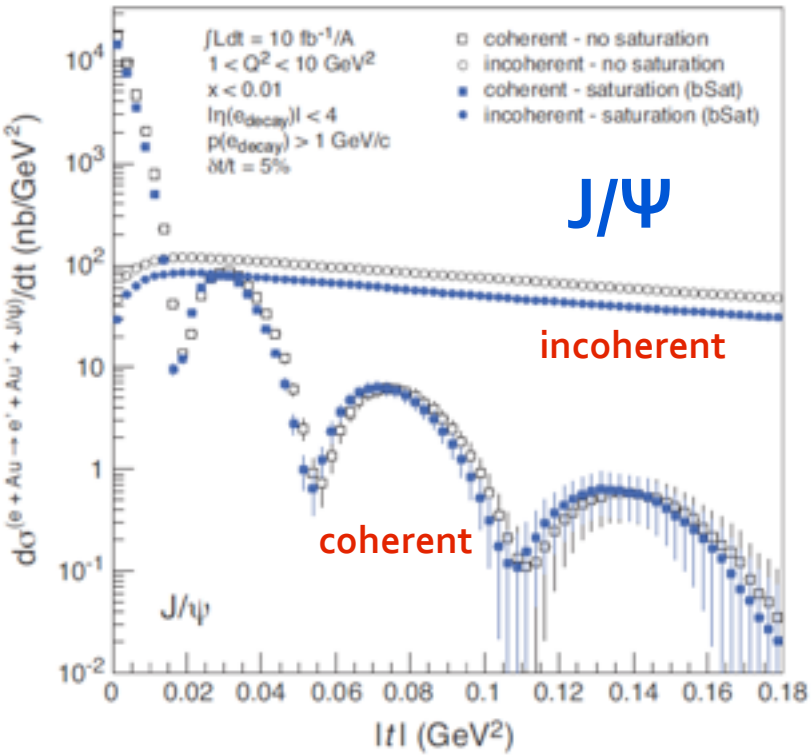
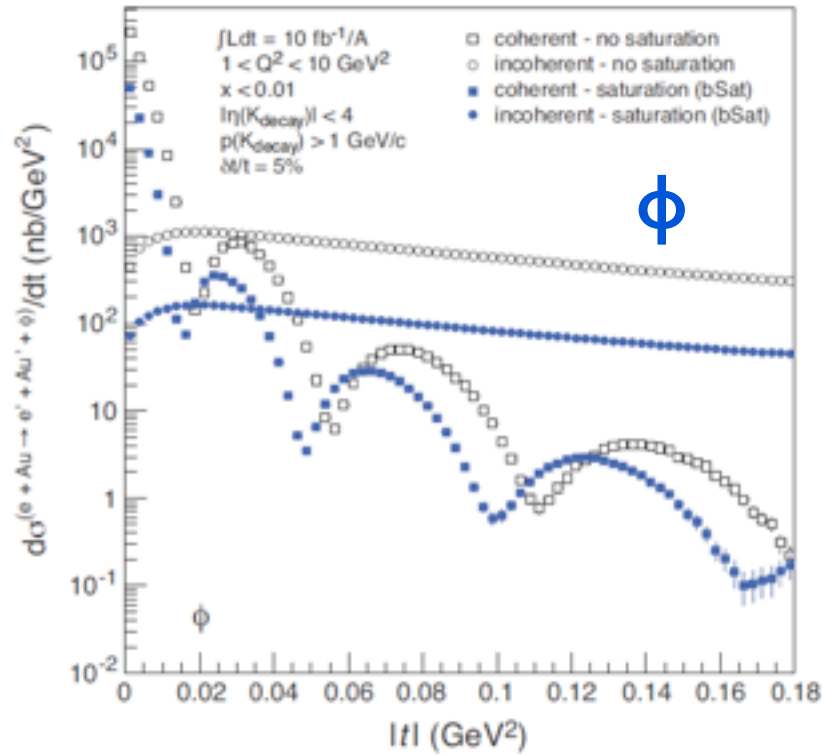
find:

- typical diffractive pattern for coherent (non-breakup) part
- as expected, J/Ψ less sensitive to saturation effects than larger ϕ meson





how does the imaging work - what do we learn?

idea: momentum transfer t conjugate to transverse position (impact parameter b)

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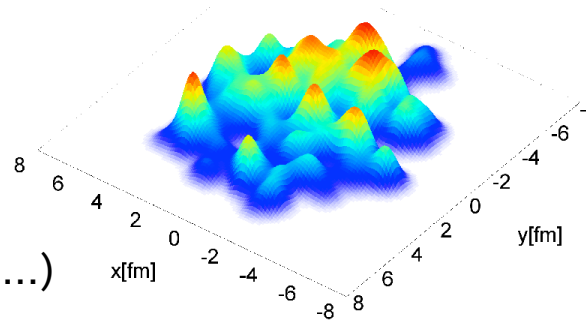

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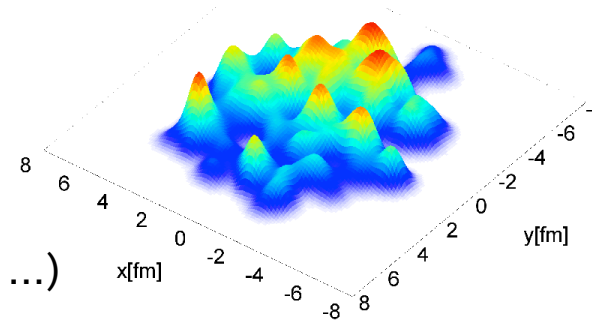

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what you need to do: $$\mathbf{F(b)} \sim \frac{\mathbf{1}}{\mathbf{2\pi}} \int_{\mathbf{0}}^{\infty} \mathbf{d\Delta\ \Delta\ J_0(\Delta\, b)} \underbrace{\sqrt{\frac{\mathbf{d\sigma}}{\mathbf{dt}}}}_{\text{"amplitude"}} \qquad \mathbf{t \simeq -\Delta^2}$$

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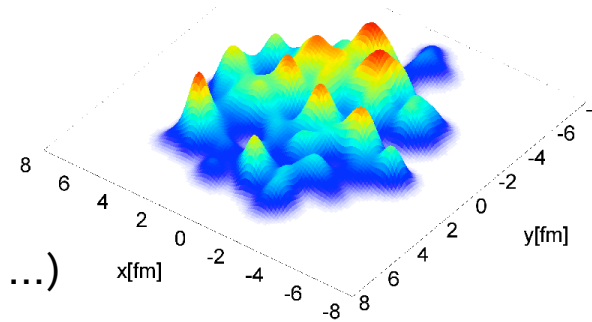

→ impact on our understanding of initial conditions of heavy ion collisions

what you need to do: $$\mathbf{F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\ \Delta\ J_0(\Delta\, b) \sqrt{\frac{d\sigma}{dt}}} \qquad \mathbf{t \simeq -\Delta^2}$$

"amplitude"

challenges:

- coherent part drops fast with t; statistical errors become large beyond ~ 4th minima
- accessible t range rather small ($|t| \lesssim 0.2$ GeV^2) for coherent part

how does the imaging work - what do we learn?

idea: momentum transfer t conjugate to transverse position (impact parameter b)

→ expect small t relevant for large b and vice versa

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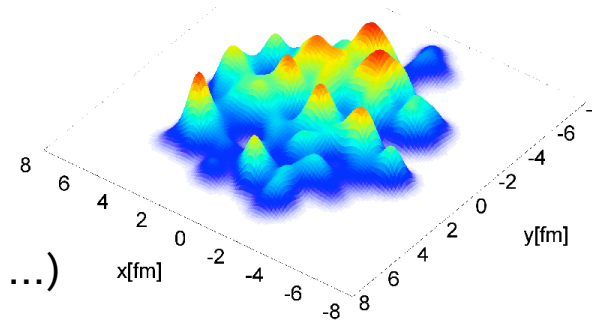

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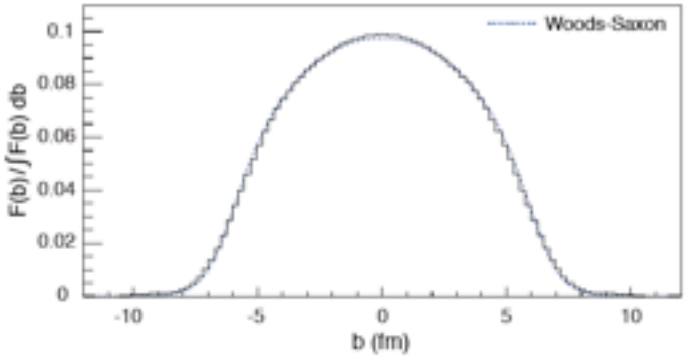
... so, does it work at all?

✓ yes, $|t|<0.15$ GeV^2 enough in eA to reconstruct Woods-Saxon potential used in simulation

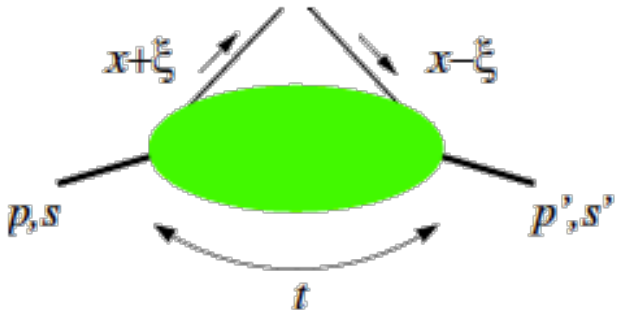


exclusive processes and GPDs

another class of (related) processes for **parton imaging**

need to introduce concept of

generalized parton distributions (GPDs)



GPDs depend on:

- momentum transfer t
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- long. momentum before and after the scattering: x, ξ

= interference between different nucleon states (not a probability)

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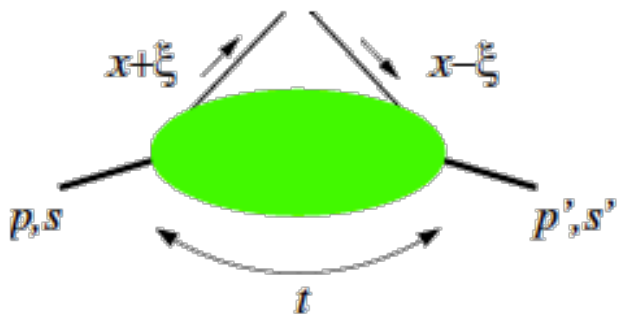

