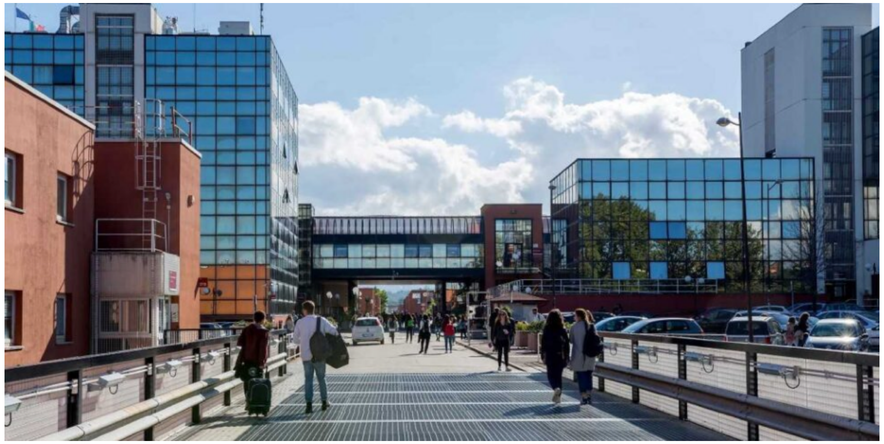


ePIC and EIC Physics Readiness Workshop (2nd edition)

Cosenza, 17-19 Mar. 2026

Opportunities in TMDs (for unpolarized quark)

INFN Istituto Nazionale di Fisica Nucleare Sezione Pavia

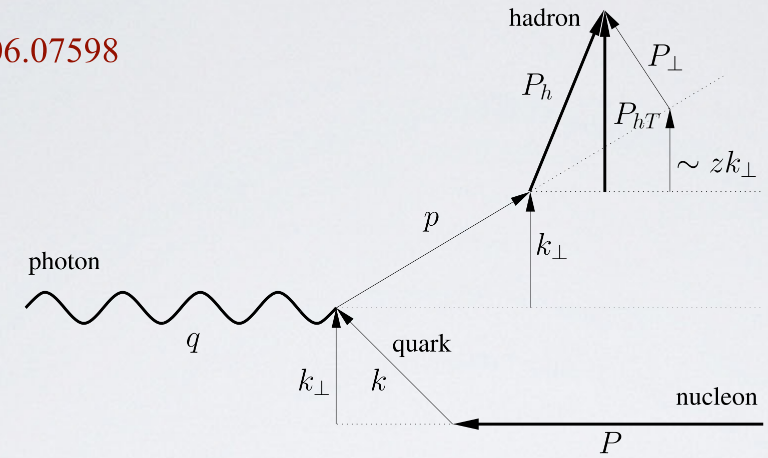
Marco Radici

ePIC

in collaboration with Lorenzo Rossi (Univ. and INFN - Milano)

some of the advantages of Semi-Inclusive DIS

Bacchetta et al. (MAP),
JHEP **10** (22) 127, arXiv:2206.07598



For large Q^2

$$\mathbf{P}_{hT} \approx z\mathbf{k}_\perp + \mathbf{P}_\perp$$

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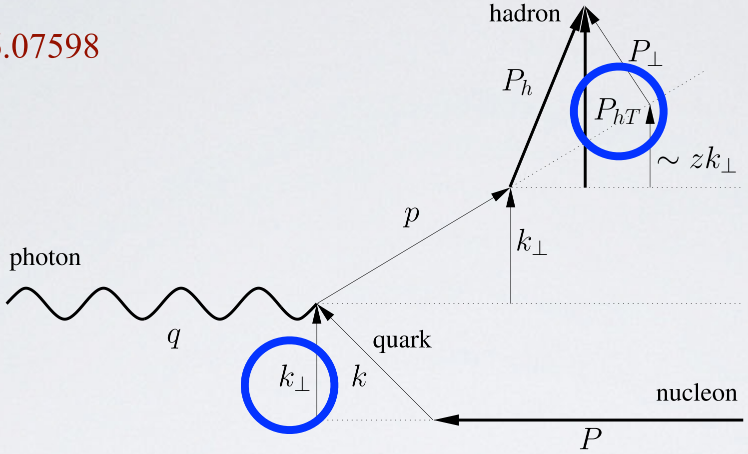

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- measuring P_{hT} of hadron => access to $k_\perp$ of parton
  => 3-dim partonic picture of target in momentum space
- different hadron species => separate $k_\perp$ of different flavors

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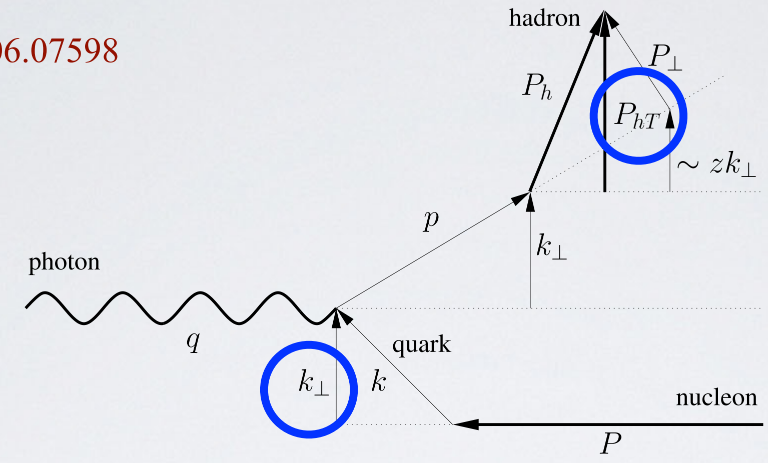

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- price to pay: 5-fold differential $d^5\sigma$ $\quad \dfrac{d^5\sigma}{dx\, dz\, dq_T\, d\phi_h\, dQ}$ $\quad q_T^2 = \dfrac{P_{hT}^2}{z^2}$

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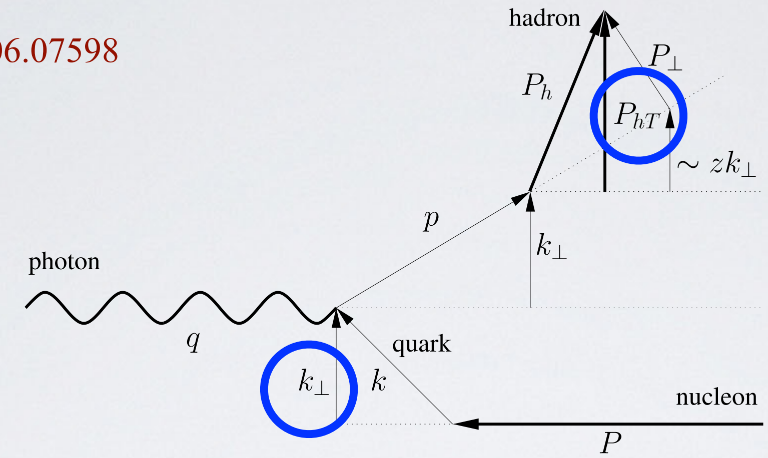

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- focus on unpolarized $d\sigma$: enters any asymmetry $\quad \dfrac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$

unpolarized SIDIS, factorized cross section

$$M^2 \ll Q^2$$

$$q_T^2 = \frac{P_{hT}^2}{z^2} \ll Q^2$$

+ integrate on final-hadron angles $\int d\phi_h$

$$\frac{d^4\sigma}{dxdzdq_TdQ} \sim \mathscr{H}(Q^2) \sum_q e_q^2 \int_0^\infty db_T\, b_T\, J_0(b_T, q_T) \; f_1^q(x, b_T^2; Q^2) \; D_1^{q\to h}(z, b_T^2; Q^2)$$

hard part — TMDPDF — TMDFF

Factorized expression: simple Bessel transform of TMDs in b_T space

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Factorized expression: simple Bessel transform of TMDs in b_T space

low b_T (large parton $k_\perp$)	← matching prescription (arbitrary) →	large b_T (small parton $k_\perp$)
perturbative		**non perturbative**
OPE expansion on PDF		parametrized
calculable		and **fitted to data**

→ b_T

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hard part — TMDPDF — TMDFF

Quality of TMD extraction:

- perturbative accuracy
- size of data set and best χ^2

low b_T (large parton $k_\perp$)	← matching →	large b_T (small parton $k_\perp$)
perturbative	prescription	**non perturbative**
OPE expansion on PDF	(arbitrary)	parametrized
calculable		and **fitted to data**

b_T →

Most recent global fits

	Accuracy	SIDIS	Drell-Yan	N of points	χ^2/N_{points}	Flavor dep.
PV 2017 arXiv:1703.10157	NLL	✔	✔	8059	1.5	✘
SV 2019 arXiv:1912.06532	$N^3LL(-)$	✔	✔ (LHC)	1039	1.06	✘
MAPTMD 2022 arXiv:2206.07598	$N^3LL(-)$	✔	✔ (LHC)	2031	1.06	✘
MAPTMD 2024 arXiv:2405.13833	N^3LL	✔	✔ (LHC)	2031	1.08	✔
ART25 arXiv:2503.11201	$N^4LL(-)$	✔	✔ (LHC)	1209	1.05	✔

increasing accuracy & precision

(-) not all ingredients available at given accuracy

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MAPTMD24: the first **high-quality** global fit with **flavor sensitivity** of the intrinsic **quark** $k_\perp$

Bacchetta et al. (MAP), JHEP **08** (24) 232, arXiv:2405.13833

Baseline: MAPTMD24 global fit

Bacchetta et al. (MAP), JHEP **08** (24) 232, arXiv:2405.13833

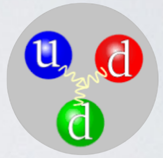
nonperturbative input

TMD PDF $f_1^q(x, b_T^2; Q_0)$

Gaussian widths depend on x

Fourier Transform of combination of 2 Gaussians + 1 weighted Gaussian

5 channels: $q = u\,,\,\bar{u}\,,\,d\,,\,\bar{d}\,,\,sea$ ("s")

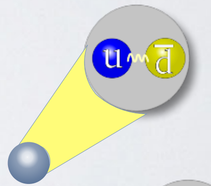


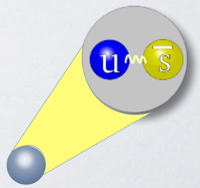
TMD FF

Gaussian widths depend on z

Fourier Transform of combination of 2 Gaussians

5 channels:
- favored pion $u \to \pi^+, \ldots$
- unfavored pion $d \to \pi^+, \ldots$
- favored Kaon $u \to K^+, \ldots$
- favored strange Kaon $\bar{s} \to K^+, \ldots$
- unfavored Kaon $d, s \to K^+, \ldots$



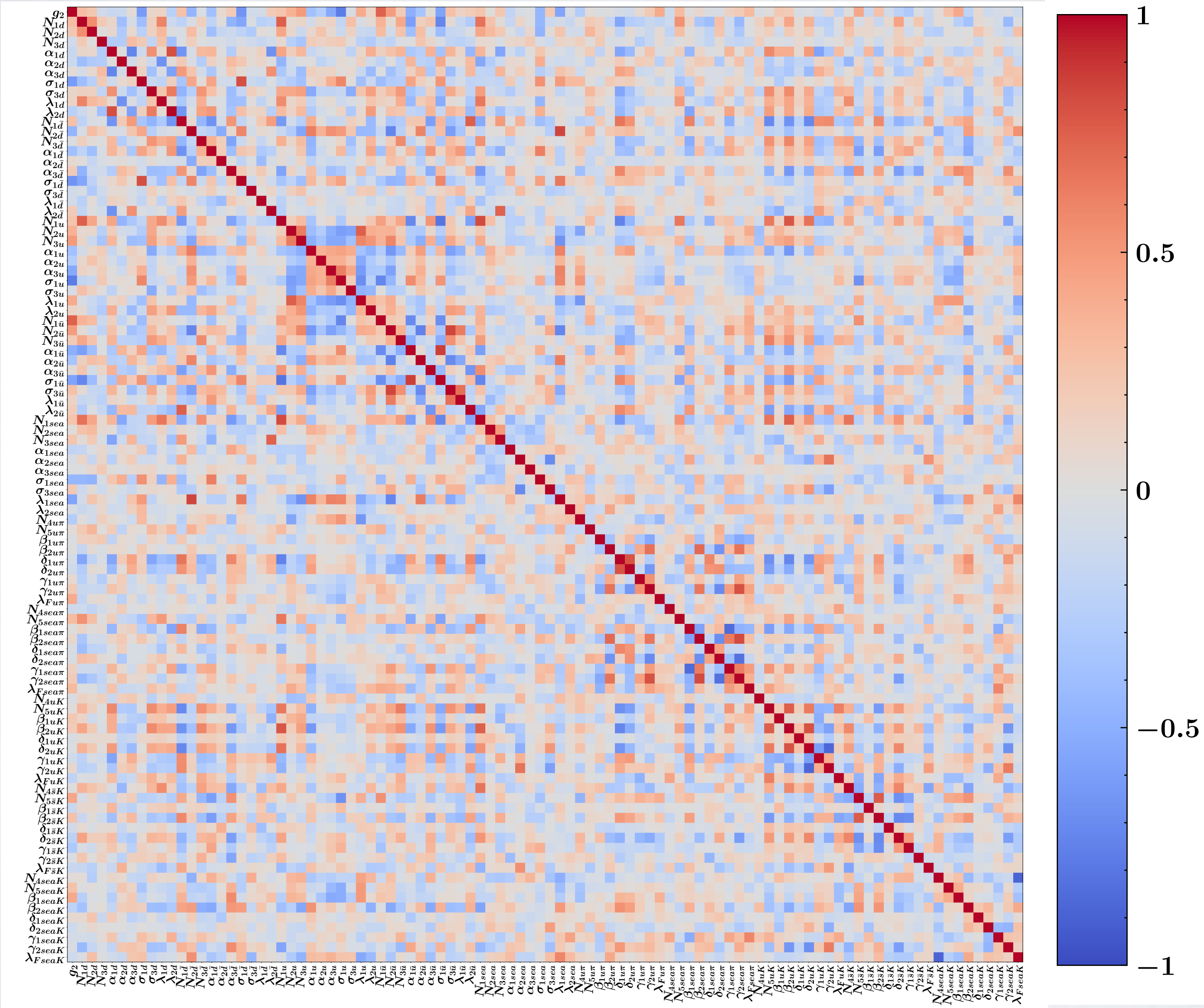


total of **96 parameters**

correlation matrix

Bacchetta et al. (MAP), JHEP **08** (24) 232, arXiv:2405.13833

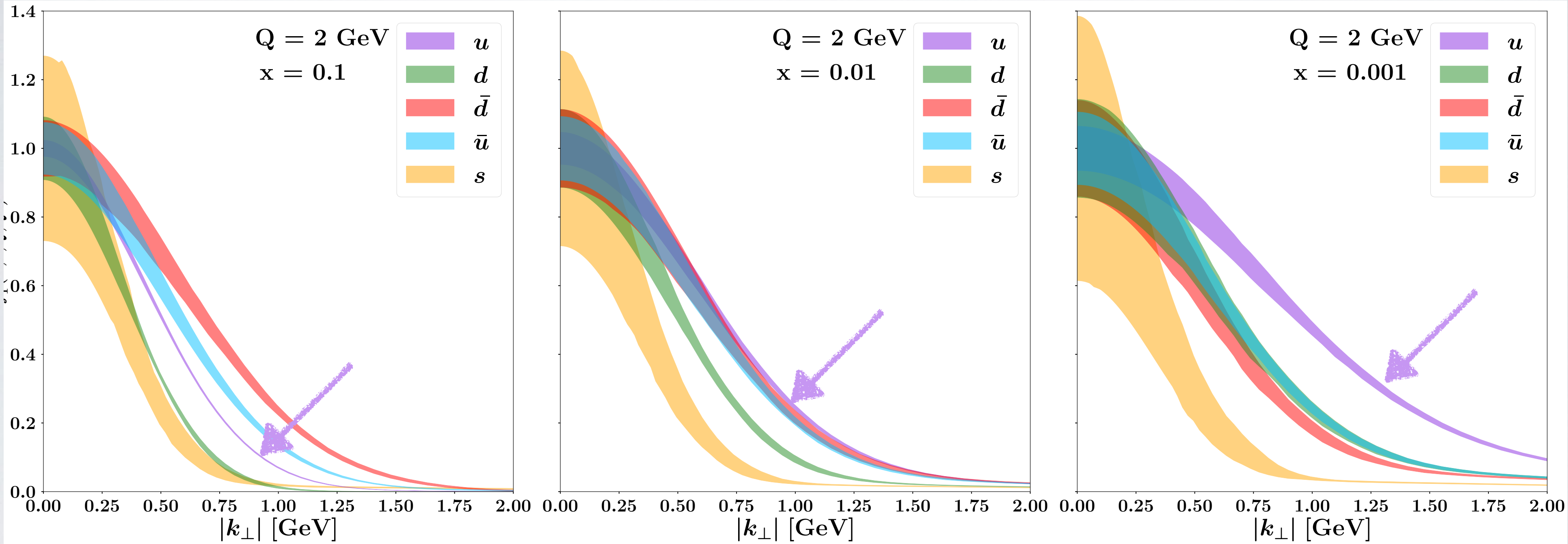
MAPTMD24 total of 96 parameters



"Normalized" MAPTMD24 TMD PDFs

$$\frac{f_1^q(x, k_\perp^2; Q)}{f_1^q(x, 0; Q)}$$

Bacchetta et al. (MAP), JHEP **08** (24) 232, arXiv:2405.13833



th. error band =
68% of all replicas

- very different k_T behavior
- it changes with x

Early Science Conditions

ESR First Draft - main report

This is the table of configurations we used at the moment in current ESR draft

	Species	Energy (GeV)	Lumi./year (fb^{-1})	e- pol.	p/A pol.
YEAR 1	e+Ag, e+Ru or e+Cu. . .	10×115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D $e+p$	10×130 10×130	11.4 4.95–5.33	LONG	NO TRANS
YEAR 3	$e+p$	10×130	4.95–5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au $e+p$	10×100 10×250	0.84 6.19–9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au $e+{}^3$He	10×100 10×166	0.84 8.65	LONG	N/A TRANS and/or LONG

Table 1: EIC Early Science Matrix. The eA luminosity is per nucleon.

