THE 3D NUCLEON STRUCTURE

Alessandro Bacchetta

3DSPIN
MAPPING THE PROTON IN 3D

erc
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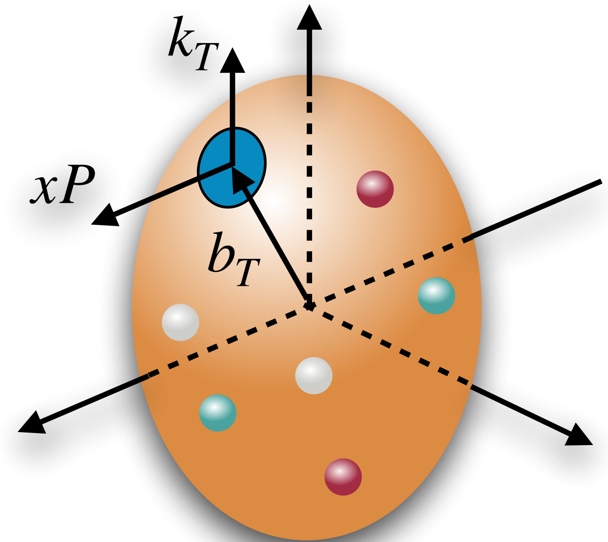
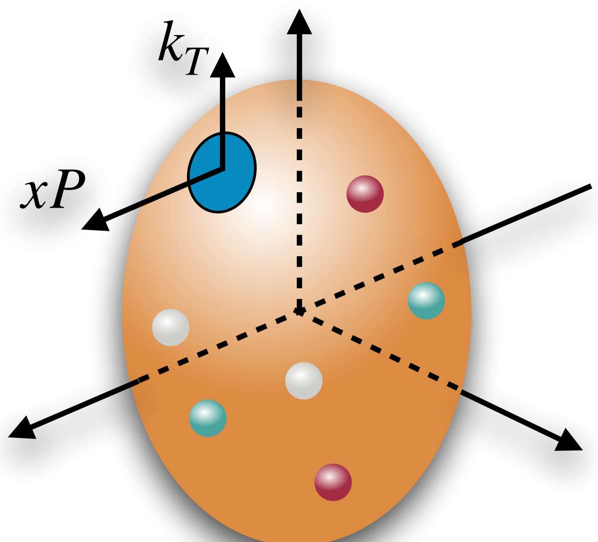
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PAVIA

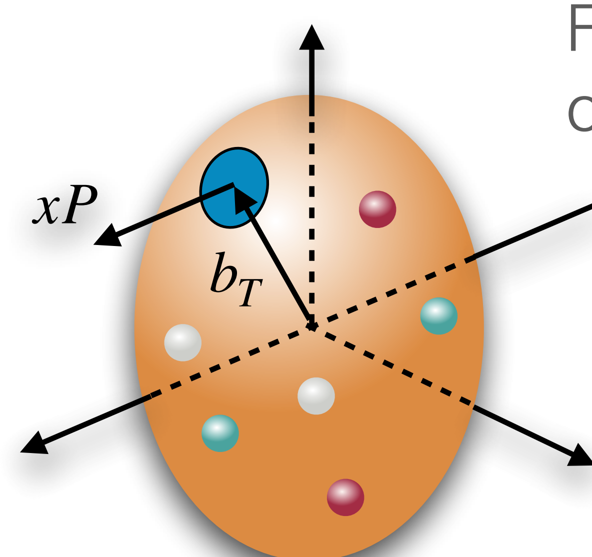
Wigner distributions (Fourier transform of GTMDs = Generalized Transverse Momentum Distributions)



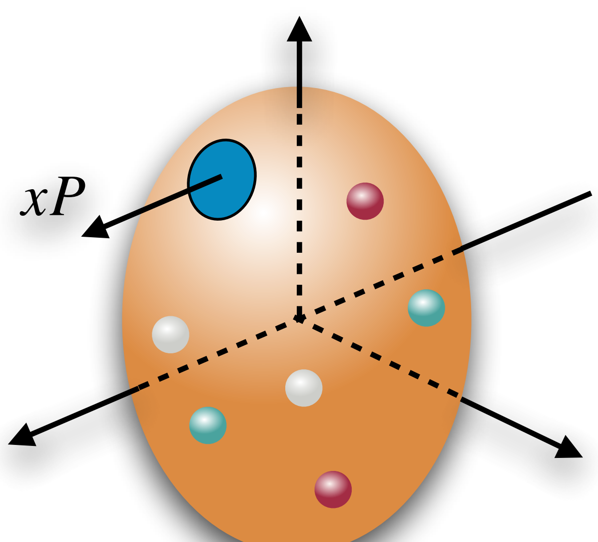
TMDs



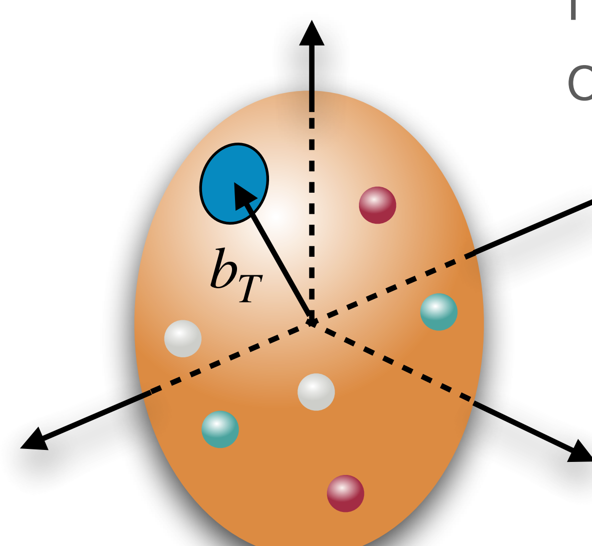
Fourier transform of GPDs



PDFs



Fourier transform of Form Factors

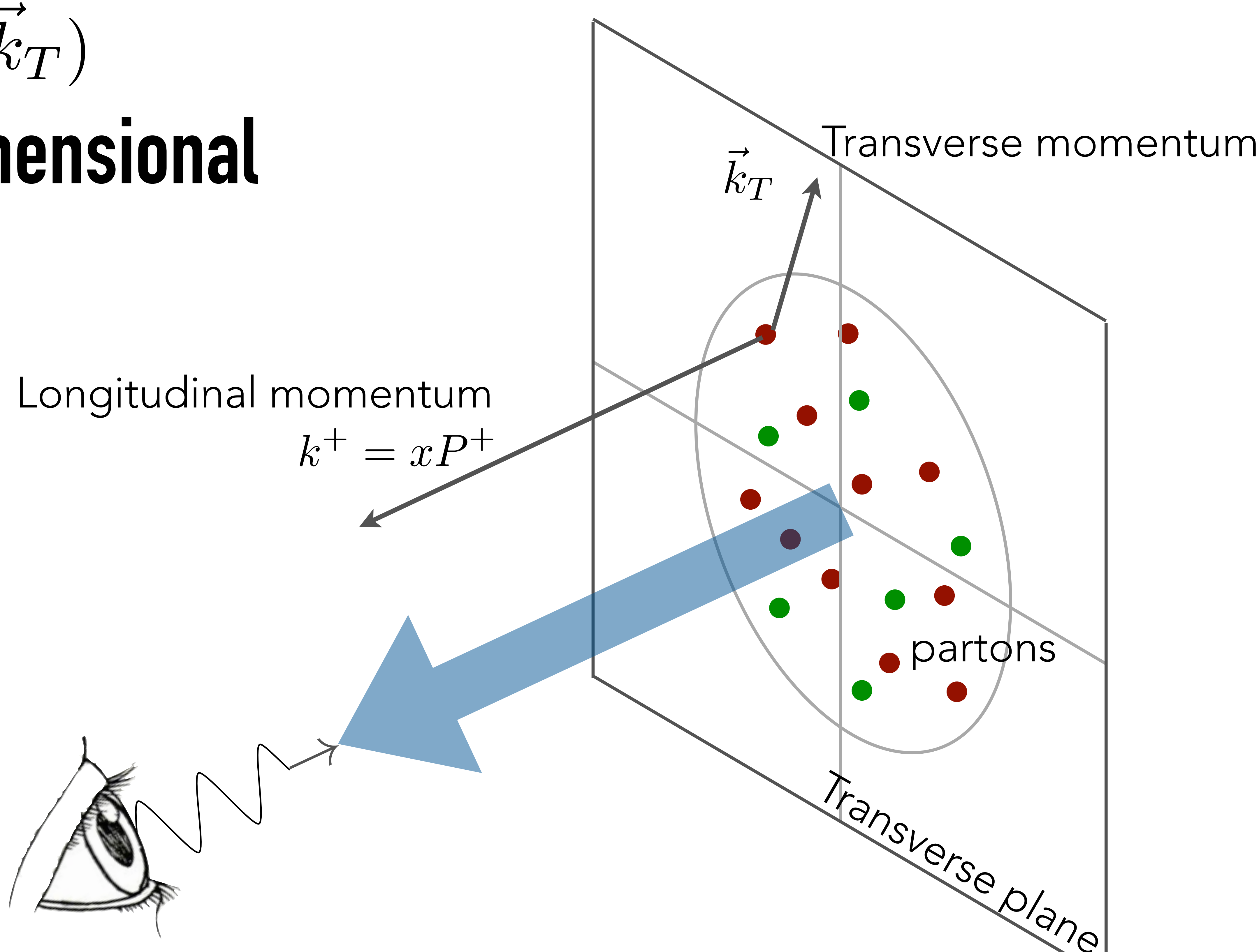


see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

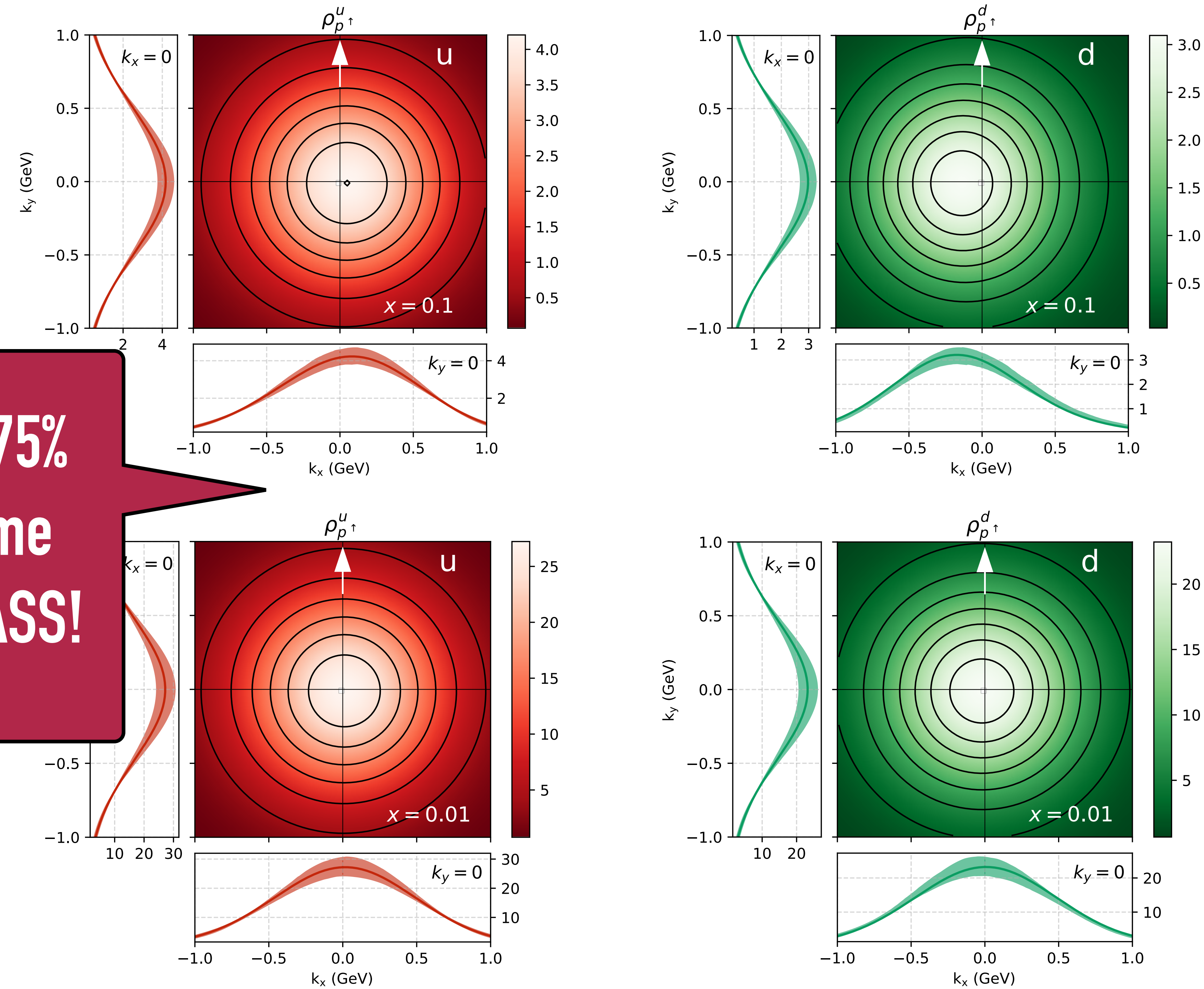
Transverse-Momentum Distributions

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

3 dimensional



3D STRUCTURE IN MOMENTUM SPACE



More than 75% of data come from COMPASS!

Q= 2GeV

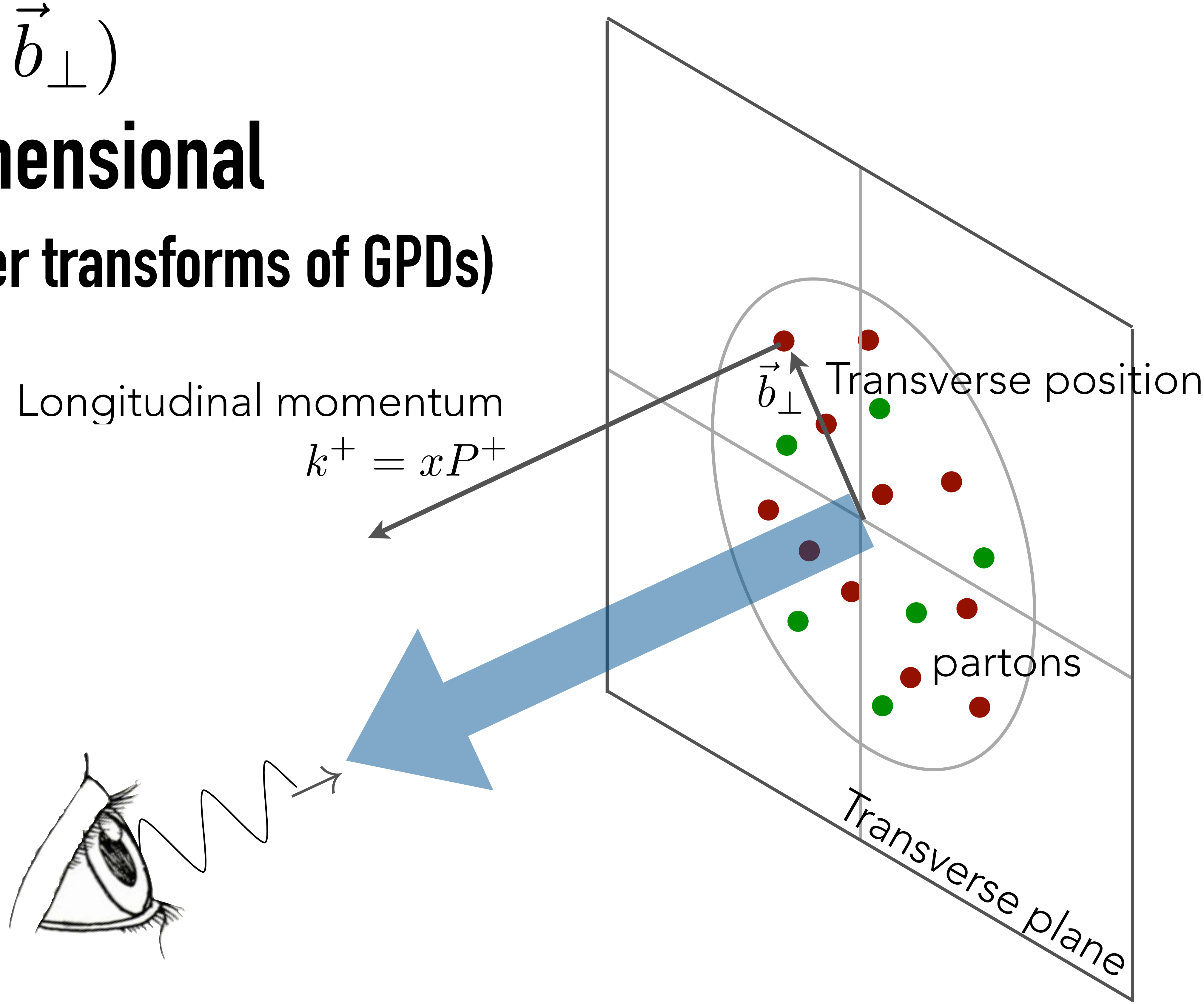
Bacchetta, Delcarro, Pisano, Radici, arXiv:2004.14278

Impact-parameter distributions

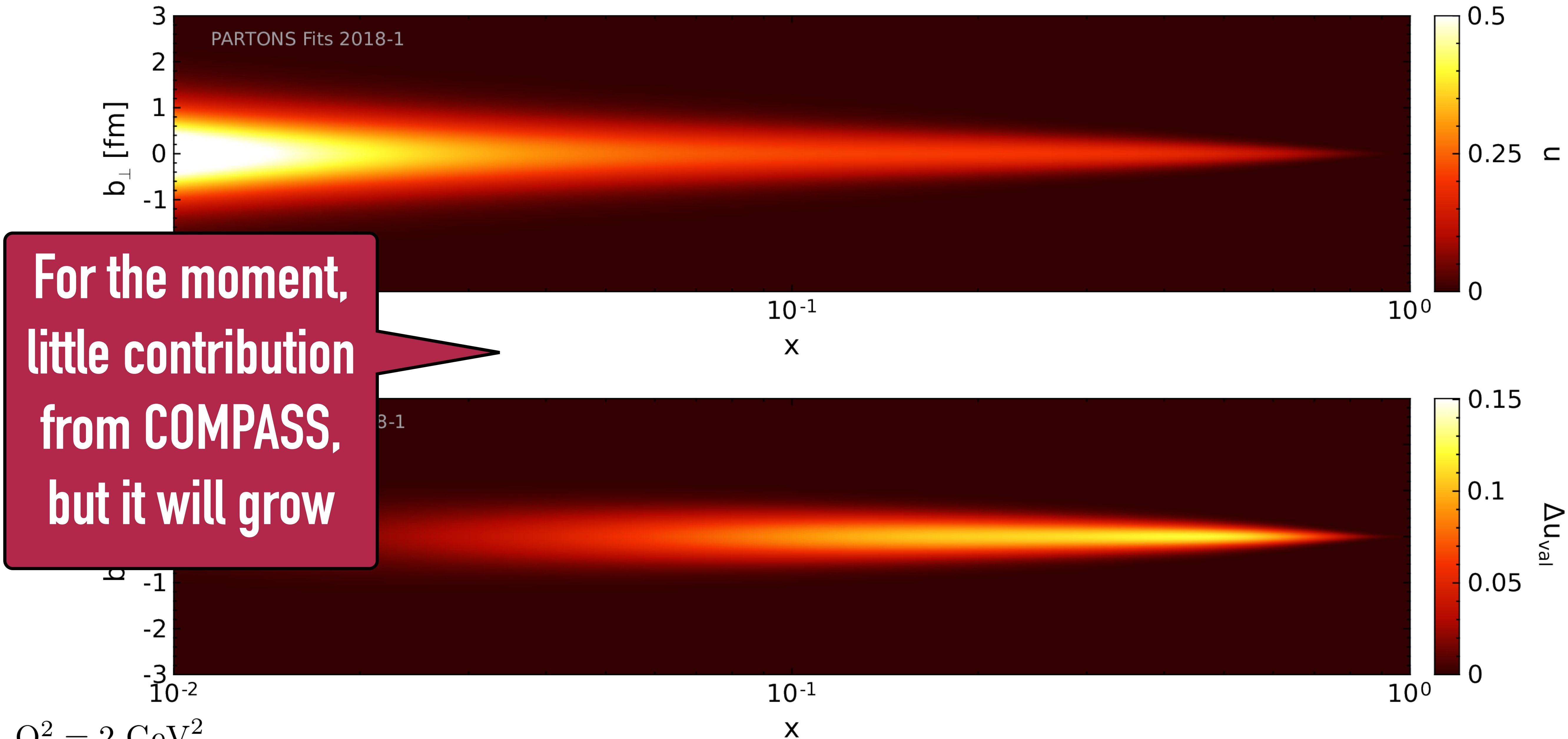
$\mathcal{F}(x, \vec{b}_\perp)$

3 dimensional

(Fourier transforms of GPDs)



