APS Topical Group on Hadronic Physics
14 April 2021

Study of unpolarized TMDs in SIDIS

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in collaboration with the Pavia group

INFN
Istituto Nazionale di Fisica Nucleare

3DSPIN
MAPPING THE PROTON IN 3D

erc
European Research Council

EIC²
EIC Center at Jefferson Lab

UNIVERSITÀ DI PAVIA

TMDs: 3D MAPS

IN MOMENTUM SPACE

Wigner distribution

$$\rho\left(x, \mathbf{k}_T, \mathbf{b}_T\right)$$

$$\int d^2\mathbf{k}_T$$

$$\int d^2\mathbf{b}_T$$

Generalized Parton Distributions

GPDs

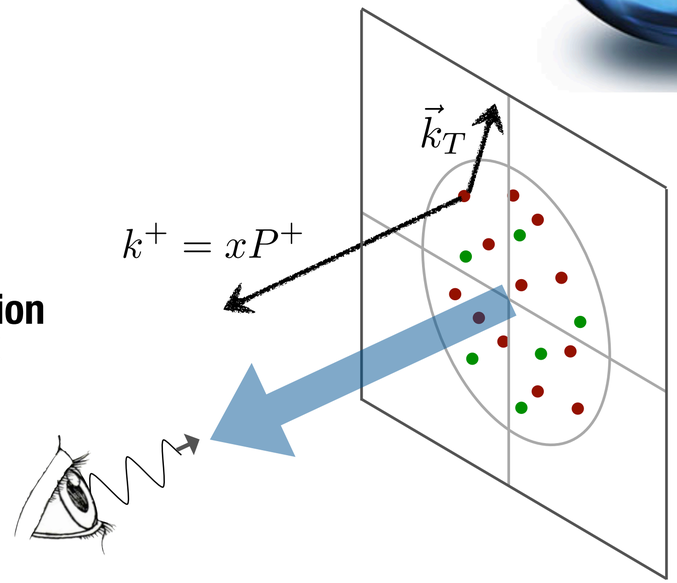
Transverse Momentum Distributions

TMDs

$$\int d^2\mathbf{k}_T$$

Parton Distribution Functions

PDFs



x: momentum fraction carried by quark

TMD PDF

factorizes as hard and longitudinal nonperturbative

matching to the collinear region

$b_T \ll 1/\Lambda_{\rm QCD}$

$$F_{f/P}(x, \mathbf{b}_T; \mu, \zeta) = \sum_j C_{f/j}(x, b_*; \mu_b, \zeta_F) \otimes f_{j/P}(x, \mu_b)$$

perturbative expansion in $\alpha_s(\mu)$

$$\times \exp\left\{ K(b_*; \mu_b) \ln \frac{\sqrt{\zeta_F}}{\mu_b} + \int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_F}}{\mu'} \right] \right\}$$

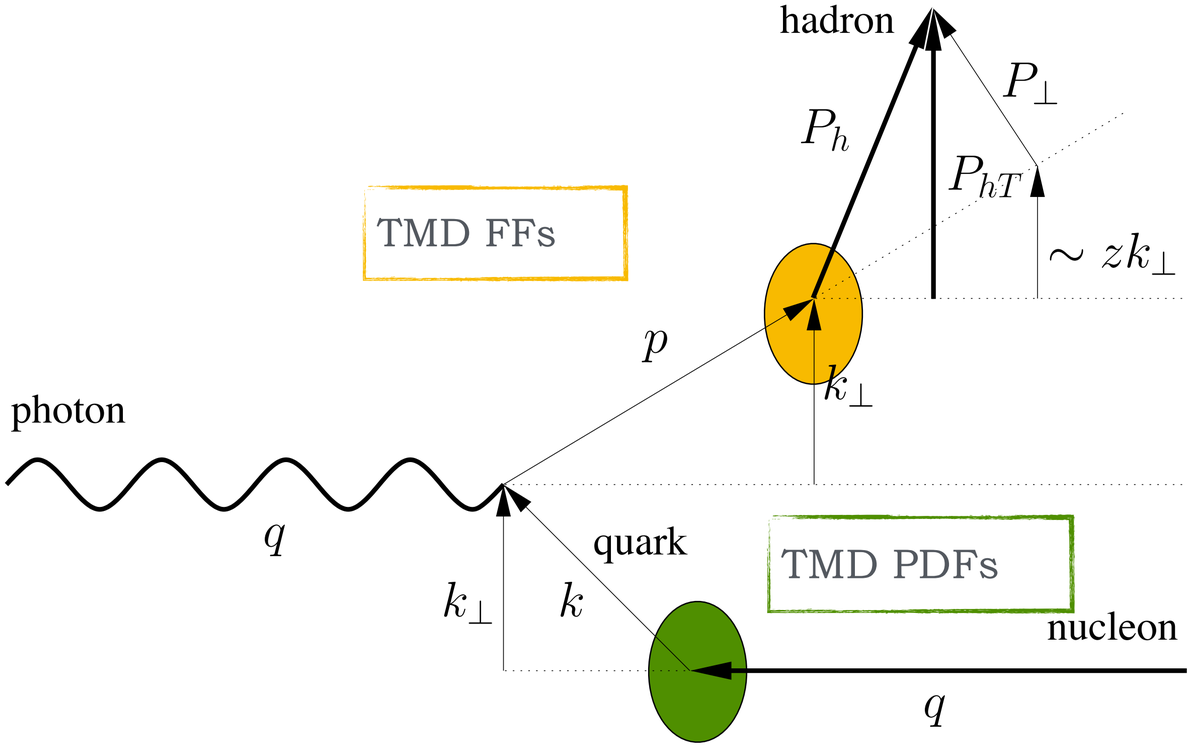
$$\times f_{\rm NP}(x, b, \zeta)$$

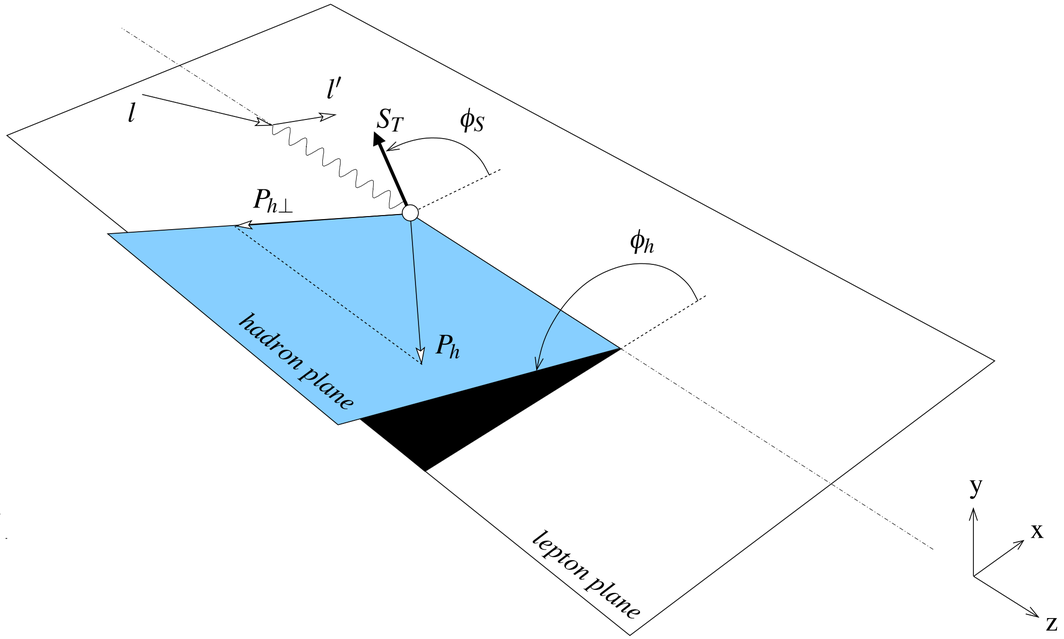
nonperturbative transverse content

parametrized and fitted to data

SIDIS

$$\ell(l) + N(p) \to \ell(l') + h(P_h) + X$$





kinematic limits

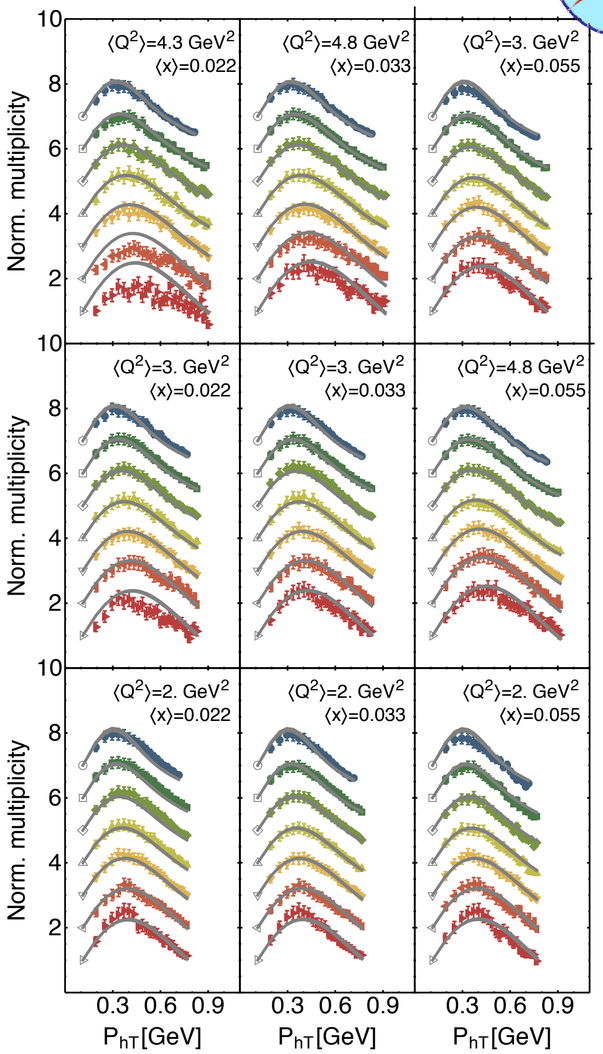
$$M^2 \ll Q^2 \qquad P_{hT}^2 \ll Q^2$$

$$\frac{d\sigma}{dq_T} \propto F_{UU,T}(x, z, q_T; Q^2) \propto \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\cdot\mathbf{q}_T} F_q(x, \mathbf{b}; \mu) D_1^{q\to h}(z, \mathbf{b}; \mu)$$