Will likely need to be adjusted and we should discuss at workshop a version for the ESR

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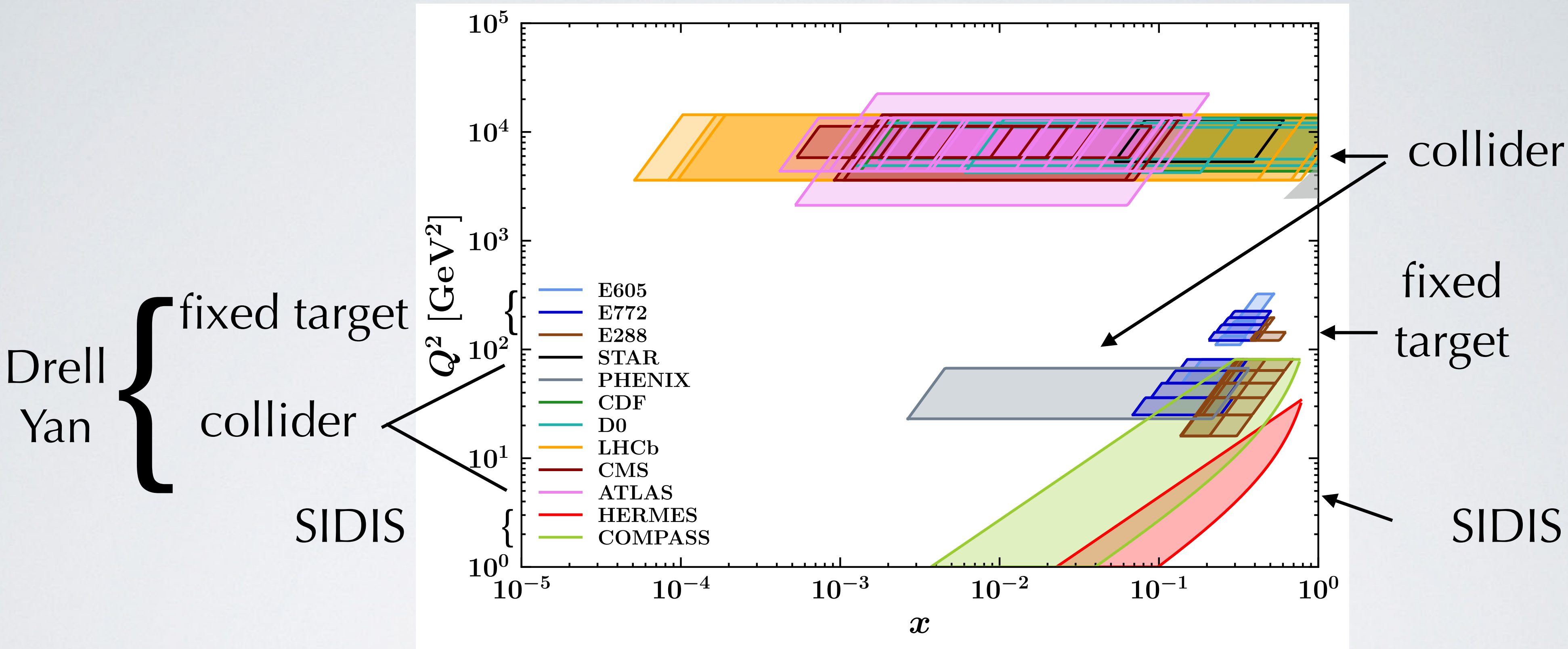
* impact studies performed with 10x130 rescaled to lumi=10 fb^{-1}

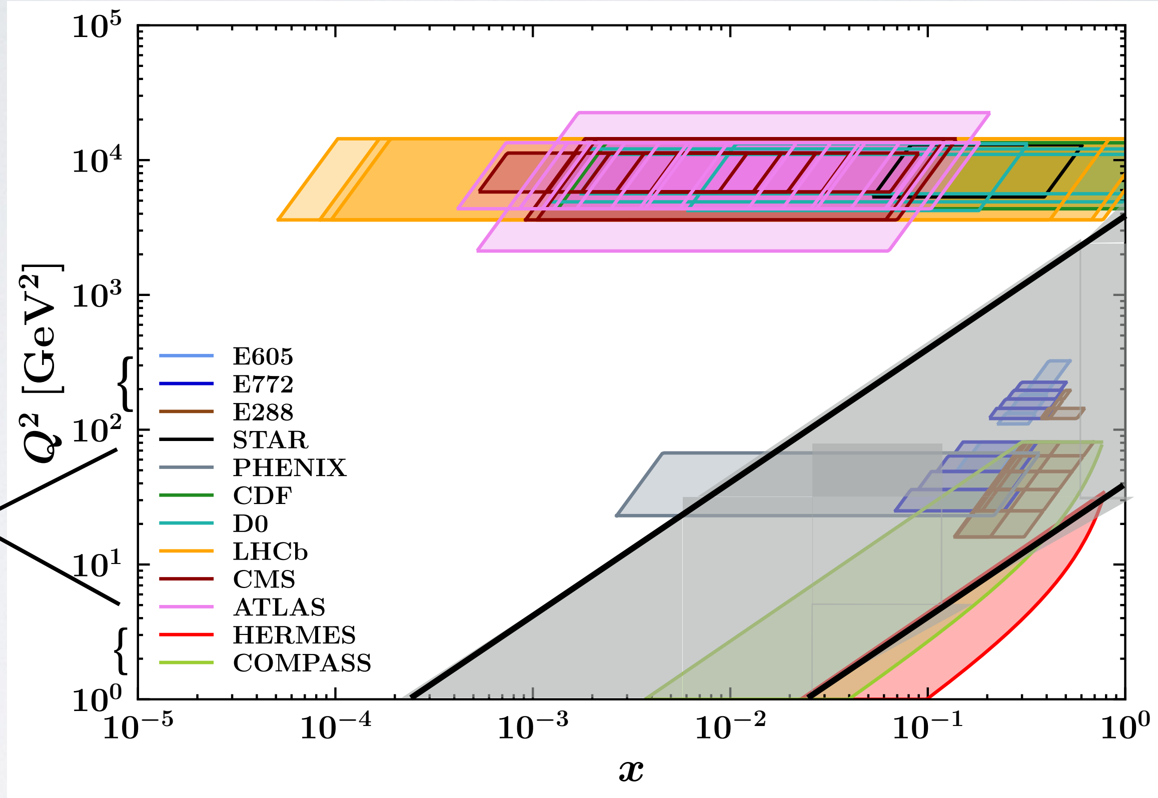
Phase space of baseline MAPTMD24



Phase space of EIC @10x130

Drell Yan { fixed target, collider

SIDIS



including EIC pseudodata in the fit: MAPTMD24 2031 pts ➞ + EIC

+ ~1700 pts π

+ ~3400 pts π+K

EIC impact studies

target = proton   final state = π , π + K   beams = 10x130 GeV

lumi = 5 , 10 fb^{-1} uncertainty band = $\left[\frac{f_1^q - \langle f_1^q \rangle}{\langle f_1^q \rangle} \right] (x, k_\perp^2; Q^2)$

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Strategy : - search in (x, Q^2) bins allowed by kinematics for which flavor q the reduction in uncertainty is maximum over all $k_\perp$;

- for these cases, analyze the $k_\perp$ distribution

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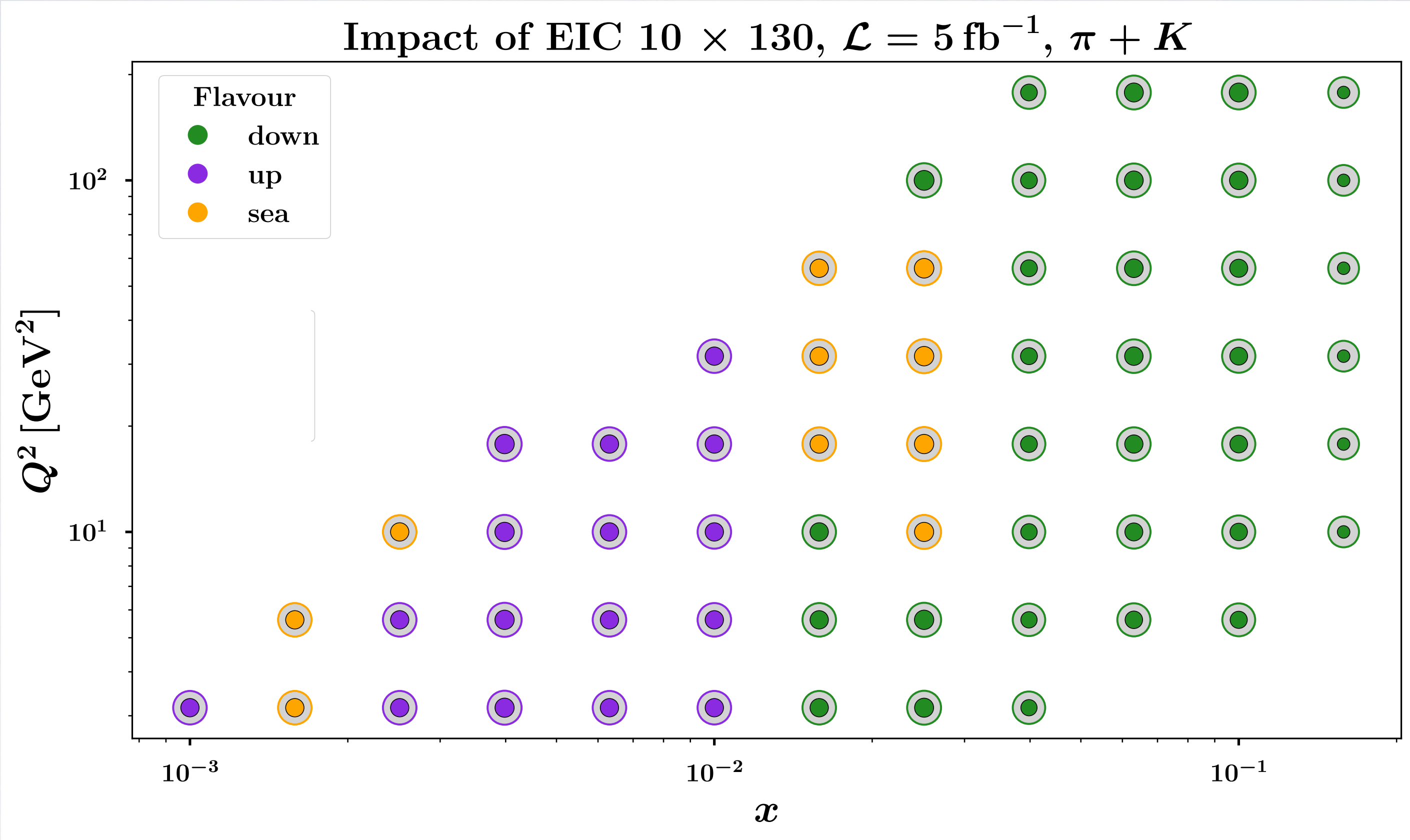
Take-away message : significant impact only for some (x, Q^2) bins and only for specific flavors q

EIC impact: 10x130, lumi=5 fb^{-1}, SIDIS π+K

color code

- up
- down
- "sea"



legenda

baseline: for the given (x,Q^2) bin, it is the max. uncertainty over all $k_\perp$ for **down**

similarly for **up** and **"sea"**

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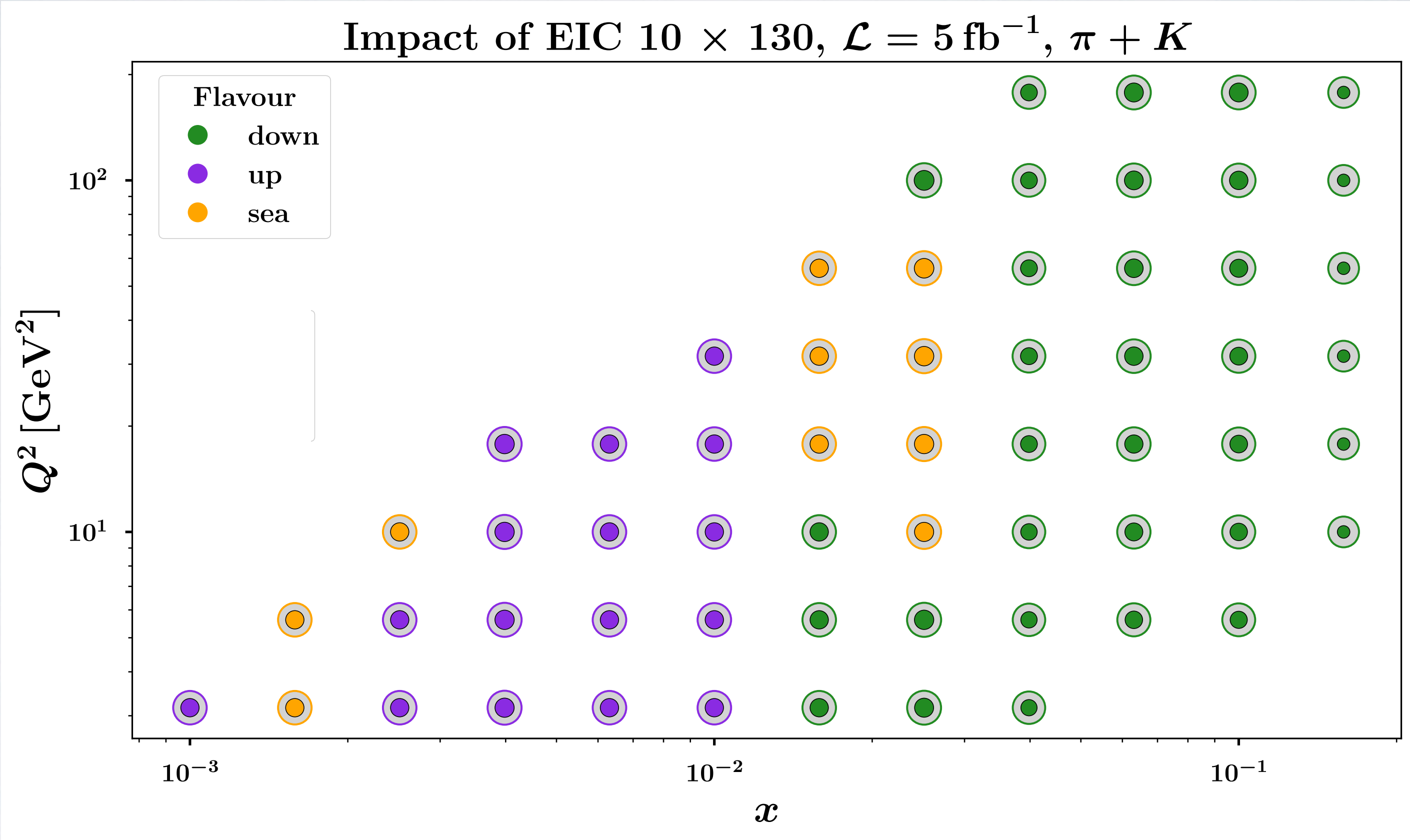

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+ EIC: same when including EIC pseudodata; at the given (x,Q^2) bin, the chosen flavor gives the max. reduction in uncertainty over all $k_\perp$; circle size proportional to reduction

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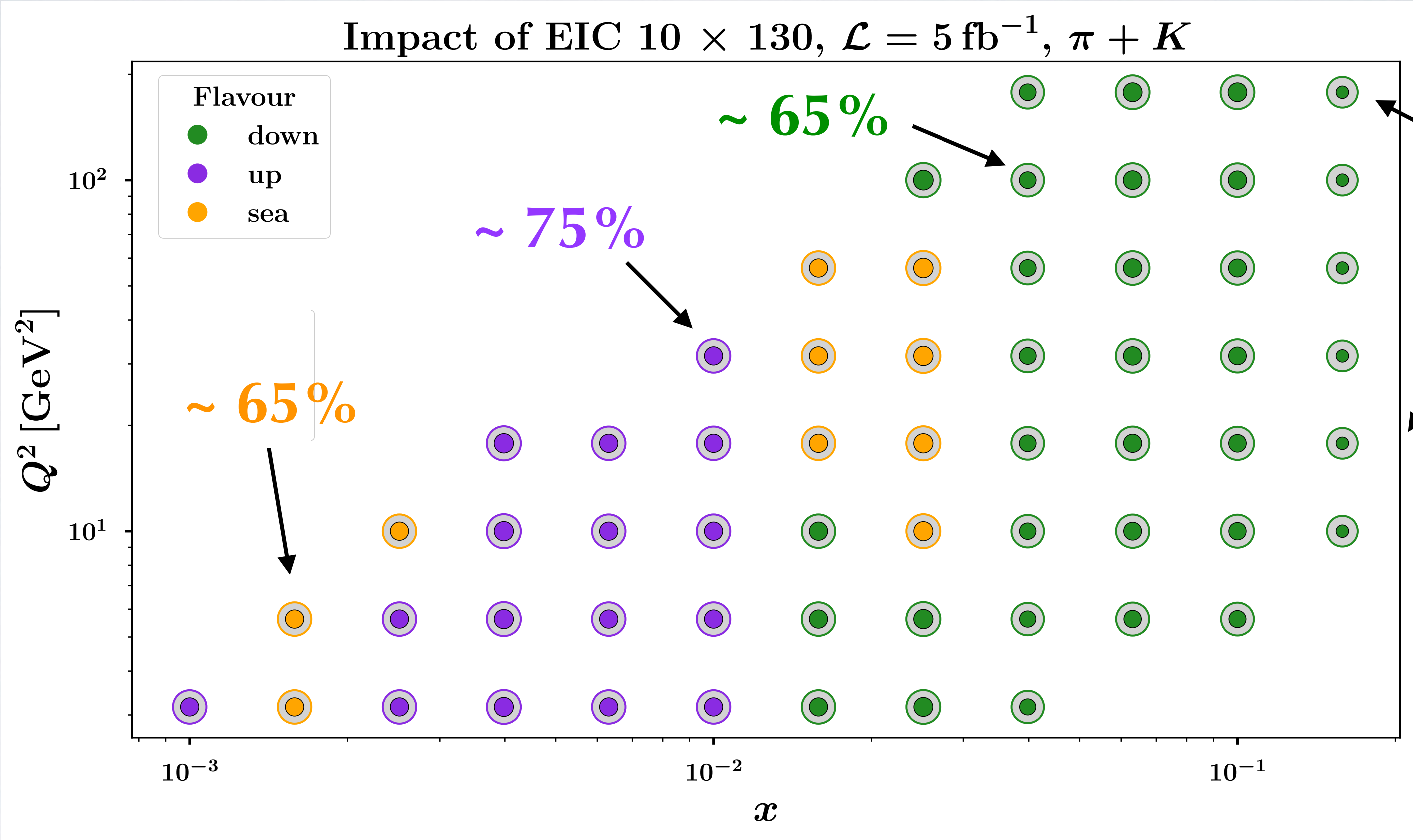

legenda

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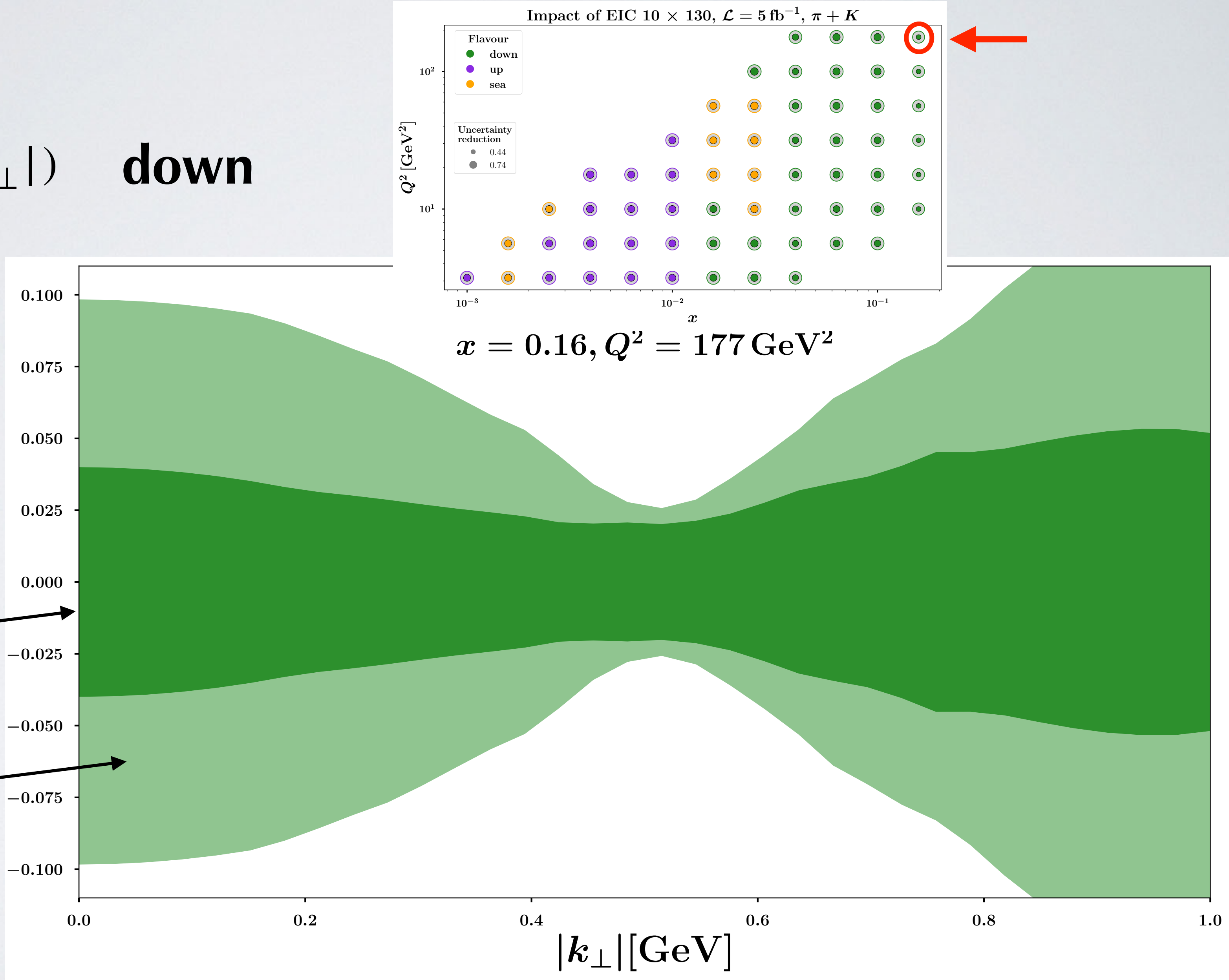
$$\left[\frac{f_1^d - \langle f_1^d \rangle}{\langle f_1^d \rangle}\right](|\mathbf{k}_\perp|)$$ **down**

+ EIC

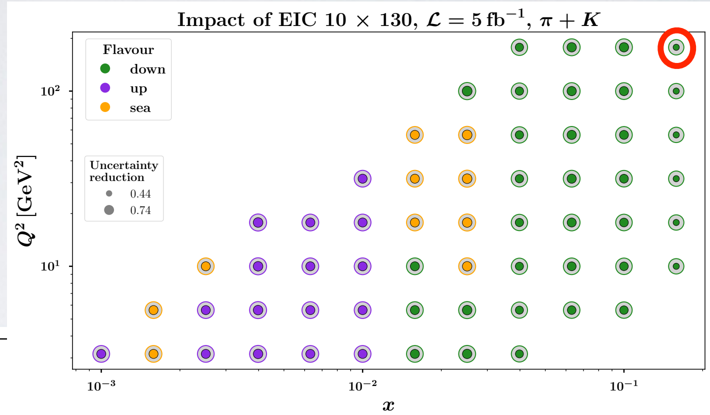
baseline MAPTMD24



EIC impact: 10x130, lumi=5 fb^{-1} , SIDIS π+K

$$\left[\frac{f_1^d - \langle f_1^d \rangle}{\langle f_1^d \rangle}\right](|\mathbf{k}_\perp|)$$

