LOOKING AT THE PROTON IN 3D (IN MOMENTUM SPACE)

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3DSPIN
MAPPING THE PROTON IN 3D

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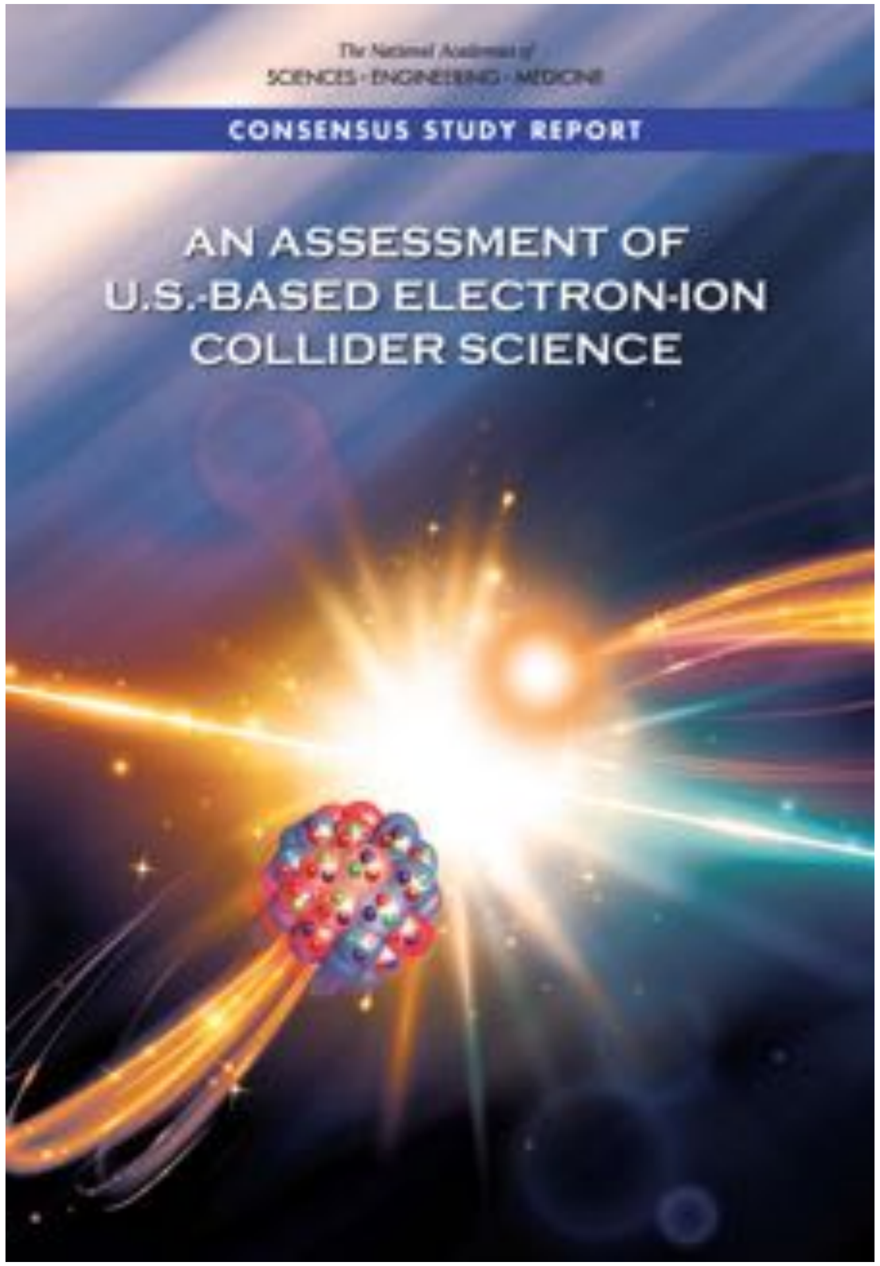
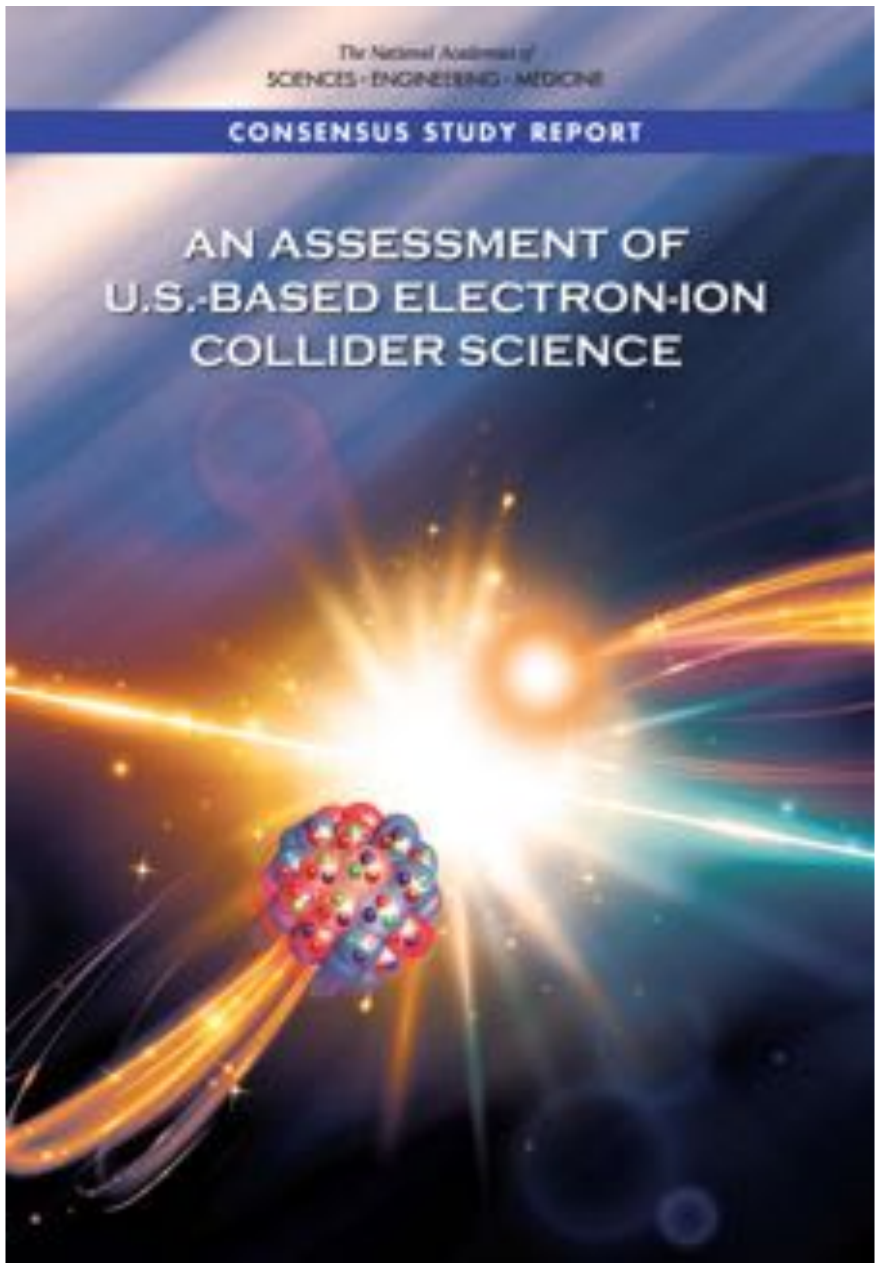
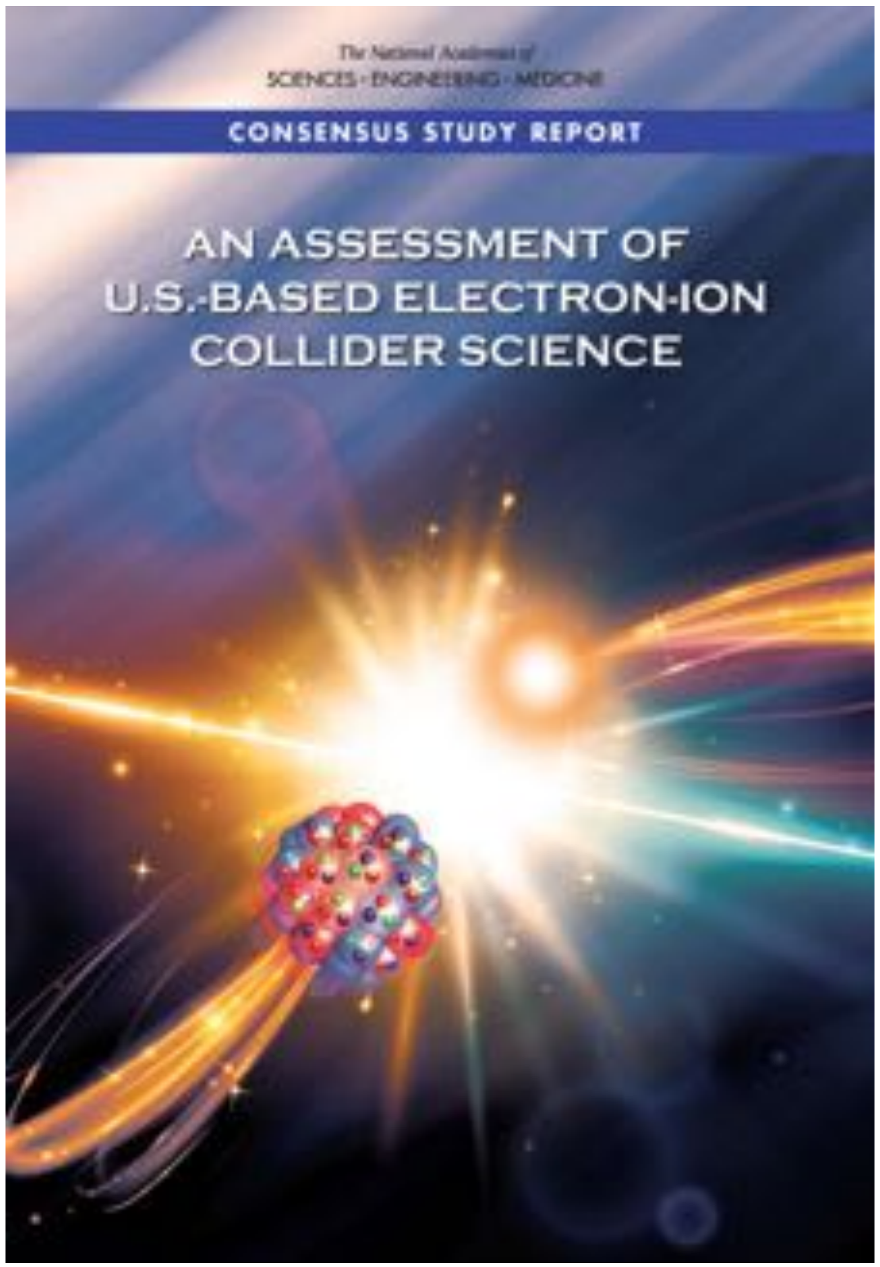
RELEVANT LITERATURE





Finding 1: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

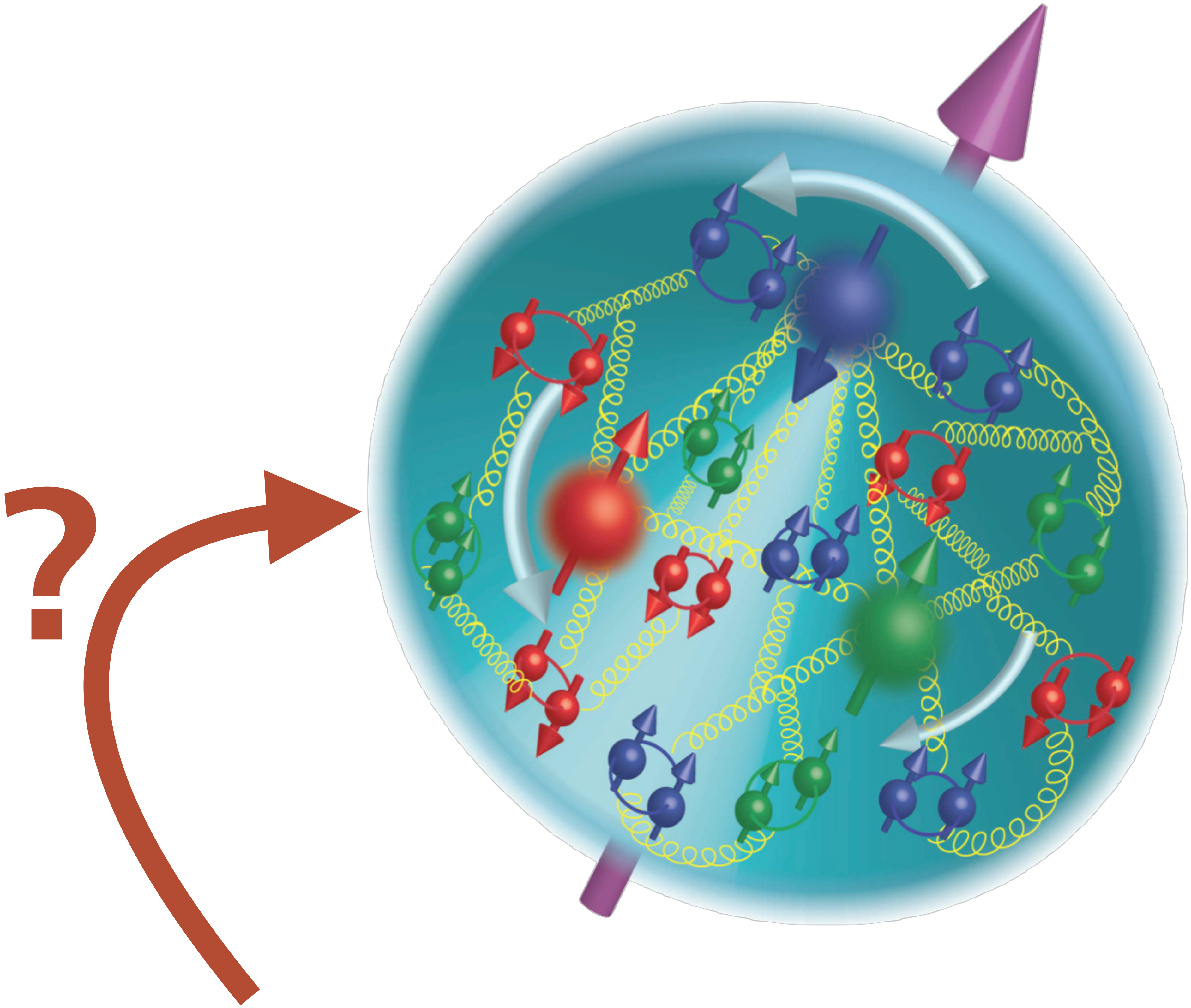
- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?



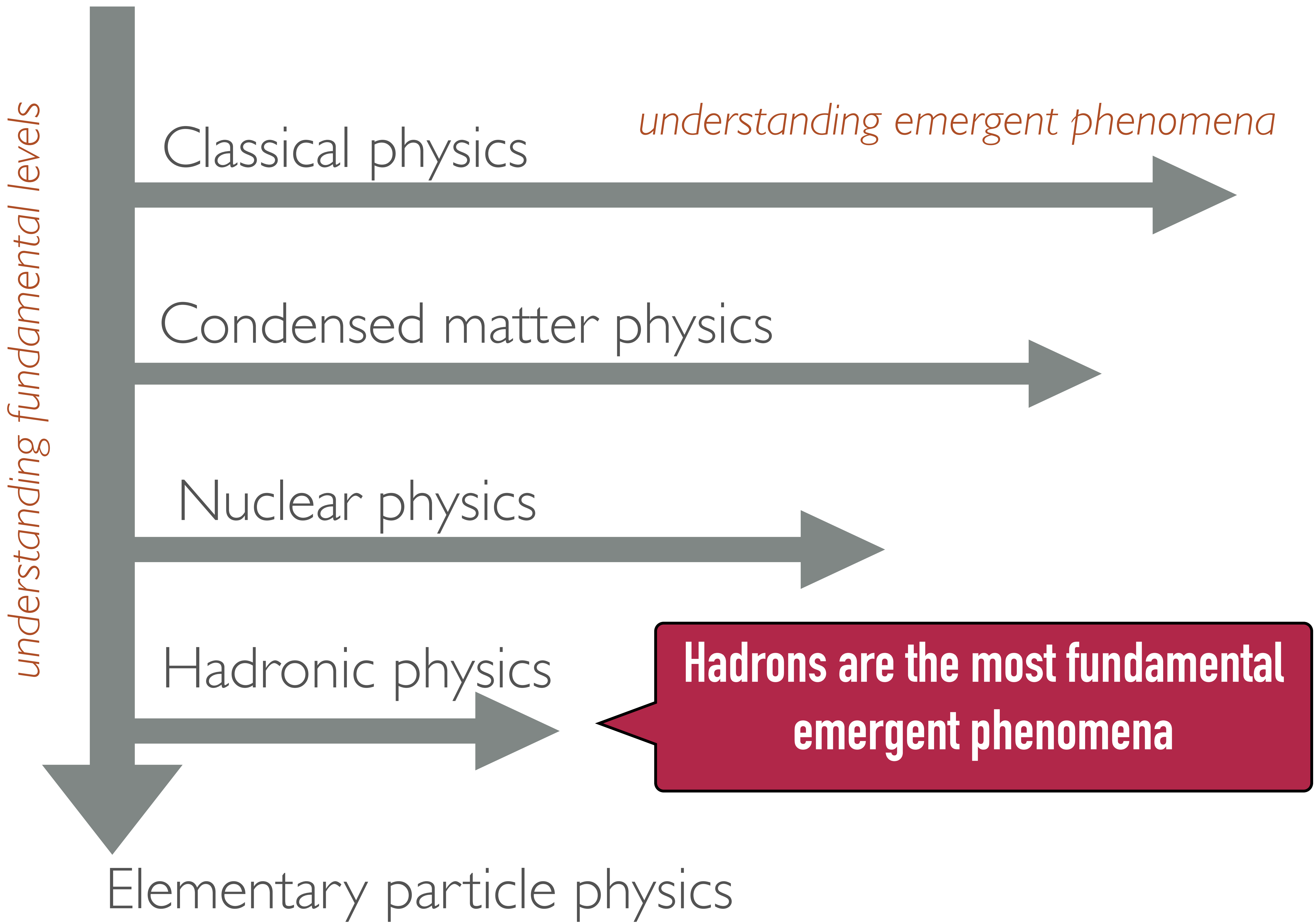
Finding 2: These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and sufficient, and variable, center-of-mass energy.

Finding 3: An EIC would be a unique facility in the world and would maintain U.S. leadership in nuclear physics.

Chicago Pile-1, 2 December 1942
The US have maintained the leadership in nuclear physics since the beginning of the “nuclear age”



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


understanding fundamental levels
understanding emergent phenomena
Classical physics
Condensed matter physics
Nuclear physics
Hadronic physics
Hadrons are the most fundamental emergent phenomena
Elementary particle physics

CONFINEMENT

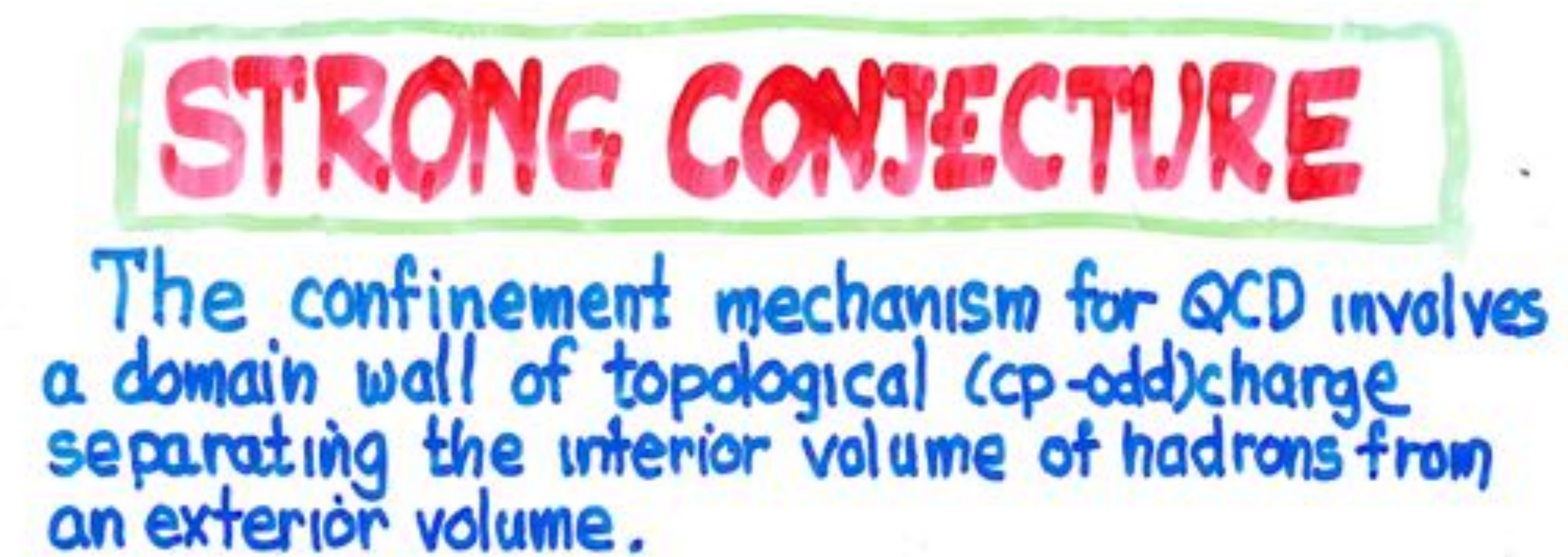
http://www.claymath.org/millennium-problems

> “Yang-Mills Existence and Mass Gap: Prove that for any compact simple gauge group G, quantum Yang-Mills theory of R4 exists and has a mass gap $\Delta > 0$.”

$1 million

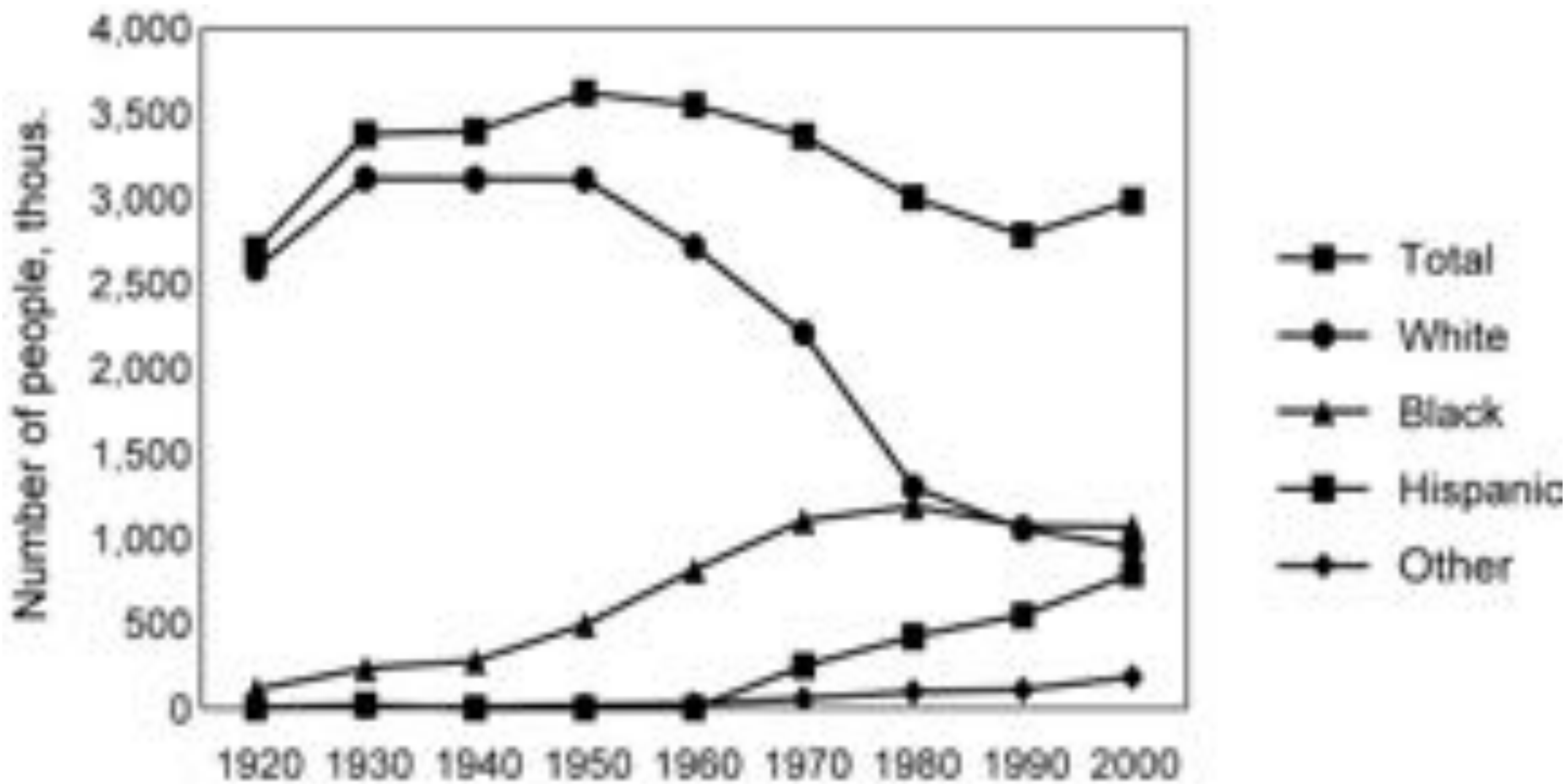
D. Sivers Strong Conjecture Prize: $50 thousand

Disprove:



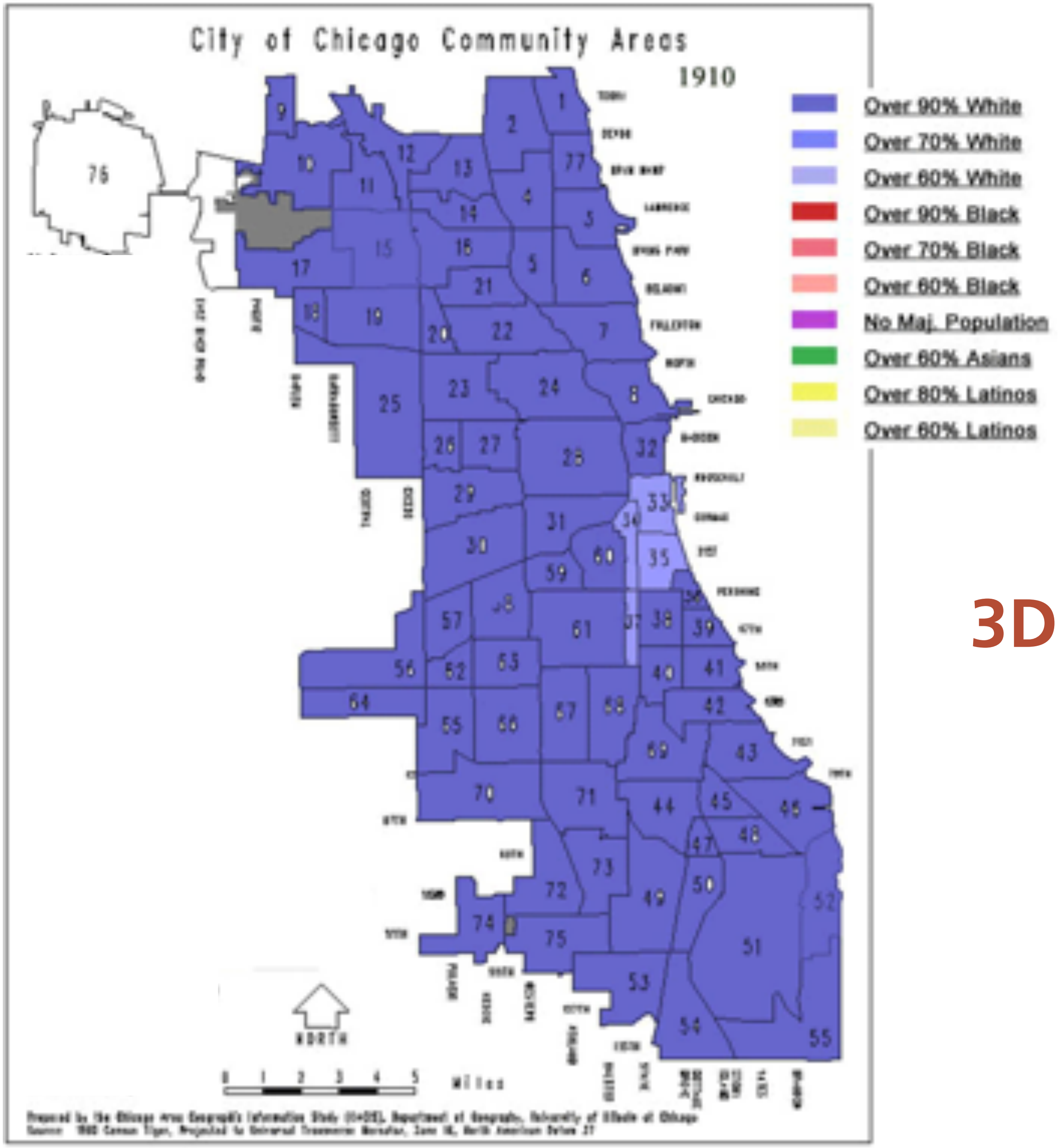
If you want to understand something, first of all you start “mapping” it

Chicago population as a function of time **1D information**



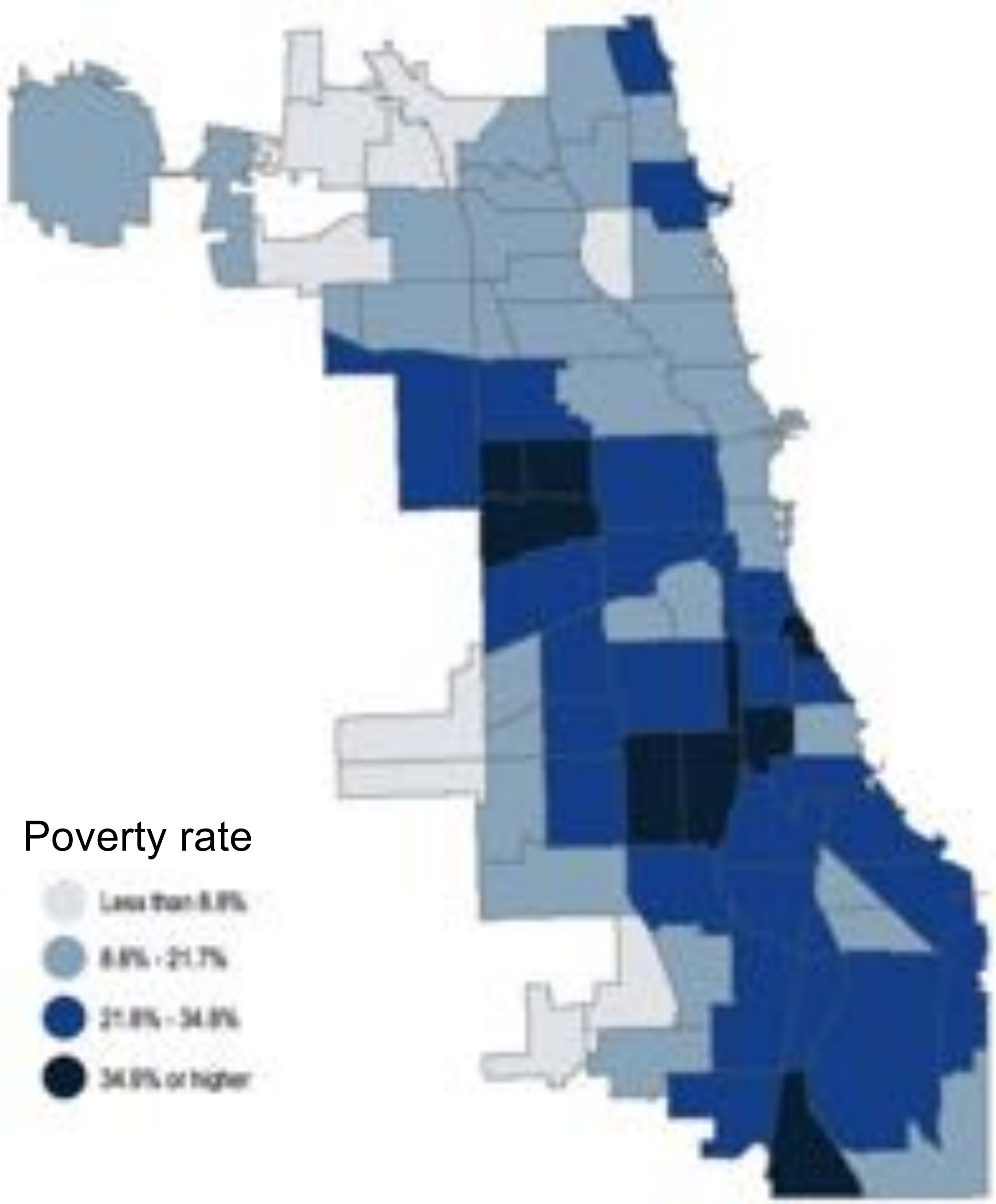
If you have a good theory, you should be able to reproduce this behavior and make predictions

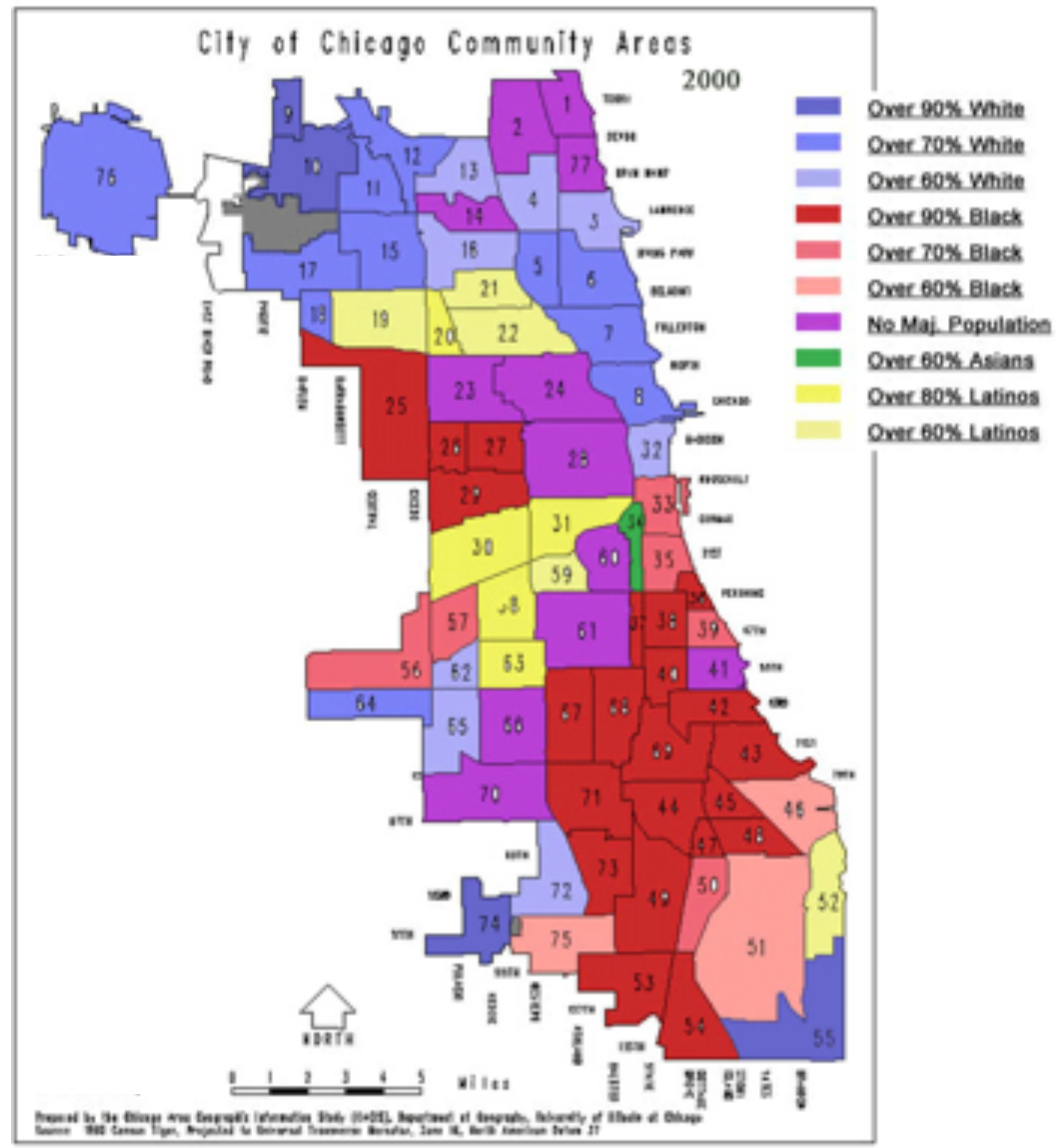
Chicago population as a function of time and location