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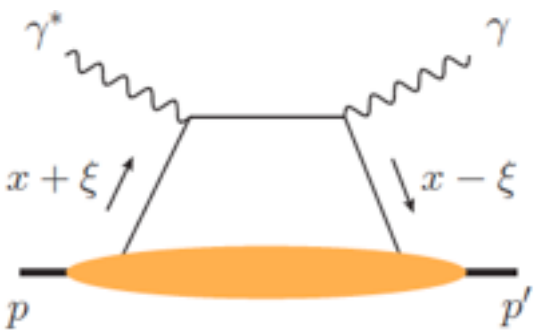
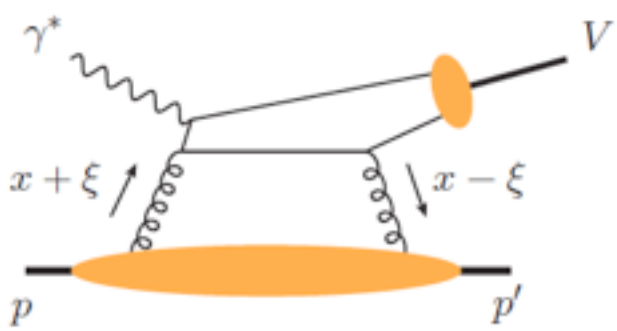
appear in theoretical description of **exclusive processes**



deeply virtual Compton scattering (DVCS)

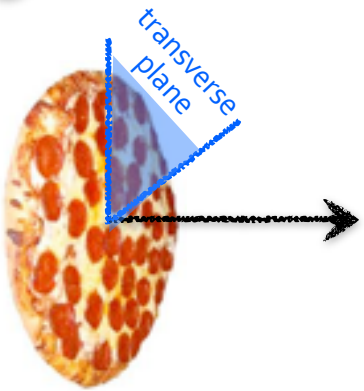


vector meson production

path to spatial imaging of partons through GPDs

recall: standard PDFs do not resolve transverse positions in the nucleon

fast moving nucleon turns into a `pizza' but transverse size remains ≃ 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

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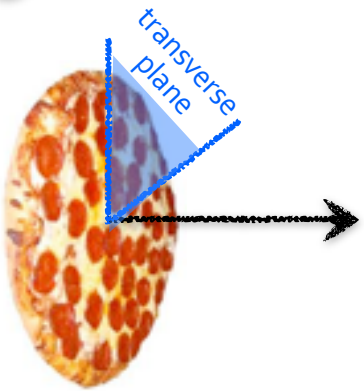

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already discussed

3-D

$$f(x, k_T)$$

transv. mom. dep. PDF

semi-inclusive DIS

$$\int d^2 k_T$$

1-D

$$f(x)$$

parton densities

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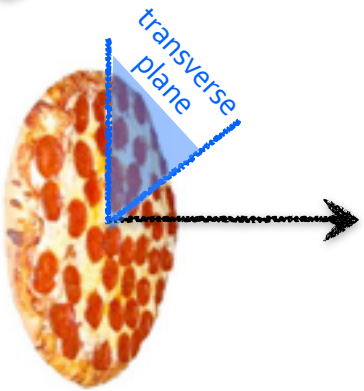

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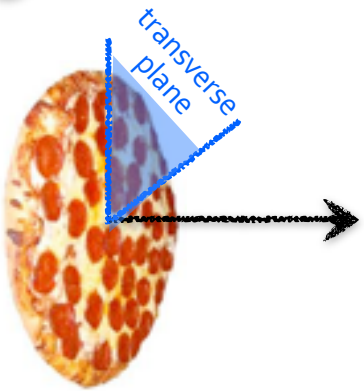

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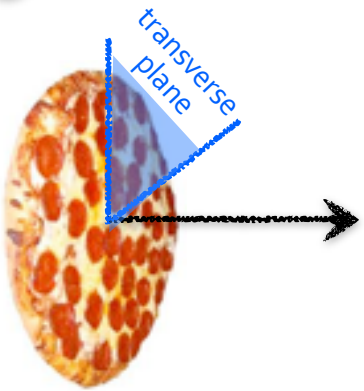

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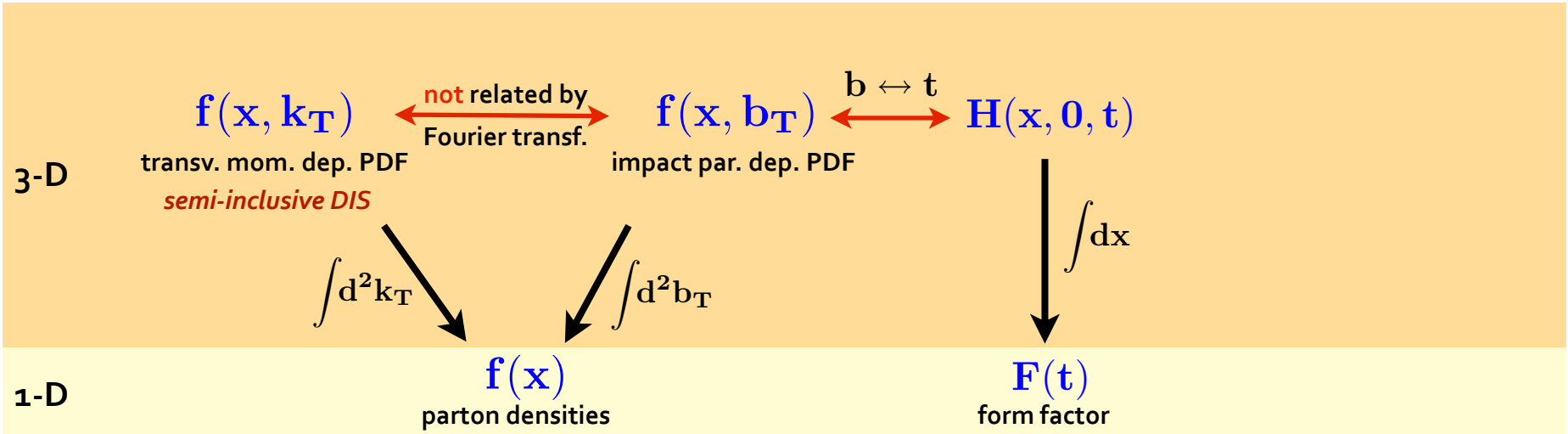

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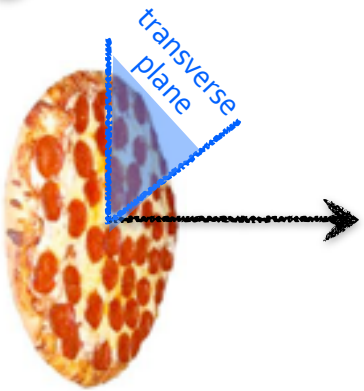

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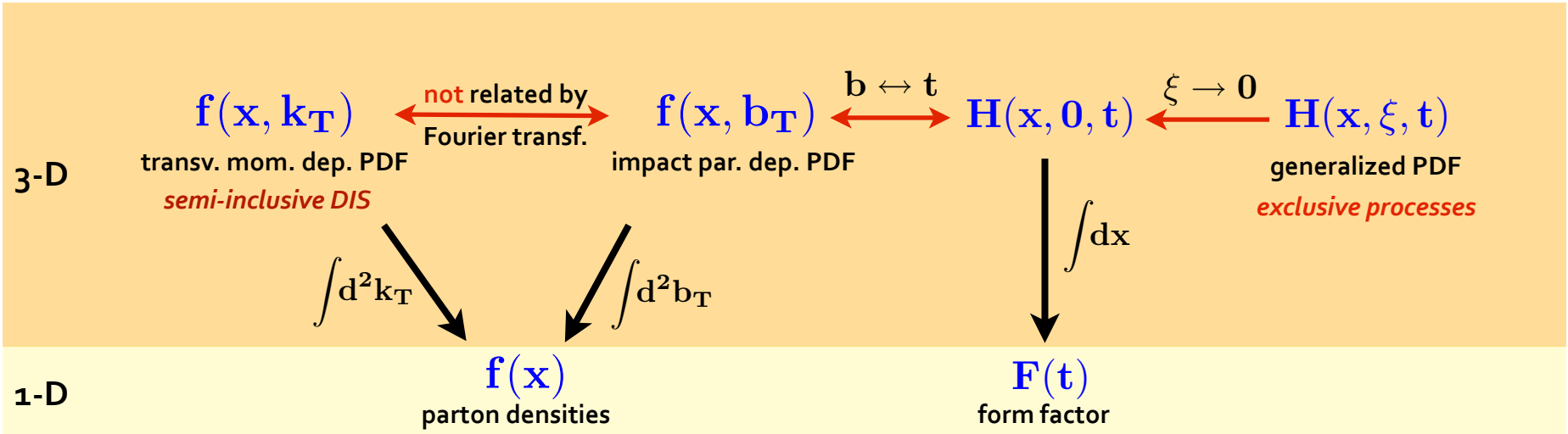

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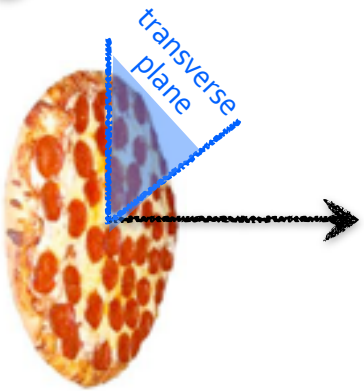