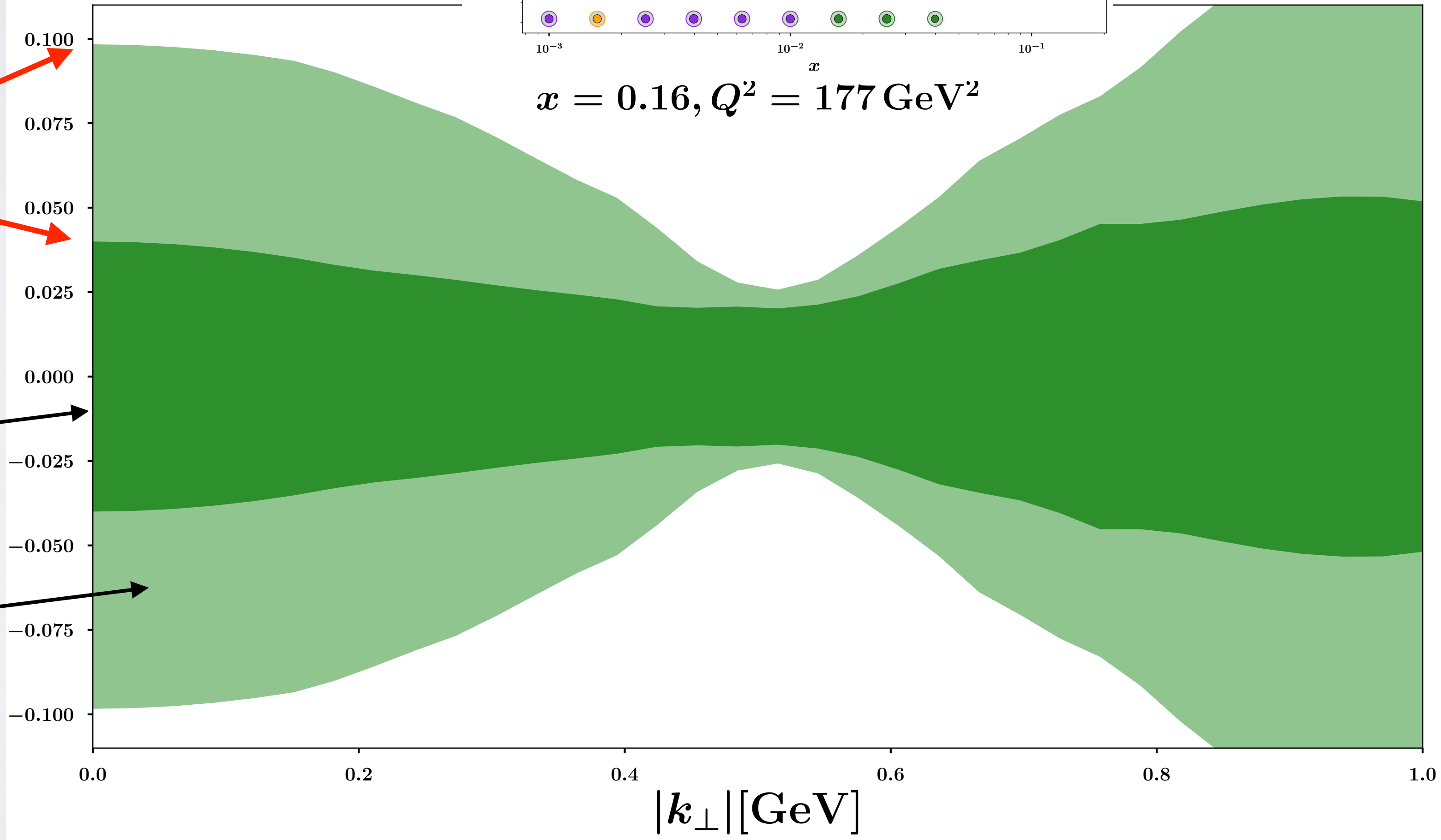
down



~ 2.4 x reduction

+ EIC

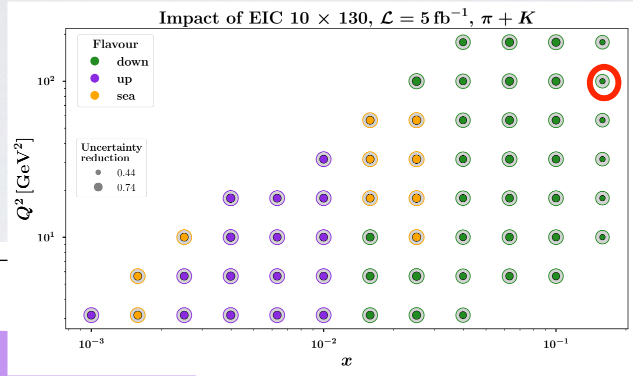
baseline MAPTMD24



EIC impact: 10x130, lumi=5 fb-1 , SIDIS π+K

$$\left[\frac{f_1^u - \langle f_1^u \rangle}{\langle f_1^u \rangle}\right](|\mathbf{k}_\perp|)$$

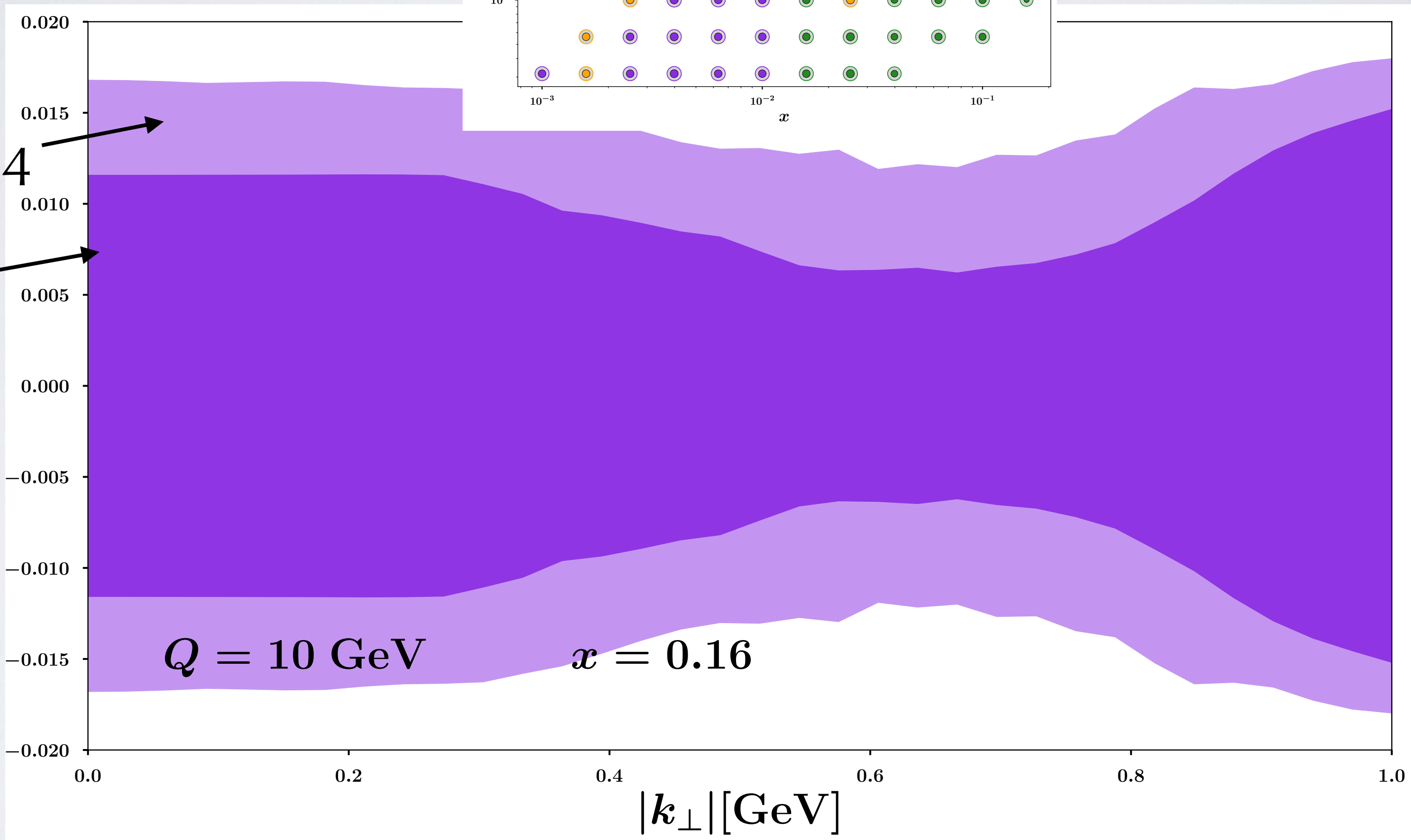
up



x=0.16
Q^2=100 GeV^2

baseline MAPTMD24

+ EIC



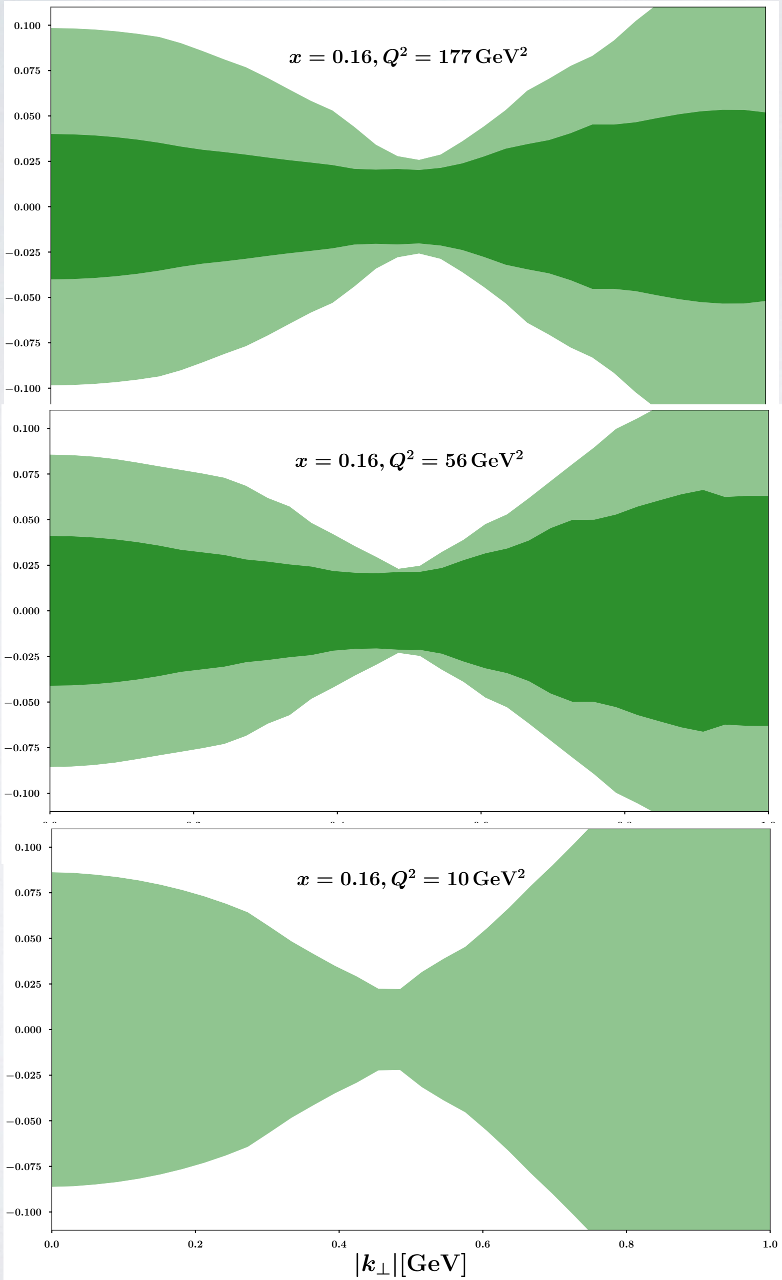
up already constrained by baseline MAPTMD24

EIC impact: 10x130, lumi=5 fb^{-1}, SIDIS π+K

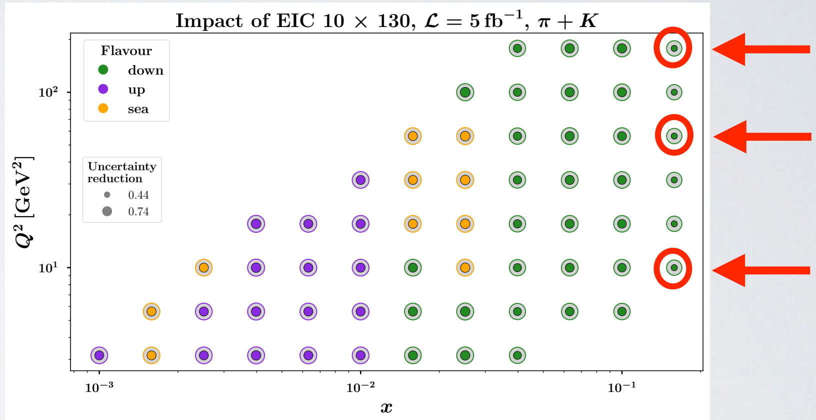
Q²=177 GeV²

Q²=56 GeV²

Q²=10 GeV²



$$\left[\frac{f_1^d - \langle f_1^d\rangle}{\langle f_1^d\rangle}\right](x = 0.16, |\mathbf{k}_\perp|)$$



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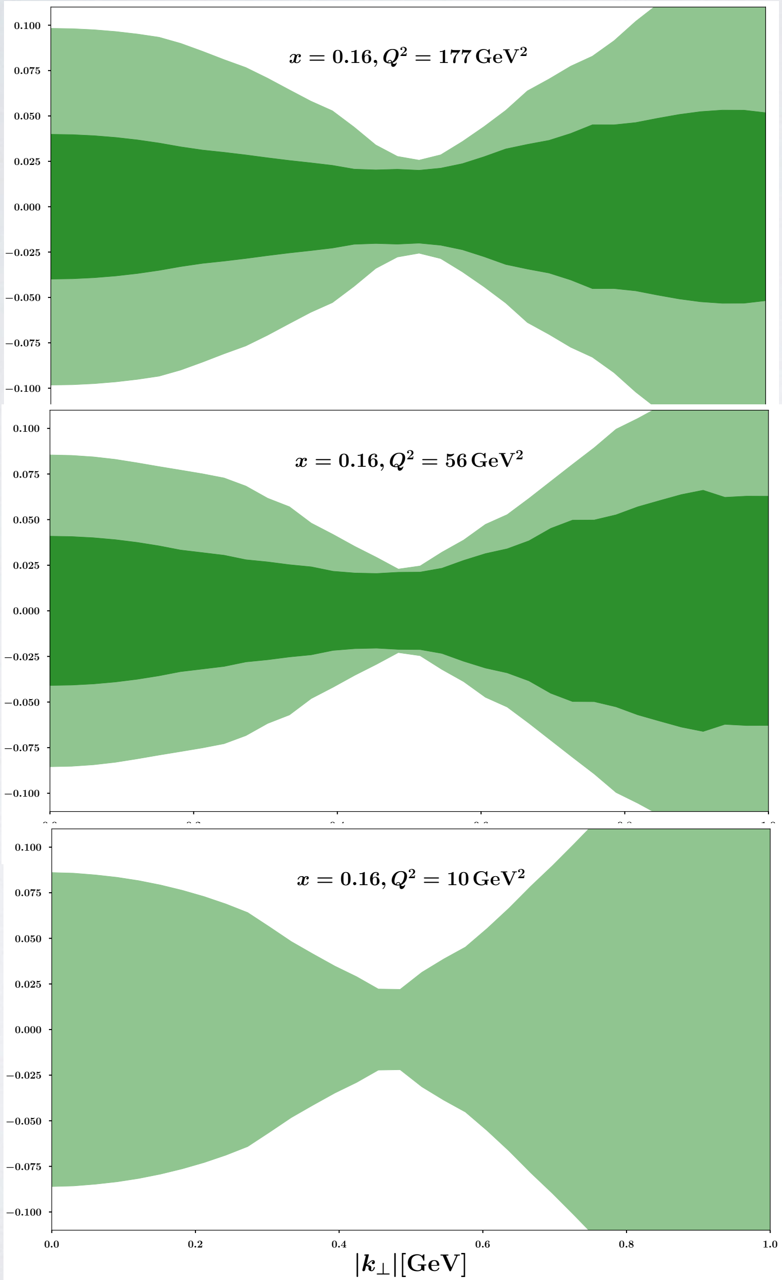

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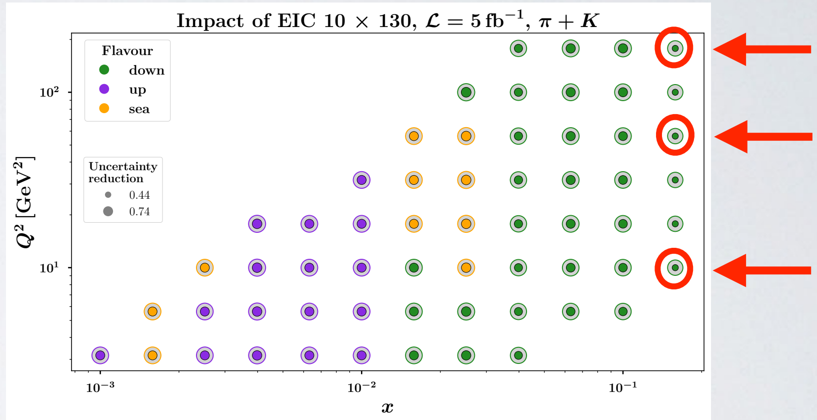

Can EIC in early phase-1 test TMD evolution ?

TMD evolution: the Collins-Soper kernel

universal: same for TMDPDF and TMDFF, it does not depend on process, hadron type , x , and flavor !

$$K(b_T) \; + \; g_K(b_T)$$

perturbative, calculable   fitted to data; input from lattice

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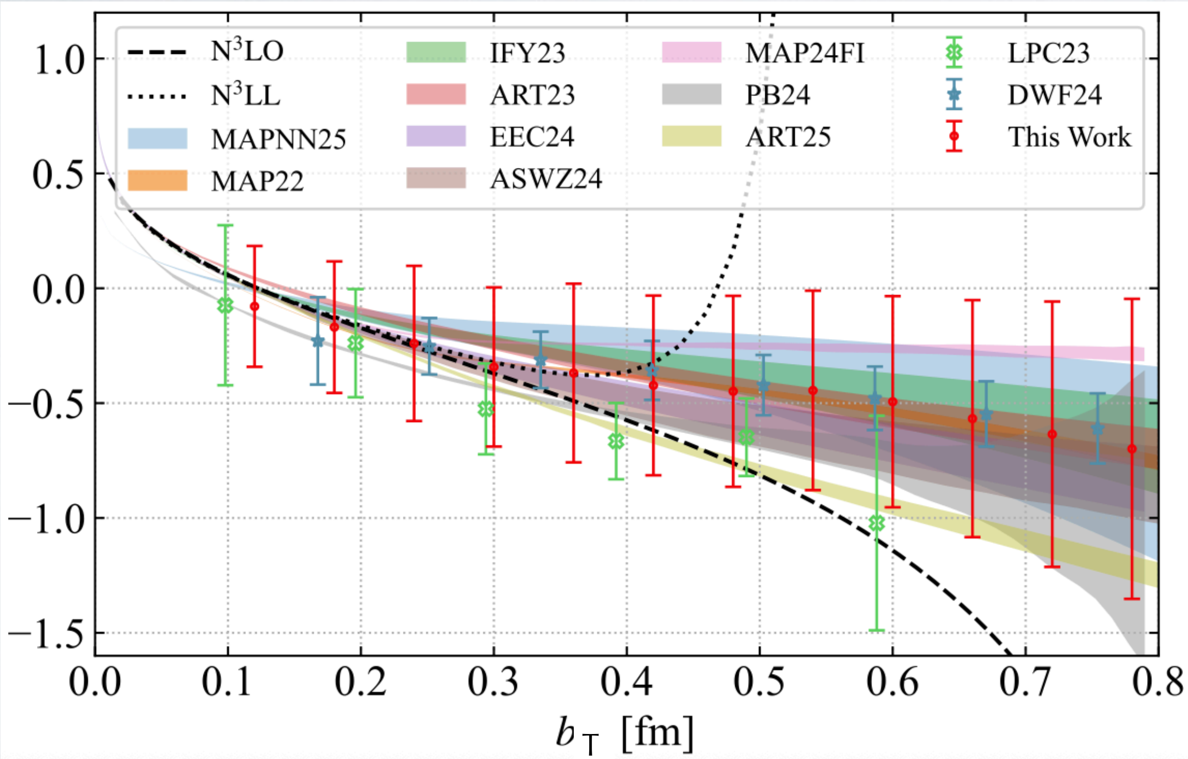

