Transversity 2024

Trieste, 3-7 June 2024

TMD EFFECTS IN UNPOLARISED PROCESSES PHENOMENOLOGY OVERVIEW

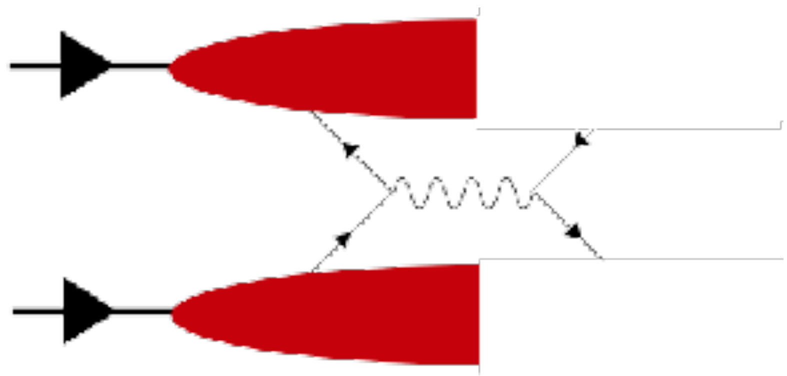
7th international workshop on transverse phenomena in hard processes

OVERVIEW

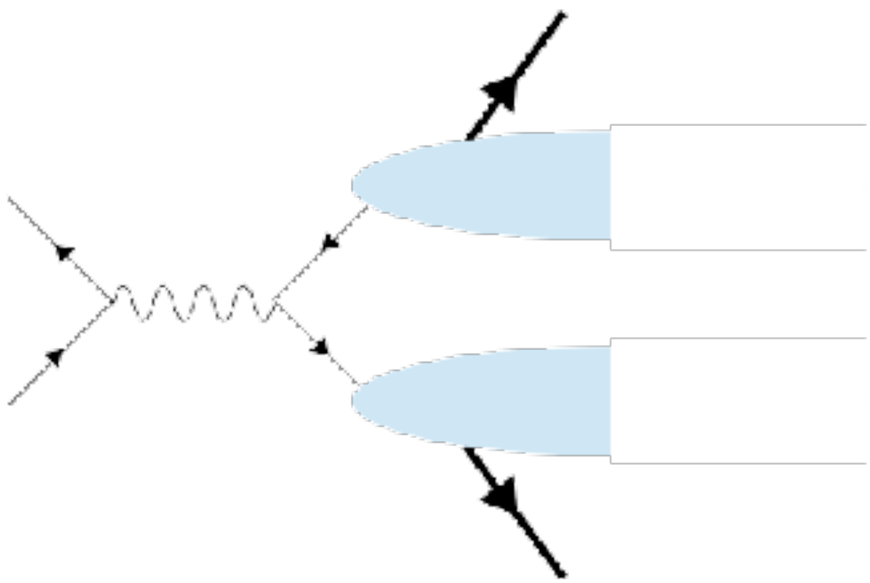
- Ingredients for phenomenology
- Recent extractions/pheno
- Some current challenges

INGREDIENTS FOR PHENOMENOLOGY

Some q_T observables

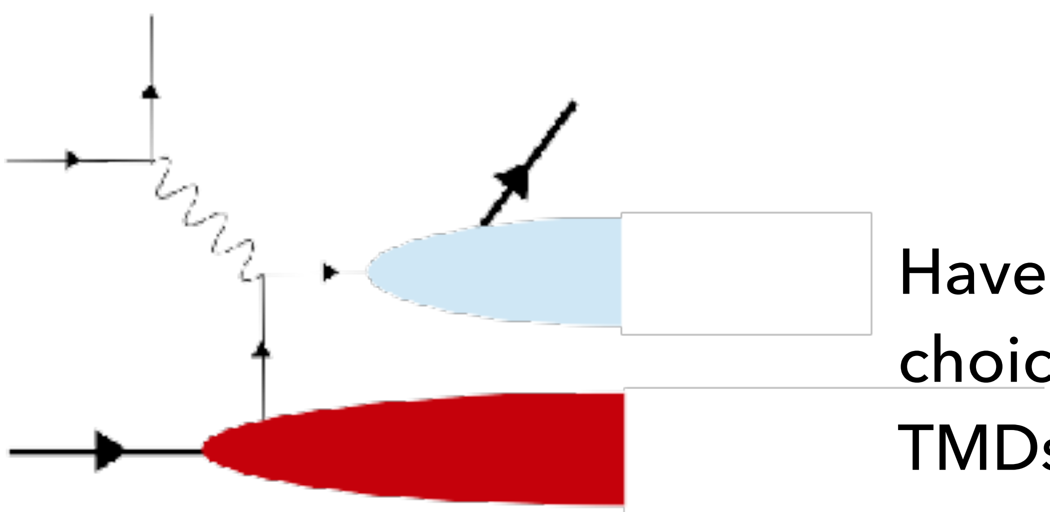


$$\sigma_{\rm DY} \sim [F_{i/a}, F_{i/b}]$$



$$\sigma_{\rm SIA} \sim [D_{a/i}, D_{b/i}]$$

Same functions for different observables: Universality, predictive power.



$$\sigma_{\rm SIDIS} \sim [F_{i/a}, D_{b/i}]$$

Have **(almost*)** no choice but to extract TMDs from data

*** Lattice!!**

Connect observables at different scales through evolution equations. Need Fourier transform to b_T space

$$\frac{\mathrm{d}\ln \tilde{f}_{j/p}(x, b_{\mathrm{T}}; \mu, \zeta)}{\mathrm{d}\ln \mu} = \gamma(\alpha_s(\mu); \zeta/\mu^2)$$

$$\frac{\mathrm{d}\ln \tilde{D}(z, \boldsymbol{b}_{\mathrm{T}}; \mu, \zeta)}{\mathrm{d}\ln \mu} = \gamma(\alpha_s(\mu); \zeta/\mu^2)$$

$$\frac{\partial \ln \tilde{f}_{j/p}(x, b_{\mathrm{T}}; \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_{\mathrm{T}}; \mu)$$

$$\frac{\partial \ln \tilde{D}(z, \boldsymbol{b}_{\mathrm{T}}; \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_{\mathrm{T}}; \mu)$$

$$\frac{\mathrm{d}\tilde{K}(b_{\mathrm{T}}; \mu)}{\mathrm{d}\ln \mu} = -\gamma_K(\alpha_s(\mu))$$

Collins-Soper kernel:

- Highly universal
- nonperturbative at long distances
- extracted simultaneously with TMDs
- great progress in lattice QCD

Theoretical constraints in the **small-b_T** limit: OPE

$$\tilde{f}_{i/a}(x, b_{\rm T}; \mu, \zeta) \sim [C^{\rm pdf}(b_{\rm T}; \mu, \zeta) \otimes f_{i/a}(\mu)](x)$$

$$\tilde{D}_{a/i}(z, b_{\rm T}; \mu, \zeta) \sim [C^{\rm ff}(b_{\rm T}; \mu, \zeta) \otimes d_{a/i}(\mu)](z)$$

Collinear functions extracted previously

C coefficients calculable in pQCD in this limit: perturbative **b_T** (**k_T**) effects.

$\tilde{K}(b_{\rm T}; \mu)$ calculable in pQCD in this limit

Theoretical constraints in the **small-b_T** limit: OPE

$$\tilde{f}_{i/a}^{\rm pheno} = [C^{\rm pdf} \otimes f_{i/a}] \, \boxed{\tilde{f}_{i/a}^{\rm NP}}$$

$$\tilde{D}_{a/i}^{\rm pheno} = [C^{\rm ff} \otimes d_{a/i}] \, \boxed{\tilde{D}_{a/i}^{\rm NP}}$$

Models in bT space

Most recent pheno on unpolarized TMDs has been carried out in two schemes:

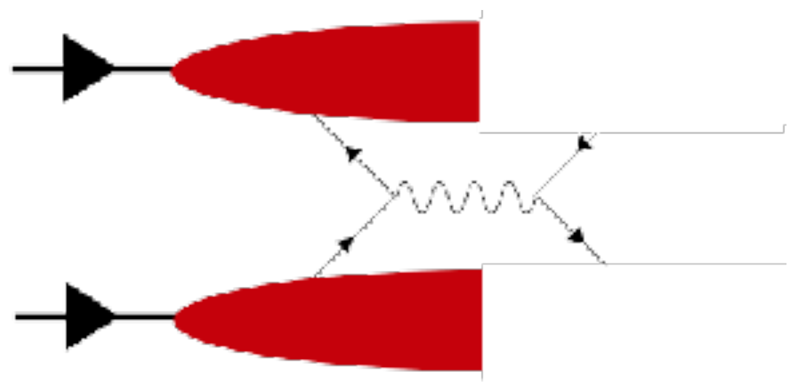
- b_* prescription (most used, e.g. **MAP, JAM, BNLY, …**)
- ζ prescription (**Madrid**)

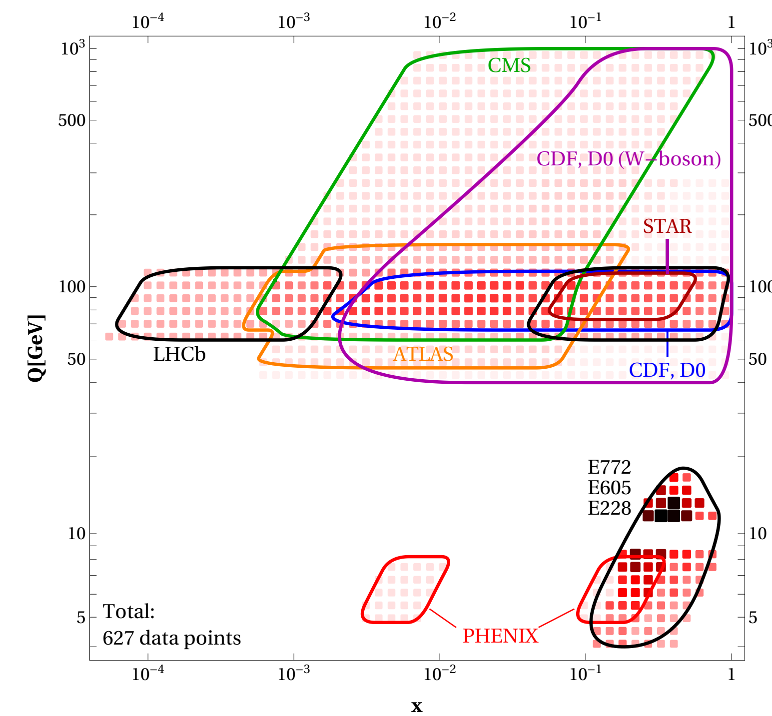
Modeling in k_T space + analogous constraints also possible

See talk by Ted Rogers

RECENT EXTRACTIONS/PHENO

See talk by Ignazio Scimemi





Γ_{cusp}	γ_V	$\mathcal{D}_{\text{small-b}}$	$C_{f\leftarrow f'}$	C_V	PDF
$a_s^5\ (\Gamma_4)$	$a_s^4\ (\gamma_4)$	$a_s^4\ (d^{(4,0)})$	$a_s^3\ (C^{[3]}_{f\leftarrow f'})$	a_s^4	NNLO

***JHEP* 05 (2024) 036 • e-Print: 2305.07473 [hep-ph]**

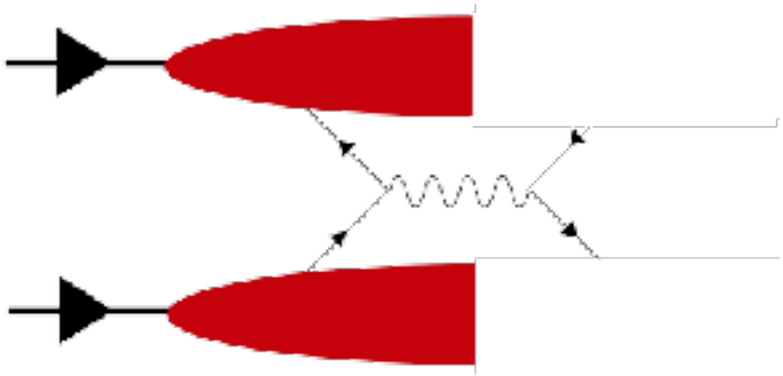
Maximum available perturbative accuracy

Large amount of data

Wide kinematical range

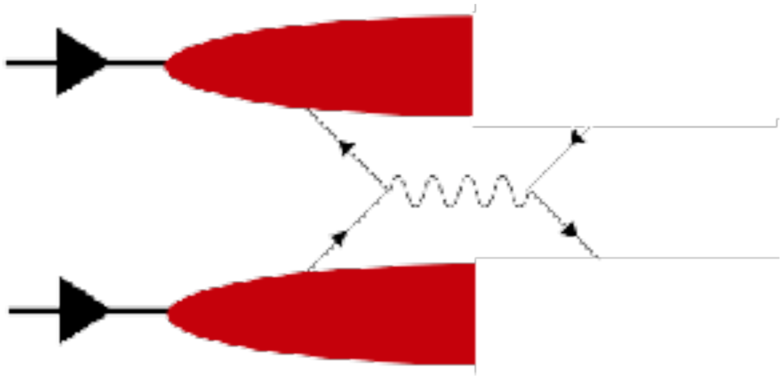
PDF uncertainties

PDF uncertainties



treatment can be computationally prohibitive

PDF uncertainties

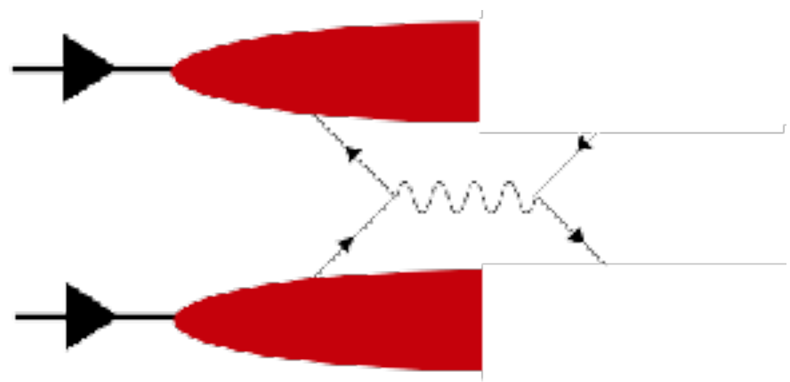


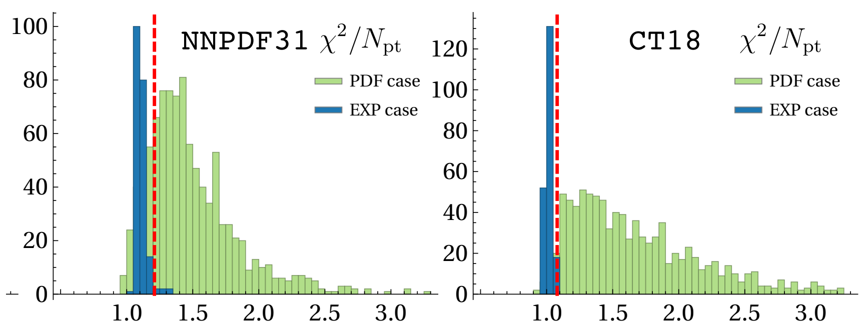
treatment can be computationally prohibitive

experimental & theory uncertainty (PDF) in the same footing?

