BNL, June 13th, 2012

eRHIC - the ultimate QCD microscope

to explore the inner structure of the nucleon

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goals of the eRHIC ep science program

complete survey of nucleon's spin and spatial structure

to-do list:

- study the distribution of **sea quarks** and **gluons** in momentum and position space
- … and their polarizations and orbital angular momenta

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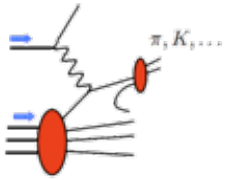

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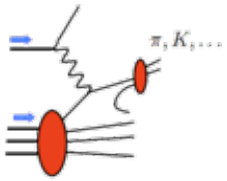

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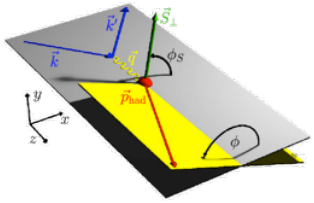

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adds their **transverse momentum dependence**

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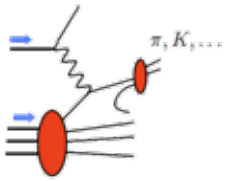

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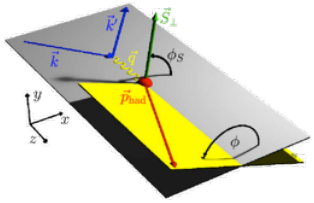

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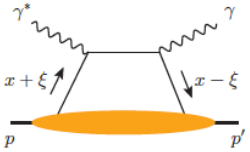

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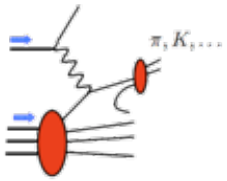

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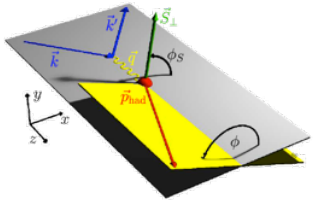

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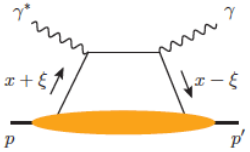

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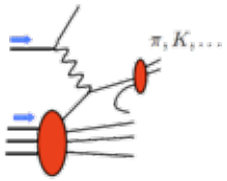

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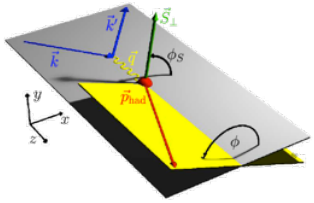

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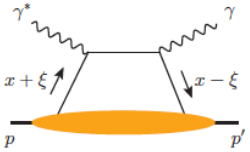

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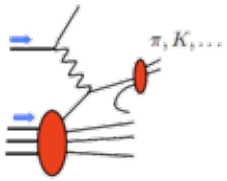

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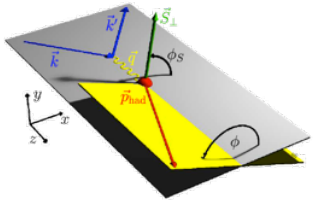

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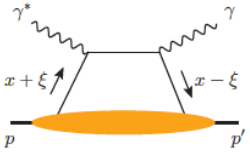

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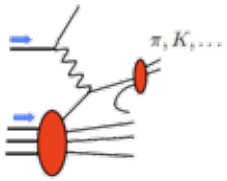

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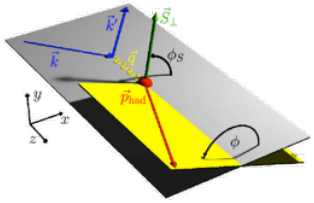

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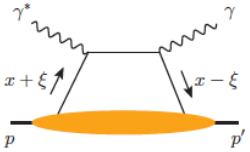

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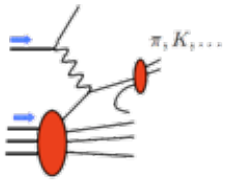

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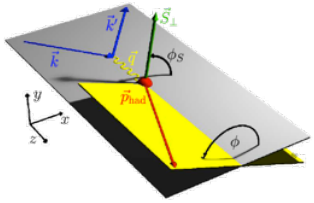

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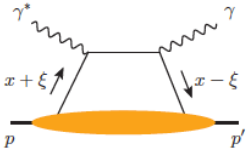

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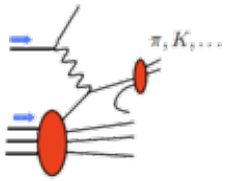

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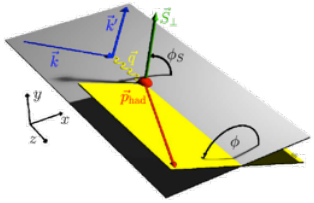

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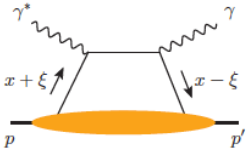

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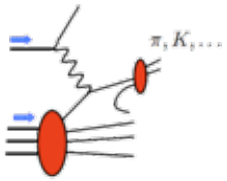

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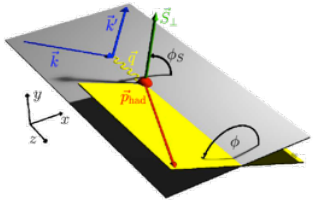

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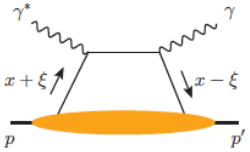

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entire science program uniquely tied to a future high-energy electron-ion collider

never been measured before & never without

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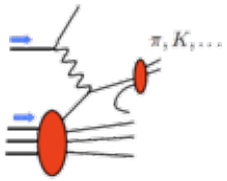

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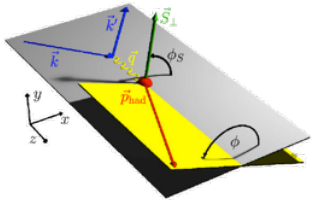

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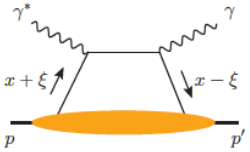

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precision studies of the proton's helicity structure

open questions

significant experimental and theoretical progress in past 25+ years, yet many unknowns

recall:

$$\Delta \mathbf{f}(\mathbf{x}) \equiv \mathbf{f}_{\rightarrow}^{\rightarrow}(\mathbf{x}) - \mathbf{f}_{\leftarrow}^{\rightarrow}(\mathbf{x})$$

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$\Delta g(x,Q^2)$

- found to be small at $0.05 < x < 0.2$ [RHIC, COMPASS, HERMES]
- RHIC can slightly extend x range & reduce uncertainties [500 GeV running & particle correlations]

yet, small x behavior completely unconstrained
(determines x-integral which enters proton spin sum)

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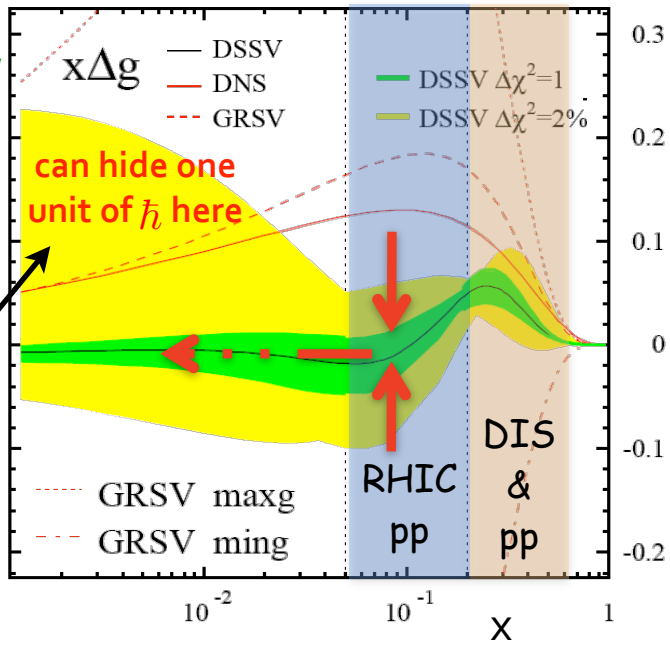
de Florian, Sassot, MS, Vogelsang



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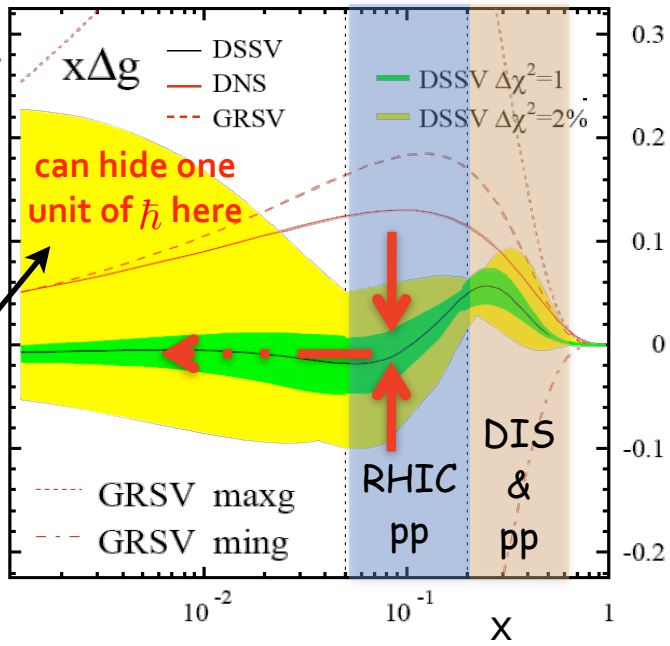

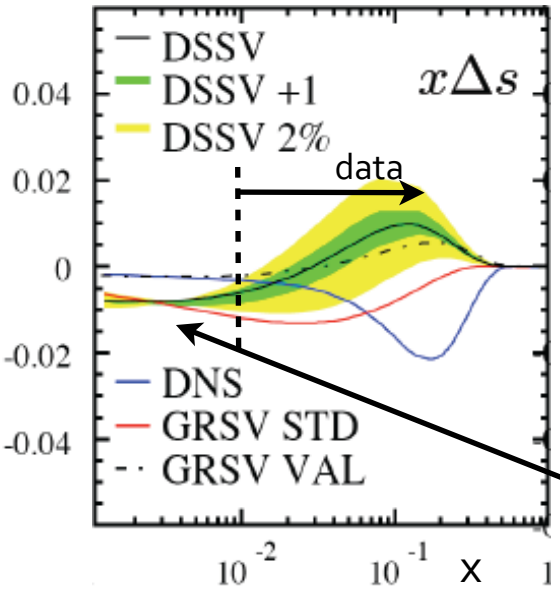

Δq's (x,Q^2)

- **known:** quarks contribute much less to proton spin than expected from quark models

yet, large uncertainties in ΔΣ from unmeasured small x

- some indications for non-trivial flavor structure of quark sea
- surprisingly small/positive Δs from SIDIS

does it fit with negative integral expected from SU(3) arguments

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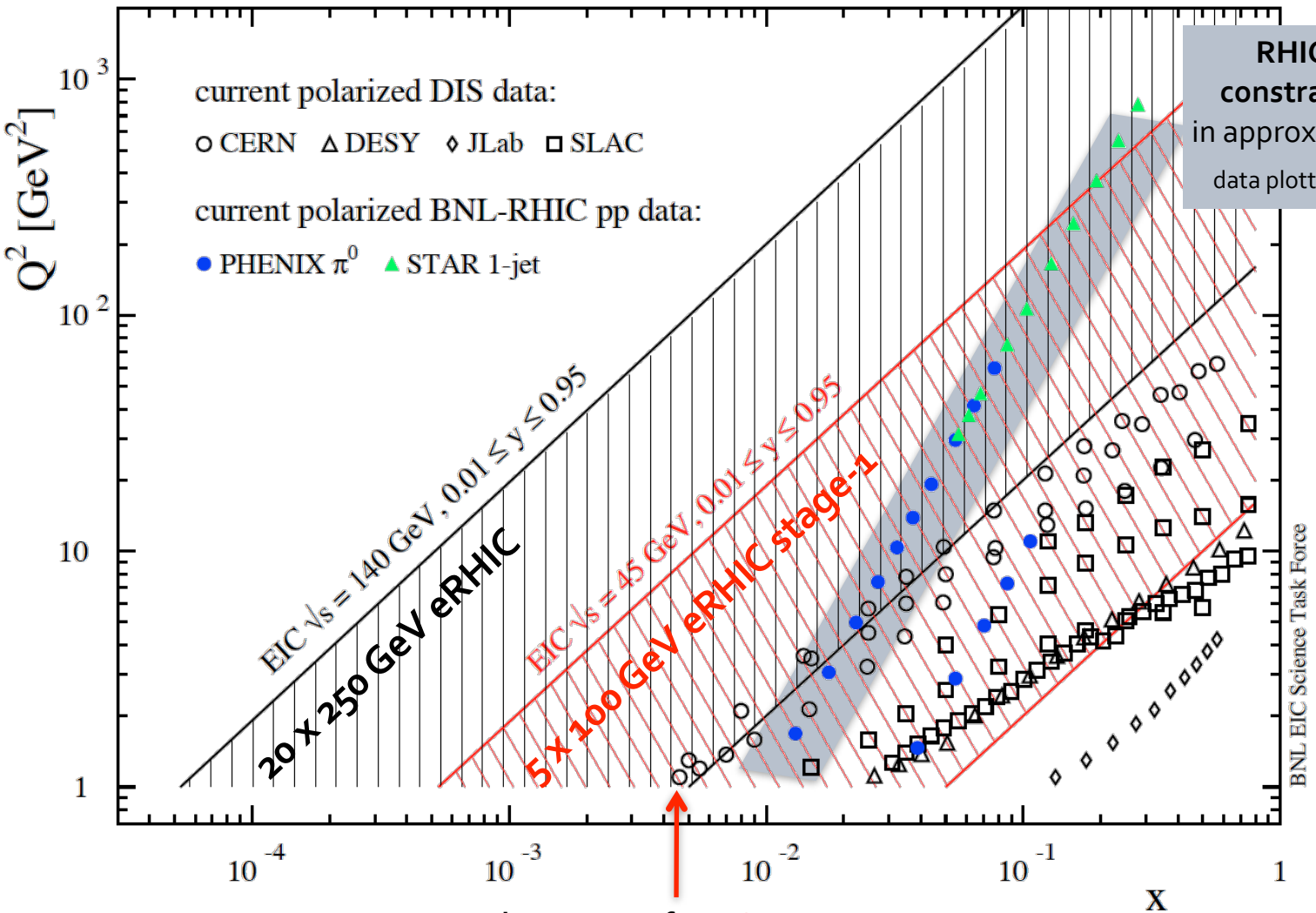
eRHIC might be realized in stages: **5 x 100 – 5 x 250 GeV** [stage-1] to **20 x 250 GeV** [full]



RHIC pp data constraining Δg(x)
in approx. **0.05 < x <0.2**
data plotted at $x_T=2p_T/\sqrt{S}$

lowest x so far **4.6 x10^{-3}**
COMPASS

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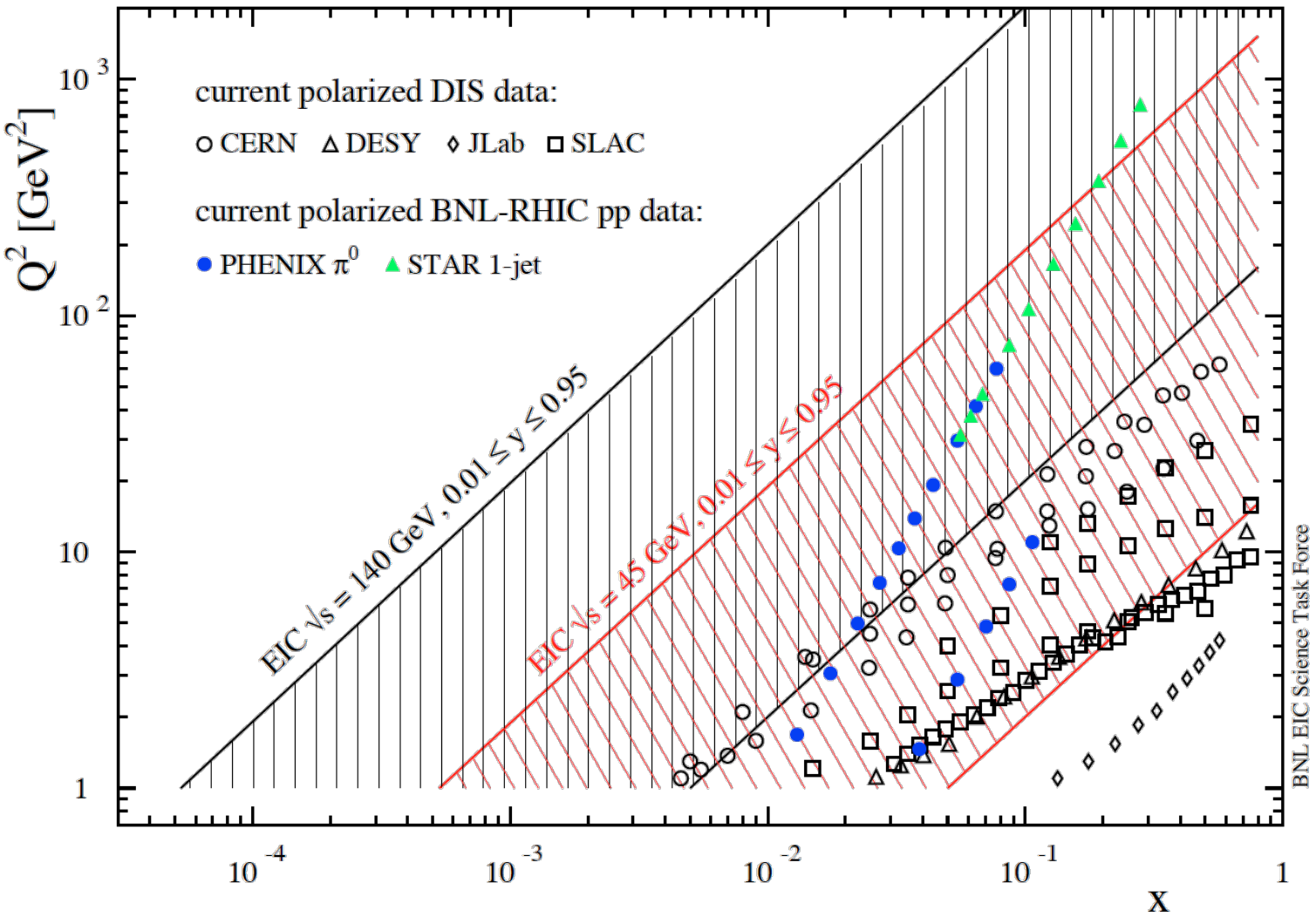

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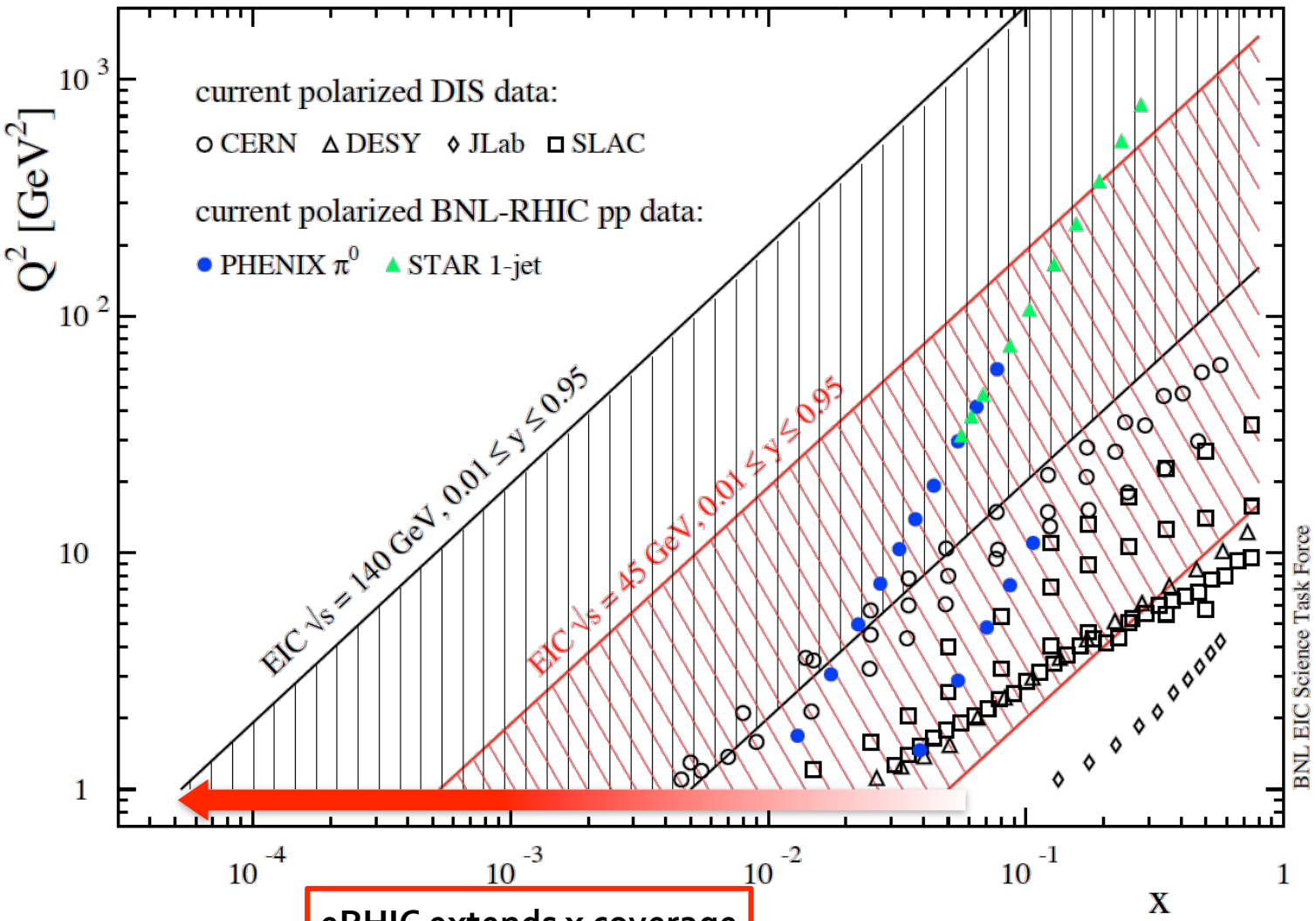

