ALESSANDRO BACCHETTA, PAVIA U. AND INFN

MULTIDIMENSIONAL STRUCTURE OF THE PROTON AND OPPORTUNITIES AT A NEW ELECTRON ION COLLIDER

THE EIC PROJECT

EXECUTIVE SUMMARY

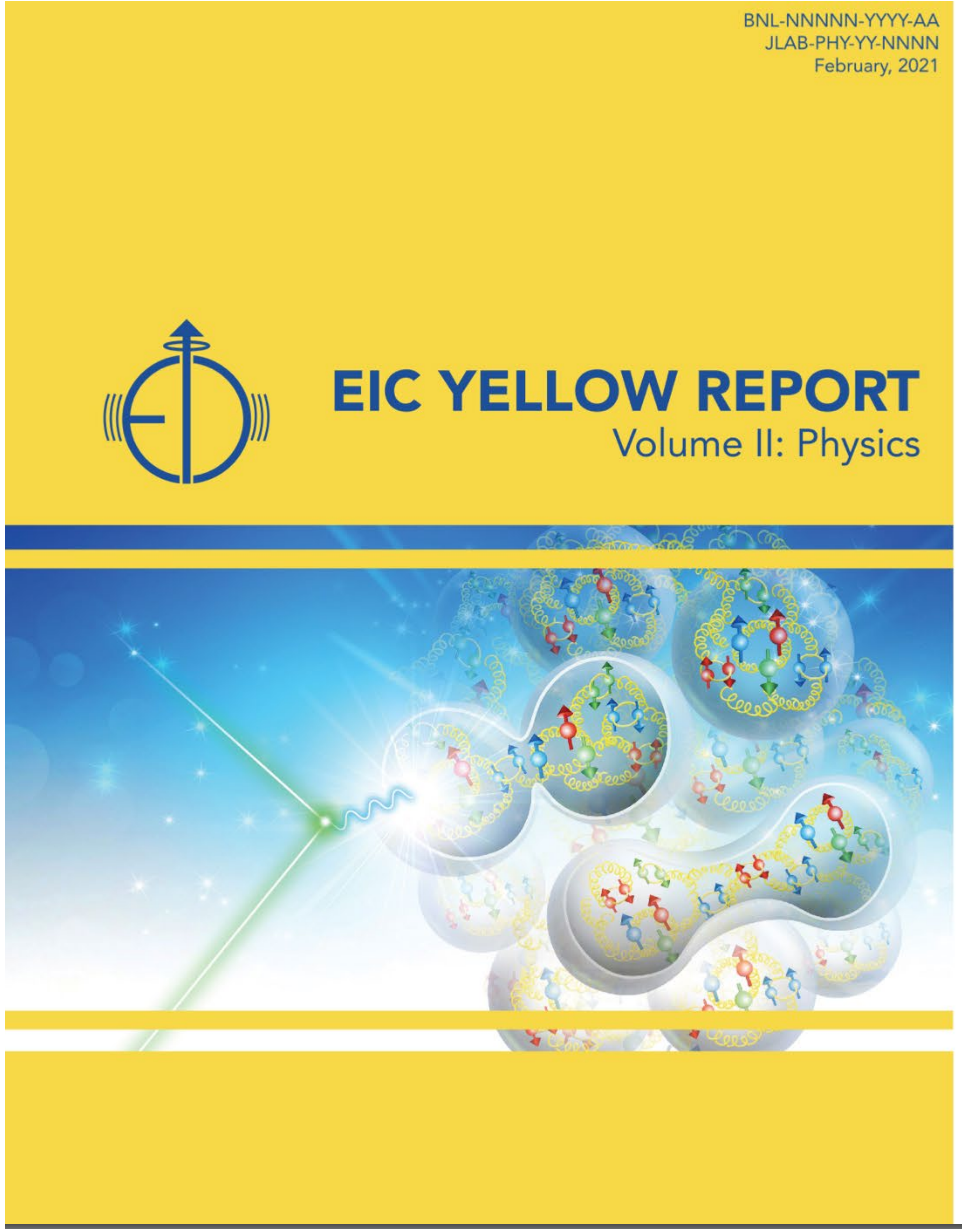
The EIC is a new electron-ion collider to be built by 2035 at Brookhaven National Laboratory.

Its main goal is to study the structure of nucleons and nuclei.

DETAILED MATERIAL

https://www.eicug.org

arXiv:2103.05419



https://science.osti.gov/-/media/np/nsac/pdf/202310/NSAC-LRP-2023-v12.pdf

RECOMMENDATION 3

We recommend the expeditious completion of the EIC as the highest priority for facility construction.

https://science.osti.gov/-/media/np/nsac/pdf/202310/NSAC-LRP-2023-v12.pdf

> The EIC is a powerful discovery machine, a precision microscope capable of taking three-dimensional pictures of nuclear matter at femtometer scales.

To achieve the scientific goals of the EIC, a parallel investment in quantum chromodynamics (QCD) theory is essential,.

Progress in theory and computing has already helped to drive and refine the physics program of the EIC.

To maximize the scientific impact of the facility and to prepare for the precision expected at the EIC, theory must advance on multiple fronts, and new collaborative efforts are required.

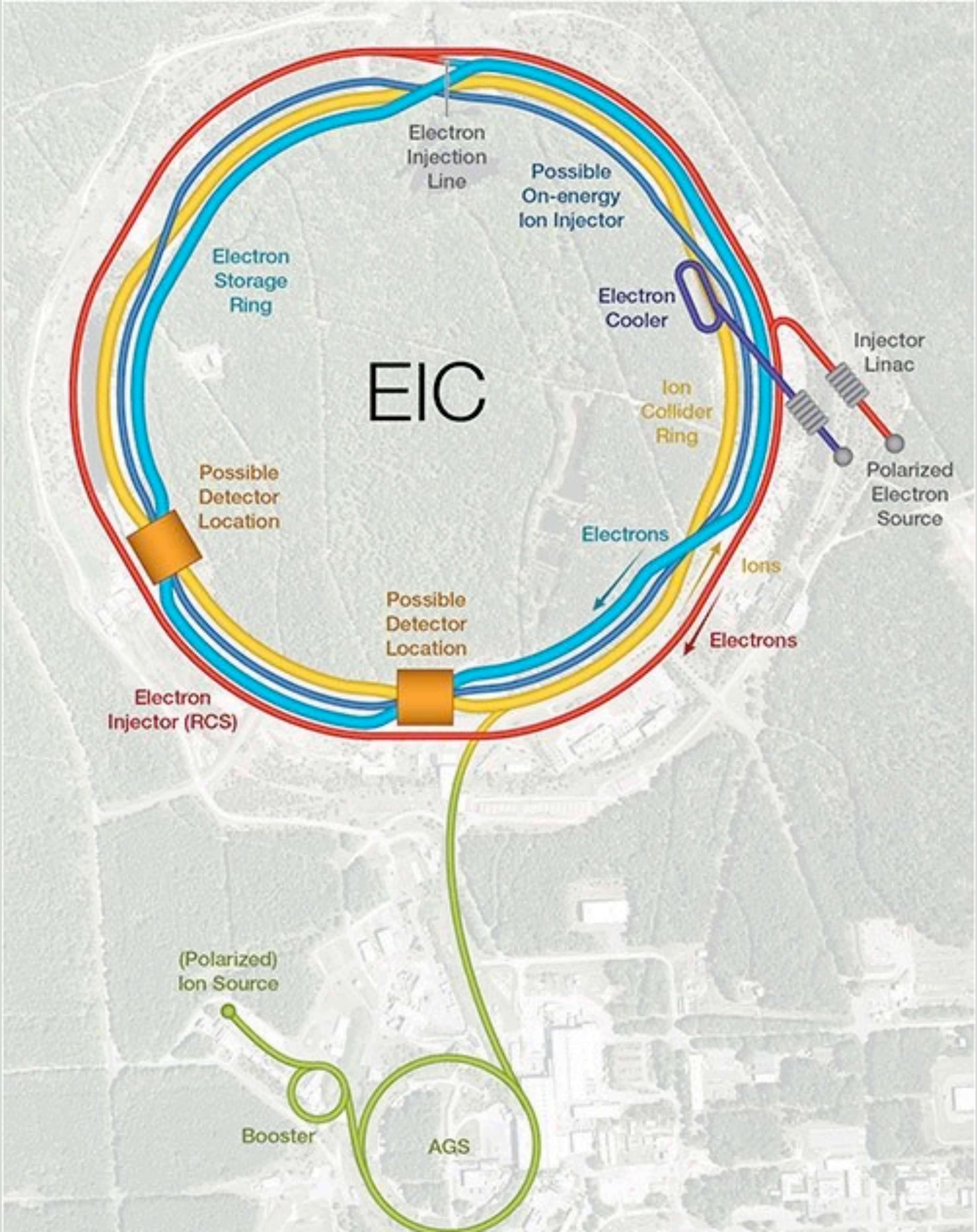

New York


New York
Brookhaven National Lab

Partnership:

BROOKHAVEN
NATIONAL LABORATORY

Jefferson Lab



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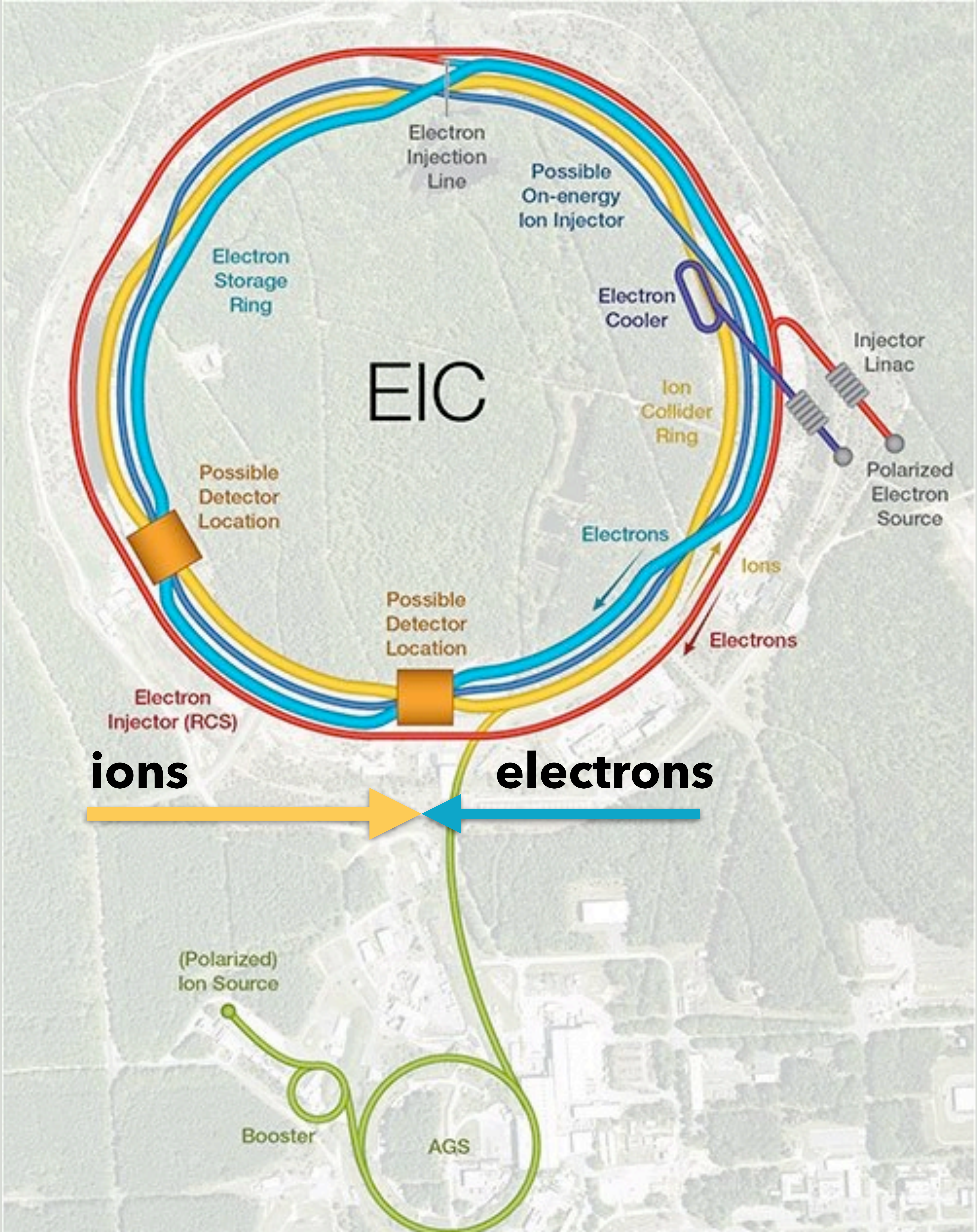


protons to uranium
electrons


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70% polarization
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41-275 GeV

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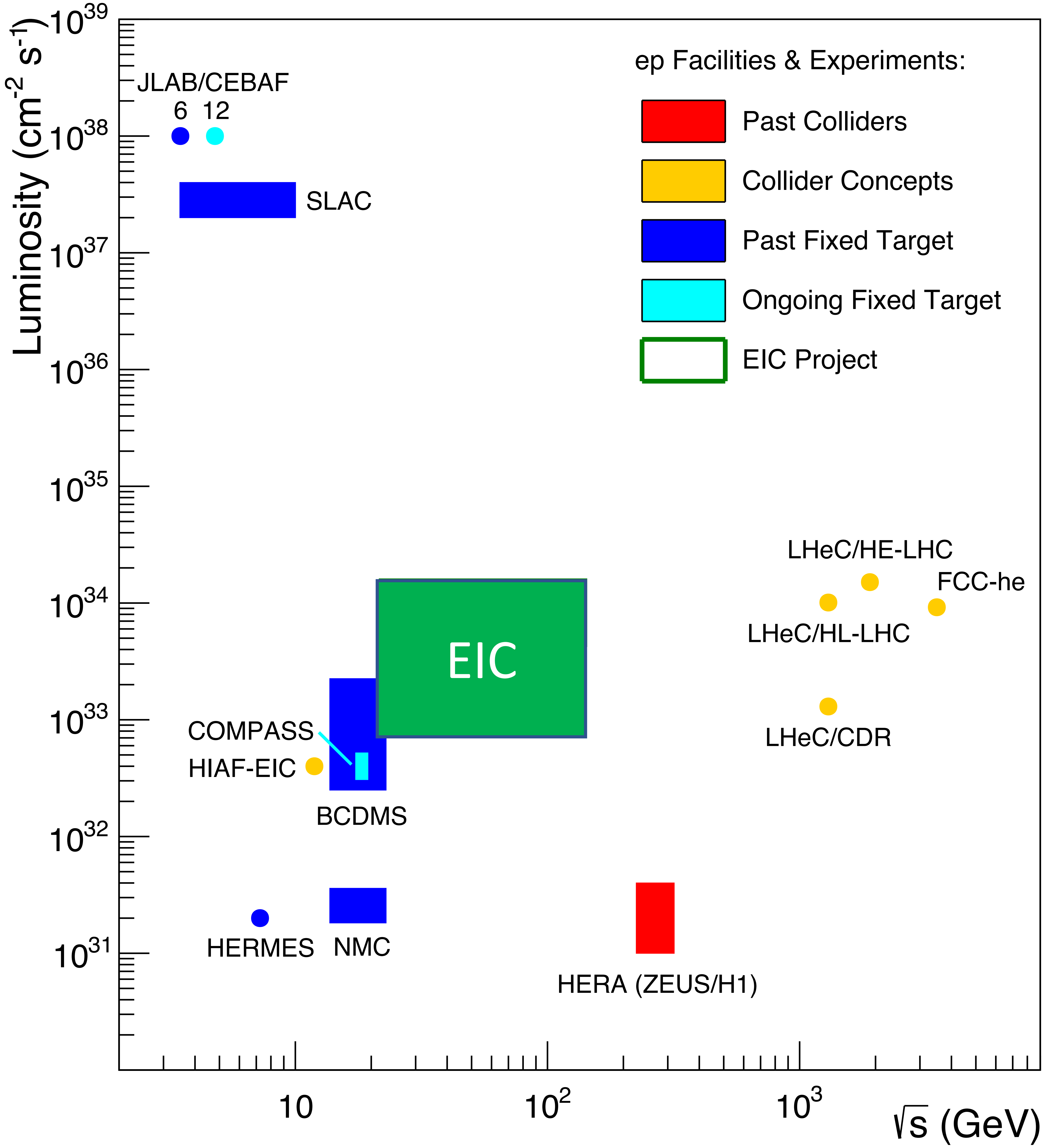
LUMINOSITY AND C.O.M. ENERGY



- **high luminosity** ~ $10^{33\text{-}34}$ cm^{-2} sec^{-1}
- **wide energy range** $\sqrt{s} \sim 29 - 140$ GeV

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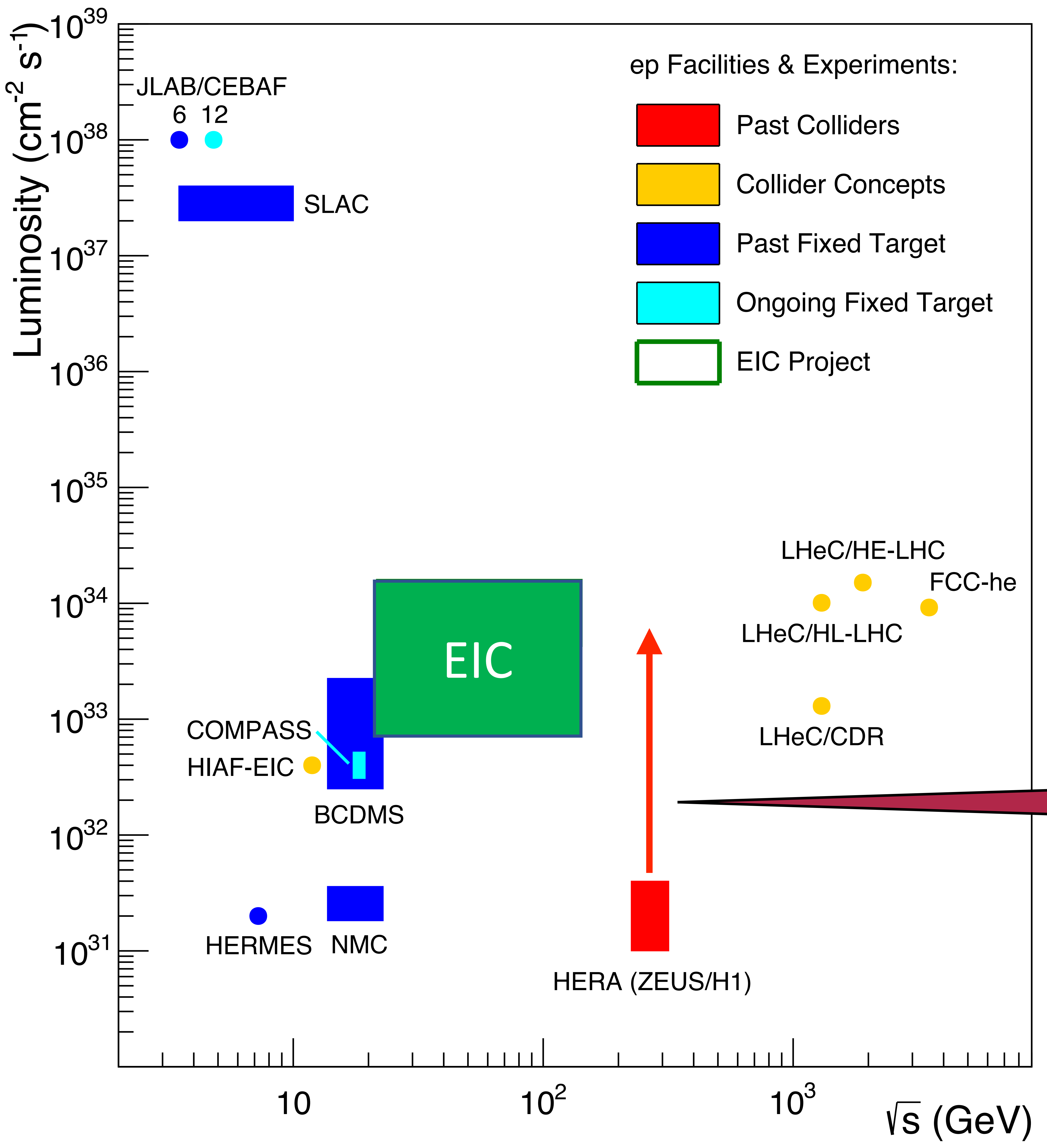
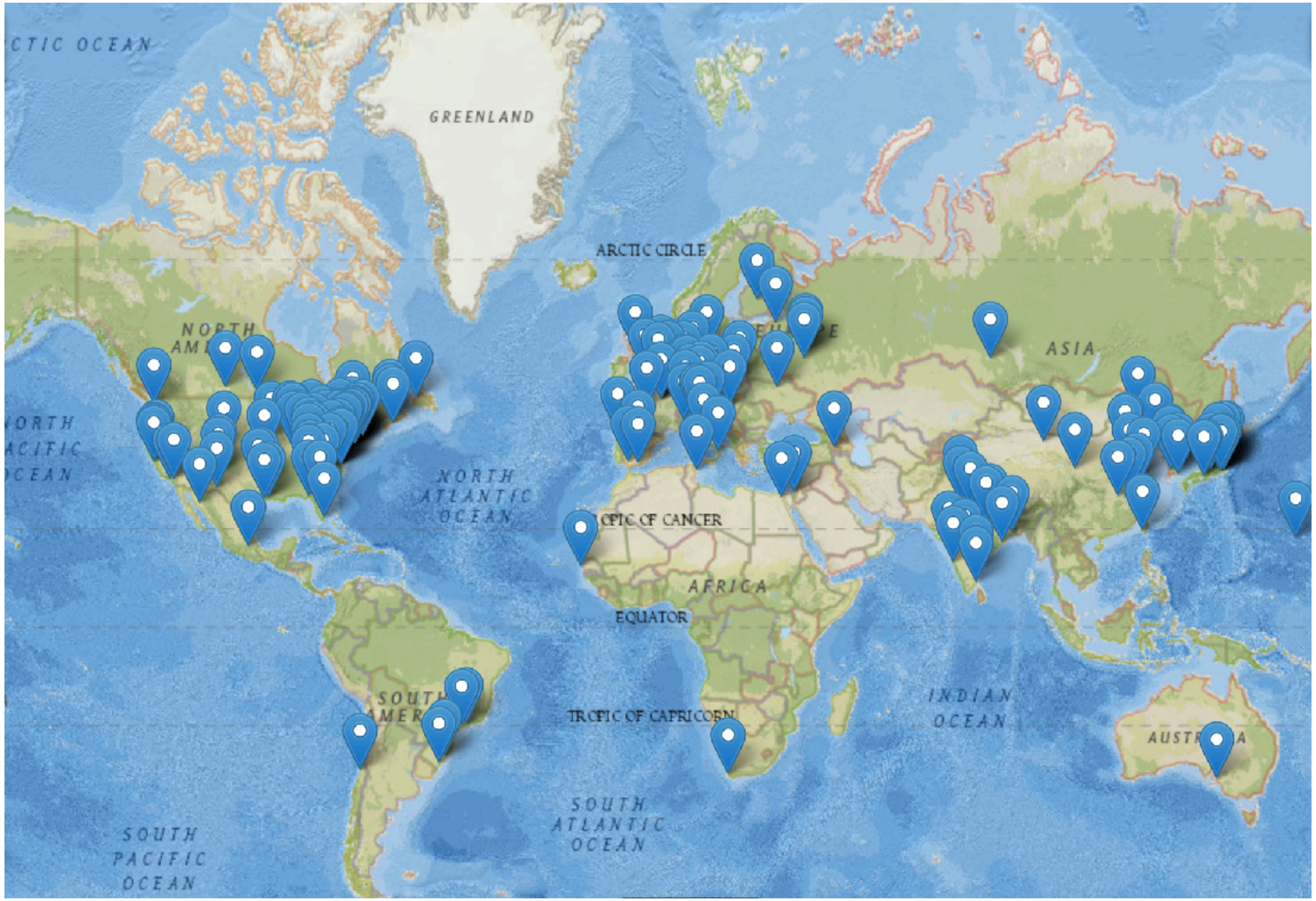


- **high luminosity** ~ $10^{33\text{-}34}$ cm^{-2} sec^{-1}
- **wide energy range** $\sqrt{s} \sim 29 - 140$ GeV

100 to 1000 times
the luminosity of HERA!
In principle, in a couple of months
can get the same statistics as HERA

INTERNATIONAL COMMUNITY (EIC USER GROUP)

https://www.eicug.org



STATISTICS

https://www.eicug.org

Phonebook statistics

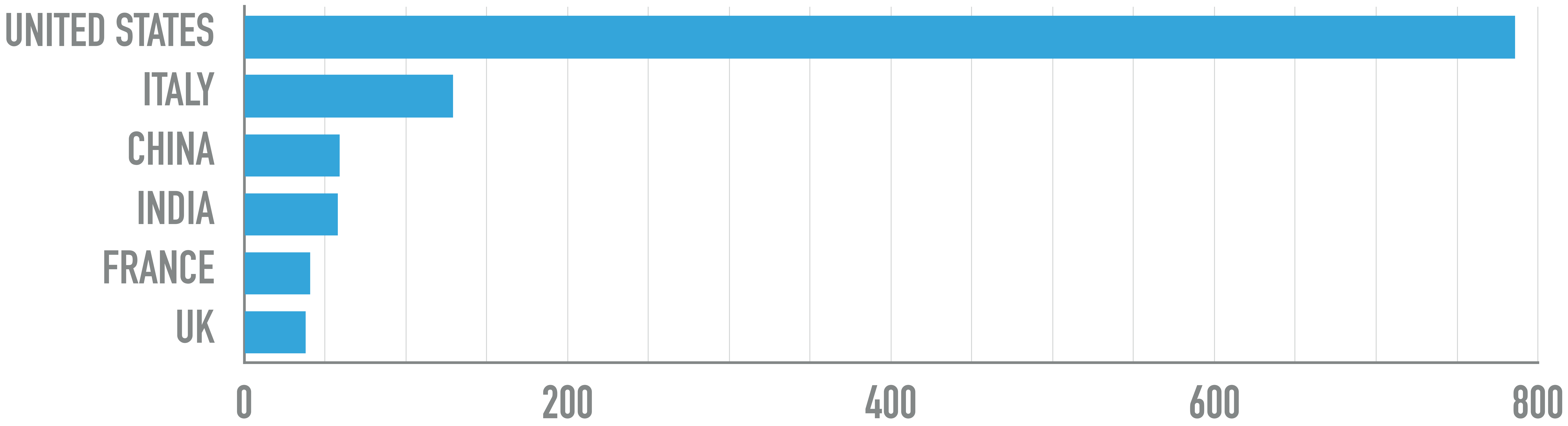
I. EIC User Group:

- **1435** members
- **295** institutions
- **40** countries (**6** world regions)

Experiment Scientists: **905**, Theory Scientists: **363**, Accelerator Scientists: **151**, Computer Scientists: **10**, Support: **3**, Other: **3**

EIC USER GROUP MEMBERS

https://www.eicug.org



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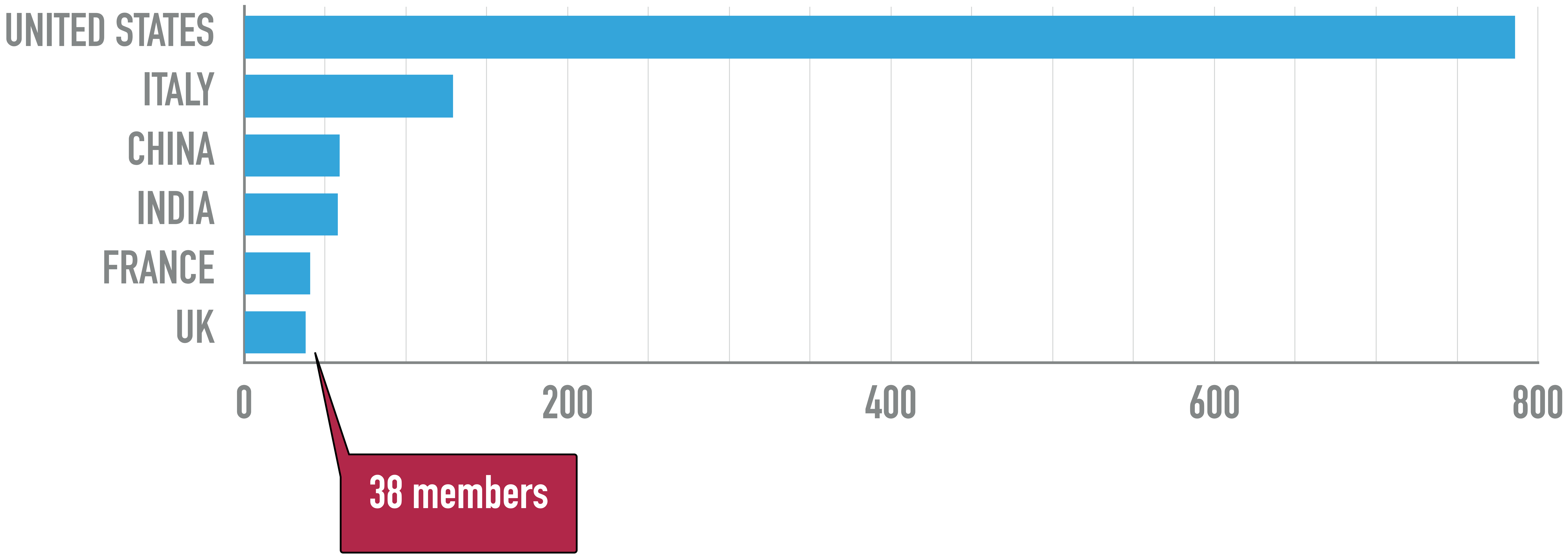

PROJECT TIMELINE

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COSTS

1.7-2.8 billion US dollars (source: DOE)

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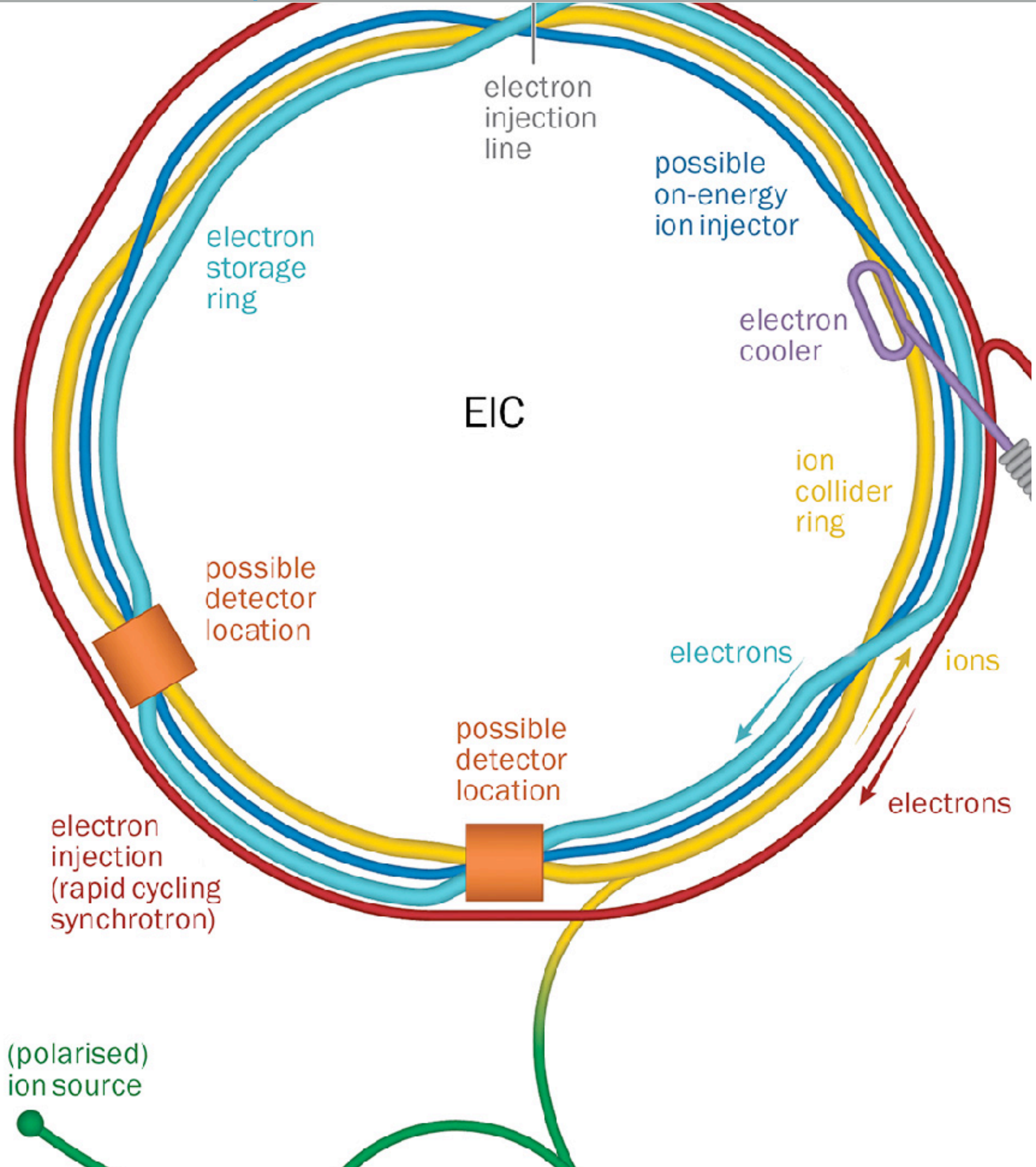
- FAIR: 2.5 billion US dollars (source: Wikipedia)
- Einstein Telescope: 2 billion US dollars (source: Scientific American)
- James Webb Telescope: 10 billion US dollars (source: Wikipedia)
- FCC: 20 billion US dollars (source: Wikipedia)

DETECTOR (OR DETECTORS)



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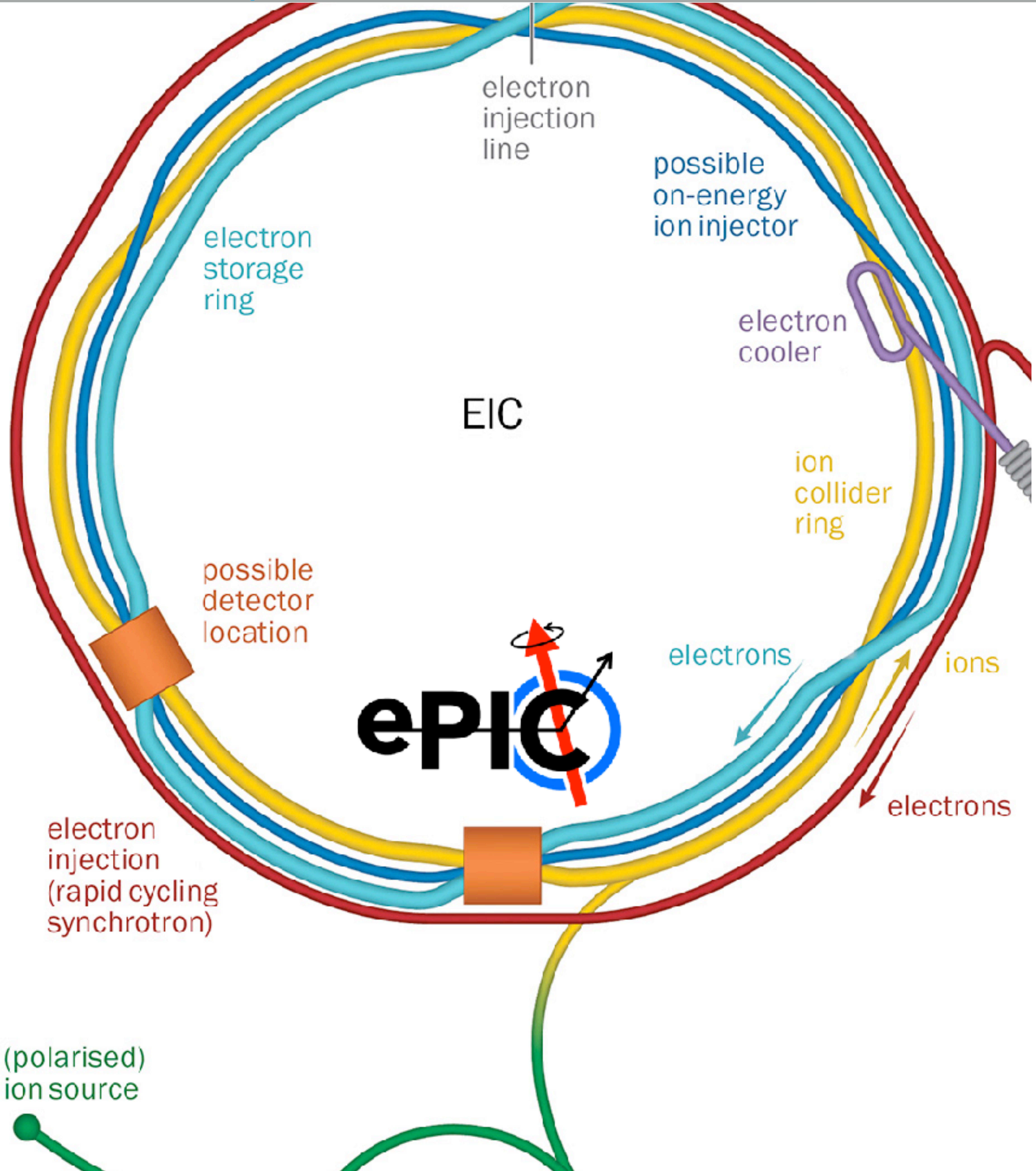


Collaboration

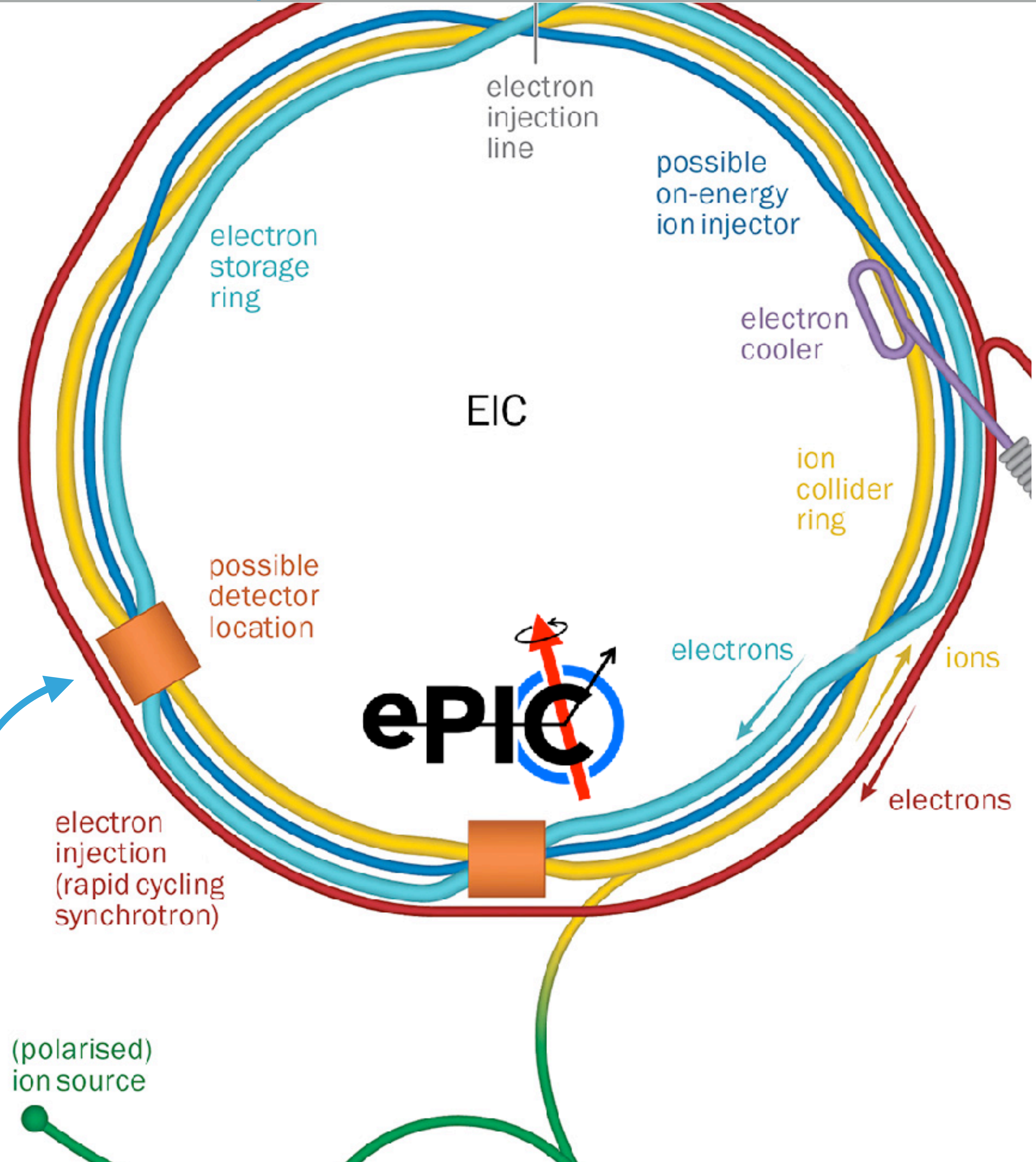
24 countries

171 Institutions

500+ members

DETECTOR (OR DETECTORS)

Possible second detector



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WHAT DO WE WANT TO DO WITH THE EIC?

EIC SCIENCE CASE

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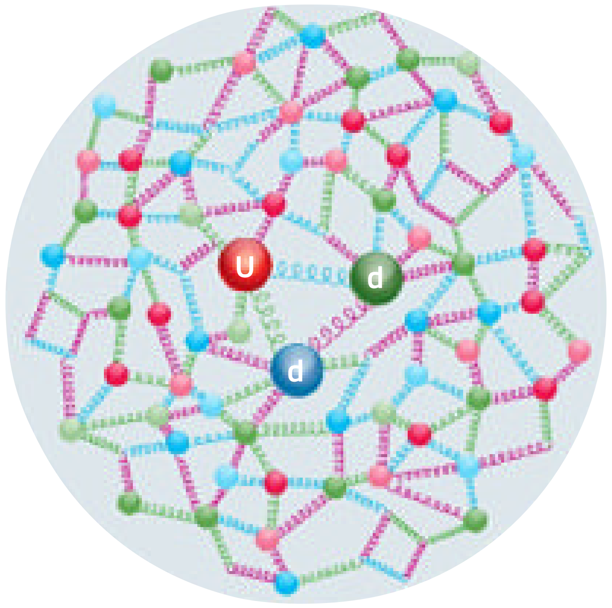
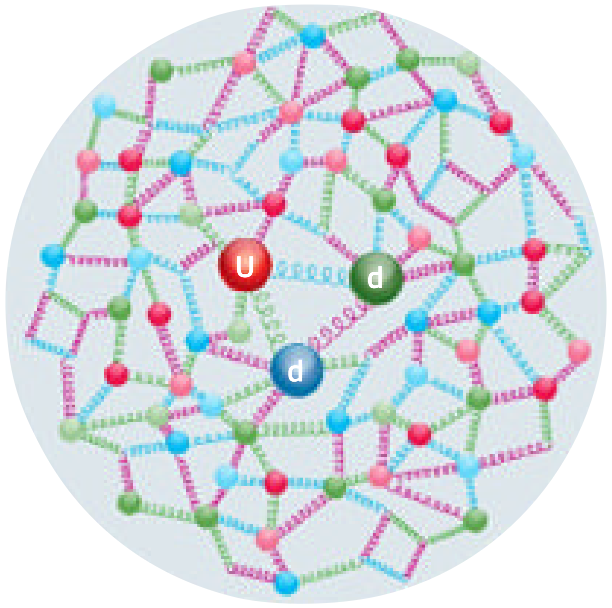


1) How are partons with their spins distributed in space and momentum inside the nucleon, such that its properties emerge from their interactions?



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Nucleon "femtography"

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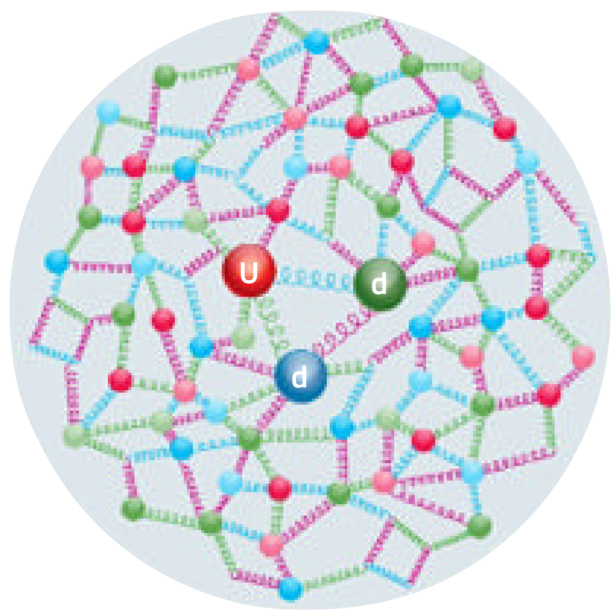

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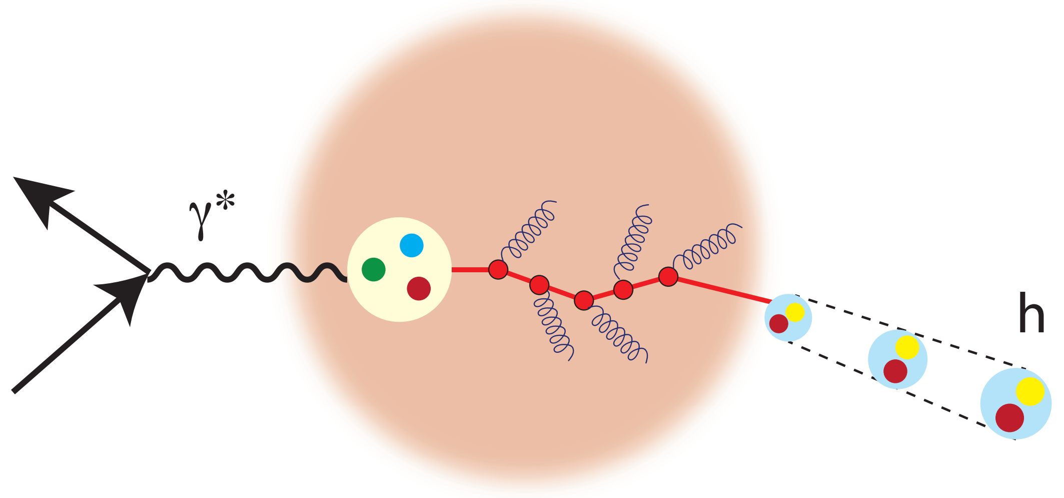

2) How do colored partons propagate and interact with nuclear medium such that eventually colorless hadrons emerge?

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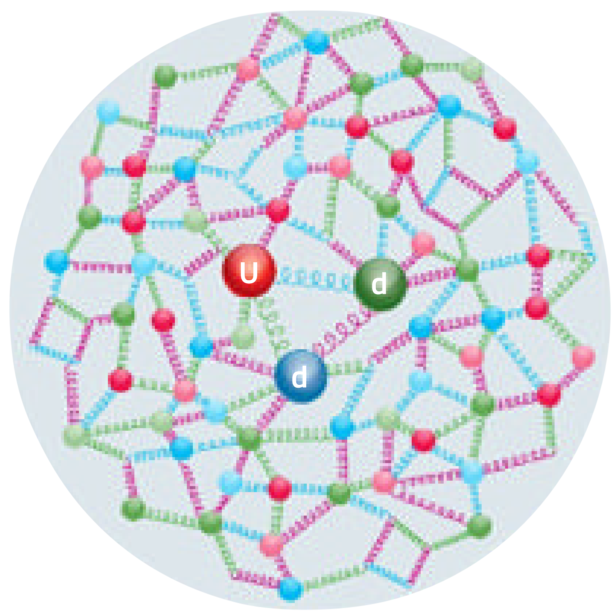

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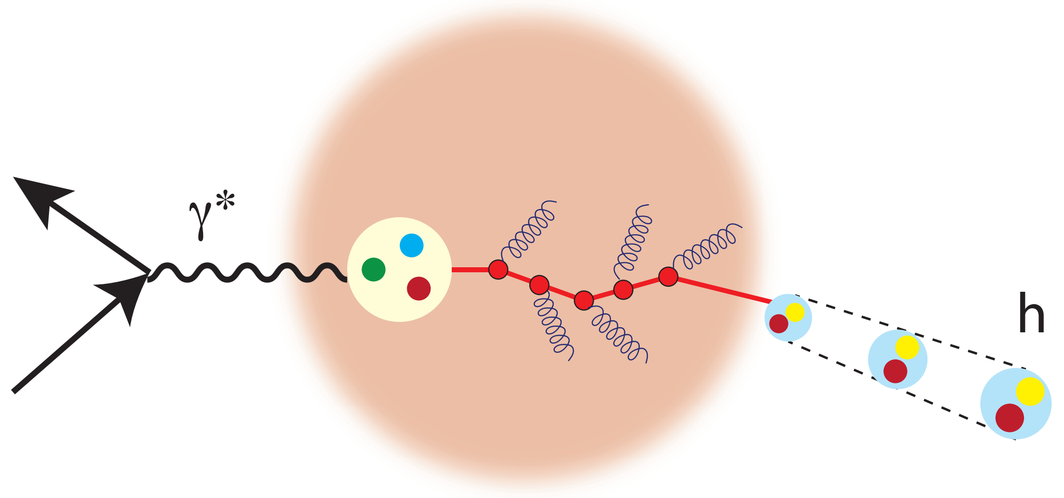

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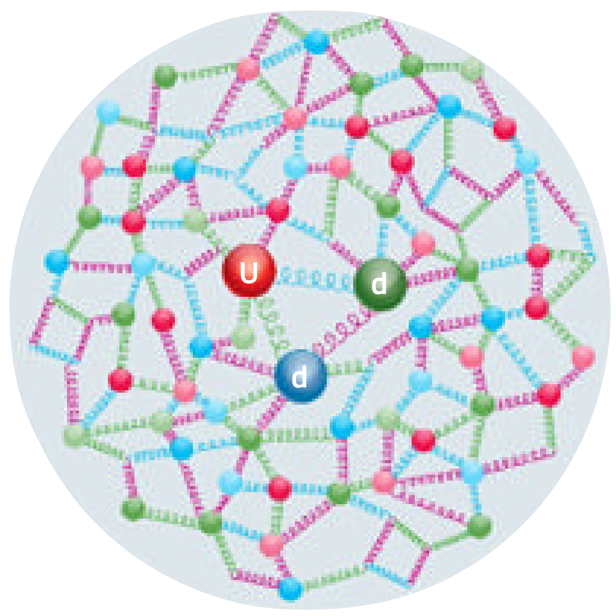

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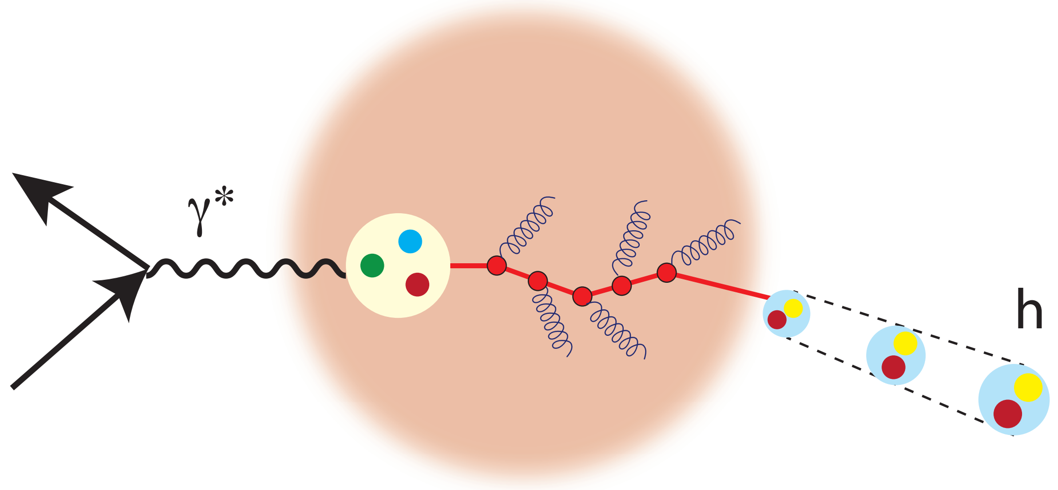

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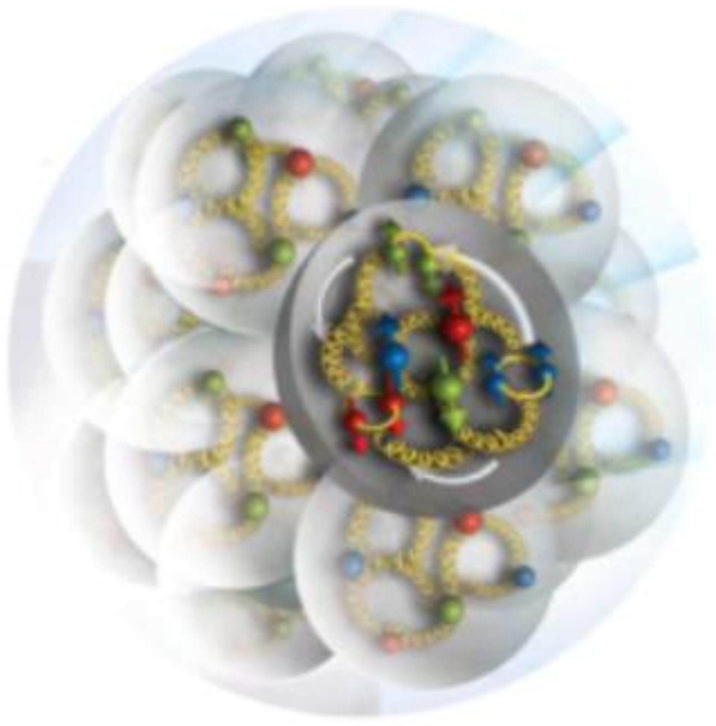

3) Does gluon density saturate at high energy, giving rise to a universal gluonic matter?

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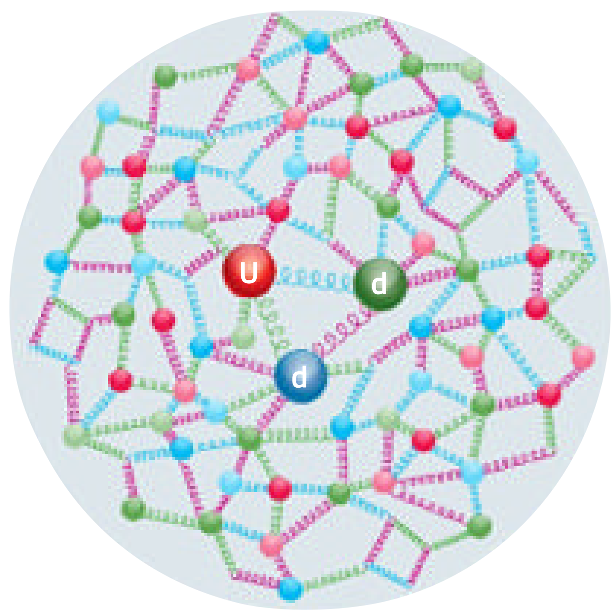

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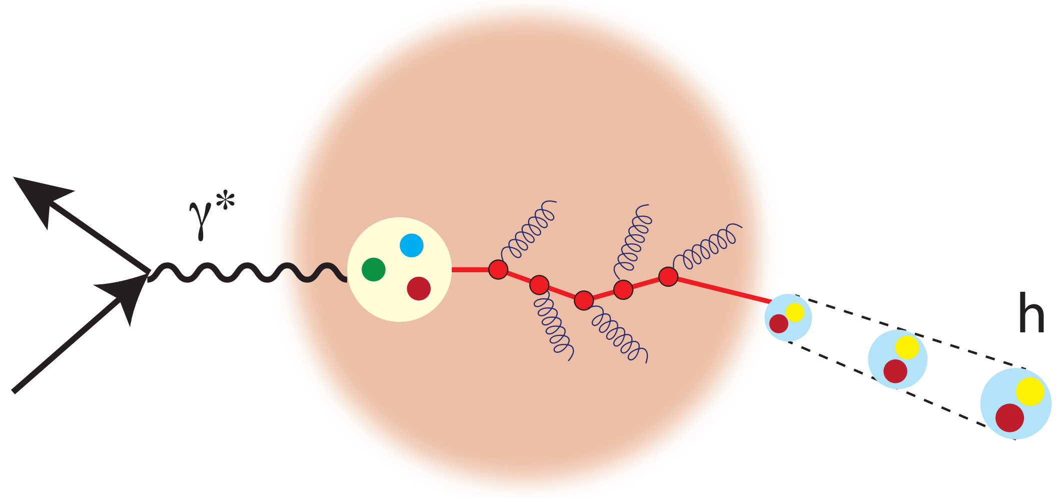

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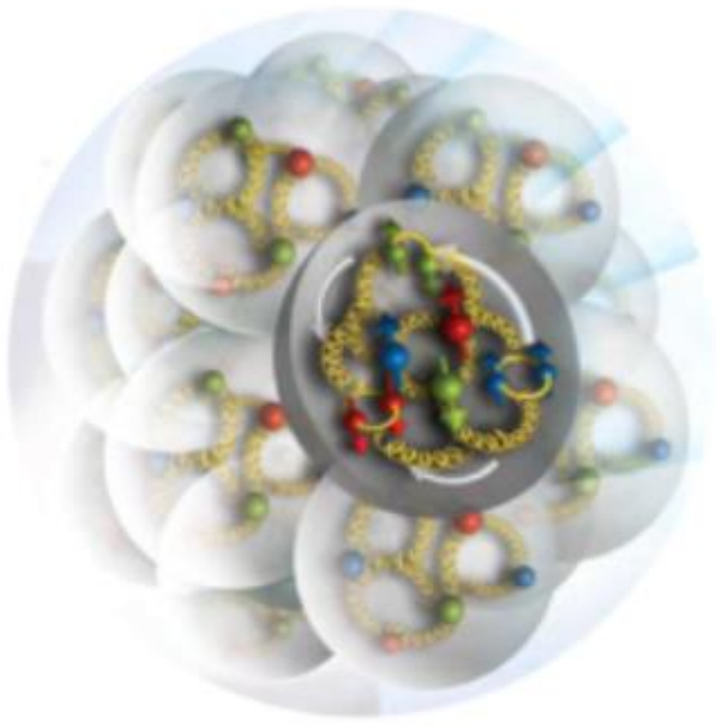

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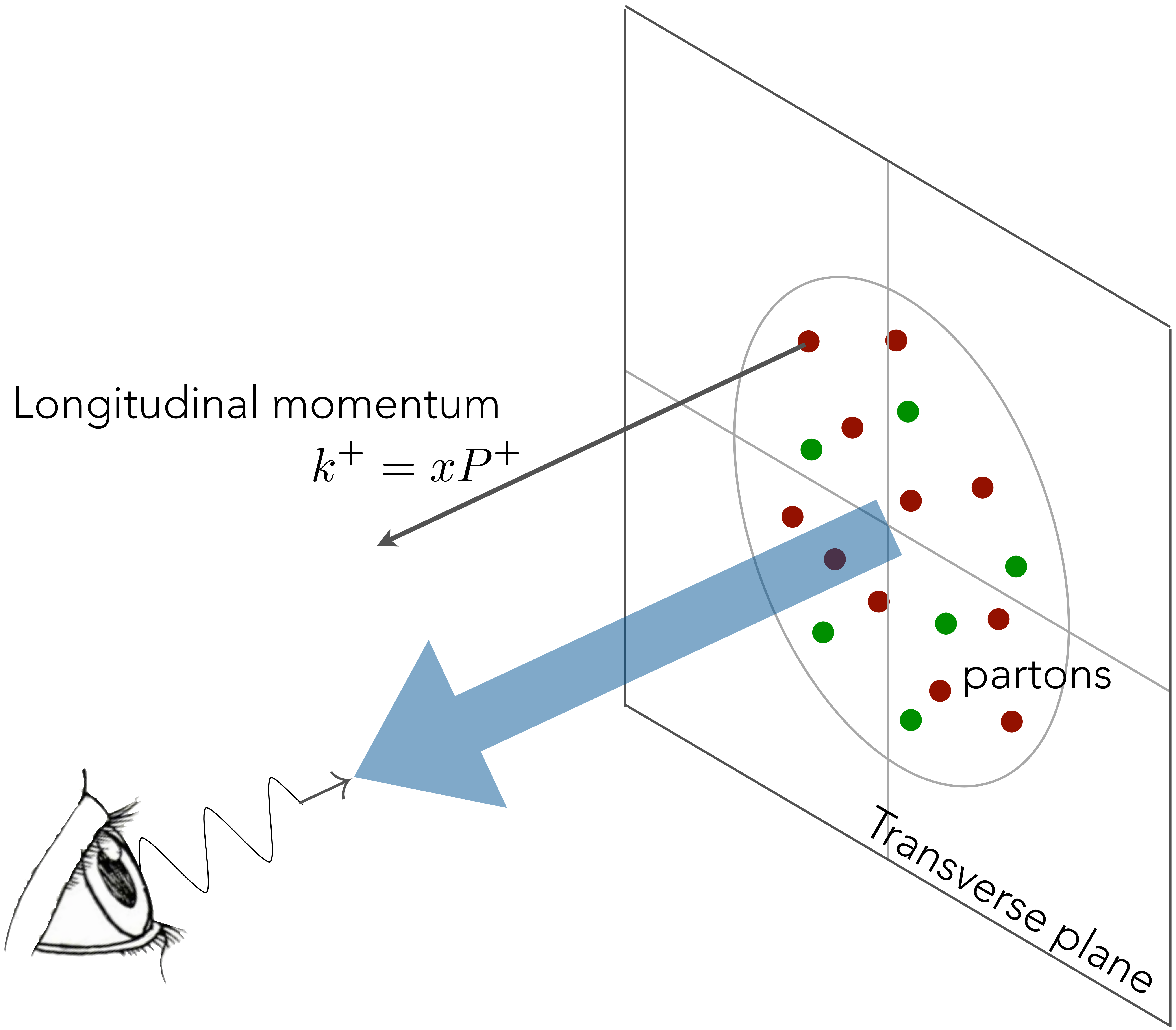
Gluon saturation

NUCLEON FEMTOGRAPHY

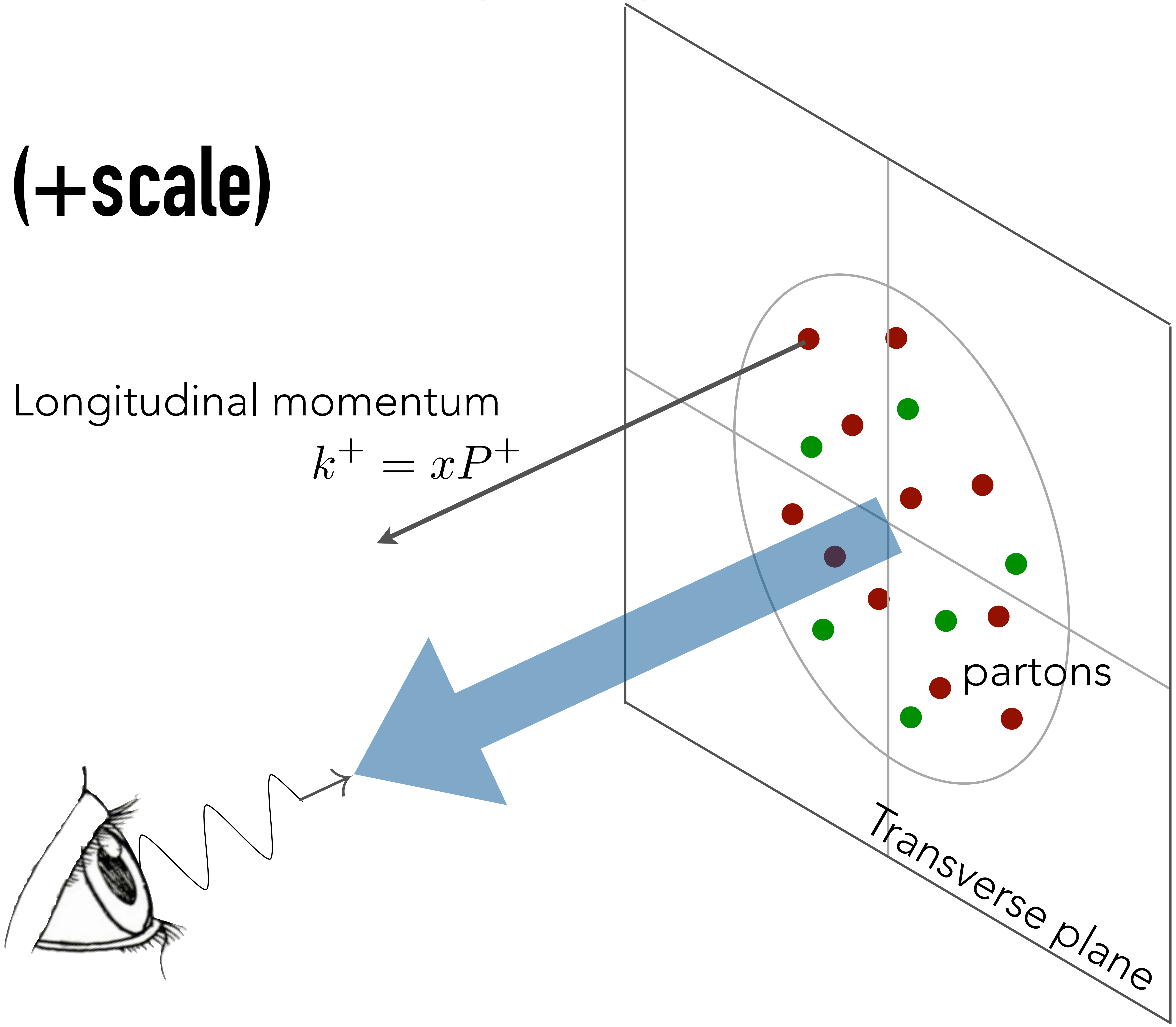


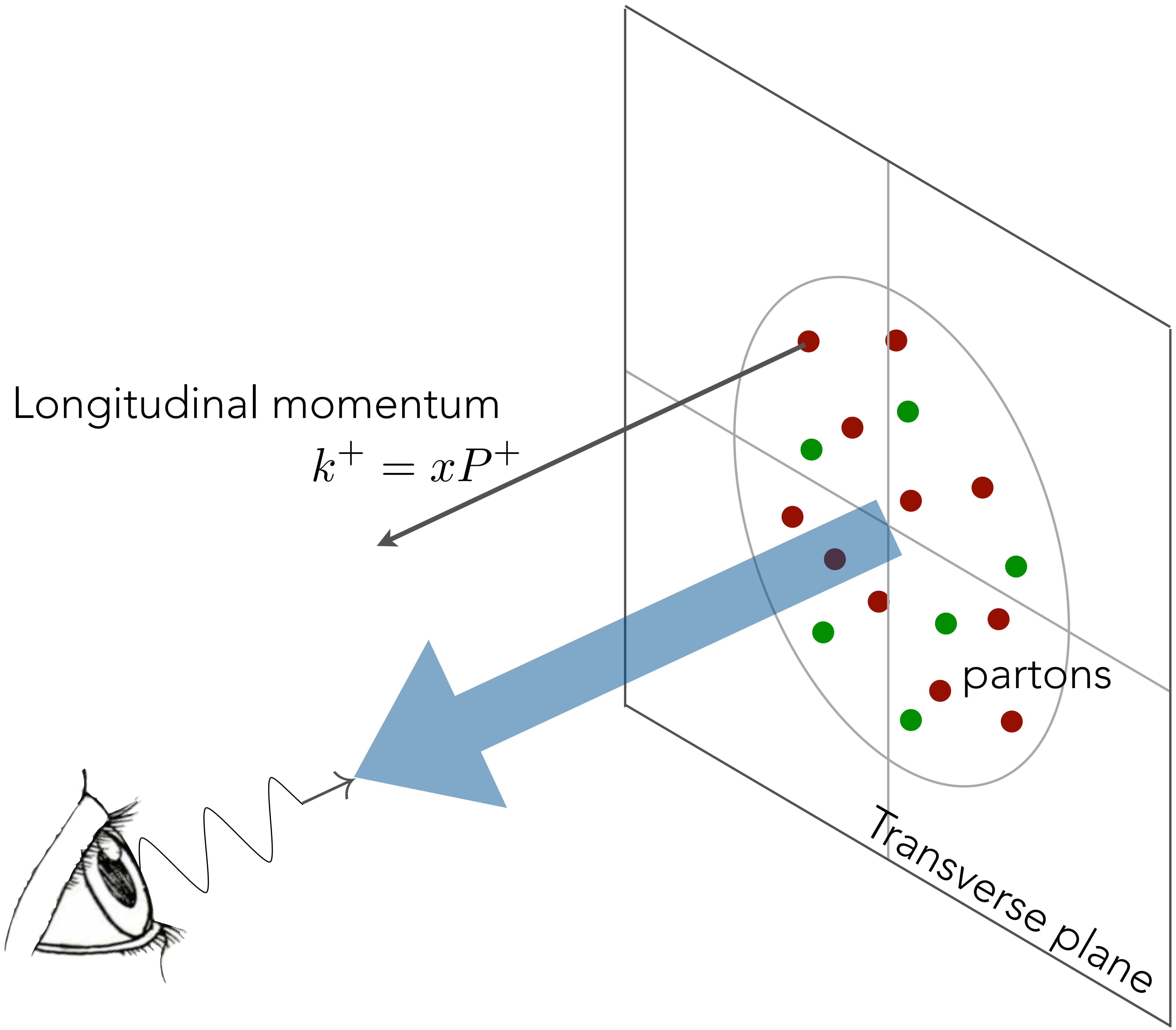
Longitudinal momentum
$k^+ = xP^+$
partons
Transverse plane