3D STRUCTURE IN LONGITUDINAL MOMENTUM+IMPACT PARAMETER

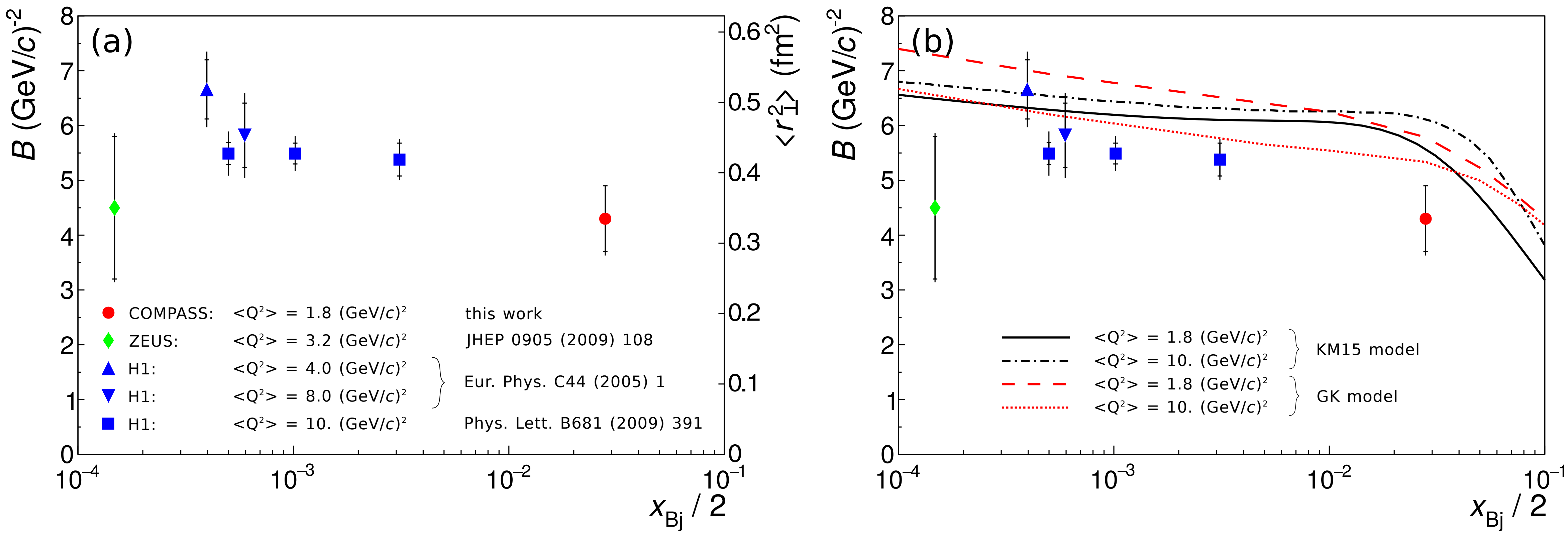


$Q^2 = 2\ \mathrm{GeV}^2$

Moutarde, Sznajder, Wagner, arXiv:1807.07620

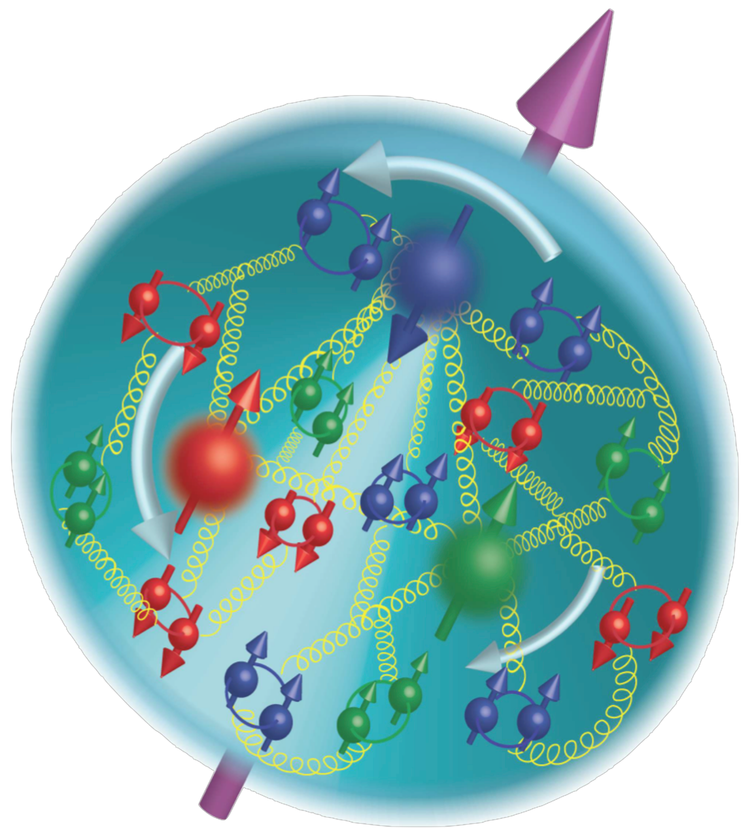
TRANSVERSE EXTENSION OF PARTONS IN THE PROTON

arXiv:1802.02739



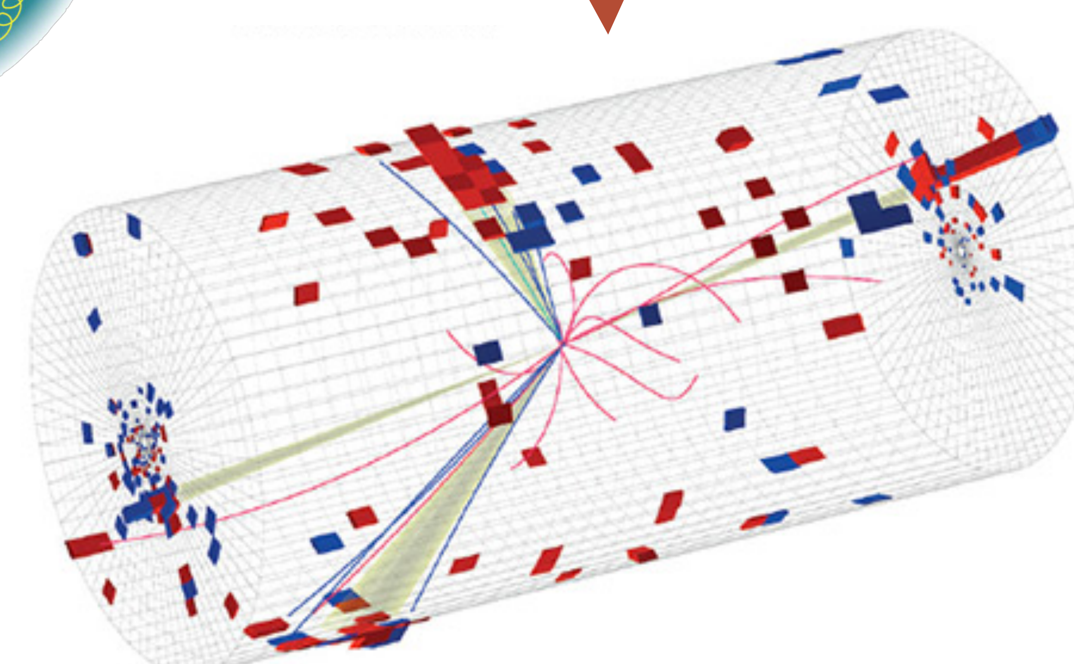
WHY IS IT INTERESTING TO MAP THE NUCLEON?

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

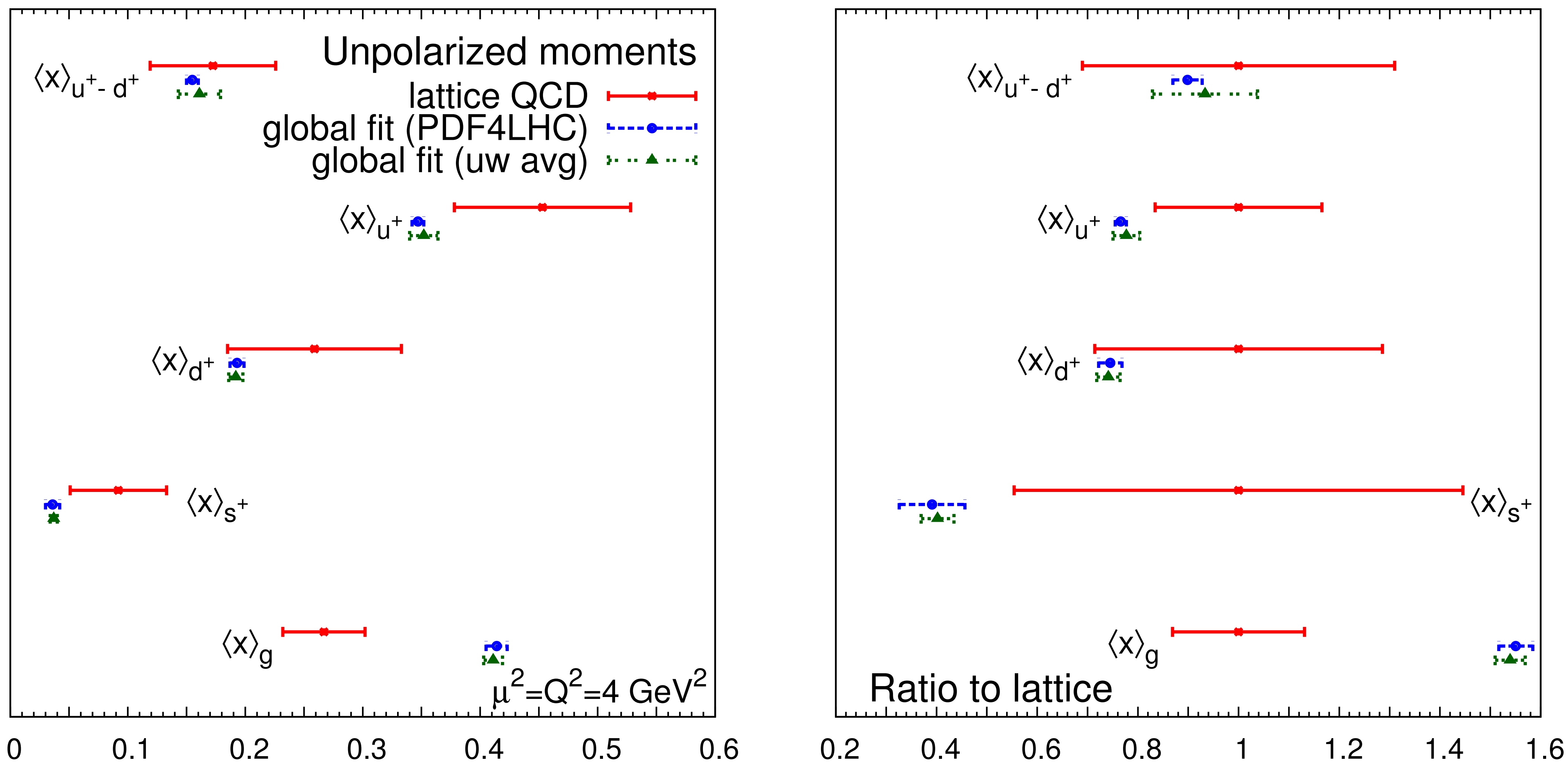


Make predictions

Check predictions



UNPOLARIZED PDF MOMENTS AND LATTICE QCD



PDFLattice White Paper, arXiv:1711.07916

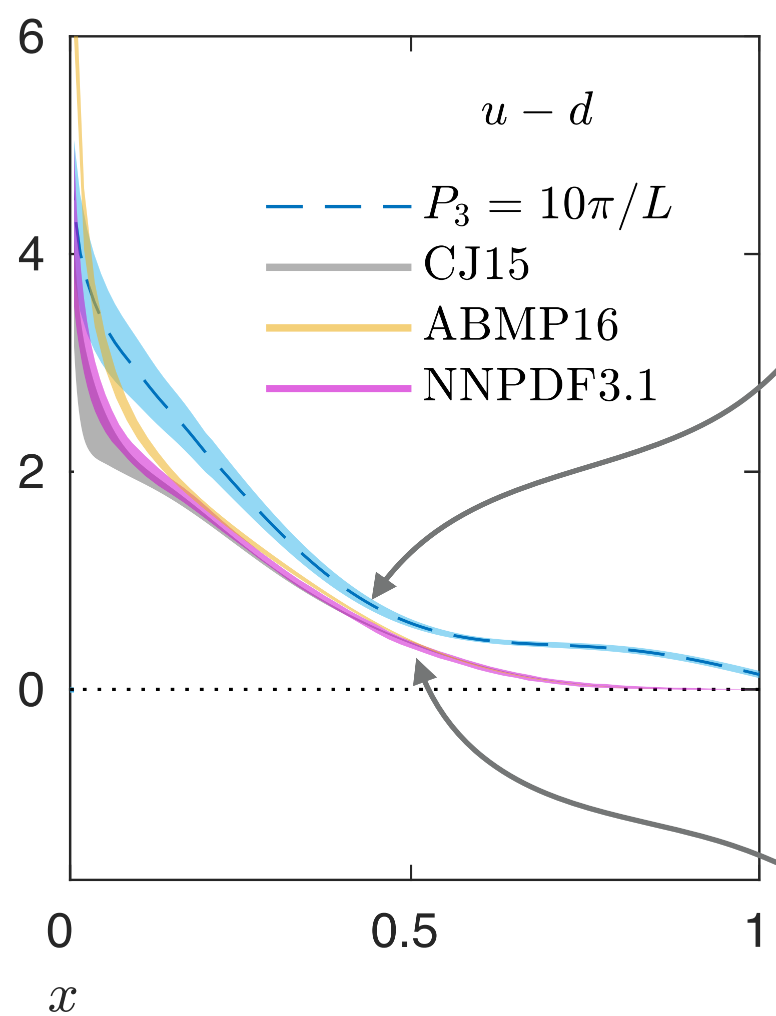
Fair agreement, but not perfect

FULL UNPOLARIZED PDF AND LATTICE QCD

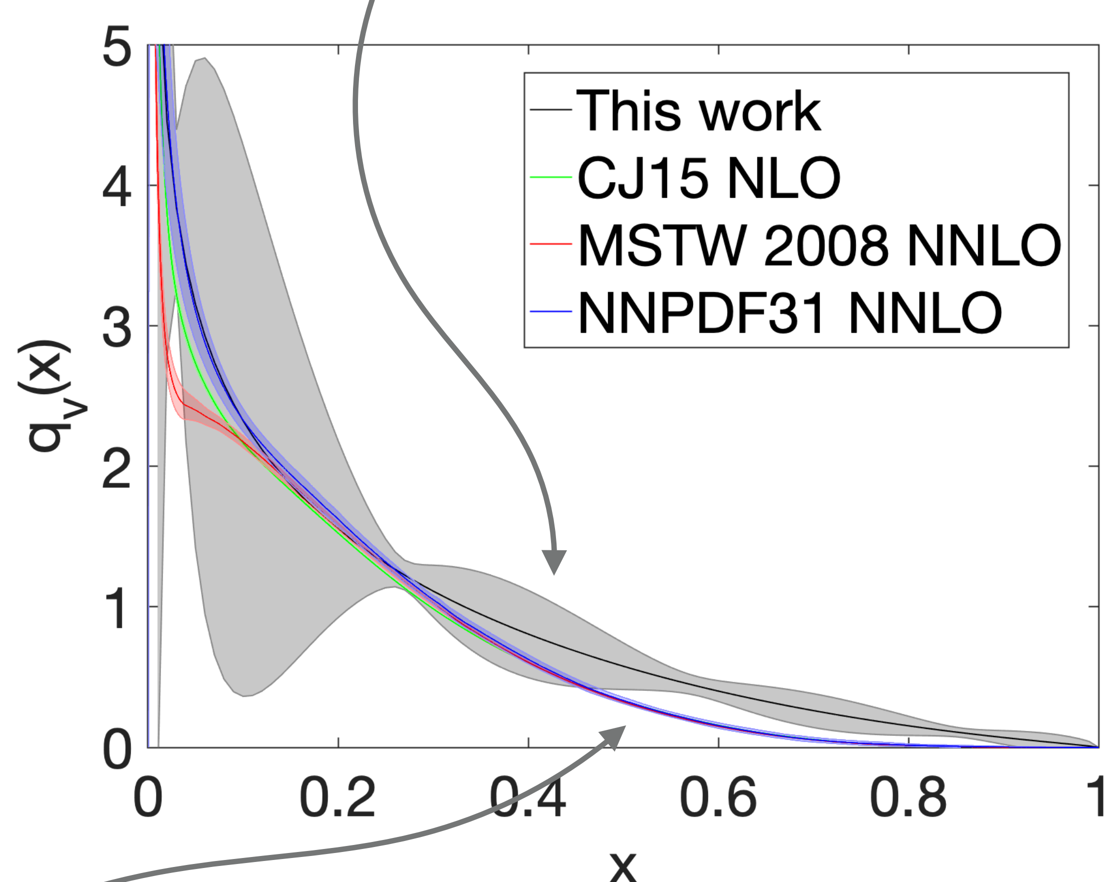
Alexandrou, Cichy, Constantinou, Hadjiyiannakou, Jansen, Scapellato, Steffens, arXiv:1902.00587

Joó, Karpie, Orginos, Radyushkin, Richards, Zafeiropoulos, arXiv:1908.09771

lattice (quasi-PDF approach)

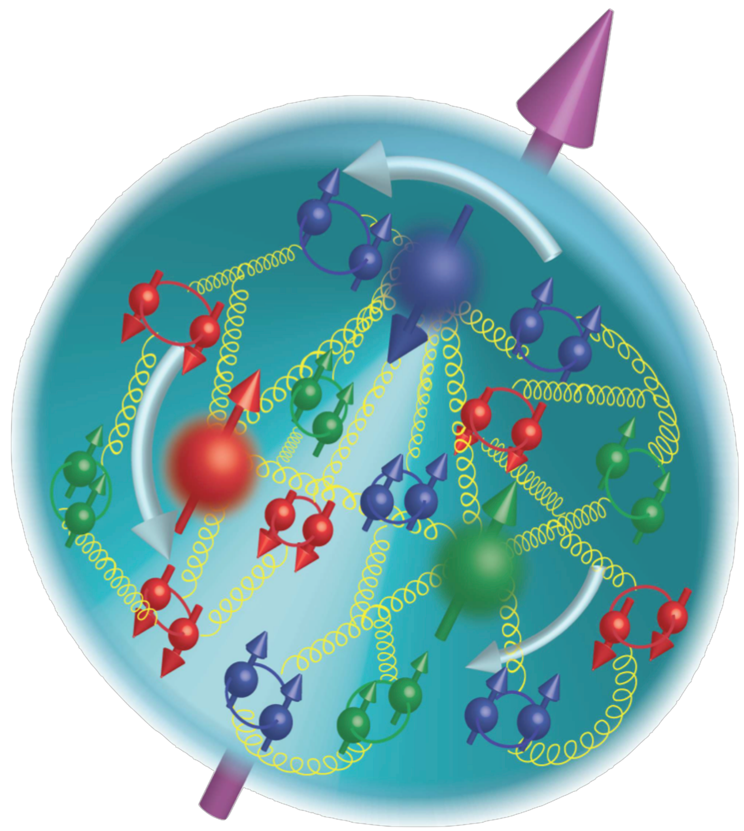


lattice (pseudo-PDF approach)

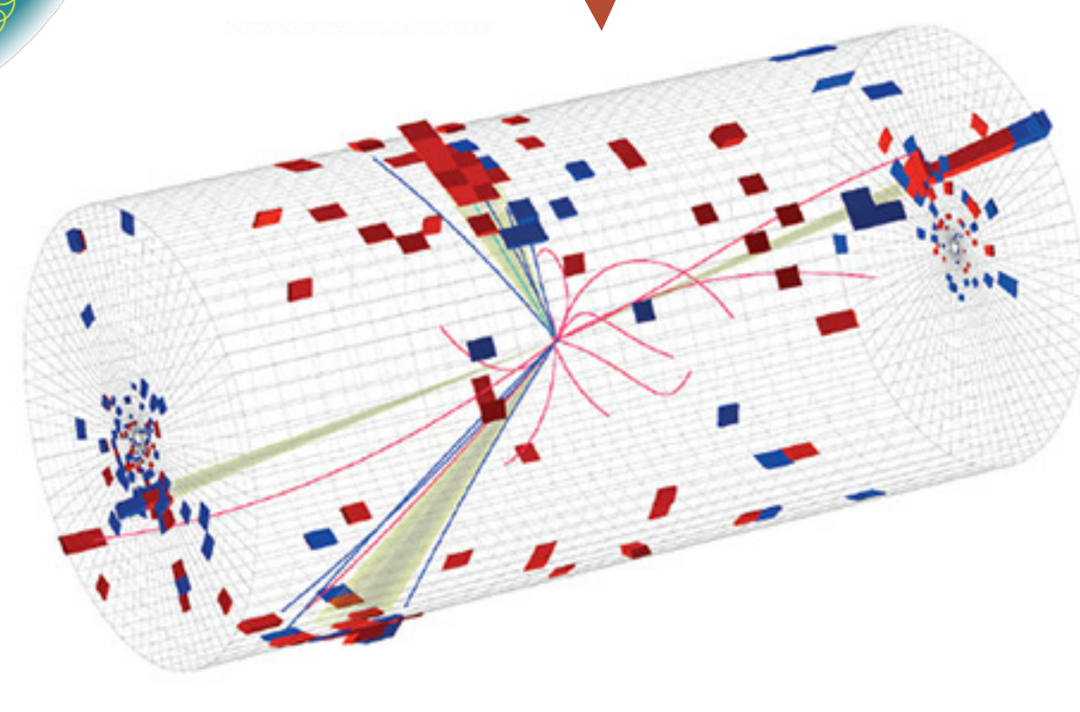


global fits

WHY IS IT INTERESTING TO MAP THE NUCLEON?



Make predictions



TOOLS USED FOR DRELL-YAN PREDICTIONS

V. Bertone's talk at LHC EW WG General Meeting, Dec 2019
https://indico.cern.ch/event/849342/

SCETlib
[https://confluence.desy.de/display/scetlib]

CuTe
[https://cute.hepforge.org]

} SCET

DYRes/DYTURBO
[https://gitlab.cern.ch/DYdevel/DYTURBO]

ReSolve
[https://github.com/fkhorad/reSolve]

} q_T-res.

RadISH
[https://arxiv.org/pdf/1705.09127.pdf]

PB-TMD
[https://arxiv.org/pdf/1906.00919.pdf]

} PB

NangaParbat
[https://github.com/vbertone/NangaParbat]

arTeMiDe
[https://teorica.fis.ucm.es/artemide/]

} TMD

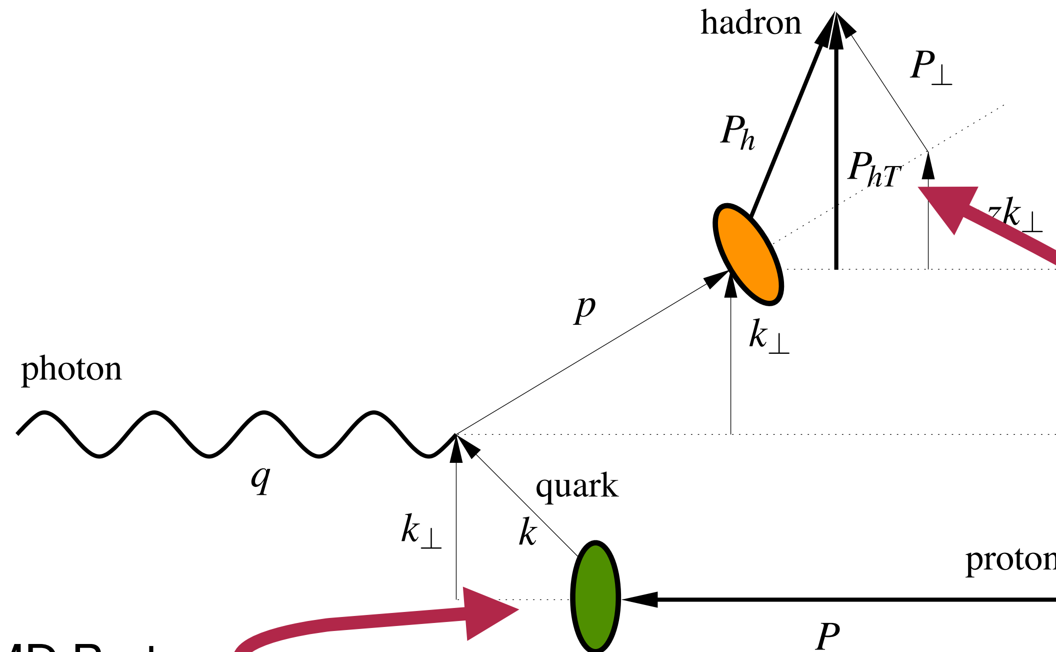
There is an entire industry of tools that make predictions for observables at LHC related to TMDs.

Most of them neglect SIDIS and the important effects coming from nonperturbative TMD components.