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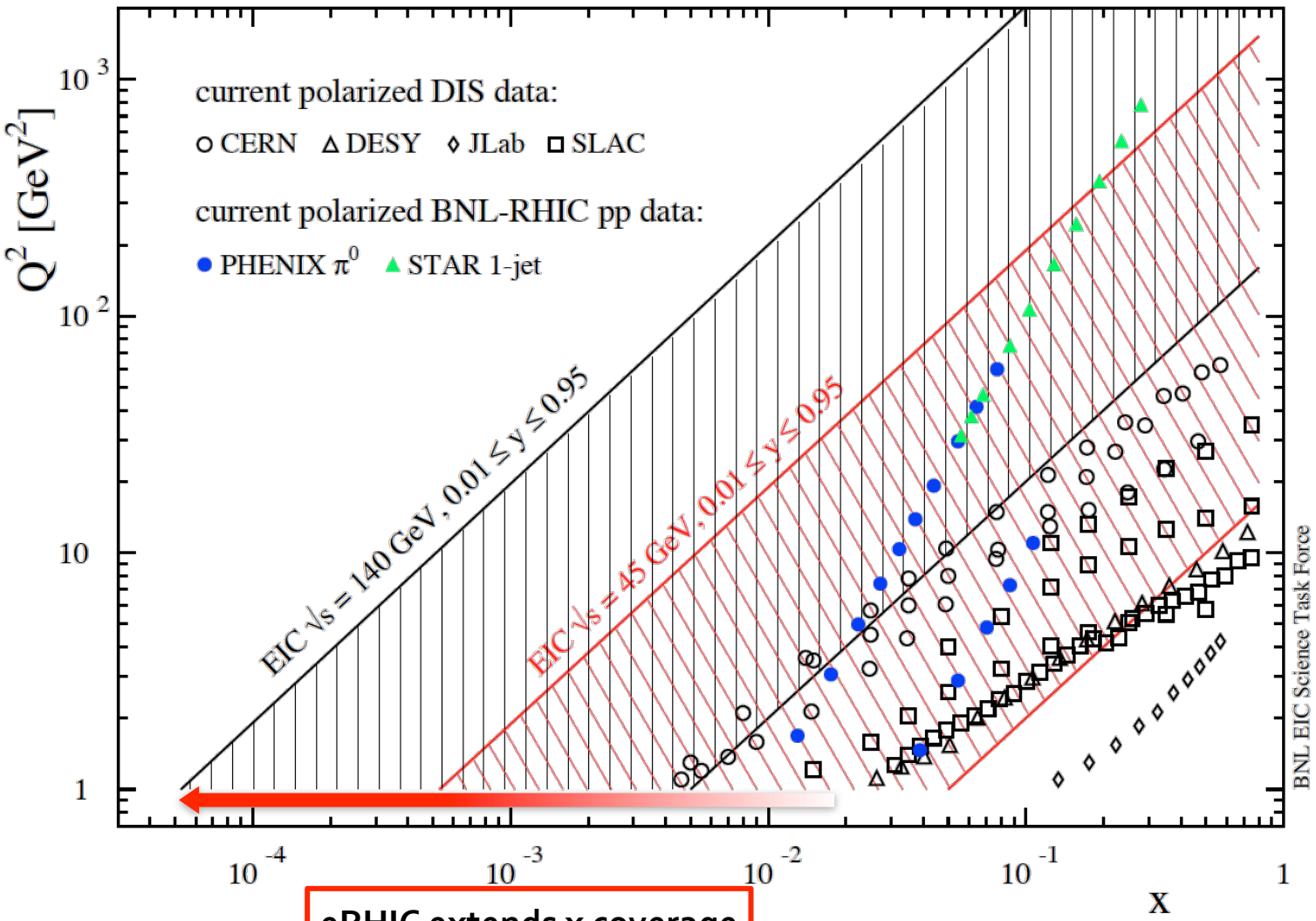

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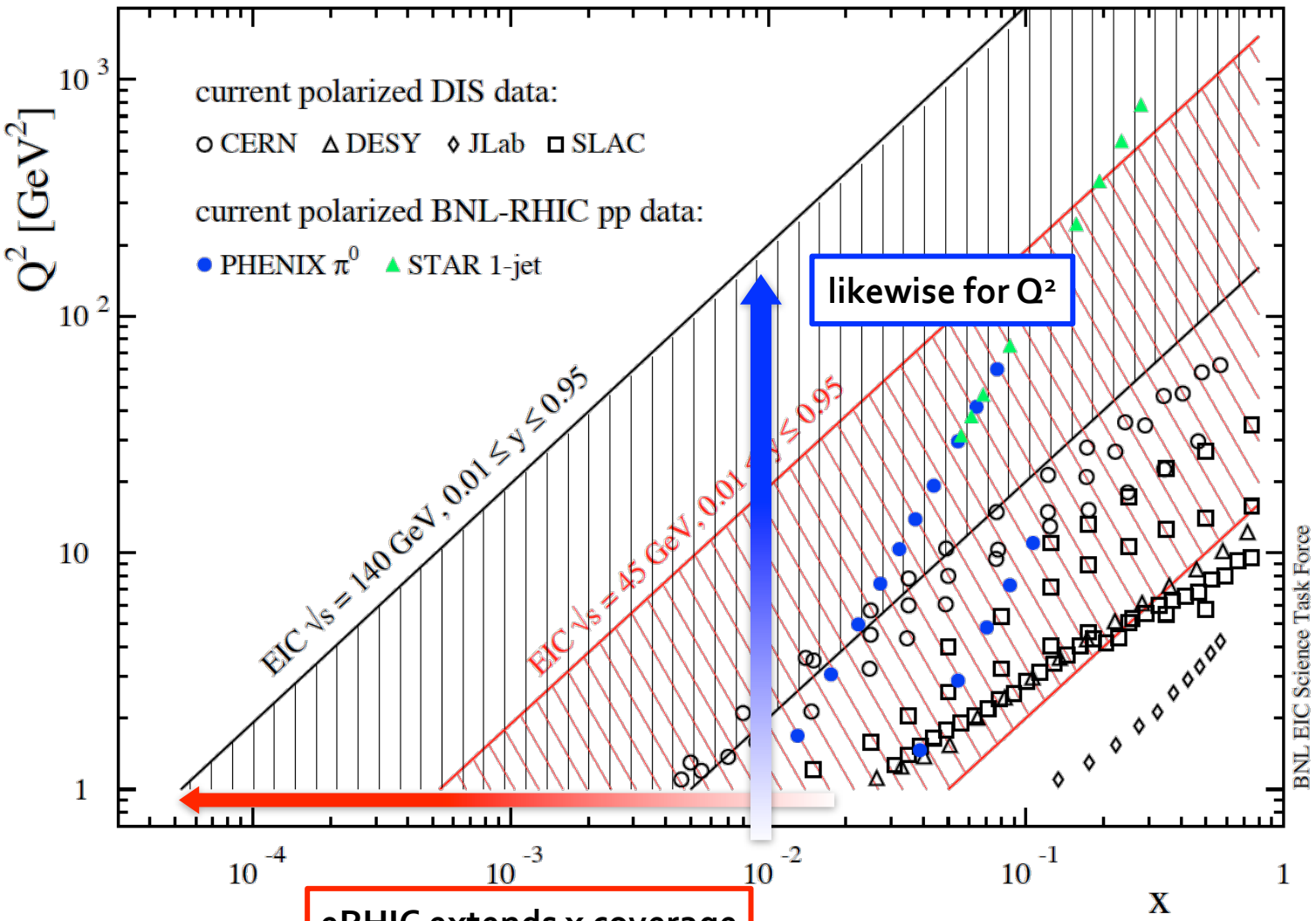

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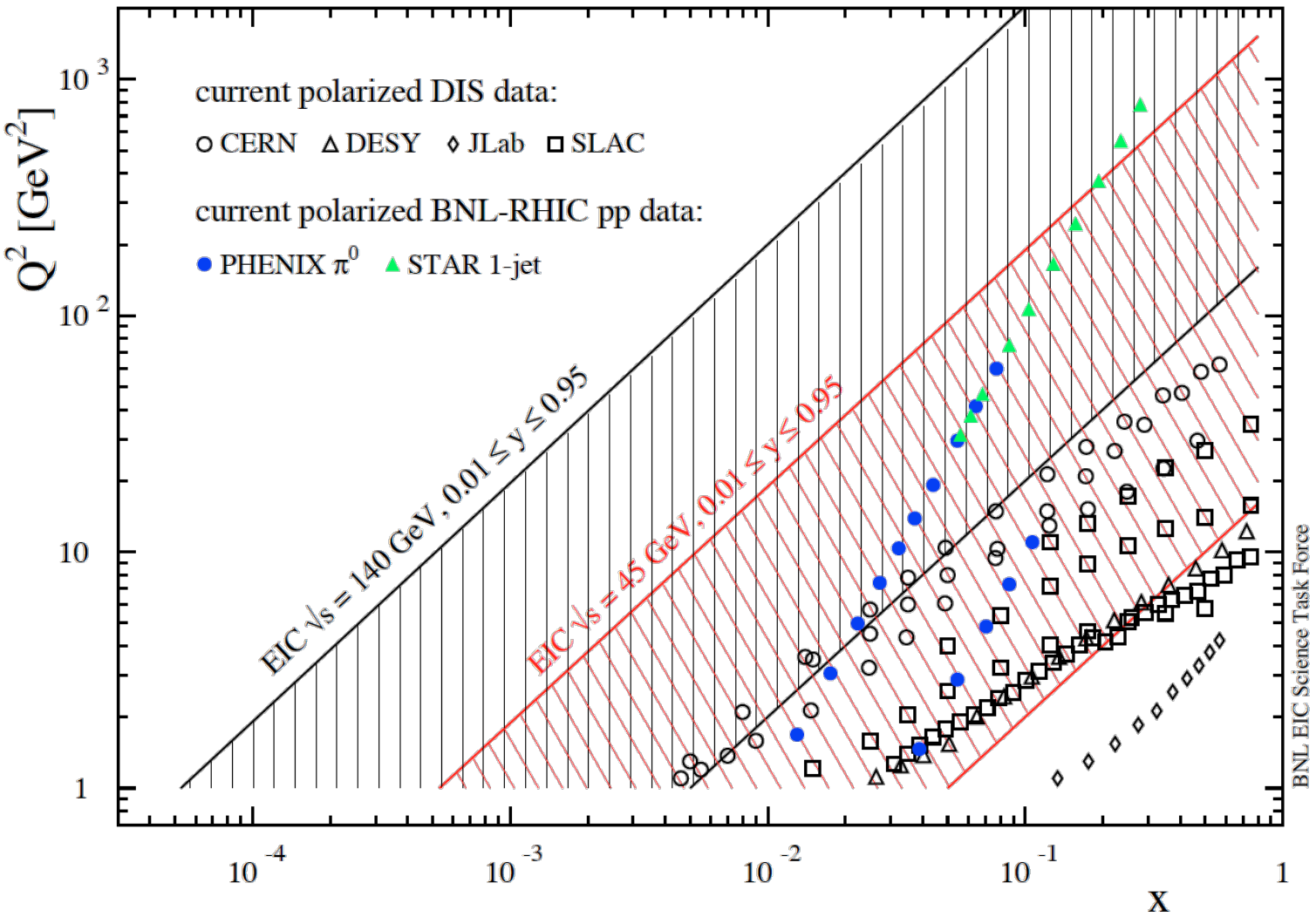

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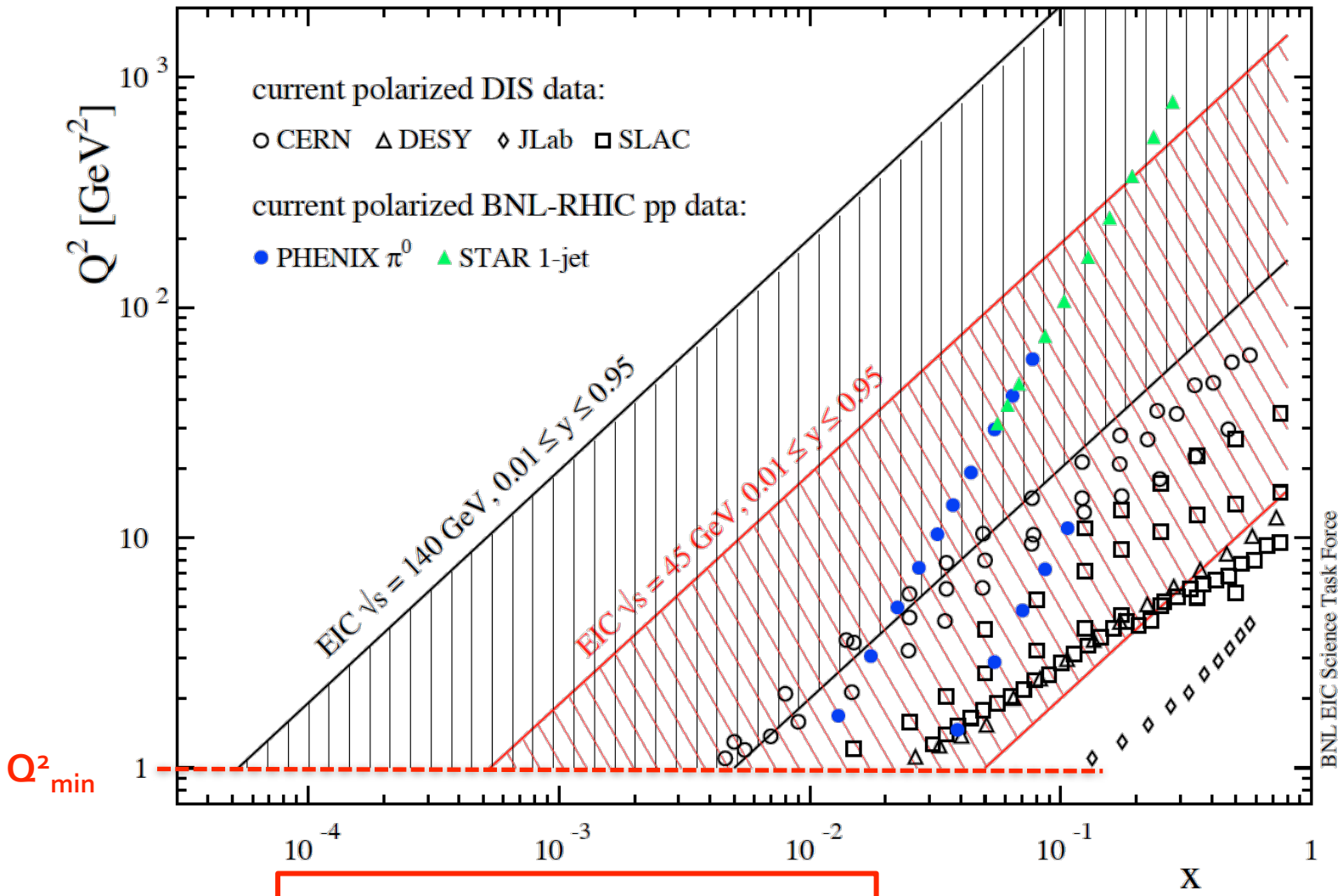

can also play with Q^2_{min} cut in fits

to map out where pQCD framework applies

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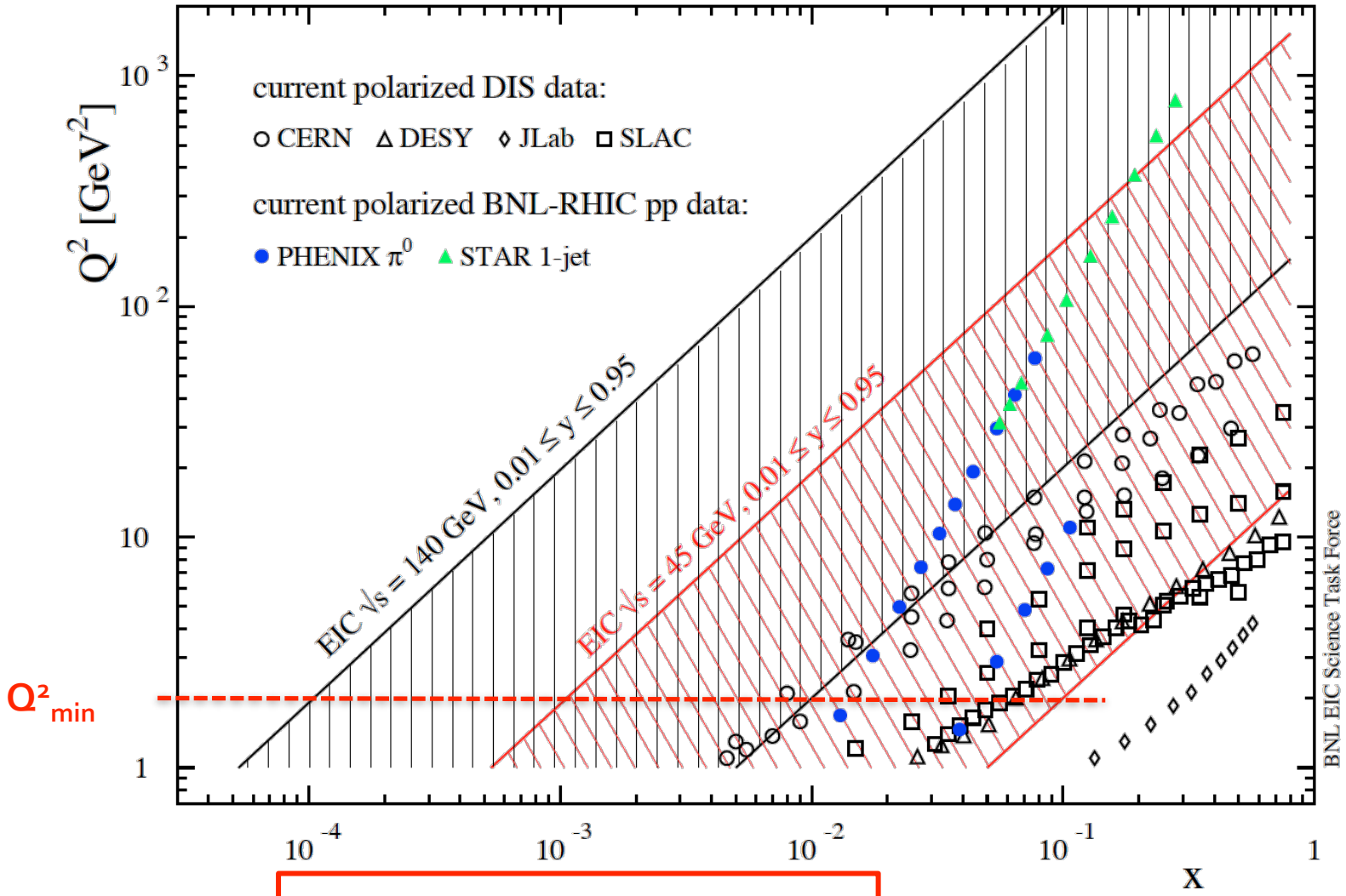

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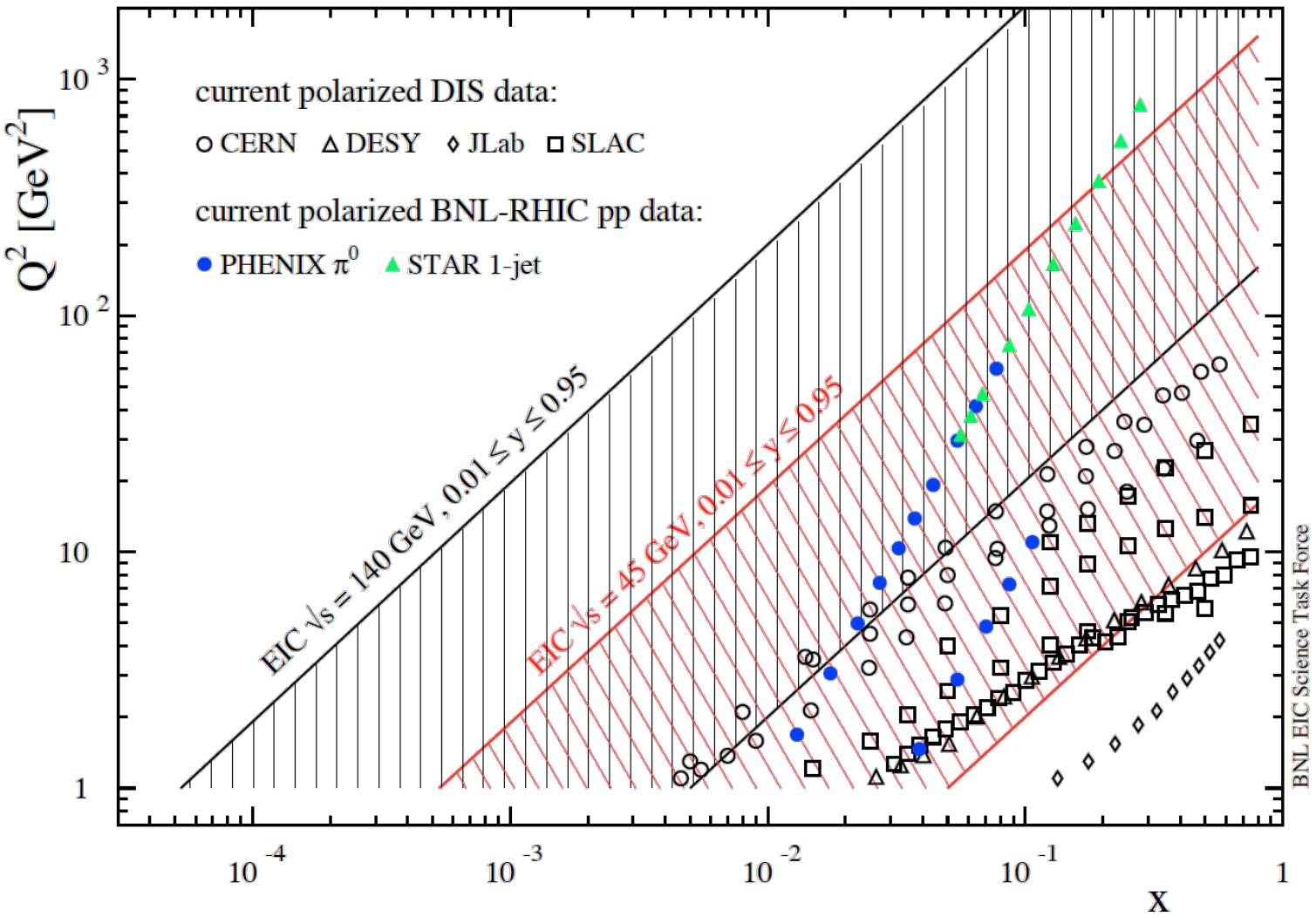