Parton Distribution Functions (PDFs)

$f(x)$

1 dimensional (+scale)





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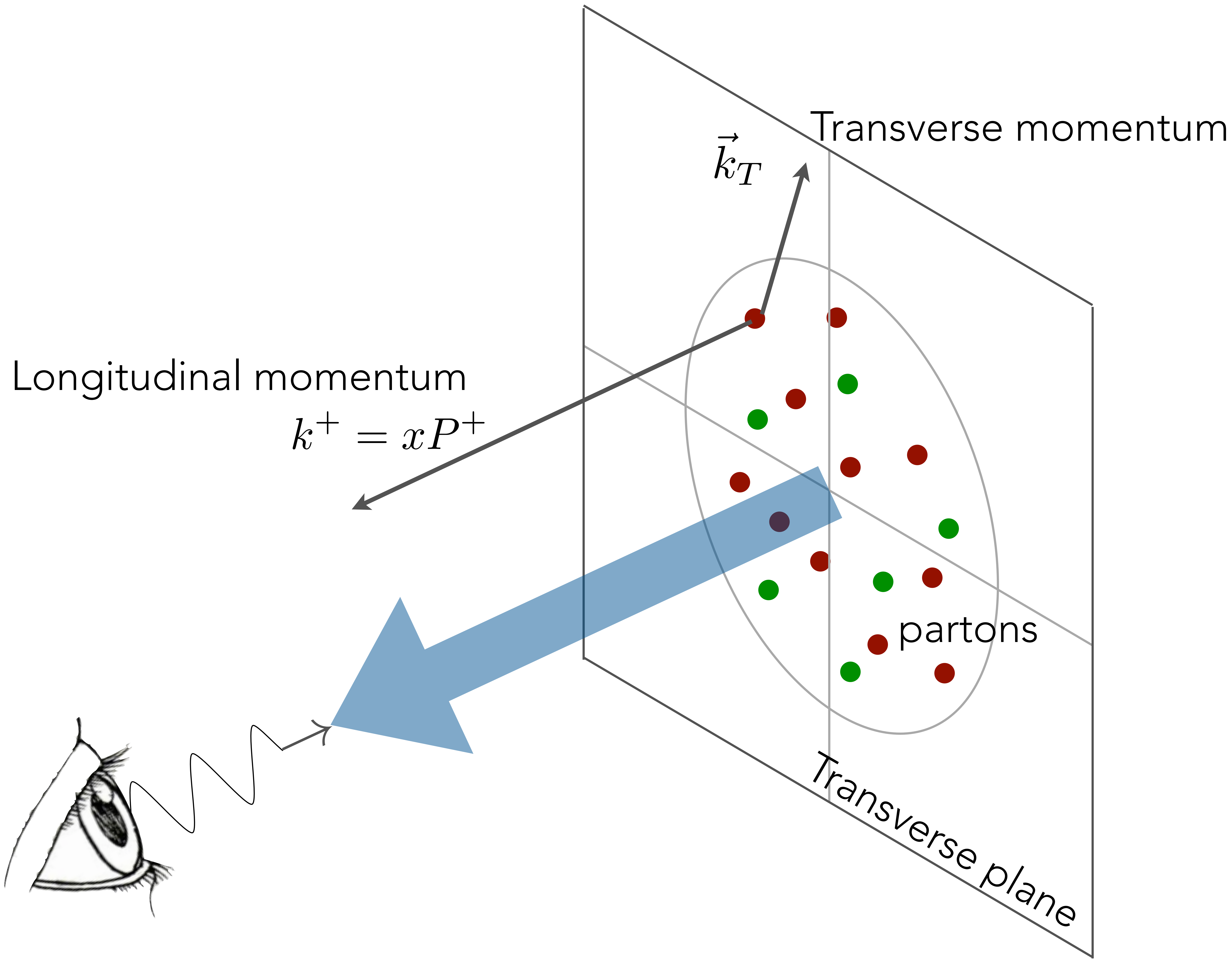
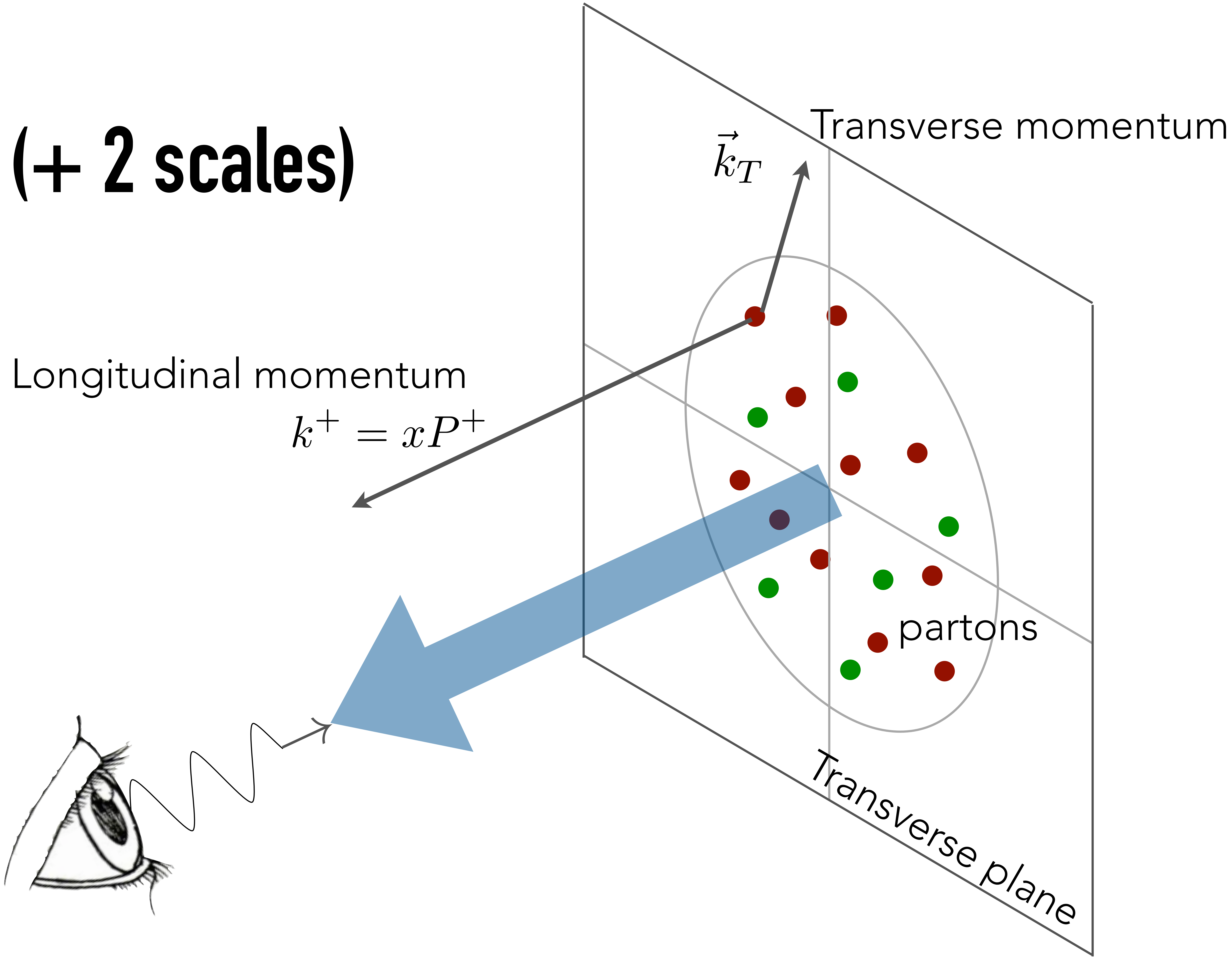


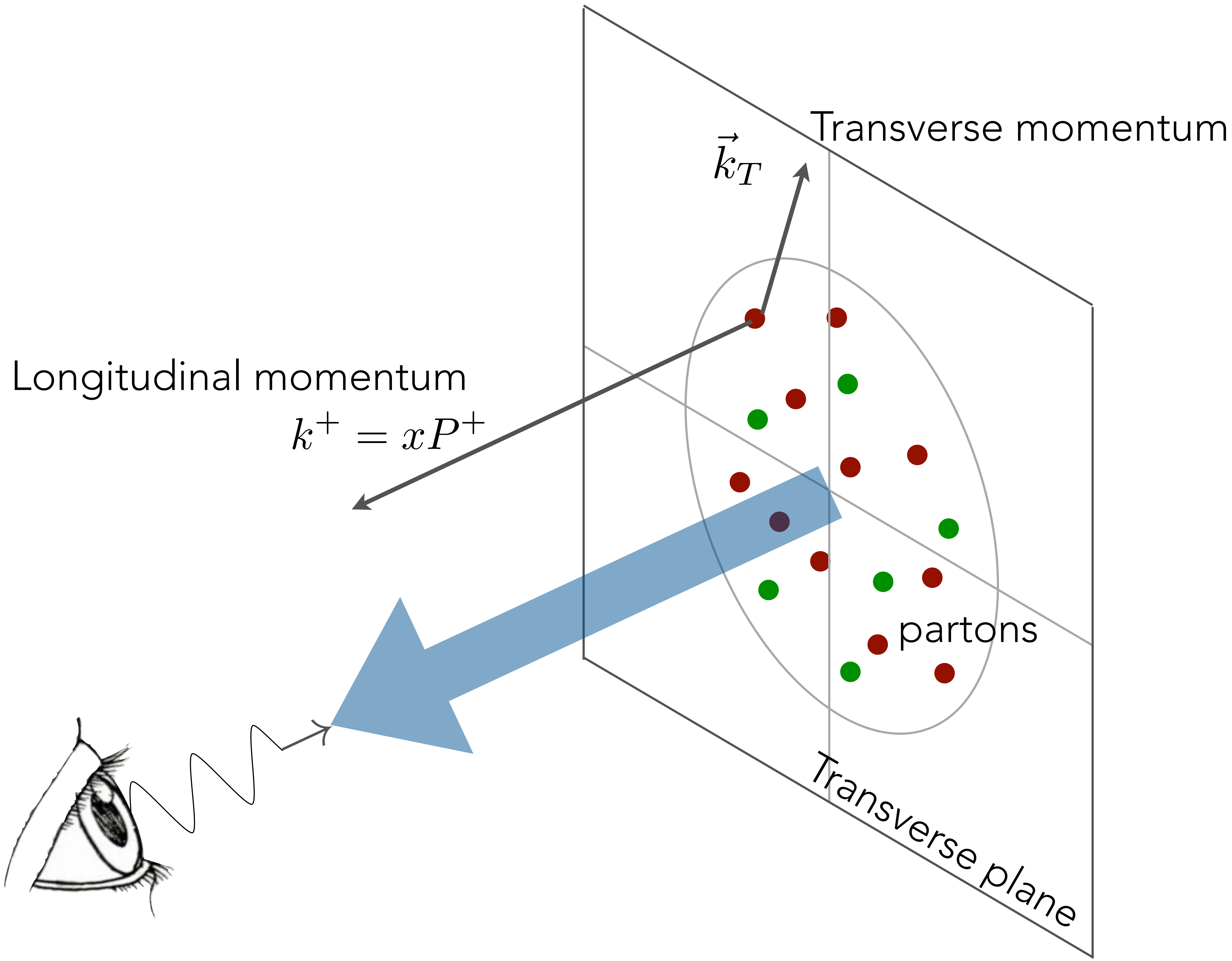
Transverse momentum
$\vec{k}_T$
Longitudinal momentum
$k^+ = xP^+$
partons
Transverse plane

Transverse-Momentum Distributions (TMDs)

$f(x, \vec{k}_T)$

3 dimensional (+ 2 scales)

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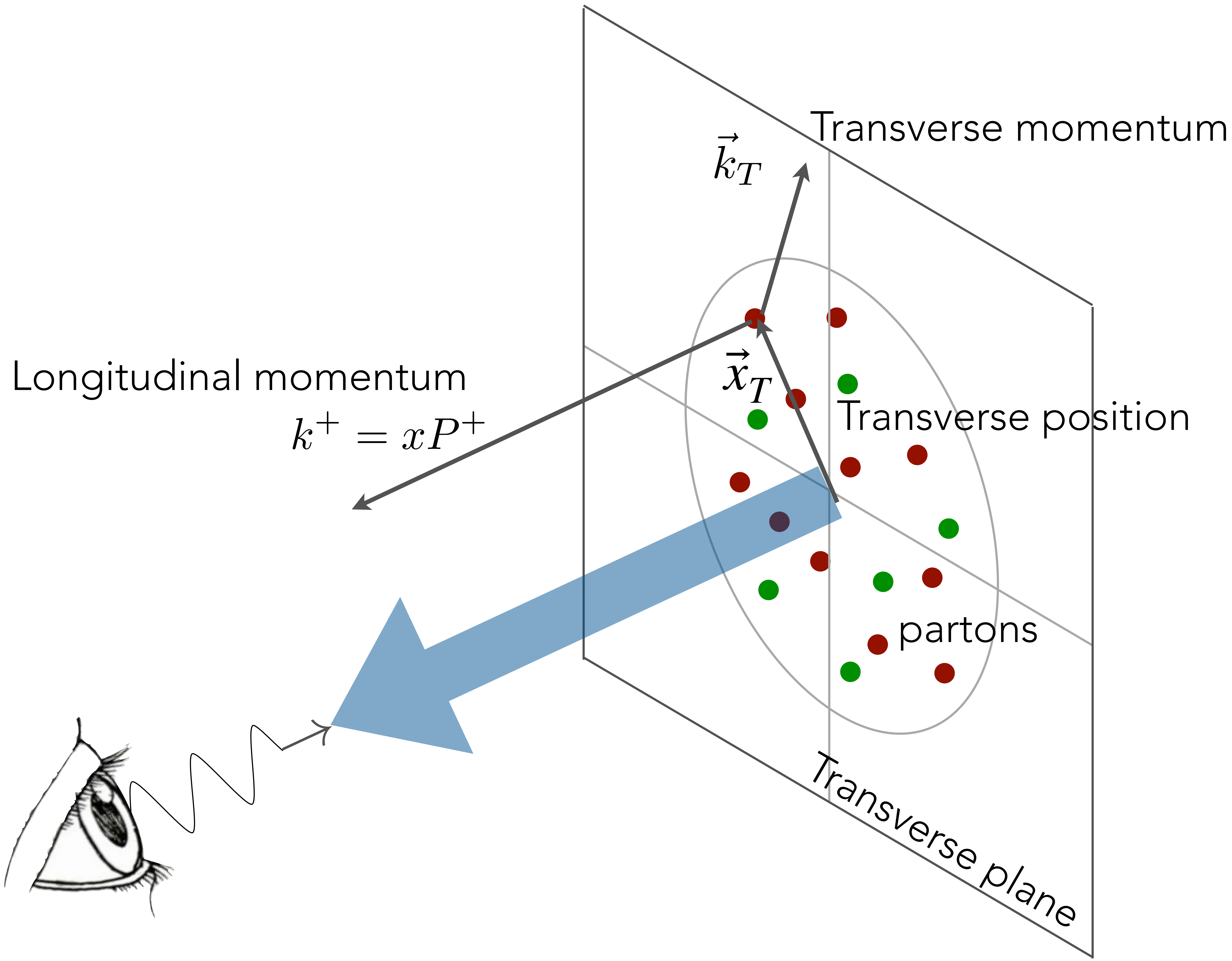
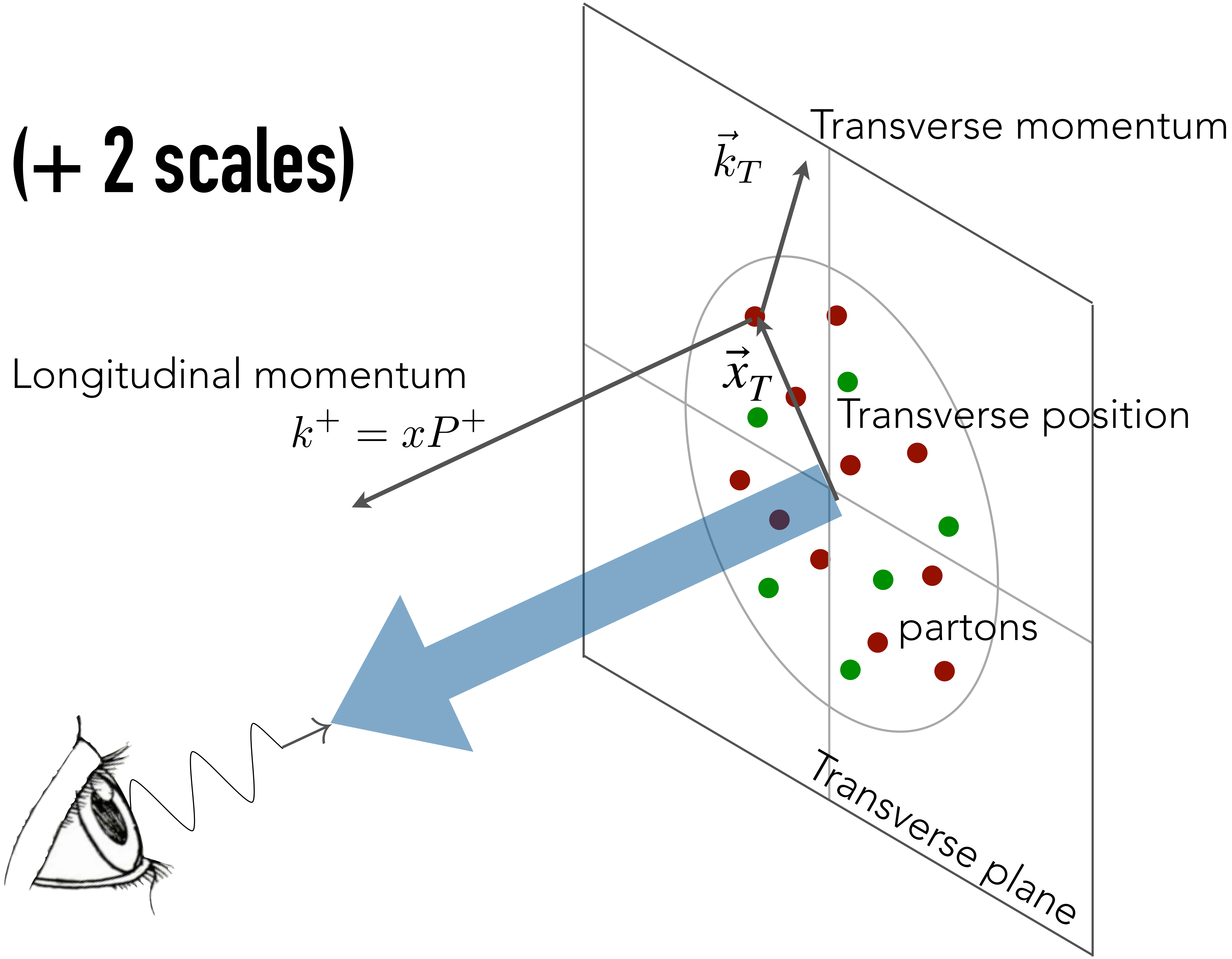


Transverse momentum
$\vec{k}_T$
Longitudinal momentum
$k^+ = xP^+$
$\vec{x}_T$
Transverse position
partons
Transverse plane

Wigner Distributions

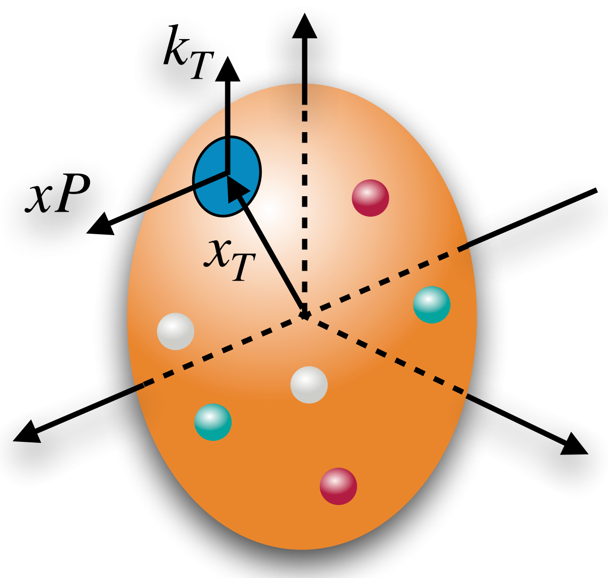
$$f(x, \vec{k}_T, \vec{x}_T)$$

5 dimensional (+ 2 scales)



MULTIDIMENSIONAL PARTONIC MAPS

Wigner distributions
(Fourier transform of
GTMDs = Generalized
Transverse Momentum Distributions)



see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

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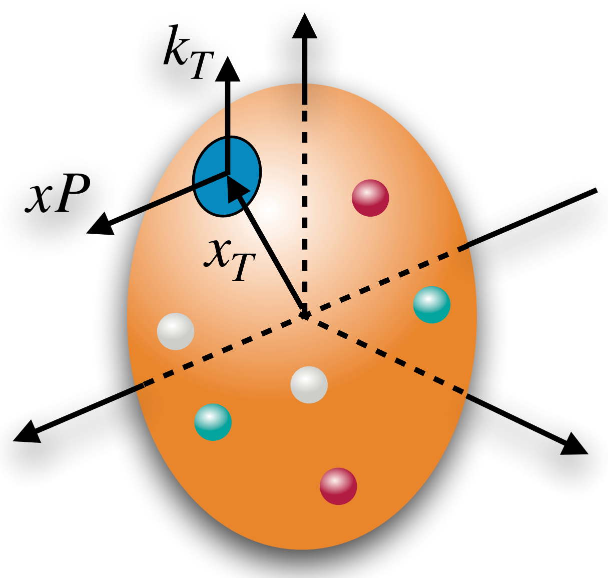
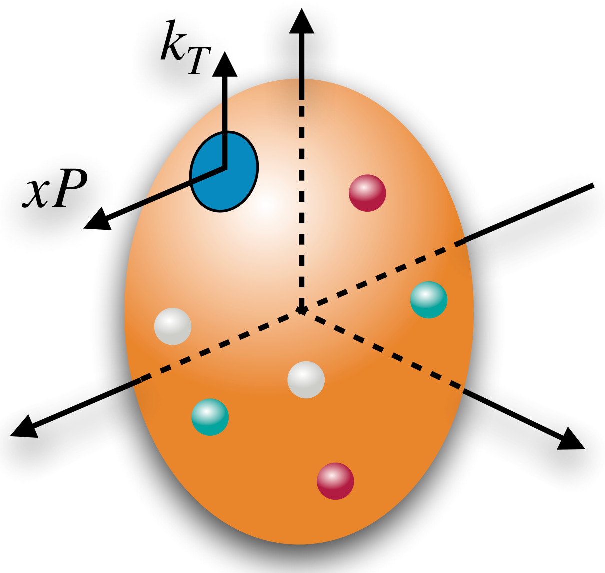


TMDs



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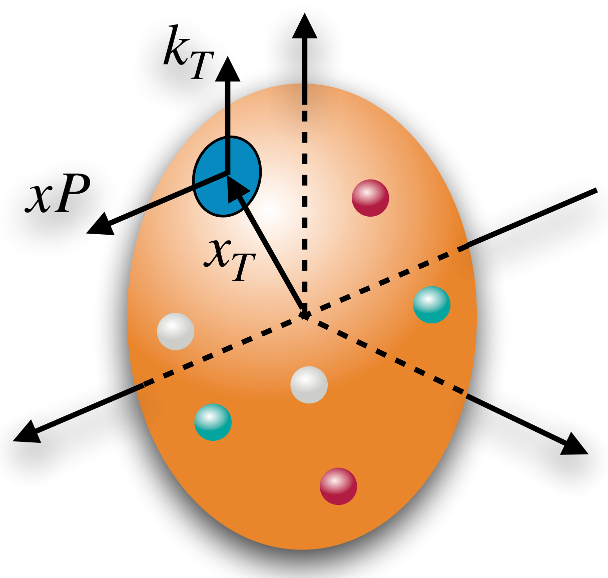

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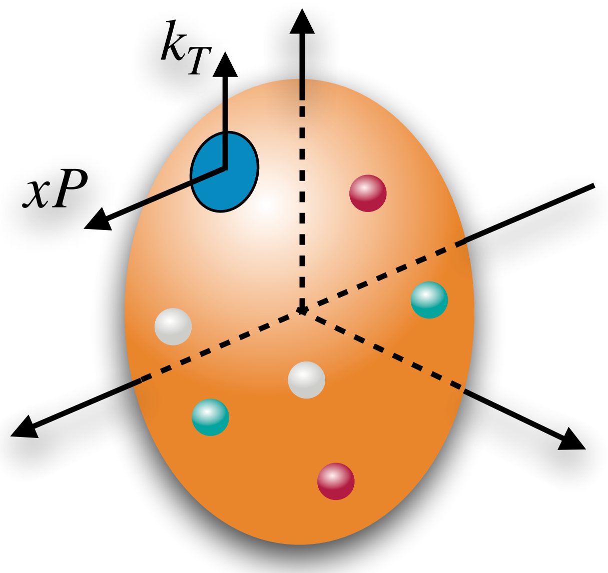

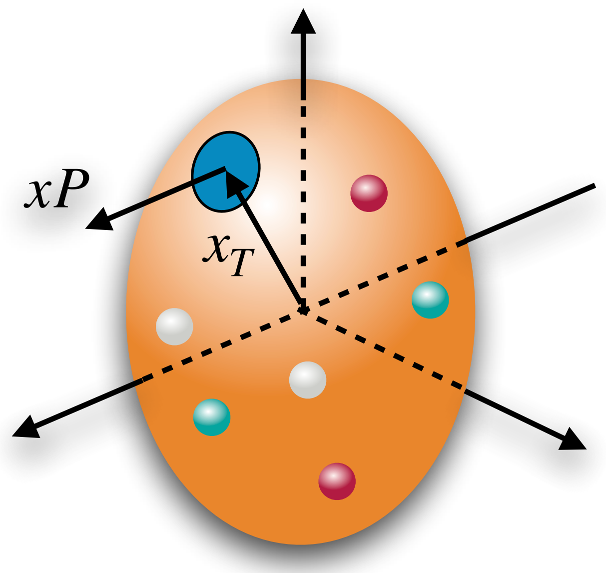

Fourier transform
of Generalized Parton
Distributions

see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

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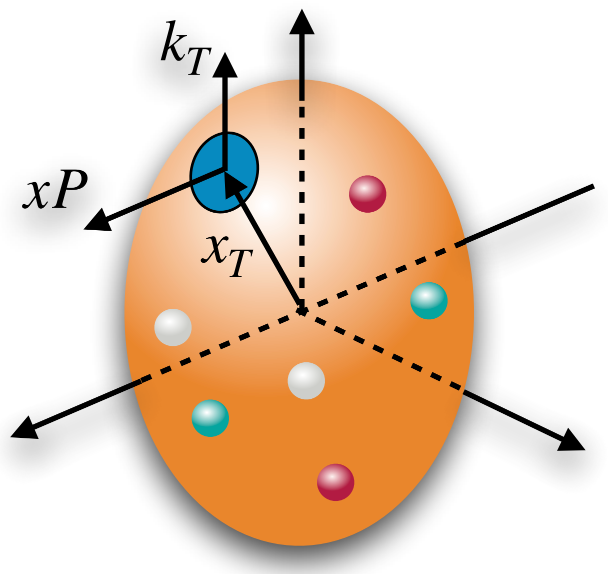

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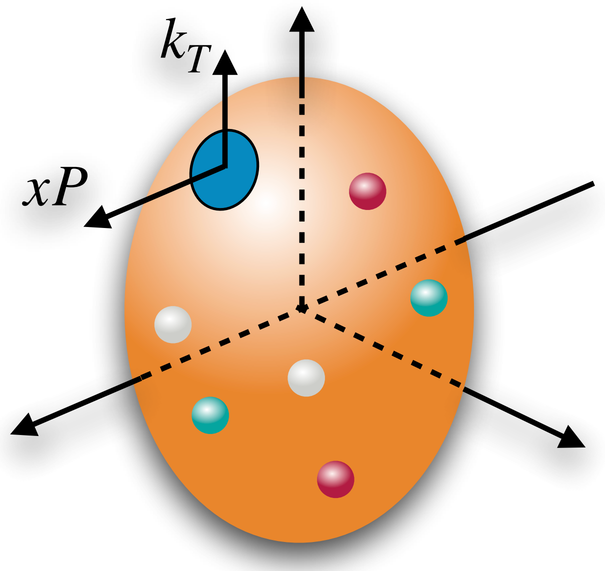

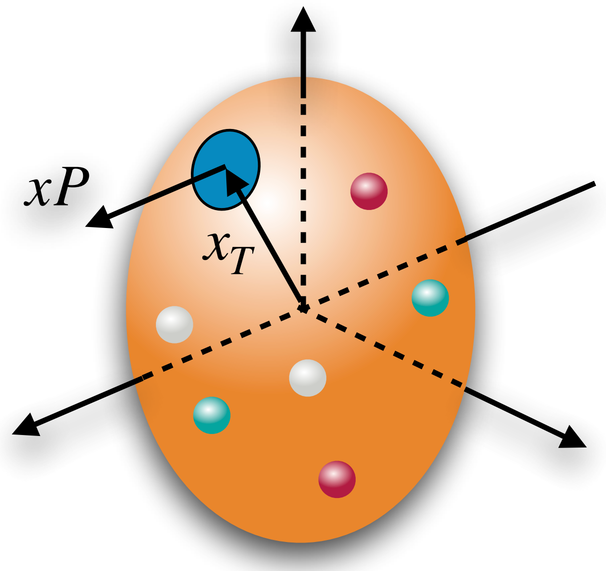

Fourier transform
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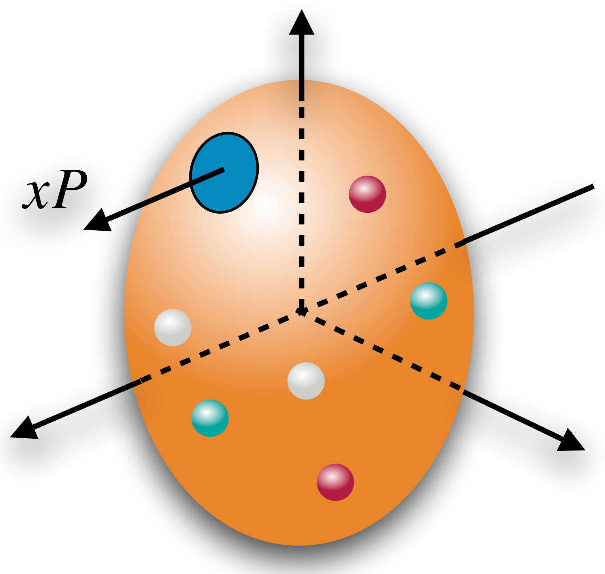
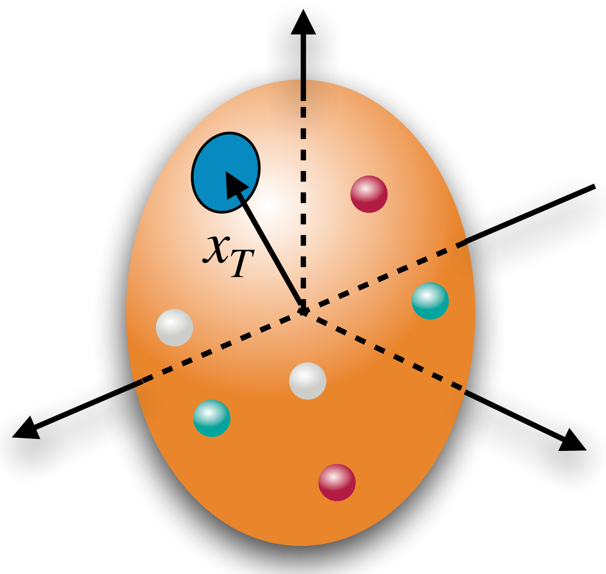
PDFs





Fourier transform
of Form Factors

see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

HOW TO RECONSTRUCT THESE MAPS?

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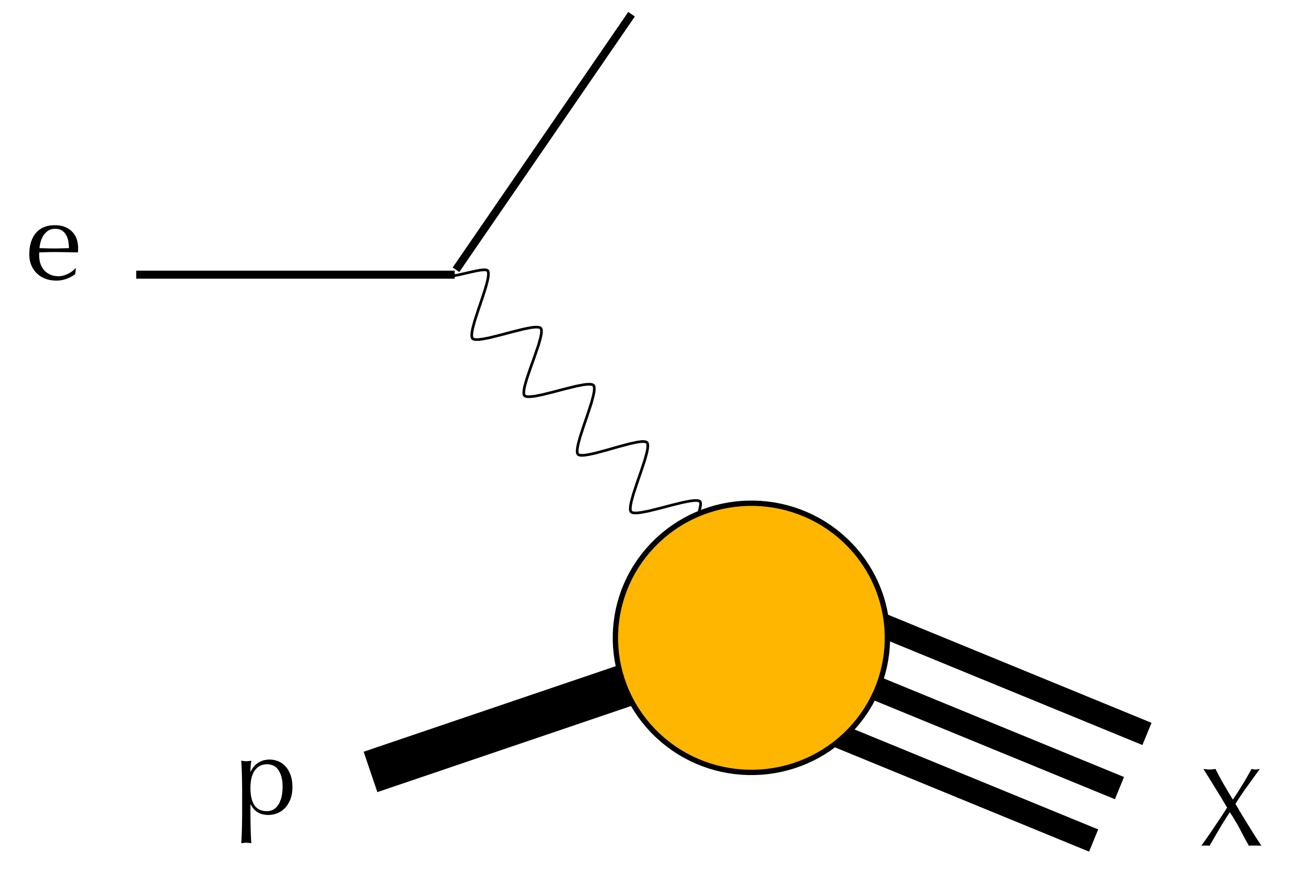
Inclusive DIS



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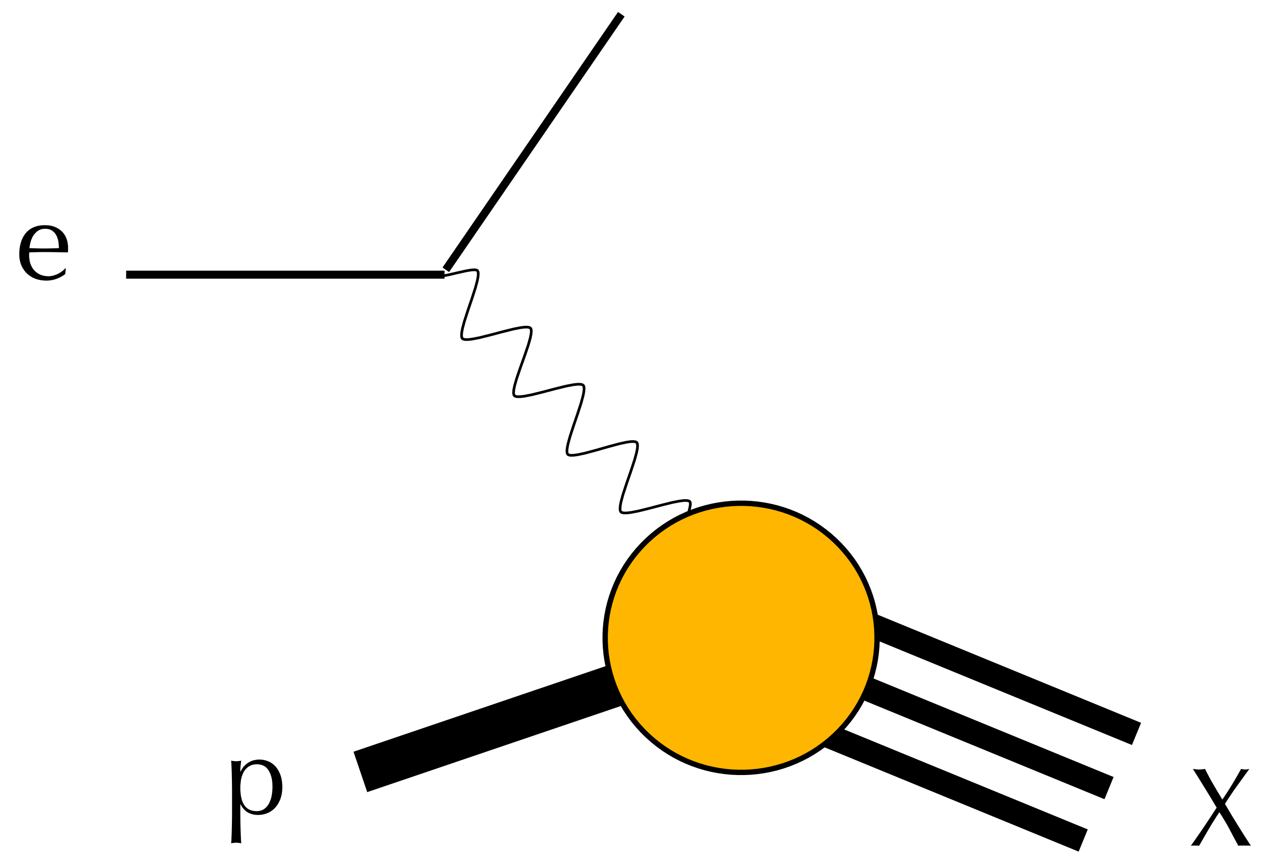

access to
Parton Distribution Functions

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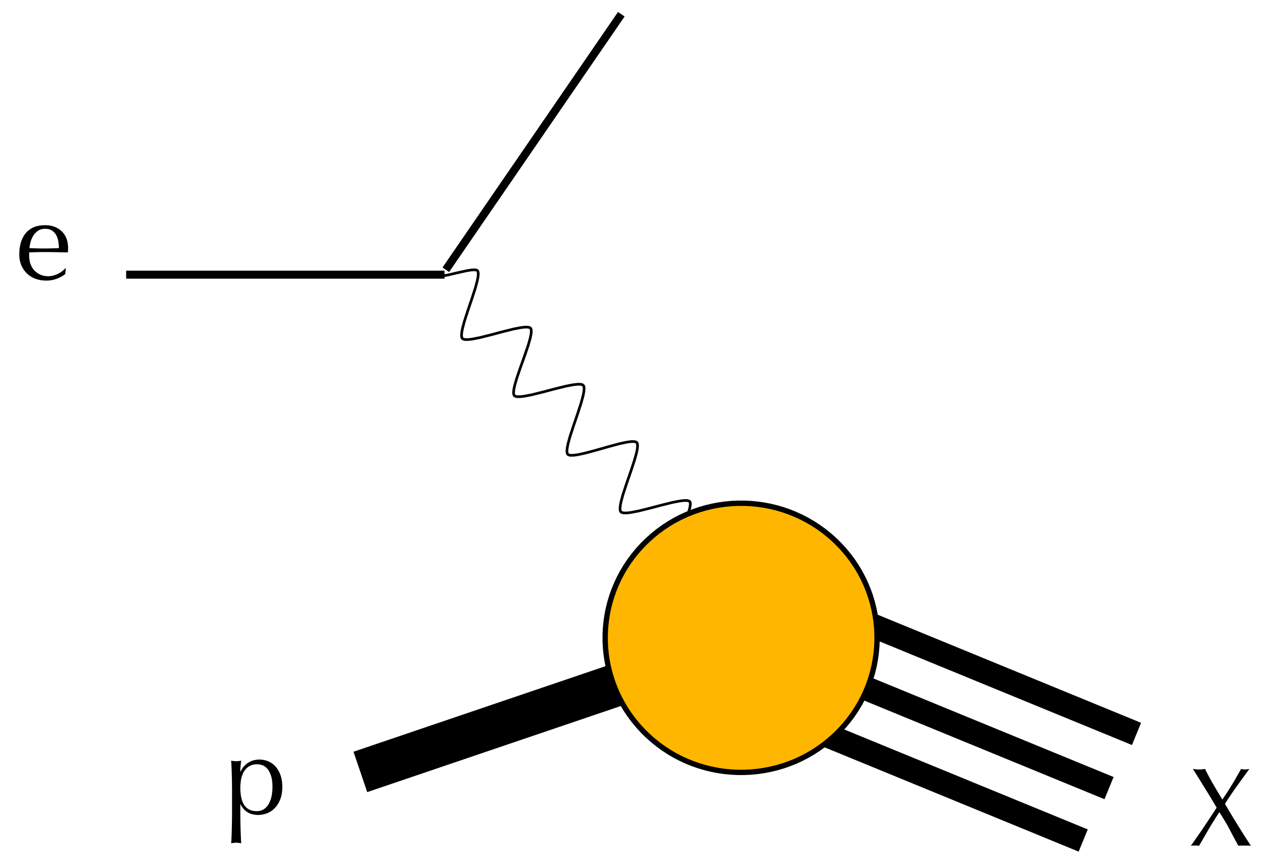

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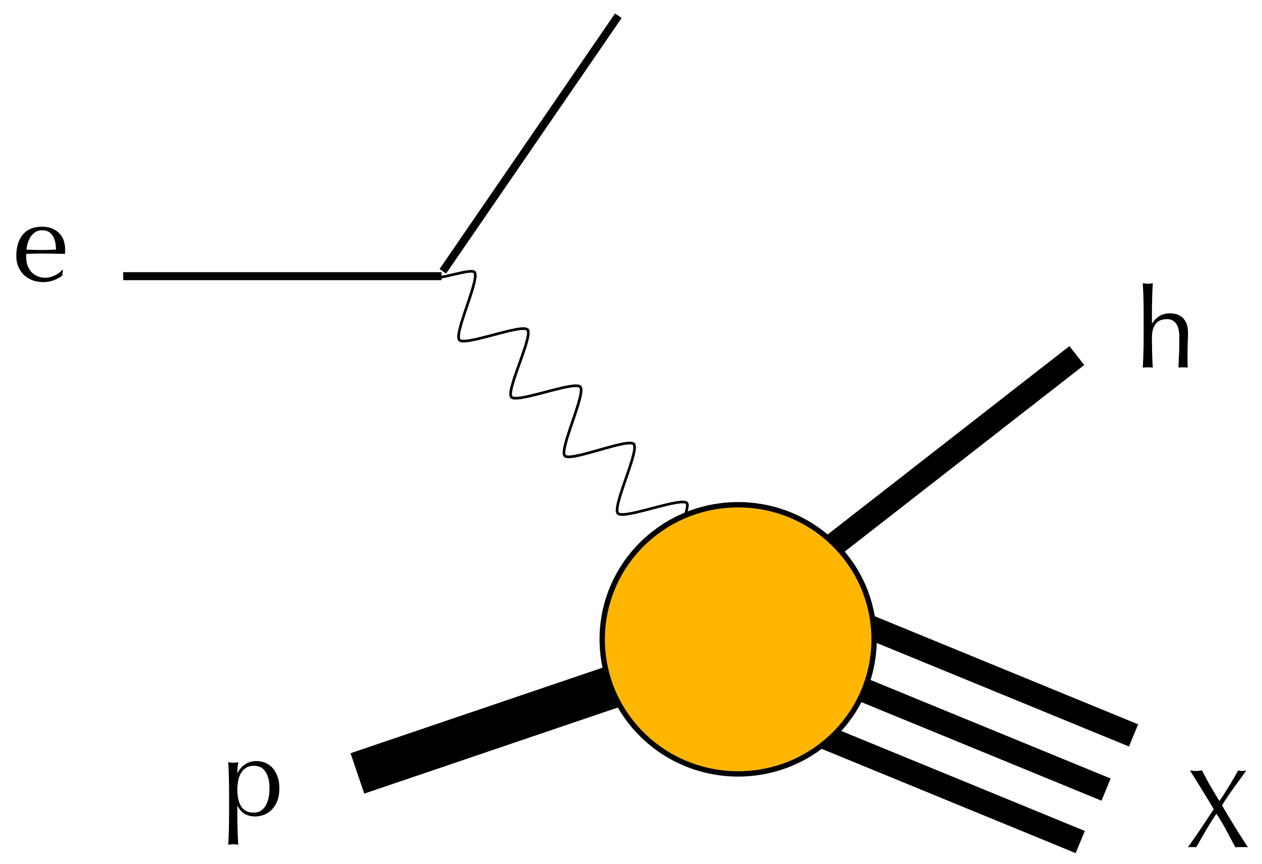

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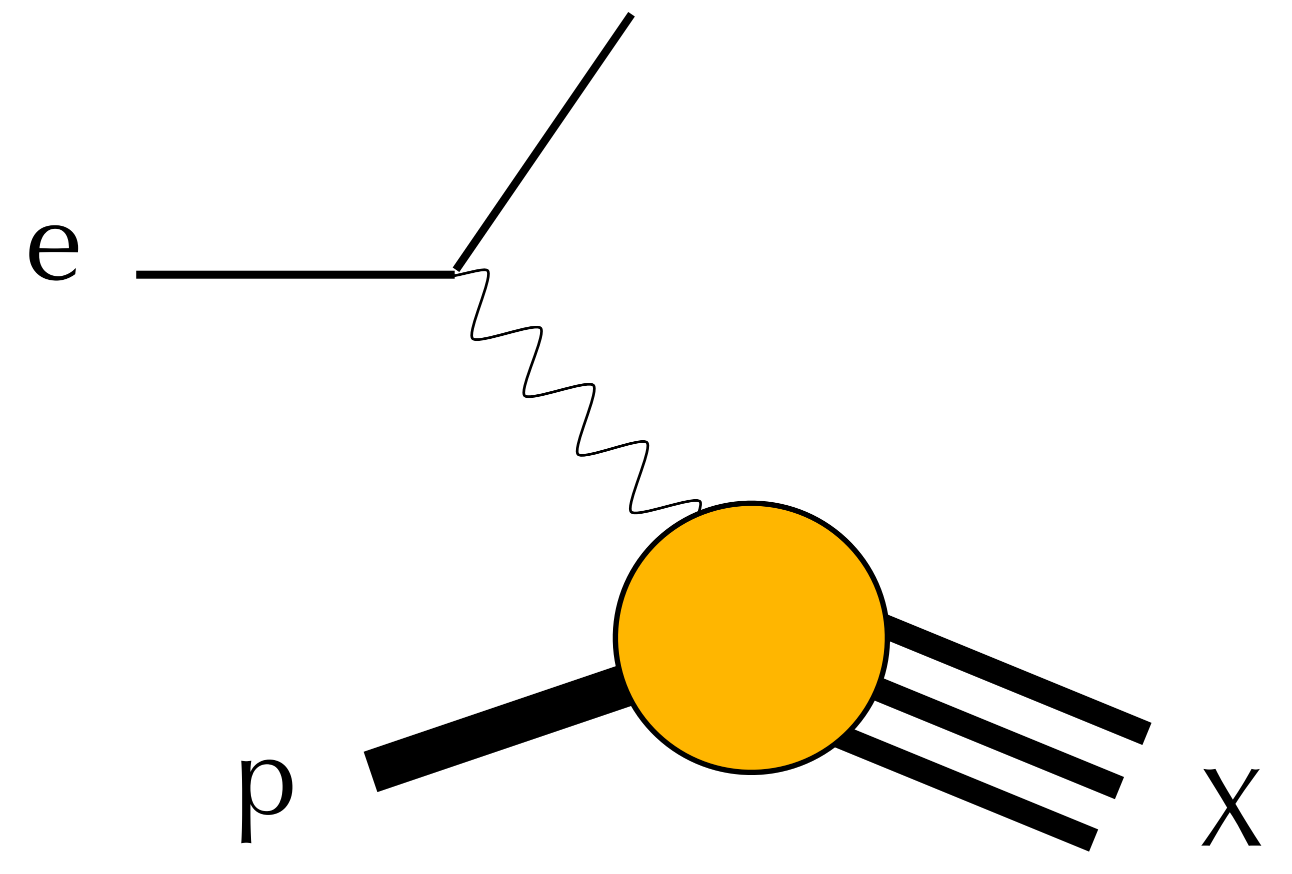

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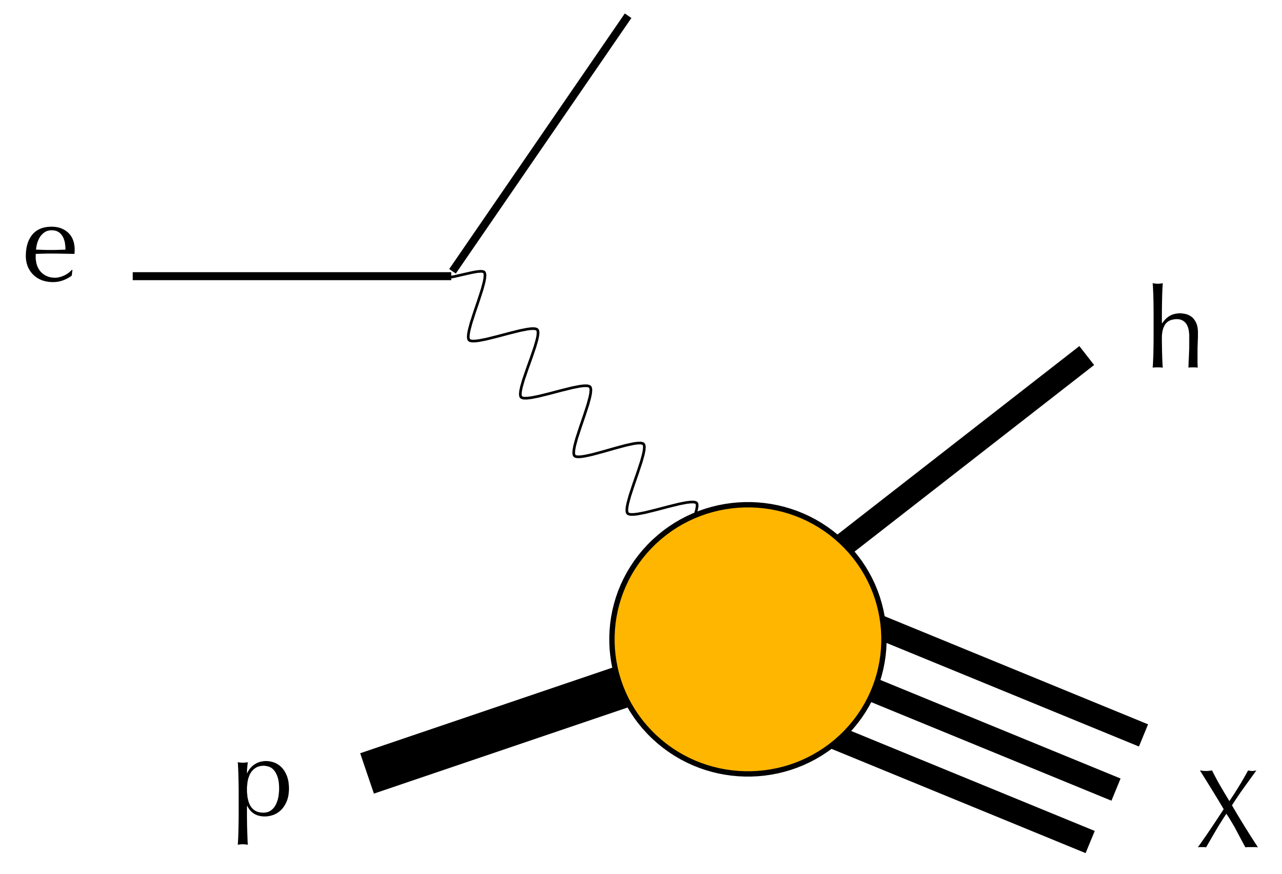

access to
Parton Distribution Functions

access to
Transverse Momentum Distributions

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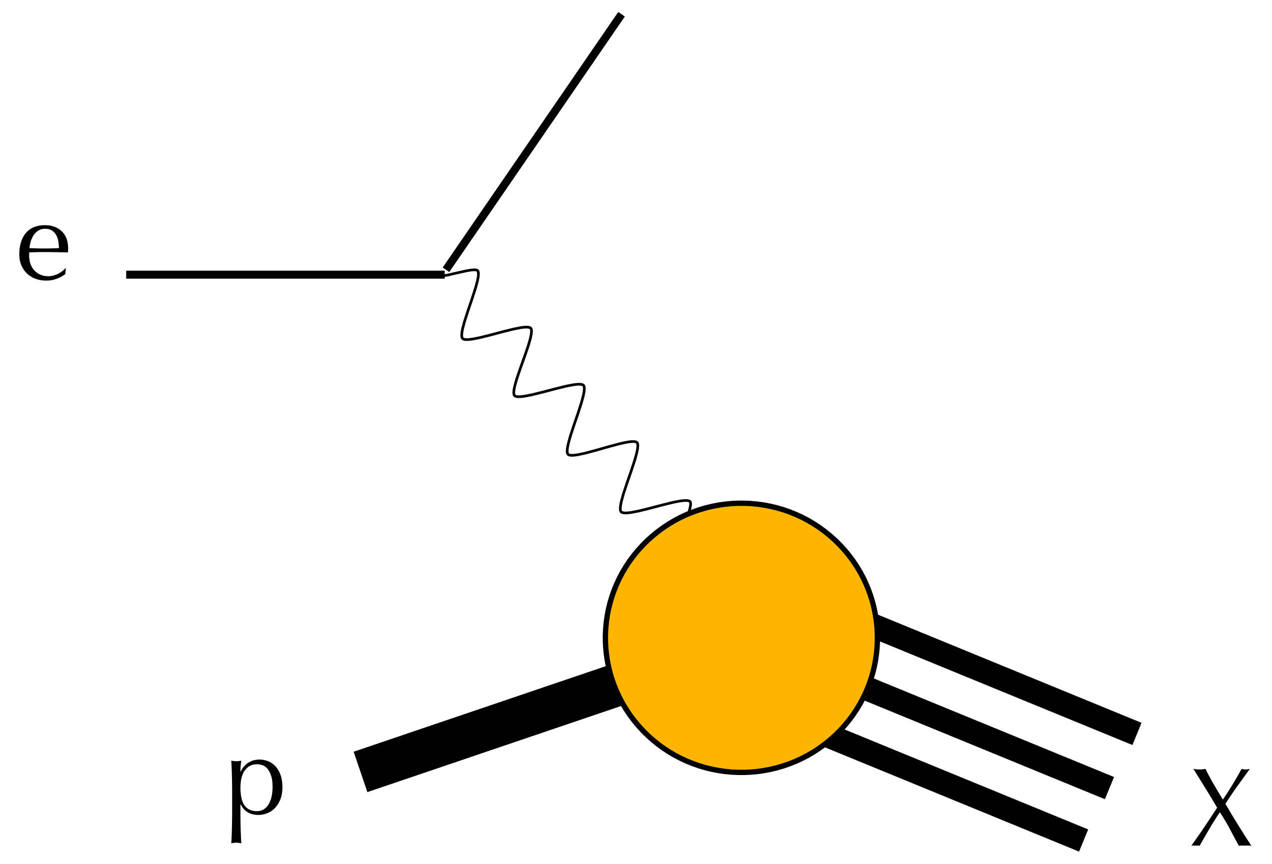

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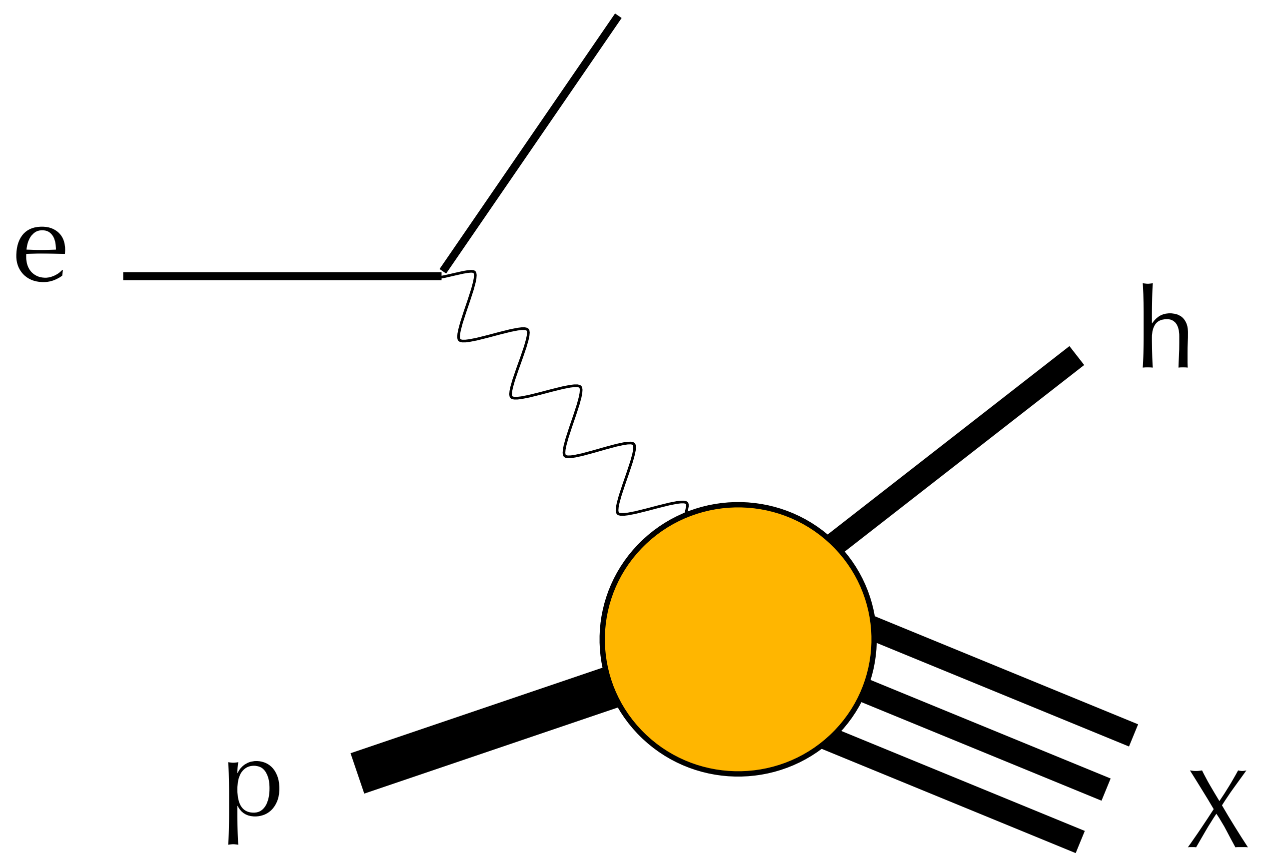
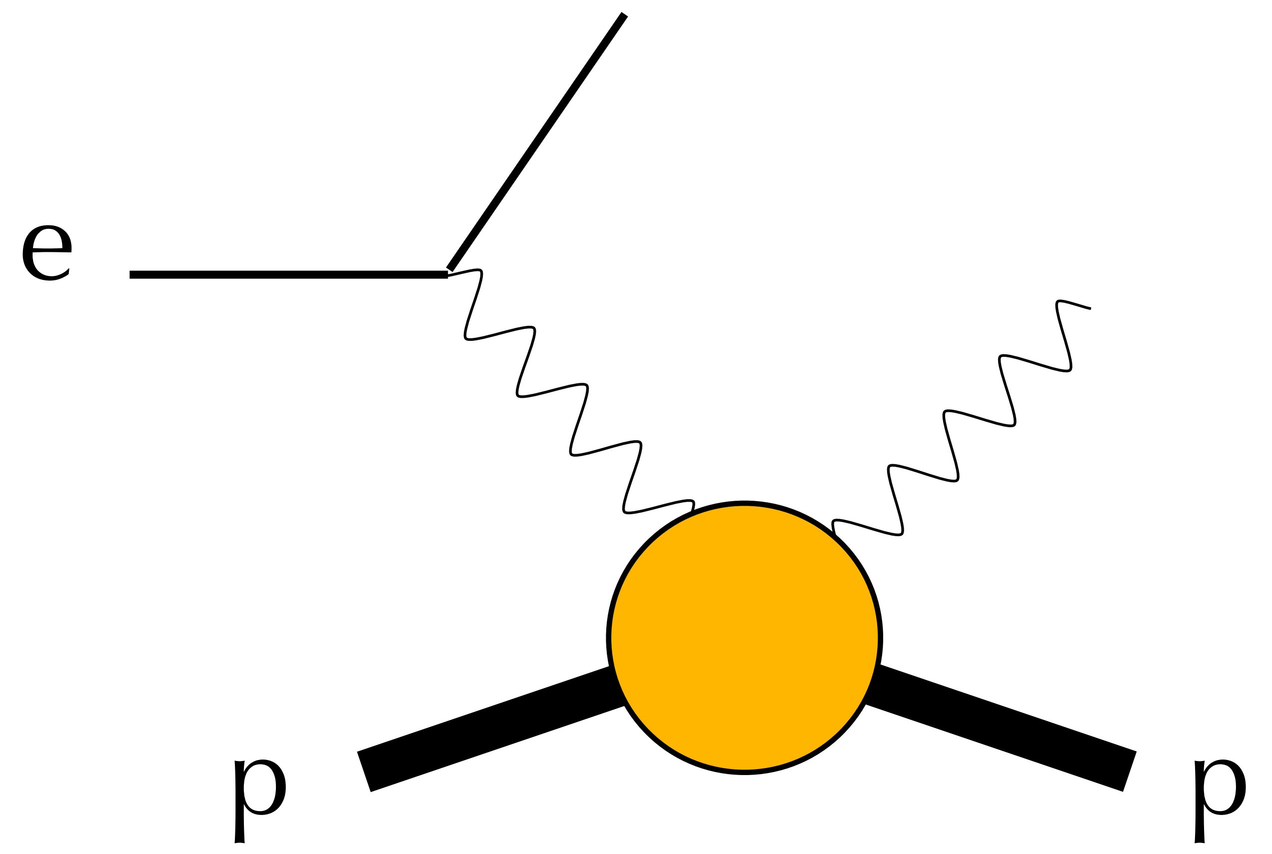


access to
Transverse Momentum Distributions

Exclusive processes



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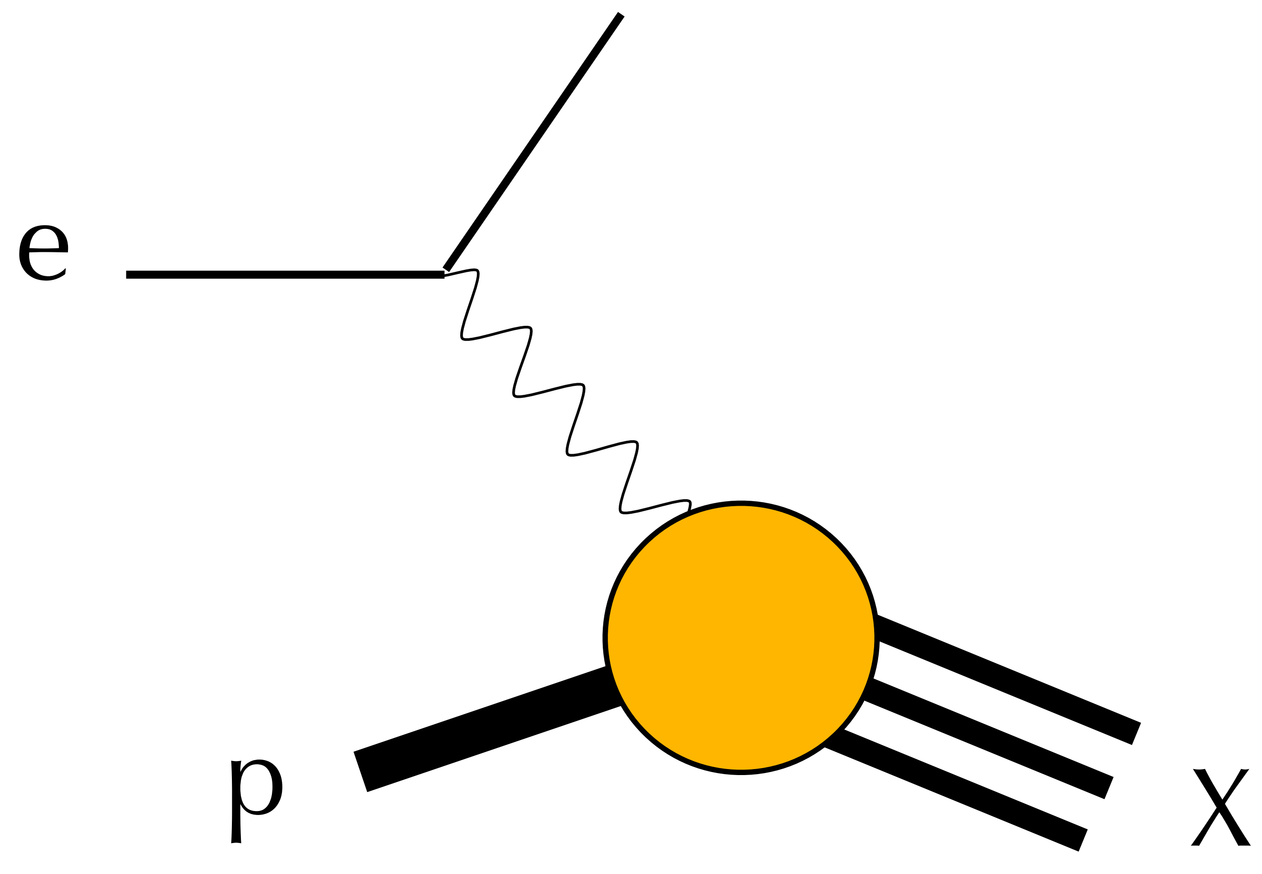

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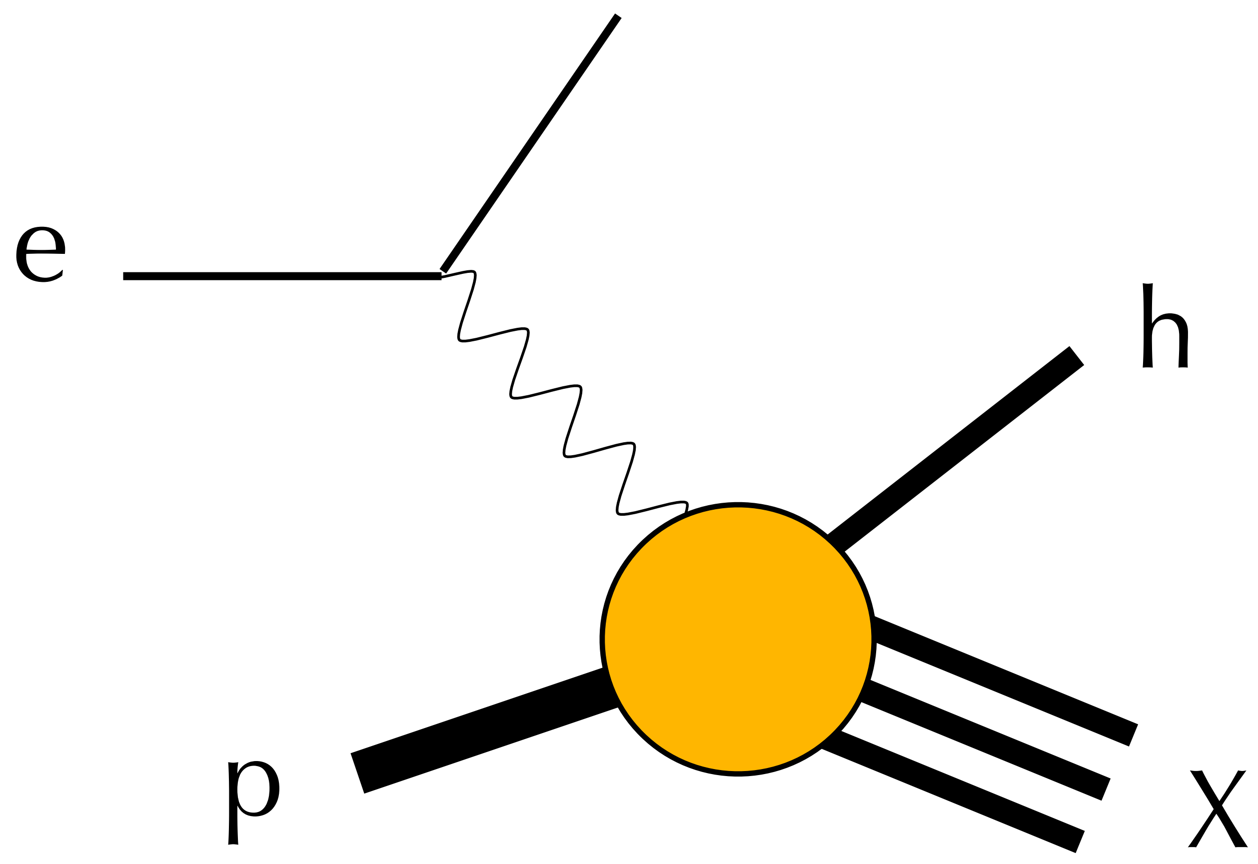

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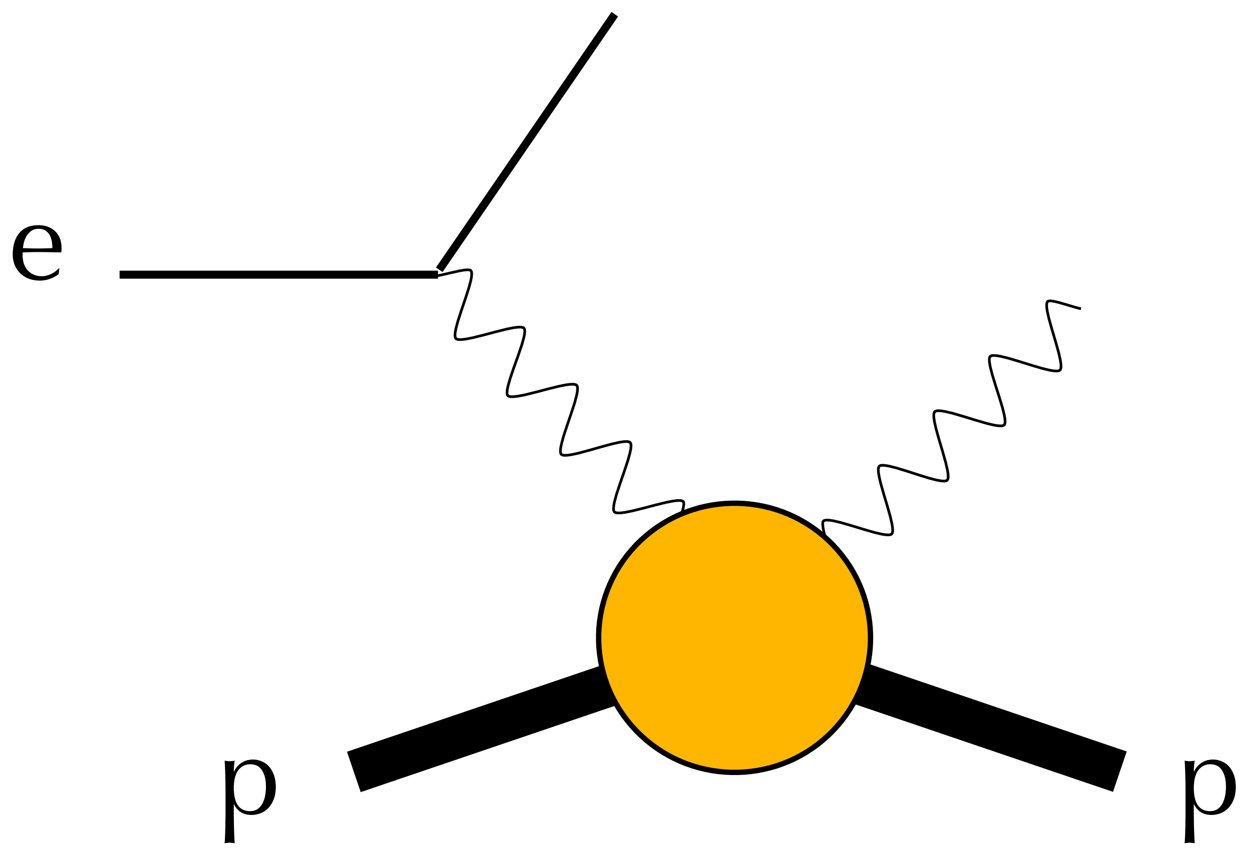
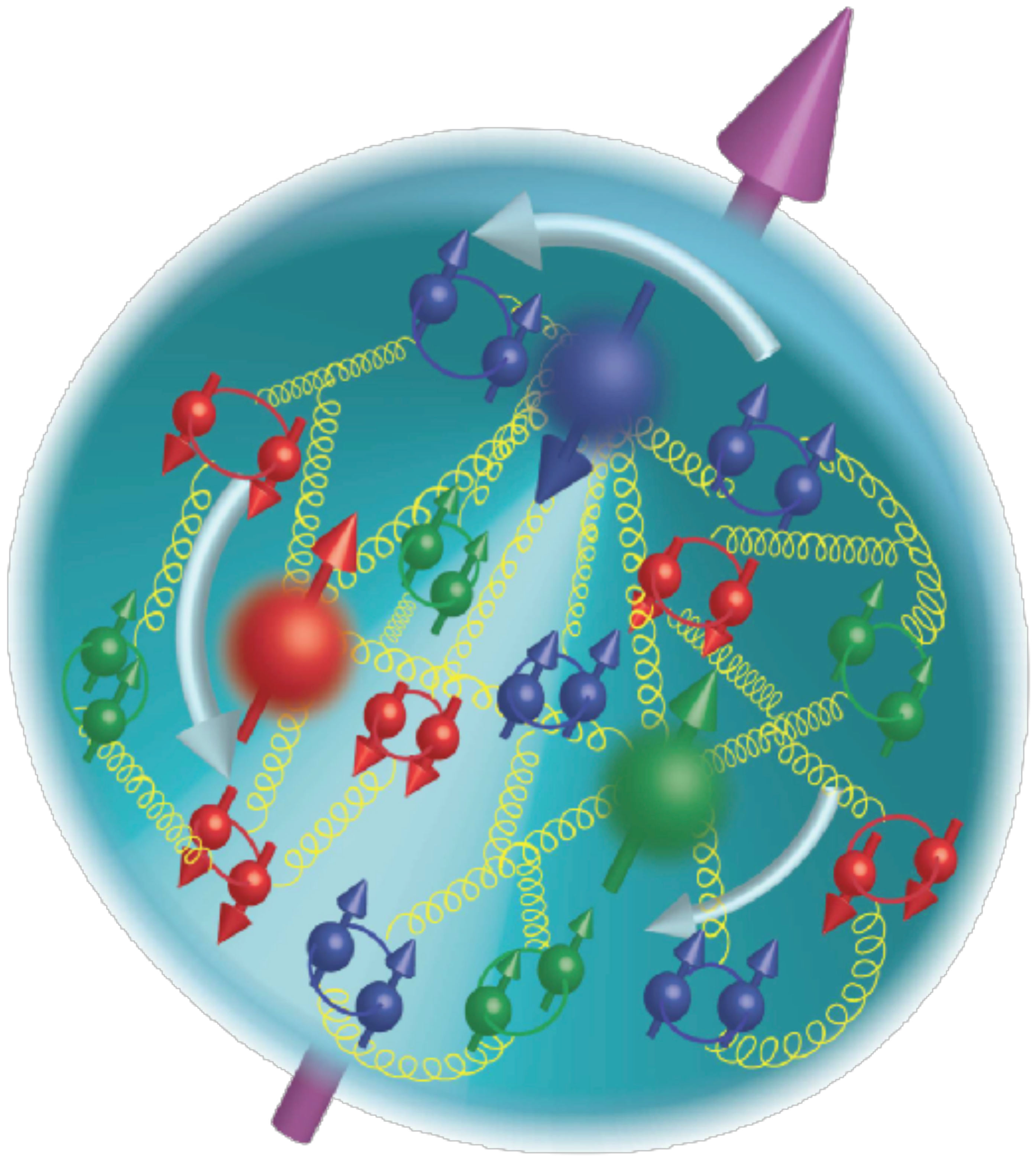


access to
Generalized Parton Distributions

WHY IS IT INTERESTING TO MAP THE NUCLEON?