PV17

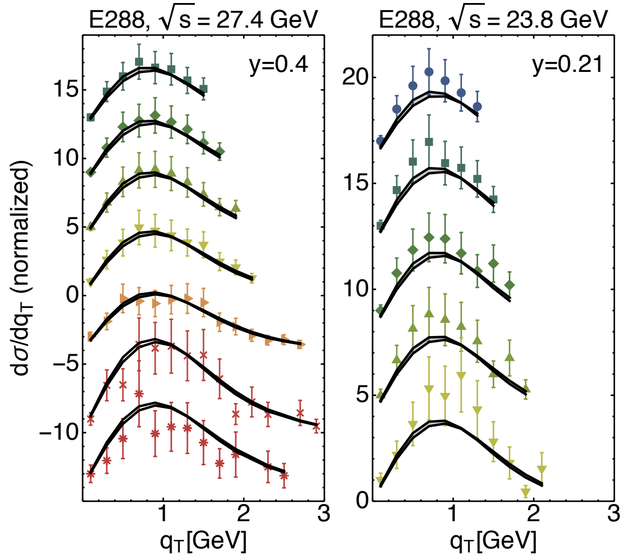
Bacchetta, Delcarro, Pisano, Radici, Signori

arXiv:1703.10157

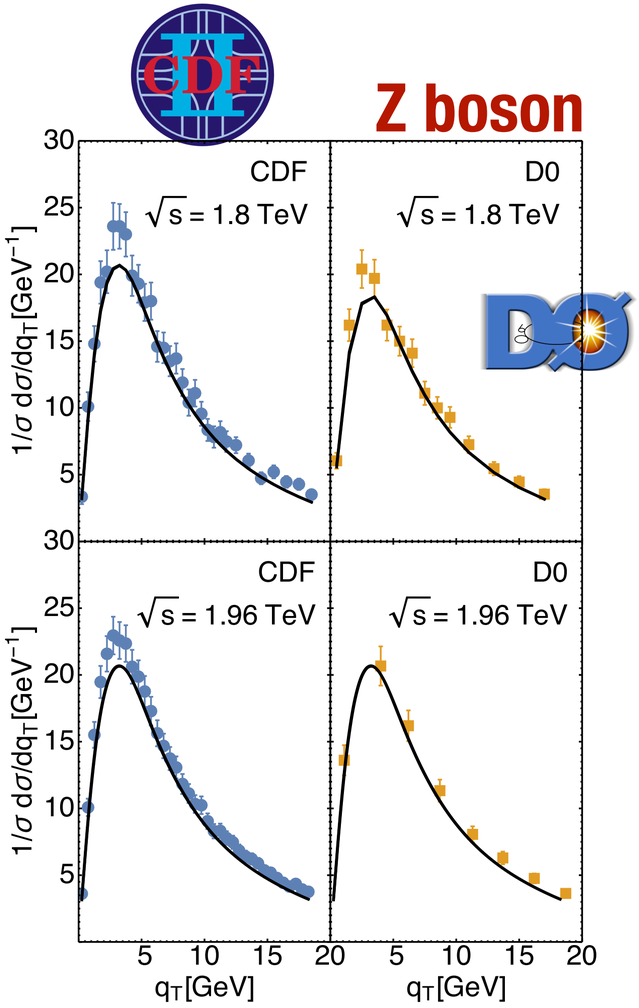


SIDIS

Fermilab



Drell-Yan



NLL

$\chi^2 = 1.55$

Total number of points:

8059

PV17 NONPERTURBATIVE FUNCTIONS

A. Bacchetta, F. Delcarro, C. Pisano, M. Radici, A. Signori
arXiv:1703.10157

$$f^a_{1\mathrm{NP}}(x,\mathbf{k}_\perp^2) = \frac{1}{\pi}\frac{\left(1+\lambda\mathbf{k}_\perp^2\right)}{g_{1a}+\lambda g_{1a}^2}e^{-\frac{\mathbf{k}_\perp^2}{g_{1a}}}$$

11 free parameters

$$D^{a\to h}_{1\mathrm{NP}}(z,\mathbf{P}_\perp^2) = \frac{1}{\pi}\,\frac{1}{g_{3a\to h}+\left(\lambda_F/z^2\right)g_{4a\to h}^2}\left(e^{-\frac{\mathbf{P}_\perp^2}{g_{3a\to h}}}+\lambda_F\frac{\mathbf{P}_\perp^2}{z^2}\,e^{-\frac{\mathbf{P}_\perp^2}{g_{4a\to h}}}\right)$$

x-dependence

$$g_1(x) = N_1\frac{(1-x)^\alpha\,x^\sigma}{(1-\hat{x})^\alpha\,\hat{x}^\sigma}$$

$$g_{3,4}(z) = N_{3,4}\,\frac{(z^\beta+\delta)\,(1-z)^\gamma}{(\hat{z}^\beta+\delta)\,(1-\hat{z})^\gamma}$$

non-perturbative Sudakov factor

$$g_K(b_T) = -g_2 b_T^2/2$$

EIC IMPACT STUDIES

EIC PSEUDODATA

generated by Ralf Seidl and available on
https://github.com/VladimirovAlexey/EIC_YR_TMD

5x41 18x275

configurations

5x100 18x100

10x100

π^+

π^-

final state hadrons

K^+

K^-

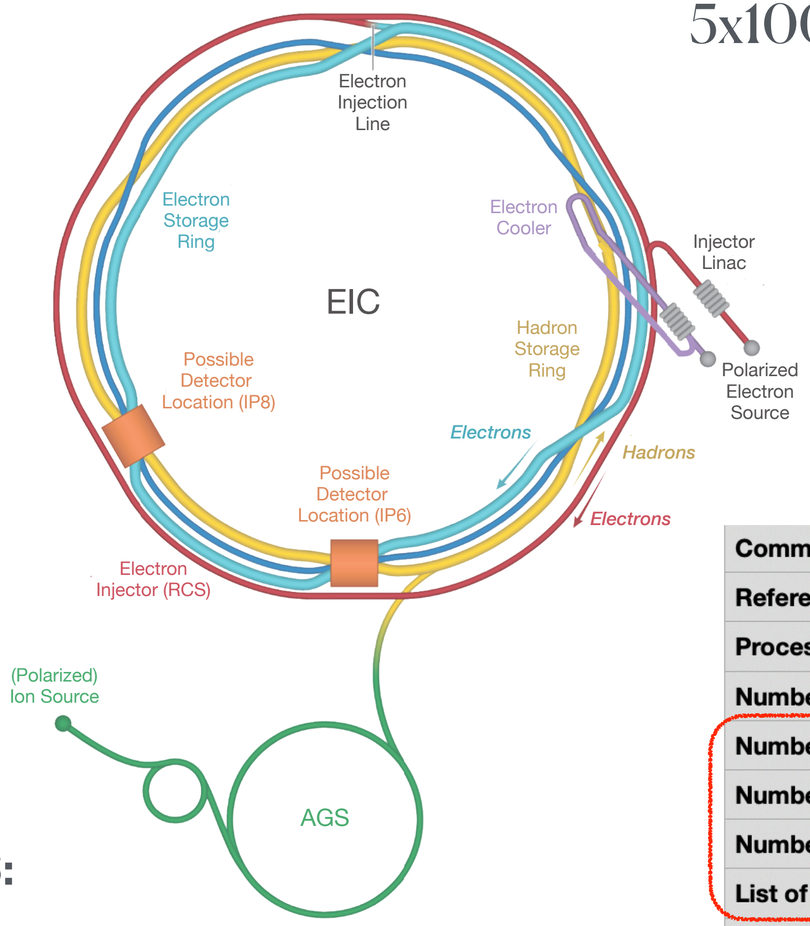


image from EIC YR
arXiv:2103.05419

Comment	Ralf's pseudo data for EIC.
Reference	Ralf
Process type	SIDIS
Number of points	2958
Number of uncorr.errors	2
Number of corr.errors	0
Number of norm.errors	1
List of norm.errors (relative)	0.03
Total cross-section normalized	False