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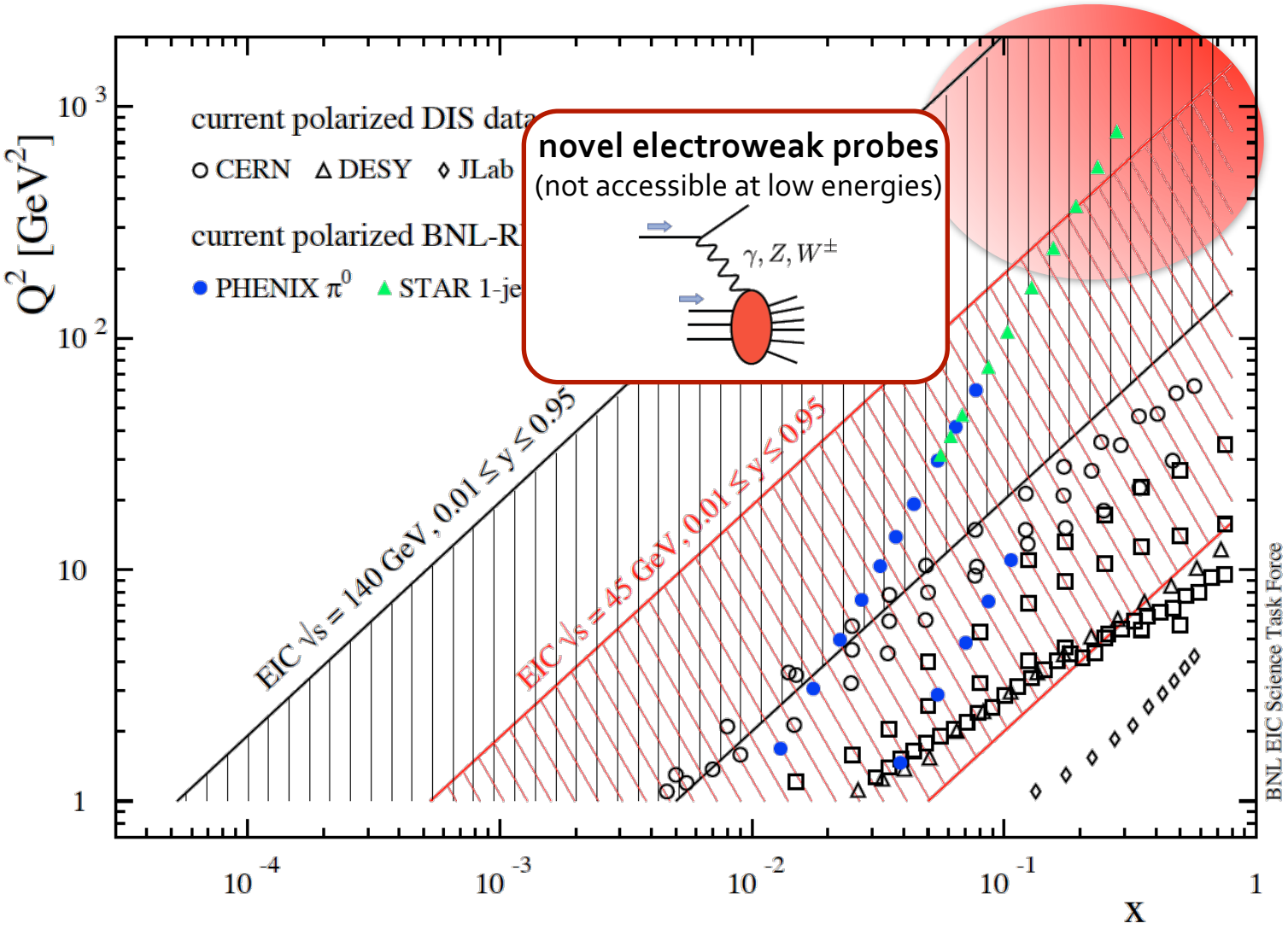
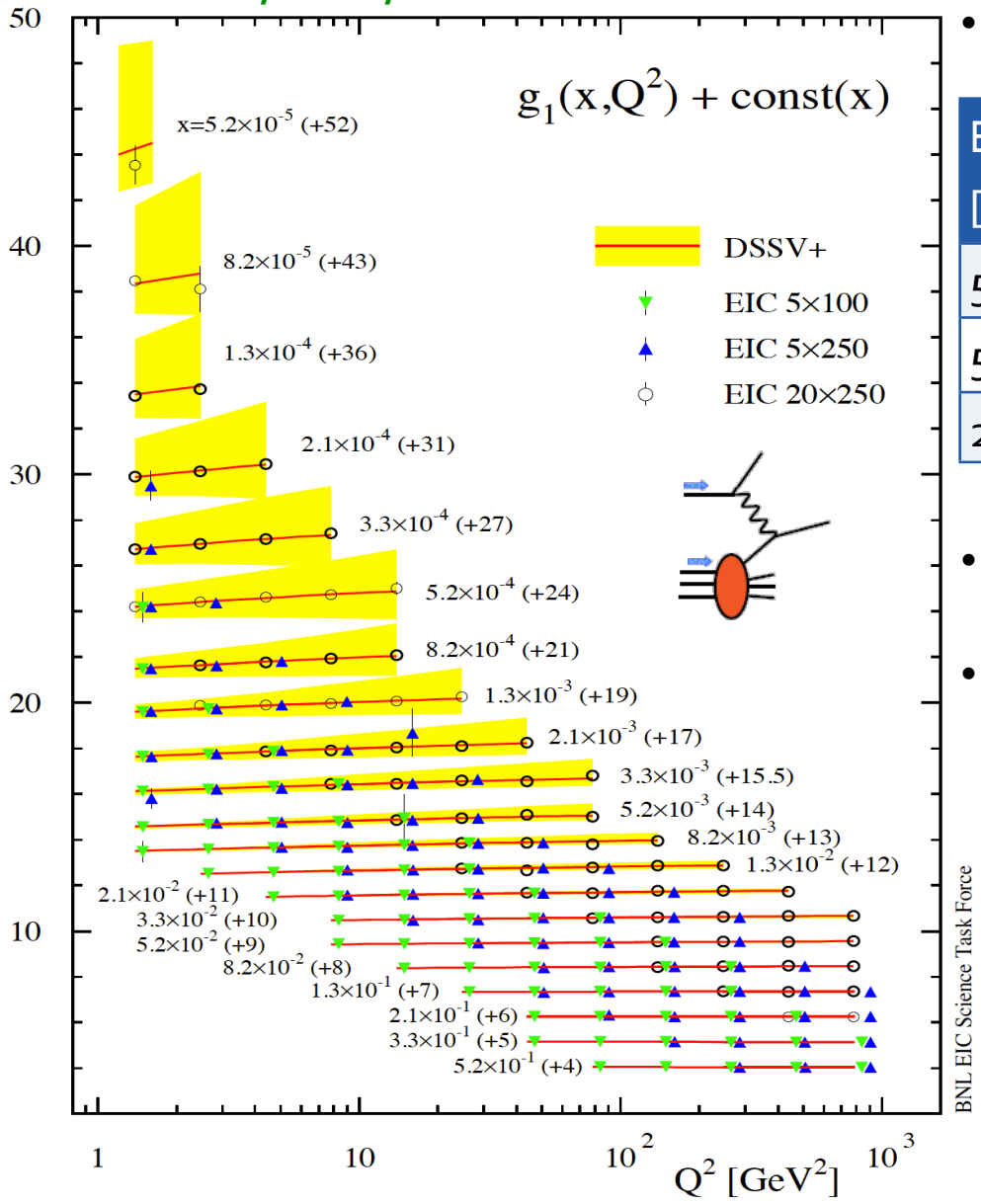


unprecedented opportunities in DIS, SIDIS, … with polarized beams

example: projected eRHIC DIS data for g_1^p

Aschenauer, Sassot, MS



- 3 sets of realistic energy settings studied:

$E_e \times E_p$ [GeV]	$\sqrt{s}$ [GeV]	x_{min} for y_{max} = 0.95 and Q^2 = 1 GeV^2	Q^2 = 2 GeV^2
5 X 100	44.7	5.3 X 10^{-4}	1.1 X 10^{-3}
5 X 250	70.7	2.1 X 10^{-4}	4.2 X 10^{-4}
20 X 250	141.4	5.3 X 10^{-5}	1.1 X 10^{-4}

- 4 [5] bins/decade in Q^2 [x] (spaced logarithmically)
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  DSSV+ estimate

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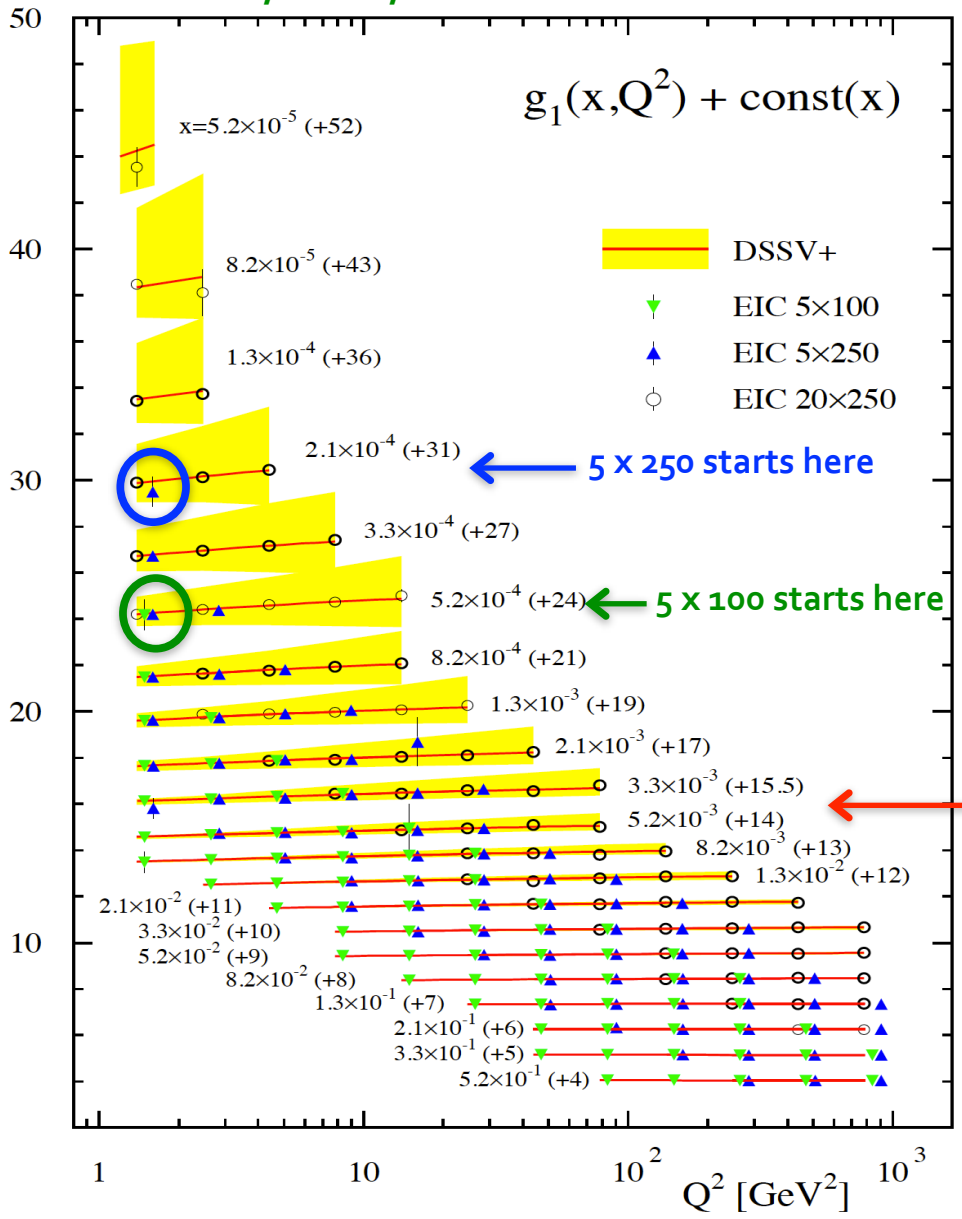

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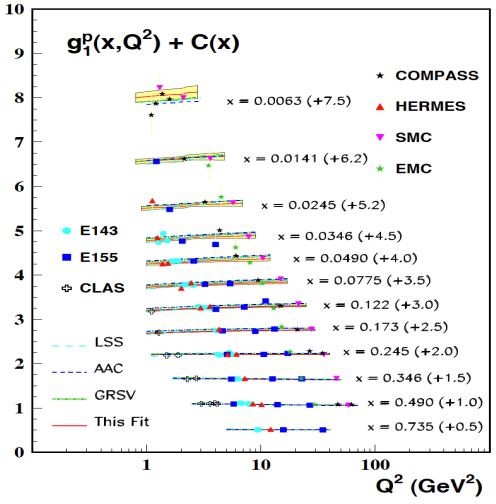
taken from Blumlein, Bottcher



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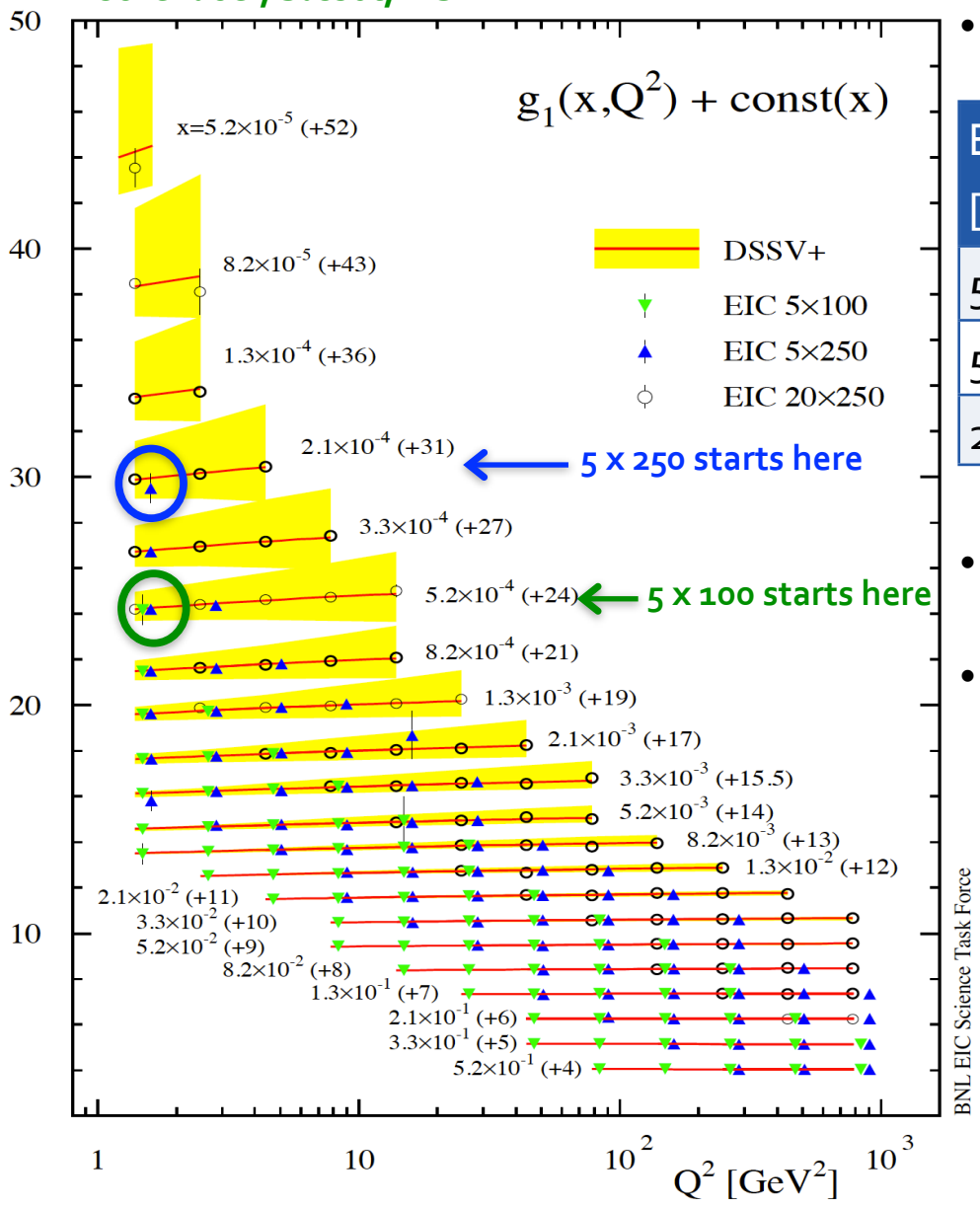

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DSSV+ estimate

similar data sets generated for SIDIS with identified charged pions and kaons

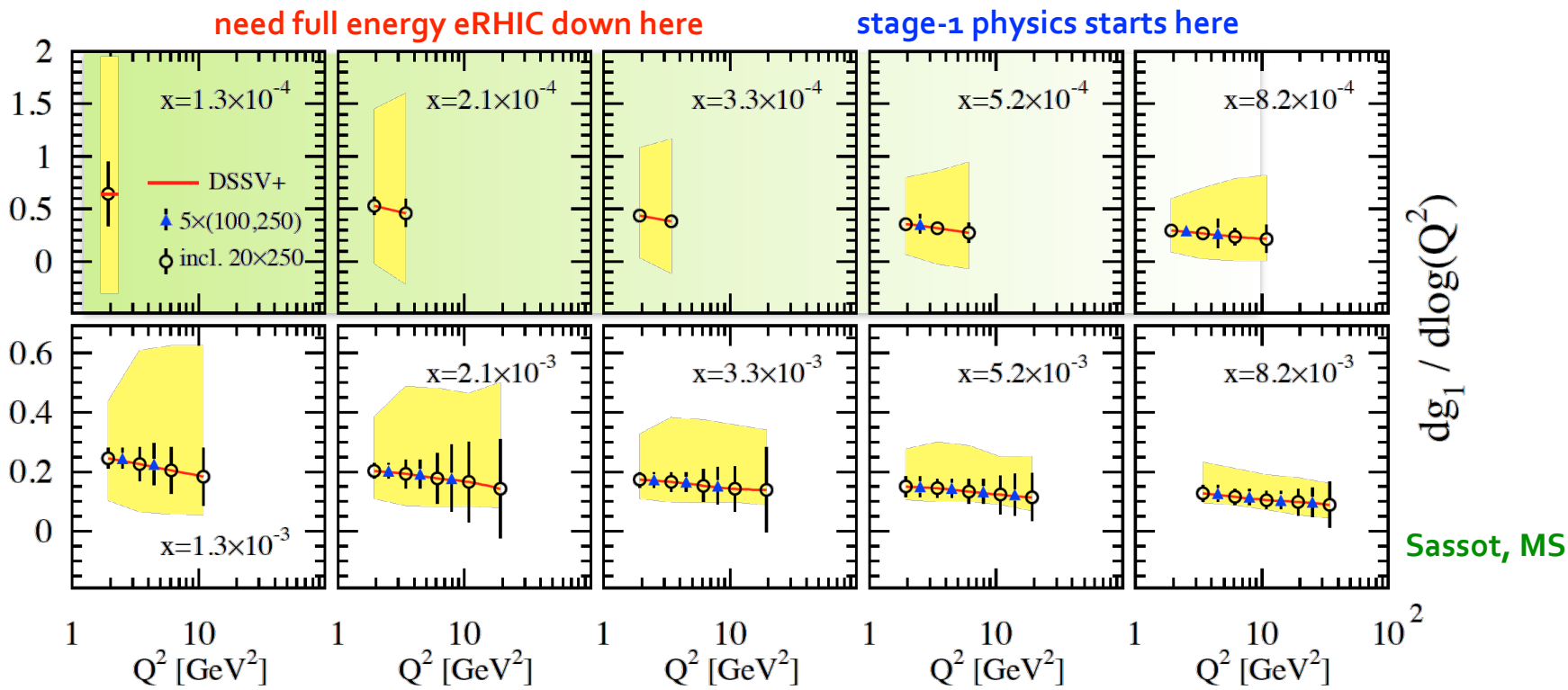
powerful tool: scaling violations at small x

rough small-x approximation to Q^2-evolution:

$$\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$

spread in $\Delta g(x,Q^2)$ translates into spread of scaling violations for $g_1(x,Q^2)$

- need x-bins with a least two Q^2 values to compute derivative (limits x reach somewhat)

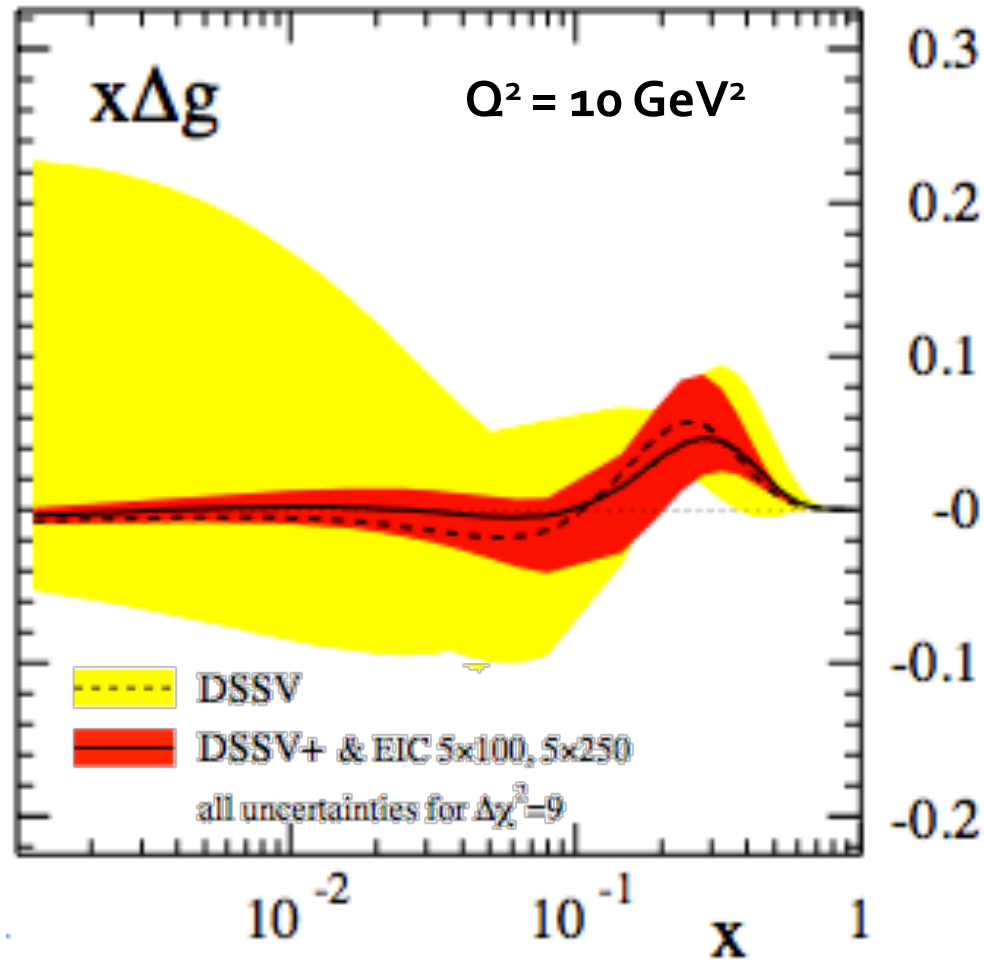


- error bars for moderate **10fb^{-1} per c.m.s. energy**; bands parameterize current DSSV+ uncertainties

impact of eRHIC data on helicity PDFs

DIS scaling violations mainly determine Δg at small x (SIDIS scaling violations add to this)