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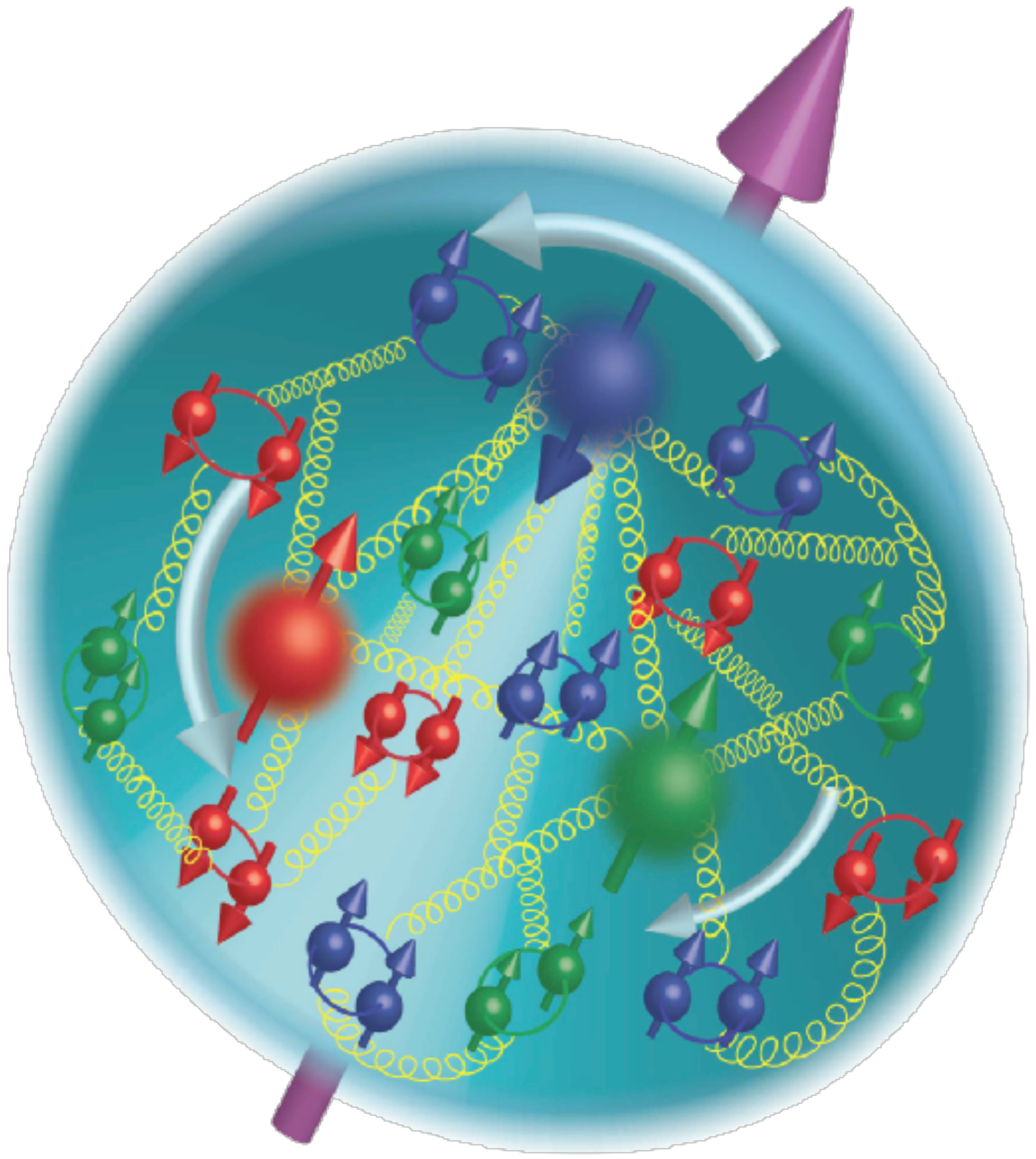
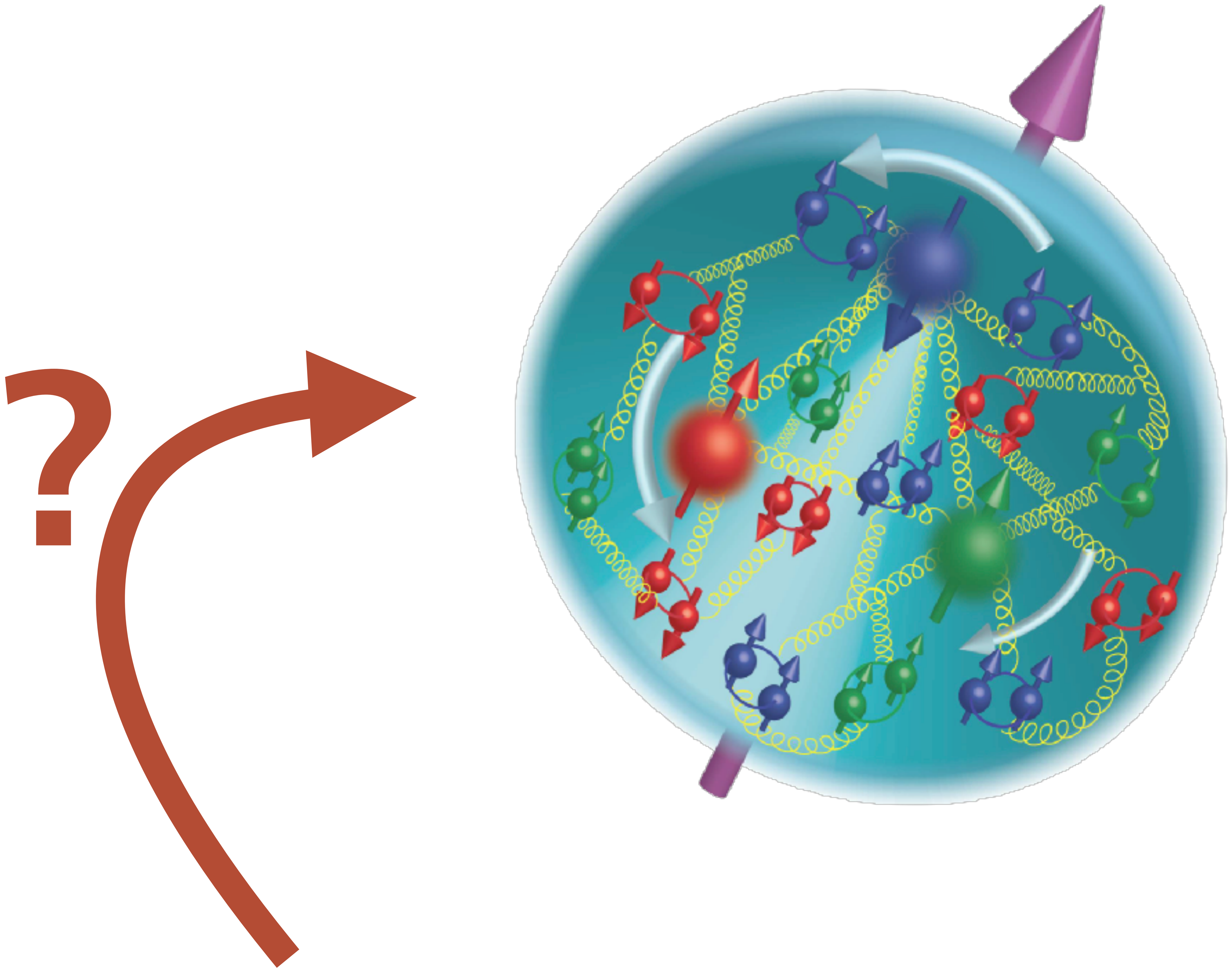


$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \overline{\psi}_q (i \not{\partial} - g \not{A} + m) \psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

WHY IS IT INTERESTING TO MAP THE NUCLEON?



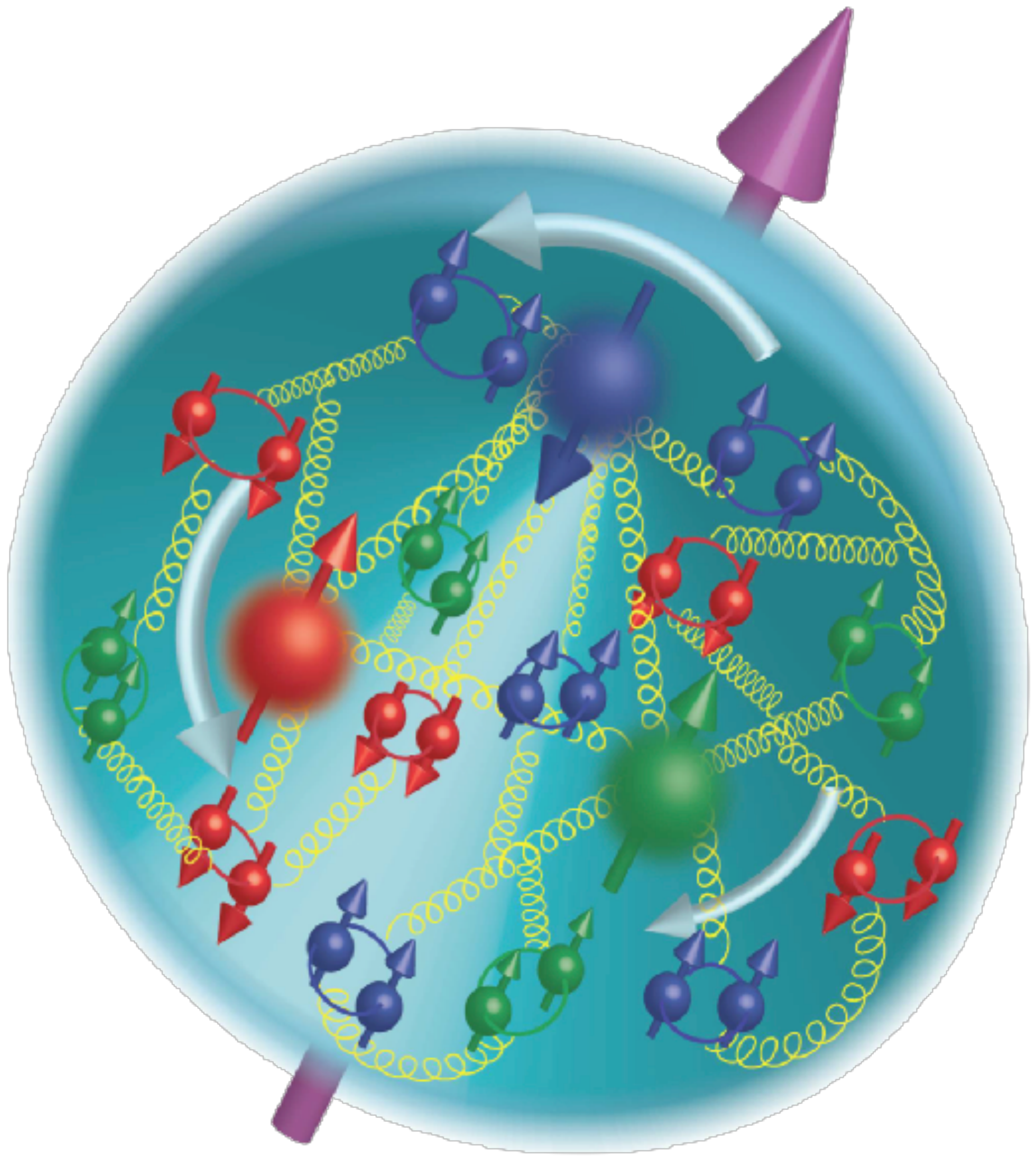
$$\mathcal{L}_{\rm QCD} = \sum_q \overline{\psi}_q (i\,\not{\partial} - g\,\not{A} + m)\psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

QCD: the WILD SIDE of the Standard Model

QCD: the **WILD SIDE** of the Standard Model

there are more things that we cannot explain than we can explain…

WHY IS IT INTERESTING TO MAP THE NUCLEON?

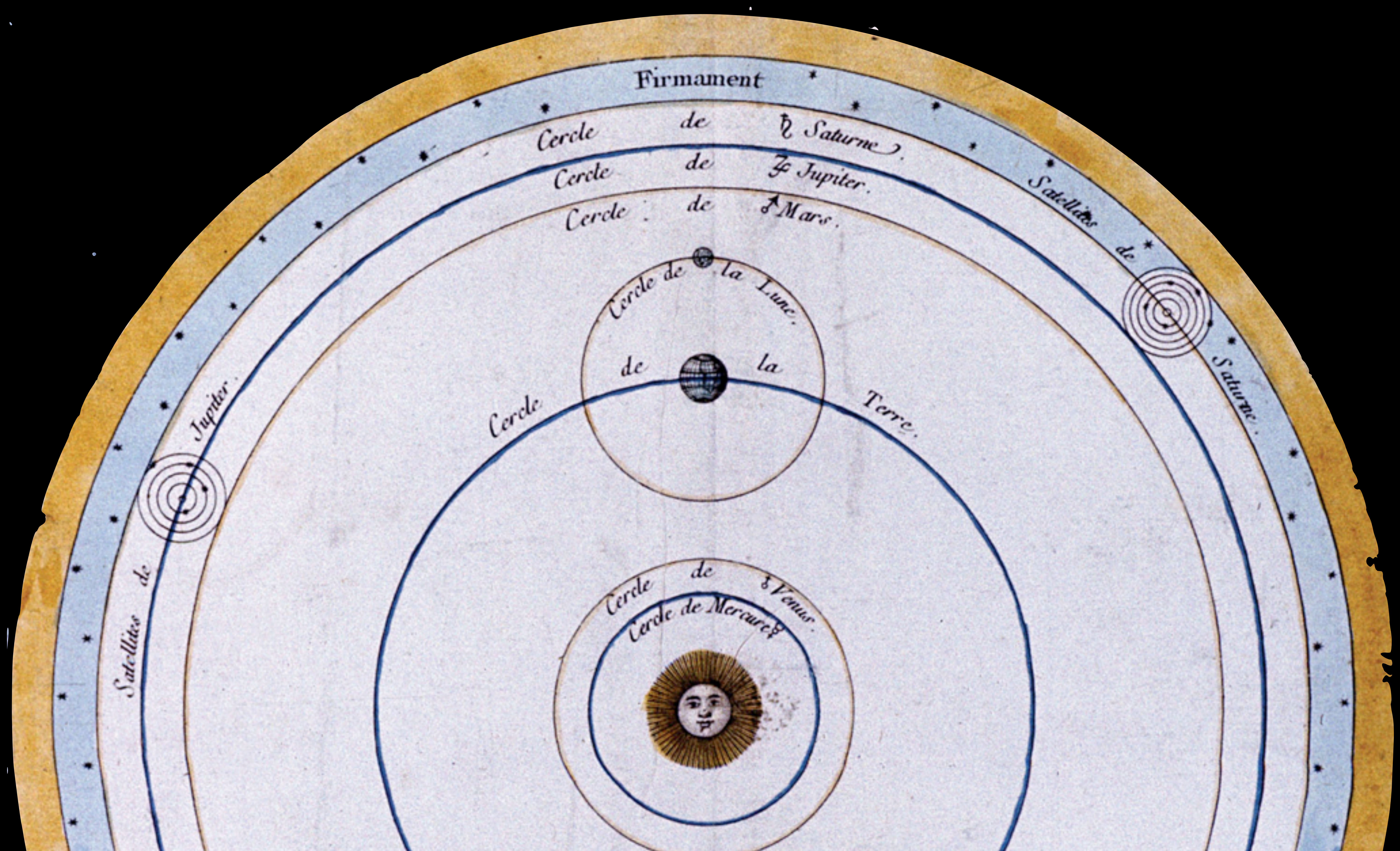


?

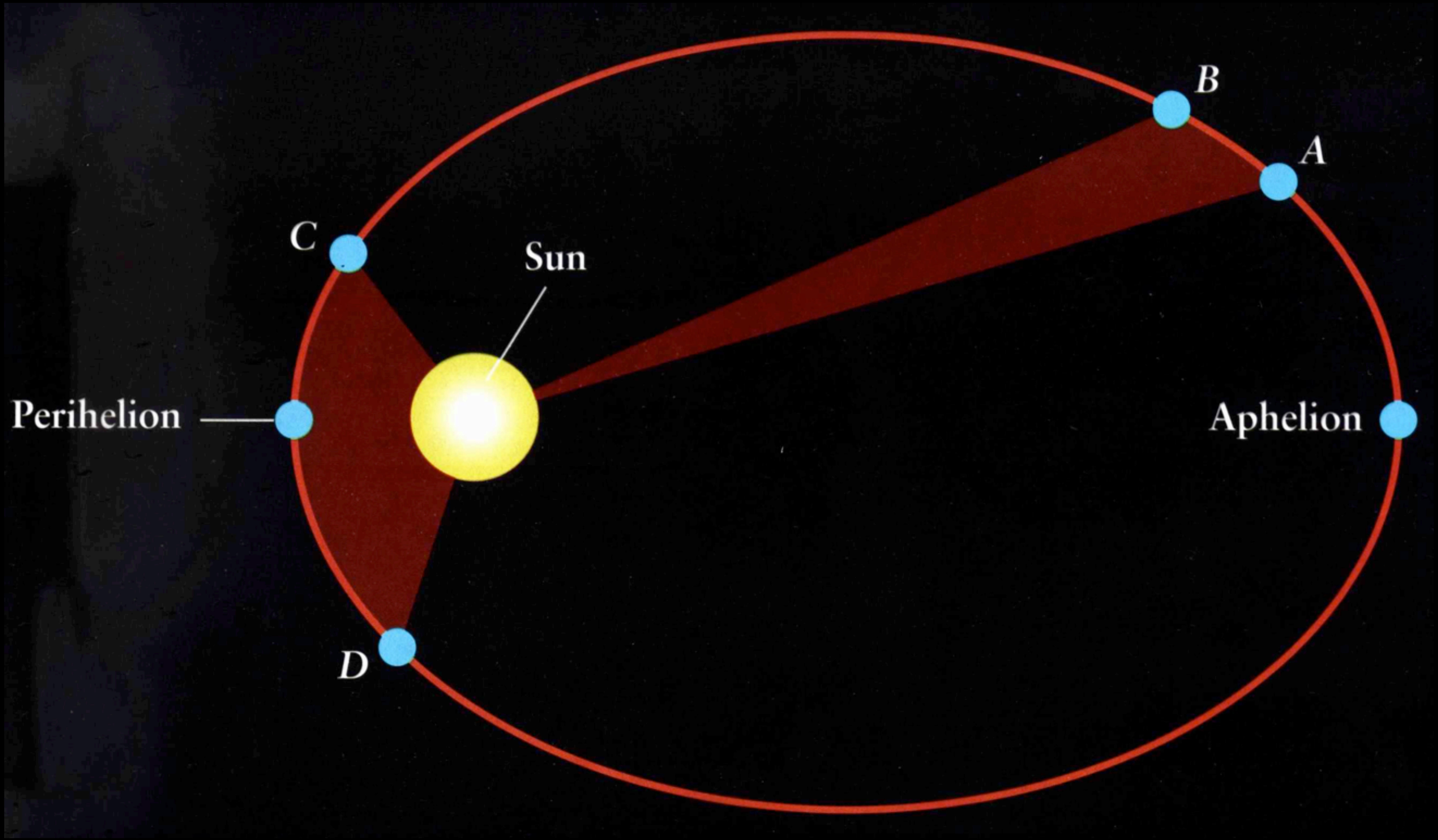
$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \overline{\psi}_q (i \not{\partial} - g \not{A} + m)\psi_q - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

WHY IS IT INTERESTING TO MAP THE SKY?

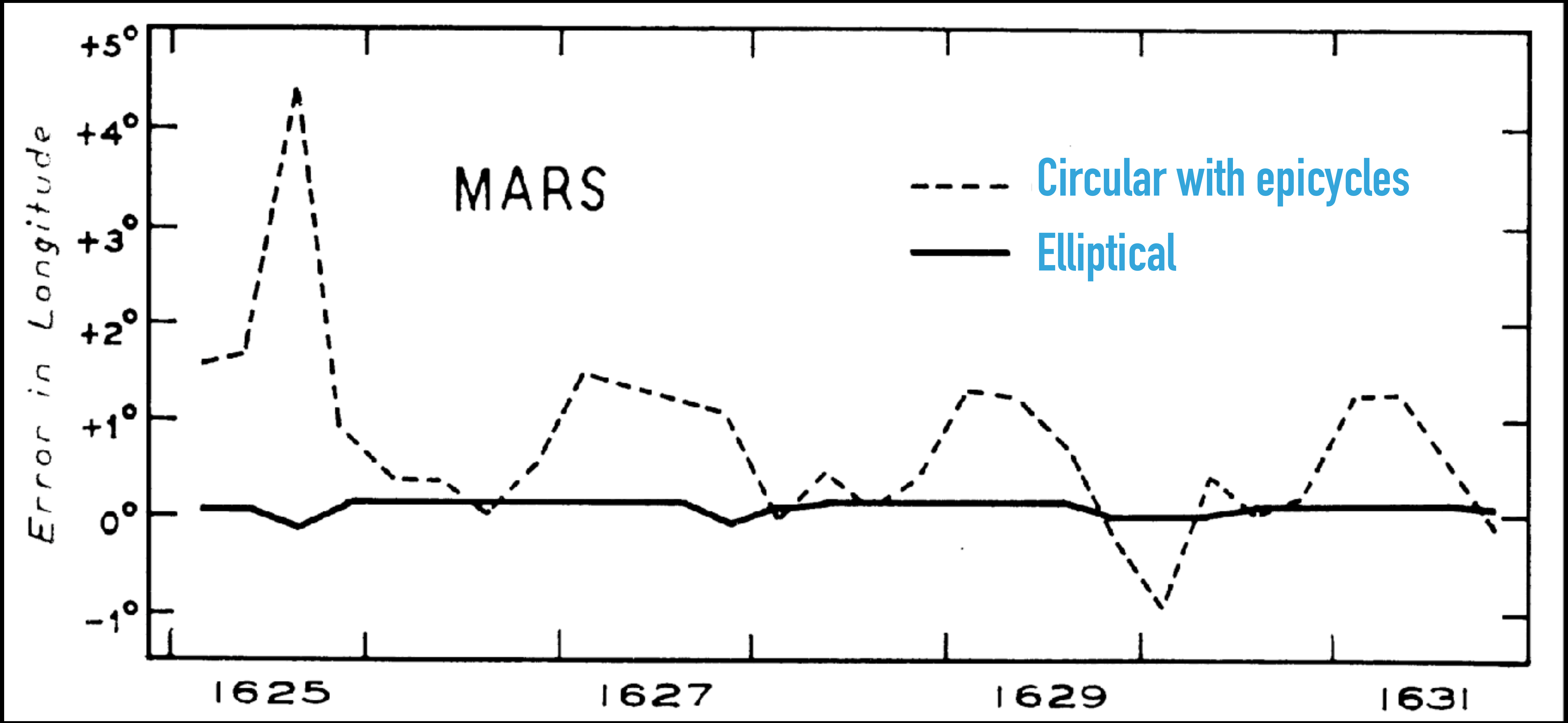
COPERNICAN MODEL



KEPLER'S MODEL

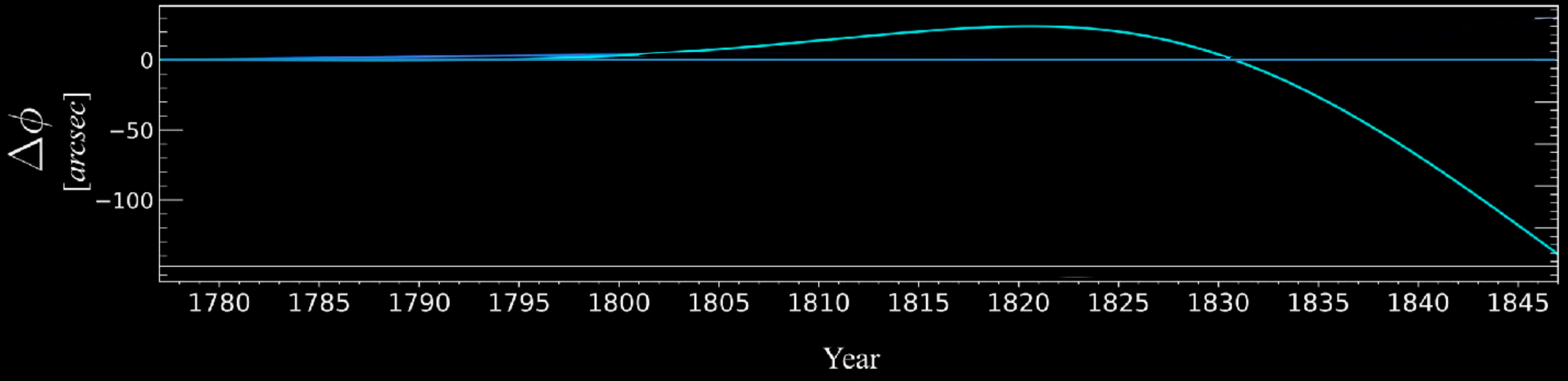


CHECK PREDICTIONS



MAKE PREDICTIONS

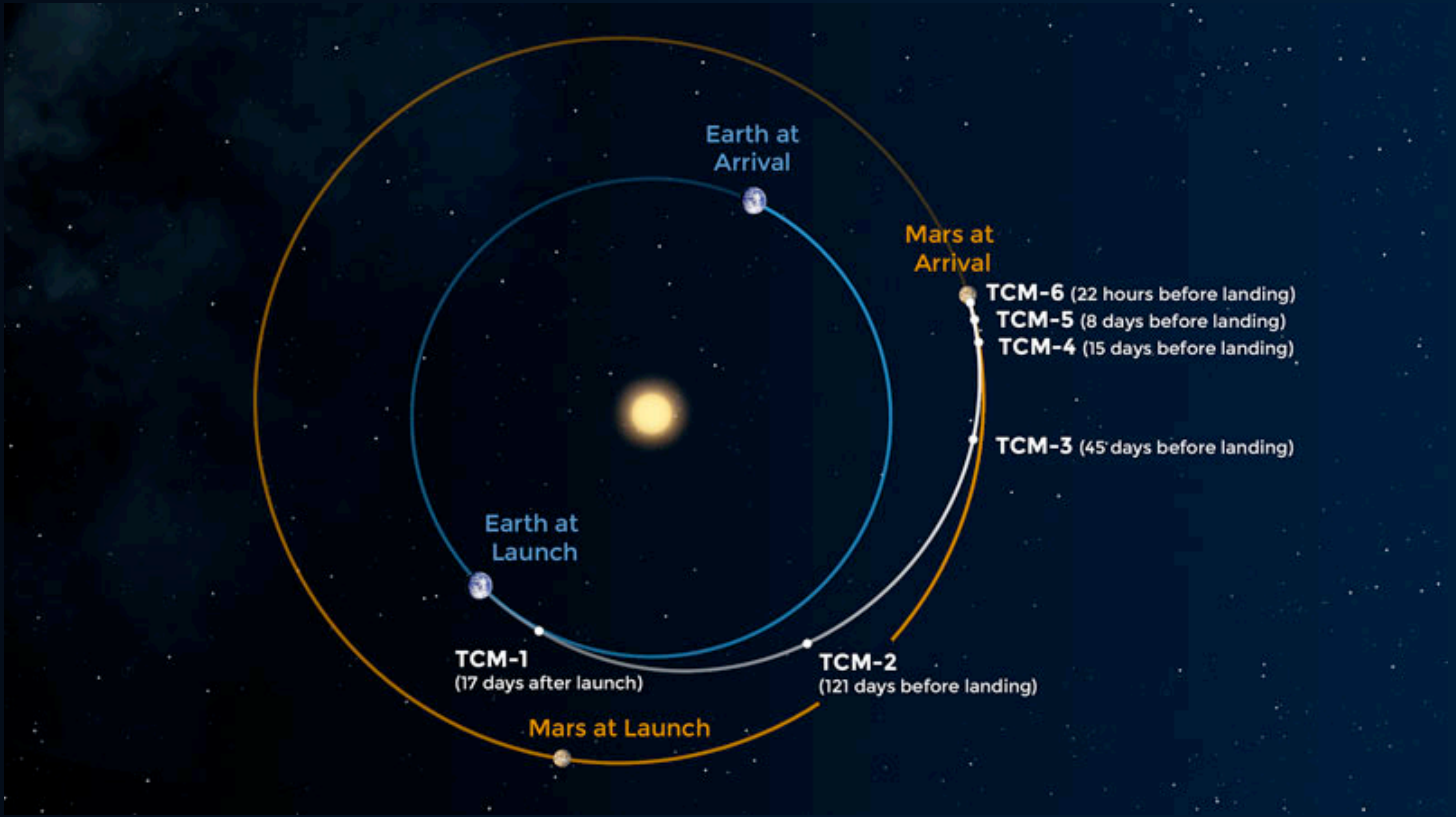
Uranus’s longitude predictions



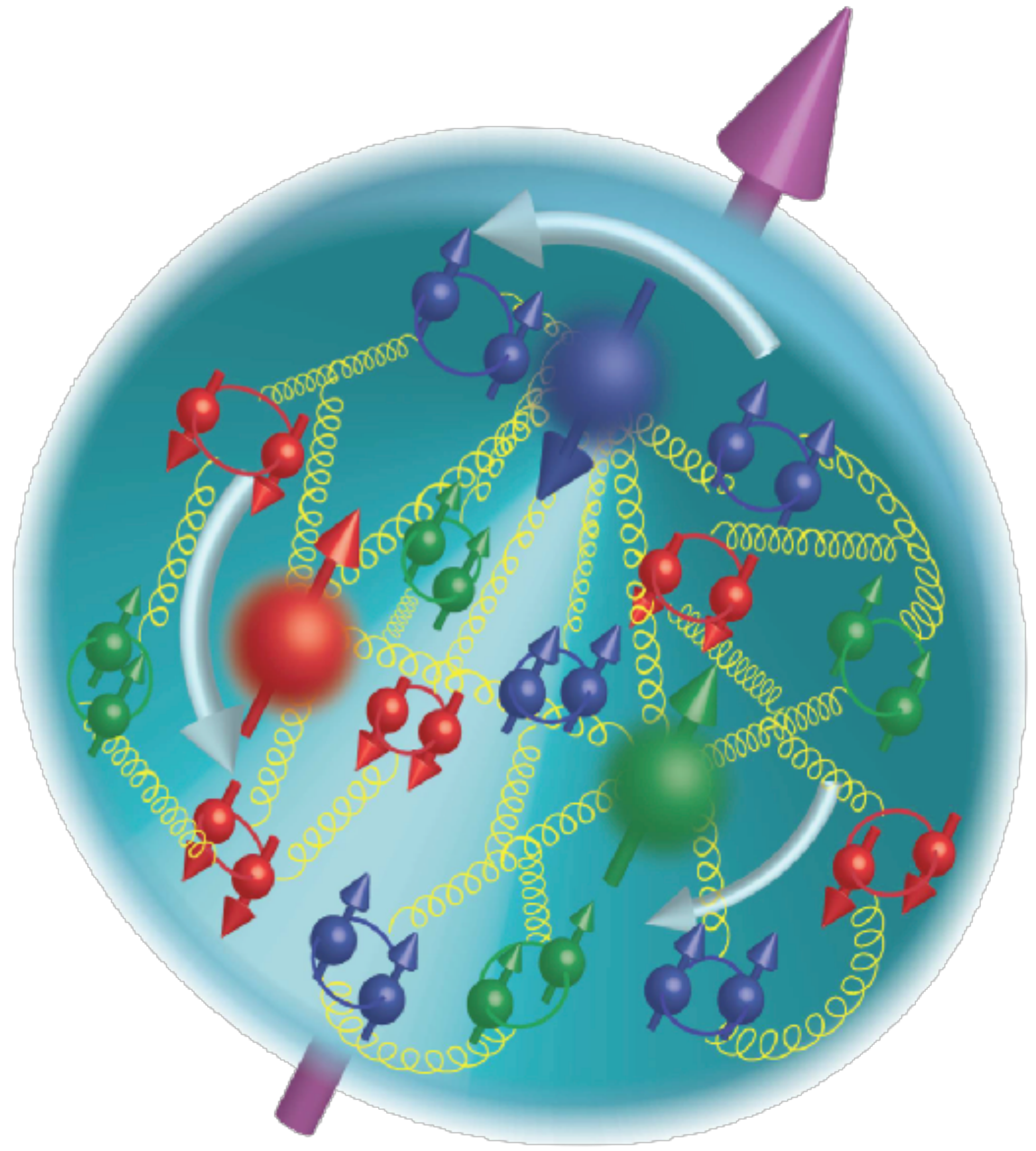
Without Neptune

With Neptune

MAKE PREDICTIONS

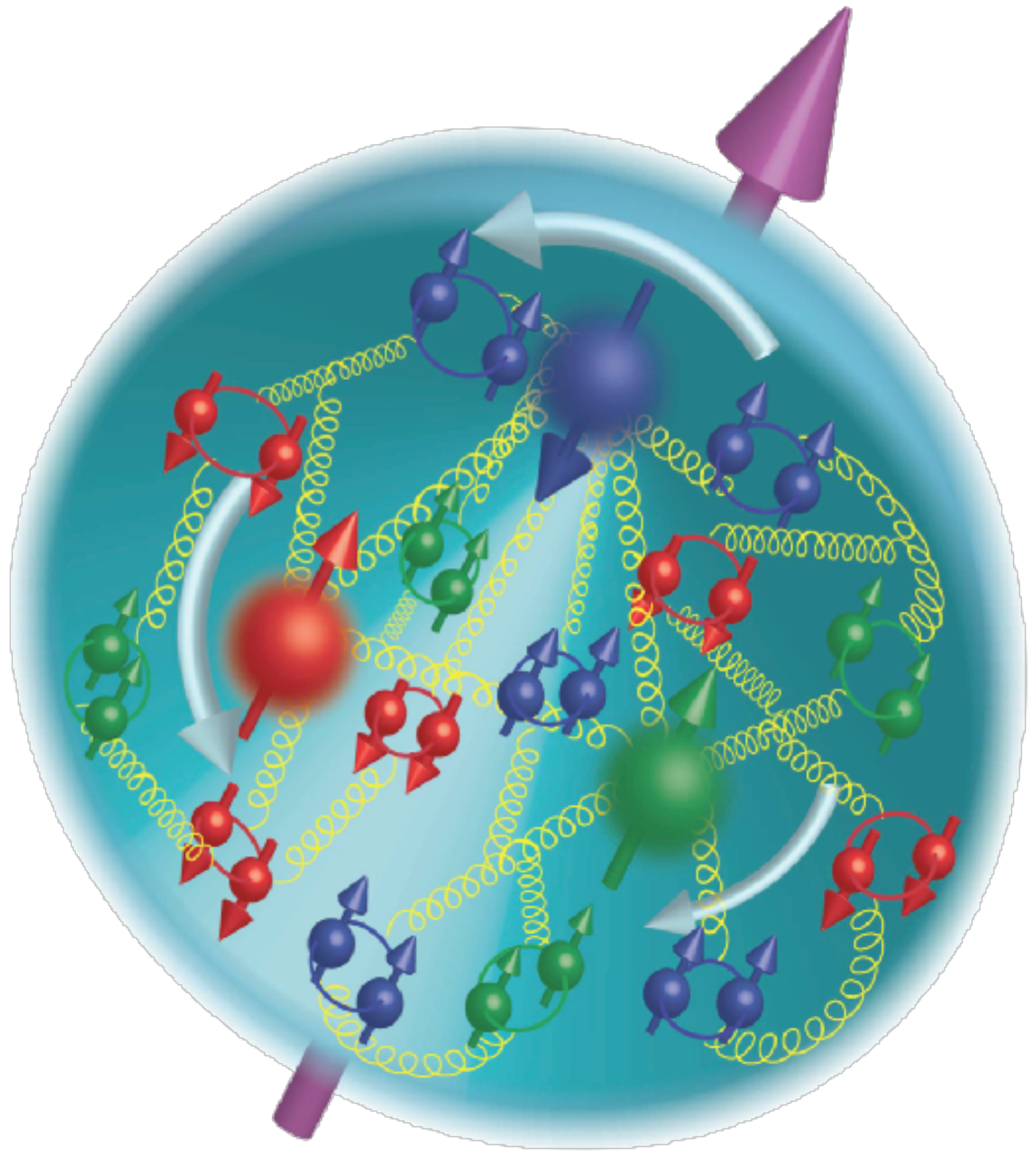


WHY IS IT INTERESTING TO MAP THE NUCLEON?



WHY IS IT INTERESTING TO MAP THE NUCLEON?

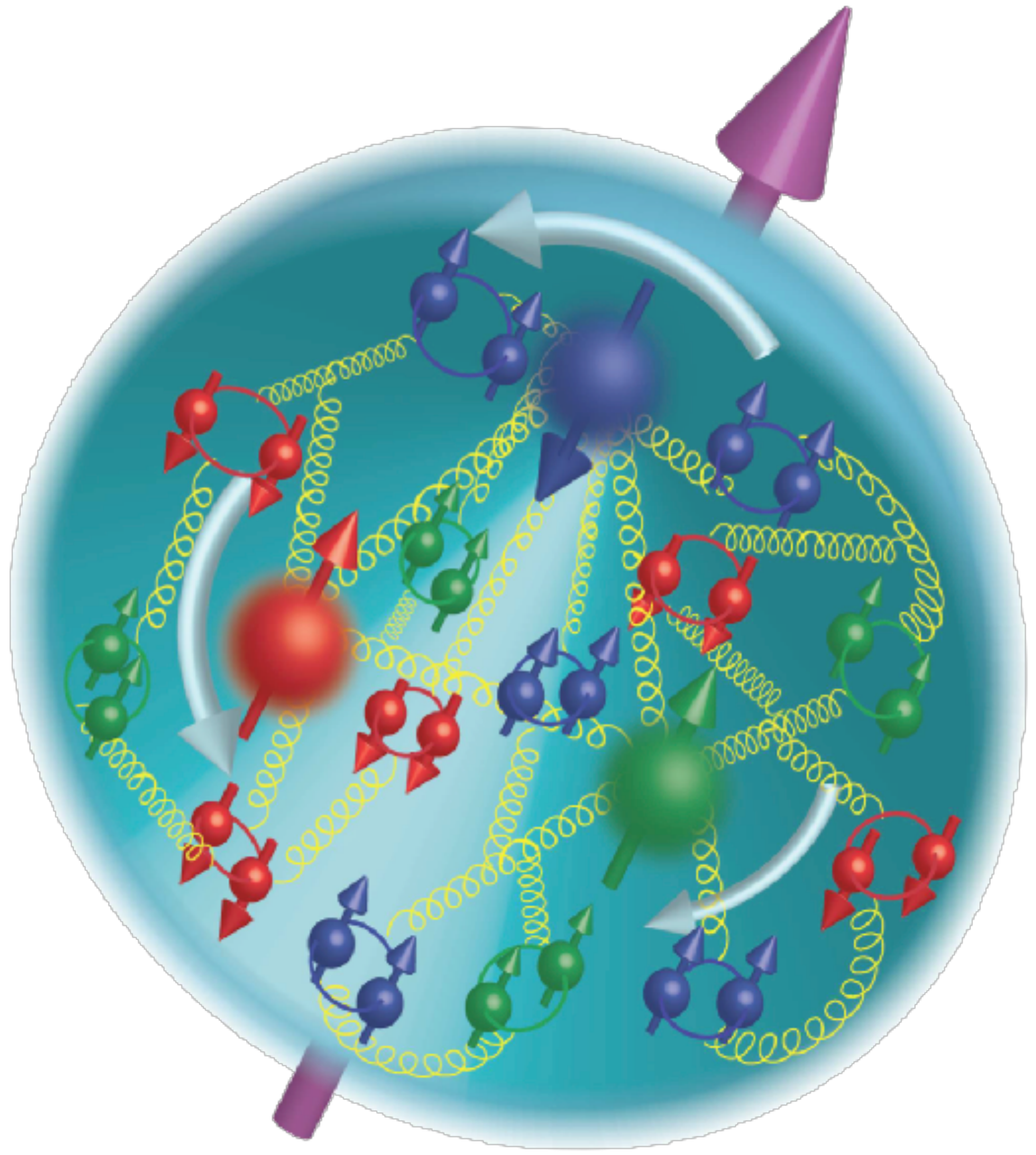
$$\mathcal{L}_{\rm QCD} = \sum_q \overline{\psi}_q (i \not\partial - g \not A + m)\psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$



Check predictions

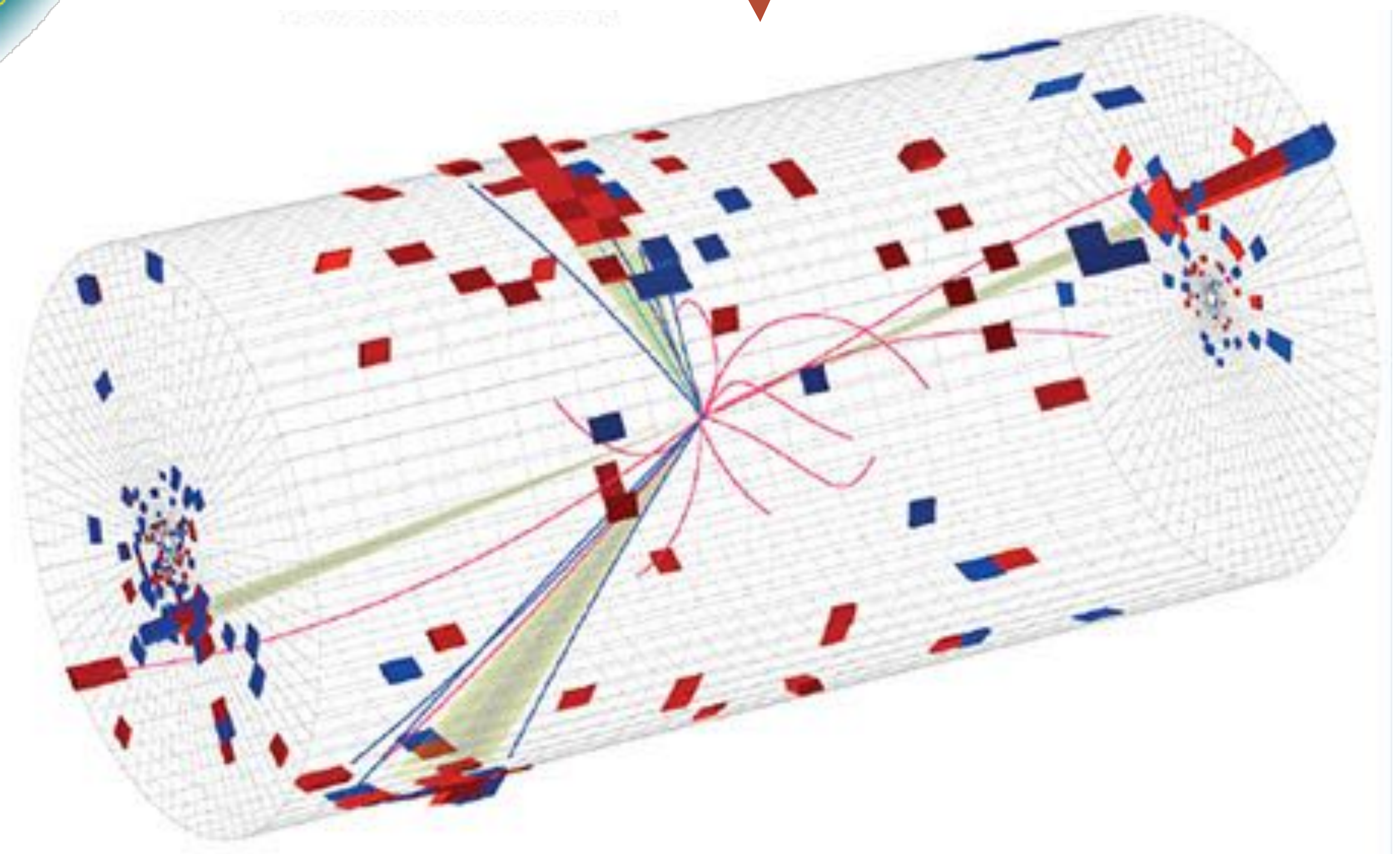
WHY IS IT INTERESTING TO MAP THE NUCLEON?

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \overline{\psi}_q (i \not\partial - g \not{A} + m) \psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

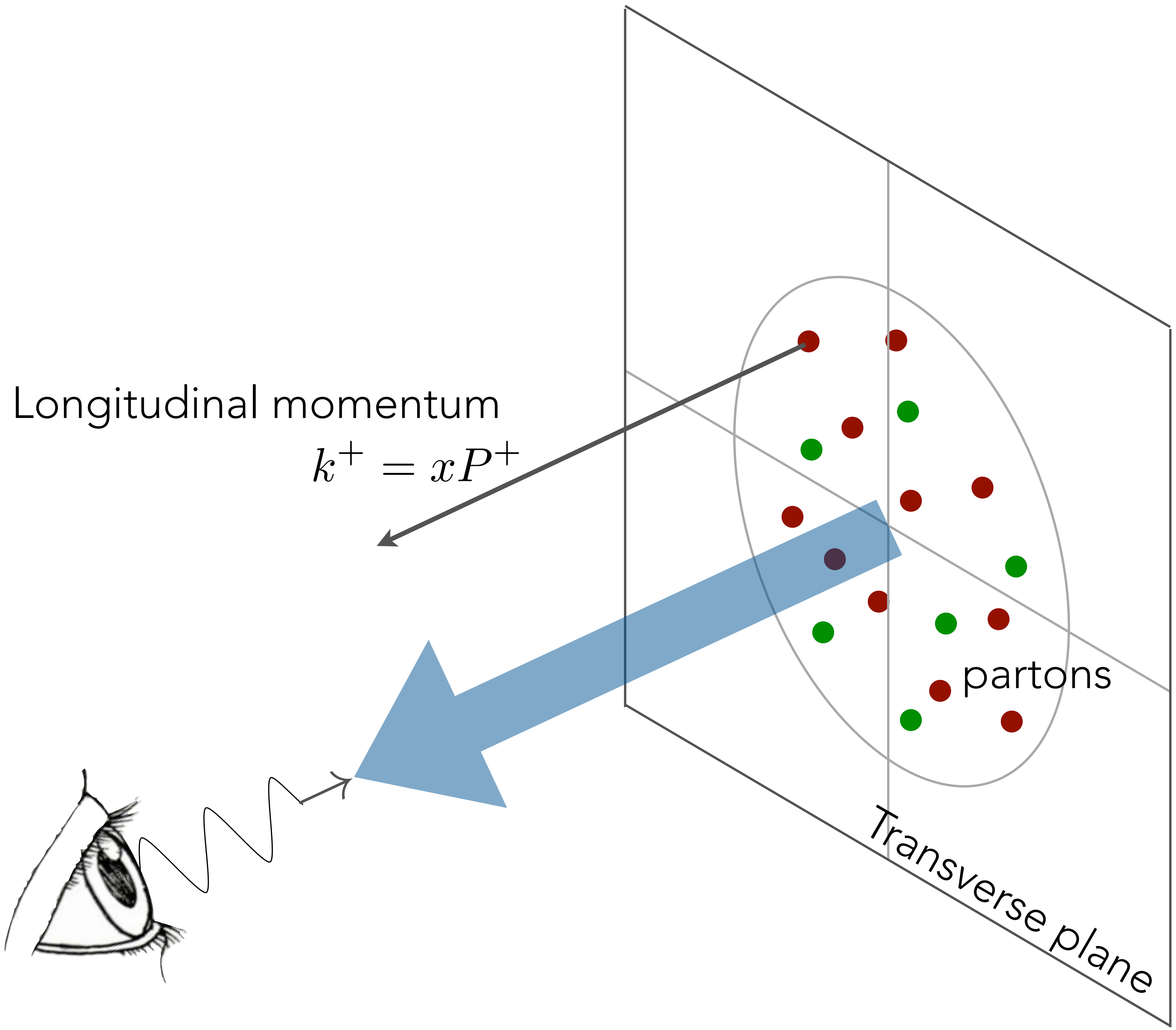


Make predictions

Check predictions



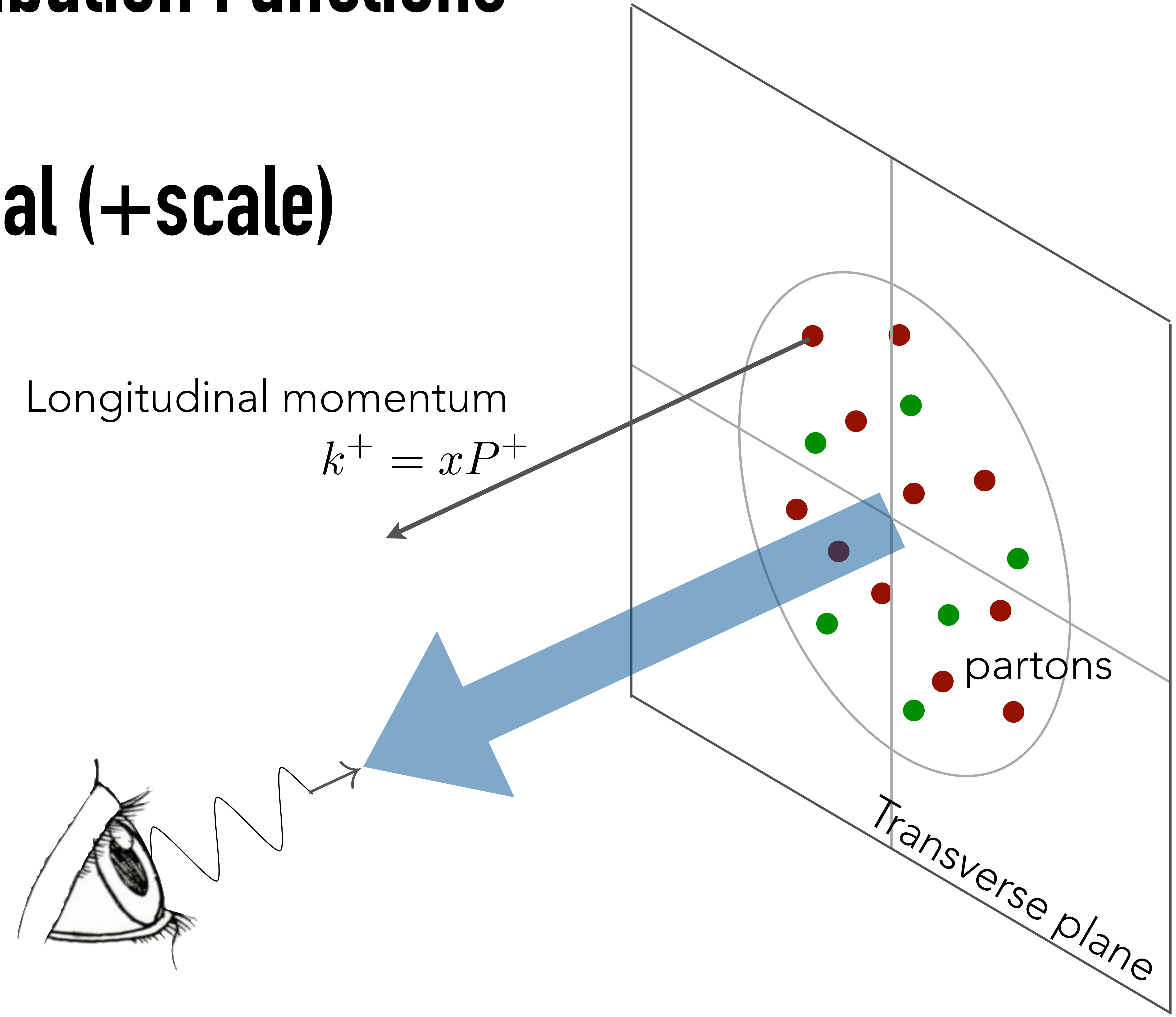
PRESENT KNOWLEDGE


Longitudinal momentum
$k^+ = xP^+$
partons
Transverse plane

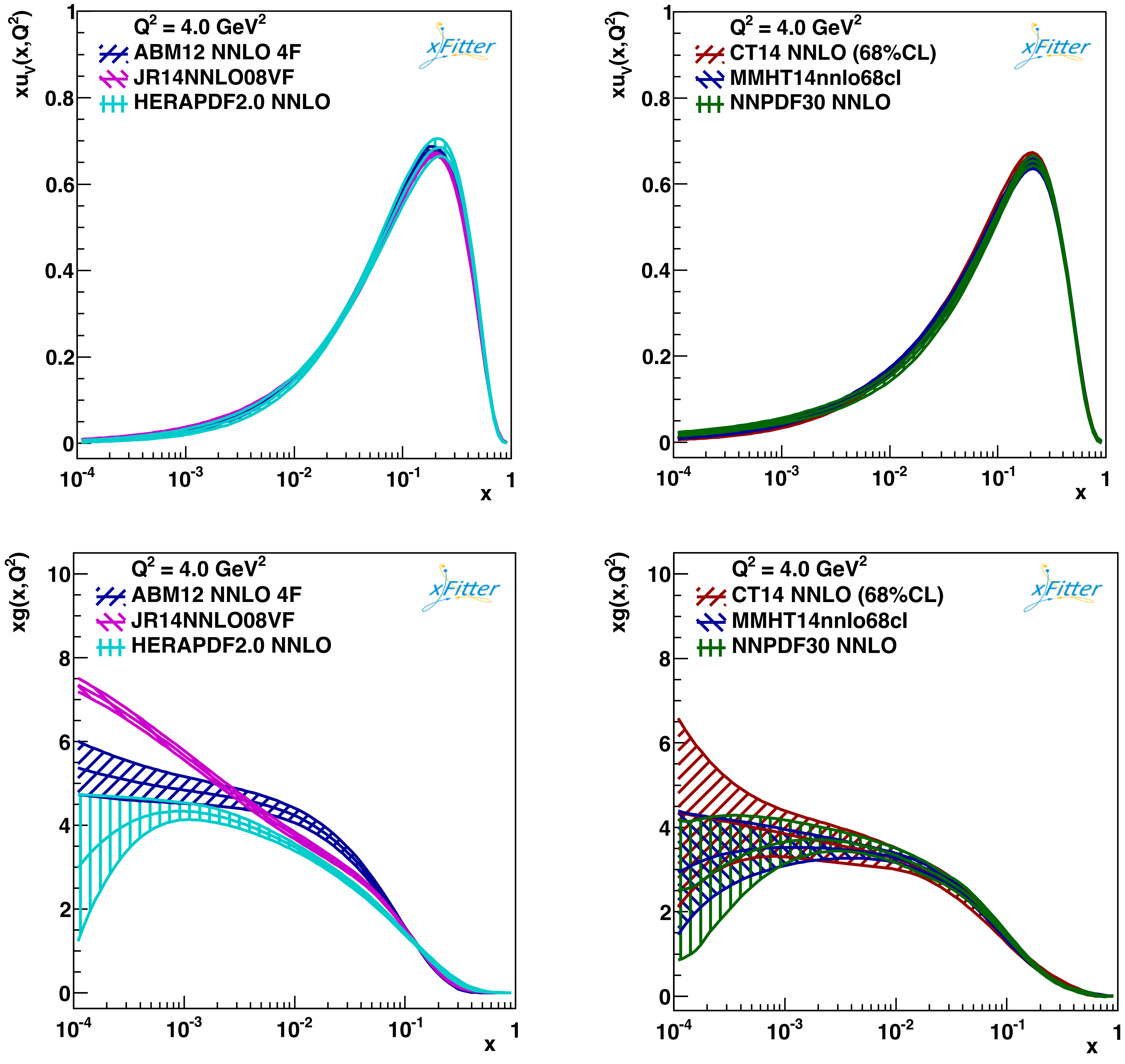
Parton Distribution Functions

$f(x)$

1 dimensional (+scale)



PARTON DISTRIBUTION FUNCTIONS



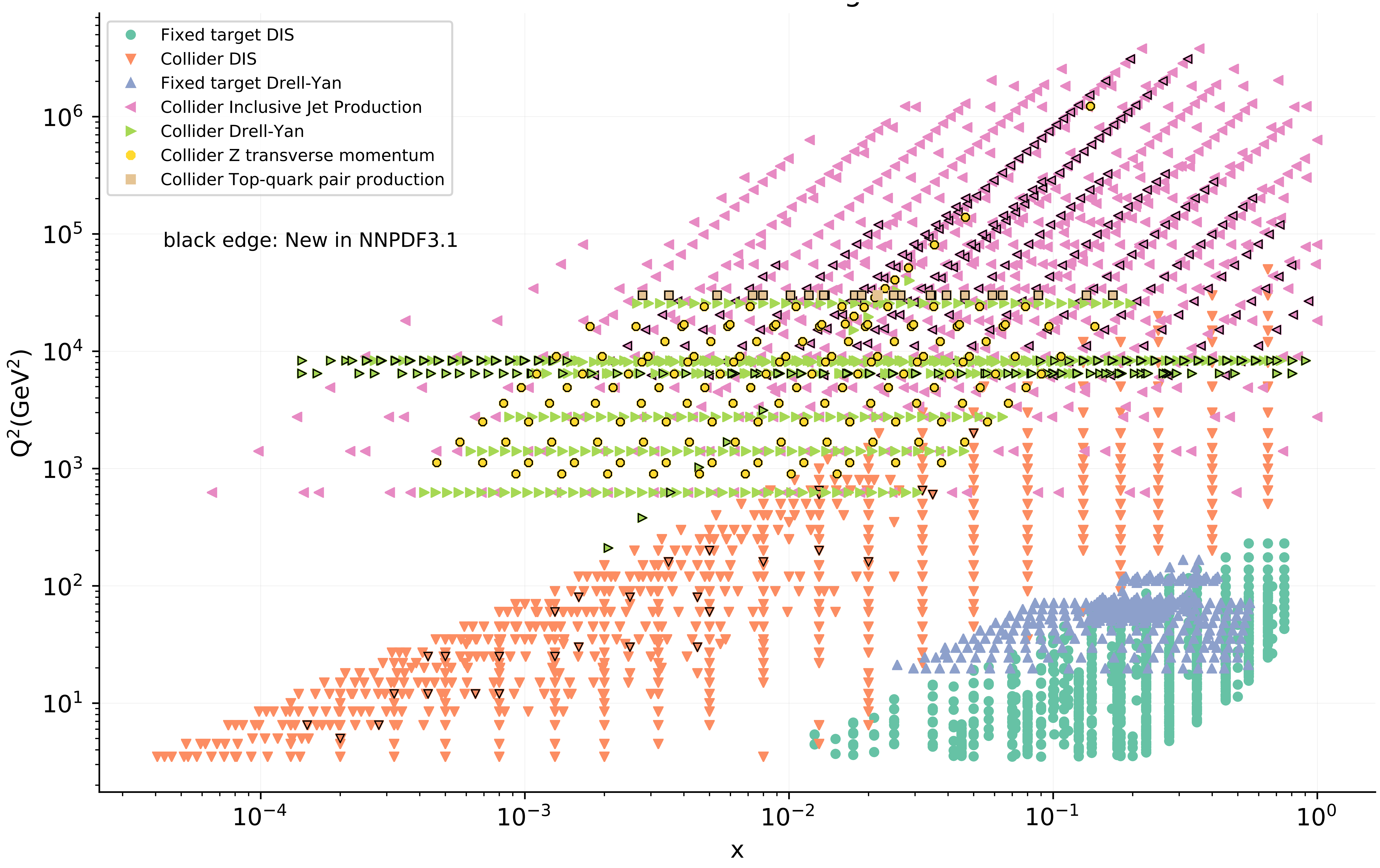
Standard collinear PDFs describe the distribution of partons in one dimension in momentum space.