SELECTED RECENT RESULTS AND PERSPECTIVES

UNPOLARIZED TMDS

TMDS IN SEMI-INCLUSIVE DIS



TMD Parton
Distribution Functions

TMD Parton
Fragmentation Functions

$$
\begin{aligned}
&F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2) \\
&\quad = x \sum_q \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int d^2\boldsymbol{k}_\perp \, d^2\boldsymbol{P}_\perp \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu^2) \, D_1^{a\to h}(z, \boldsymbol{P}_\perp^2; \mu^2) \, \delta(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp) \\
&\quad = x \sum_a \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int db_T b_T J_0(b_T |\boldsymbol{P}_{h\perp}|) \hat{f}_1^q(x, z^2 b_\perp^2; \mu^2) \, \hat{D}_1^{a\to h}(z, b_\perp^2; \mu^2)
\end{aligned}
$$

hard factor

TMD FACTORIZATION

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

perturbative Sudakov form factor

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

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

collinear PDF

matching coefficients (perturbative)

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)
Scimemi, Vladimirov, arXiv:1912.06532

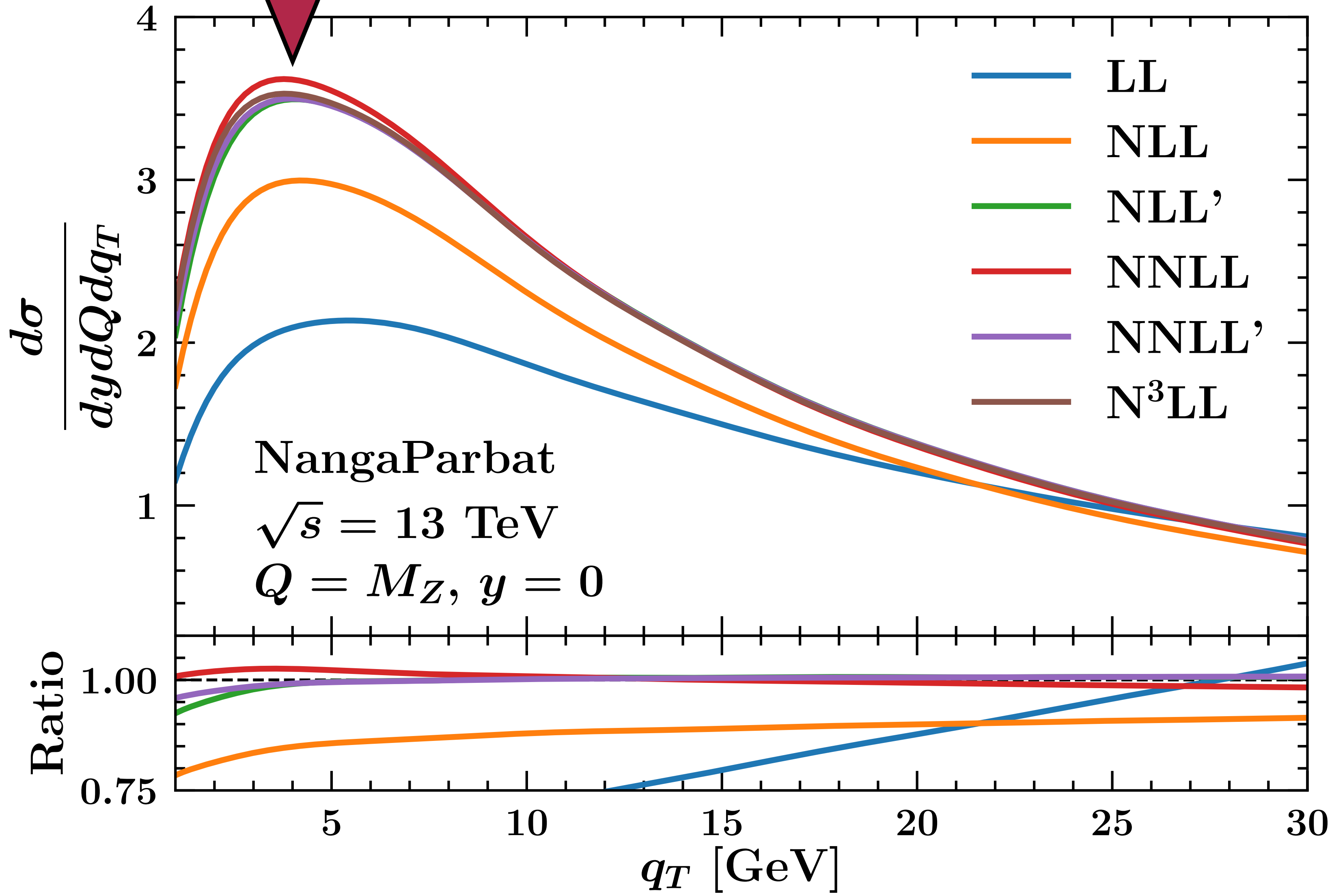
RECENT TMD FITS OF UNPOLARIZED DATA

	Framework	HERMES	COMPASS	DY	Z production	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059	1.55
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔	309	1.23
BSV 2019 arXiv:1902.08474	NNLL′	✘	✘	✔	✔	457	1.17
SV 2019 arXiv:1912.06532	NNLL′	✔	✔	✔	✔	1039	1.06
Pavia 2019 arXiv:1912.07550	N^3LL	✘	✘	✔	✔	353	1.02

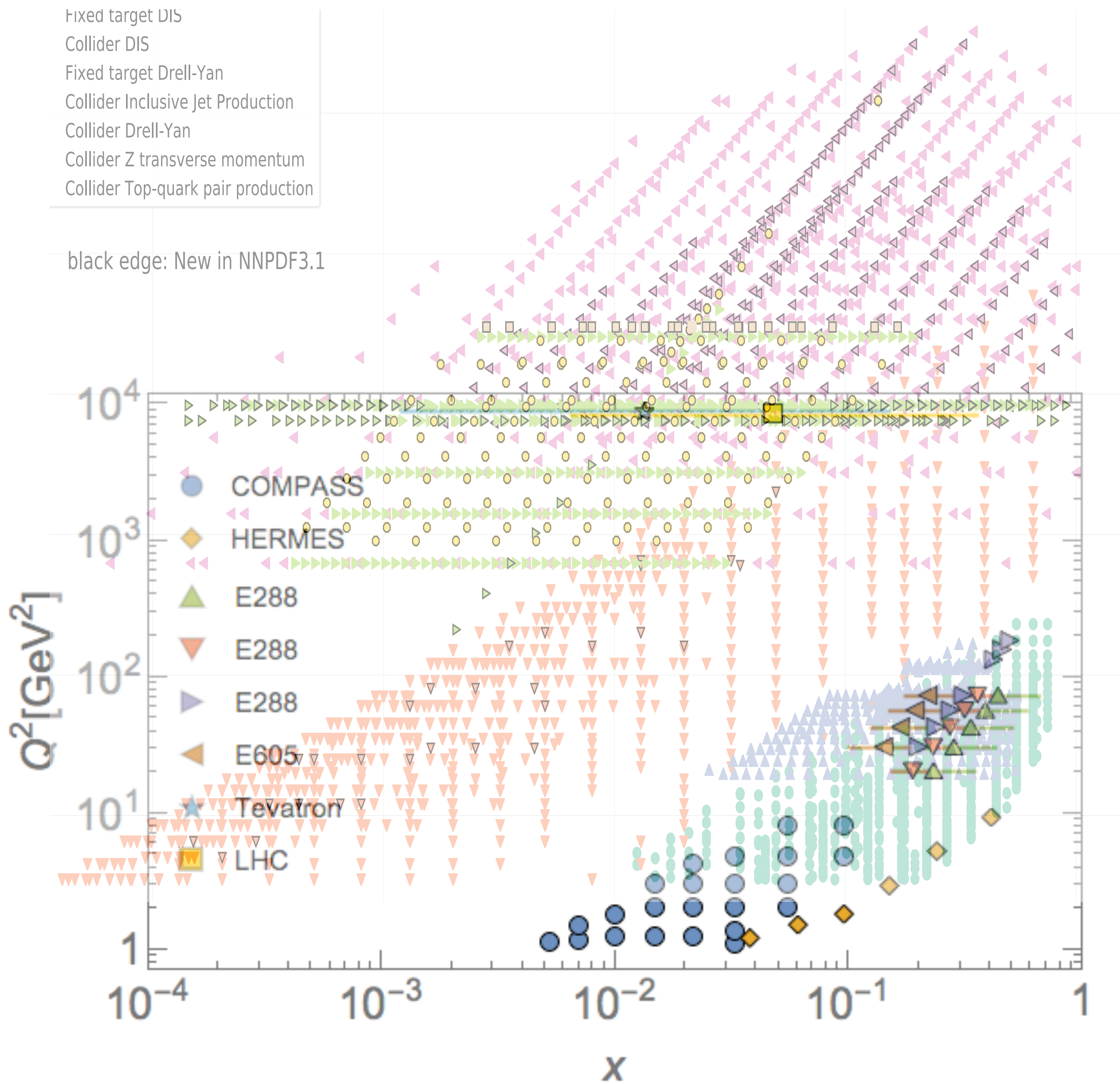
HIGH LEVEL OF ACCURACY

V. Bertone's talk at LHC EW WG General Meeting, Dec 2019
https://indico.cern.ch/event/849342/

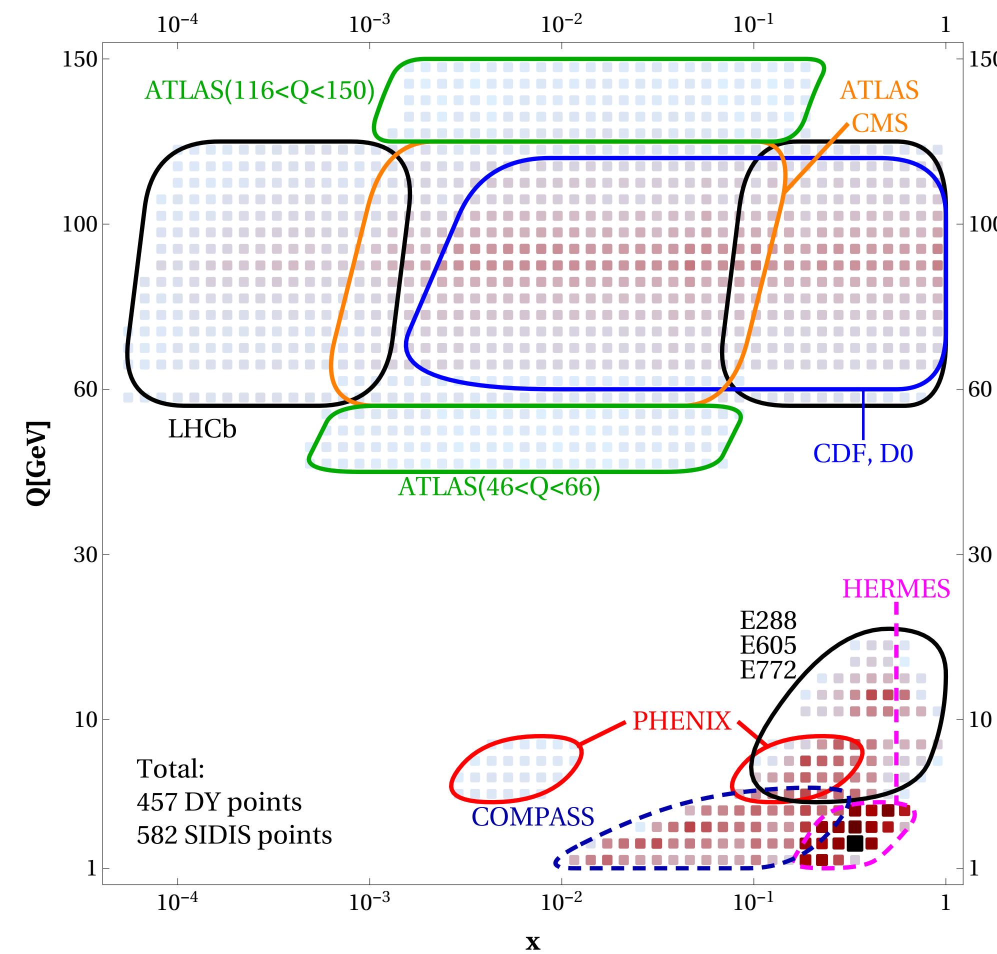
Nice convergence of perturbative series



WIDE x–Q² COVERAGE



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



Scimemi, Vladimirov, arXiv:1912.06532

AVAILABLE TOOLS: NANGA PARBAT

https://github.com/vbertone/NangaParbat

Nanga Parbat: a TMD fitting framework

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

Download

You can obtain NangaParbat directly from the github repository:

https://github.com/vbertone/NangaParbat/releases

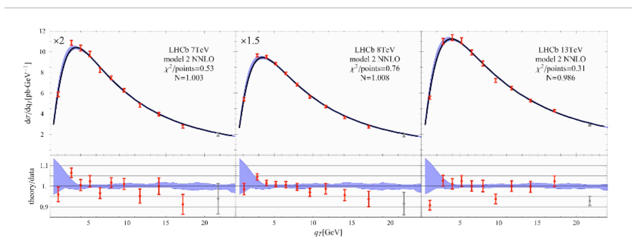
For the last development branch you can clone the master code:

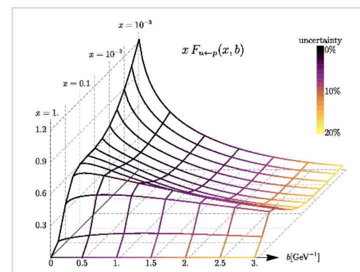
```
git clone git@github.com:vbertone/NangaParbat.git
```

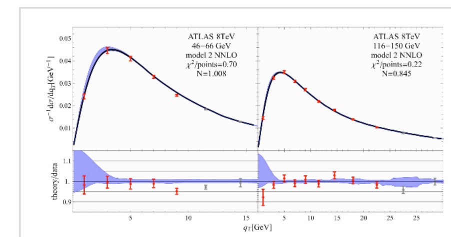
AVAILABLE TOOLS: ARTEMIDE

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

arTeMiDe







News

12 Dec 2019: Version 2.02 released (+manual update).

23 Feb 2019: Version 1.4 released (+manual update).

21 Jan 2019: Artemide now has a repository.

Archive of older links/news.

Articles, presentations & supplementary materials

Extra pictures for the paper arXiv:1902.08474

Seminar of A.Vladimirov in Pavia 2018 on TMD evolution.

Link to the text in Inspire.

Archive of older links/news.

Download

Recent version/release can be found in repository

About us & Contacts

If you have found mistakes, or have suggestions/questions, please, contact us.

Some extra materials can be found on Alexey's web-page

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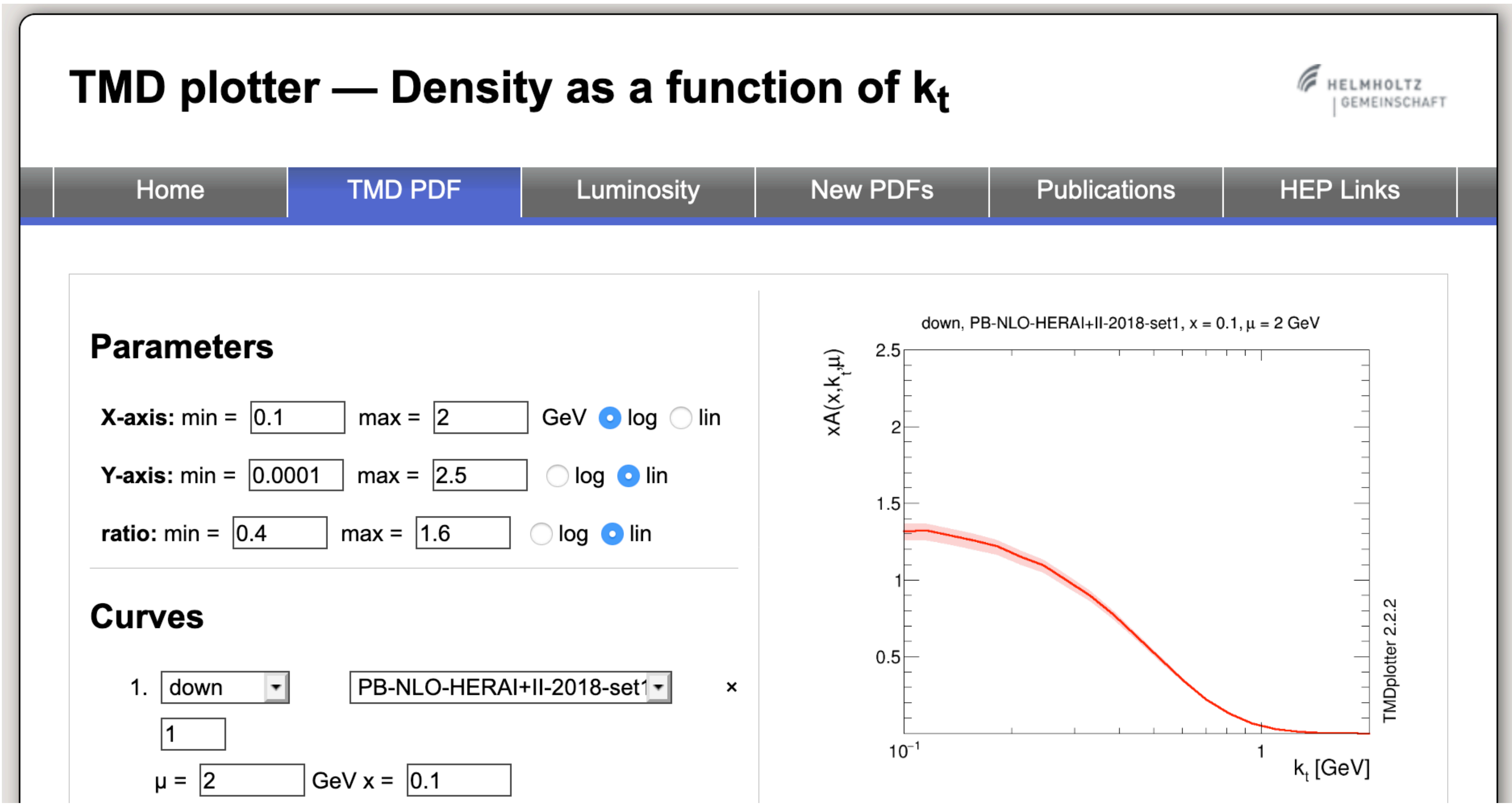
Ignazio Scimemi ignazios@fis.ucm.es

AVAILABLE TOOLS: TMDLIB AND TMDPLOTTER

https://tmdlib.hepforge.org/



Soon more TMD parametrisation will be available

PROBLEMS WITH SIDIS NORMALIZATION

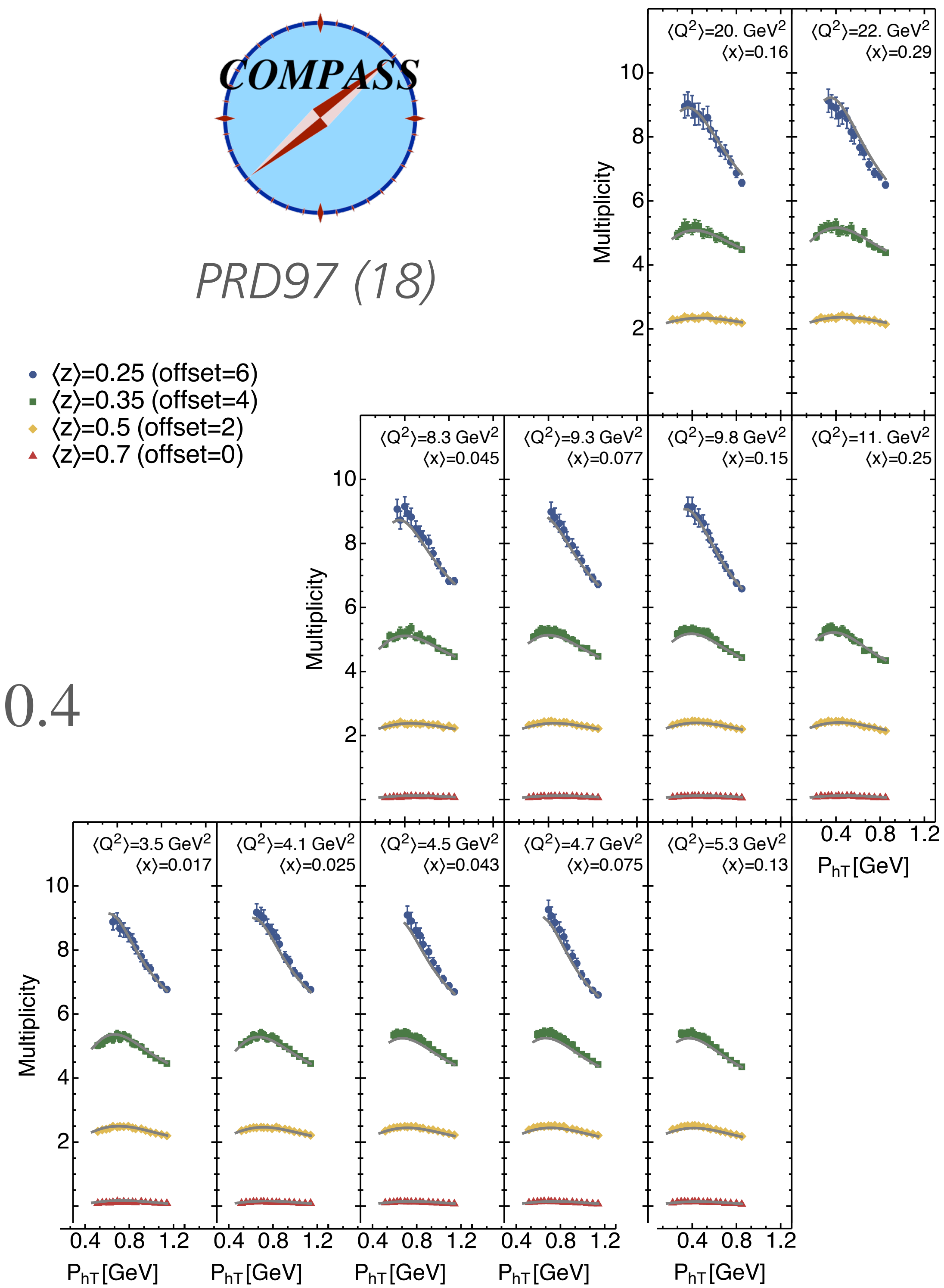
Comparing the PV17 extraction with the new COMPASS data, without normalization factors, at NLL the agreement is very good

PRD97 (18)

NLL $\quad H = 1$

NLL′ $\quad H = 1 + \frac{C_F}{\pi}\left(-4 + \frac{\pi^2}{12}\right)\alpha_S \approx 1 - 0.4$