Sassot, MS



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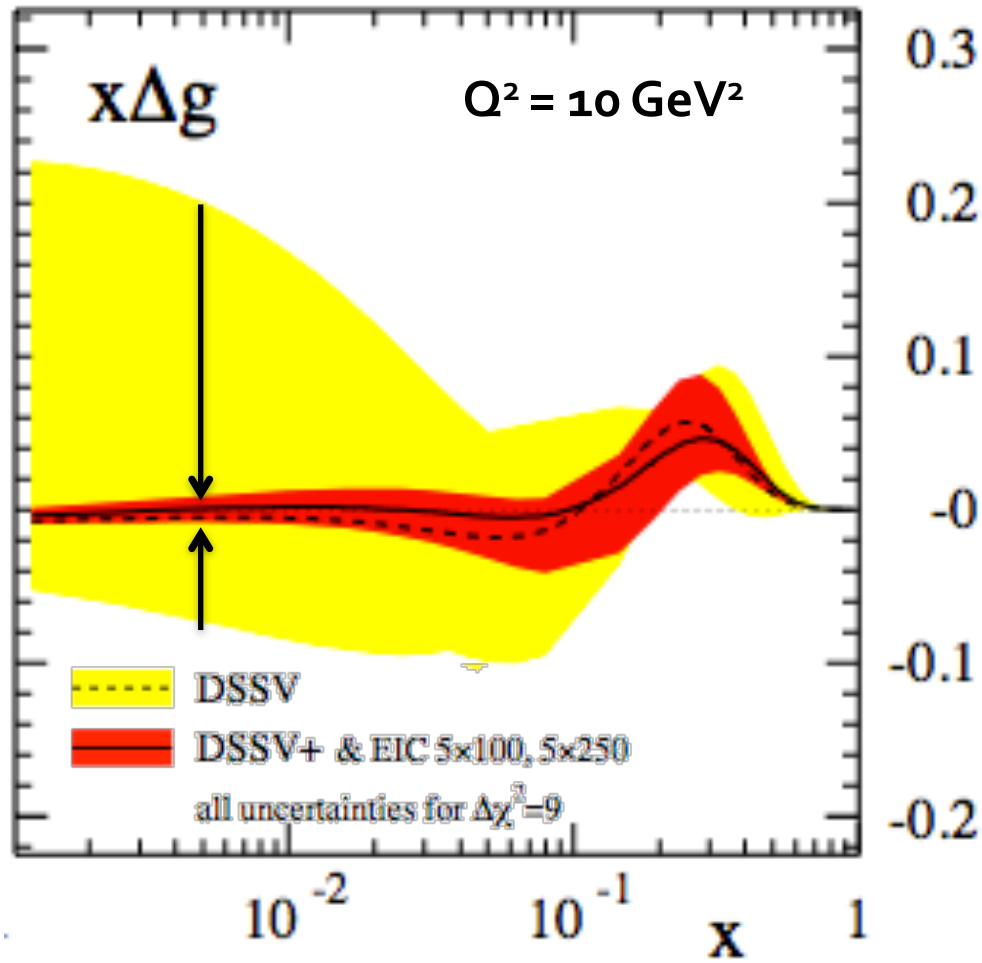

dramatic reduction of uncertainties:

"before"

"after"

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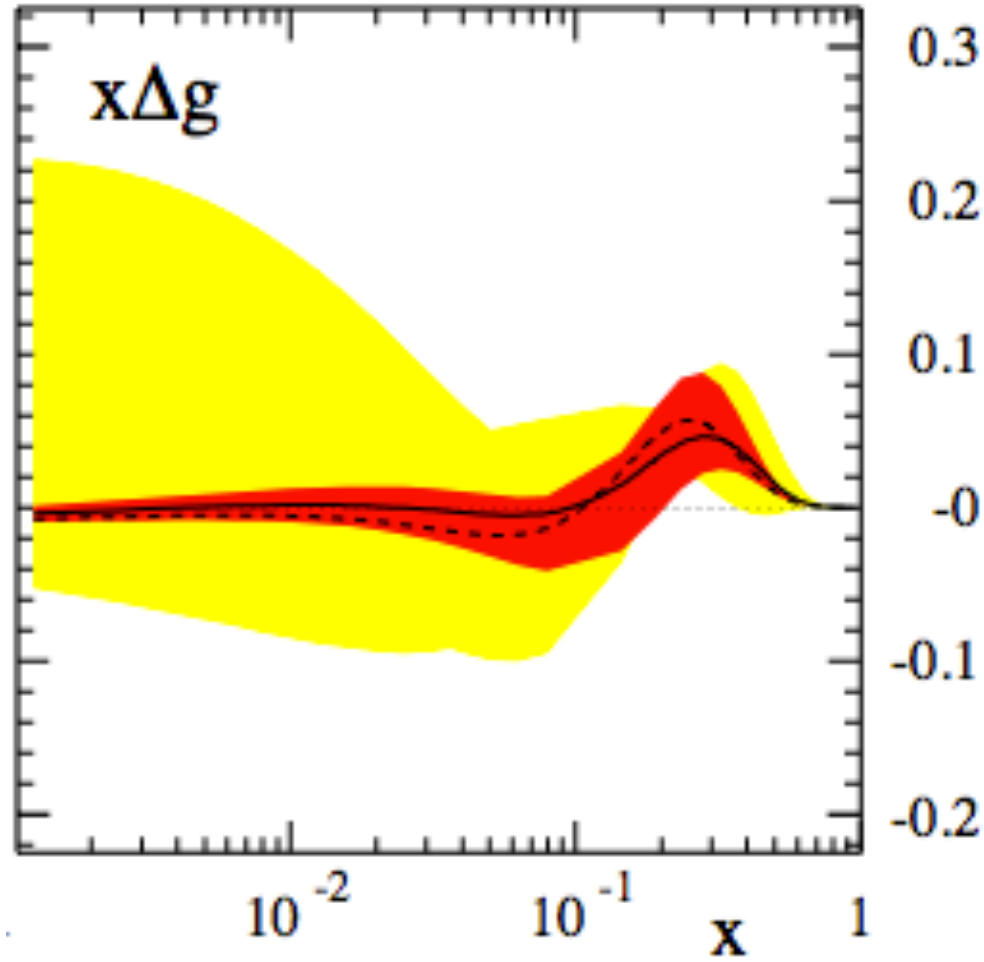
in addition, **SIDIS data provide detailed flavor separation of quark sea**



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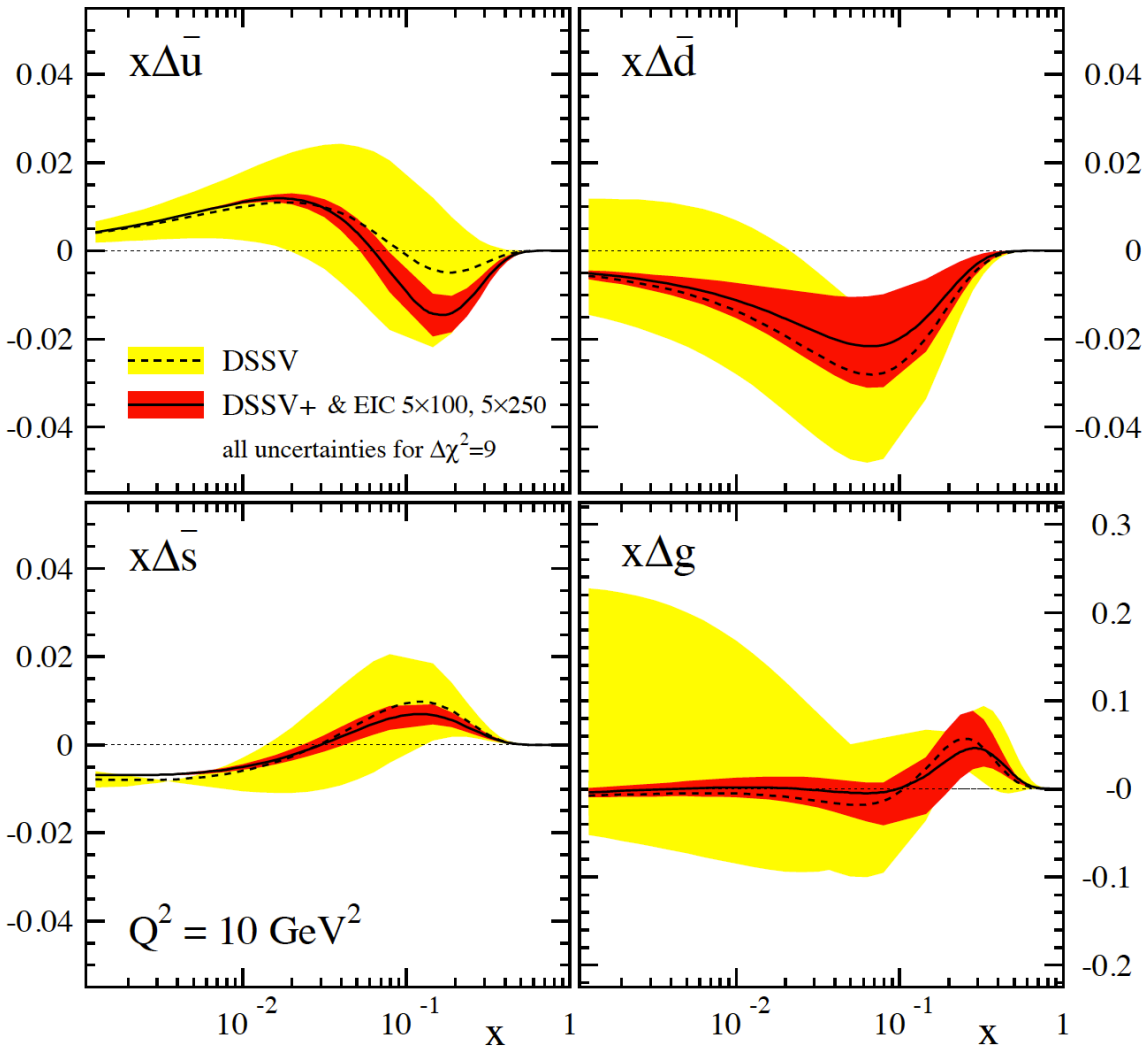

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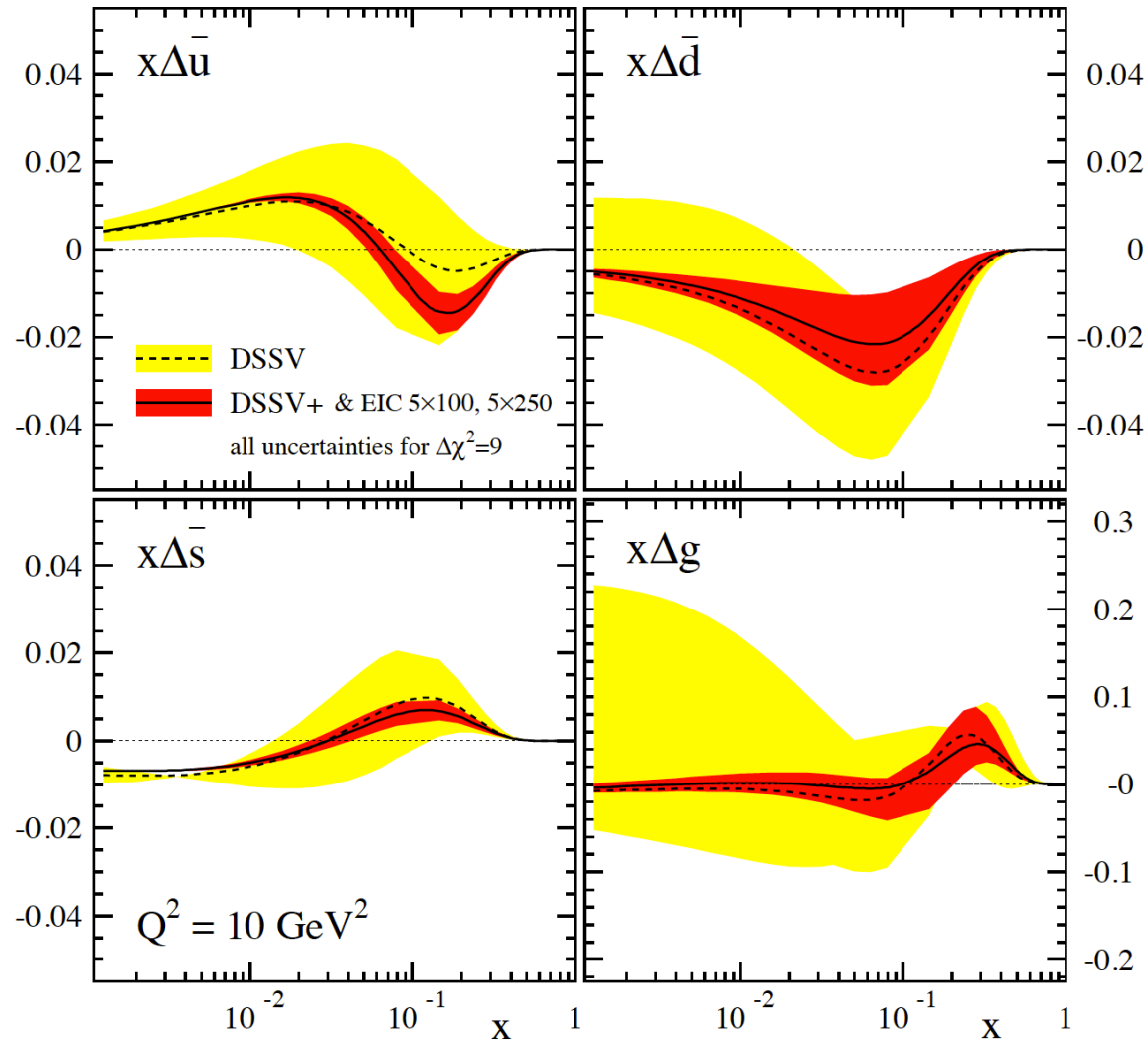


- **includes only "stage-1 data"**
  [even then Q^2_{min} can be 2-3 GeV²]
- can be pushed to $x=10^{-4}$ with 20 x 250 GeV data
  [still one can play with Q^2_{min}]

"issues":

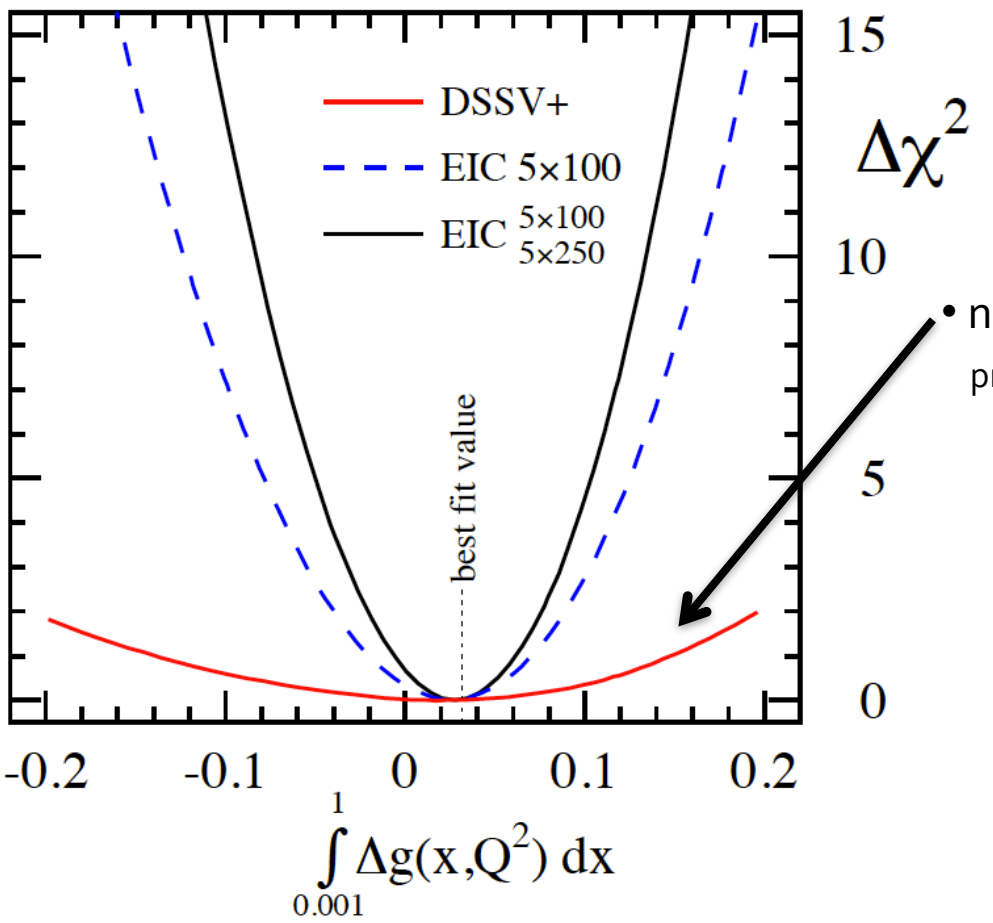
- (SI)DIS @ eRHIC limited by **systematic uncertainties**
  need to control rel. lumi, polarimetry, detector performance, ... very well
- **QED radiative corrections**
  need to "unfold" true x,Q²
  well known problem (HERA)
  BNL-LDRD project to sharpen tools

impact of eRHIC data in terms of χ^2 profiles

- dramatic improvements for [truncated] first moments $\int_{x_{min}}^{x_{max}} \Delta f(x, Q^2) dx$

  best visualized by χ^2 profiles obtained with Lagrange multipliers

- **example**: **Δg** in x-range **0.001-1** without/with stage-1 eRHIC data



- not well constrained by current data

  profile not parabolic

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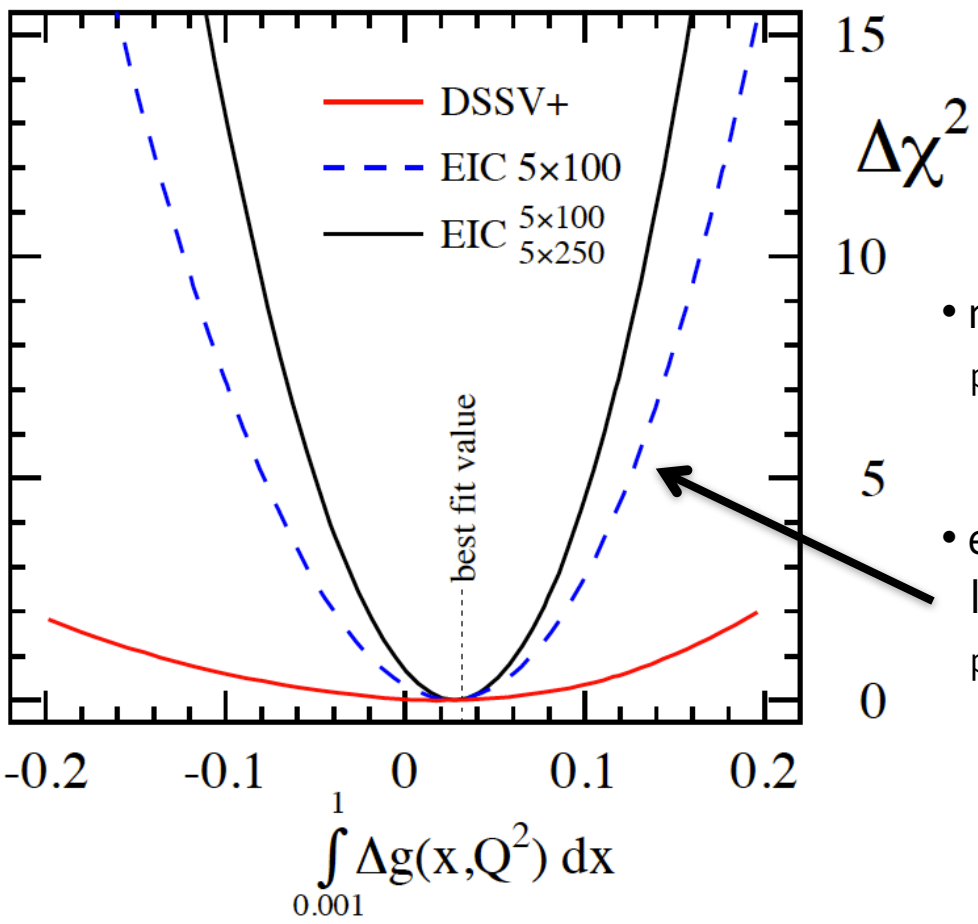

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- eRHIC [stage-1] DIS data lead to significant improvement

  profile parabolic; Hessian method also works

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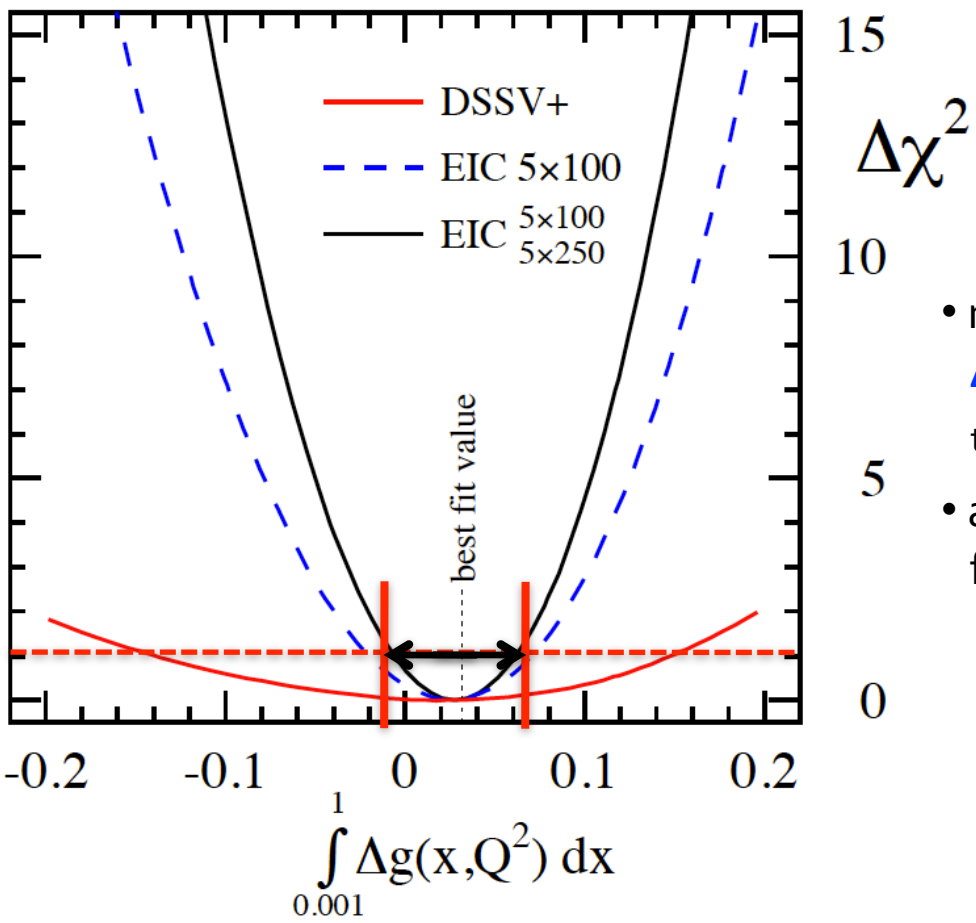