uncertainties

eight options for EIC settings:
we choose option 8

EIC PSEUDODATA

EIC pseudodata
generated by Ralf Seidl

PV17 TMDs
predictions using global fit
of Pavia 2017

we took the average **kinematic variables** of each point
and the **relative uncertainty** on the observable

$$F_{UU,T}(x, z, q_T; Q^2)$$

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

APFEL++

NANGAPARBAT

https://github.com/vbertone/NangaParbat

Sensitivity coefficients

EIC IMPACT STUDIES

SENSITIVITY COEFFICIENTS

from E. Aschenauer, I. Borsa, G. Lucero, A. S. Nunes, R. Sassot
arXiv:2007.08300

$$F_{UU,T}(x, z, q_T; Q^2)$$

observable

distribution

TMD parameters

$$S[f_i, \mathcal{O}] = \frac{\langle \mathcal{O} \cdot f_i \rangle - \langle \mathcal{O} \rangle \langle f_i \rangle}{\xi \Delta \mathcal{O} \Delta f_i}$$

experimental uncertainty
(from pseudodata)

$$\xi \equiv \frac{\delta \mathcal{O}}{\Delta \mathcal{O}}$$

theoretical uncertainty

$$\langle \mathcal{O} \rangle = \frac{1}{N} \sum_{k=1}^{N} \mathcal{O}[f_i^{(k)}]$$

number of replicas of PV17
N = 200

EIC IMPACT STUDIES

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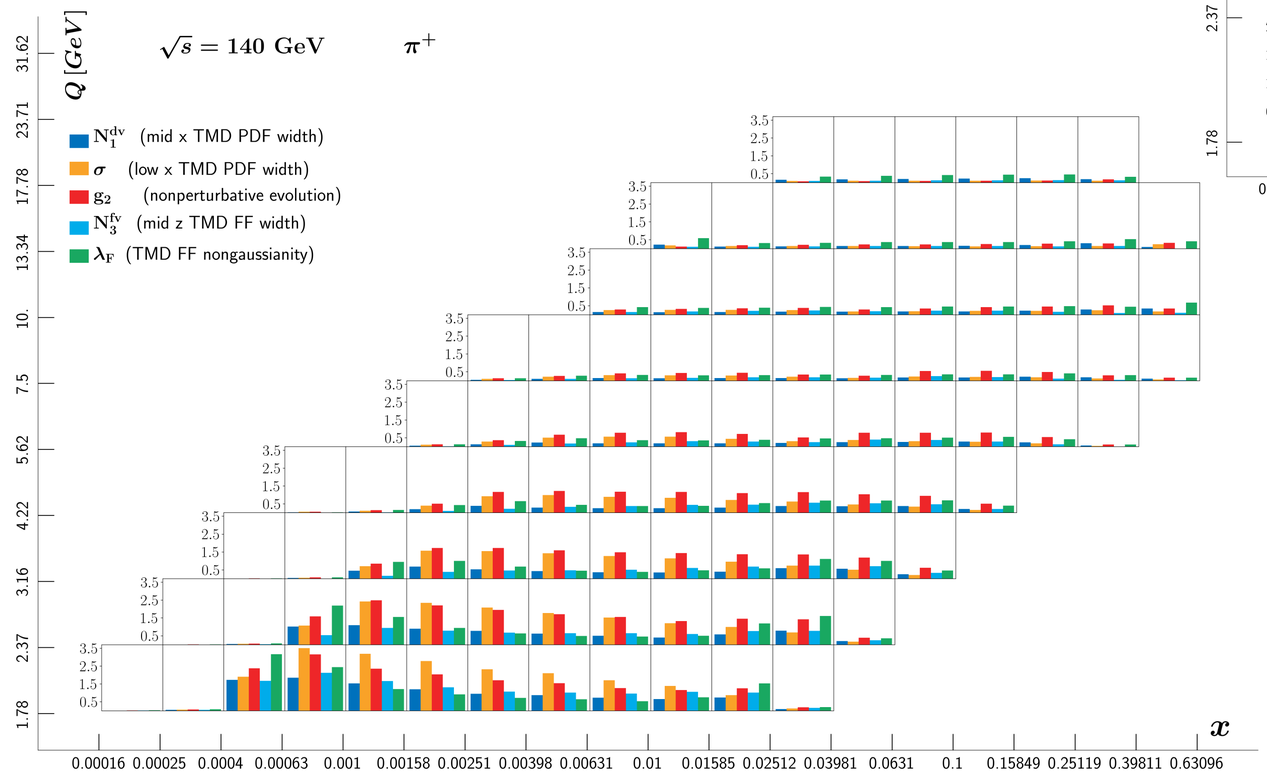
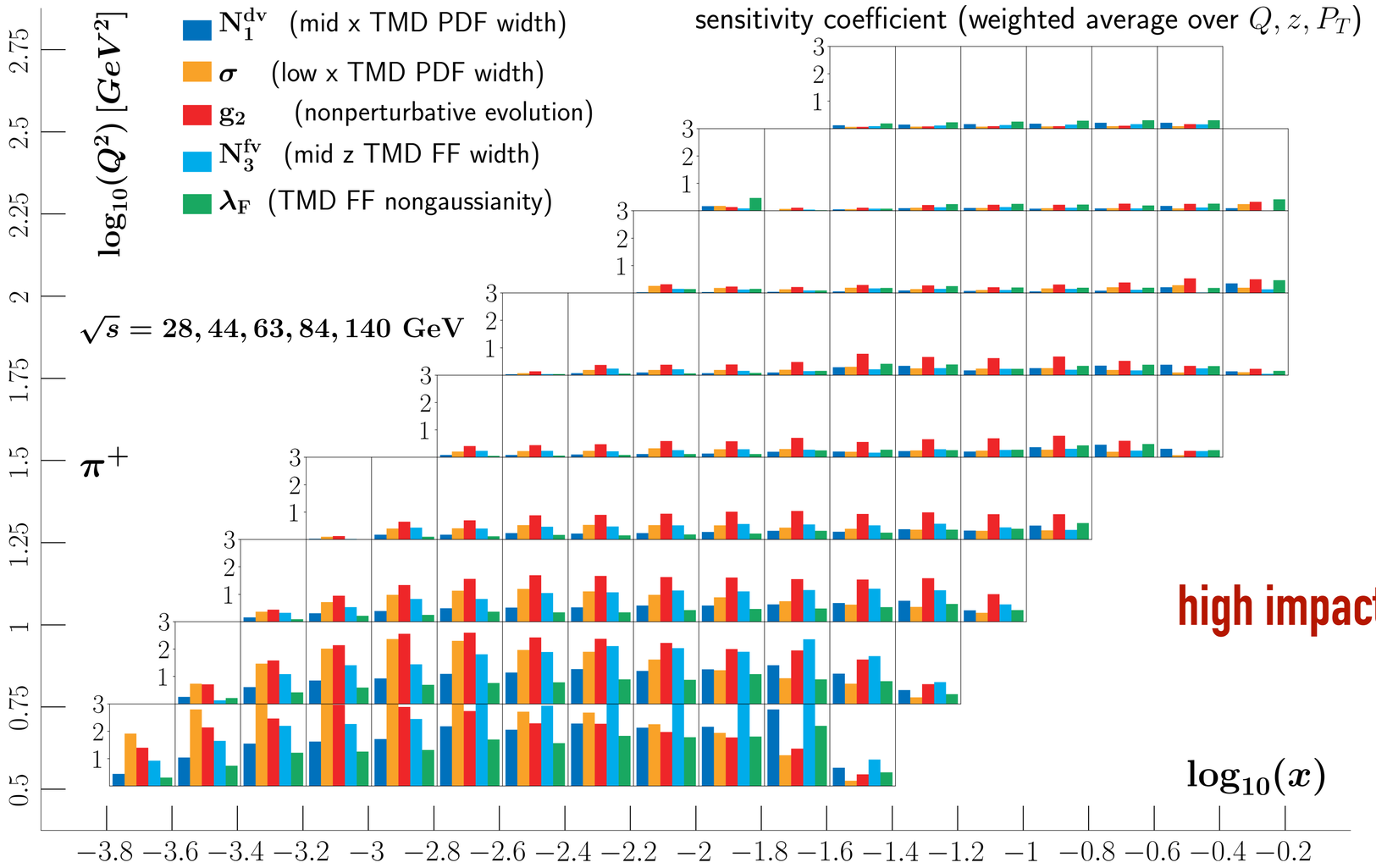


higher impact for low $\sqrt{s}$

EIC IMPACT STUDIES

SENSITIVITY COEFFICIENTS

$$S[f_i, \mathcal{O}] = \frac{\langle \mathcal{O} \cdot f_i \rangle - \langle \mathcal{O} \rangle \langle f_i \rangle}{\delta \mathcal{O} \Delta f_i}$$

