Uncovering New Dimensions with Transverse Momentum Physics at the EIC

Iain Stewart

MIT & U.Vienna

Uncovering New Laws of Nature at the EIC

Brookhaven National Lab, NY

November 22, 2024

Massachusetts Institute of Technology

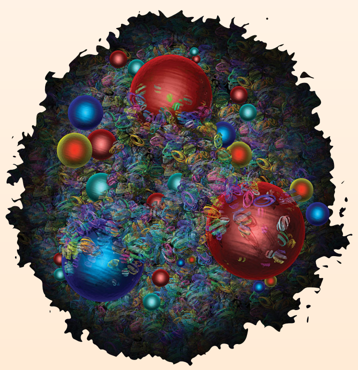
universität wien

QCD is the richest known QFT

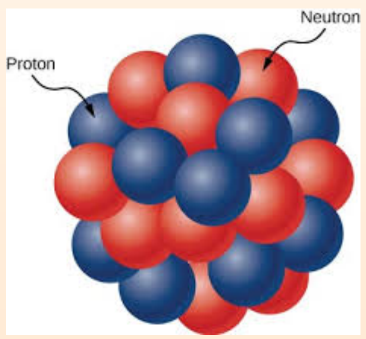
$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \bar{\psi}_i (i\not{D} - m_i)\psi_i$$

Responsible for a plethora of interesting states, phenomena, and fields of physics

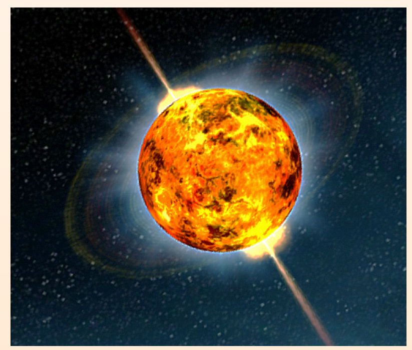
Hadrons



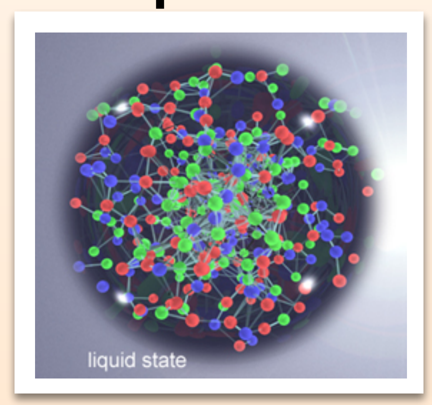
Nuclei



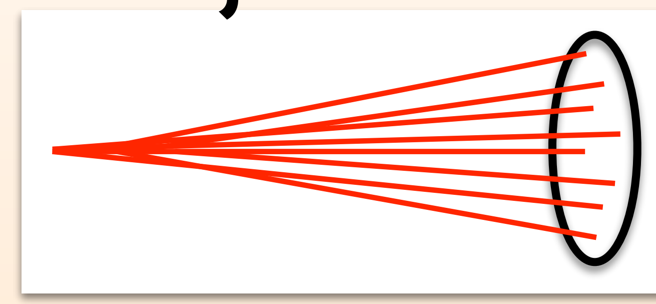
Neutron stars



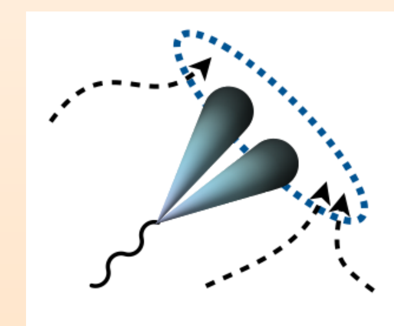
Quark-gluon plasma



jets



jet substructure



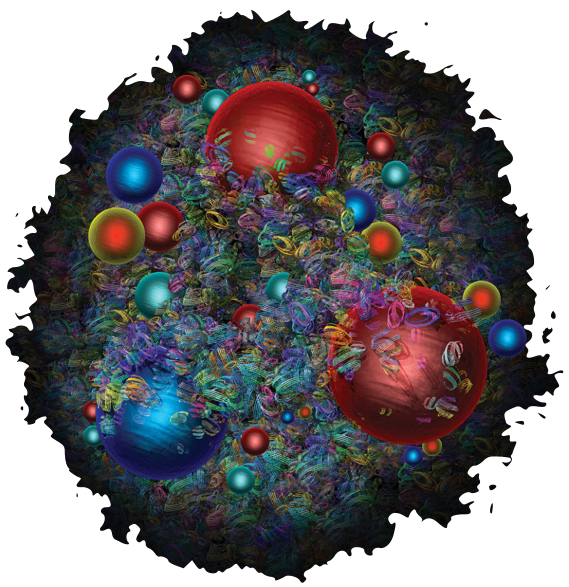
- Asymptotic Freedom
- Confinement
- Chiral Symmetry breaking, pions
- QCD phases and phase transitions
- Non-relativistic confined quarks $Q\bar{Q}$
- Exotic bound states, X, T, Z …
- large Nc

…

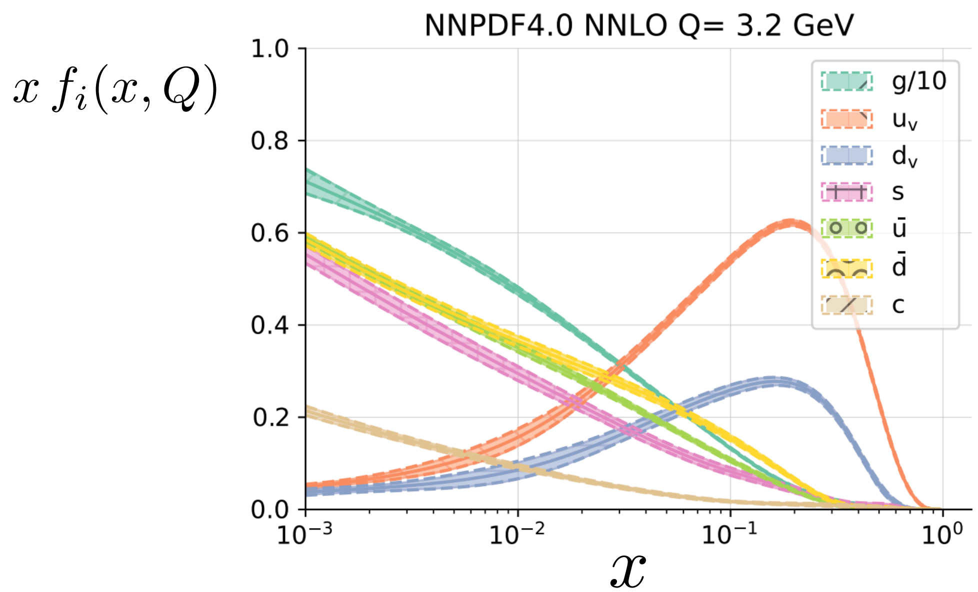
- Collider physics
- Factorization & Resummation
- Gluon saturation
- Multiloop QFT, Amplitudes
- Flavor physics
- Lattice QCD
- Models