- read off uncertainties for given $\Delta\chi^2$

  $\Delta\chi^2 = 1$ usually not leading to a faithful error

  take conservative **$\Delta\chi^2 = 9$** as in DSSV analysis

- appropriate tolerance $\Delta\chi^2$ can be further refined once data are available

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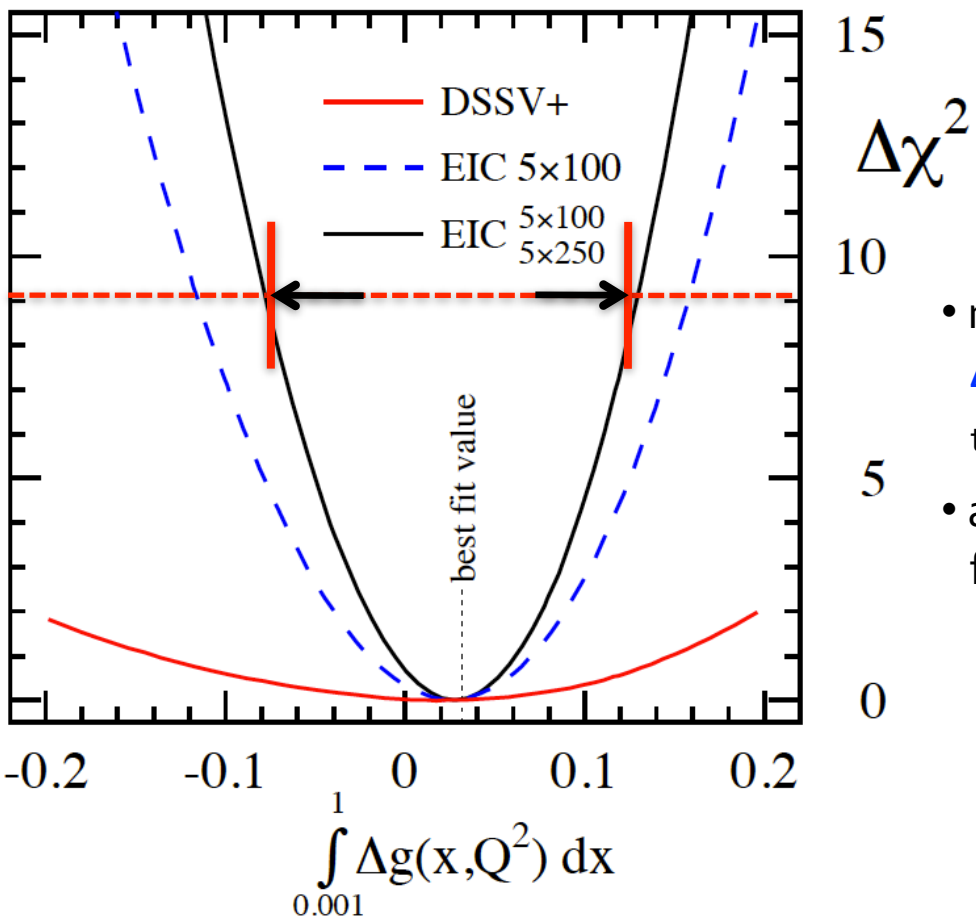

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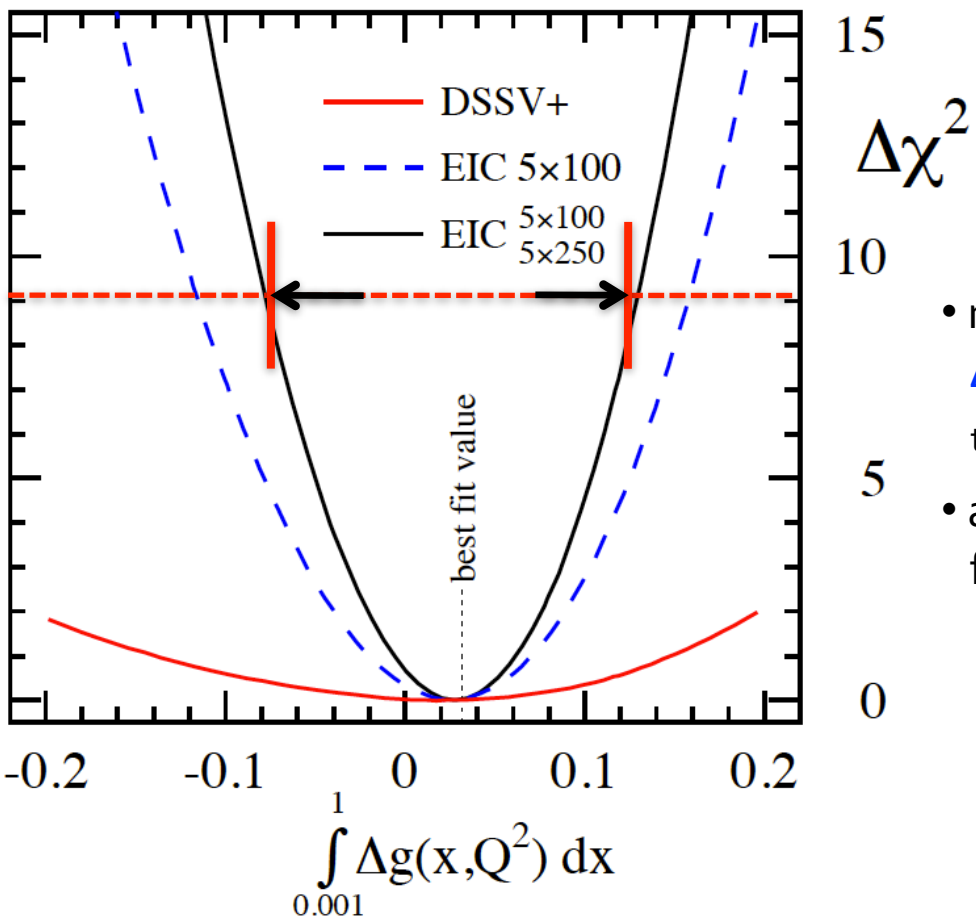

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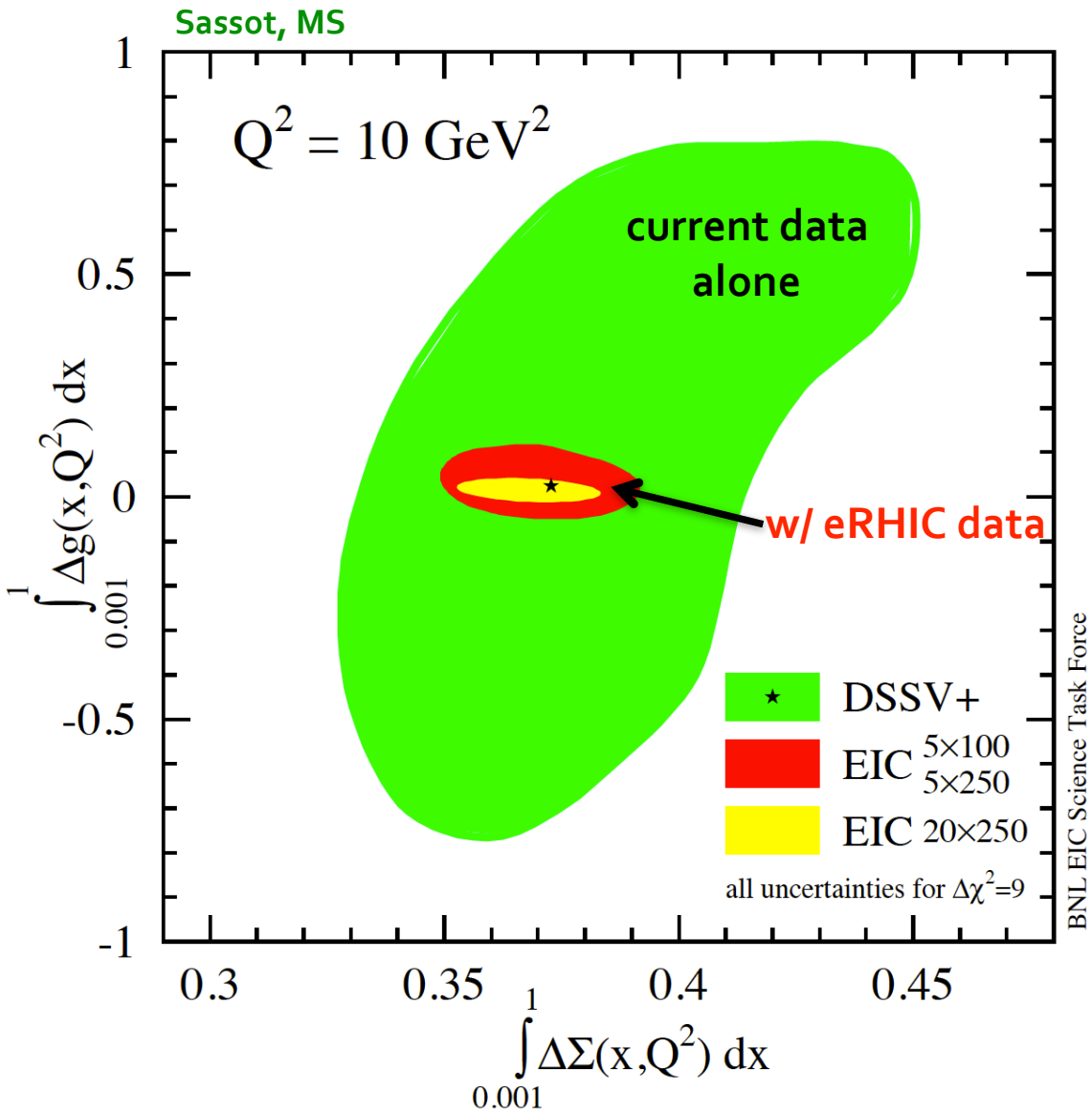
similar improvements can be found for all quark flavors

closing in on the spin sum rule

- combined correlated uncertainties for ΔΣ and Δg



- results obtained with two Lagrange multipliers
- similar improvement for 0.0001-1 moments

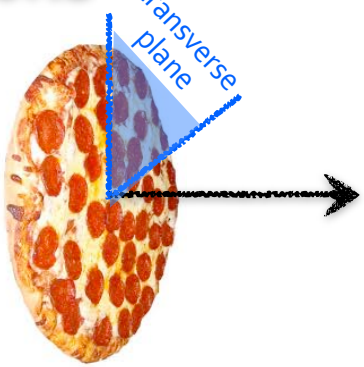
  needs 20 x 250 GeV data
- can expect approx. 5-10% uncertainties on ΔΣ and Δg

  but need to control systematics

three-dimensional quantum phase space tomography of the nucleon

the path to imaging quarks and gluons

- 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



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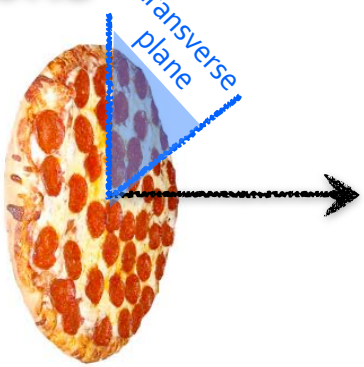

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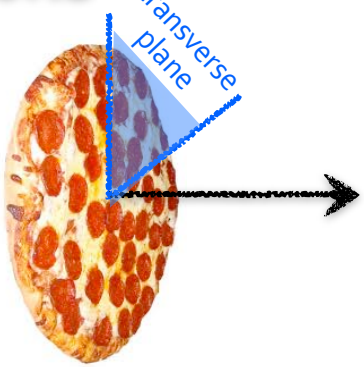

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required set of measurements & theoretical concepts

1-D $\mathbf{f(x)}$
parton densities

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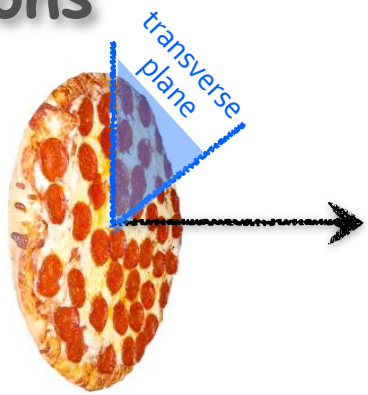

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$$\mathbf{f(x, k_T)}$$

transv. mom. dep. PDF

semi-inclusive DIS

$$\int \mathbf{d^2 k_T}$$

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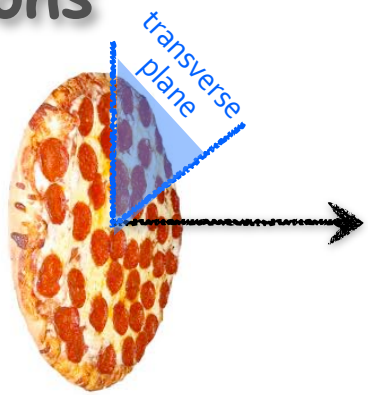

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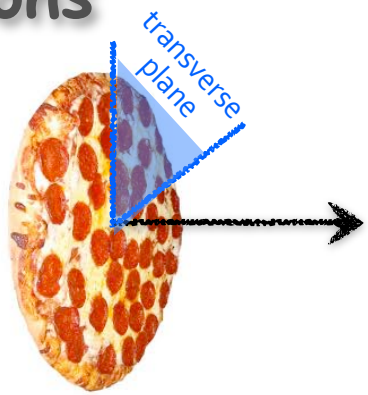

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$f(x, k_T)$ — transv. mom. dep. PDF — *semi-inclusive DIS*

$\xleftrightarrow[\text{Fourier transf.}]{\text{not related by}}$

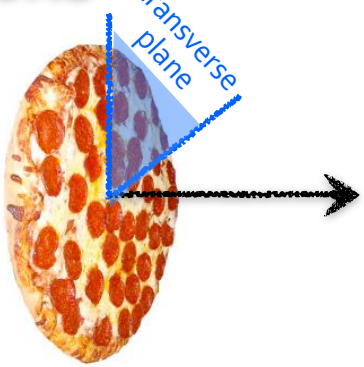
$f(x, b_T)$ — impact par. dep. PDF

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

1-D

$f(x)$ — parton densities

the path to imaging quarks and gluons



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$\mathbf{f(x, b_T)}$ — impact par. dep. PDF

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

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

$\int \mathbf{d^2 k_T}$ $\searrow$ $\swarrow$ $\int \mathbf{d^2 b_T}$

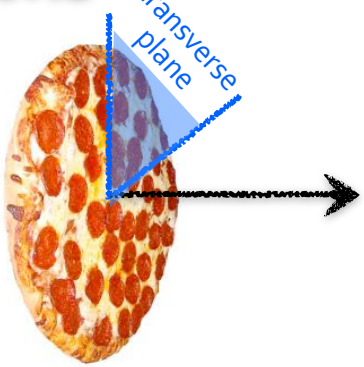
$\downarrow \int \mathbf{dx}$

1-D

$\mathbf{f(x)}$ — parton densities

$\mathbf{F(t)}$ — form factor

the path to imaging quarks and gluons



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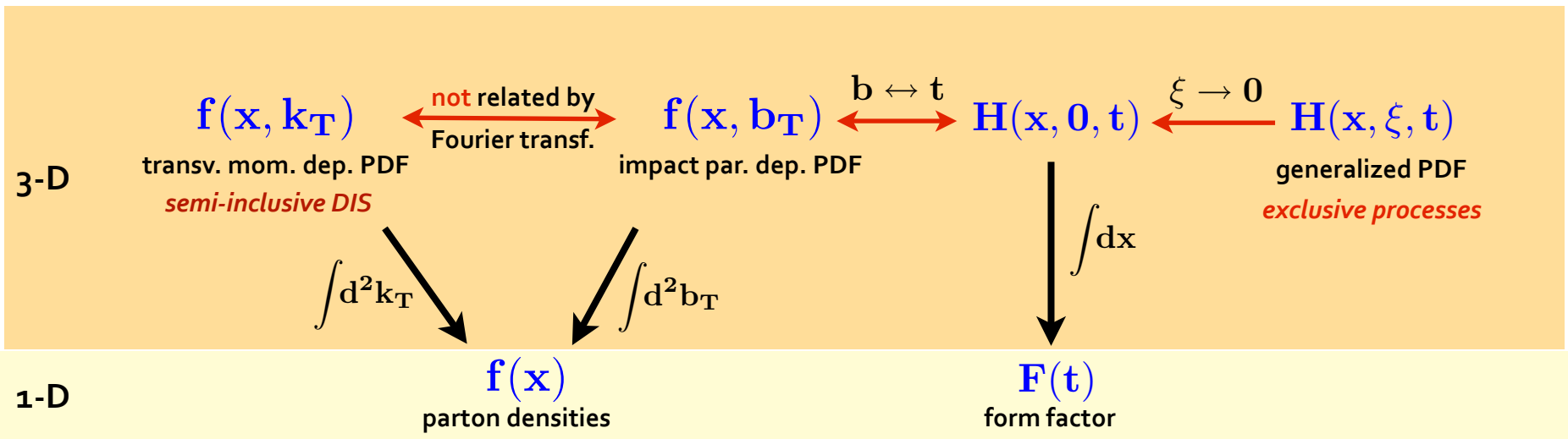

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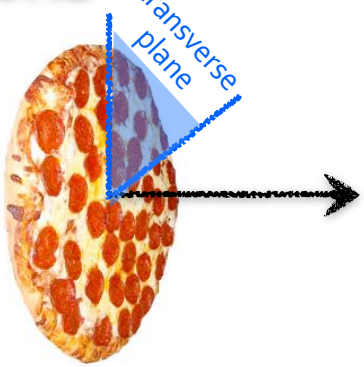

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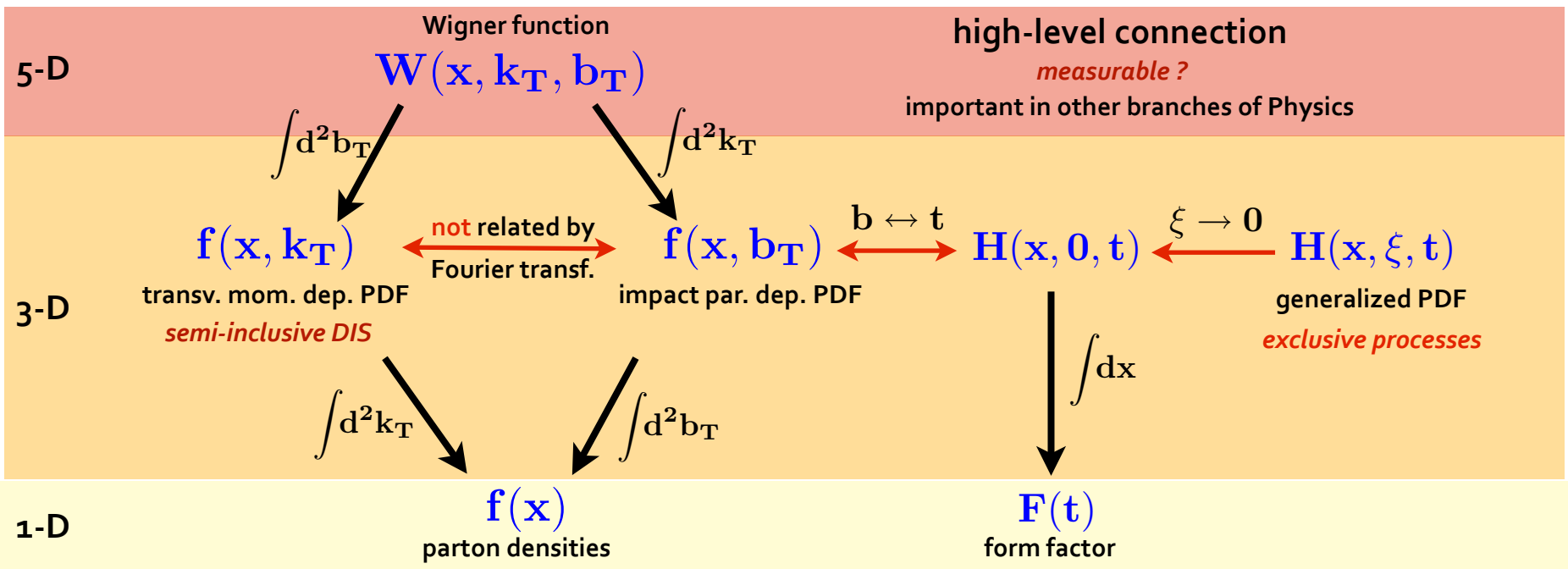
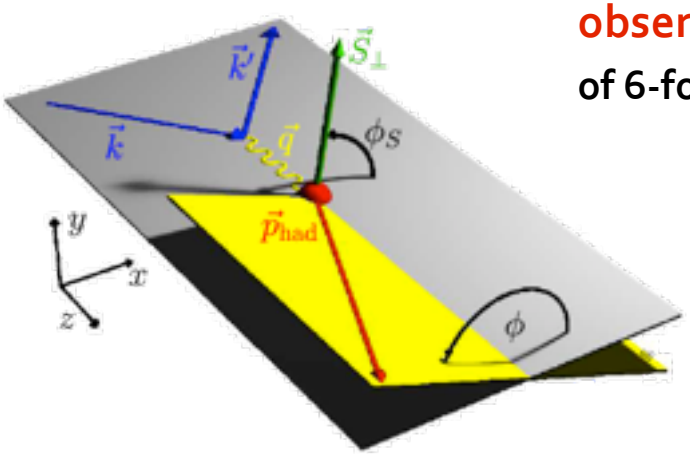


physics of transverse momentum dependent PDFs



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

- theoretically interesting multi-scale problem: Q^2, p_T^h
- TMD framework/factorization applicable for $Q^2 \gg p_T^h$
- so far only valence quark TMDs extracted from fixed target data
- slew of different TMDs can be defined