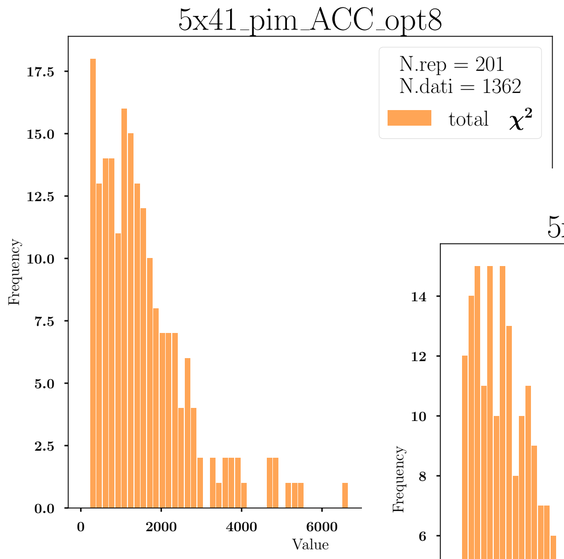


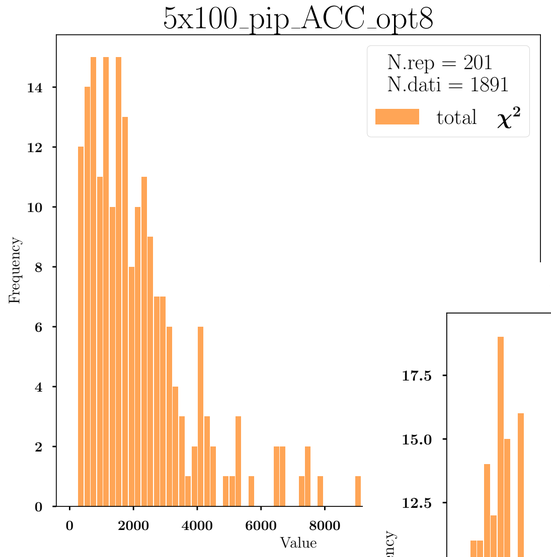
high impact at low Q and low x

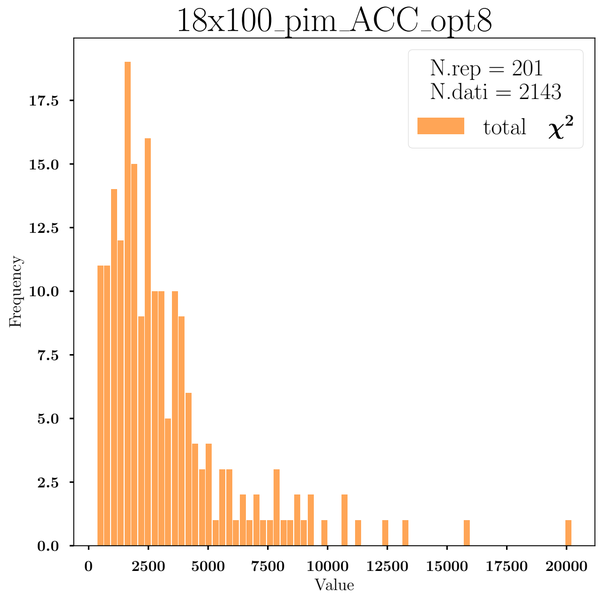
Reweighing

EIC IMPACT STUDIES

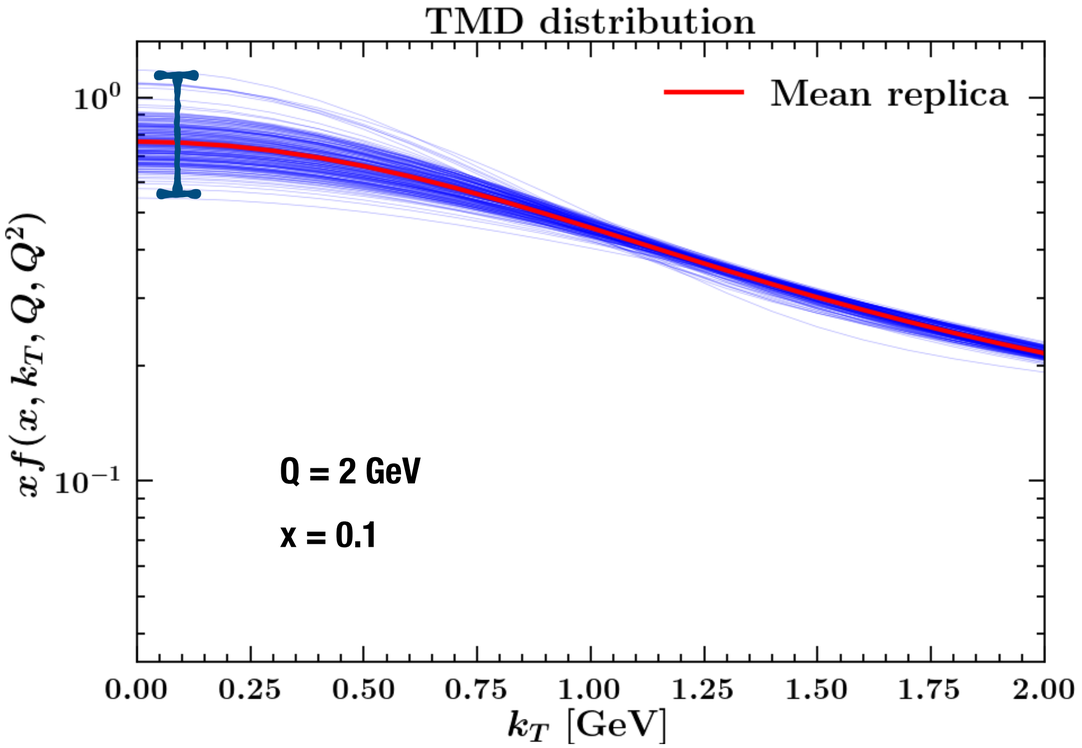
REWEIGHING





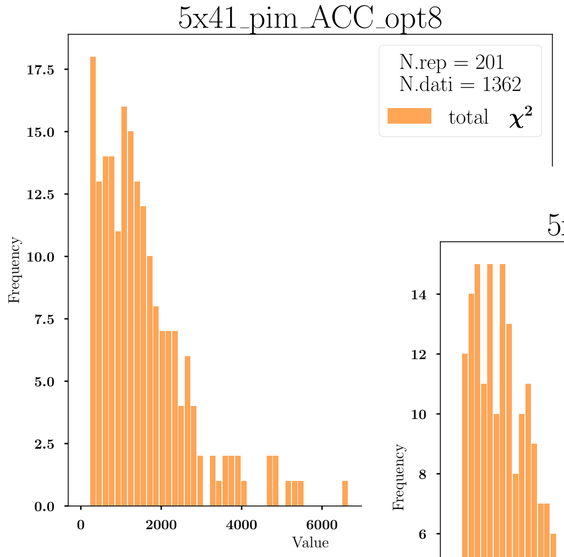


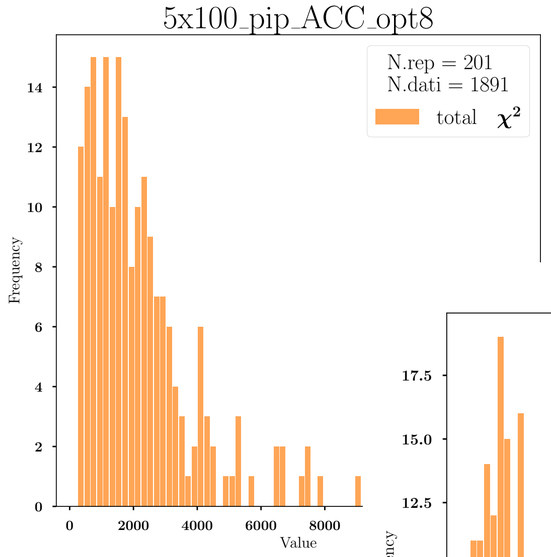
200 replicas are
compared with pseudodata