They are extracted through global fits

Accardi et al., arXiv:1603.08906

KINEMATIC COVERAGE OF DATA USED FOR PDF FITS

PDFLattice White Paper, arXiv:1711.07916



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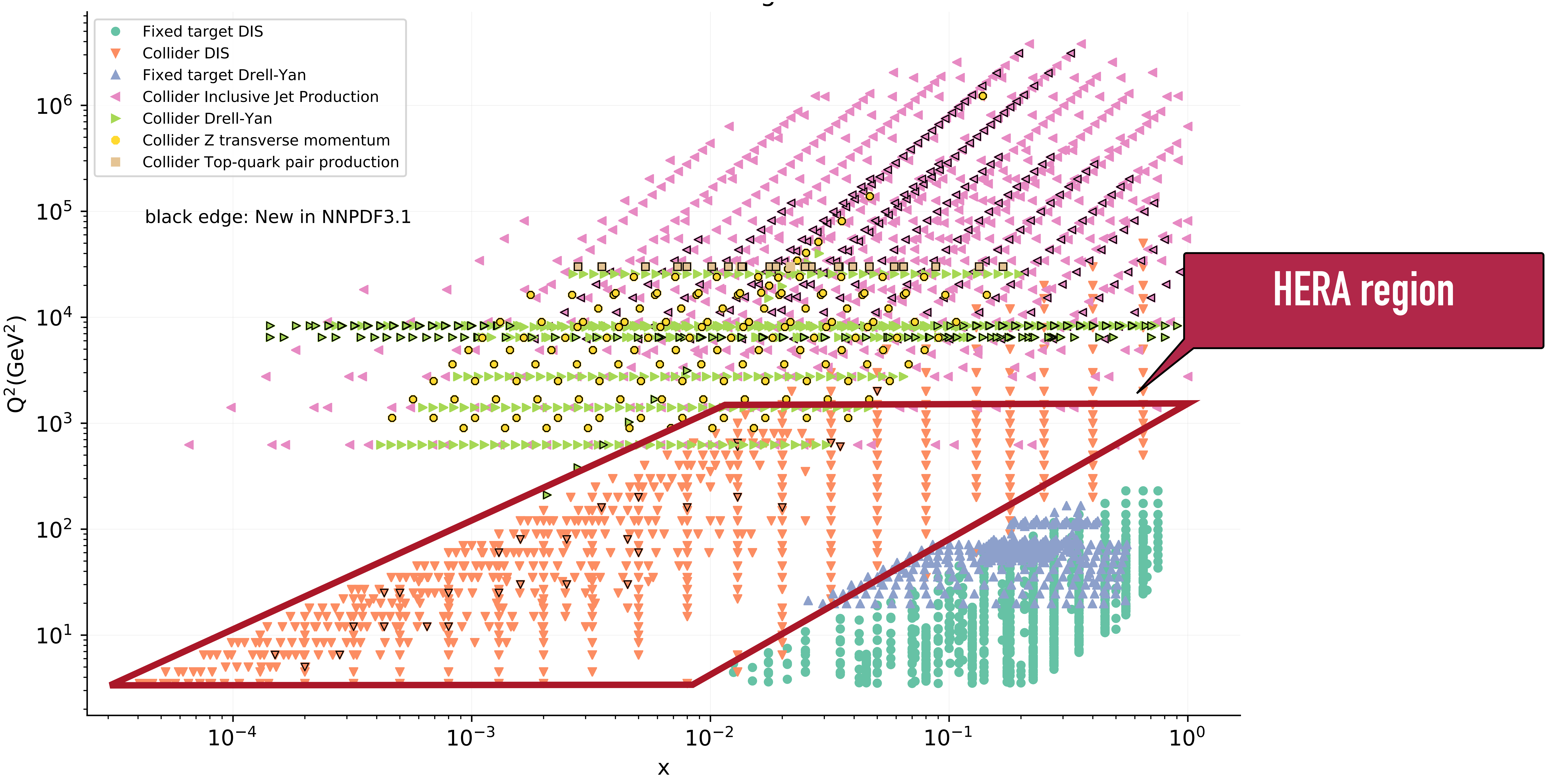
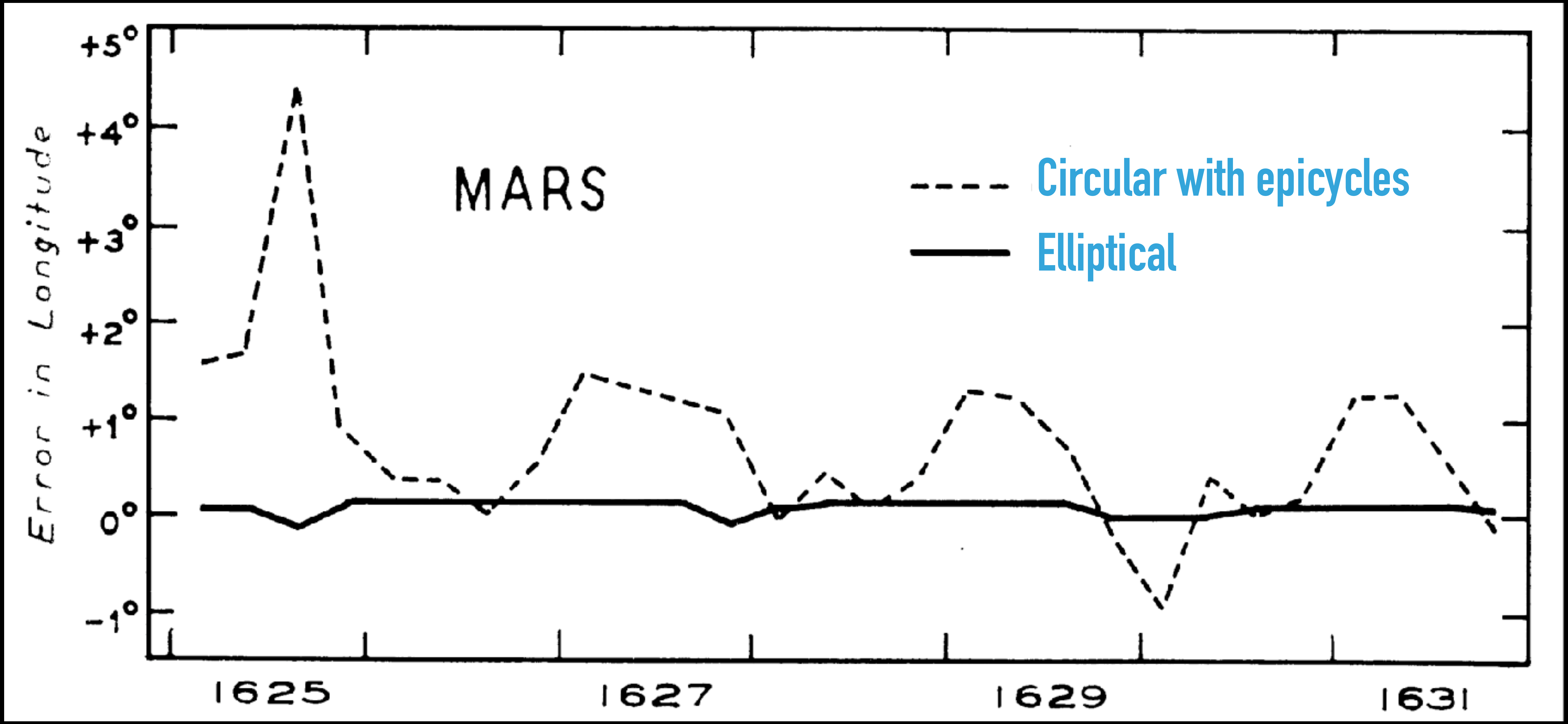
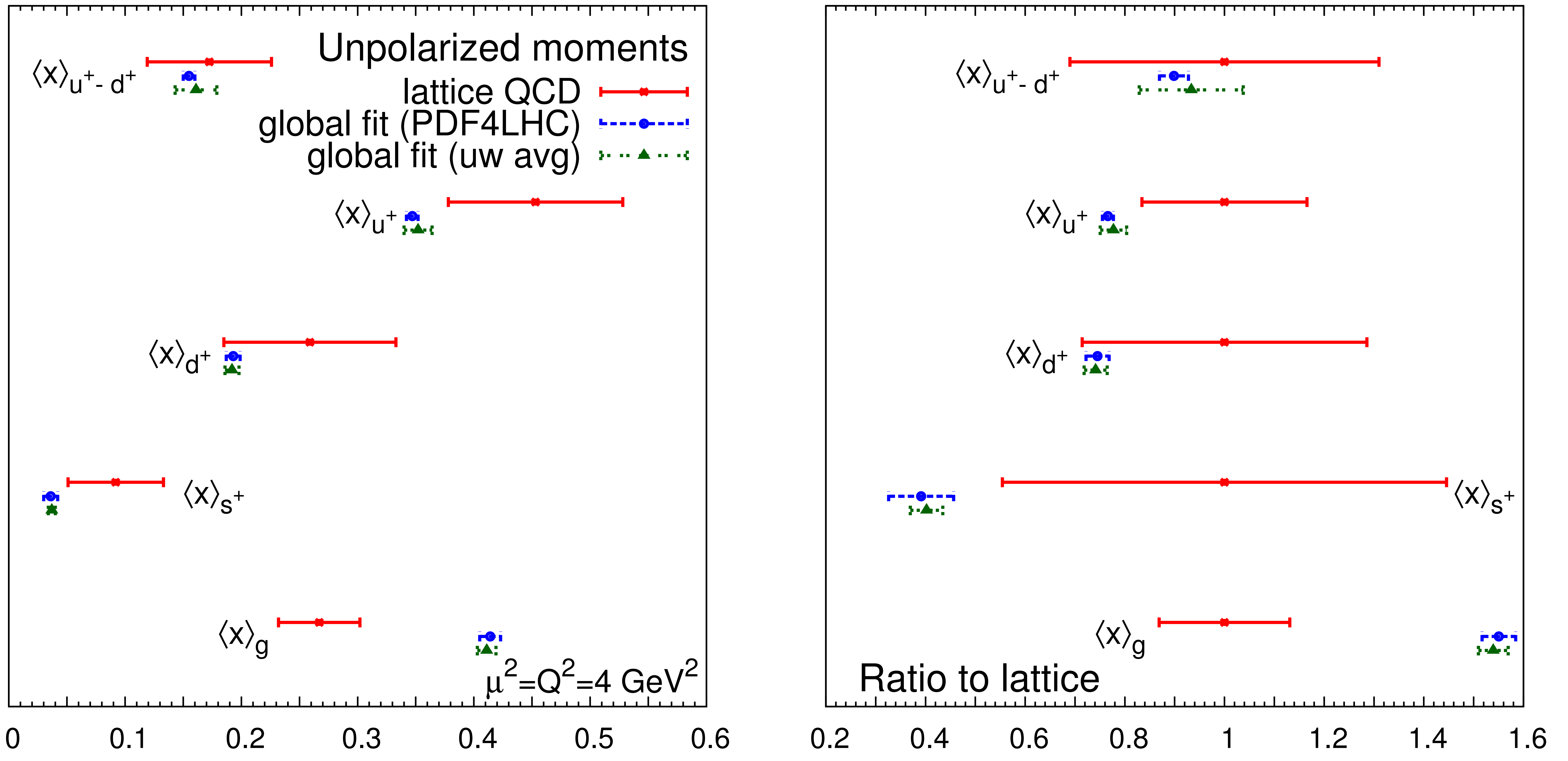


CHECK PREDICTIONS

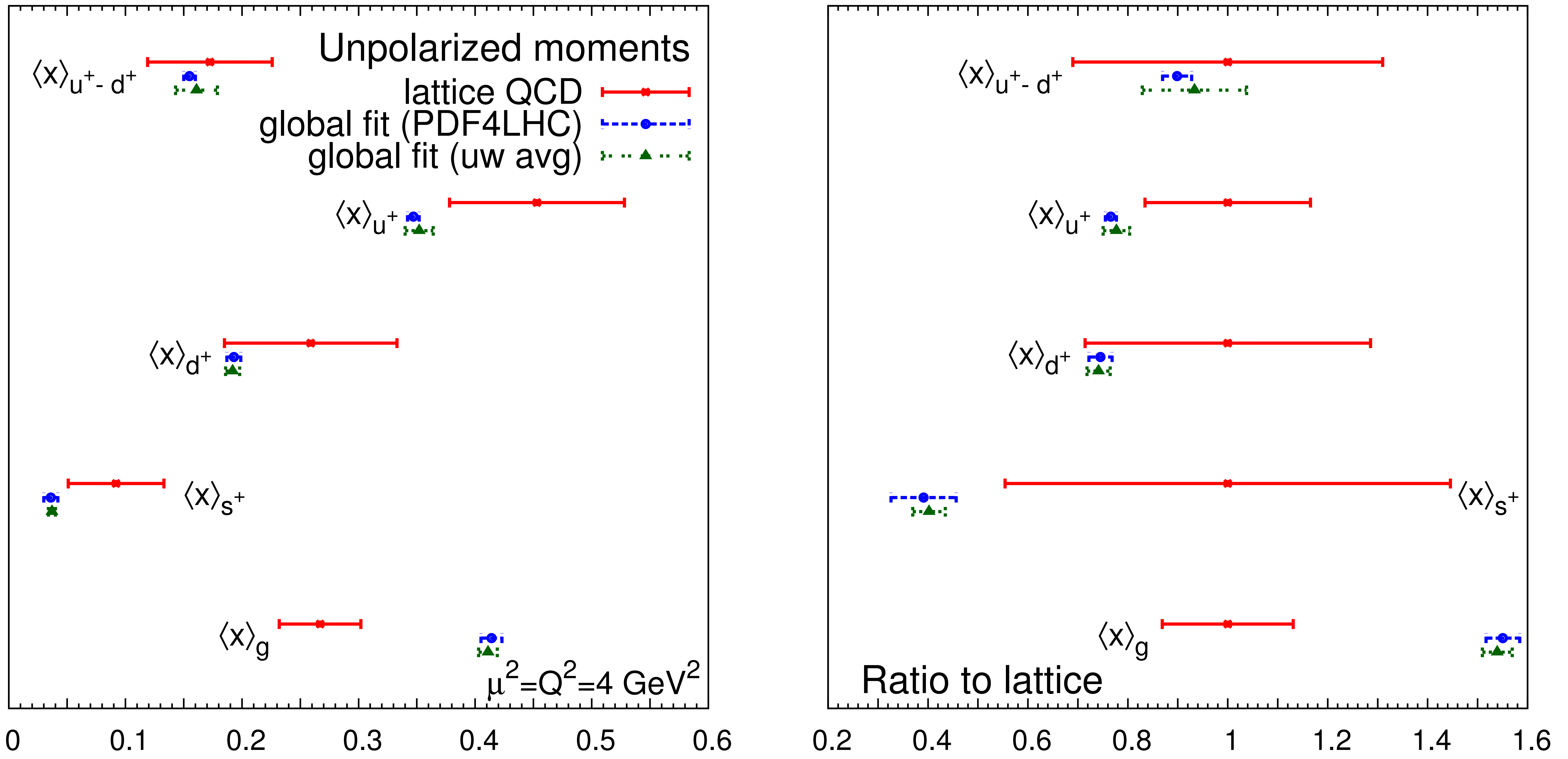


CHECK PREDICTIONS OF LATTICE QCD



PDFLattice White Paper, arXiv:1711.07916

CHECK PREDICTIONS OF LATTICE QCD

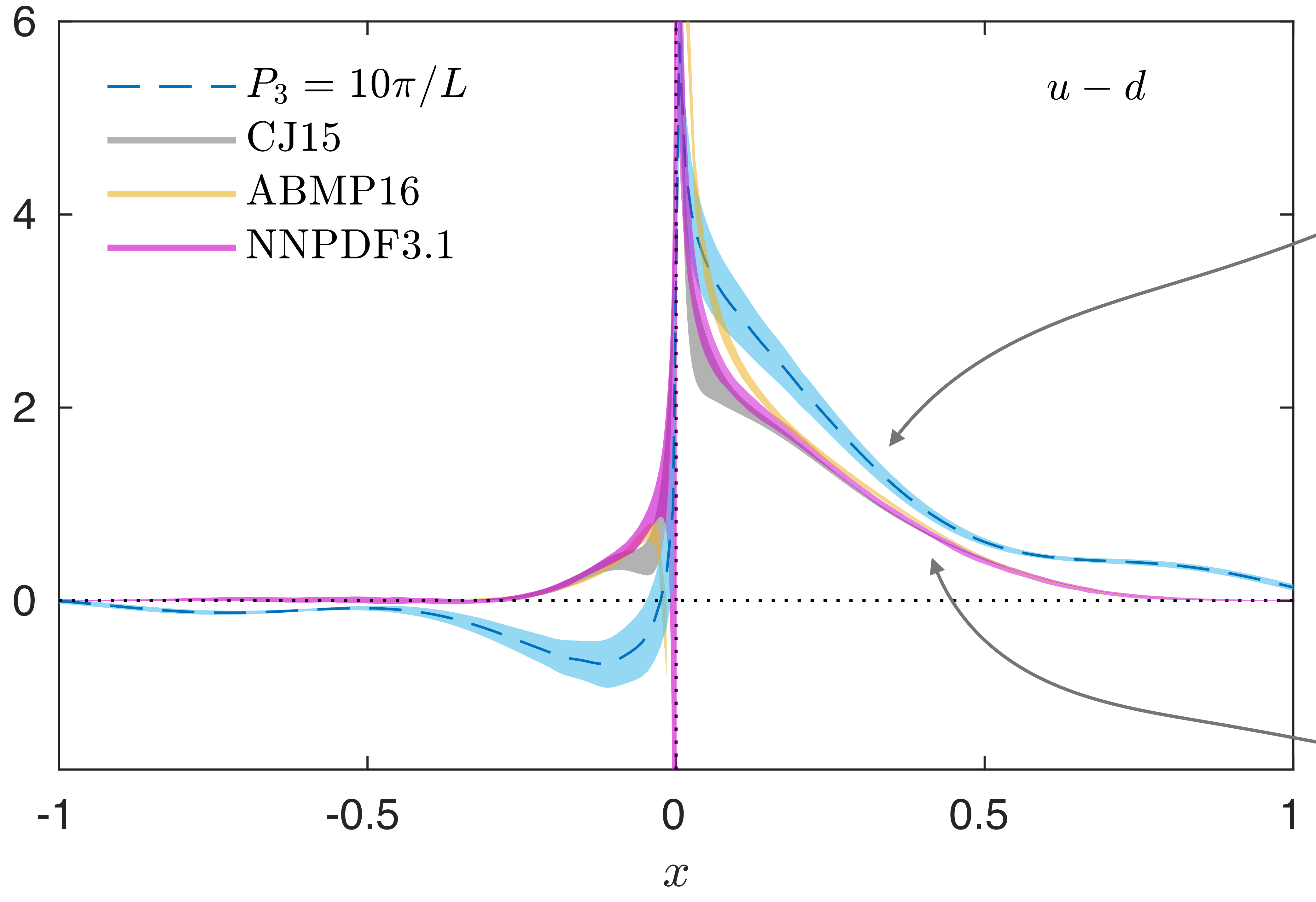


PDFLattice White Paper, arXiv:1711.07916

Fair agreement, but far from perfect

COMPARISON OF FULL PDF WITH LATTICE QCD

Alexandrou, Cichy, Constantinou, Hadjiyiannakou, Jansen, Scapellato, Steffens, arXiv:1902.00587



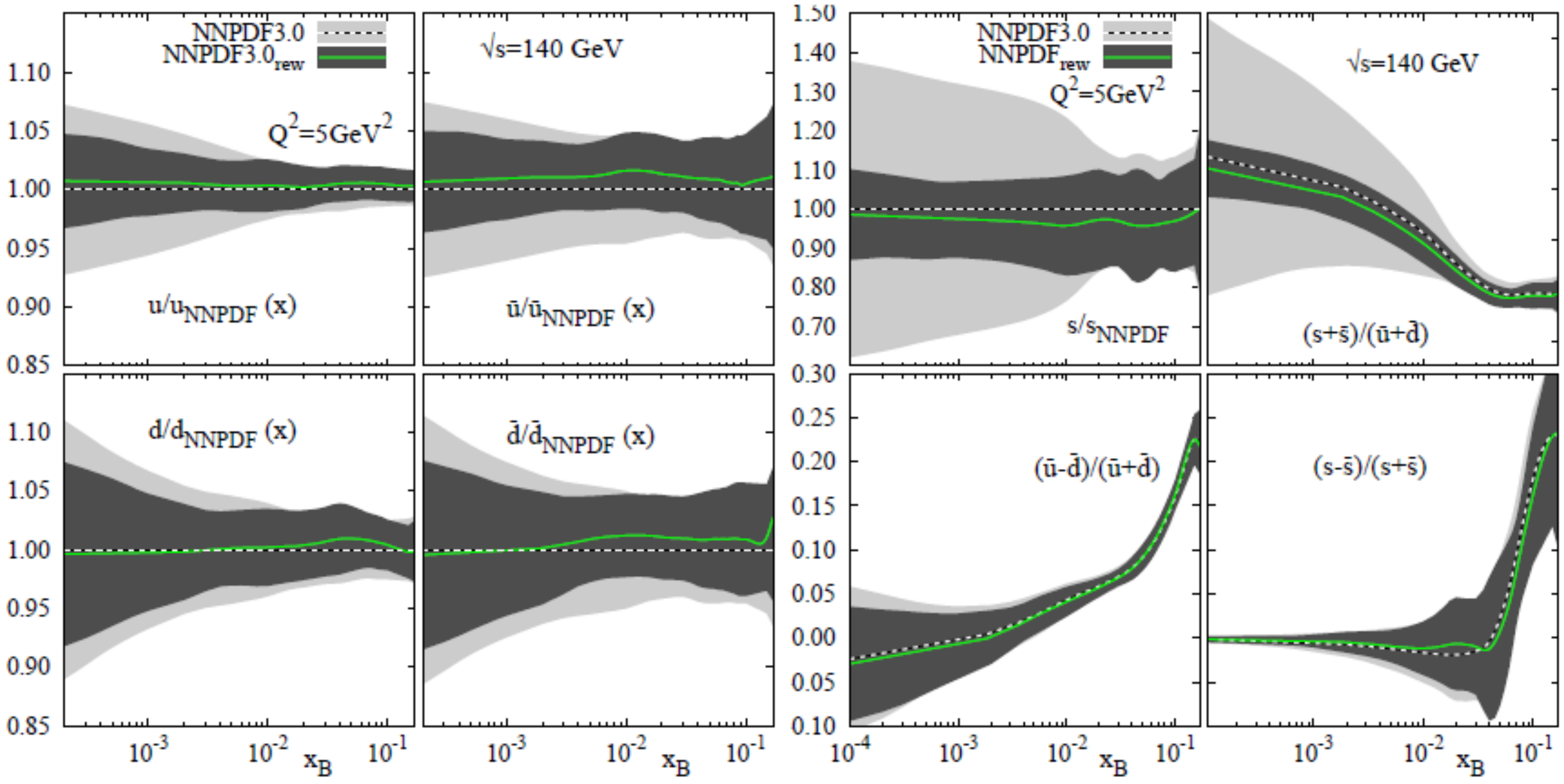
lattice calculation (quasi-PDF approach)

global fits

antiquarks

quarks

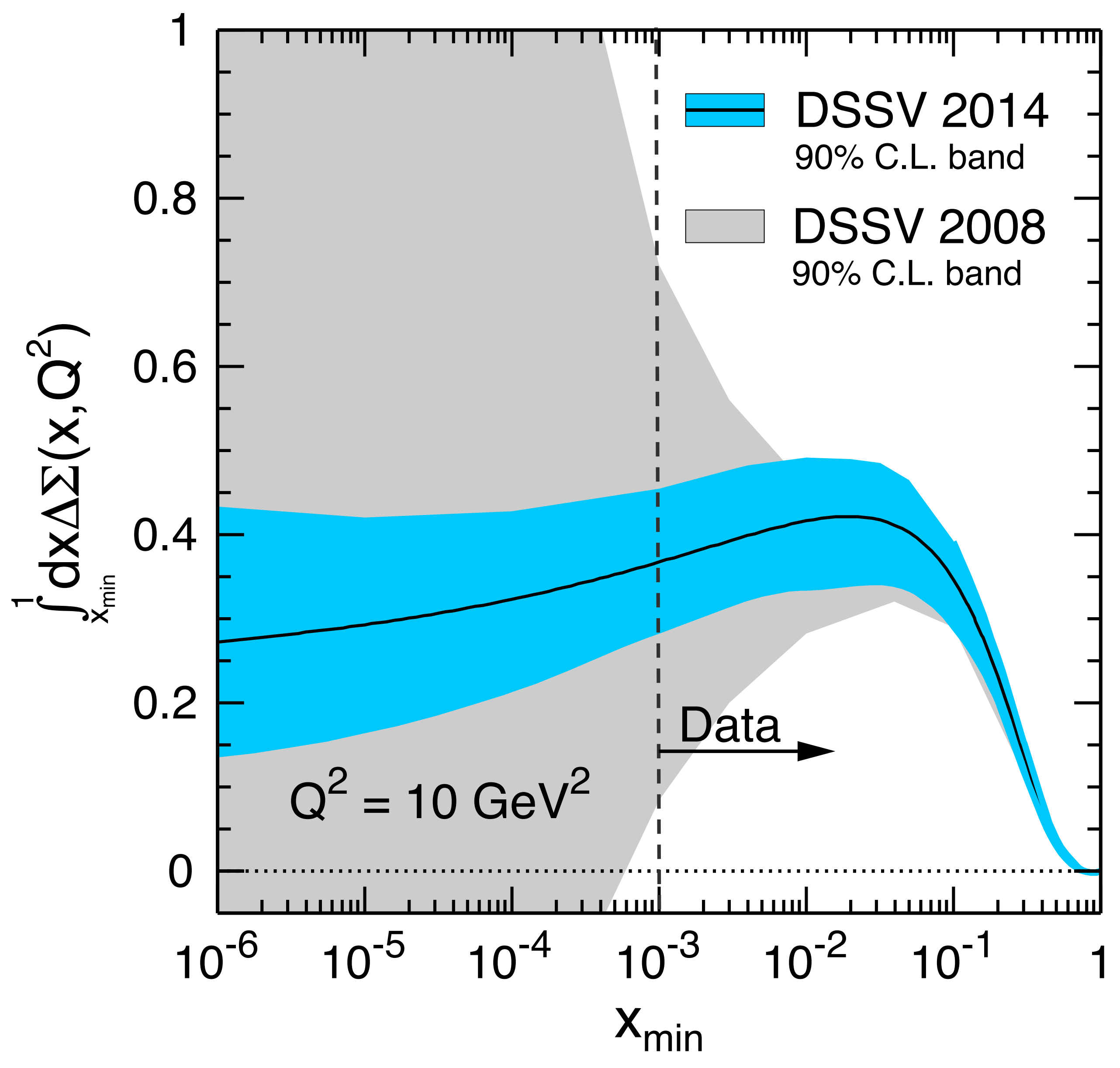
EIC IMPACT ON UNPOLARIZED PDFS



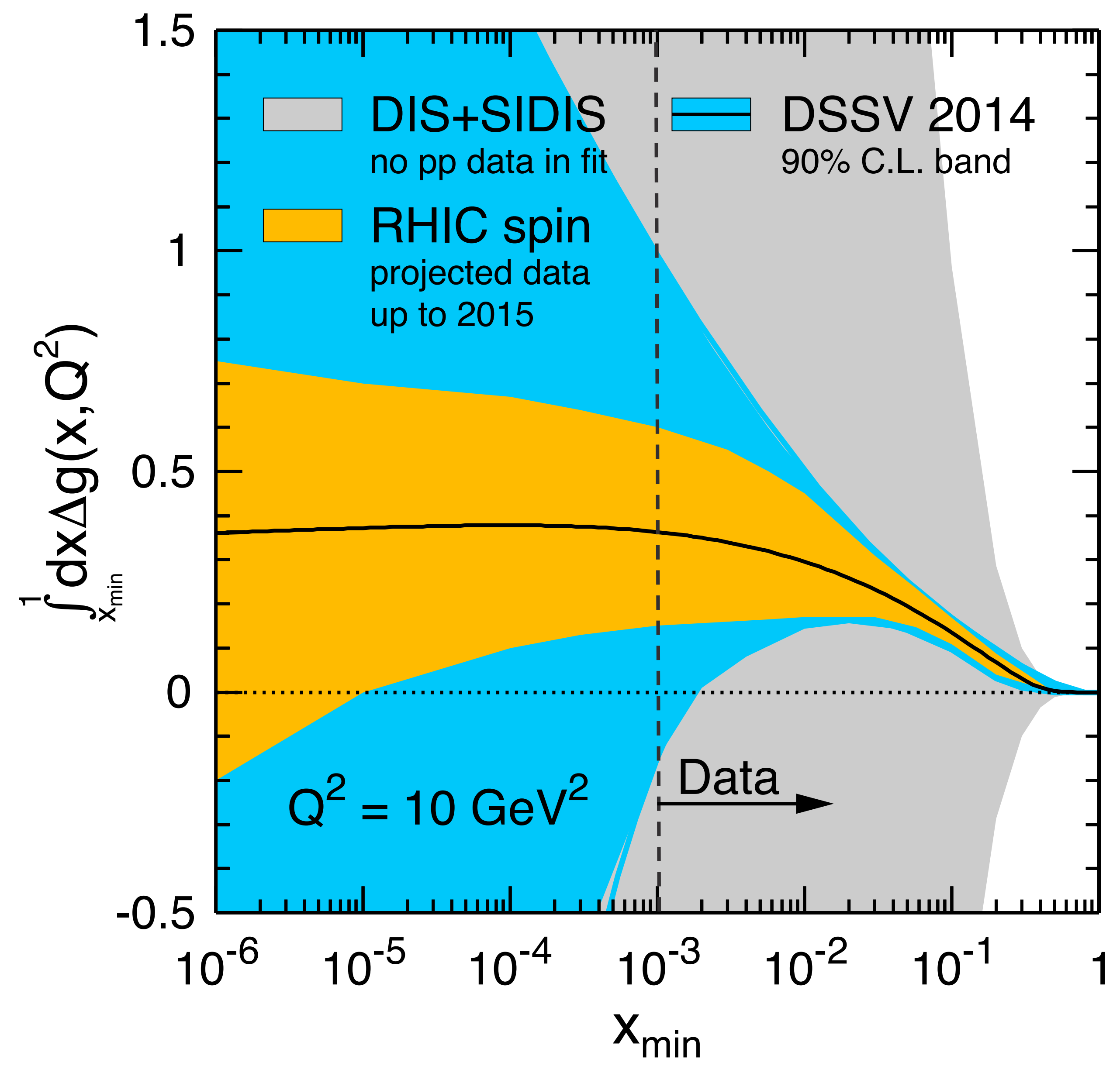
EIC IMPACT ON POLARIZED PDFS

Aschenauer et al., arXiv:1708.01527 and arXiv:1509.06489

quark spin



gluon spin



EIC IMPACT ON POLARIZED PDFS

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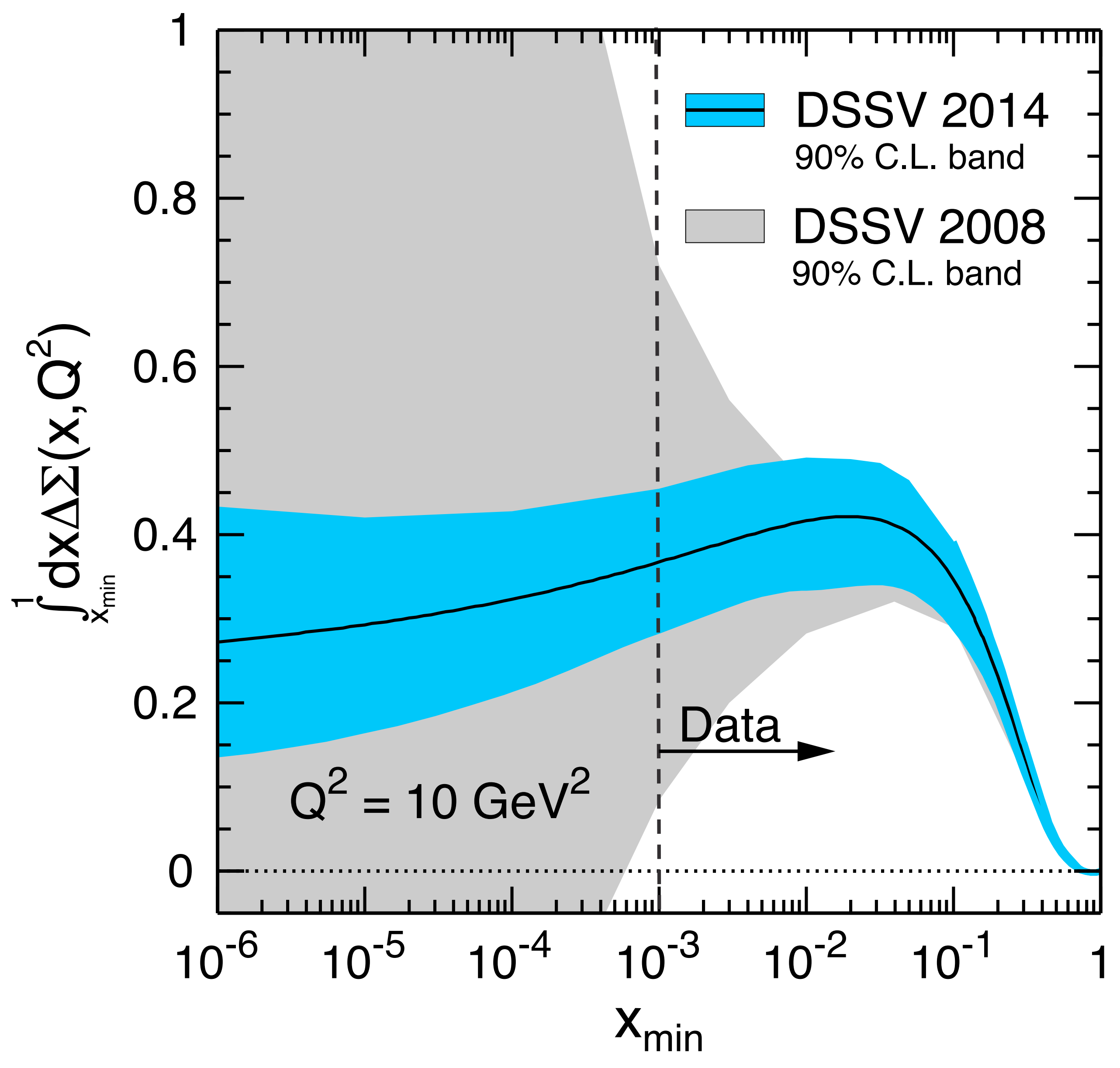
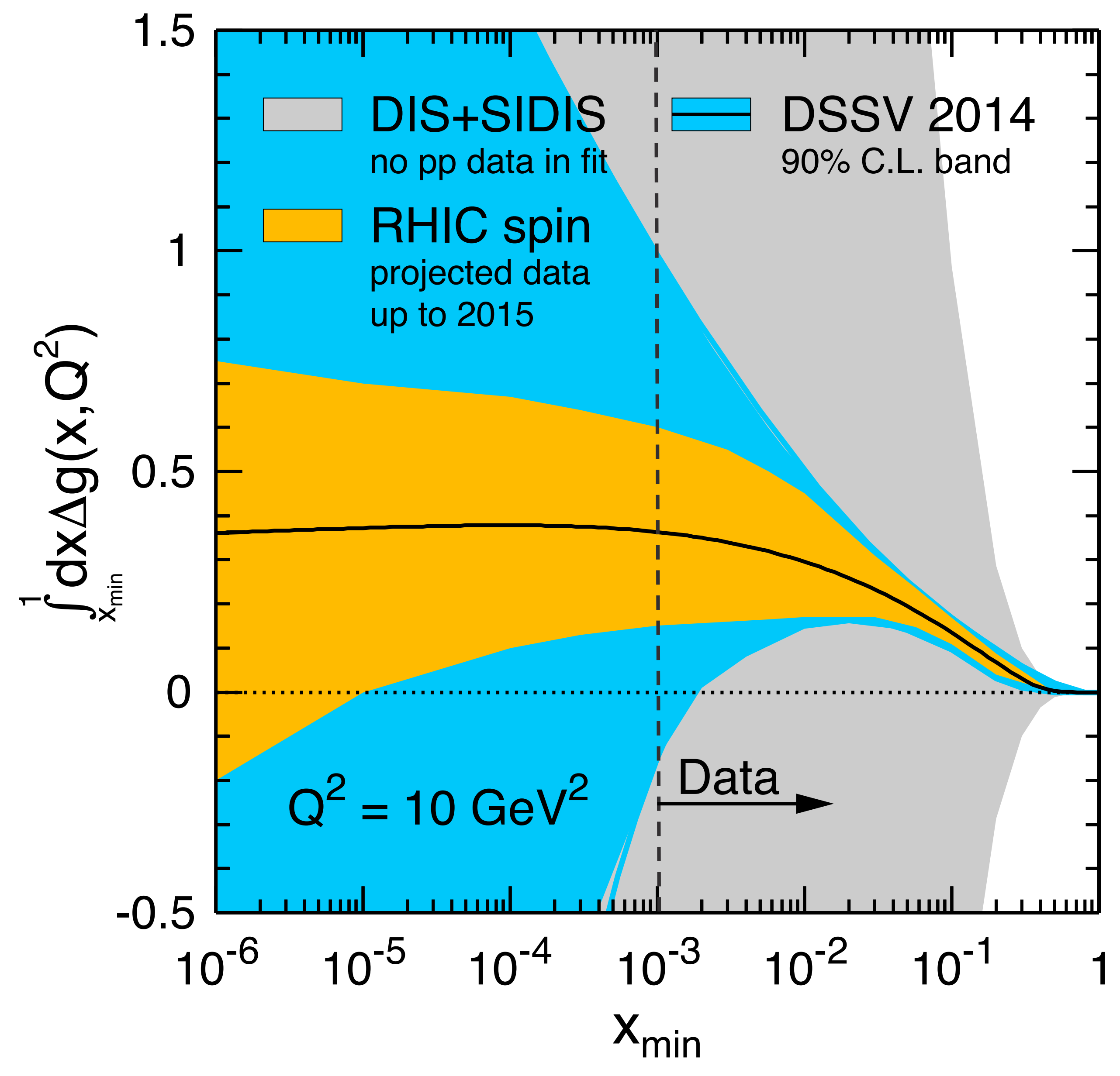
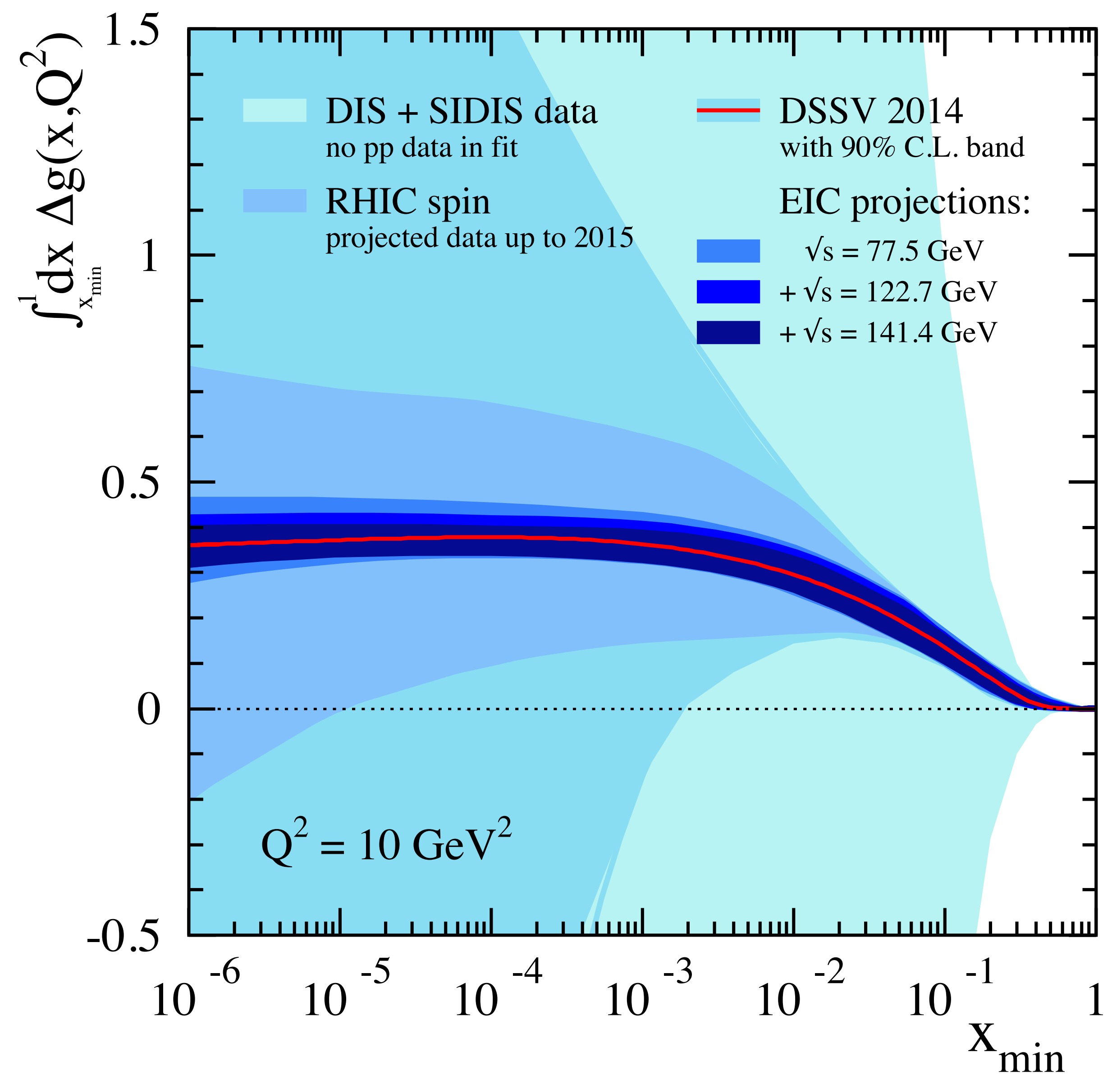


gluon spin



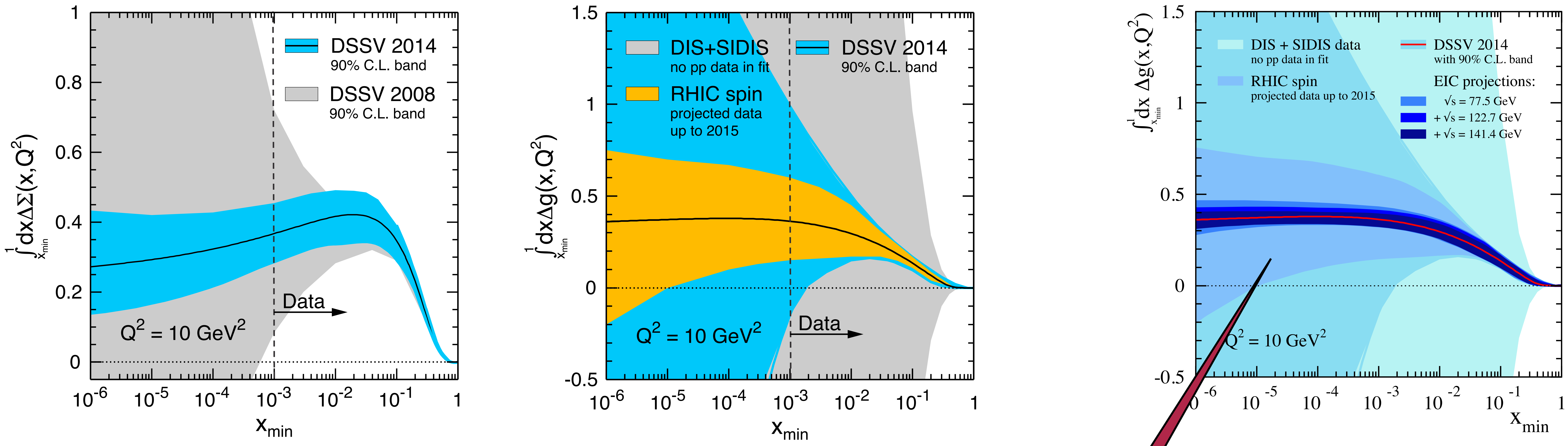
gluon spin w/ EIC



EIC IMPACT ON POLARIZED PDFS

Aschenauer et al., arXiv:1708.01527 and arXiv:1509.06489

quark spin | gluon spin | gluon spin w/ EIC



Enormous impact

EIC IMPACT ON SPIN SUM RULE

Aschenauer et al., arXiv:1708.01527 and arXiv:1509.06489

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

EIC IMPACT ON SPIN SUM RULE

Aschenauer et al., arXiv:1708.01527 and arXiv:1509.06489

quark spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

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quark spin

gluon spin

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quark spin

gluon spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

quark and gluon orbital angular momentum

EIC IMPACT ON SPIN SUM RULE

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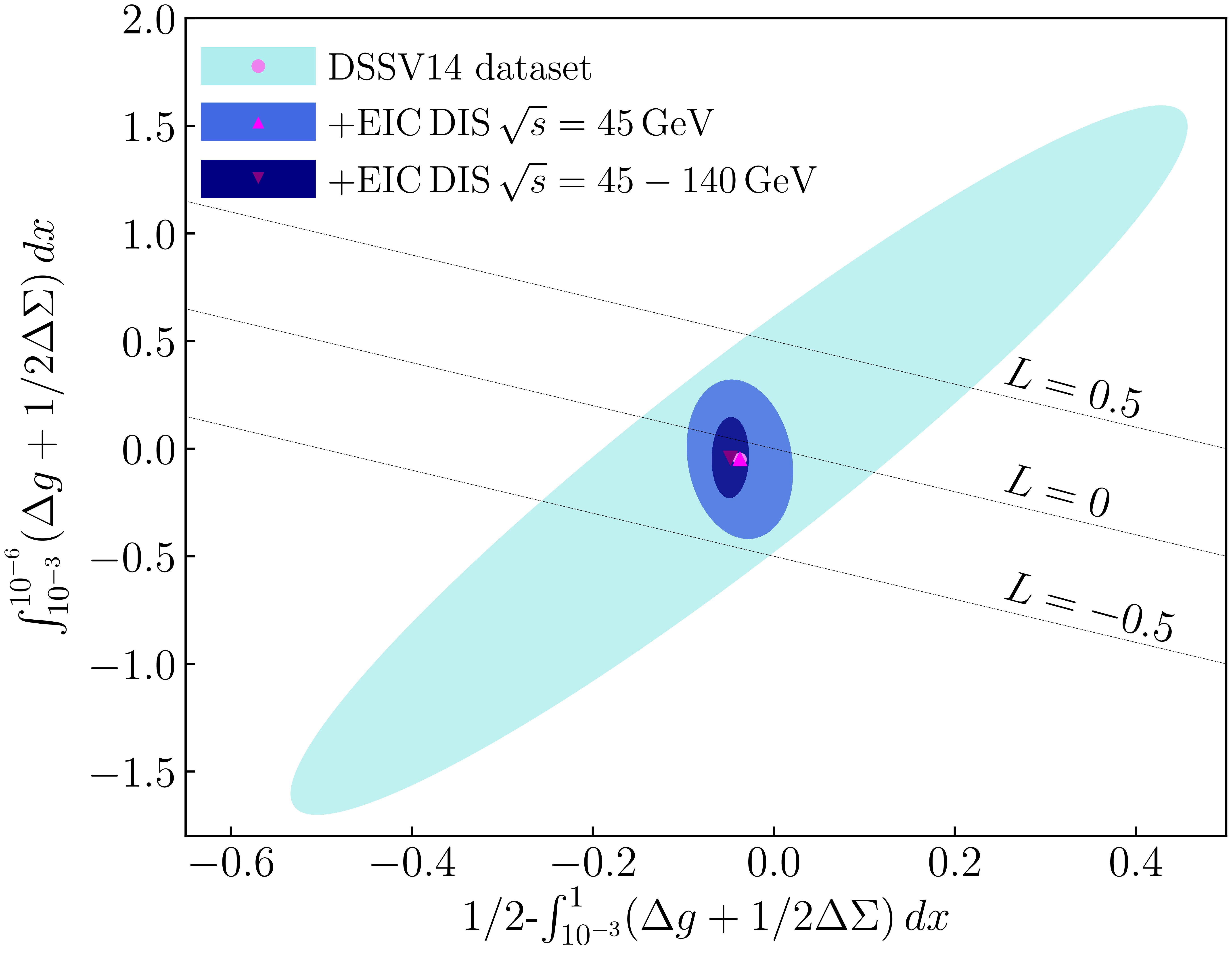


quark spin

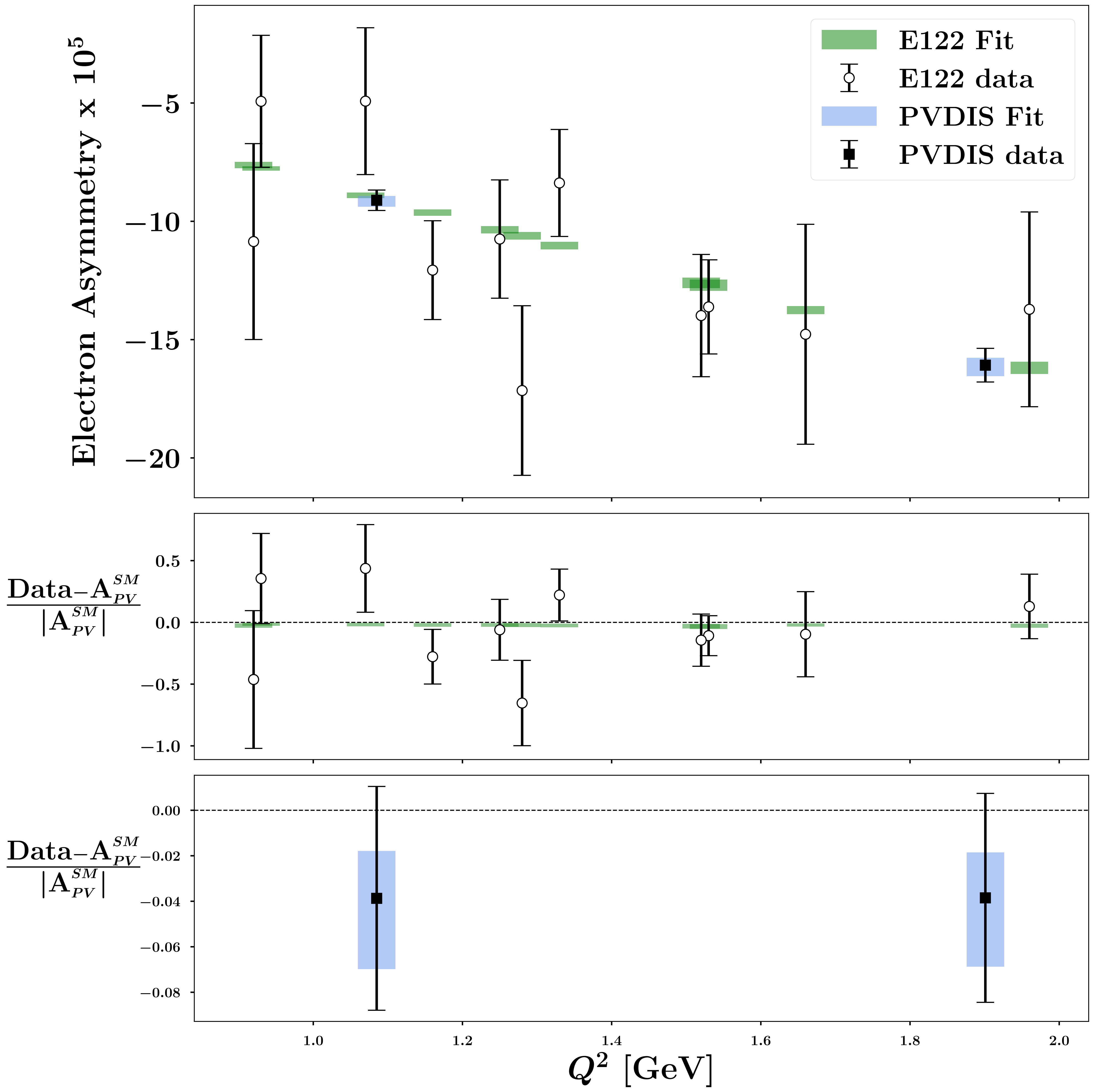
gluon spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

quark and gluon orbital angular momentum

CAN THERE STILL BE SURPRISES?

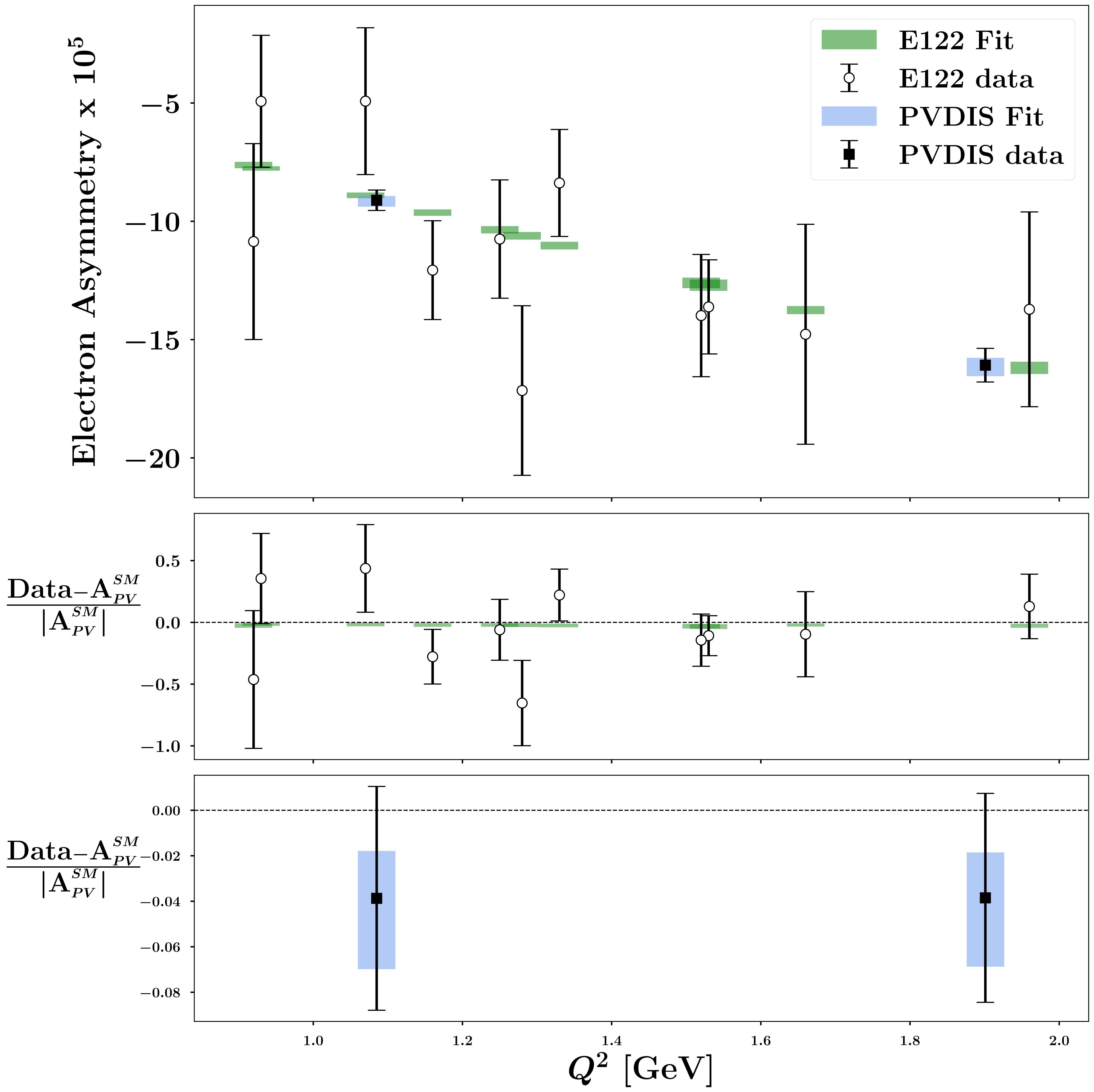
STRONG PARITY VIOLATING PDFS?



Bacchetta, Cerutti, Manna, Radici, Zheng, arxiv:2306.04704

A_{PV} asymmetry (with polarized leptons)

STRONG PARITY VIOLATING PDFS?

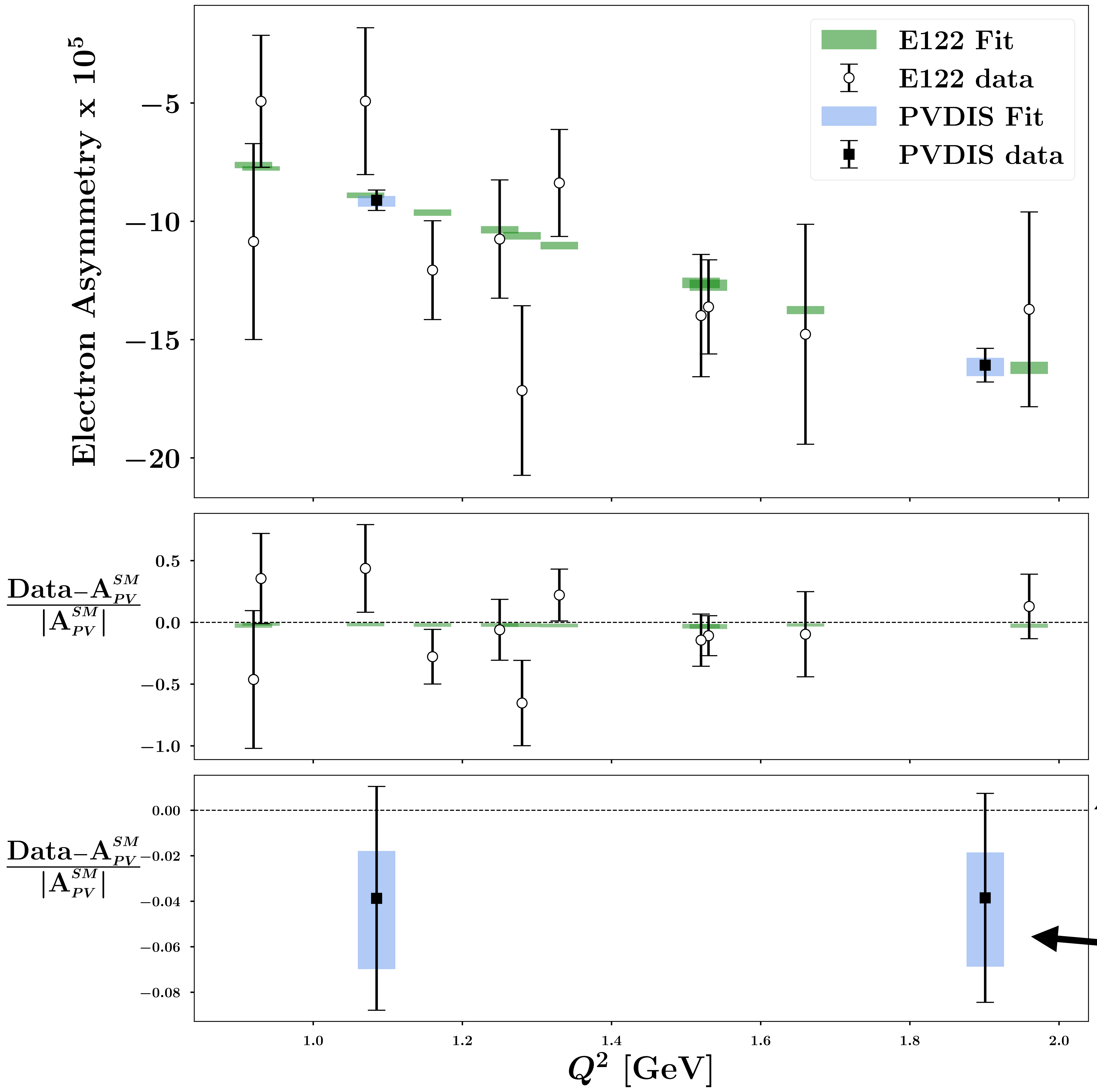


[Bacchetta, Cerutti, Manna, Radici, Zheng, arxiv:2306.04704]

A_{PV} asymmetry (with polarized leptons)

Standard Model prediction

STRONG PARITY VIOLATING PDFS?



Bacchetta, Cerutti, Manna, Radici, Zheng, arxiv:2306.04704

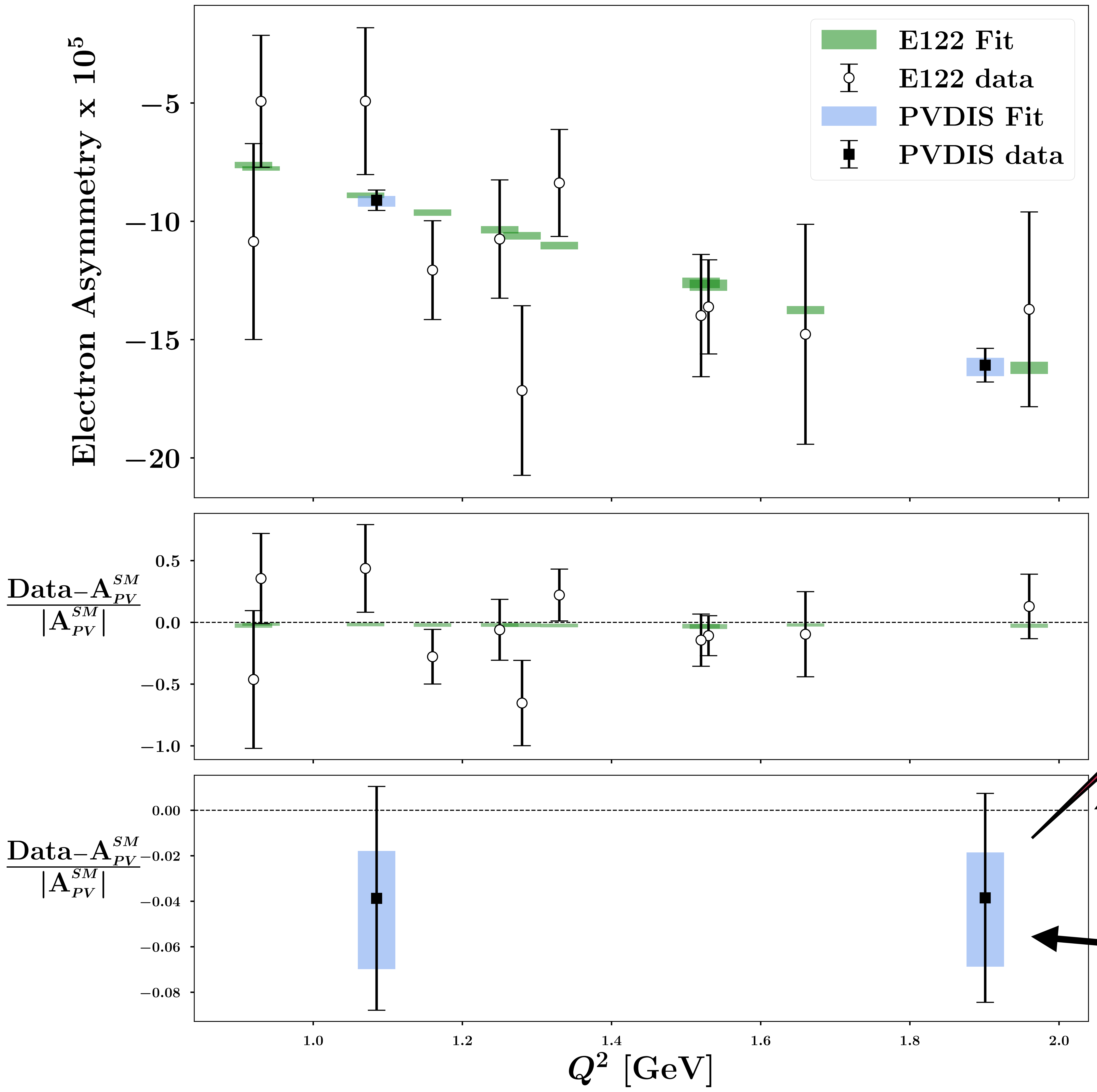
A_{PV} asymmetry (with polarized leptons)

Standard Model prediction

Fit with the inclusion of a strong parity violating parton distribution function

STRONG PARITY VIOLATING PDFS?