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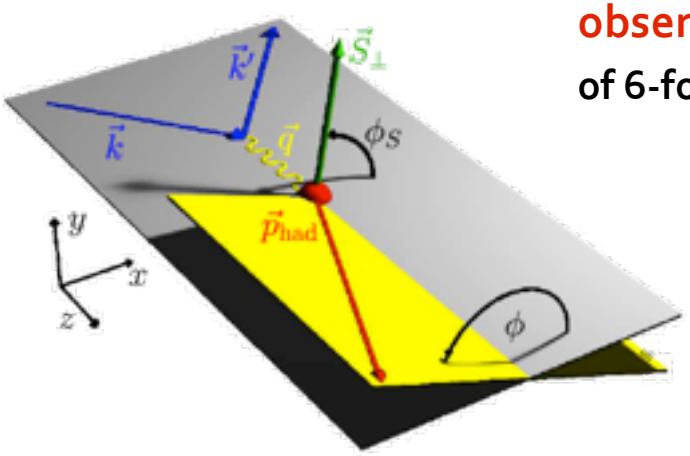

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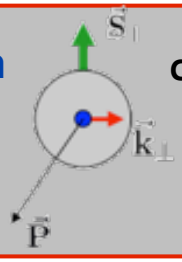
example: **Sivers function**

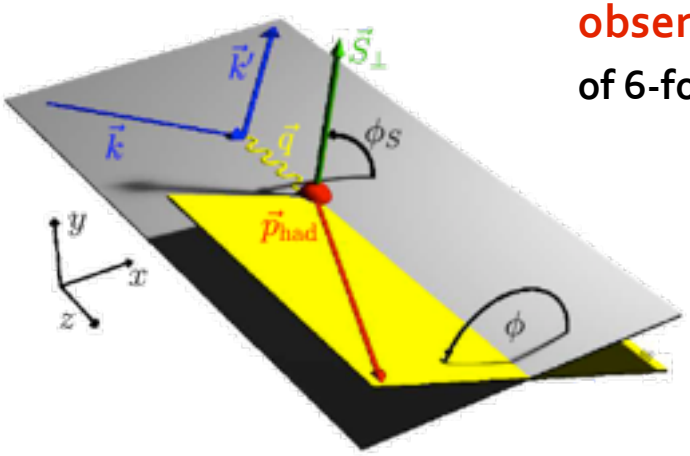
$\sin(\phi_h - \phi_S)$ modulation



correlation of nucleon's transverse spin with the k_T of an *unpolarized* quark

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

physics of transverse momentum dependent PDFs



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

- theoretically interesting multi-scale problem: Q^2, p_T^h
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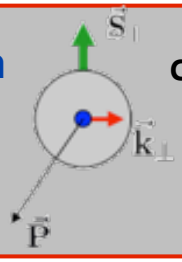

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unintegrated PDF f_1

important link to physics of gluon saturation at small x

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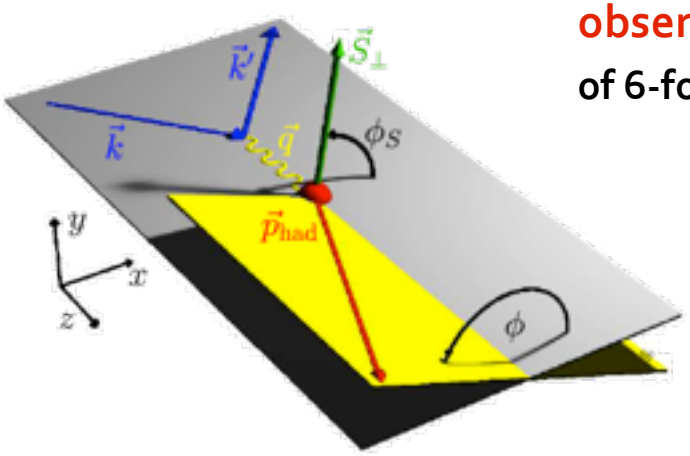

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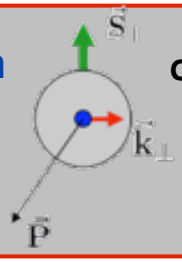

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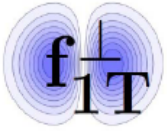


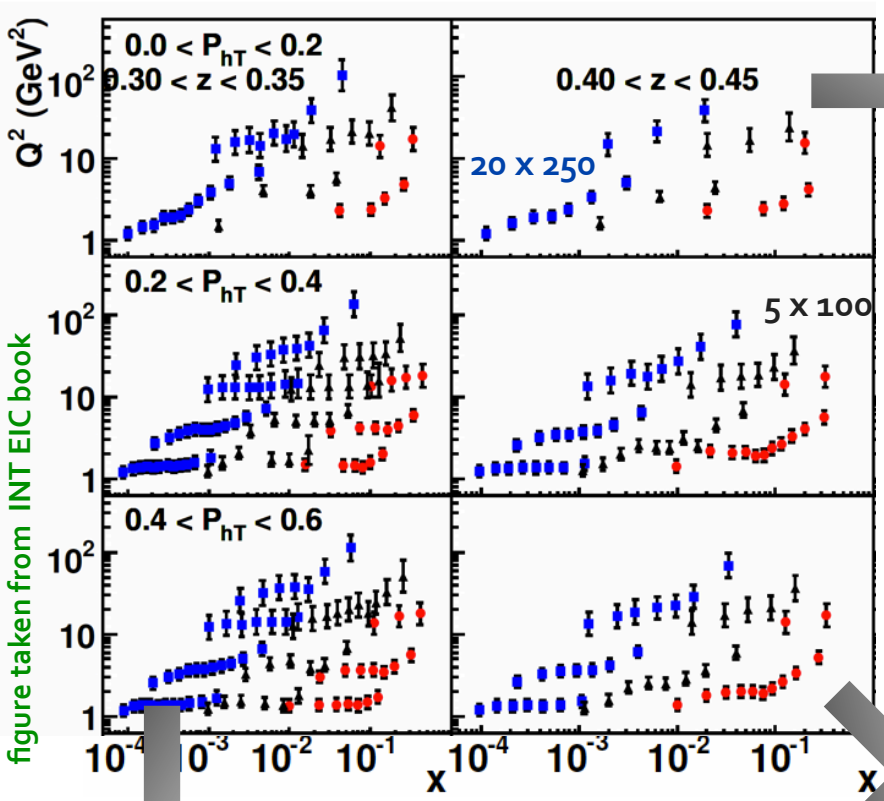
Sivers function

important link to physics of gluon saturation at small x

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

impact of eRHIC on TMD studies

multi-dim. binning possible thanks to eRHIC luminosity



z binning up to 0.8

up to

$\mathbf{p_T^h = 1\,GeV}$ with $\int \mathcal{L}\mathbf{dt} = \mathcal{O}(\mathbf{10})\,\mathrm{fb}^{-1}$

$\mathbf{p_T^h = 1 \div 2\,GeV}$ with $\int \mathcal{L}\mathbf{dt} = \mathcal{O}(\mathbf{100})\,\mathrm{fb}^{-1}$

impact of eRHIC on TMD (Sivers) studies

Prokudin

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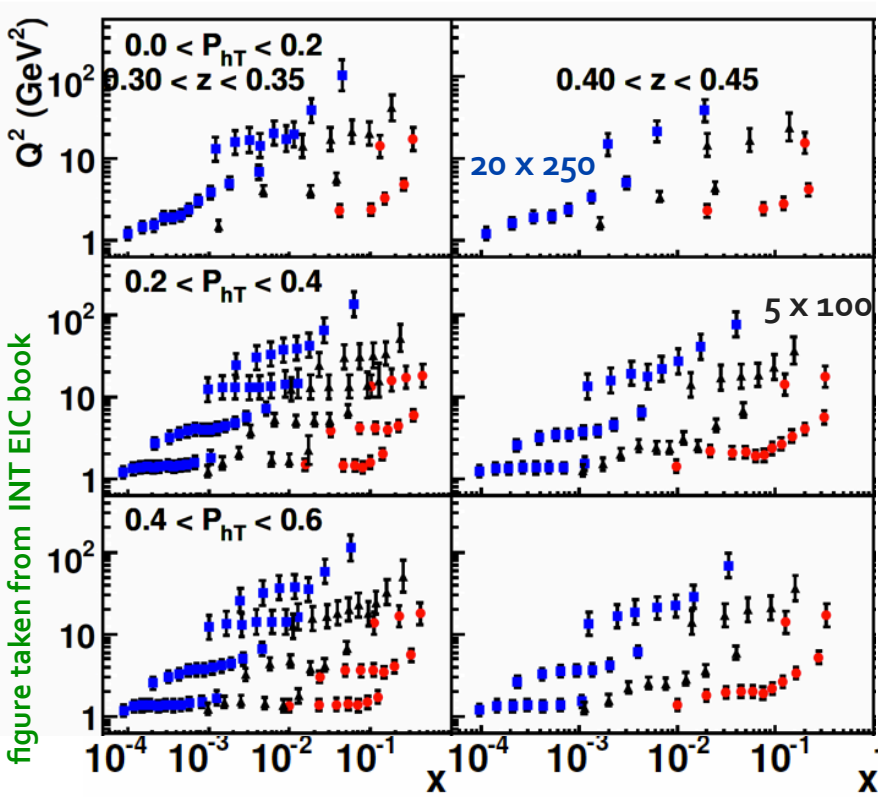

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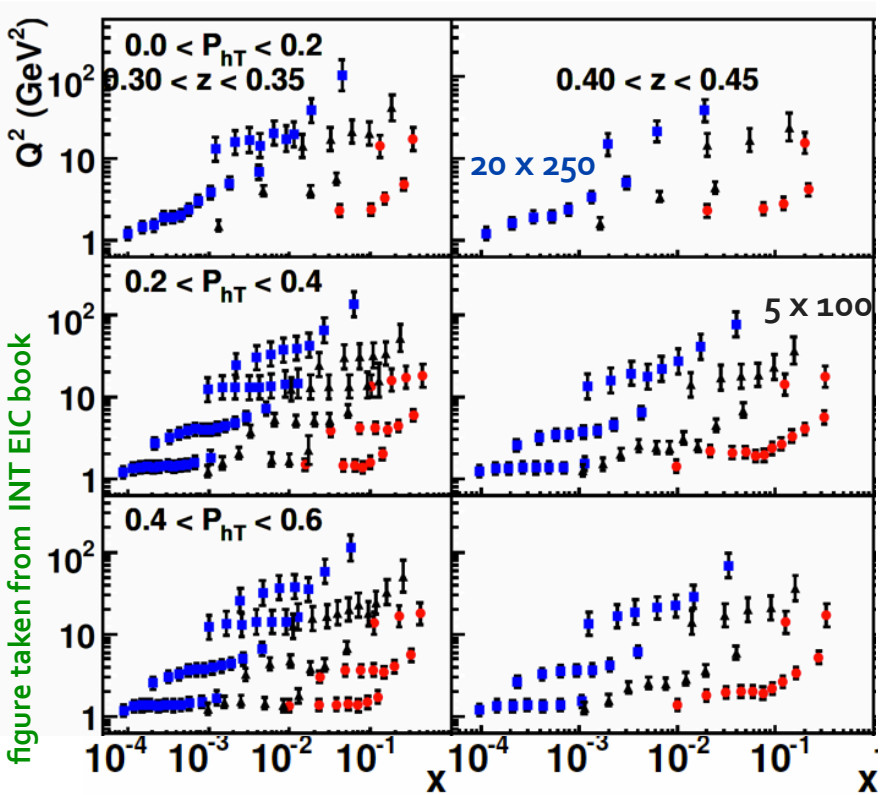
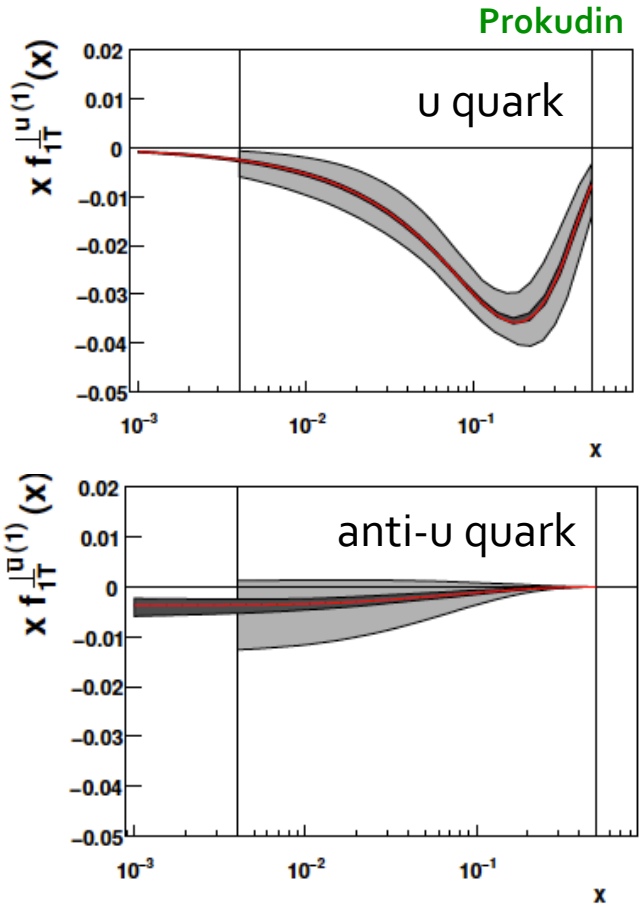


use 5 x100 pseudo-data in **global TMD fit**



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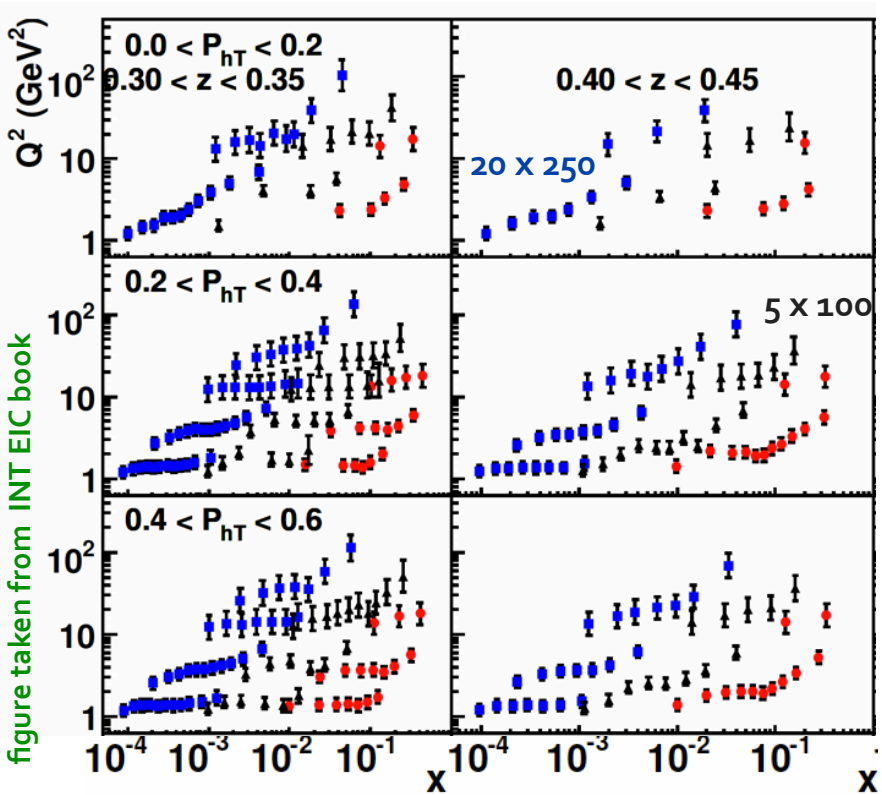

figure taken from INT EIC book

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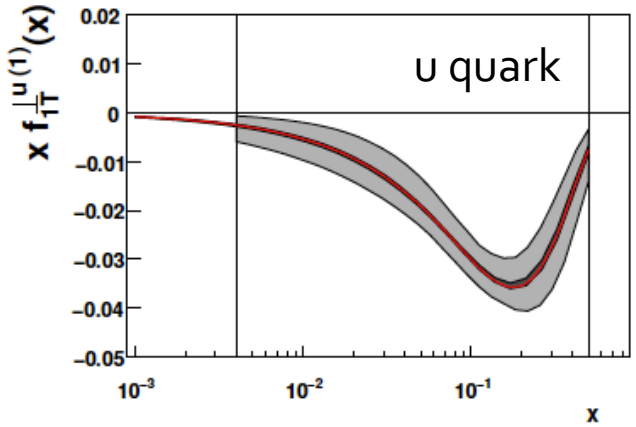
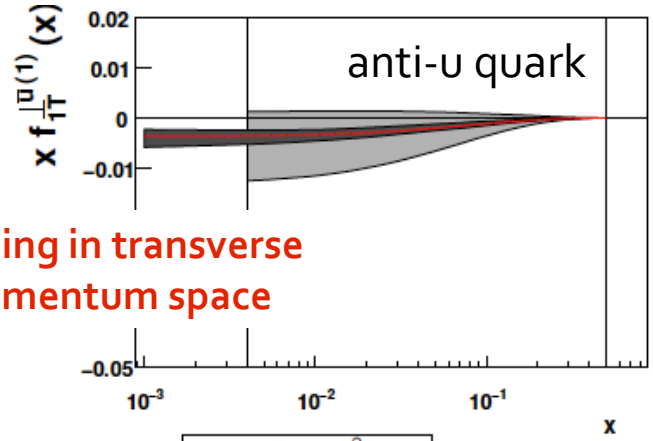
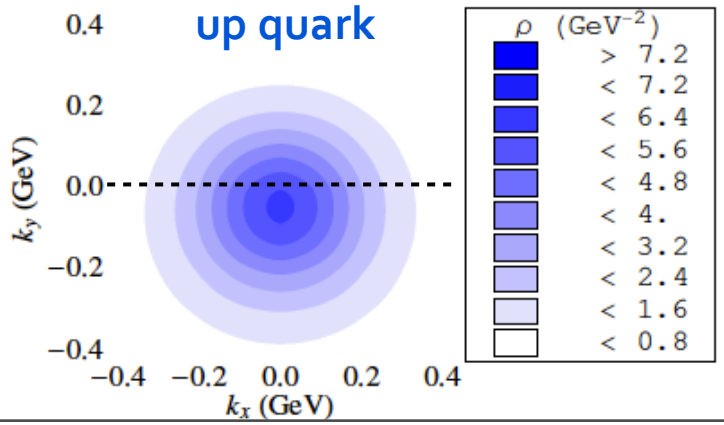
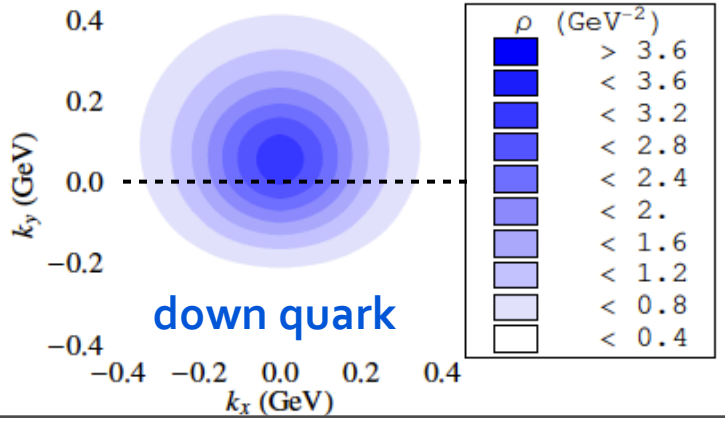




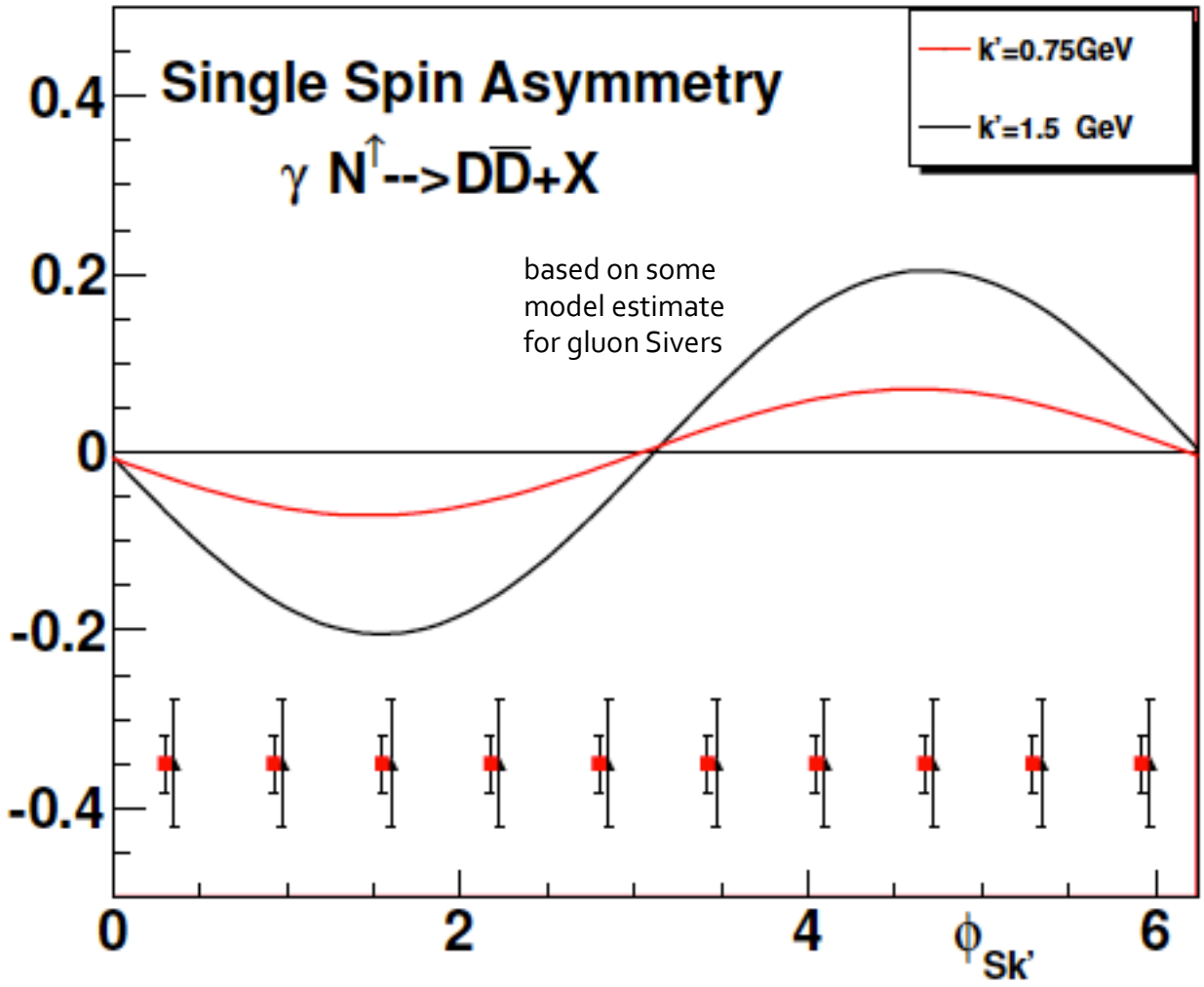
imaging in transverse momentum space





accessing the gluon Sivers function

another unique opportunity at eRHIC: study azimuthal asymmetry correlating the transverse momentum of D-$\overline{D}$ pair with transverse proton spin