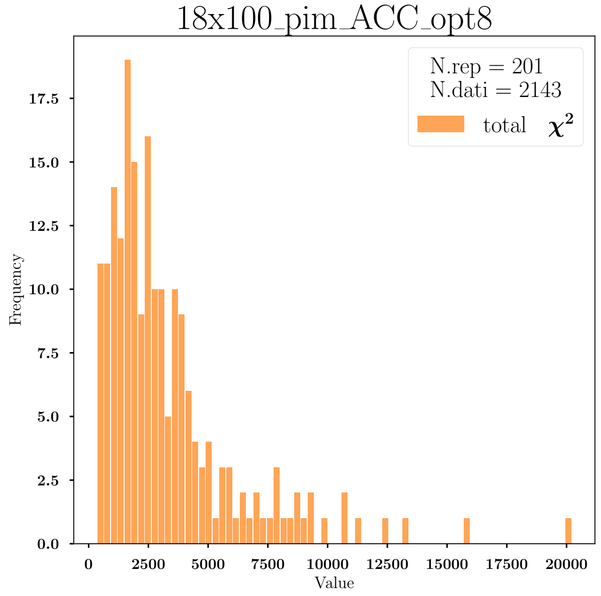


EIC IMPACT STUDIES

REWEIGHING







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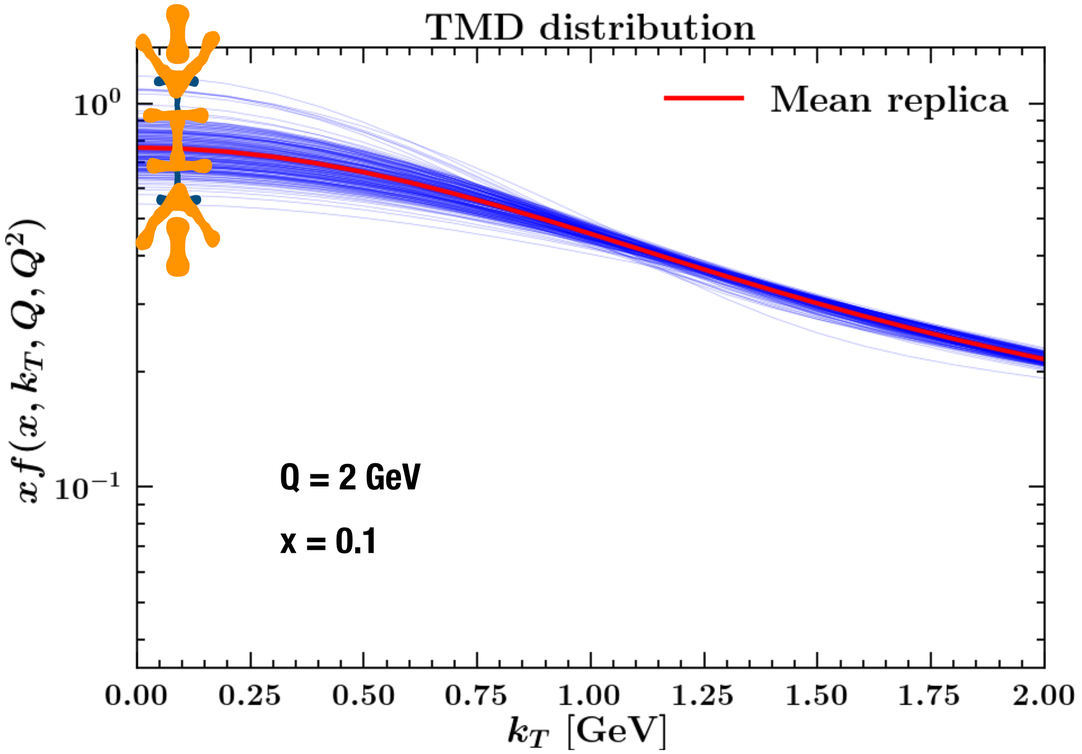

EIC IMPACT STUDIES

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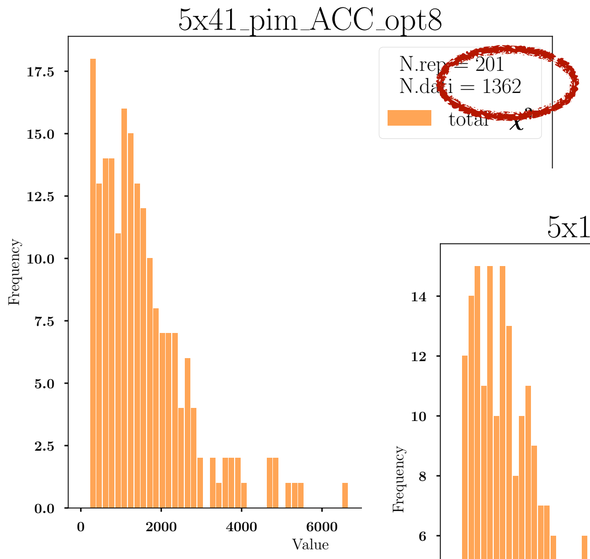

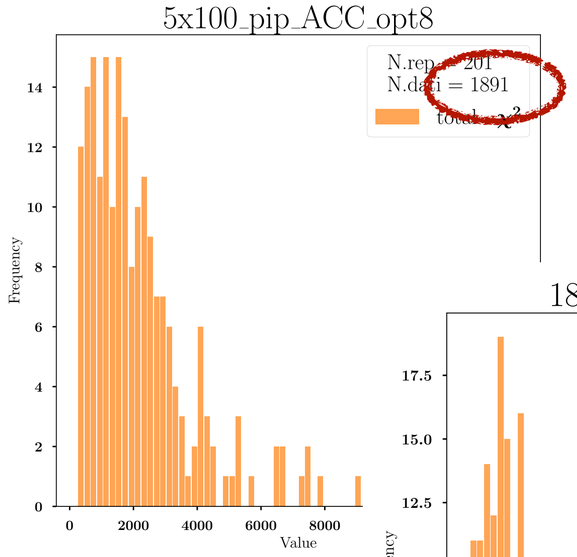

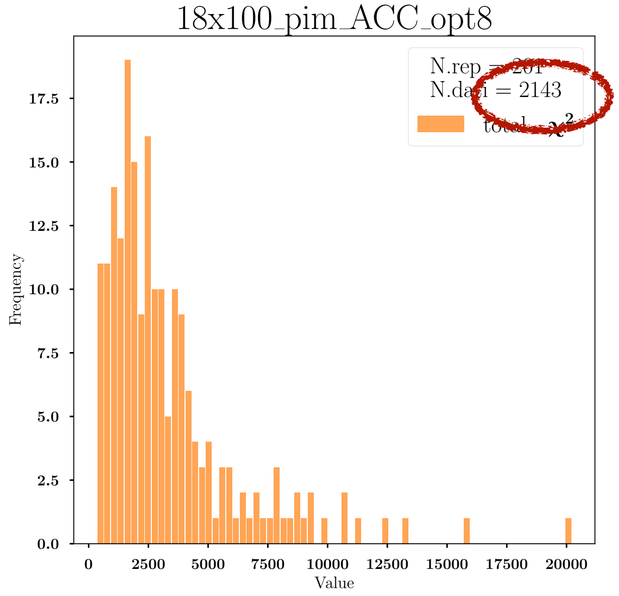

200 replicas are
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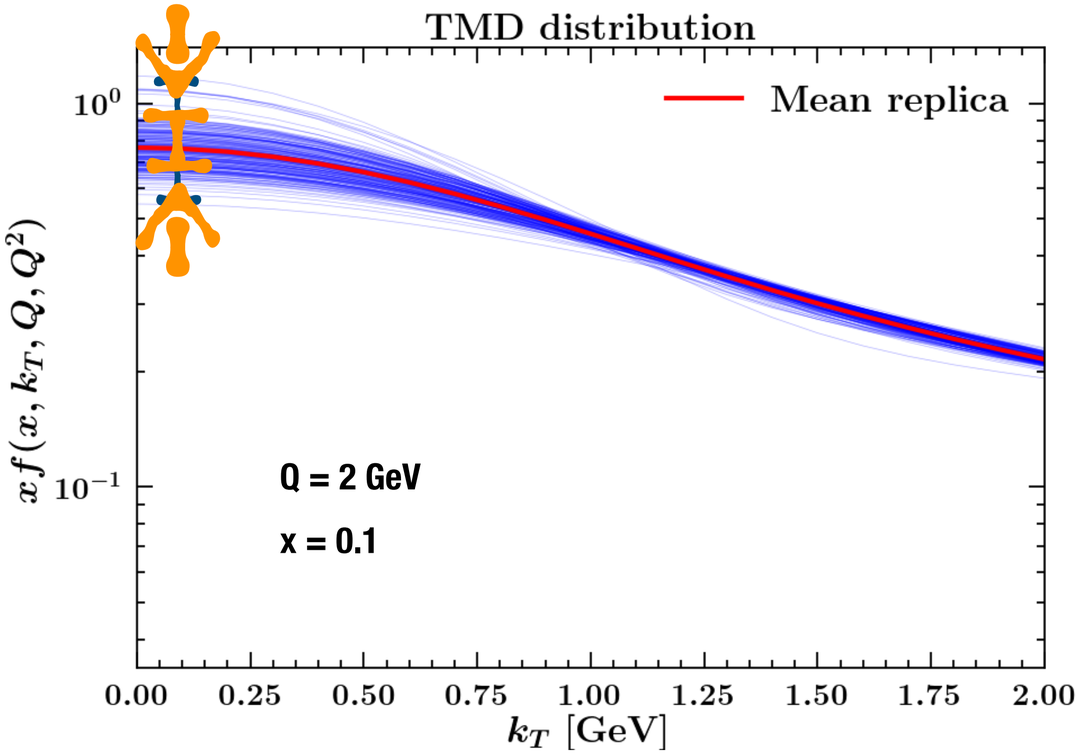