3D information

And then you also look for **correlations**

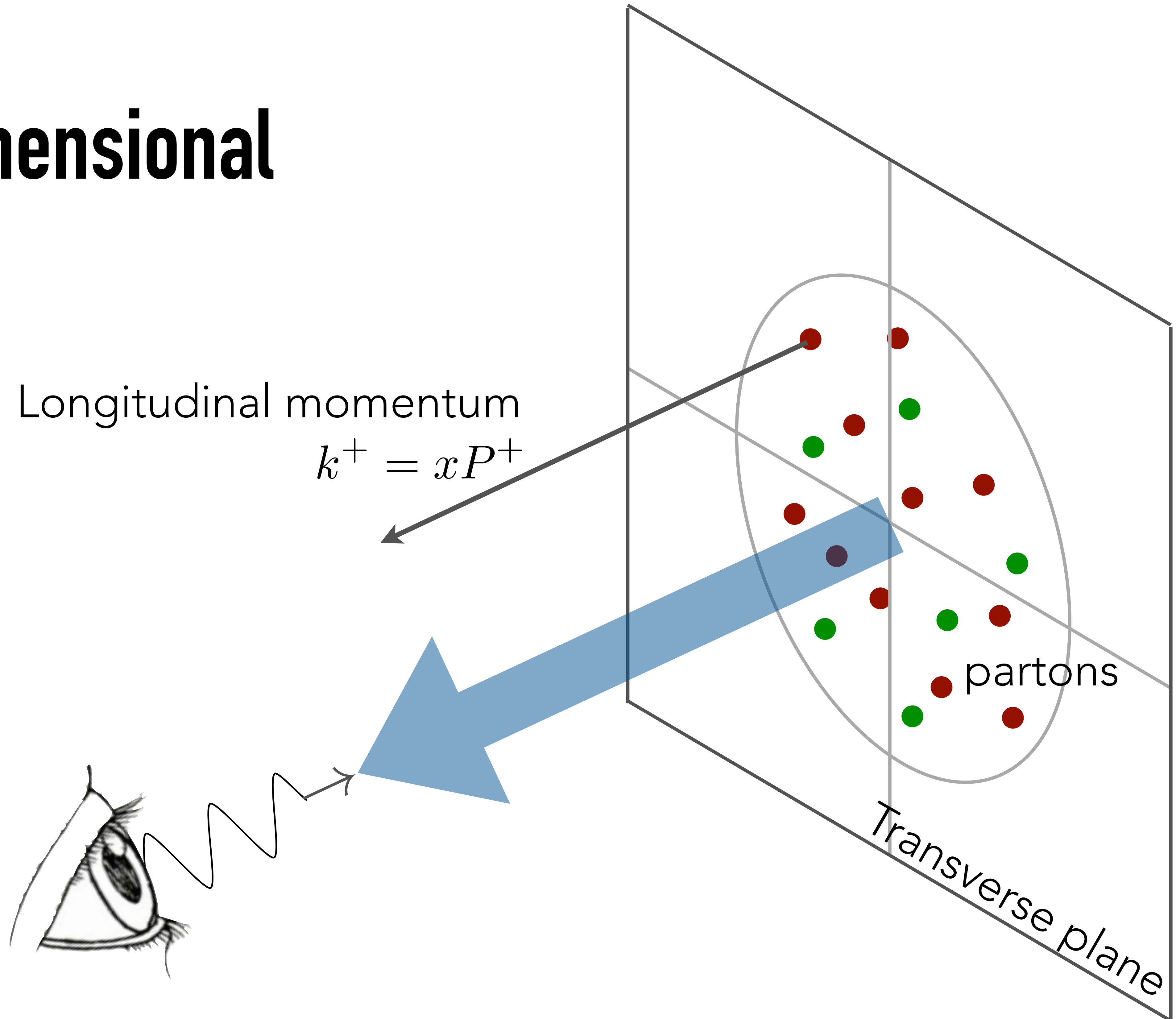




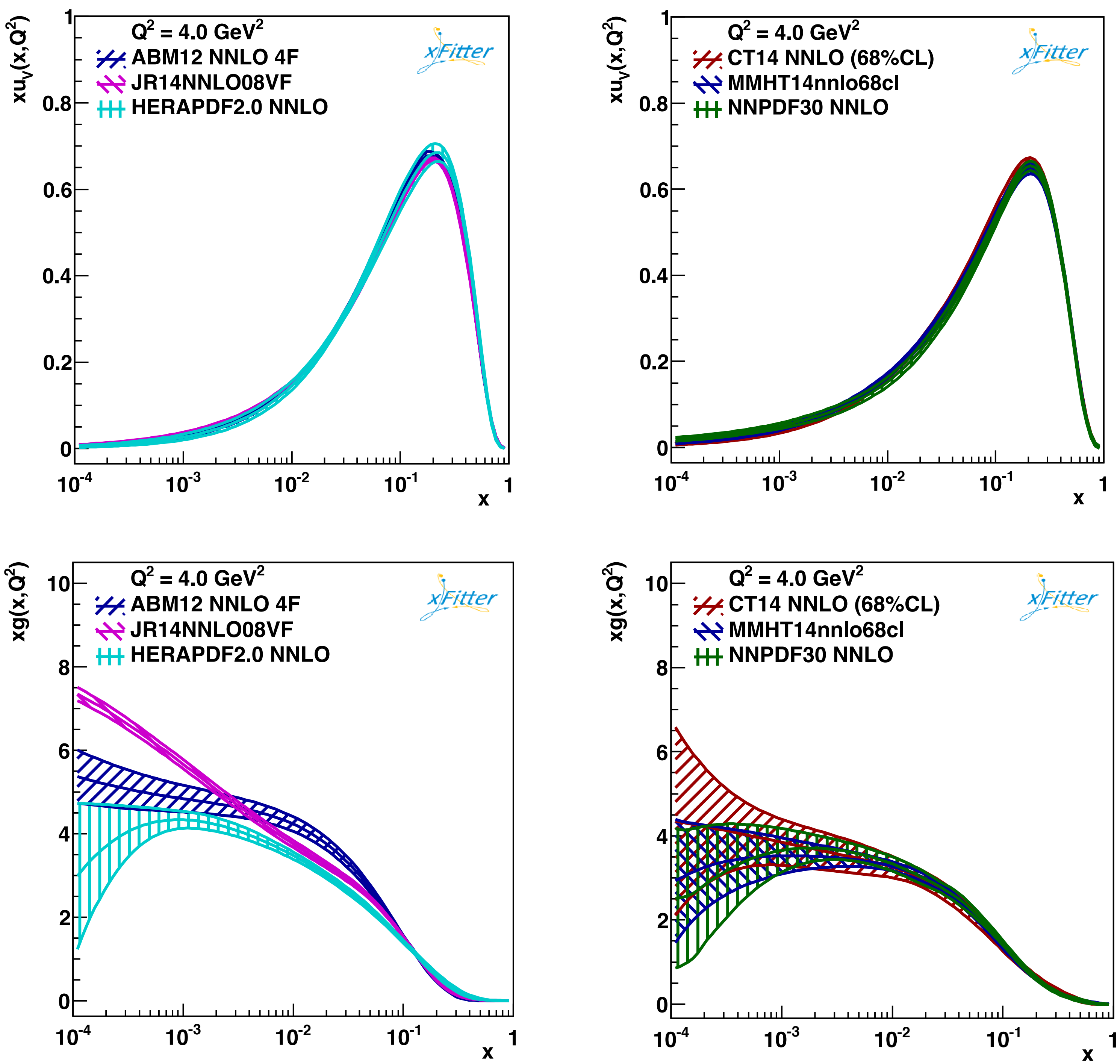
Parton Distribution Functions

$f(x)$

1 dimensional



STANDARD PARTON DISTRIBUTION FUNCTIONS



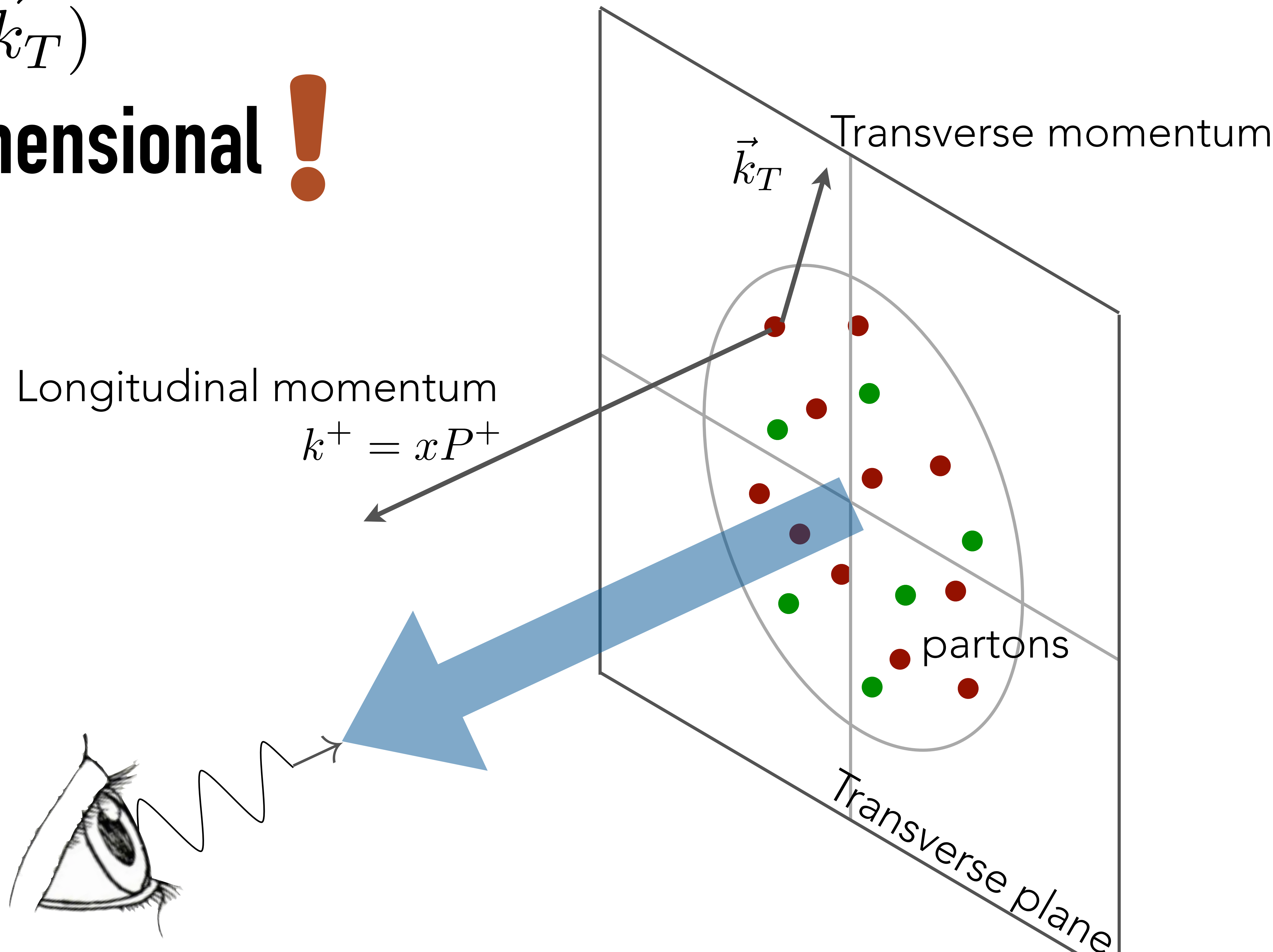
Standard collinear PDFs describe the distribution of partons in one dimension in momentum space. They are extracted through global fits

Accardi et al., arXiv:1603.08906

Transverse-Momentum Distributions

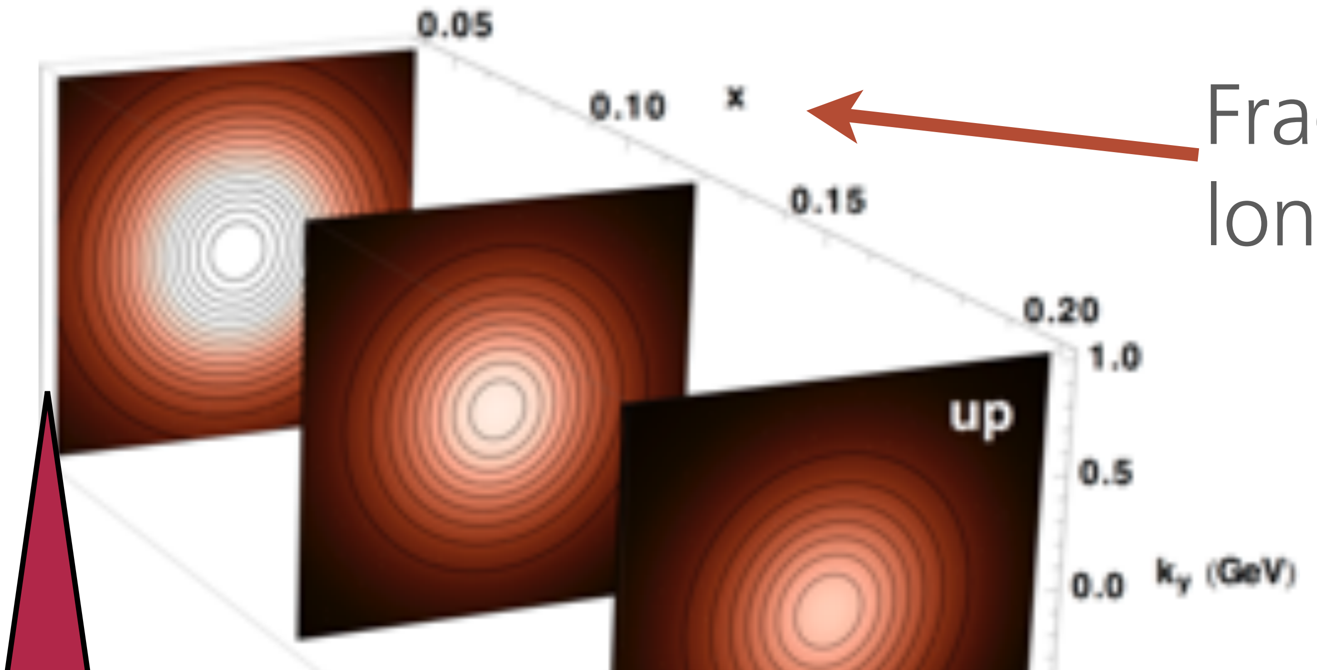
$f(x, \vec{k}_T)$

3 dimensional !



TRANSVERSE MOMENTUM DISTRIBUTIONS

TMDs describe the distribution of partons in three dimensions in momentum space. They also have to be extracted through global fits.



Fraction of longitudinal momentum

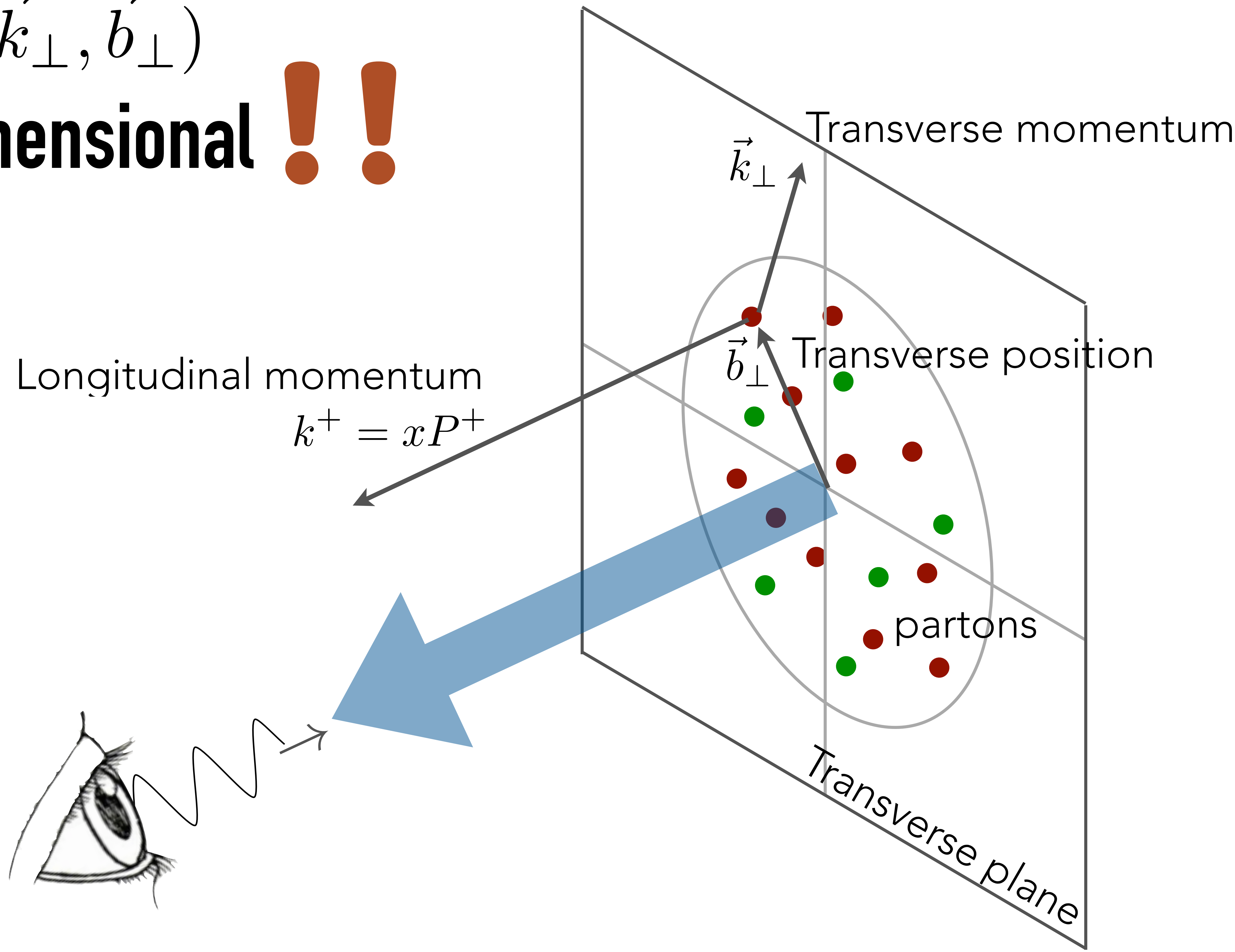
How “wide” is the distribution?
Is there a difference between flavors?
Does it get wider at low x?

momentum

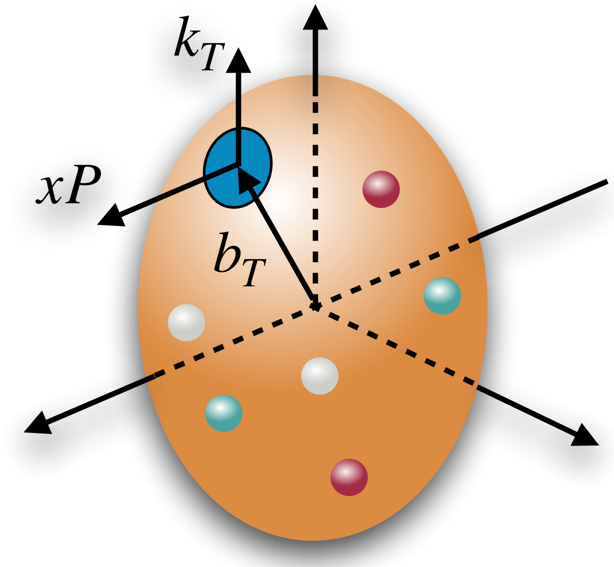
Wigner distributions

$\rho(x, \vec{k}_\perp, \vec{b}_\perp)$

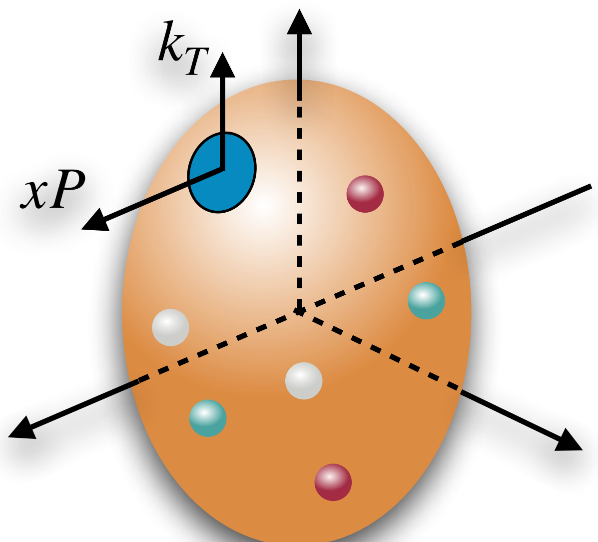
5 dimensional ‼



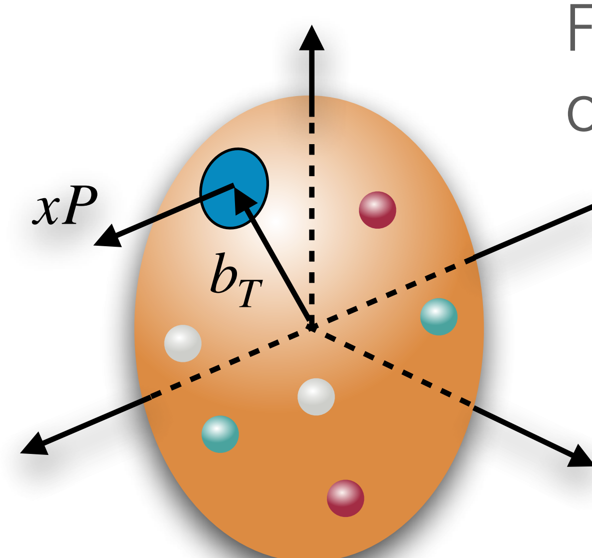
Wigner distributions (Fourier transform of GTMDs = Generalized Transverse Momentum Distributions)



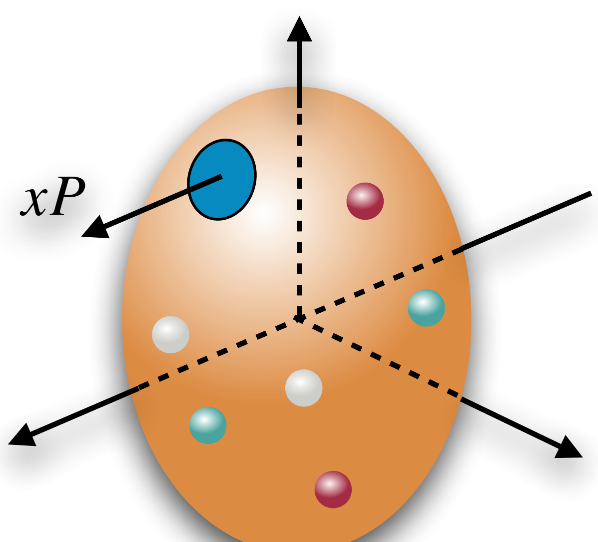
TMDs



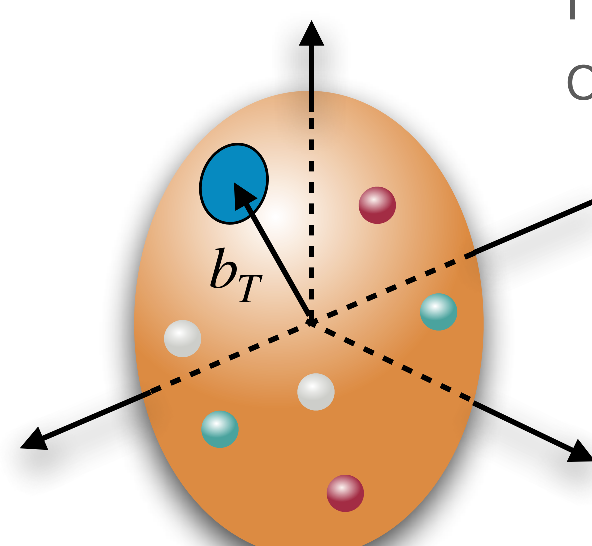
Fourier transform of GPDs



PDFs

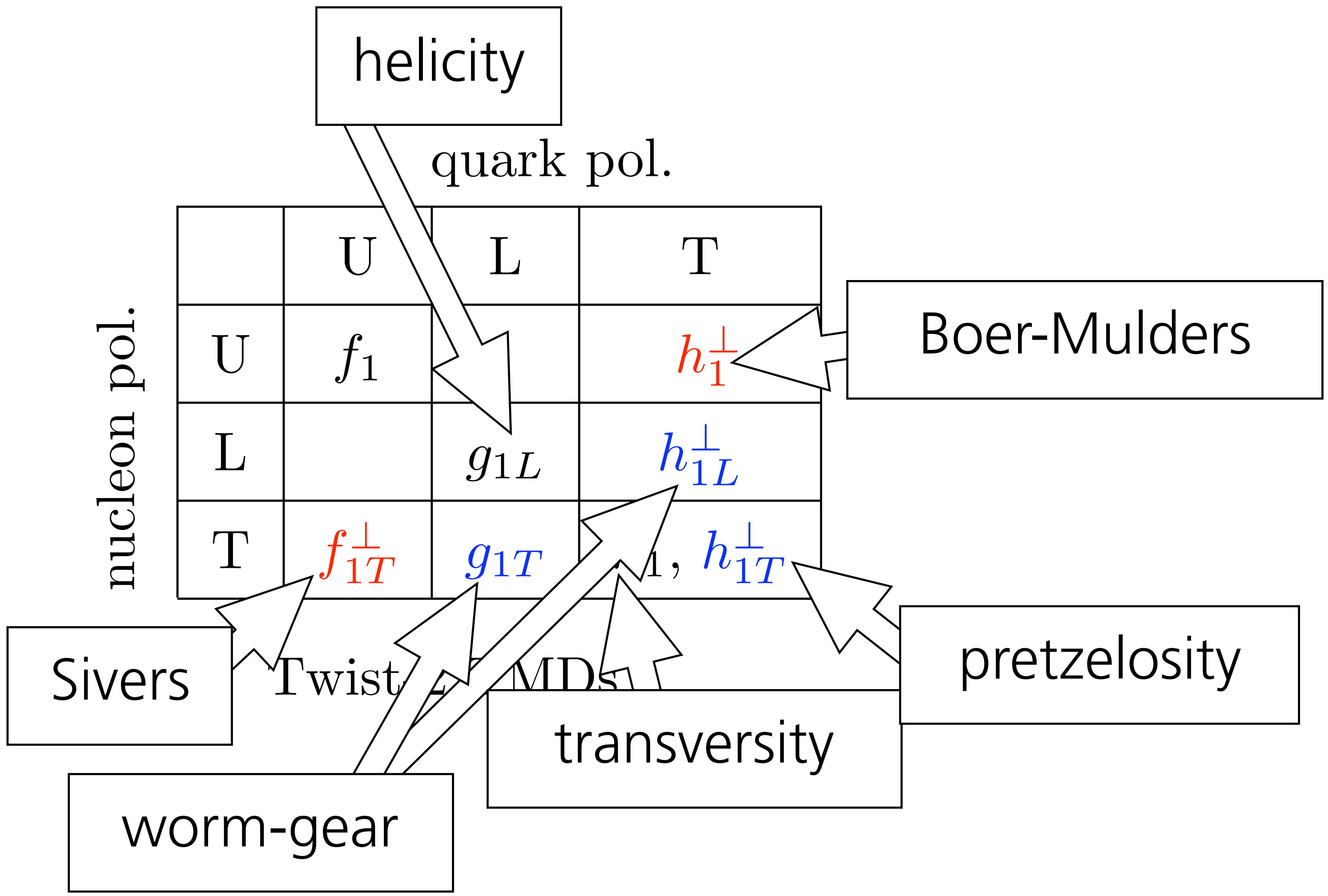


Fourier transform of Form Factors



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

TMD TABLE



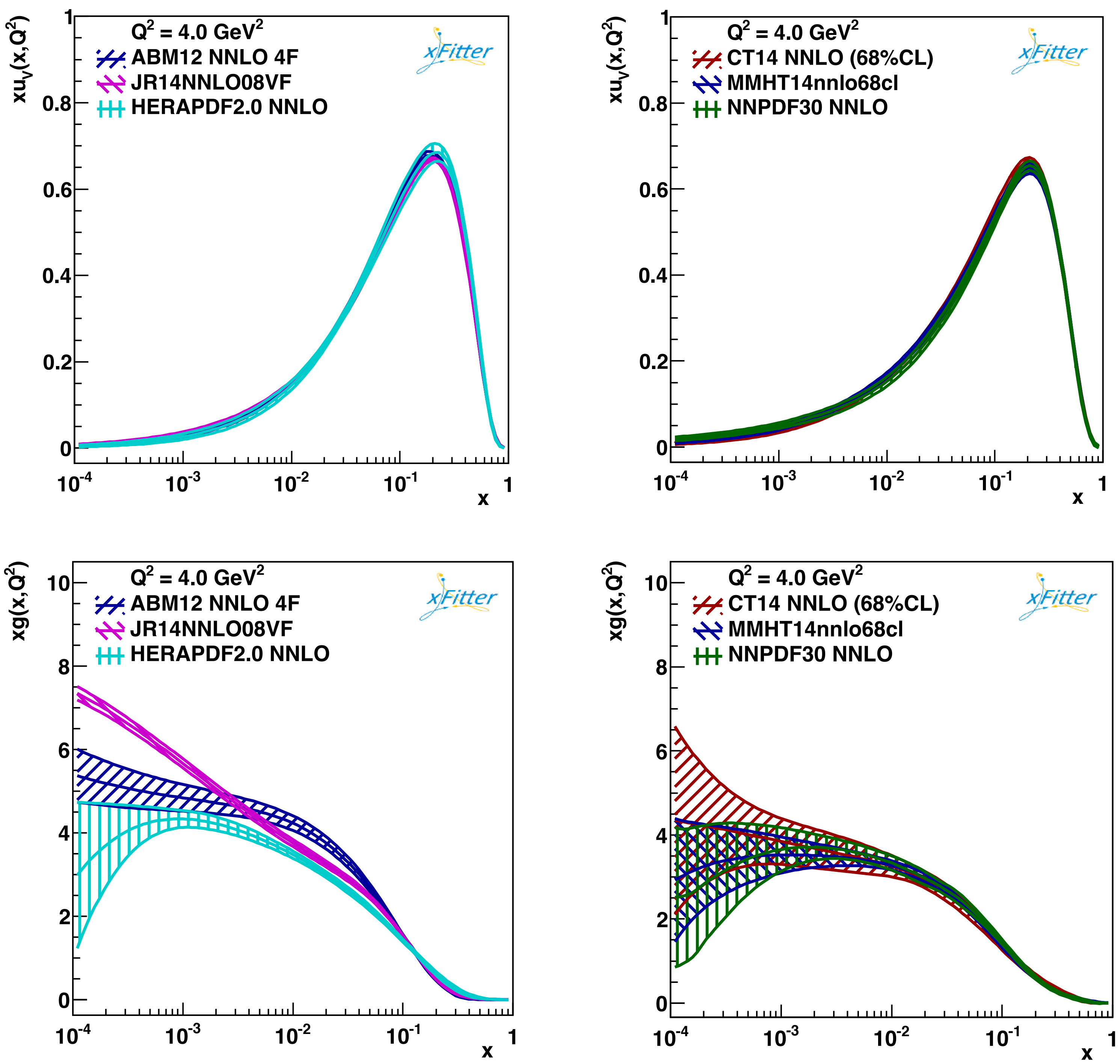
TMDs in black survive integration over transverse momentum
TMDs in red are time-reversal odd

Mulders-Tangerman, NPB 461 (96)
Boer-Mulders, PRD 57 (98)

On top of these, there are twist-3 functions (correlations!)

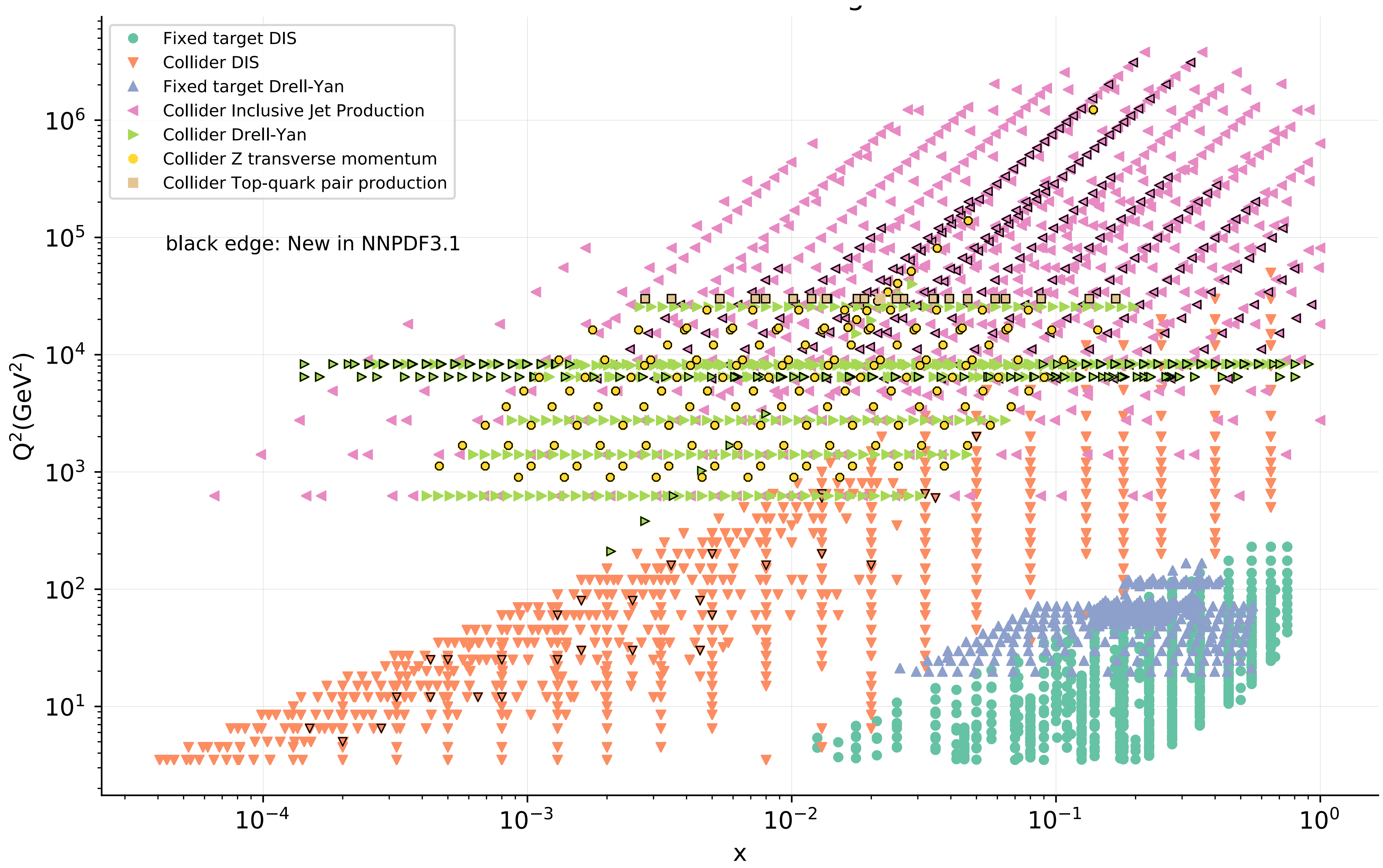
1D UNPOLARISED

STANDARD PARTON DISTRIBUTION FUNCTIONS



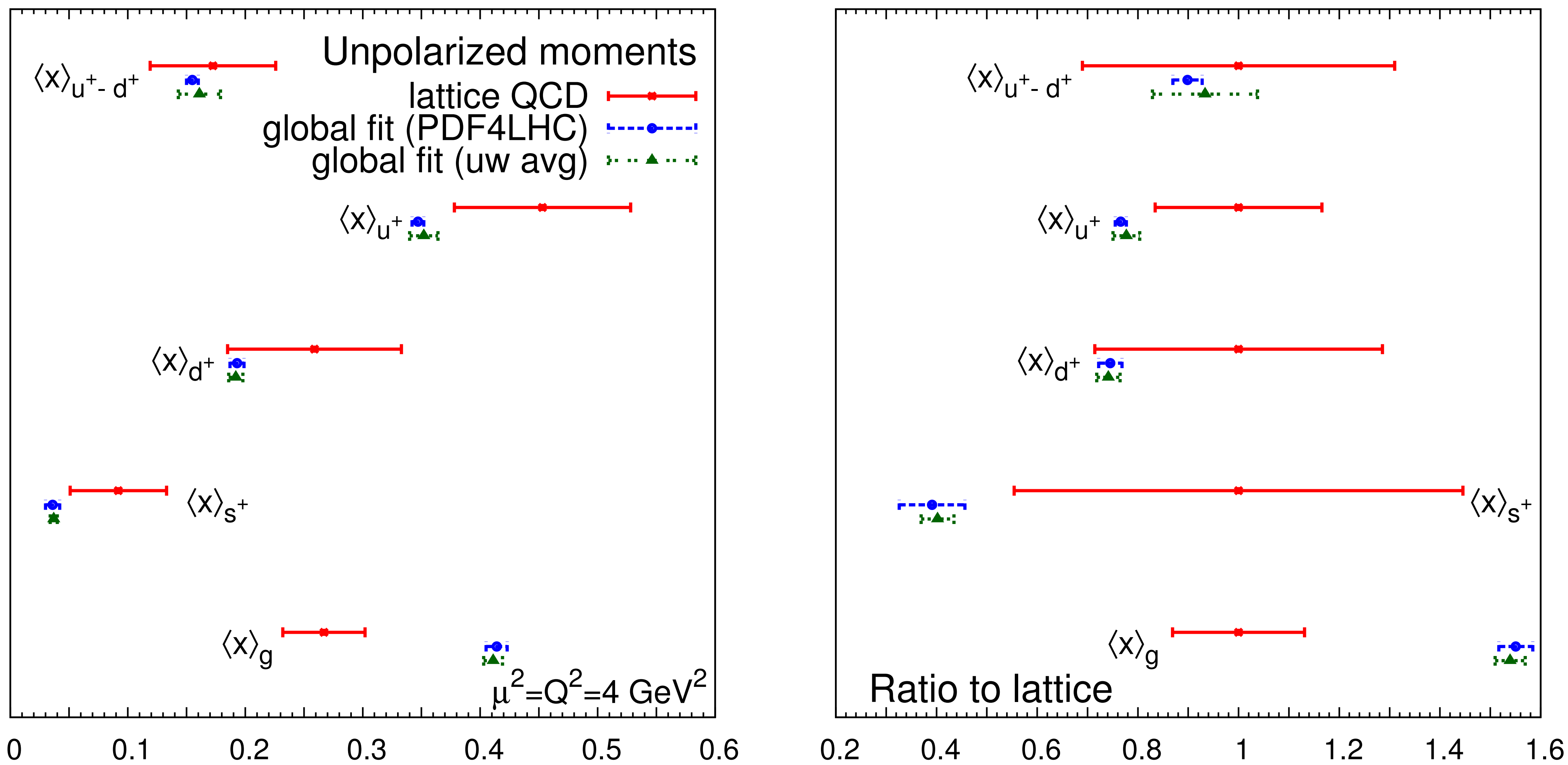
Accardi et al., arXiv:1603.08906

KINEMATIC COVERAGE OF DATA USED FOR PDF FITS



PDFLattice White Paper, arXiv:1711.07916

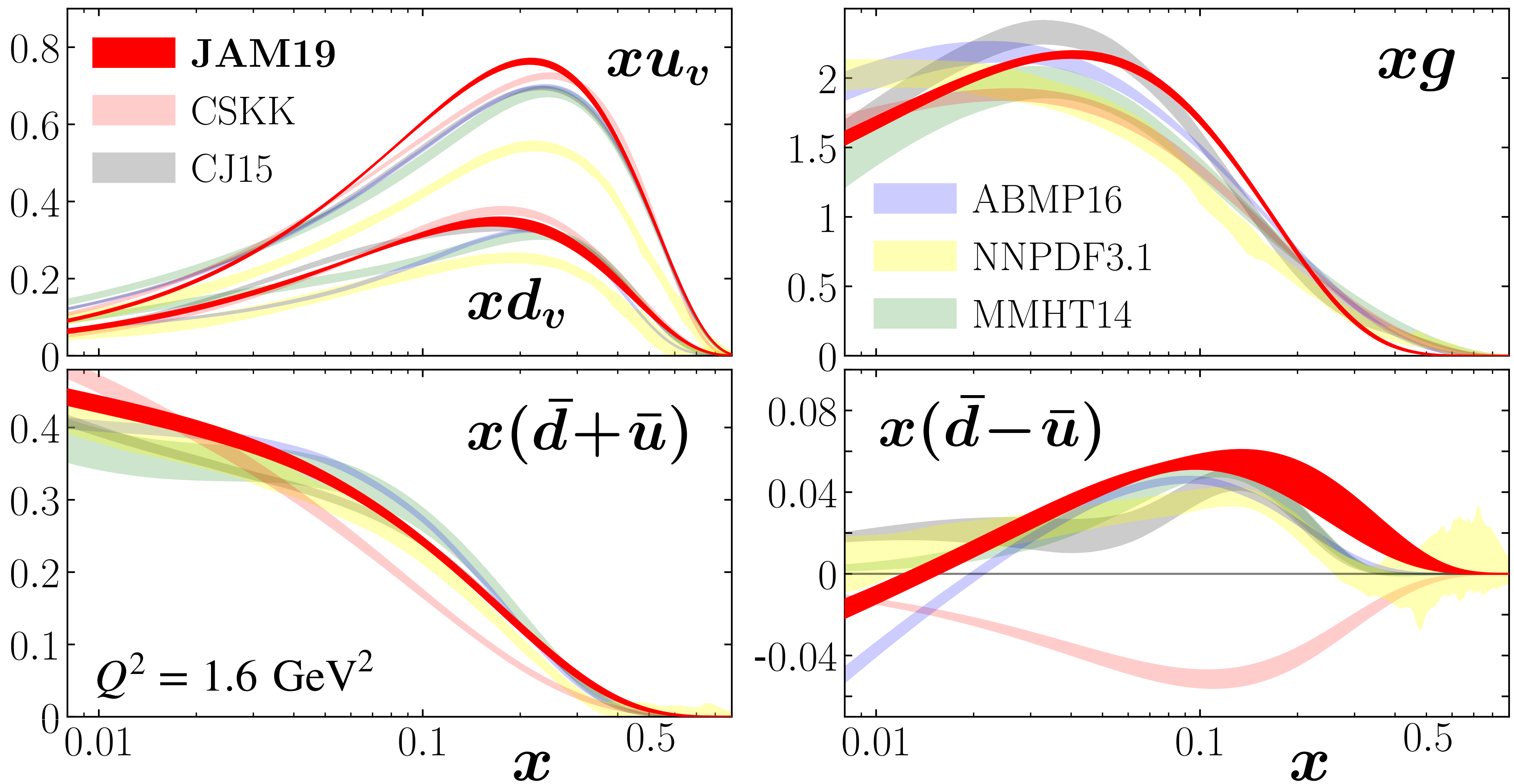
COMPARISON OF PDF MOMENTS WITH LATTICE QCD



