Future perspectives of TMD phenomenology

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3DSPIN MAPPING THE PROTON IN 3D

erc European Research Council

INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PAVIA

A tribute to the Armenian contribution

TMD theoretical developments 1990s

Kotzinian NPB 441 (1995)

$$
\begin{aligned}
&\frac{1-\epsilon}{2Q^2} l_{\mu\nu} W^{\mu\nu} \\
&= \frac{1}{2}\left(H_{11}^{(0)} + H_{22}^{(0)}\right) + \epsilon H_{00}^{(0)} + \sqrt{2\epsilon(1+\epsilon)} Re H_{01}^{(0)} \cos\phi_h^l + \frac{\epsilon}{2}\left(H_{11}^{(0)} - H_{22}^{(0)}\right)\cos 2\phi_h^l \\
&+\lambda\sqrt{2\epsilon(1-\epsilon)} Im H_{01}^{(0)} \sin\phi_h^l \\
&-S_{(\gamma h)}^1\left[\sqrt{2\epsilon(1+\epsilon)} Re H_{021}^{(S)} \sin\phi_h^l + \epsilon Re H_{121}^{(S)} \sin 2\phi_h^l\right] \\
&-S_{(\gamma h)}^2\left[\frac{1}{2}\left(H_{112}^{(S)} + H_{222}^{(S)}\right) + \epsilon H_{002}^{(S)} + \sqrt{2\epsilon(1+\epsilon)} Re H_{012}^{(S)} \cos\phi_h^l + \frac{\epsilon}{2}\left(H_{112}^{(S)} - H_{222}^{(S)}\right)\cos 2\phi_h^l\right] \\
&-S_{(\gamma h)}^3\left[\sqrt{2\epsilon(1+\epsilon)} Re H_{023}^{(S)} \sin\phi_h^l + \epsilon Re H_{123}^{(S)} \sin 2\phi_h^l\right] \qquad (16) \\
&+\lambda S_{(\gamma h)}^1\left[-\sqrt{1-\epsilon^2} Im H_{121}^{(S)} + \sqrt{2\epsilon(1-\epsilon)} Im H_{021}^{(S)} \cos\phi_h^l\right] \\
&-\lambda S_{(\gamma h)}^2\left[\sqrt{2\epsilon(1-\epsilon)} Im H_{012}^{(S)} \sin\phi_h^l\right] \\
&+\lambda S_{(\gamma h)}^3\left[-\sqrt{1-\epsilon^2} Im H_{123}^{(S)} + \sqrt{2\epsilon(1-\epsilon)} Im H_{023}^{(S)} \cos\phi_h^l\right],
\end{aligned}
$$

Decomposition of SIDIS cross section

Kotzinian, Mulders PLB 406 (1997)

Concept of weighted asymmetries

$$
A_T(x,y,z;|S_T|) \equiv \frac{\int d\phi^l \int d^2 P_{h\perp} \frac{|P_{h\perp}|}{zM_h} \sin(\phi_s^\ell + \phi_h^\ell)\ (d\sigma^\uparrow - d\sigma^\downarrow)}{\int d\phi^l \int d^2 P_{h\perp} (d\sigma^\uparrow + d\sigma^\downarrow)}
$$

HERMES long. asymmetry 2000

Probably the first measurement related to polarized TMDs

VOLUME 84, NUMBER 18 PHYSICAL REVIEW LETTERS 1 MAY 2000

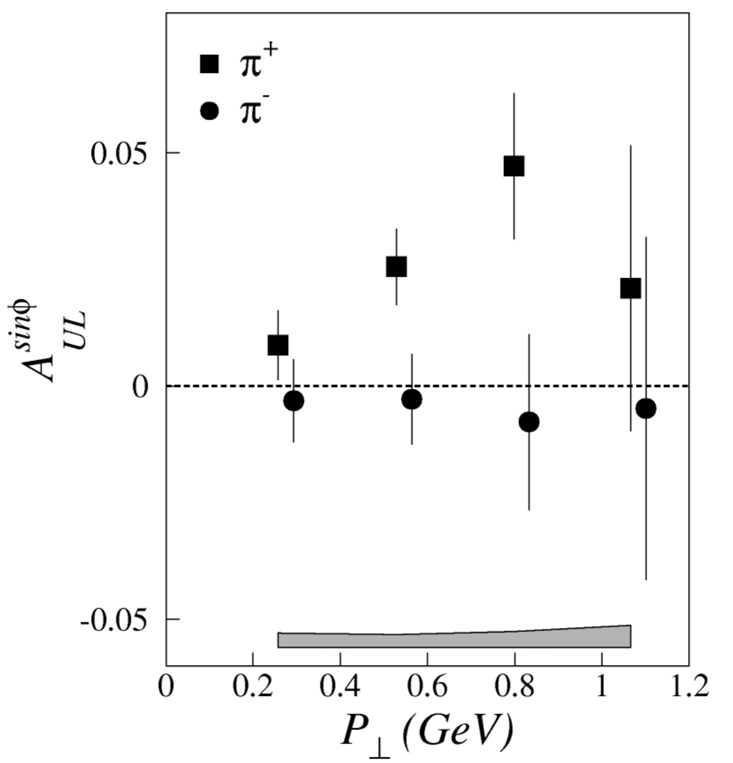
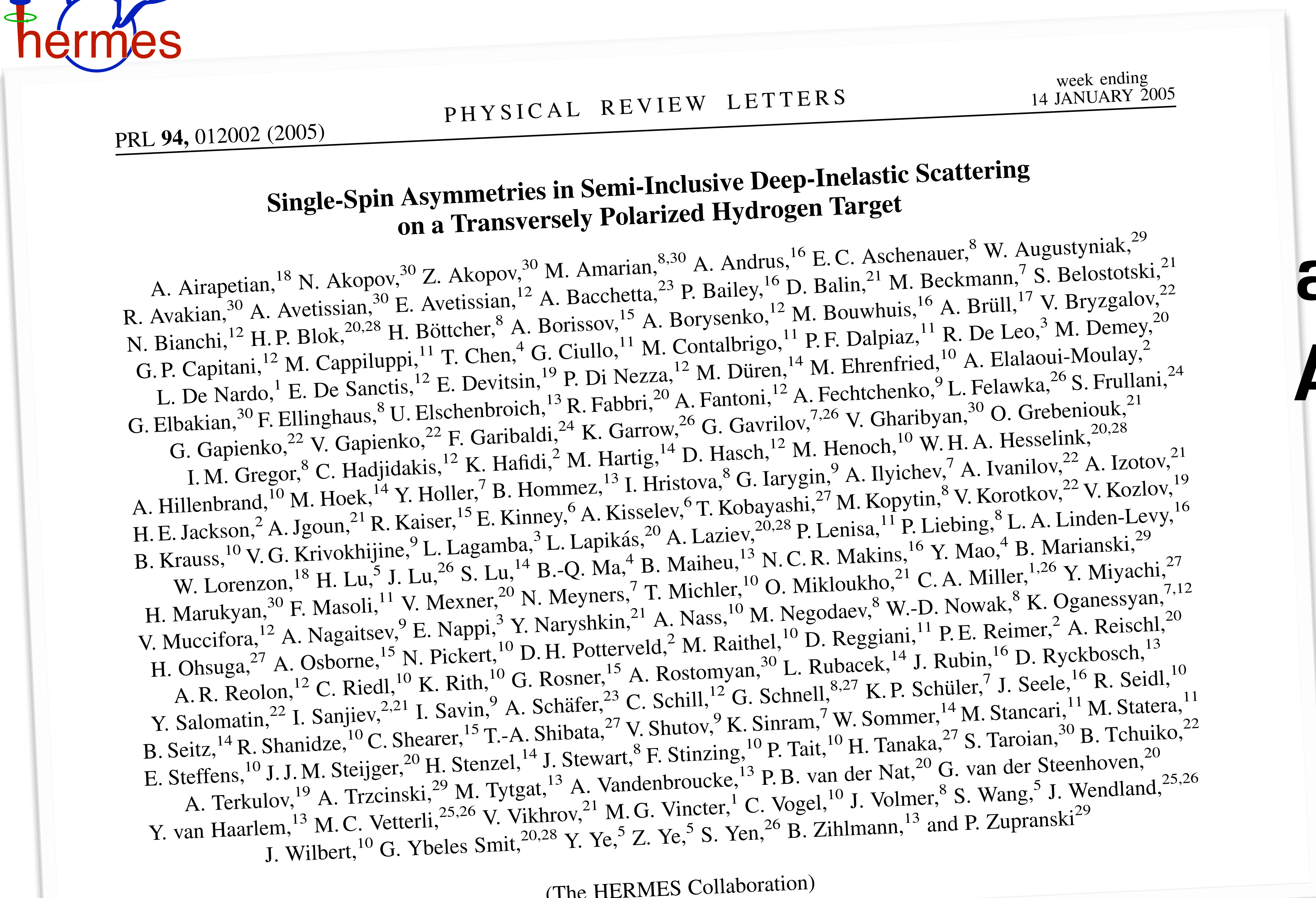


FIG. 3. Target-spin analyzing powers in the sinϕ moment as a function of transverse momentum, for π^+ (squares) and π^- (circles). Error bars show the statistical uncertainties and the band represents the systematic uncertainties.

HERMES Sivers asymmetry 2005

More than 650 citations, the most cited paper by HERMES and the third by HERA!



PRL 94, 012002 (2005) PHYSICAL REVIEW LETTERS week ending 14 JANUARY 2005

Single-Spin Asymmetries in Semi-Inclusive Deep-Inelastic Scattering on a Transversely Polarized Hydrogen Target