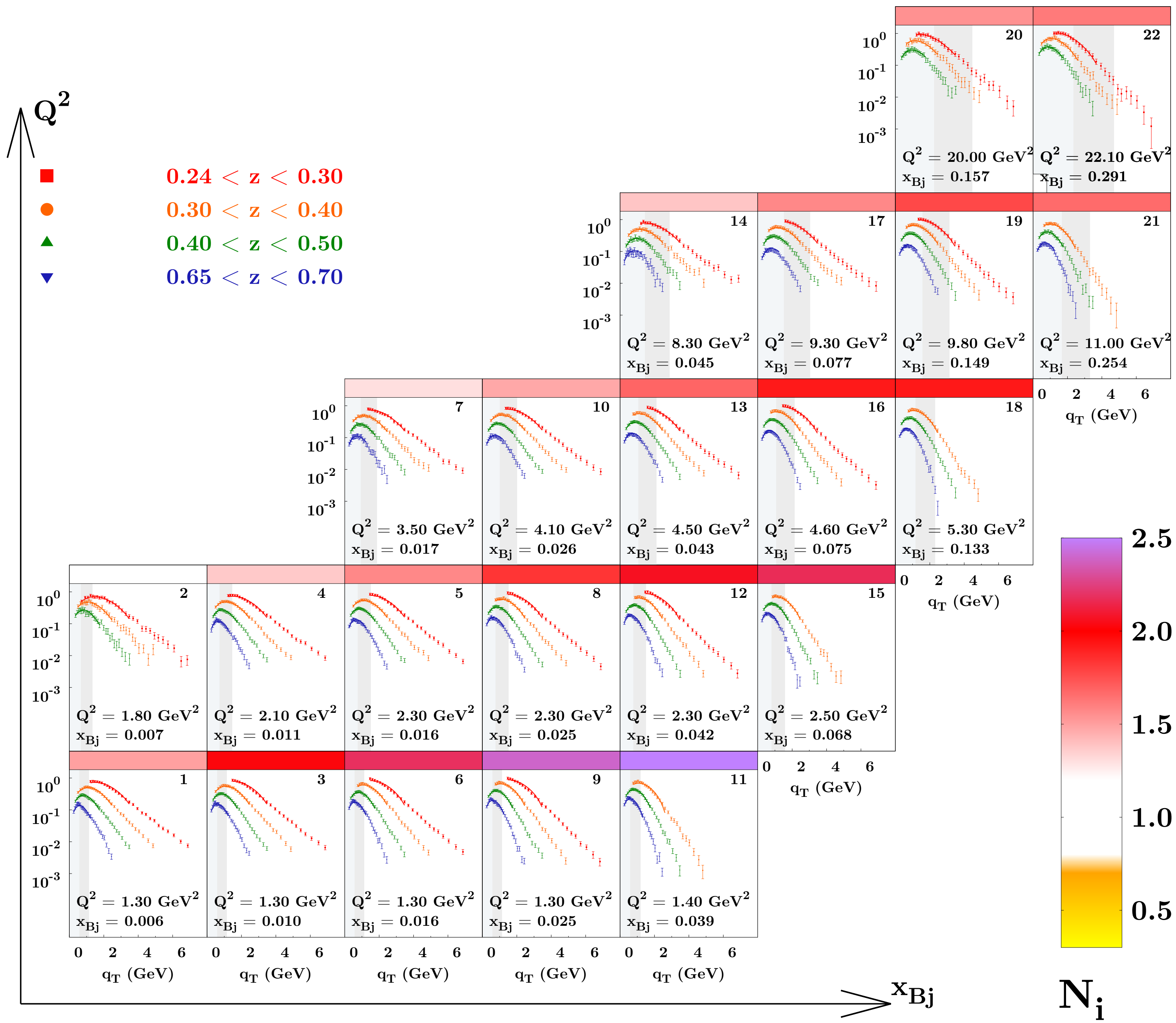
Going to NLL′ or NNLL the situation dramatically worsens!



from F. Piacenza's PhD thesis

PROBLEMS WITH SIDIS NORMALIZATION

talk by O. Gonzalez at DIS2019



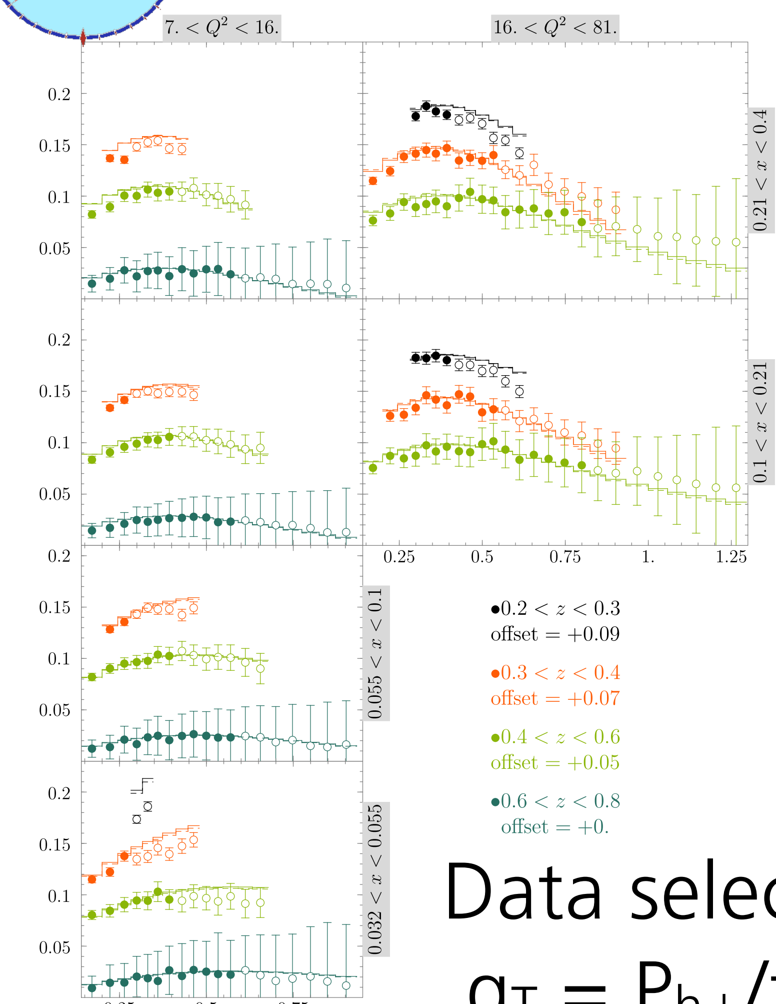
Torino's group also confirmed that large normalisation factors have to be introduced to describe COMPASS data

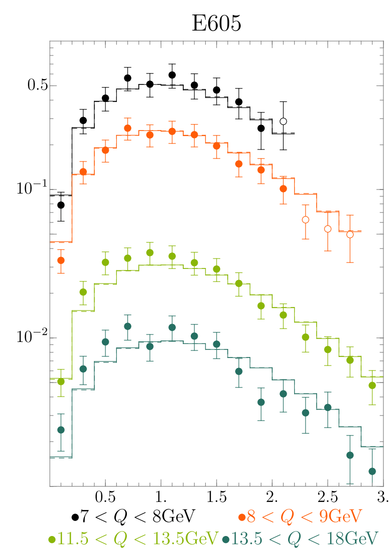
THE SCIMEMI-VLADIMIROV 19 EXTRACTION

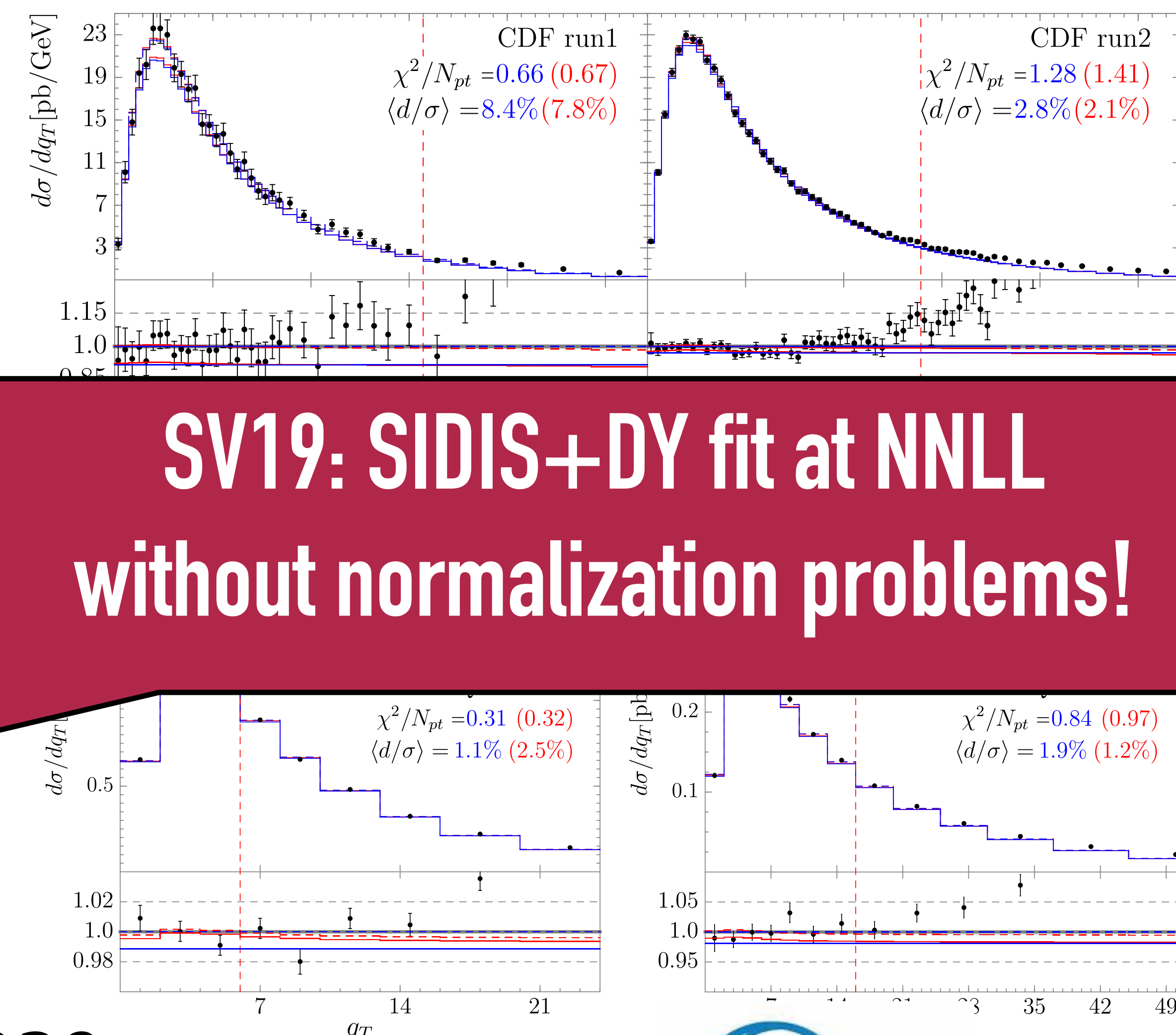
Scimemi, Vladimirov, arXiv:1912.06532

$z^2 \times M(z, p_T)$

$d \to h^+$







SV19: SIDIS+DY fit at NNLL without normalization problems!

Data selection:

$q_T = P_{h\perp}/z < 0.25\ Q$

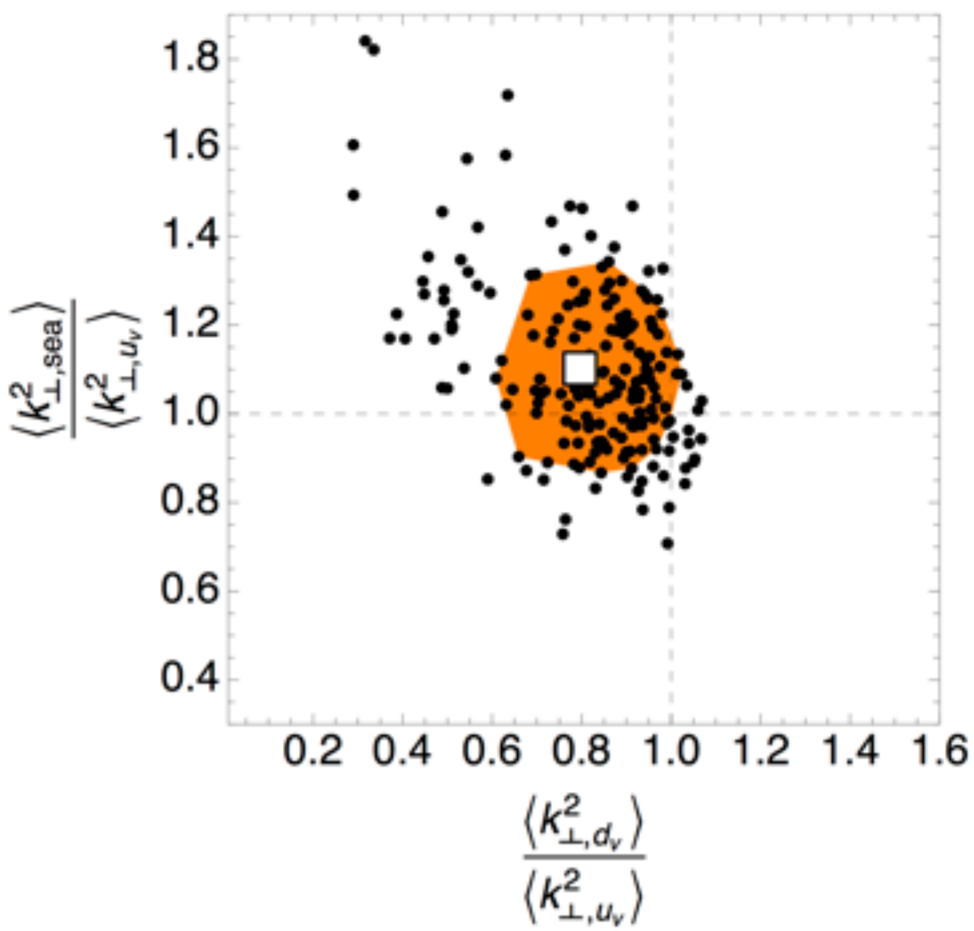
Number of data points: 1039

Global χ^2/dof = 1.06

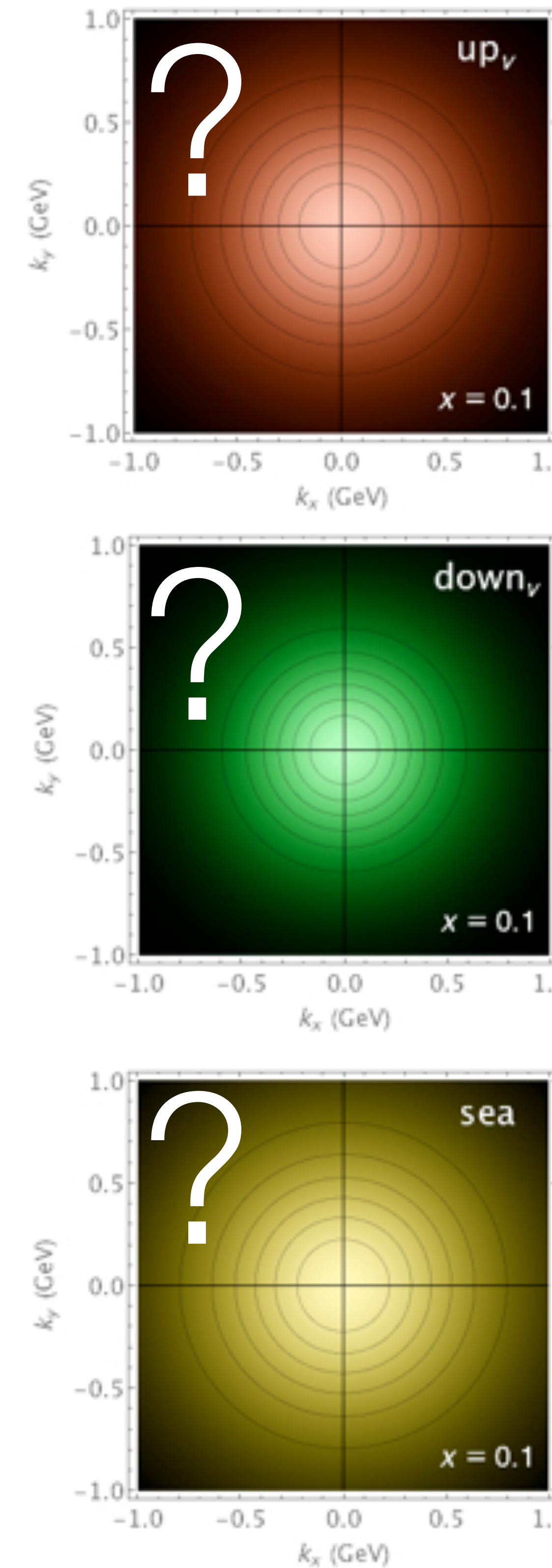
FLAVOR DEPENDENCE OF TMDS

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

Ratio of width of sea / width of up valence



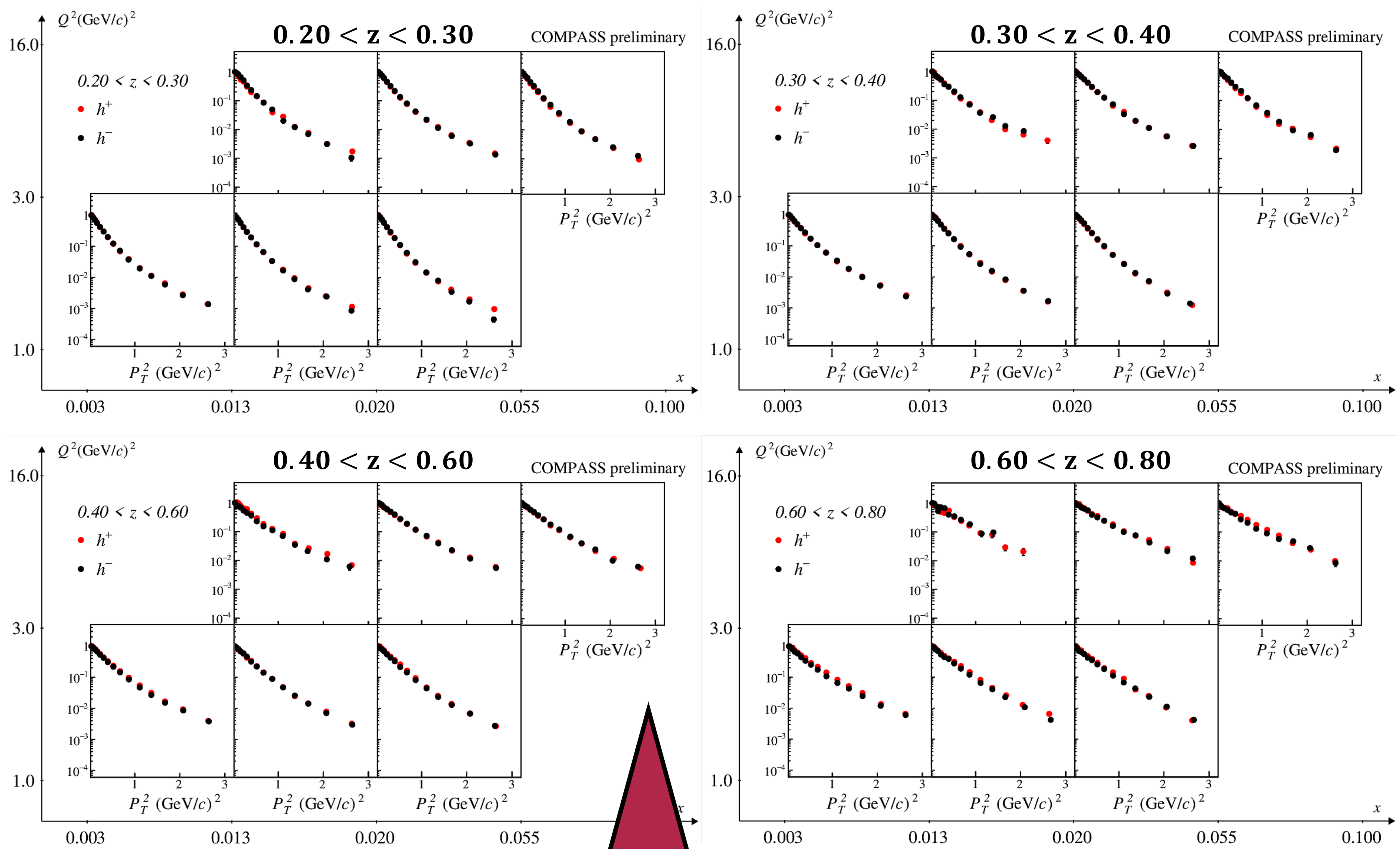
Ratio width of down valence/ width of up valence



Still unknown!