PDFLattice White Paper, arXiv:1711.07916

Fair agreement, but not perfect

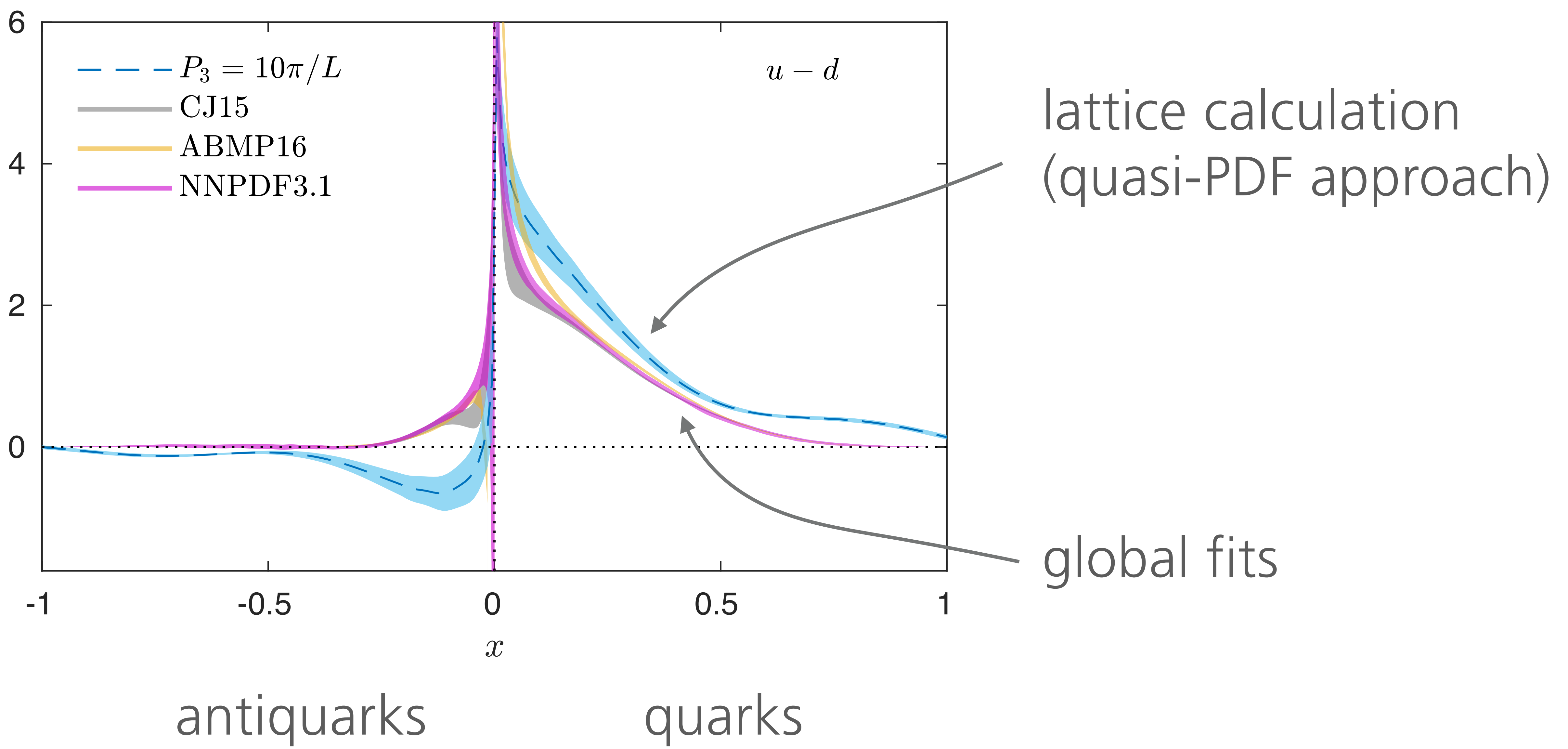
RECENT EXTRACTION (PDF AND FF SIMULTANEOUSLY)



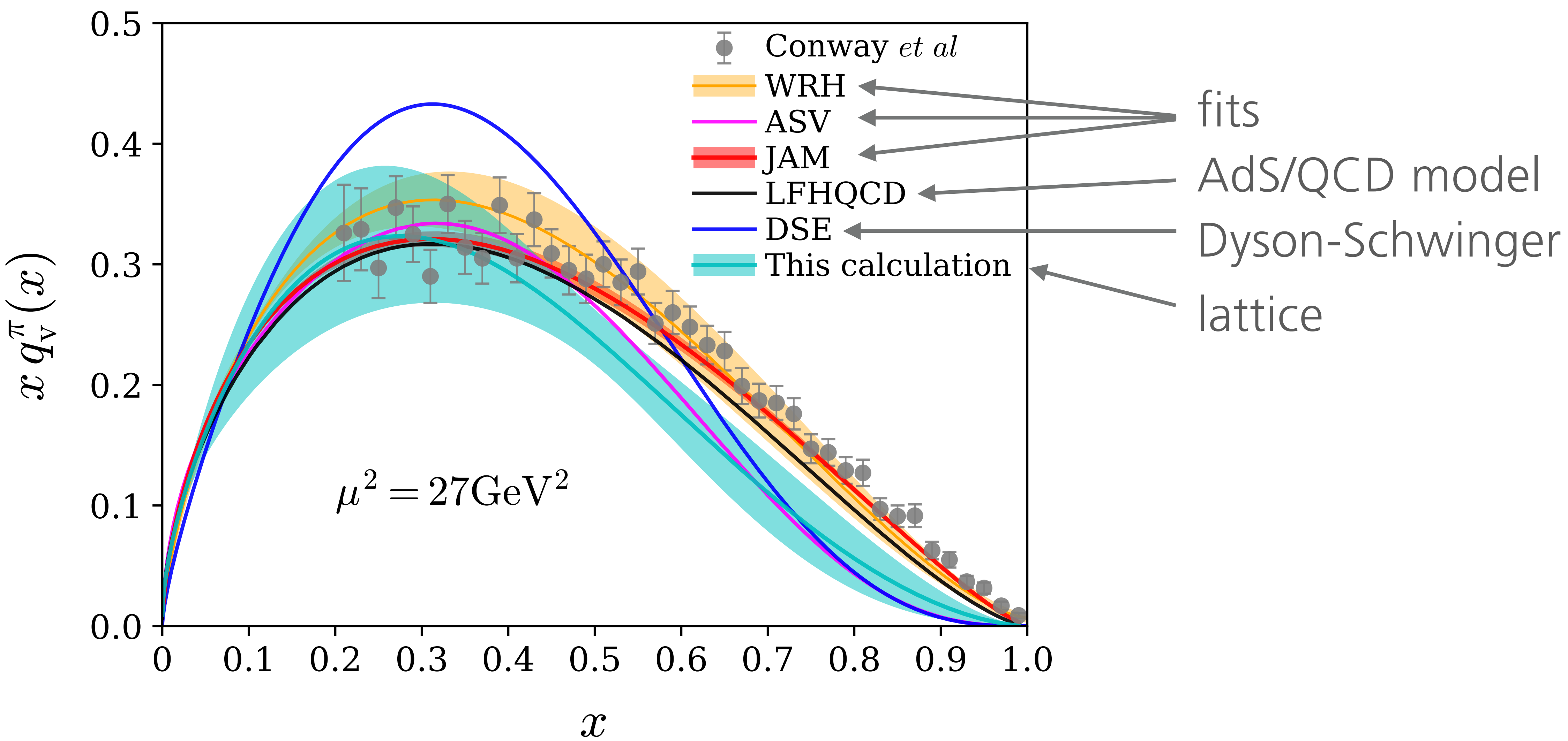
Sato, Andres, Ethier, Melnitchouk, arXiv:1905.03788

COMPARISON OF FULL PDF WITH LATTICE QCD

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



PION PARTON DISTRIBUTION FUNCTIONS

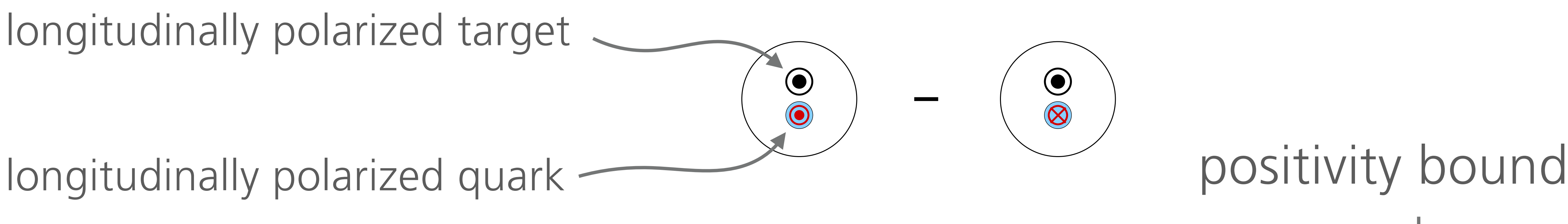


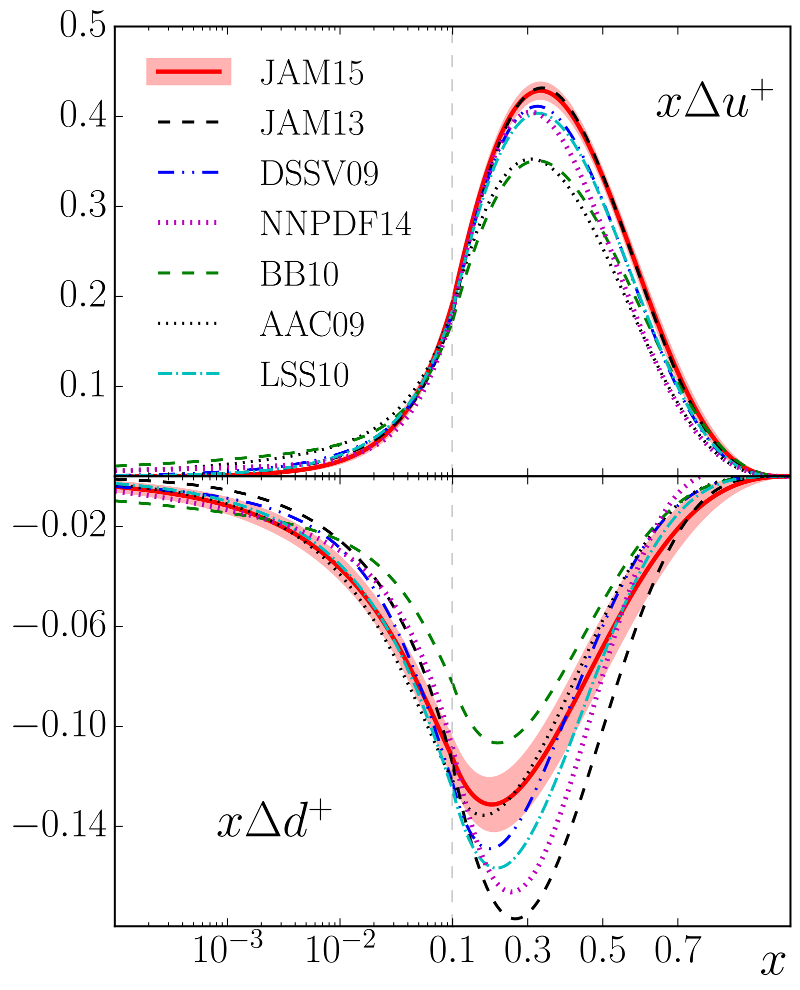
Sabbir Sufian, Karpie, Egerer, Orginos, Jian-Wei Qiu, Richards, arXiv:1901.03921

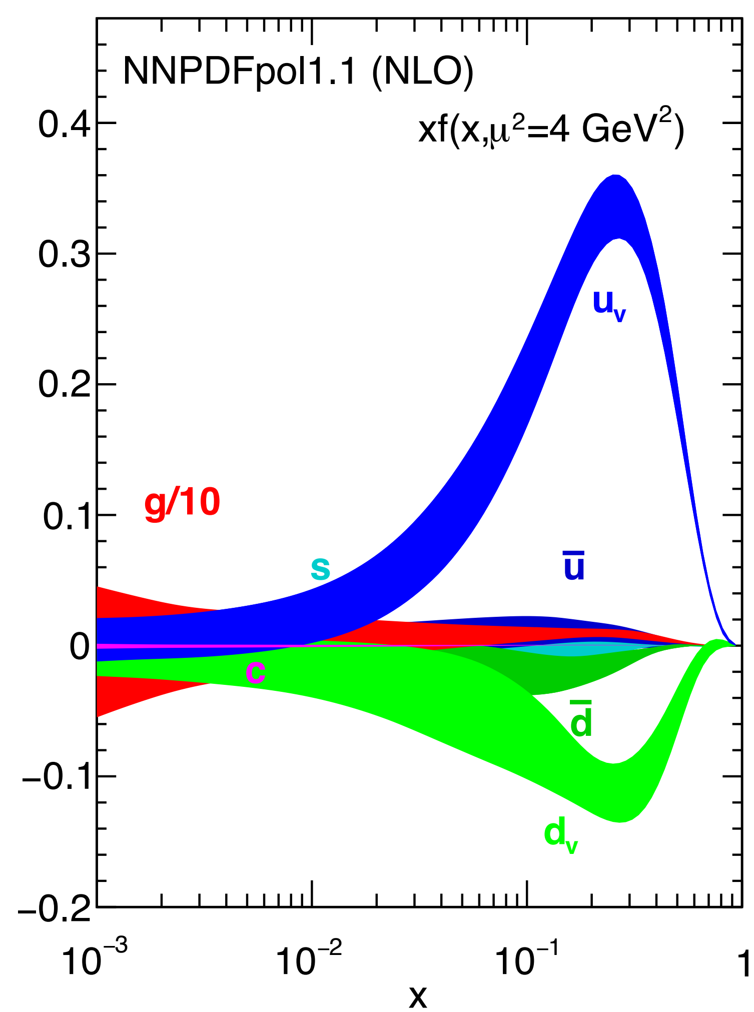
We don't know the pion very well, even if it is the simplest hadron

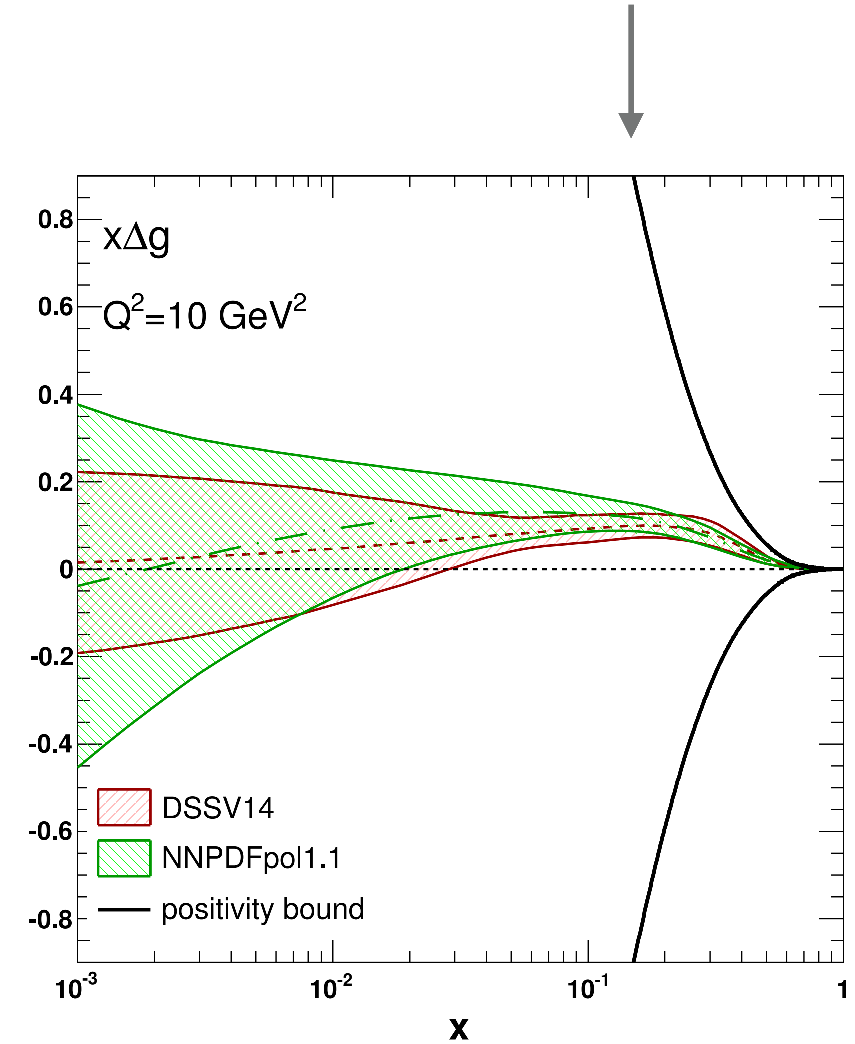
1D + SPIN

HELICITY PARTON DISTRIBUTION FUNCTIONS









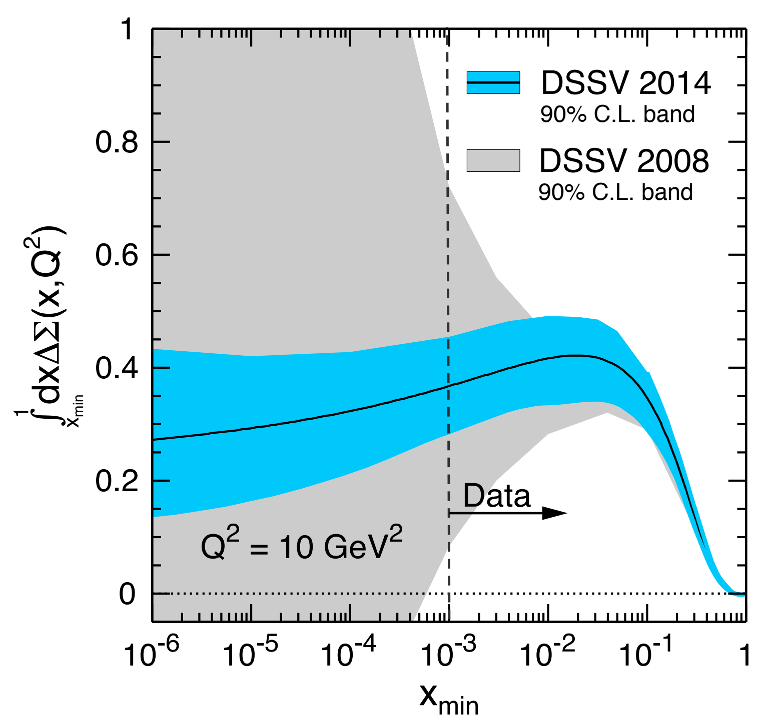
Sato et al., arXiv:1601.07782

PDFLattice White Paper, arXiv:1711.07916

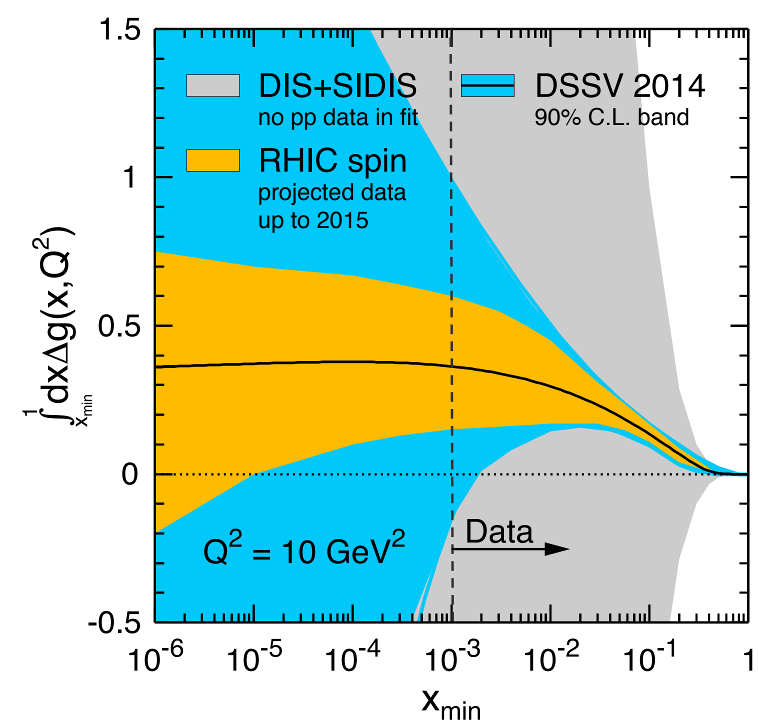
SPIN CONTRIBUTIONS TO ANGULAR MOMENTUM

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

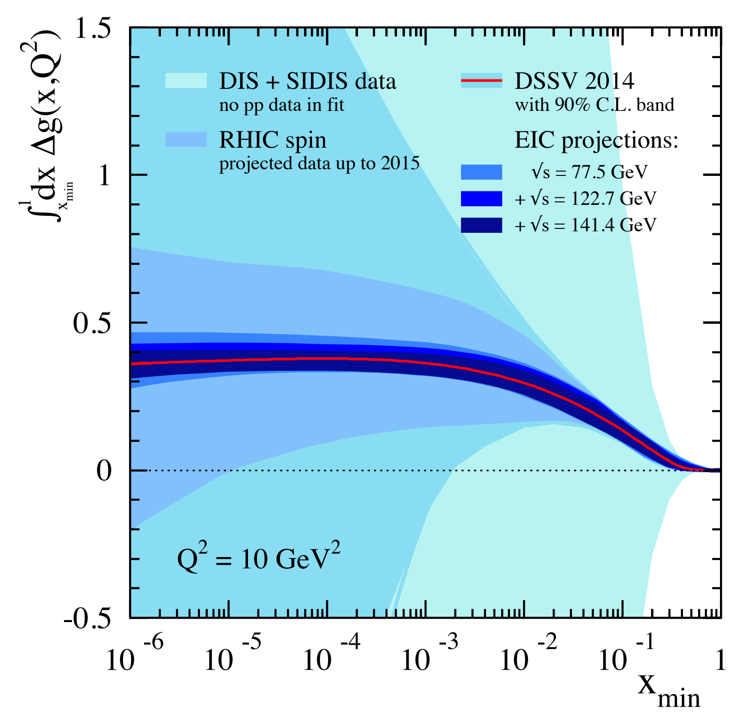
quark spin



gluon spin

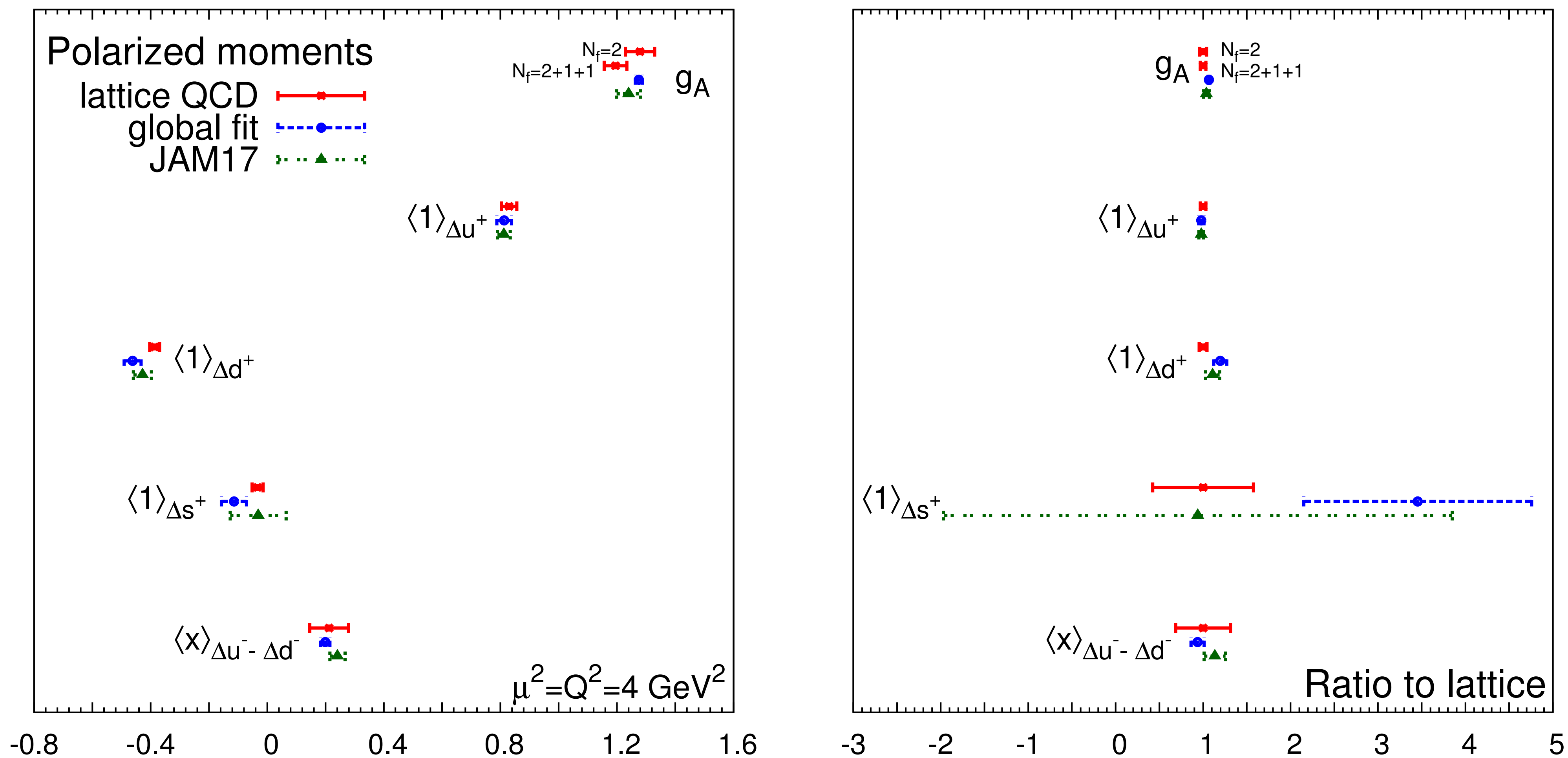


gluon spin w/ EIC



We are constantly improving the knowledge of the contributions to the spin of the proton

COMPARISON WITH LATTICE

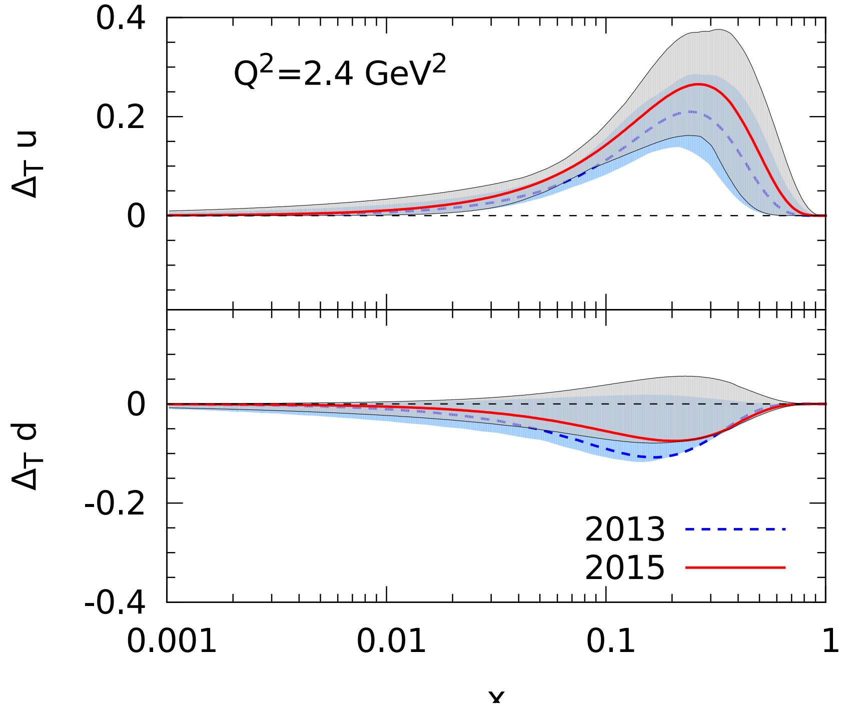


PDFlattice White Paper, arXiv:1711.07916

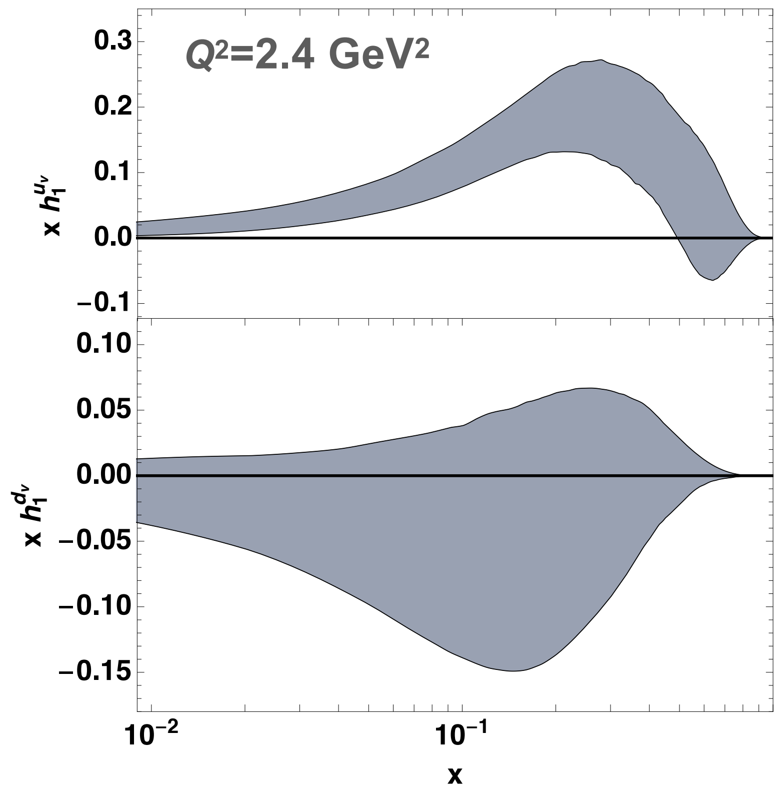
Remarkable agreement between extracted moments of quark helicity distributions and lattice QCD calculations

TRANSVERSITY PARTON DISTRIBUTION FUNCTION

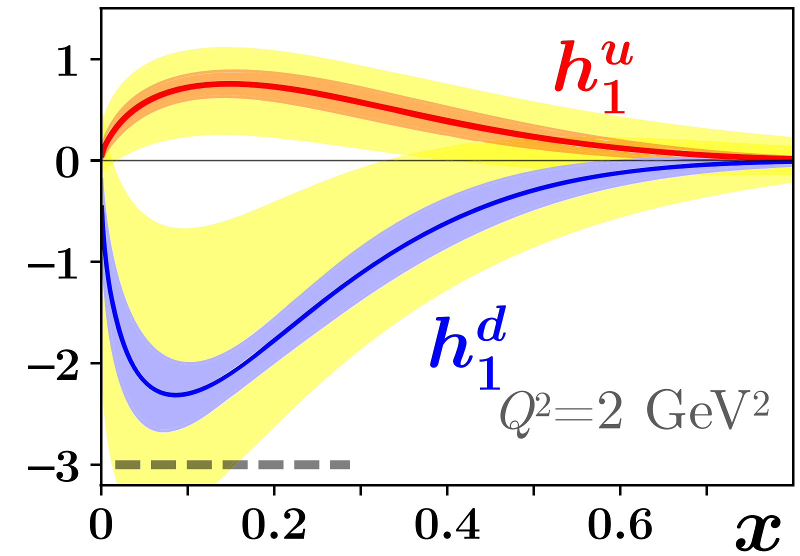
Anselmino et al.,
arXiv:1510.05389



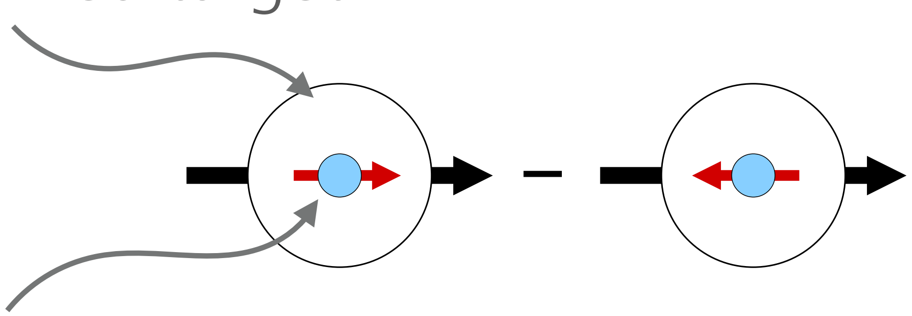
Radici, Bacchetta,
arXiv:1802.05212



Lin et al.,
arXiv:1710.09858



transversely polarized target



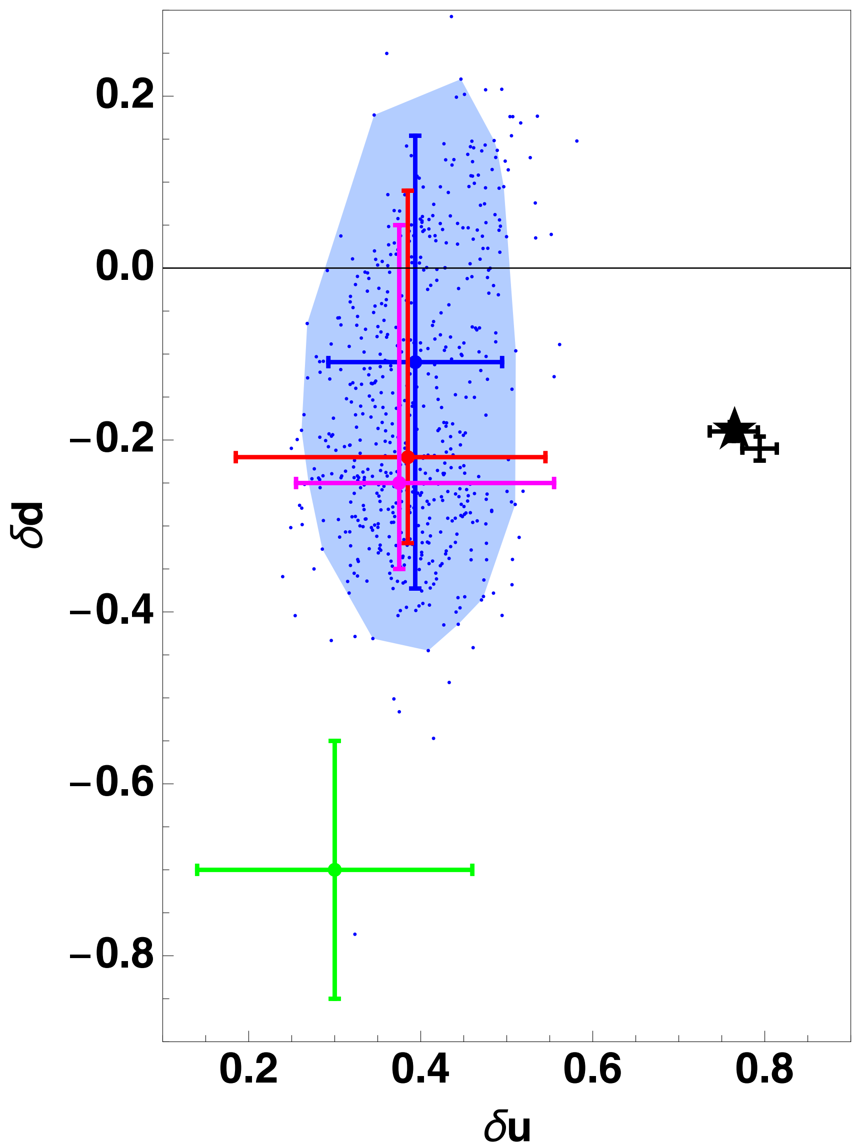
transversely polarized quark

Transversity is constrained by the Soffer bound

TRANSVERSE SPIN

Tensor charge

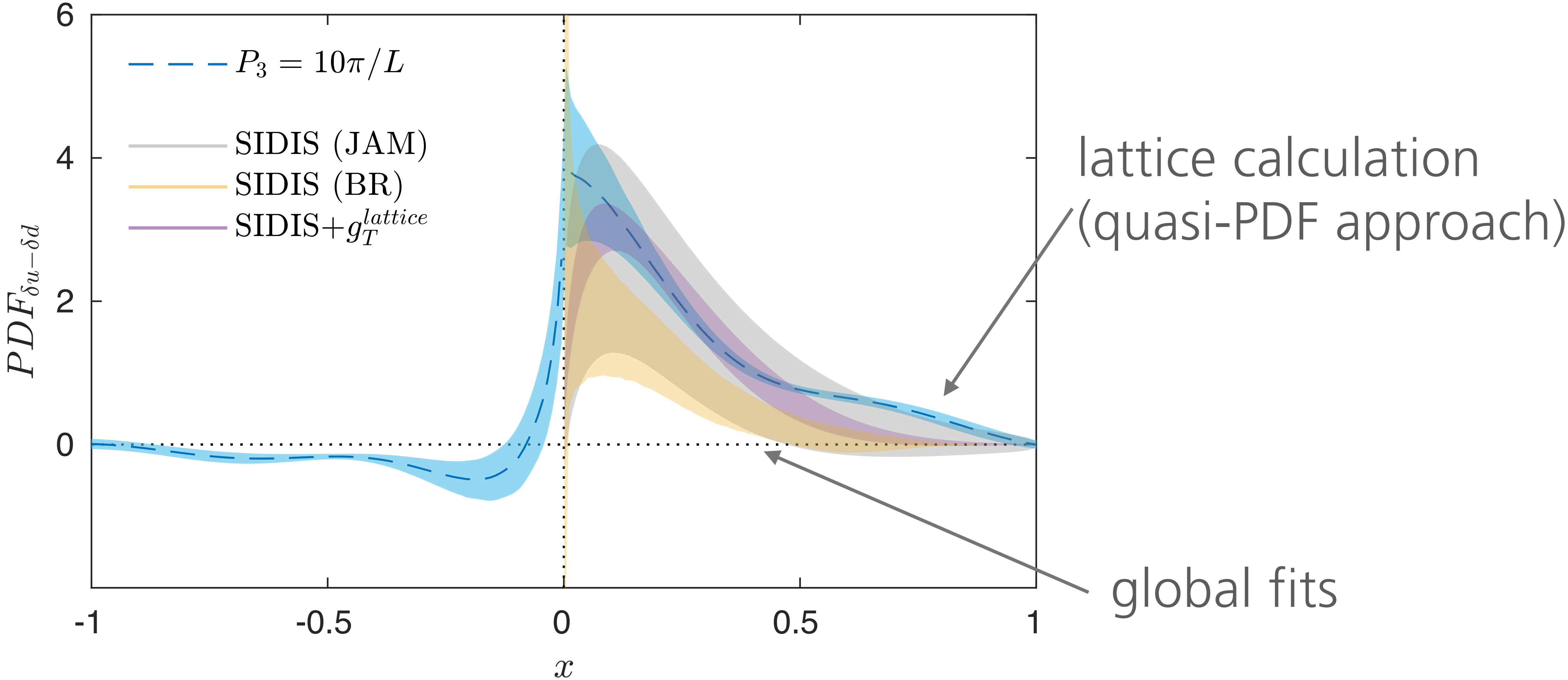
$$\delta q \equiv g_T^q = \int_0^1 dx \;\; \left[h_1^q(x, Q^2) - h_1^{\bar{q}}(x, Q^2) \right]$$



- ★ Alexandrou et al., arXiv:1703.08788
- ● Gupta et al., arXiv:1806.09006
- ● Anselmino et al., arXiv:1303.3822
- ● Kang et al., arXiv:1505.05589
- ● Lin et al., arXiv:1710.09858
- ● Radici et al., arXiv:1802.05212

At the moment, there is a clear tension between extractions and lattice calculations

COMPARISON OF FULL TRANSVERSITY PDF WITH LATTICE QCD

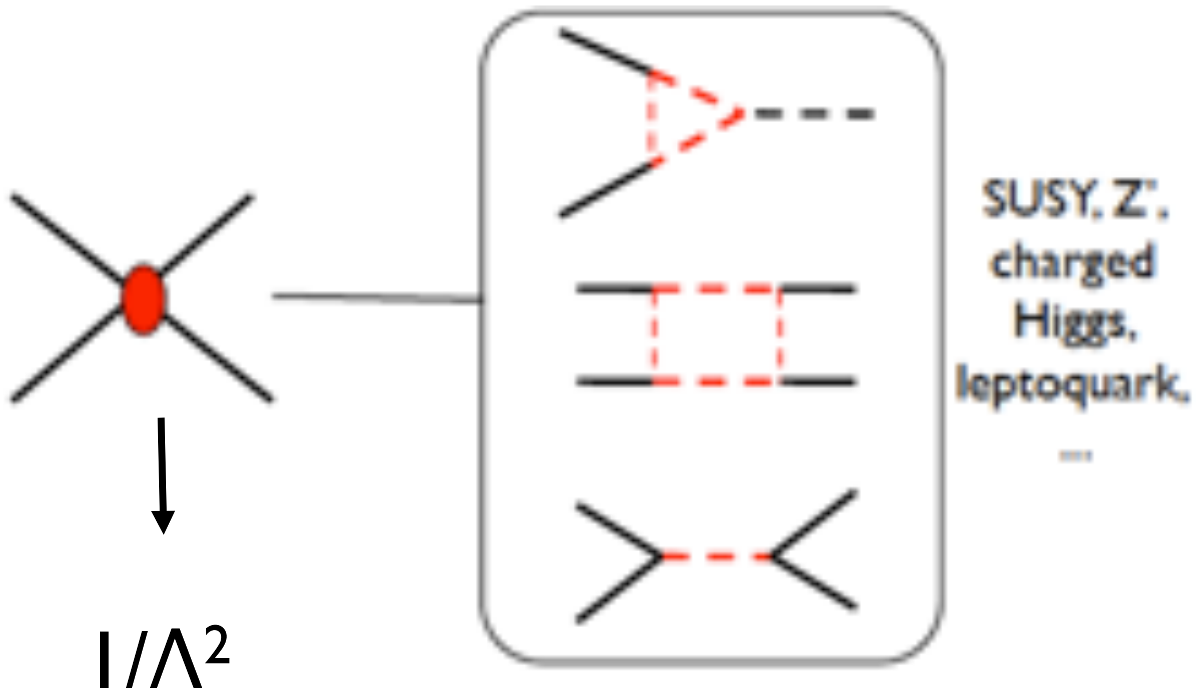


plot courtesy of F. Steffens

Alexandrou, at al. arXiv:1902.00587
Radici, Bacchetta, arXiv:1802.05212
Lin et al., arXiv:1710.09858