A. Airapetian,[18] N. Akopov,[30] Z. Akopov,[30] M. Amarian,[8,30] A. Andrus,[16] E. C. Aschenauer,[8] W. Augustyniak,[29] R. Avakian,[30] A. Avetissian,[30] E. Avetissian,[12] A. Bacchetta,[23] P. Bailey,[16] D. Balin,[21] M. Beckmann,[7] S. Belostotski,[21] N. Bianchi,[12] H. P. Blok,[20,28] H. Böttcher,[8] A. Borissov,[15] A. Borysenko,[12] M. Bouwhuis,[16] A. Brüll,[17] V. Bryzgalov,[22] G. P. Capitani,[12] M. Cappiluppi,[11] T. Chen,[4] G. Ciullo,[11] M. Contalbrigo,[11] P. F. Dalpiaz,[11] R. De Leo,[3] M. Demey,[20] L. De Nardo,[1] E. De Sanctis,[12] E. Devitsin,[19] P. Di Nezza,[12] M. Düren,[14] M. Ehrenfried,[10] A. Elalaoui-Moulay,[2] G. Elbakian,[30] F. Ellinghaus,[8] U. Elschenbroich,[13] R. Fabbri,[20] A. Fantoni,[12] A. Fechtchenko,[9] L. Felawka,[26] S. Frullani,[24] G. Gapienko,[22] V. Gapienko,[22] F. Garibaldi,[24] K. Garrow,[26] G. Gavrilov,[7,26] V. Gharibyan,[30] O. Grebeniouk,[21] I. M. Gregor,[8] C. Hadjidakis,[12] K. Hafidi,[2] M. Hartig,[14] D. Hasch,[12] M. Henoch,[10] W. H. A. Hesselink,[20,28] A. Hillenbrand,[10] M. Hoek,[14] Y. Holler,[7] B. Hommez,[13] I. Hristova,[8] G. Iarygin,[9] A. Ilyichev,[7] A. Ivanilov,[22] A. Izotov,[21] H. E. Jackson,[2] A. Jgoun,[21] R. Kaiser,[15] E. Kinney,[6] A. Kisselev,[6] T. Kobayashi,[27] M. Kopytin,[8] V. Korotkov,[22] V. Kozlov,[19] B. Krauss,[10] V. G. Krivokhijine,[9] L. Lagamba,[3] L. Lapikás,[20] A. Laziev,[20,28] P. Lenisa,[11] P. Liebing,[8] L. A. Linden-Levy,[16] W. Lorenzon,[18] H. Lu,[5] J. Lu,[26] S. Lu,[14] B.-Q. Ma,[4] B. Maiheu,[13] N. C. R. Makins,[16] Y. Mao,[4] B. Marianski,[29] H. Marukyan,[30] F. Masoli,[11] V. Mexner,[20] N. Meyners,[7] T. Michler,[10] O. Mikloukho,[21] C. A. Miller,[1,26] Y. Miyachi,[27] V. Muccifora,[12] A. Nagaitsev,[9] E. Nappi,[3] Y. Naryshkin,[21] A. Nass,[10] M. Negodaev,[8] W.-D. Nowak,[8] K. Oganessyan,[7,12] H. Ohsuga,[27] A. Osborne,[15] N. Pickert,[10] D. H. Potterveld,[2] M. Raithel,[10] D. Reggiani,[11] P. E. Reimer,[2] A. Reischl,[20] A. R. Reolon,[12] C. Riedl,[10] K. Rith,[10] G. Rosner,[15] A. Rostomyan,[30] L. Rubacek,[14] J. Rubin,[16] D. Ryckbosch,[13] Y. Salomatin,[22] I. Sanjiev,[2,21] I. Savin,[9] A. Schäfer,[23] C. Schill,[12] G. Schnell,[8,27] K. P. Schüler,[7] J. Seele,[16] R. Seidl,[10] B. Seitz,[14] R. Shanidze,[10] C. Shearer,[15] T.-A. Shibata,[27] V. Shutov,[9] K. Sinram,[7] W. Sommer,[14] M. Stancari,[11] M. Statera,[11] E. Steffens,[10] J. J. M. Steijger,[20] H. Stenzel,[14] J. Stewart,[8] F. Stinzing,[10] P. Tait,[10] H. Tanaka,[27] S. Taroian,[30] B. Tchuiko,[22] A. Terkulov,[19] A. Trzcinski,[29] M. Tytgat,[13] A. Vandenbroucke,[13] P. B. van der Nat,[20] G. van der Steenhoven,[20] Y. van Haarlem,[13] M. C. Vetterli,[25,26] V. Vikhrov,[21] M. G. Vincter,[1] C. Vogel,[10] J. Volmer,[8] S. Wang,[5] J. Wendland,[25,26] J. Wilbert,[10] G. Ybeles Smit,[20,28] Y. Ye,[5] Z. Ye,[5] S. Yen,[26] B. Zihlmann,[13] and P. Zupranski[29]

(The HERMES Collaboration)

about 10% Armenian

The TMD acronym

My personal recollection is that the acronym was coined by Harut before 2008

I think however that Italians were among the "fist followers"
(see D(erek) Sivers https://www.youtube.com/watch?v=fW8amMCVAJQ)

see, e.g.,
Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin,Turk, PRD75 (07)
Pasquini, Cazzaniga, Boffi, PRD 78 (08)
Bacchetta, Conti, Radici, PRD 78 (08)

Apart from the acronym, Harut was and still is one of the main actors of the TMD program at Jefferson Lab

Harut recently complained about the ambiguous use of the acronym

To avoid possible troubles, this is what I taught at the
TMD Collaboration Summer School in Philadelphia in 2017

About names and acronyms

- TMD as an adjective stands for Transverse Momentum Dependent
- TMD as a noun stands for Transverse Momentum Distribution and it is usually meant to encompass both transverse-momentum-dependent PDFs and Fragmentation Functions (FFs)

Younger generations

Theory of
Fragmentation Functions

Analysis Coordinator of
COMPASS experiment

Back to TMD perspectives...

In the last (great) workshop in Yerevan (2009) I was asked to speak about TMD perspectives

IN FIVE TO TEN YEARS

- COMPASS and HERMES and JLab: all structure functions (including unpolarized cross sections), weighted asymmetries, multidimensional binning *K. Hafidi, M. Aghasyan talks*
- BELLE and BABAR unpolarized cross sections and Collins (also for etas and kaons) *I. Garzia's talk*
- RHIC: jet-jet, photon-jet, hadron-hadron correlations at forward rapidities *L. Bland's talk*
- Fermilab: improvement of unpolarized Drell-Yan
- Polarized Drell-Yan at COMPASS and RHIC *C. Quintans, L. Bland talks*

IN FIVE TO TEN YEARS

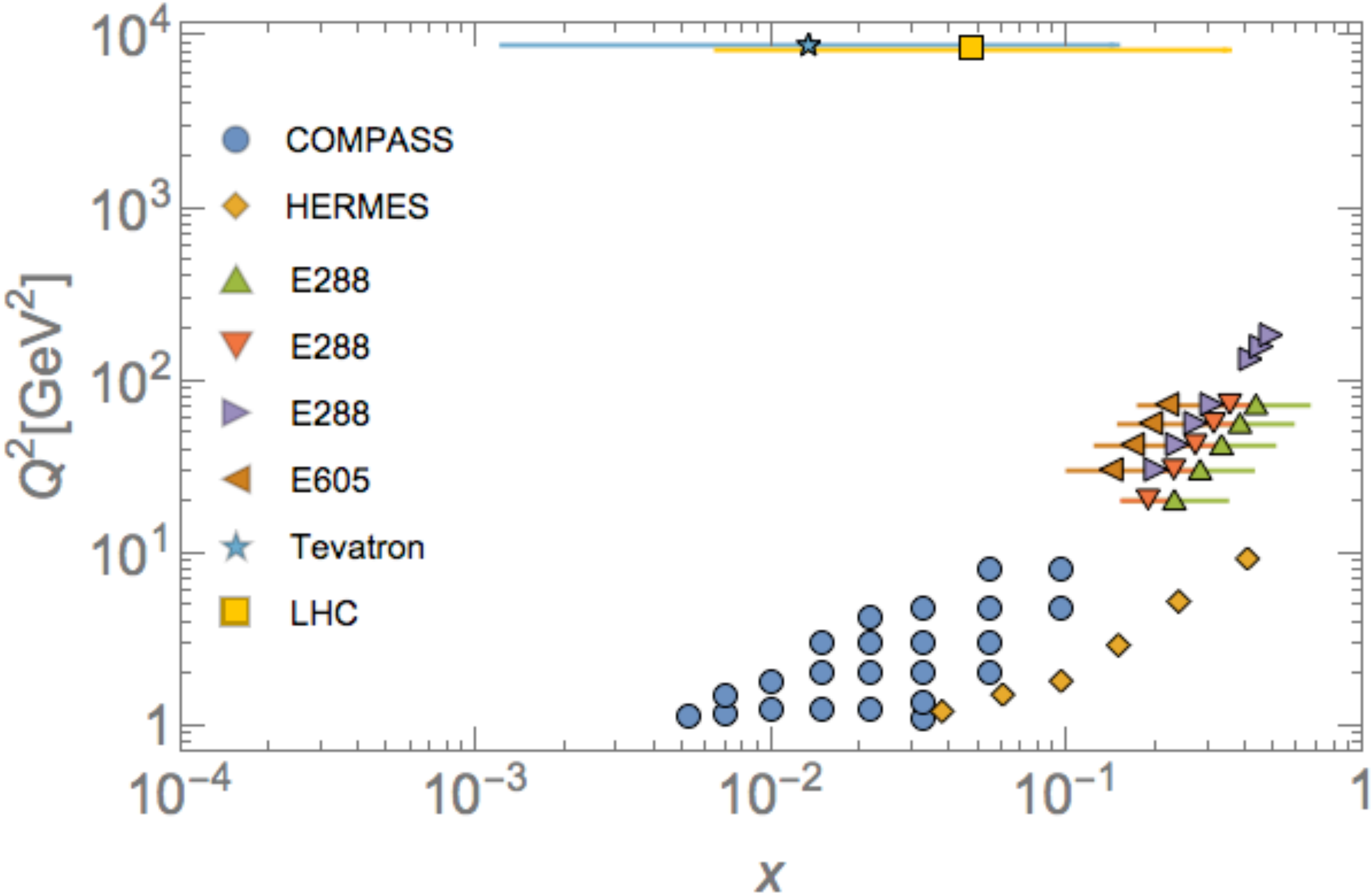
- ✔ Details and subtleties in TMD factorization sorted out
- ◒ Understanding of TMD factorization (or lack of it) in hadron-hadron collisions to hadrons
- ◒ Evolution equations of all TMDs known
- ◒ Numerical implementation of evolution functions up and working

IN FIVE TO TEN YEARS

- ✔ More and improved fits (including evolution, more data, different approaches)
- ✘ Parametrization that can describe both TMDs and GPDs
- ✔ Coarse and qualitative 3D pictures
- ☯ Hints about orbital angular momentum