Lattice

DWF24 Bollweg et al., arXiv:2403.00664

LPC23 Chu et al. (LPC), arXiv:2306.06488

ASWZ24 Avkhadiev et al., arXiv:2402.06725

"This work" Bollweg et al., arXiv:2504.04625

pQCD

N^3LL Vladimirov, arXiv:1610.05791

N^3LO Li&Zhu, arXiv:1604.01404

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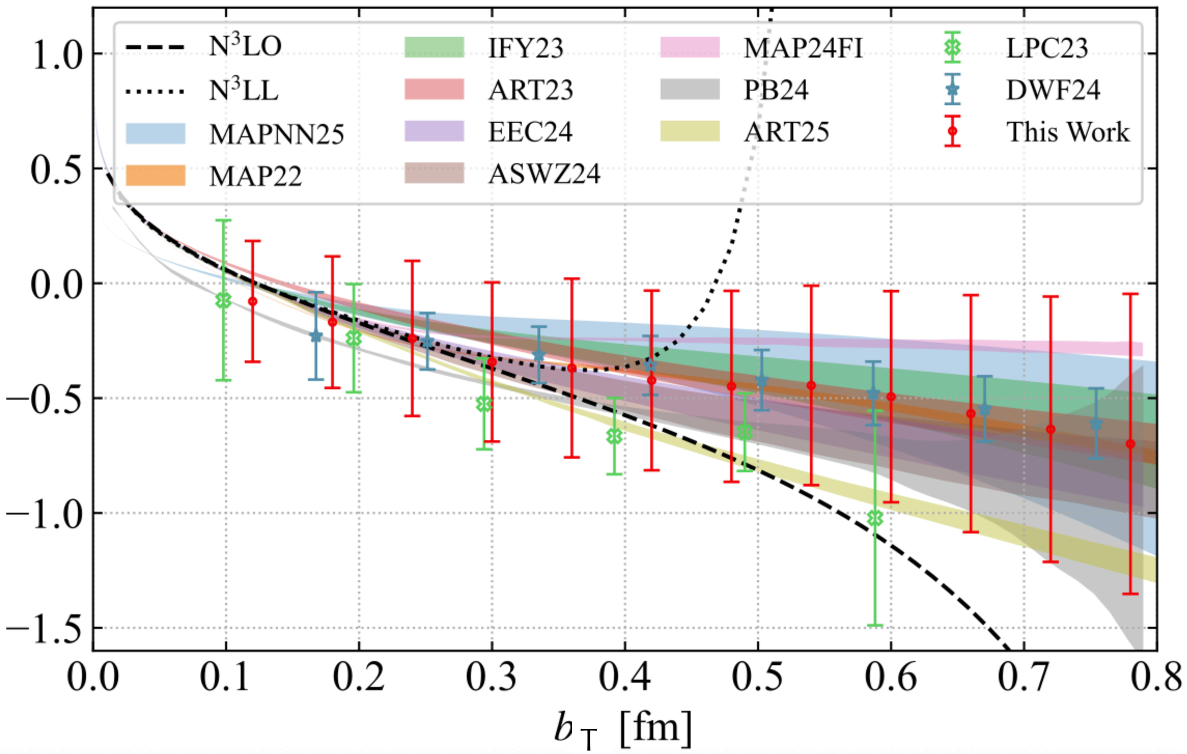

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Pheno

IFY23 (ResBos) Isaacson et al., arXiv:2311.09916

EEC24 Kang et al., arXiv:2410.21435

PB24 Martinez et al., arXiv:2412.21116

MAP Collaboration

MAP-22 arXiv:2206.07598 -24 arXiv:2405.13833

-NN arXiv:2502.04166

Artemide Collaboration

ART-23 arXiv:2305.07473 -25 arXiv:2503.11201

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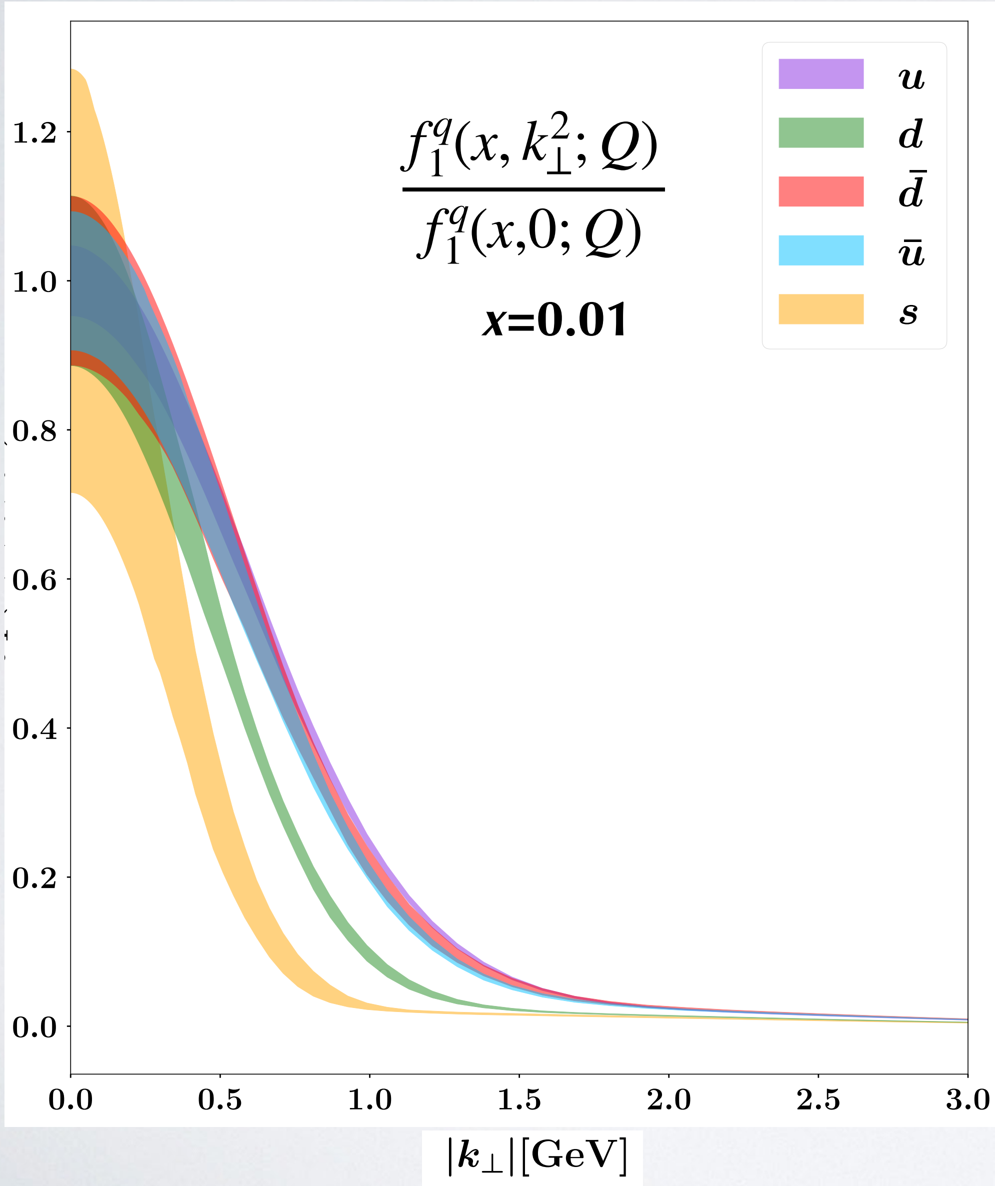
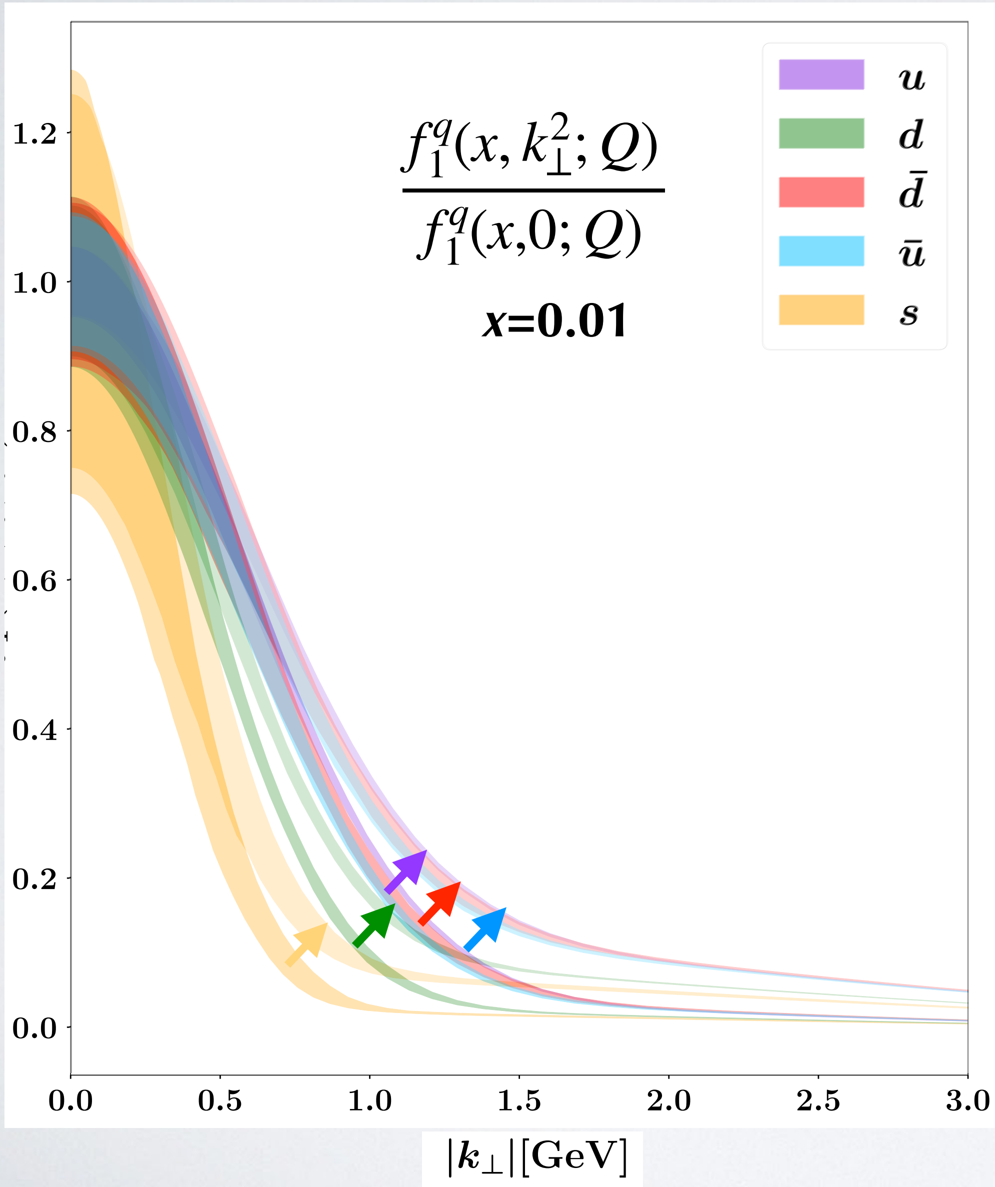
Evolution of MAPTMD24 TMD PDFs



Q^2=4 GeV^2

Evolution of MAPTMD24 TMD PDFs



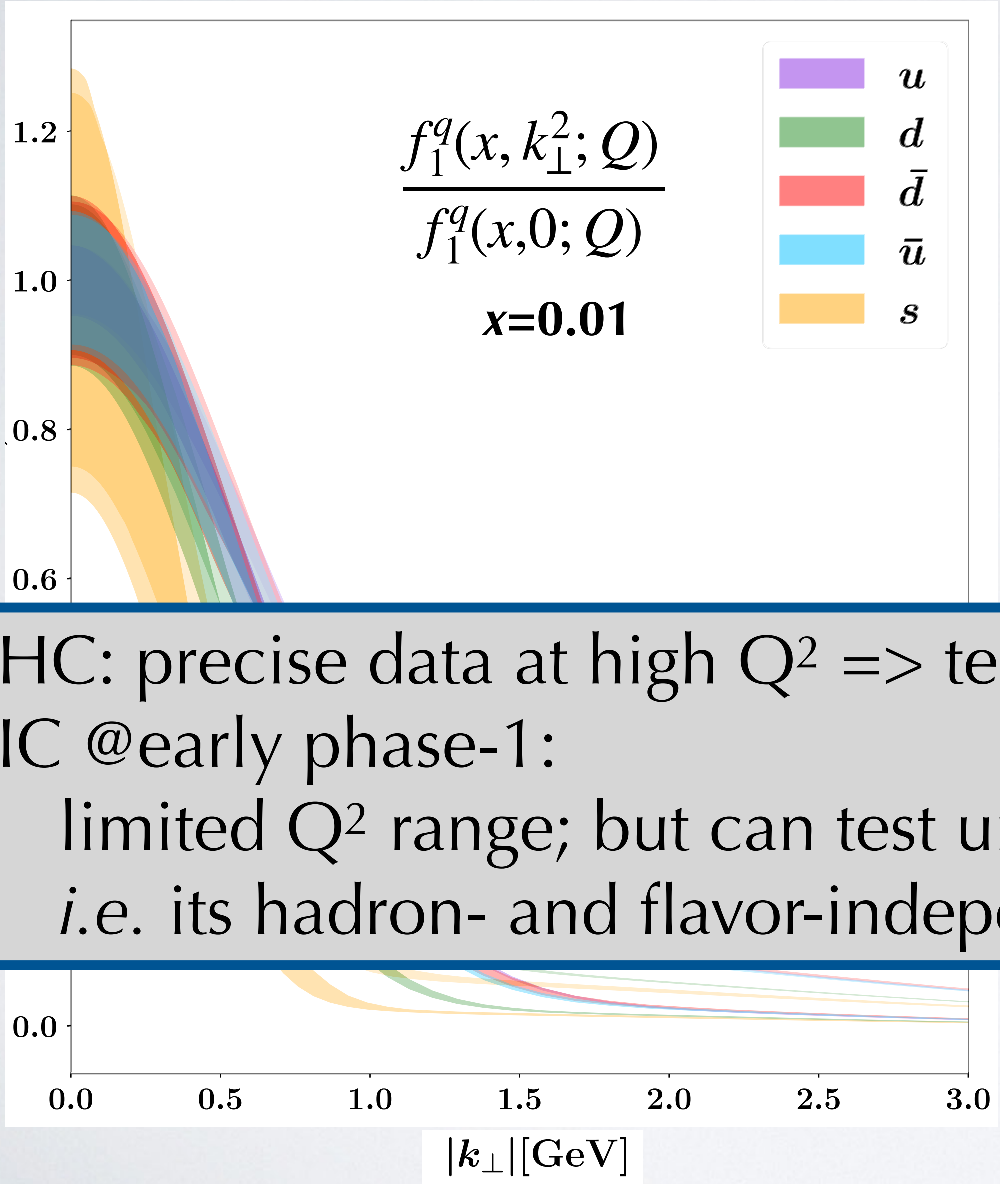
Q^2=4 GeV^2

↓

Q^2=100 GeV^2

(mild) widening of TMD PDFs with increasing Q^2

Evolution of MAPTMD24 TMD PDFs



Q^2=4 GeV^2

↓

Q^2=100 GeV^2

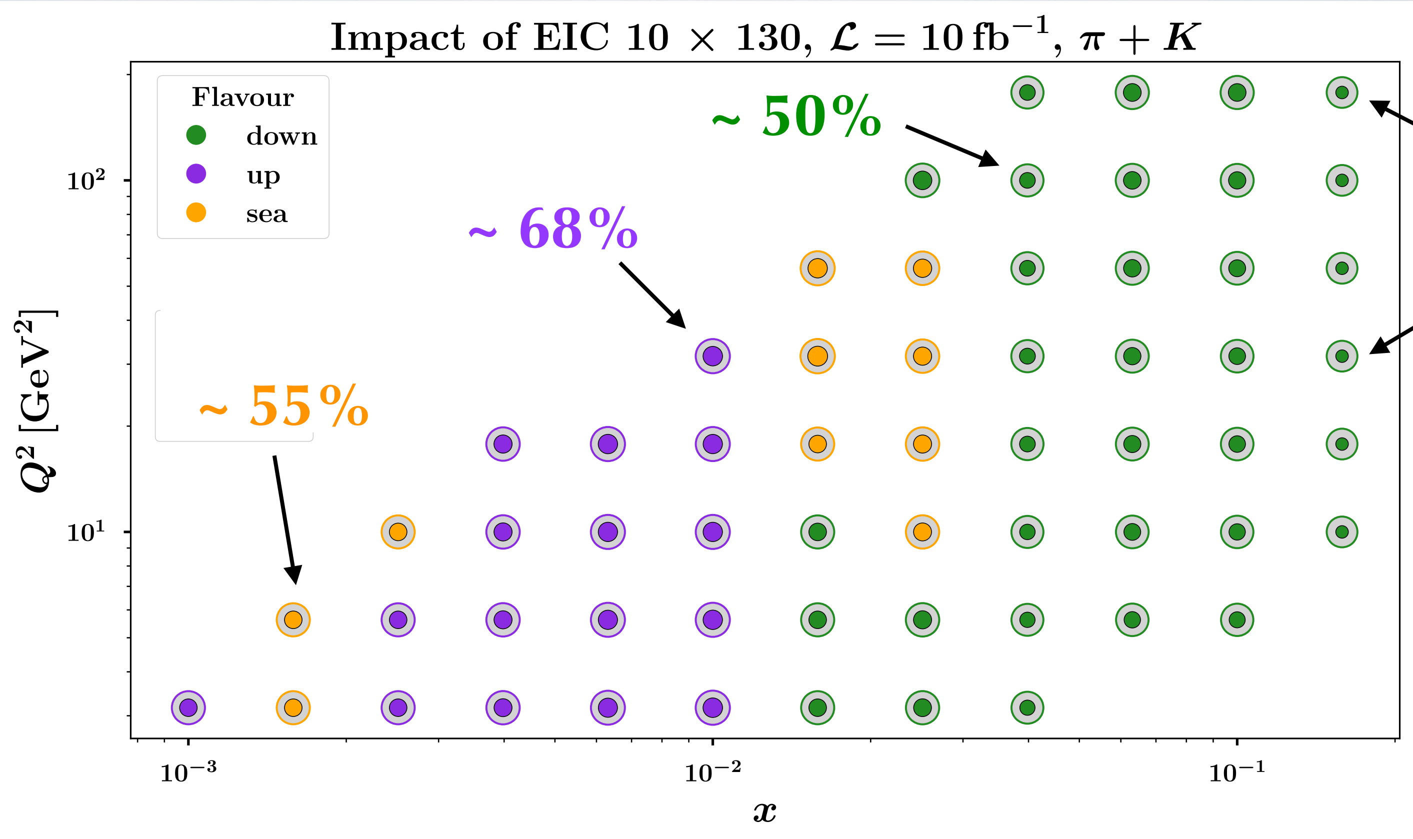
(mild) widening of TMD PDFs with increasing Q^2

LHC: precise data at high Q^2 => test (flavor-blind) evolution
EIC @early phase-1:
limited Q^2 range; but can test universality of CS kernel, *i.e.* its hadron- and flavor-independence

EIC impact: 10x130, lumi=10 fb-1 , SIDIS π+K

color code

- up
- down
- "sea"



legenda

baseline: for the given (x,Q²) bin, it is the max. uncertainty over all $k_\perp$ for **down**

+ EIC: same when including EIC pseudodata; at the given (x,Q²) bin, the chosen flavor gives the max. reduction in uncertainty over all $k_\perp$; circle size proportional to reduction

similarly for **up** and **"sea"**

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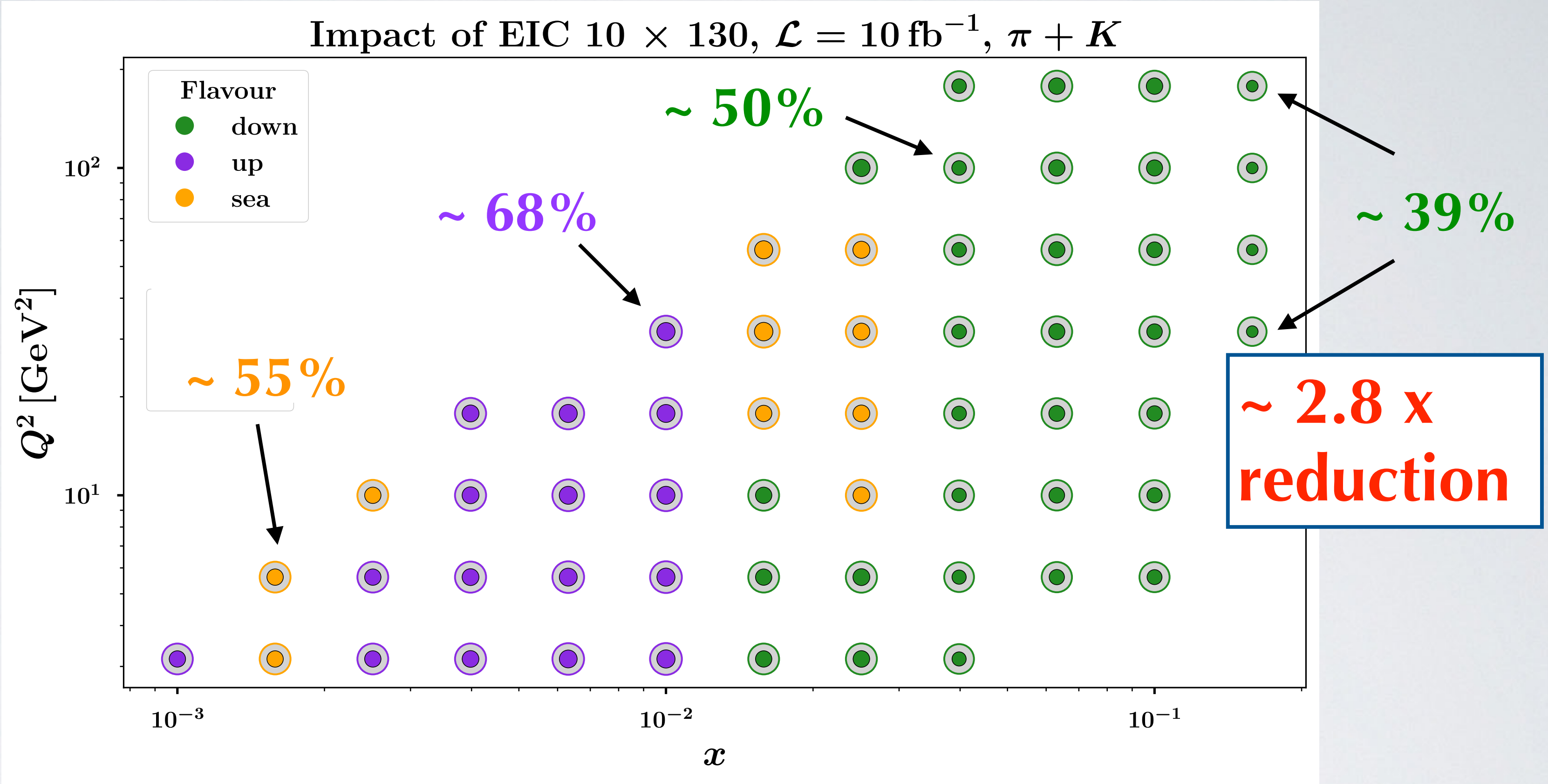