PDF uncertainties

(transversity 2022 , Pia Zurita)





. JHEP 10 (2022) 118 [2201.07114].

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More work on methods for error propagation would be useful

PDF uncertainties

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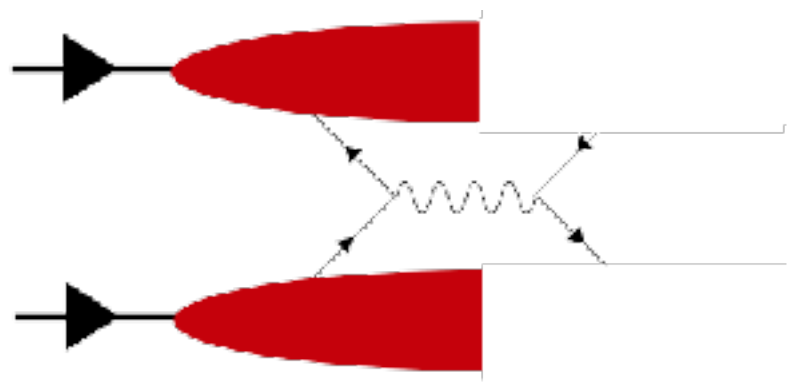
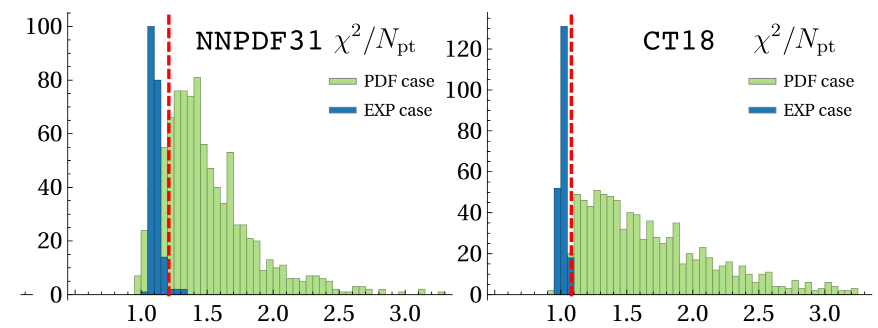




. **JHEP 10 (2022) 118 [2201.07114].**

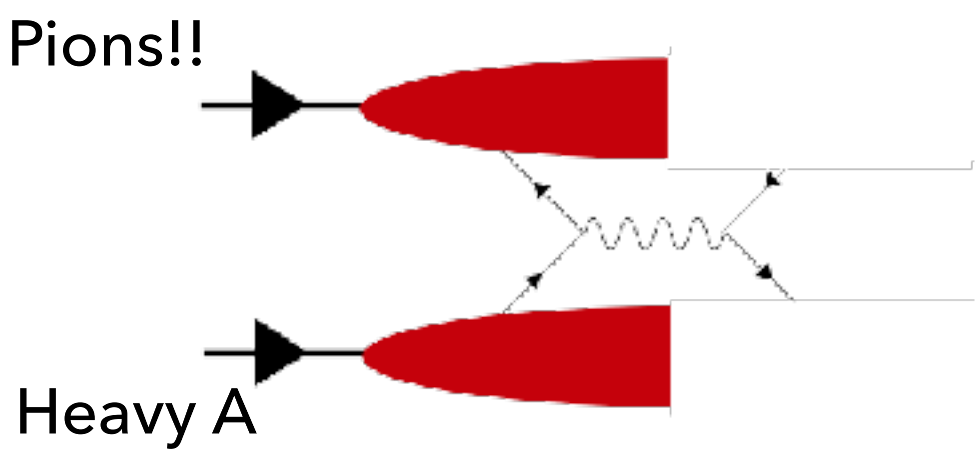
treatment can be computationally prohibitive

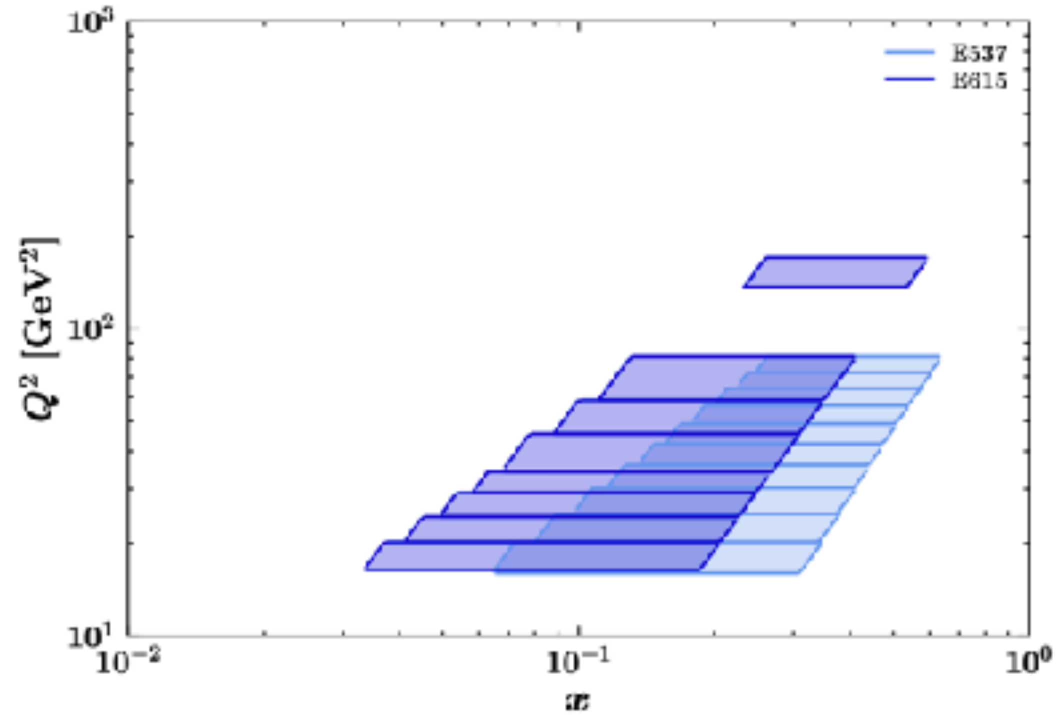
experimental & theory uncertainty (PDF) in the same footing?

More work on methods for error propagation would be useful

(perhaps spy on other fields of physics or statisticians)

Not quite as many data





Phys.Rev.D 107 (2023) 1, 014014 • e-Print: 2210.01733

Pion TMDs interesting on their own right

Further studies on nuclear TMDs
(how good are current treatments?)

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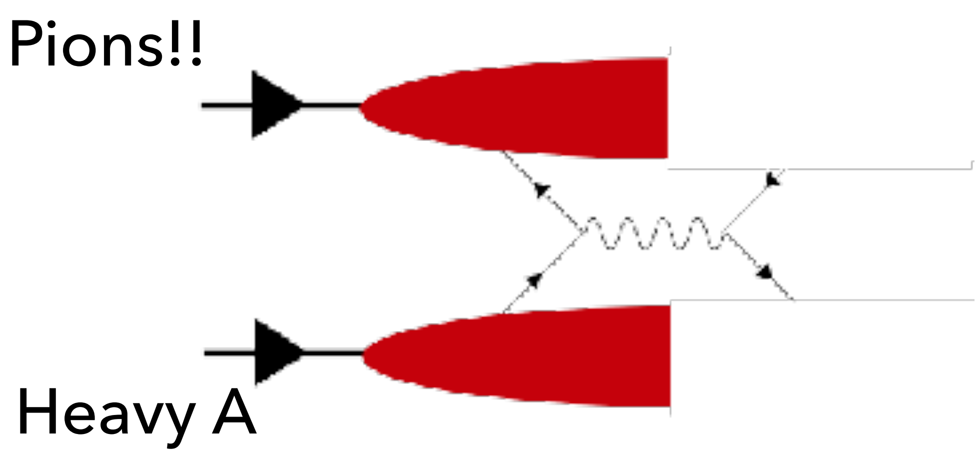

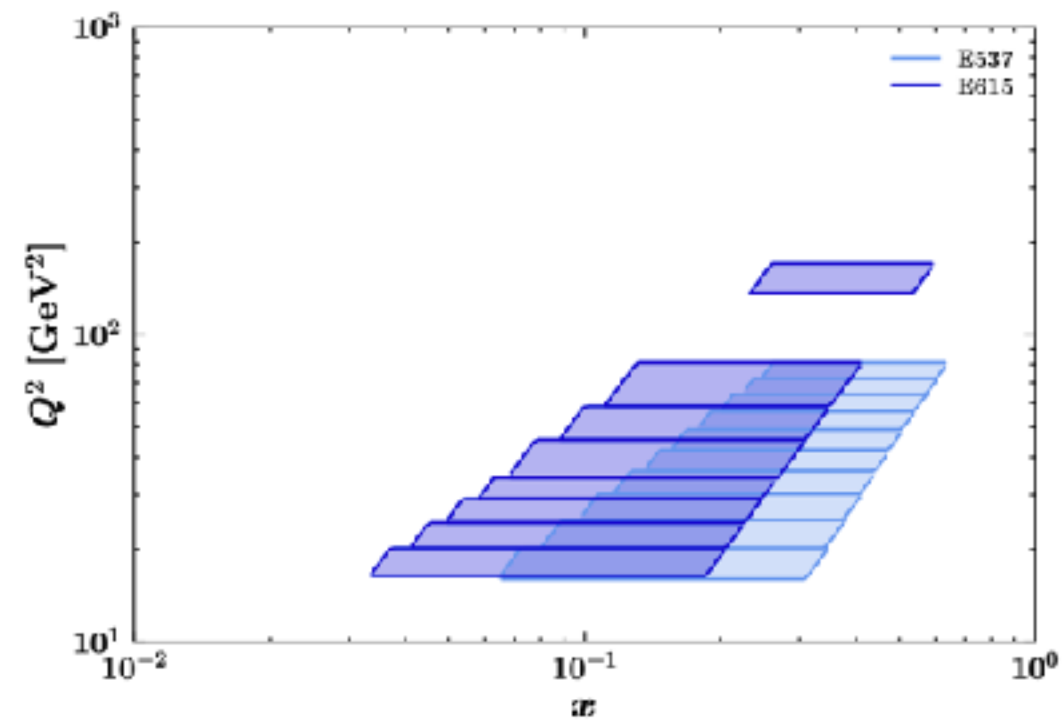

Pion TMDs interesting on their own right

Further studies on nuclear TMDs
(how good are current treatments?)

Phenomenological analyses find reasonable agreement to data in their fits.