The unpolarized TMD as case study

Available data

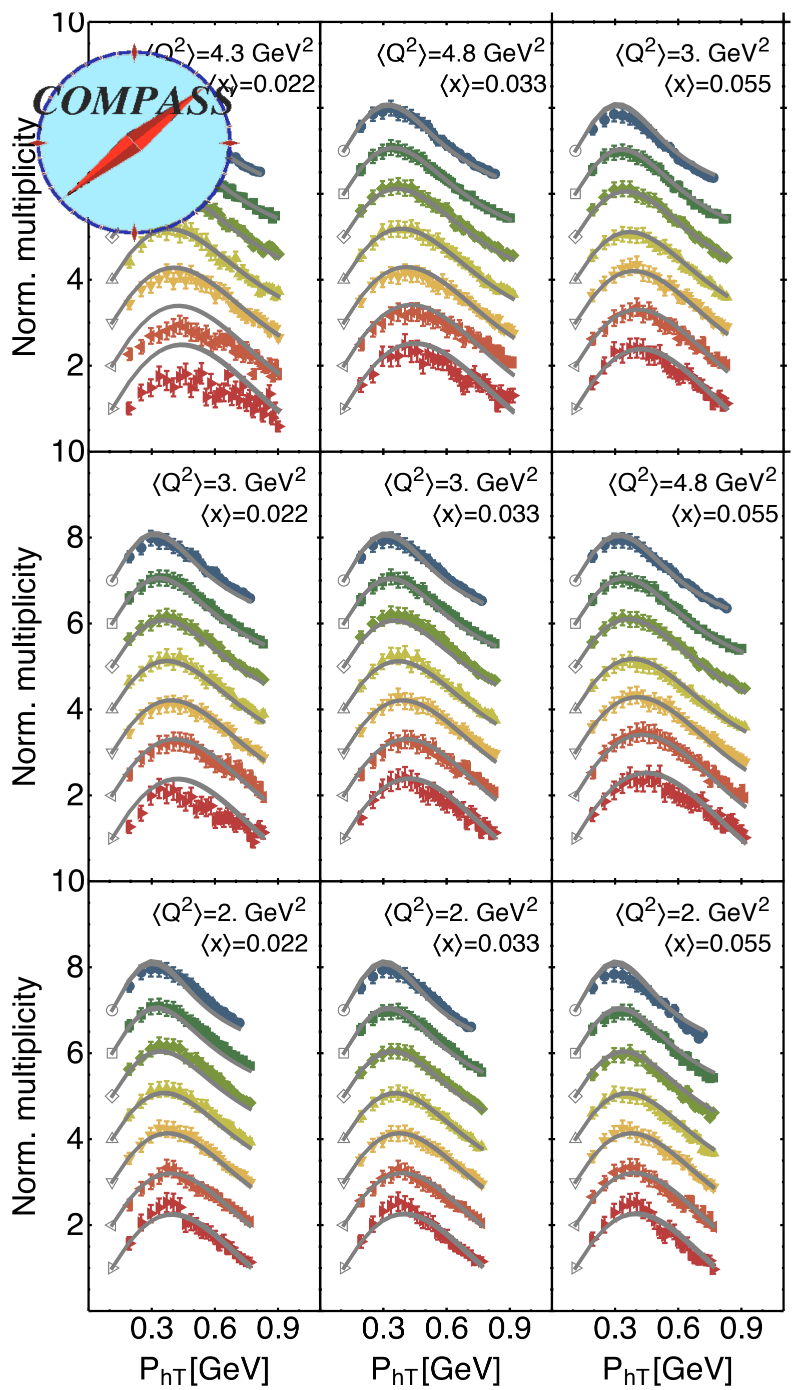


Quark unpol. TMD: extractions

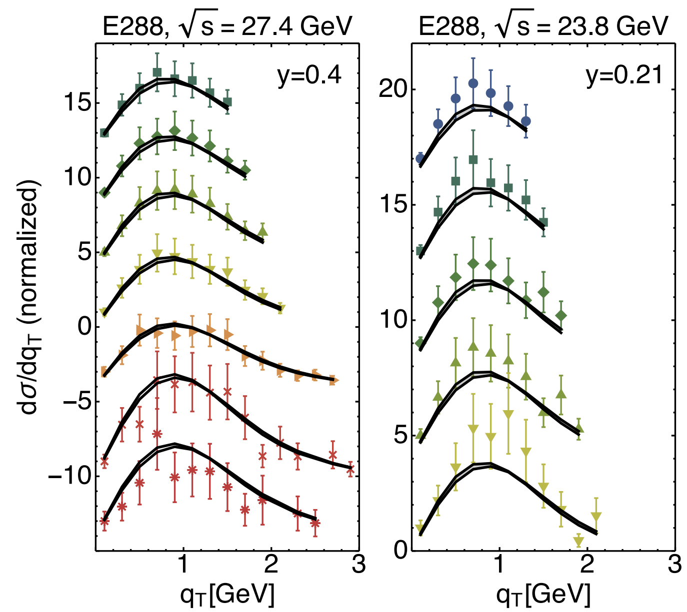
		Framework	HERMES	COMPASS	DY	Z production	N of points
PAST	KN 2006 hep-ph/0506225	NLL/NLO	✘	✘	✔	✔	98
	Pavia 2013 arXiv:1309.3507	No evo	✔	✘	✘	✘	1538
	Torino 2014 arXiv:1312.6261	No evo	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
	DEMS 2014 arXiv:1407.3311	NNLL/ NLO	✘	✘	✔	✔	223
	EIKV 2014 arXiv:1401.5078	NLL/LO	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
PRESENT	Pavia 2016 arXiv:1703.10157	NLL/LO	✔	✔	✔	✔	8059
	SV 2017 arXiv:1706.01473	NNLL/ NNLO	✘	✘	✔	✔	309

First global fit of TMDs

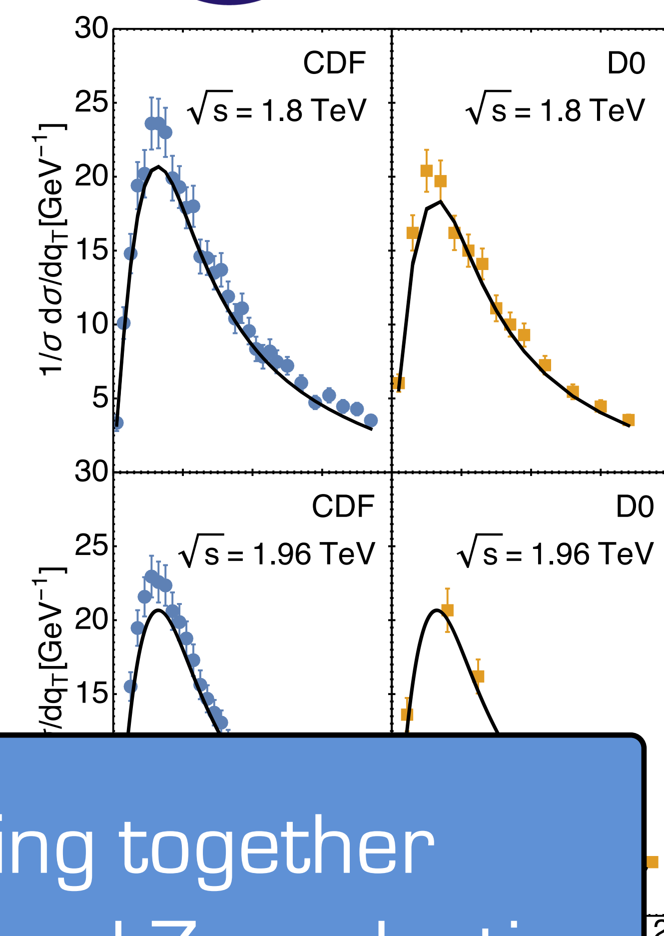
SIDIS



Drell-Yan



Z production



Number of data points: 8059

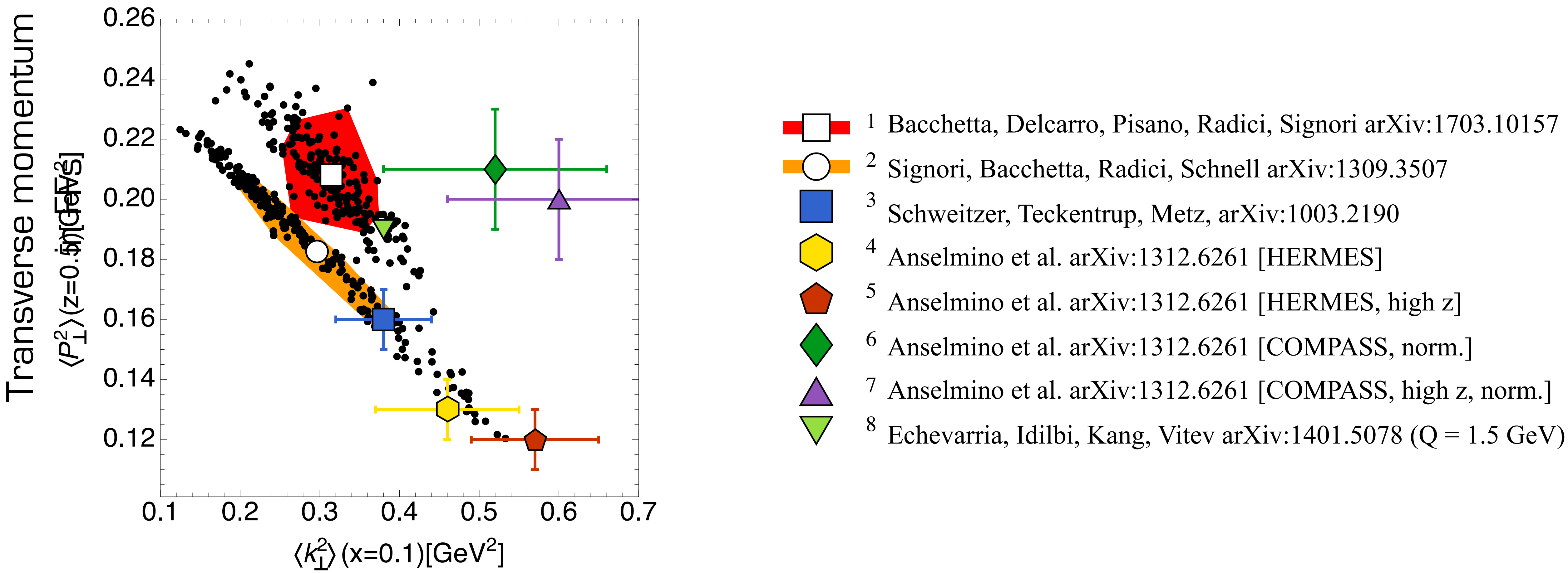
Global χ^2/dof = 1.55

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

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


It's the dawn of TMD global fits era
. . . but there's still a lot of climbing to be done

Mean transverse momentum squared



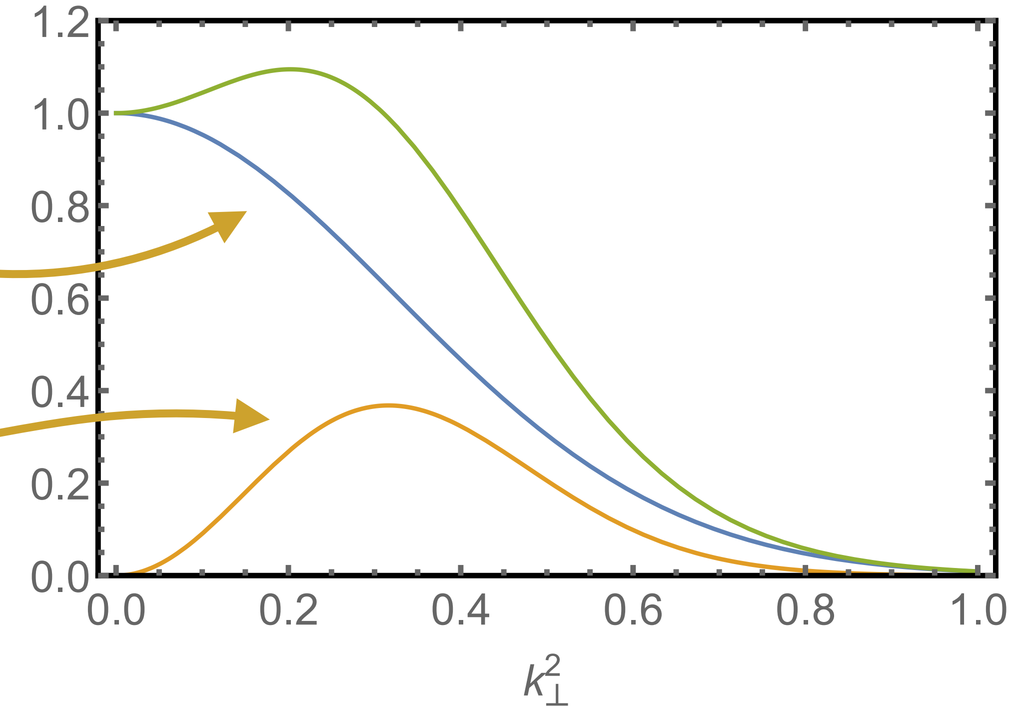
Transverse momentum
in PDFs

CAVEAT: intrinsic transverse momentum depends on TMD evolution "scheme" and its parameters. Not the best quantity to consider.