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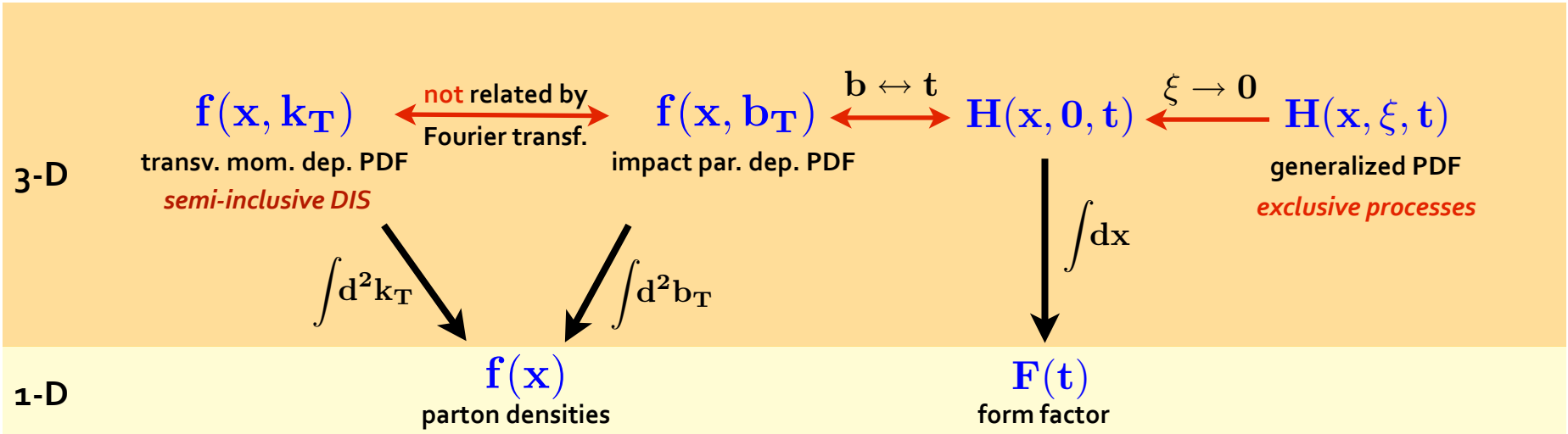

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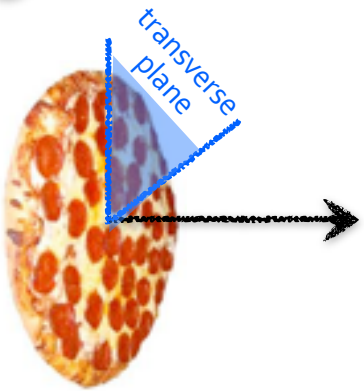

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$\xleftrightarrow{\mathbf{b \leftrightarrow t}}$

$\mathbf{H(x, 0, t)}$

$\xleftarrow{\xi \to 0}$

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

$\int d^2 k_T$

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$\int dx$

1-D

$\mathbf{f(x)}$ — parton densities

$\mathbf{F(t)}$ — form factor

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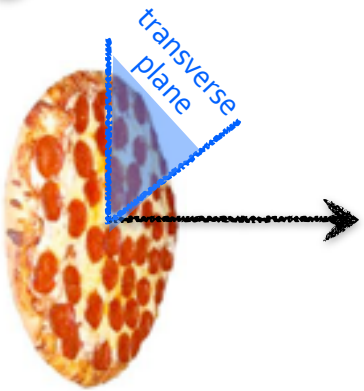

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GPD's appear here

again, need Fourier transform to get what we want

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not related by Fourier transf.

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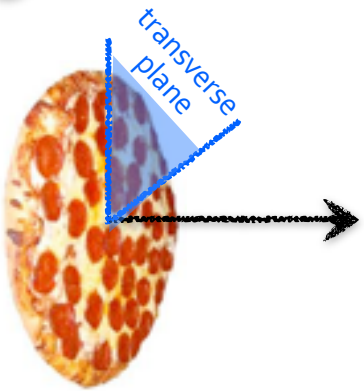

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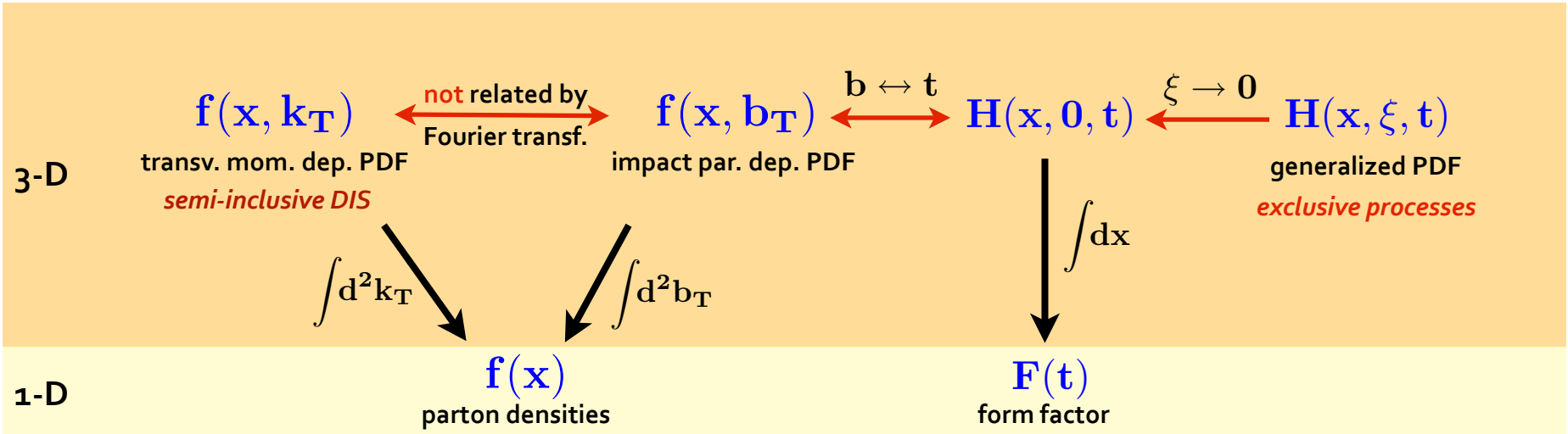

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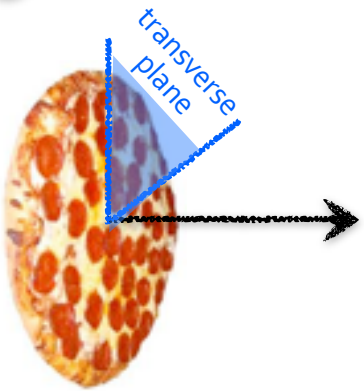

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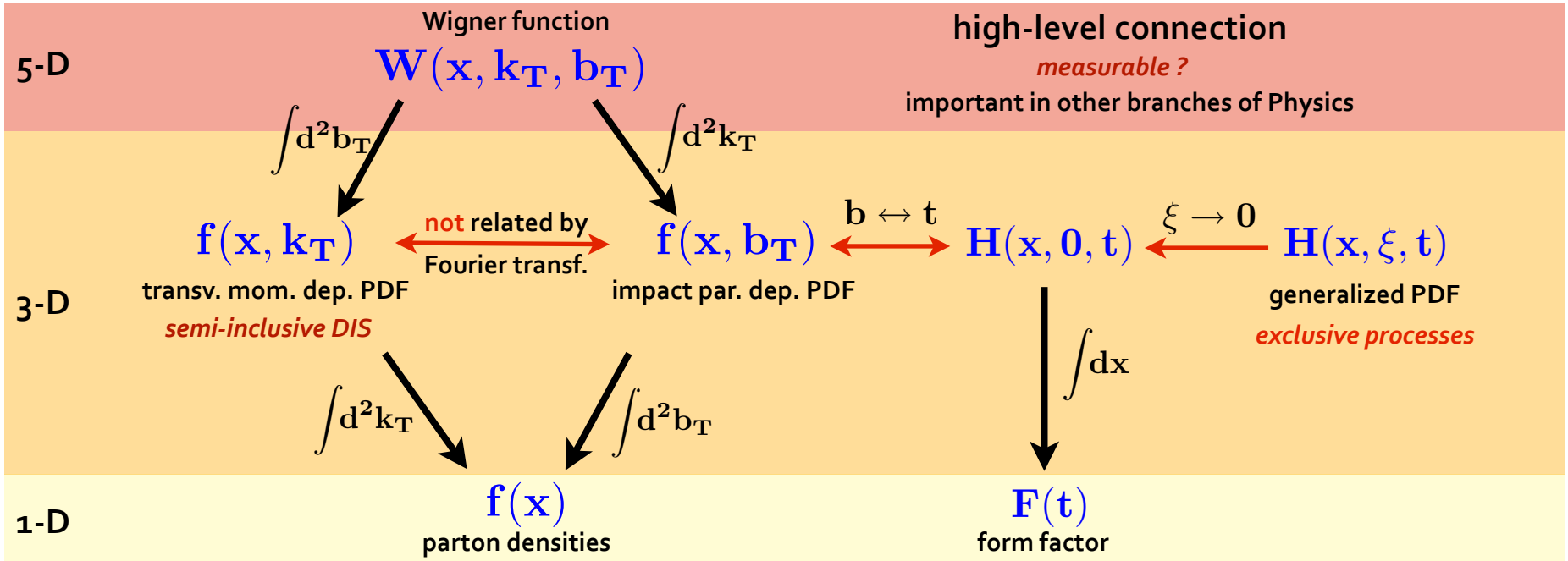

roadmap for transverse imaging of the proton

- obtain GPDs from global analysis of DVCS and vector meson data in ep scattering

  slew of angular & polarization observables (+ use of positron beams) to disentangle H and E

4 GPDs per flavor, e.g.,

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p', s' | \bar{q}(-\frac{z}{2})\, \mathcal{W}\, \gamma^+ q(\frac{z}{2}) | p, s \rangle_{z^+=0, \mathbf{z}=\mathbf{0}}$$

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no PDF limit; involves helicity flip

indicator of OAM; key part in Ji's sum rule

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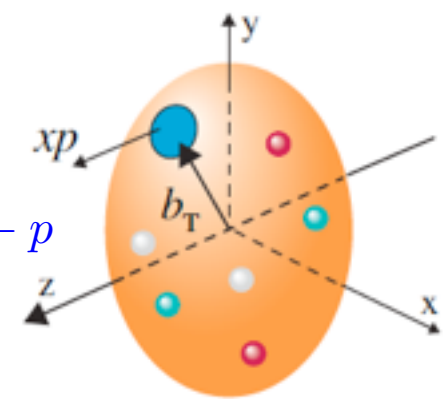
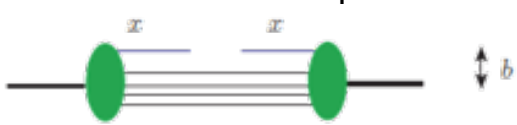
e.g. $q(x, b^2) \simeq \int d^2\mathbf{\Delta} e^{-ib\mathbf{\Delta}} H^q(x, \xi = 0, t = -\mathbf{\Delta}^2)$ where $\mathbf{\Delta} = p' - p$



gives distribution of quarks with



- longitudinal momentum fraction x
- transverse distance b from proton center

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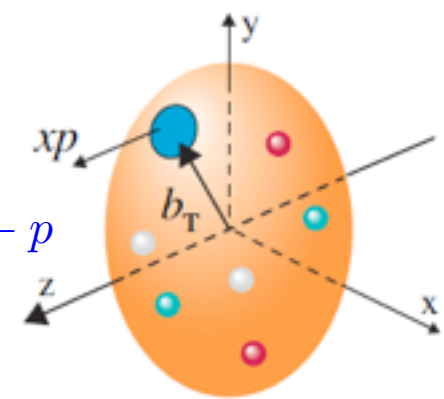

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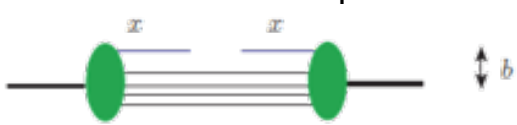

- longitudinal momentum fraction x
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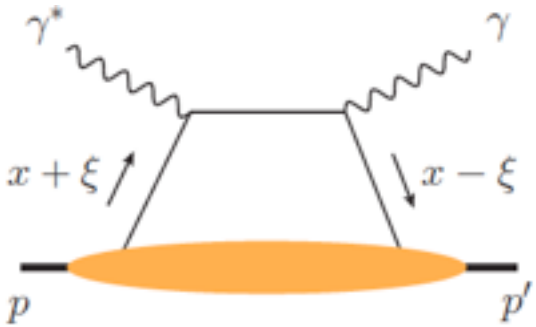
challenges:

- need to resolve small distances in proton
- no diffractive pattern in accessible t range

→ need dσ/dt in larger t-range than in eA

example: DVCS - what do we know?