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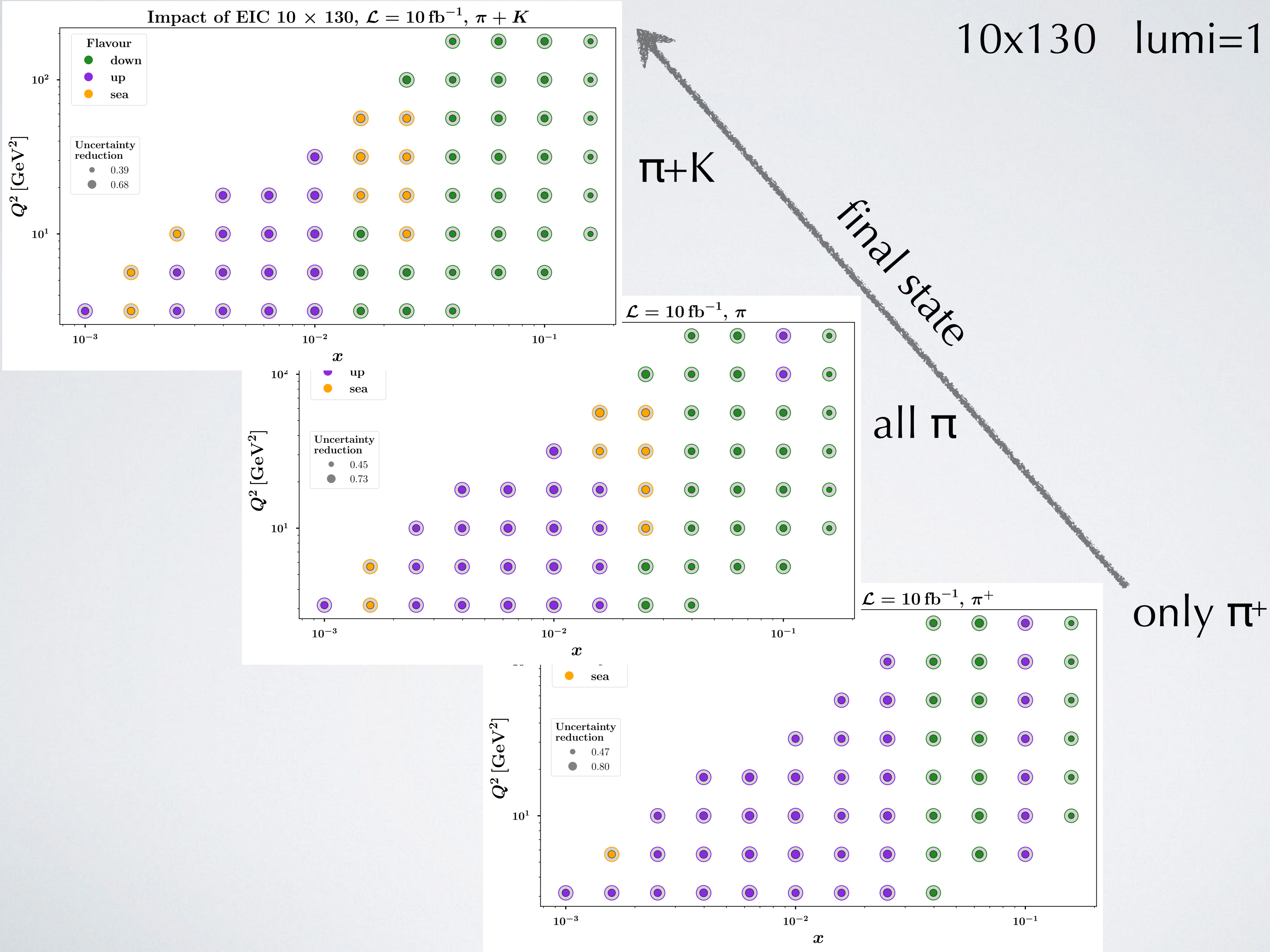
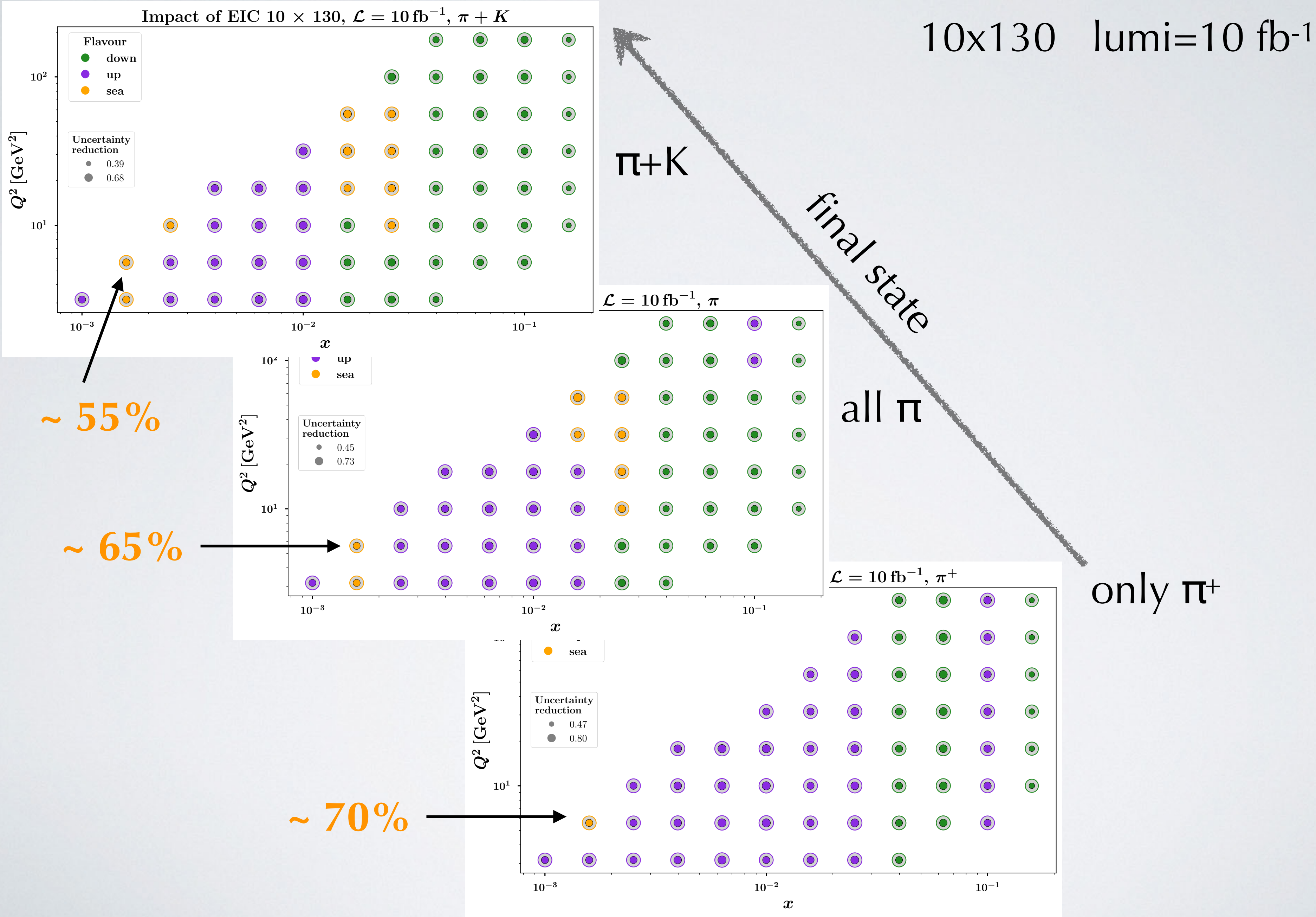
Effect of Kaon data

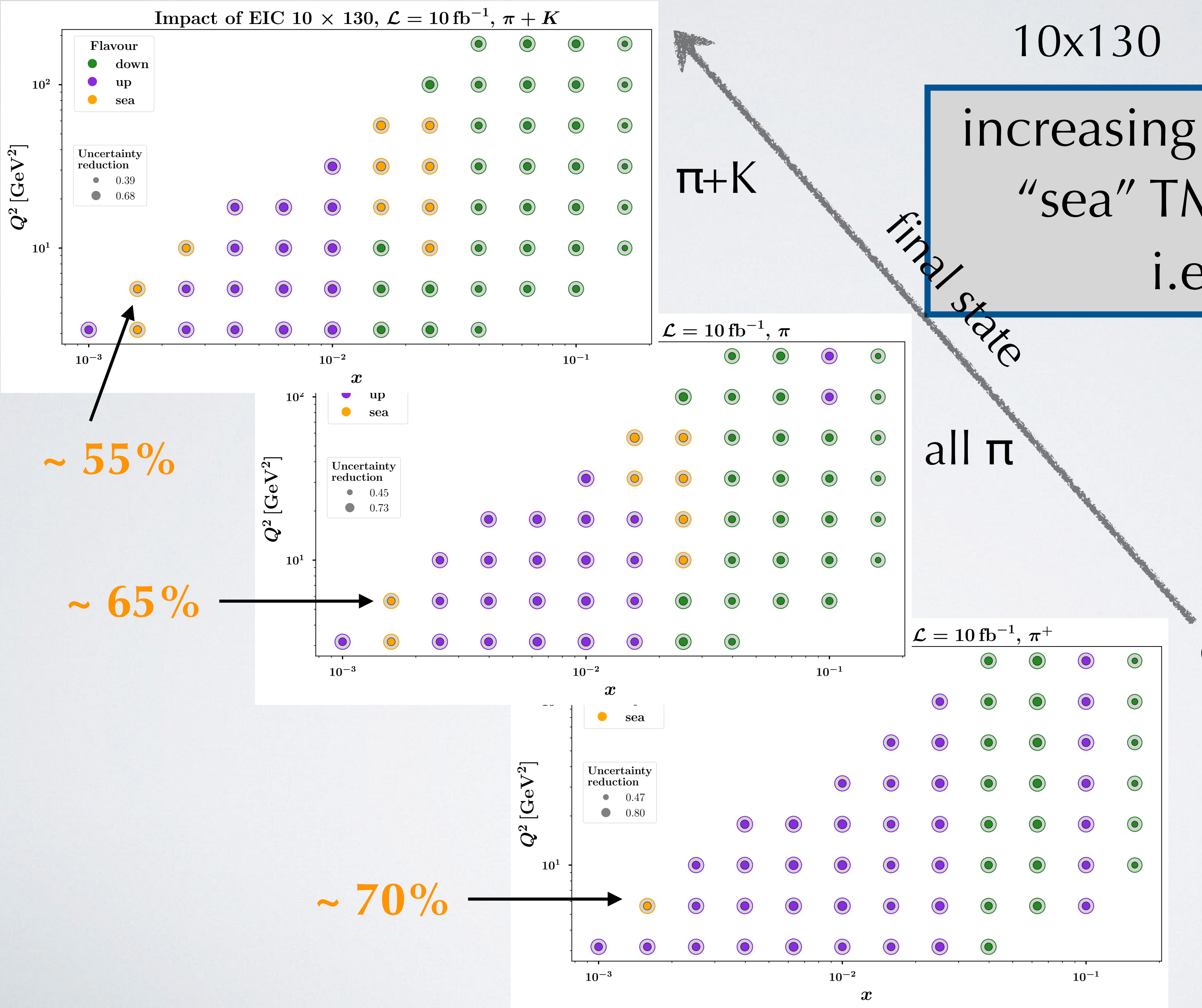
10x130 lumi=10 fb^{-1}



Effect of Kaon data



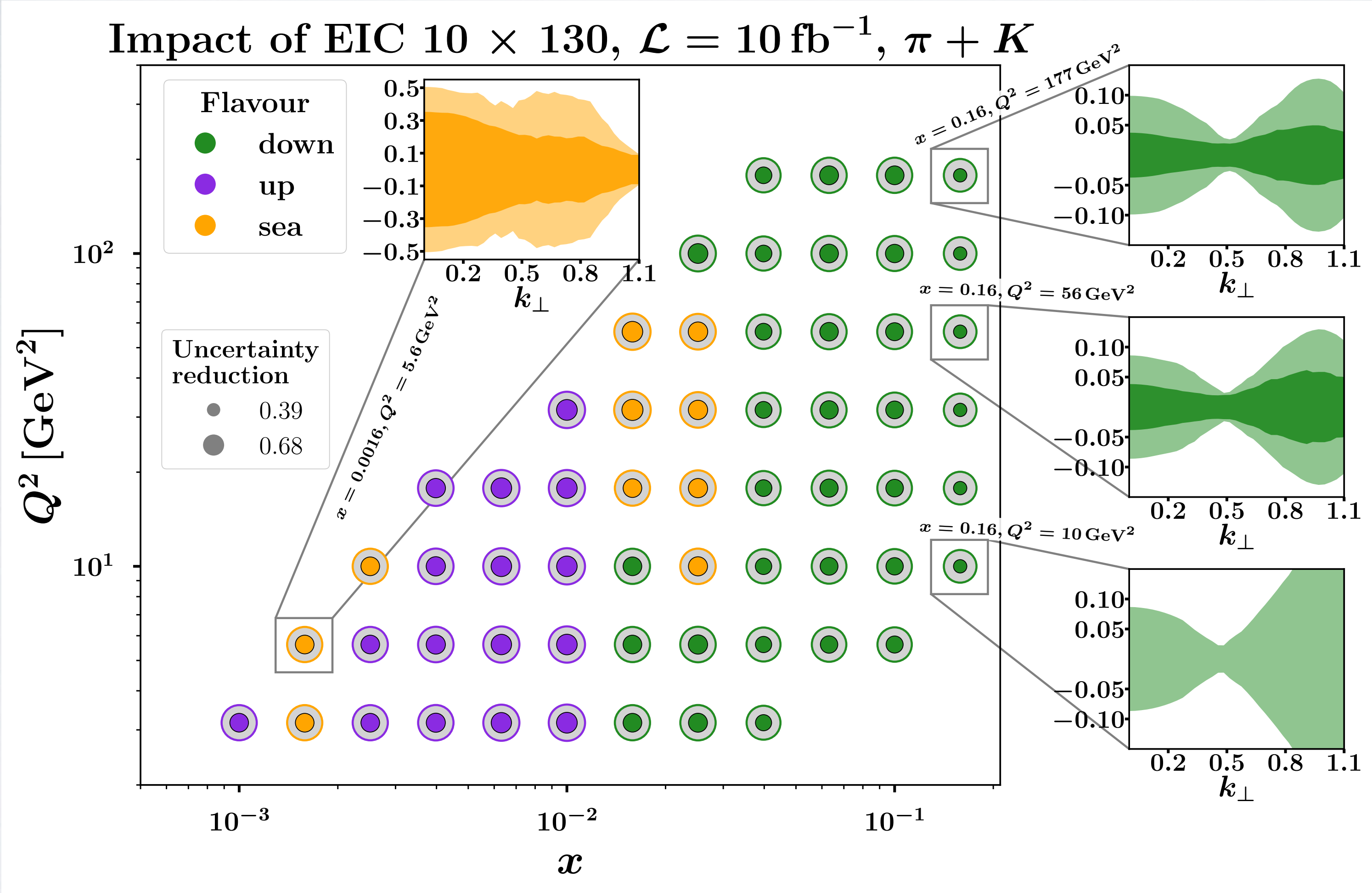
Effect of Kaon data



10x130 lumi=10 fb^{-1}

increasing precision on "sea" TMD $\neq \bar{u}, \bar{d}$ i.e. $s, \bar{s}$

Proposed plot for the ESR



attempt to draw a 4-dim object (flavor, x, Q^2, $k_\perp$)
in a 2-dim plot…

Summary

- unpol. SIDIS important for 3-dim picture in momentum space;
  it influences extraction of all other polarized TMDs

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- Kaon data might be important to constrain strange TMD

Summary

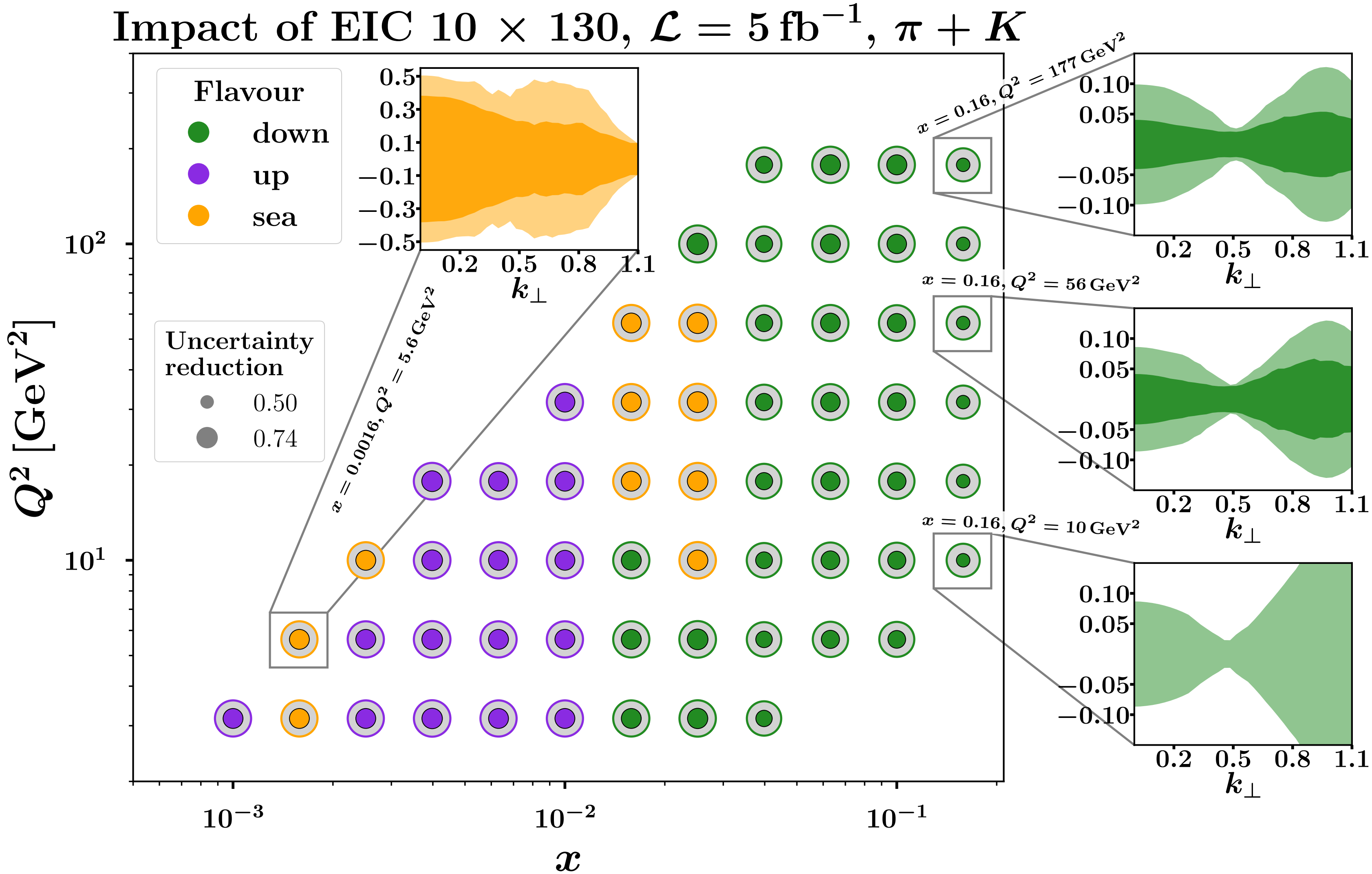
- unpol. SIDIS important for 3-dim picture in momentum space; it influences extraction of all other polarized TMDs

EIC @early phase-1:

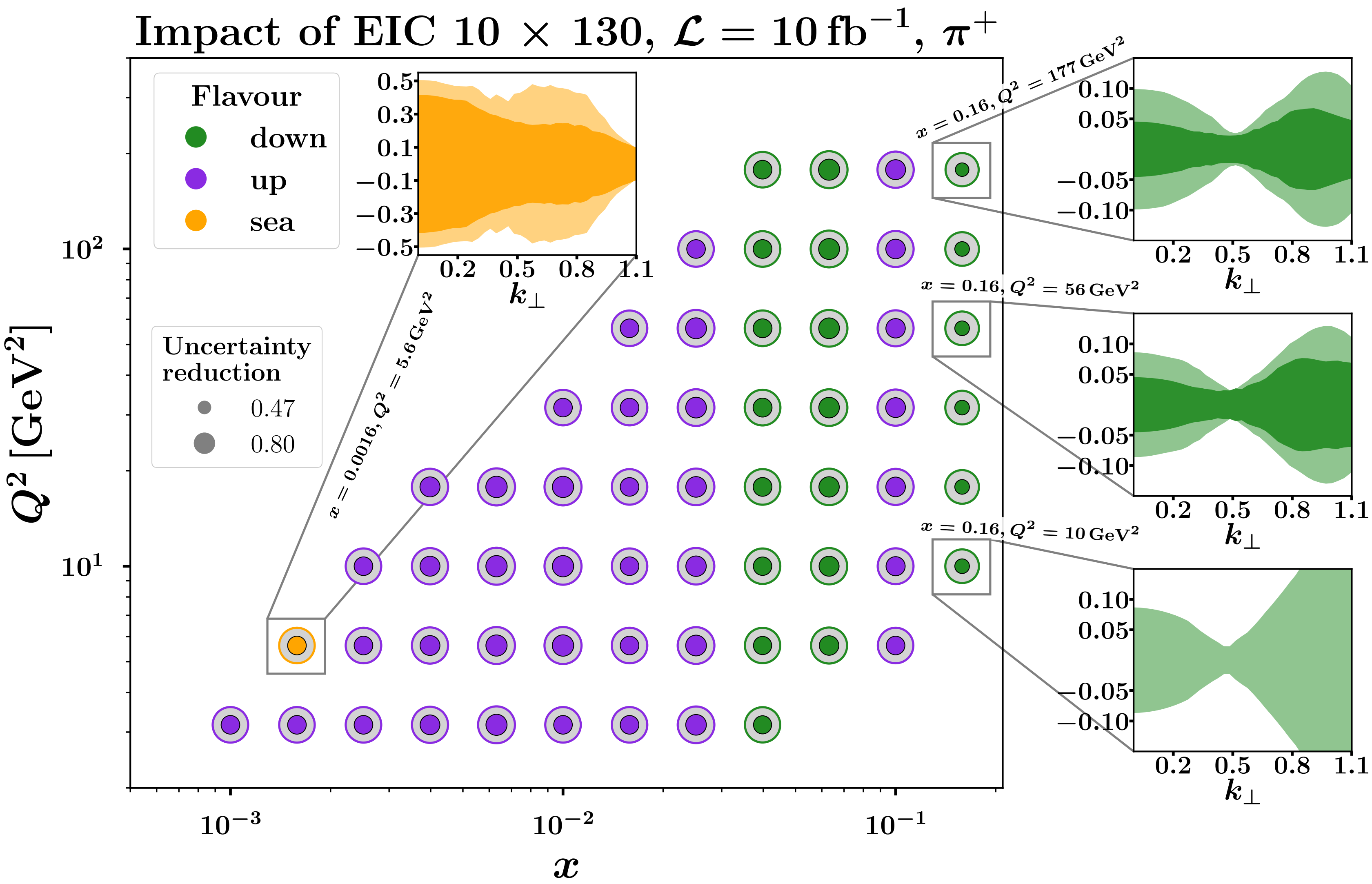
- significant impact only for some (x,Q^2) and for some flavors
- could test universality of TMD evolution kernel
- Kaon data might be important to constrain strange TMD

Backup

10x130, lumi = 5 fb^{-1}, SIDIS π+K



10x130, lumi = 10 fb^{-1}, SIDIS π^+



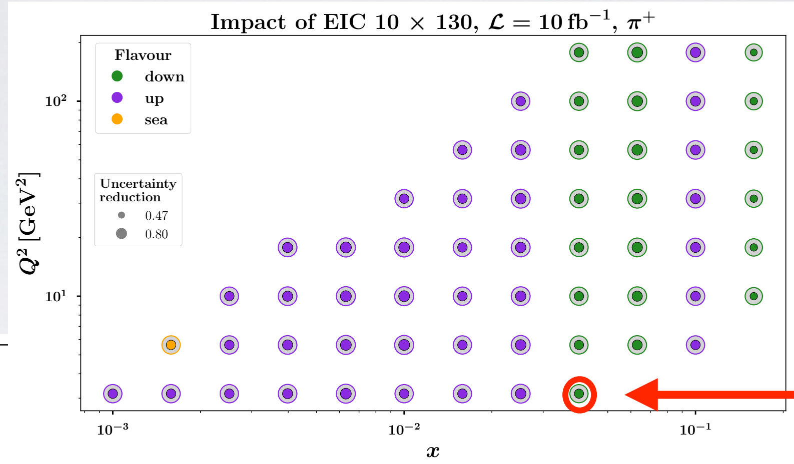
10x130, lumi = 10 fb^{-1}, SIDIS π^+

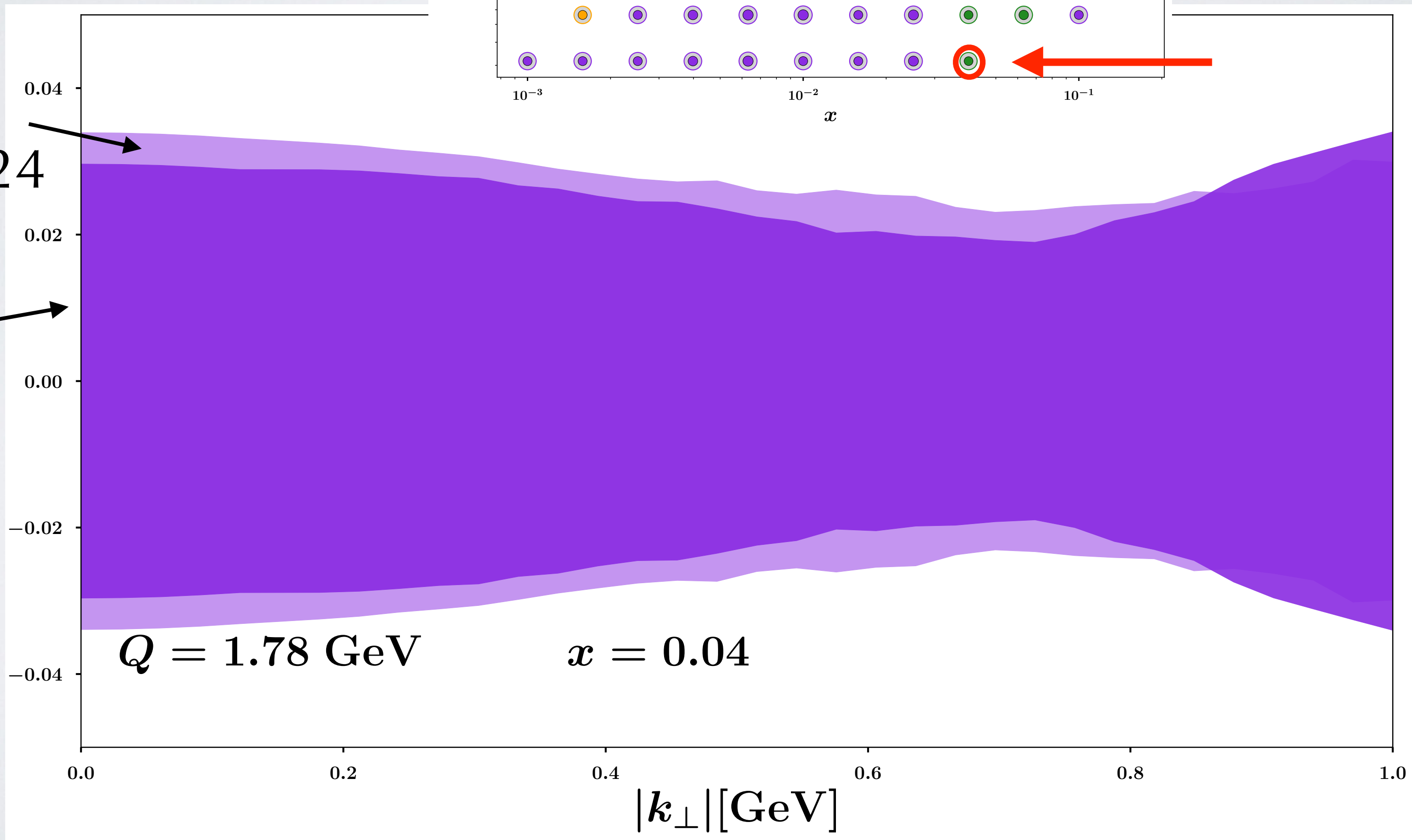
$$\left[\frac{f_1^u - \langle f_1^u \rangle}{\langle f_1^u \rangle}\right](|\mathbf{k}_\perp|)$$ **up**

x=0.04
Q²=3.17 GeV²

baseline
MAPTMD24

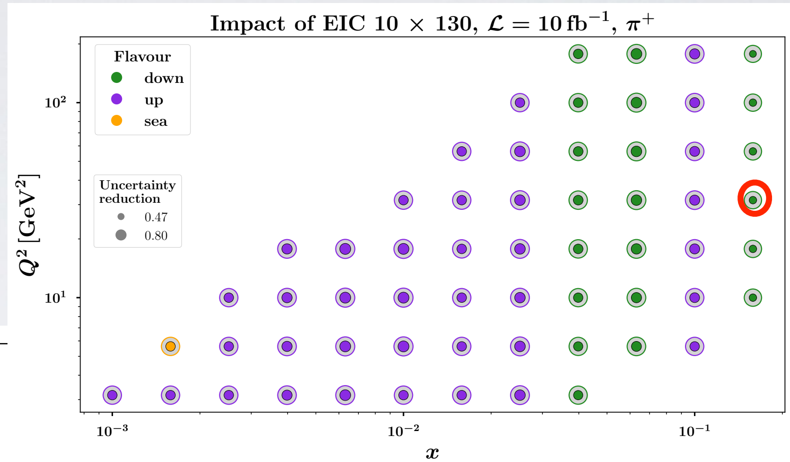
+ EIC





10x130, lumi = 10 fb^{-1} , SIDIS π^+

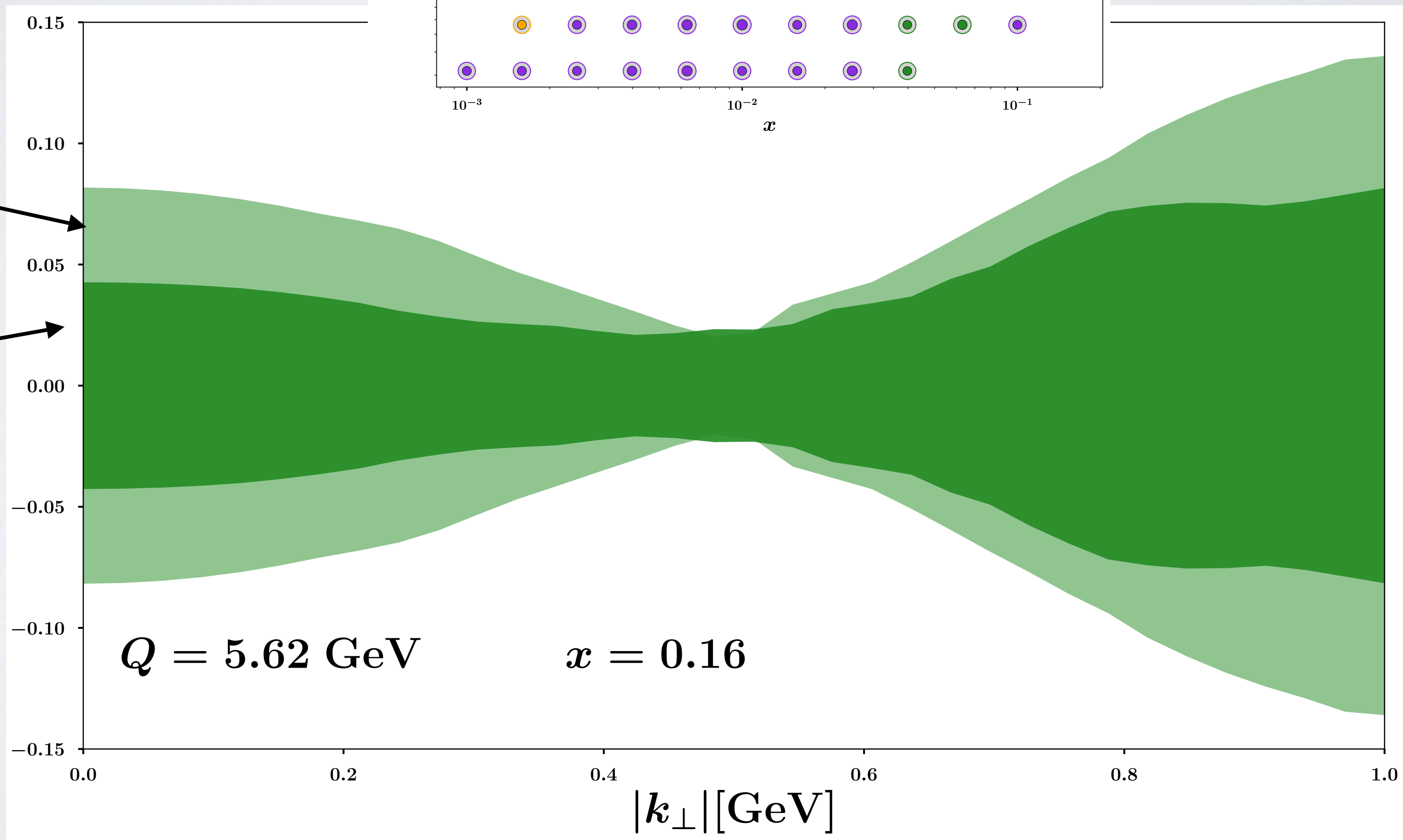
$$\left[\frac{f_1^d - \langle f_1^d \rangle}{\langle f_1^d \rangle}\right](|\mathbf{k}_\perp|)$$ **down**



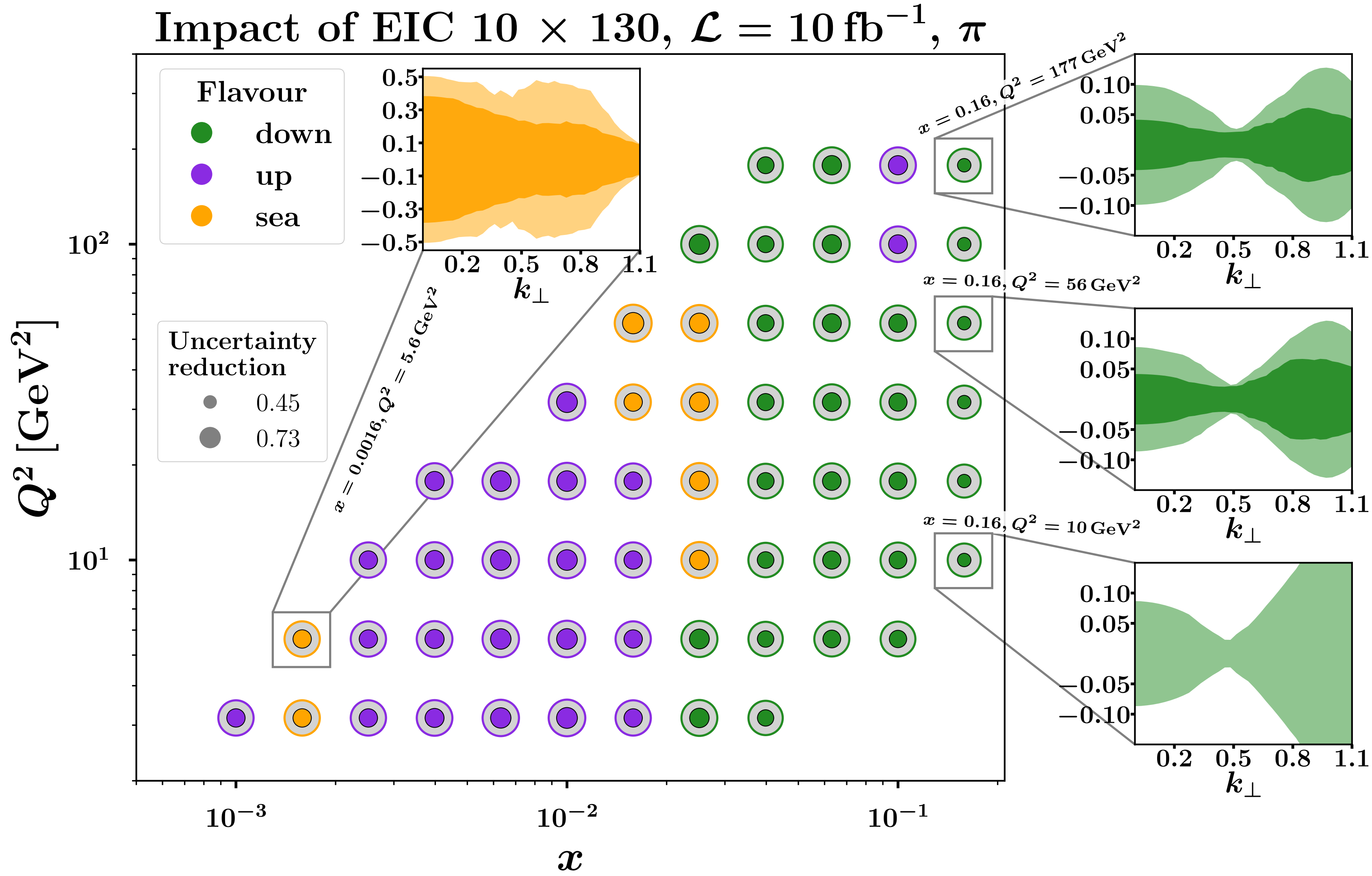
x=0.16
Q^2=31.6 GeV^2

baseline
MAPTMD24

+ EIC



10x130, lumi = 10 fb^{-1}, SIDIS all π



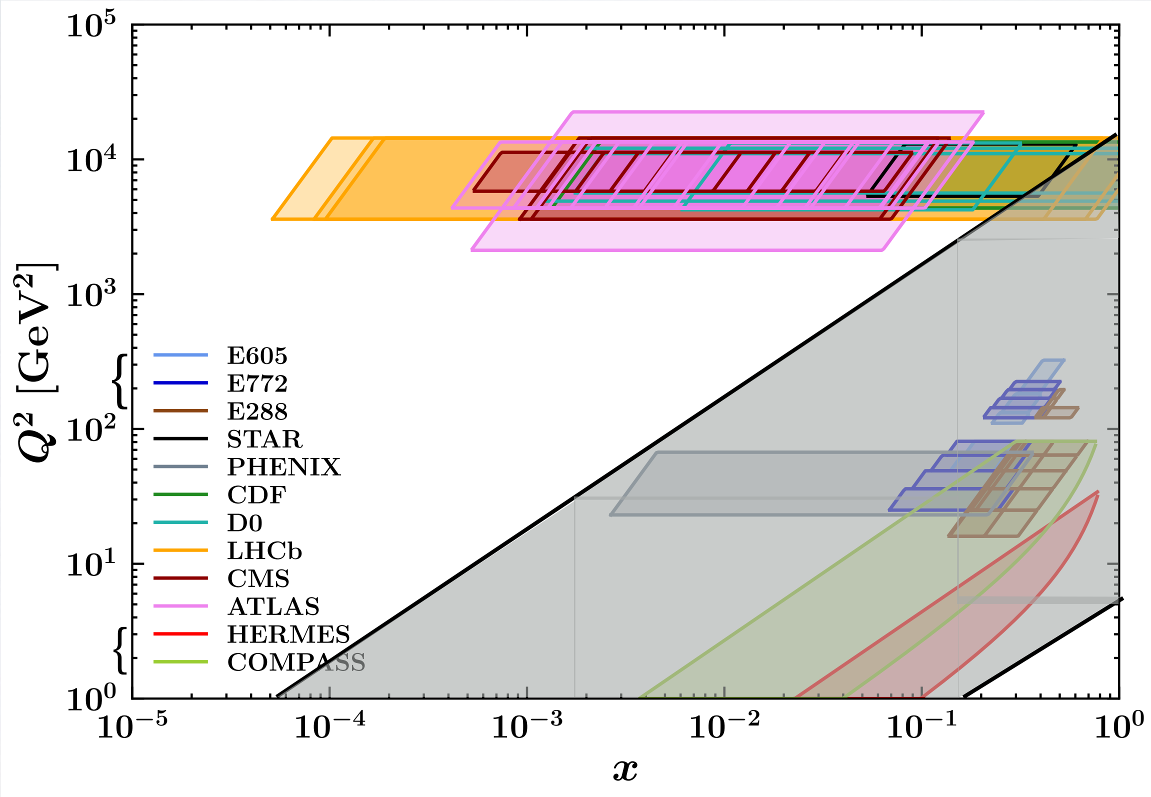
EIC impact

All energies (5x41, 10x100, 18x275)
at max. lumi (campaign of May ’24)
proton target, SIDIS with only $\pi+$