TENSOR CHARGE AND BSM

Tensor couplings, not present in the SM Lagrangian, could be the footprints of new physics at higher scales



$$\varepsilon_T \, g_T \longrightarrow M_W^2 \, / \, M_{BSM}^2$$

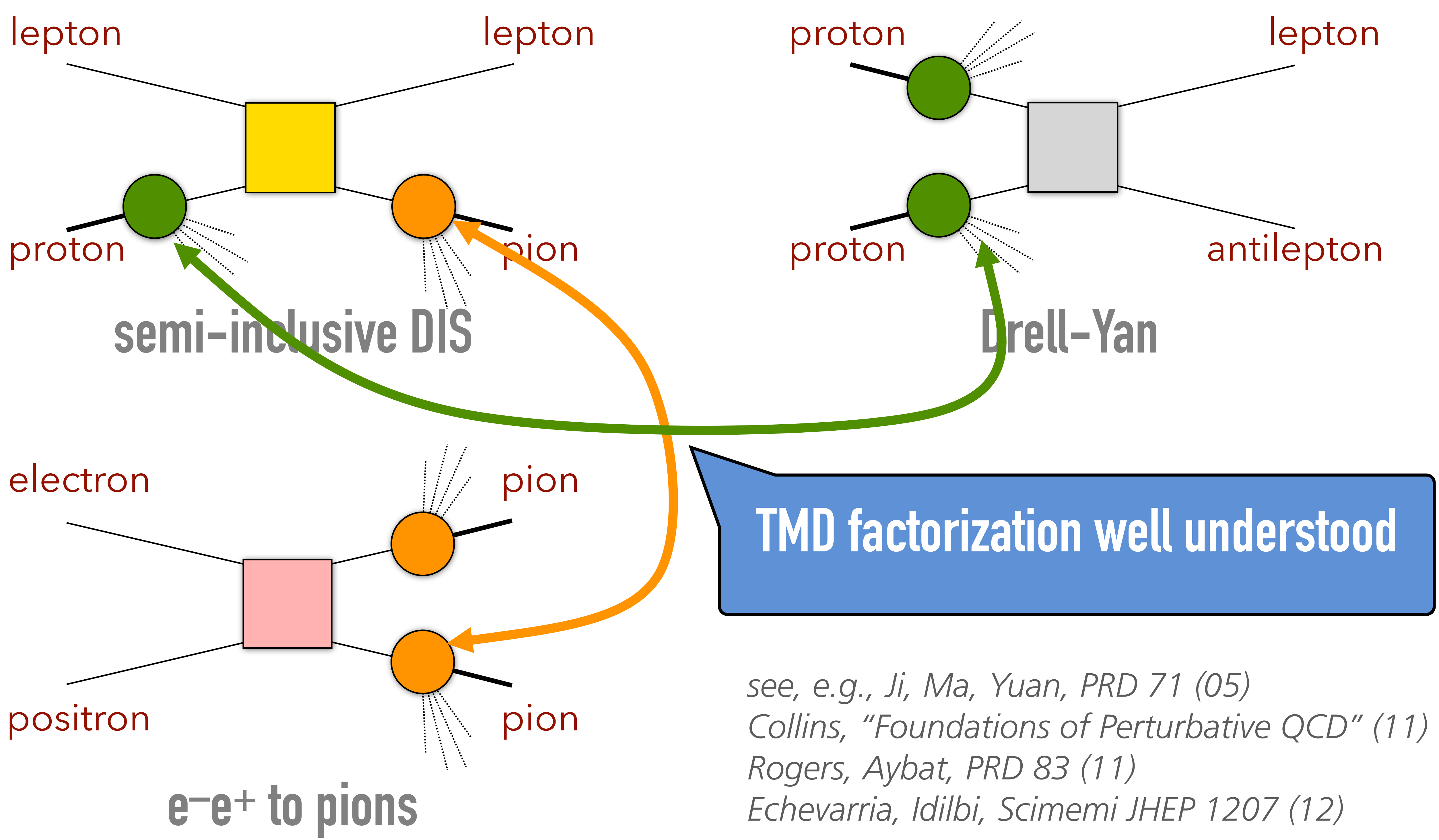
Current precision of 0.1% ⇒ [3-5] TeV bound for BSM scale

Knowledge of tensor charge is crucial

Bhattacharya et al, PRD 85 (12)
Pattie et al., P.R. C88 (13)
Courtoy, Baeßler, González-Alonso, Liuti, PRL 115 (15)

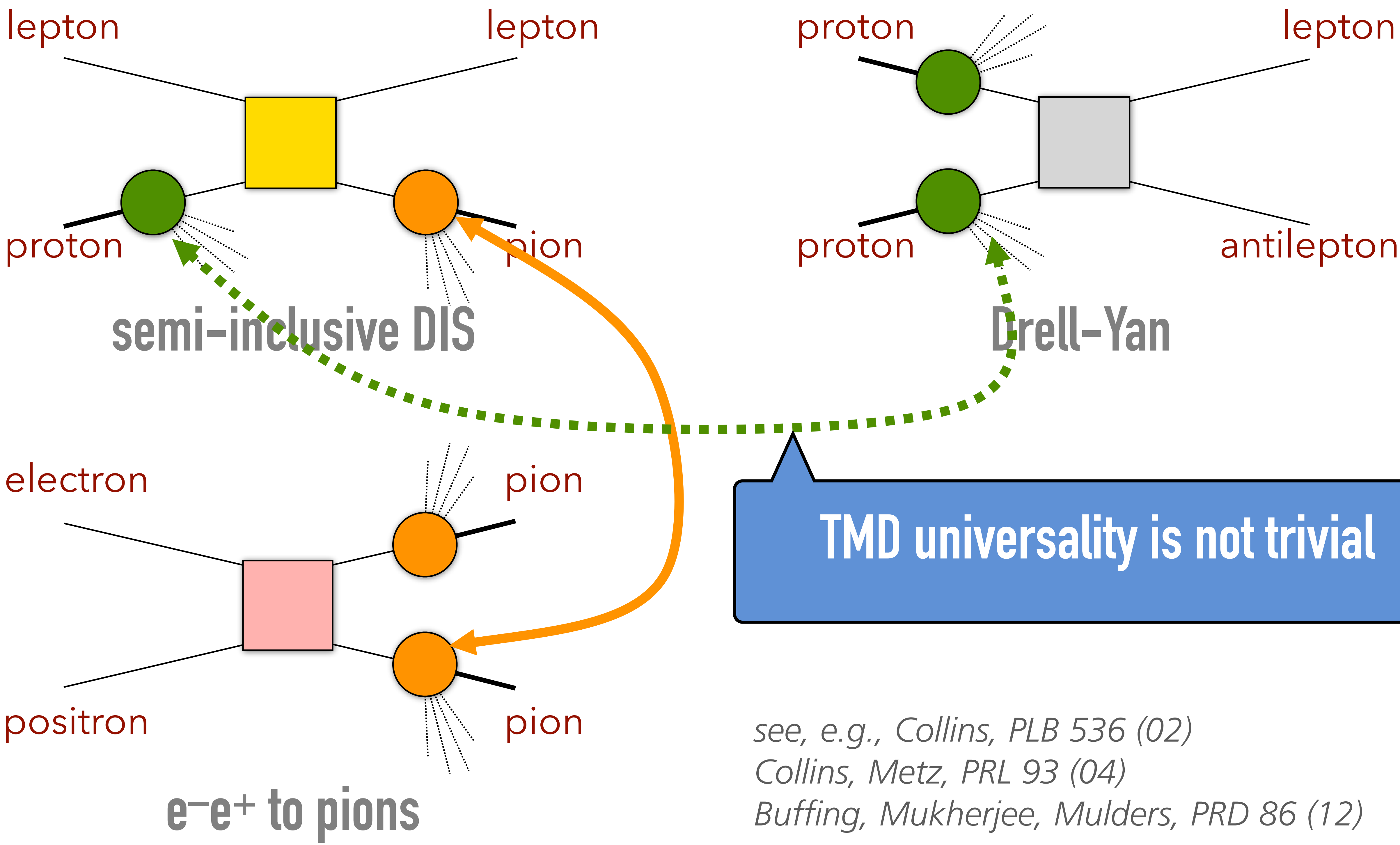
3D UNPOLARISED

FACTORIZATION AND UNIVERSALITY



see, e.g., Ji, Ma, Yuan, PRD 71 (05)
Collins, "Foundations of Perturbative QCD" (11)
Rogers, Aybat, PRD 83 (11)
Echevarria, Idilbi, Scimemi JHEP 1207 (12)

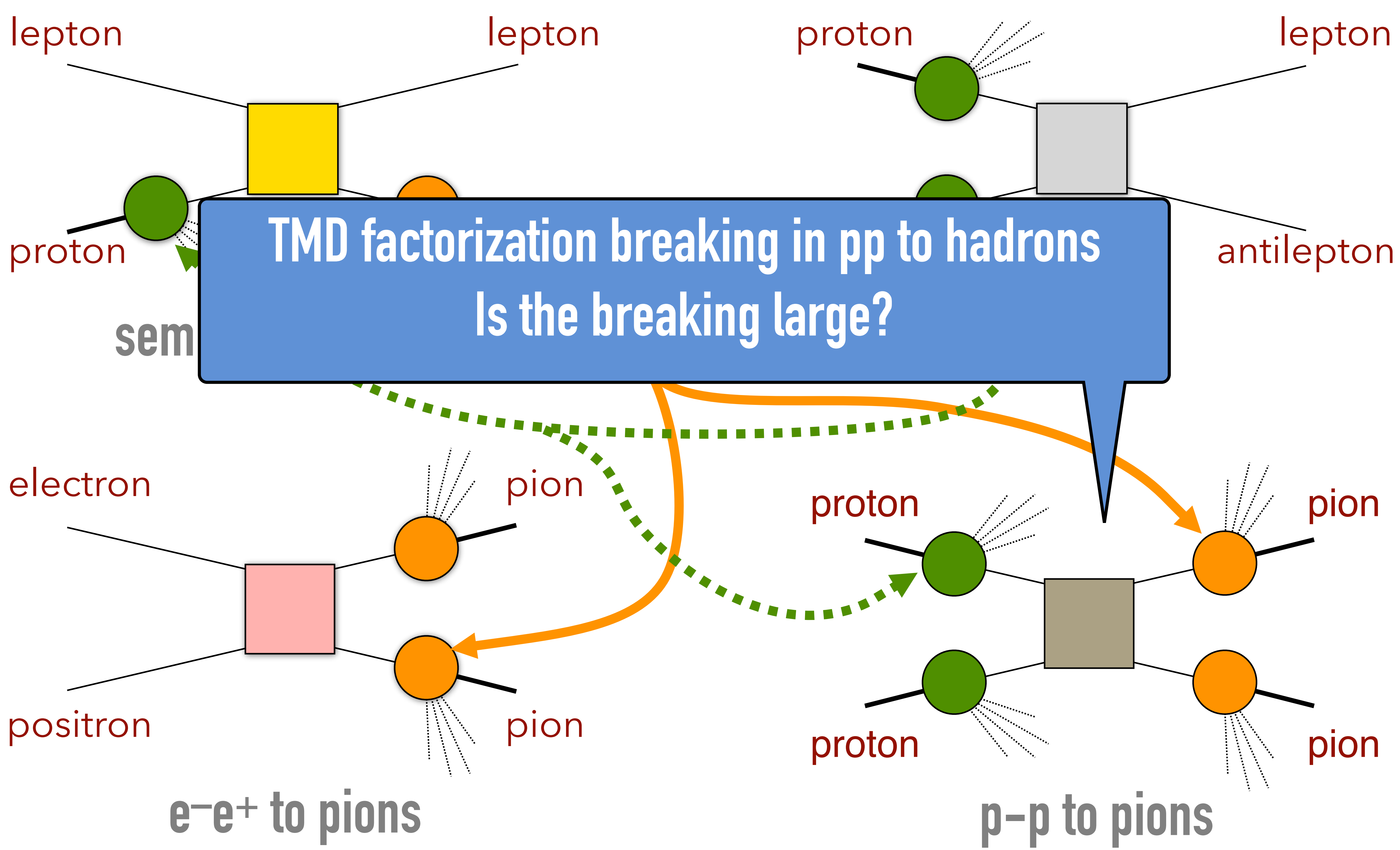
FACTORIZATION AND UNIVERSALITY



TMD universality is not trivial

see, e.g., Collins, PLB 536 (02)
Collins, Metz, PRL 93 (04)
Buffing, Mukherjee, Mulders, PRD 86 (12)

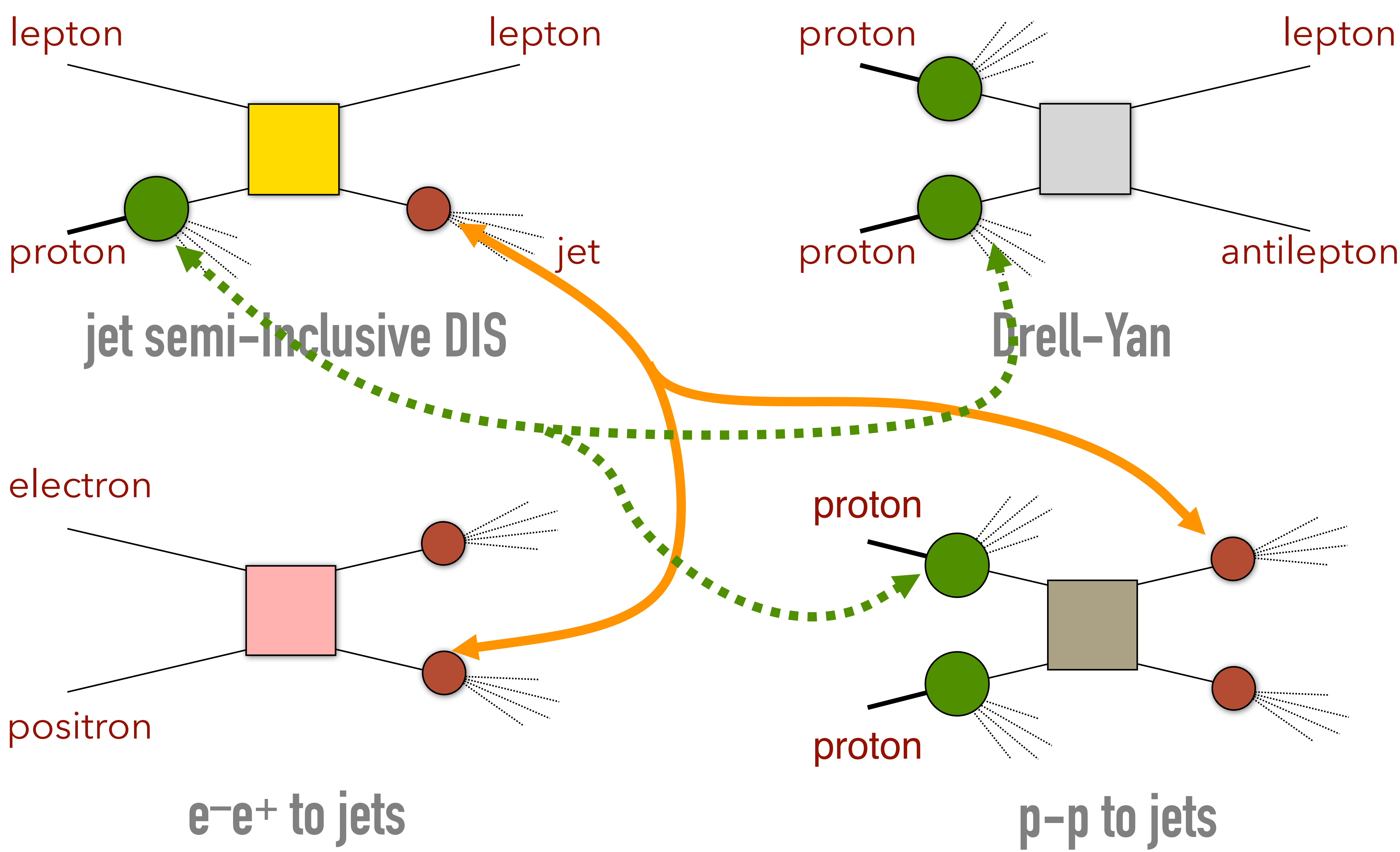
FACTORIZATION AND UNIVERSALITY



see, e.g., Rogers, Mulders, PRD81 (10)

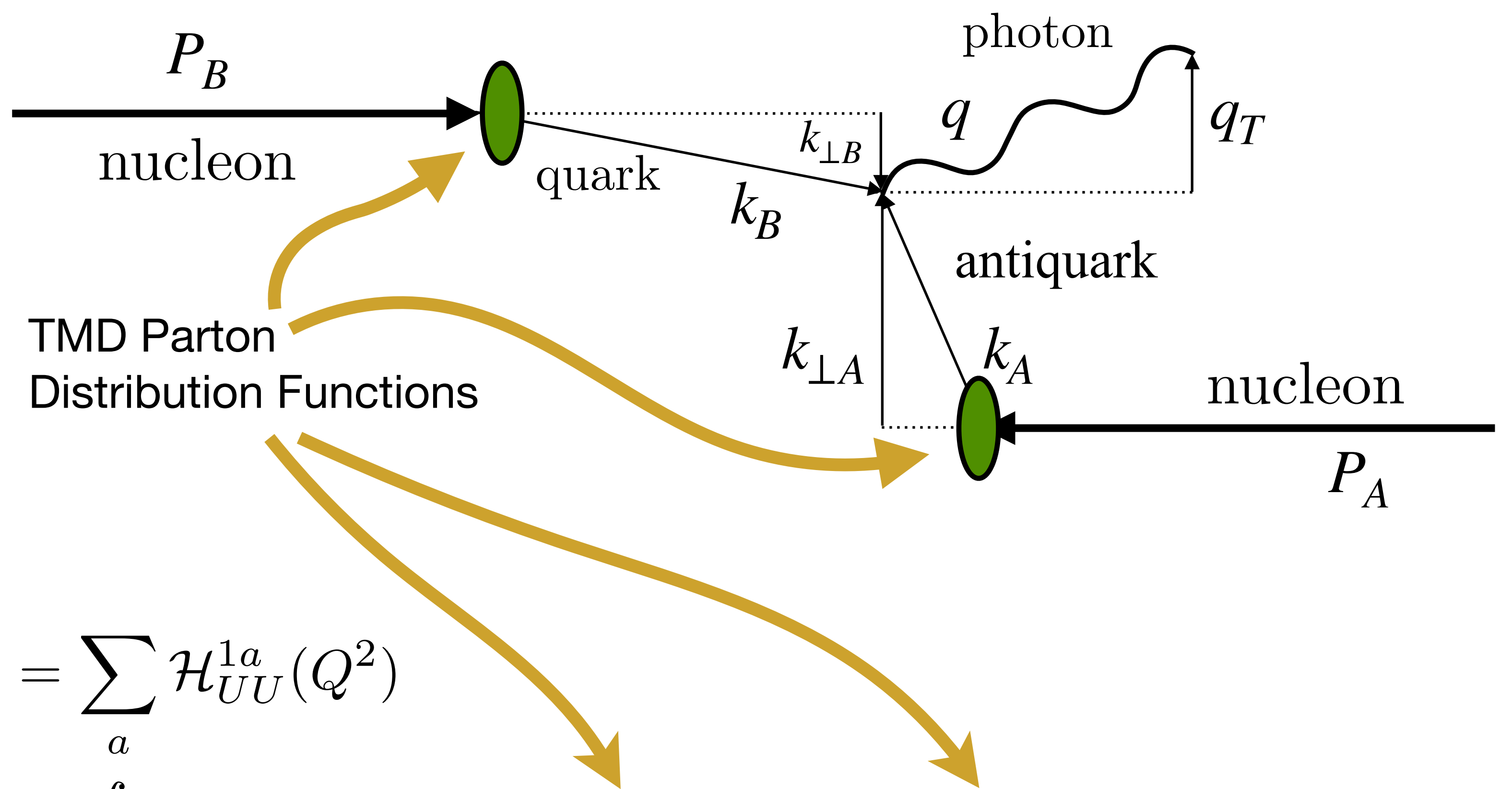
Buffing, Kang, Lee, Liu, arXiv:1812.07549

FACTORIZATION AND UNIVERSALITY



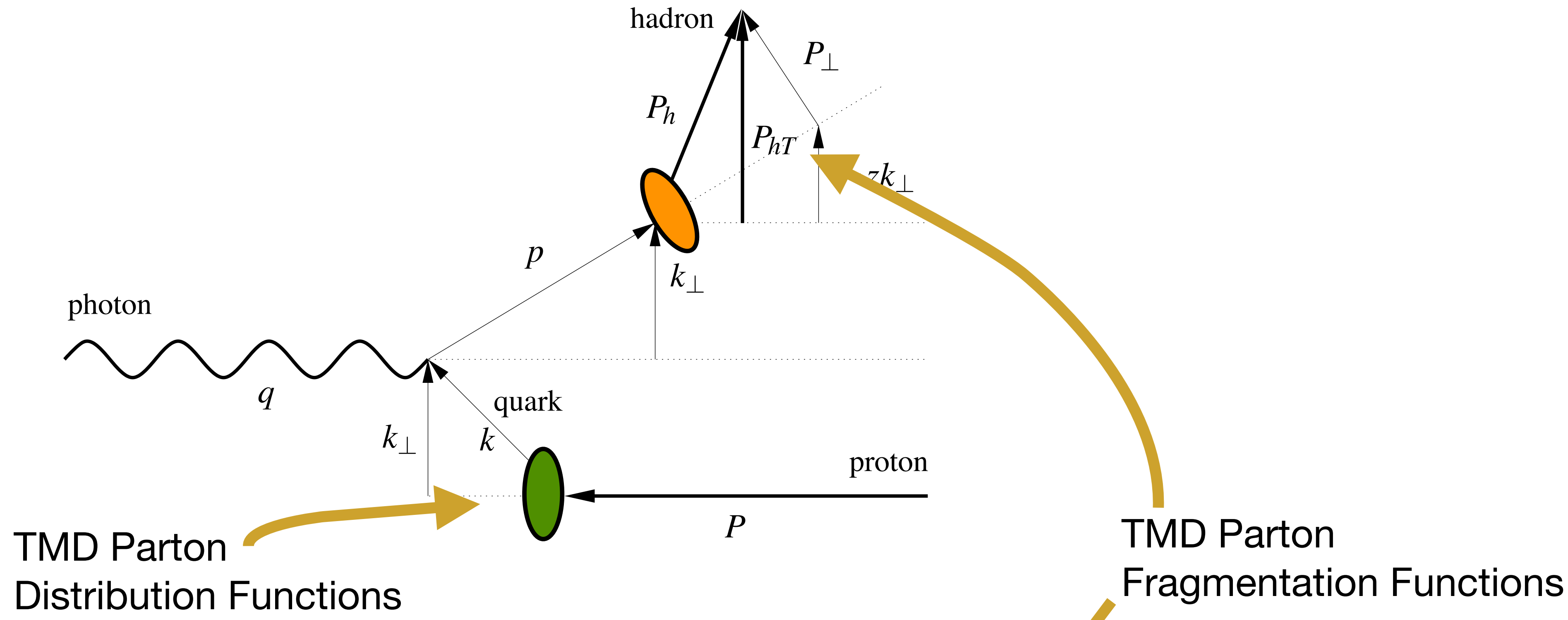
see also talk by F. Petriello

TMDS IN DRELL-YAN PROCESSES



$$F_{UU}^{1}(x_A, x_B, \boldsymbol{q}_T^2, Q^2) = \sum_a \mathcal{H}_{UU}^{1a}(Q^2)$$
$$\times \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^a(x_A, \boldsymbol{k}_{\perp A}^2; Q^2)\, f_1^{\bar{a}}(x_B, \boldsymbol{k}_{\perp B}^2; Q^2)\, \delta^{(2)}\big(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B}\big)$$
$$+ Y_{UU}^{1}(Q^2, \boldsymbol{q}_T^2) + \mathcal{O}\big(M^2/Q^2\big)\,.$$

TMDS IN SEMI-INCLUSIVE DIS



$$F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2) = \sum_a \mathcal{H}_{UU,T}^a(Q^2; \mu^2) \int d\boldsymbol{k}_\perp \, d\boldsymbol{P}_\perp \, f_1^a\big(x, \boldsymbol{k}_\perp^2; \mu^2\big) \, D_1^{a\to h}\big(z, \boldsymbol{P}_\perp^2; \mu^2\big) \, \delta\big(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp\big)$$
$$+ Y_{UU,T}\big(Q^2, \boldsymbol{P}_{hT}^2\big) + \mathcal{O}\big(M^2/Q^2\big)$$

TMD FACTORIZATION

W term

$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = x\sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2)\int \frac{d\boldsymbol{b}_\perp^2}{4\pi} J_0(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|)\tilde{f}_1^a(x,z^2\boldsymbol{b}_\perp^2;\mu^2)\,\tilde{D}_1^{a\to h}(z,\boldsymbol{b}_\perp^2;\mu^2)$$
$$+\,Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

The Y term guarantees that the calculation at high P_{hT} agrees with perturbative calculation done with collinear factorization

$$\widetilde{f}_1^a(x,b_T;\mu^2) = \sum_i (\tilde{C}_{a/i}\otimes f_1^i)(x,b_*;\mu_b)e^{\tilde{S}(b_*;\mu_b,\mu)}e^{g_K(b_T)\ln\frac{\mu}{\mu_0}}\hat{f}^a_{\text{NP}}(x,b_T)$$

collinear PDF

pQCD

nonperturbative part of evolution

nonperturbative part of TMD

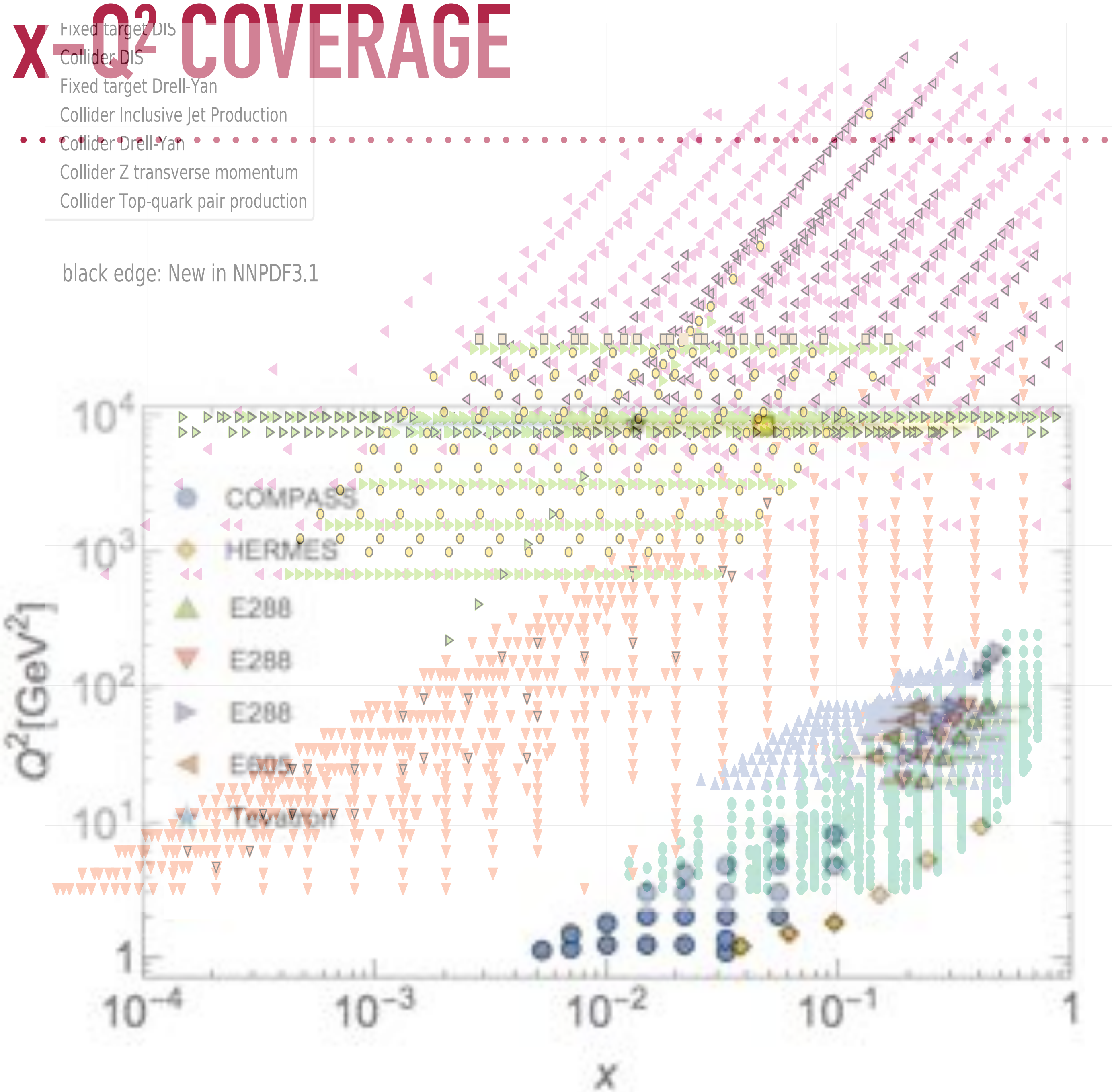
see, e.g., Rogers, Aybat, PRD 83 (11),
Collins, "Foundations of Perturbative QCD" (11)

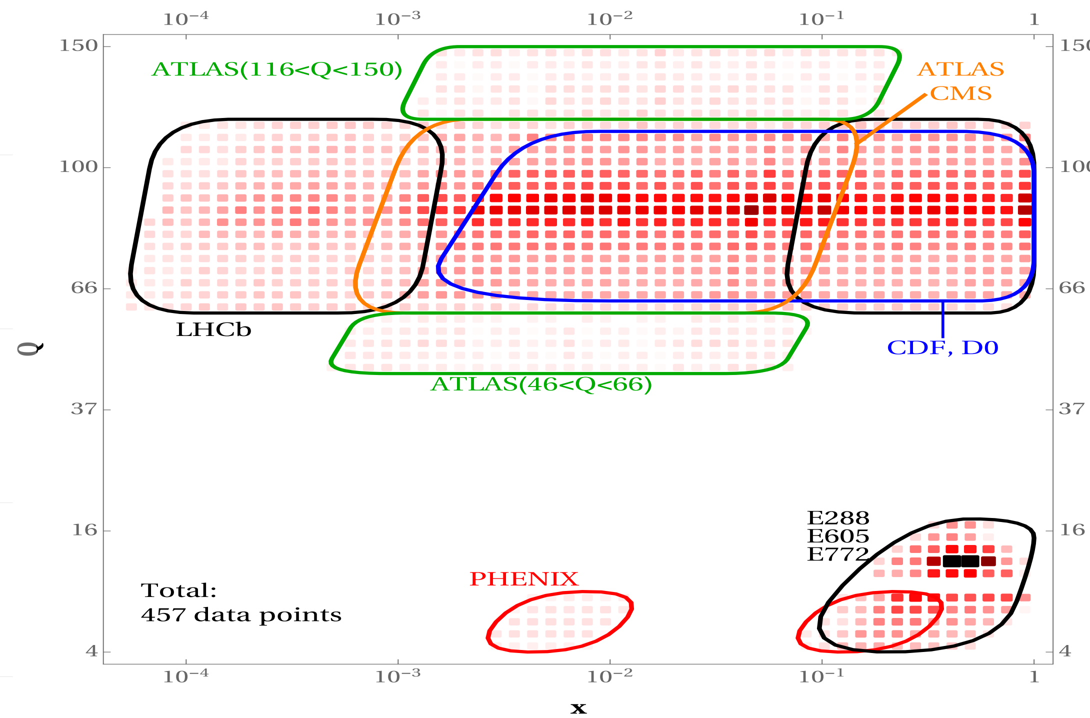
other possible schemes, e.g.,
Laenen, Sterman, Vogelsang, PRL 84 (00)
Bozzi, Catani, De Florian, Grazzini, NPB737 (06)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

TMD FITS OF UNPOLARIZED DATA

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	✘	✘	✔	✔	98
Pavia 2013 arXiv:1309.3507	LO	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	LO	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
SIYY 2014 arXiv:1406.3073	NLO-NLL	✘	✔	✔	✔	200 (?)
Pavia 2017 arXiv:1703.10157	LO-NLL	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	✘	✘	✔	✔	309
BSV 2019 arXiv:1902.08474	NNLO-NNLL	✘	✘	✔	✔	457

x-Q^2 COVERAGE



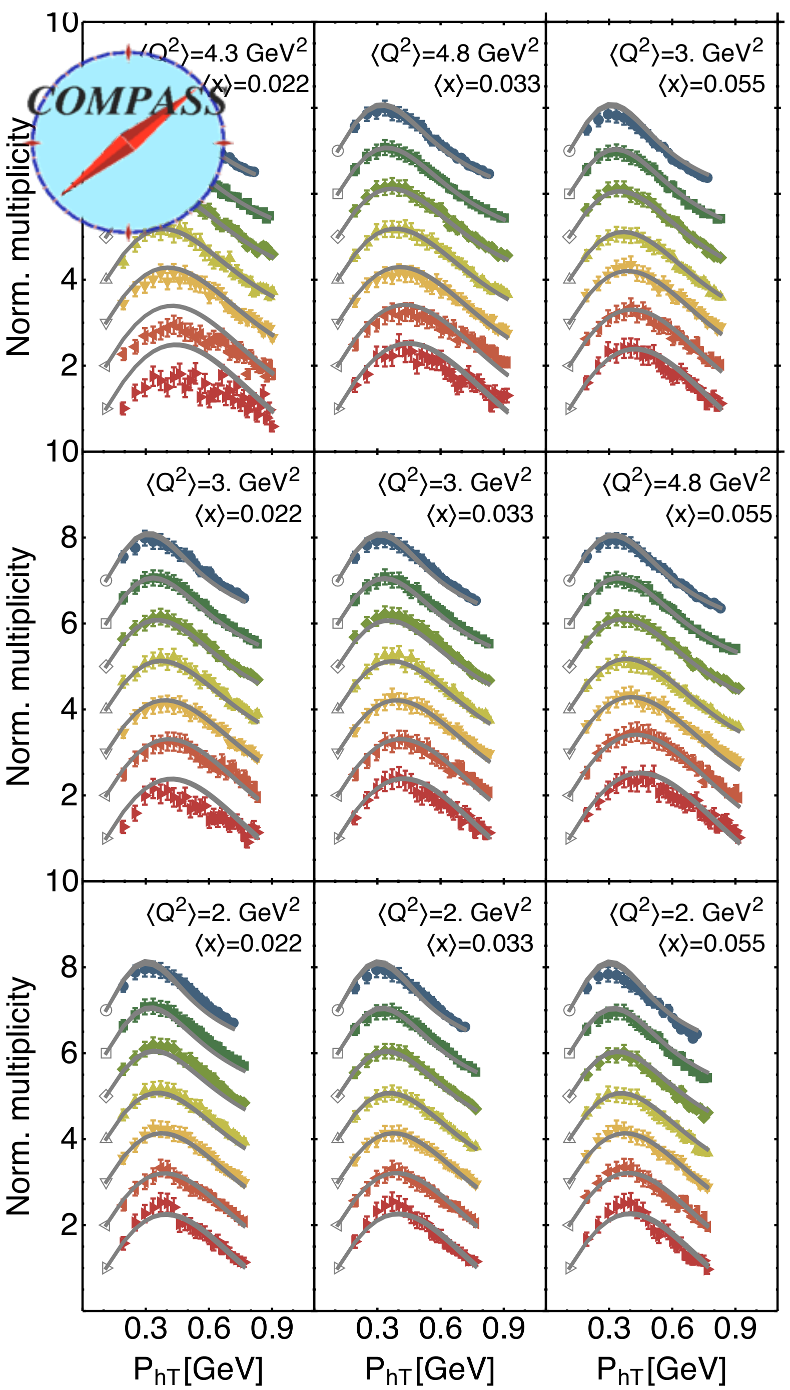


Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

Bertone, Scimemi, Vladimirov, arXiv:1902.08474

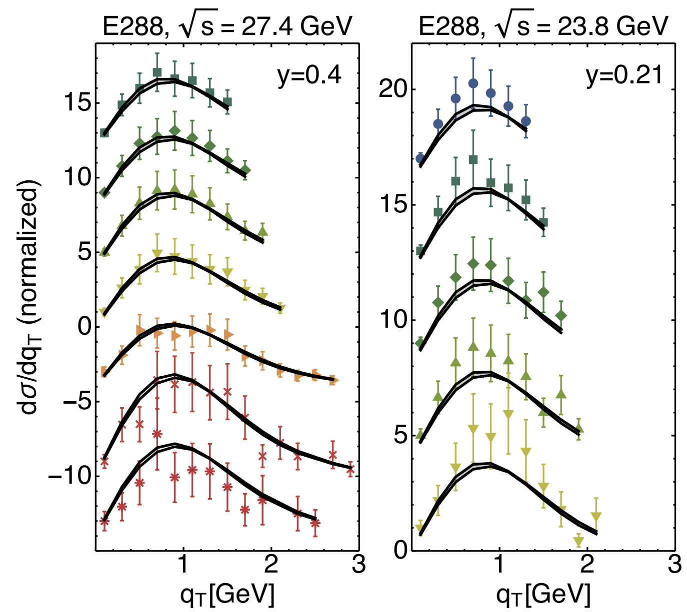
FIRST TMD GLOBAL FIT

SIDIS

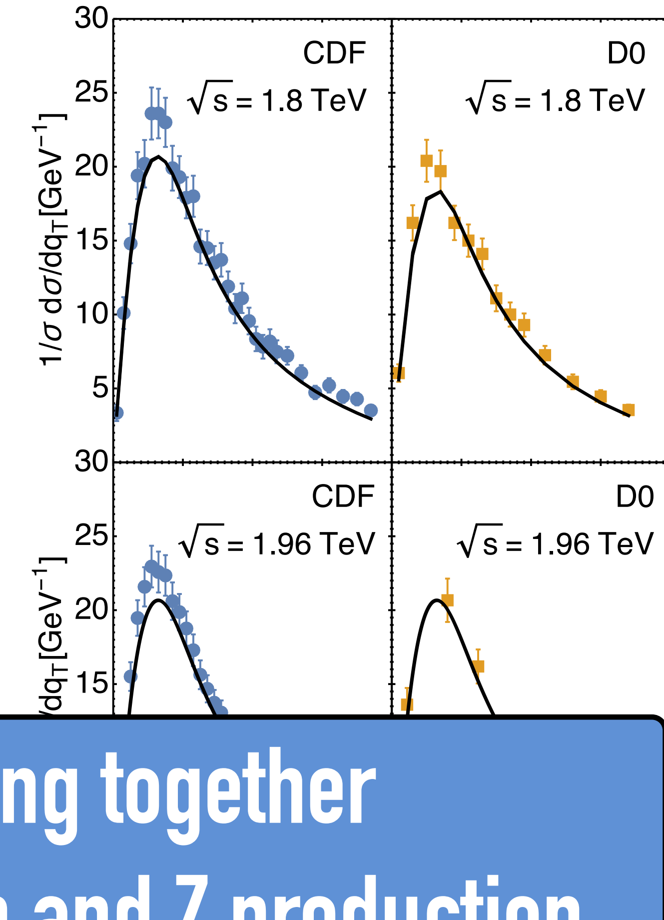


Drell-Yan

Fermilab



Z production



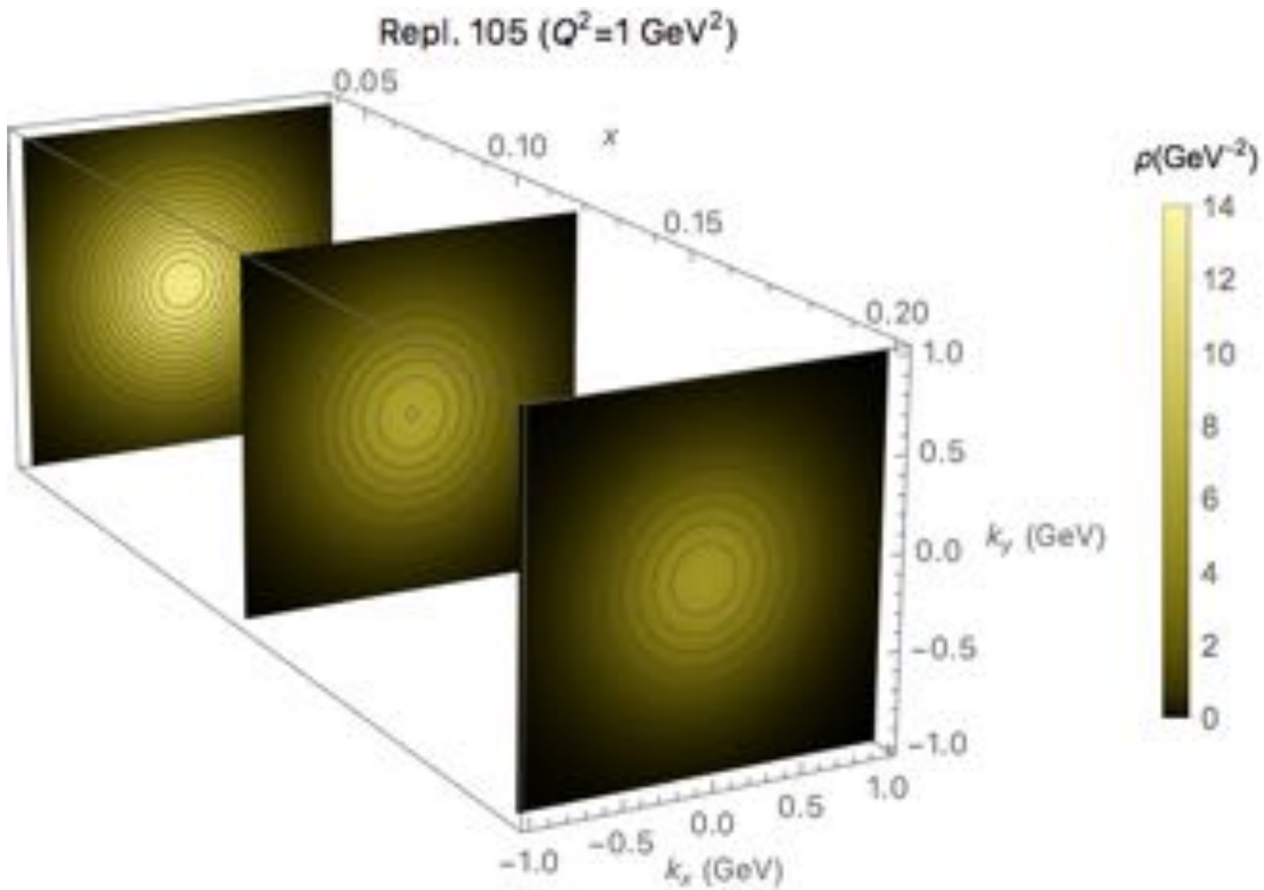
Number of data points: 8059

Global χ^2/dof = 1.55

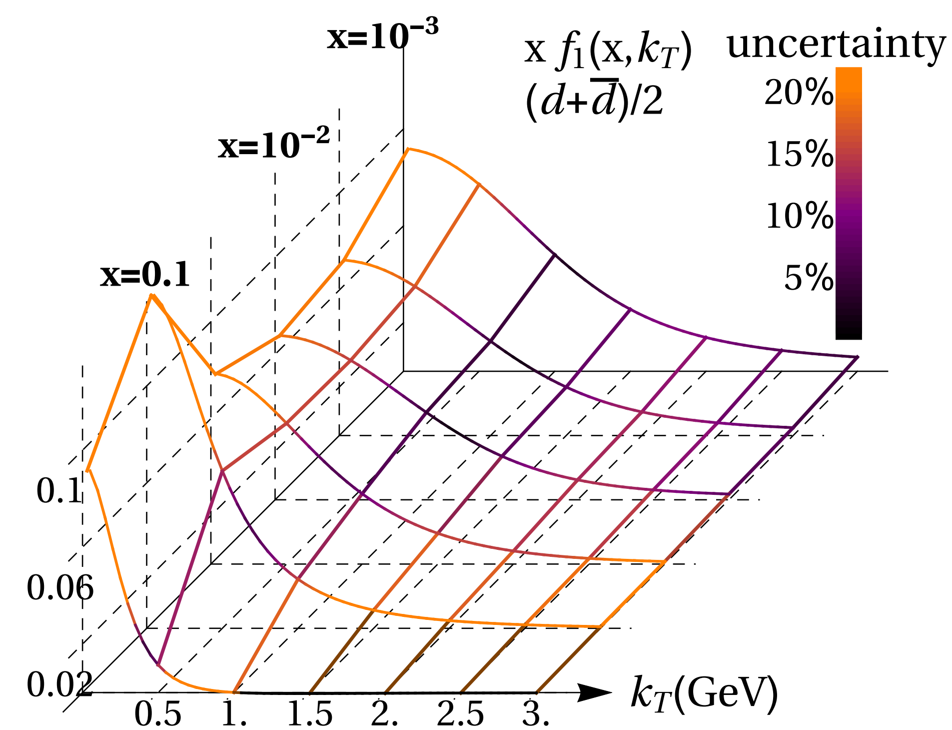
Pavia2016: first fit putting together semi-inclusive DIS, Drell-Yan and Z production

Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

3D DISTRIBUTIONS EXTRACTED FROM DATA



Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

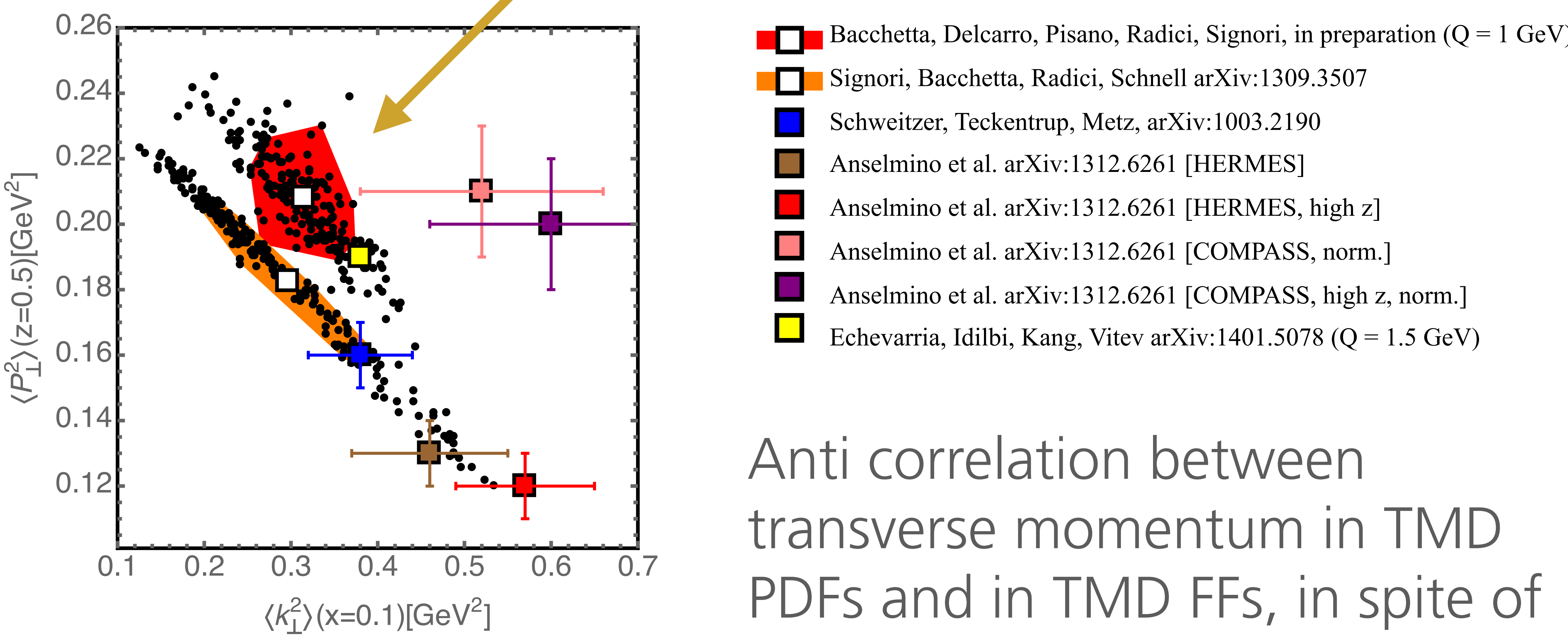


Bertone, Scimemi, Vladimirov, arXiv:1902.08474

MEAN TRANSVERSE MOMENTUM SQUARED

Pavia2016 results, Q^2=1 GeV^2

Transverse momentum in FFs



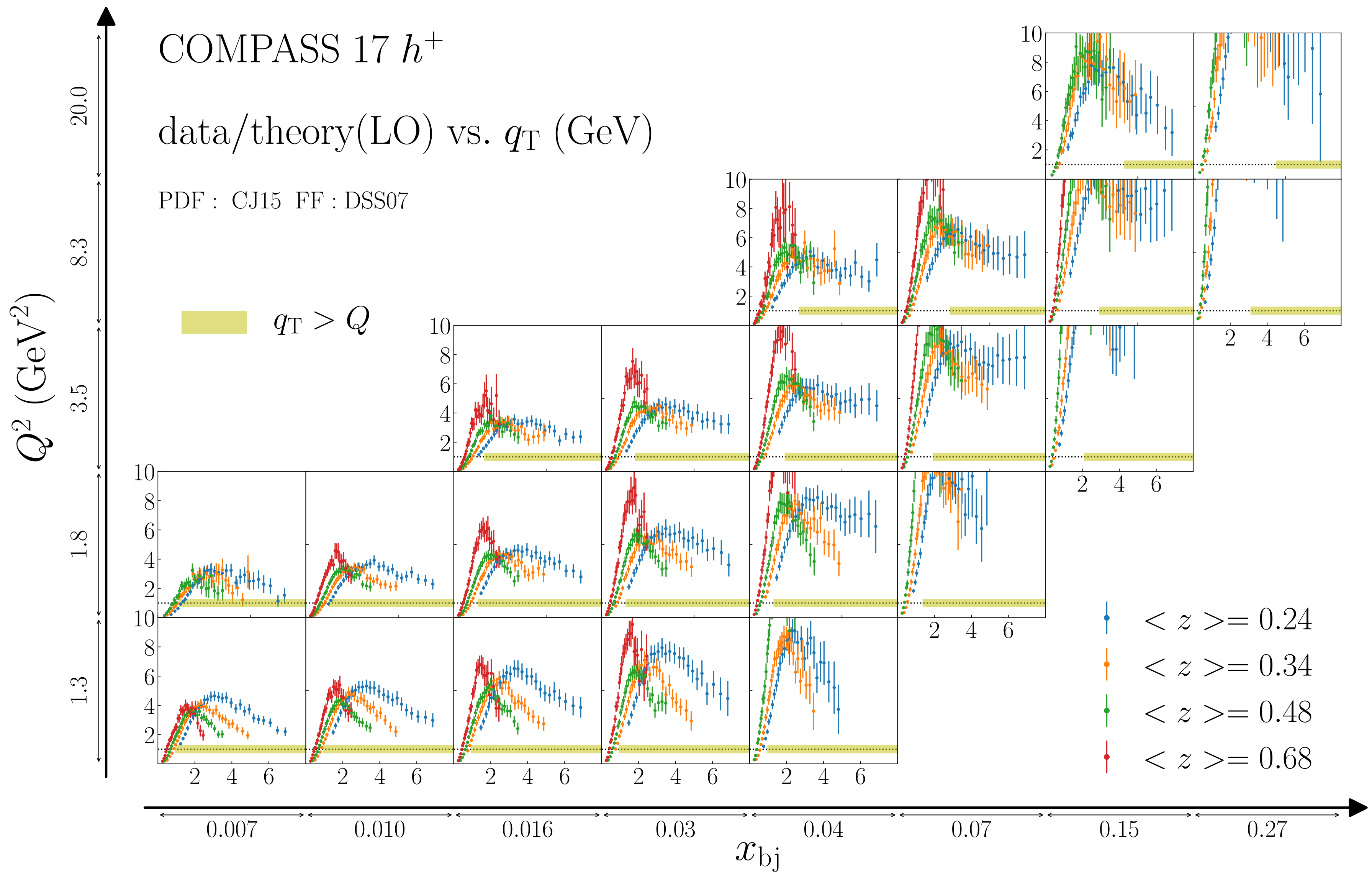
Transverse momentum in PDFs

Anti correlation between transverse momentum in TMD PDFs and in TMD FFs, in spite of Drell-Yan data

CAVEAT: intrinsic transverse momentum depends on TMD evolution "scheme" and its parameters

PROBLEMS WITH HIGH TRANSVERSE MOMENTUM

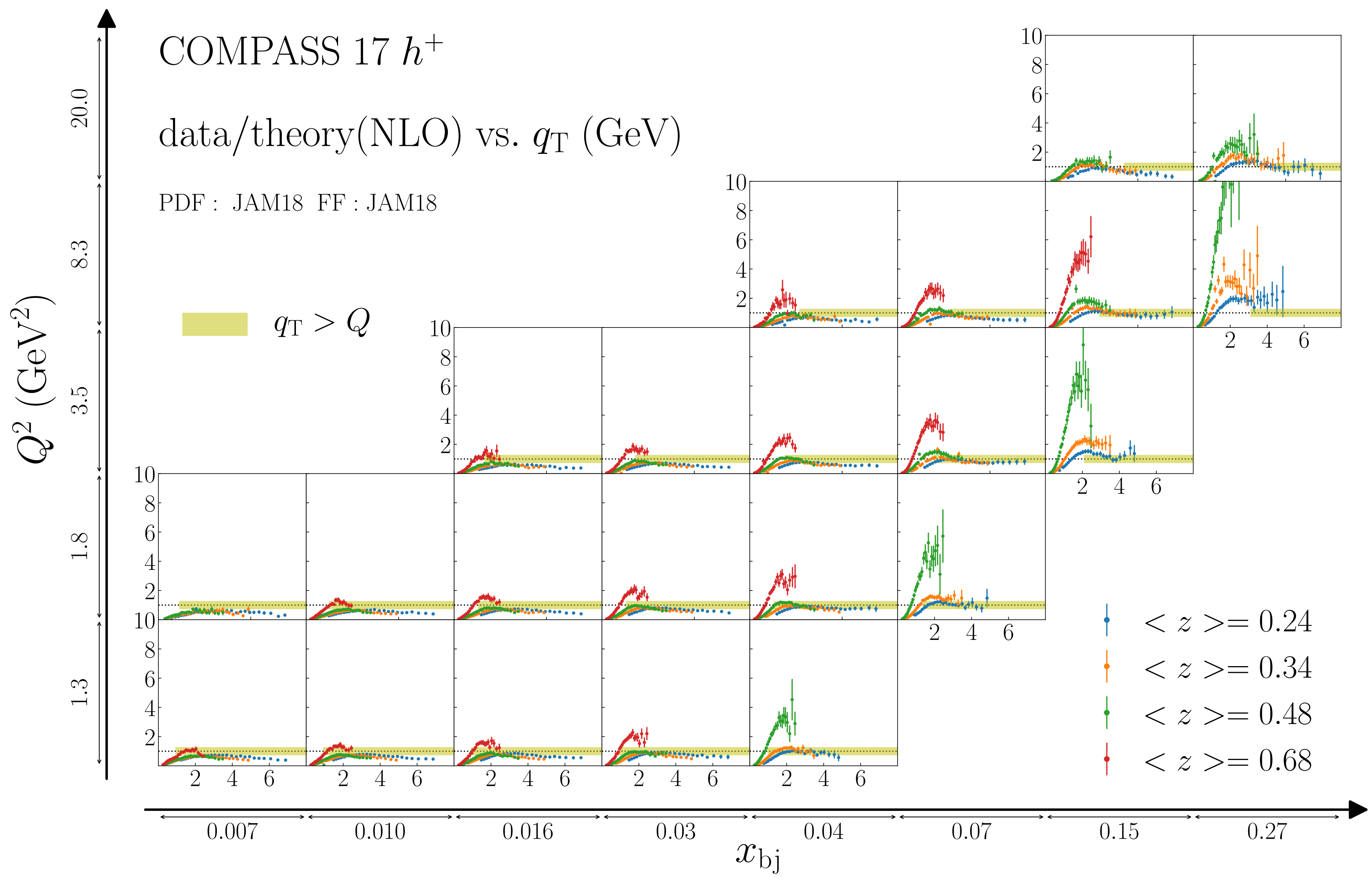
Gonzalez-Hernandez, Rogers, Sato, Wang arXiv:1808.04396



At high q_T, the collinear formalism should be valid, but large discrepancies are observed

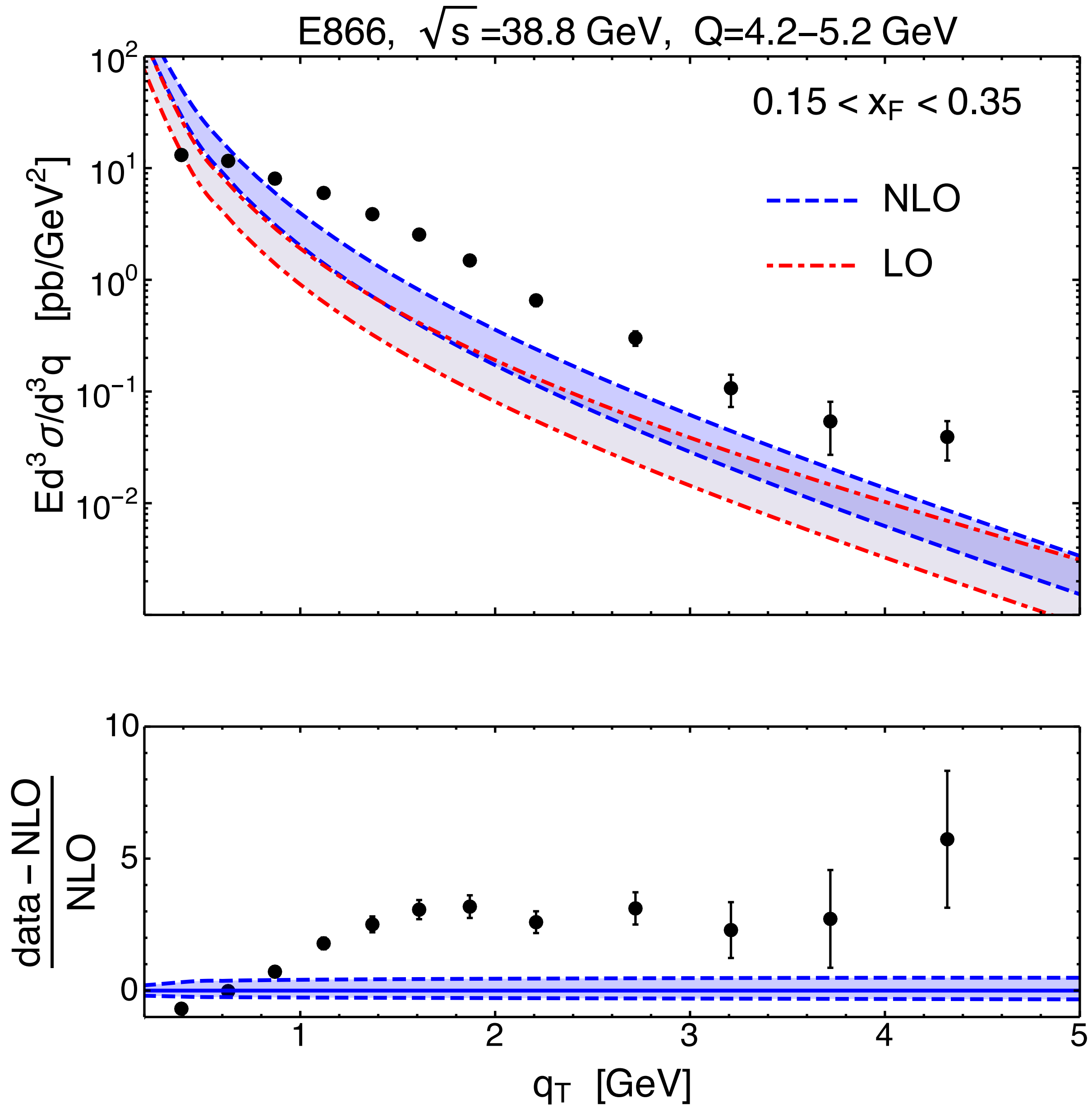
PROBLEMS WITH HIGH TRANSVERSE MOMENTUM

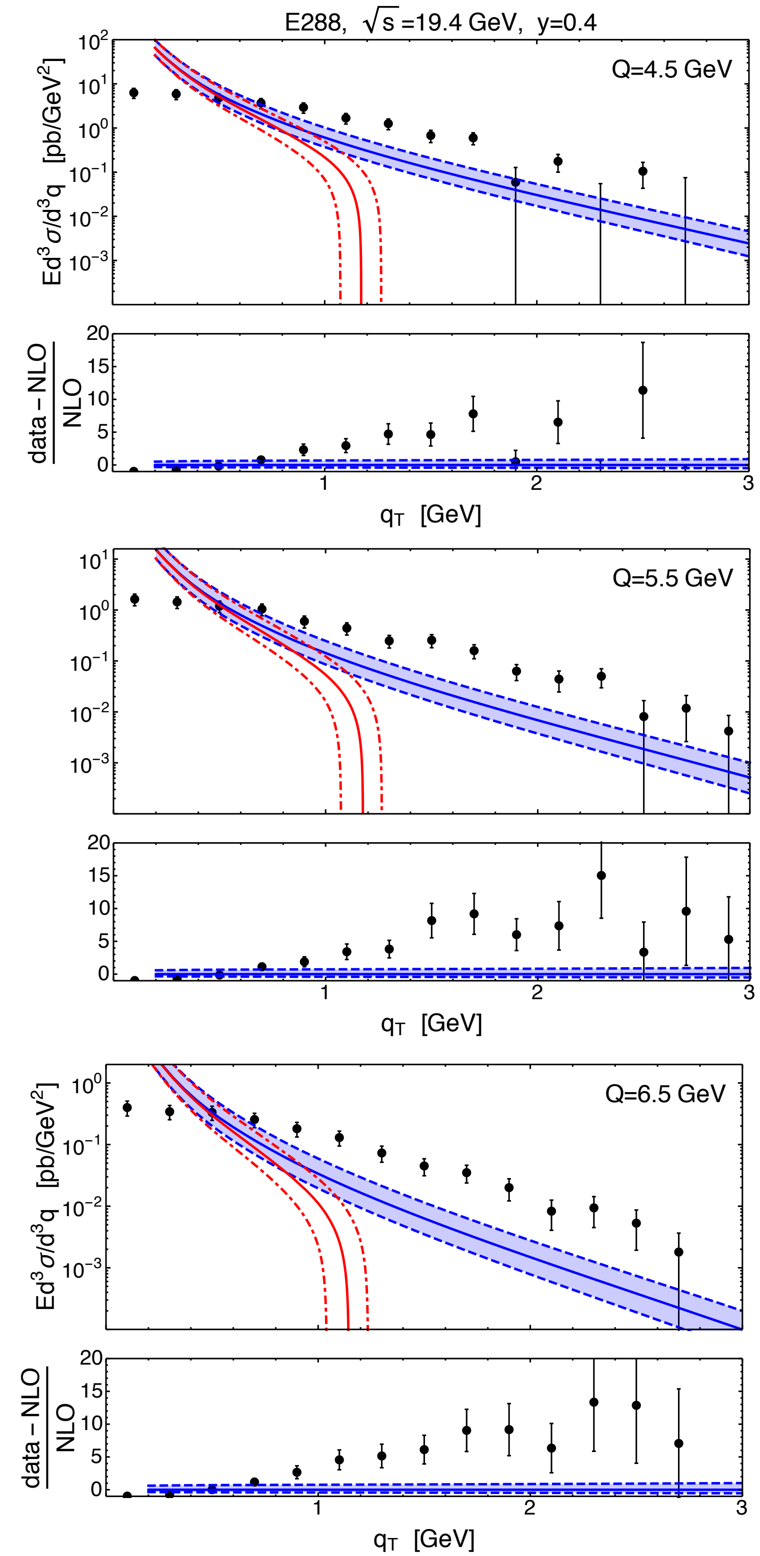
Gonzalez-Hernandez, Rogers, Sato, Wang arXiv:1808.04396



The discrepancies could be largely resolved by including NLO and modifying the gluon collinear fragmentation function

However, large discrepancies are found also in low-energy DY scattering data

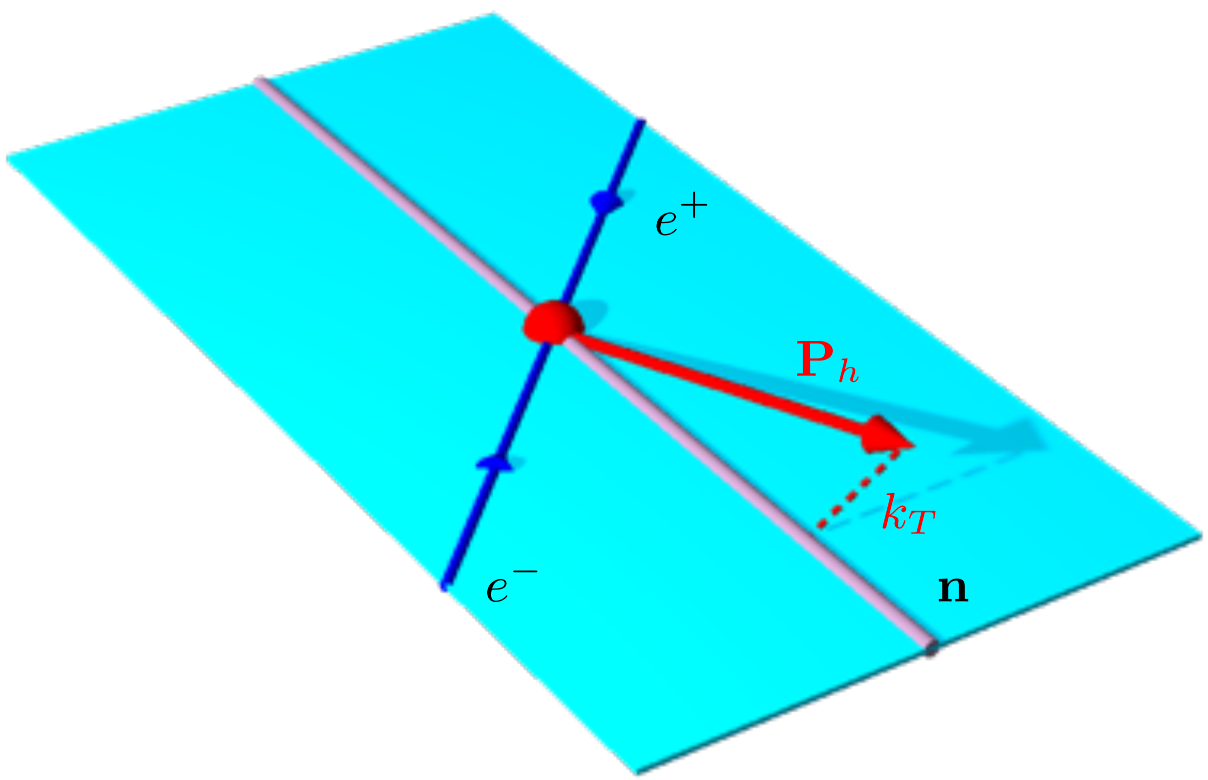


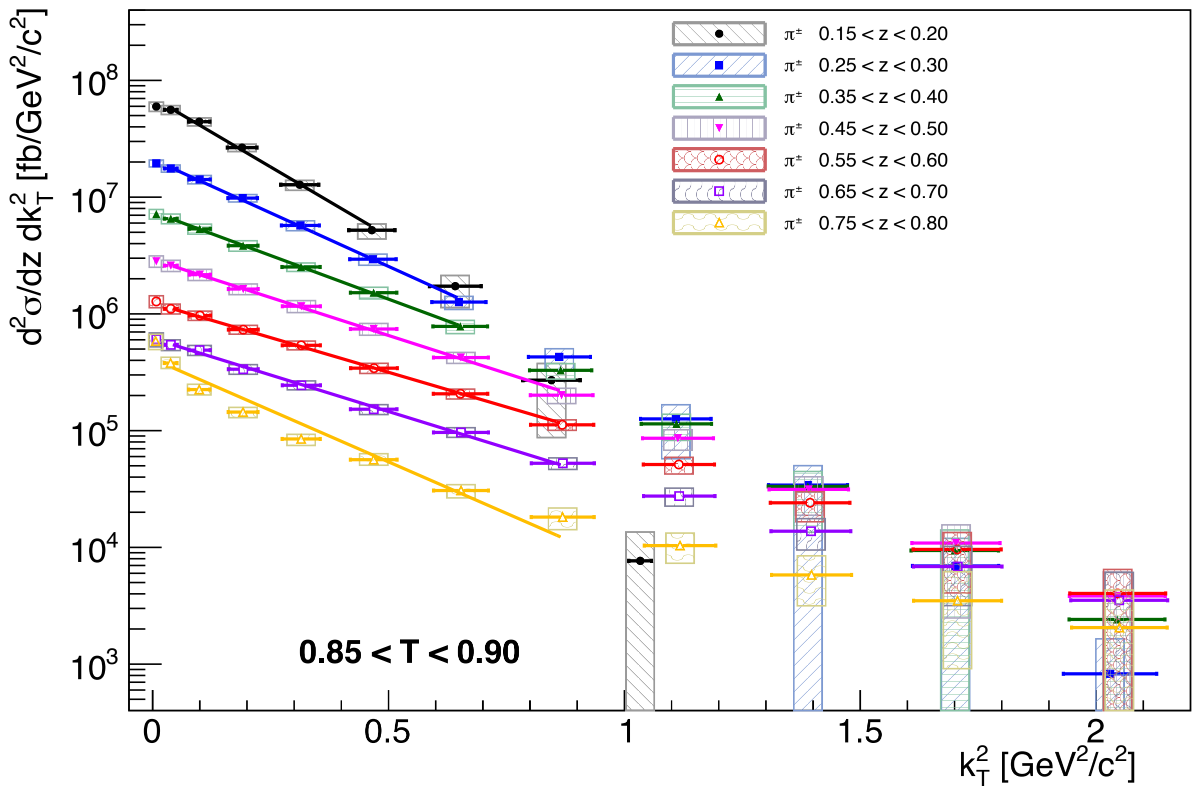


Bacchetta, Bozzi, Lambertsen, Piacenza, Steinglechner, Vogelsang arXiv:1901.06916

TRANSVERSE MOMENTUM IN FRAGMENTATION FUNCTIONS

Seidl et al., arXiv:1807.02101





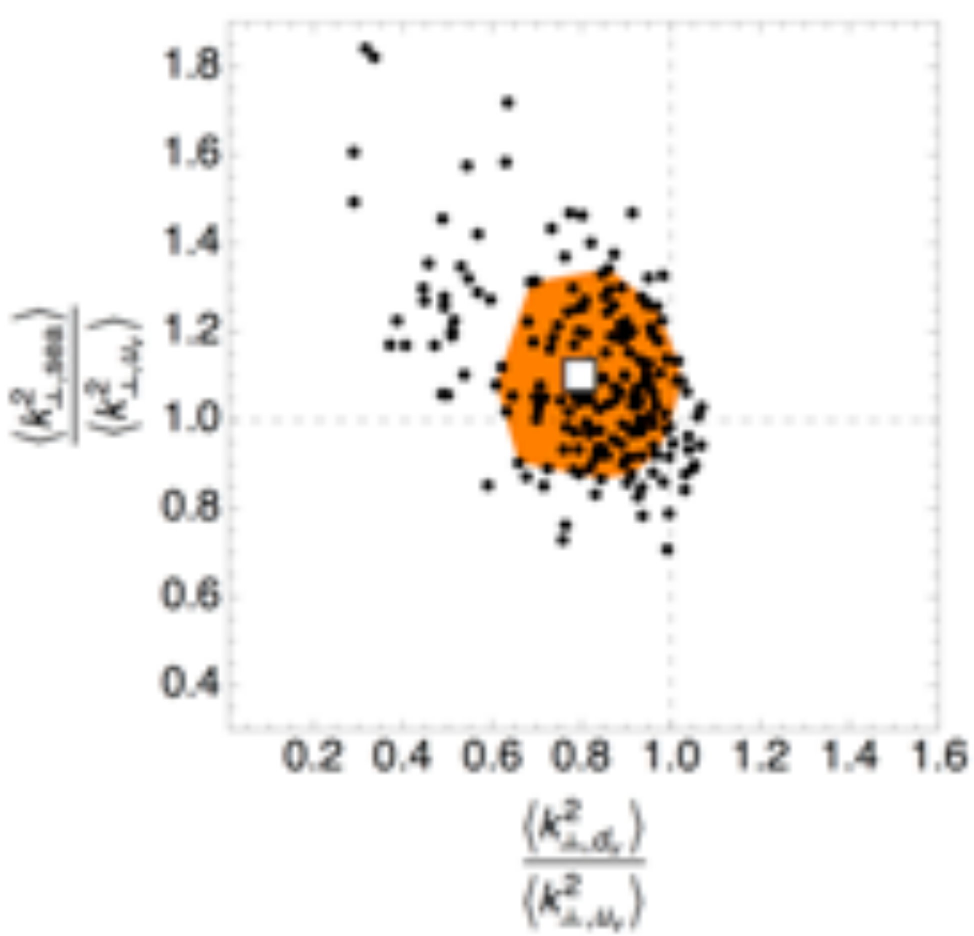
First direct measurement of TMD effects in fragmentation functions

Makes use of thrust axis: the formalism should take it into account

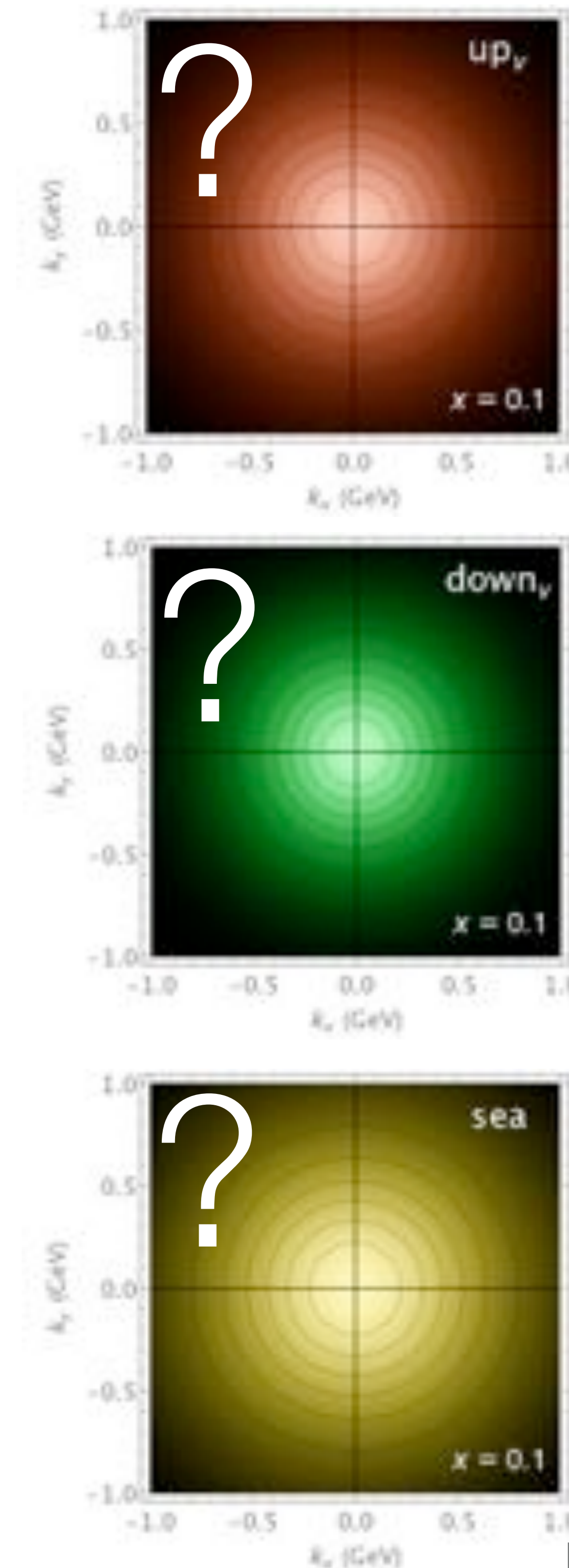
FLAVOR DEPENDENCE OF TMDS

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

Ratio of width of sea /
width of up valence



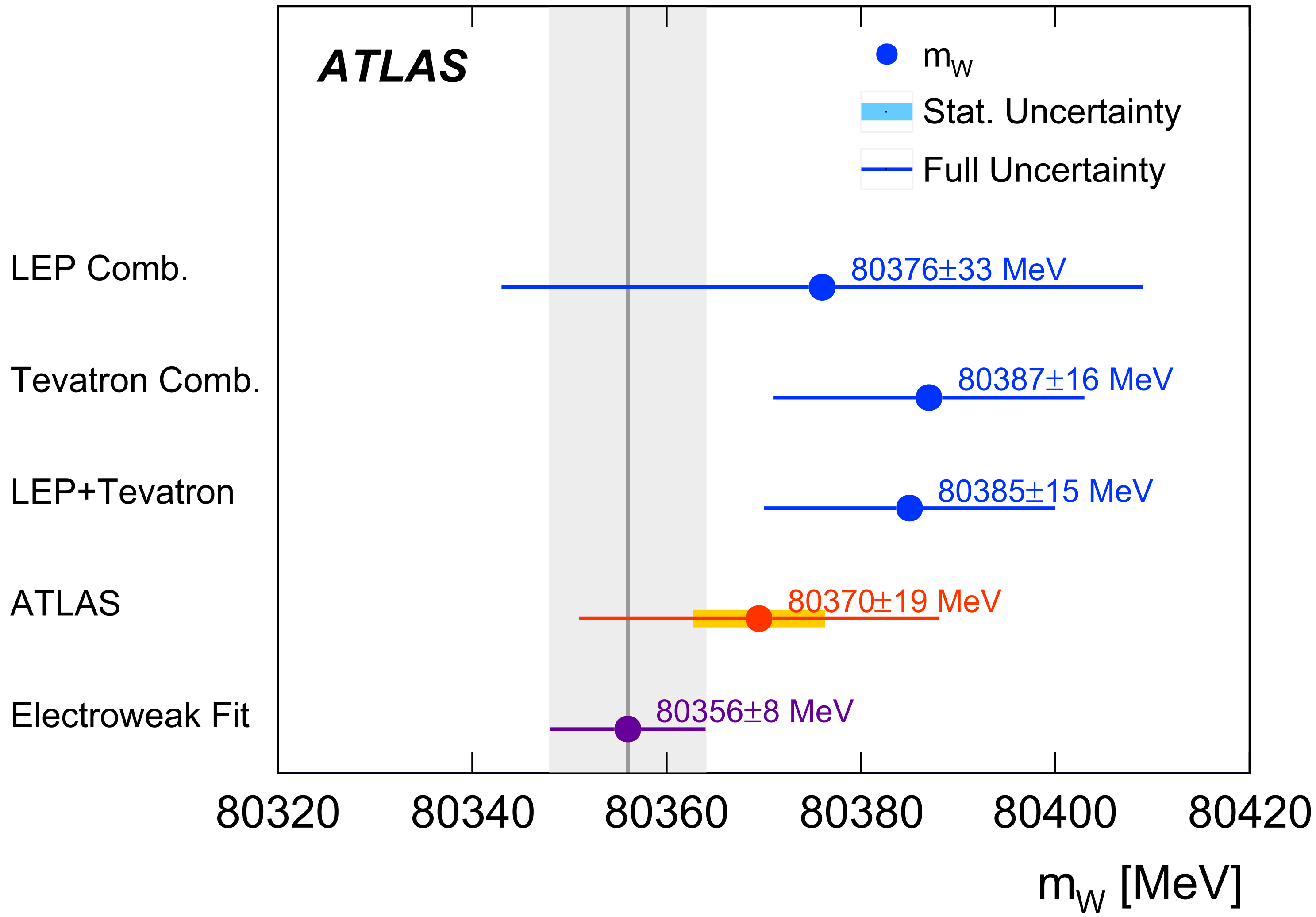
Ratio width of down valence/
width of up valence