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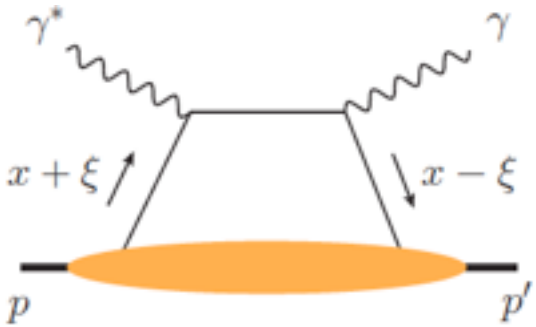

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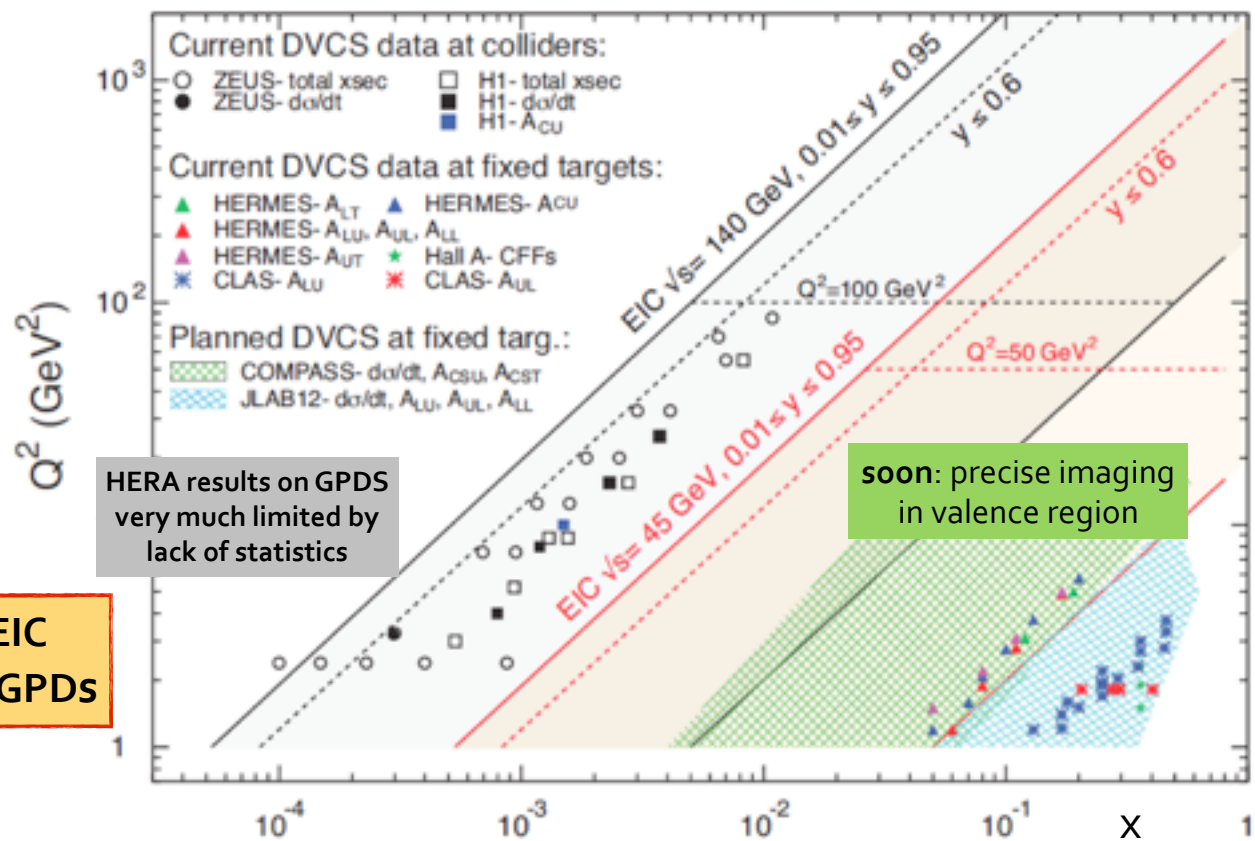
DVCS measurements past-present-future



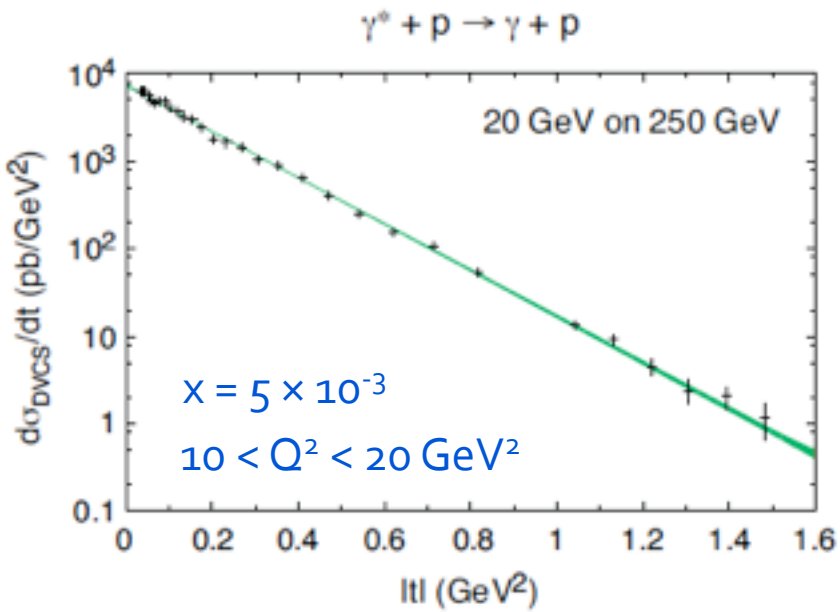
HERA results on GPDS very much limited by lack of statistics

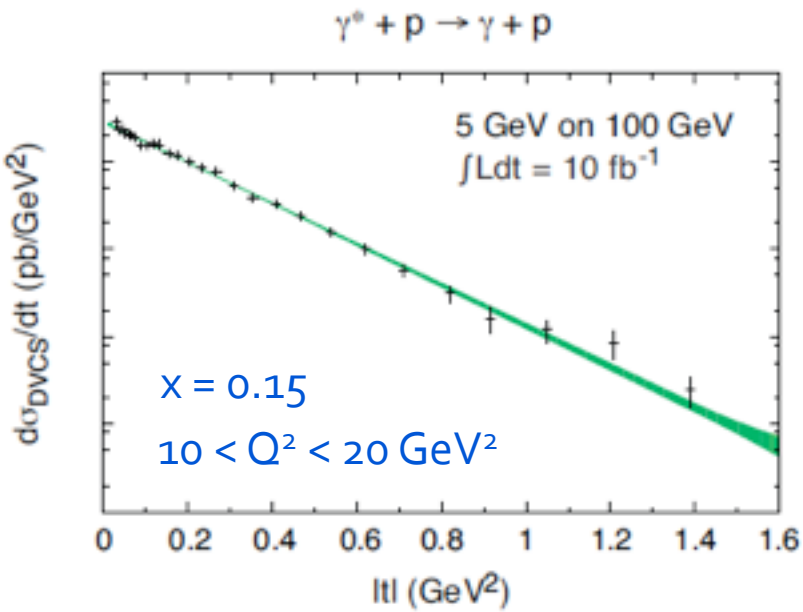
soon: precise imaging in valence region

plenty of opportunities at an EIC to map out gluon and sea-quark GPDs

DVCS - how well does it work out?