EIC impact in full glory

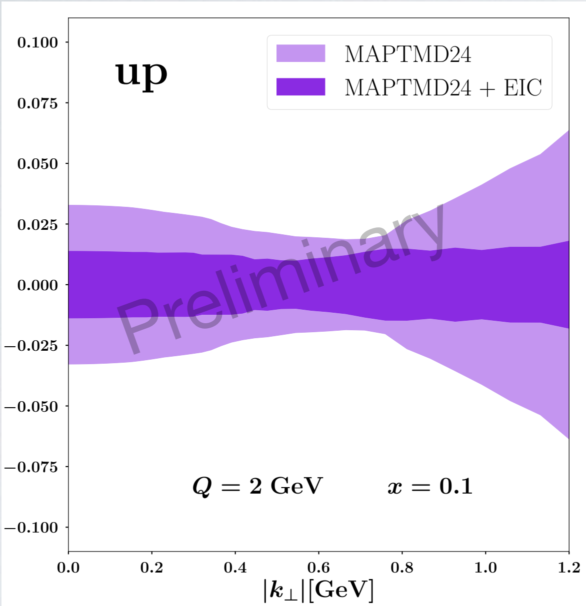
Drell Yan { fixed target / collider

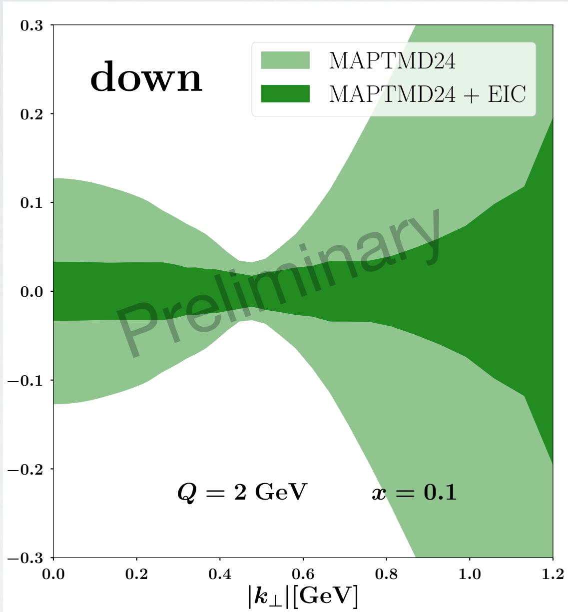
SIDIS



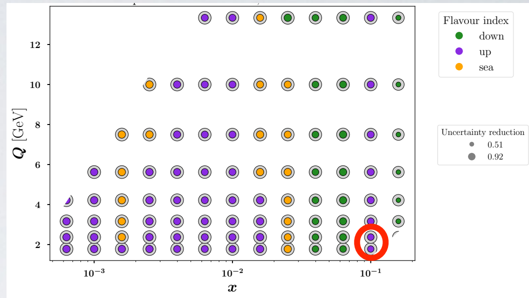
EIC coverage

The EIC impact at x=0.1, Q=2 GeV



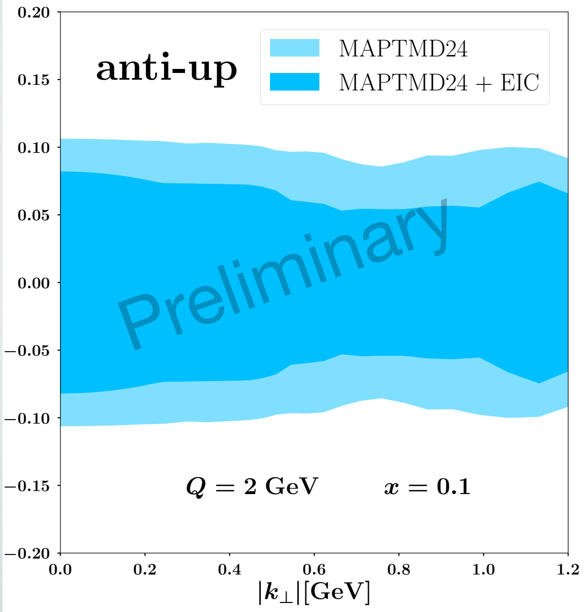


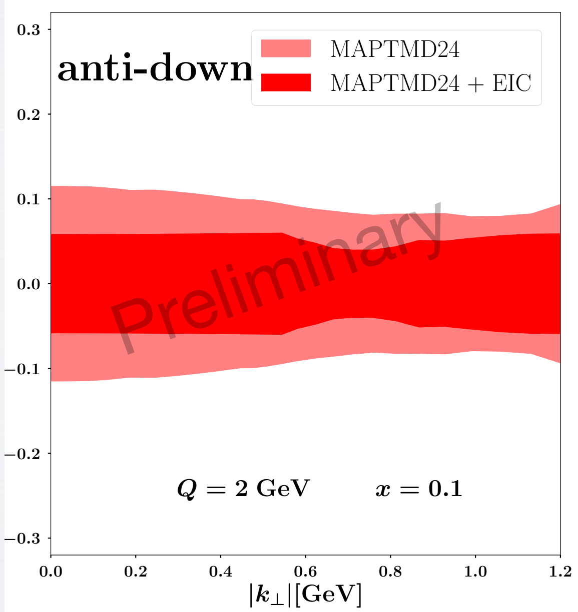
x=0.1 Q=2 GeV

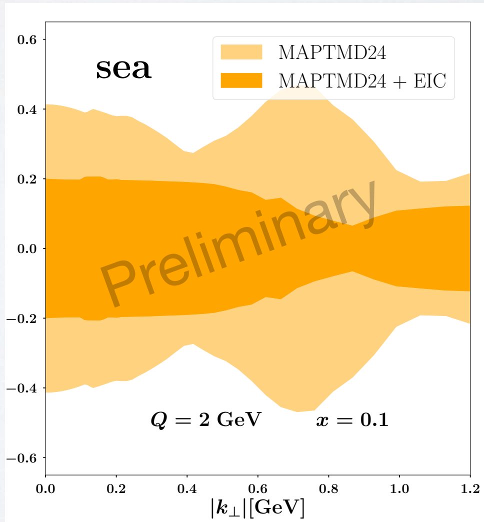


MAPTMD24	2031	
EIC	**# pts.**	**lumi [fb^{-1}]**
5x41	1273	2.85
10x100	1611	51.3
18x275	1648	10

(simulation May '24, **only π+ production**)







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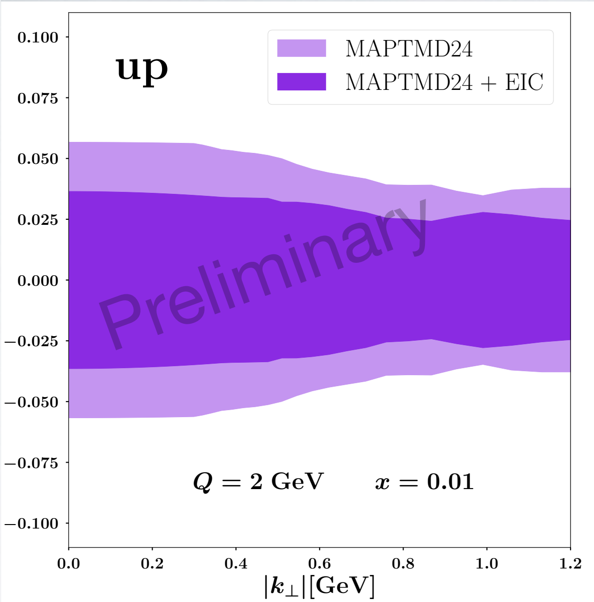
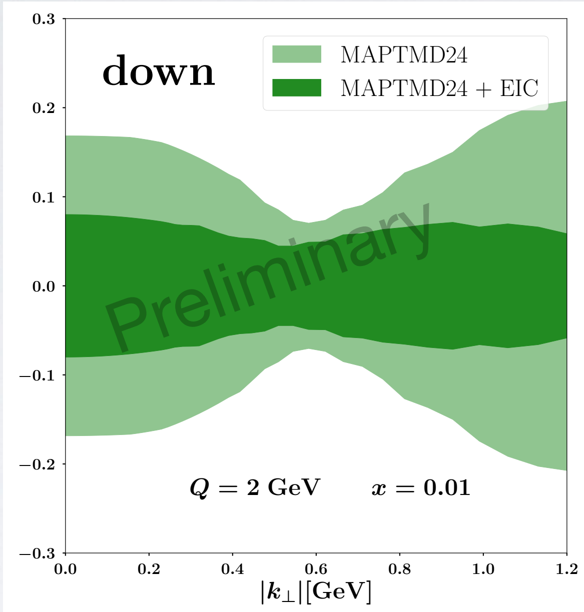
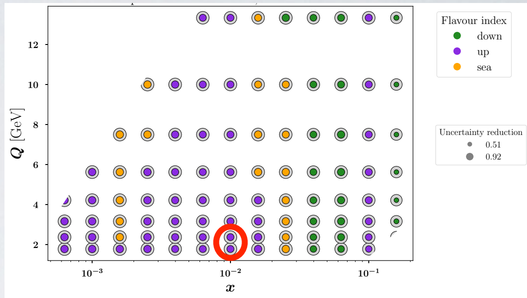
The EIC impact at x=0.01, Q=2 GeV





x=0.01 Q=2 GeV



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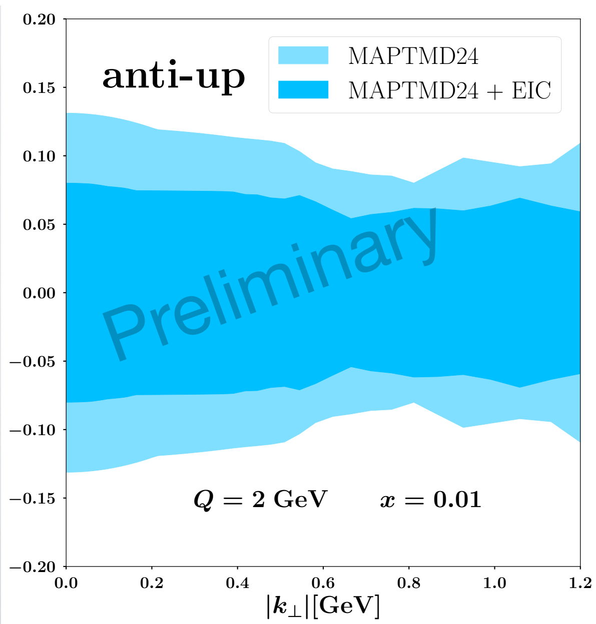

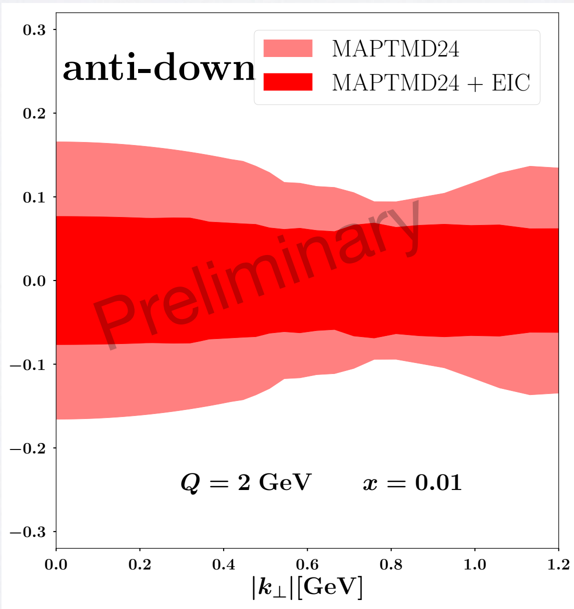

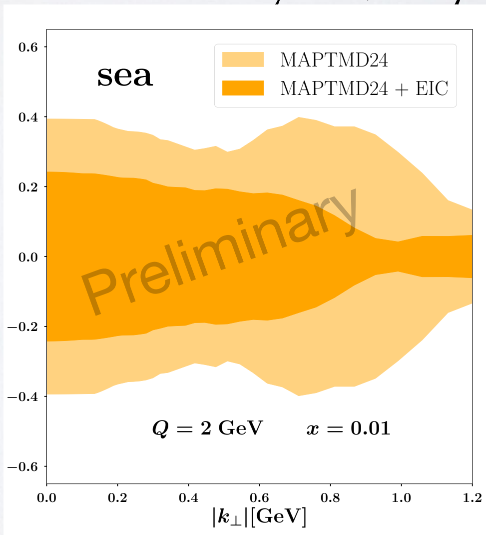

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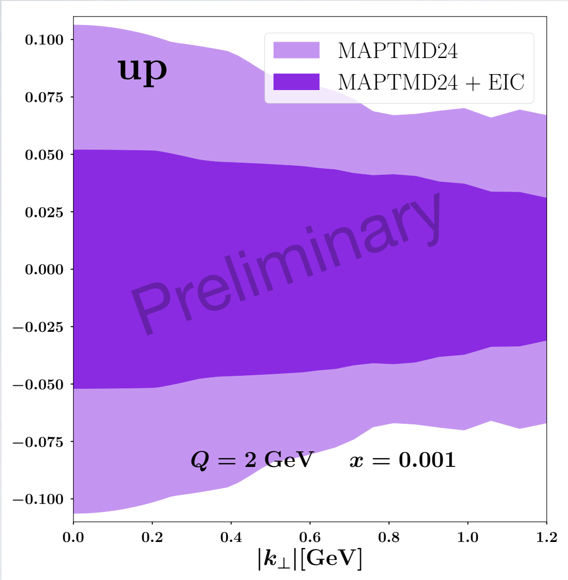
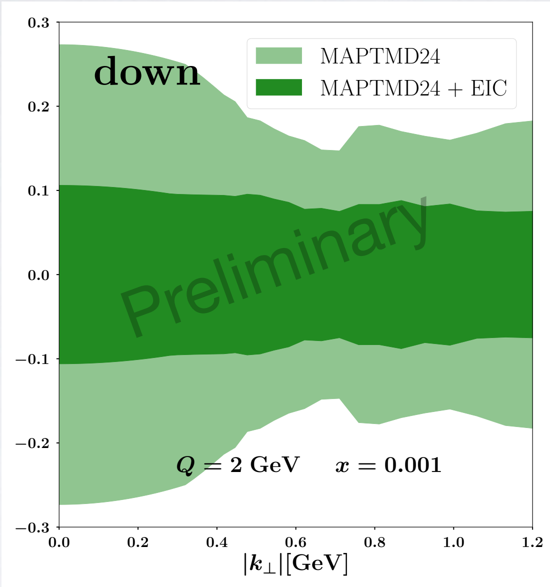
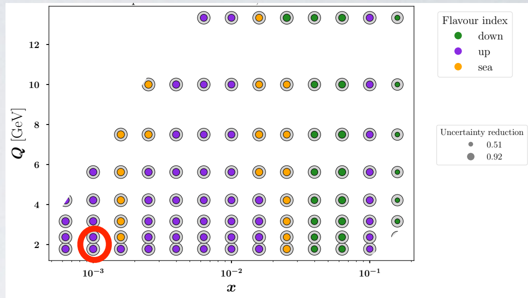
The EIC impact at x=0.001, Q=2 GeV





x=0.001 Q=2 GeV



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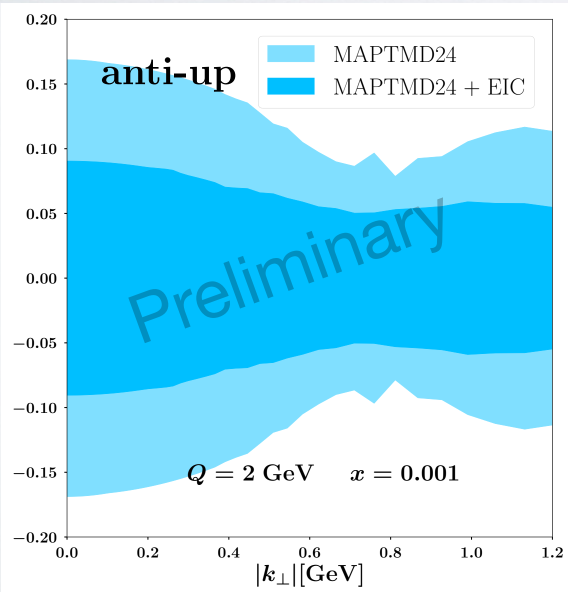

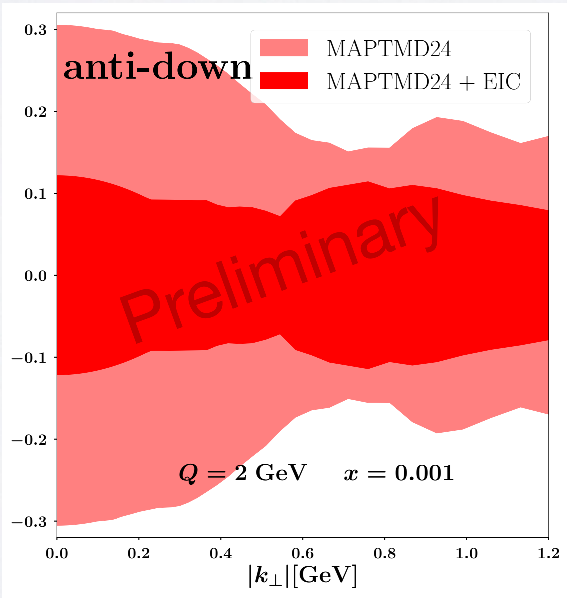

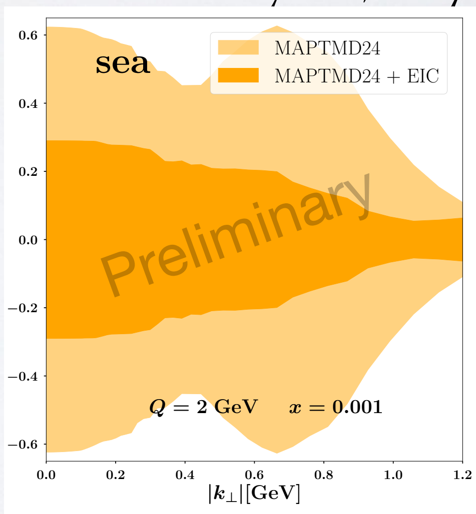

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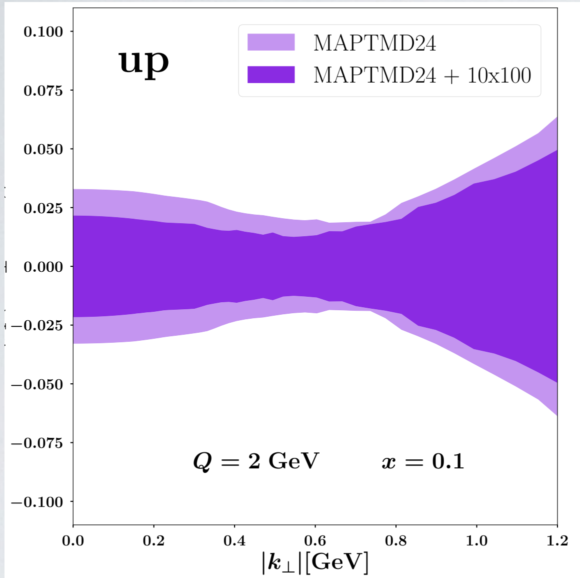
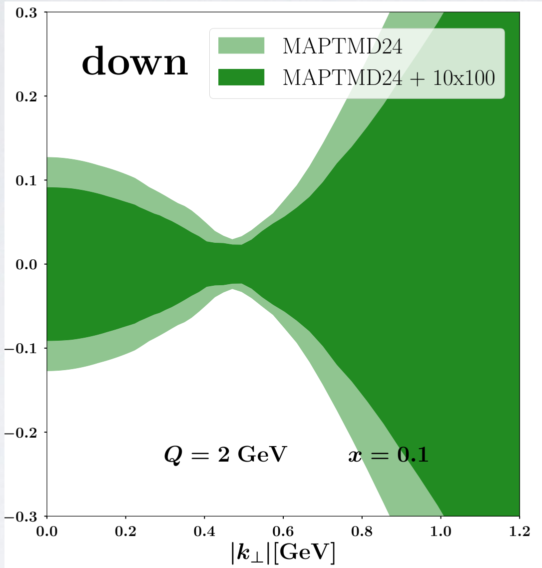
The EIC impact with 10x100 at x=0.1, Q=2 GeV