MAP 2023

Experiments	N_{cut}	χ^2_D/N_{cut}	χ^2_λ/N_{cut}	χ^2_0/N_{cut}
E537	64	1.00	0.57	1.57
E615	74	0.31	1.22	1.53
Total	138	0.63	0.92	1.55

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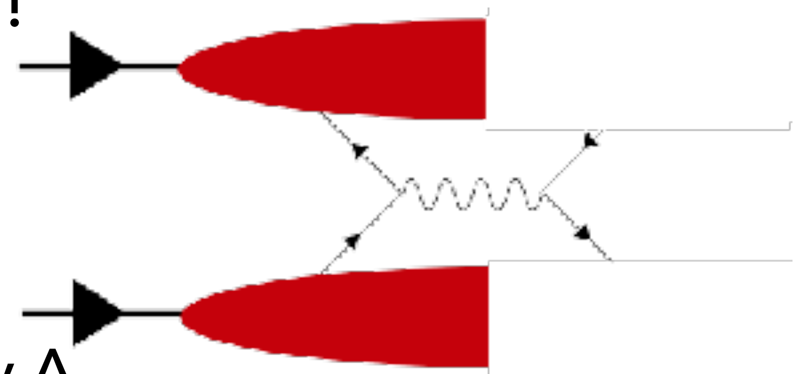
JAM 2023

q_T-dep. πA DY	E615 [95]	21.8	1.45	1.85
$\pi W \to \mu^+\mu^- X$	E537 [96]	15.3	0.97	0.03

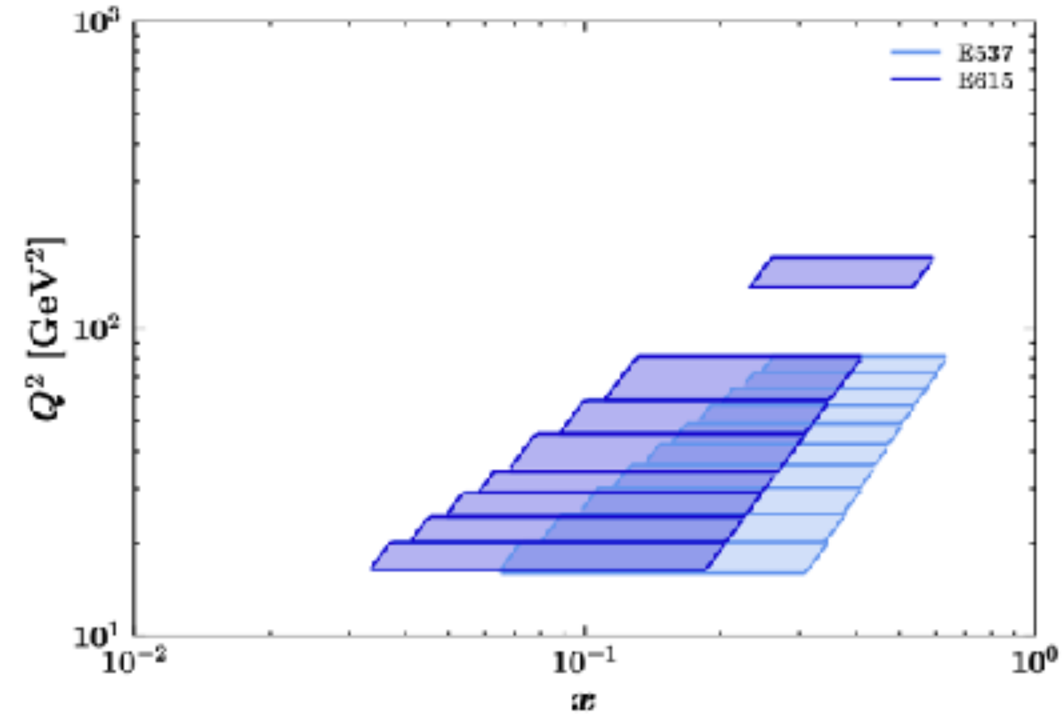
Phys.Rev.D 108 (2023) 9, L091504 • e-Print: 2302.01192

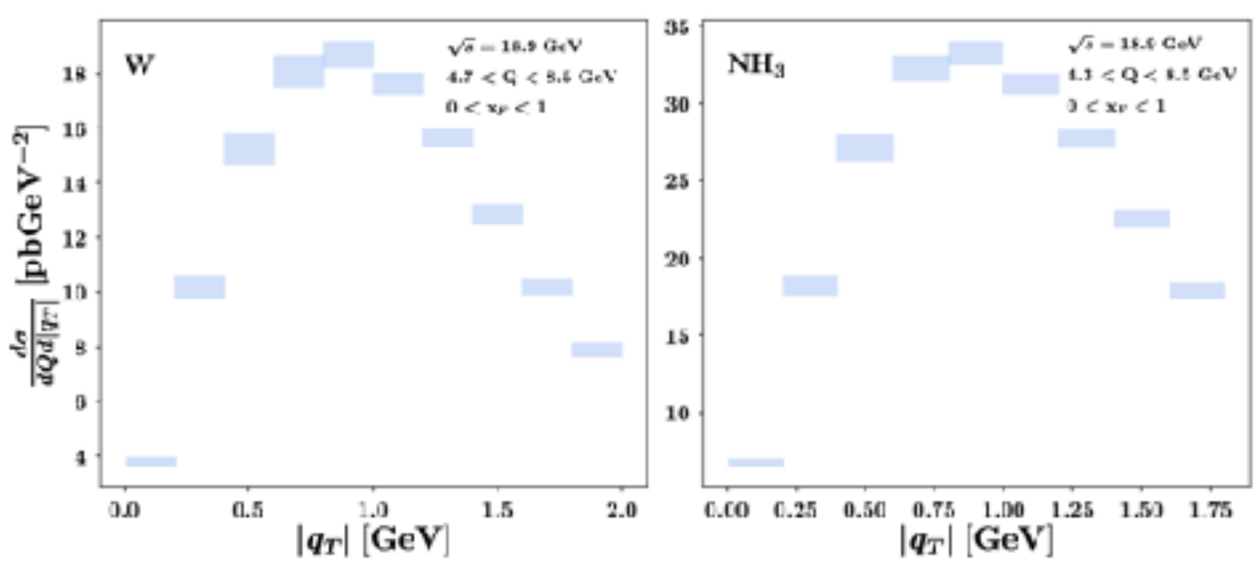
Not quite as many data

Pions!!



Heavy A





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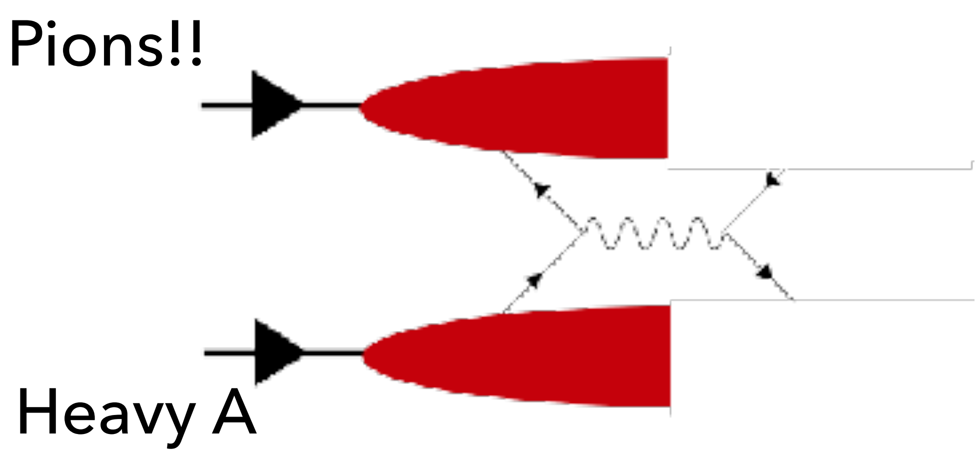
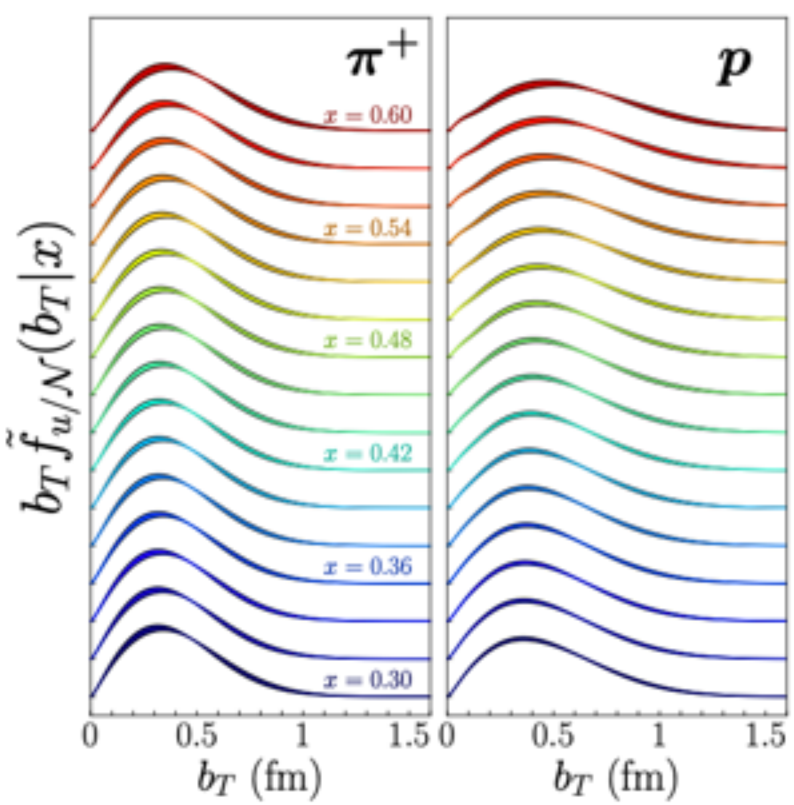
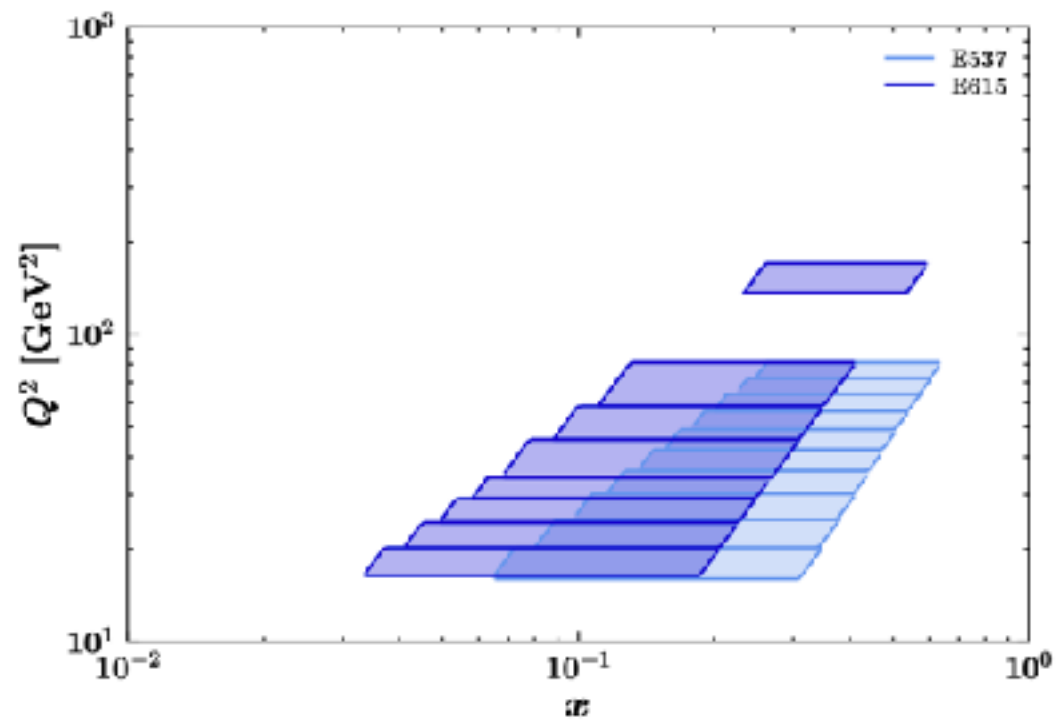
(Full blown) Predictions at COMPASS kinematics:
need to test the theory / factorization theorem /model / …

Not quite as many data







Interesting insight/interpretation:
proton vs pions

See talk by Patrick Barry

JAM 2023

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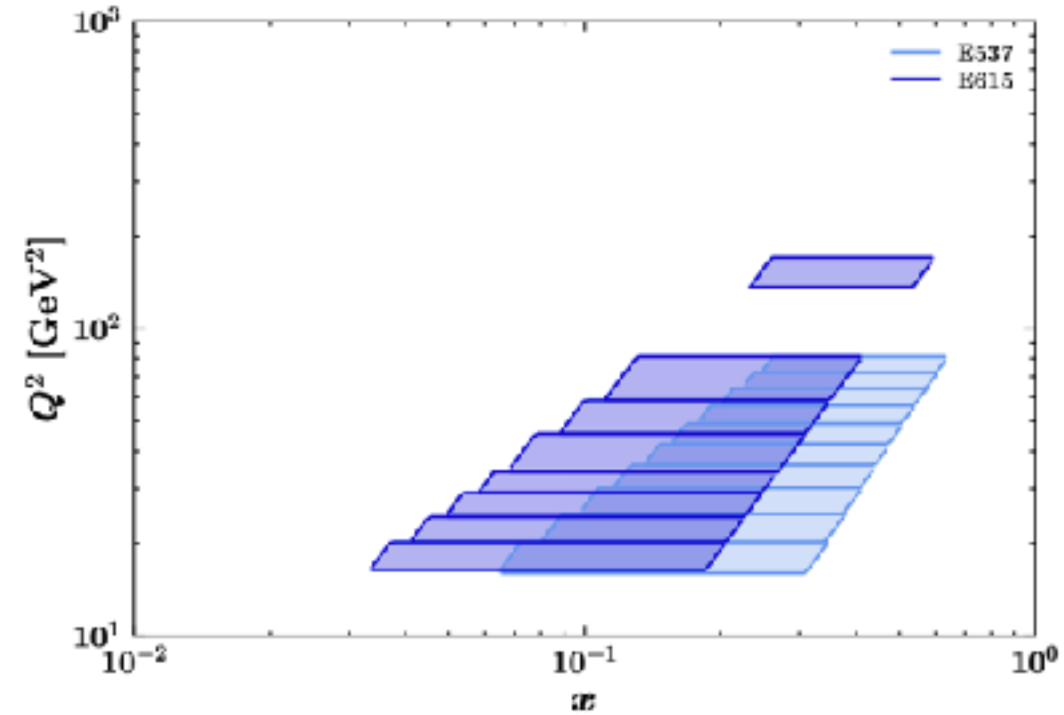
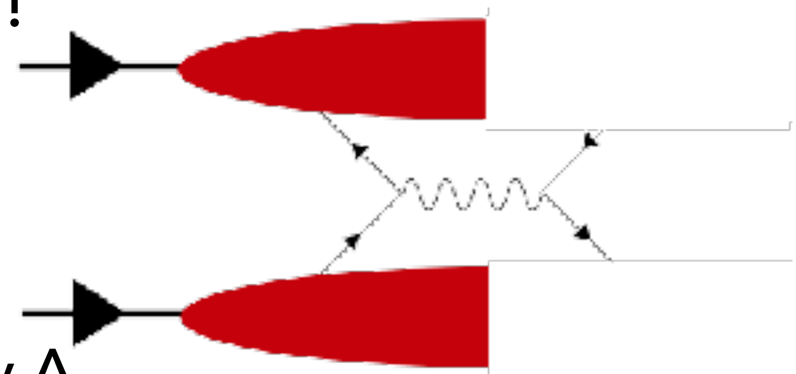


Pions!!