examples of simulated DVCS data including acceptance cuts and resolution effects





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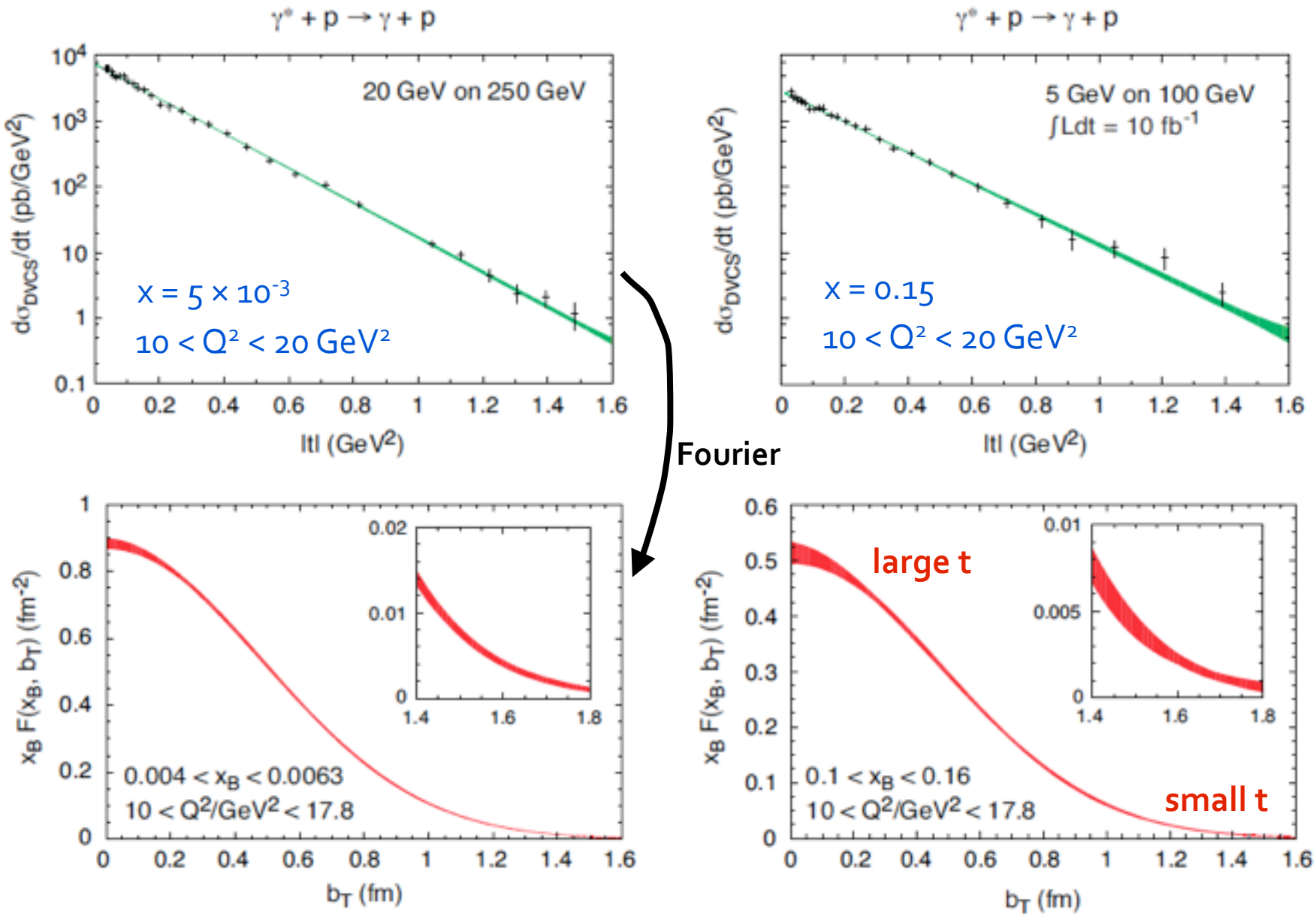

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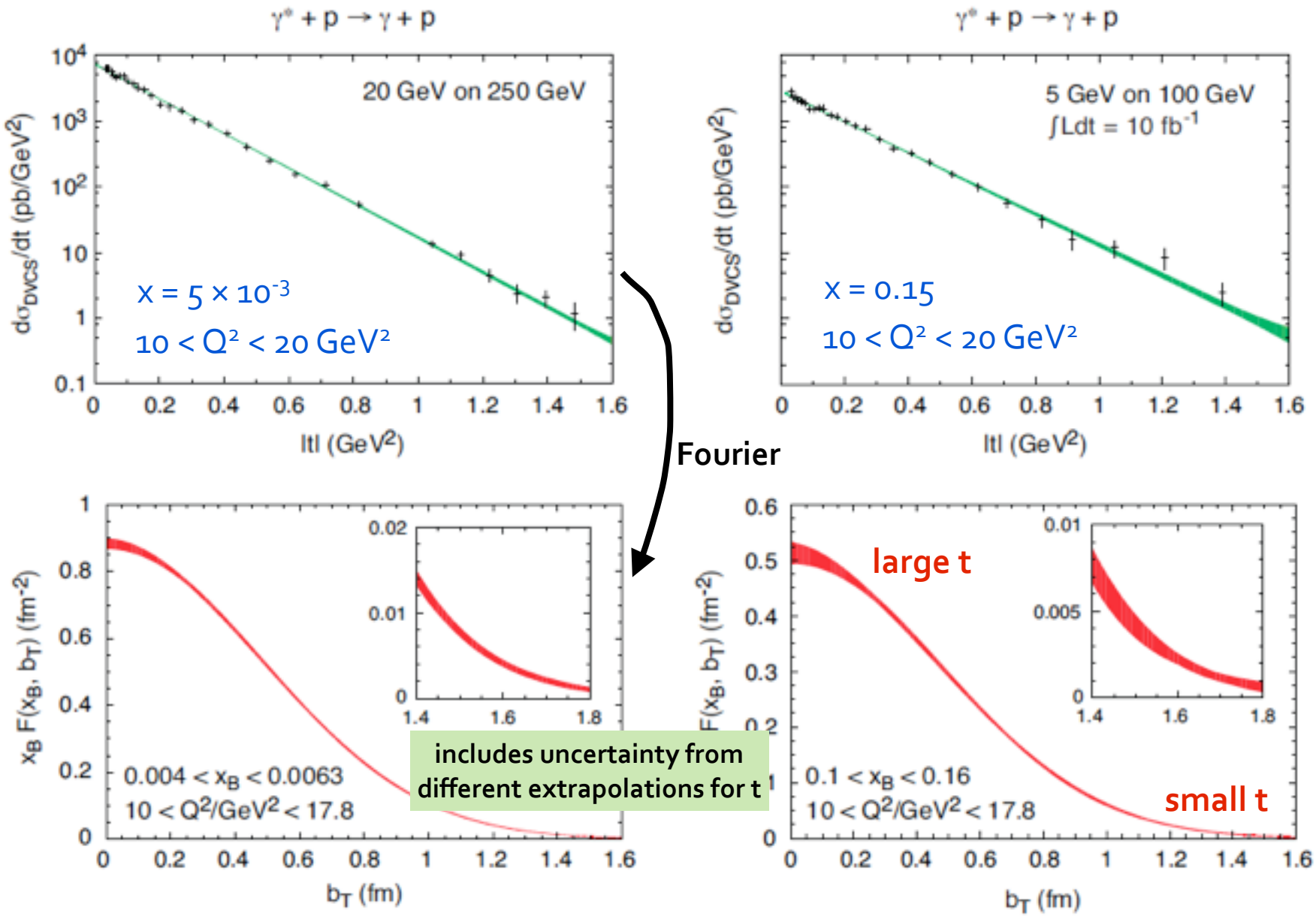

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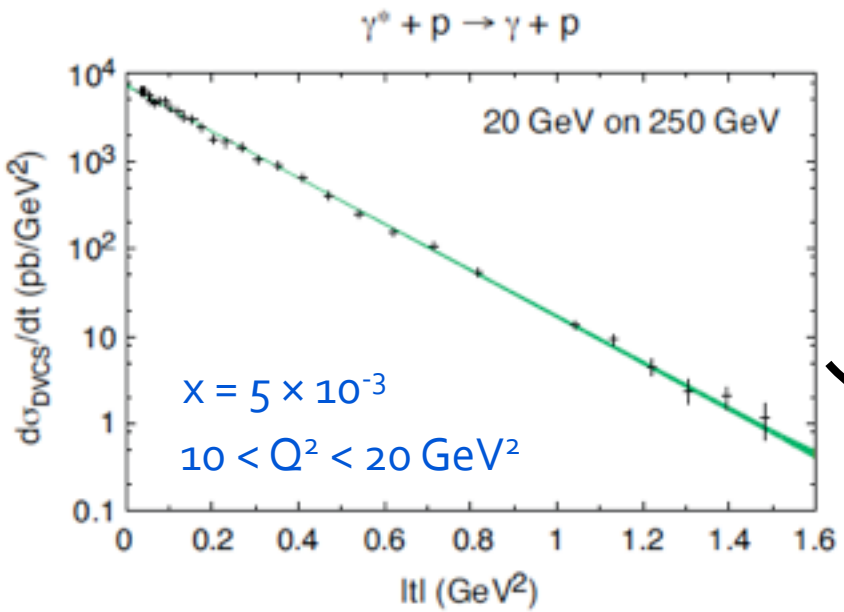
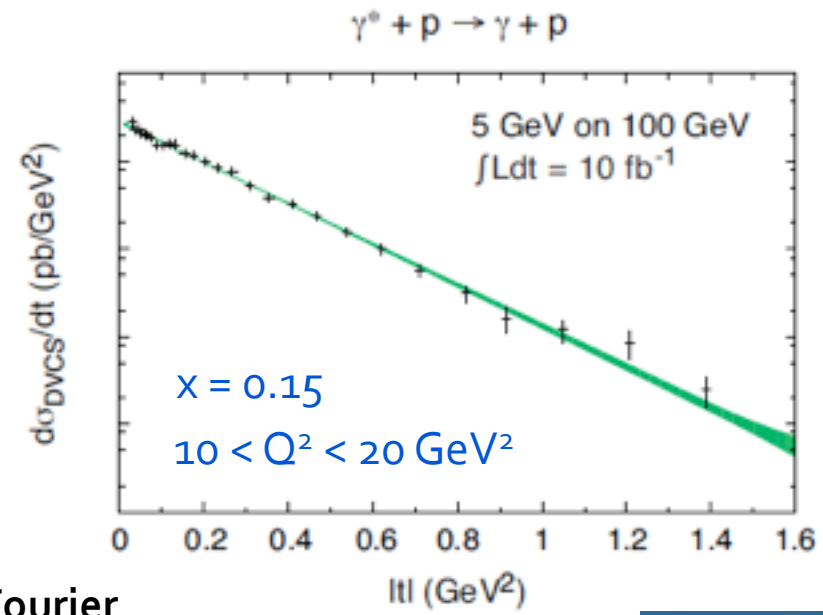
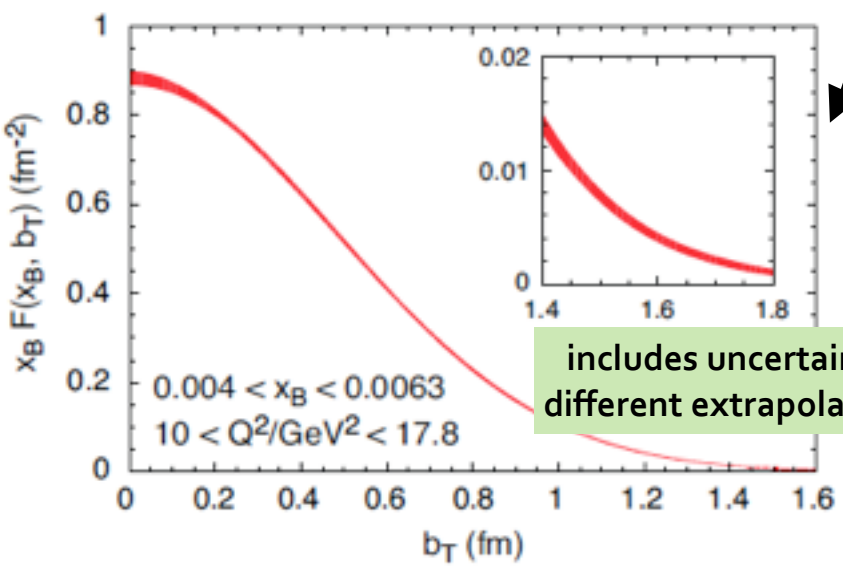
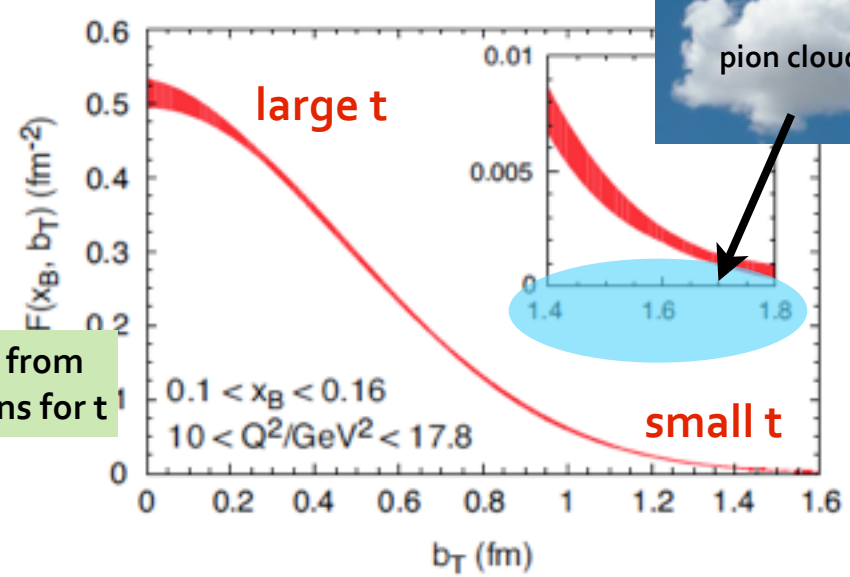