…

Unravelling the Mysteries of Relativistic Hadronic Bound States



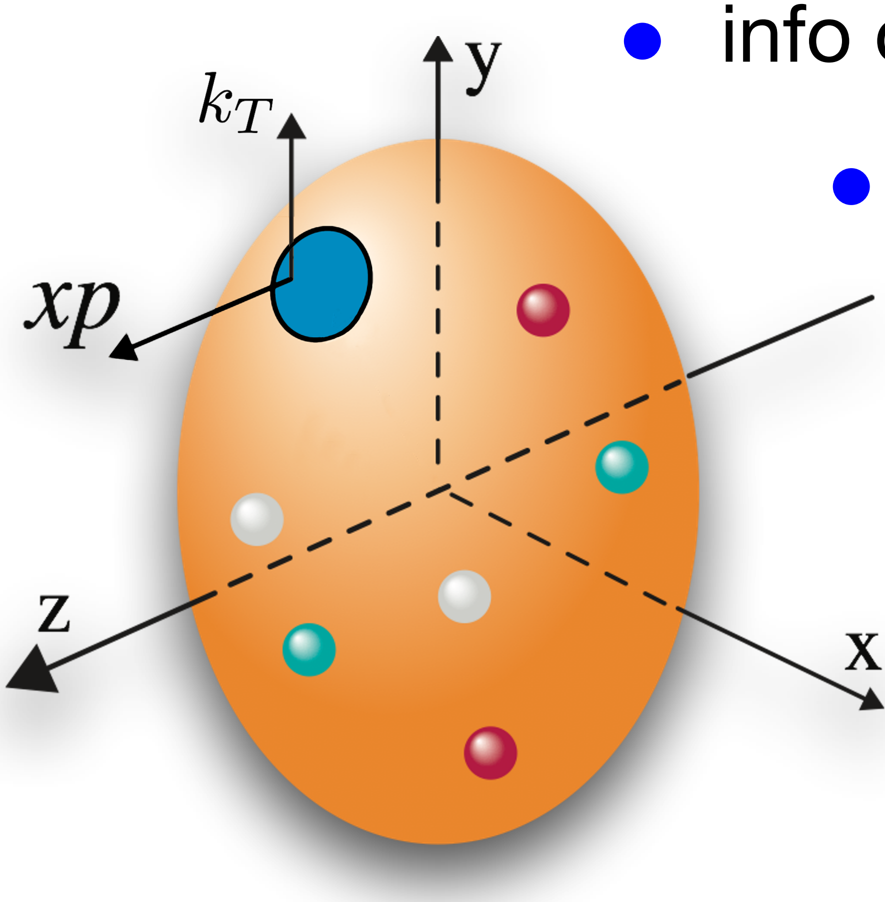
- Parton distributions provide useful snapshots



1D image of the confined constituents

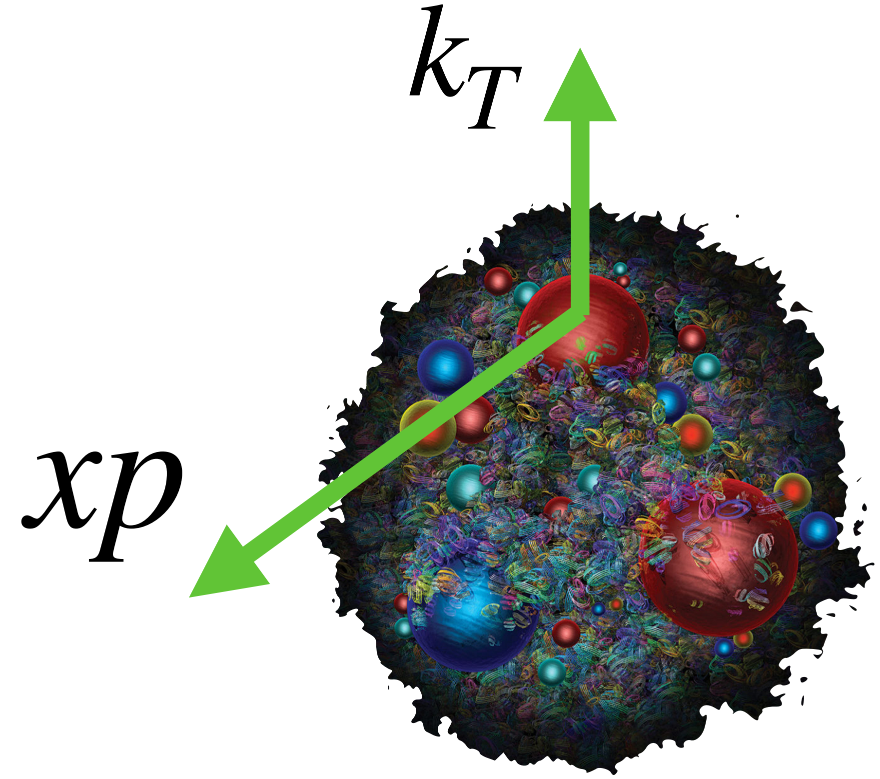
we know how image changes with $\mu^2 = Q^2$

- $f(x, k_T)$ Transverse Momentum Dependent distributions (TMDs) provide:
  - info on dynamics of hadronization (frag. functions)
  - microscope for the proton's **"fine-structure"**
  - key component for precision collider physics (Higgs q_T, Drell-Yan q_T , …)
  - quantum correlations inside the proton
  - access to **"new dimensions"**