IMPORTANCE OF COMPASS DATA

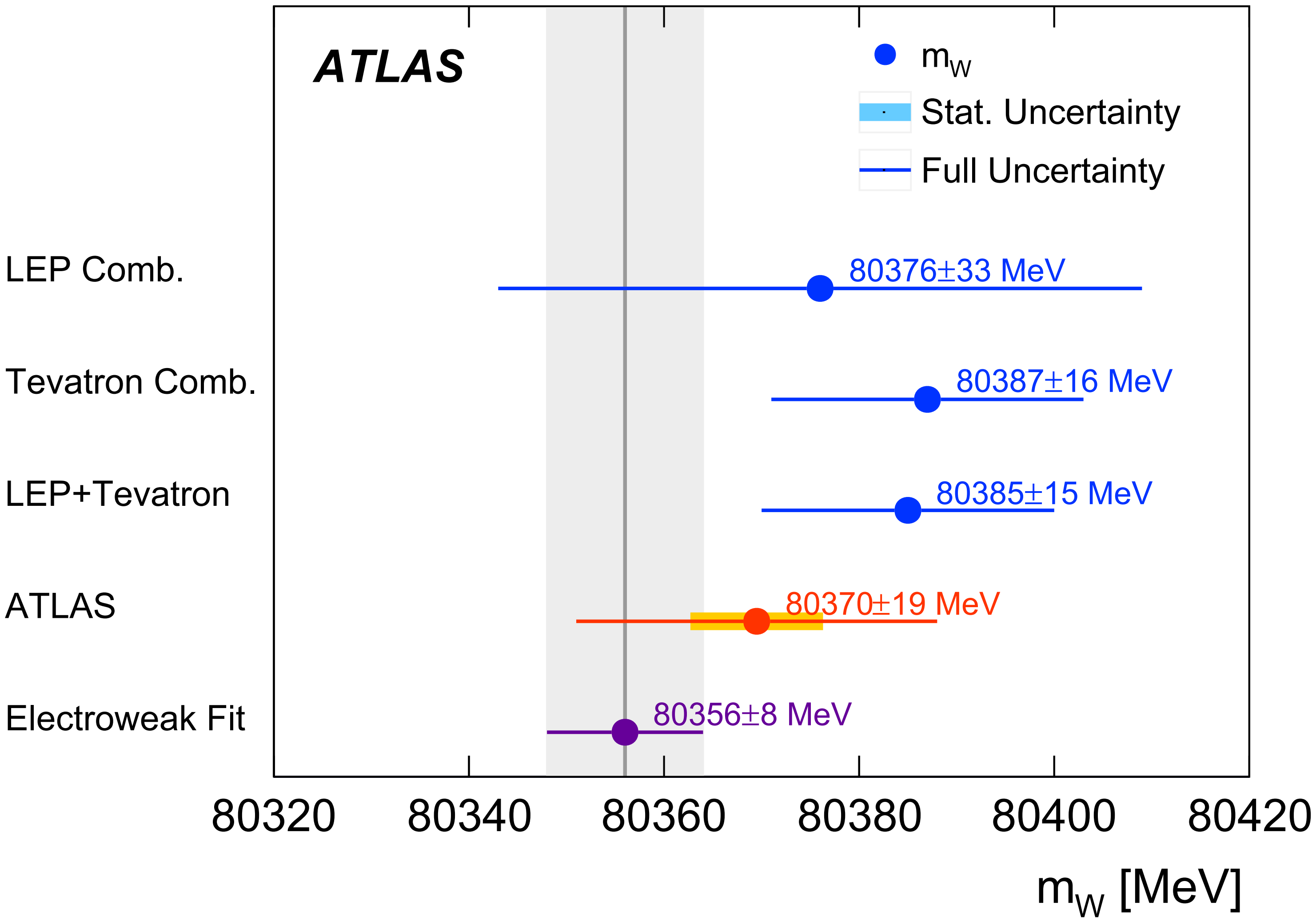
A. Moretti's talk at ICNFP 2020
https://indico.cern.ch/event/868045/contributions/3996129/



Proton data (in addition to published deuteron data) will be extremely important to pin down flavor dependence of TMDs

IMPACT ON W MASS DETERMINATION

ATLAS Collab. arXiv:1701.07240



All analyses assume that TMDs are not flavor 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

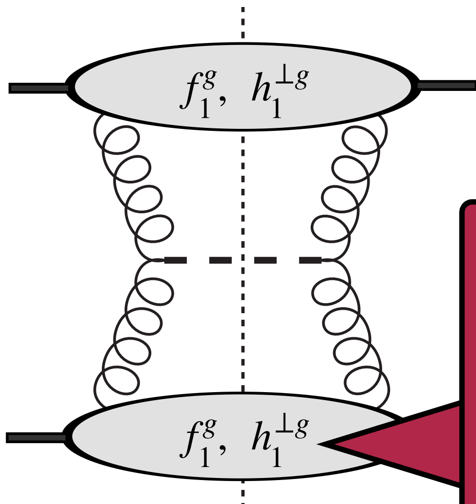
	ΔM_{W^+}		ΔM_{W^-}	
Set	m_T	$p_{T\ell}$	m_T	$p_{T\ell}$
1	0	-1	-2	3
2	0	-6	-2	0
3	-1	9	-2	-4
4	0	0	-2	-4
5	0	4	-1	-3

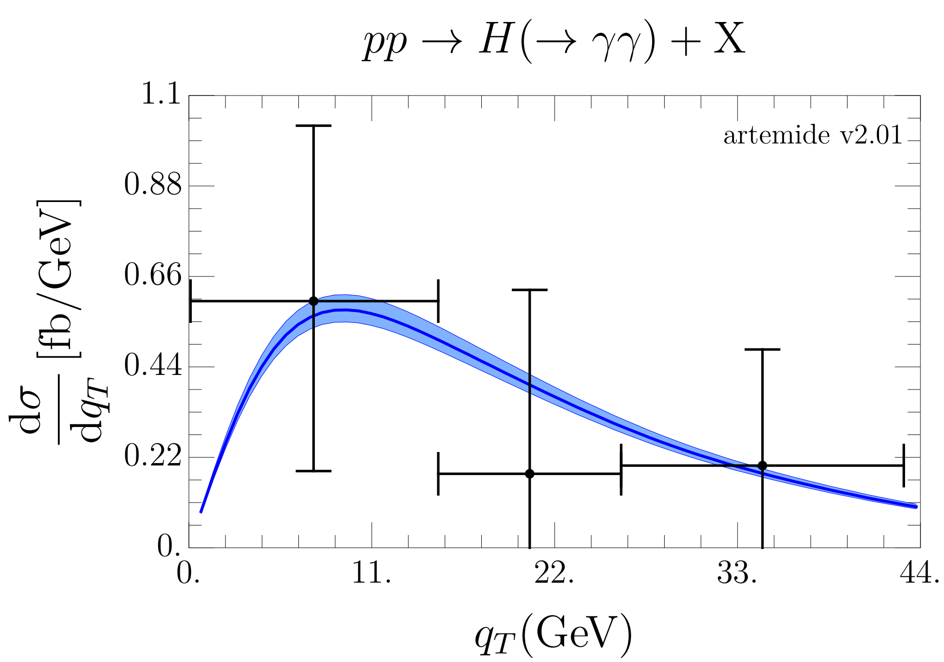
Not taking into account the flavour dependence of TMDs can lead to errors in the determination of the W mass

GLUON TMDS

Higgs production

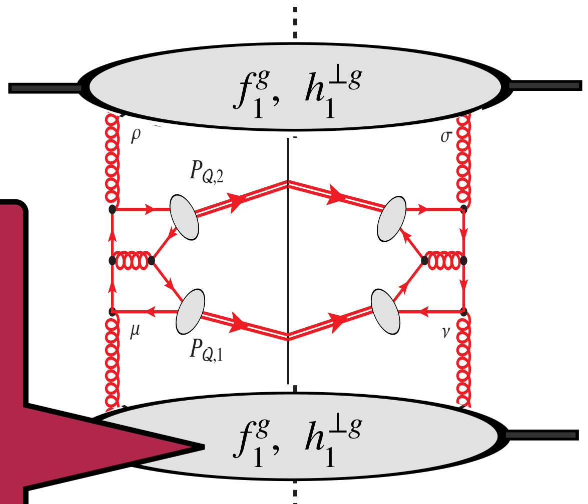
Gutierrez-Reyes, Leal-Gomez, Scimemi, Vladimirov, arXiv:1907.03780

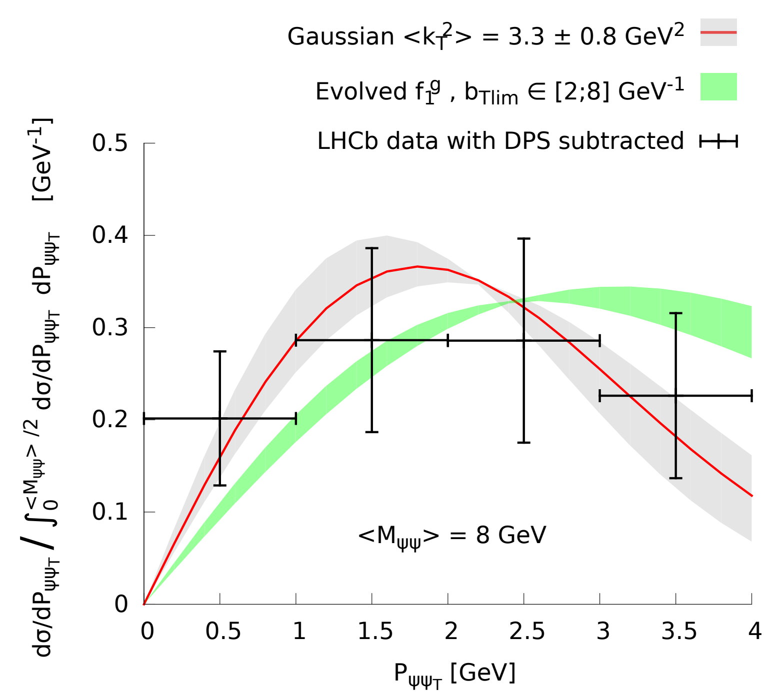




Quarkonium-pair production

Scarpa, Boer, Echevarria, Lansberg, Pisano, Schlegel, arXiv:1909.05769





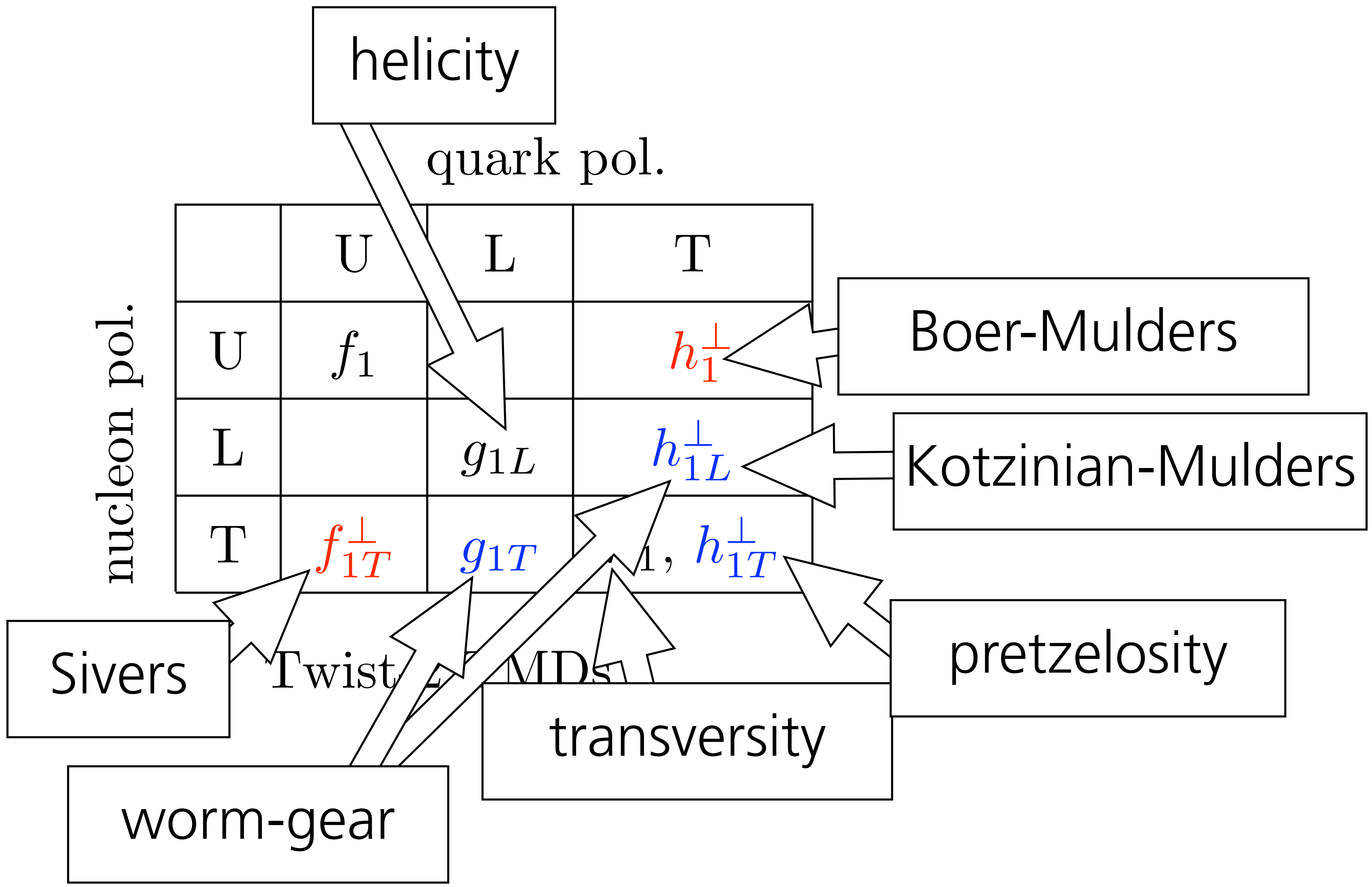
Also linearly polarized gluon TMD is involved!

see talk by D. Boer

POLARIZED TMDS

see also M. Radici's talk

TMD TABLE



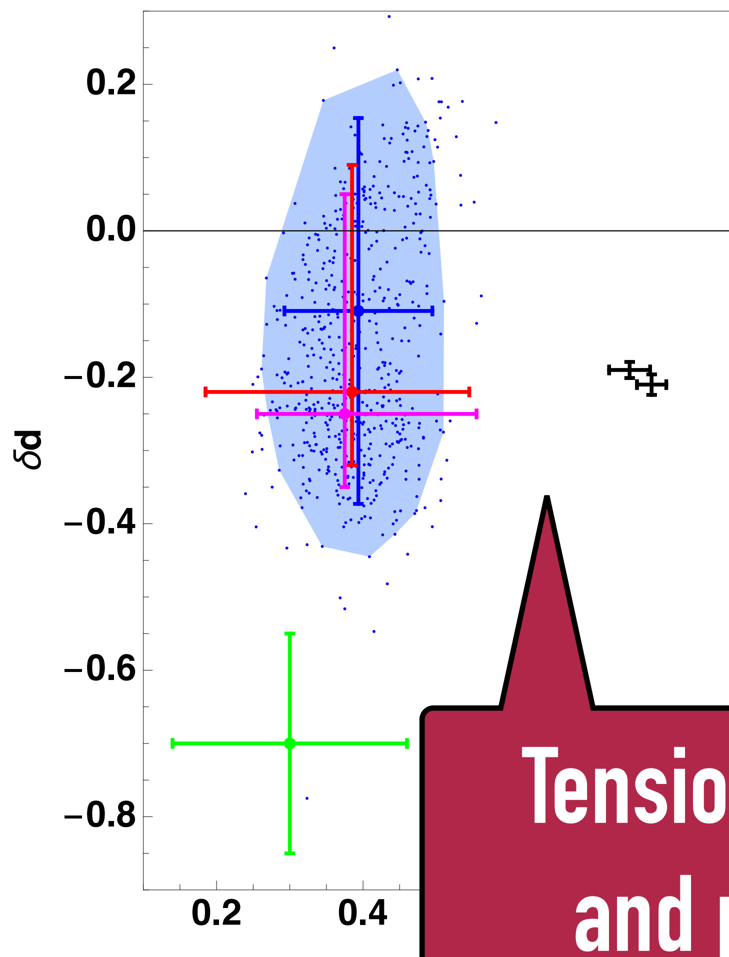
TMDs in black survive integration over transverse momentum
TMDs in red are time-reversal odd

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

On top of these, there are twist-3 functions

TENSOR CHARGE FROM TRANSVERSITY

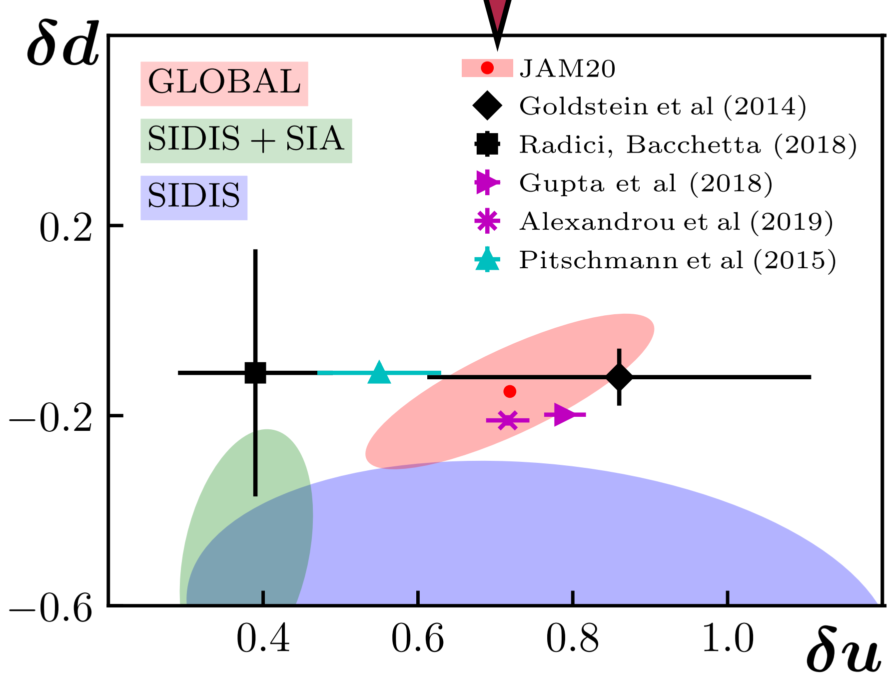
Tensor charge
$$\delta q \equiv g_T^q = \int_0^1 dx \;\; \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right]$$



- ★ 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

Tension between lattice and phenomenology

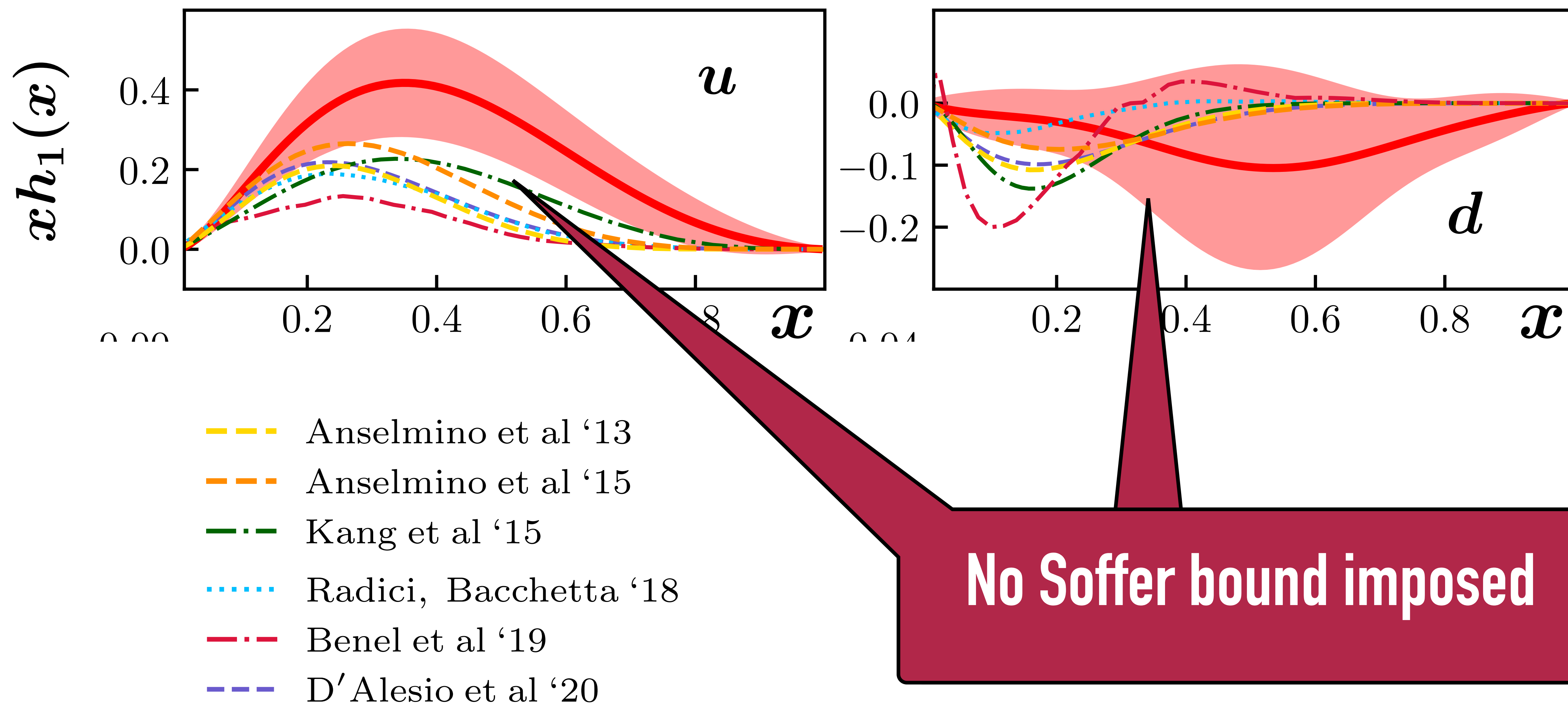
No tension?



Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato, arXiv:2002.08384

TRANSVERSITIES

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato, arXiv:2002.08384

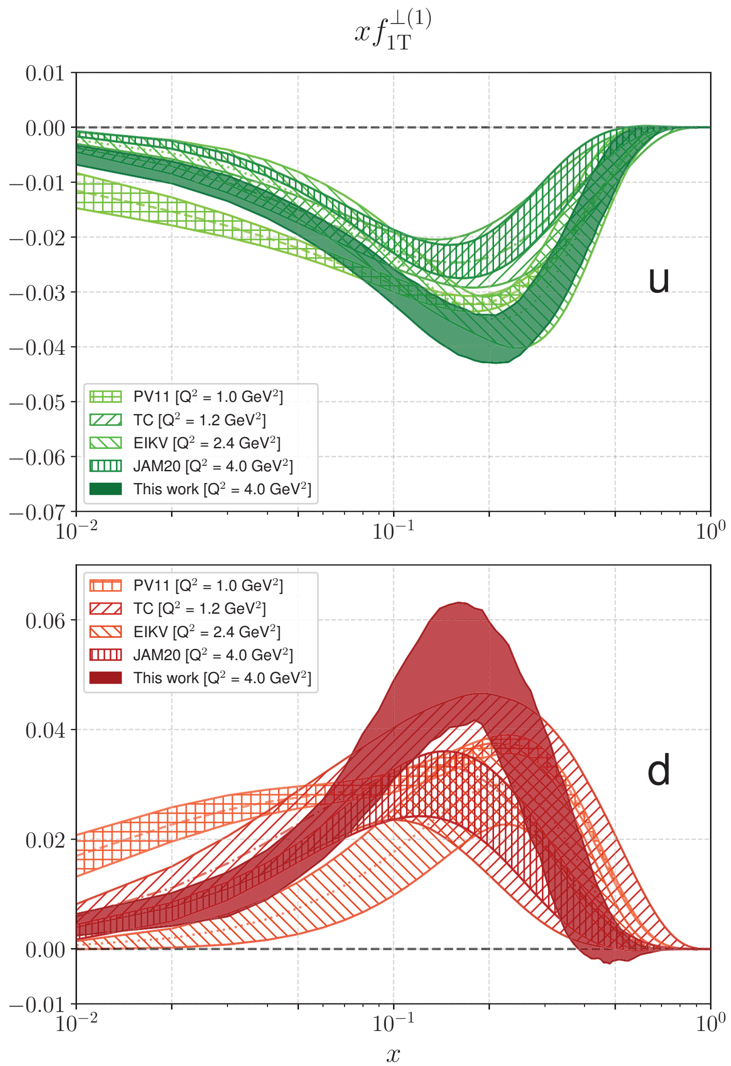


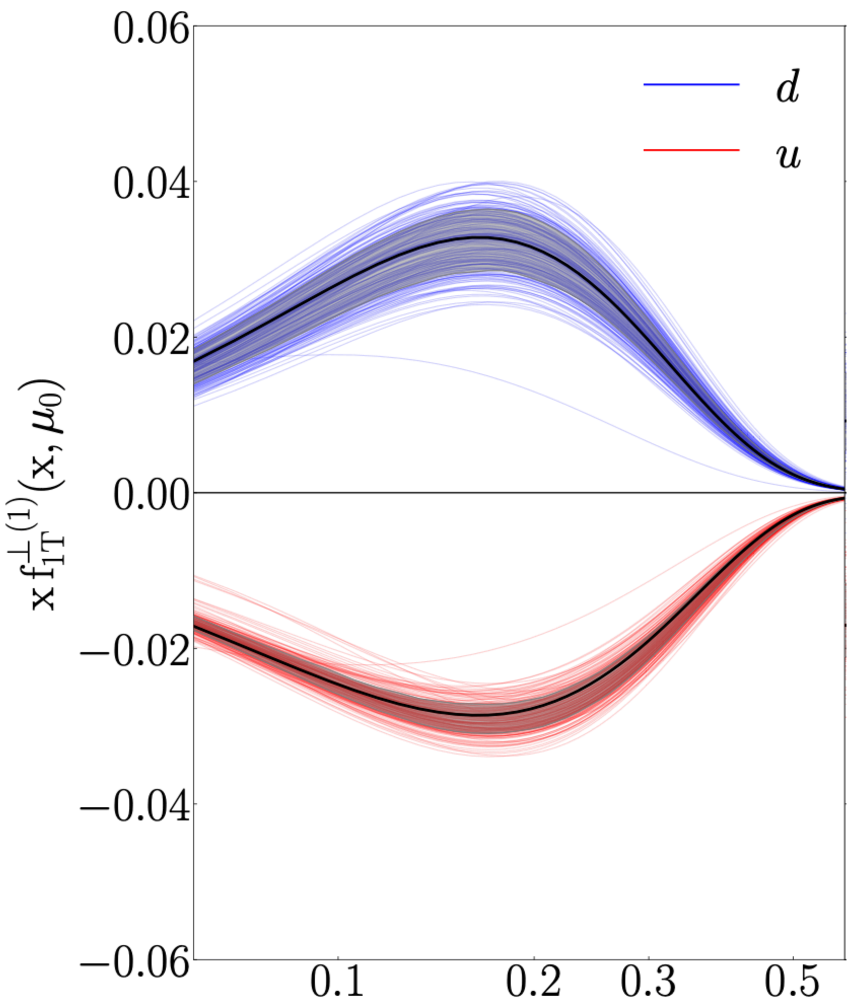
No Soffer bound imposed

see M. Radici’s talk

SIVERS FUNCTION

Without RHIC W & Z data



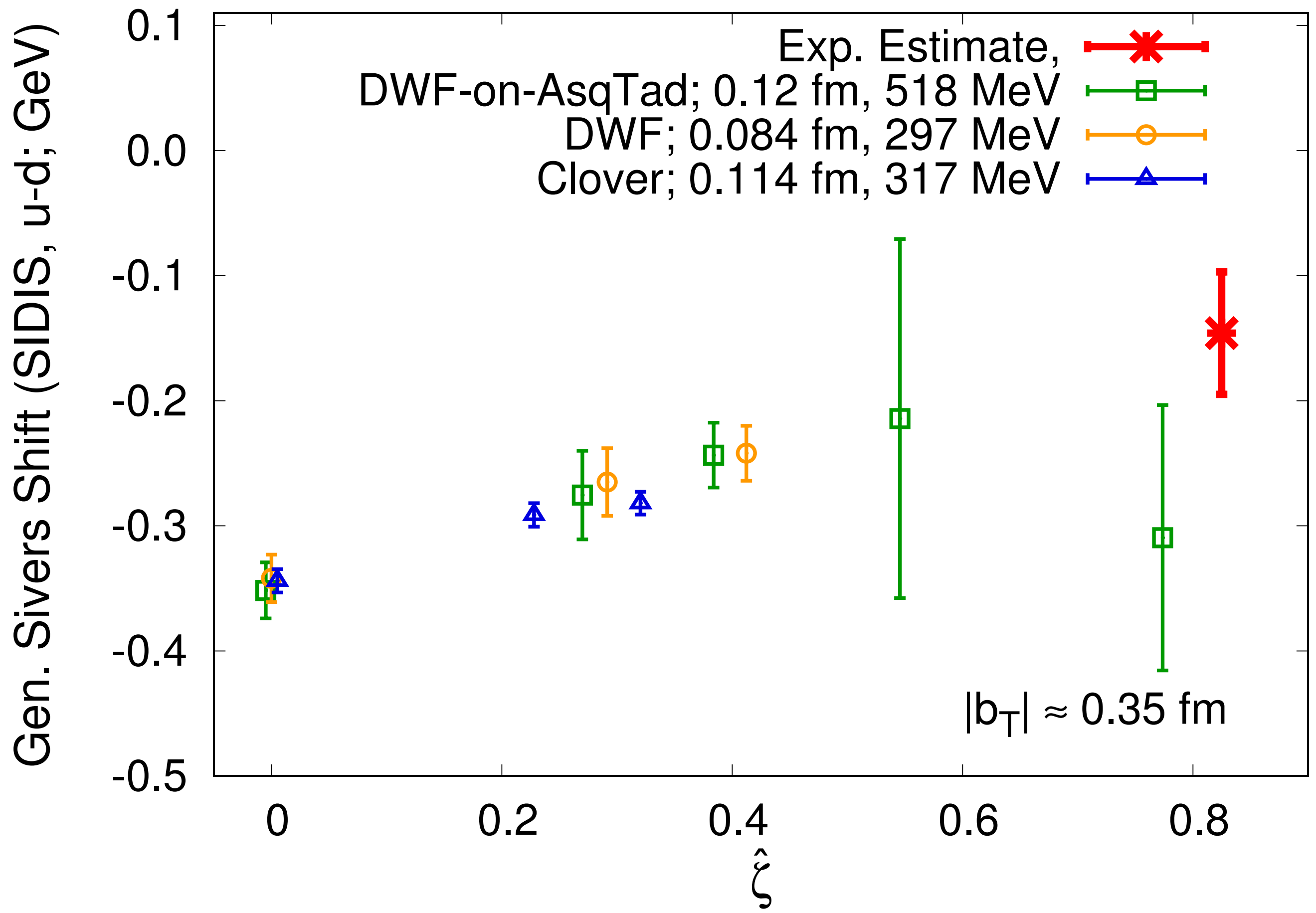


Bacchetta, Delcarro, Pisano, Radici, arXiv:2004.14278

Echevarria, Kang, Terry, arXiv:2009.10710

see J. Terry's talk

SIVERS SHIFT IN LATTICE QCD



Yoon et al., arXiv:1706.03406

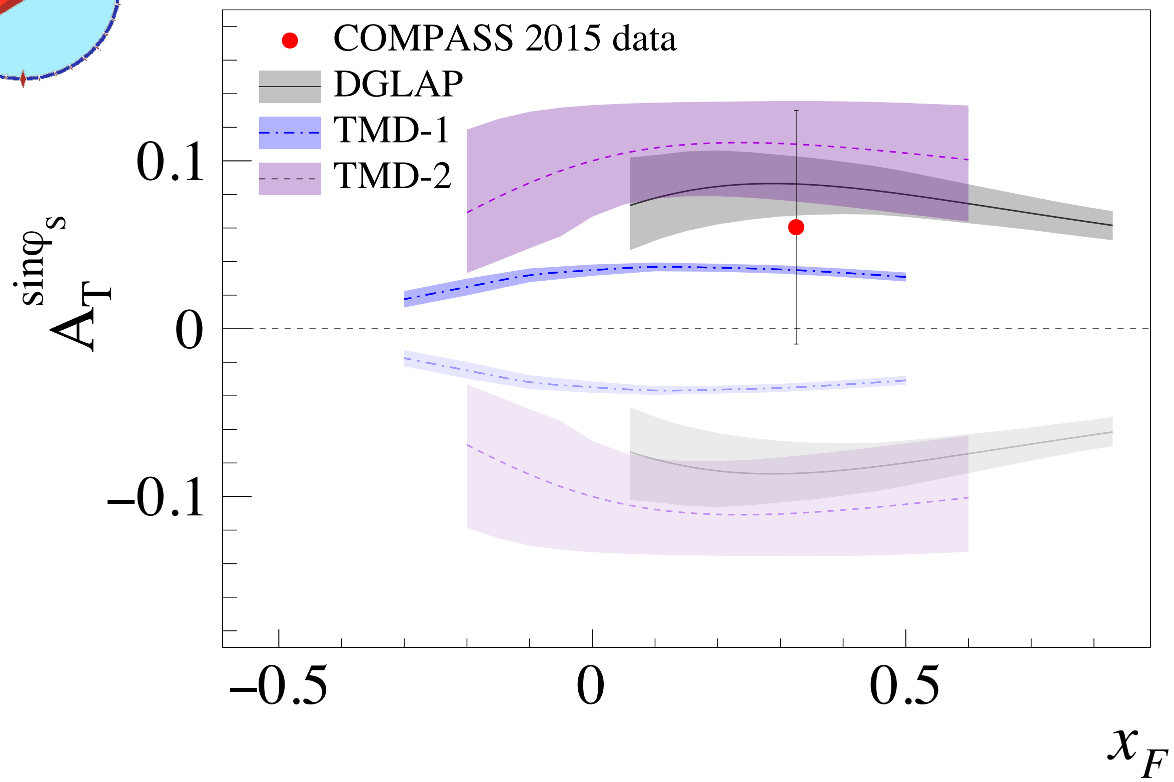
Pioneering lattice studies are in agreement with phenomenology

SIGN CHANGE?

Sivers function SIDIS = – Sivers function Drell-Yan

Collins, PLB 536 (02)

arXiv:1704.00488

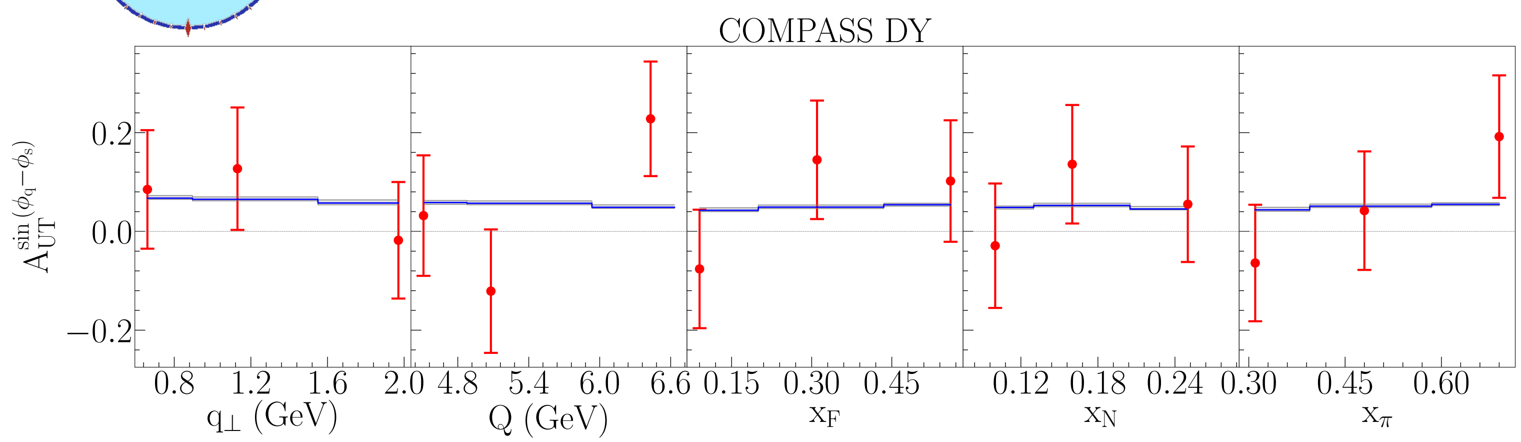


sign change

no sign change

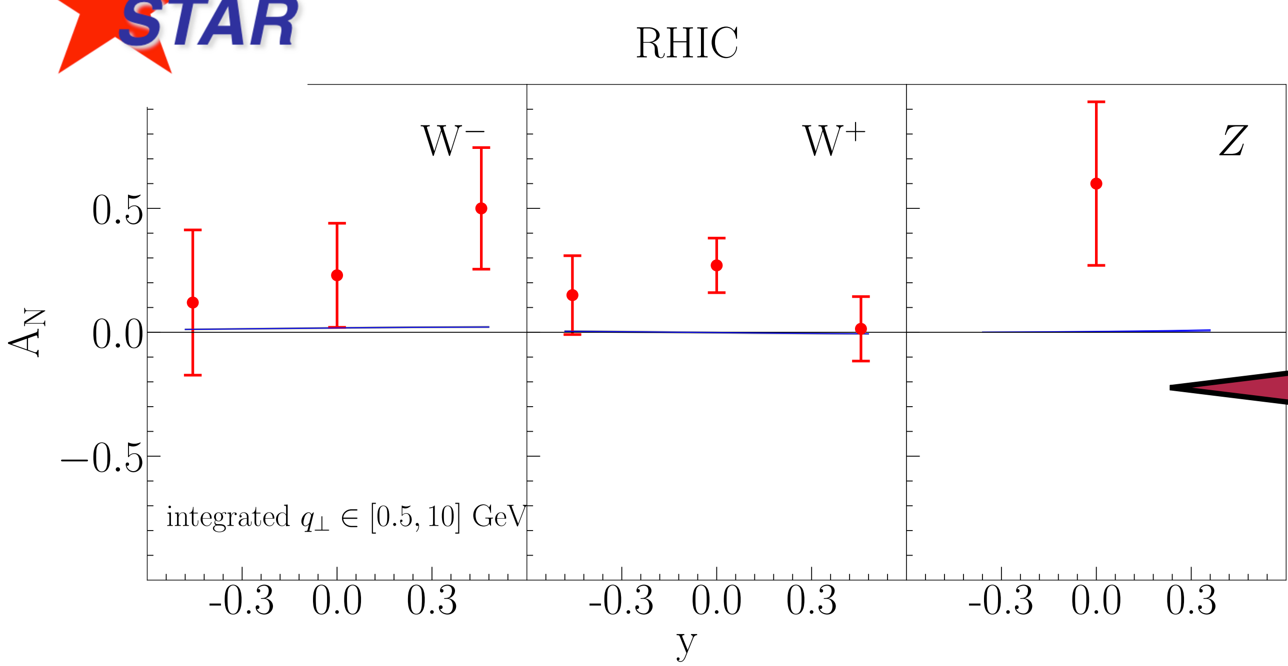
PROBLEMS WITH DY DATA?

Echevarria, Kang, Terry, arXiv:2009.10710



Ok

Collab	Ref	Process	Q_{avg}	N_{data}	χ^2/N_{data}
COMPASS	[46]	$\pi^- p \to \gamma^* X$	5.34	15	0.658
RHIC	[47]	$pp \to W^+ X$	M_W	8	2.189
		$pp \to W^- X$	M_W	8	1.684
		$pp \to Z^0 X$	M_Z	1	3.270

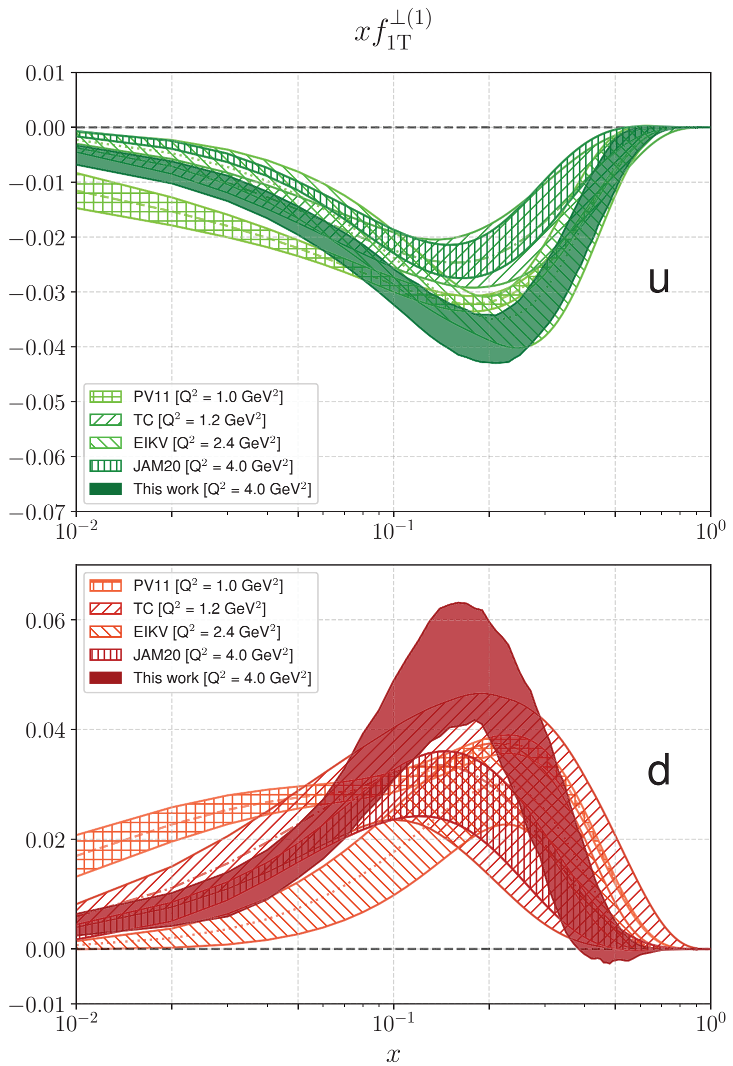


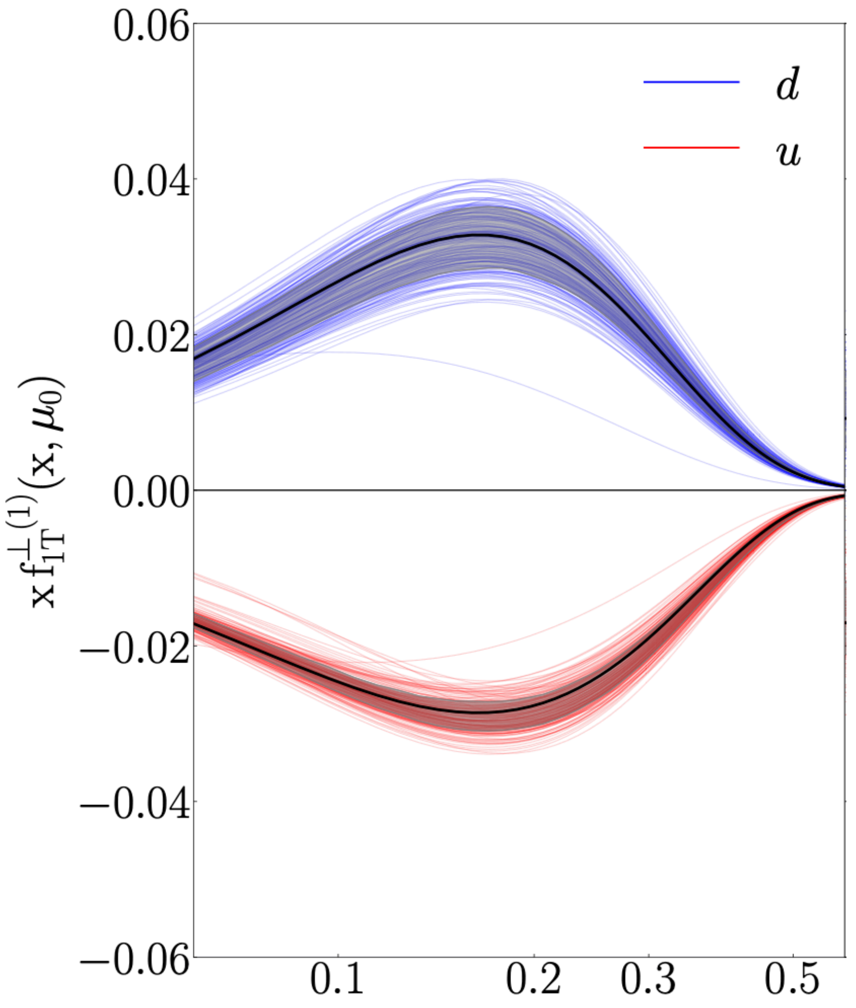
Not so Ok, but not because of sign...

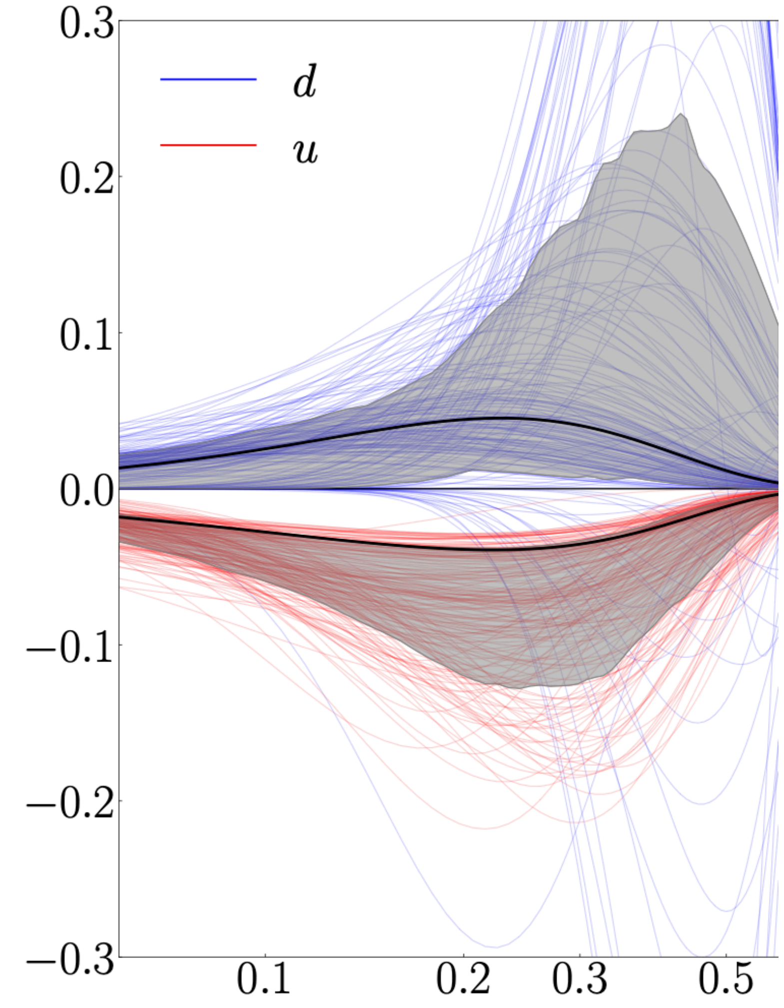
SIVERS FUNCTION

Without RHIC W & Z data

With RHIC W & Z data







Bacchetta, Delcarro, Pisano, Radici, arXiv:2004.14278

Echevarria, Kang, Terry, arXiv:2009.10710

see J. Terry's talk

WEIGHTED ASYMMETRIES

Unweighted

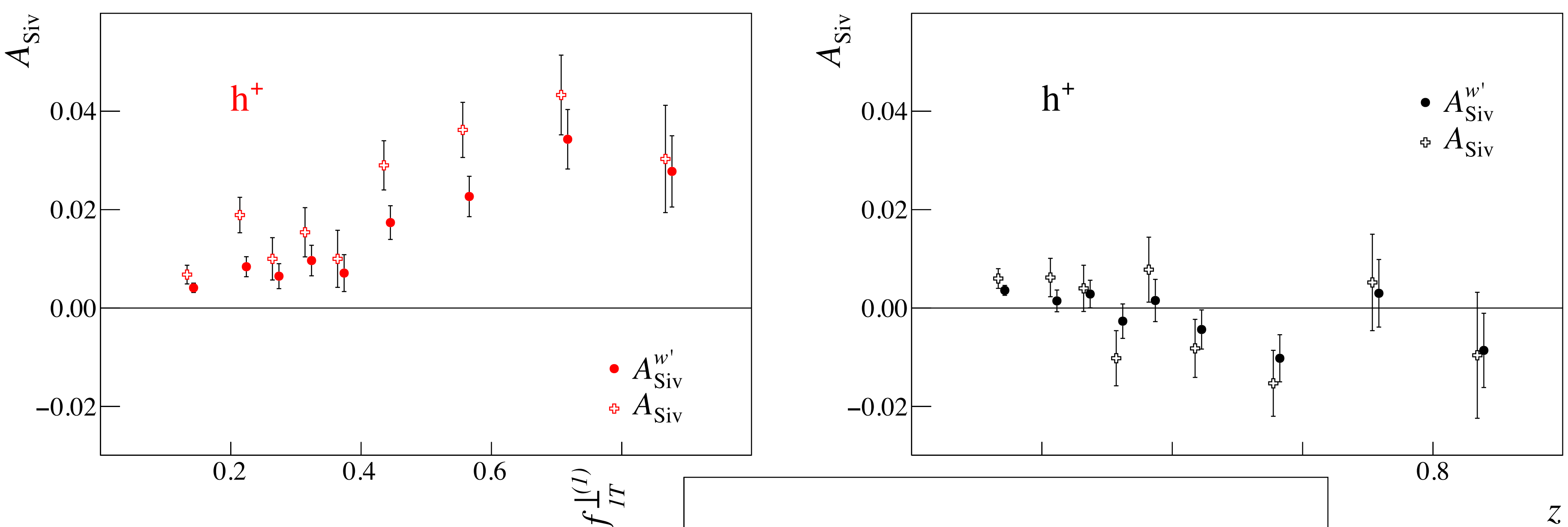
$$A_{\mathrm{Siv}}(x,z,P_T) = \frac{\sum_q e_q^2 x \mathscr{C}\left[\frac{P_T\cdot k_T}{MP_T} f_{1T}^{\perp q}(x,k_T^2) D_1^q(z,p_T^2)\right]}{\sum_q e_q^2 x \mathscr{C}\left[f_1^q(x,k_T^2) D_1^q(z,p_T^2)\right]}$$