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

IMPACT ON W MASS DETERMINATION

ATLAS Collab. arXiv:1701.07240



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

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

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

IMPACT ON W MASS DETERMINATION

Bacchetta, Bozzi, Radici, Ritzmann, Signori, arXiv:1807.02101

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
5	0.42	0.38	0.29	0.57	0.27

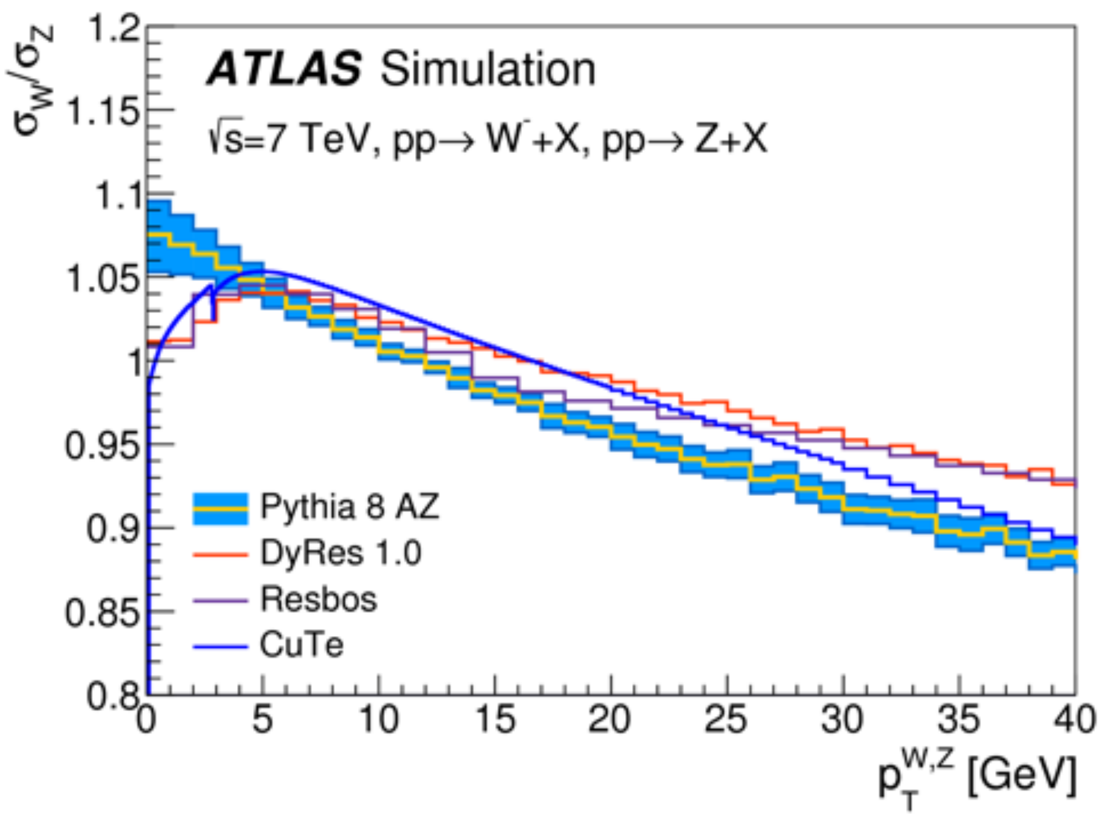
narrow, medium, large
narrow, large, narrow
large, narrow, large
large, medium, narrow
medium, narrow, large

	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

Not taking into account the flavour dependence of TMDs can lead to errors in the determination of the W mass

3D STRUCTURE AND MC GENERATORS

from A. Apyan's talk at LHC EW Precision sub-group workshop
https://indico.cern.ch/event/801961/



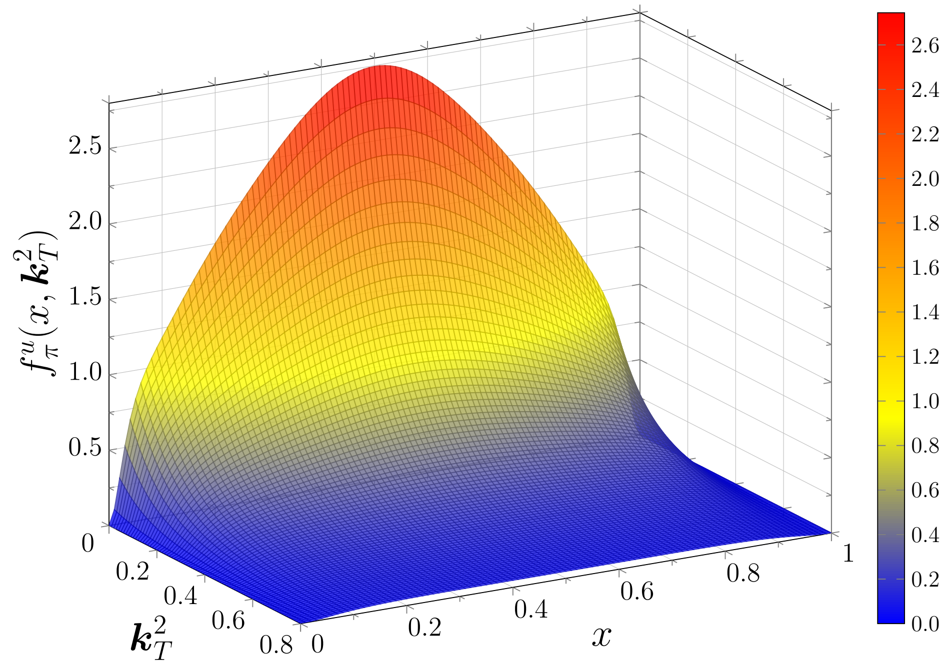
also
ResBos2
Radish
SCETlib
…

Precision measurements require well-tuned MC tools. Important effects at low pT come from nonperturbative TMD components

PION TMDS

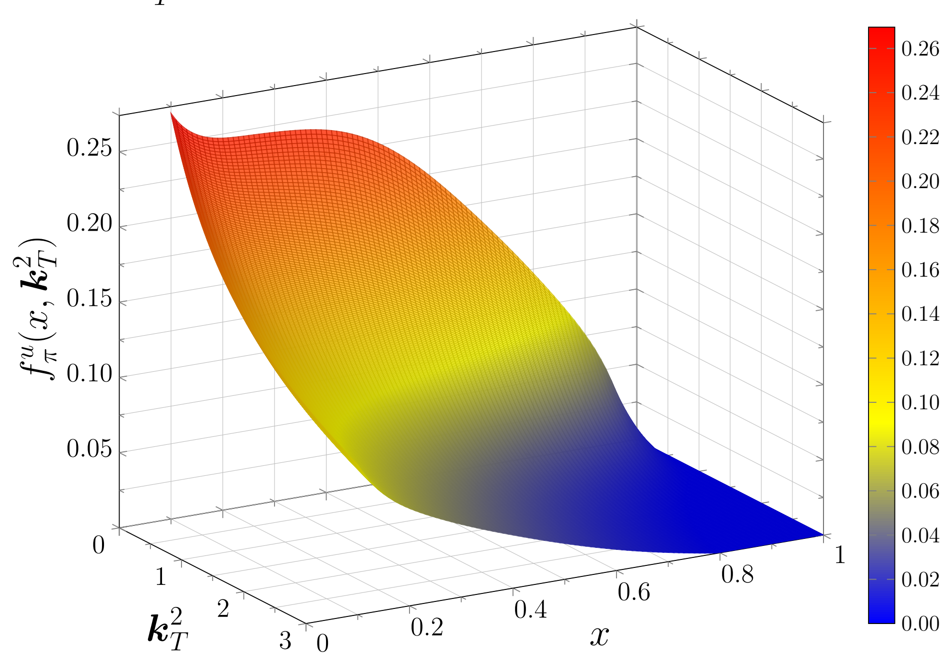
Shi, Cloet, arXiv:1806.04799

calculation of pion TMD
based on Dyson-Schwinger equations



$Q^2 = 0.52\ \mathrm{GeV}^2$

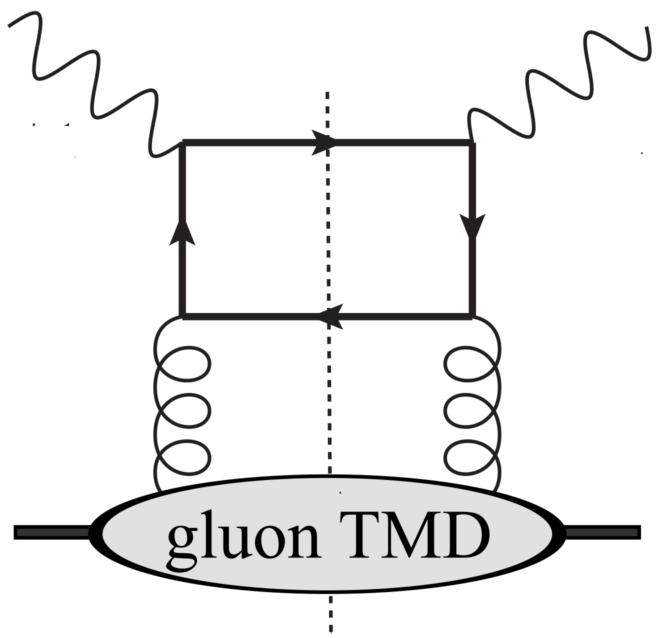
after TMD evolution



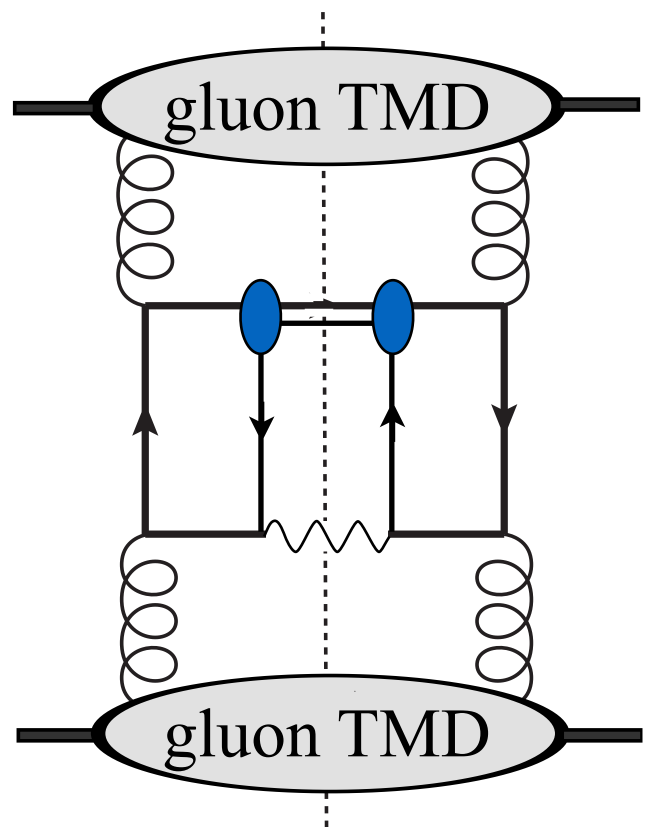
$Q^2 = 36\ \mathrm{GeV}^2$

GLUON TMDS

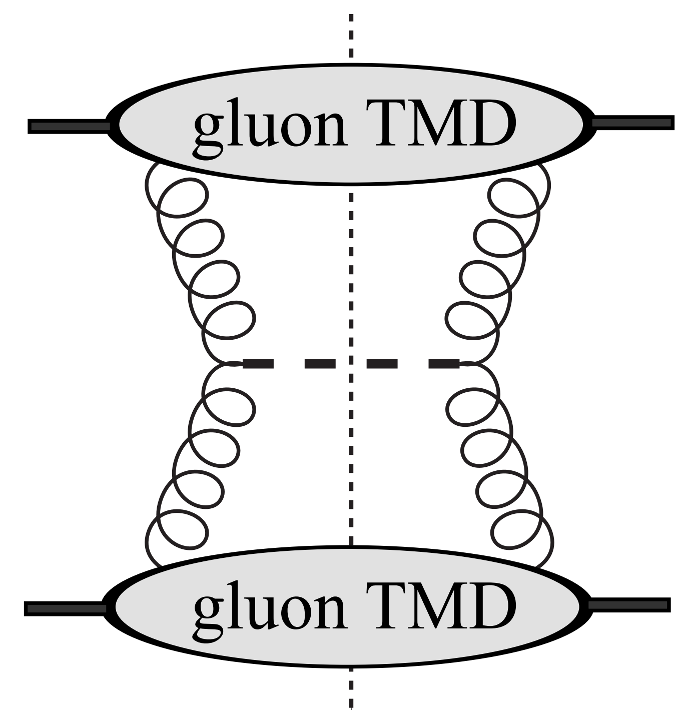
$e\,p \rightarrow e$ jet jet X



$p\,p \rightarrow J/\psi\,\gamma\,X$



$p\,p \rightarrow \eta_c\,X$

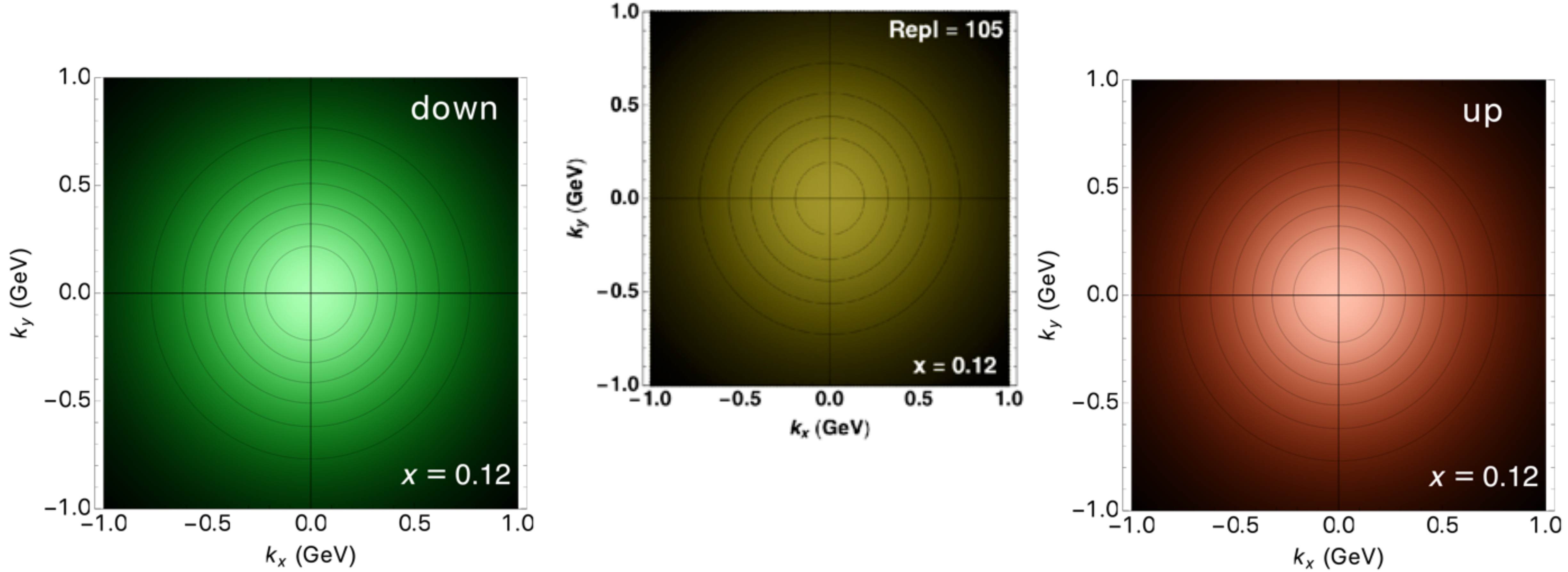


Only explorations so far

Boer, den Dunnen, Pisano, Schlegel, Vogelsang, PRL108 (12)
den Dunnen, Lansberg, Pisano, Schlegel, PRL 112 (14)
Mukherjee, Rajesh, PRD 93 (16)

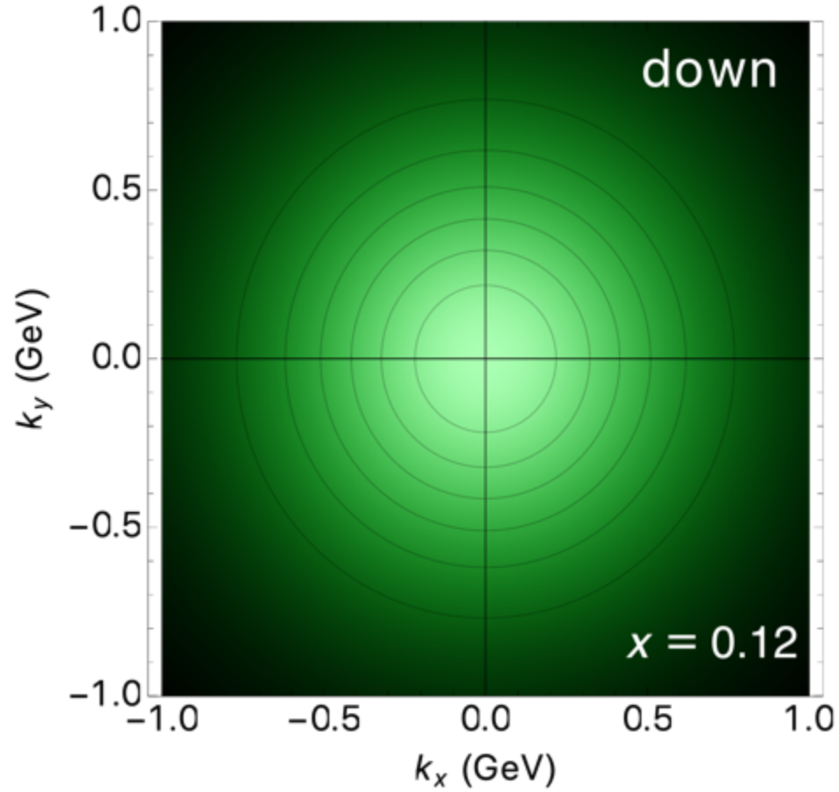
3D + SPIN

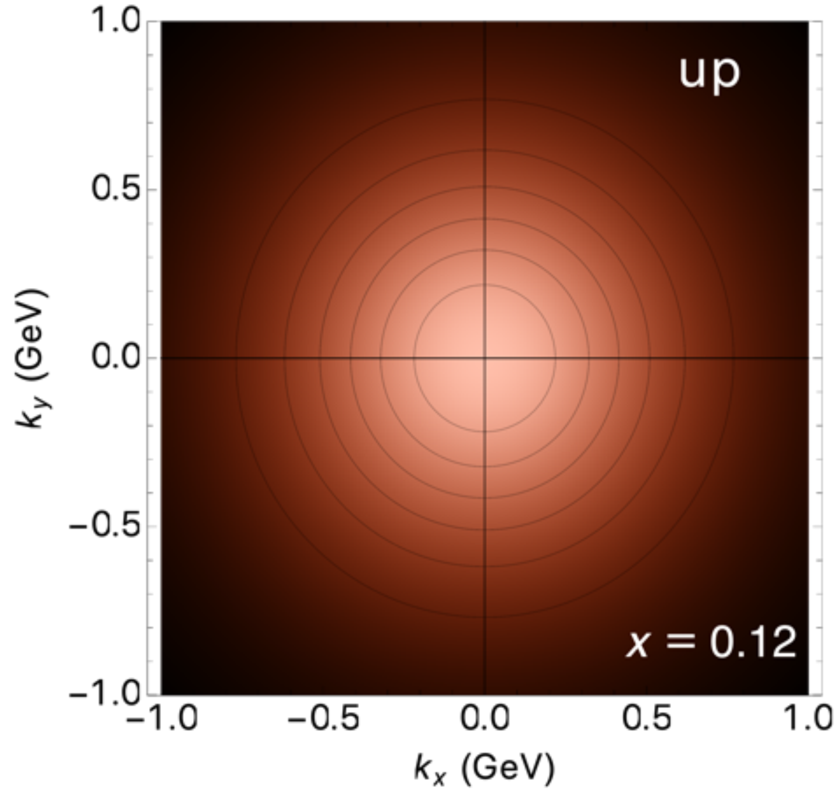
THE PROTON IN 3D (IN MOMENTUM SPACE)



At the moment, the unpolarized analysis is done with no flavour dependence

THE PROTON IN 3D (IN MOMENTUM SPACE)

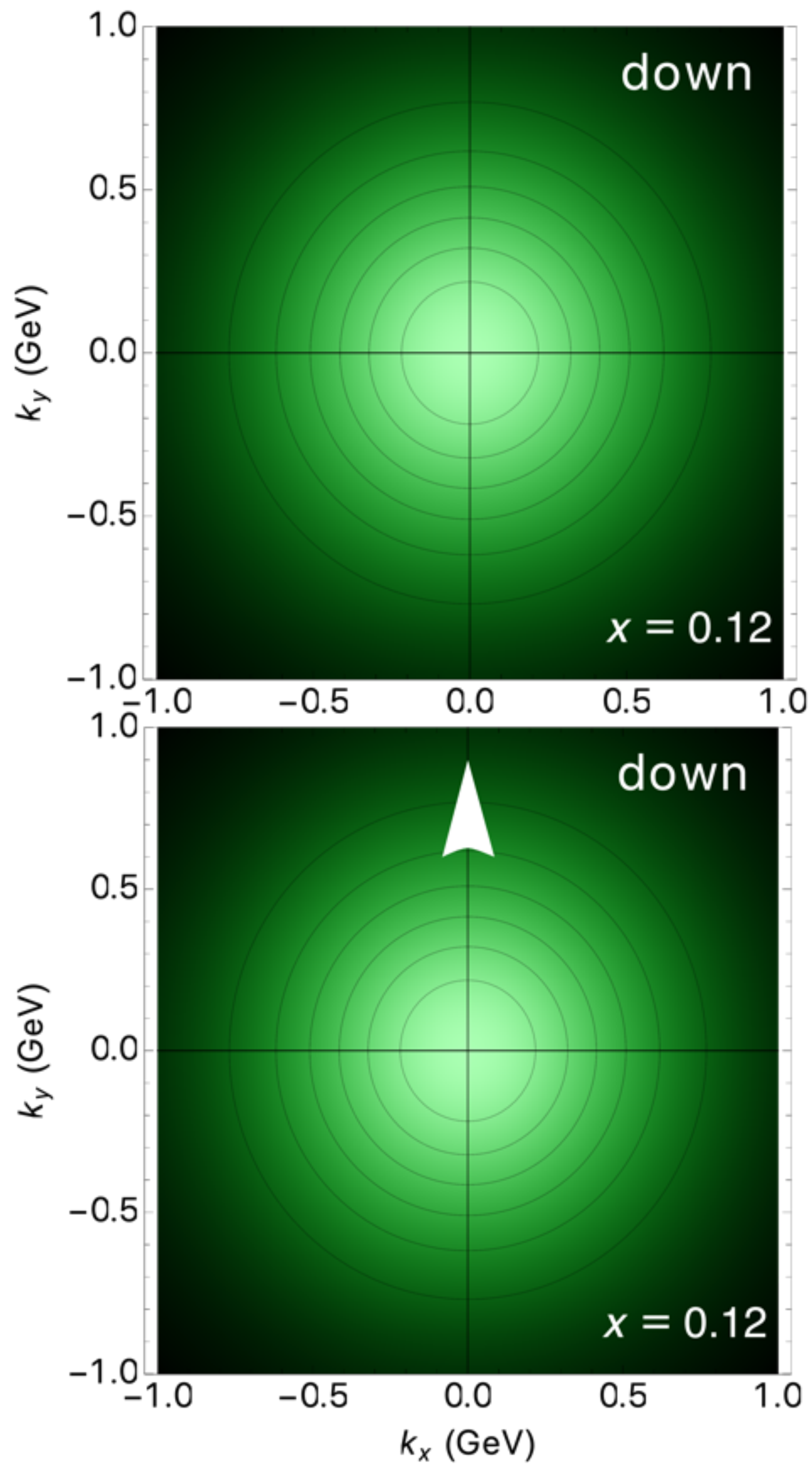




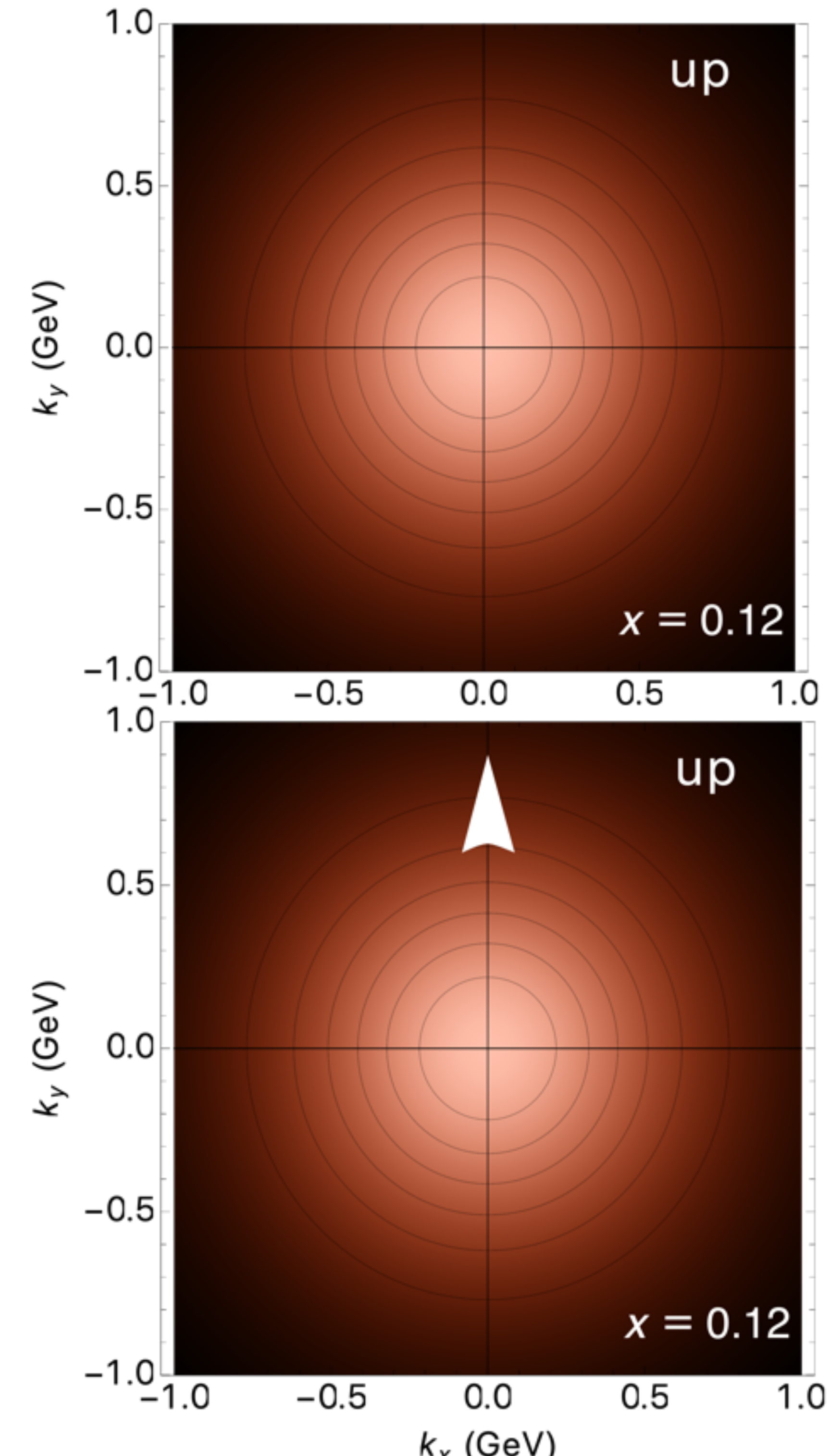
This is an image of the quark structure averaged over spin.

What happens if we include spin?

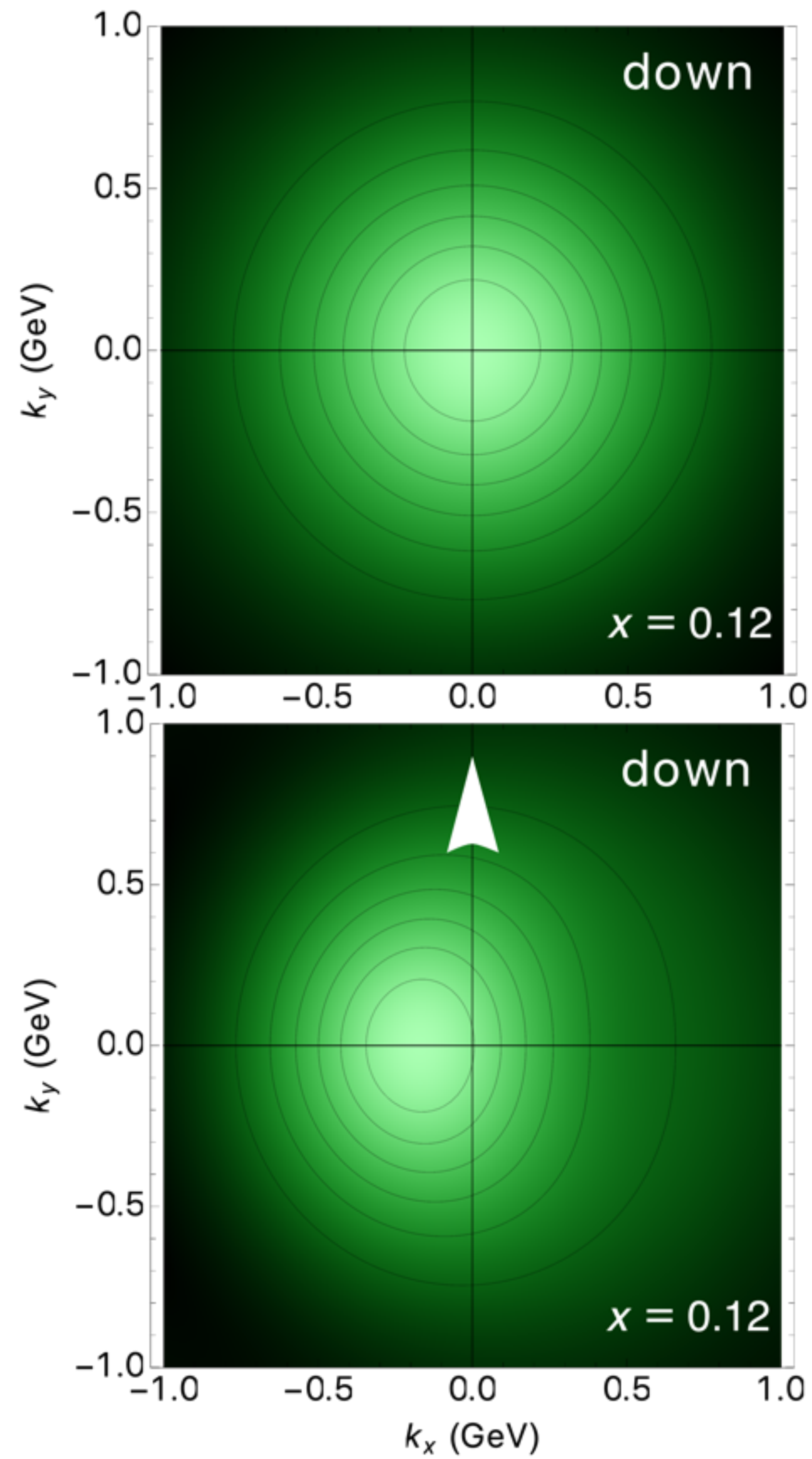
THE PROTON IN 3D (IN MOMENTUM SPACE)



without
orbital angular momentum



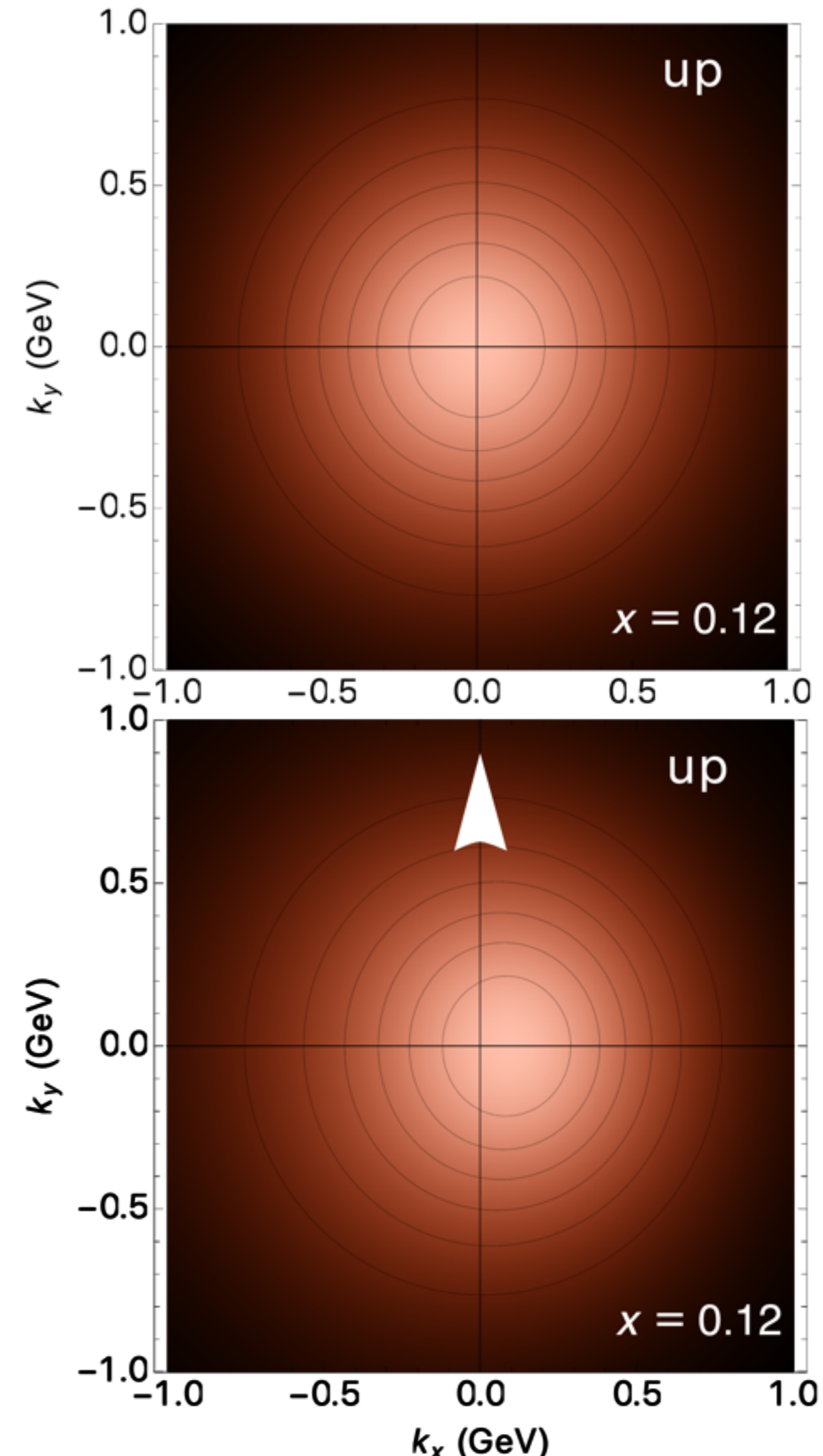
THE PROTON IN 3D (IN MOMENTUM SPACE)



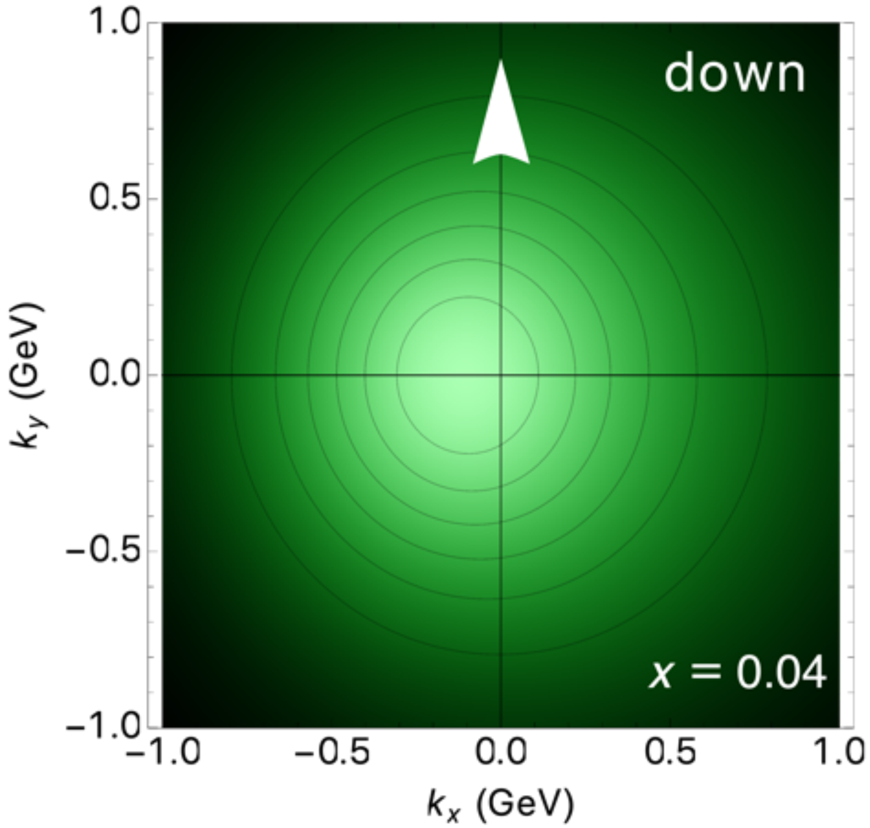
with

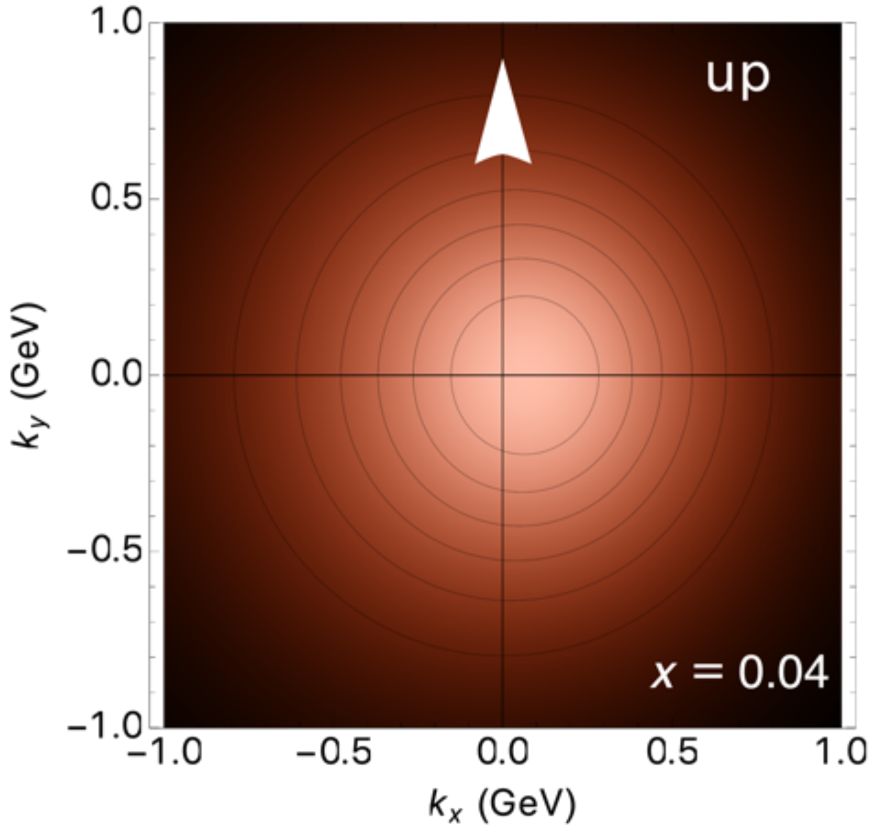
orbital angular momentum

"Sivers effect"