Functional form of TMDs

$$\hat{f}^a_{\rm NP} = \text{F.T. of} \left(e^{-\frac{k_\perp^2}{\langle k_{\perp,a}^2 \rangle}} + \lambda k_\perp^2 \, e^{-\frac{k_\perp^2}{\langle k_{\perp,a}^2 \rangle'}} \right)$$

$$\langle \boldsymbol{k}_{\perp,a}^2 \rangle (x) = \langle \hat{\boldsymbol{k}}_{\perp,a}^2 \rangle \, \frac{(1-x)^\alpha x^\sigma}{(1-\hat{x})^\alpha \hat{x}^\sigma} \,,$$



We go beyond a simple Gaussian.

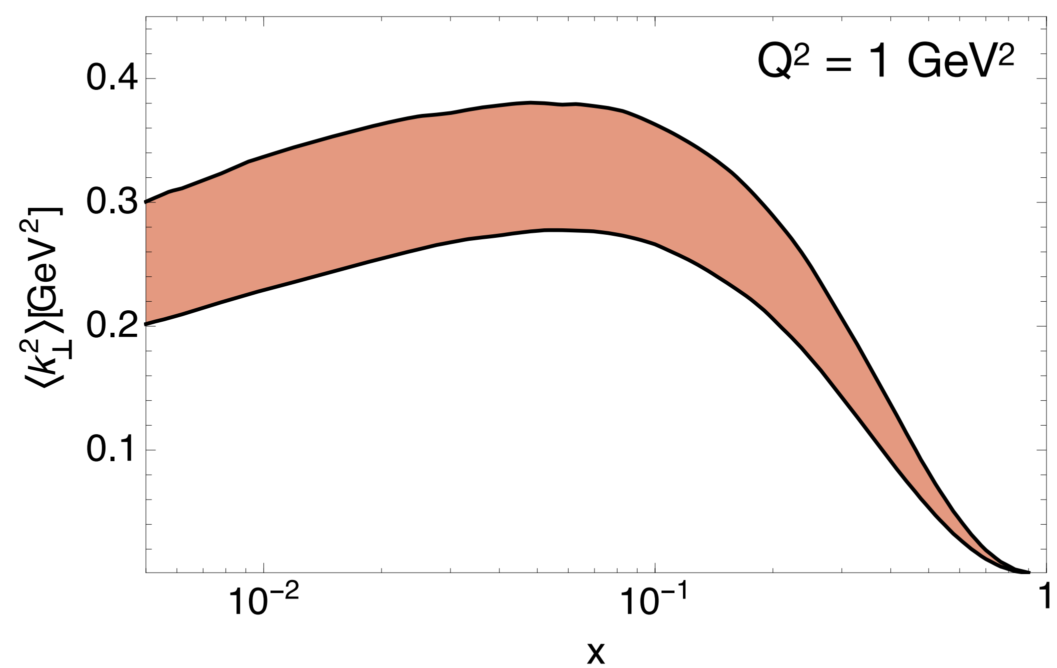
In scalar diquark model, the two components would be f_1+g_1 and f_1-g_1

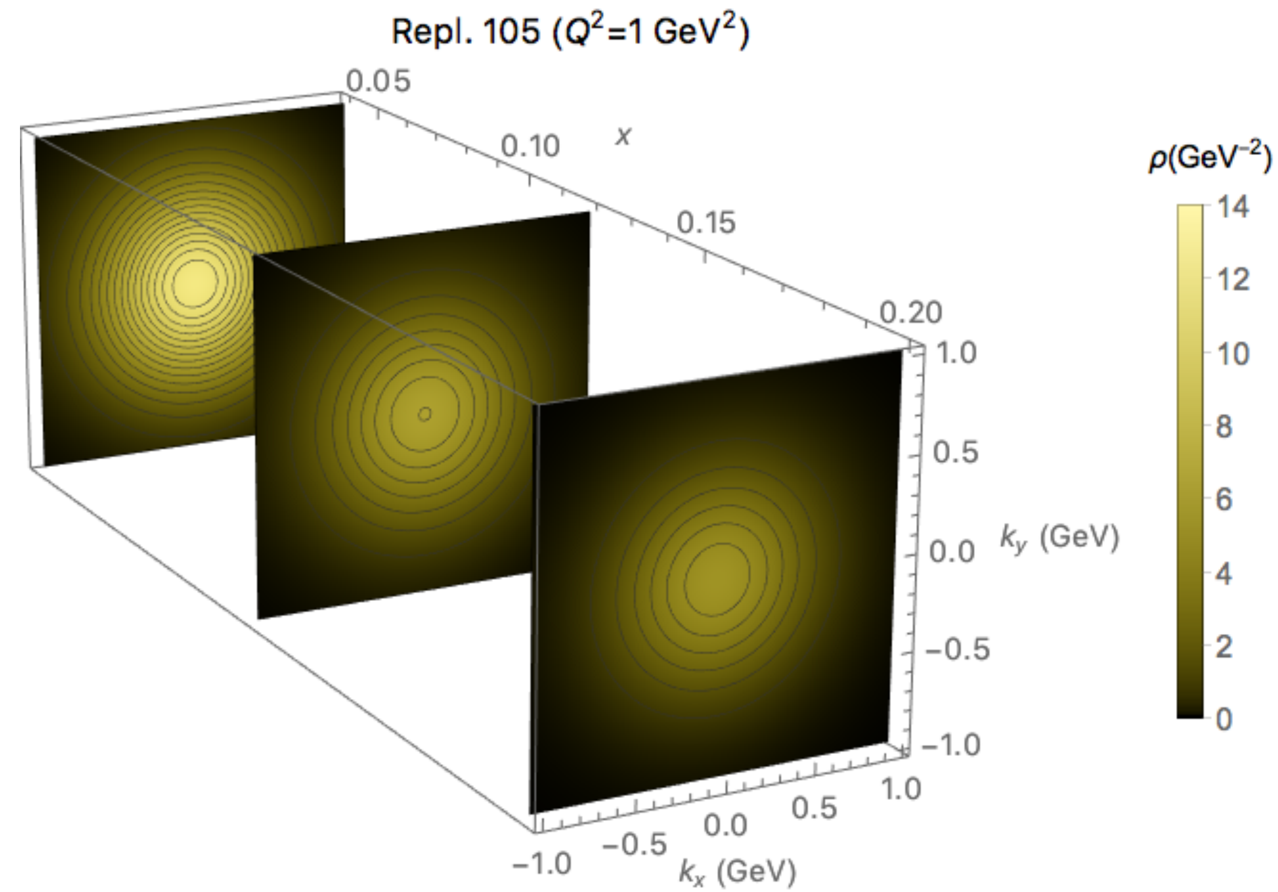
Scimemi and Vladimirov tried

$$f_{NP}(b) = \frac{\cosh\left(\left(\frac{\lambda_2}{\lambda_1} - \frac{\lambda_1}{2}\right) b\right)}{\cosh\left(\left(\frac{\lambda_2}{\lambda_1} + \frac{\lambda_1}{2}\right) b\right)} \qquad f_{NP}(z,b) = \exp\left(\frac{-\lambda_2 z b^2}{\sqrt{1 + z^2 b^2 \frac{\lambda_2^2}{\lambda_1^2}}} \right)$$

Transverse size in momentum space

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



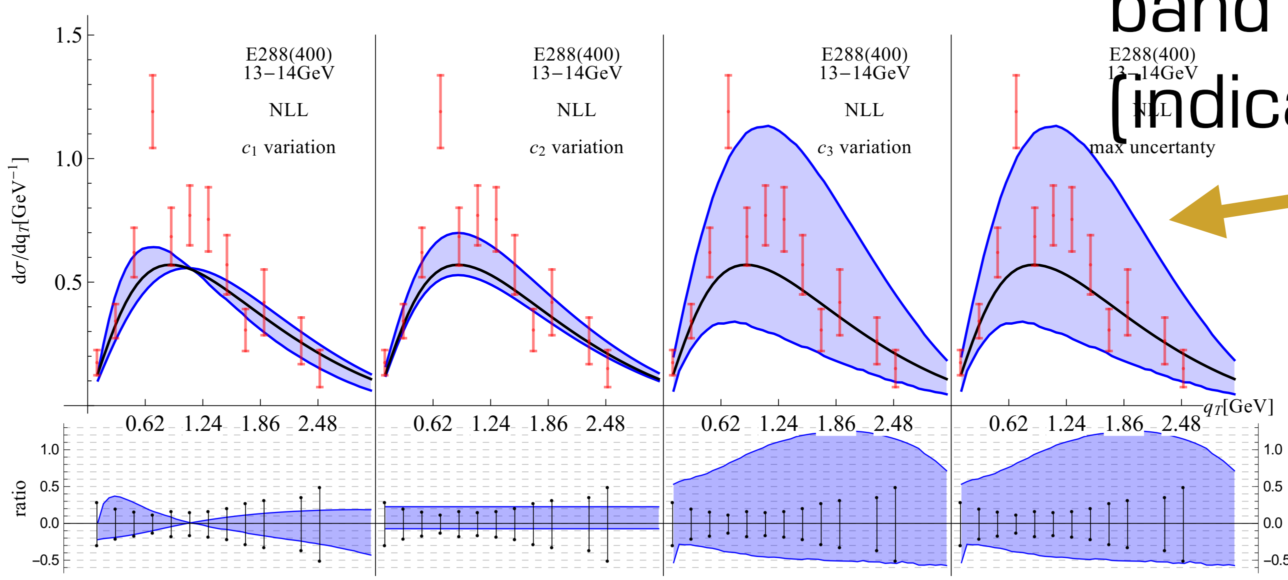


The fact that it goes to zero at x=1 is built in, but the sharp decrease is coming from data. However, it could still be an artefact of x and Q^2 correlations