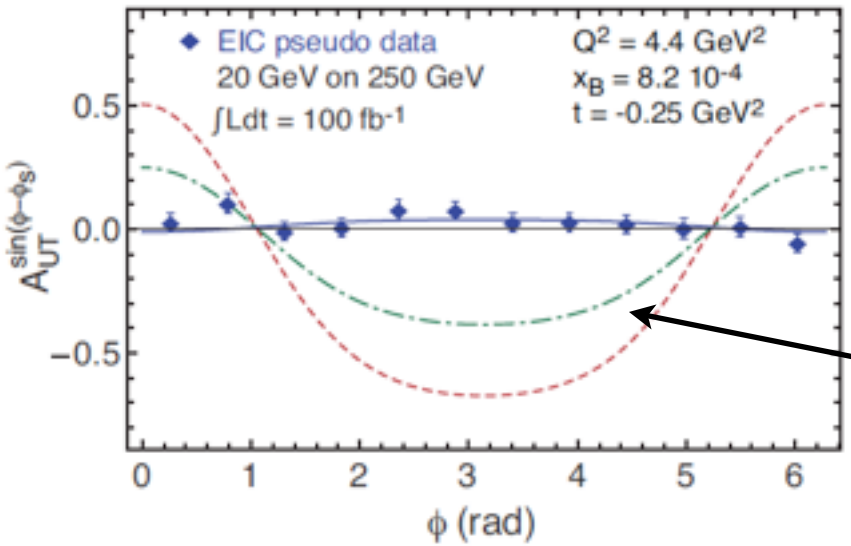
Fourier



includes uncertainty from different extrapolations for t



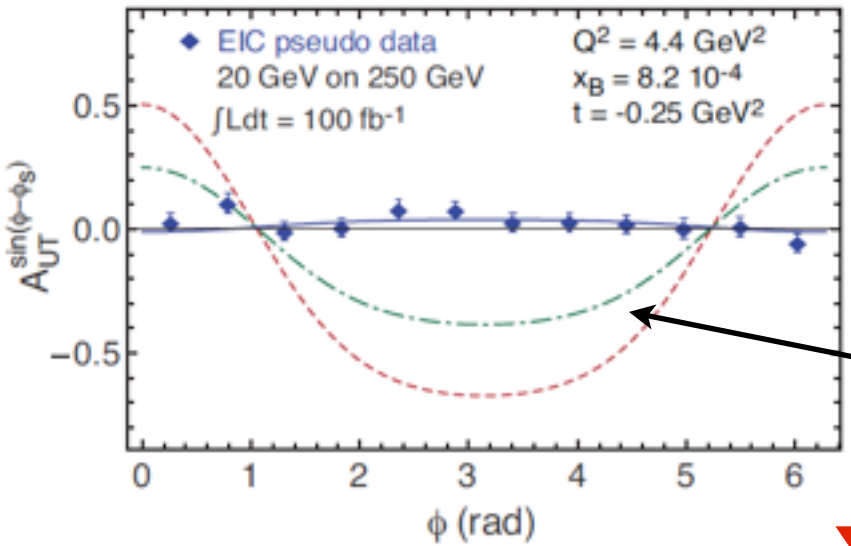
DVCS - what can we learn?



- unpolarized DVCS mainly sensitive to GPD H
- unknown GPD E from angular asymmetries with transversely polarized protons

different assumptions for GPD E

DVCS - what can we learn?



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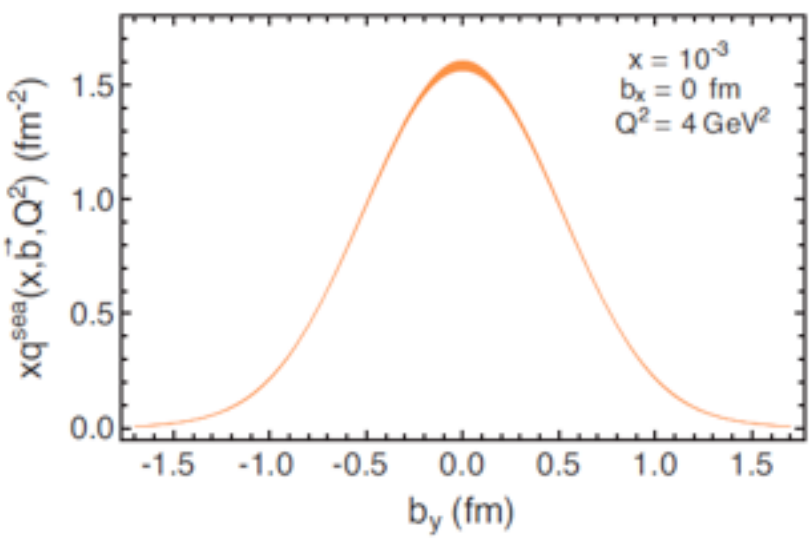
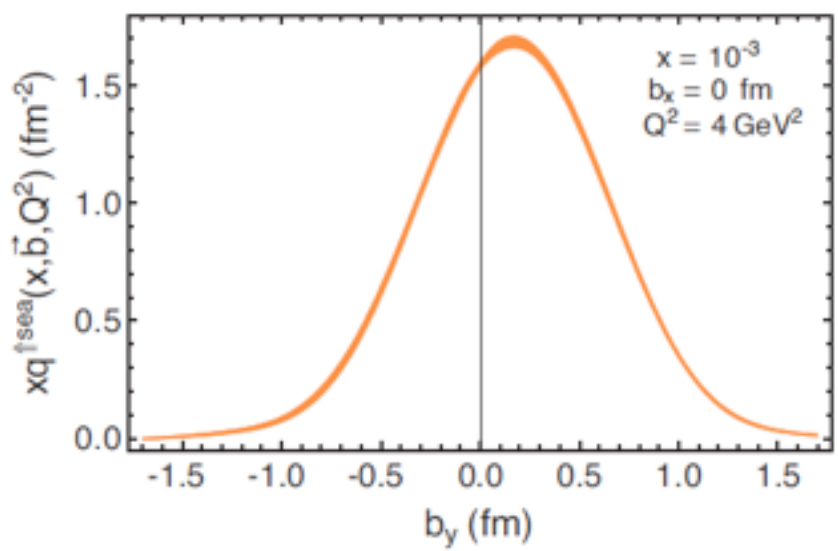
different assumptions for GPD E

global QCD fits to data & Fourier transform to b space

quarks (unpolarized proton)

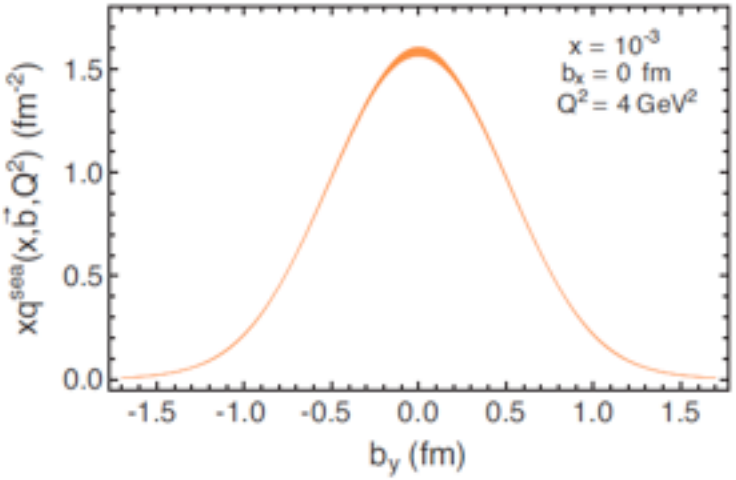


quarks (transversely pol. proton)



DVCS - what can we learn? - cont'd

quarks (unpolarized proton)