“REAL” 3D IMAGES IN MOMENTUM SPACE

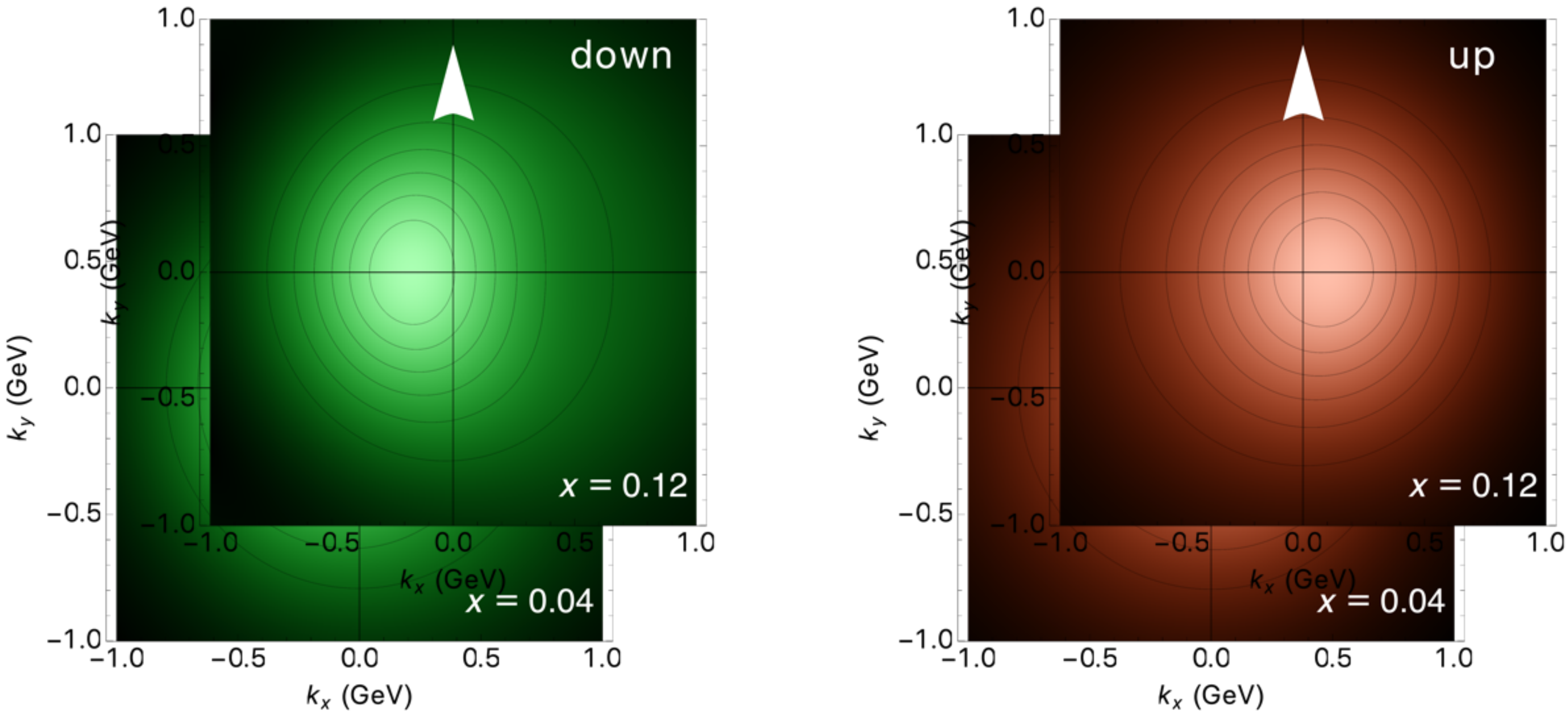




These are images entirely based on data (polarized and unpolarized)

Bacchetta, Delcarro, Pisano, Radici, in preparation

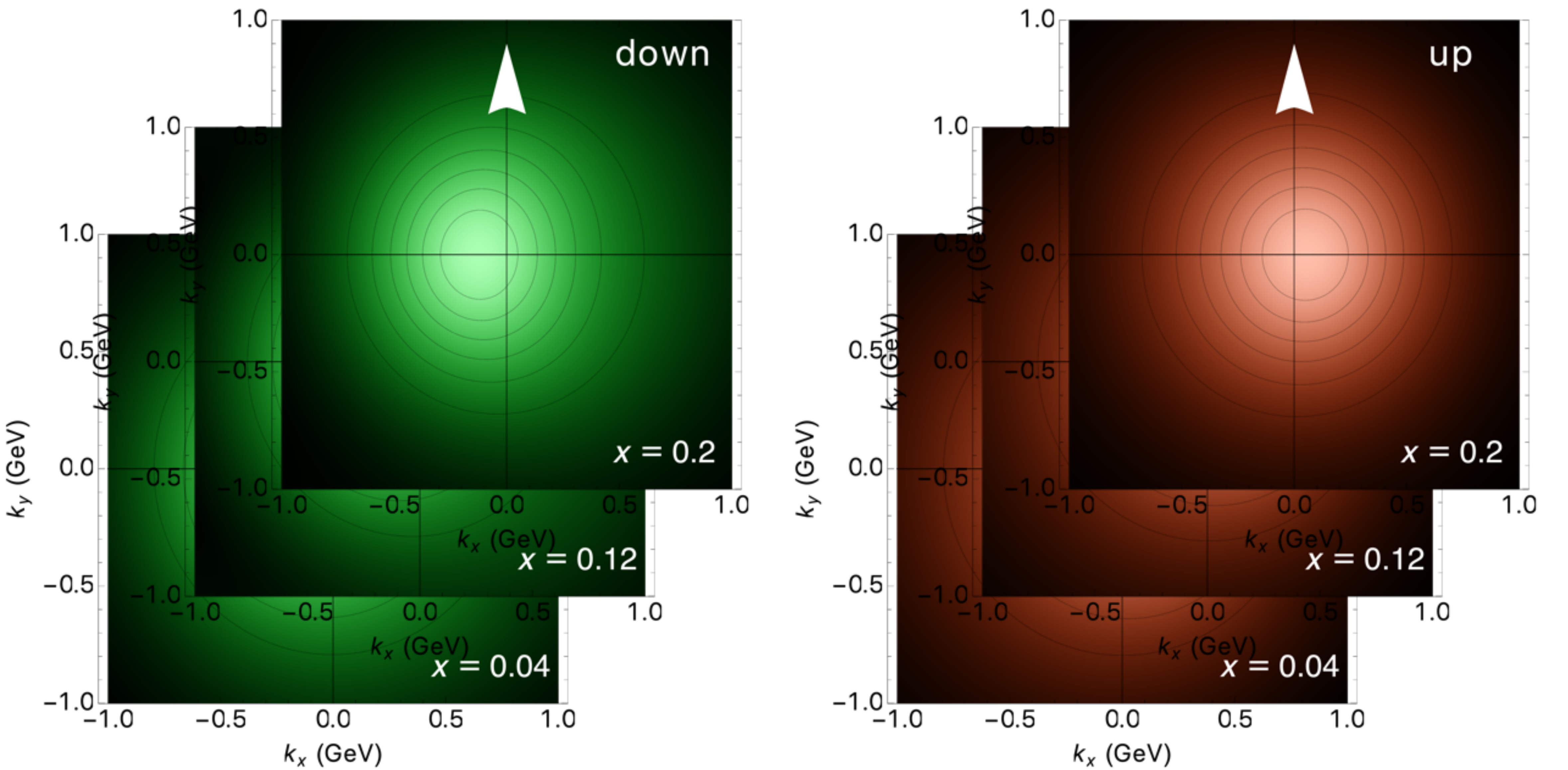
"REAL" 3D IMAGES IN MOMENTUM SPACE



These are images entirely based on data (polarized and unpolarized)

Bacchetta, Delcarro, Pisano, Radici, in preparation

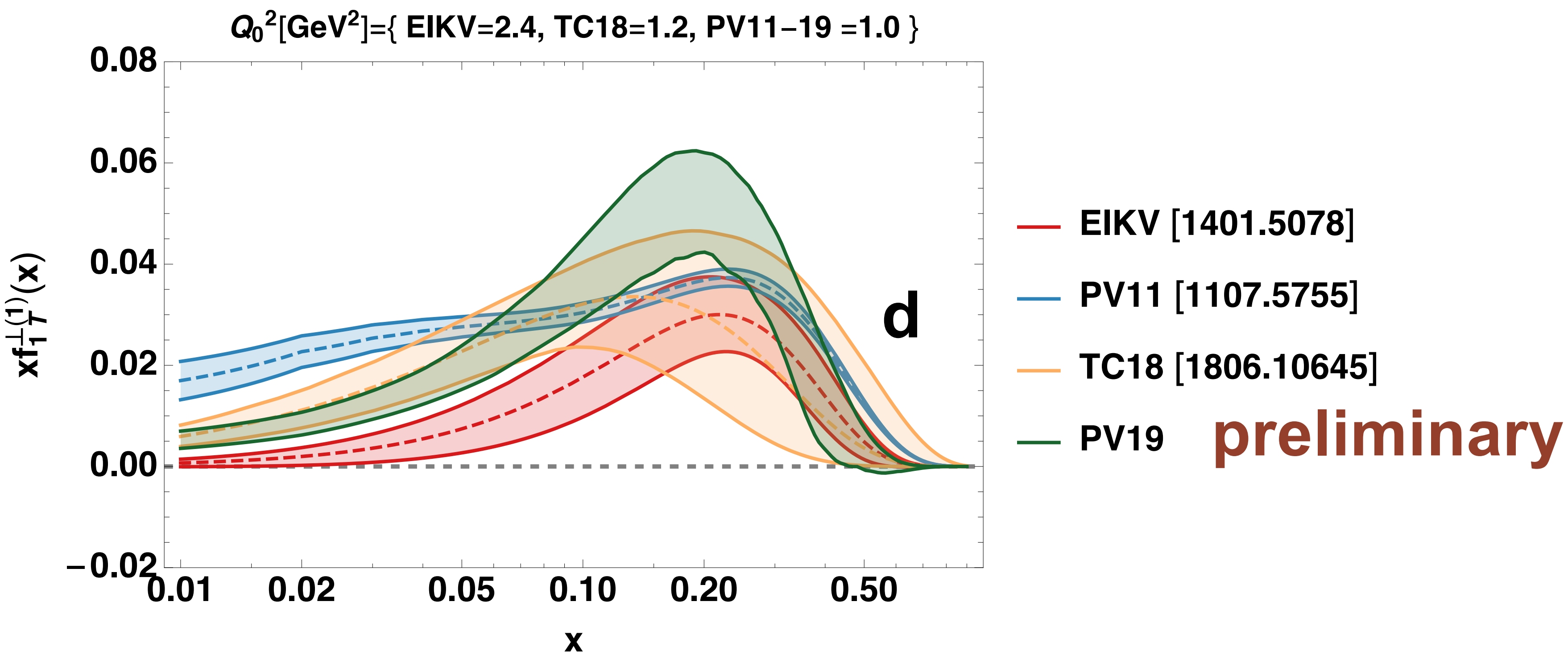
"REAL" 3D IMAGES IN MOMENTUM SPACE

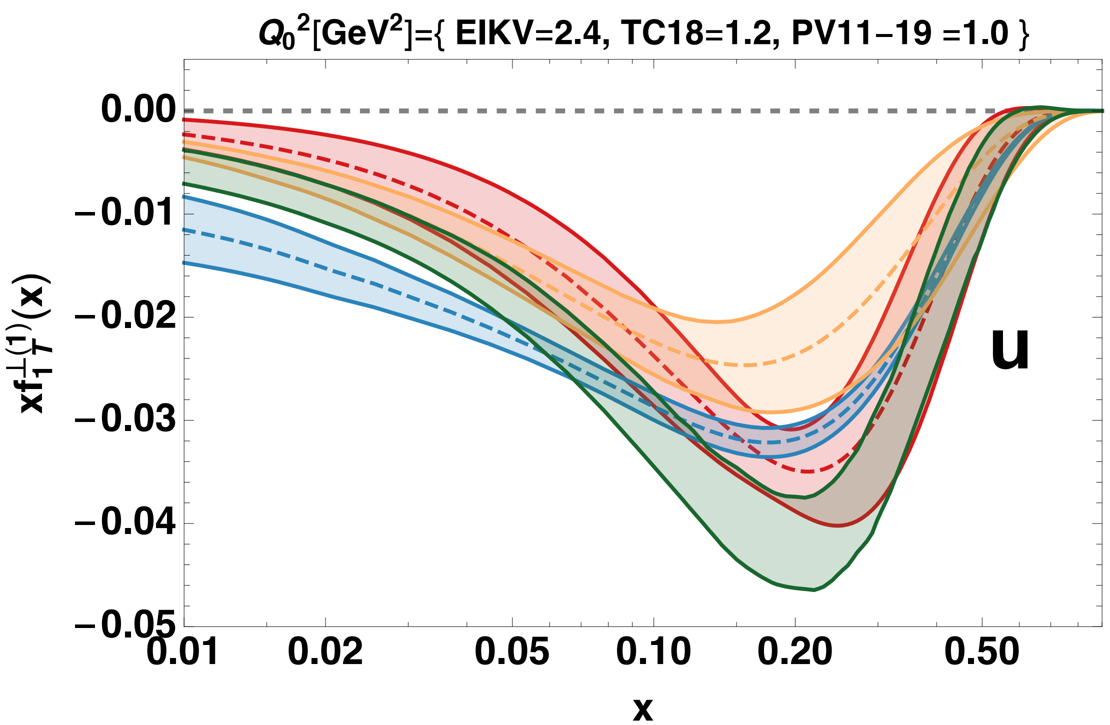


These are images entirely based on data (polarized and unpolarized)

Bacchetta, Delcarro, Pisano, Radici, in preparation

SIVERS FUNCTION EXTRACTIONS



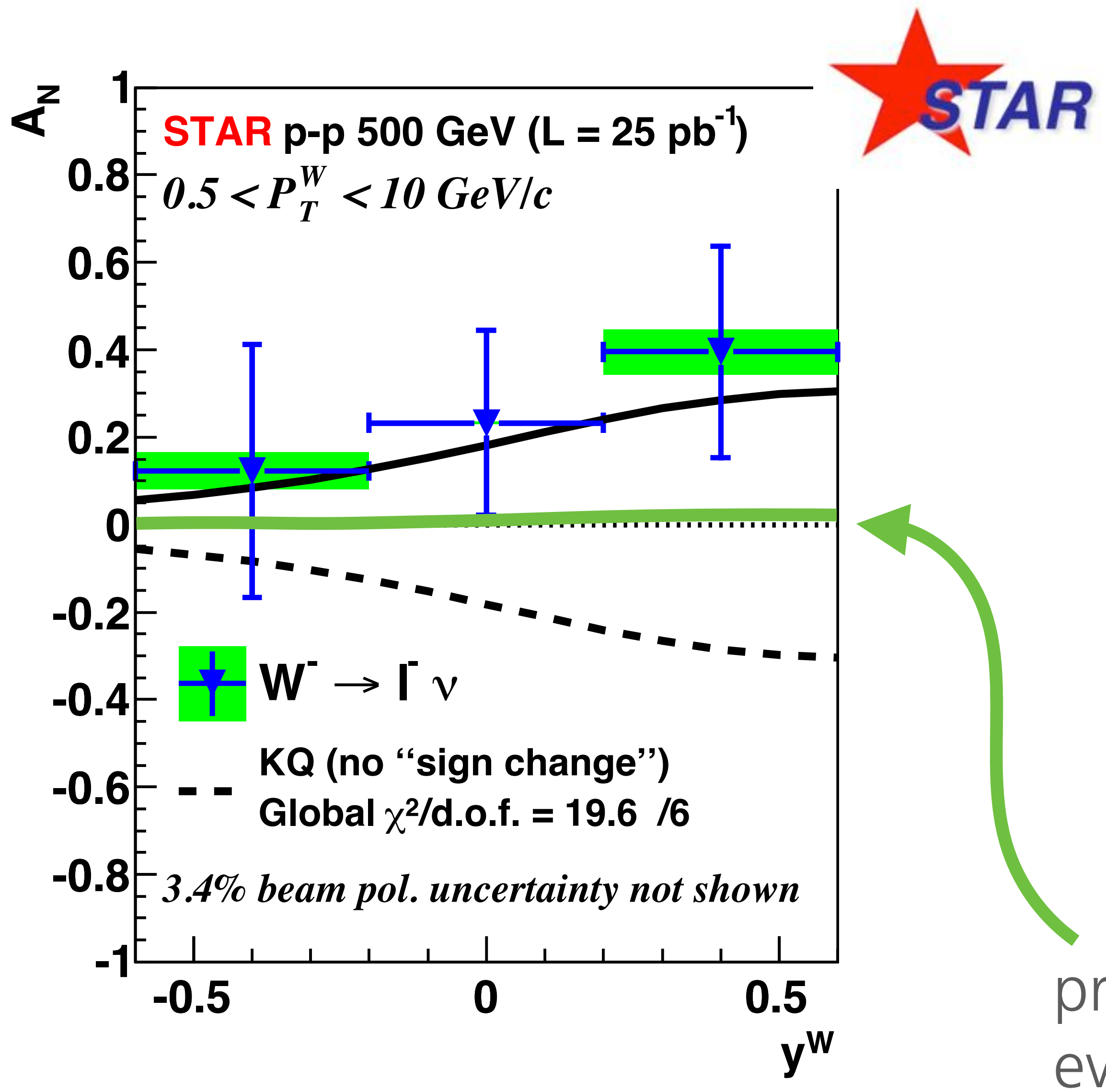


see talks by Filippo Delcarro and John Terry

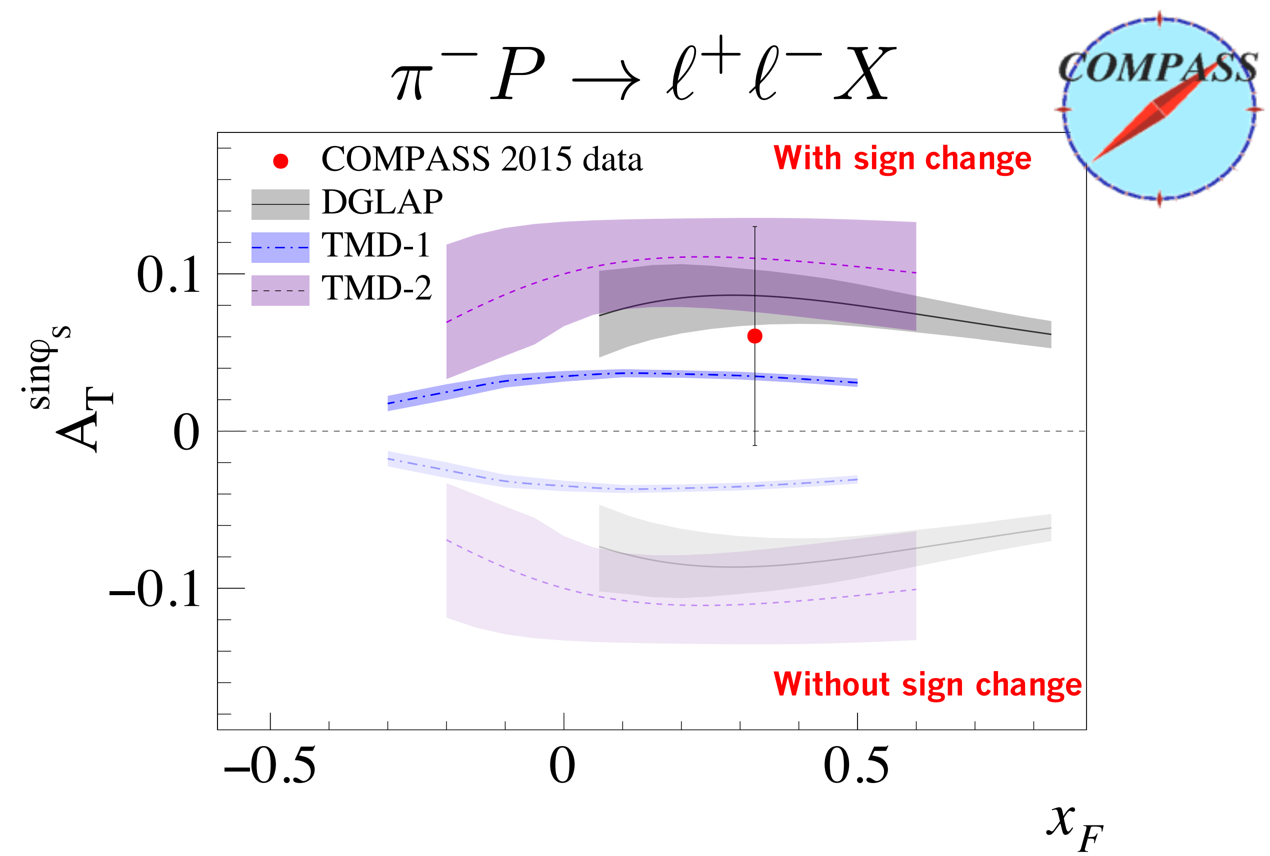
SIVERS FUNCTION SIGN CHANGE

Sivers function SIDIS = – Sivers function Drell-Yan

Collins, PLB 536 (02)



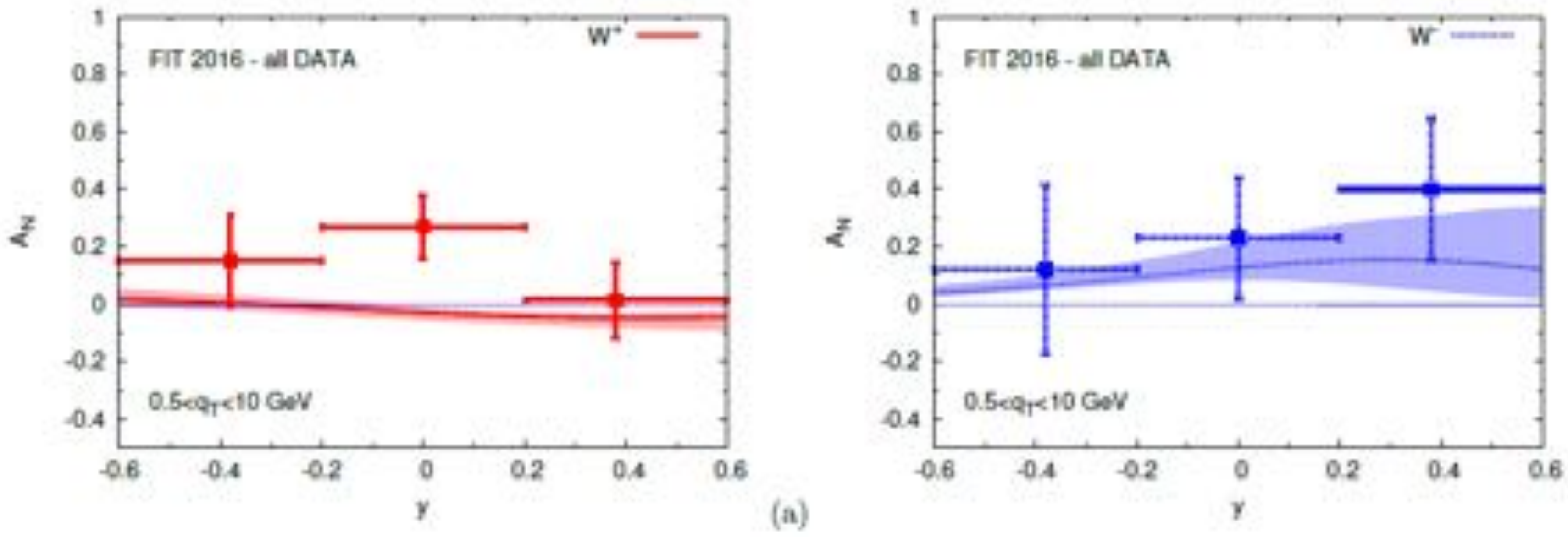
STAR Collab. arXiv:1511.06003

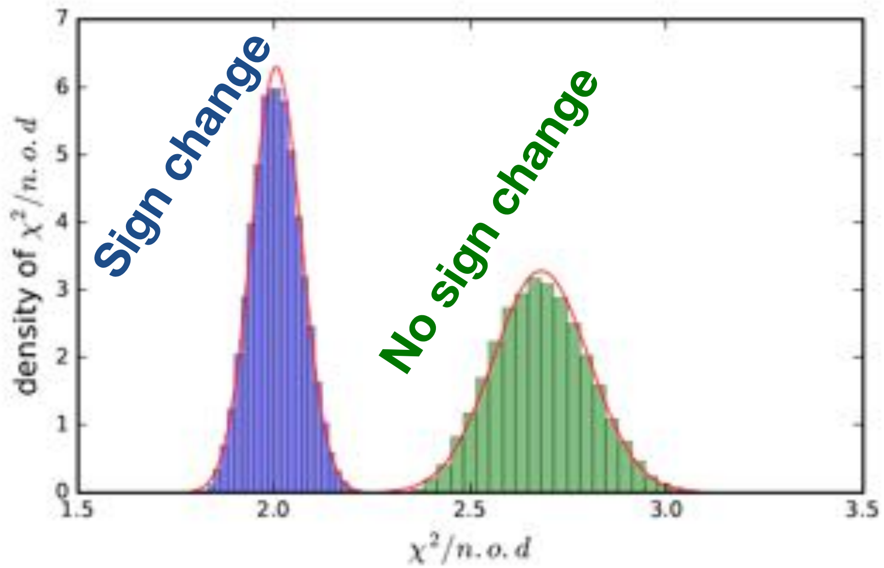


prediction with TMD evolution equations

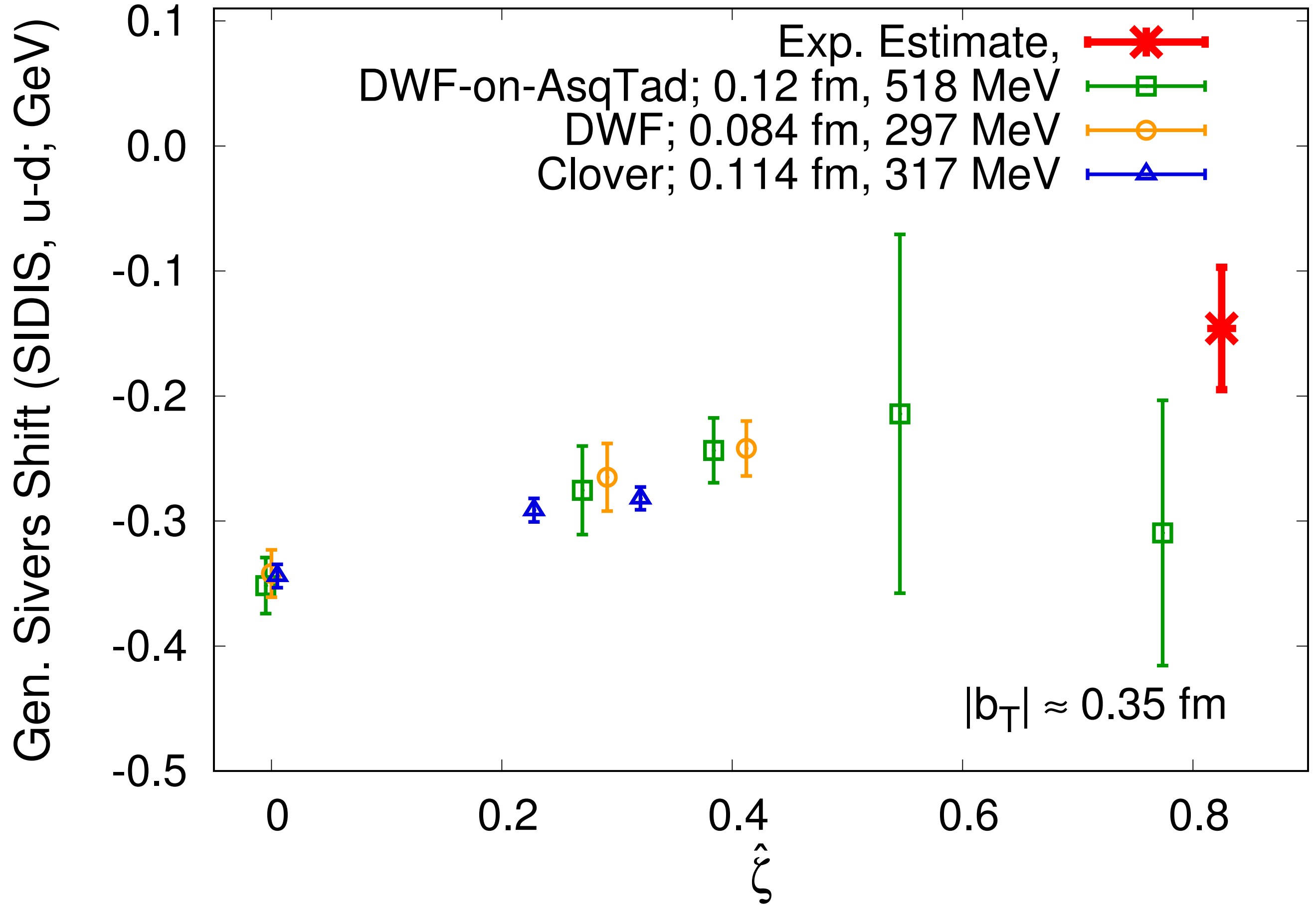
SIVERS FUNCTION SIGN CHANGE

Anselmino, Boglione, D'Alesio, Murgia, Prokudin JHEP 1704 (2017) 046





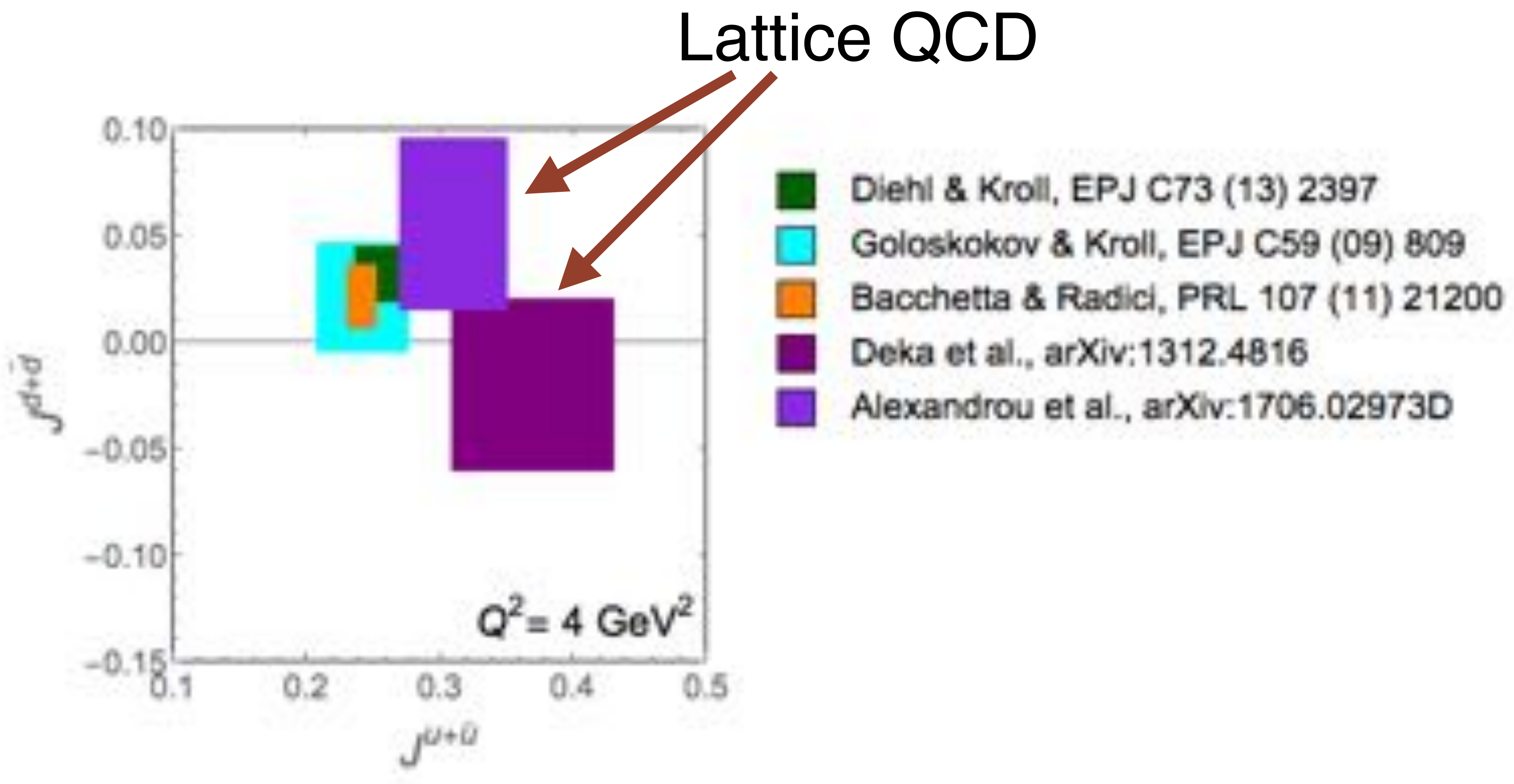
SIVERS SHIFT IN LATTICE QCD

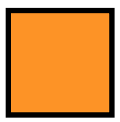


Yoon et al., arXiv:1706.03406

Pioneering lattice studies are in agreement with phenomenology

CONNECTION WITH TOTAL ANGULAR MOMENTUM

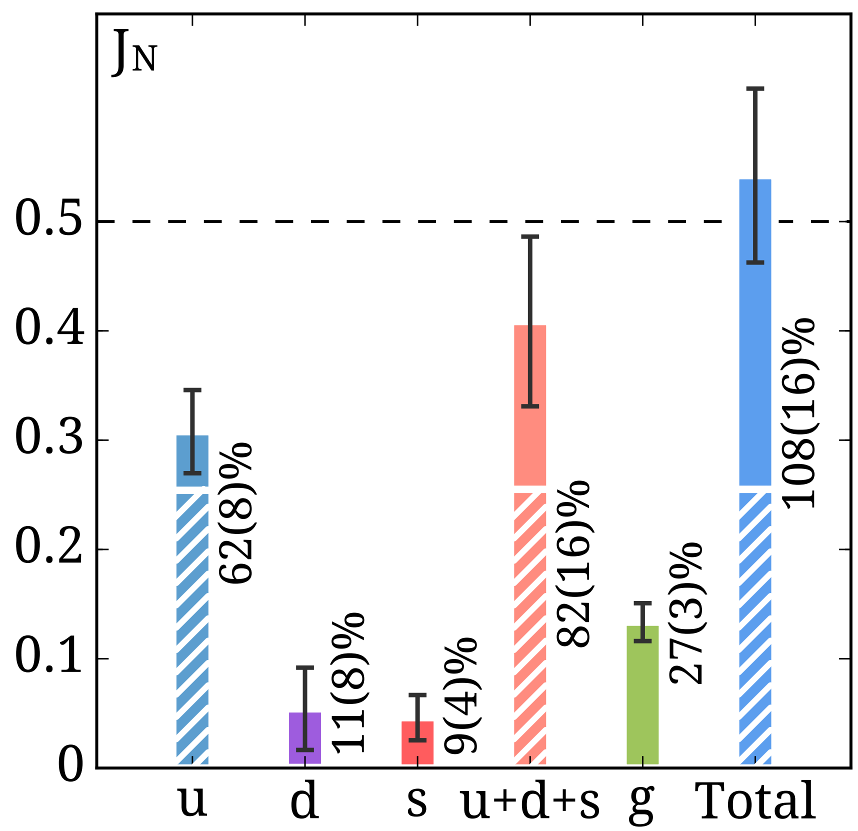




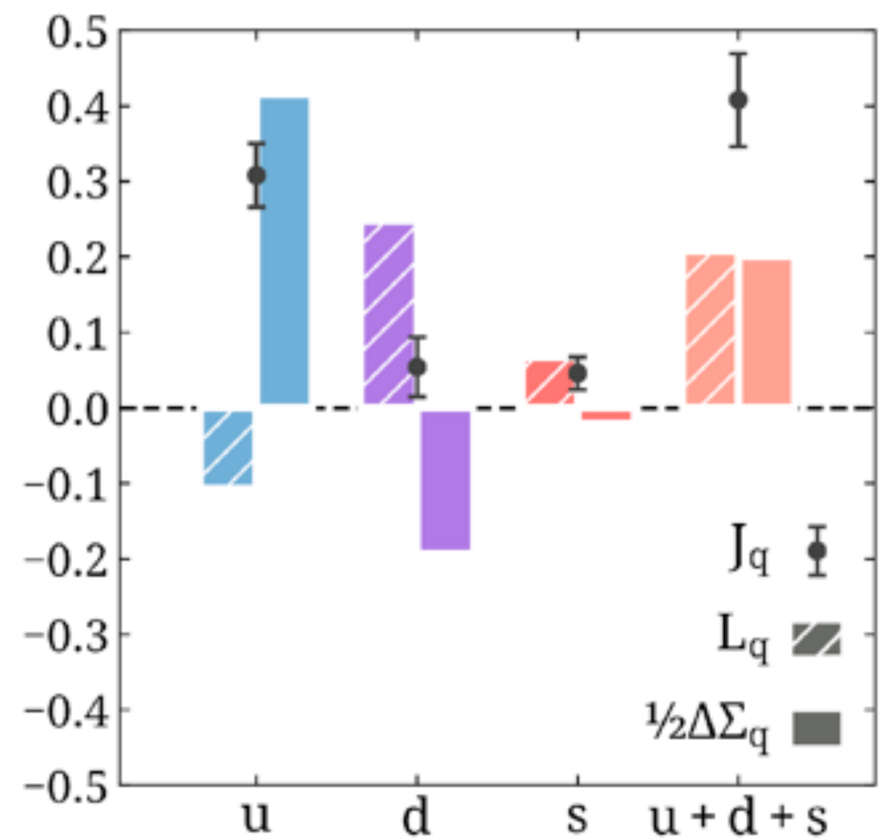
Estimate of angular momentum based on model assumptions + Sivers fit

PROTON SPIN BUDGET ACCORDING TO LATTICE QCD

C. Alexandrou et al, arXiv:1706.02973



Total angular momentum (quarks+antiquarks)

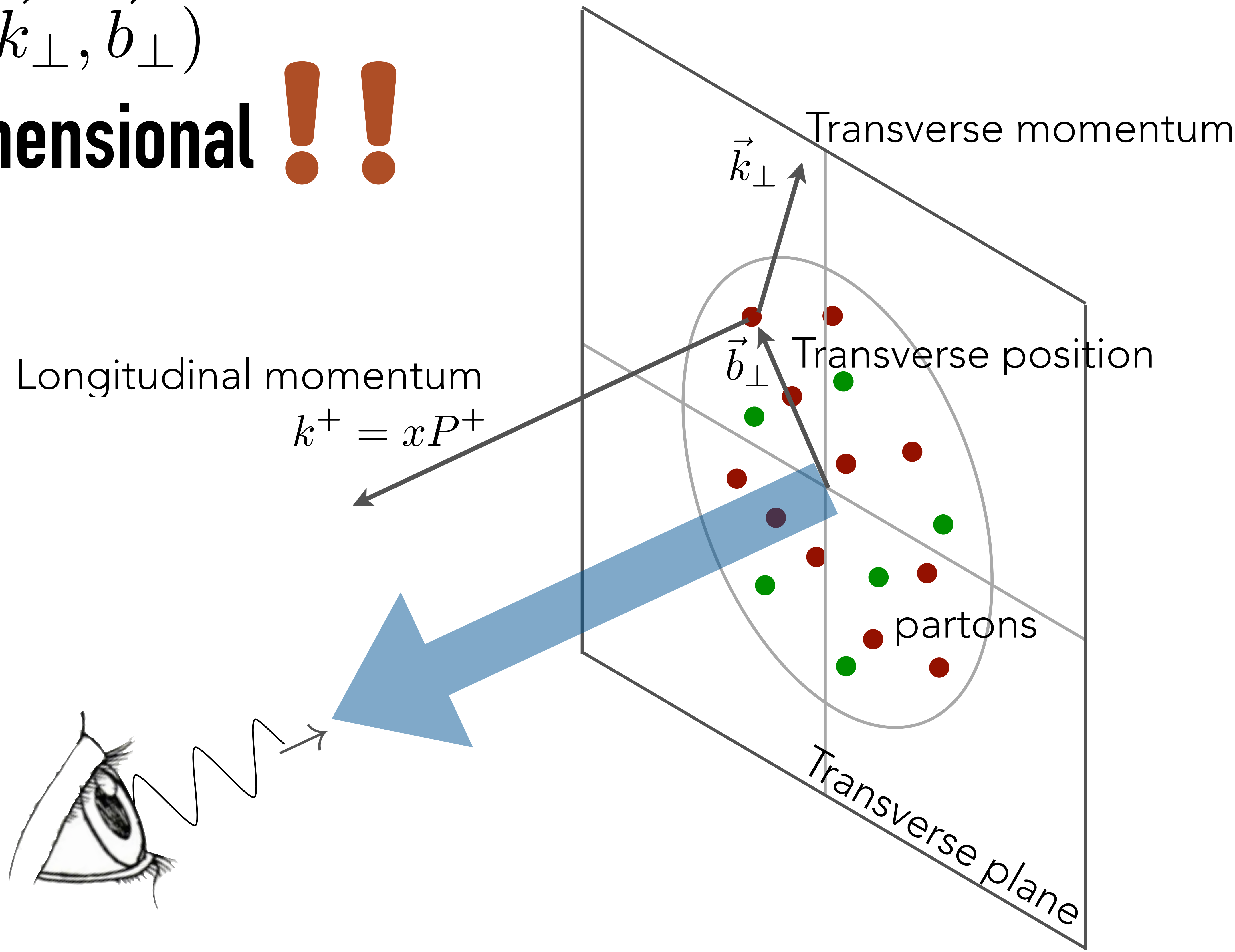


Separate OAM and spin (quarks+antiquarks)