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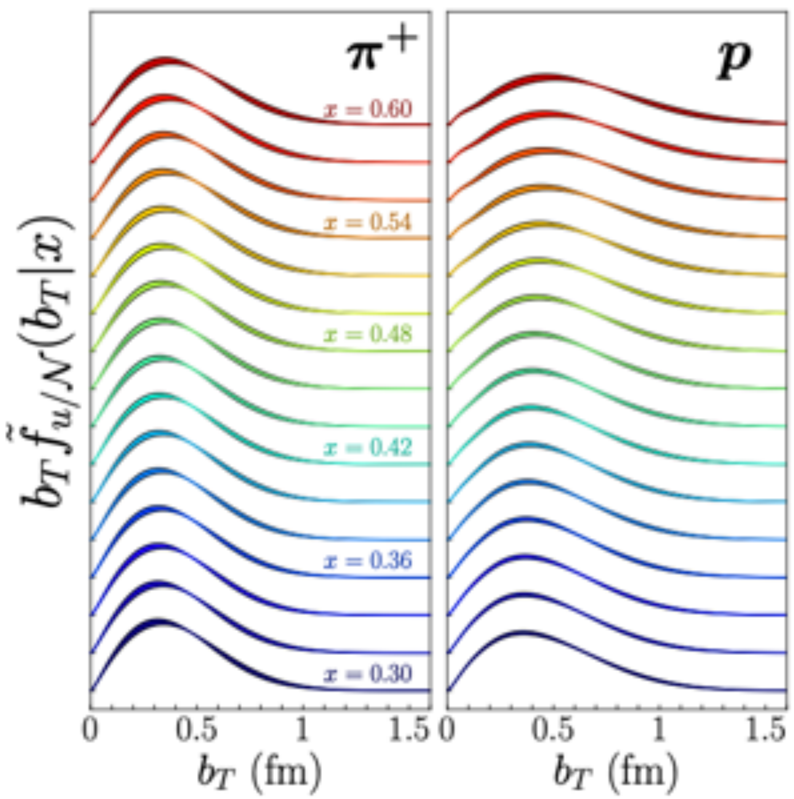

Interesting insight/interpretation:
proton vs pions

(do we) can we have predictions for COMPASS as well?

See talk by Patrick Barry

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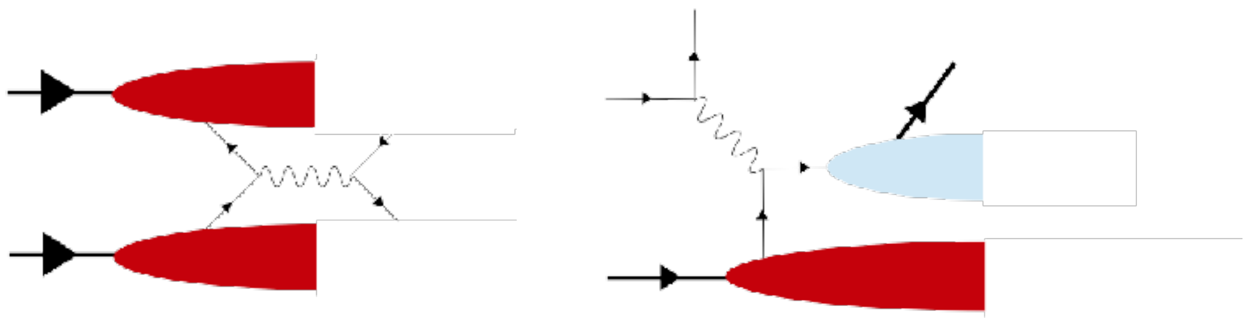


Most recent global fits on DY (like) + SIDIS

MAP 2024

- pdf uncertainty
- large amount of data
- high perturbative accuracy
- a lot of information from SIDIS (low scale)

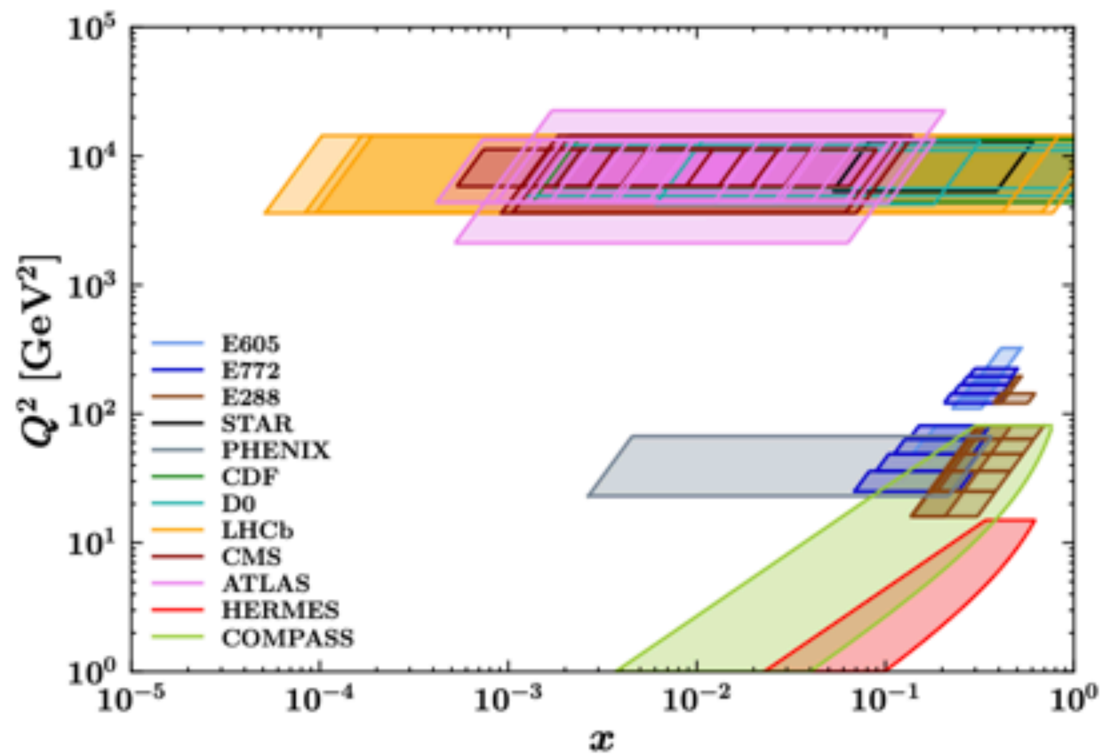
Drell-Yan data 484

Fixed-target:
E288, E605, E772

Collider mode:
RHIC, Tevatron, LHC

SIDIS data 1547

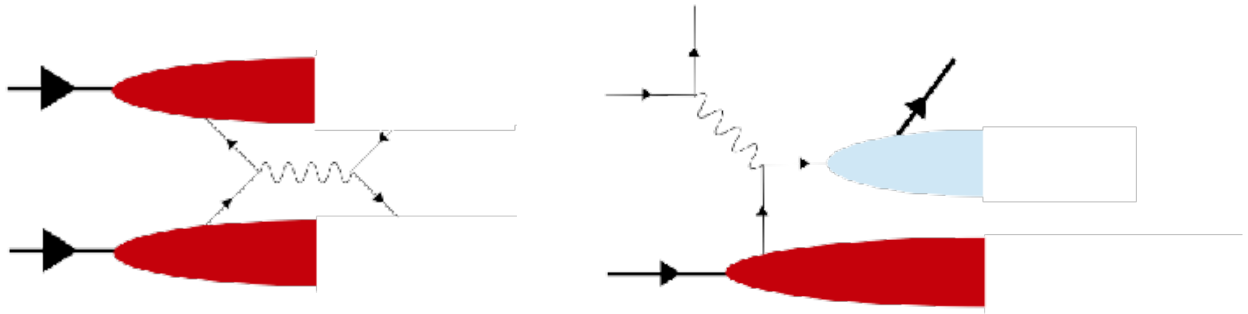
HERMES, COMPASS



Total number of data: 2031

(Matteo Cerutti QCD evolution)

See talk by Lorenzo Rossi



Most recent global fits on DY (like) + SIDIS

MAP 2024

- pdf uncertainty
- large amount of data
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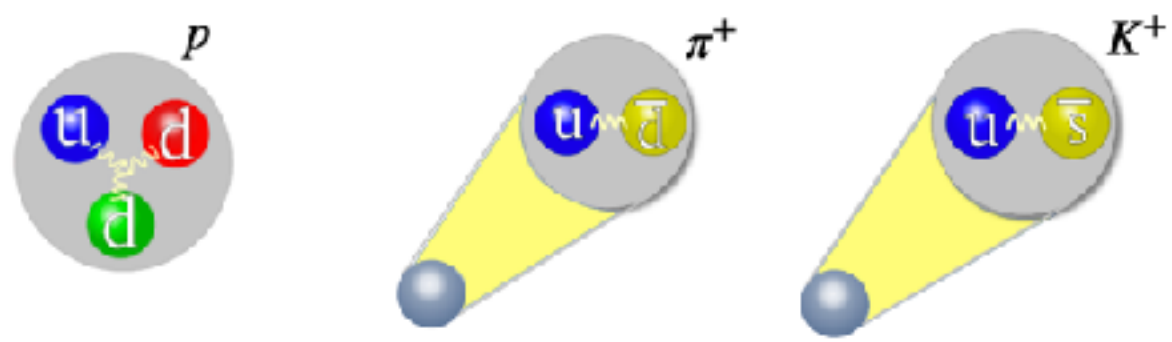
MAPTMD24: new approach

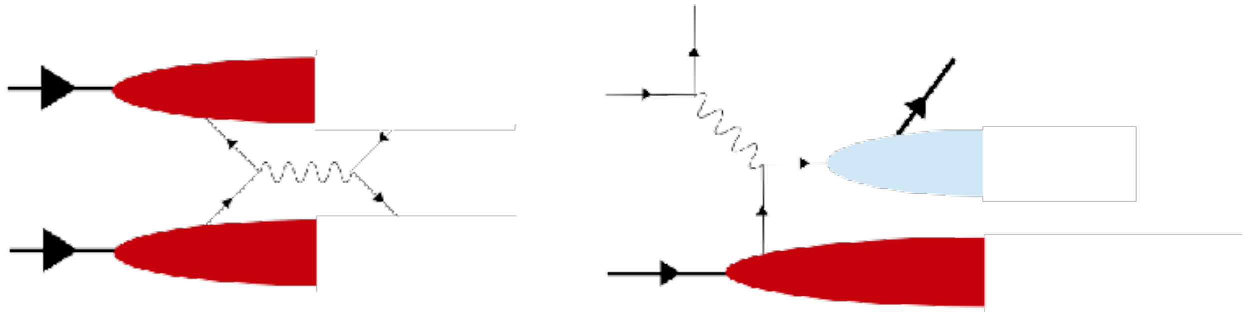
Solution: we need **flavor dependence** to obtain a good agreement between theory and experiments



u, d	$u \to \pi^+, \ldots$	$u \to K^+, \ldots$
$\bar{u}, \bar{d}$	$d \to \pi^+, \ldots$	$\bar{s} \to K^+, \ldots$
s (sea)		$d \to K^+, \ldots$

charge conjugation

(Matteo Cerutti QCD evolution)