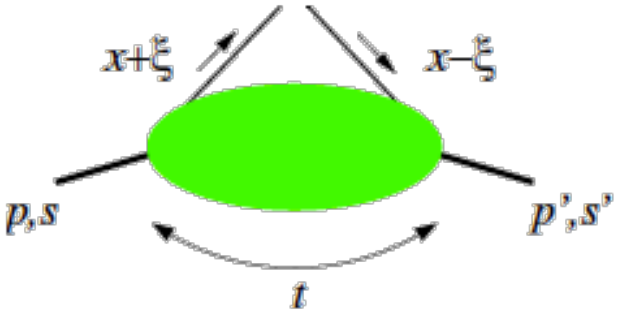


T. Burton, F. Yuan, ...

error estimate assuming 100 fb^{-1}

angle between proton spin and k_T of D-meson pair

generalized parton densities in a nutshell



GPDs depend on:

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

= interference between different nucleon states (not a probability)

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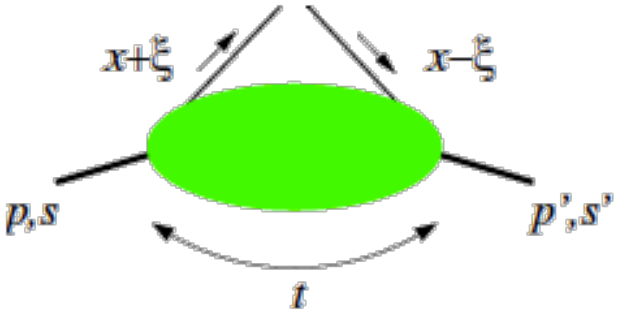

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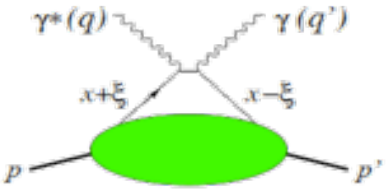
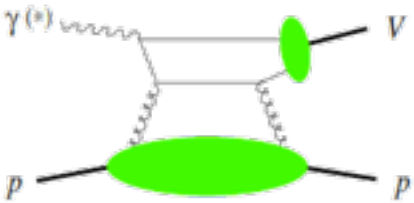


deeply virtual Compton scattering (DVCS)



vector meson production

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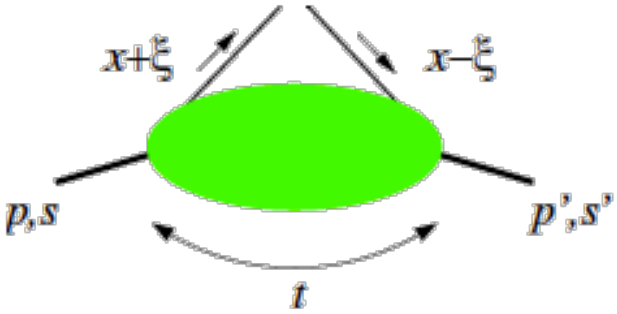

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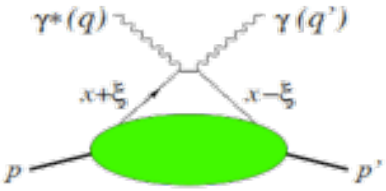

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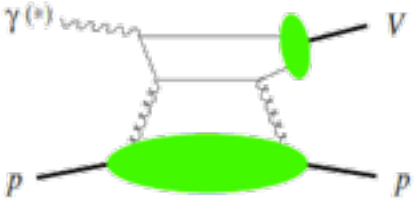

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4 GPDs per flavor, e.g.,

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

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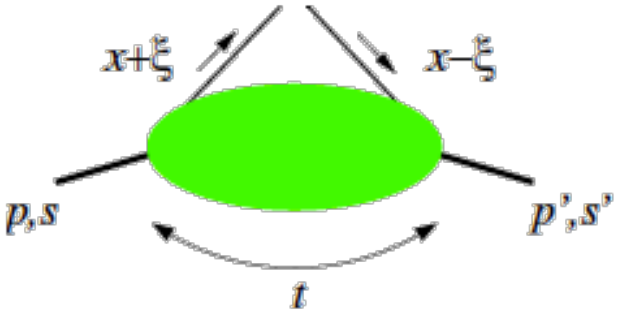

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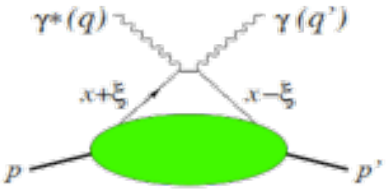

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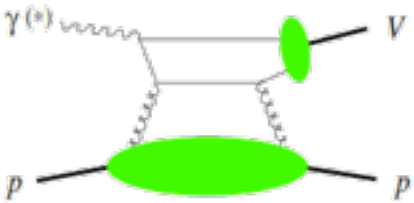

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recover PDFs in limit

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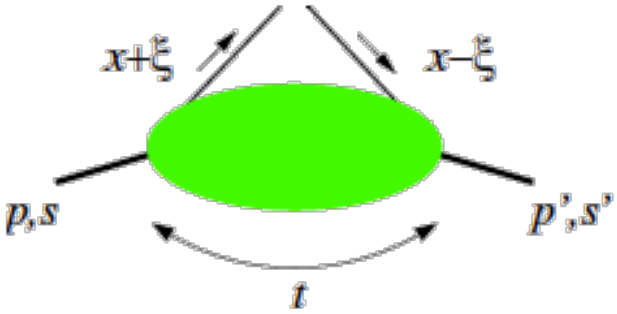

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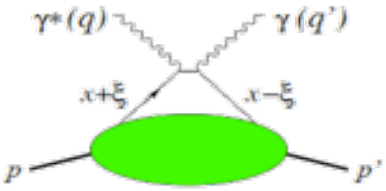

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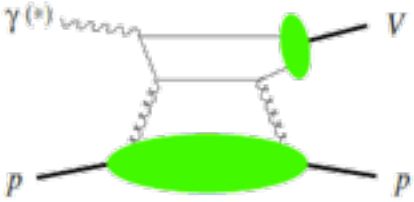

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recover PDFs in limit $s = s', \xi = 0, t = 0$

no PDF limit; involves helicity flip
indicator of OAM; key part in Ji's sum rule

imaging in transverse position space

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

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

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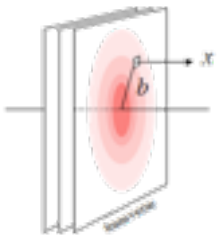

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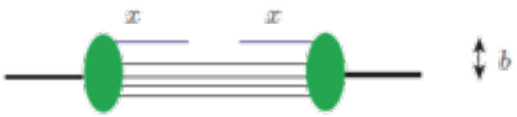

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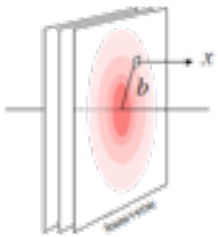

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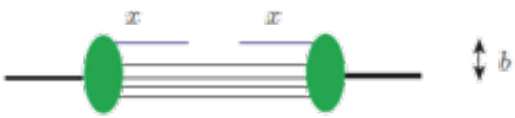

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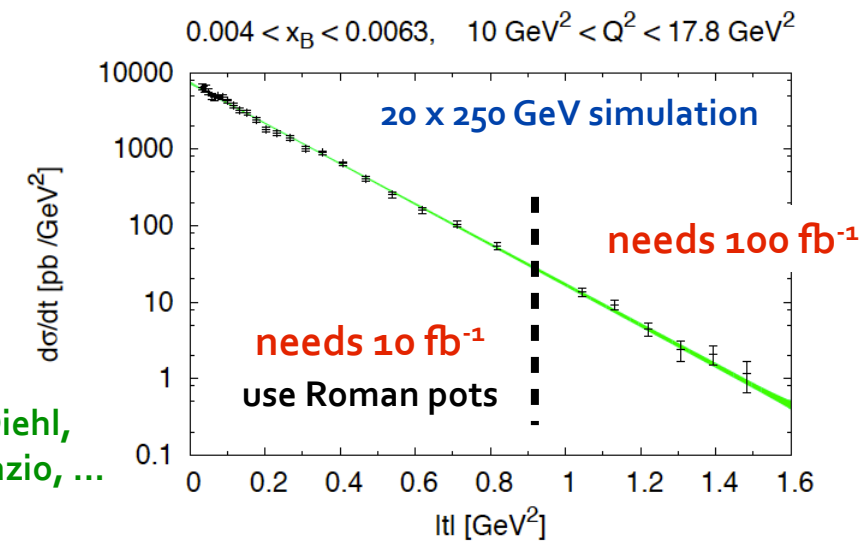

M. Diehl,
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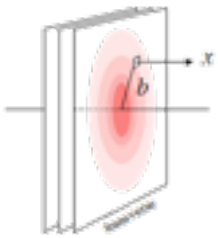

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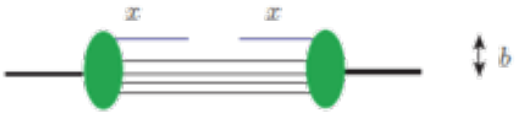

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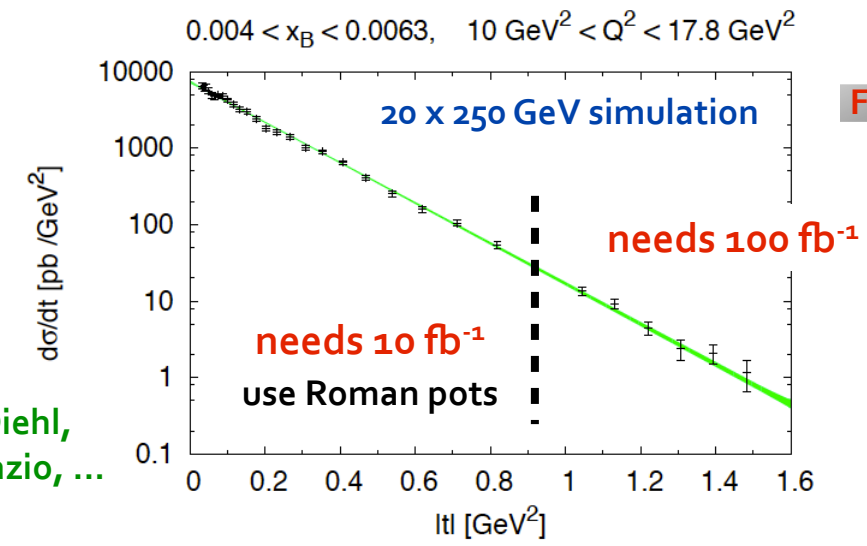
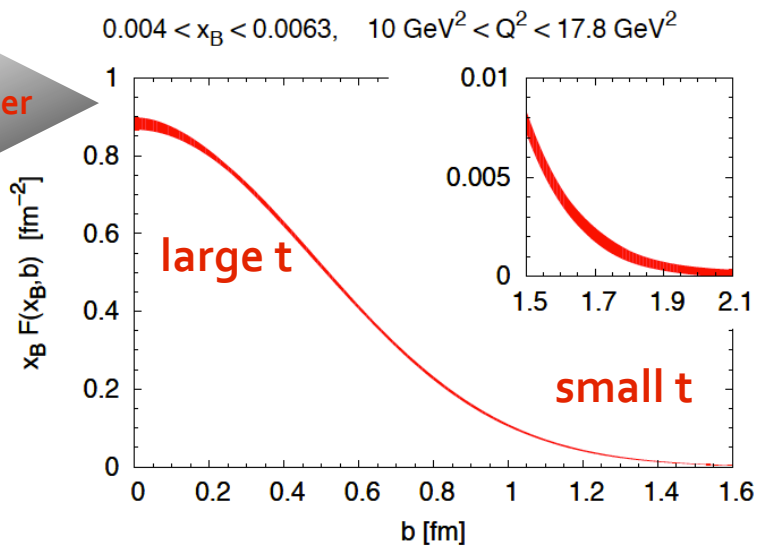


Fourier



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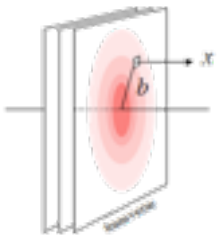

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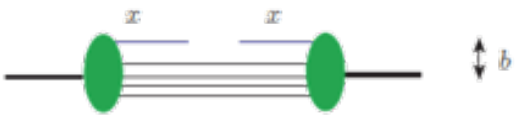

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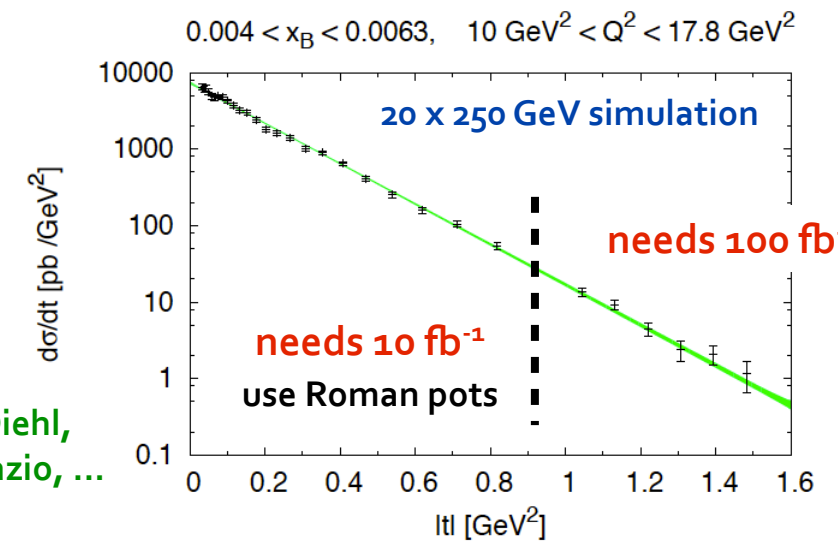

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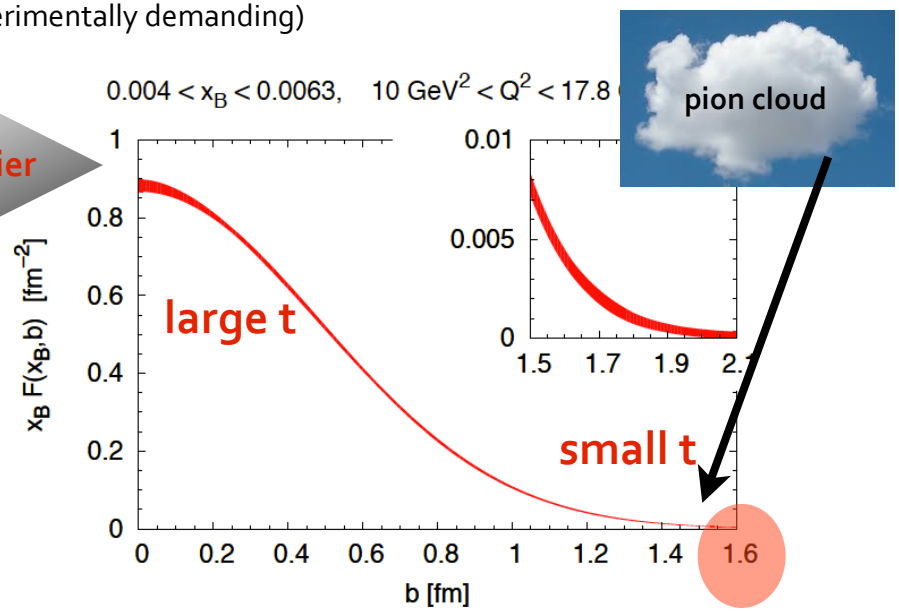
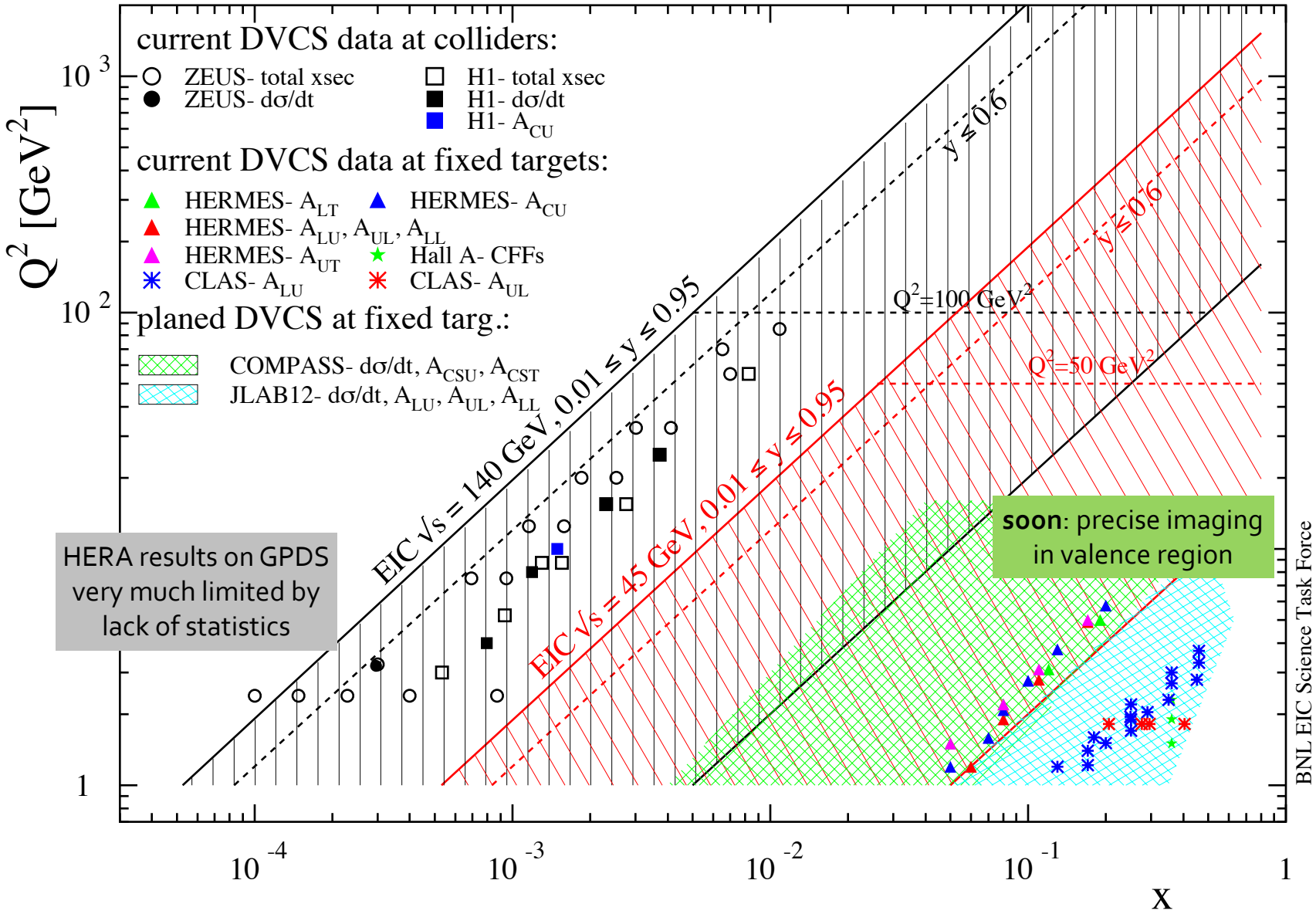


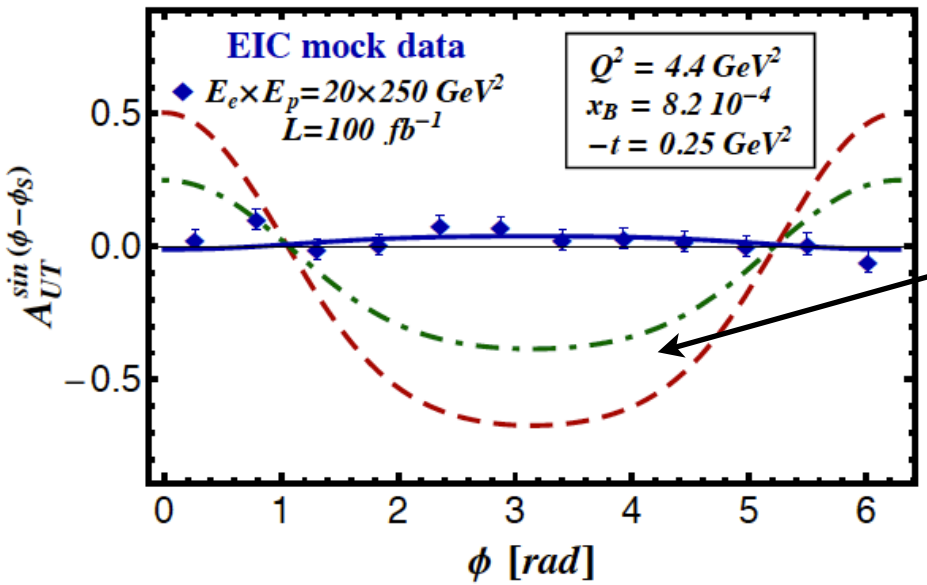
M. Diehl,
S. Fazio, ...