Problems and open questions

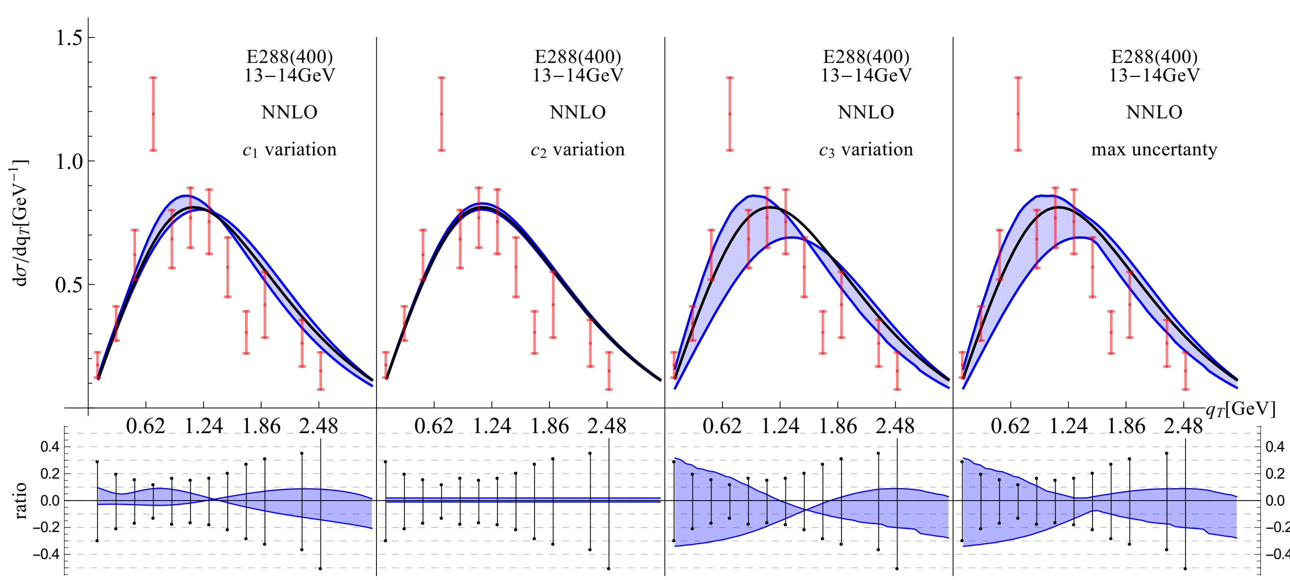
Improvement in perturbative accuracy

NLL/LO



band due to scale variation
(indication of theory accuracy)