Bacchetta, Cerutti, Manna, Radici, Zheng, arxiv:2306.04704



A_{PV} asymmetry (with polarized leptons)

Precise DIS data may expose signals of strong parity violation

Standard Model prediction

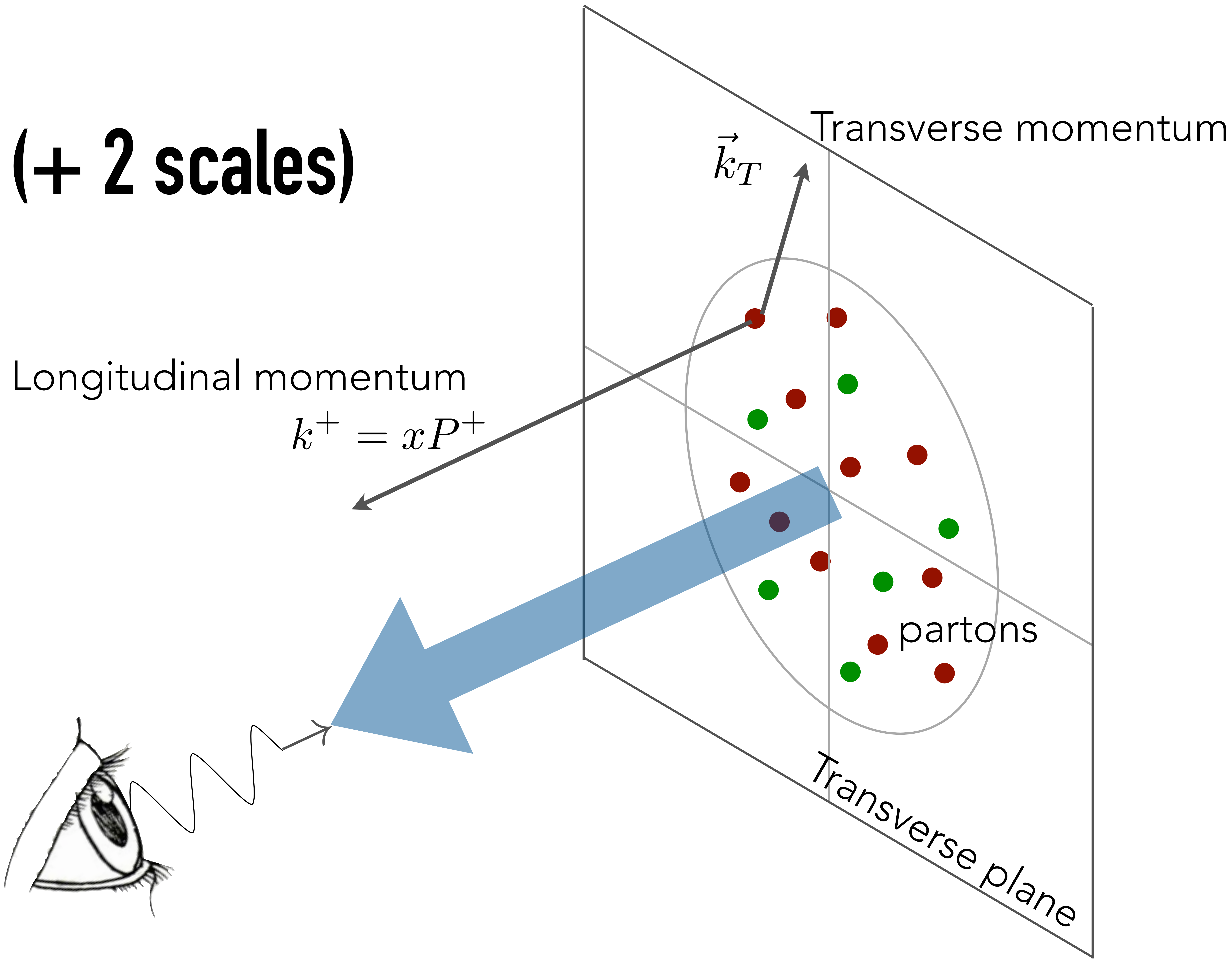
Fit with the inclusion of a strong parity violating parton distribution function

3-DIMENSIONAL MAPS

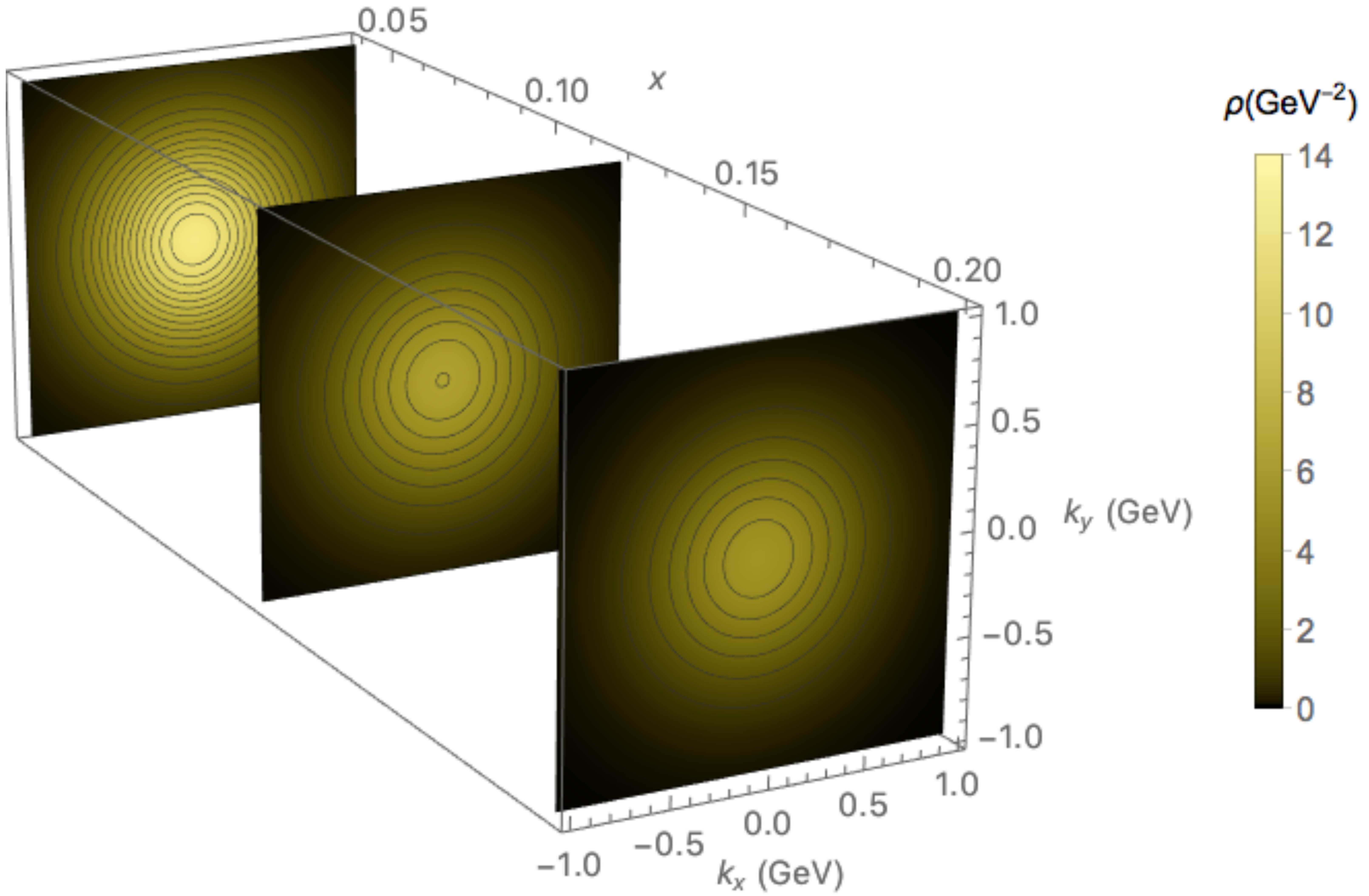
Transverse-Momentum Distributions

$f(x, \vec{k}_T)$

3 dimensional (+ 2 scales)

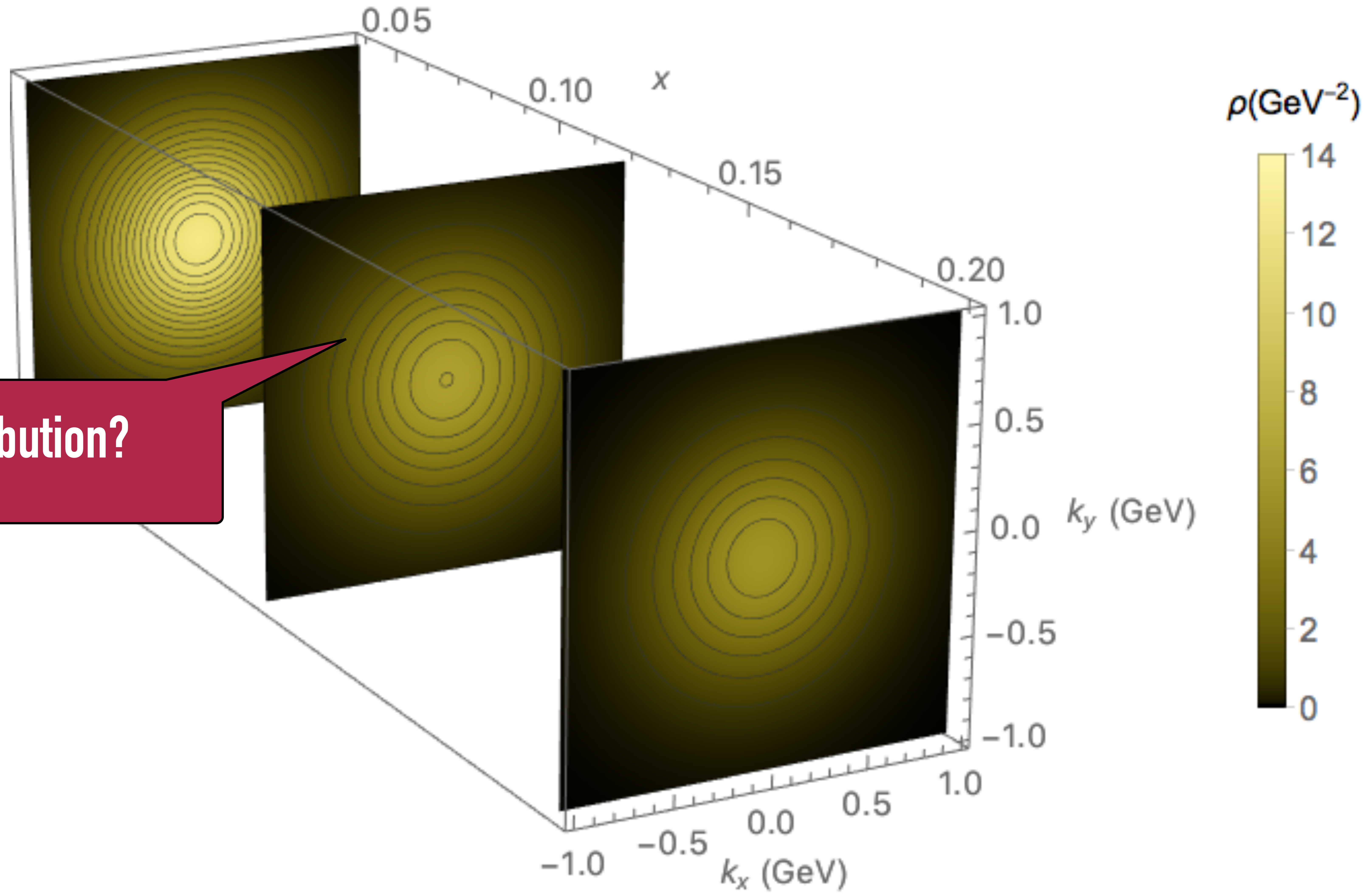


QUESTIONS



0.05
0.10
x
0.15
0.20
1.0
0.5
0.0
−0.5
−1.0
k_y (GeV)
−1.0
−0.5
0.0
0.5
1.0
k_x (GeV)
ρ(GeV⁻²)
14
12
10
8
6
4
2
0

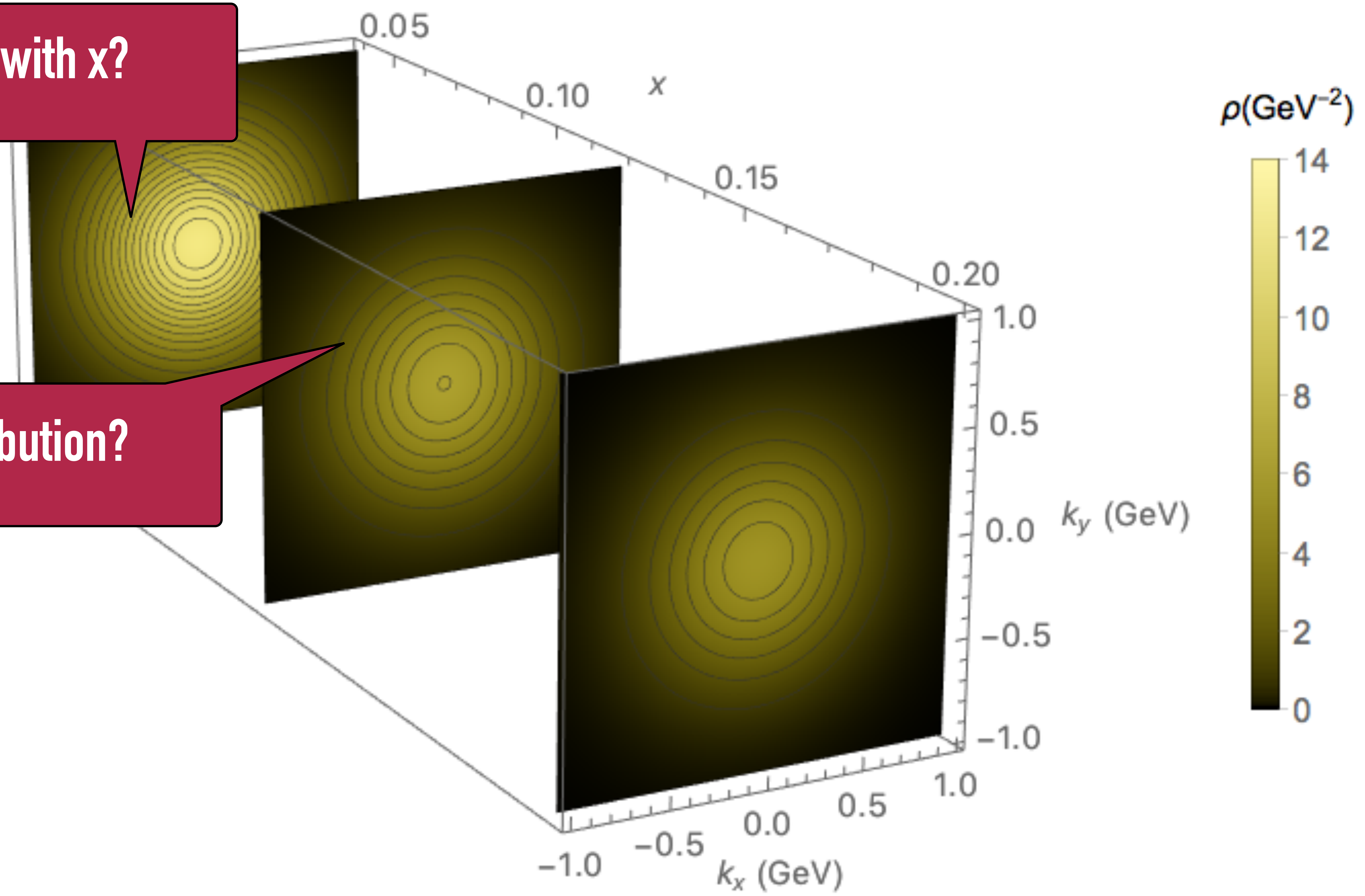
QUESTIONS



How “wide” is the distribution?

QUESTIONS

How does it change with x?



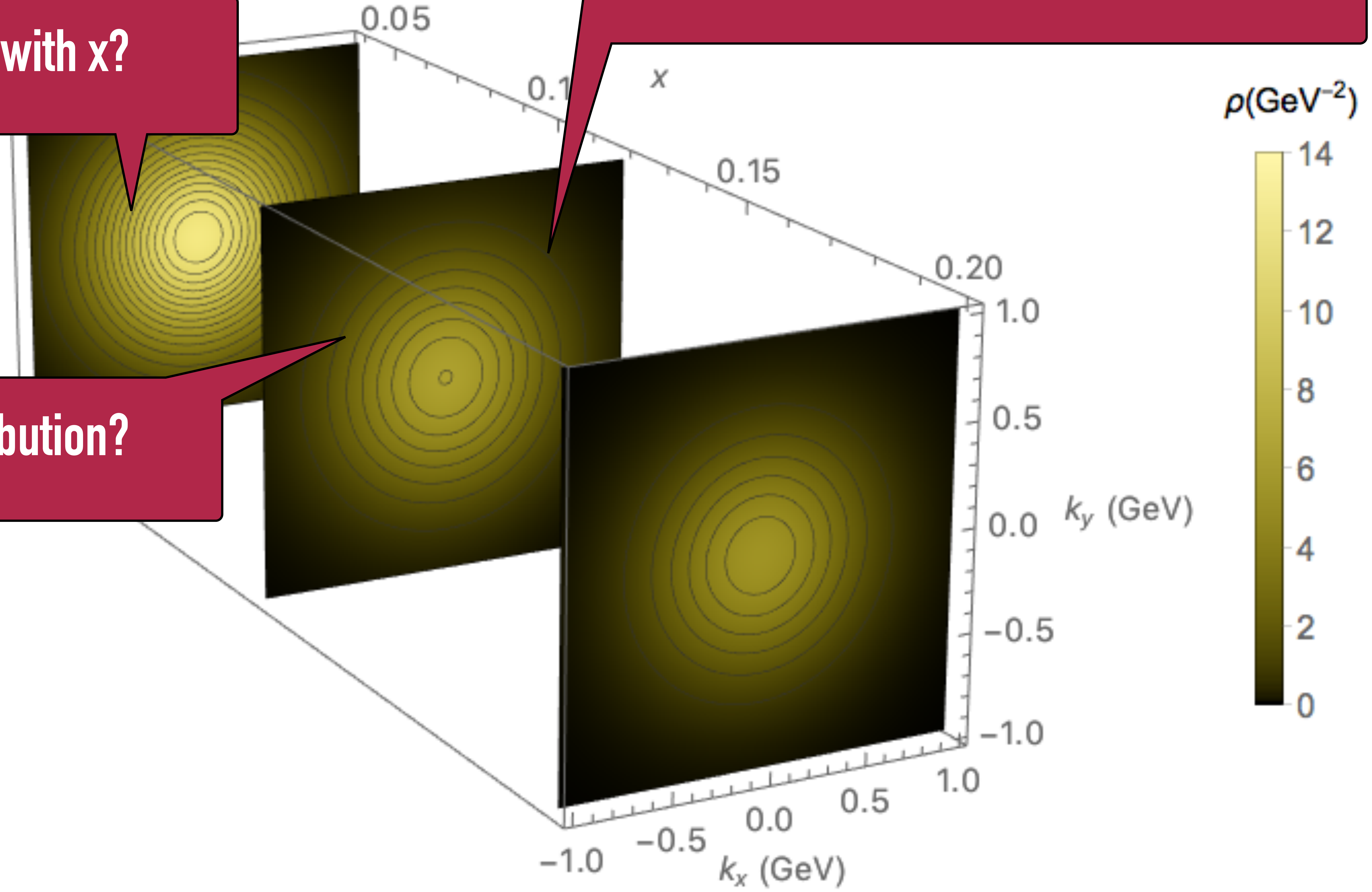
How “wide” is the distribution?

QUESTIONS

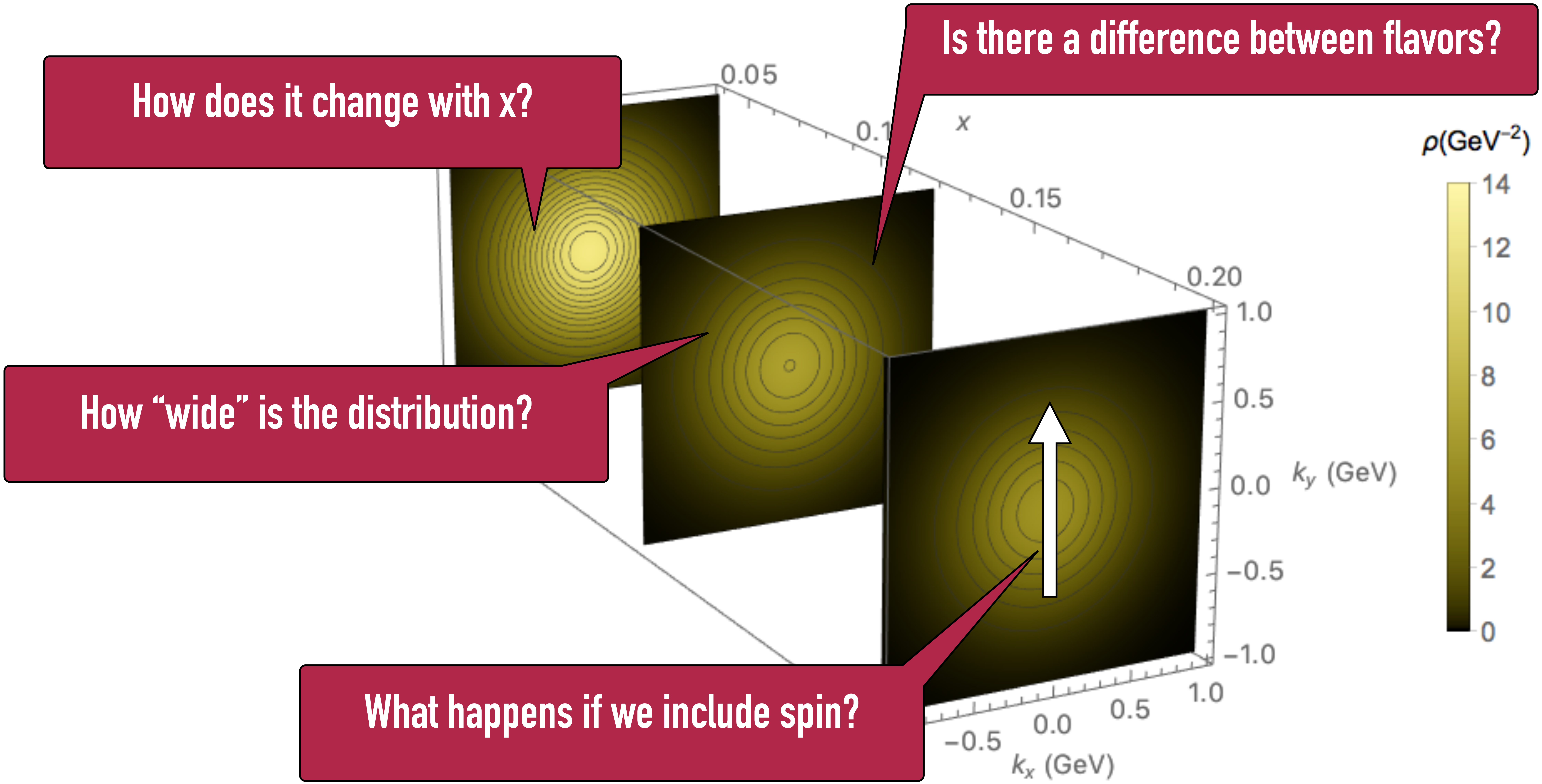
How does it change with x?

Is there a difference between flavors?

How “wide” is the distribution?

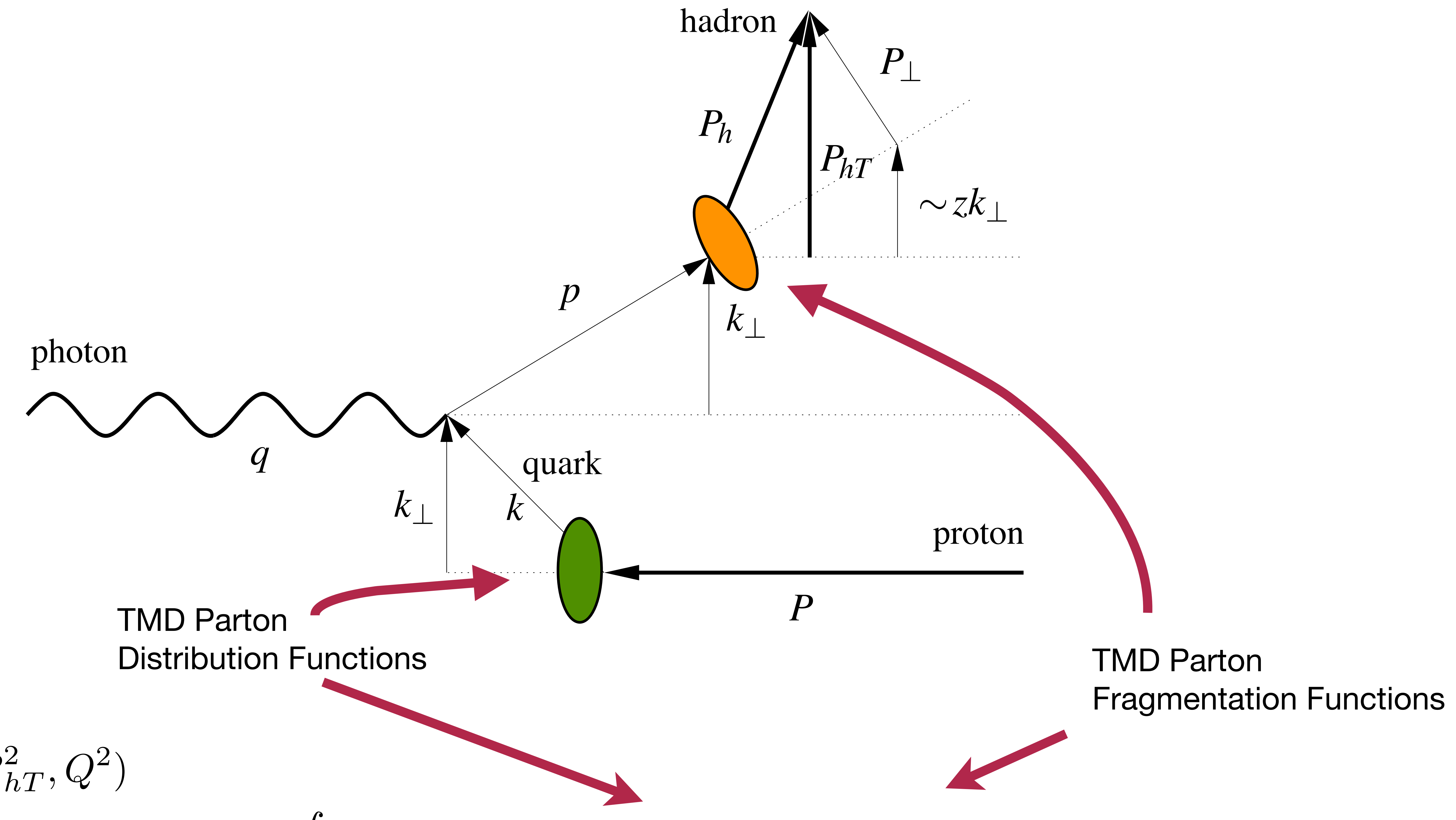


QUESTIONS



How does it change with x?
Is there a difference between flavors?
How "wide" is the distribution?
What happens if we include spin?
0.05
0.1
0.15
0.20
x
1.0
0.5
0.0
−0.5
−1.0
k_y (GeV)
−0.5
0.0
0.5
1.0
k_x (GeV)
$\rho(\mathrm{GeV}^{-2})$
14
12
10
8
6
4
2
0

TMDS IN SEMI-INCLUSIVE DIS (SIDIS)



$$F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2)$$

$$= x \sum_q \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int d^2\boldsymbol{k}_\perp \, d^2\boldsymbol{P}_\perp \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu^2) \, D_1^{a\to h}(z, \boldsymbol{P}_\perp^2; \mu^2) \, \delta(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp)$$

$$= x \sum_a \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int db_T b_T J_0(b_T|\boldsymbol{P}_{h\perp}|) \hat{f}_1^q(x, z^2 b_\perp^2; \mu^2) \, \hat{D}_1^{a\to h}(z, b_\perp^2; \mu^2)$$

TMD STRUCTURE

$$\hat{f}_1^a(x, |\boldsymbol{b}_T|; \mu, \zeta) = \int d^2\boldsymbol{k}_\perp \, e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp} \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu, \zeta)$$

see, e.g., Collins, "Foundations of Perturbative QCD" (11)
TMD collaboration, "TMD Handbook," arXiv:2304.03302

TMD STRUCTURE

$$\hat{f}_1^a(x, |\boldsymbol{b}_T|; \mu, \zeta) = \int d^2\boldsymbol{k}_\perp \, e^{i\boldsymbol{b}_T \cdot \boldsymbol{k}_\perp} \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu, \zeta)$$

$$\hat{f}_1^a(x, b_T^2; \mu_f, \zeta_f) = [C \, \otimes \, f_1](x, \mu_{b_*}) \; e^{\int_{\mu_{b_*}}^{\mu_f} \frac{d\mu}{\mu} \left(\gamma_F - \gamma_K \, \ln \, \frac{\sqrt{\zeta_f}}{\mu}\right)} \left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\mathrm{resum}} + g_K}$$

see, e.g., Collins, "Foundations of Perturbative QCD" (11)
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TMD STRUCTURE

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$$\mu_b = \frac{2e^{-\gamma_E}}{b_T}$$

see, e.g., Collins, "Foundations of Perturbative QCD" (11)
TMD collaboration, "TMD Handbook," arXiv:2304.03302

TMD STRUCTURE

$$\hat{f}_1^a(x, |\boldsymbol{b}_T|; \mu, \zeta) = \int d^2\boldsymbol{k}_\perp \, e^{i\boldsymbol{b}_T \cdot \boldsymbol{k}_\perp} \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu, \zeta)$$

perturbative Sudakov
form factor

$$\hat{f}_1^a(x, b_T^2; \mu_f, \zeta_f) = [C \otimes f_1](x, \mu_{b_*}) \, e^{\int_{\mu_{b_*}}^{\mu_f} \frac{d\mu}{\mu} \left(\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_f}}{\mu}\right)} \left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\mathrm{resum}} + g_K}$$

collinear PDF

Collins-Soper kernel
(perturbative and
nonperturbative)

$$\mu_b = \frac{2e^{-\gamma_E}}{b_T}$$

matching coefficients
(perturbative)

[see, e.g., Collins, "Foundations of Perturbative QCD" (11)](#)
[TMD collaboration, "TMD Handbook," arXiv:2304.03302](#)

TMD STRUCTURE

$$\hat{f}_1^a(x, |\boldsymbol{b}_T|; \mu, \zeta) = \int d^2\boldsymbol{k}_\perp \, e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp} \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu, \zeta)$$

perturbative Sudakov form factor

$$\hat{f}_1^a(x, b_T^2; \mu_f, \zeta_f) = [C \otimes f_1](x, \mu_{b_*}) \, e^{\int_{\mu_{b_*}}^{\mu_f} \frac{d\mu}{\mu} \left(\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_f}}{\mu}\right)} \left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\text{resum}} + g_K}$$

collinear PDF

matching coefficients (perturbative)

Collins-Soper kernel (perturbative and nonperturbative)

$$\mu_b = \frac{2e^{-\gamma_E}}{b_T}$$

$$\Downarrow$$

$$\mu_{b*} = \frac{2e^{-\gamma_E}}{\bar{b}_*}$$

see, e.g., Collins, "Foundations of Perturbative QCD" (11)
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TMD STRUCTURE

$$\hat{f}_1^a(x, |\boldsymbol{b}_T|; \mu, \zeta) = \int d^2\boldsymbol{k}_\perp \, e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp} \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu, \zeta)$$

perturbative Sudakov form factor

$$\hat{f}_1^a(x, b_T^2; \mu_f, \zeta_f) = [C \otimes f_1](x, \mu_{b_*}) \; e^{\int_{\mu_{b_*}}^{\mu_f} \frac{d\mu}{\mu} \left(\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_f}}{\mu}\right)} \left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\text{resum}} + g_K} f_{1\,NP}(x, b_T^2; \zeta_f, Q_0)$$

collinear PDF

matching coefficients (perturbative)

Collins-Soper kernel (perturbative and nonperturbative)

nonperturbative part of TMD

$$\mu_b = \frac{2e^{-\gamma_E}}{b_T}$$

$$\Downarrow$$

$$\mu_{b^*} = \frac{2e^{-\gamma_E}}{\bar{b}_*}$$

see, e.g., Collins, "Foundations of Perturbative QCD" (11)
TMD collaboration, "TMD Handbook," arXiv:2304.03302

TMD GLOBAL FITS

	Accuracy	SIDIS HERMES	SIDIS COMPASS	DY fixed target	DY collider	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059	1.55
SV 2019 arXiv:1912.06532	N^3LL^-	✔	✔	✔	✔	1039	1.06
MAP22 arXiv:2206.07598	N^3LL^-	✔	✔	✔	✔	2031	1.06

RESULTING TMDS

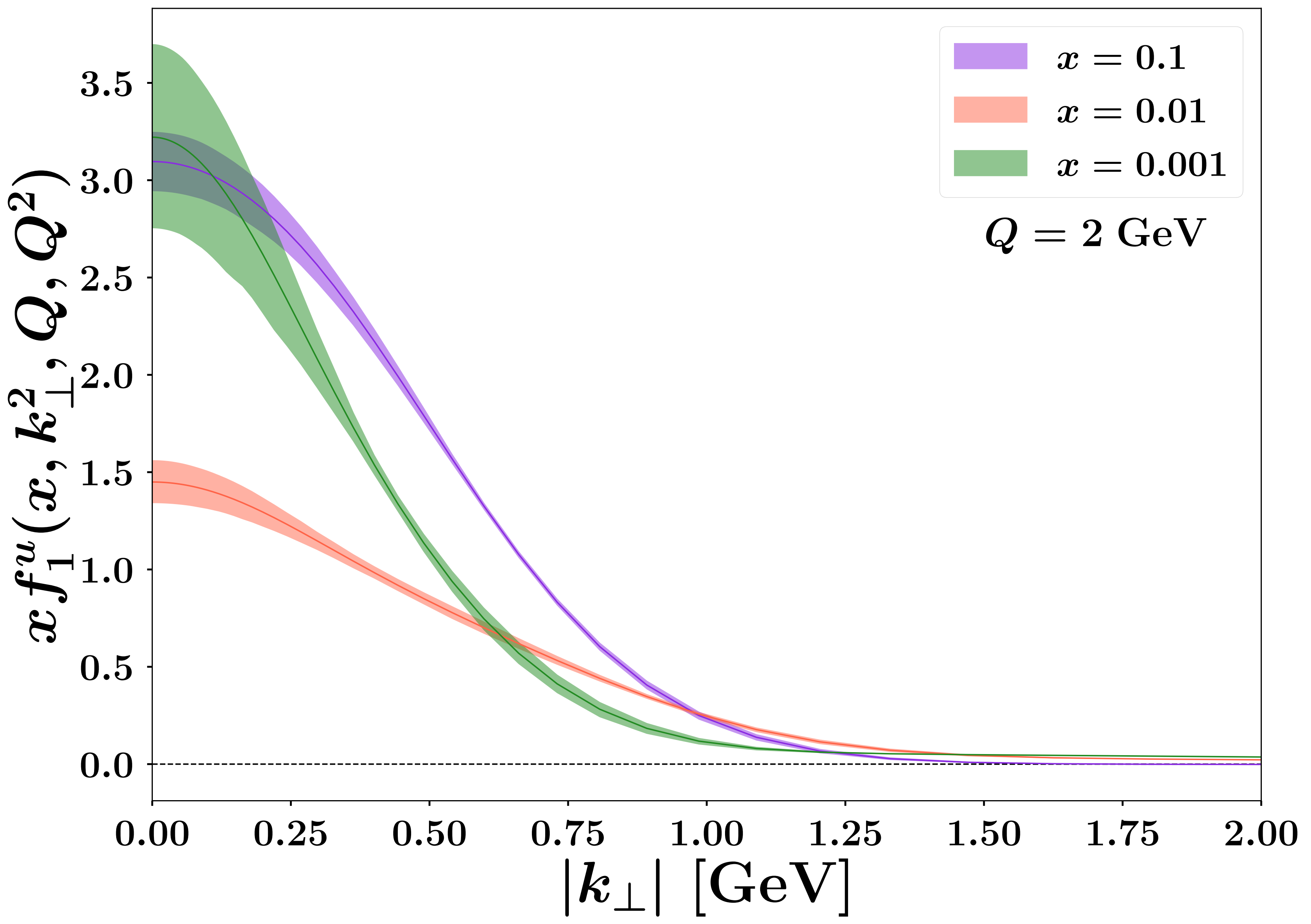


FIG. 13: The TMD PDF of the up quark in a proton at $\mu = \sqrt{\zeta} = Q = 2$ GeV (left panel) and 10 GeV (right panel) as a function of the partonic transverse momentum $|\boldsymbol{k}_\perp|$ for $x = 0.001$, 0.01 and 0.1. The uncertainty bands represent the 68% CL.

RESULTING TMDS

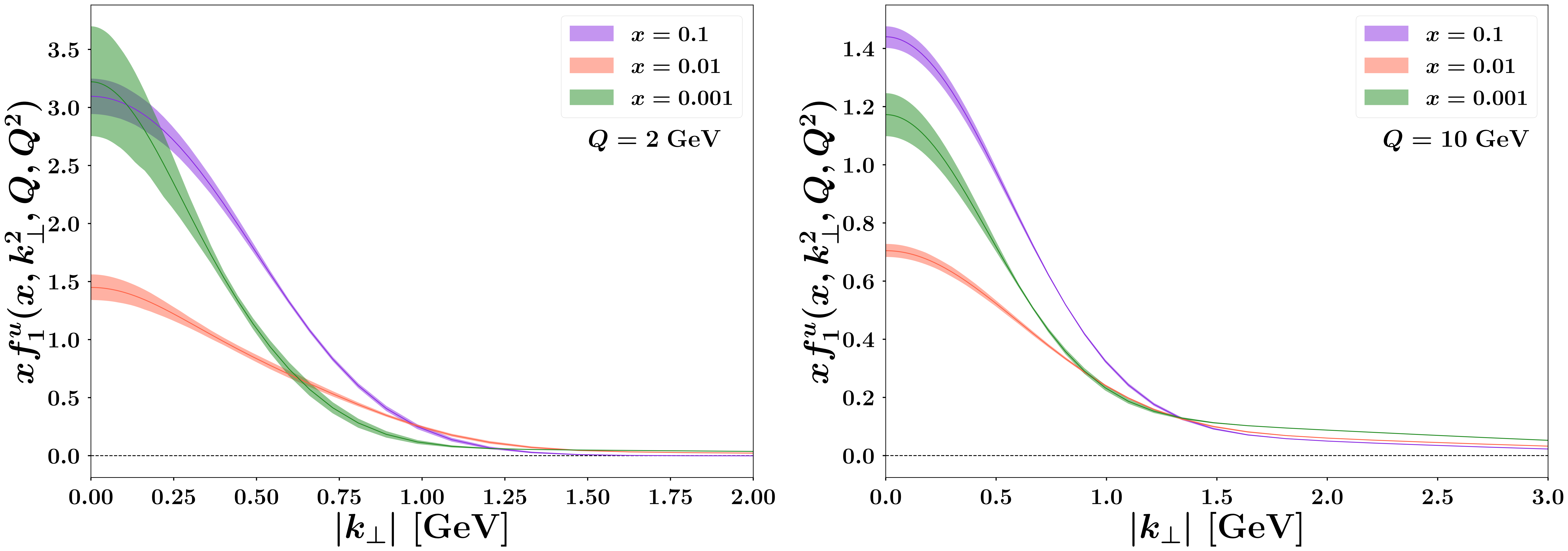
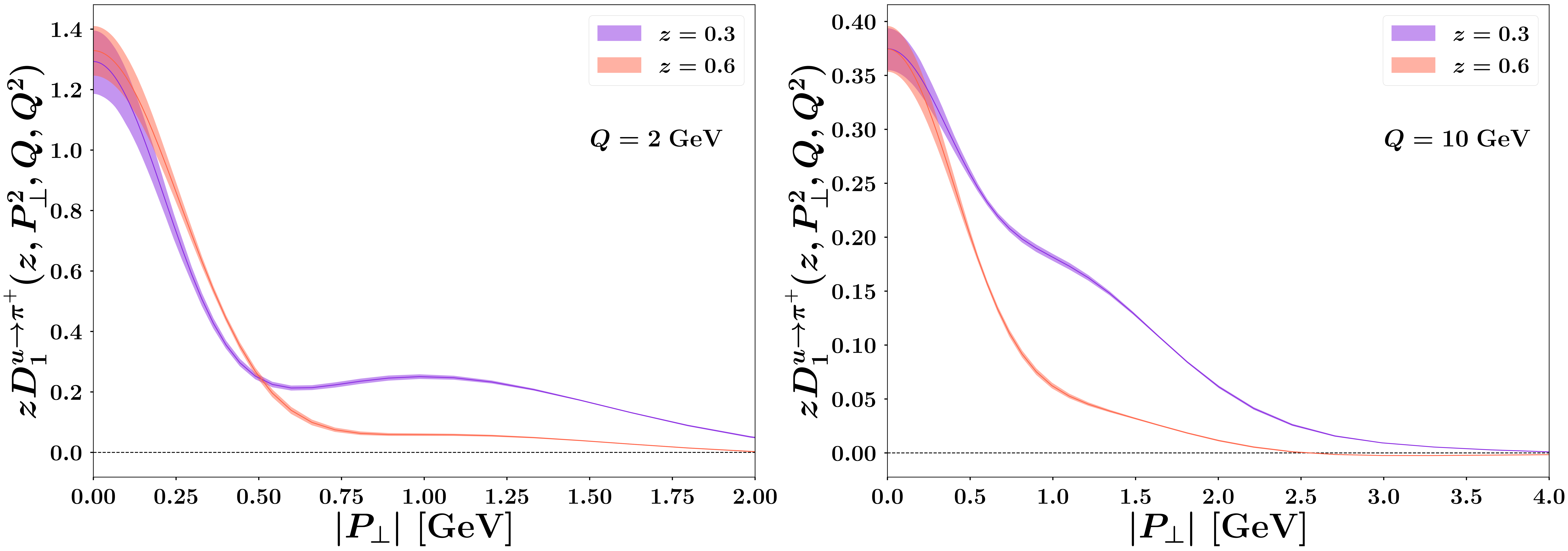


FIG. 13: The TMD PDF of the up quark in a proton at $\mu = \sqrt{\zeta} = Q = 2$ GeV (left panel) and 10 GeV (right panel) as a function of the partonic transverse momentum $|\boldsymbol{k}_\perp|$ for $x = 0.001$, 0.01 and 0.1. The uncertainty bands represent the 68% CL.

RESULTING TMD FRAGMENTATION FUNCTIONS



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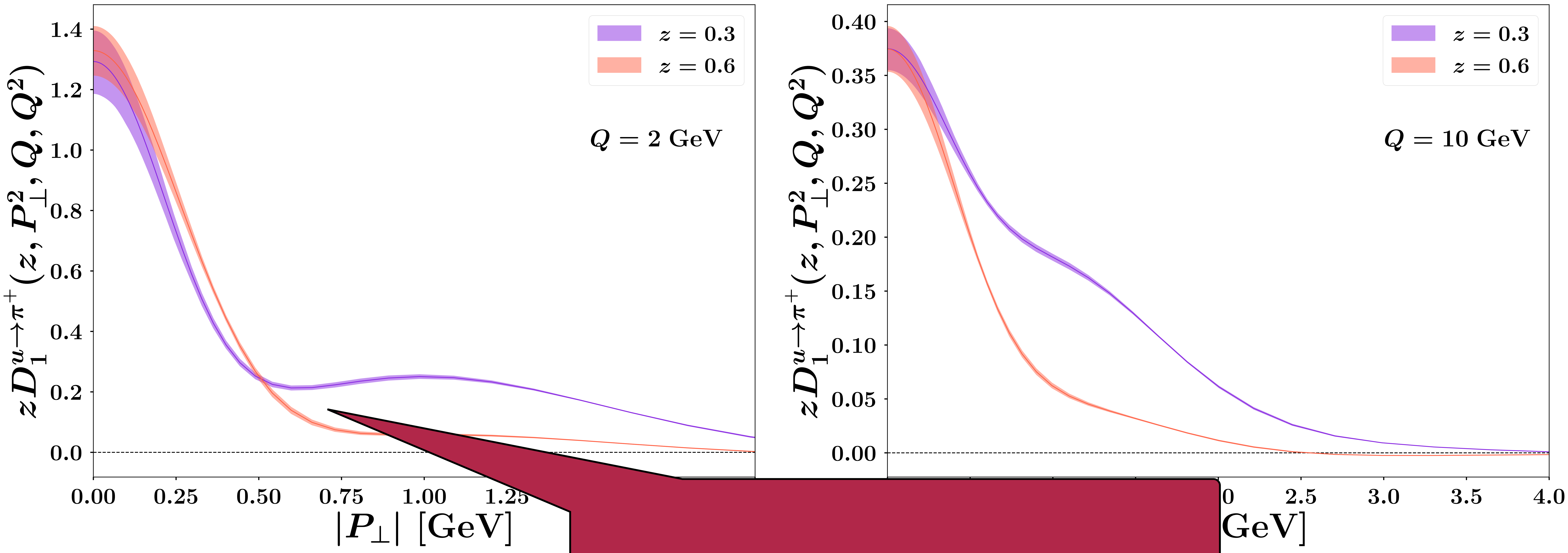
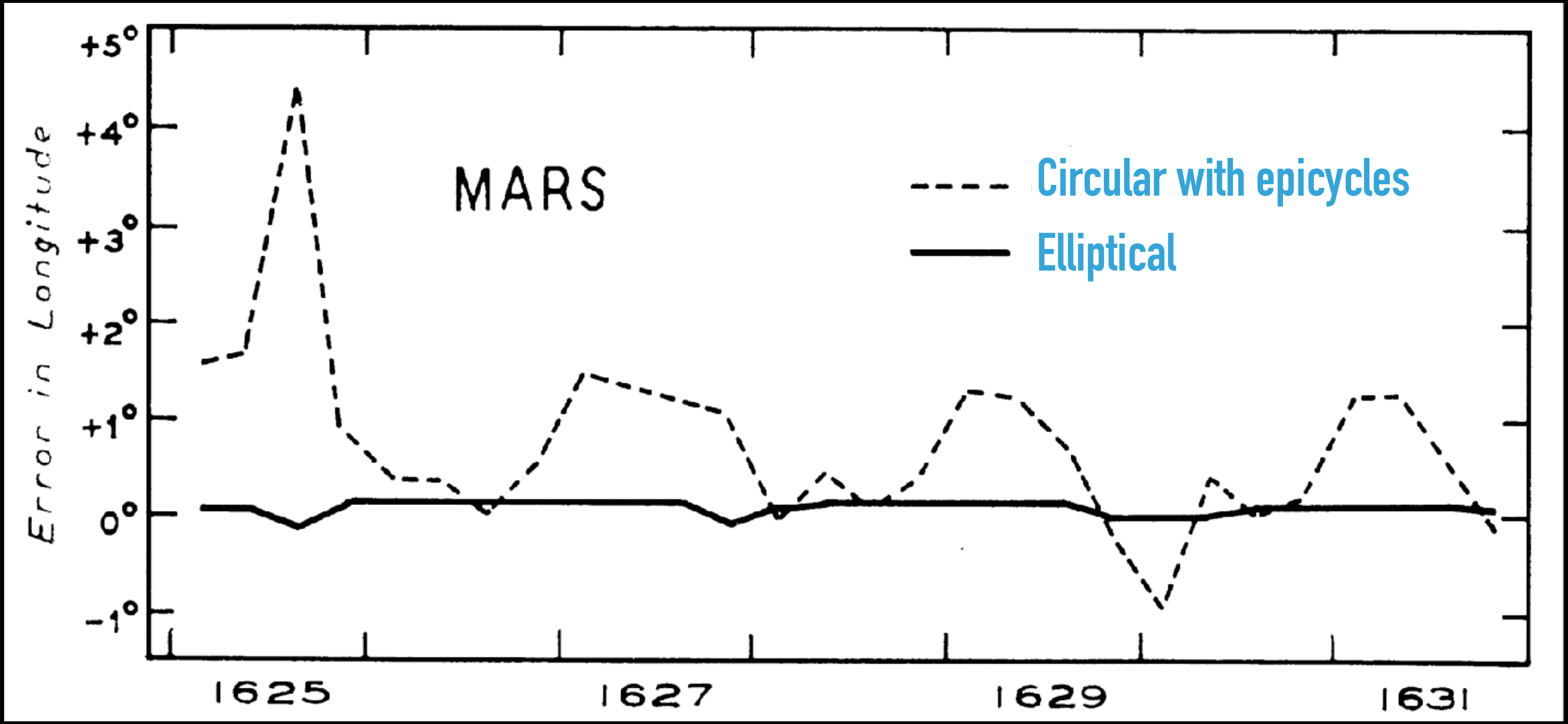


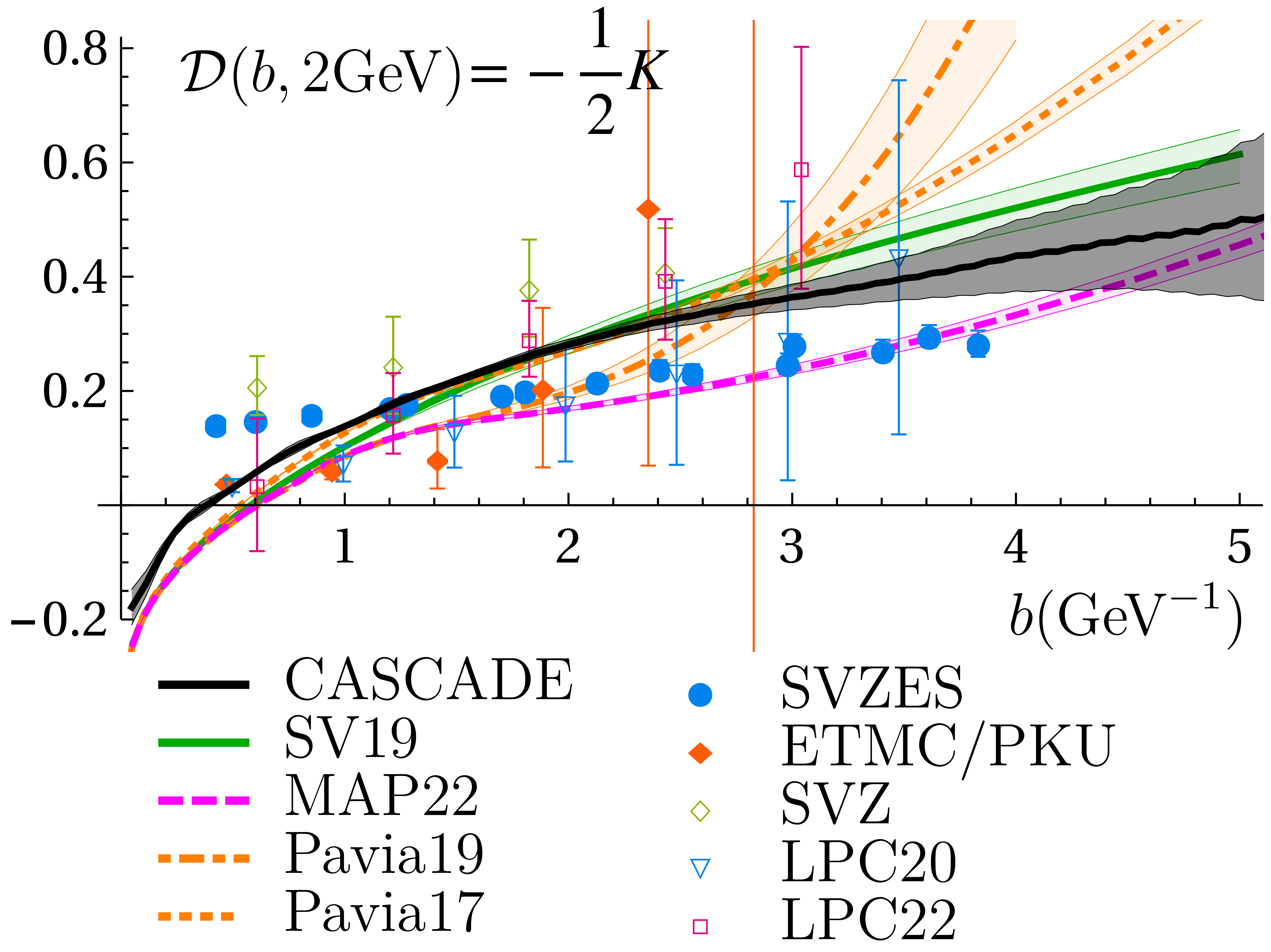
Different from a simple Gaussian
(relation with talk of P. Skands)

CHECK PREDICTIONS



CONNECTIONS WITH LATTICE QCD: COLLINS–SOPER KERNEL

[Bermudez Martinez, Vladimirov, arXiv:2206.01105](#)



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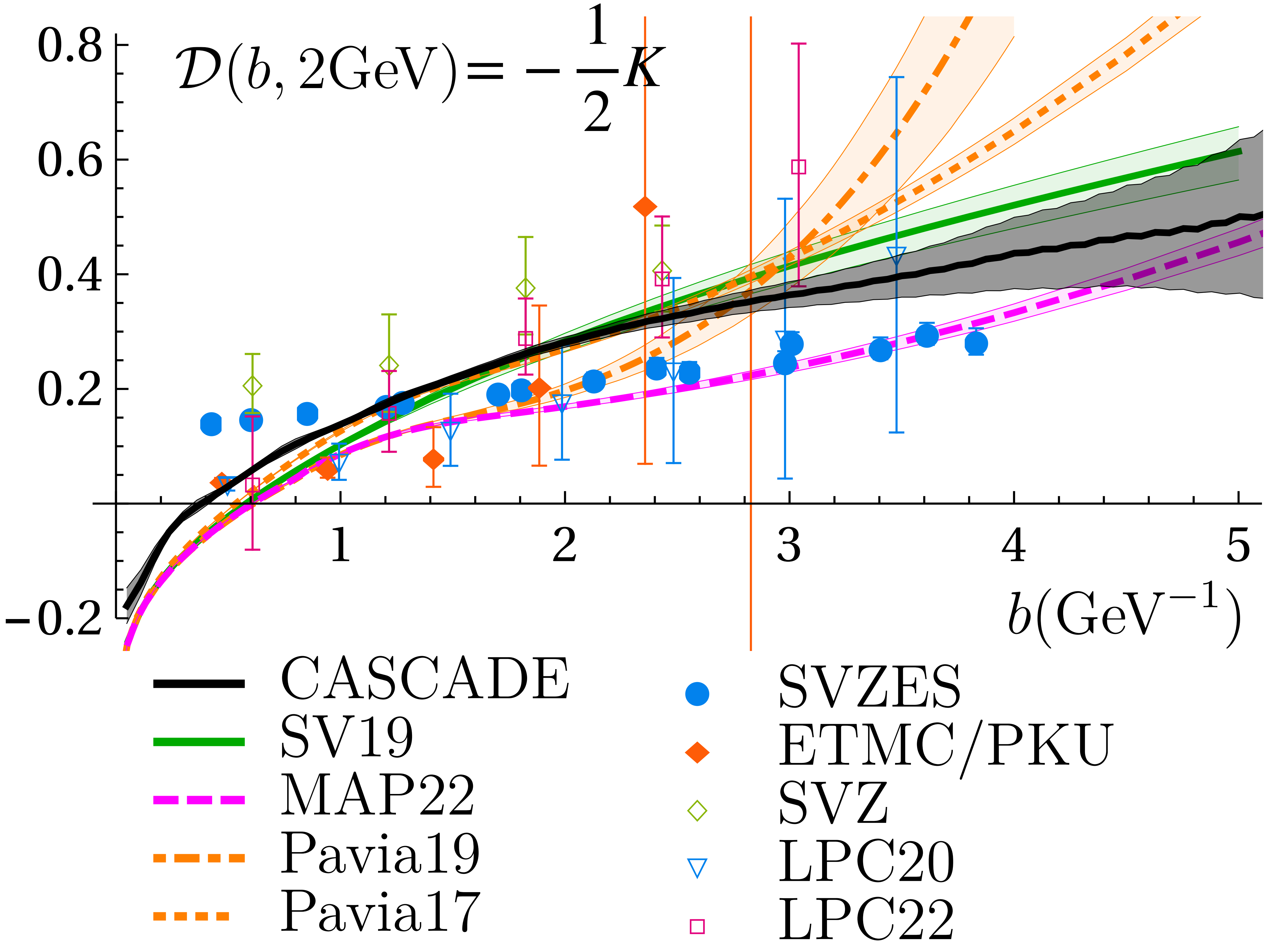
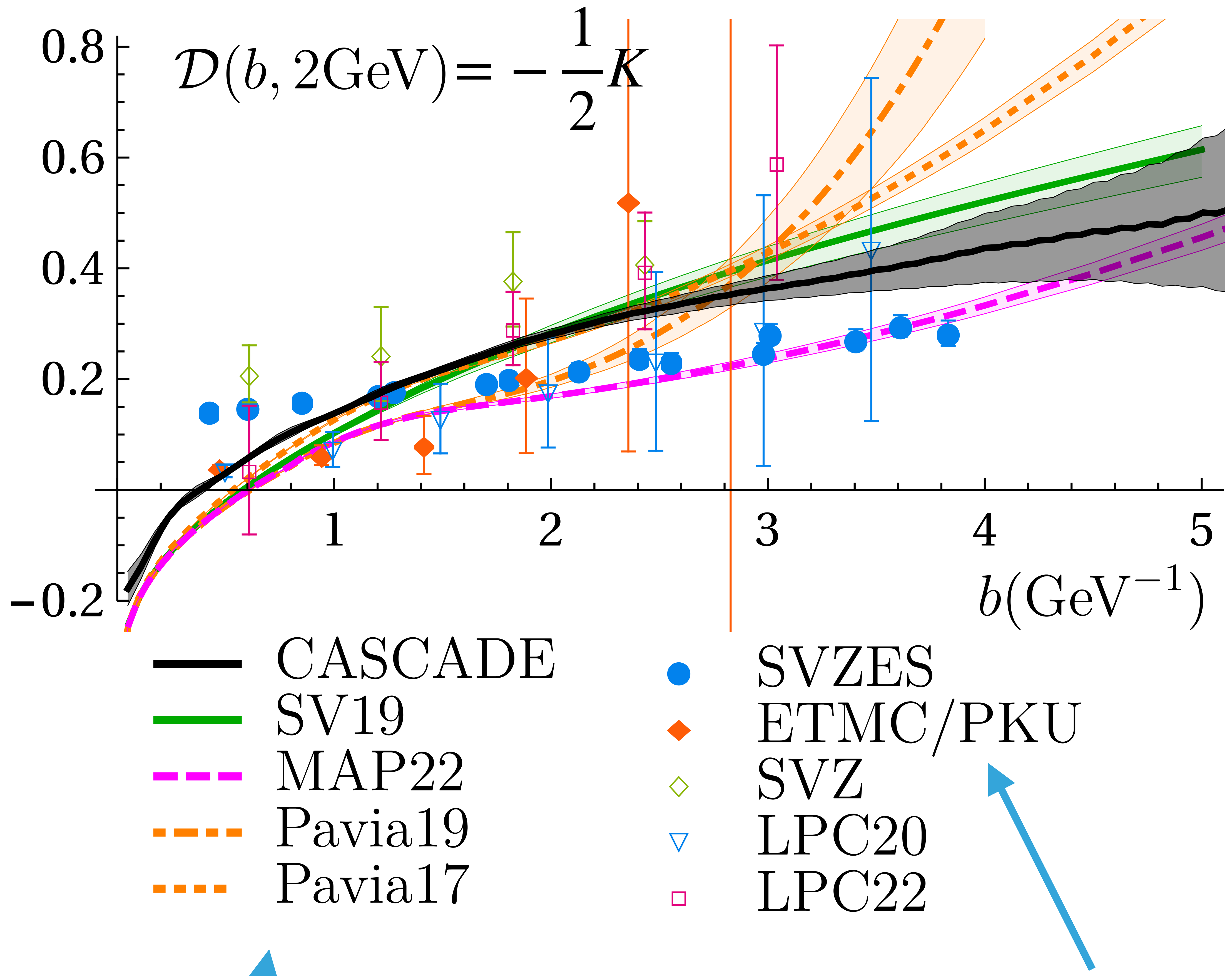


TMD phenomenology

CONNECTIONS WITH LATTICE QCD: COLLINS–SOPER KERNEL

[Bermudez Martinez, Vladimirov, arXiv:2206.01105](https://arxiv.org/abs/2206.01105)



TMD phenomenology

Lattice QCD

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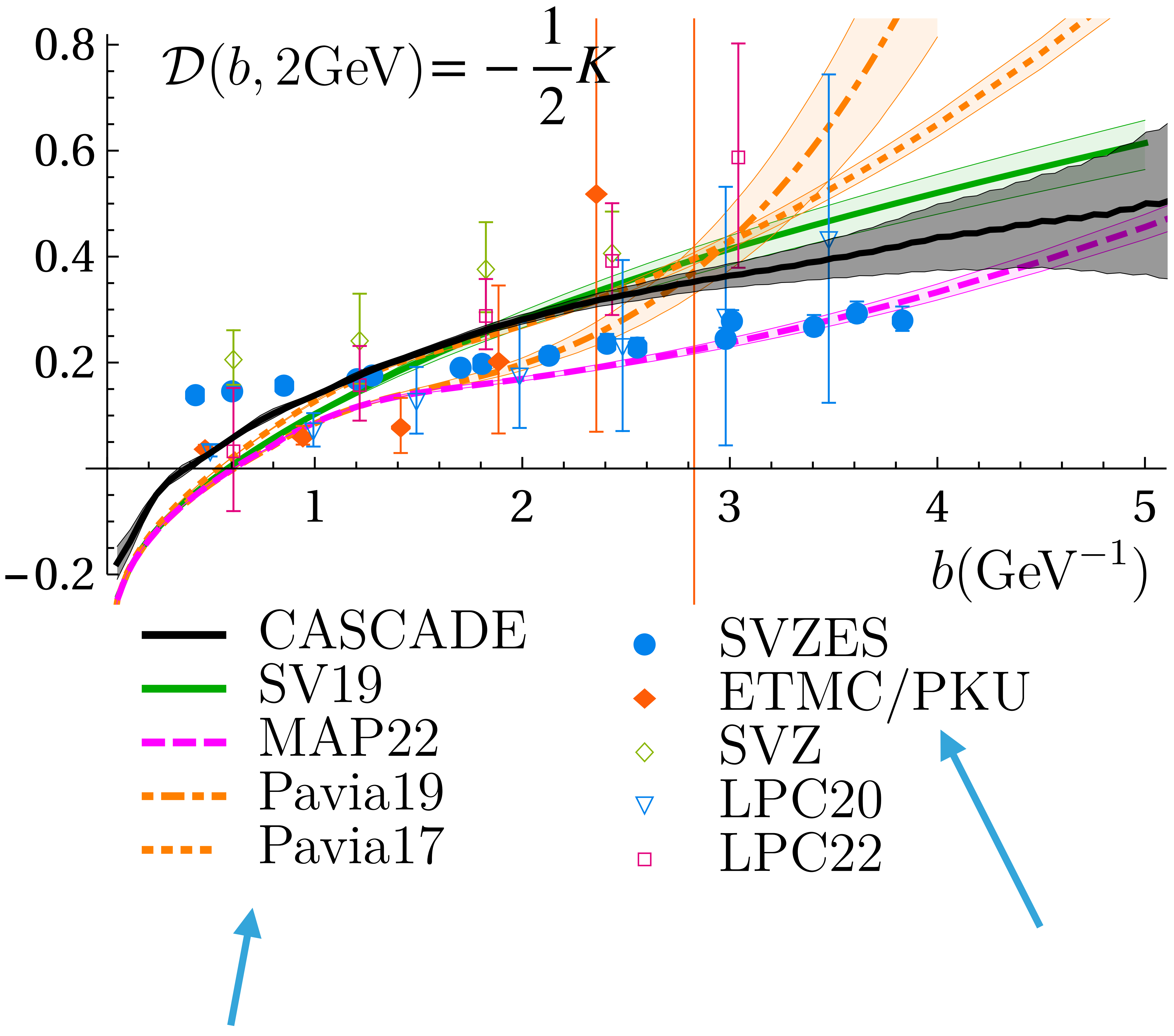
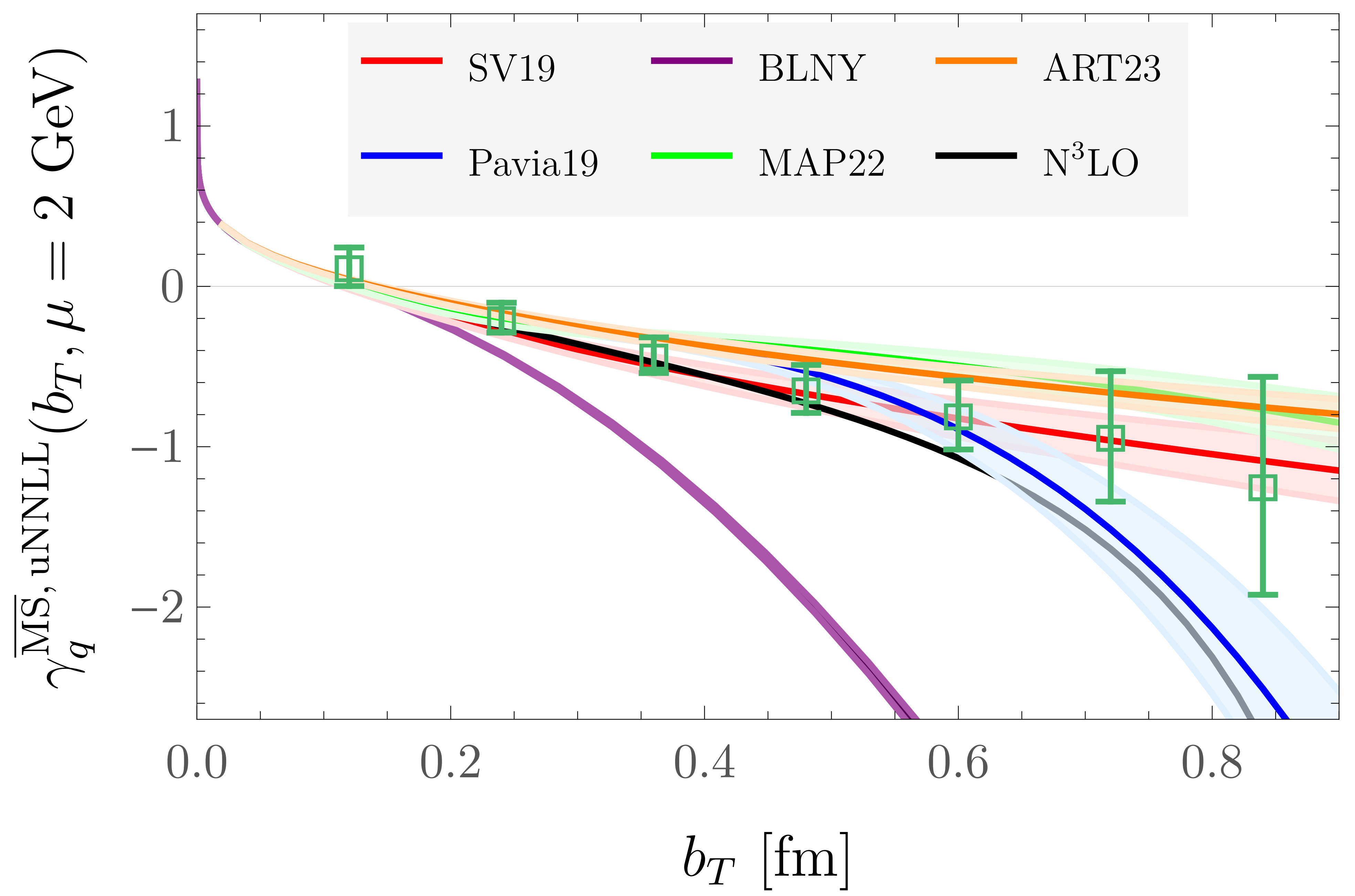


TMD phenomenology

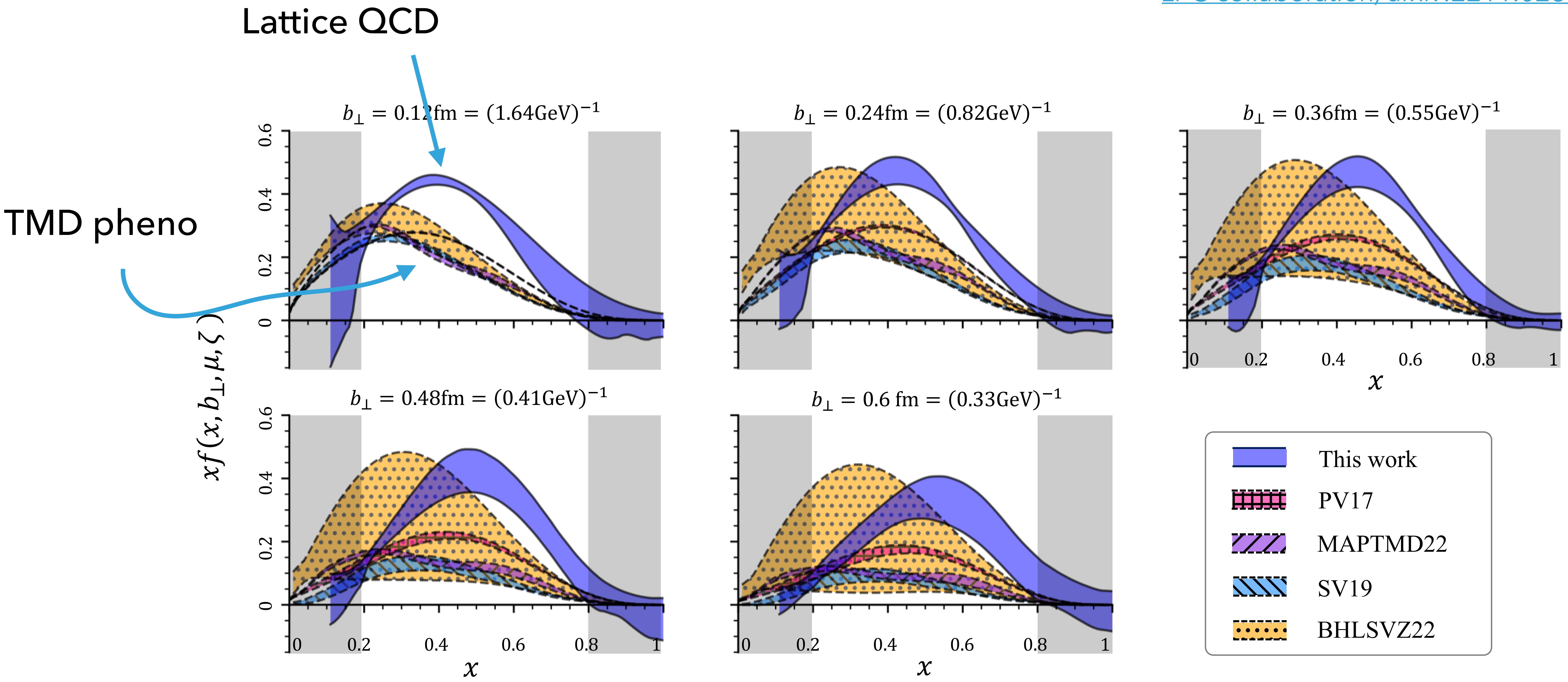
Lattice QCD

Avkhadiev, Shanahan, Wagman, Zhao, arXiv:2307.12359

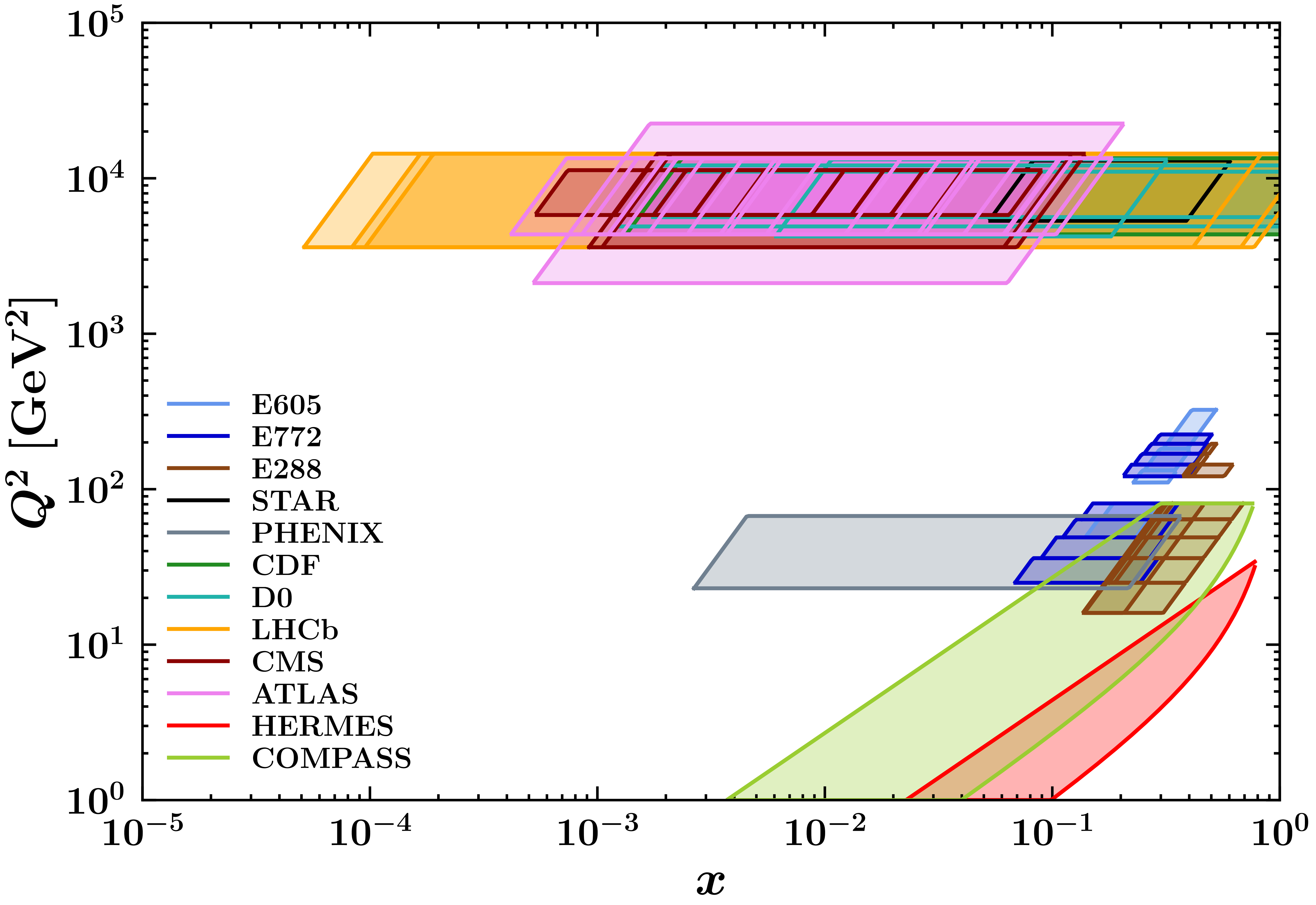


CHECK LATTICE QCD PREDICTIONS

LPC collaboration, arxiv:2211.02340



EIC IMPACT



Q^2 [GeV^2]
x
10^5
10^4
10^3
10^2
10^1
10^0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
E605
E772
E288
STAR
PHENIX
CDF
D0
LHCb
CMS
ATLAS
HERMES
COMPASS