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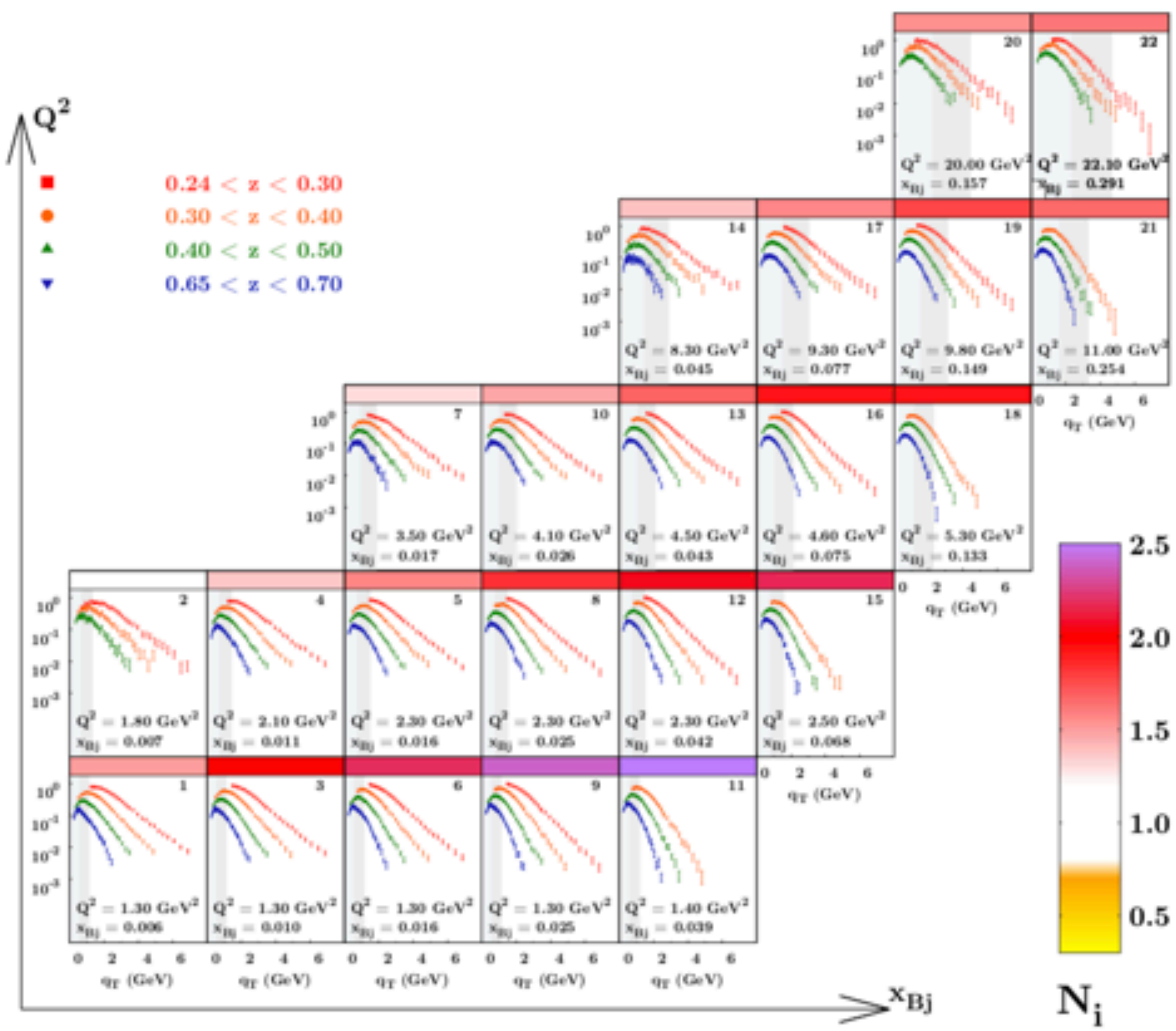


Normalization: some issues with SIDIS fits, see for instance:

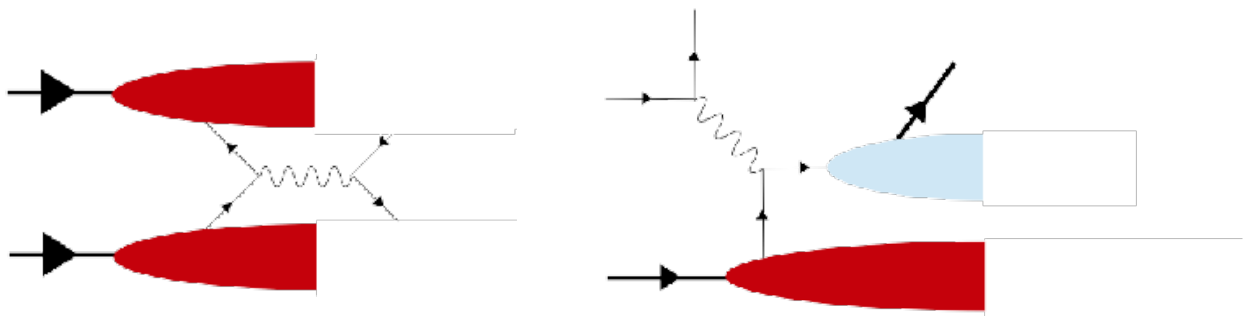
JOGH, *PoS* DIS2019 (2019) 176

Old fit at O(alpha_s)

Decent fit

Need to introduce spurious normalizations

Red means N ~ 2.0



MAP 2024

- large amount of data
- high perturbative accuracy
- a lot of information from **SIDIS (low scale)**

Normalise predictions such that integral over P_{hT} gives $d\sigma/dxdQdz$:

$$M(x,z,P_{hT},Q) = \mathcal{N}\frac{\frac{d\sigma}{dxdQdzdP_{hT}}}{\frac{d\sigma}{dxdQ}} \qquad \mathcal{N} = \frac{\frac{d\sigma}{dxdQdz}}{\int dP_{hT}\frac{d\sigma}{dxdQdzdP_{hT}}}$$

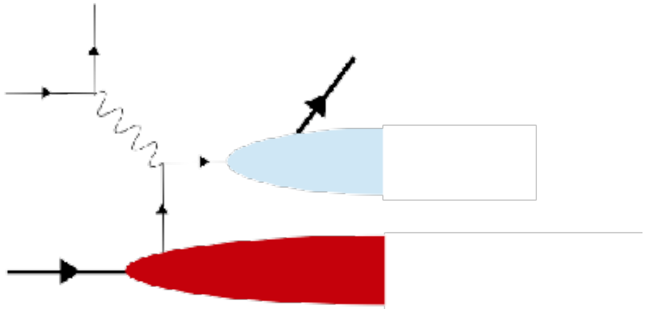
Theoretically justified normalisation and **not fitted**.

(Valerio Bertone , Transversity 2022)

Theory motivated fix

Even in most recent fits by MAP
(high pQCD accuracy)
this issue persist

Normalization: some issues with SIDIS fits



Non-perturbative structure of semi-inclusive deep-inelastic and Drell-Yan scattering at small transverse momentum

JHEP 06 (2020) 137 • e-Print: 1912.06532 [hep-ph]

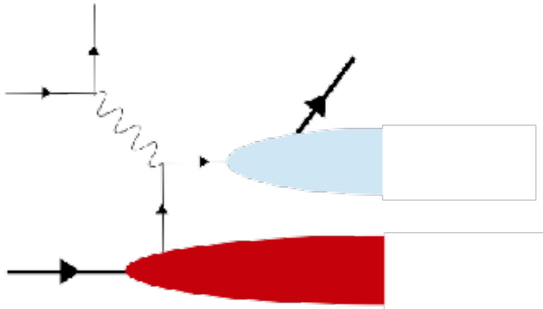
Ignazio Scimemi[1] Alexey Vladimirov[2]

Contrary to some observations in the literature [14, 18], we have not found any problem with the normalization of HERMES and COMPASS data, although the systematic experimental errors quit precision to the final result.

[18] A. Bacchetta, F. Delcarro, C. Pisano, M. Radici and A. Signori, *Extraction of partonic transverse momentum distributions from semi-inclusive deep-inelastic scattering, Drell-Yan and Z-boson production*, *JHEP* **06** (2017) 081, [1703.10157].

Do we agree on this issue?

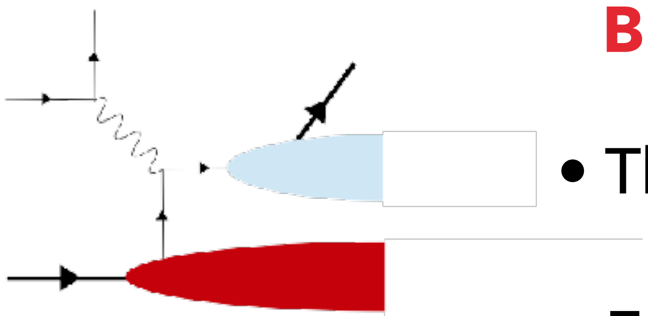
Normalization: some issues with SIDIS fits



Brainstorming:

- There is no issue

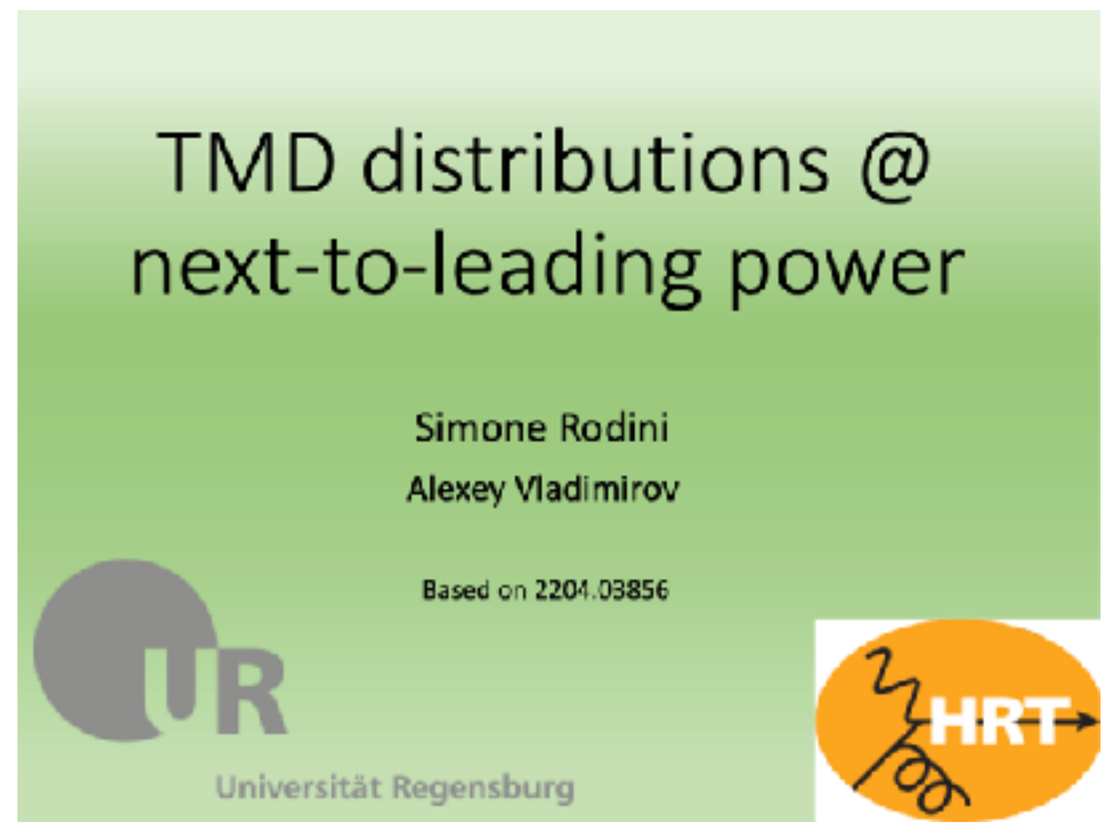
Normalization: some issues with SIDIS fits



Brainstorming:

- There is no issue
- Errors of factorization are too large

- Next-to-leading power formalisms: Theorist have been very active on this front. (Pheno?)



(Simone Rodini , Transversity 2022)

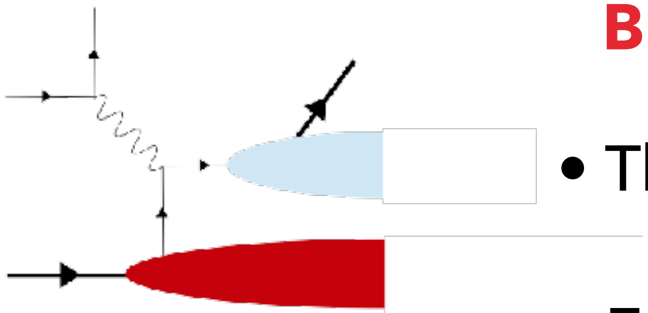
A few more examples, not comprehensive

Transverse momentum dependent operator expansion at next-to-leading power
Alexey Vladimirov (Regensburg U.), Valentin Moos (Regensburg U.), Ignazio Scimemi (Madrid U.) (Sep 20, 2021)
Published in: *JHEP* 01 (2022) 110 • e-Print: 2109.09771 [hep-ph]

Transverse momentum dependent factorization for SIDIS at next-to-leading power
Simone Rodini (Ecole Polytechnique, CPHT), Alexey Vladimirov (Madrid U.) (Jun 15, 2023)
e-Print: 2306.09495 [hep-ph]

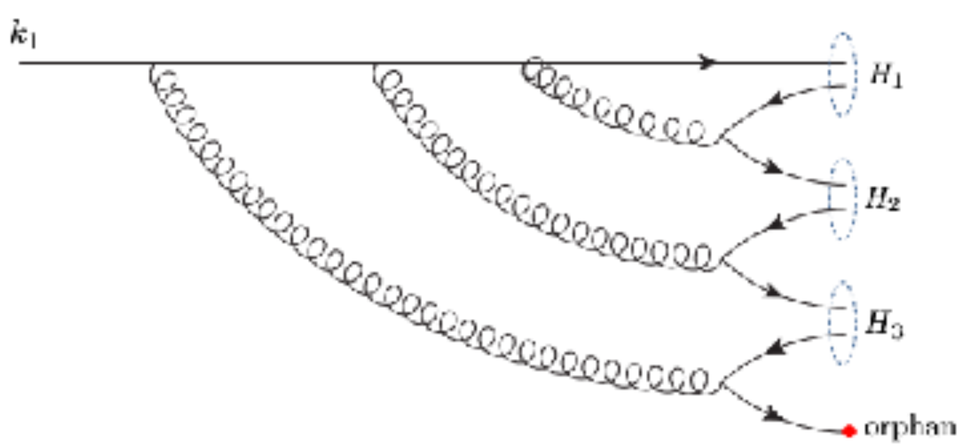
$1/Q^2$ power corrections to TMD factorization for Drell-Yan hadronic tensor
Ian Balitsky (Old Dominion U.) (Apr 23, 2024)
e-Print: 2404.15116 [hep-ph]

Normalization: some issues with SIDIS fits



Brainstorming:

- There is no issue
- Errors of factorization are too large
- We are missing something about the fragmentation functions

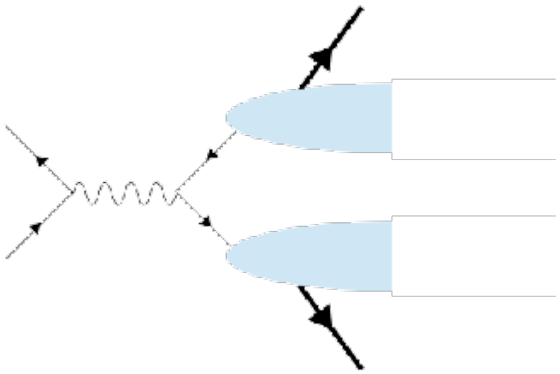


New insights from theory. (pheno?)