CHALLENGE

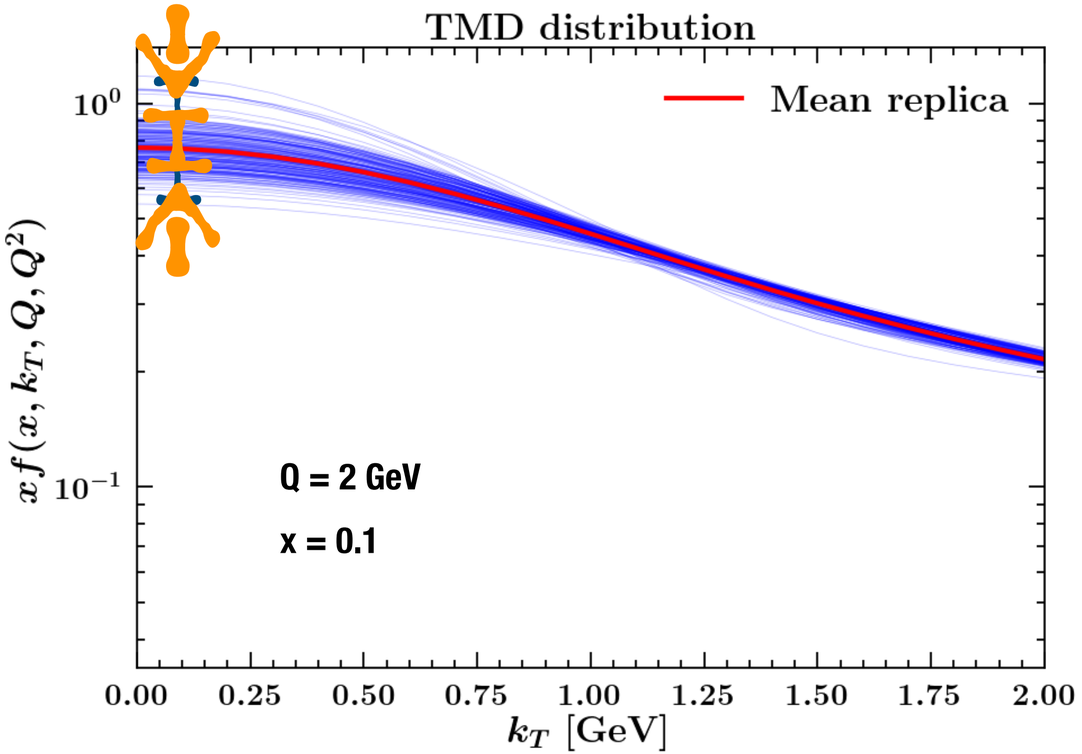
huge amount of EIC pseudo data

REWEIGHING

χ^2 of 200 replicas

weights
to assign to each replica

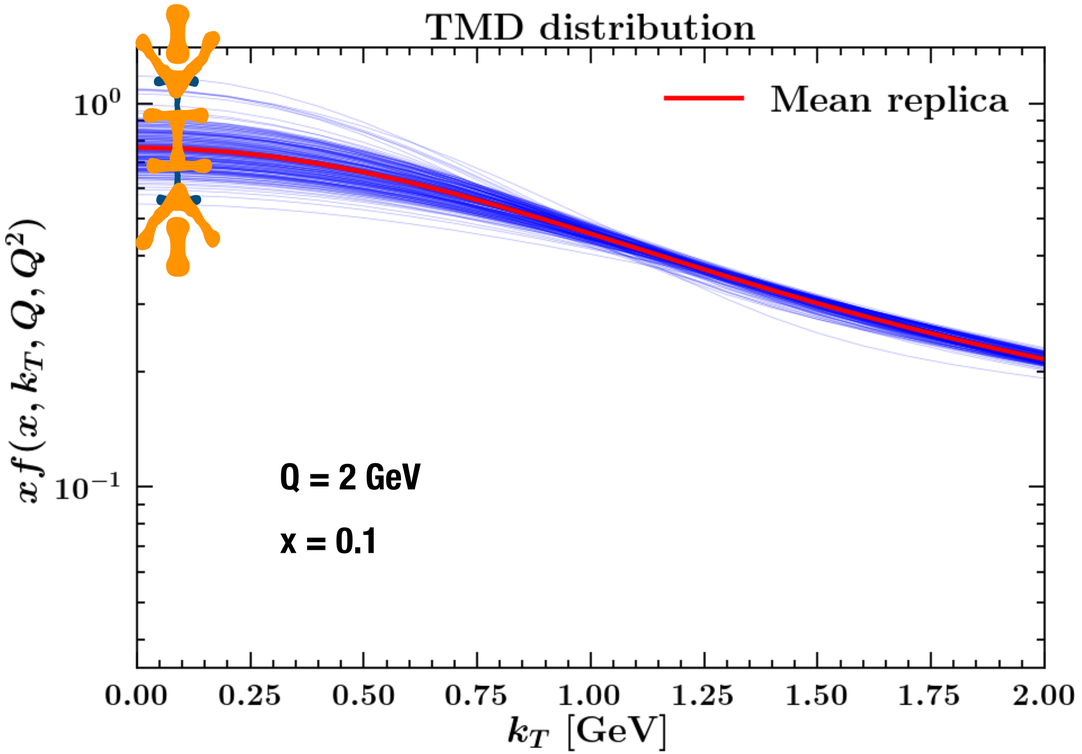
re-compute TMD uncertainty bands



EIC IMPACT STUDIES

REWEIGHING

200 replicas are compared with pseudodata



different mathematical formulas
to compute the weights

N. Sato, J. Owens, H. Prosper, PRD 89 (2014) 114020;
H. Paukkunen, P. Zurita, JHEP 12 (2014) 100

$$w_k \propto \mathcal{P}(f_k|\chi_k) \propto e^{-\frac{1}{2}\chi_k^2}$$

selects replicas with very low χ^2

NNPDF Collaboration
arXiv:1108.1758

total number of points

$$w_k \propto \mathcal{P}(f_k|\chi_k) \propto \chi_k^{n-1} e^{-\frac{1}{2}\chi_k^2}$$

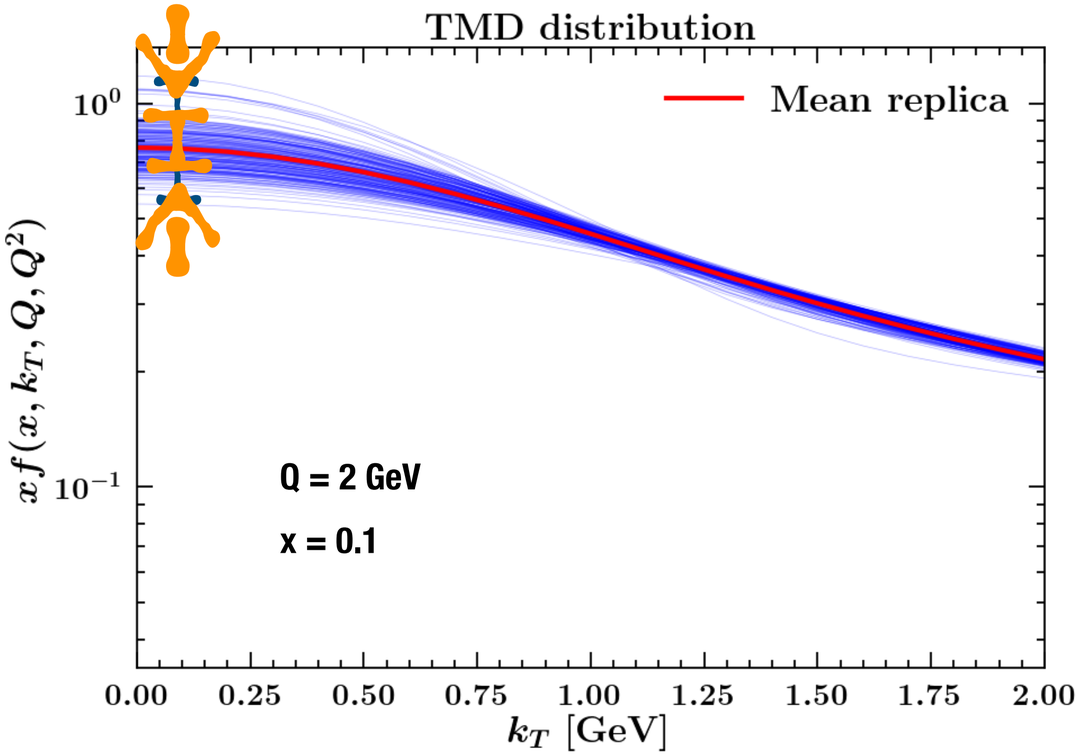
suppresses replicas with very high AND very low χ^2