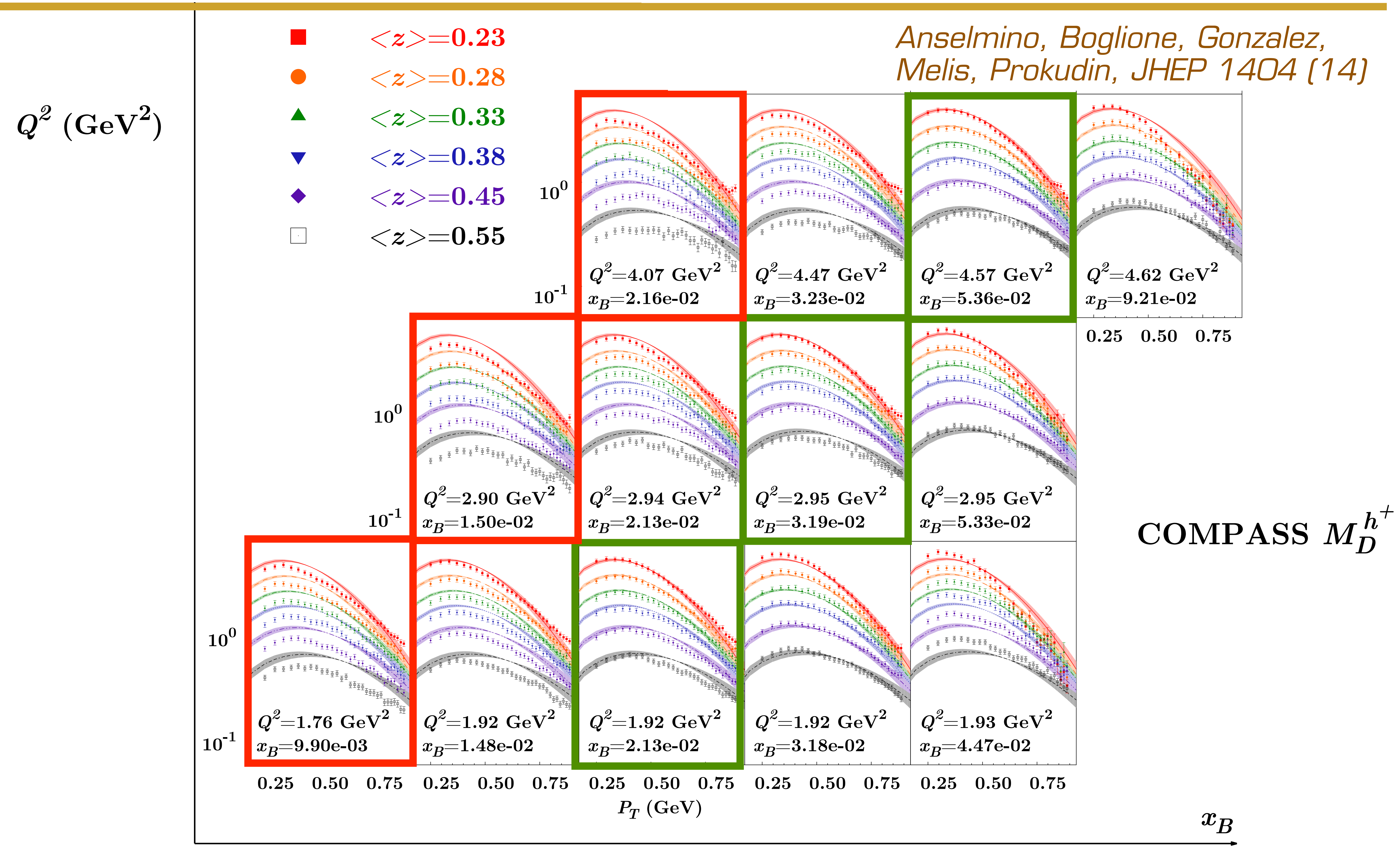
NNLL/NNLO



Huge improvement for low-energy experiments

talk by A. Vladimirov at EIC UG meeting 2017

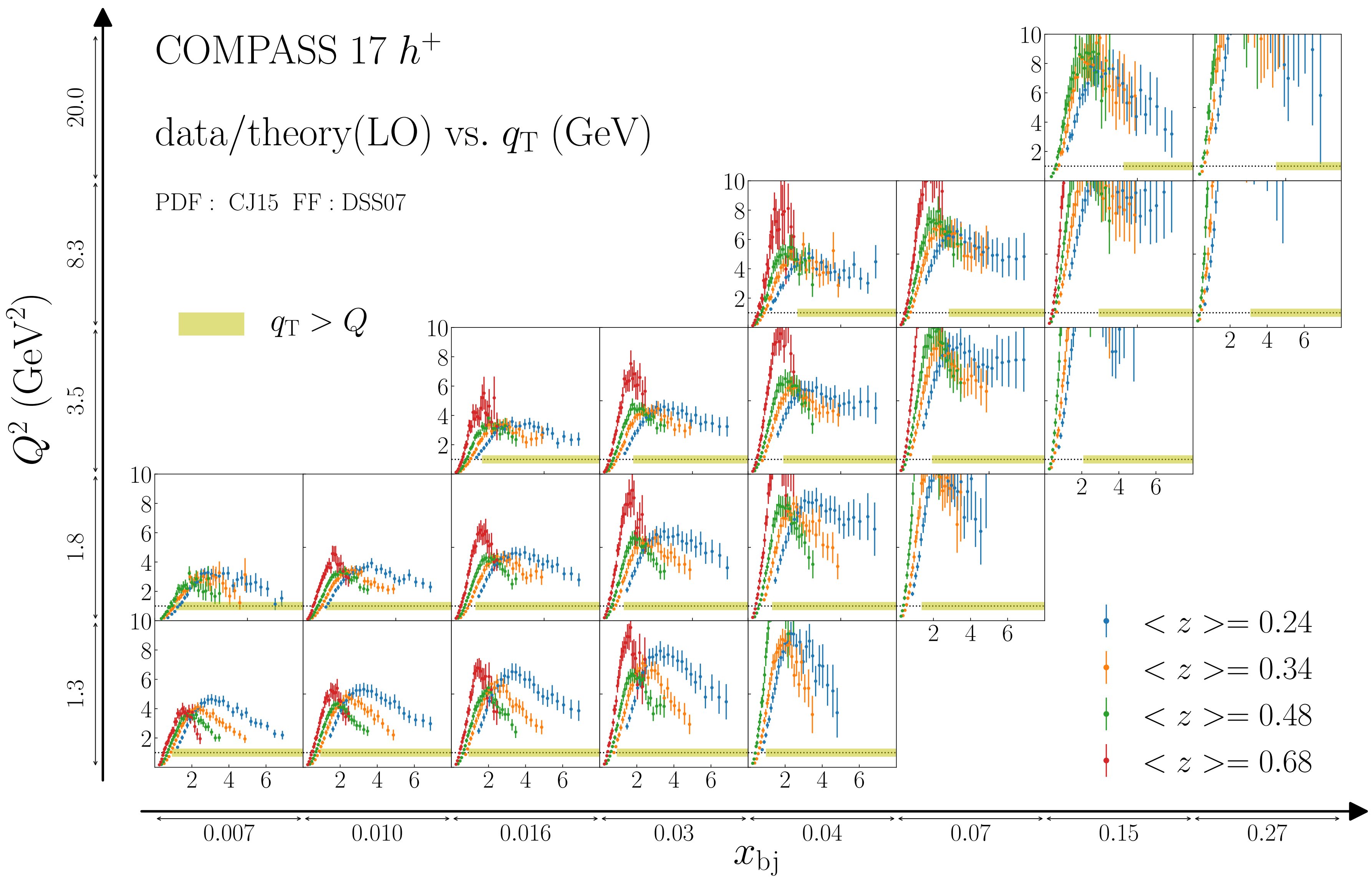
Problems with normalisation



The problem is unresolved even with new COMPASS data

Problems with matching in SIDIS

N. Sato's talk at SPIN 2018 and arXiv:1808.04396

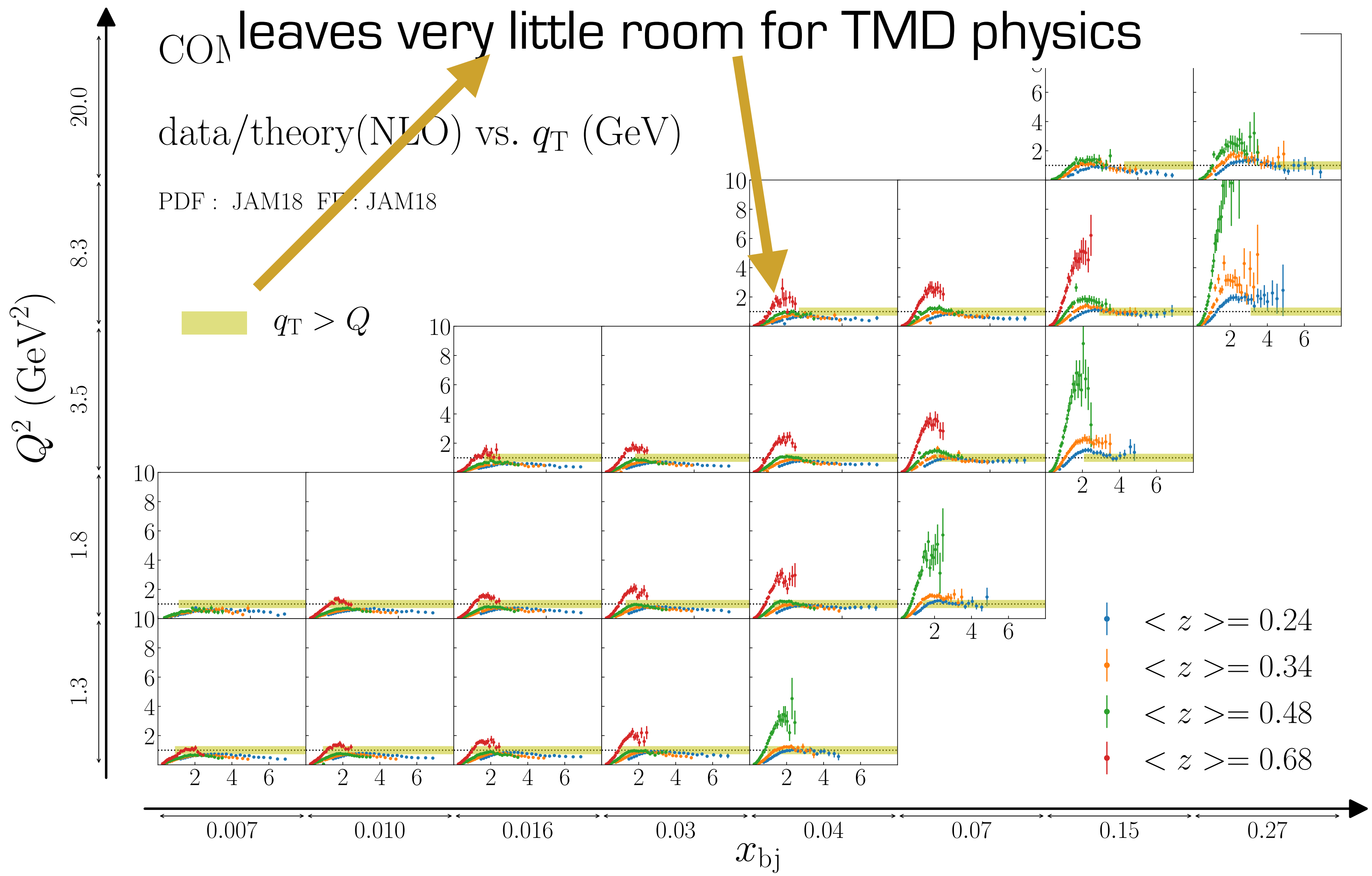


At high q_T, the collinear formalism should be valid, but large discrepancies are observed

Problems with matching in SIDIS

N. Sato's talk at SPIN 2018 and arXiv:1808.04396

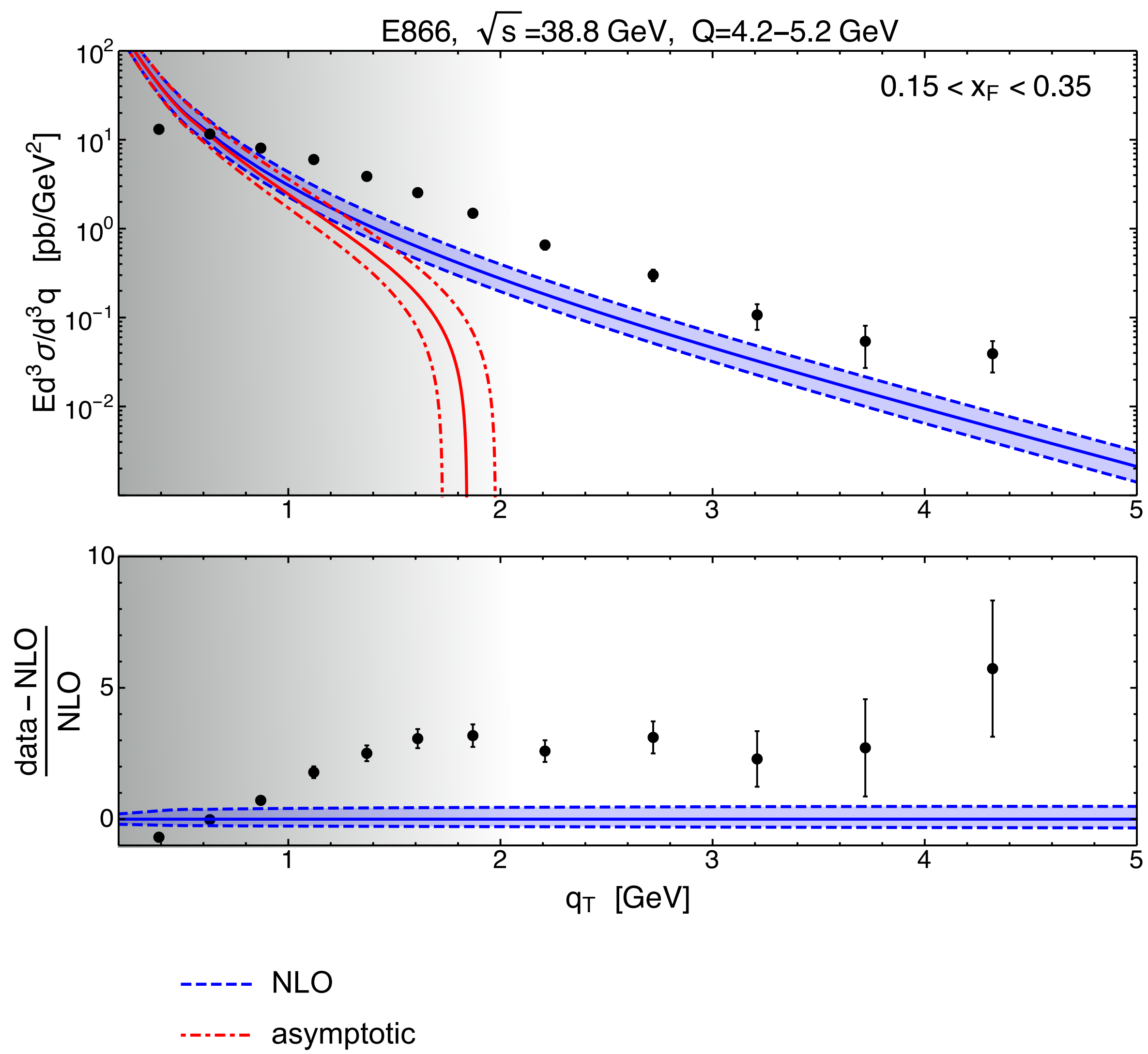
a strict application of the $q_T < Q$ requirement leaves very little room for TMD physics



The discrepancies could be largely resolved by sharply modifying the gluon collinear fragmentation function

Problems with matching in DY

F. Piacenza's talk at SPIN 2018, article in preparation



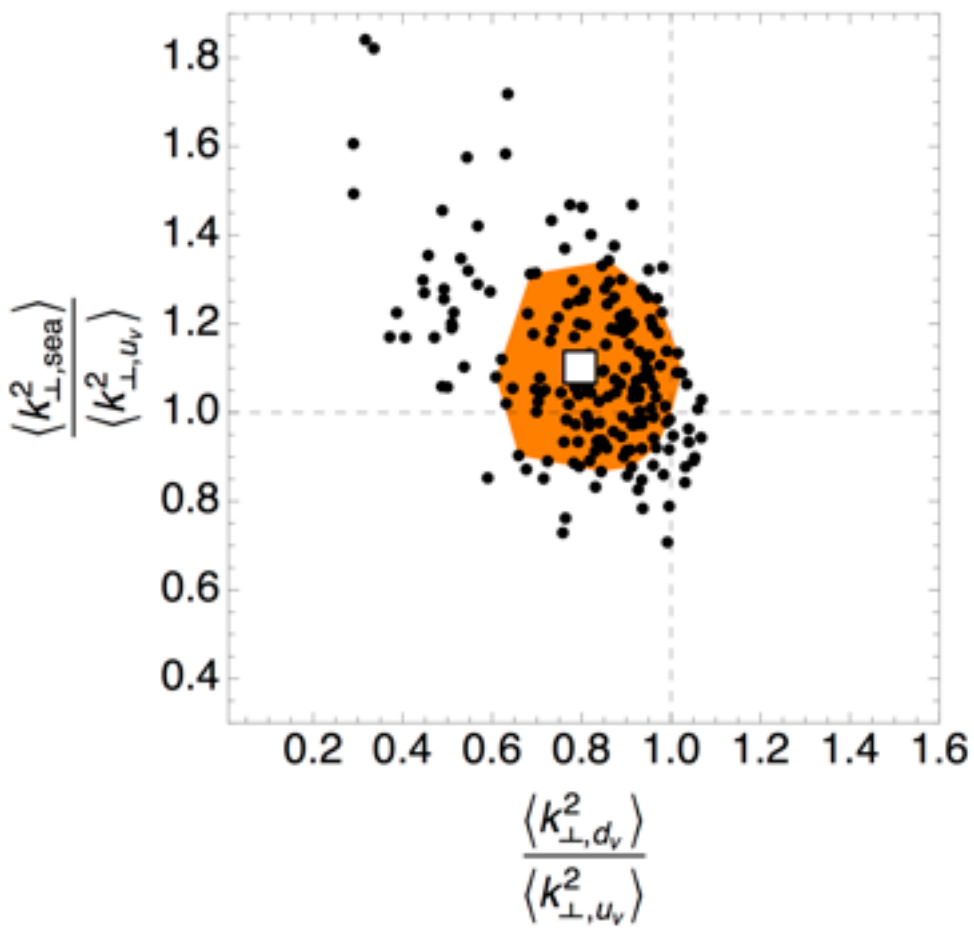
Cannot be fixed by changing fragmentation functions…

Higher twist? QED radiation?