Definition of fragmentation functions and the violation of sum rules #1

John Collins (Penn State U.), Ted C. Rogers (Old Dominion U. and Jefferson Lab) (Sep 6, 2023)

Published in: *Phys.Rev.D* 109 (2024) 1, 016006 • e-Print: 2309.03346 [hep-ph]



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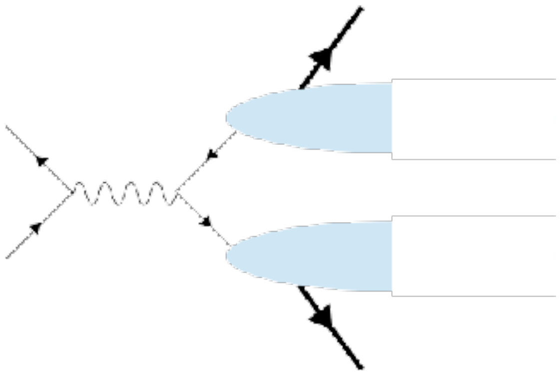
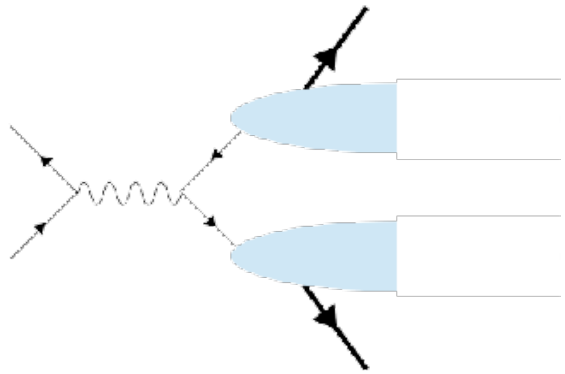


No data available

Other related processes?

See talk by A. Vossen



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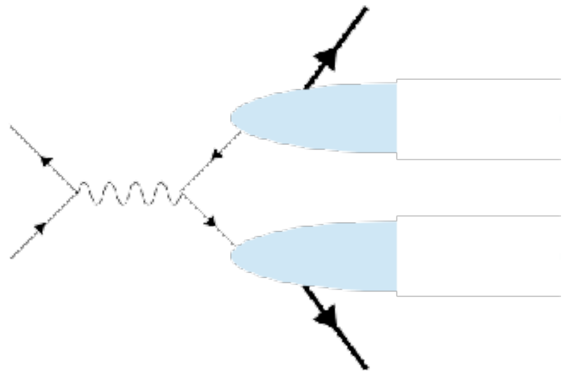
Other related processes?

- theory+pheno of **e^+e^- –> h X**
- missing full treatment of thrust
- Same CS kernel
- Different TMD ff (related to SIDIS)

(Andrea Simonelli, Transversity 2022)



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(Andrea Simonelli, Transversity 2022)

JHEP 02 (2022) 013 • e-Print: 2109.11497

Phys.Rev.D 106 (2022) 7, 074024 • e-Print: 2206.08876

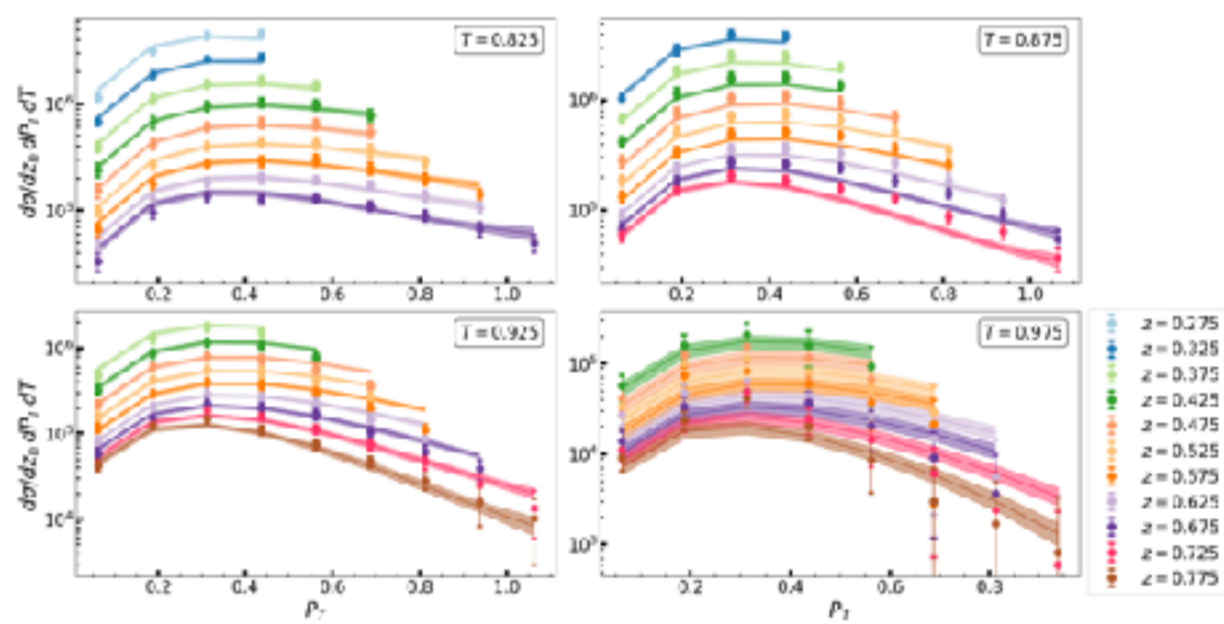
Full treatment of thrust

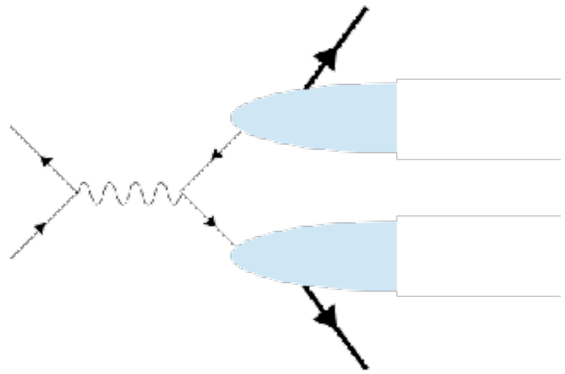
Boglione, Simonelli

JHEP 09 (2023) 006 • e-Print: 2306.02937

JHEP 02 (2022) 013 • e-Print: 2109.11497

See talk by Andrea Simonelli





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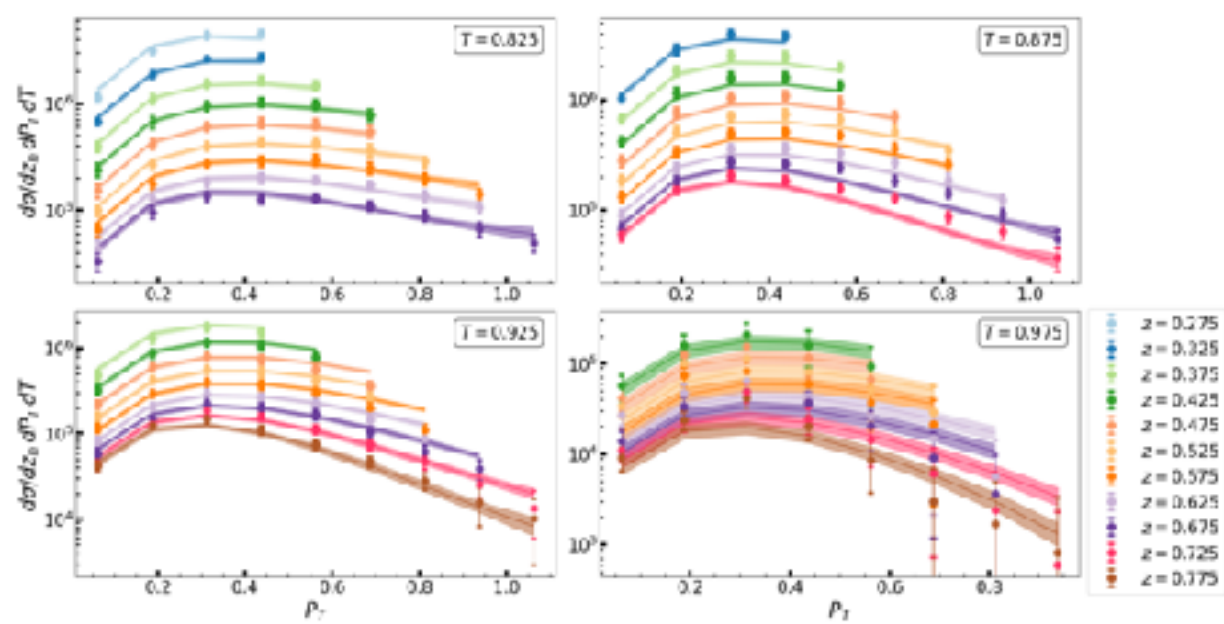
Boglione, Simonelli

JHEP 09 (2023) 006 • e-Print: 2306.02937

JHEP 02 (2022) 013 • e-Print: 2109.11497

See talk by Andrea Simonelli



Other relevant work (not comprehensive)

Modarres, Taghavi *Phys.Rev.D* 104 (2021)11,114004 e-Print: 2111.06190

Makris, et.al. *JHEP* 02 (2021) 070 • e-Print: 2009.1187

Kang, et.al. *JHEP* 12 (2020) 127 • e-Print: 2007.14425

HSO approach

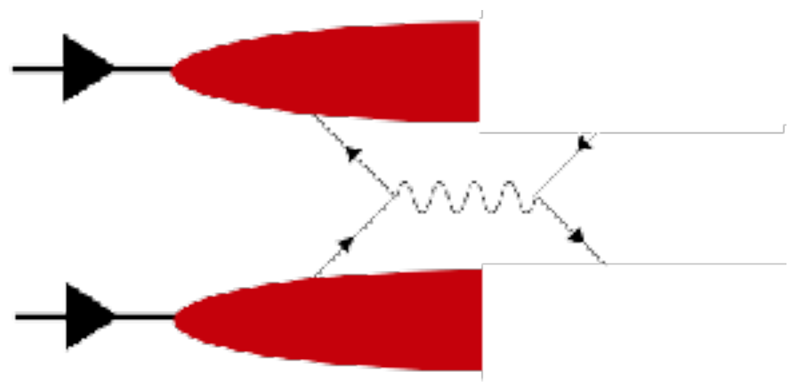
-Use theoretical constraints, don't trust the fit will do this job by itself.

-Check/improve constraints

-Prioritize the role of lower scale data (more information about intrinsic kT)

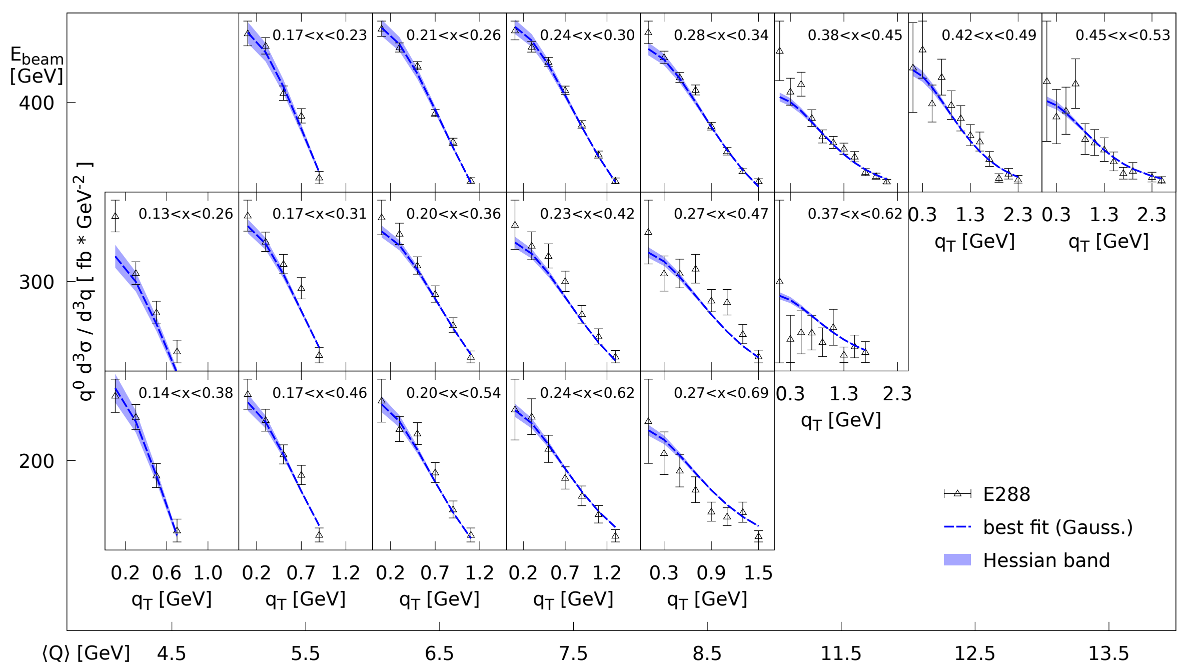
-Emphasize the role of predictive aspect of factorization theorems