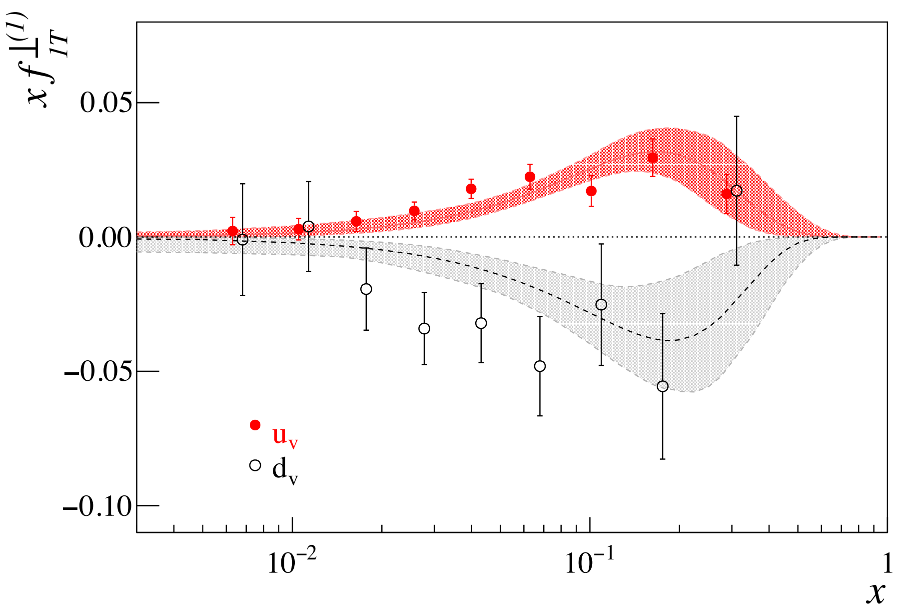
convolution

Weighted

$$A^w_{\mathrm{Siv}}(x,z) = 2\,\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) D_1^q(z)}{\sum_q e_q^2 x f_1^q(x) D_1^q(z)}$$

product



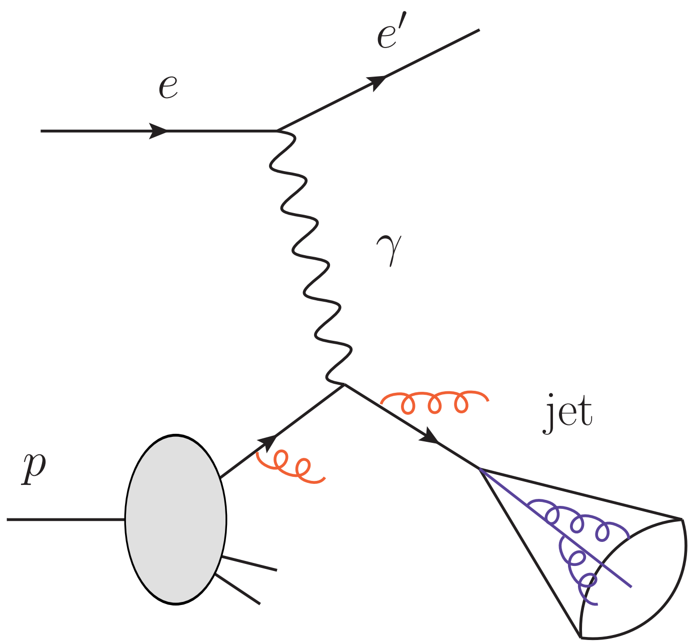


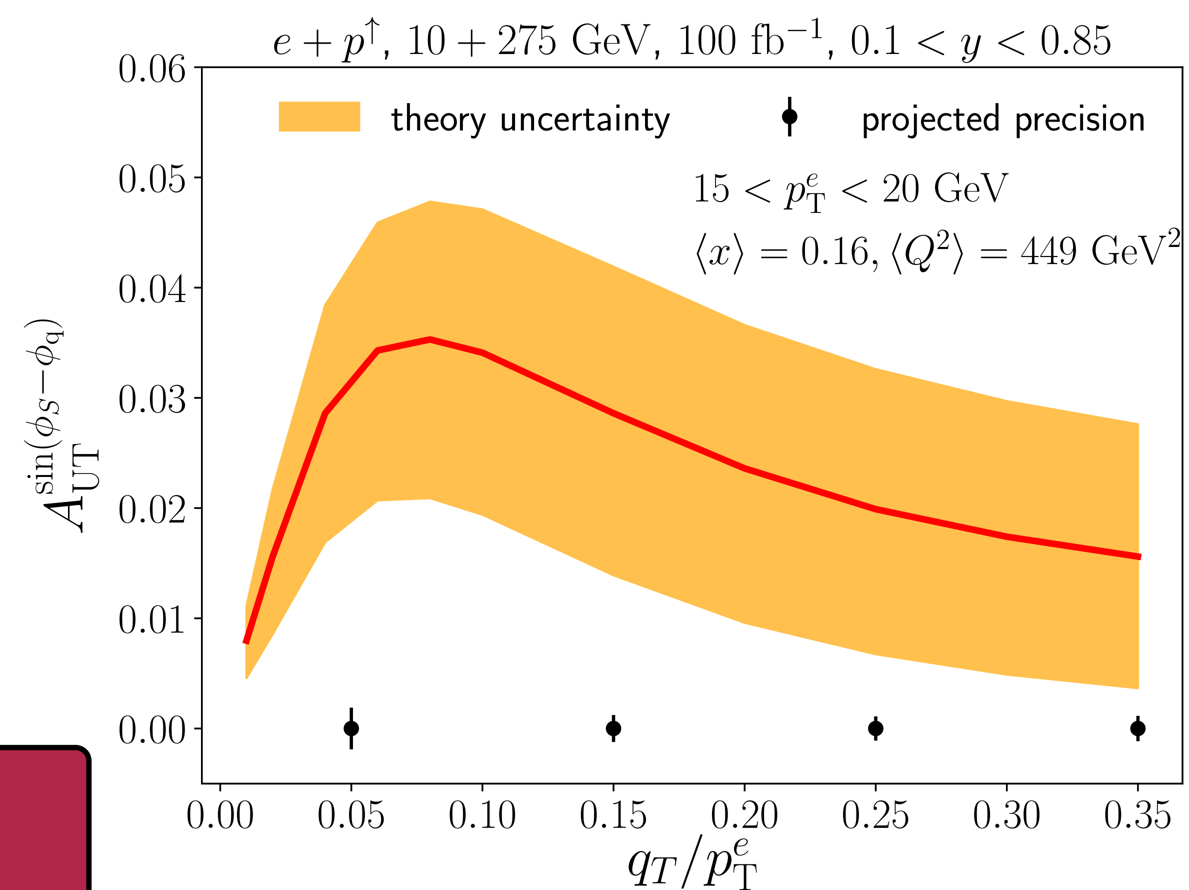
arXiv:1809.02936

see T. Rogers's talk

JET ASYMMETRIES (AT EIC)

Arratia, Kang, Prokudin, Ringer, arXiv:2007.077281



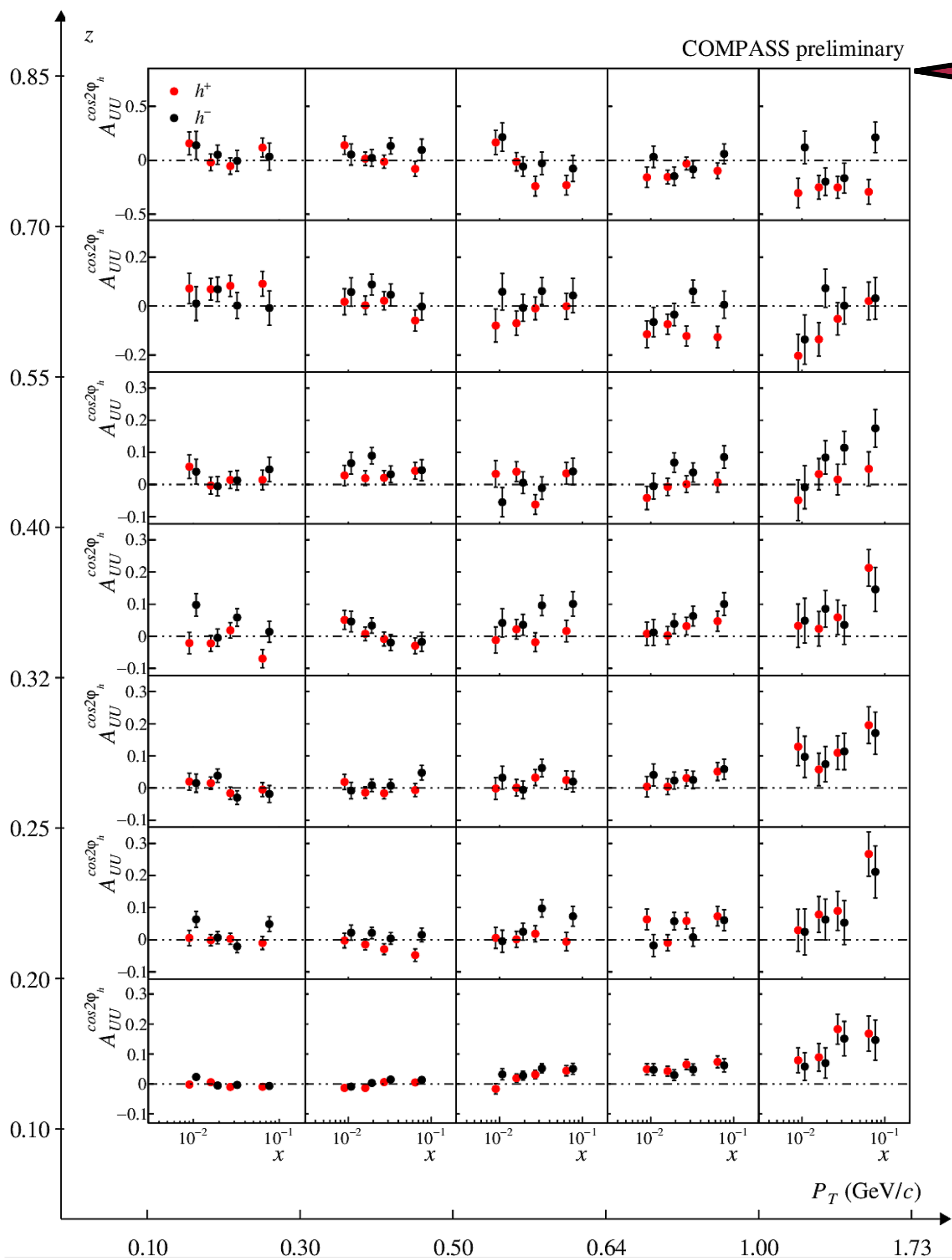


Exciting opportunities for TMD physics with jets

see also workshop next week (https://indico.bnl.gov/event/8066/)

BOER-MULDERS FUNCTION

A. Moretti's talk at ICNFP 2020
https://indico.cern.ch/event/868045/contributions/3996129/



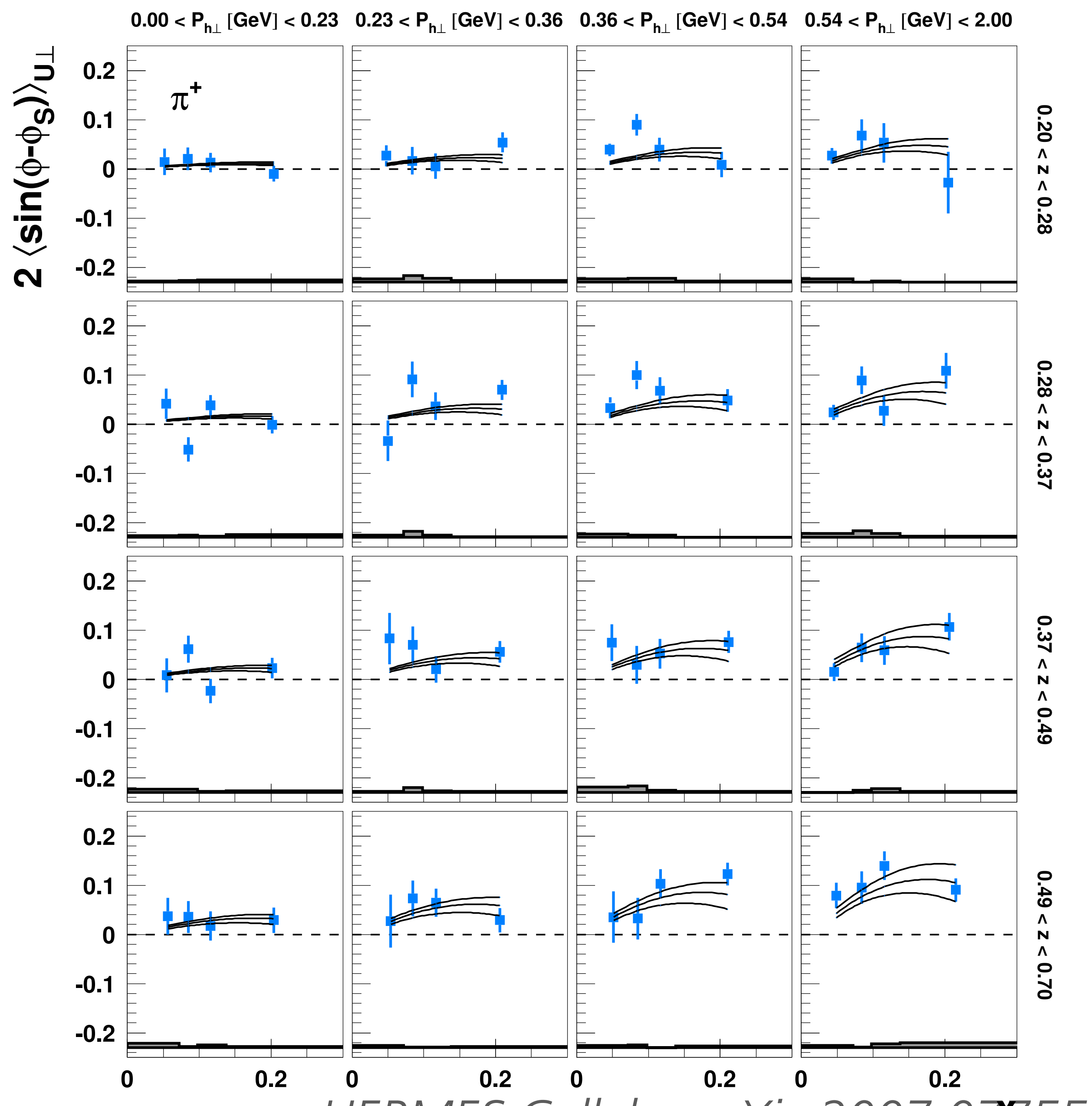
Cos2φ asymmetries sensitive to Boer-Mulders function.

Not much phenomenology in the last years about this signal, but it will come

THE FUTURE

"NEW" DATA FROM HERMES!

Multidimensional binning

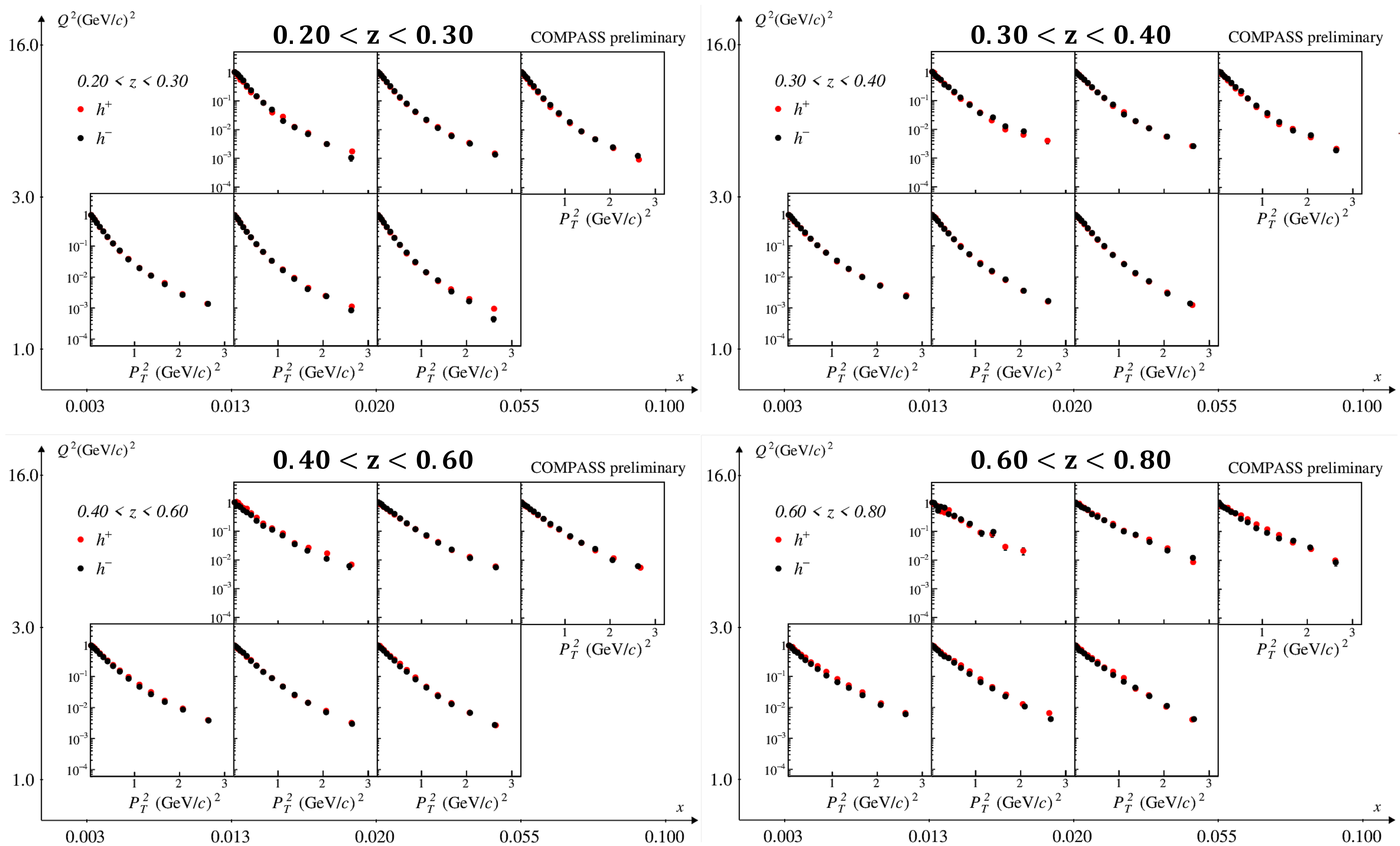


HERMES Collab., arXiv:2007.07755

Even if HERMES was closed 10 years ago, the collaboration is still producing results

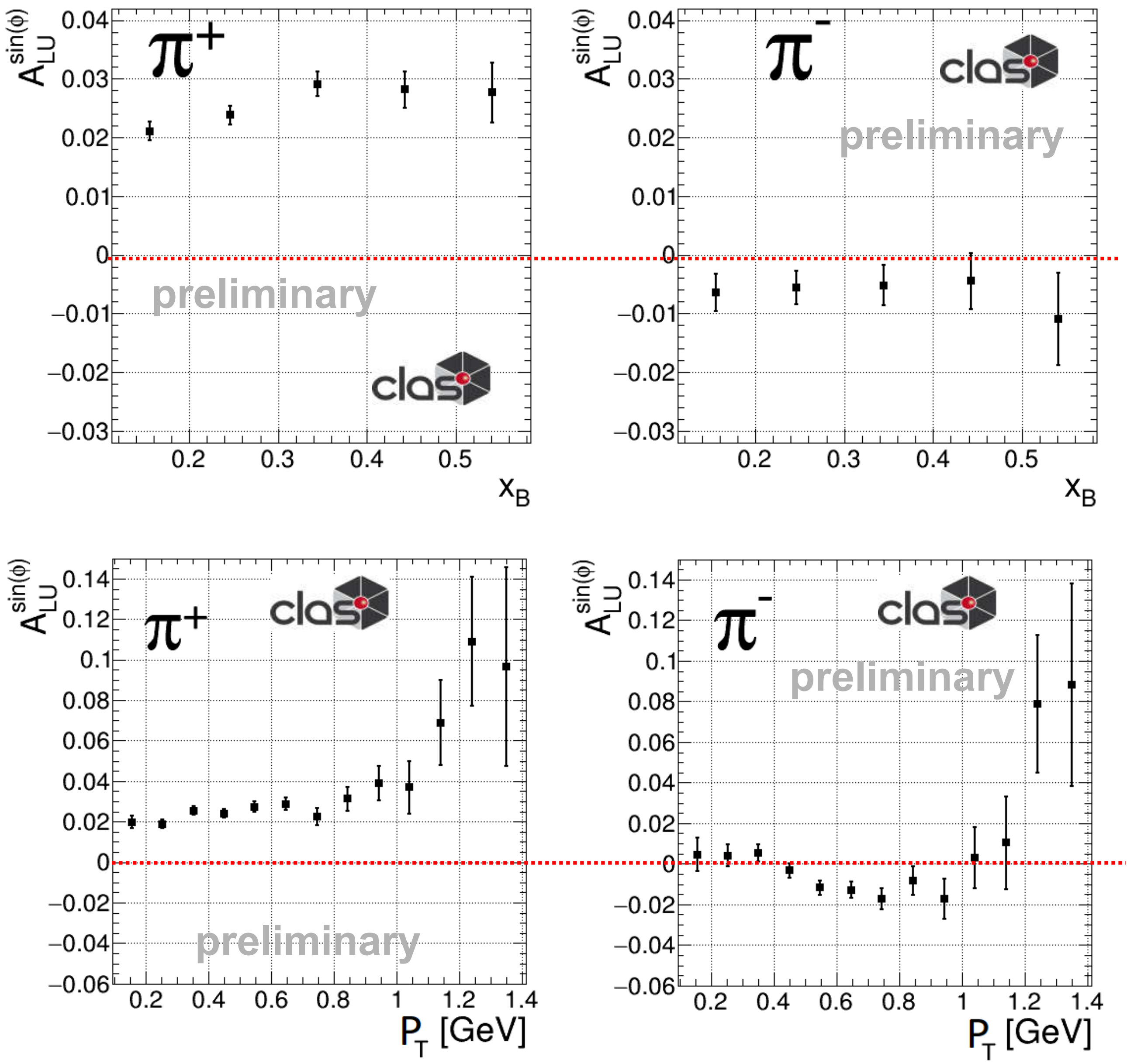
BRAVO!