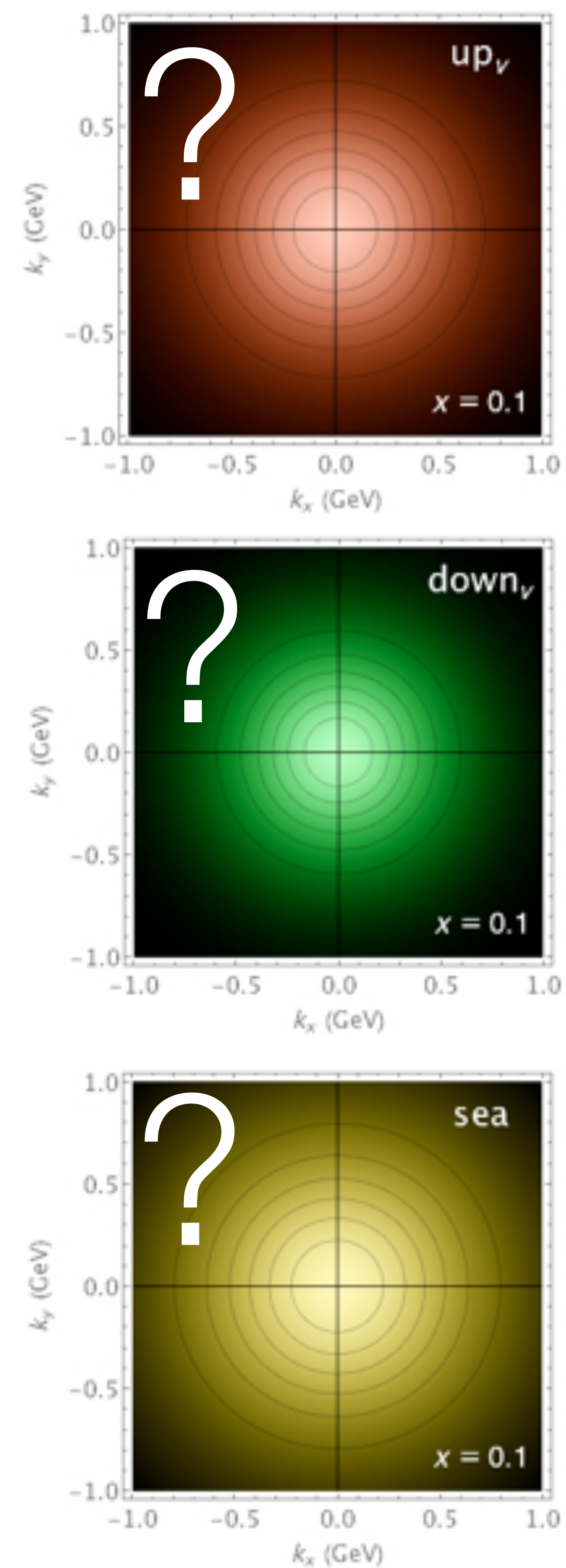
Problems with flavour structure

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

Ratio of width of sea / width of up valence



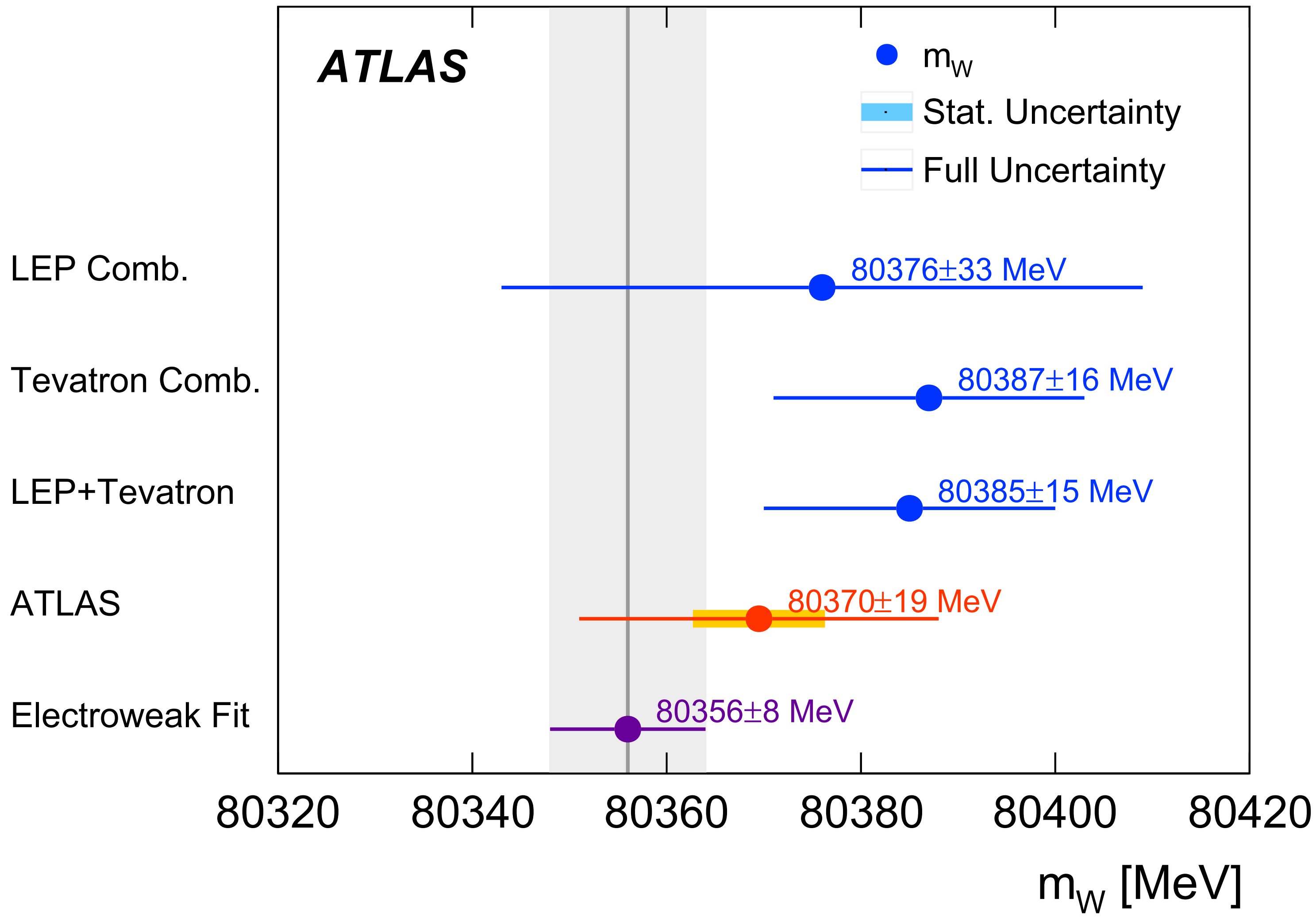
Ratio width of down valence/ width of up valence



The bottom message is: there is room for flavour dependence, but we don't control it well

TMDs impact on precision observables

ATLAS Collab. arXiv:1701.07240



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

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

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

TMDs impact on precision observables

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

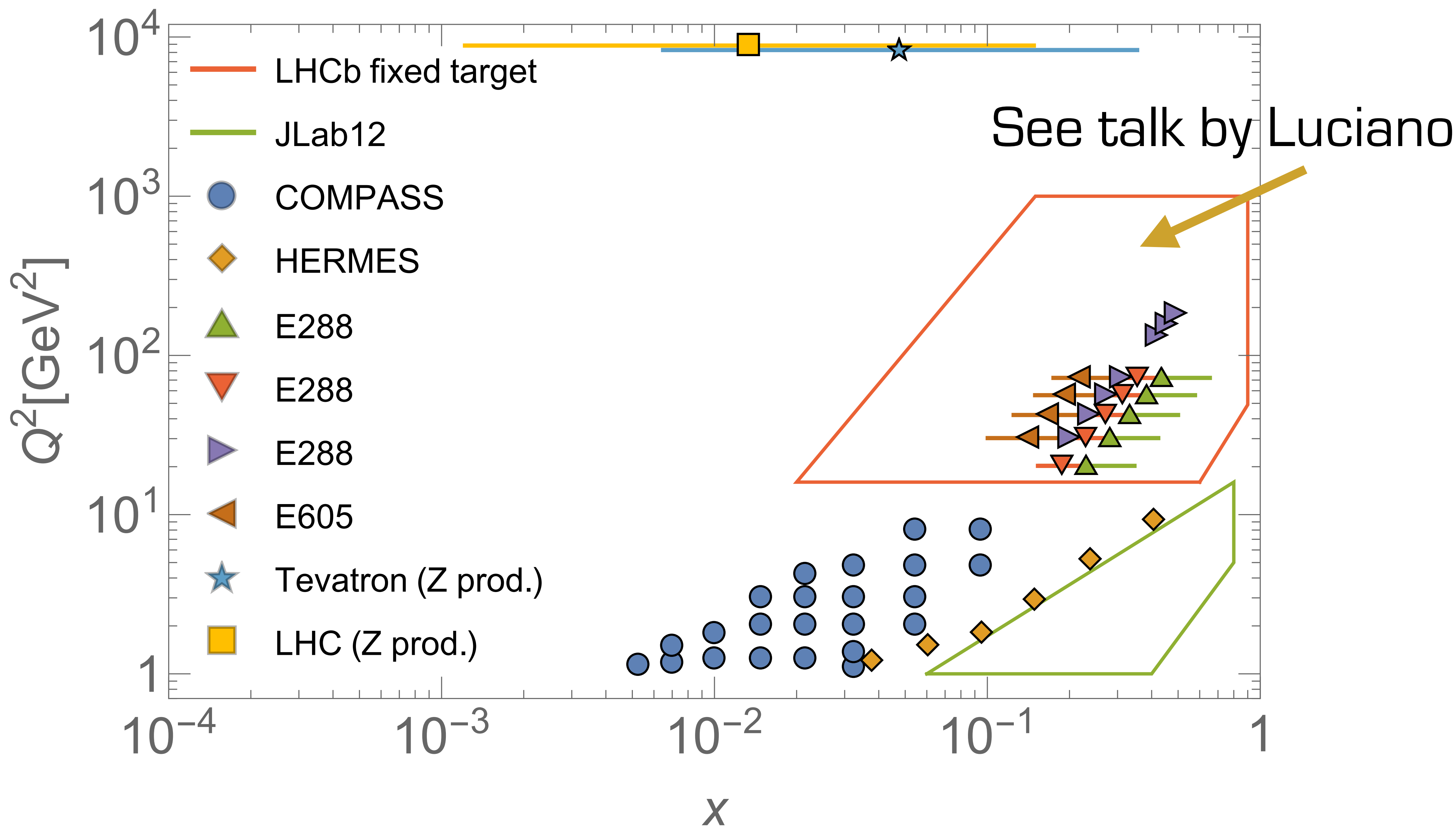
We tried some judicious choices of flavour dependent widths and checked

Set	u_v	d_v	u_s	d_s	s	
1	0.34	0.26	0.46	0.59	0.32	narrow, medium, large
2	0.34	0.46	0.56	0.32	0.51	narrow, large, narrow
3	0.55	0.34	0.33	0.55	0.30	large, narrow, large
4	0.53	0.49	0.37	0.22	0.52	large, medium, narrow
5	0.42	0.38	0.29	0.57	0.27	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