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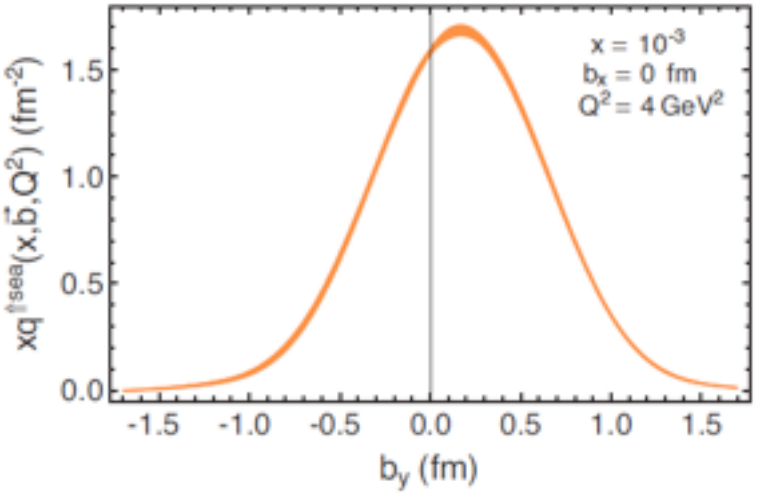
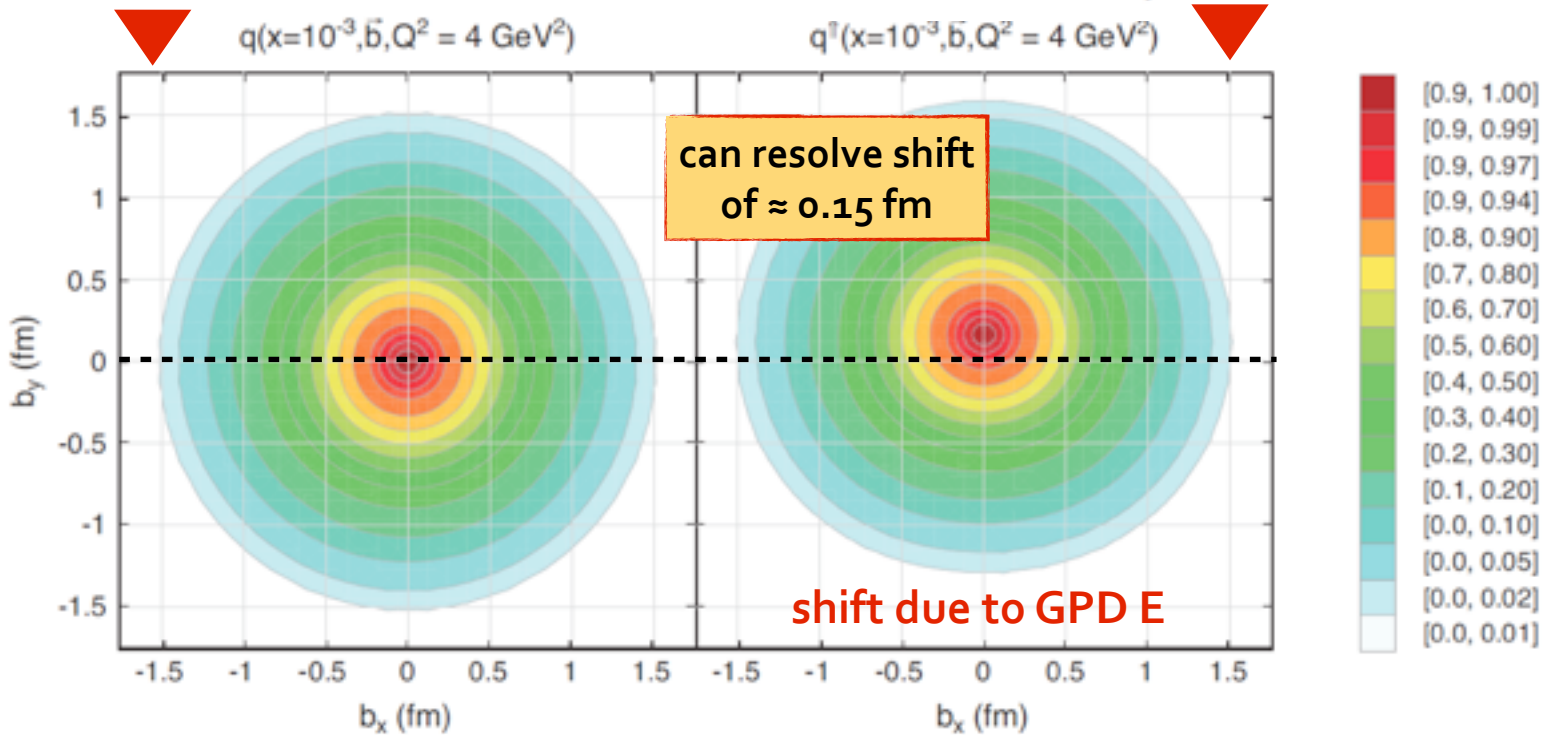
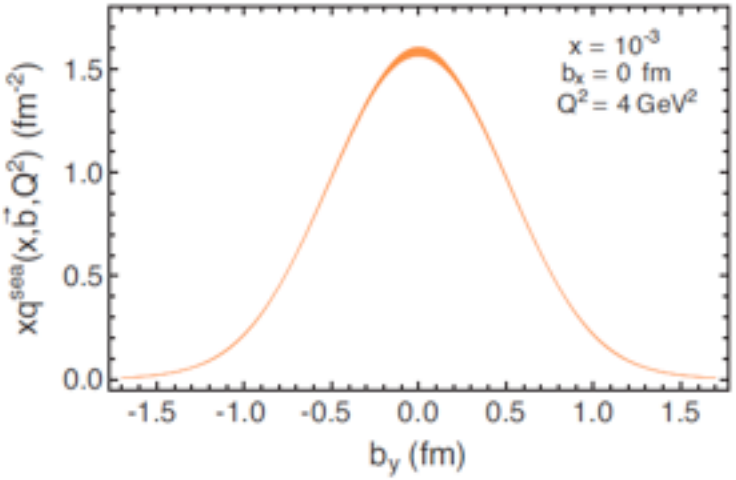


density of partons in transverse plane

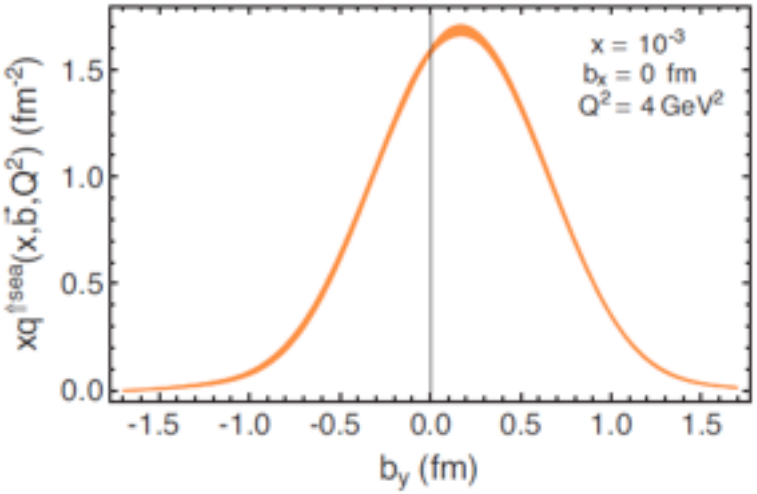


DVCS - what can we learn? - cont'd

quarks (unpolarized proton)



quarks (transversely pol. proton)



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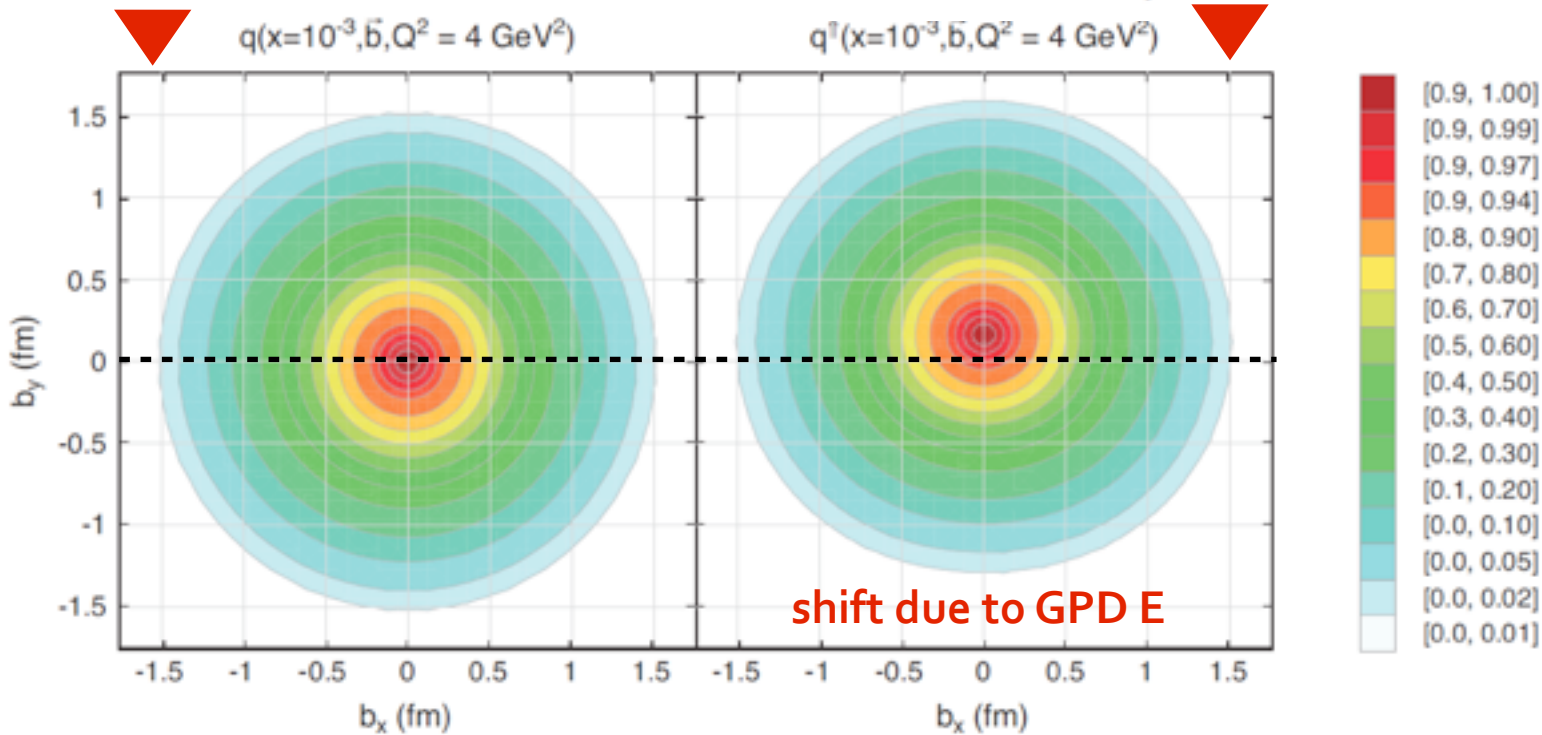
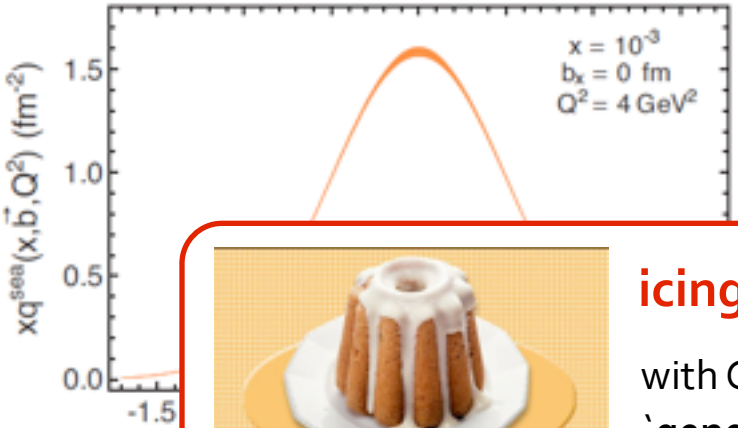