REWEIGHING

200 replicas are compared with pseudodata

$$\chi^2_k = \chi^2_{k,\mathrm{EIC}} + \chi^2_{k,\mathrm{PV17}}$$

'original' χ^2 with respect to PV17 data



weights

$$w_k \propto \mathcal{P}(f_k|\chi_k) \propto \chi_k^{n-1} e^{-\frac{1}{2}\chi_k^2}$$

used to select replicas

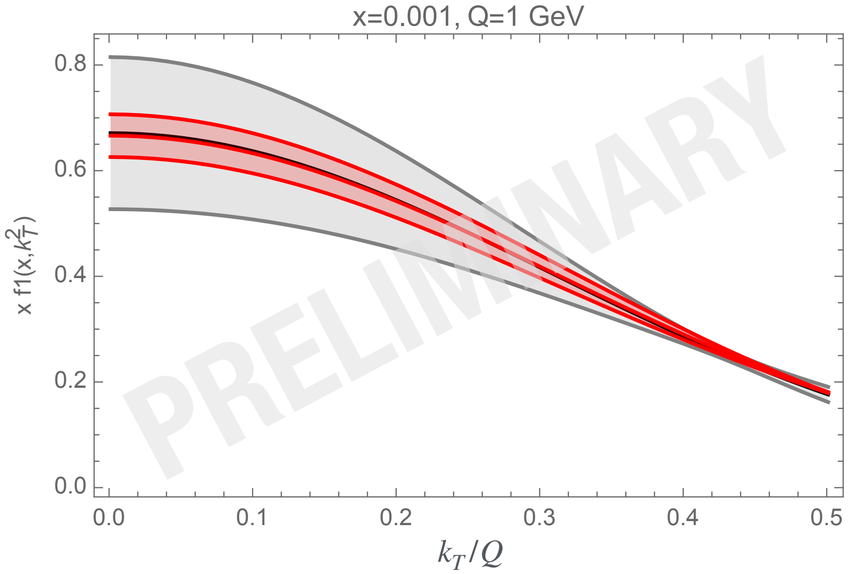
→ reflect the impact of EIC data on extracted TMDs

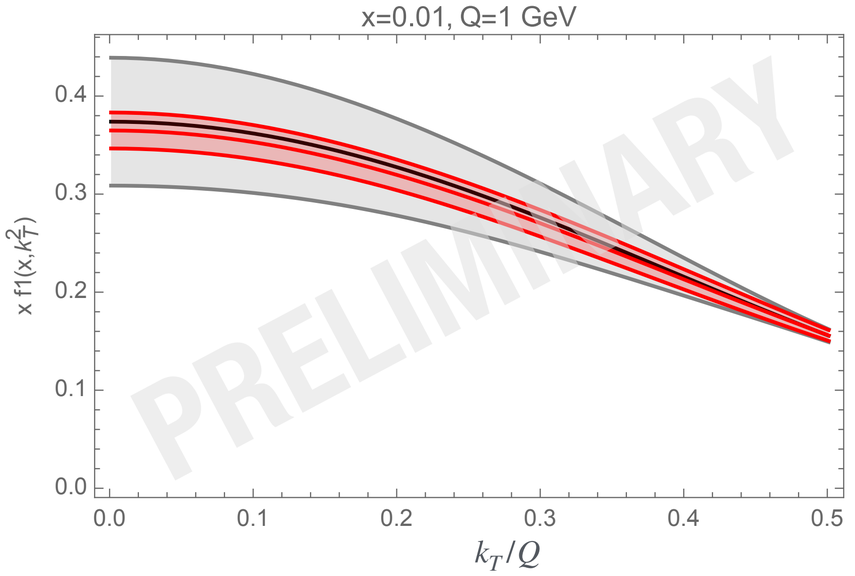
from NNPDF Collaboration
arXiv:1108.1758

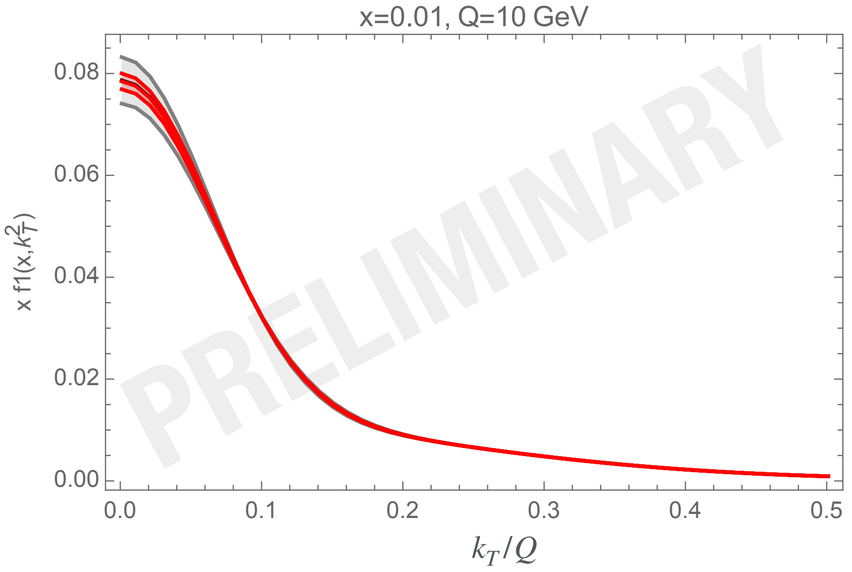
EIC IMPACT ON TMDs

FROM REWEIGHING

68% C.L.





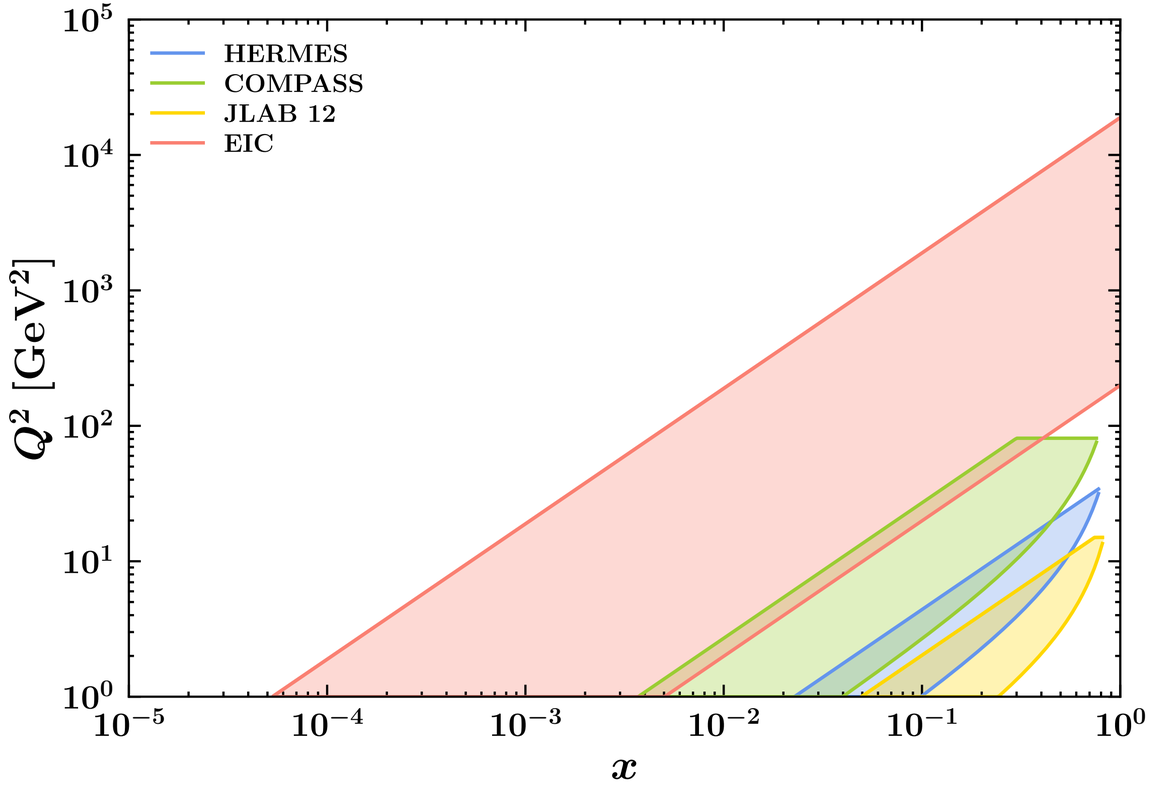


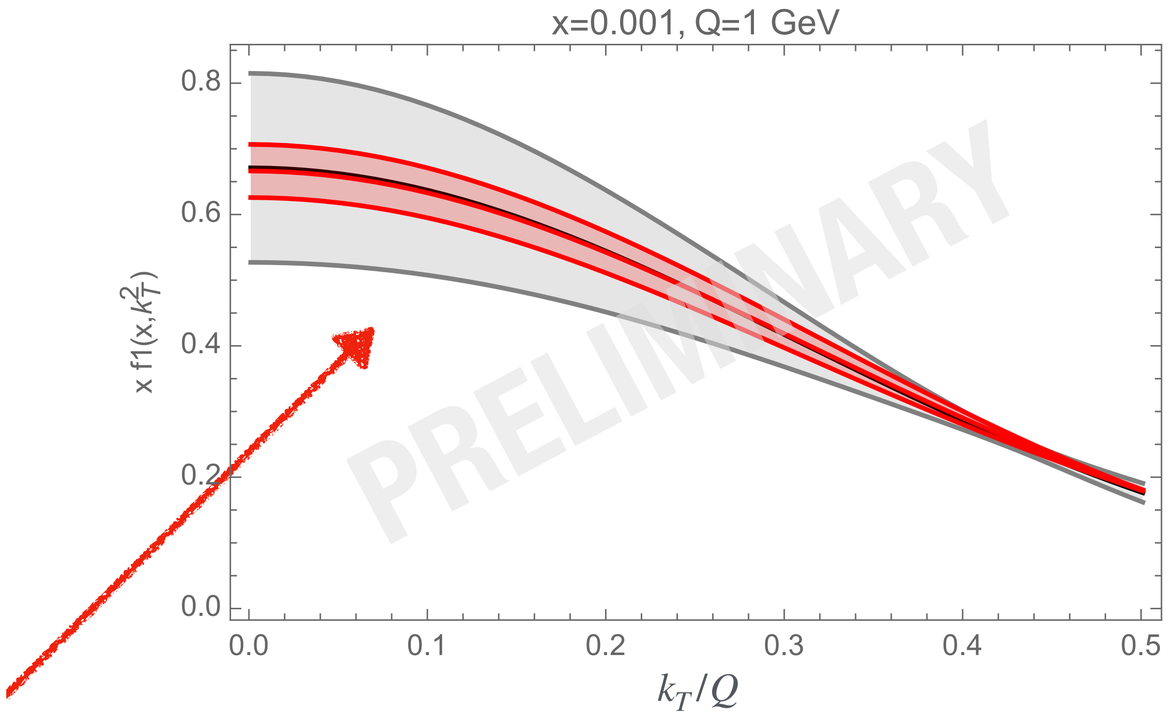
we combined pseudodata of different configurations