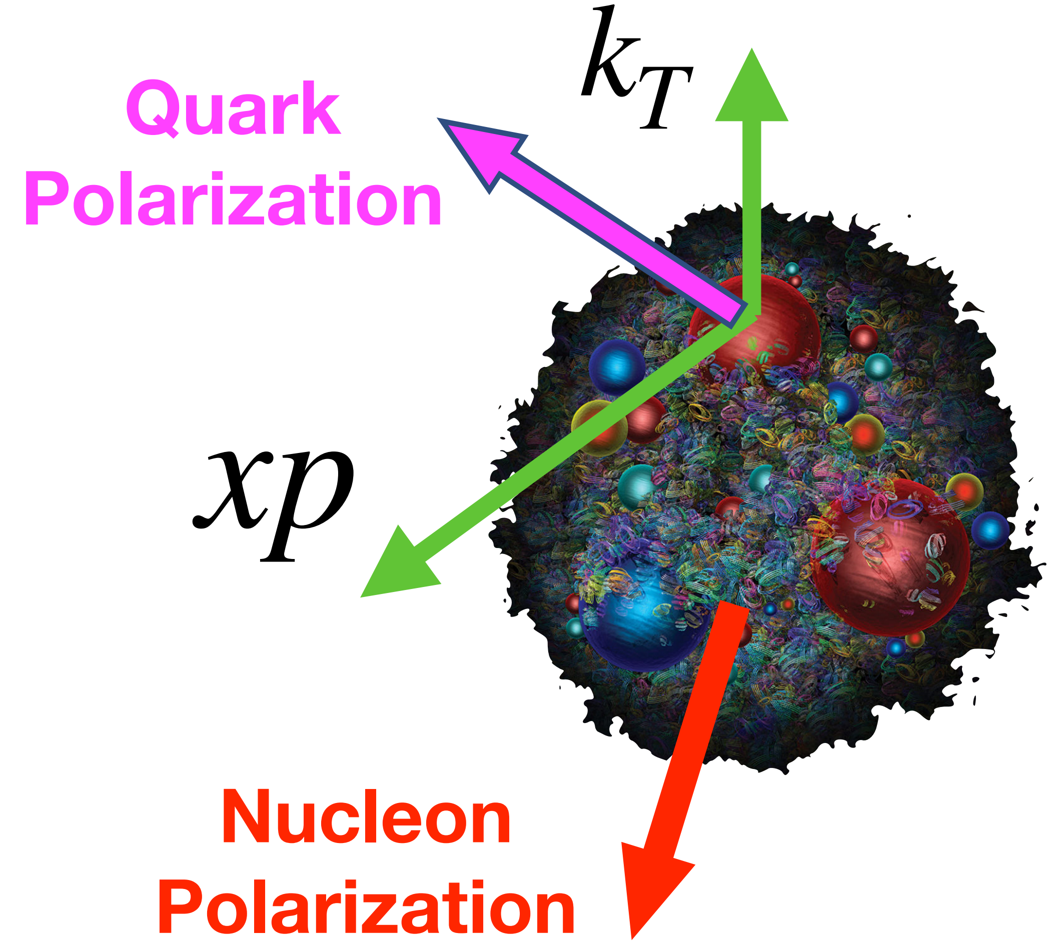
New Dimensions

- 1D $\rightarrow$ 3D imaging



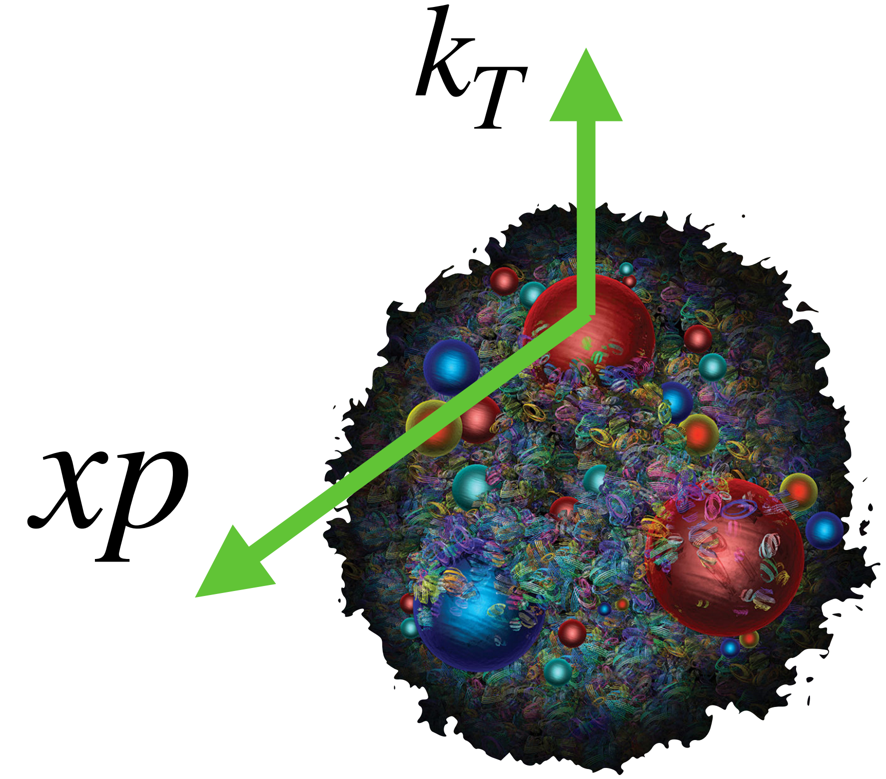
New Dimensions

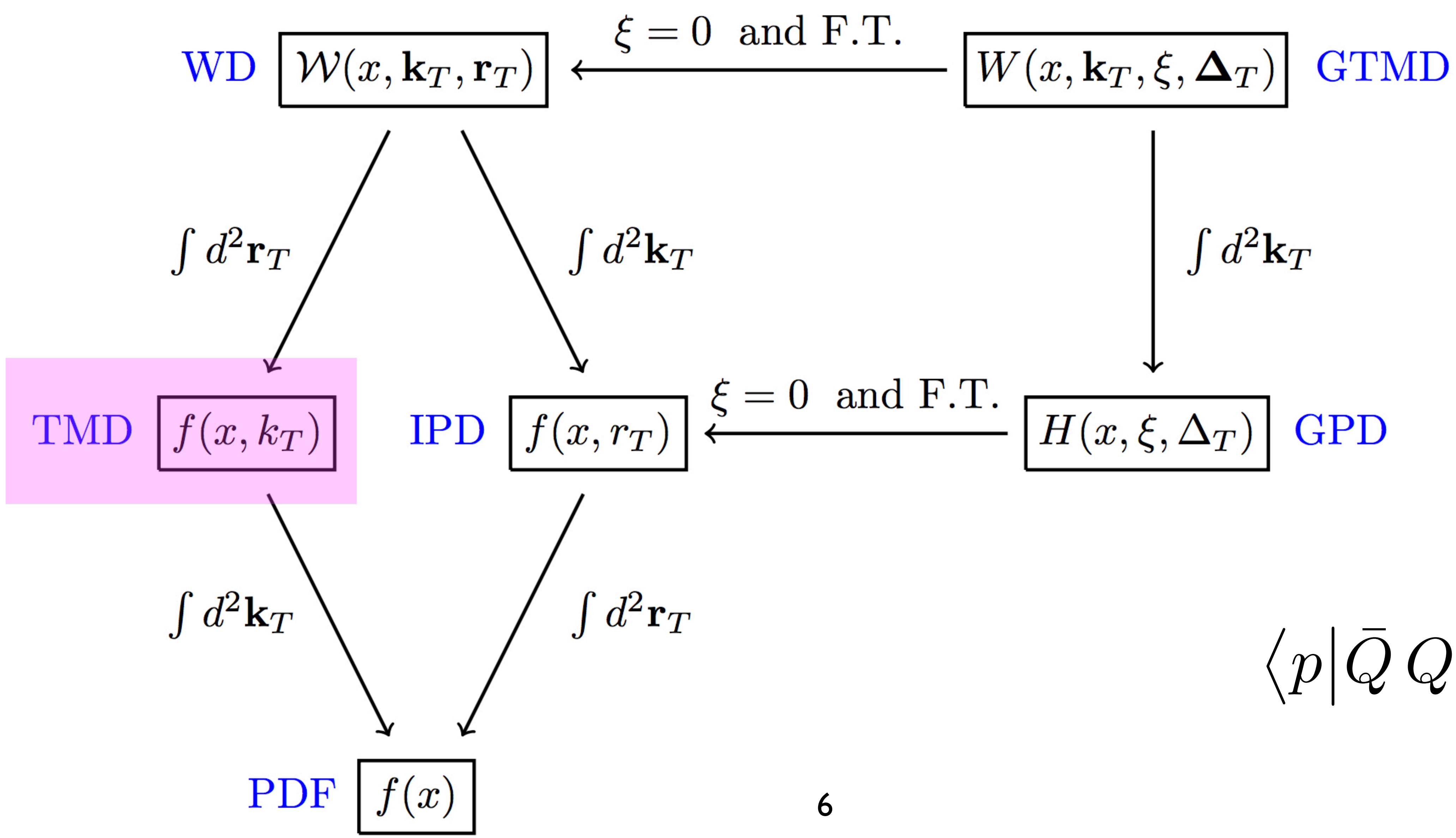
- 1D → 3D imaging
- Spin-kT correlations
  (8 leading TMDs for each of
  q or g and PDF or FF)