Wigner distributions

$$\rho(x, \vec{k}_\perp, \vec{b}_\perp)$$

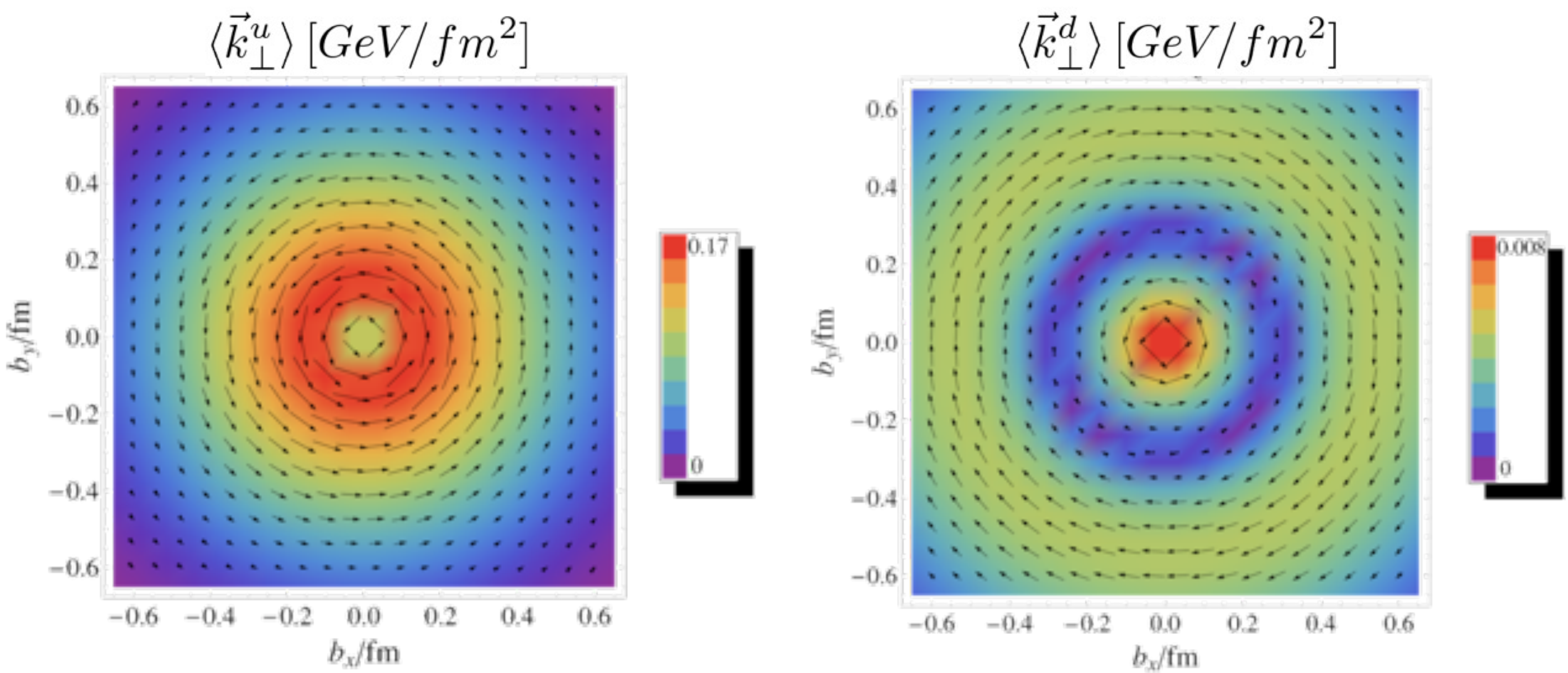
5 dimensional ‼



GENERALIZED TMDS AND WIGNER DISTRIBUTIONS

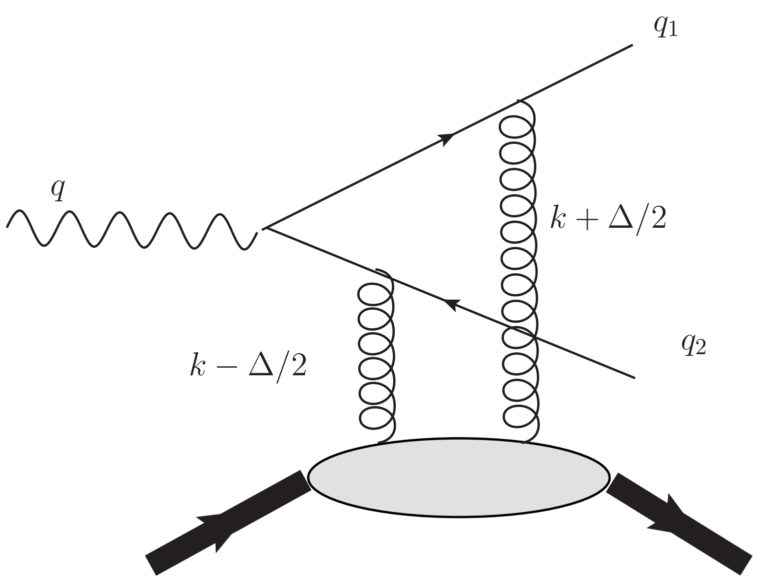
Only way to provide direct access to partonic orbital angular momentum

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



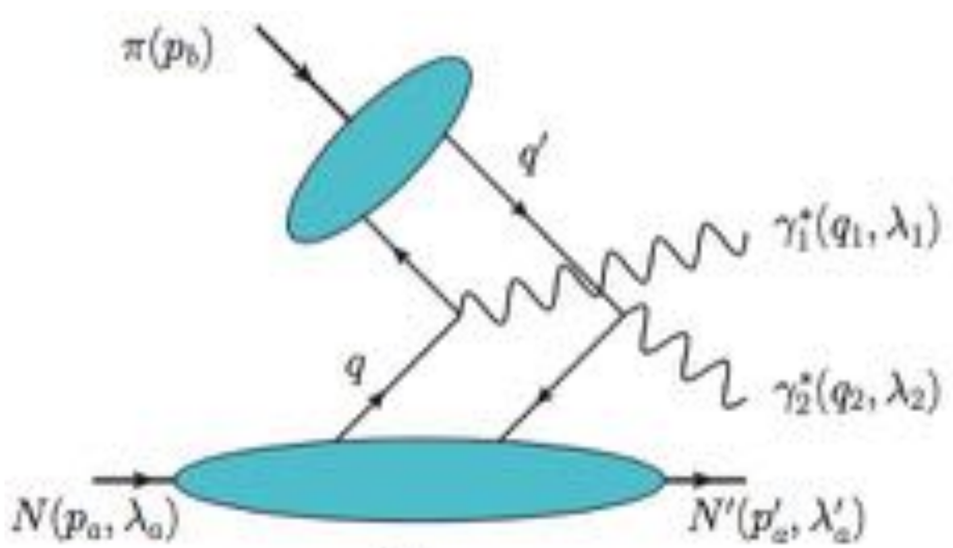
based on Pasquini, Lorcé, Xiong, Yuan, PRD 85 (12)

WIGNER DISTRIBUTIONS



Exclusive dijet production

Hatta, Xiao, Yuan, arXiv:1601.01585
Hatta, Nakagawa, Xiao, Yuan, Zhao, arXiv:1612.02445
Ji, Yuan, Zhao, arXiv:1612.02438

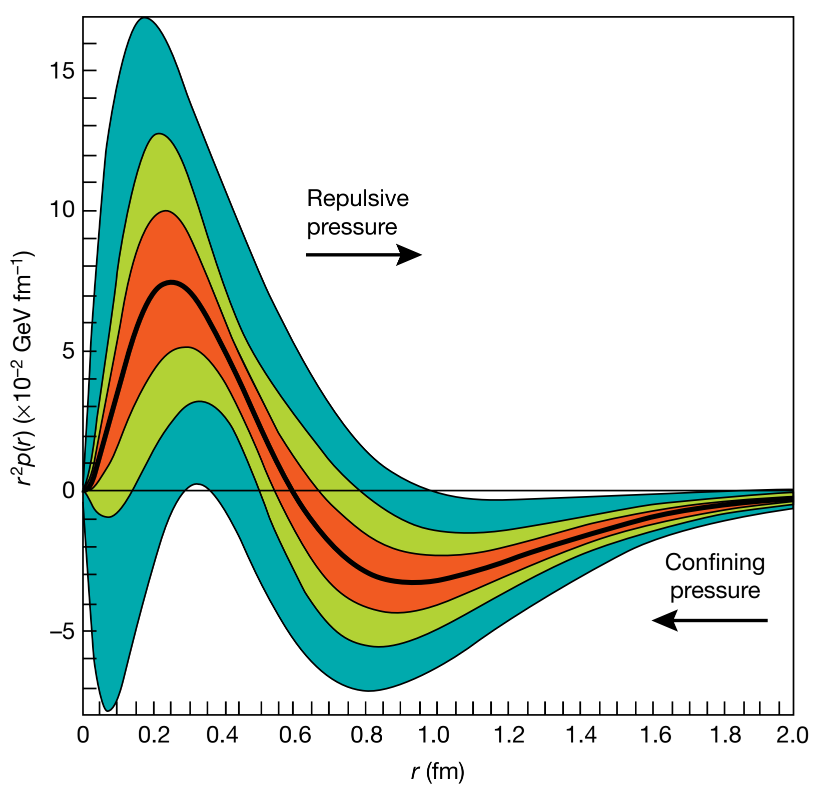


Exclusive double Drell-Yan

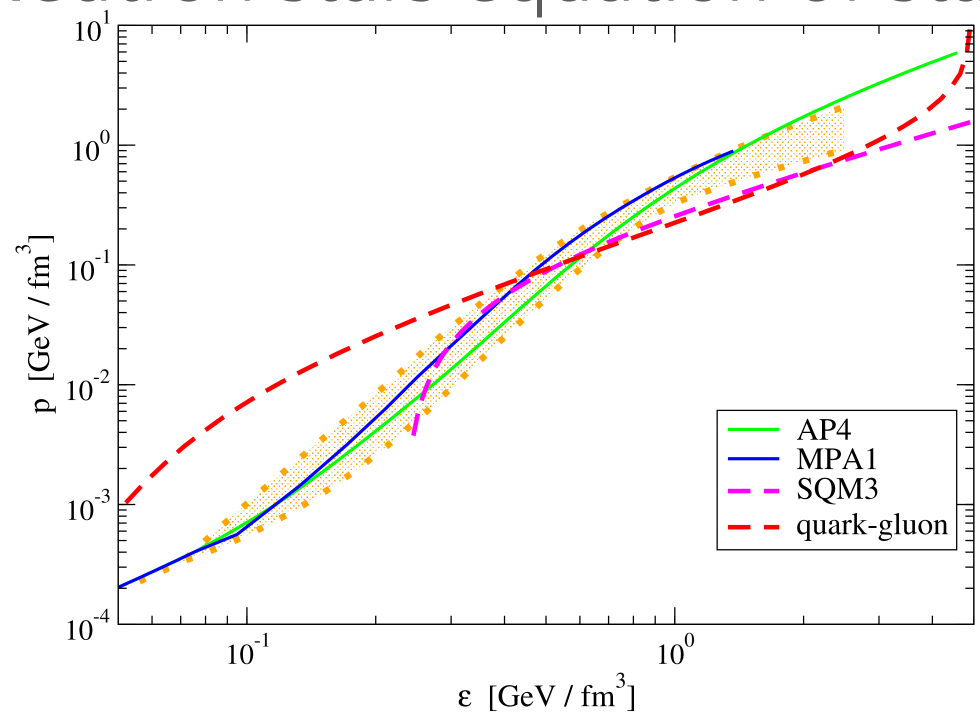
Bhattacharya, Metz, Zhou, arXiv:1702.04387

PRESSURE DISTRIBUTION IN THE PROTON

The study of the multidimensional structure of the proton can in principle allow us to access the proton energy-momentum tensor



Neutron stars equation of state



Burkert, Elouadrhiri, Girod, Nature 577 (18)

Liuti, Rajan, Yagi, arXiv:1812.01479

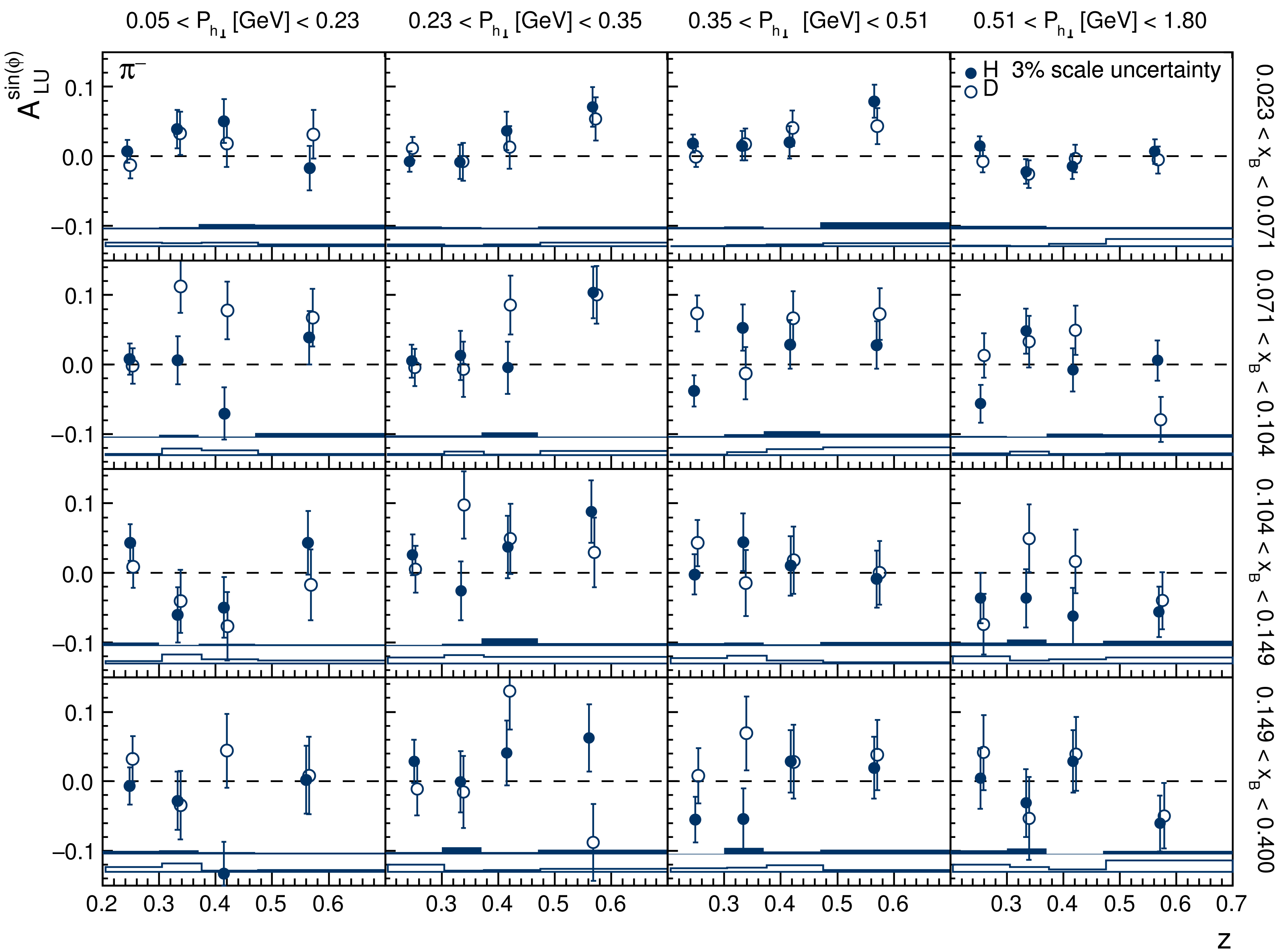
The knowledge of pressure in hadronic matter can in principle allow us to make predictions on the behaviour of neutron stars

Tantalizing results. Need more solid underpinning.

THE FUTURE

“NEW” DATA FROM HERMES!

Multidimesional binning

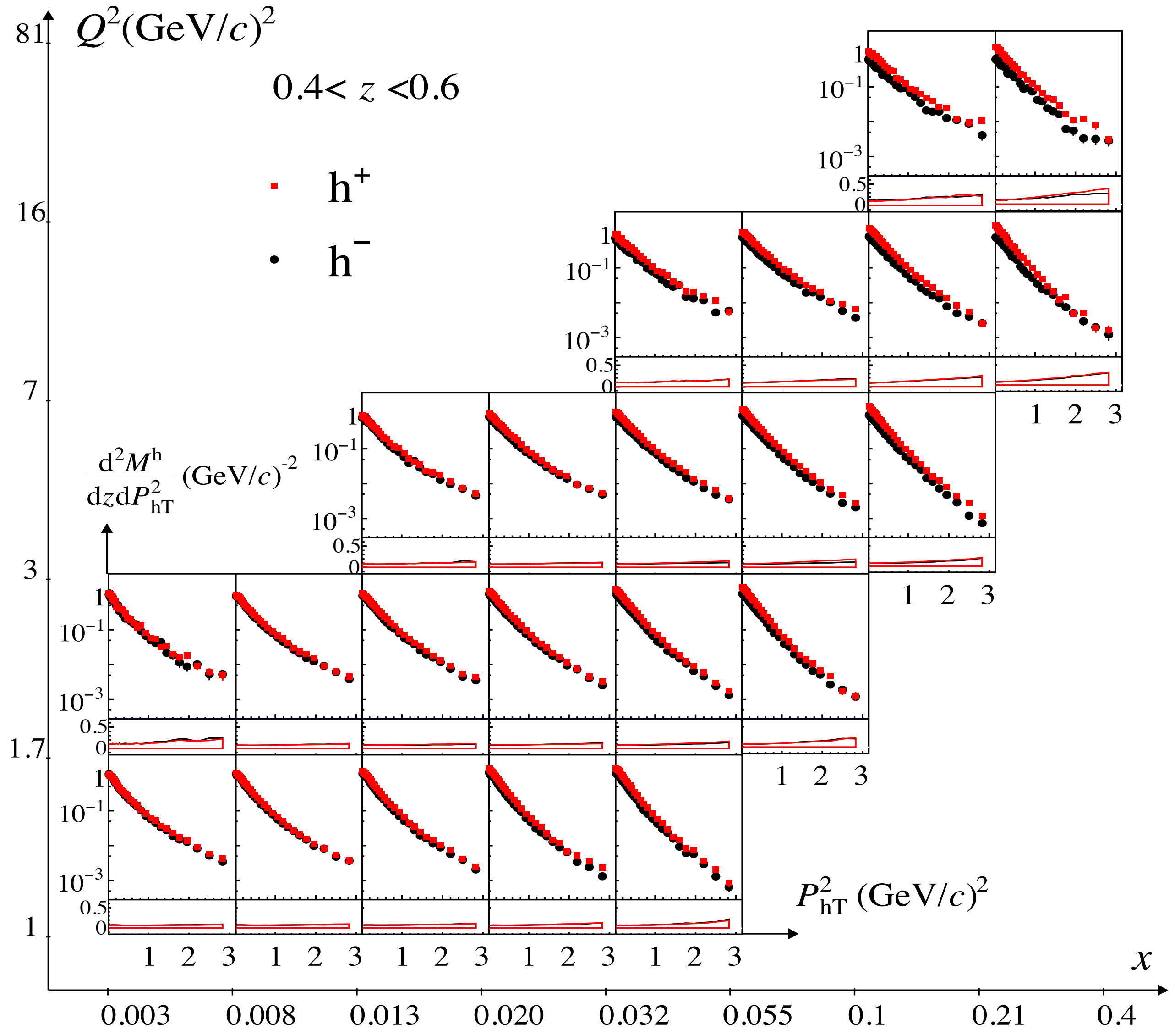


HERMES Collab., arXiv:1903.08544

Even if the experiments was closed 10 years ago, they are still producing results

NEW DATA FROM COMPASS

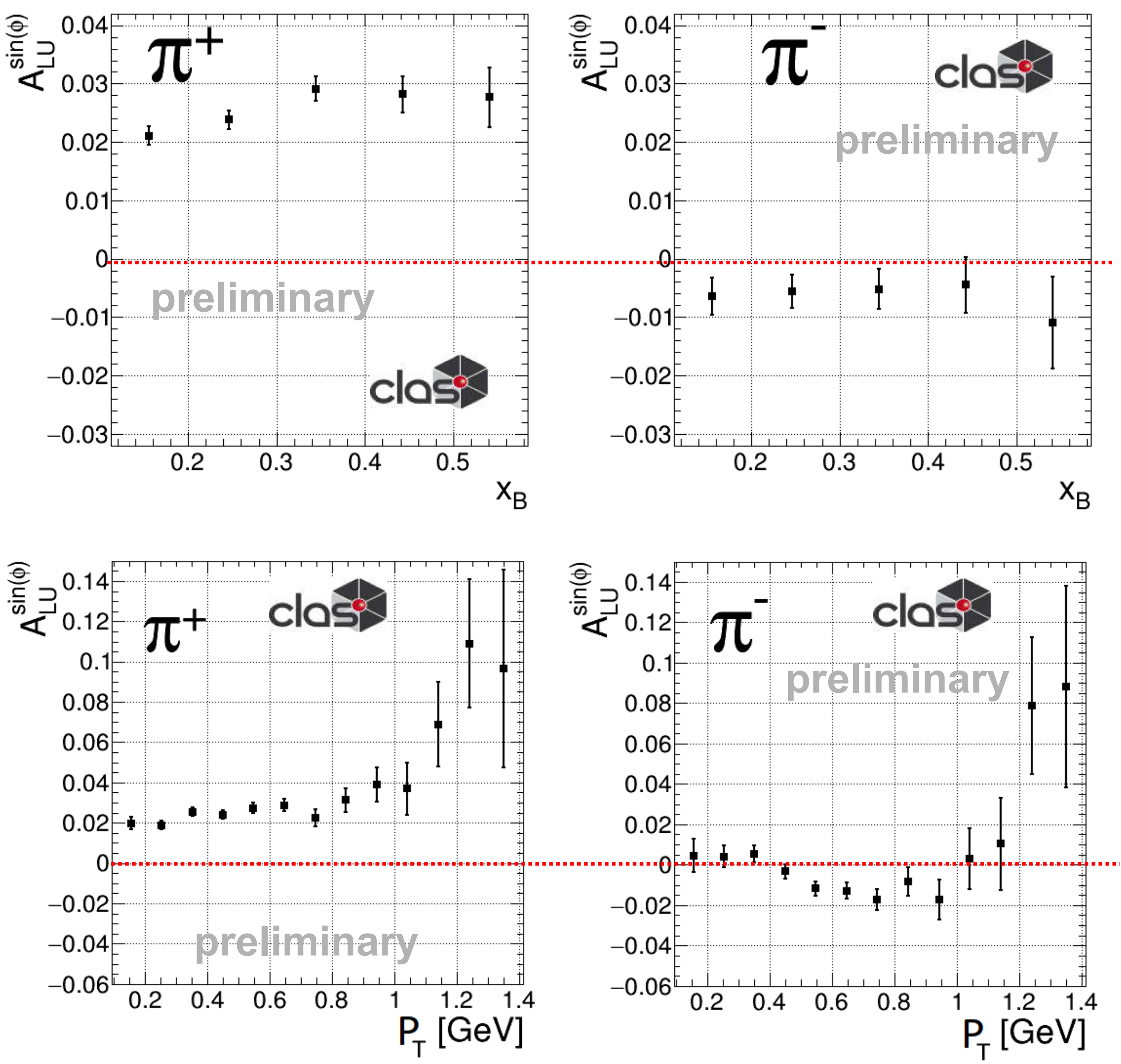
Multidimesional binning

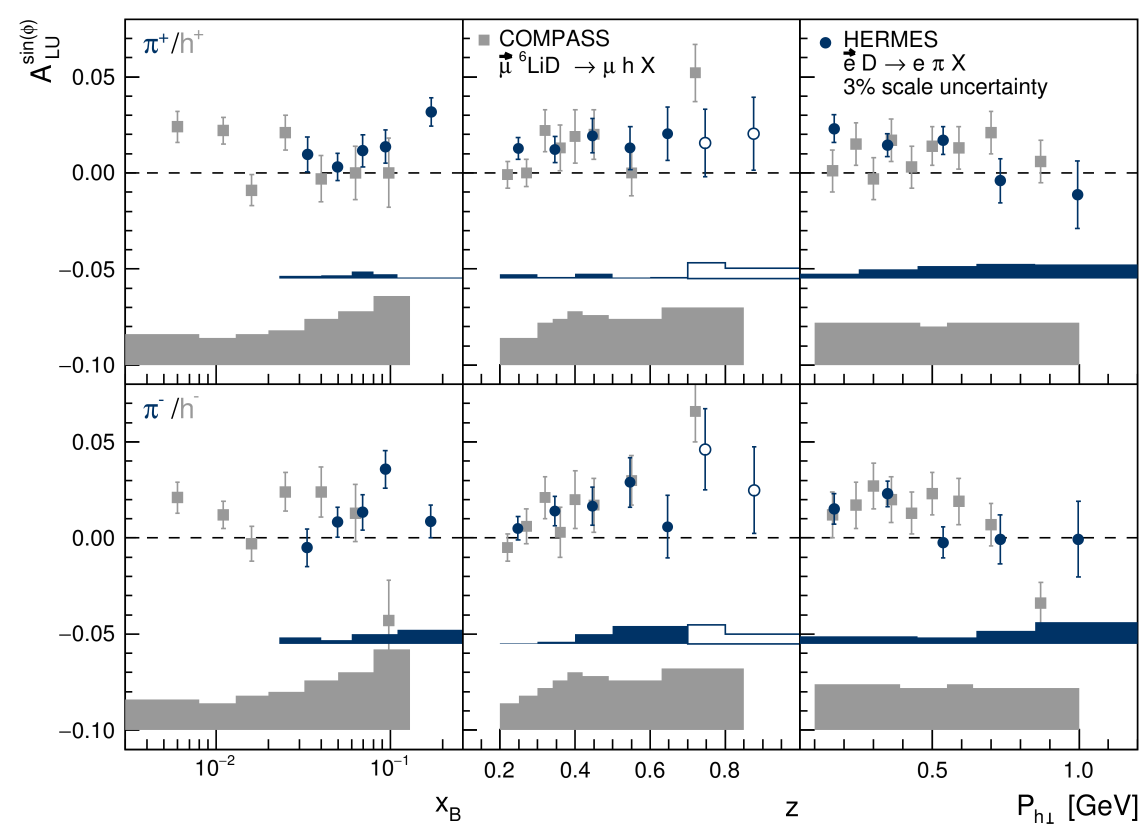


COMPASS Collab., arXiv:1709.07374

COMPASS is in “full swing” mode.
Will provide data about pion structure as well.

FIRST JLAB PRELIMINARY DATA



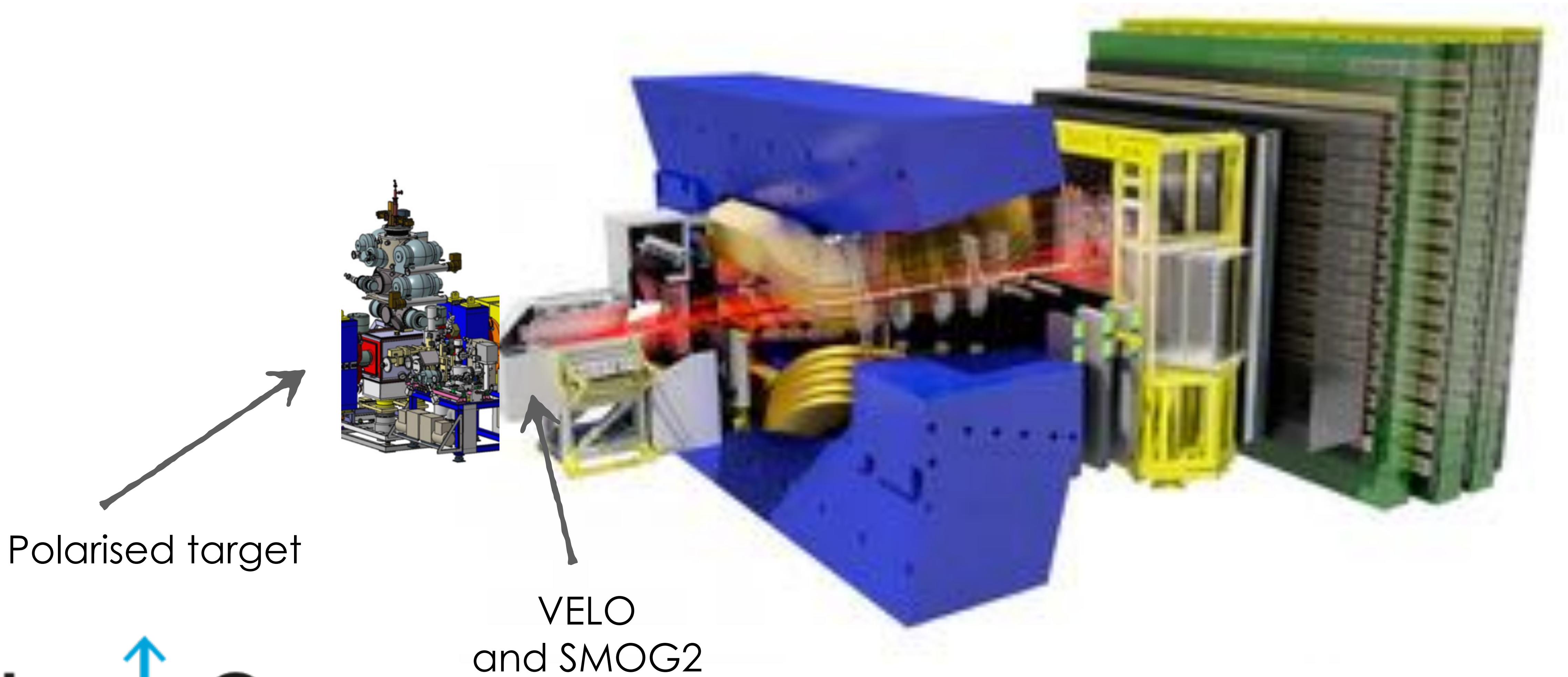


Only 2% of approved data taking

AWESOME!

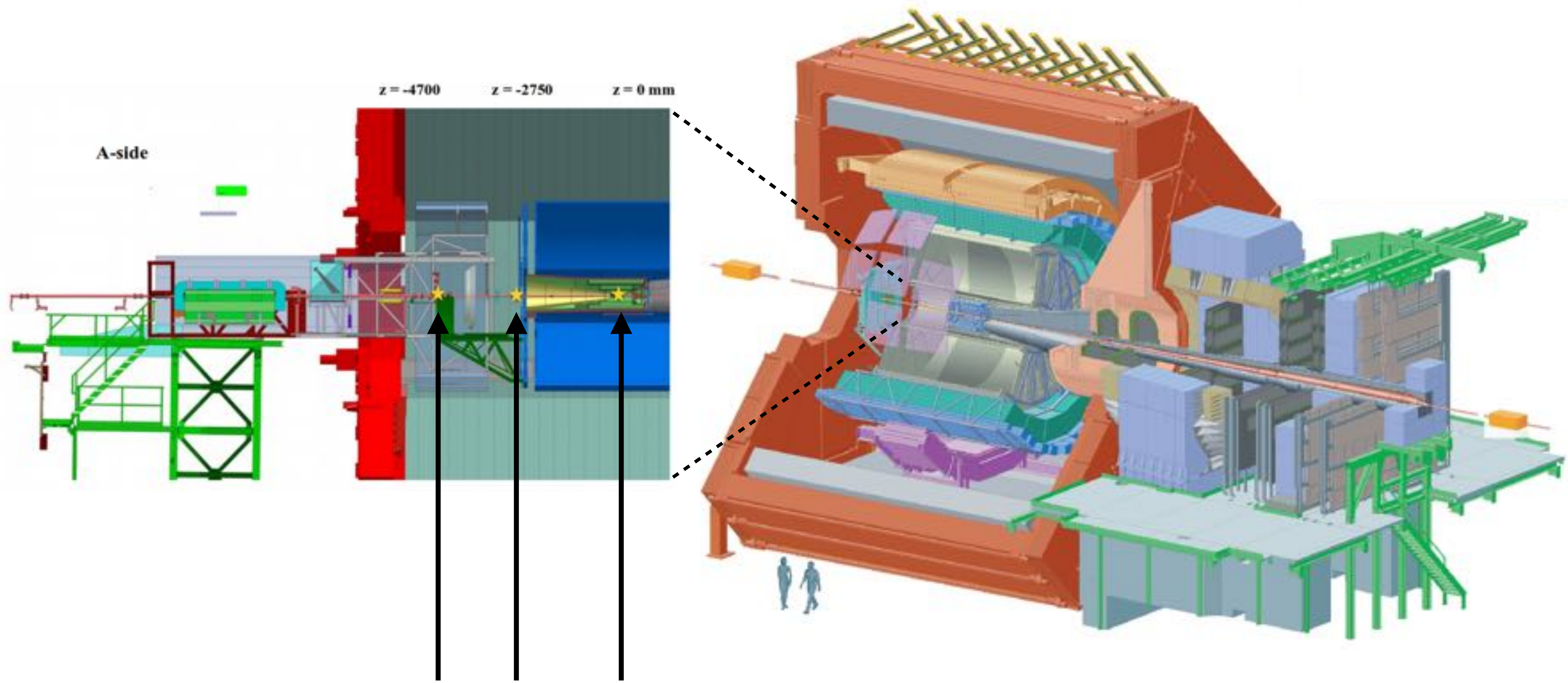
LHCb FIXED TARGET, INCLUDING POLARISATION

https://indico.cern.ch/event/755856/



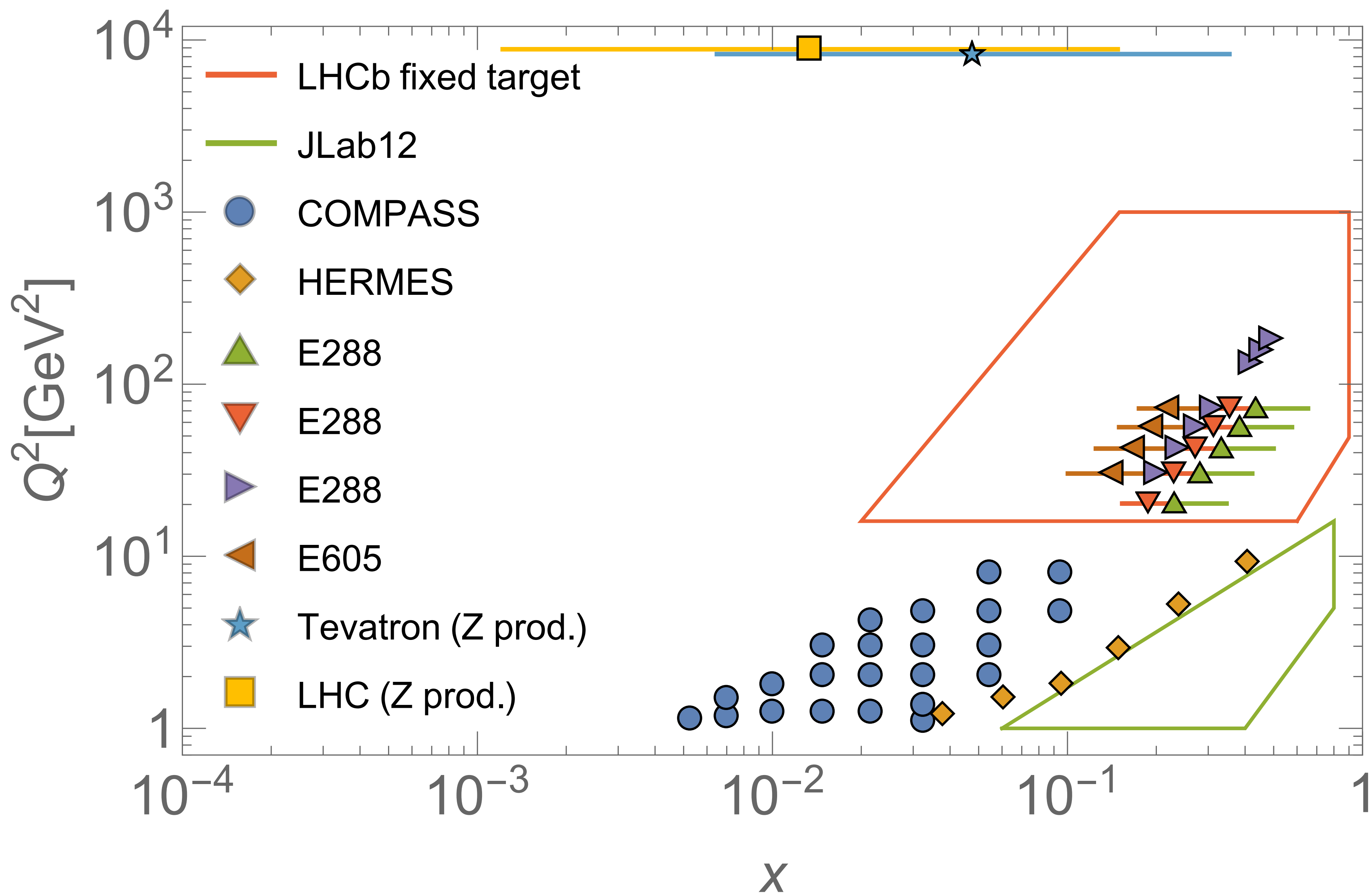
ALICE FIXED TARGET

https://indico.cern.ch/event/755856/



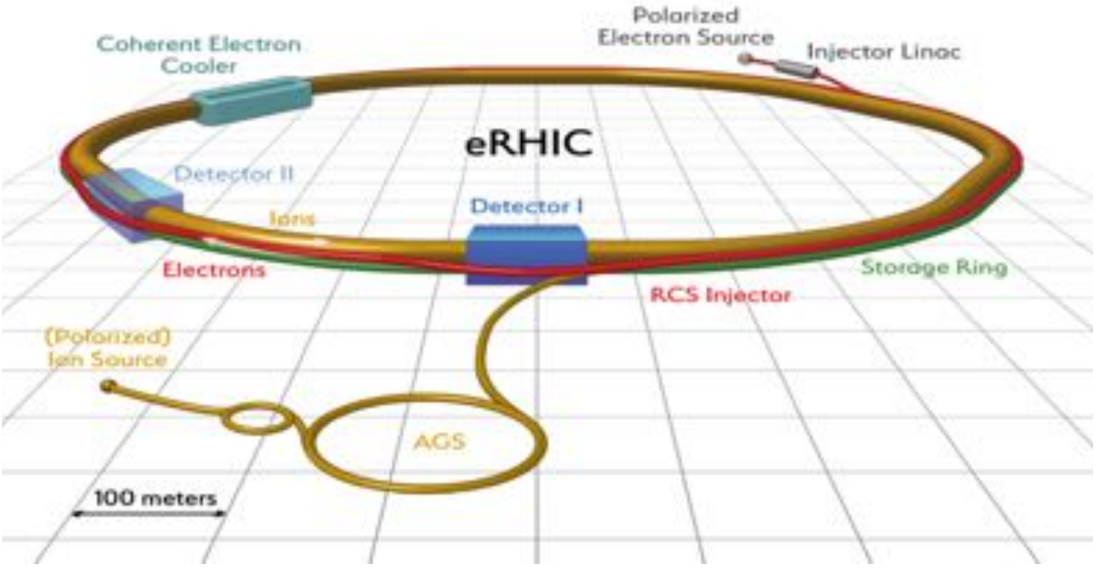
Possible fixed-target positioning

EXPECTED EXTENSION OF DATA RANGE

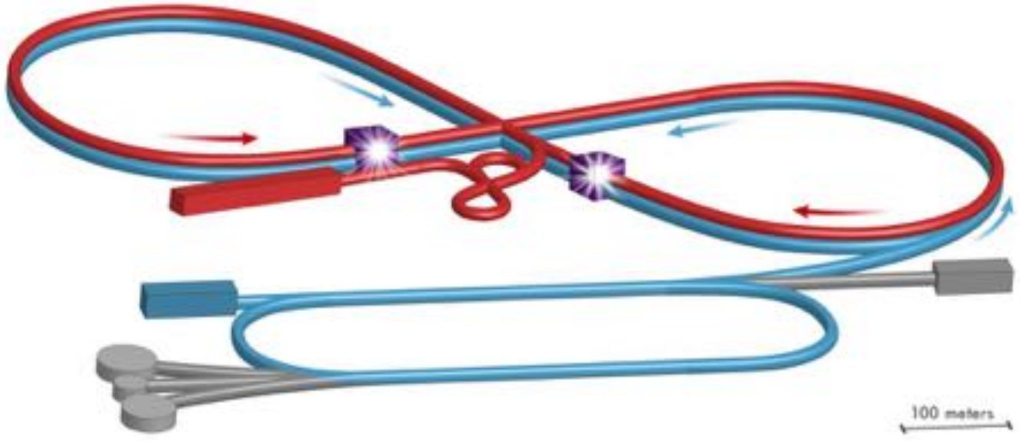


THE ELECTRON-ION COLLIDER PROJECT

BNL concept



JLab concept



- High luminosity: (10^{34} cm^{-2} s^{-1})
- Variable CM energy: 20-100 GeV
- Highly polarized beams
- Protons and other nuclei

Opened on 2 december 1942 when Chicago Pile-1 went critical. Donated to Argonne

I promise to offer a (better) bottle if the EIC starts operating

CONCLUSIONS

- We are on the way to mapping the proton in higher details in 3D momentum space
- We are on the way to providing useful information for other applications (W mass, beyond standard model physics, astrophysics…)
- We are on the way to test lattice QCD calculation and other nonperturbative QCD models
- The EIC will open a new era