5x41, 5x100, 10x100, 18x275

CONCLUSIONS

- the EIC will have an enormous impact on TMD extractions





...STILL WORK IN PROGRESS

BACKUP

SEMI-INCLUSIVE DIS
IN TERMS OF TMDs

$$\frac{d\sigma}{dx\,dy\,dz\,d\psi\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{$$

$F_{UU,T}(x,z,P_{h\perp}^2,Q^2)$ → 4D quantities

$+\,\epsilon\,F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi_h)\,F_{UU}^{\cos\phi_h} + \epsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$ → unpolarized

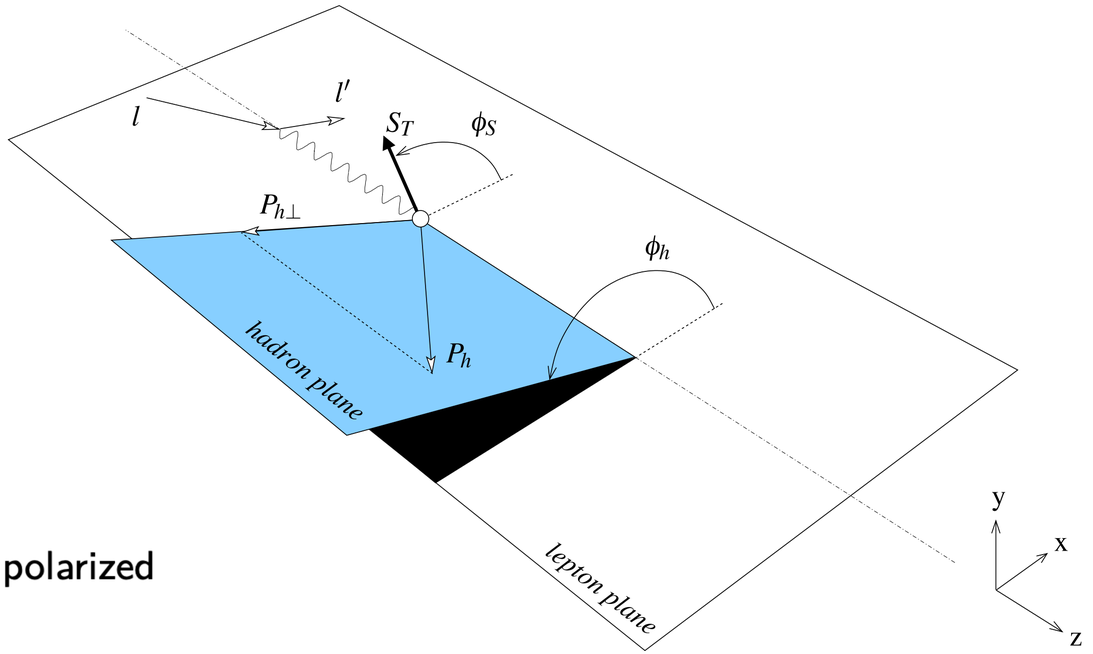
$+\,\lambda_e\Big[\ldots 1\,\mathsf{SF}\ldots\Big]$ → polarized terms

$+\,S_{||}\Big[\ldots 2\,\mathsf{SFs}\ldots\Big] +$

$+\,S_{||}\,\lambda_e\Big[\ldots 2\,\mathsf{SFs}\ldots\Big]$

$+\,S_\perp\Big[\ldots 6\,\mathsf{SFs}\ldots\Big]$

$+\,S_\perp\,\lambda_e\Big[\ldots 3\,\mathsf{SFs}\ldots\Big]\Big\}$



$$\frac{d\sigma}{dx dy dz d^2P_{hT}} =$$

$$= \frac{4\pi^2\alpha^2}{2xQ^2}\,\frac{y}{(1-\varepsilon)}\Big[F_{UU,T}(x,z,P_{hT}^2,Q^2) + \varepsilon F_{UU,L}(x,z,P_{hT}^2,Q^2)\Big]$$

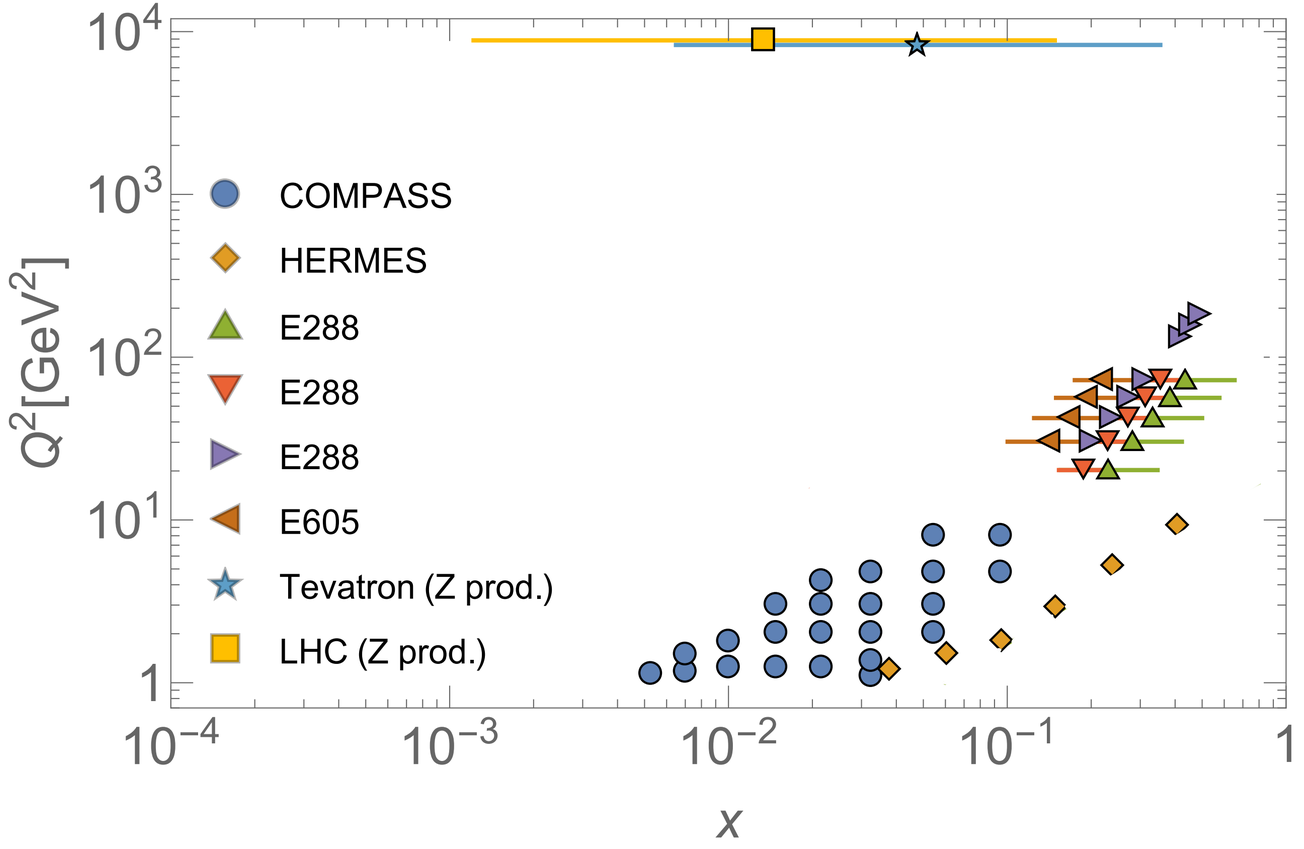
slide from A.Signori

PV17

A. Bacchetta, F. Delcarro, C. Pisano, M. Radici, A. Signori
arXiv:1703.10157

GLOBAL FIT at NLL

SIDIS DRELL-YAN Z BOSON PROD.



Total number of points:

8059

cuts applied to select data points:

$$Q^2 > 1.4 \text{ GeV}^2$$

$$0.2 < z < 0.7$$

$$P_{hT}, q_T < \text{Min}[0.2\ Q, 0.7\ Qz] + 0.5 \text{ GeV}$$

EXPERIMENTAL DATA
FOR TMDs