New Dimensions

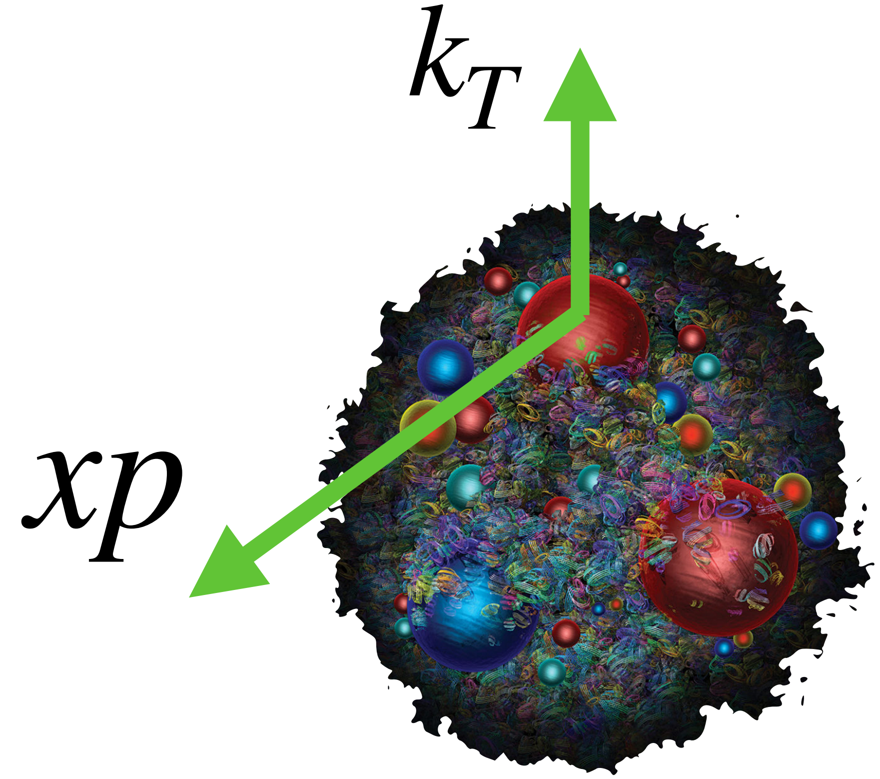
- 1D → 3D imaging
- Spin-kT correlations
  (8 leading TMDs)
- TMDs are part of a larger family





$$\langle p | \bar{Q}\, Q | p \rangle$$

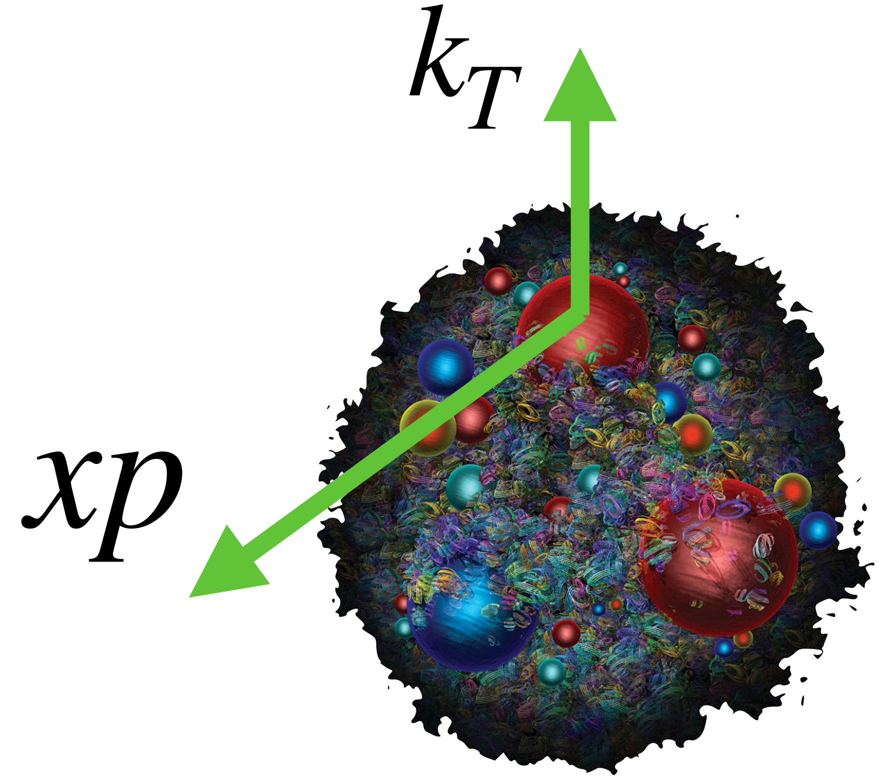
New Dimensions



- 1D → 3D imaging
- Spin-kT correlations
  (8 leading TMDs)
- TMDs are part of a larger family
- Most prominent among many quantum TMD correlators

leading TMDs	$\langle p \vert \bar{Q}\, Q \vert p \rangle$
next-to-leading TMDs	$\langle p \vert \bar{Q}\, G\, Q \vert p \rangle \quad \langle p \vert G\, G\, G \vert p \rangle$
N^2-leading TMDs	$\langle p \vert \bar{Q}\, Q\, \bar{Q}\, Q \vert p \rangle \quad \langle p \vert \bar{Q}\, G\, G\, Q \vert p \rangle \quad \cdots$
⋮	