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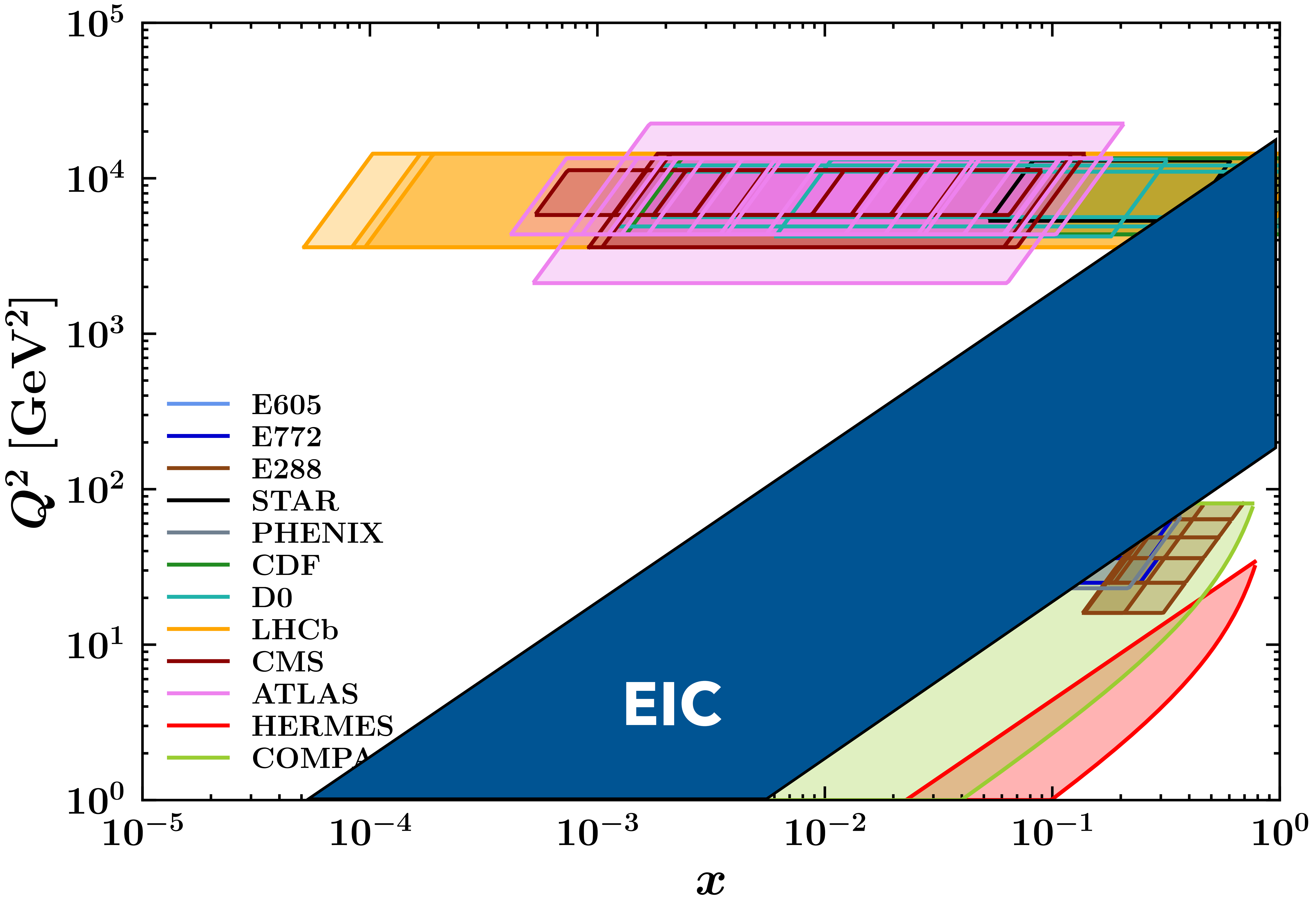

10^5
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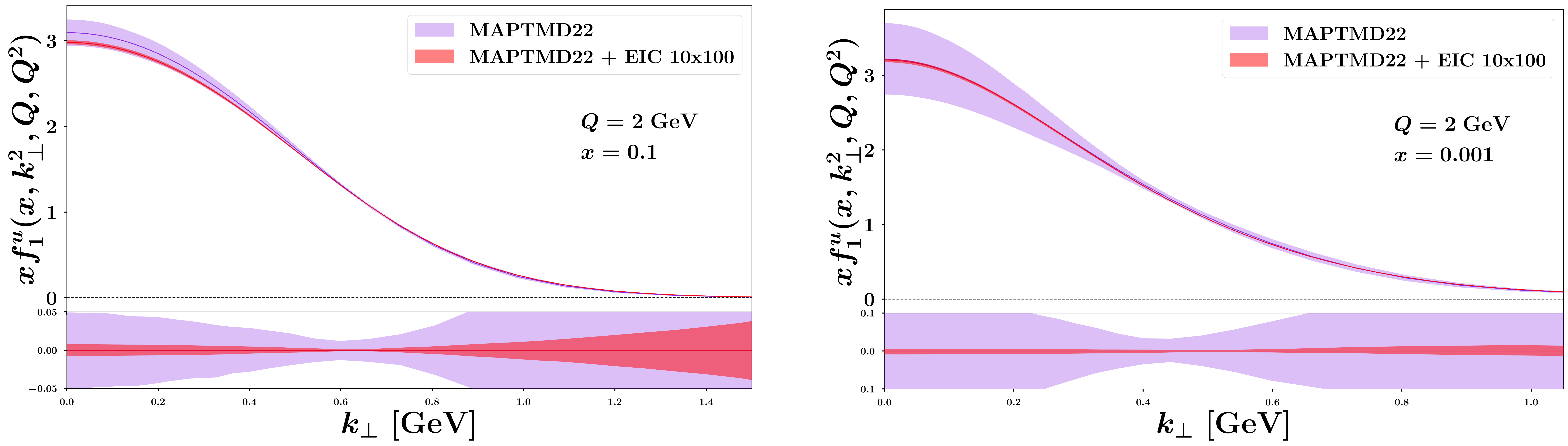
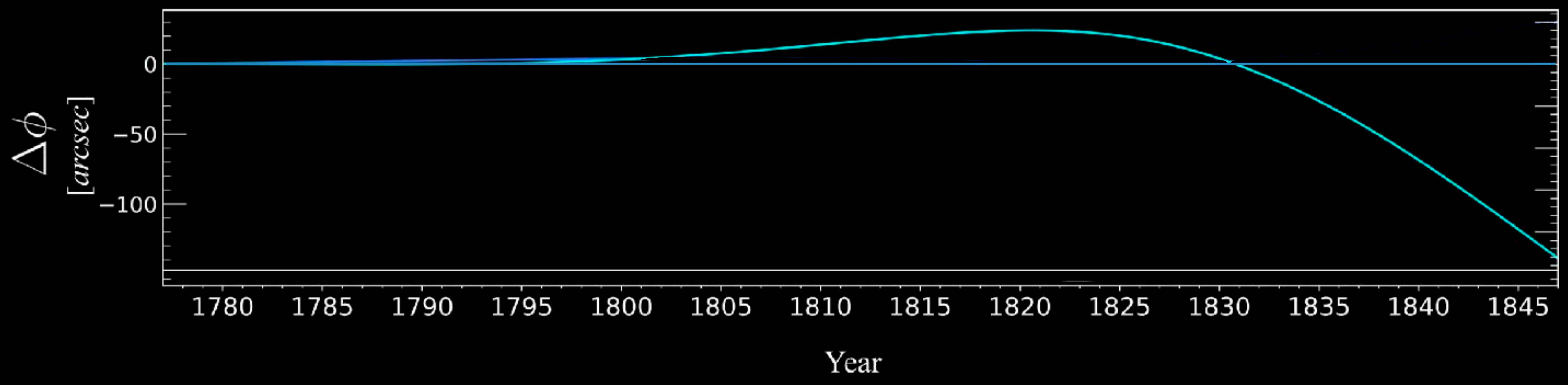


EIC

MAKE PREDICTIONS

Uranus's longitude predictions

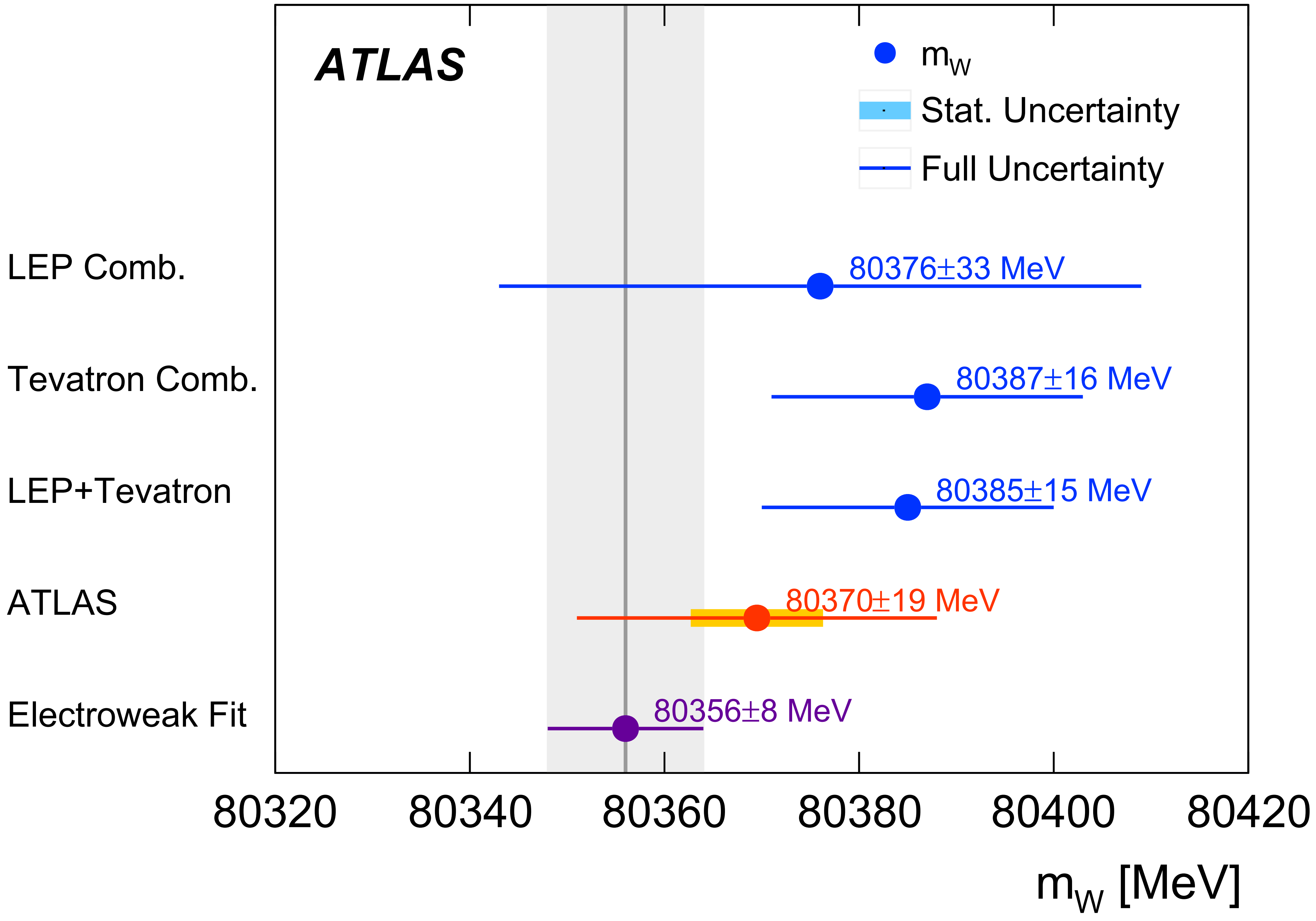


Without Neptune

With Neptune

TMDS AND W MASS

[ATLAS Collab. arXiv:1701.07240](https://arxiv.org/abs/1701.07240)



$$
\begin{aligned}
m_W &= 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV} \\
&= 80370 \pm 19\ \text{MeV},
\end{aligned}
$$

$$
m_{W^+} - m_{W^-} = -29 \pm 28\ \text{MeV}.
$$

TMDS AND W MASS

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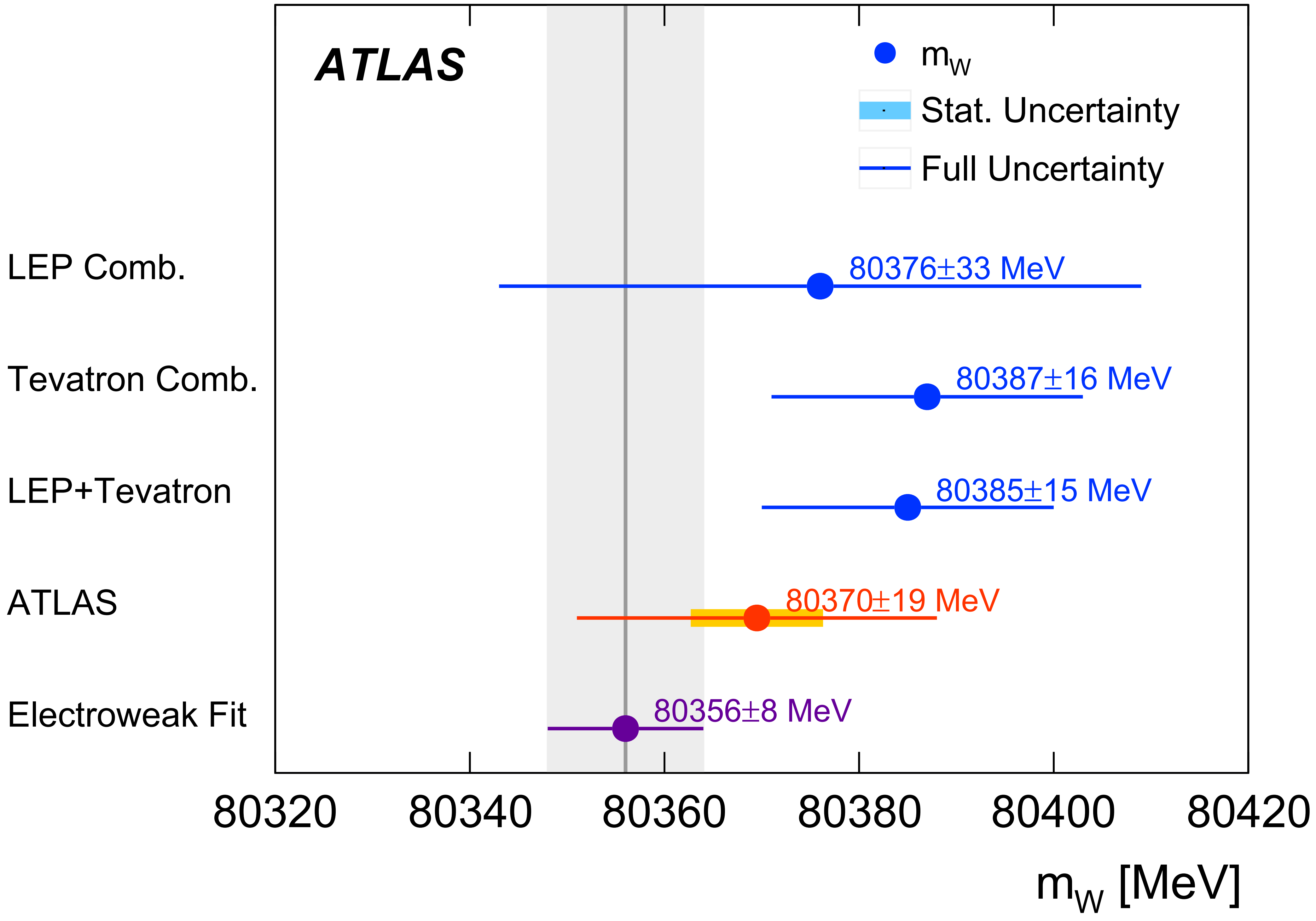
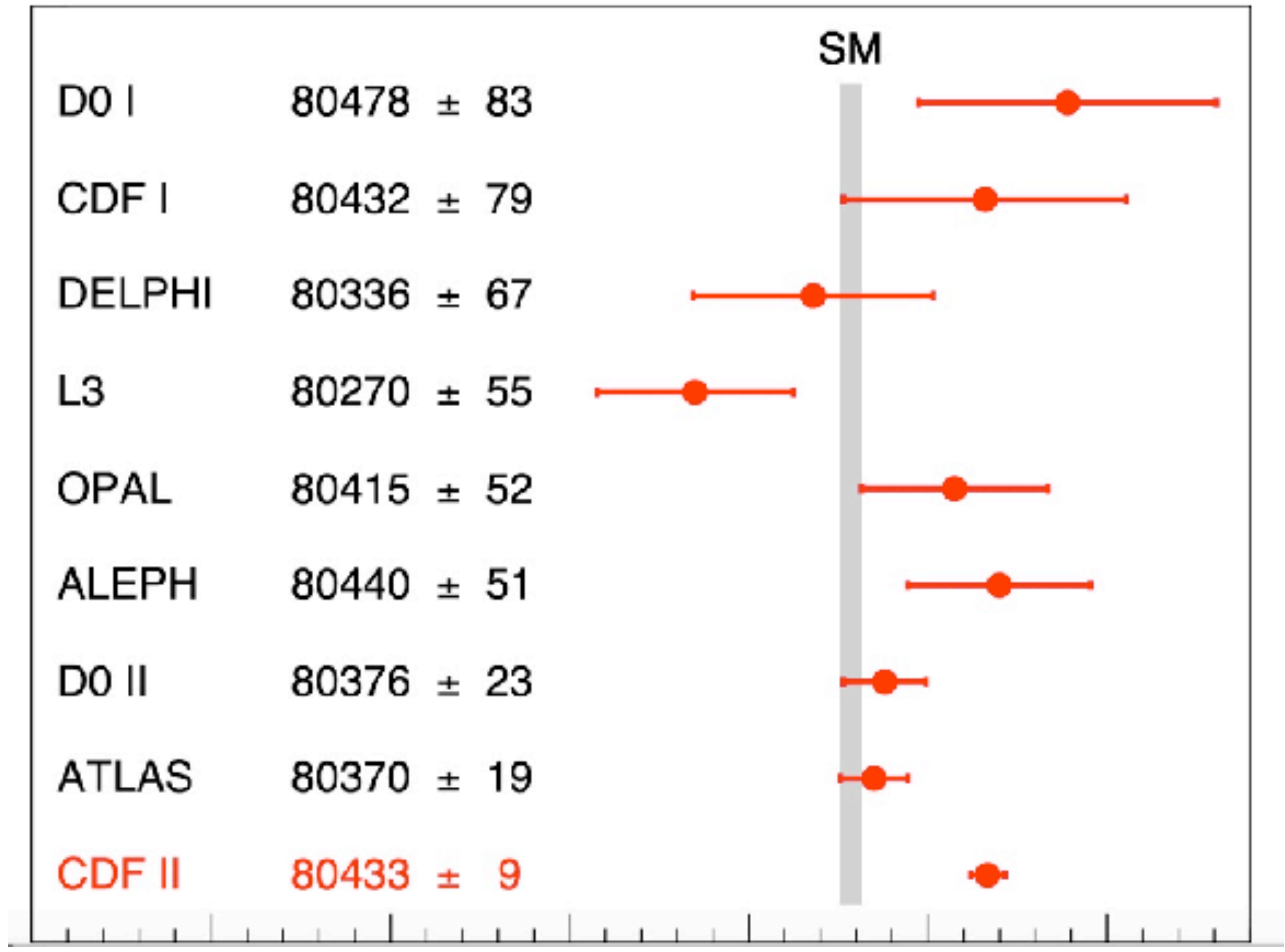
CDF Collab.. Science 2022





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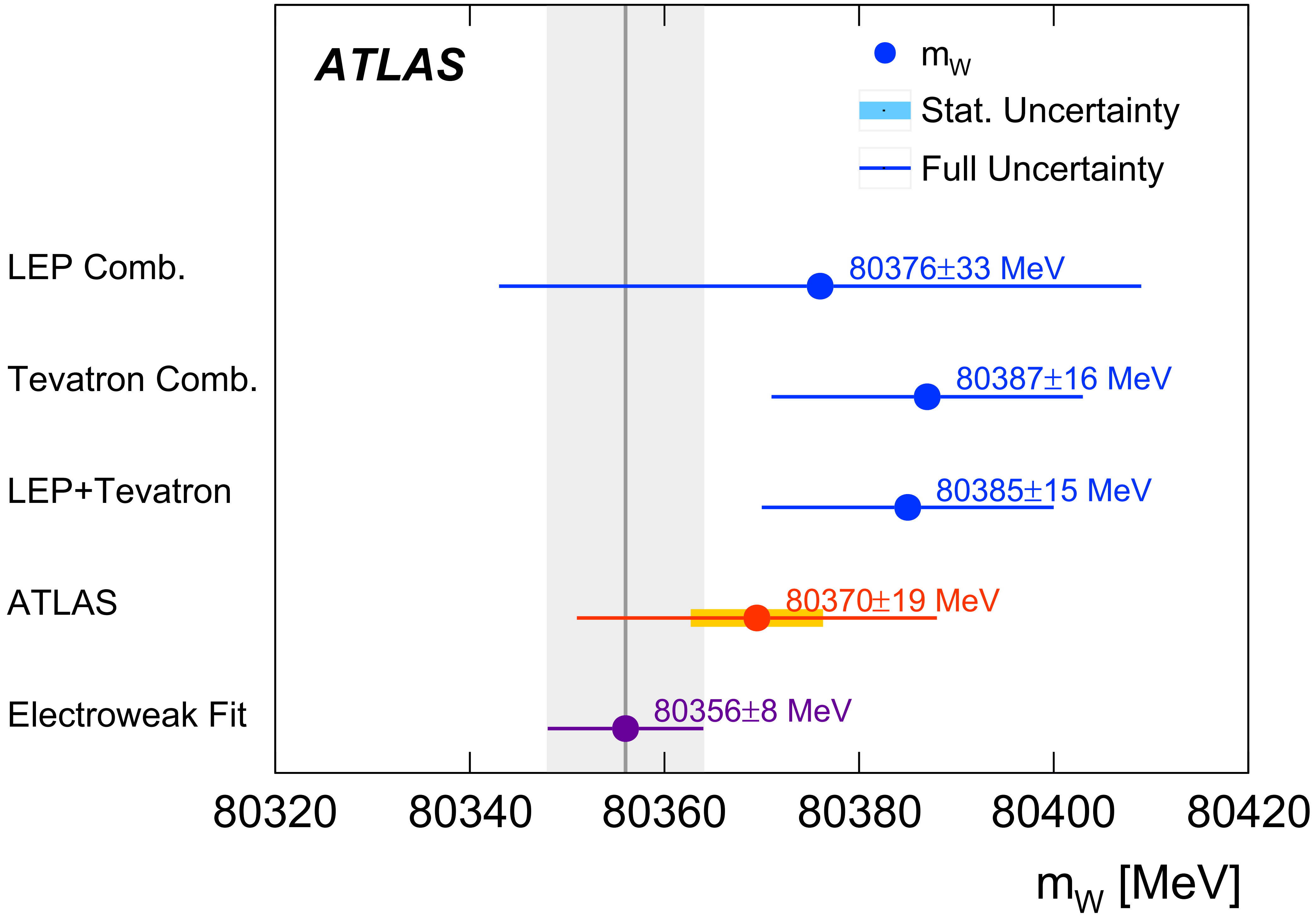

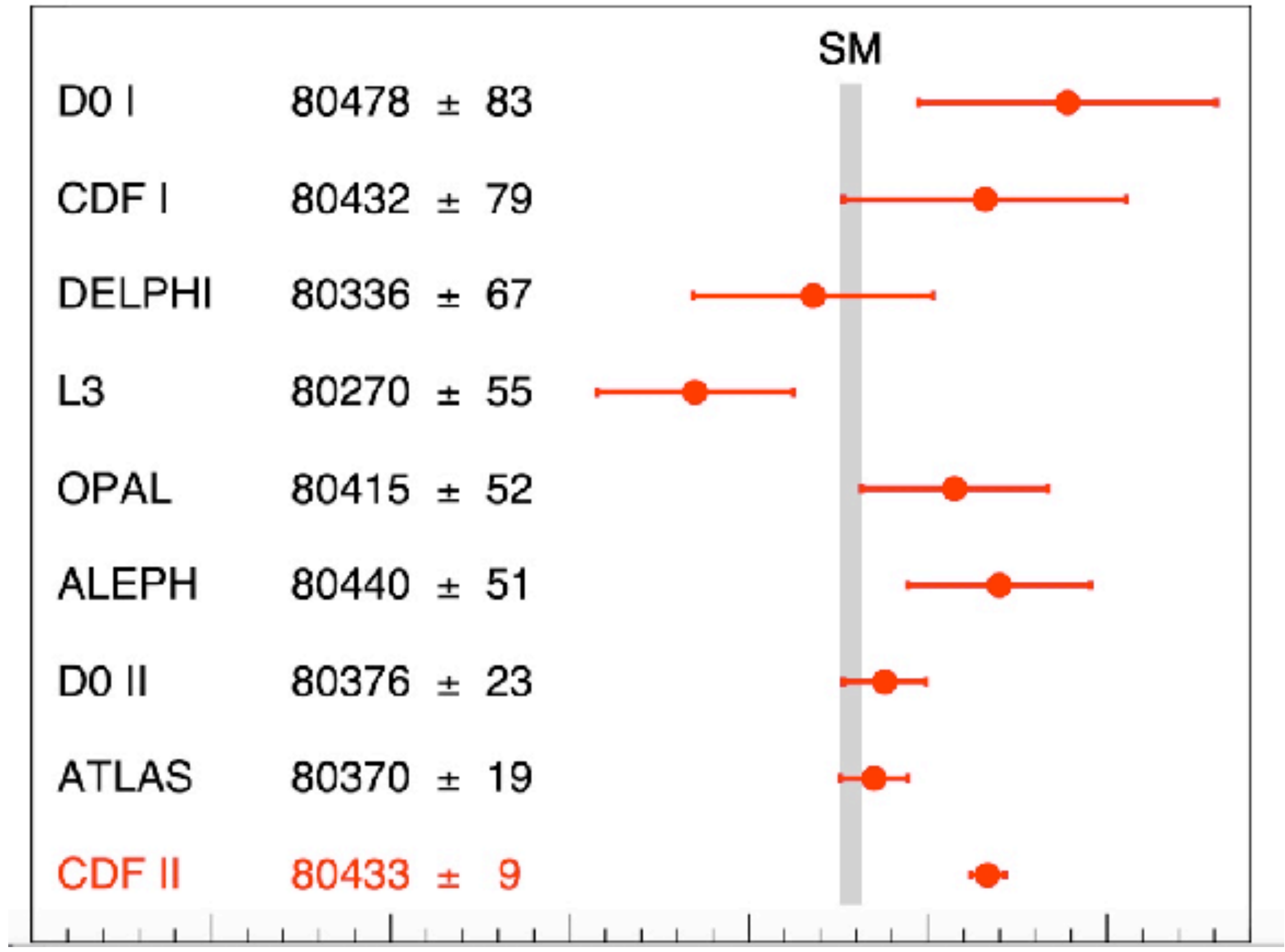

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All analyses assume that TMDs are not flavor dependent. What happens if they are?

TMDS AND W MASS

[Bacchetta, Bozzi, Radici, Ritzmann, Signori, arXiv:1807.02101](#)

Try some judicious choices of flavour dependent widths and check

TMDS AND W MASS

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Try some judicious choices of flavour dependent widths and check

Set	u_v	d_v	u_s	d_s	s
1	0.34	0.26	0.46	0.59	0.32
2	0.34	0.46	0.56	0.32	0.51
3	0.55	0.34	0.33	0.55	0.30
4	0.53	0.49	0.37	0.22	0.52
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narrow, medium, large
narrow, large, narrow
large, narrow, large
large, medium, narrow
medium, narrow, large

TMDS AND W MASS

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They all describe the Z spectrum very well

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	ΔM_{W+}		ΔM_{W-}	
Set	m_T	$p_{T\ell}$	m_T	$p_{T\ell}$
1	0	-1	-2	3
2	0	-6	-2	0
3	-1	9	-2	-4
4	0	0	-2	-4
5	0	4	-1	-3

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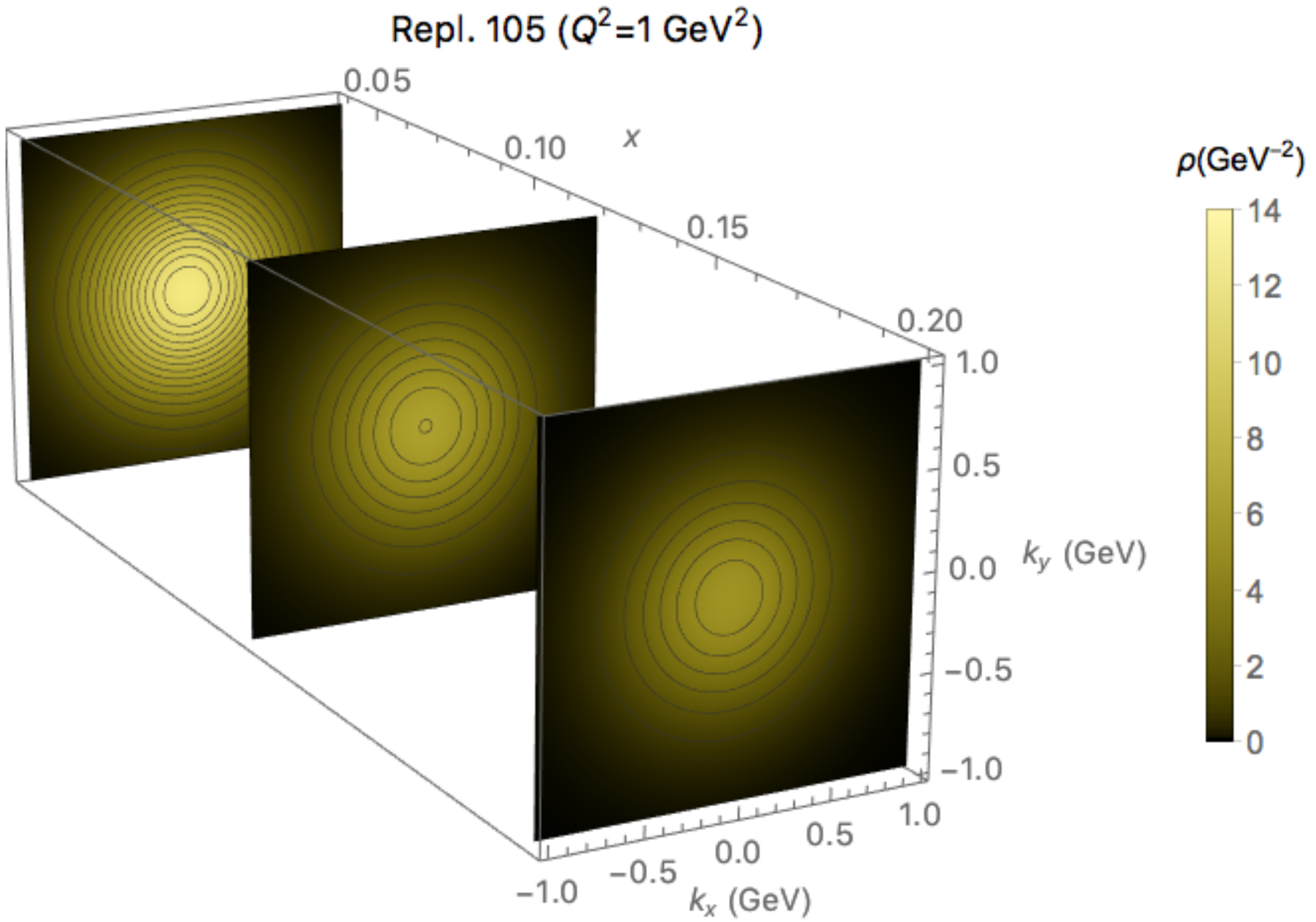
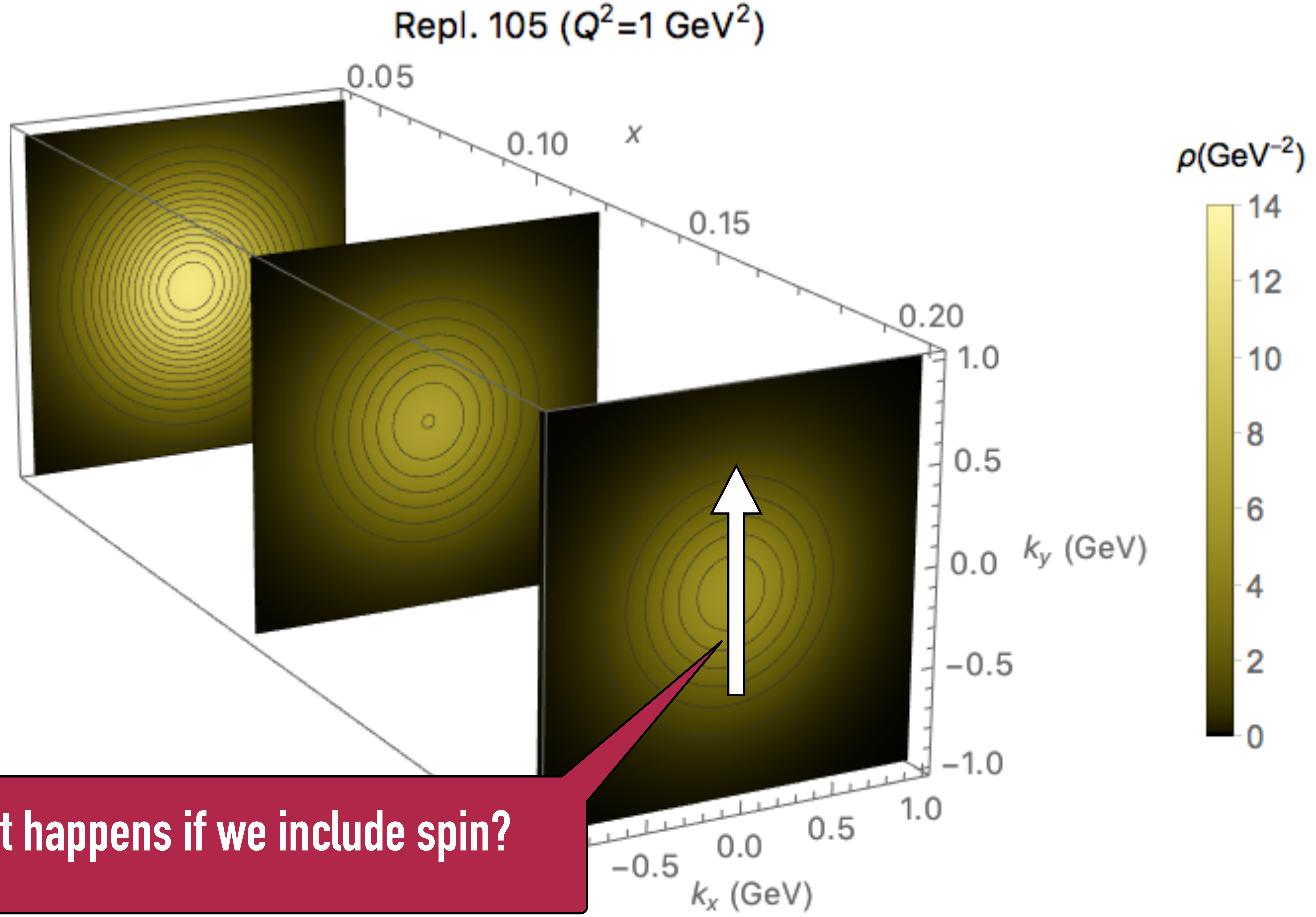
5	0	4	-1	-3

Not taking into account the flavor dependence of TMDs can lead to errors in the determination of the W mass, of the order of a few MeVs

QUESTIONS

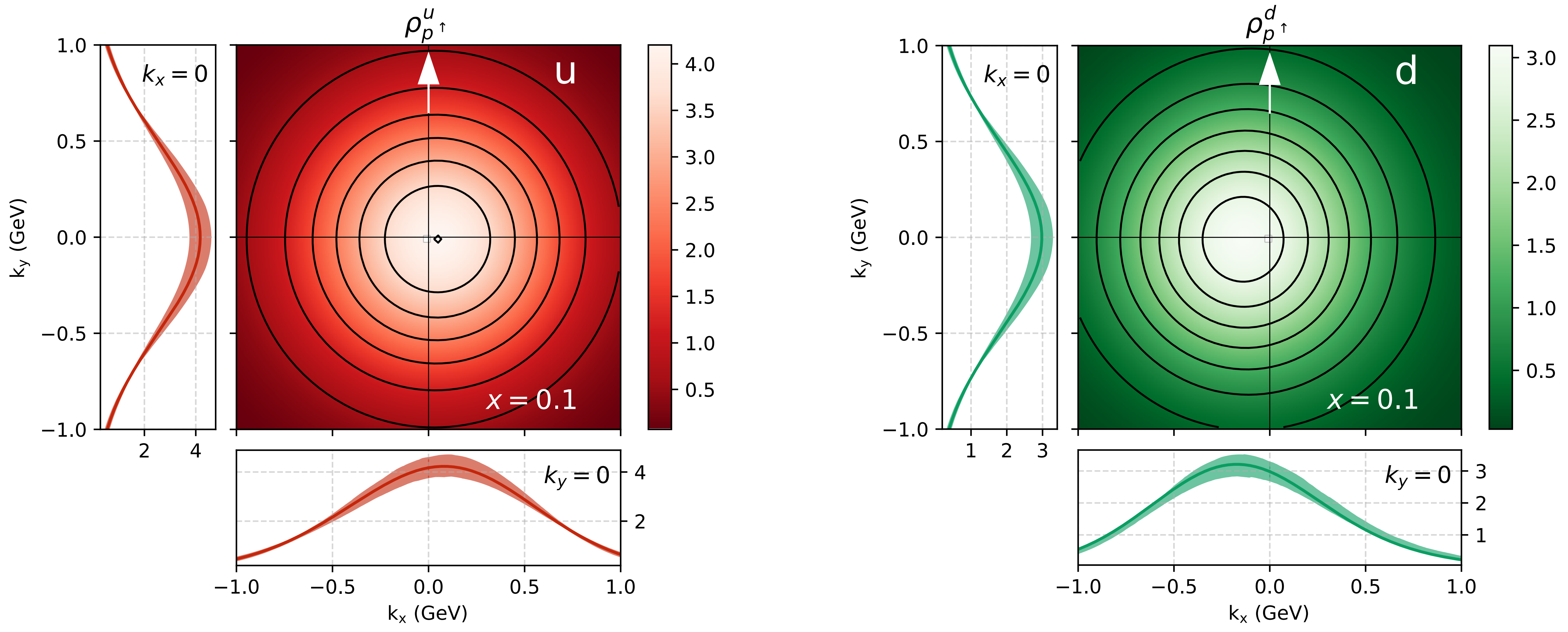

Repl. 105 (Q^2=1 GeV^2)
0.05
0.10
0.15
0.20
x
1.0
0.5
0.0
−0.5
−1.0
k_y (GeV)
−1.0
−0.5
0.0
0.5
1.0
k_x (GeV)
ρ(GeV^{-2})
14
12
10
8
6
4
2
0

QUESTIONS



What happens if we include spin?

3D STRUCTURE IN MOMENTUM SPACE



Q= 2GeV

[Bacchetta, Delcarro, Pisano, Radici, arXiv:2004.14278]()

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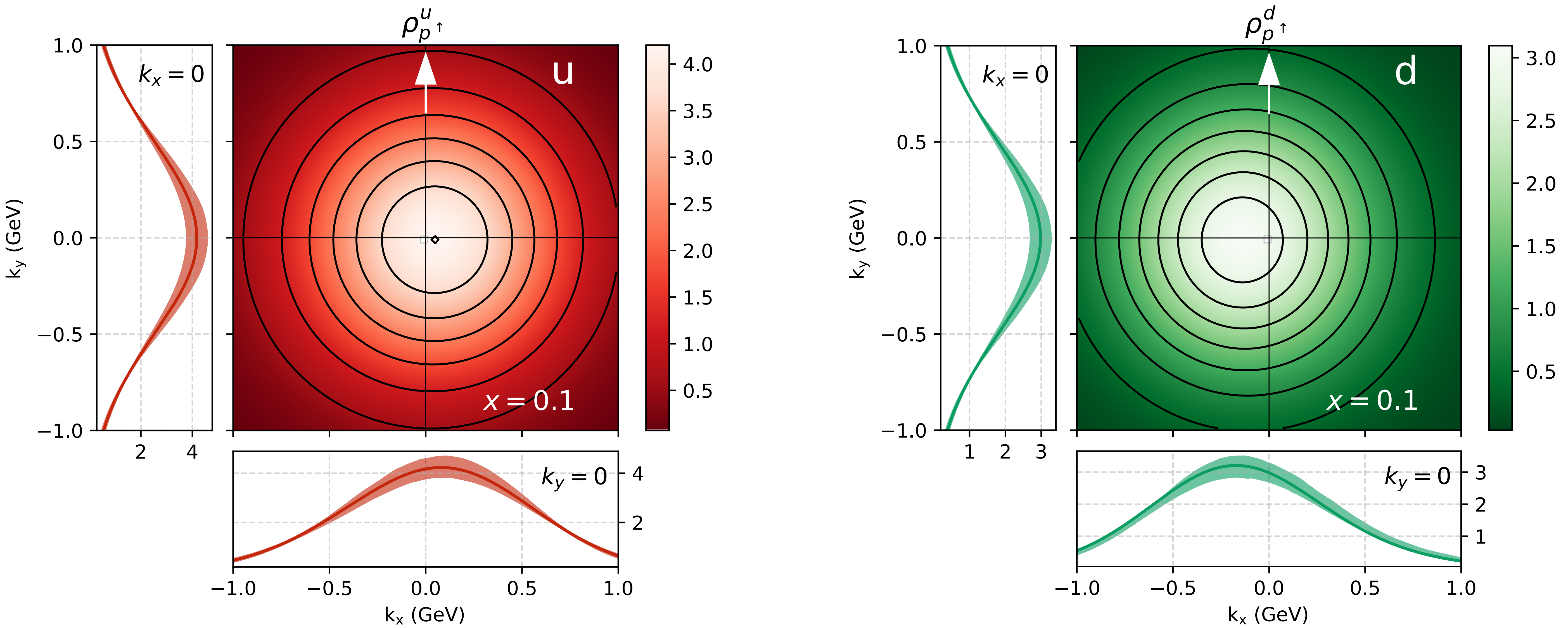

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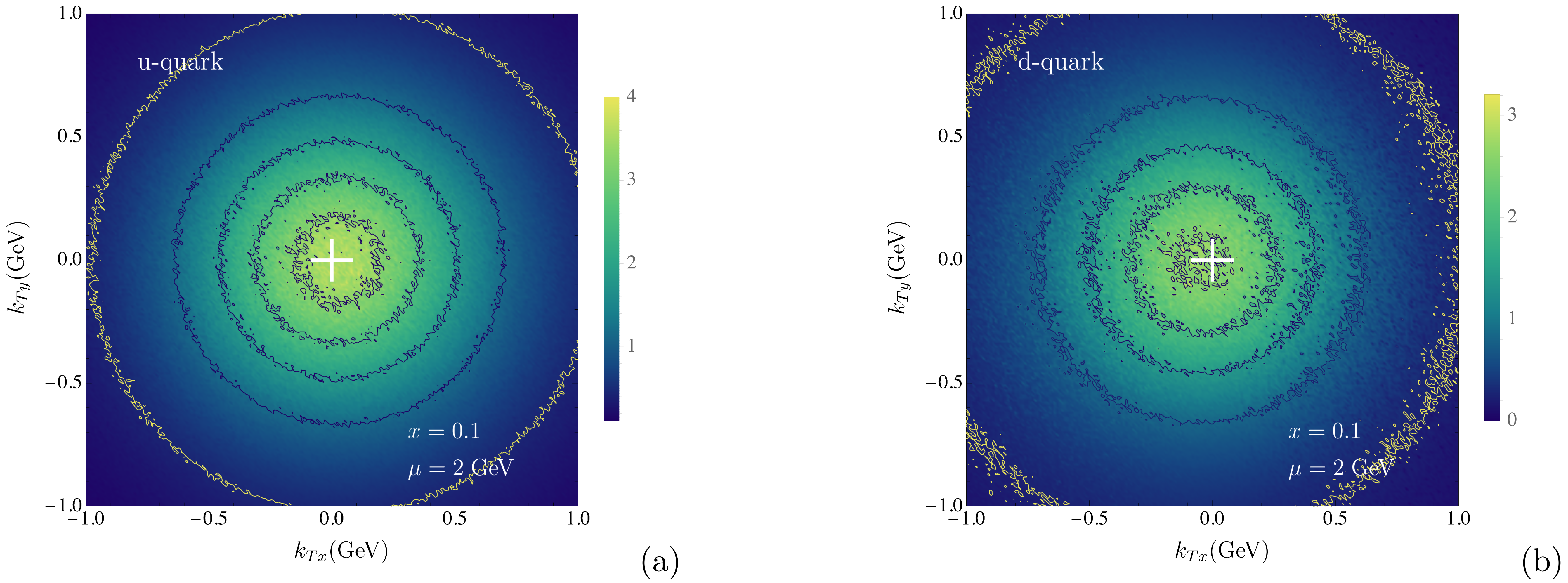
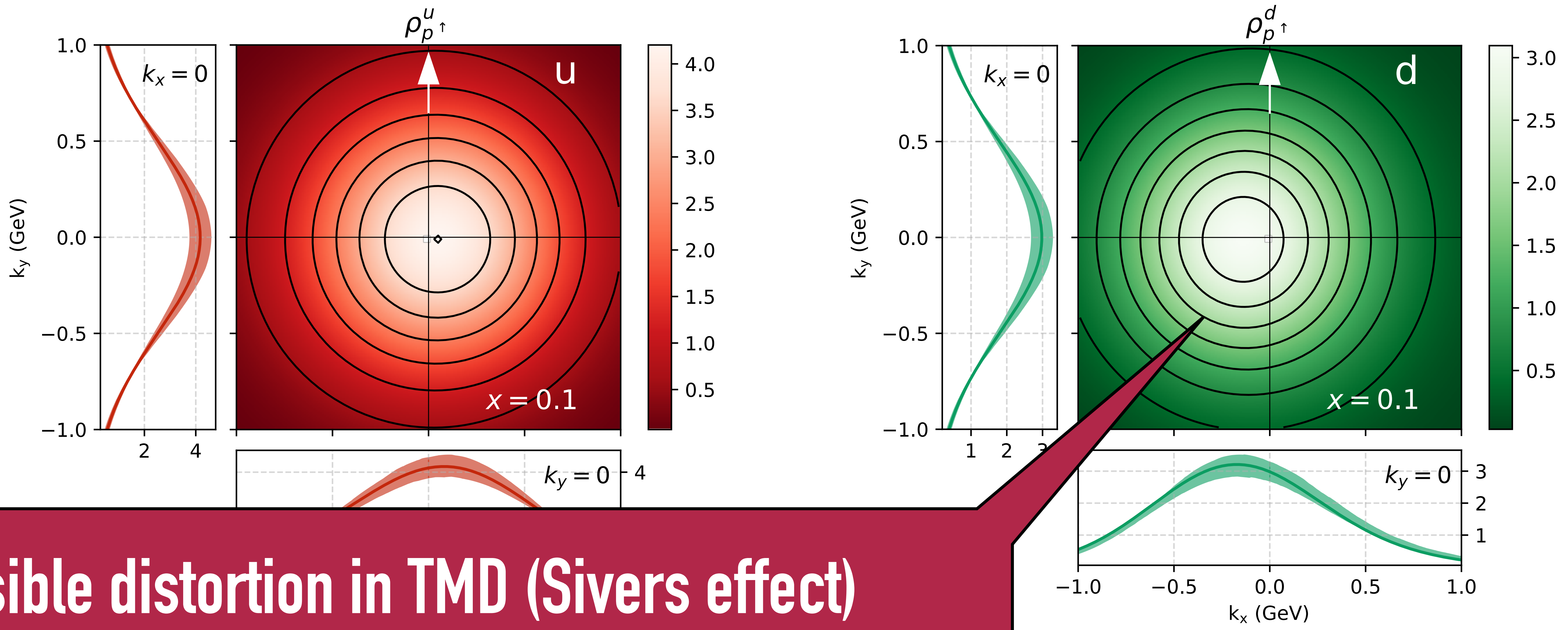


Bury, Prokudin, Vladimirov, arXiv:2103.03270

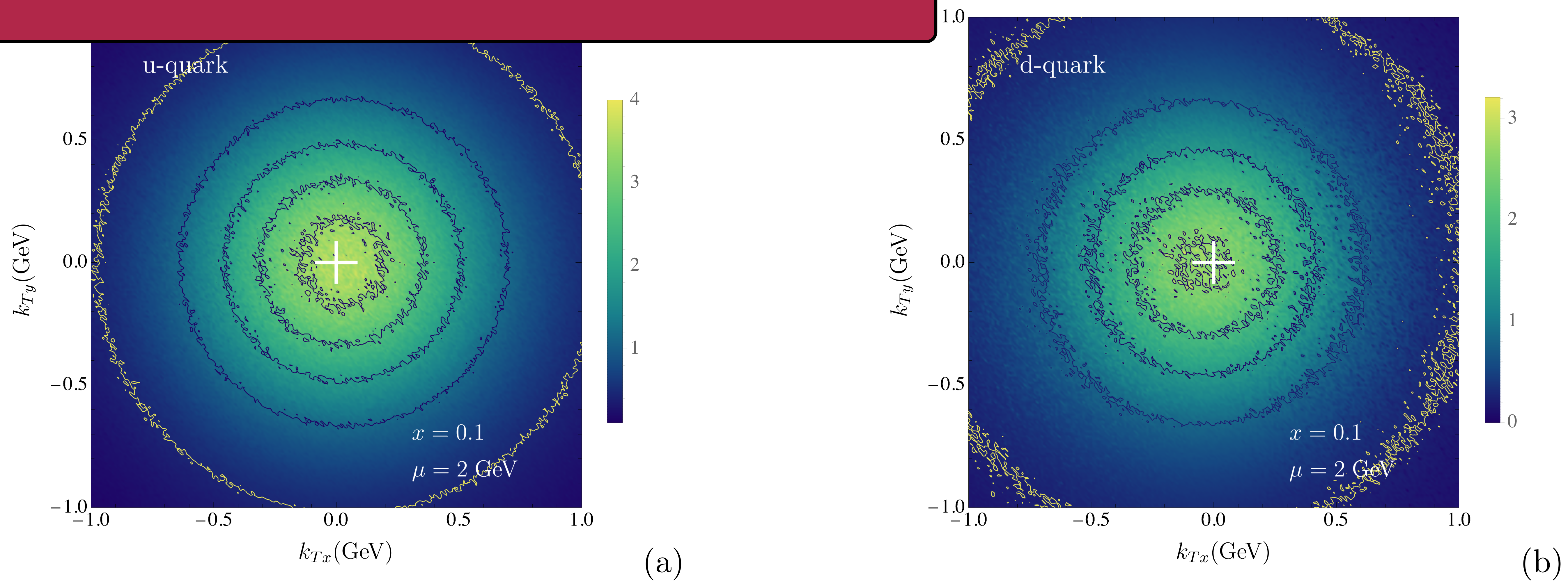
3D STRUCTURE IN MOMENTUM SPACE



Possible distortion in TMD (Sivers effect)

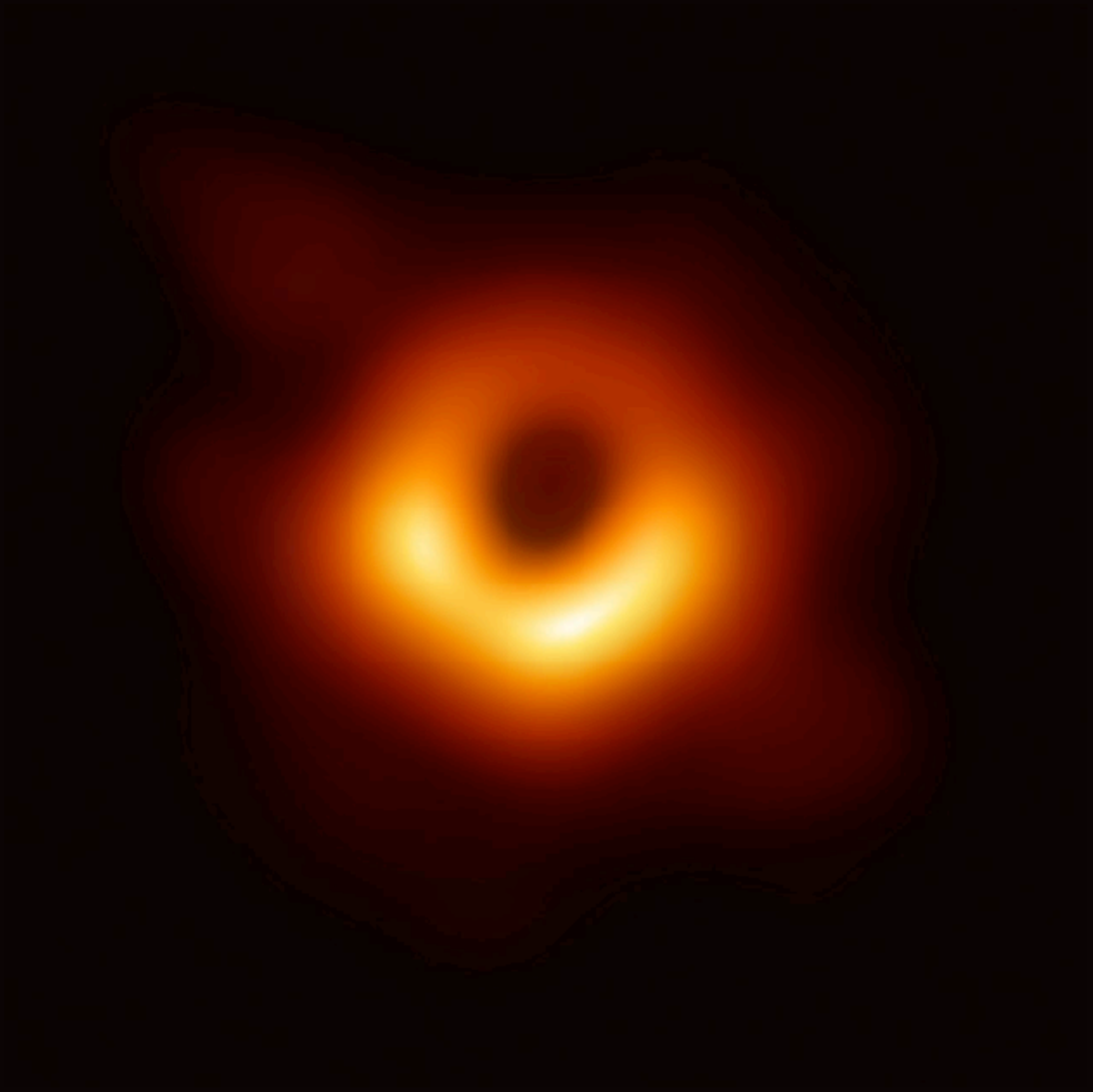
Q= 2GeV

Bacchetta, Delcarro, Pisano, Radici, arXiv:2004.14278



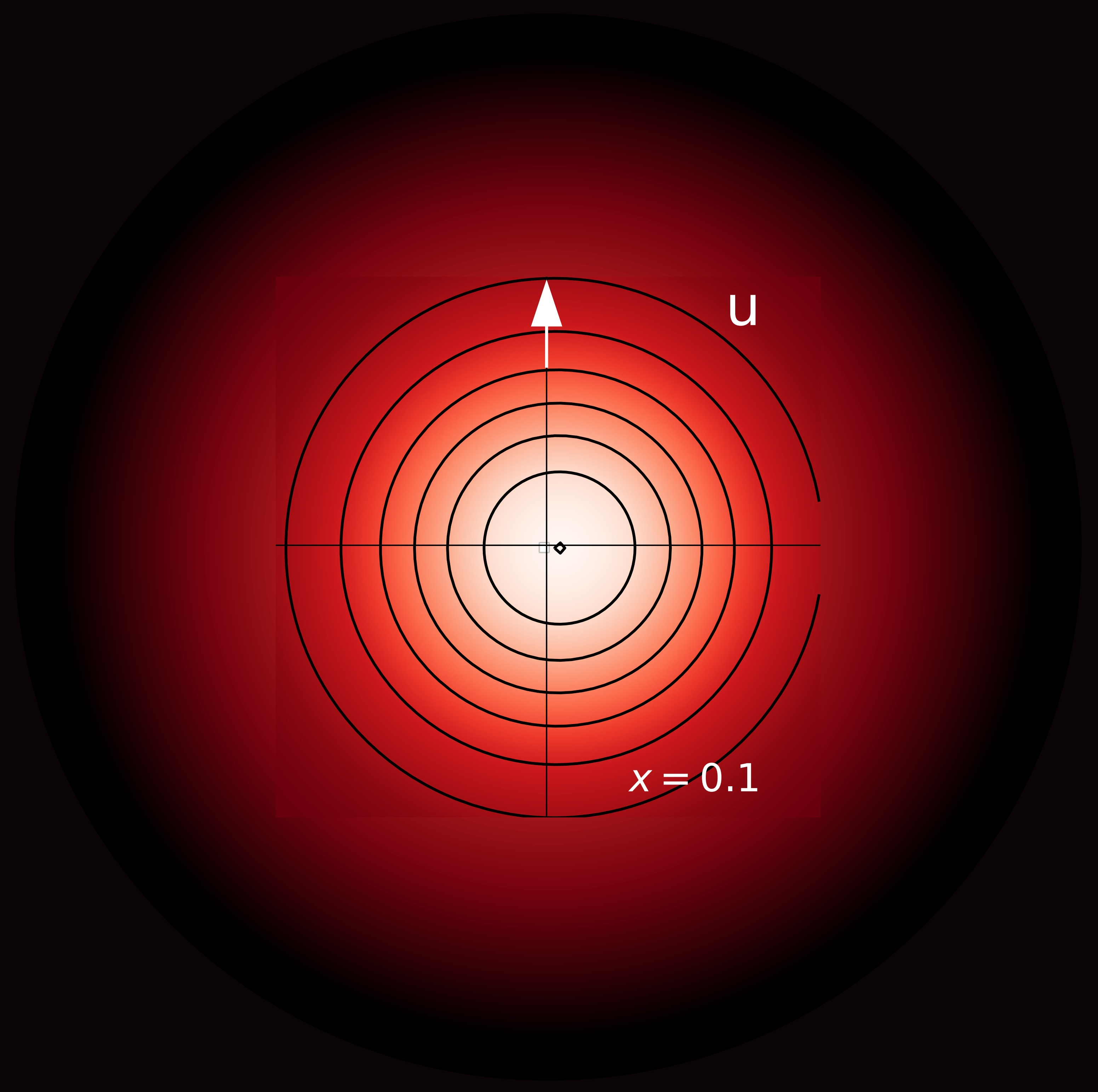
Bury, Prokudin, Vladimirov, arXiv:2103.03270

A picture of a black hole (2019)



A picture of a black hole (2019)

A picture of a proton (2020)



TECHNOLOGY?

TECHNOLOGY?

Our world is made of electrons, photons, quarks, and gluons:
I believe we will find ways to use them before we use the Higgs bosons or black holes.