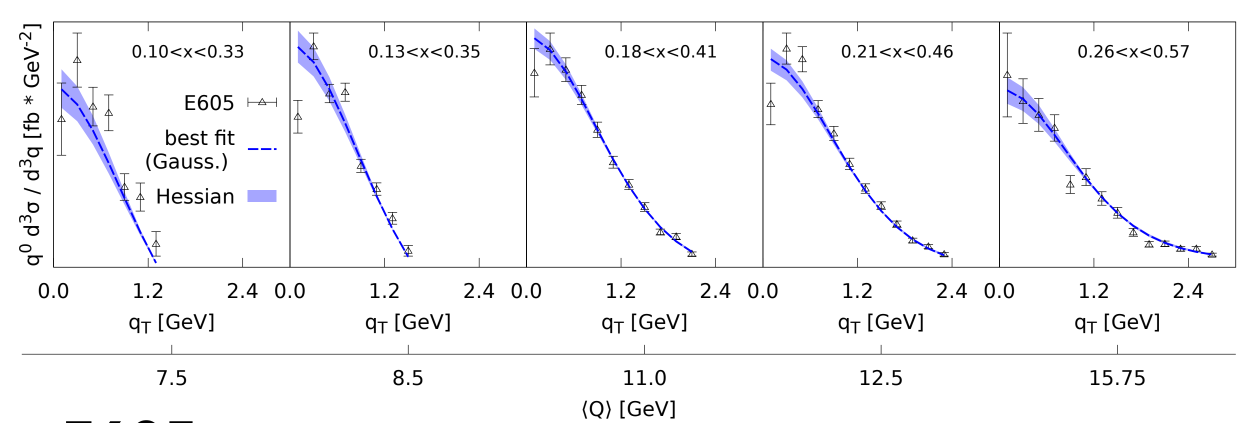
(JOGH, QCD evolution 2024)



Some proof-of-concept pheno lowest order (just starting)

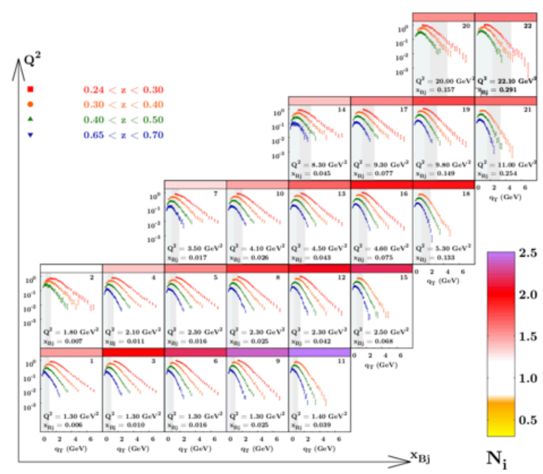
E288





E605

SOME CURRENT CHALLENGES



Normalization issue (**?**)
in SIDIS **TMD region**

qT<<Q

We can only fit
small qT data

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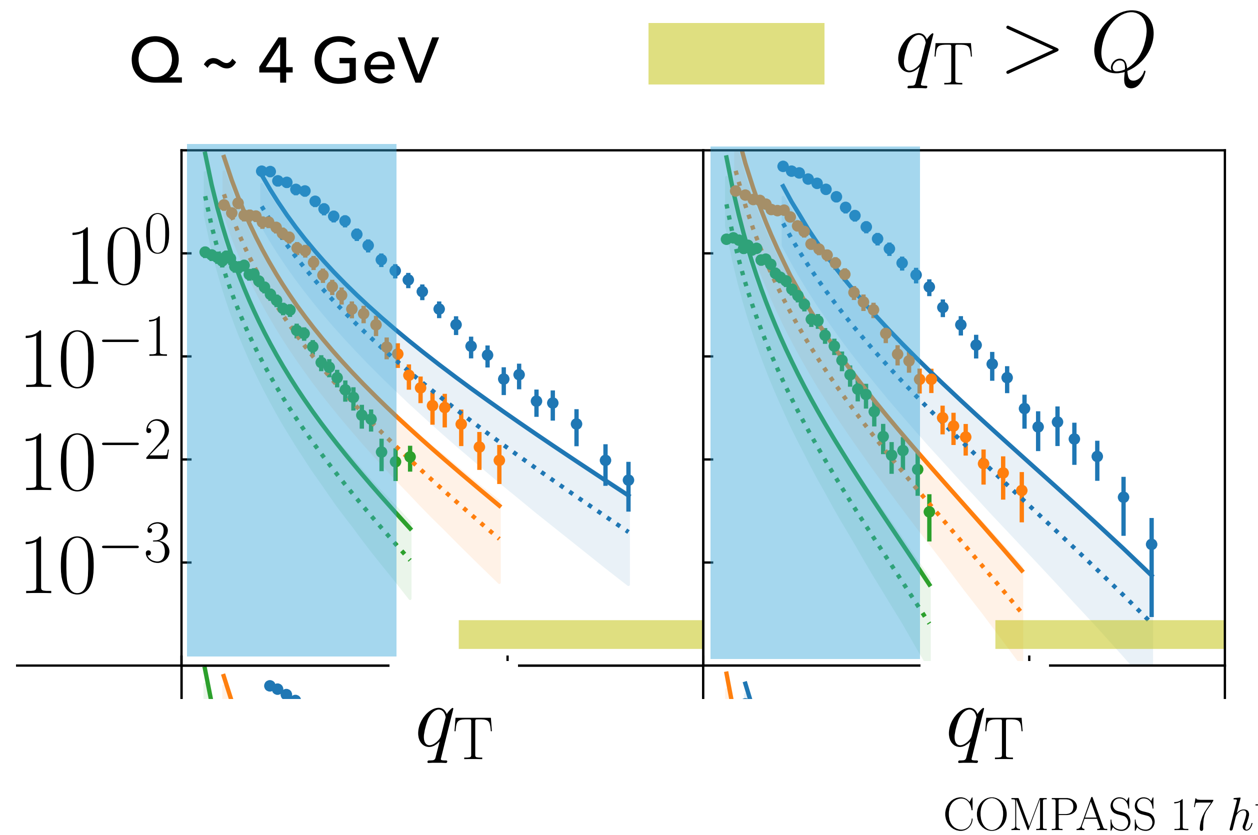
Large qT, **collinear**
factorization (**no** TMDs)

qT ~ Q

We should predict
with existing
collinear functions
(no further fitting)



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Large qT, **collinear**
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qT ~ Q

We should predict
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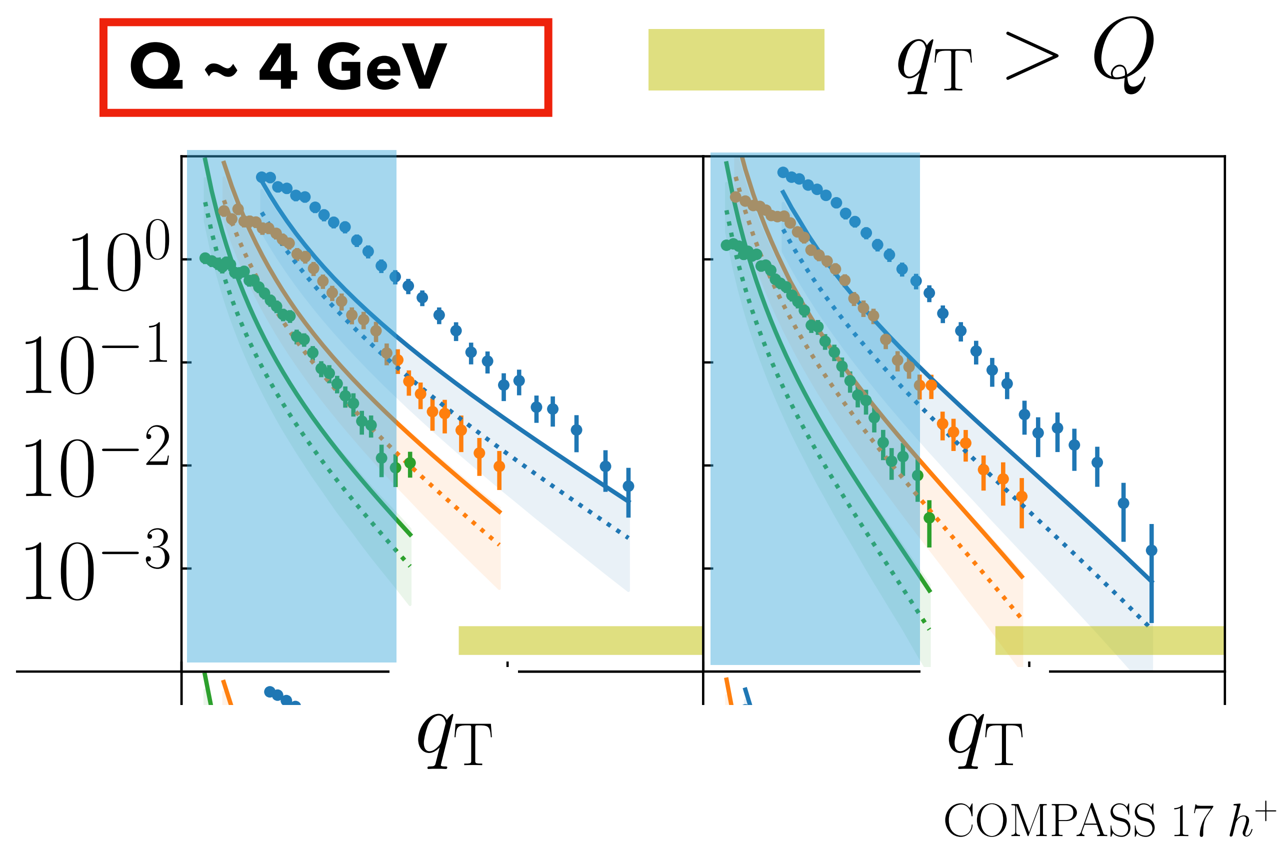
(no further fitting)

We can't

Is this scale too low to trust factorization?

Q ~ 4 GeV



Normalization issue (?) in SIDIS **TMD region**

qT<<Q

We can only fit small qT data

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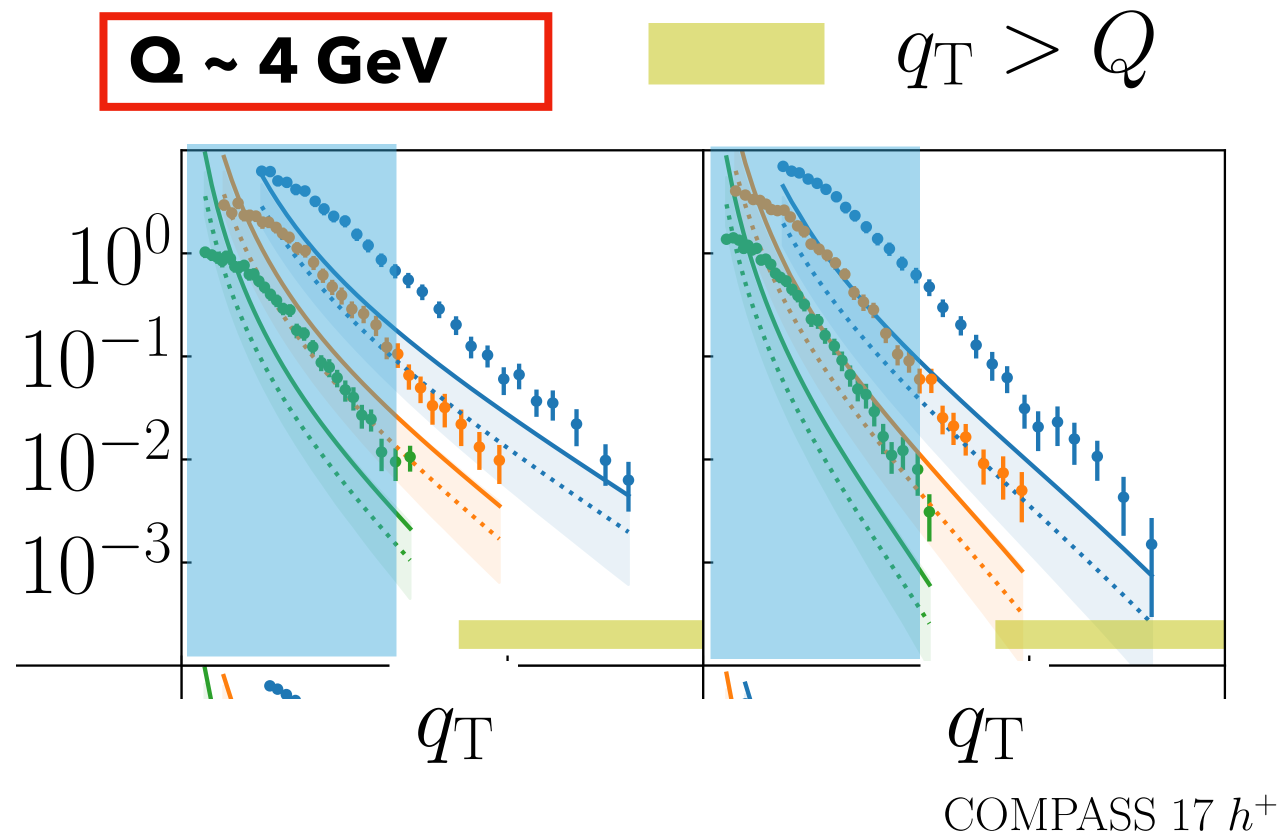
We should predict with existing collinear functions (no further fitting)

Is this scale too low to trust factorization?

recall we DY fits start at about these scales



Normalization issue (**?**) in SIDIS **TMD region**

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We can only fit small qT data

Large qT, **collinear** factorization (**no** TMDs)