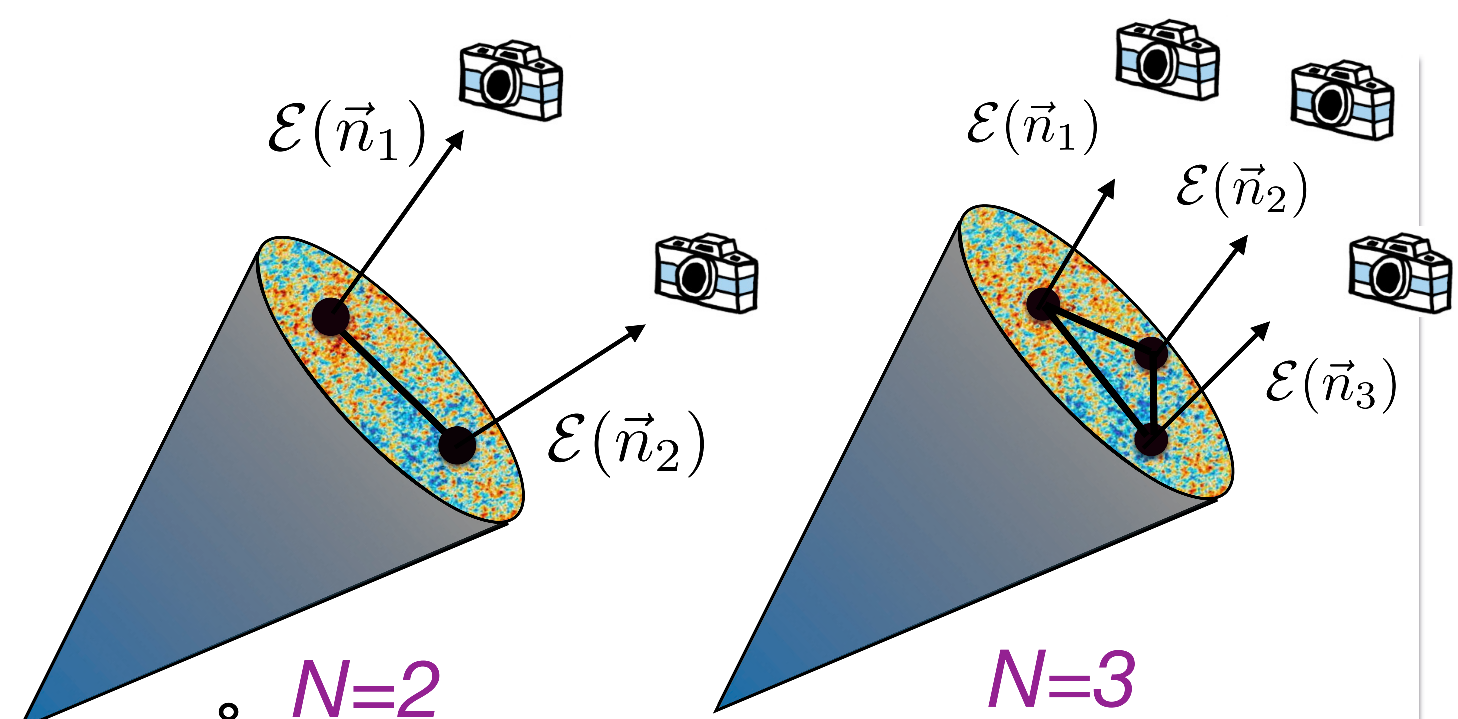
New Dimensions



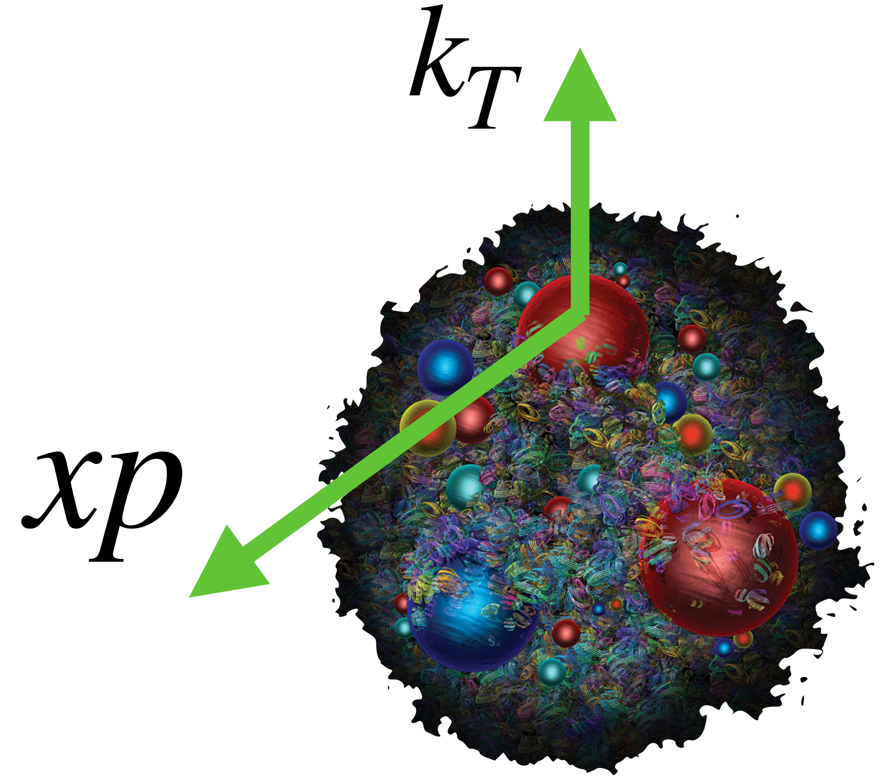
- 1D → 3D imaging
- Spin-kT correlations
(8 leading TMDs)
- TMDs are part of a larger family
- Most prominent among many quantum TMD correlators
- Connected to other interesting observables

Energy Correlators (ENC)

$$d\sigma \propto \langle O^\dagger \mathcal{E}(\vec{n}_1) \cdots \mathcal{E}(\vec{n}_N) O \rangle$$