CONCLUSIONS

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- The EIC will be a groundbreaking machine for QCD studies

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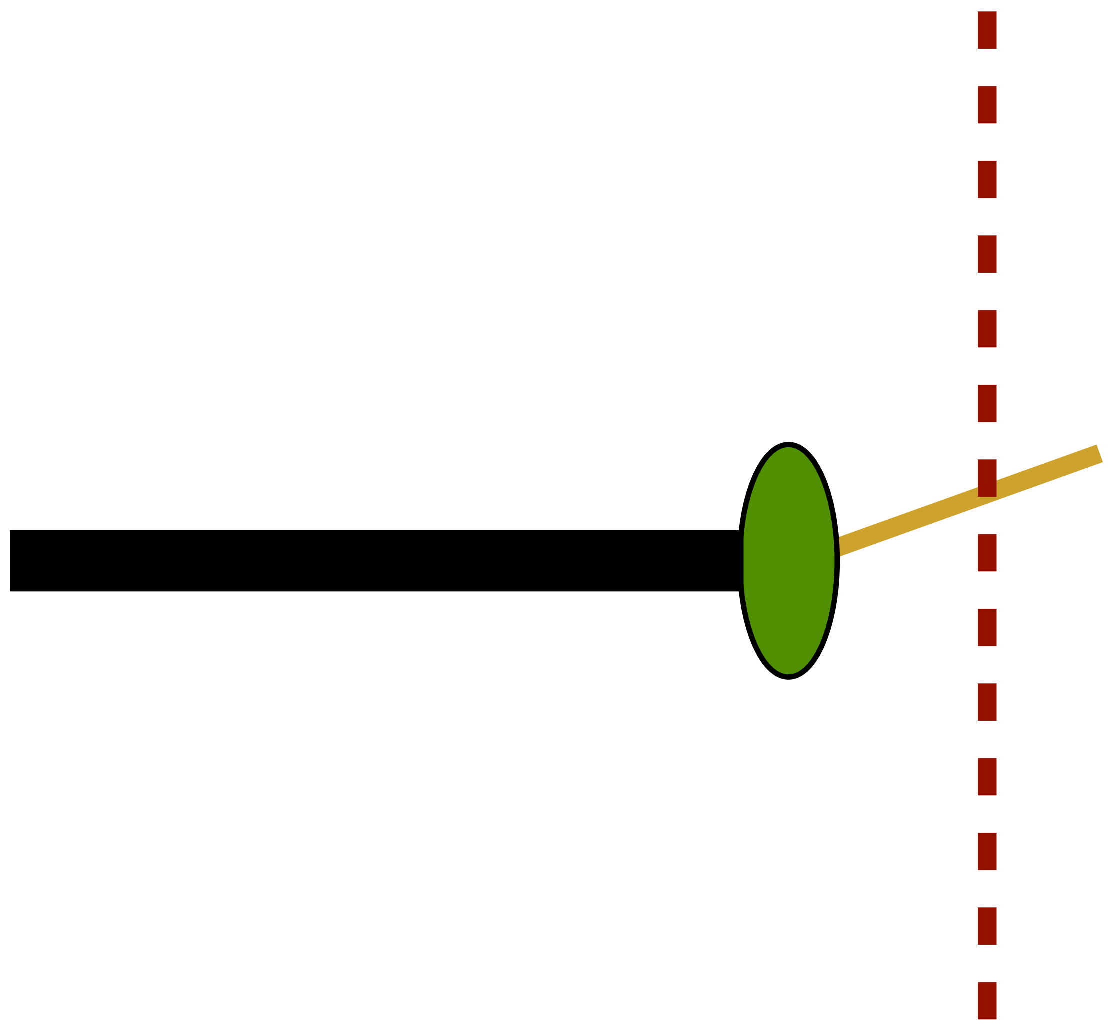
- The EIC will be a groundbreaking machine for QCD studies
- I discussed some opportunities to study the multidimensional structure of nucleons, but there are many more
- Results can be used to check lattice QCD predictions and look for new physics
- The long-term goal is the capability of computing the multidimensional structure of the nucleon, and eventually of the nucleus, and the hadronization process, all based on QCD

BACKUP

DIFFERENT CONTRIBUTIONS TO TRANSVERSE MOMENTUM

"intrinsic"
transverse
momentum

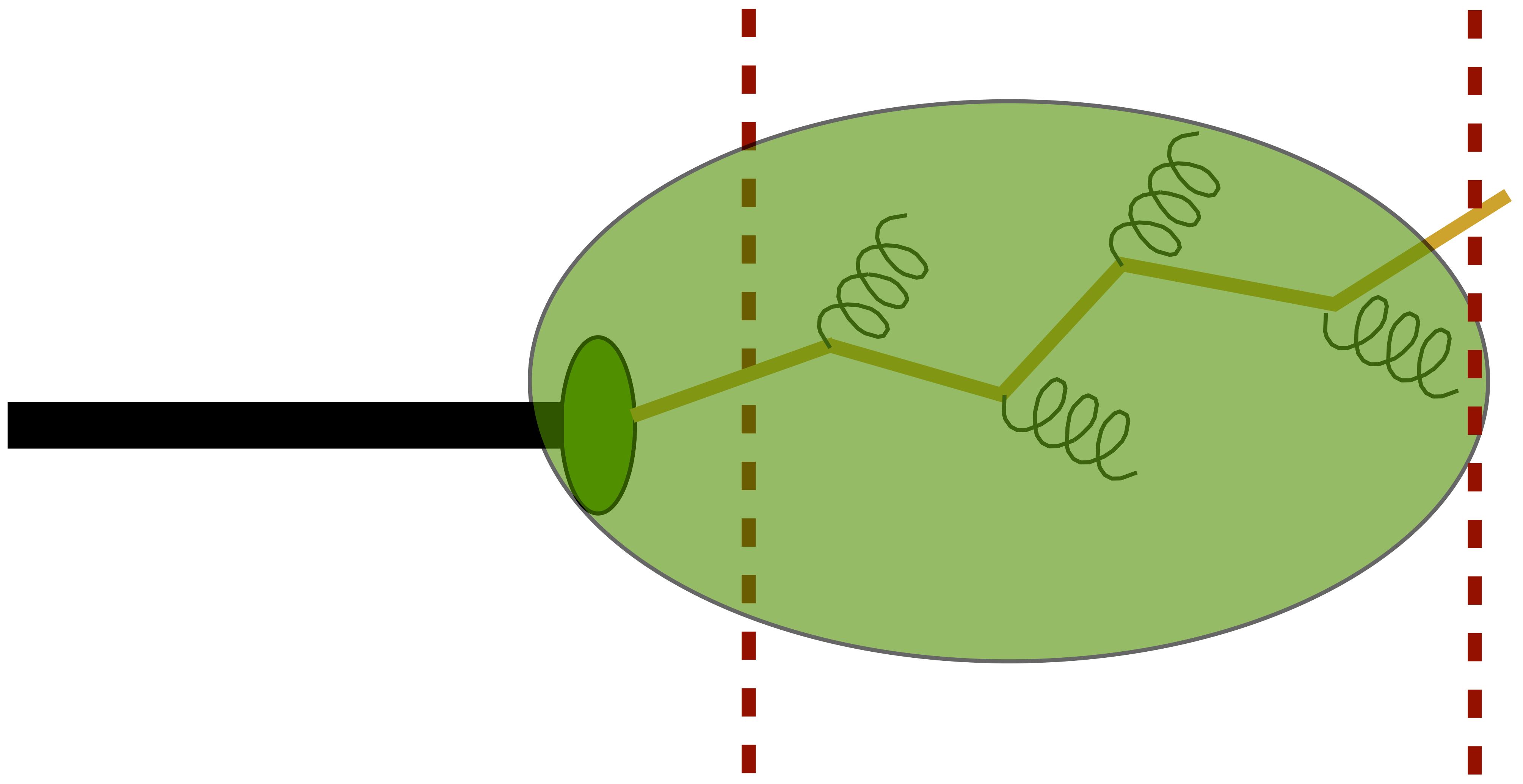


$$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$$

DIFFERENT CONTRIBUTIONS TO TRANSVERSE MOMENTUM

"intrinsic" transverse momentum

soft and collinear gluon radiation



$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$

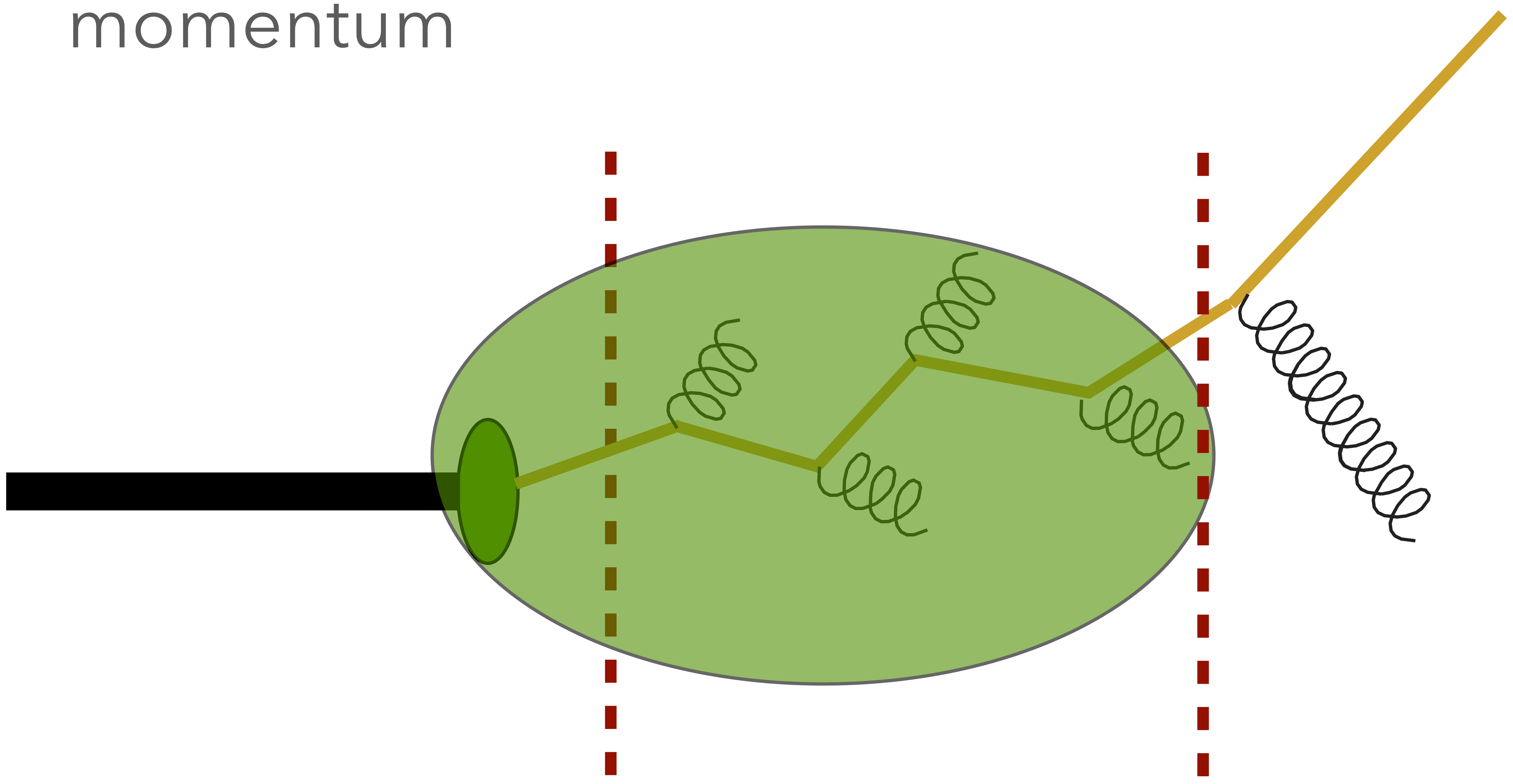
$|k_\perp| \ll Q$

DIFFERENT CONTRIBUTIONS TO TRANSVERSE MOMENTUM

"intrinsic" transverse momentum

soft and collinear gluon radiation

hard gluon radiation (not in TMD region)



$|k_\perp| \sim \Lambda_{\rm QCD}$ $|k_\perp| \ll Q$ $|k_\perp| \sim Q$

LOGARITHMIC ACCURACY

Sudakov form factor

LL $\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$

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LOGARITHMIC ACCURACY

	Sudakov form factor	matching coeff.
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NLL′	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$	$\left(C^0 + \alpha_S C^1\right)$

the difference between the two is formally NNLL $\alpha_S^n \ln^{2n-2}\left(\frac{Q^2}{\mu_b^2}\right)$

LOW-b_T MODIFICATIONS

$$\log\left(Q^2 b_T^2\right) \to \log\left(Q^2 b_T^2 + 1\right)$$

see, e.g., Bozzi, Catani, De Florian, Grazzini
hep-ph/0302104

LOW-b_T MODIFICATIONS

$$\log\left(Q^2 b_T^2\right) \to \log\left(Q^2 b_T^2 + 1\right)$$

see, e.g., Bozzi, Catani, De Florian, Grazzini
hep-ph/0302104

$$b_*(b_c(b_\mathrm{T})) = \sqrt{\frac{b_\mathrm{T}^2 + b_0^2/(C_5^2 Q^2)}{1 + b_\mathrm{T}^2/b_\mathrm{max}^2 + b_0^2/(C_5^2 Q^2 b_\mathrm{max}^2)}}$$

$$b_\mathrm{min} \equiv b_*(b_c(0)) = \frac{b_0}{C_5 Q}\sqrt{\frac{1}{1 + b_0^2/(C_5^2 Q^2 b_\mathrm{max}^2)}}$$

Collins et al.
arXiv:1605.00671

PAVIA 2019 b_* PRESCRIPTION

$$b_* \equiv \frac{b_T}{\sqrt{1 + b_T^2/b_{\max}^2}}$$

Collins, Soper, Sterman, NPB250 (85)

PAVIA 2019 b_* PRESCRIPTION

$$\mu_0 = 1\,\mathrm{GeV}$$

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$$\mu_b = 2e^{-\gamma_E}/b_*$$

$$\bar{b}_* \equiv b_{\max}\left(\frac{1 - e^{-b_T^4/b_{\max}^4}}{1 - e^{-b_T^4/b_{\min}^4}}\right)^{1/4}$$

$$b_{\max} = 2e^{-\gamma_E}$$

$$b_{\min} = \frac{2e^{-\gamma_E}}{Q}$$

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$$b_{\min} = \frac{2e^{-\gamma_E}}{Q}$$

These are all choices that should be at some point checked/challenged

PAVIA 2019 b_* PRESCRIPTION

$$\hat{f}_1^q(x, b_T; \mu^2) = \sum_i \big(C_{qi} \otimes f_1^i\big)(x, b_*; \mu_b) e^{\tilde{S}(b_*;\mu_b,\mu)} e^{g_K(b_T) \ln \frac{\mu}{\mu_0}} \hat{f}_{\mathrm{NP}}^q(x, b_T)$$

$$\mu_0 = 1\,\mathrm{GeV}$$

$$b_* \equiv \frac{b_T}{\sqrt{1 + b_T^2/b_{\max}^2}}$$

Collins, Soper, Sterman, NPB250 (85)

$$\mu_b = 2e^{-\gamma_E}/b_*$$

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$$b_{\max} = 2e^{-\gamma_E}$$

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These are all choices that should be at some point checked/challenged

EFFECTS OF b_* PRESCRIPTION

$$\mu_b = 2e^{-\gamma_E}/b_* \qquad \bar{b}_* \equiv b_{\max}\left(\frac{1-e^{-b_T^4/b_{\max}^4}}{1-e^{-b_T^4/b_{\min}^4}}\right)^{1/4} \qquad b_{\max} = 2e^{-\gamma_E}$$

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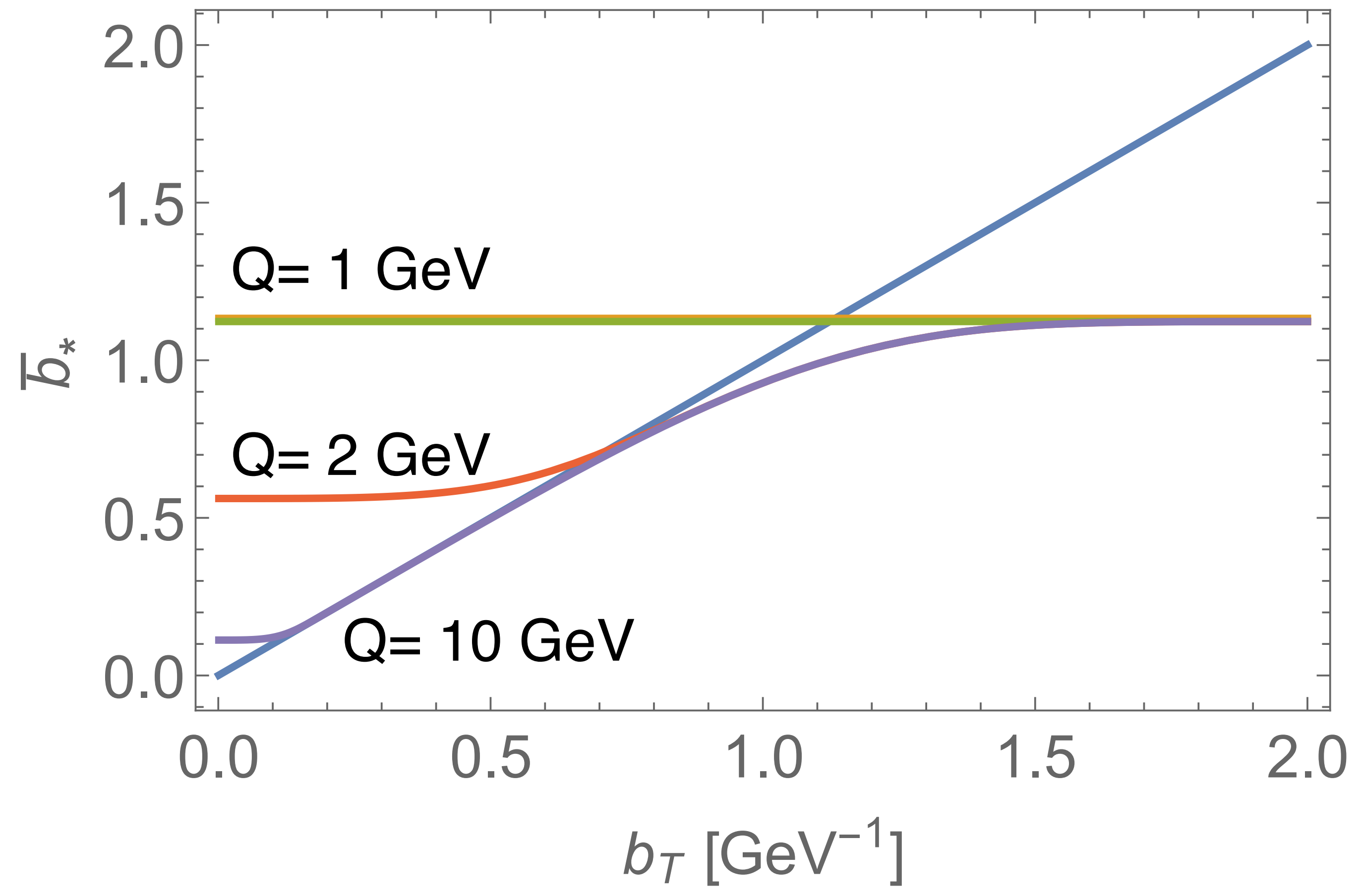

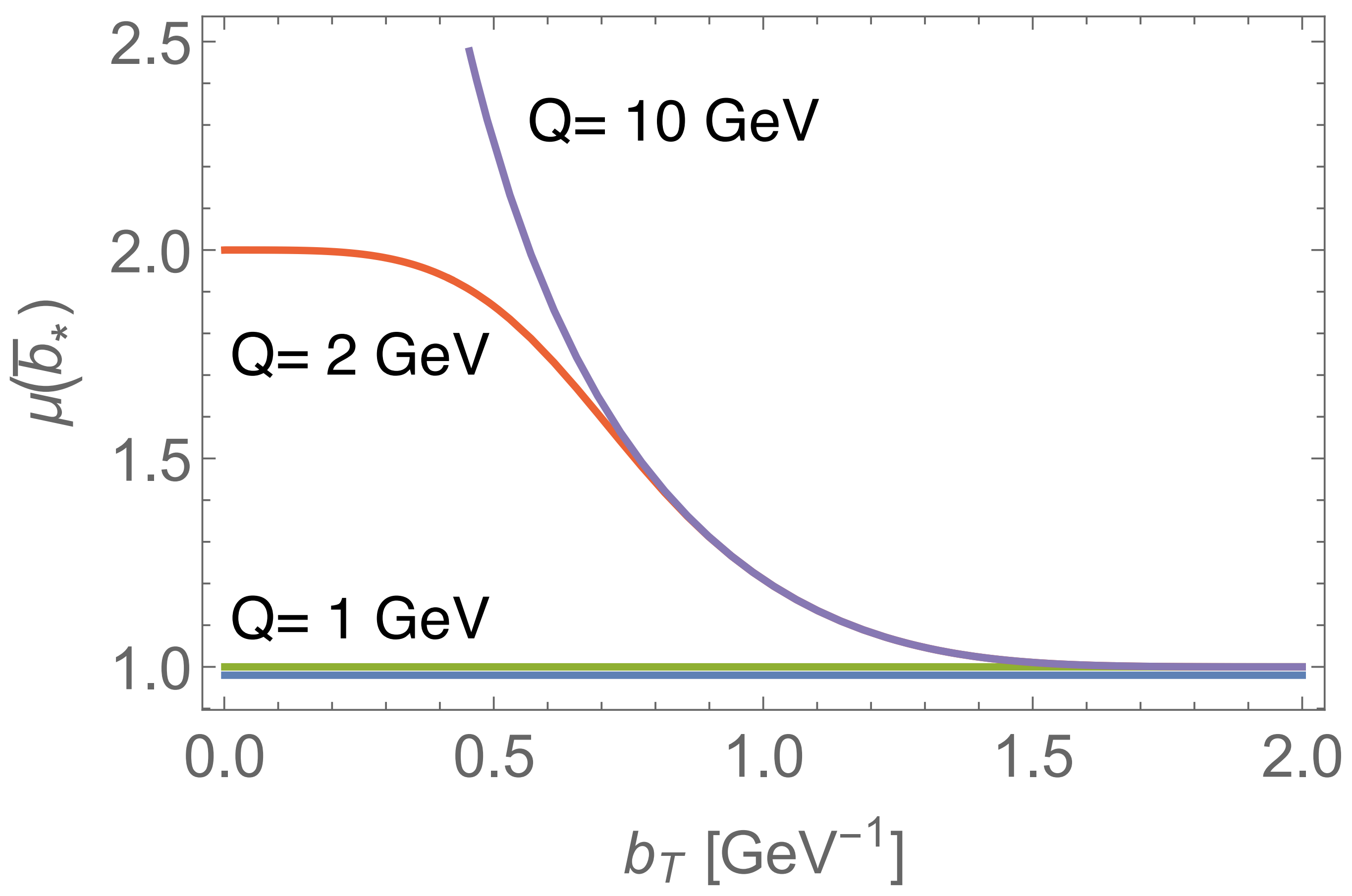

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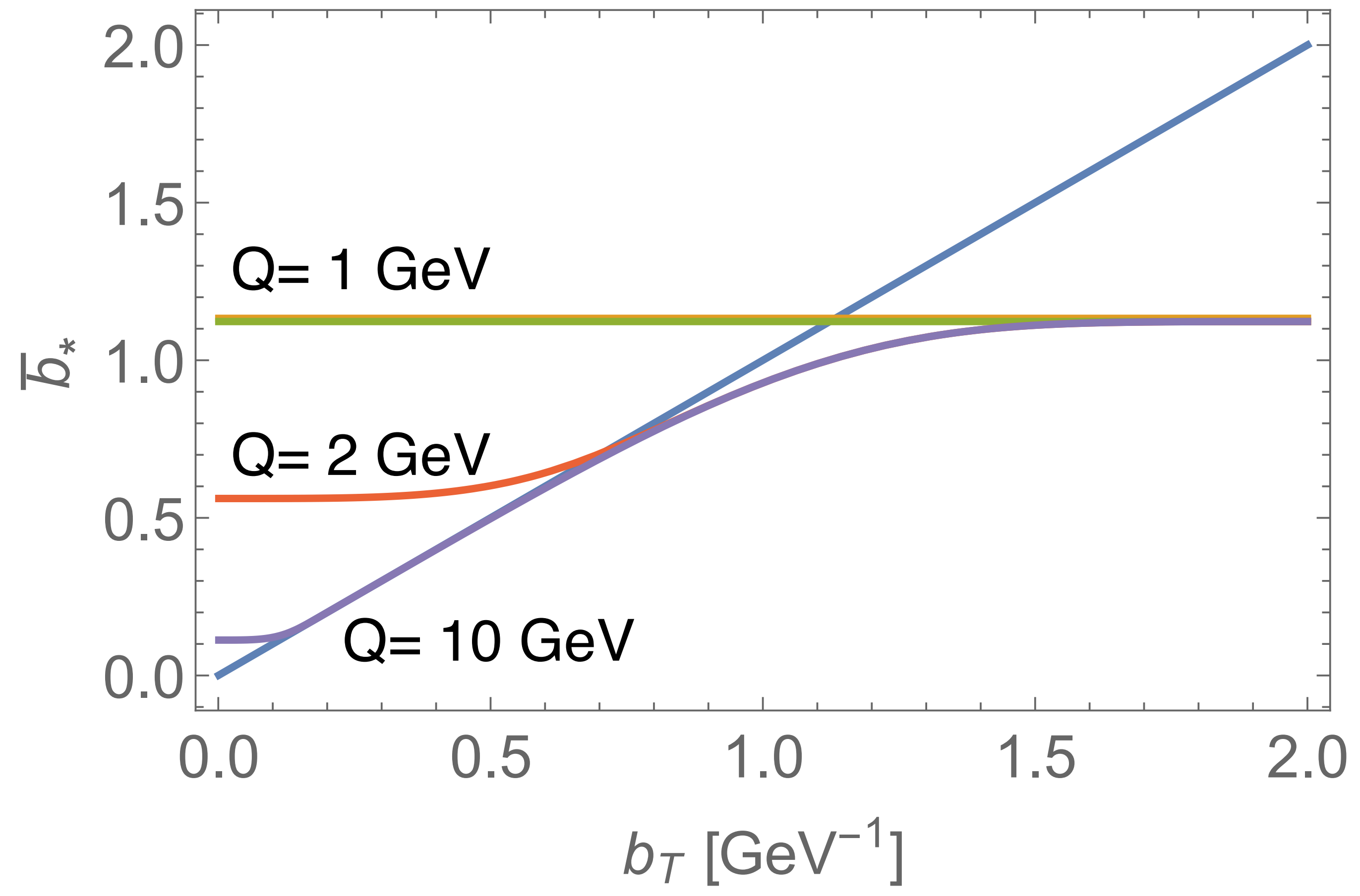

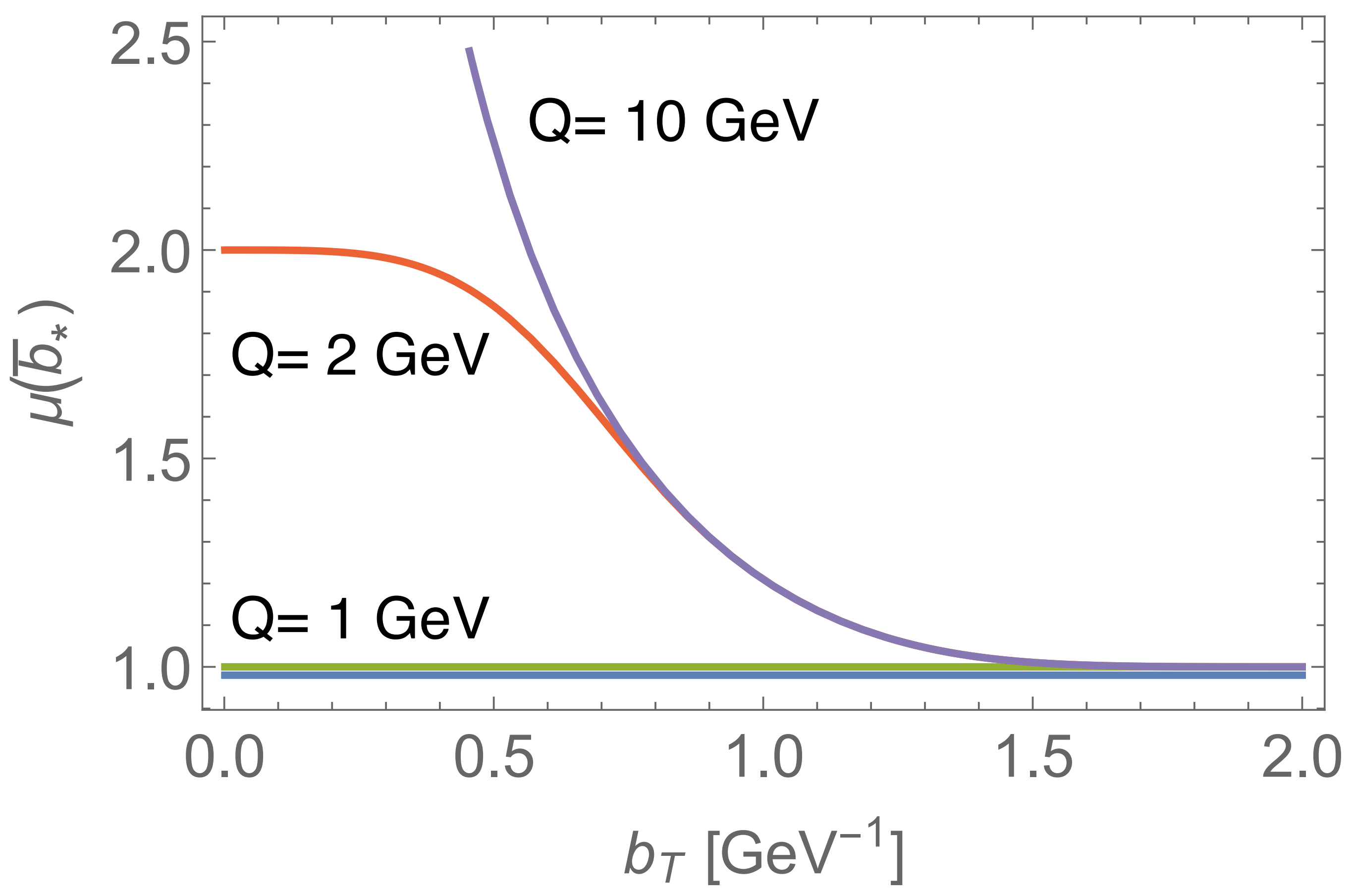

No significant effect at high Q, but large effect at low Q (inhibits perturbative contribution)

MAP22 TENTATIVE SOLUTION

ENHANCEMENT PREFACTOR $= \dfrac{\left.\dfrac{d\sigma}{dx\,dz\,dQ^2}\right|_{\text{nonmix.}}}{\int \text{TMD}\; d^2P_{hT}}$

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The prefactor is independent of the fitting parameters

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$$= \frac{\left.\frac{d\sigma}{dx\,dz\,dQ^2}\right|_{\text{nonmix.}}}{\int \text{TMD}\; d^2P_{hT}}$$

The prefactor is independent of the fitting parameters

Higher-order corrections decrease the role of the TMD region.
We need to enhance it with a prefactor.

NONMIXED TERMS IN COLLINEAR SIDIS CROSS SECTION

$$
\left.\frac{d\sigma^h}{dx\,dQ^2\,dz}\right|_{\mathcal{O}(\alpha_s^1)} = \sigma_0 \sum_{ff'} \frac{e_f^2}{z^2} \left(\delta_{f'f} + \delta_{f'g}\right) \frac{\alpha_s}{\pi} \Bigg\{ \left[D_1^{h/f'} \otimes C_1^{f'f} \otimes f_1^{f/N}\right](x, z, Q)
$$

$$
\cancel{+ \frac{1-y}{1+(1-y)^2} \left[D_1^{h/f'} \otimes C_L^{f'f} \otimes f_1^{f/N}\right](x, z, Q)} \Bigg\},
$$

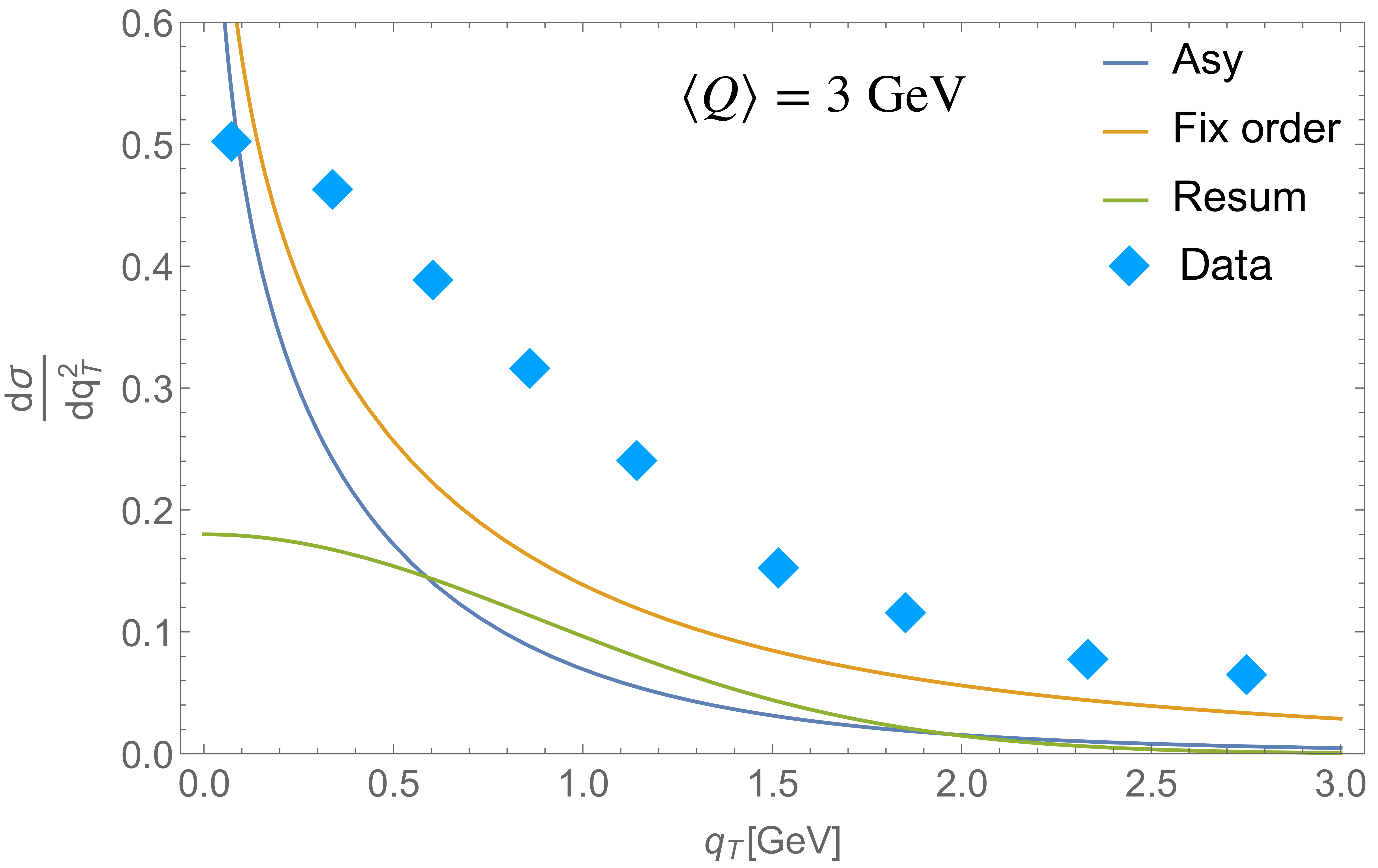
$$
C_1^{qq} = \frac{C_F}{2} \Bigg\{ -8\delta(1-x)\delta(1-z)
$$

$$
+ \delta(1-x)\left[P_{qq}(z)\ln\frac{Q^2}{\mu_F^2} + L_1(z) + L_2(z) + (1-z)\right]
$$

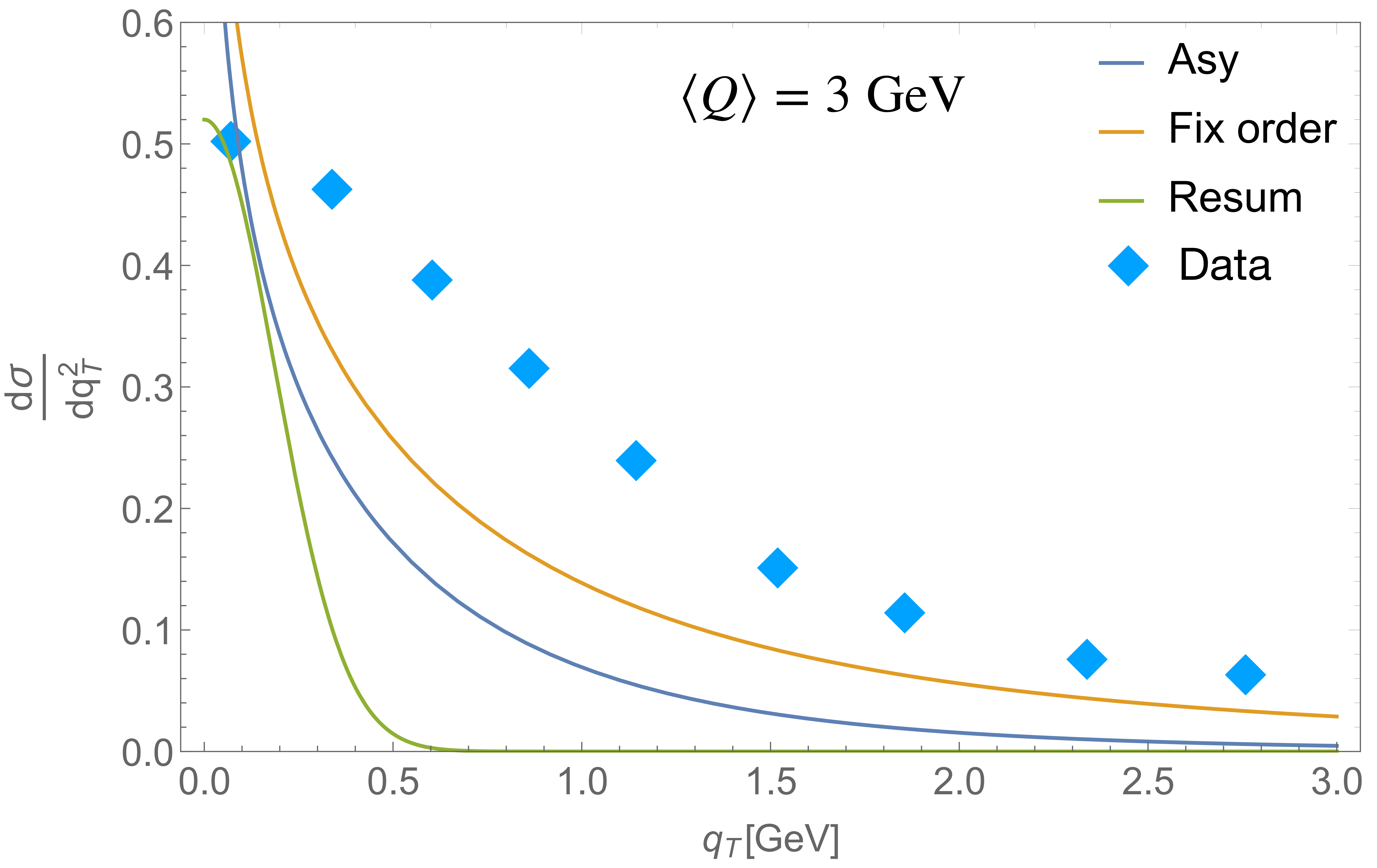
$$
+ \delta(1-z)\left[P_{qq}(x)\ln\frac{Q^2}{\mu^2} + L_1(x) - L_2(x) + (1-x)\right]
$$

$$
\cancel{+ 2\frac{1}{(1-x)_+}\frac{1}{(1-z)_+} - \frac{1+z}{(1-x)_+} - \frac{1+x}{(1-z)_+}} + 2(1+xz) \Bigg\},
$$

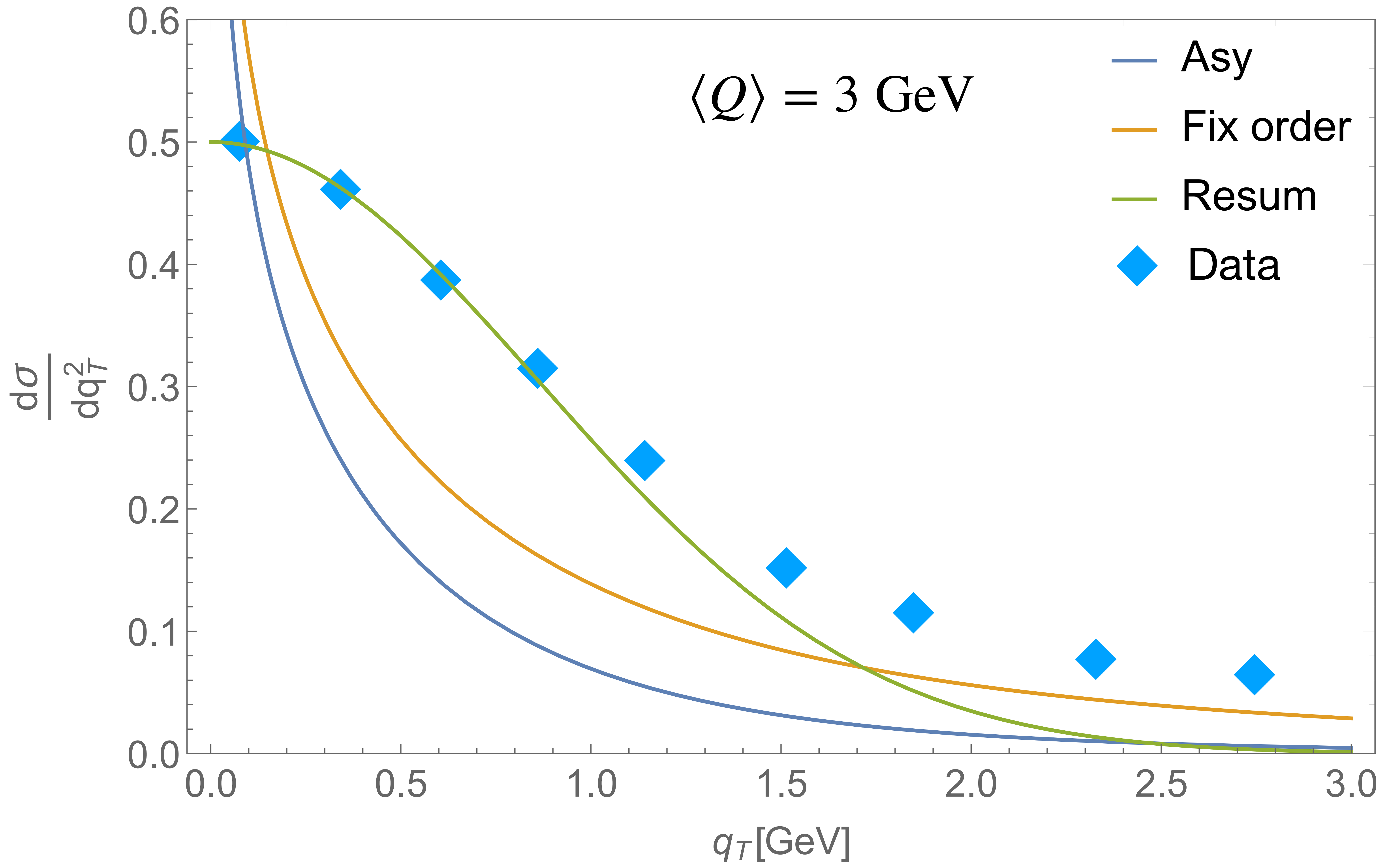
SOME JUSTIFICATION: INITIAL SITUATION



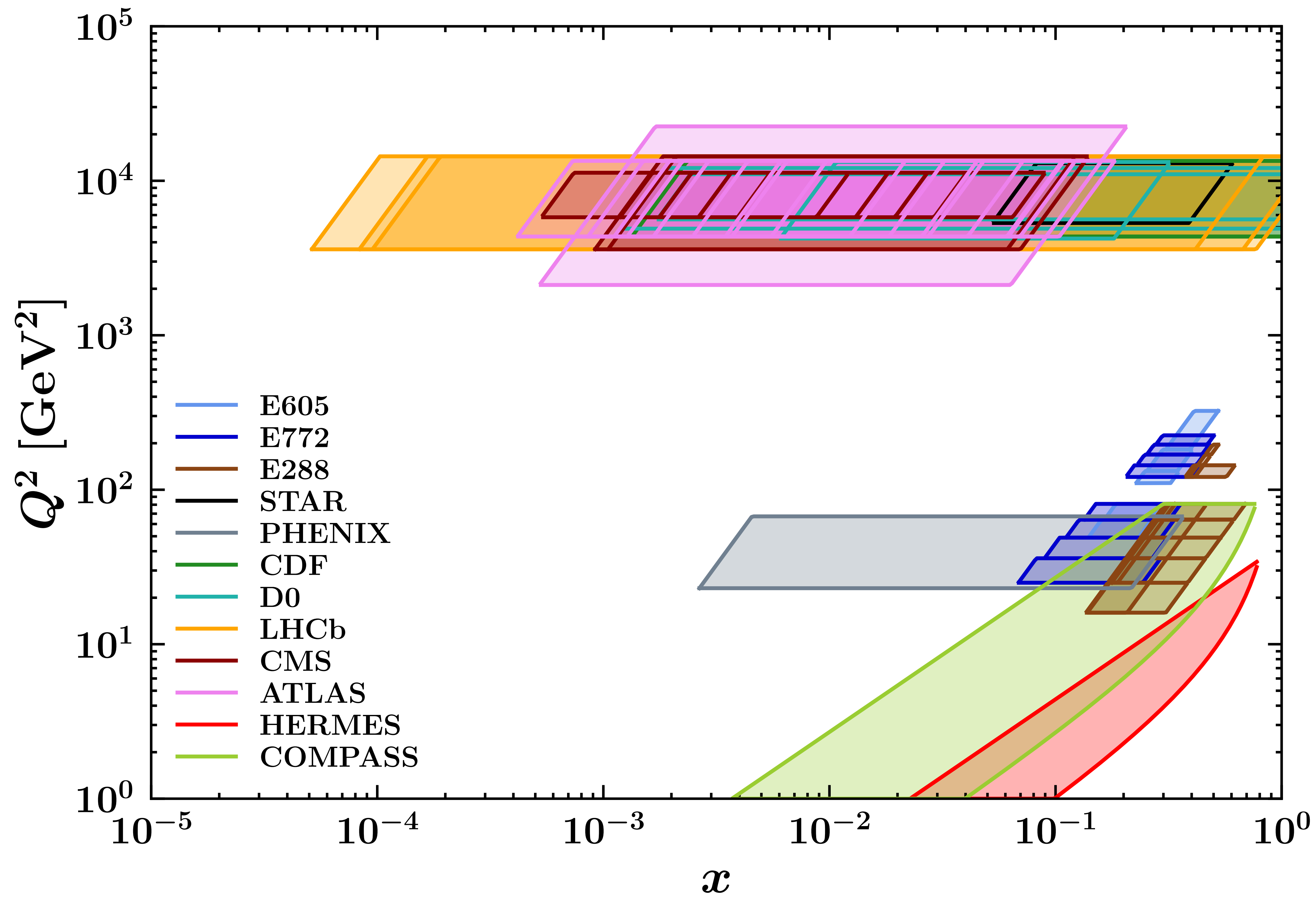
SOLUTION 1: RESTRICT TMD REGION

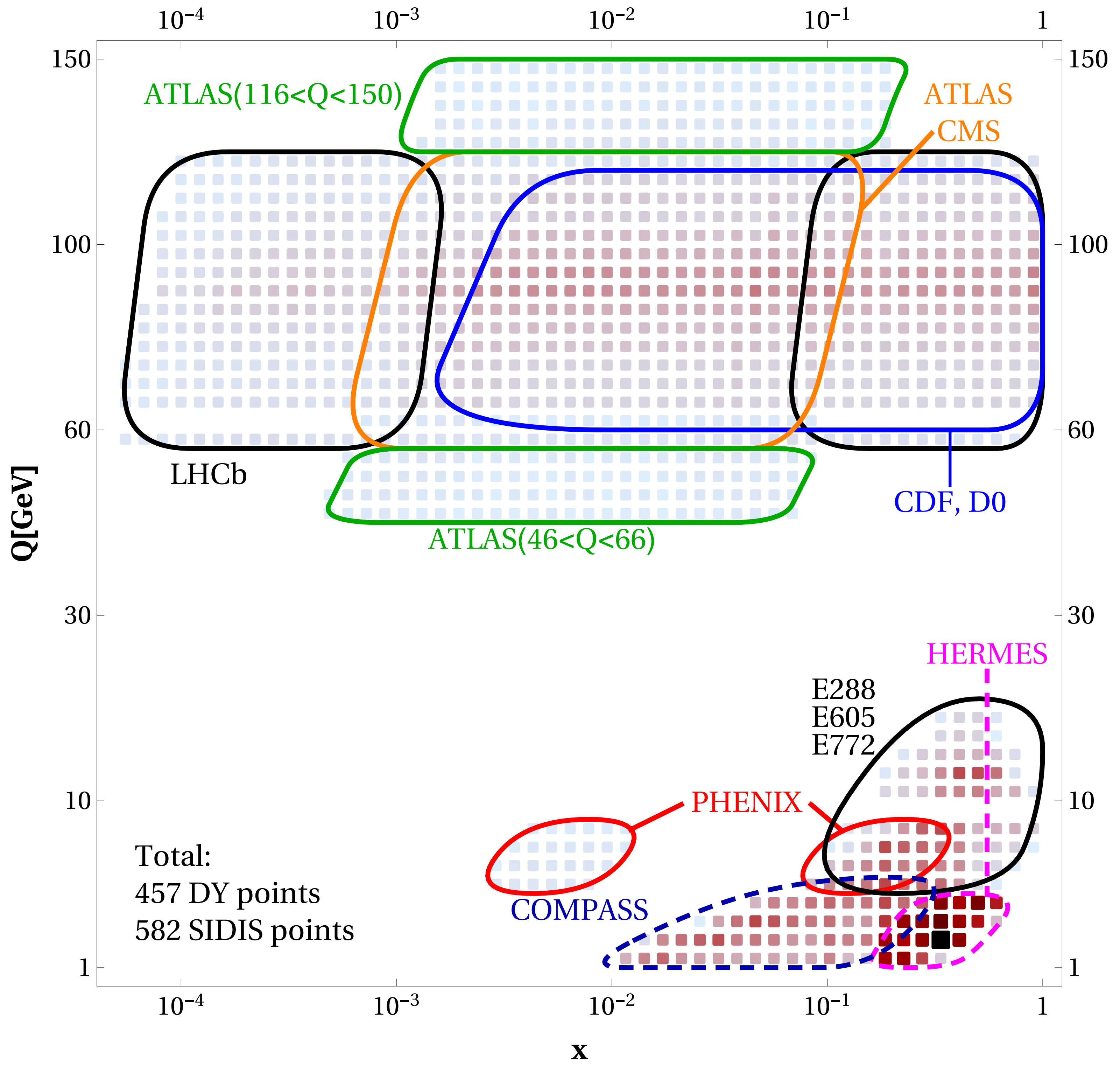


SOLUTION 2: ENHANCE TMD CONTRIBUTIONS



x–Q² COVERAGE





[MAP Collaboration
Bacchetta, Bertone, Bissolotti, Bozzi, Cerutti, Piacenza, Radici, Signori, arXiv:2206.07598]

[Scimemi, Vladimirov, arXiv:1912.06532]

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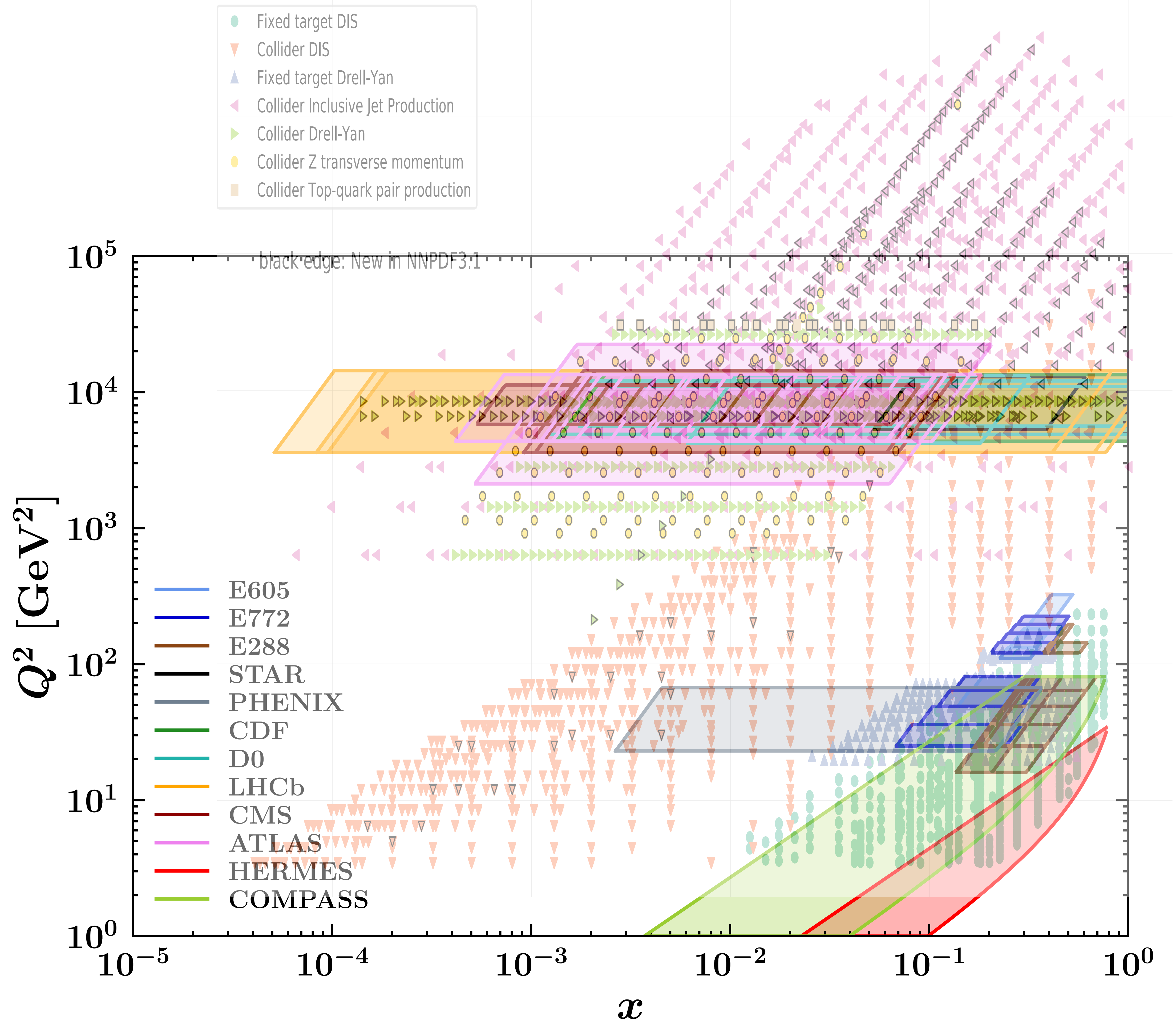

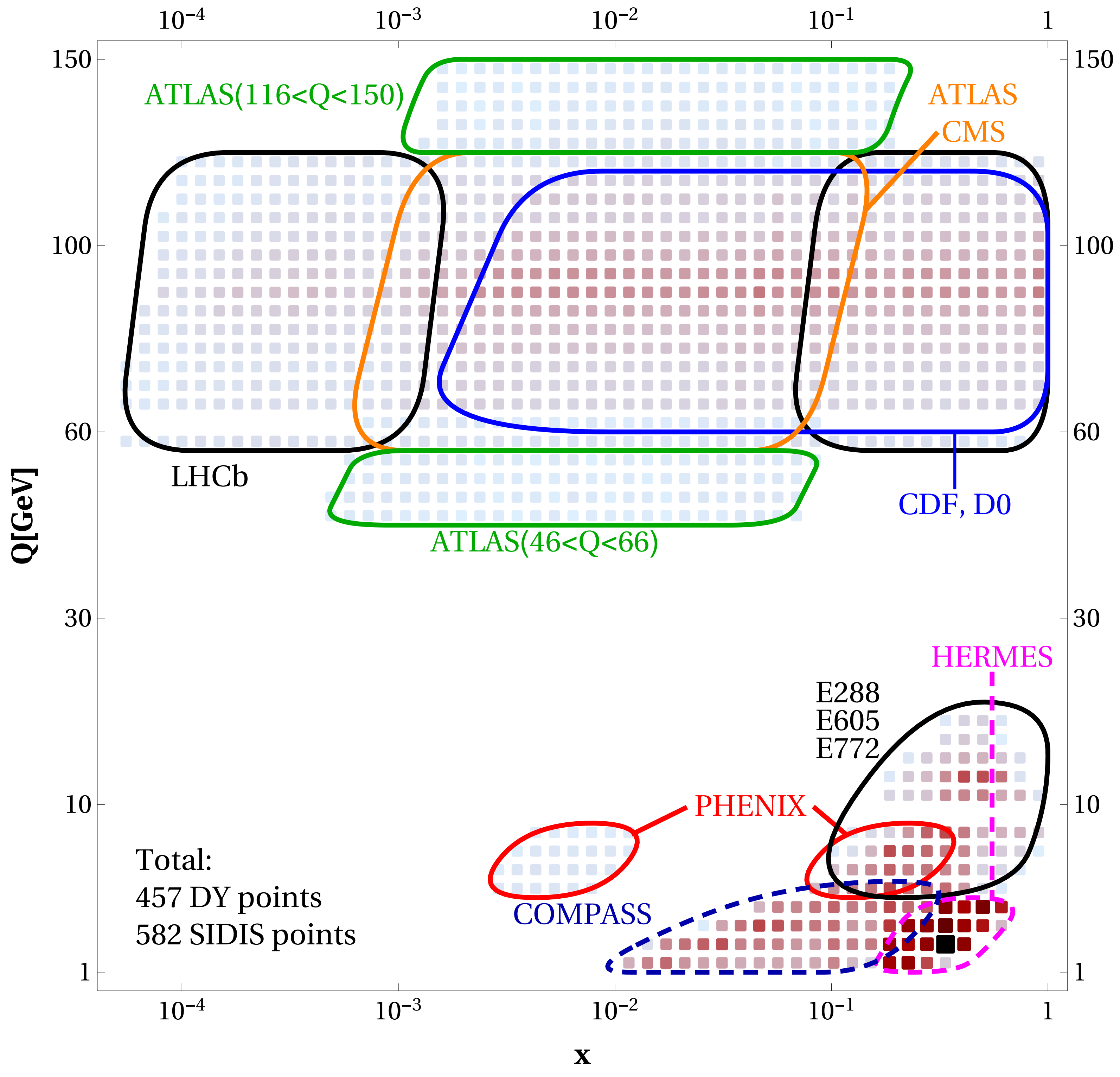

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Data set	N_{dat}	$\chi^2_D/N_{\mathrm{dat}}$	$\chi^2_\lambda/N_{\mathrm{dat}}$	$\chi^2_0/N_{\mathrm{dat}}$
Tevatron total	71	0.87	0.06	0.93
LHCb total	21	1.15	0.3	1.45
ATLAS total	72	4.56	0.48	5.05
CMS total	78	0.53	0.02	0.55
PHENIX 200	2	2.21	0.88	3.08
STAR 510	7	1.05	0.10	1.15
DY collider total	251	1.86	0.2	2.06
DY fixed-target total	233	0.85	0.4	1.24
HERMES total	344	0.48	0.23	0.71
COMPASS total	1203	0.62	0.3	0.92
SIDIS total	1547	0.59	0.28	0.87
Total	**2031**	**0.77**	**0.29**	**1.06**

AVAILABLE TOOLS: NANGA PARBAT

https://github.com/MapCollaboration/NangaParbat

README.md

Nanga Parbat is a fitting framework aimed at the determination of the non-perturbative component of TMD distributions.

Download

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For the last development branch you can clone the master code:

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Also:

ARTEMIDE

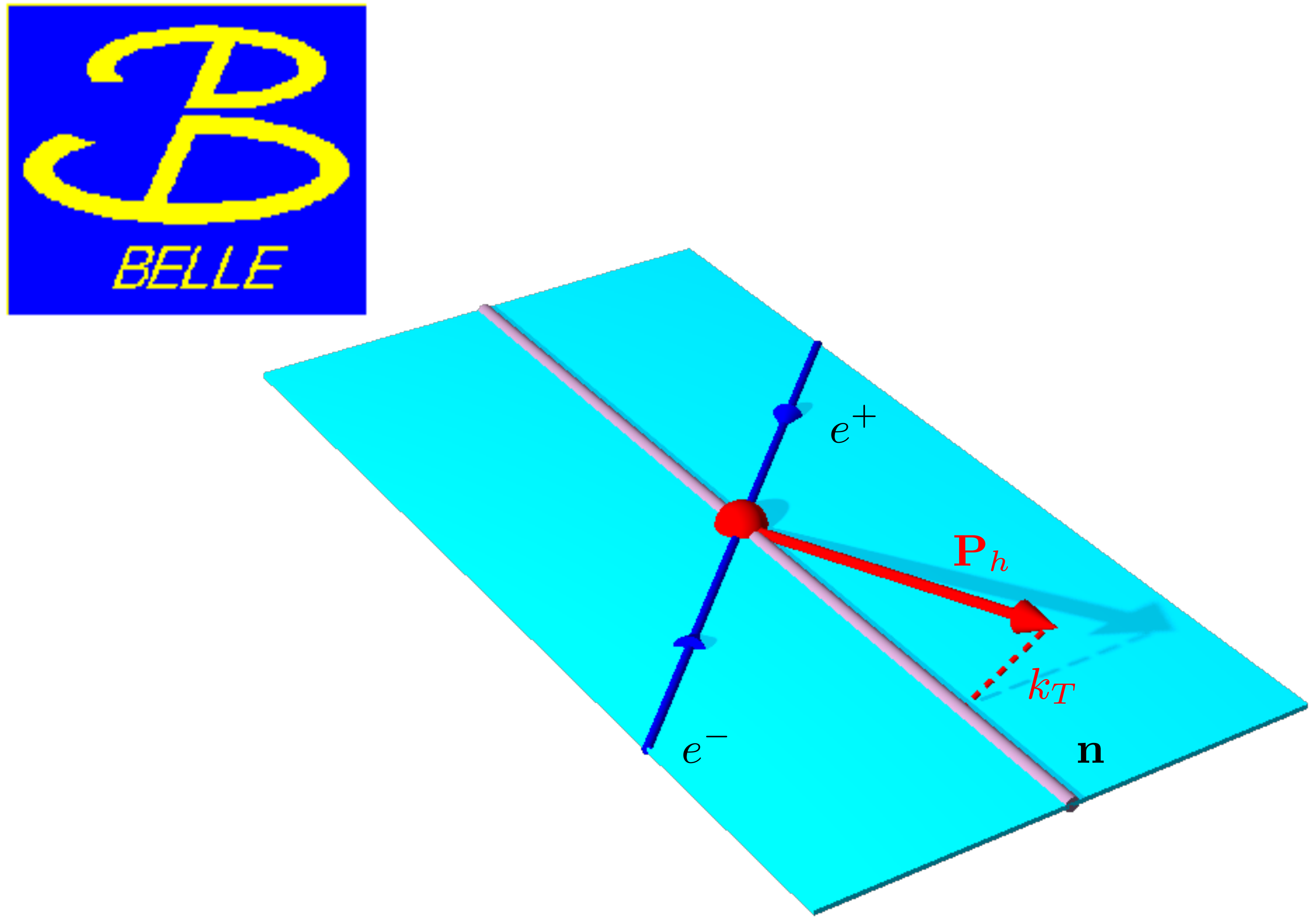
https://teorica.fis.ucm.es/artemide/

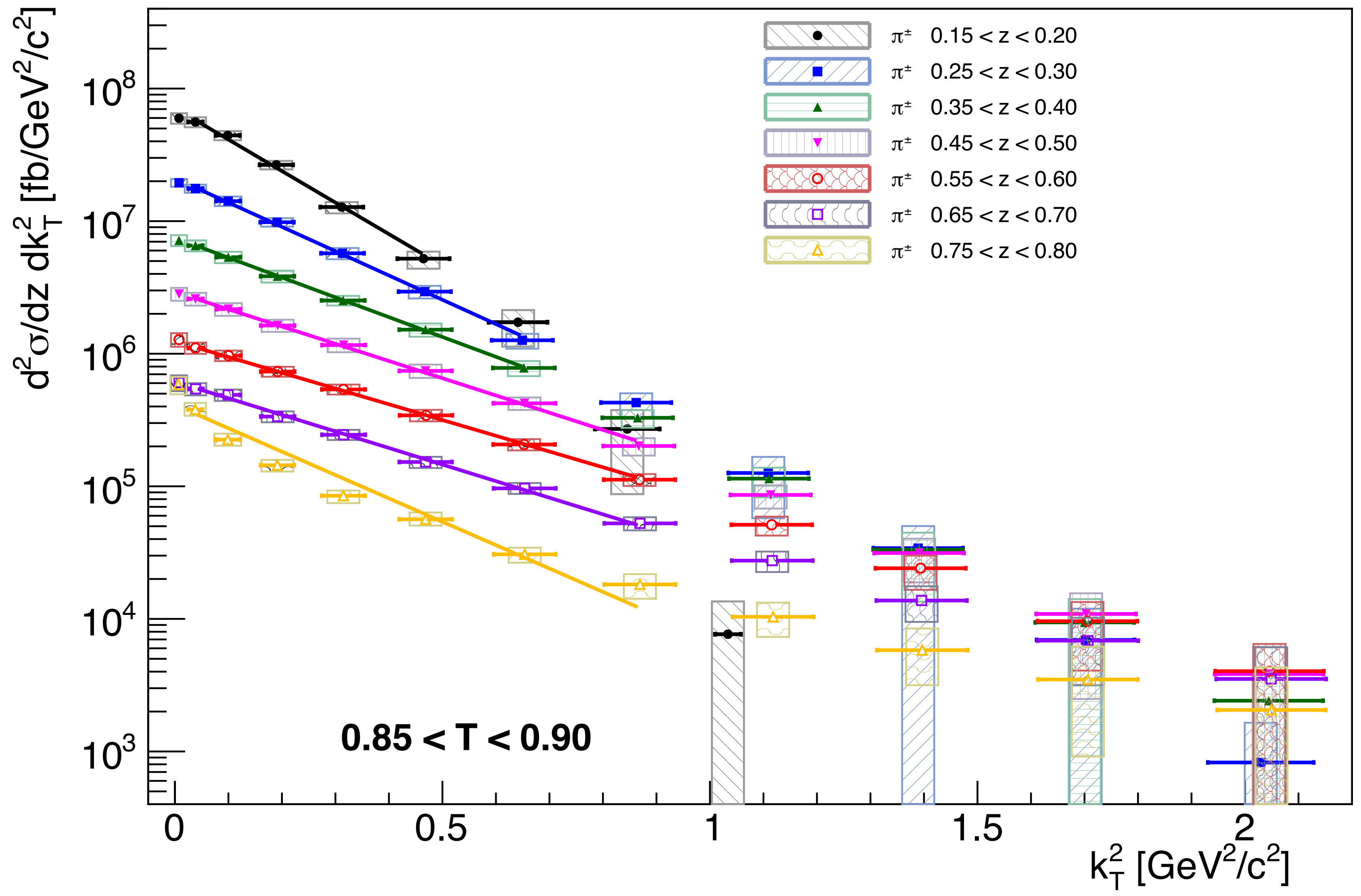
TMDLIB

https://tmdlib.hepforge.org/

TRANSVERSE MOMENTUM IN FRAGMENTATION FUNCTIONS

Seidl et al., arXiv:1902.01552





First direct measurement of TMD effects in fragmentation functions
Makes use of thrust axis: the formalism should take it into account

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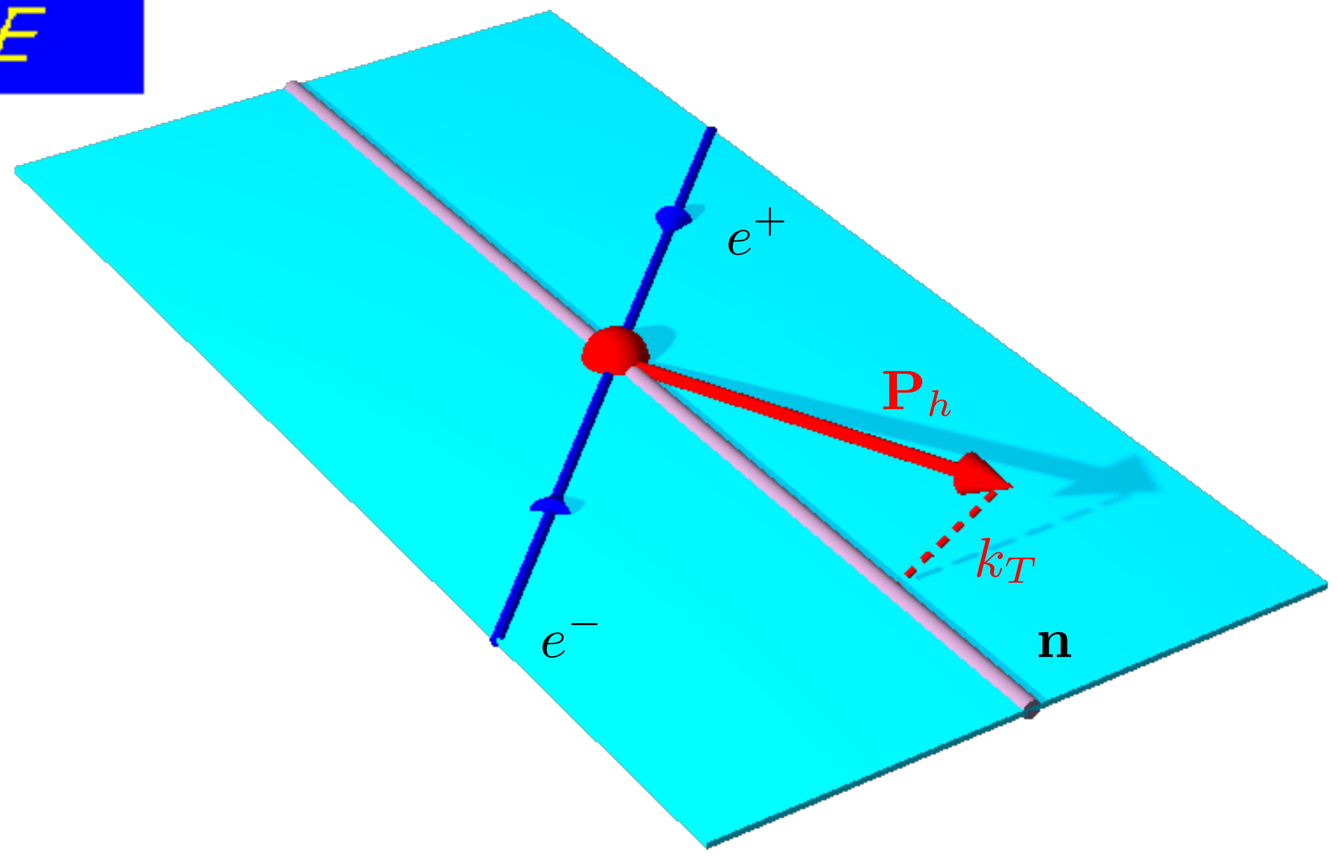
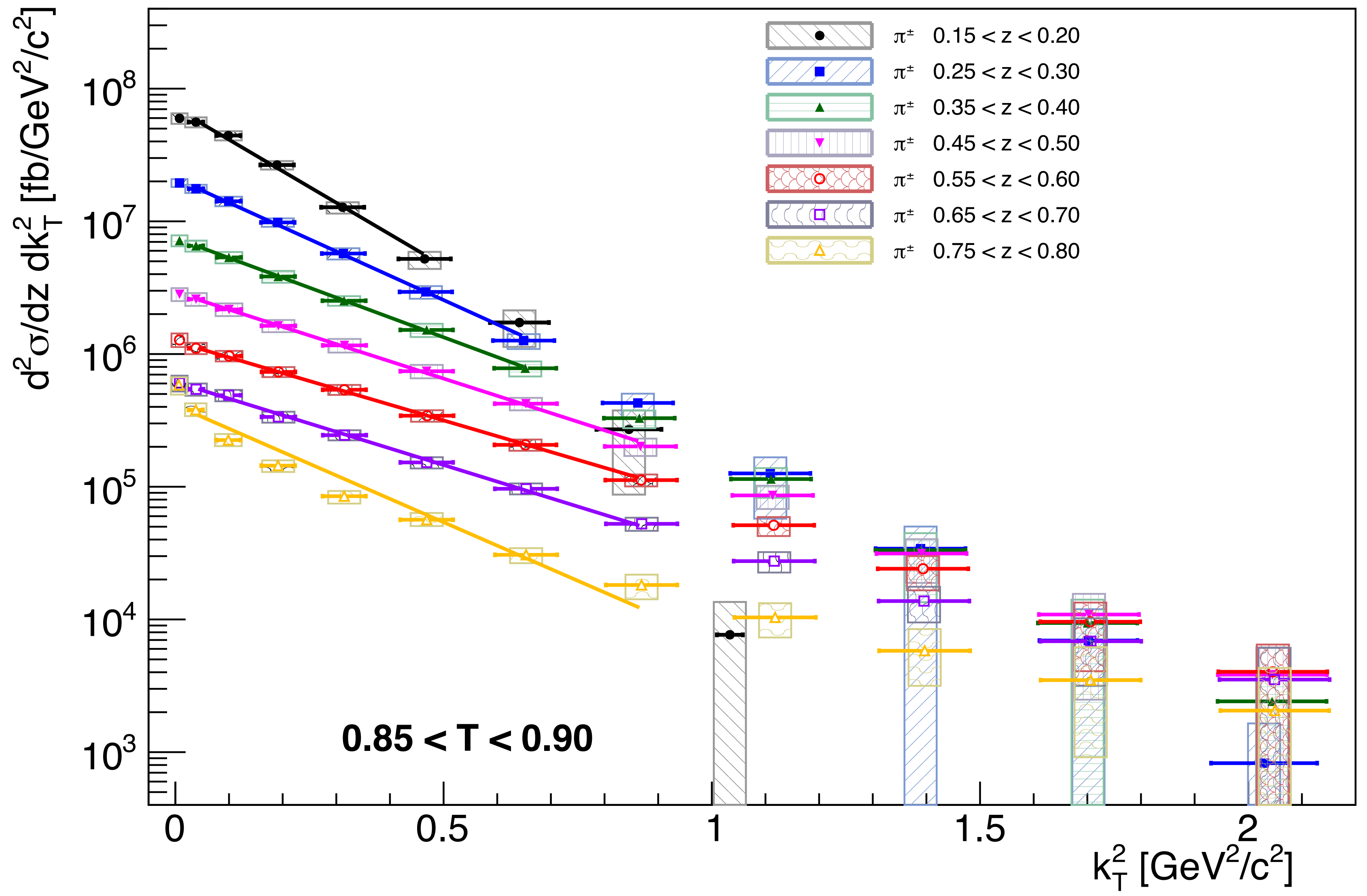


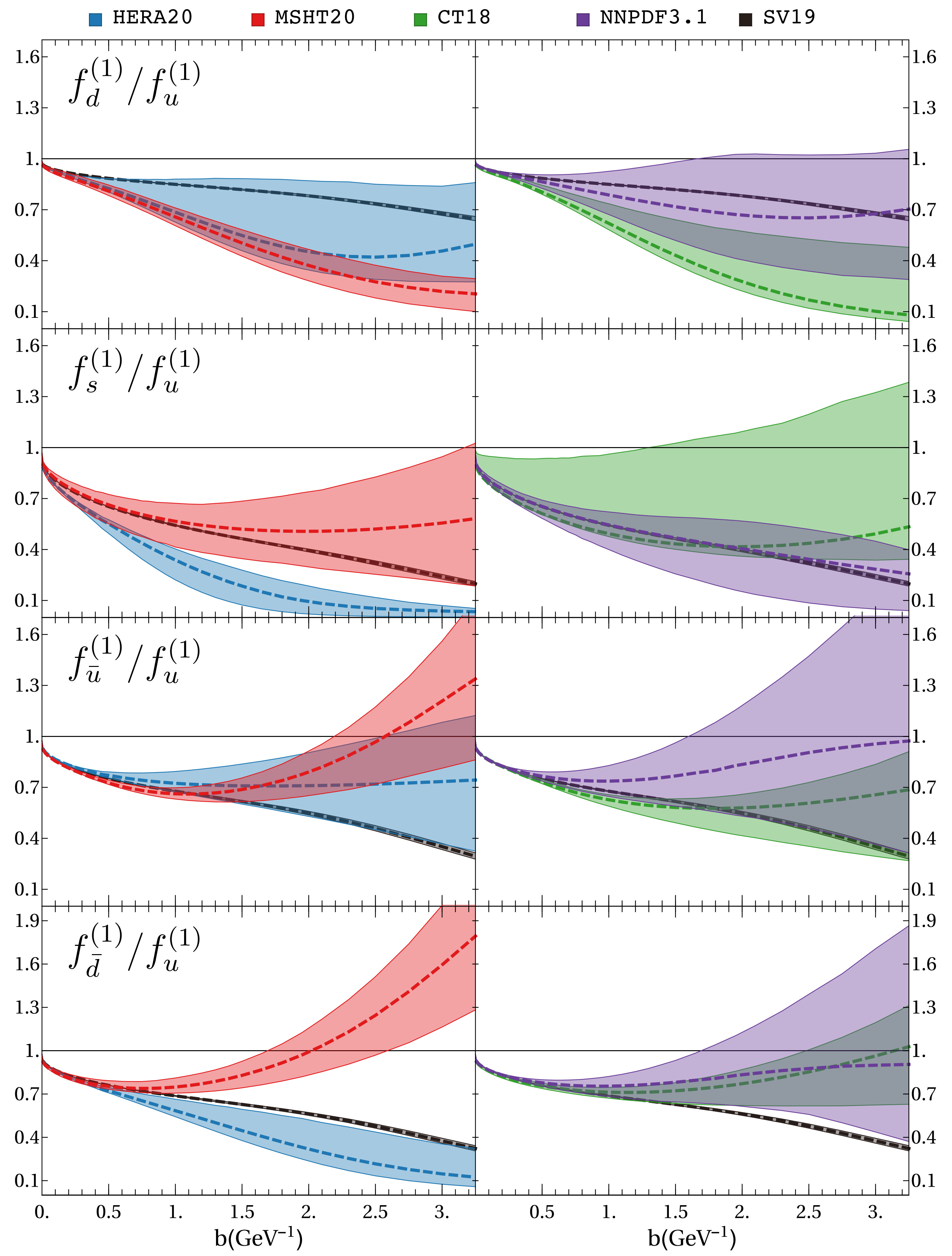


First direct measurement of TMD effects in fragmentation functions
Makes use of thrust axis: the formalism should take it into account