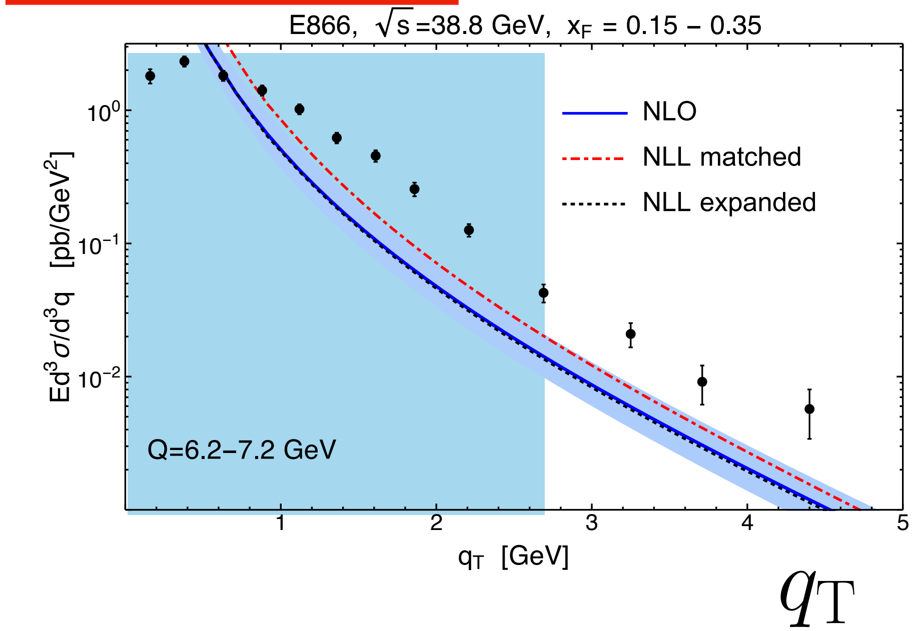
qT ~ Q

We should predict with existing collinear functions (no further fitting)

Is this scale too low to trust factorization?

recall we DY fits start at about these scales

Q ~ 6.5 GeV



Phys.Rev.D 100 (2019) 1, 014018 • e-Print: 1901.06916

NO Normalization issue in DY **TMD region**

qT<<Q

Large qT, **collinear** factorization (**no** TMDs)

qT ~ Q

Can't describe DY "tails" very well either

The case for an EIC Theory Alliance: Theoretical Challenges of the EIC

- Theoretical and phenomenological exploration of QCD factorization theorems and expanding the region of their applicability, for instance by inclusion of power corrections in q_T/Q. A crucial ingredient will be matching collinear factorization ($\Lambda_{\text{QCD}} \ll q_T \sim Q$) and TMD factorization ($\Lambda_{\text{QCD}} \lesssim q_T \ll Q$) in the overlap region $\Lambda_{\text{QCD}} \ll q_T \ll Q$ in a stable and efficient way. Such a matching is needed for our ability to describe the measured quantities, differential in transverse momentum, in the widest possible region of phase space. In turn, this will lead to a much more reliable understanding of both collinear and TMD related functions and uncertainties in their determinations.

e-Print: 2305.14572

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Fancy talk to say
"interpolate these two"

TMD region

qT<<Q

a.k.a. "Matching"

Large qT, **collinear** factorization (**no** TMDs)

qT ~ Q

Need consistency
conditions
between cross section
in the two limits

"Matching"

TMD region

$q_T << Q$

Large qT, **collinear**
factorization (**no** TMDs)

$q_T \sim Q$

Need **consistency conditions** between cross section in the two limits

$$\tilde{f}^{\text{pheno}}_{i/a} = [C^{\text{pdf}} \otimes f_{i/a}] \boxed{\tilde{f}^{\text{NP}}_{i/a}}$$

$$\tilde{D}^{\text{pheno}}_{a/i} = [C^{\text{ff}} \otimes d_{a/i}] \boxed{\tilde{D}^{\text{NP}}_{a/i}}$$

Some progress in this direction: HSO approach

Phys.Rev.D 107 (2023) 9, 094029 • e-Print: 2303.04921

See talk by Ted Rogers

Impose **conditions** on nonperturbative models

(Done in momentum space)

$$\texttt{pQCD tail} = \frac{1}{2\pi}\frac{1}{k_{\text{T}}^2}\left[A_{i/p}(x;\mu_{Q_0}) + B_{i/p}(x;\mu_{Q_0})\ln\left(\frac{Q_0^2}{k_{\text{T}}^2}\right) + A^g_{i/p}(x;\mu_{Q_0})\right]$$

$$2\pi\int_0^{\mu_{Q_0}} \mathrm{d}k_{\text{T}}\, k_{\text{T}} f^{\text{operator}}_{i/p}(x,\boldsymbol{k}_{\text{T}};\mu_{Q_0},\mu^2_{Q_0}) = f^{\overline{\text{MS}}}_{i/p}(x;\mu_{Q_0}) + \Delta_{i/p}(\alpha_s(\mu_{Q_0})) + O\left(\frac{m^2}{\mu^2_{Q_0}}\right)$$

Integral relation

JOGH, T Rogers, N Sato
Phys.Rev.D 106 (2022) 3, 034002 • e-Print: 2205.05750

See also talk by Ignazio Scimemi

Need **consistency conditions**
between cross section
in the two limits

$$\tilde{f}_{i/a}^{\rm pheno} = [C^{\rm pdf} \otimes f_{i/a}] \boxed{\tilde{f}_{i/a}^{\rm NP}}$$

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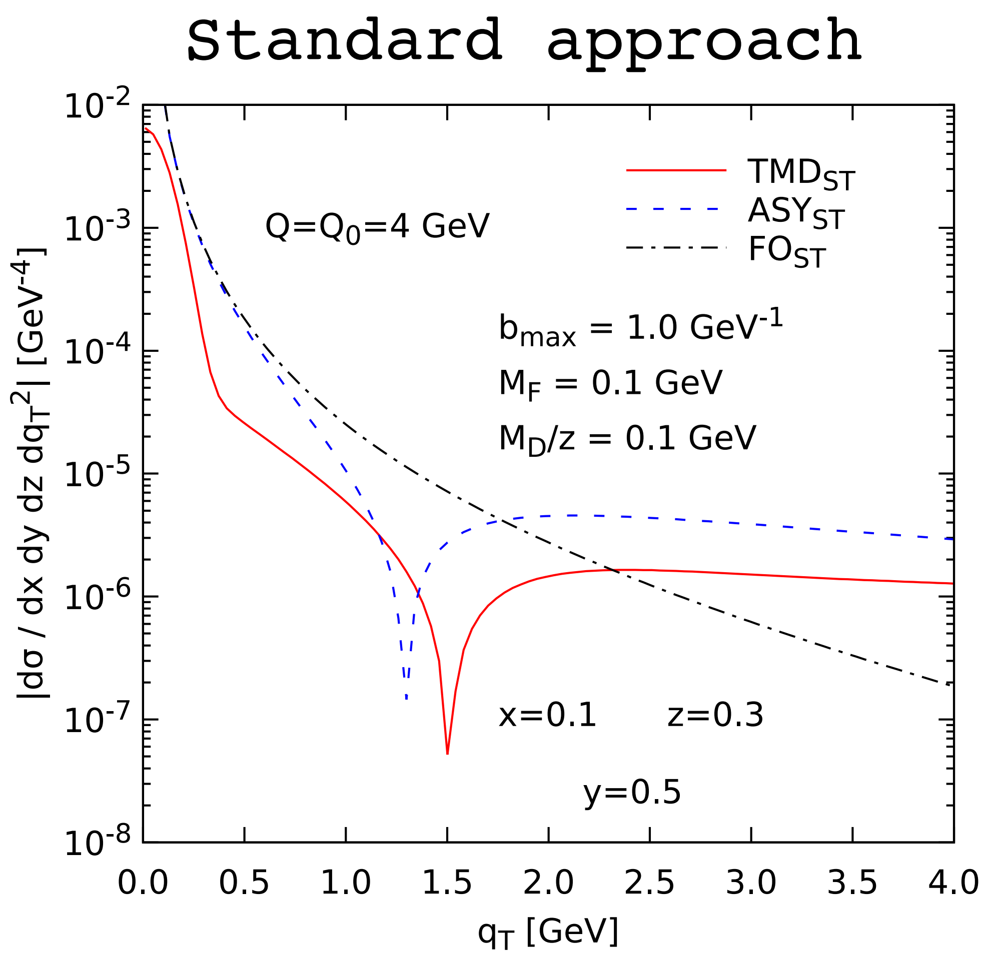
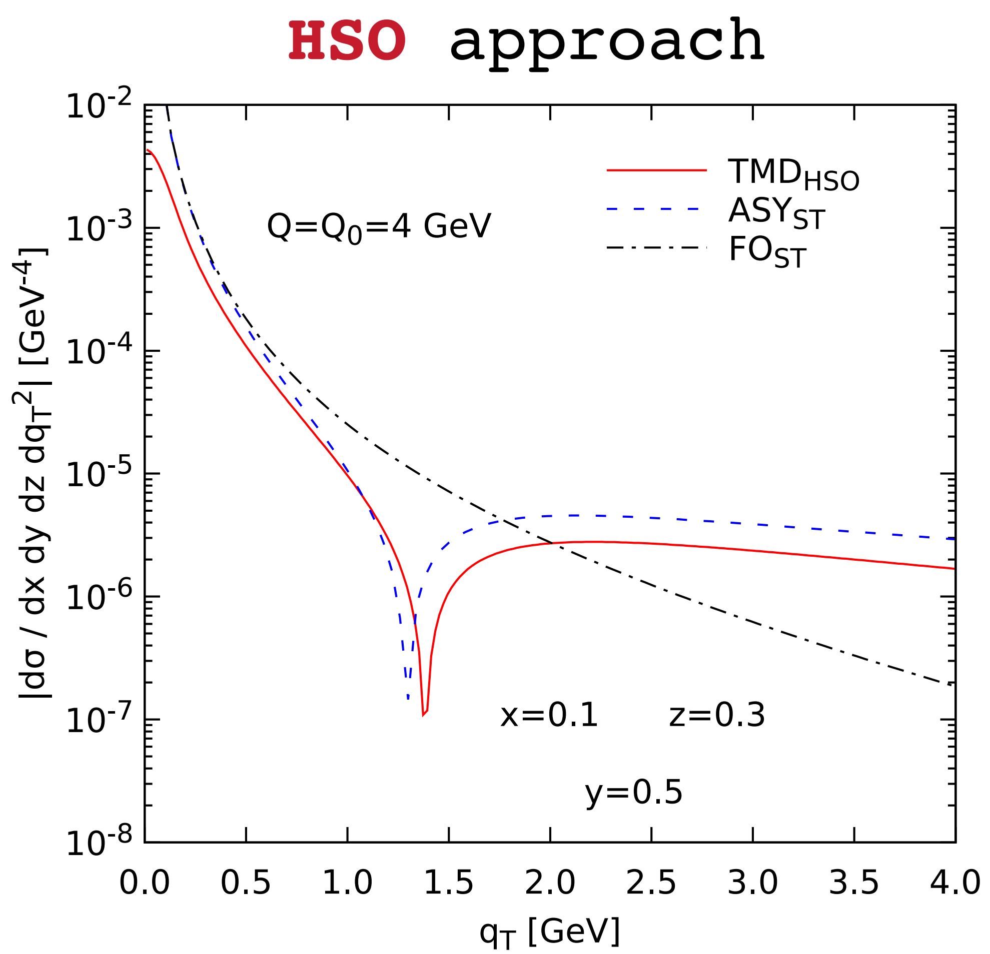
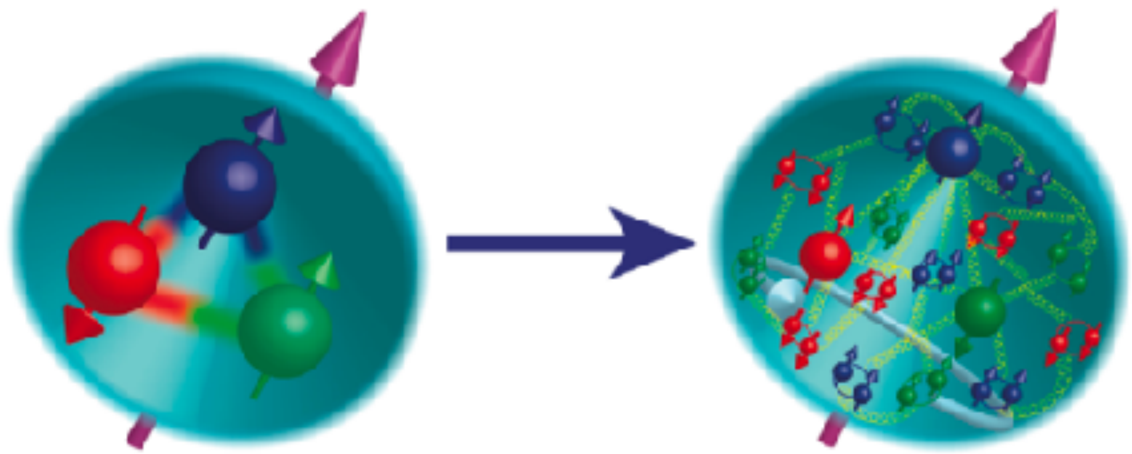


Unconstrained models



Constrained models

Quark TMDs more easily accessible



Can't forget the "glue that binds us all"

No picture will be complete without gluon TMDs

See talk by Daniël Boer

(PERSONAL)CONCLUSIONS

- Big progress on the extraction of TMDs from data: high accuracy in pQCD, flavor dependence, theoretical errors, pions!
- Important theory developments (pheno?)
- Some current challenges remain: large qT tails on data, normalization issue in SIDIS (did we agree?)
- Nice to see predictions

Thanks