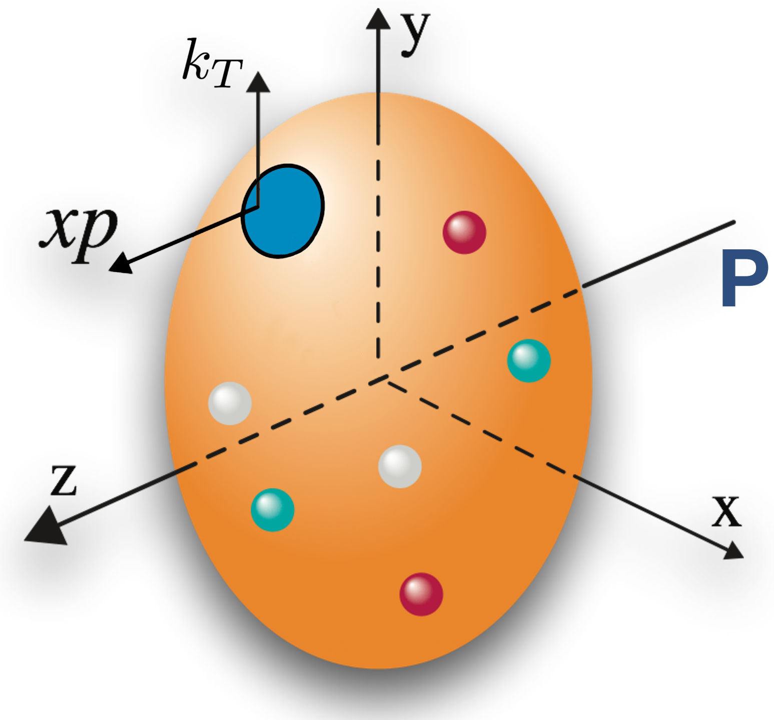
New Dimensions



- $1D \rightarrow 3D$ imaging
- Spin-kT correlations
  (8 leading TMDs)
- TMDs are part of a larger family
- Most prominent among many quantum TMD correlators
- Connected to other interesting species
- And to interesting phenomena
  eg. saturation, final-state interactions, fact. violation