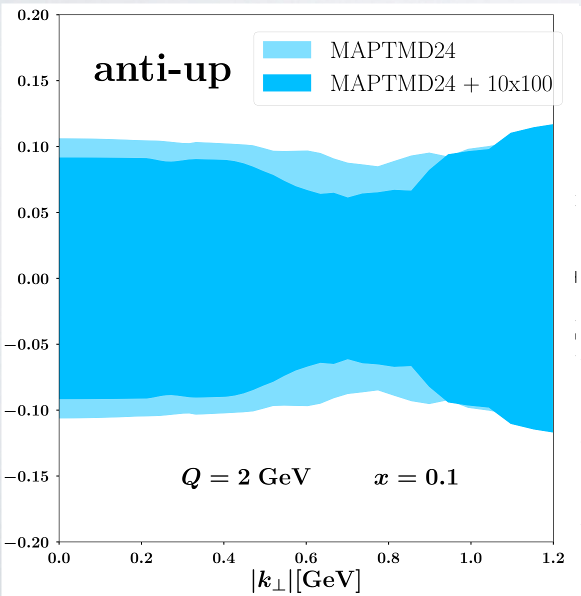


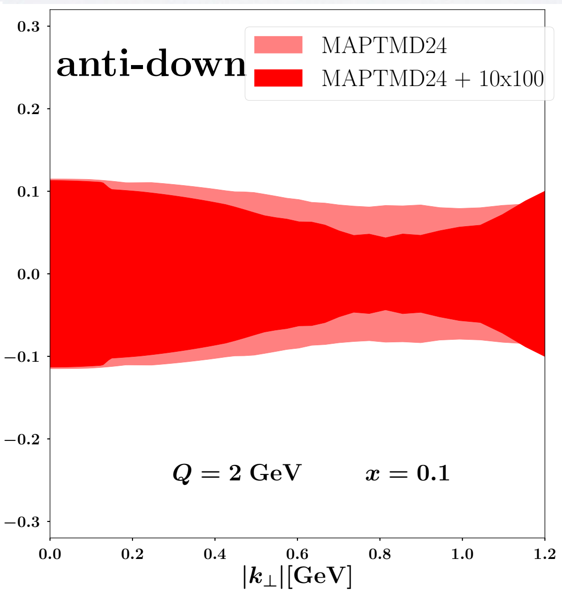
$$\frac{\text{TMD}^q - \langle\text{TMD}^q\rangle}{\langle\text{TMD}^q\rangle}$$

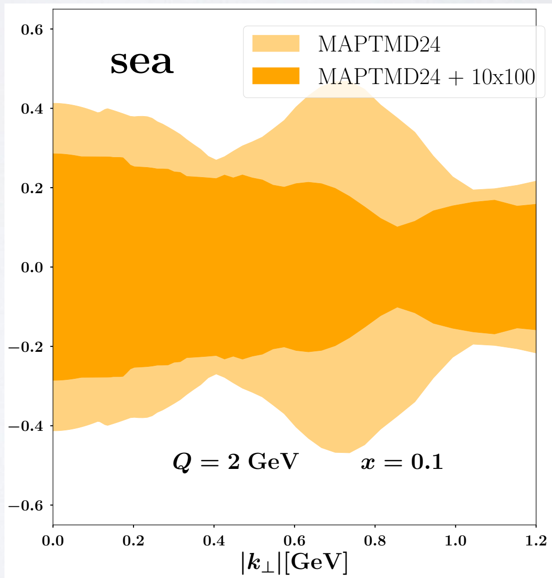
x=0.1

MAPTMD24	2031	
EIC	**# pts.**	**lumi [fb^{-1}]**
10x100	1611	51.3

(simulation campaign of May 2024)







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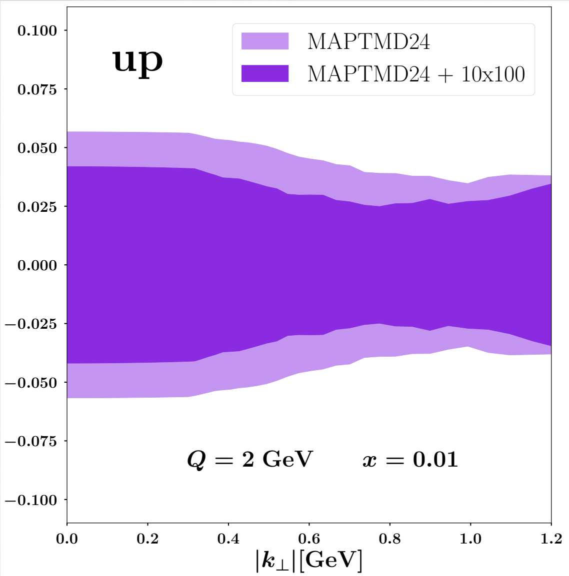
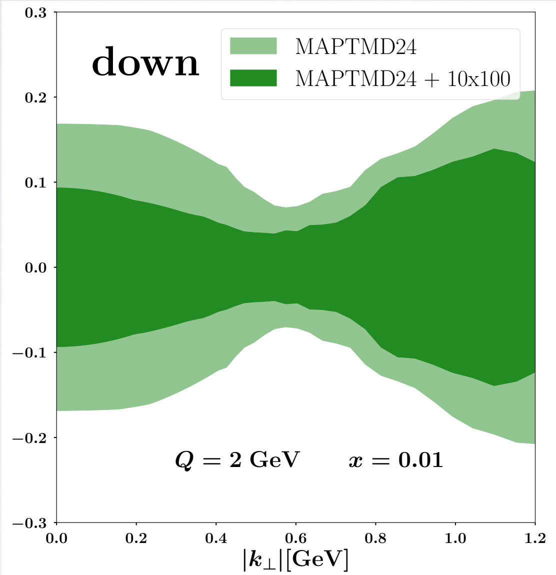
The EIC impact with 10x100 at x=0.01, Q=2 GeV





$$\frac{\text{TMD}^q - \langle\text{TMD}^q\rangle}{\langle\text{TMD}^q\rangle}$$

x=0.01

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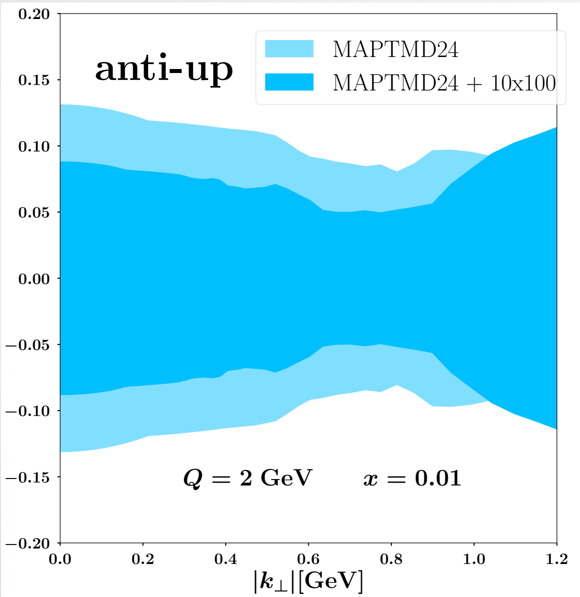
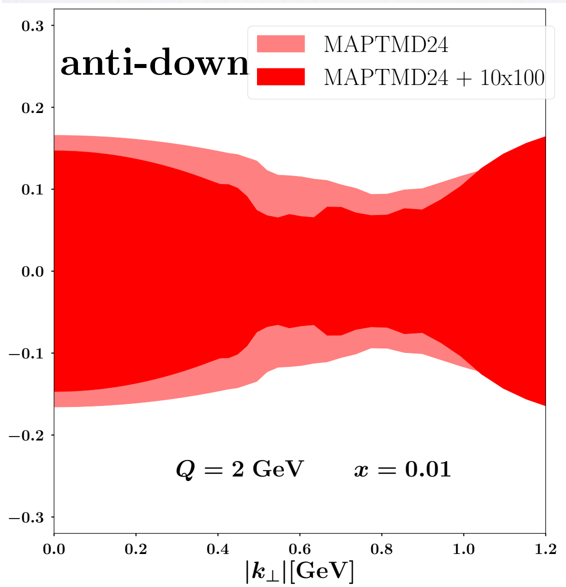
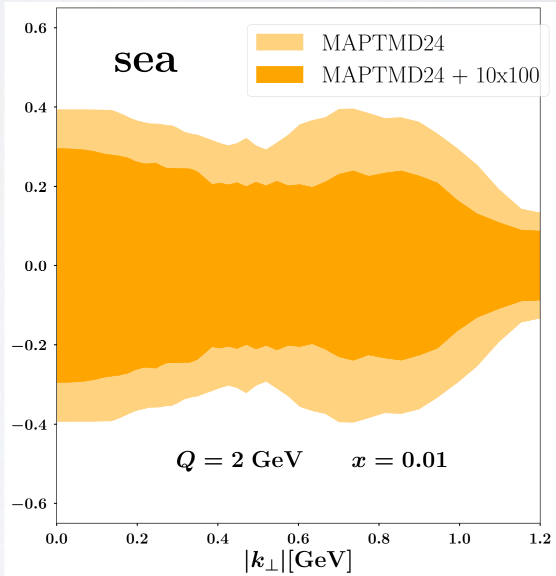
(simulation campaign of May 2024)







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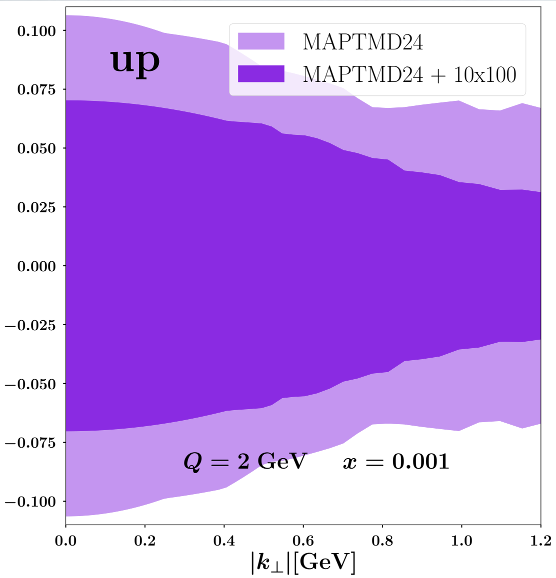
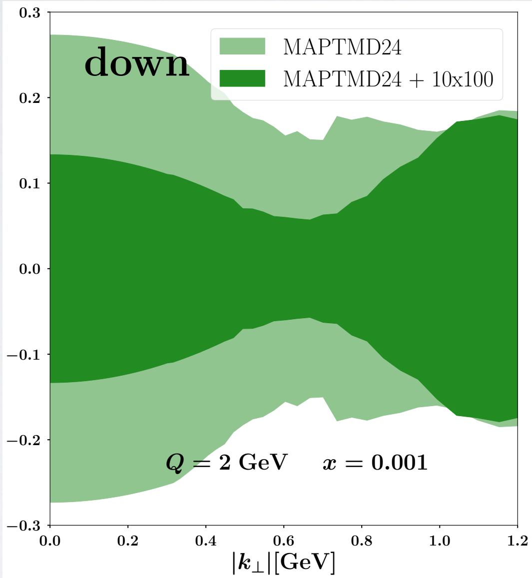
The EIC impact with 10x100 at x=0.001, Q=2 GeV





$$\frac{\text{TMD}^q - \langle \text{TMD}^q \rangle}{\langle \text{TMD}^q \rangle} \quad \mathbf{x=0.001}$$

MAPTMD24	2031	
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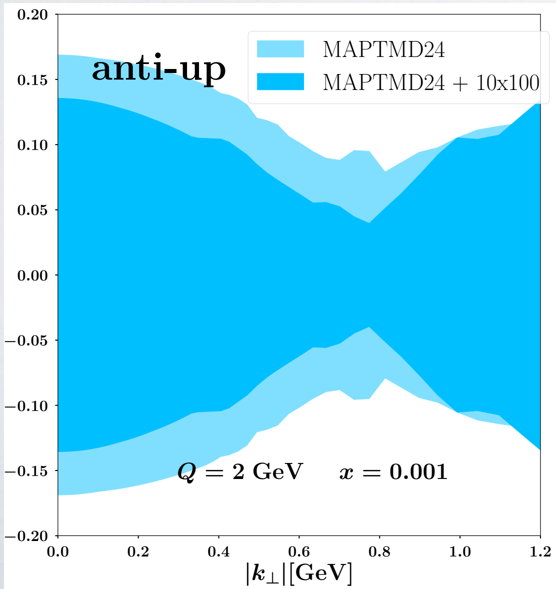

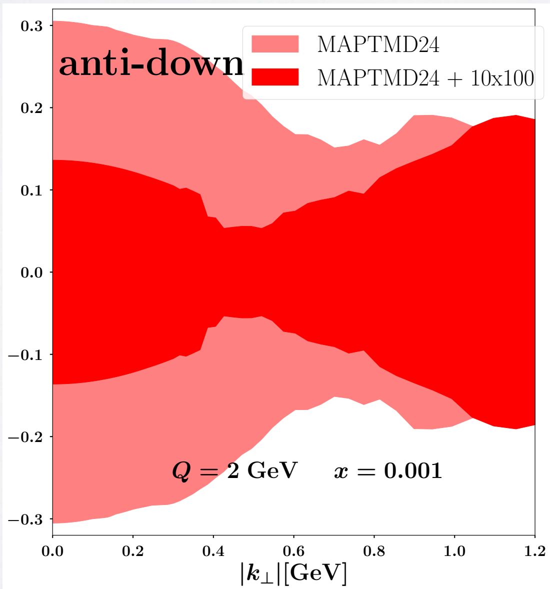

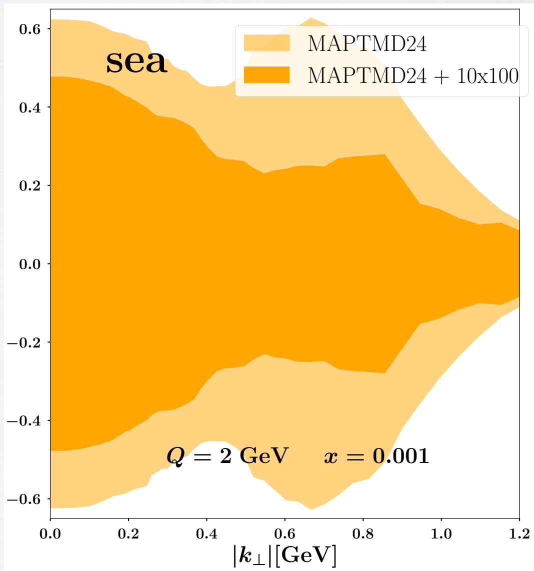

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Evolution of TMDs

$$\frac{d\sigma}{dx\,dz\,dq_T\,dQ} \sim \mathcal{H}^{\rm SIDIS}(Q^2)\,\frac{1}{2\pi}\int_0^\infty db_T\, b_T\, J_0(b_T, q_T)\ \tilde{f}_1^q(x, b_T^2; Q, Q^2)\ \tilde{D}_1^{q\to h}(z, b_T^2; Q, Q^2)$$

$$\tilde{f}_1^q(x, b_T^2; \mu_f, \zeta_f) = \exp\left[\int_{\mu_{b_*}}^{\mu_f}\frac{d\mu}{\mu}\left(\gamma_F - \gamma_K \log\frac{\sqrt{\zeta_f}}{\mu}\right)\right] \exp\left[K(b_*, \mu_b)\log\frac{\sqrt{\zeta_f}}{\mu_b}\right] \times \exp\left[g_K(b_T)\log\frac{\sqrt{\zeta_f}}{Q_0}\right] f_{\rm NP}(x, b_T)$$

$$\times \sum_i \left[C_{qi}(x, b_*; \mu_b, \mu_b^2)\otimes f_1^i(x, \mu_b)\right]$$

similar formula for $\tilde{D}_1^{q\to h}$

perturbative α_S^n

accuracy	$\mathcal{H}$ and C	K and γ_F	γ_K	PDF and α_S	FF
LL	0	-	1	-	-
NLL	0	1	2	LO	LO
NLL'	1	1	2	NLO	NLO
NNLL	1	2	3	NLO	NLO
NNLL'	2	2	3	NNLO	NNLO
N^3LL(-)	2	3	4	NNLO	NLO
N^3LL	2	3	4	NNLO	NNLO
N^3LL'	3	3 4	5	N^3LO	N^3LO
N^4LL(-)	3	3 4	5	N^3LO	NNLO
N^4LL	3	3 4	5	N^3LO	N^3LO

Errors Analysis

bootstrap method: fitting M replicas of fluctuated exp. data

=> extract M TMDs

complete statistical information is contained in the set of all M TMDs, but

quality indicator: χ_0^2 of *central* replica (fitting not unfluctuated data)

$\chi_0^2 \sim \langle \chi^2 \rangle_{\text{replicas}}$

include exp. / th. errors **uncorrelated** and **correlated**

$$\chi^2 = \chi_D^2 + \chi_\lambda^2$$

penalty for correlated errors

$$\sum_{\text{bins}} \left(\frac{\text{exp} - \overline{\text{th}}}{\sigma} \right)^2$$

$$\sigma^2 = \sigma_{\text{stat}}^2 + \sigma_{\text{uncorr}}^2$$

$$\overline{\text{th}} = \text{th} + \sum_\alpha \lambda_\alpha \sigma_{\text{corr}}^{(\alpha)}$$

$$\chi_\lambda^2 = \sum_\alpha \lambda_\alpha^2$$

nuisance params.

propagate (correlated) th. errors from PDFs & FFs using the whole Monte Carlo set of PDF = NNPDF3.1 & FF = MAPFF1.0

quality of MAPTMD24:

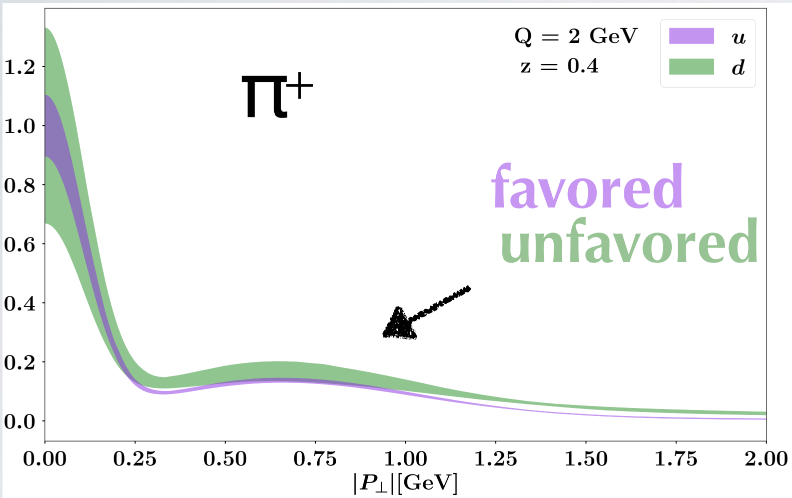
nonperturbative precision $N = 2031$, $\chi_0^2/N = 1.08$

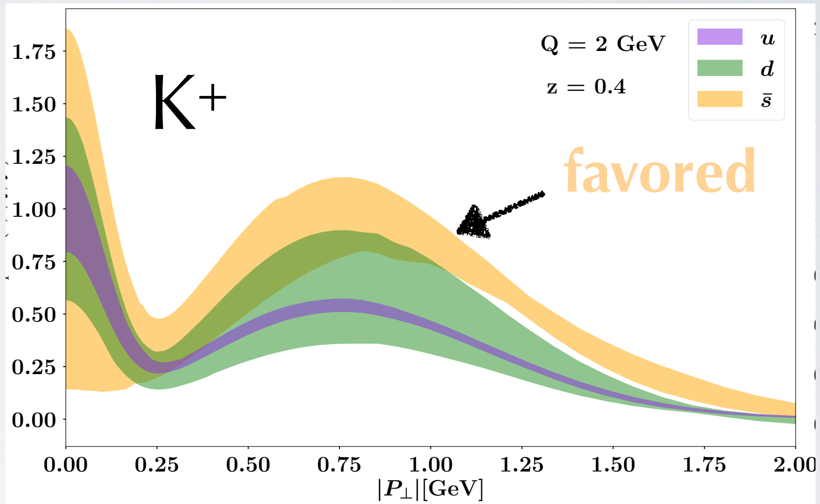
perturbative accuracy N³LL + NNLO

"Normalized" MAPTMD24 TMD FF

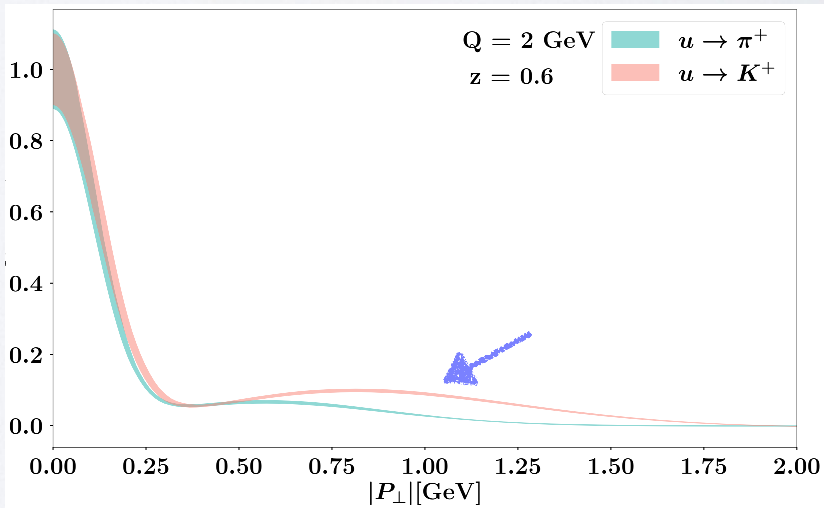
$$\frac{D_1(z,P_T;Q)}{D_1(z,0;Q)}$$

Bacchetta et al. (MAP), JHEP **08** (24) 232, arXiv:2405.13833





- favored better constrained than unfavored
- signs of favored ≠ unfavored



- evidence of final-hadron dependence