DVCS phase space: past-present-future



eRHIC pseudo-data and their impact

S. Fazio, D. Mueller, ...



- unpolarized DVCS mainly sensitive to GPD H
- unknown GPD E from angular asymmetries

different assumptions for E

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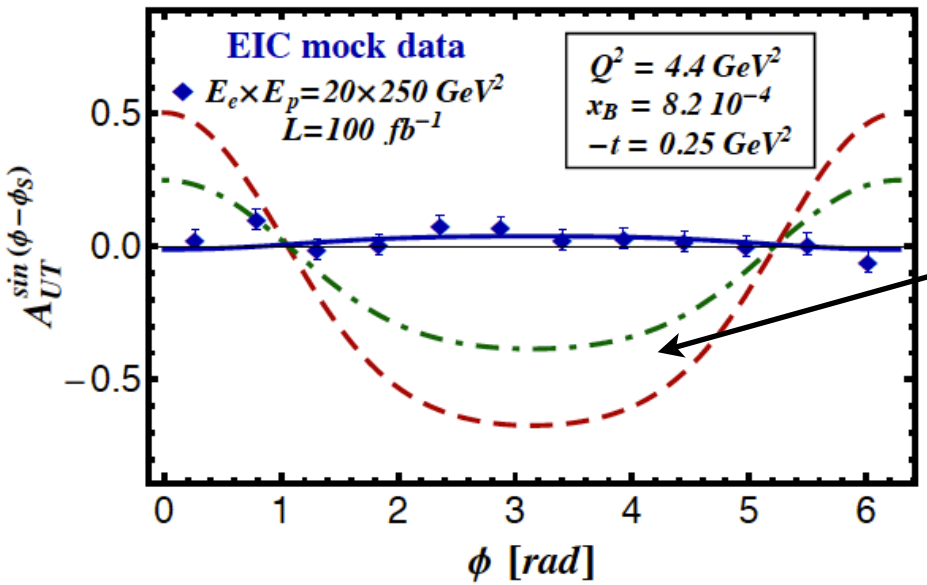

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▼

perform fits to combined set of pseudo-data

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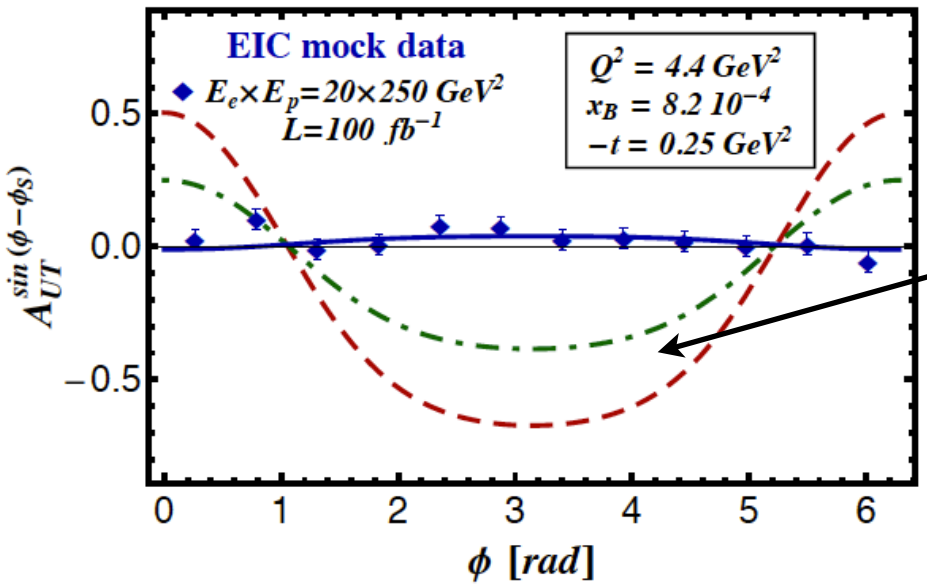

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Fourier transform to impact parameter space

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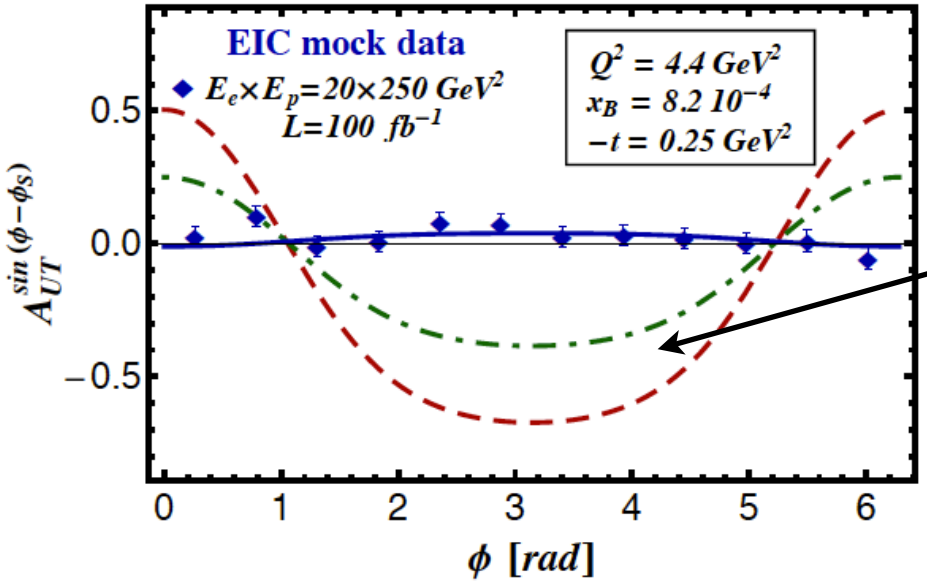

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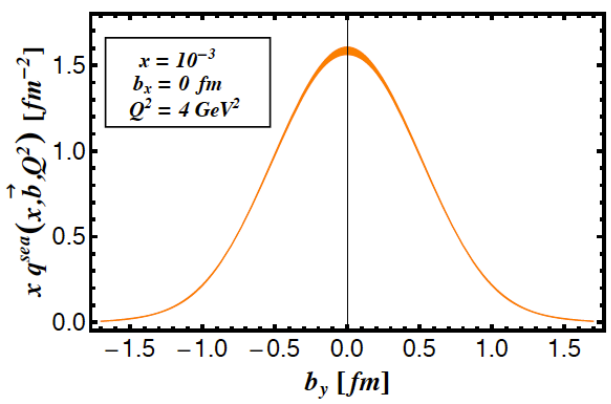
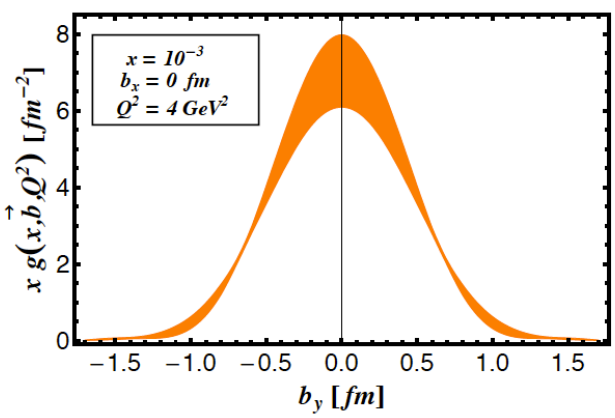
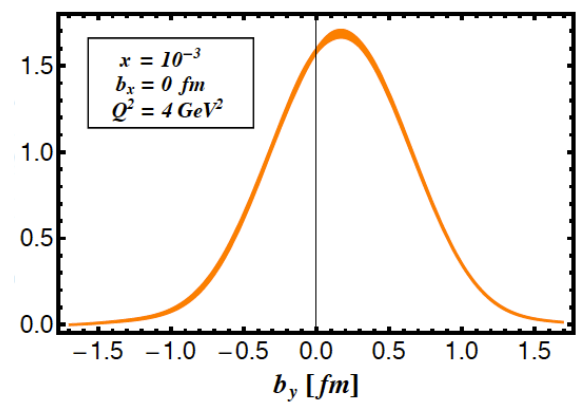


quarks



gluons

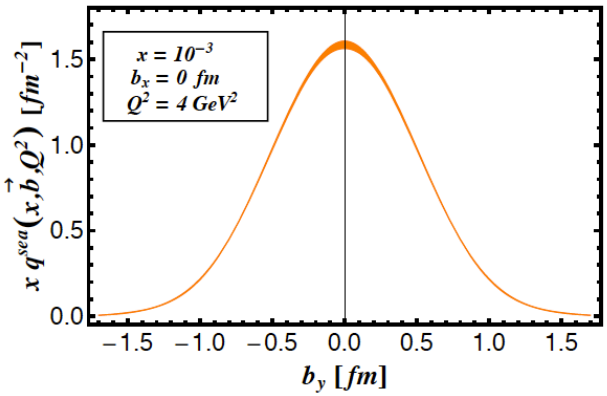


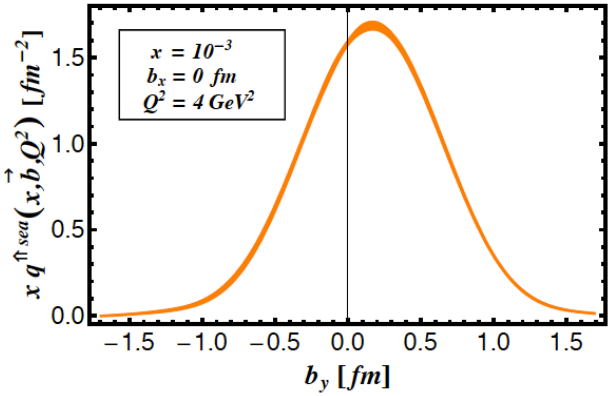
quarks

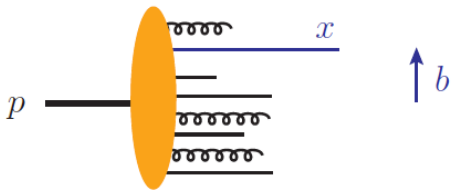
transversely polarized proton

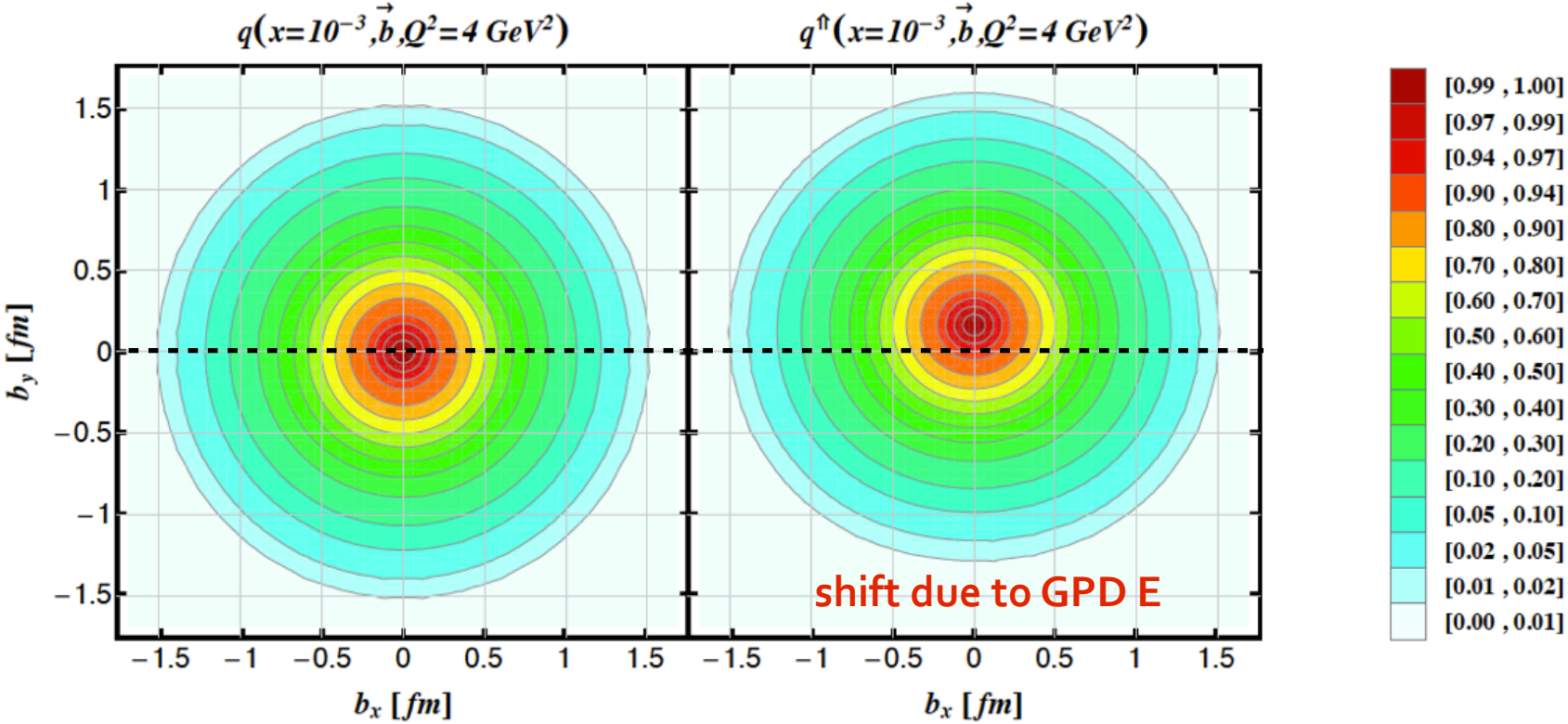
spatial imaging at work

D. Mueller









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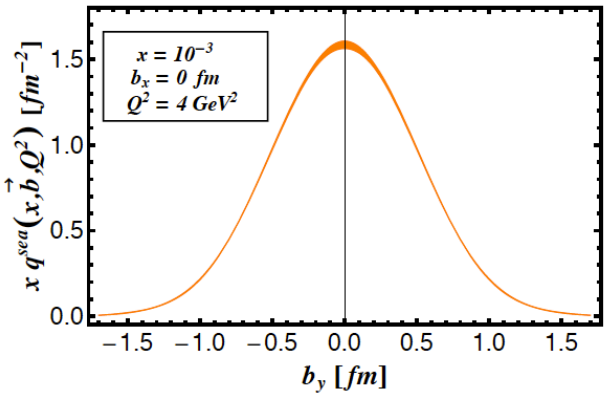

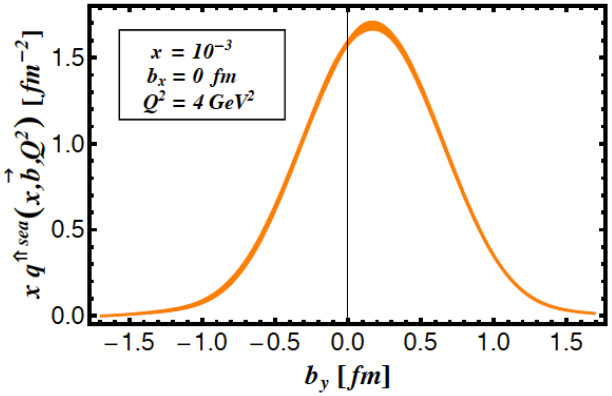

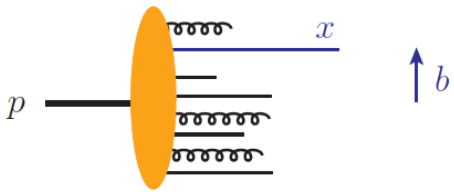

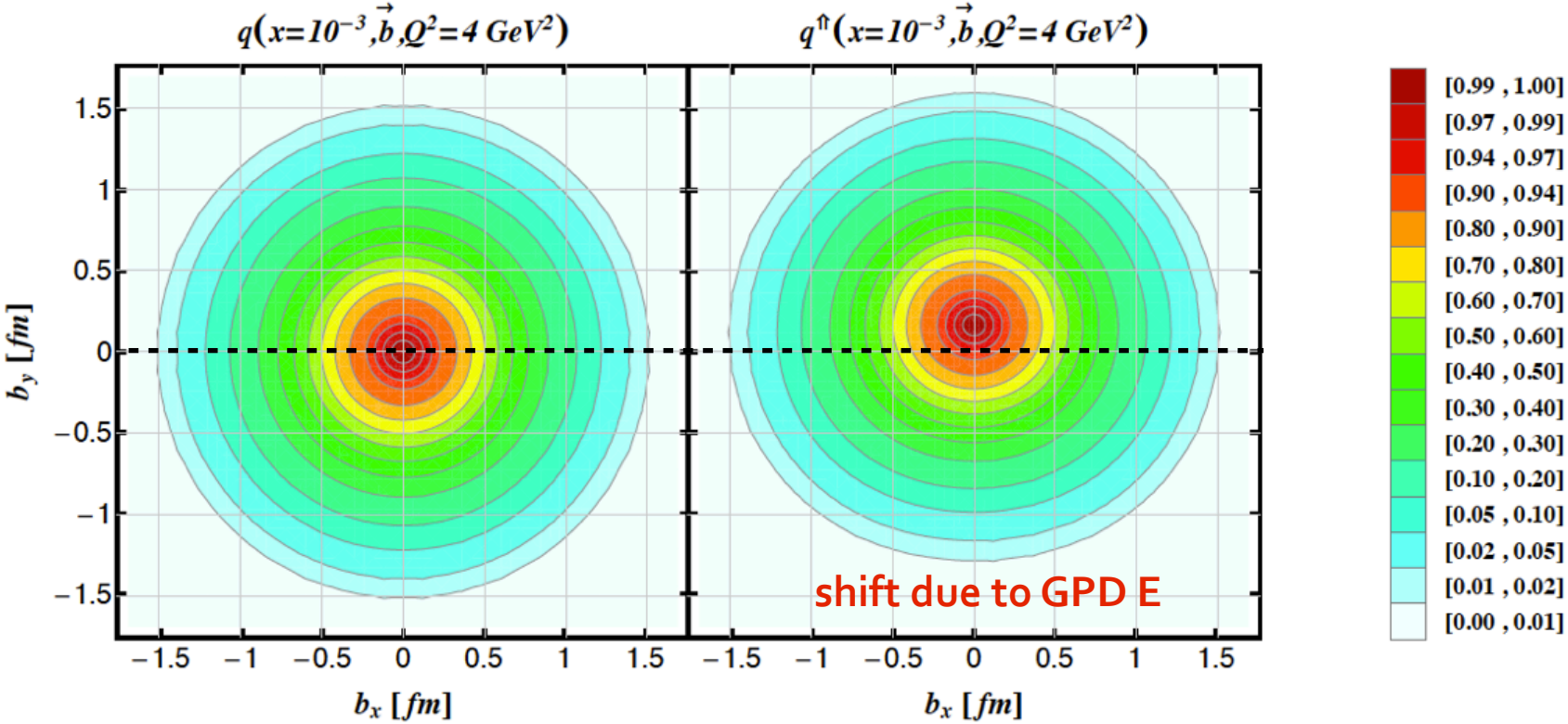

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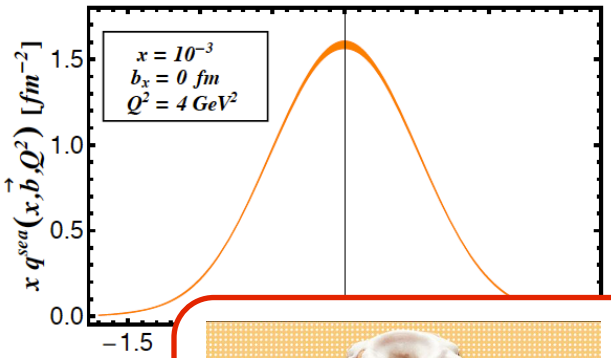
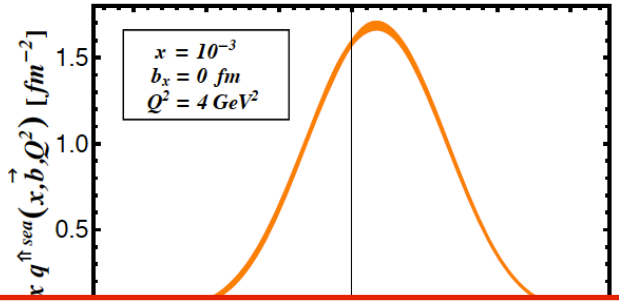
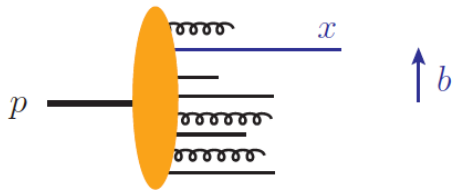






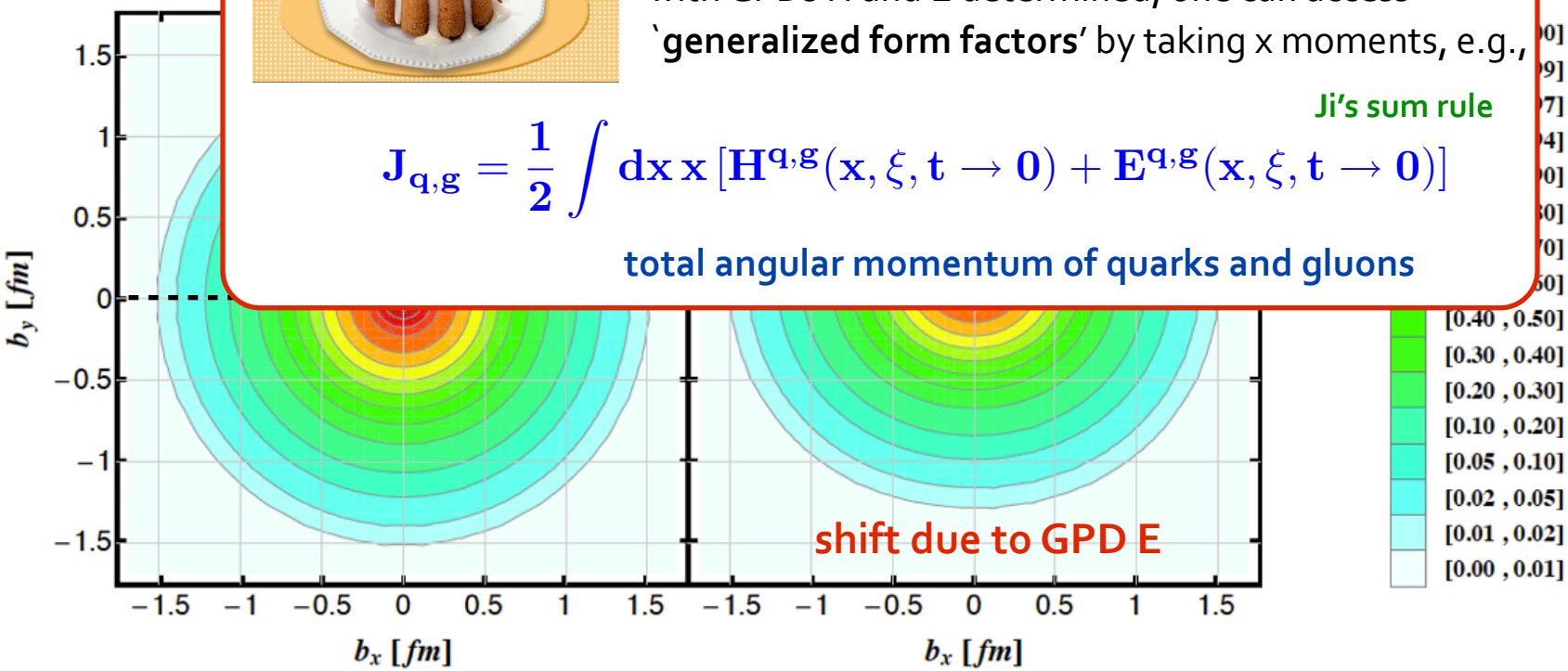
icing on the cake:

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



quarks

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take away message

eRHIC offers many unique opportunities to greatly advance our understanding of the nucleon structure

precision studies of PDFs, TMDs, and GPDs will lead to the most comprehensive picture of the nucleon ever: 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