Key Targets for EIC

TMDs



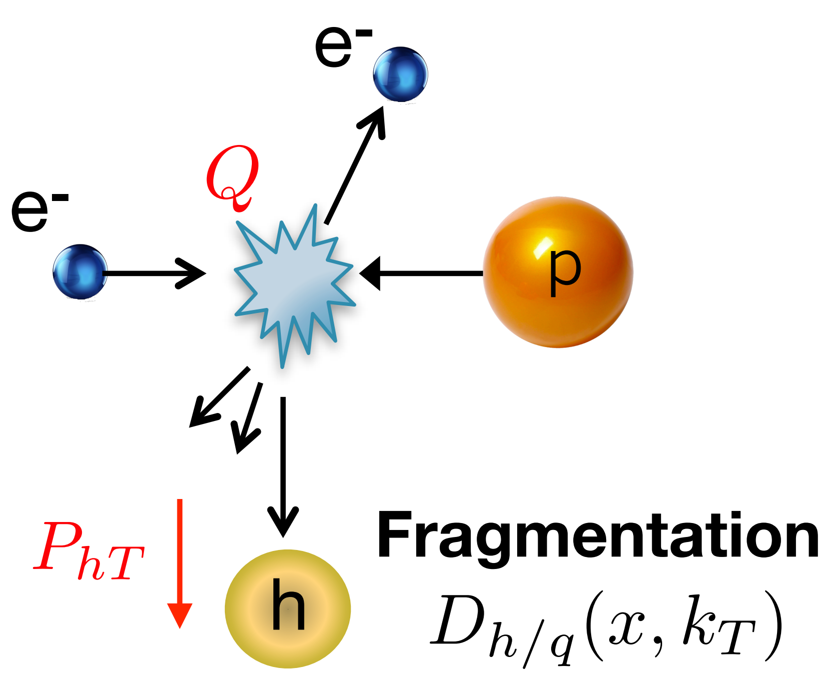
3D momentum distributions

PDF $f_{q/P}(x, \vec{k}_T, \mu, \zeta)$ **of confined partons**

FF $D_{\pi/q}(x, \vec{k}_T, \mu, \zeta)$ **of hadronizing partons**

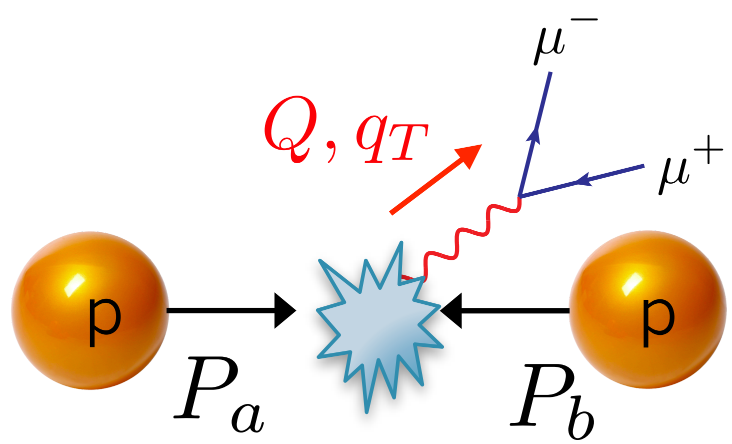
Semi-Inclusive DIS

$\sigma \sim f_{q/P}(x, k_T) D_{h/q}(x, k_T)$



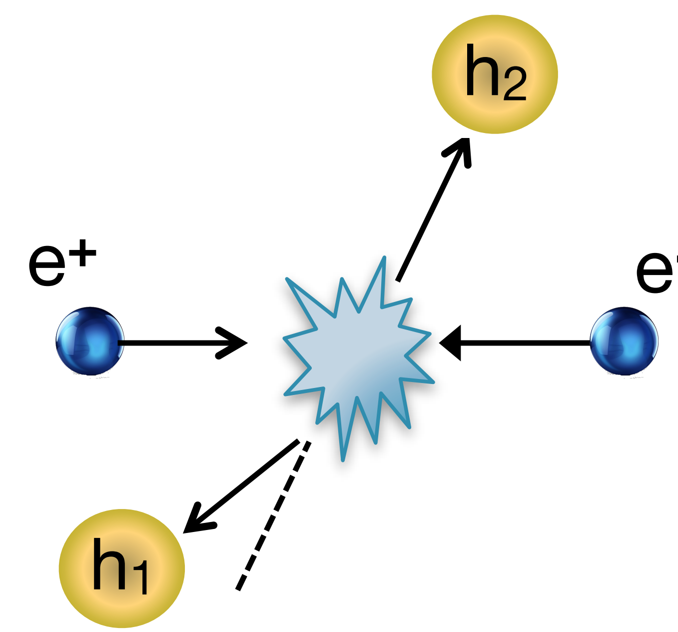
Drell-Yan

$\sigma \sim f_{q/P}(x, k_T) f_{q/P}(x, k_T)$



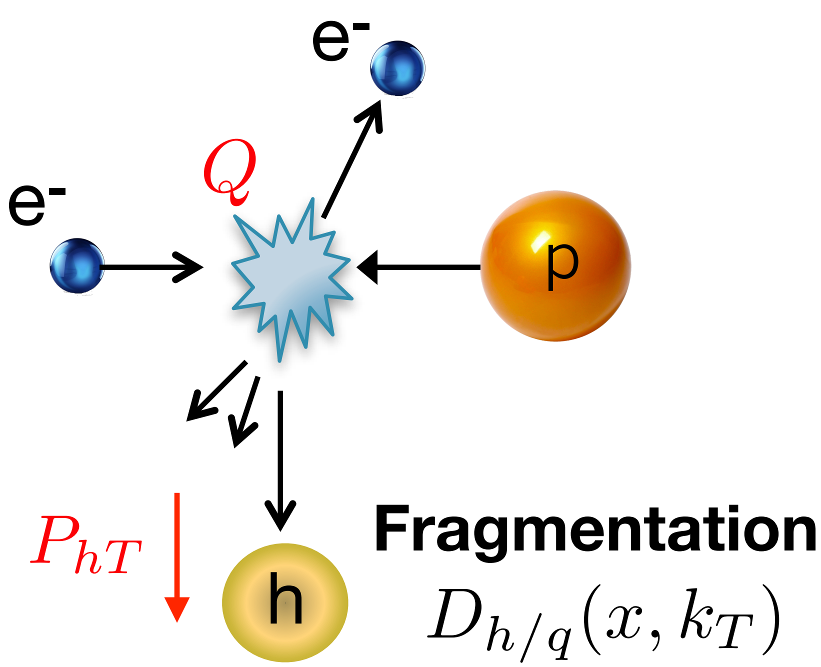
Dihadron in e+e-

$\sigma \sim D_{h_1/q}(x, k_T) D_{h_2/q}(x, k_T)$



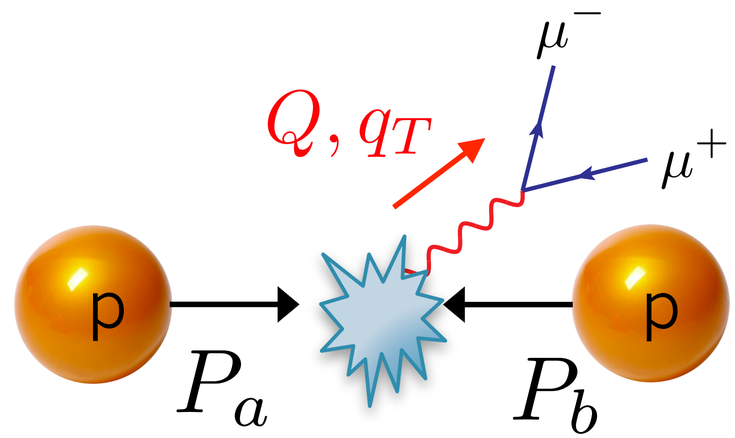
Semi-Inclusive DIS

$$\sigma \sim f_{q/P}(x, k_T) D_{h/q}(x, k_T)$$



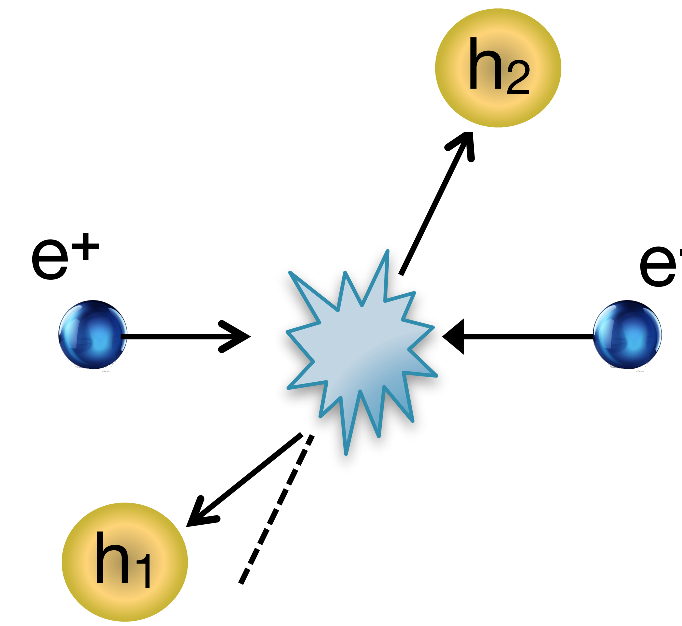
Drell-Yan

$$\sigma \sim f_{q/P}(x, k_T) f_{q/P}(x, k_T)$$



Dihadron in e+e-

$$\sigma \sim D_{h_1/q}(x, k_T) D_{h_2/q}(x, k_T)$$



Two Scale probe: Q, q_T

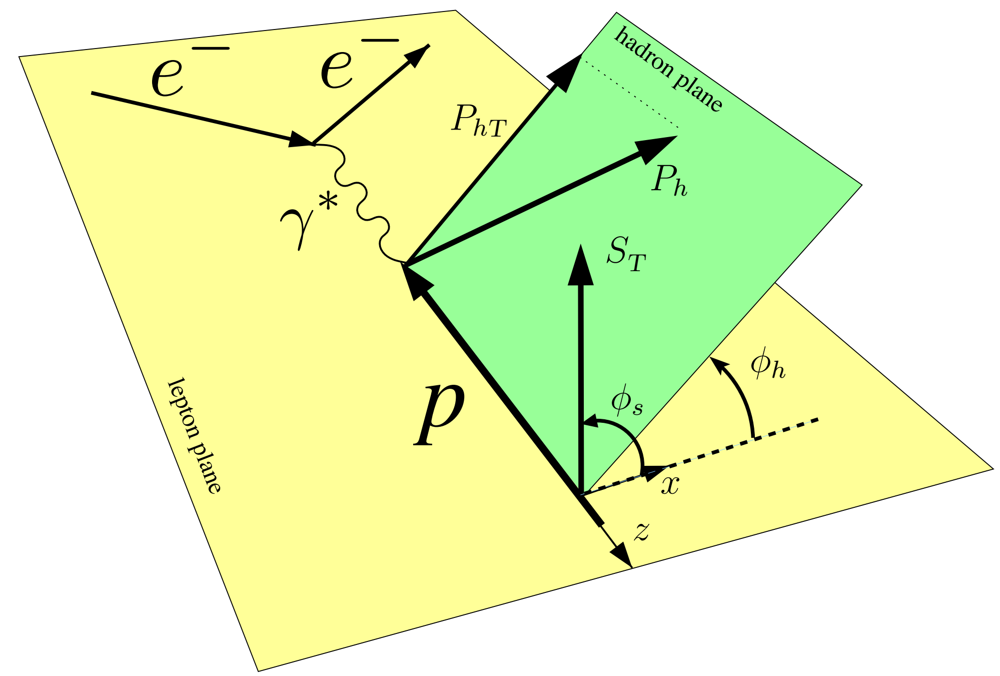
$Q, q_T \gg \Lambda_{\rm QCD}$	collinear factorization (1D)
$Q \gg q_T \sim \Lambda_{\rm QCD}$	TMD factorization (3D)
$Q \gg q_T \gg \Lambda_{\rm QCD}$	TMD (& collinear) factorization

$$f(x, k_T) = C\left(\frac{x}{\xi}, k_T\right) \otimes f(\xi) + \ldots$$

Observables (leading order in $q_T \ll Q$)