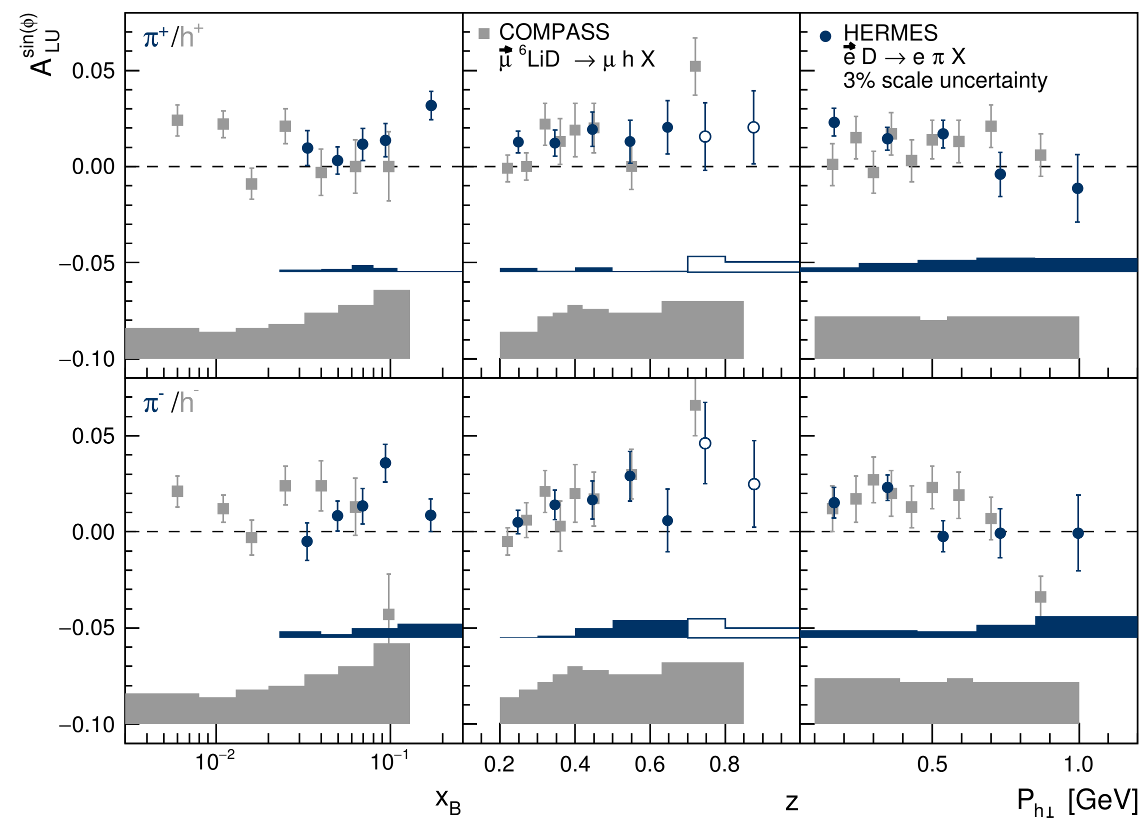
NEW DATA FROM COMPASS



COMPASS is in “full swing” mode **CONGRATS!**

FIRST JLAB PRELIMINARY DATA



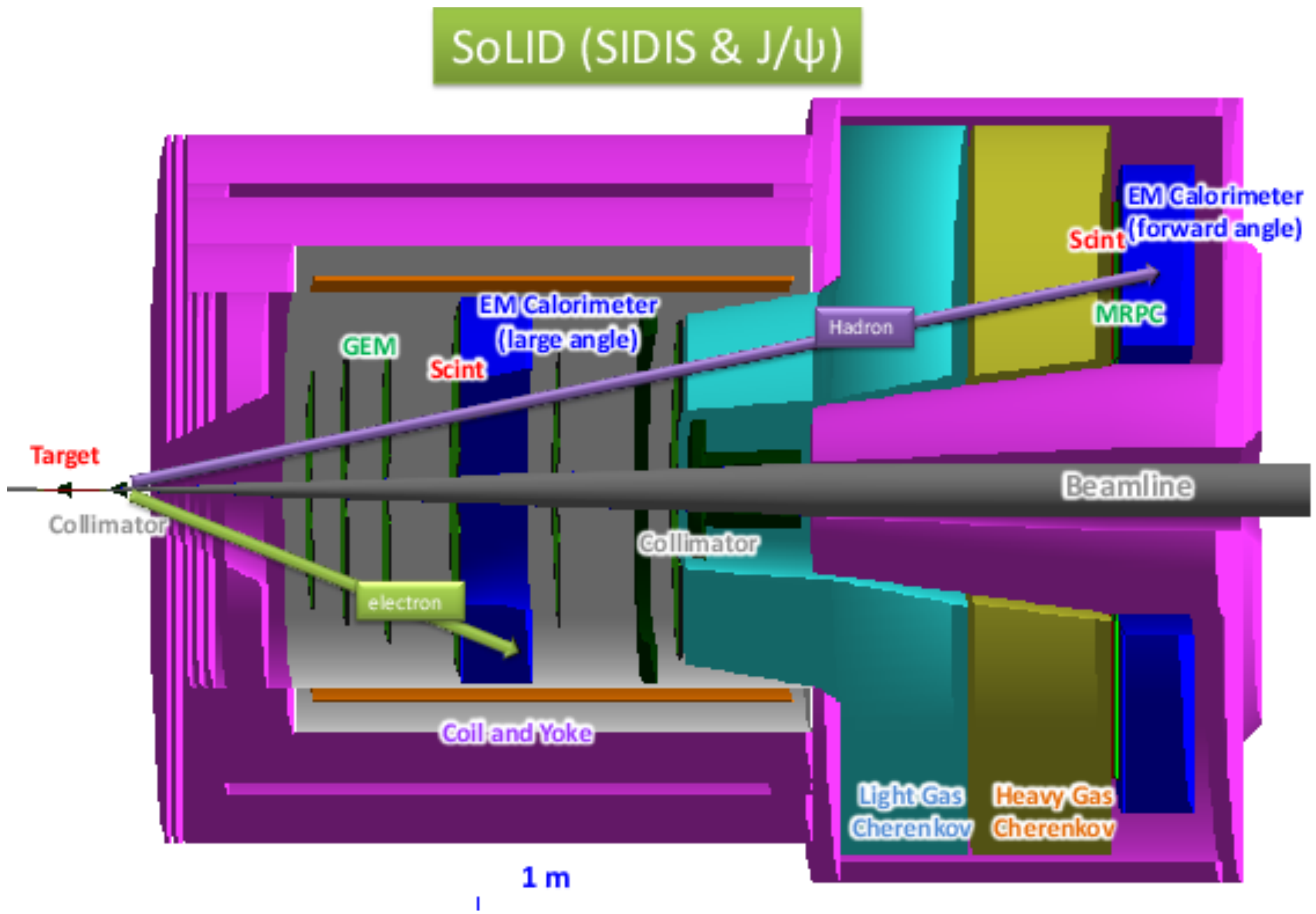


Only 2% of approved data taking

AWESOME!

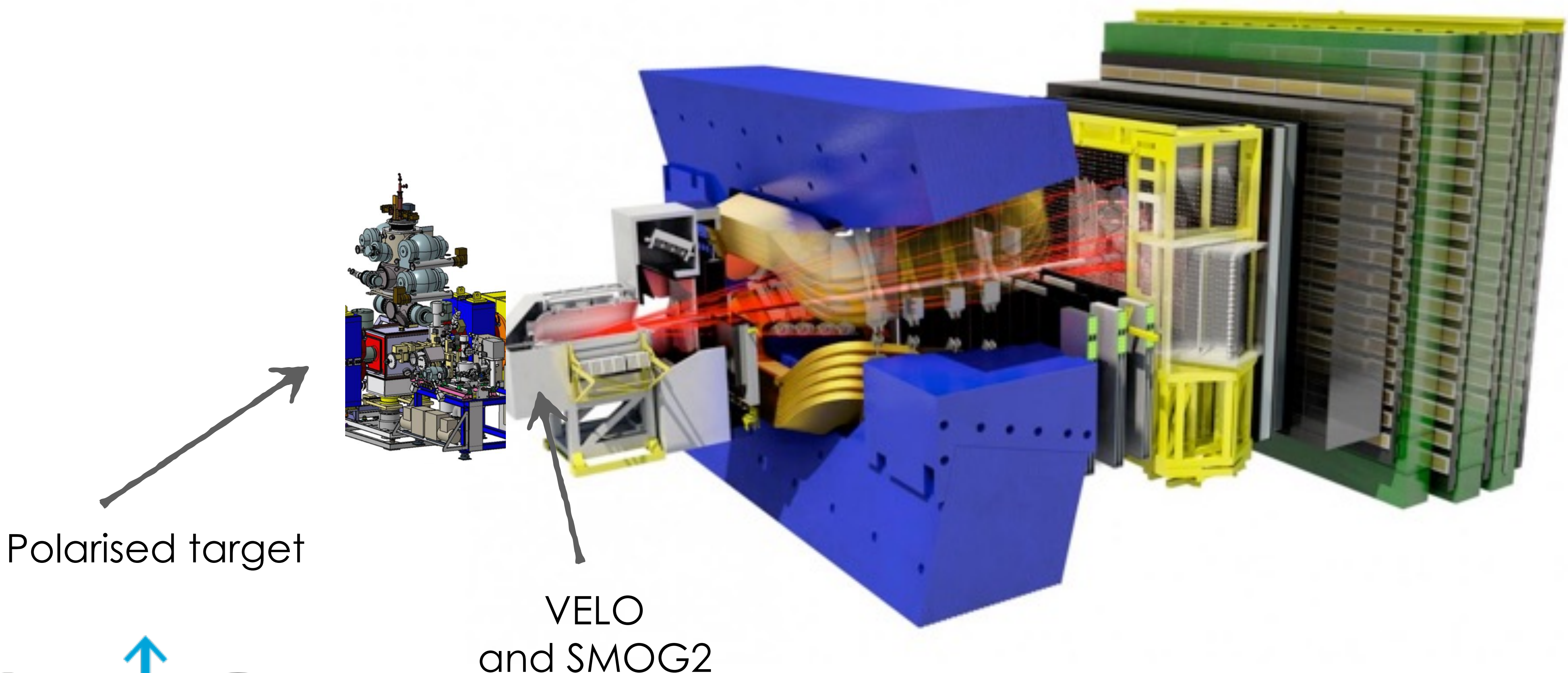
SOLID @ JLAB

https://hallaweb.jlab.org/12GeV/SoLID/



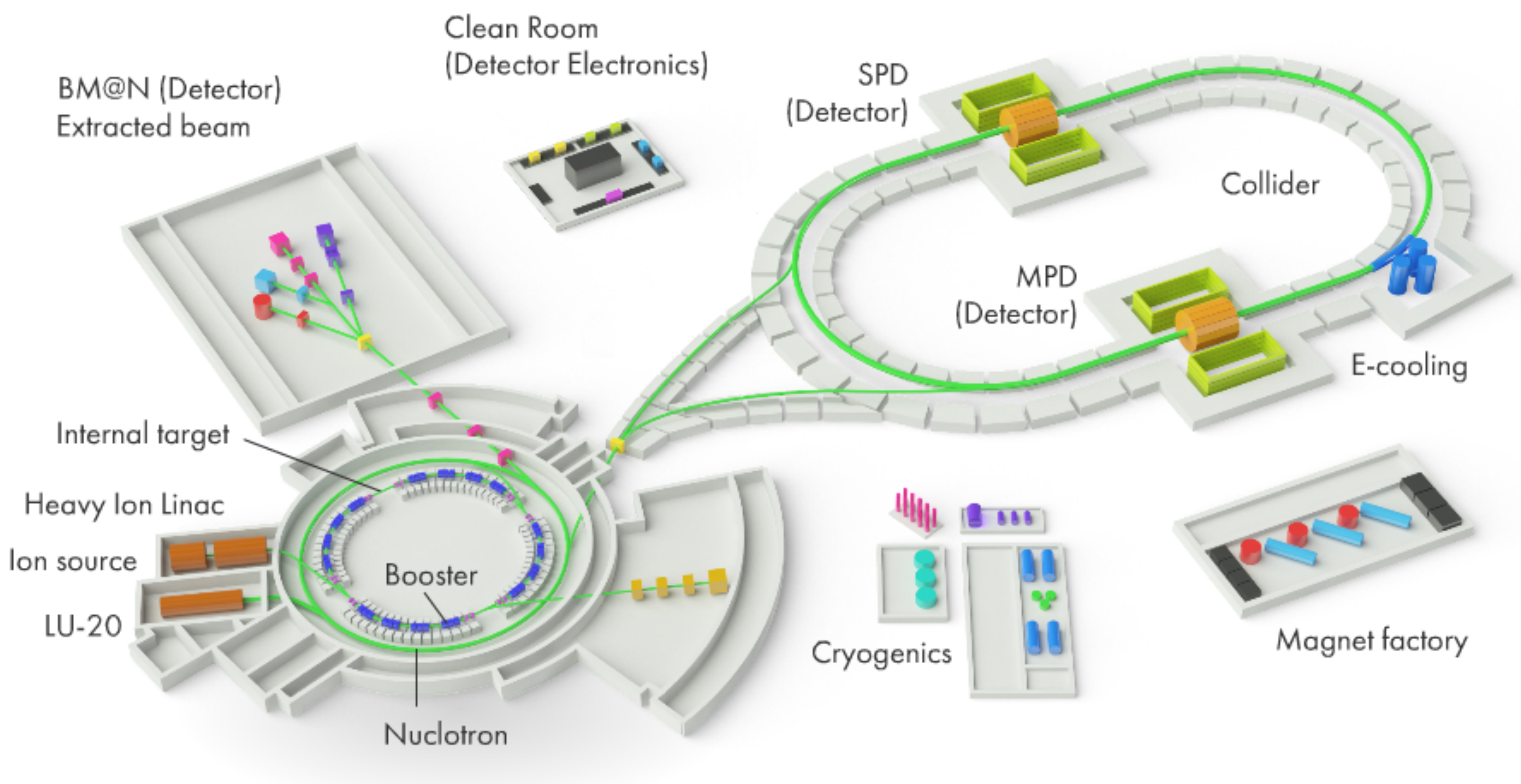
LHC FIXED TARGET, INCLUDING POLARISATION

arXiv:1901.08002

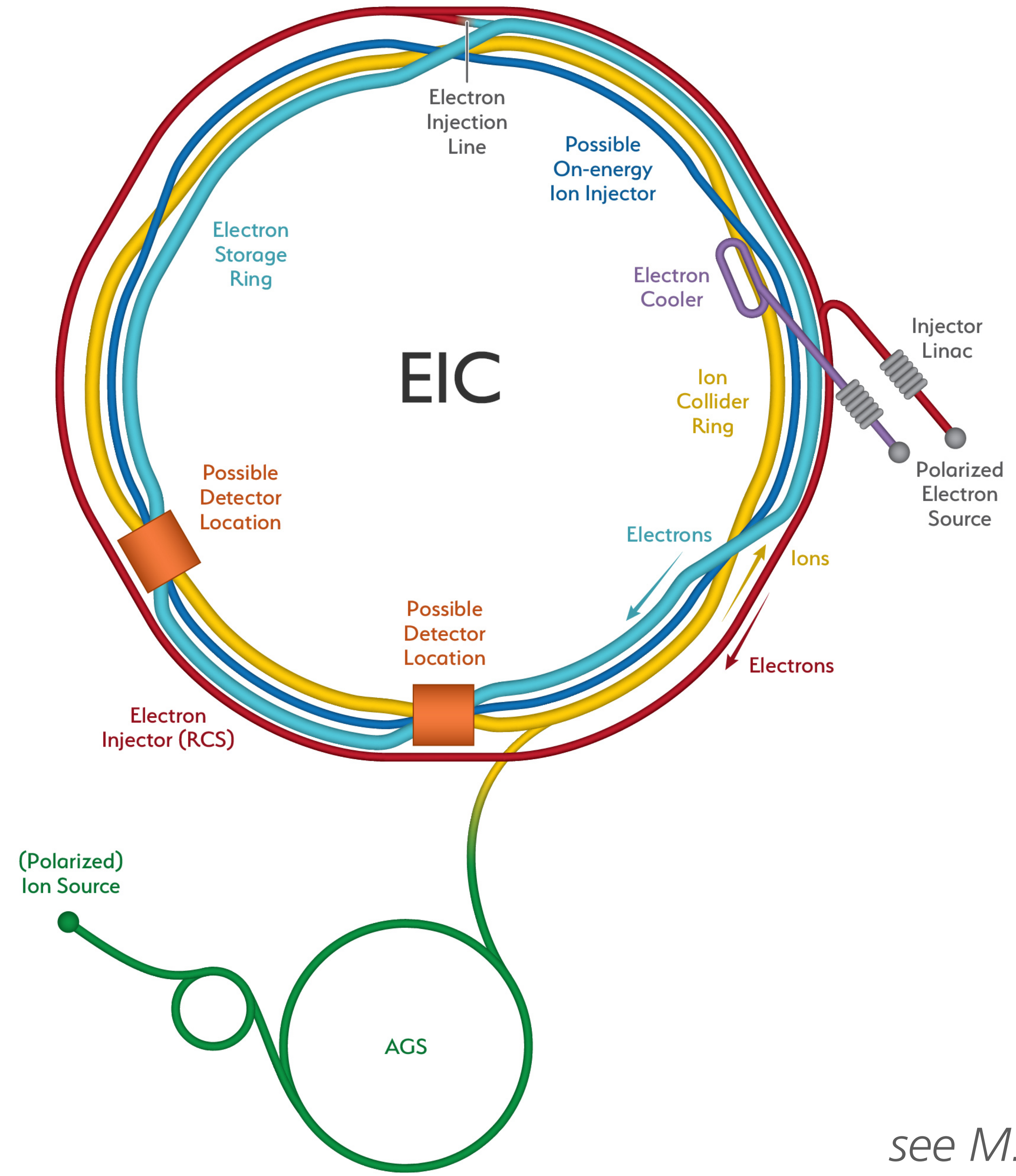


NUCLOTRON-BASED ION COLLIDER FACILITY

https://nica.jinr.ru/

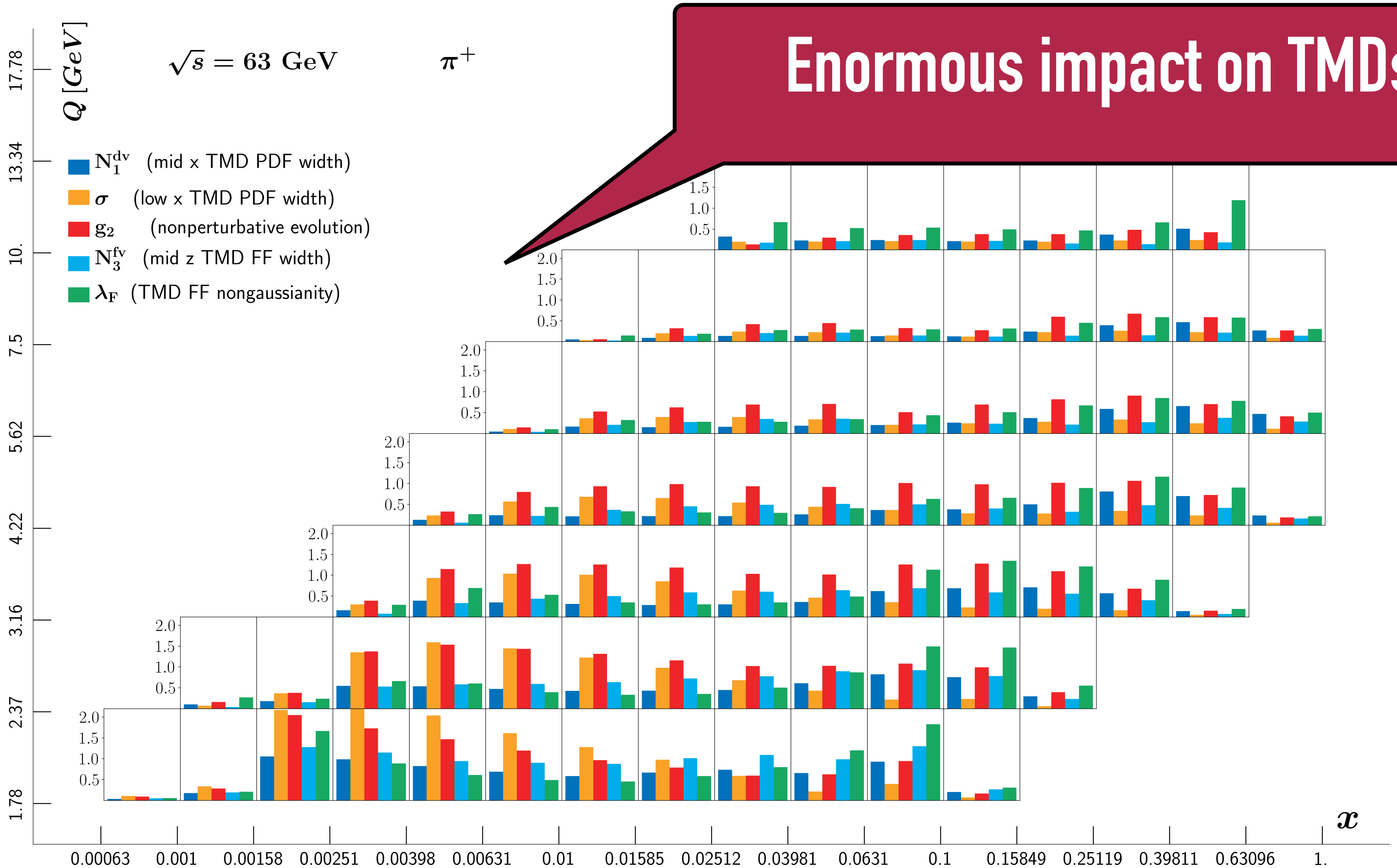


THE ELECTRON-ION COLLIDER



see M. Contalbrigo's talk

FORESEEN EIC IMPACT



Enormous impact on TMDs

Sensitivity coefficients: measure of the correlation between fit parameters and measurable quantities at EIC

CONCLUSIONS

- Unpolarized TMDs: full-fledged TMD extractions up to NN^3LL accuracy are coming out and being constantly improved
- Simple Gaussians and no x-dependence have to be abandoned
- Flavor dependence should come next
- There are still several contradictory results, especially for polarized TMDs
- New ideas keep coming
- Many results are expected to come in the next years