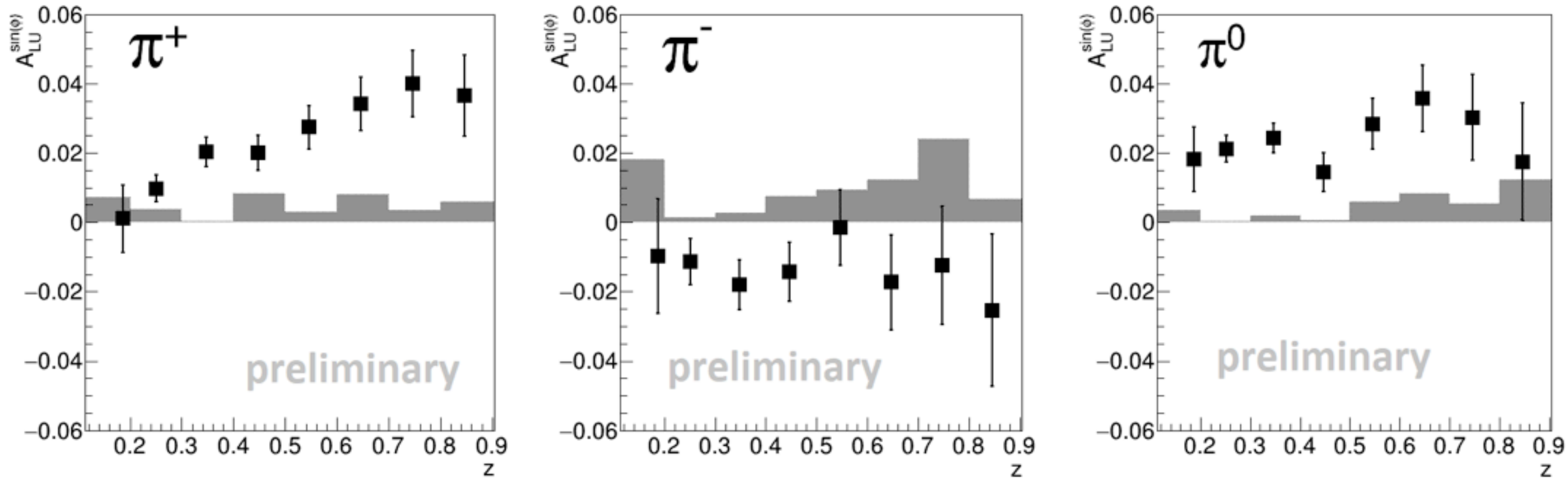
Not taking into account the flavour dependence of TMDs can lead to errors in the determination of the W mass

Future experimental data



JLab data

Patrizia's talk and M. Mirazita's talk at SPIN 2018



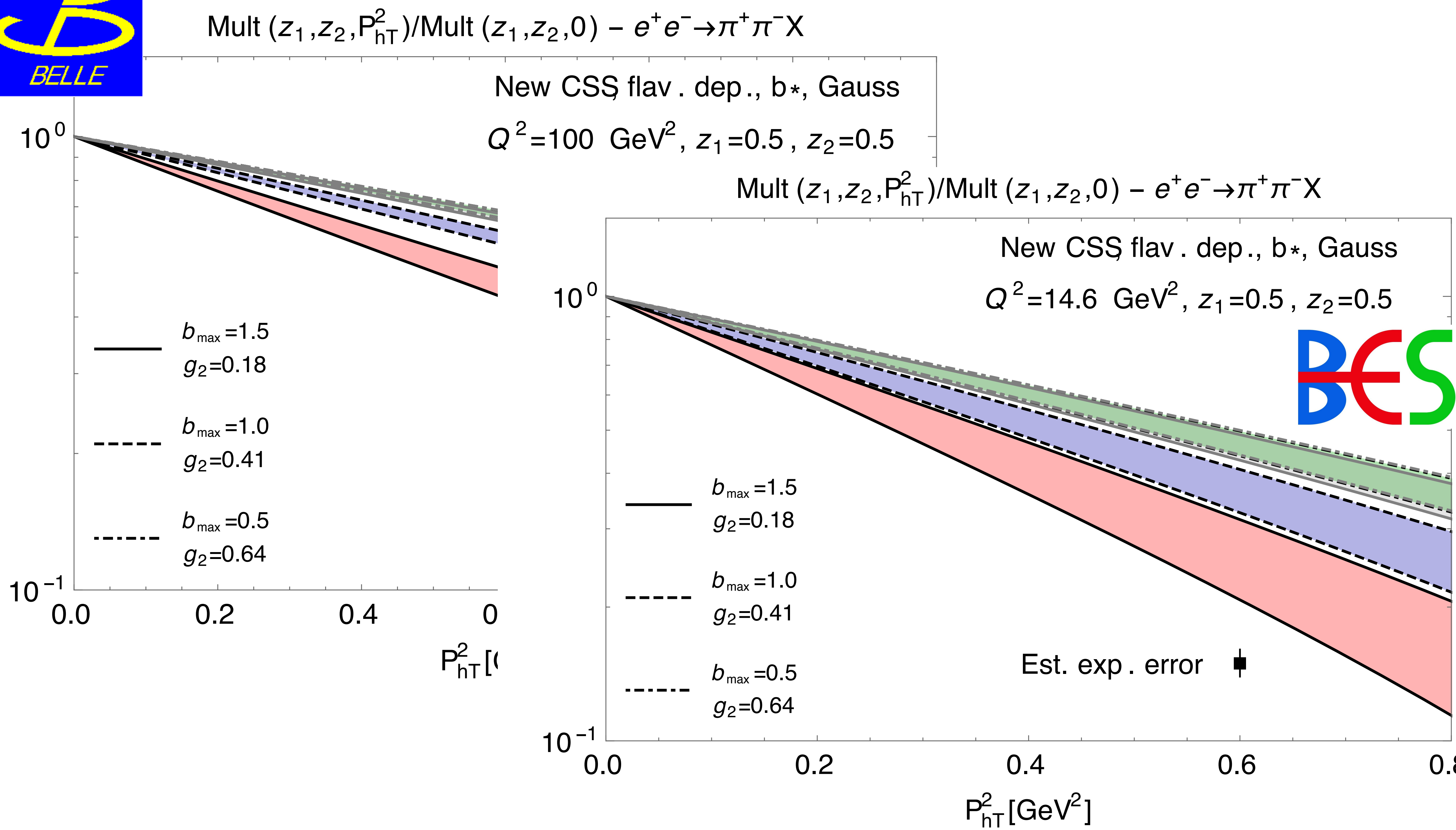
Just one day

AWESOME!

(But remember that we want them in multidimensional binning)

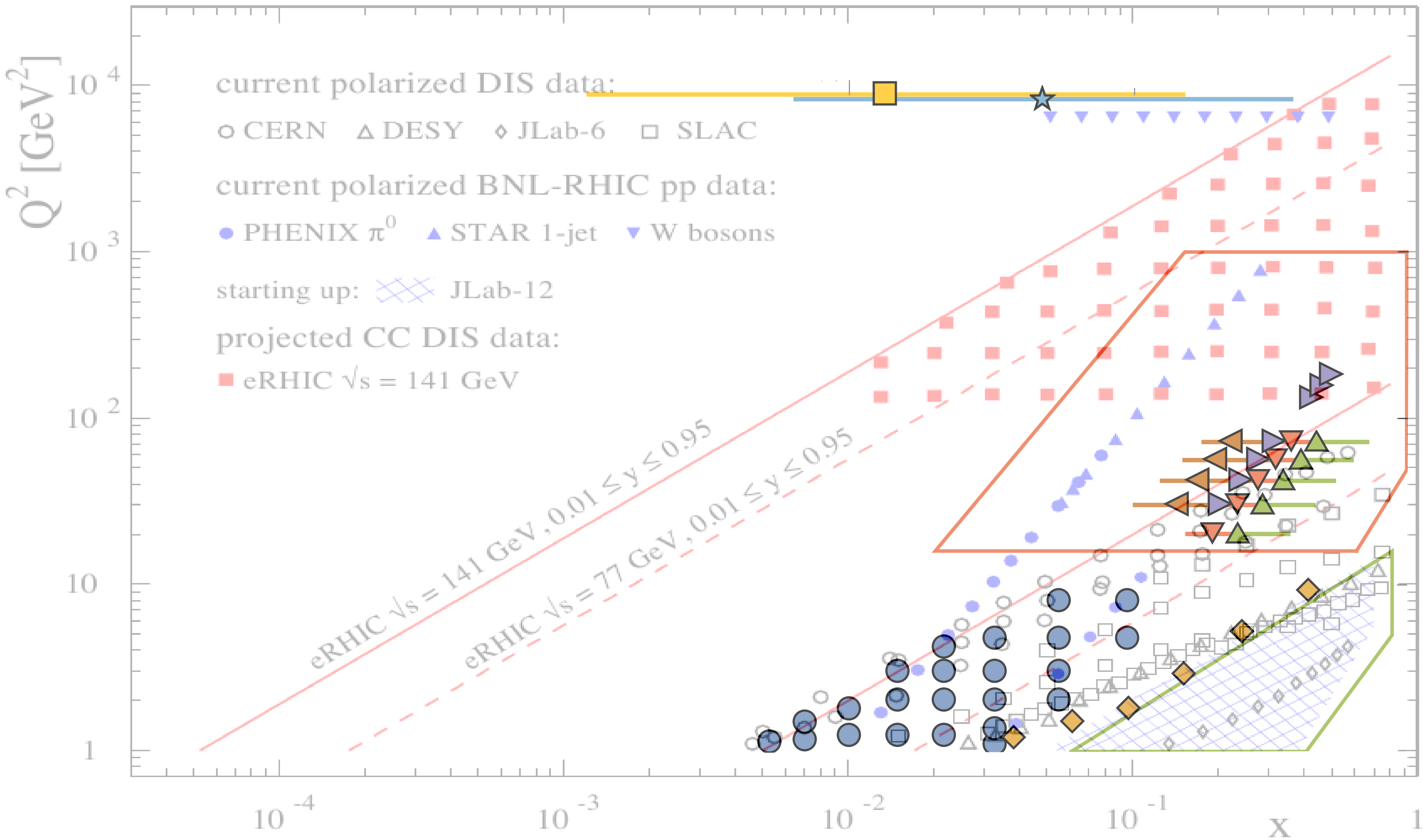
Evolution of TMD fragmentation funct.

Bacchetta, Echevarria, Signori, Radici, arXiv:1508.00402



Measurements of TMD multiplicities will be really useful!

Future experimental data



To better test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2.

In five to ten years

- TMD multiplicities for pions and kaons, off protons and deuterons, from COMPASS and JLab
- Drell-Yan and Z measurements from CERN, RHIC, FermiLab (COMPASS with pions)
- TMD multiplicities for pions and kaons in e^+e^- from BELLE and BES
- Better understanding and control of higher-order QCD corrections
- More flexible functional forms, flavour dependence, at least two or three alternative extractions
- Use TMDs for something else (W mass… comparison with lattice… Wigner distributions…)
- **READY TO USE EIC DATA**