DVCS - what can we learn? - cont'd

quarks (unpolarized proton)



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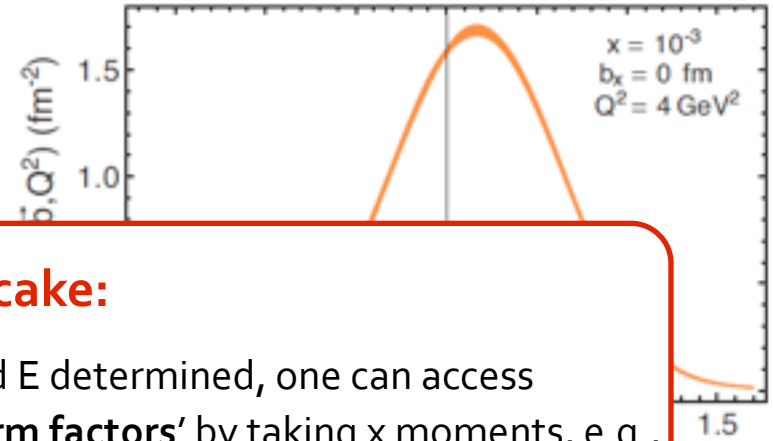


icing on the cake:

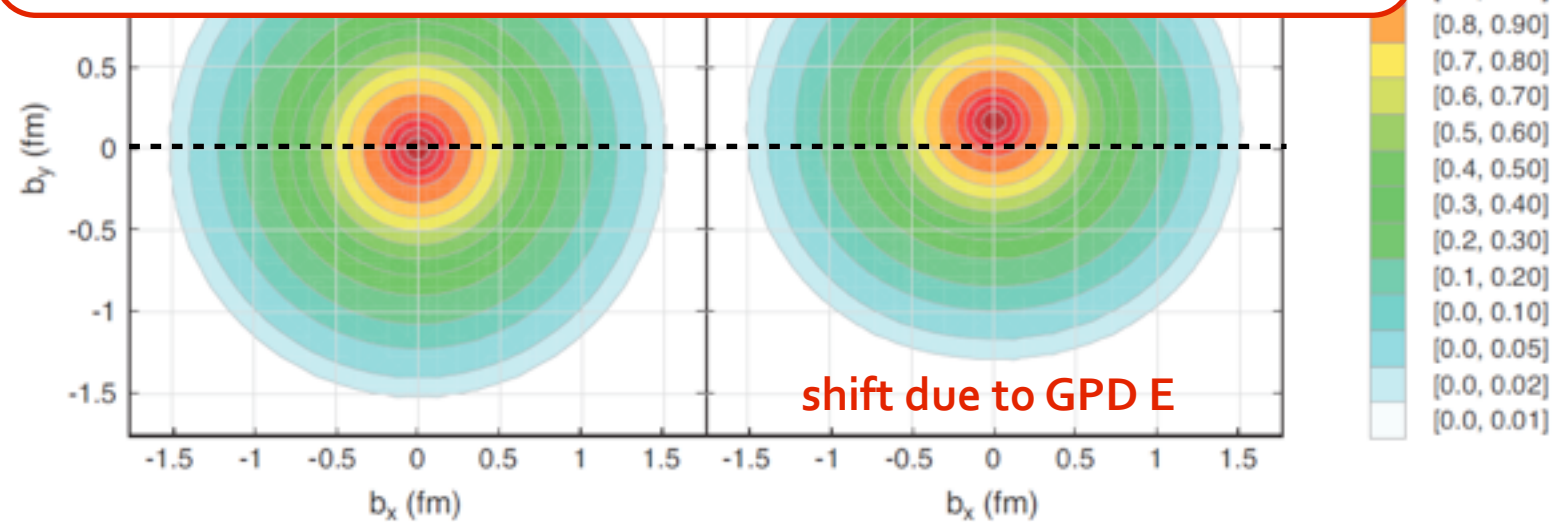
with GPDs H and E determined, one can access '**generalized form factors**' by taking x moments, e.g.,

Ji's sum rule

$$\mathbf{J_{q,g} = \frac{1}{2}\int dx\, x\, [H^{q,g}(x,\xi,t\to 0) + E^{q,g}(x,\xi,t\to 0)]}$$

total angular momentum of quarks and gluons

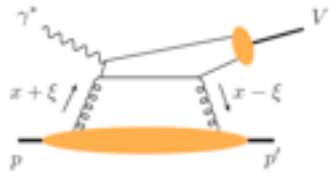
density of partons in transverse plane

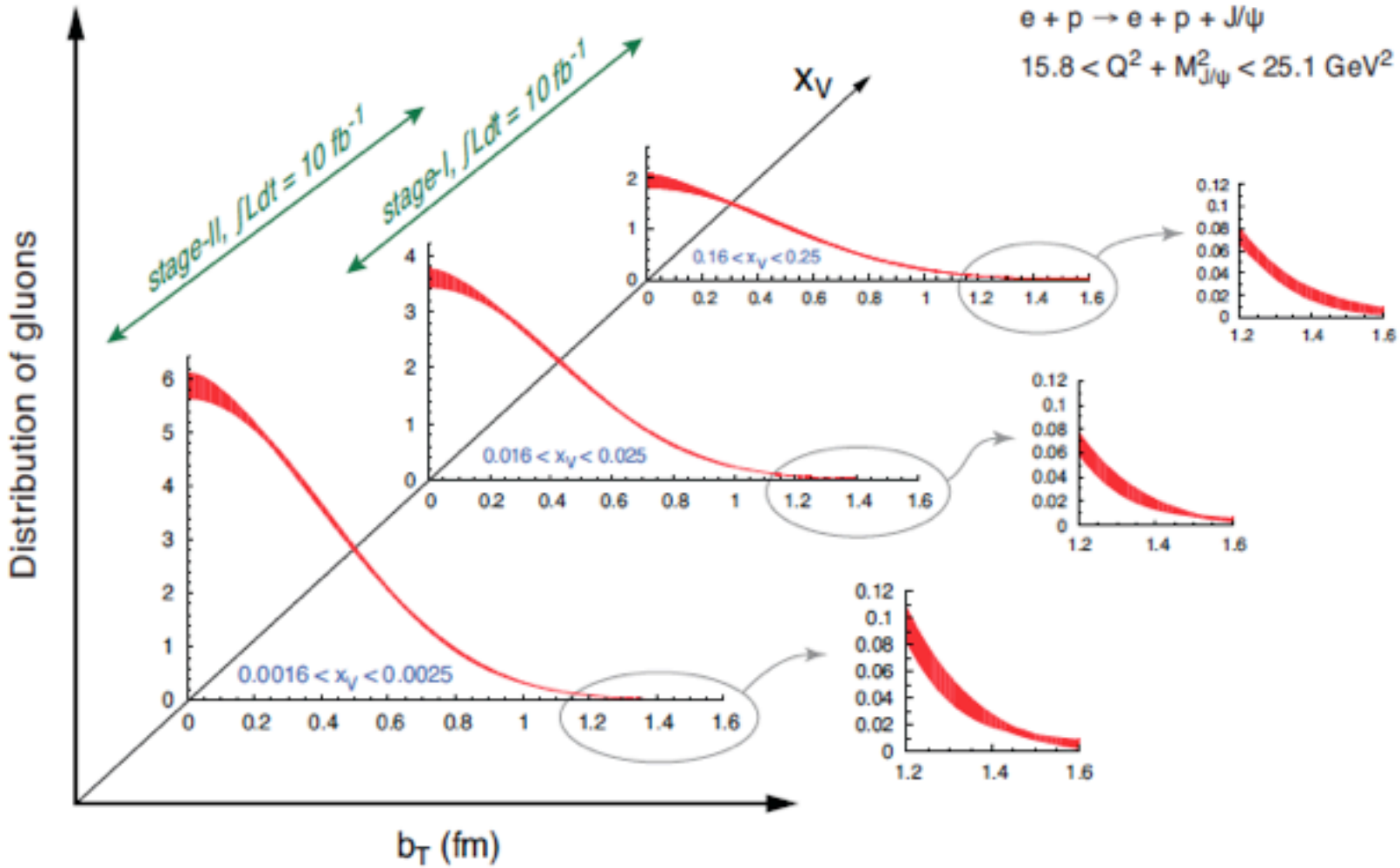


shift due to GPD E

gluon imaging through J/Ψ production

- DVCS permits determination of gluon GPD through Q^2 evolution (similar to DIS)
- can be further improved by adding vector meson observables





take away message

an EIC offers many unique opportunities
to greatly advance our understanding of
the structure of nucleons and nuclei

precision studies of PDFs, TMDs, and GPDs
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its flavor, spin, and spatial structure

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requirements

- large enough c.m.s. energy to explore small x region
- sufficient luminosity for multi-dimensional binning, ...
- sufficient control of systematic uncertainties
- state-of-the-art detector systems, well integrated into IR

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entire science program uniquely tied to a future high-energy electron-ion collider

never been measured before & never without

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