See https://arxiv.org/abs/2206.08876

RECENT STUDY WITH FLAVOR DEPENDENCE

Bury, Hautmann, Leal-Gomez, Scimemi, Vladimirov, Zurita, arxiv:2201.07114



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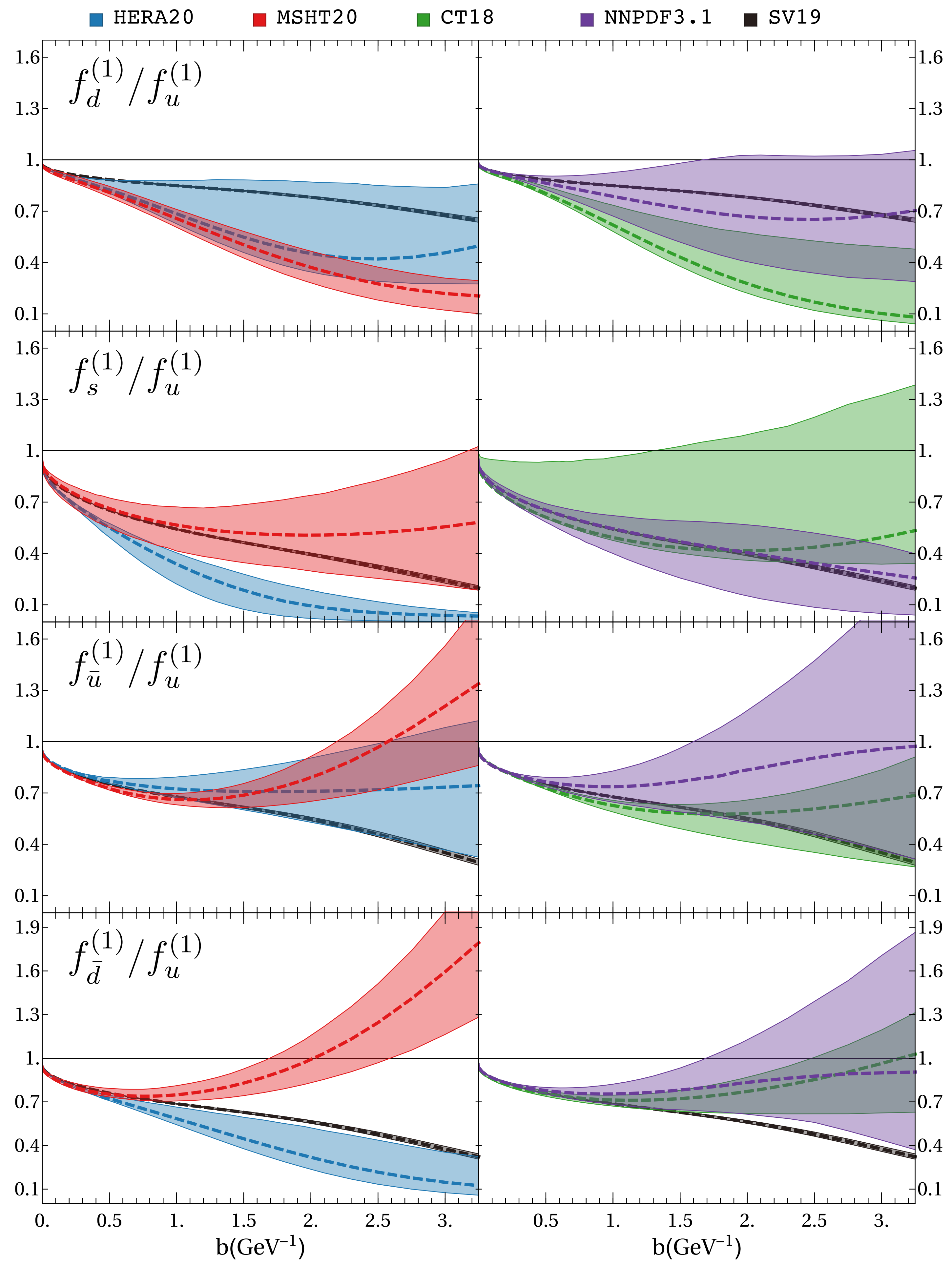
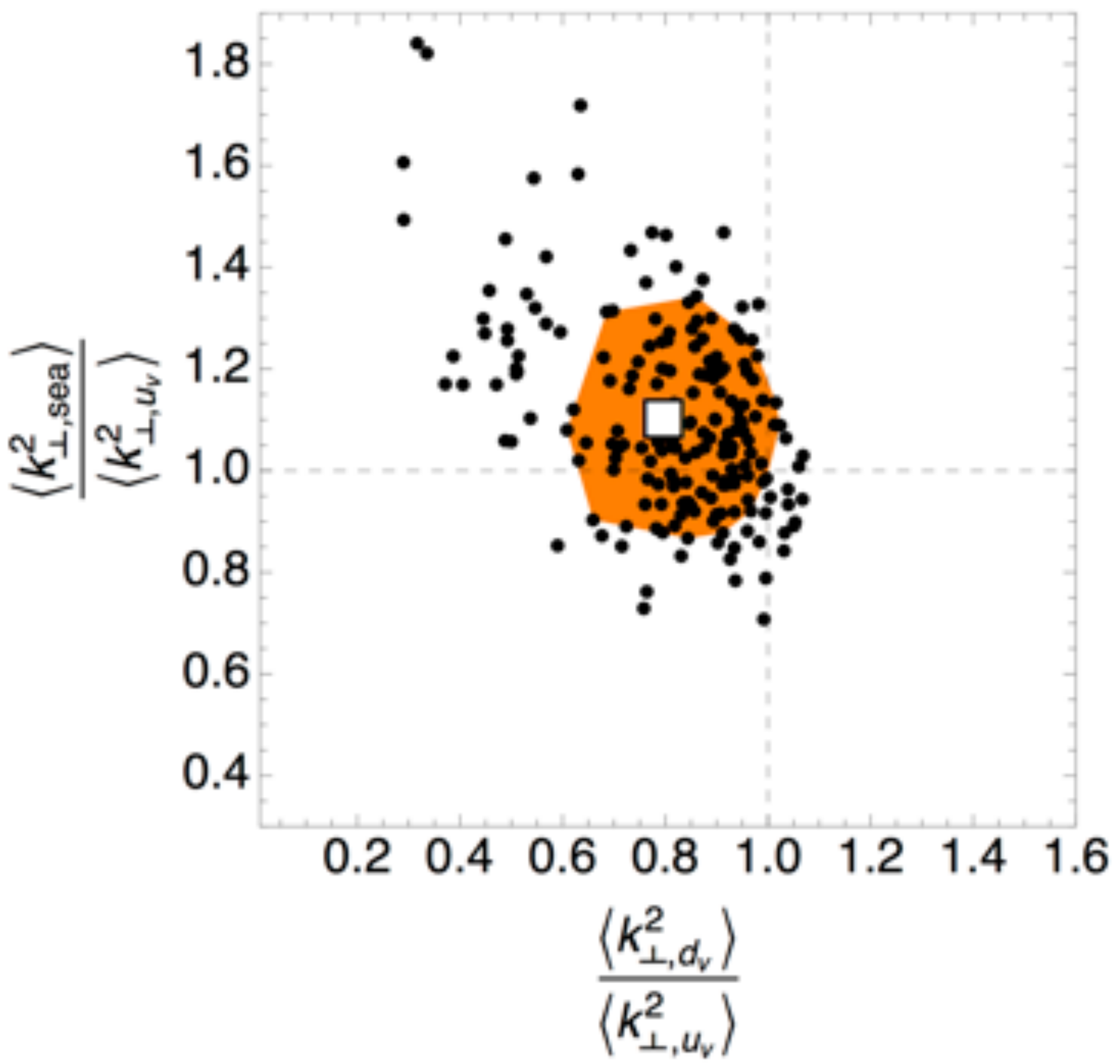


There seems to be a lot of room for flavor dependence.
Different collinear PDFs lead to different results…

FLAVOR DEPENDENCE OF TMDS

Signori, Bacchetta, Radici, Schnell JHEP 1311 (13)

Ratio of width of sea / width of up valence



Ratio width of down valence/ width of up valence

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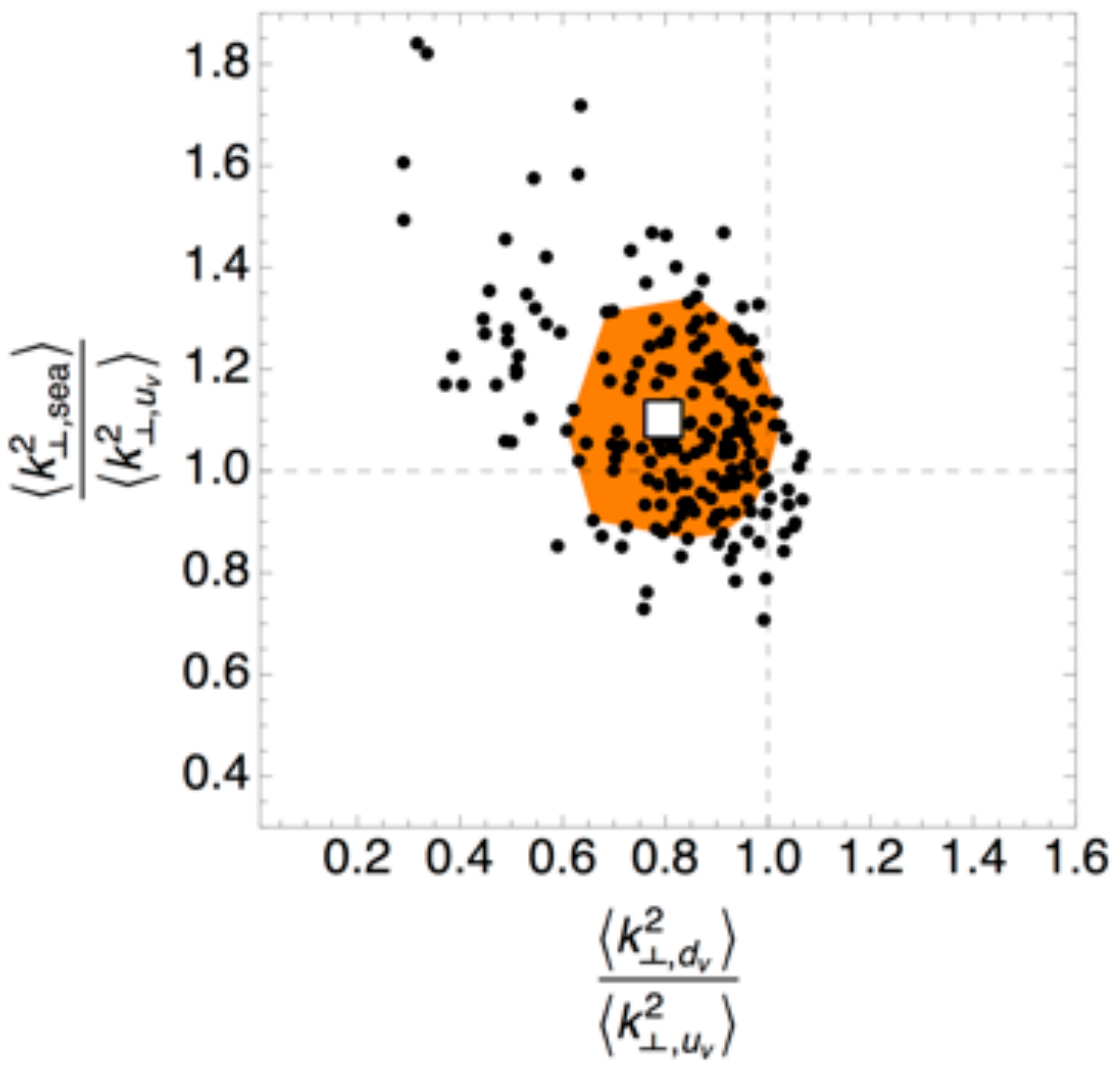

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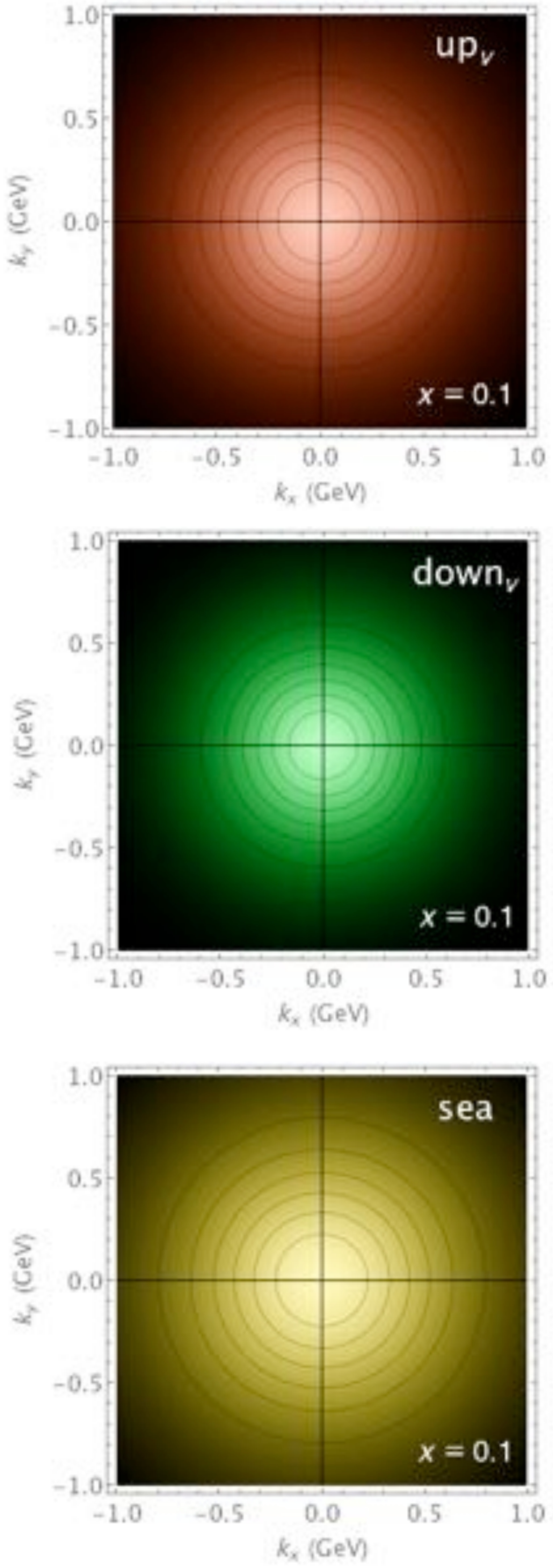

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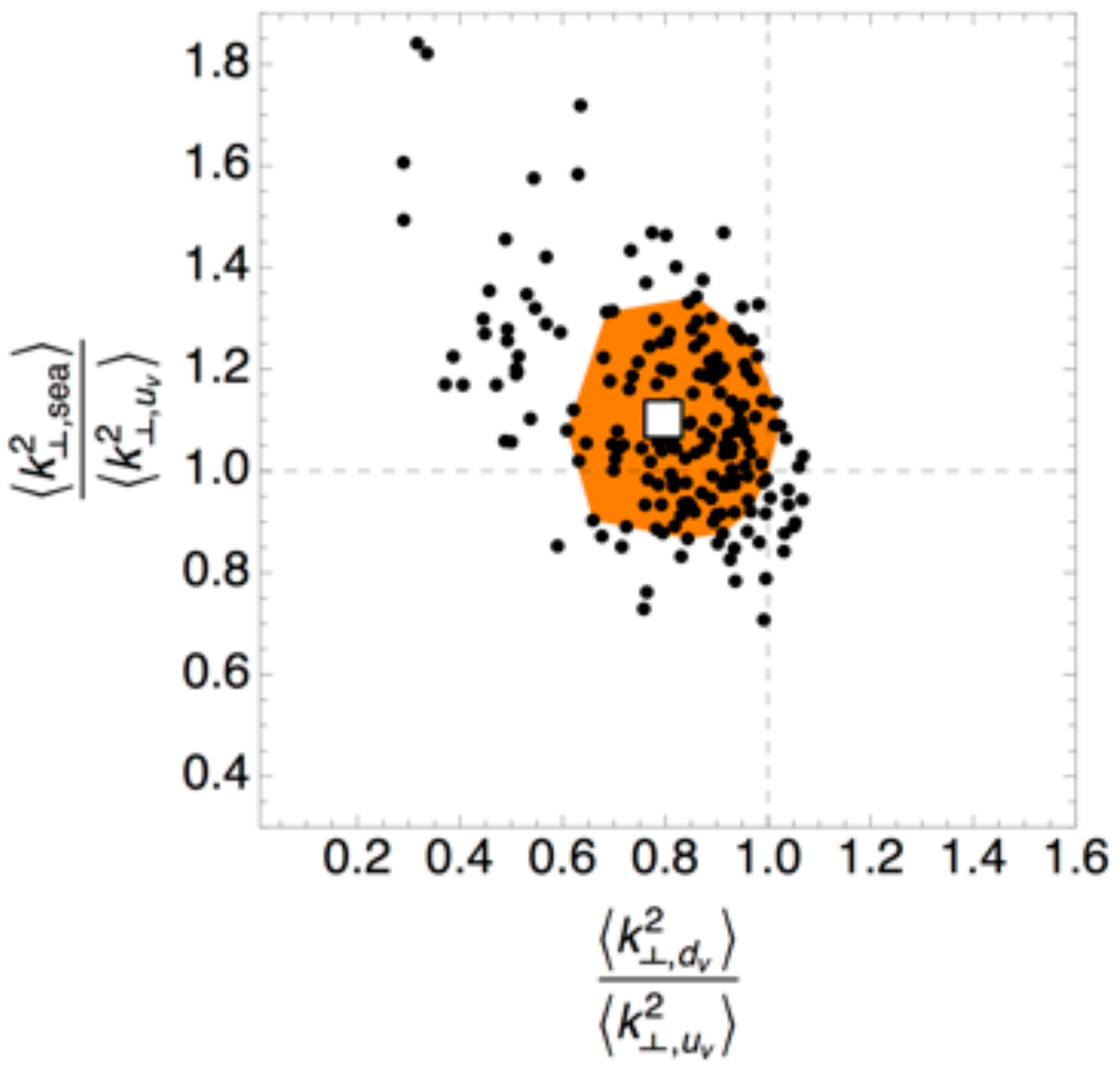

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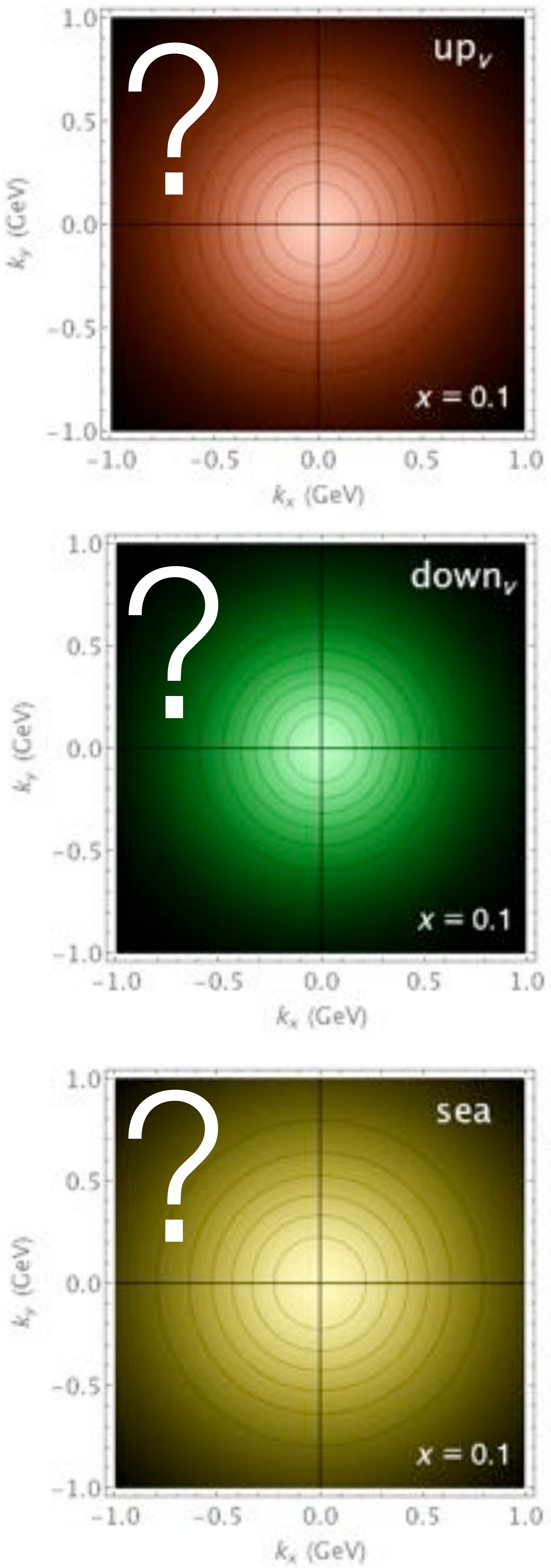

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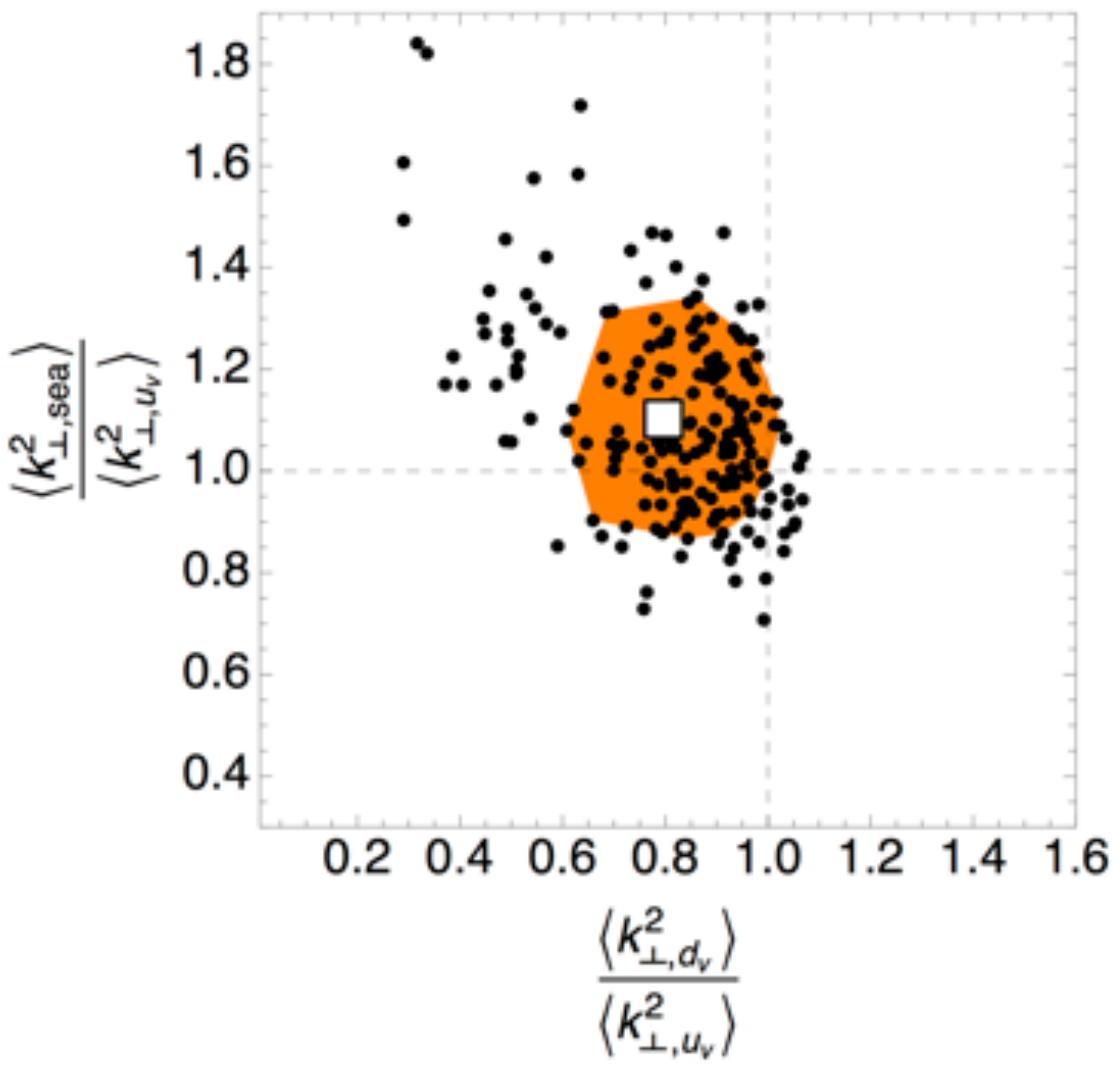

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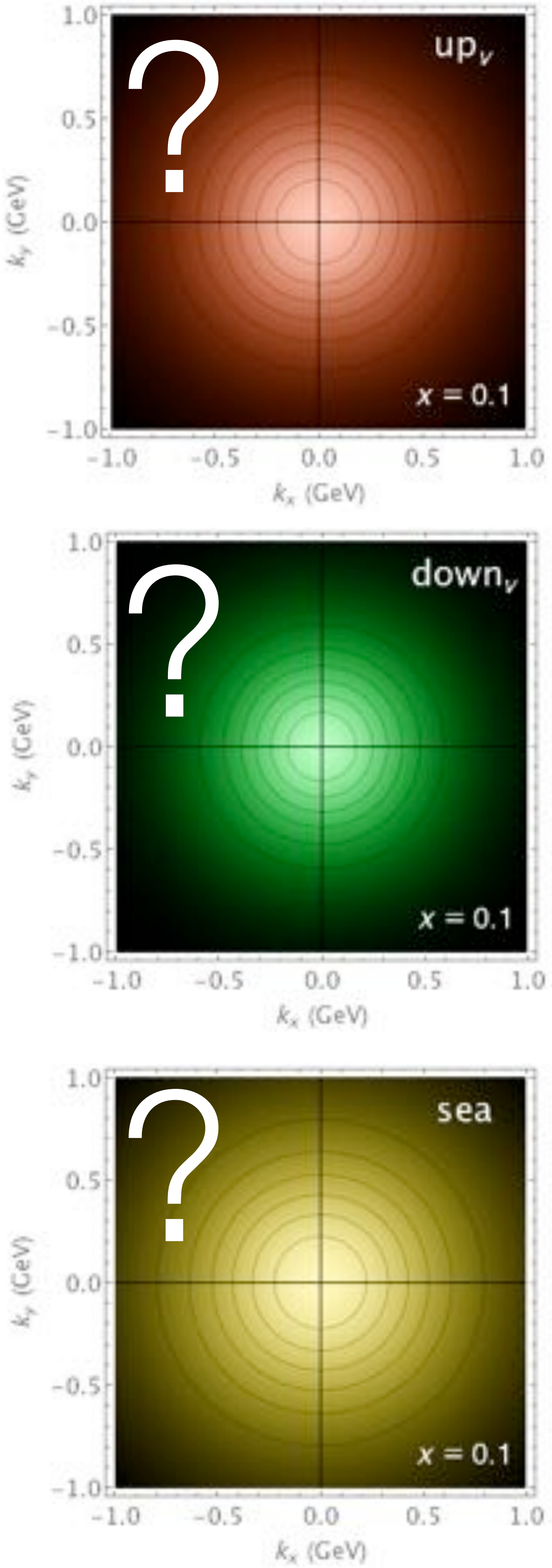
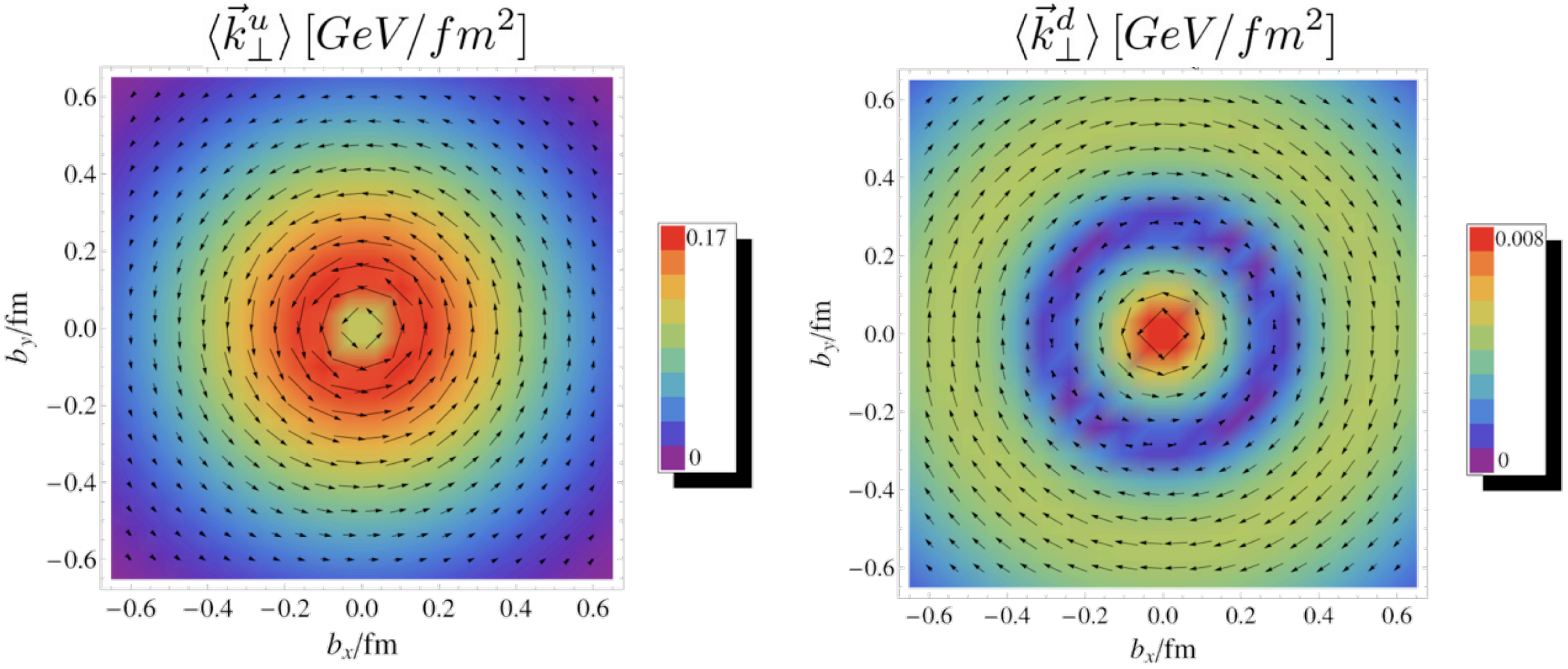


There is room for flavour dependence,
but we don't control it well

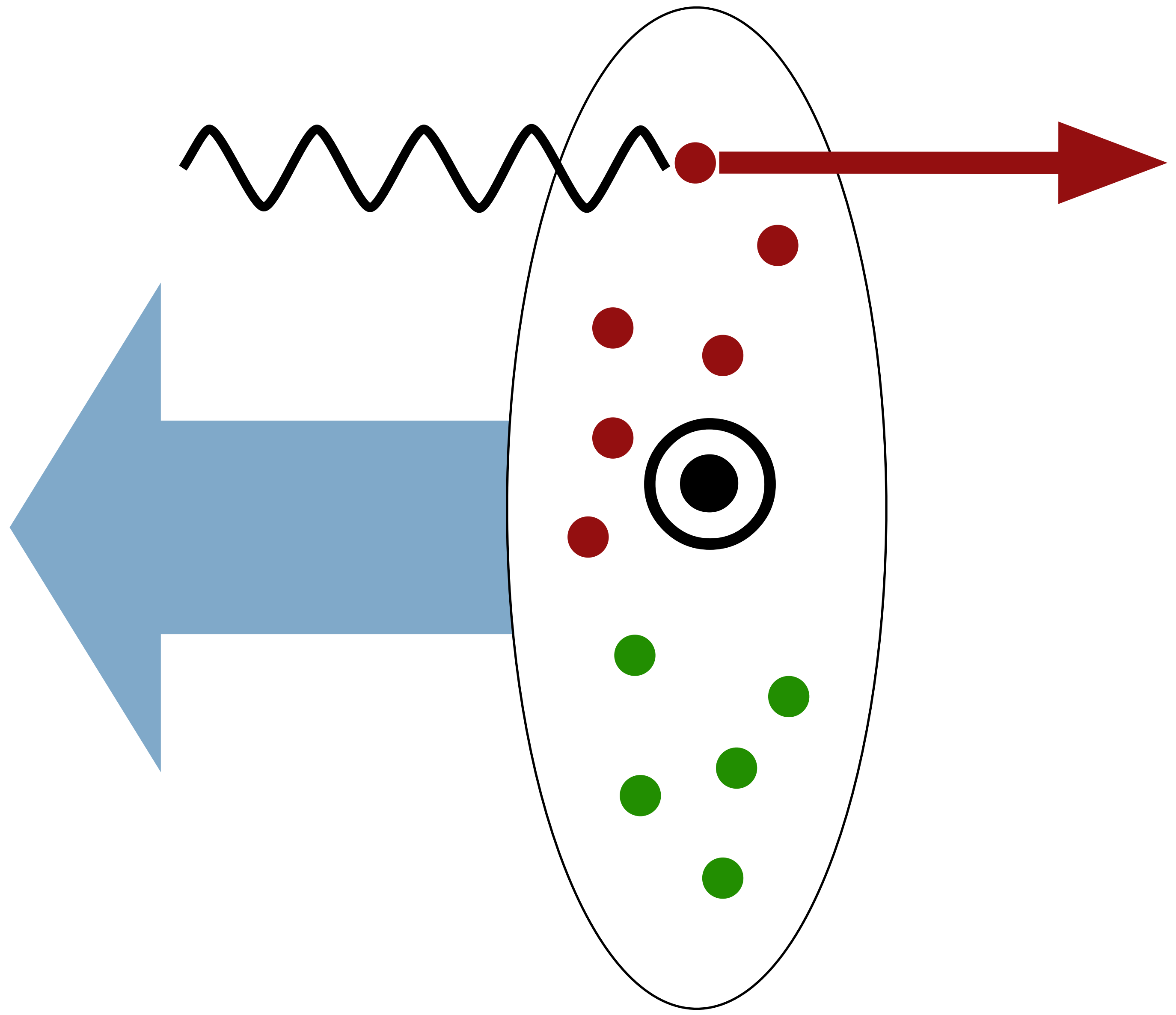
Only way to provide direct access to partonic orbital angular momentum

$$\mathcal{L}_z^q = \int \mathrm{d}x \mathrm{d}^2\vec{k}_\perp \mathrm{d}^2\vec{b}_\perp (\vec{b}_\perp \times \vec{k}_\perp) \rho^q_{LU}(\vec{b}_\perp, \vec{k}_\perp, x)$$



[based on Pasquini, Lorcé, Xiong, Yuan, PRD 85 (12)]

SIVERS FUNCTION AND ORBITAL ANGULAR MOMENTUM



based on Burkardt, PRD66 (02)

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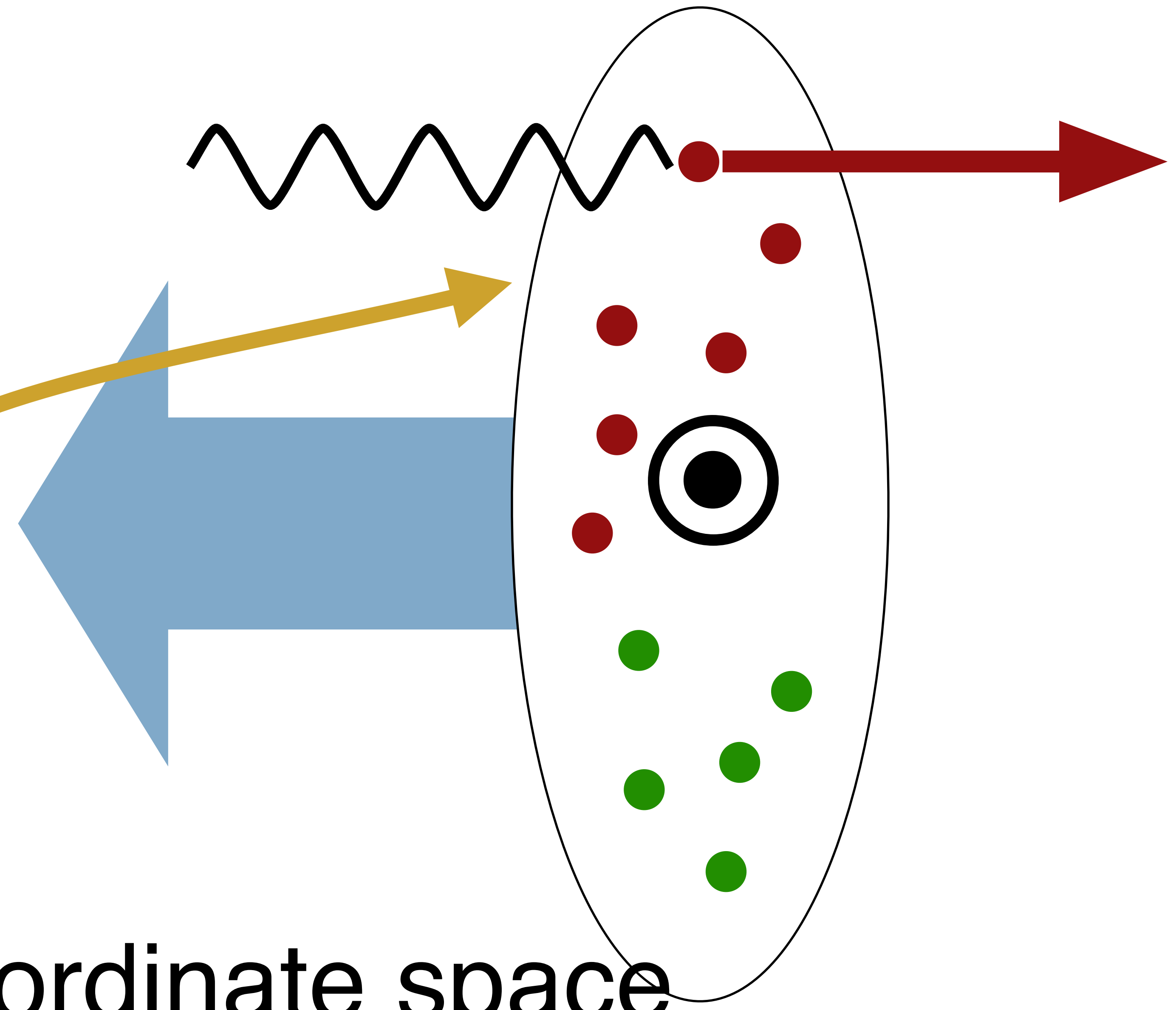
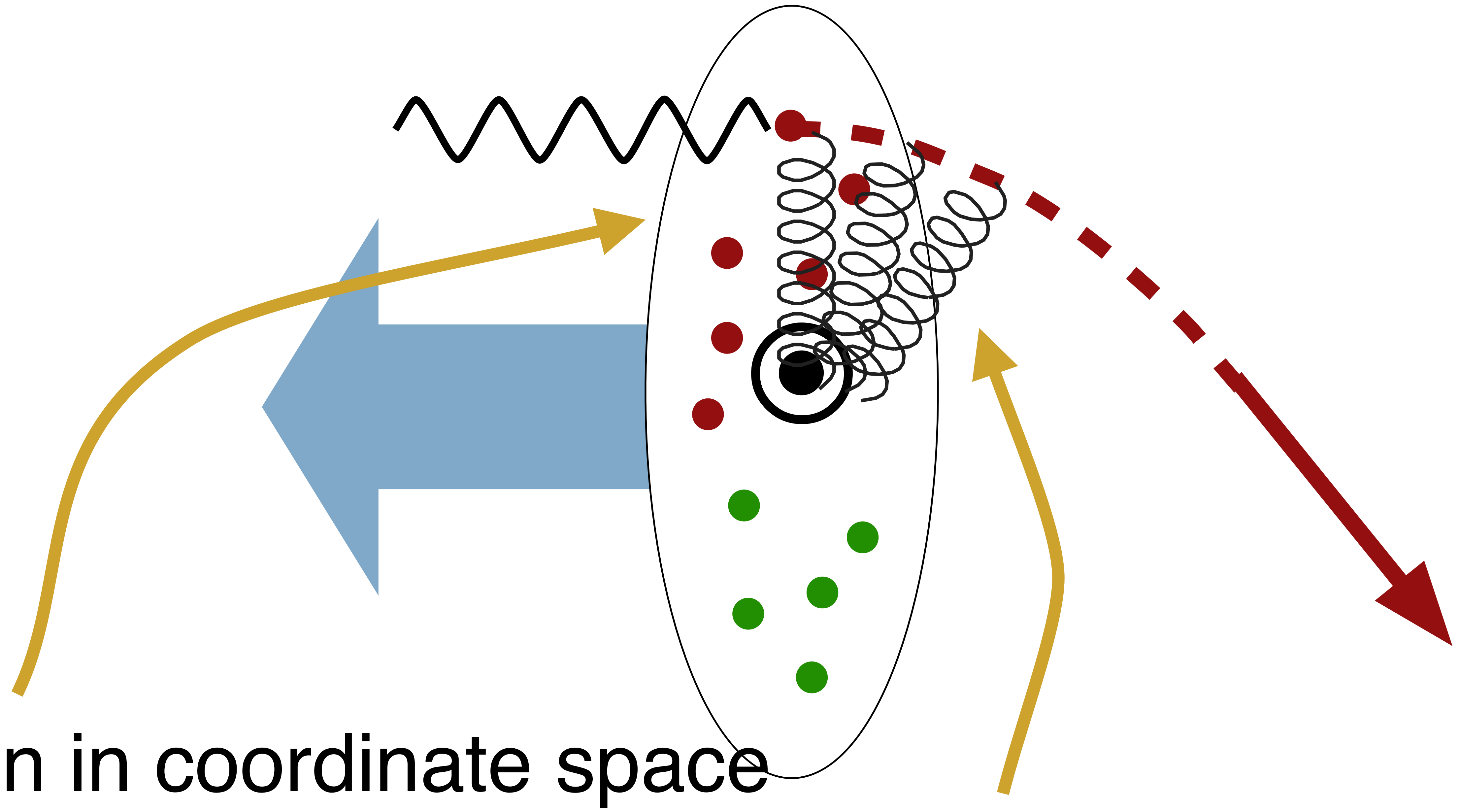


Distortion in coordinate space related to orbital angular momentum

based on Burkardt, PRD66 (02)

SIVERS FUNCTION AND ORBITAL ANGULAR MOMENTUM

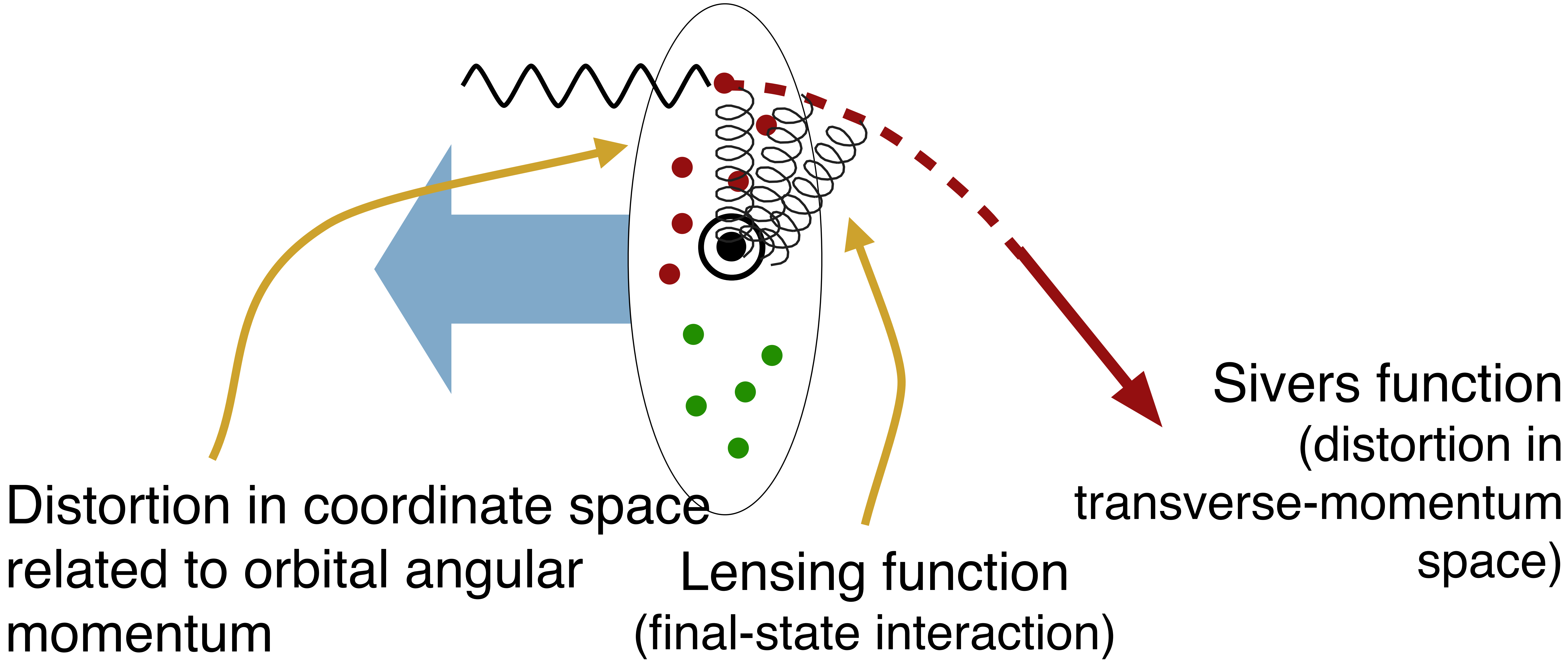


Distortion in coordinate space related to orbital angular momentum

Lensing function (final-state interaction)

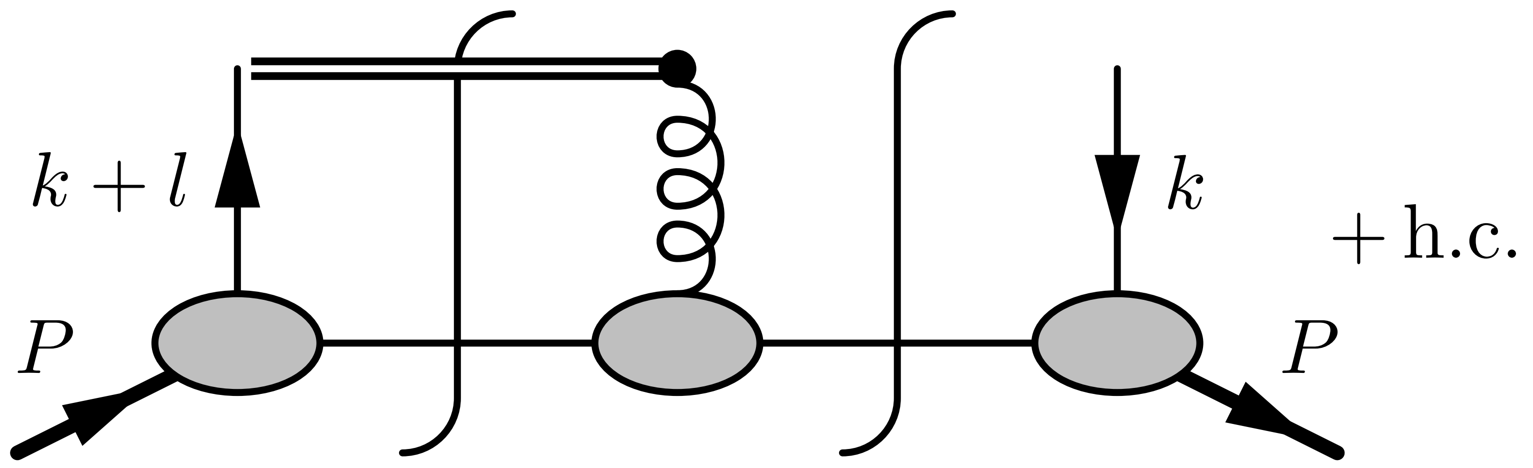
based on Burkardt, PRD66 (02)

SIVERS FUNCTION AND ORBITAL ANGULAR MOMENTUM



based on Burkardt, PRD66 (02)

SPECTATOR MODEL RESULTS



$$f_{1T}^{\perp(0)a}(x;Q_L^2) = -\frac{3MC_F\alpha_S}{2(1-x)}\;E^a(x,0,0;Q_L^2)$$

Burkardt, Hwang, PRD69 (04)
Lu, Schmidt, PRD75 (07)
Bacchetta, Conti, Radici, PRD 78 (08)

This relation holds only in simple models

Bacchetta, Pasquini, Rodini, https://arxiv.org/abs/1907.06960

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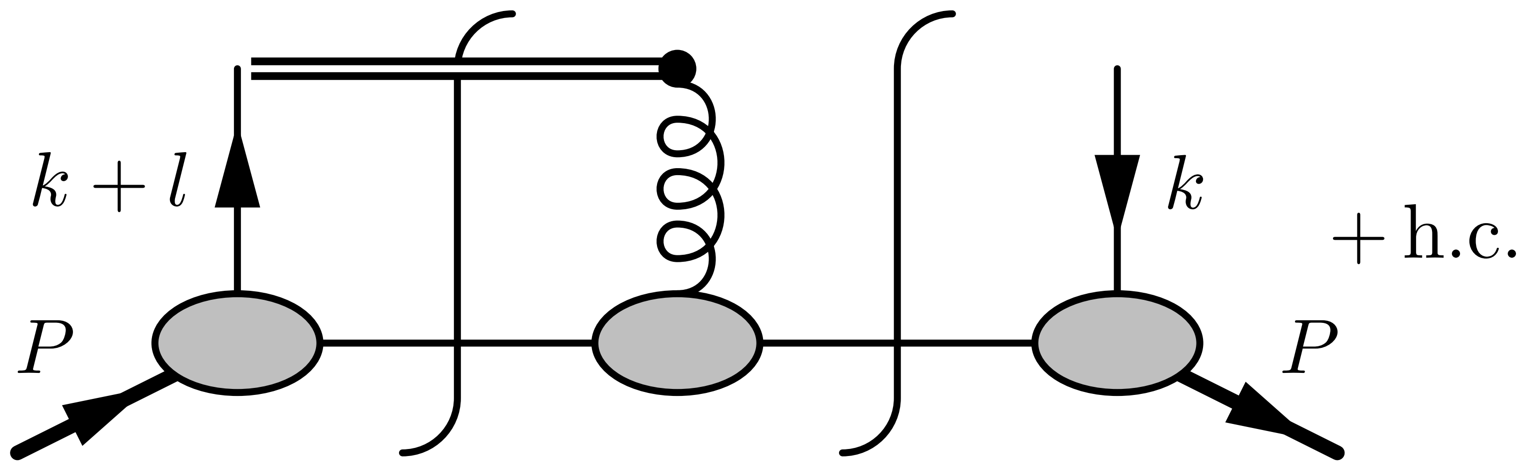

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Lensing function (flavor independent)

Burkardt, Hwang, PRD69 (04)
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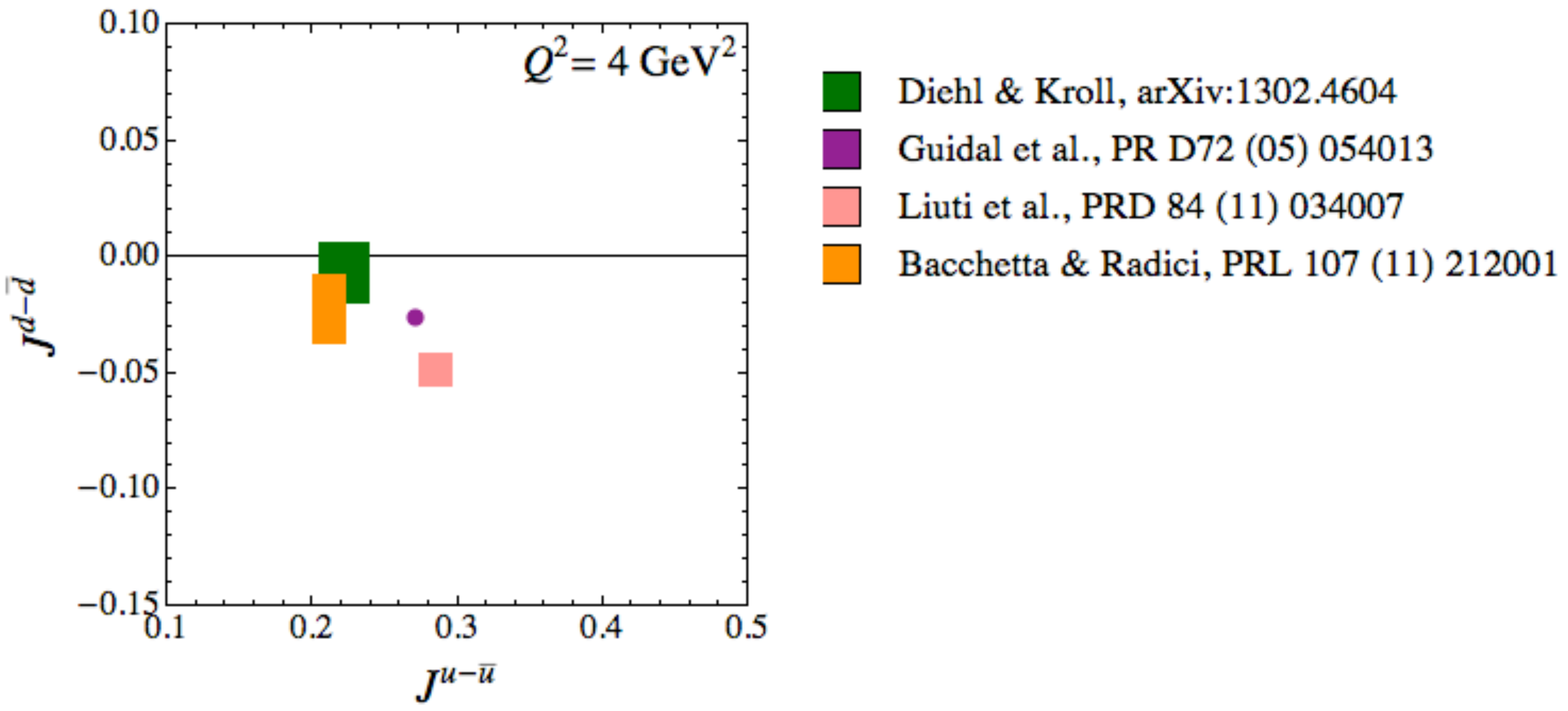
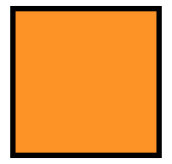
COMPARISON WITH OTHER RESULTS

Other results obtained through form factors + assumptions

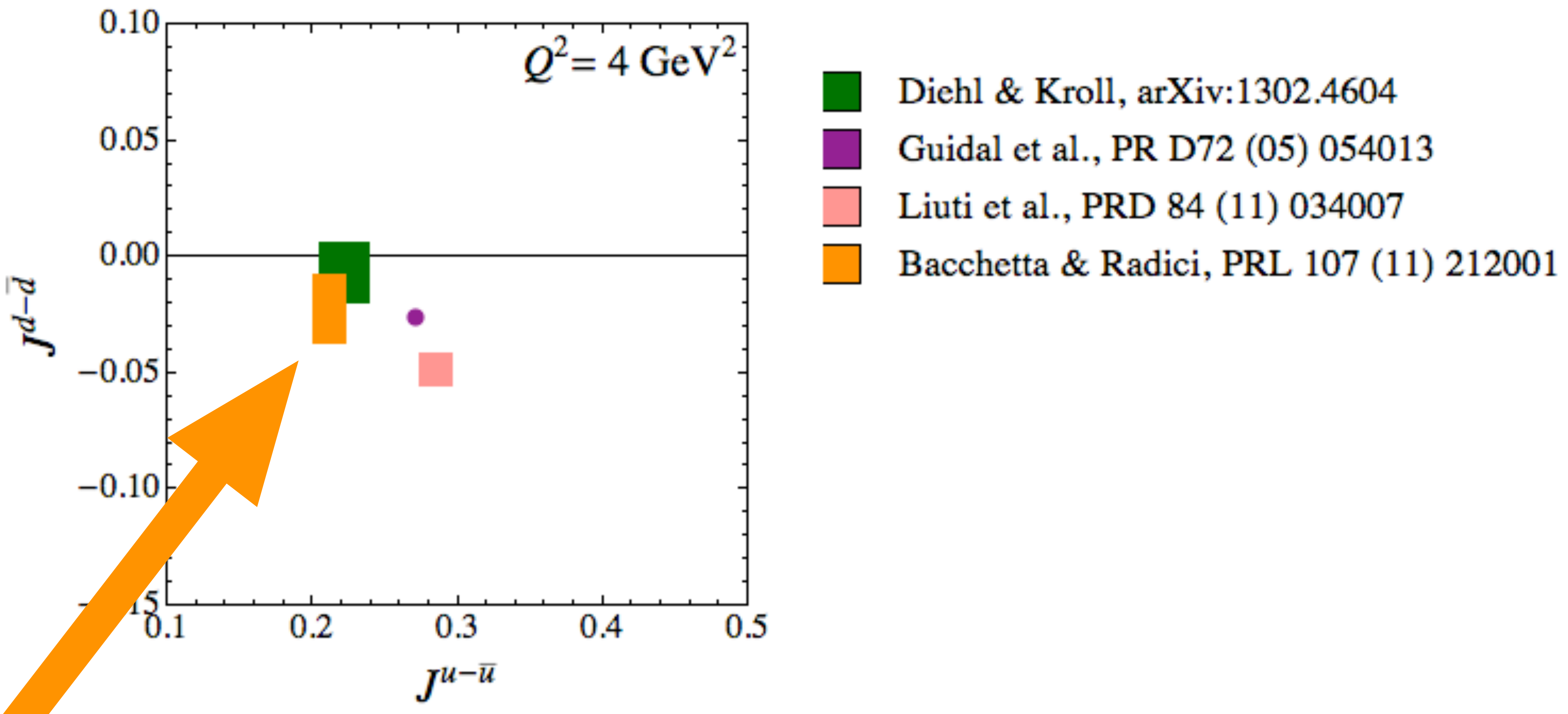


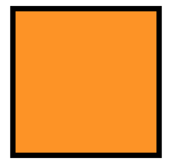


Estimate of angular momentum based on model assumptions + Sivers fit

COMPARISON WITH OTHER RESULTS

Other results obtained through form factors + assumptions





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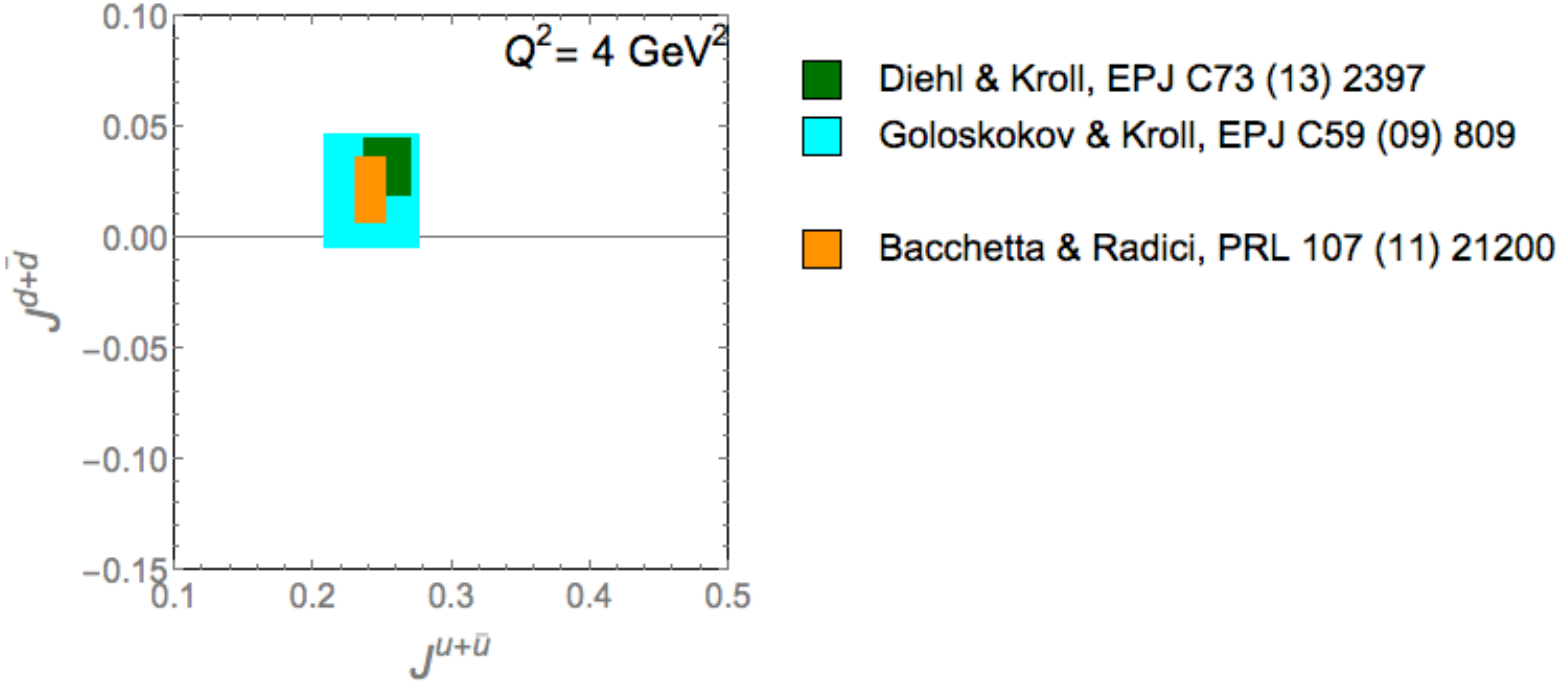

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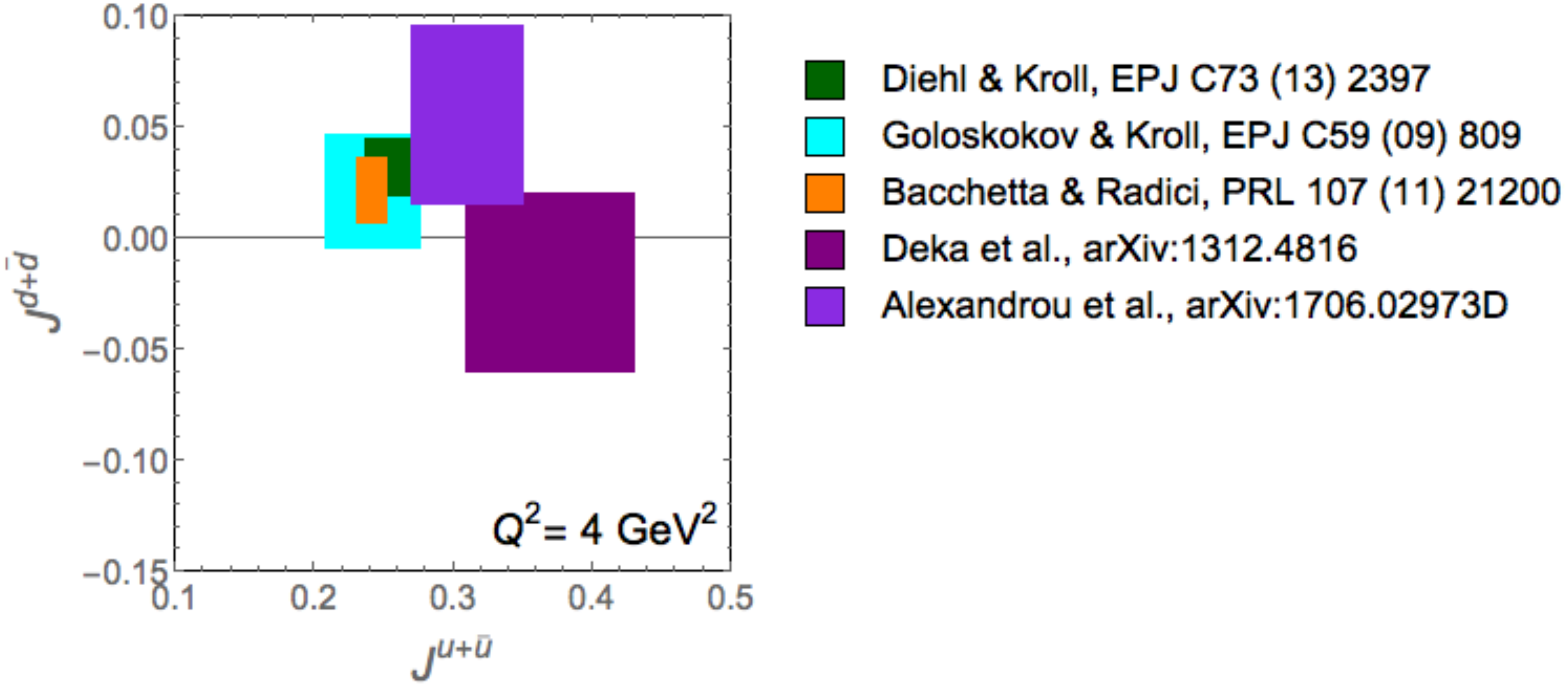

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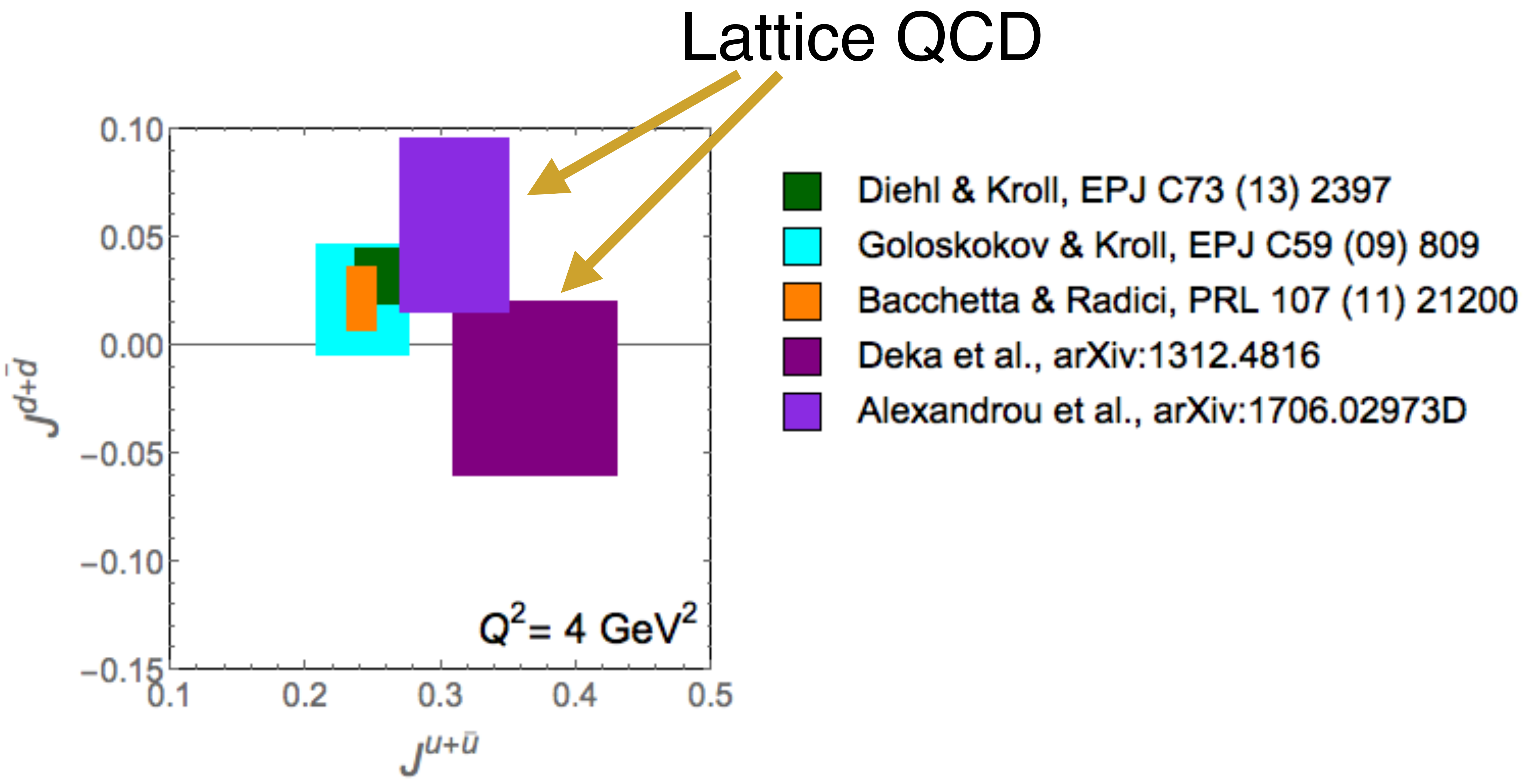

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