SIDIS with polarized electron & proton: $e^- p \xrightarrow{\gamma^*} e^- h X$

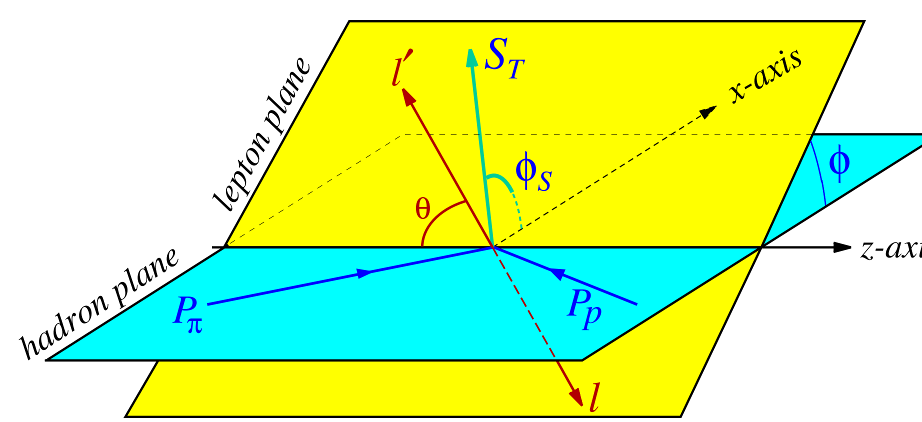
$$\frac{d^6\sigma}{dx_B\, dy\, dz_h\, d\phi_S\, d\phi_h\, dP_{hT}^2} = \frac{\alpha_{em}^2}{x_B\, y\, Q^2}\left(1 - y + \frac{1}{2}y^2\right)\Big[F_{UU,T} + \cos(2\phi_h)\, p_1\, F_{UU}^{\cos(2\phi_h)}$$
$$+ S_L \sin(2\phi_h)\, p_1\, F_{UL}^{\sin(2\phi_h)} + S_L\, \lambda p_2\, F_{LL}$$
$$+ S_T \sin(\phi_h - \phi_S)\, F_{UT,T}^{\sin(\phi_h-\phi_S)}$$
$$+ S_T \sin(\phi_h + \phi_S)\, p_1\, F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \lambda\, S_T \cos(\phi_h - \phi_S)\, p_2\, F_{LT}^{\cos(\phi_h-\phi_S)}$$
$$+ S_T \sin(3\phi_h - \phi_S)\, p_1\, F_{UT}^{\sin(3\phi_h-\phi_S)}\Big]$$



TMDPDFs * TMDFFs: $f_{1,p} D_{1,h},\ h_{1,p}^{\perp} H_{1,h}^{\perp},\ \ldots$

Drell-Yan with pol. proton: $\pi p \xrightarrow{\gamma^*} \ell^+ \ell^- X$

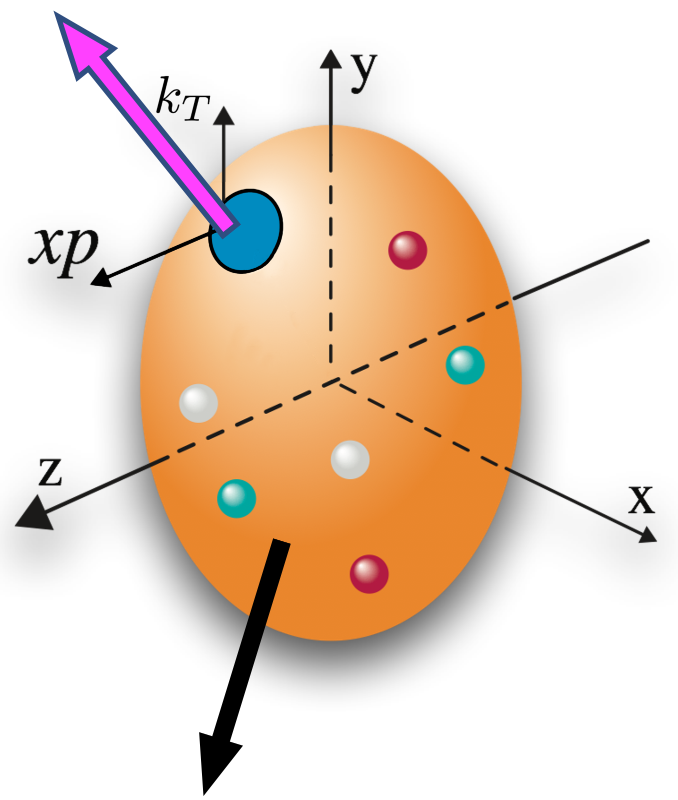
$$\frac{d\sigma}{d^4q\, d\Omega} = \frac{\alpha_{em}^2}{F\, Q^2}\Big\{\Big[(1 + \cos^2\theta) F_{UU}^1 + \sin^2\theta \cos(2\phi) F_{UU}^{\cos 2\phi}\Big] + \ldots\Big\}$$



products of TMDPDFs: $f_{1,\pi} f_{1,p},\ h_{1,\pi}^{\perp} h_{1,p}^{\perp},\ \ldots$

TMDs with Polarization

Quark Polarization Γ



Nucleon Polarization

$S_L, \vec{S}_T$

Leading Quark TMDPDFs (○→ Nucleon Spin; ⊙→ Quark Spin)

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	f_1 = Unpolarized		$h_1^\perp$ = − Boer-Mulders
	L		g_1 = − Helicity	$h_{1L}^\perp$ = − Worm-gear
	T	$f_{1T}^\perp$ = − Sivers	$g_{1T}^\perp$ = − Worm-gear	h_1 = − Transversity $h_{1T}^\perp$ = − Pretzelosity

8 different TMDs which encode spin-momentum correlations

eg. $$f_i^{[\gamma^+]}(x,\vec{k}_T) = f_1(x,k_T) - \frac{\epsilon_T^{\rho\sigma} k_{T\rho} S_{T\sigma}}{M} f_{1T}^\perp(x,k_T)$$

Field Theory

- **Rigorous Factorization Theorems** Cross Sections ⟷ TMDs

$$\frac{d\sigma}{dQ\,dY\,dq_T^2} = H(Q,\mu)\int d^2\vec{b}_T\, e^{i\vec{q}_T\cdot\vec{b}_T}\, f_q(x_a,\vec{b}_T,\mu,\zeta_a)\, f_q(x_b,\vec{b}_T,\mu,\zeta_b)\Big[1+\mathcal{O}\Big(\frac{q_T^2}{Q^2}\Big)\Big]$$

CSS (Collins, Soper, Sterman)

SCET (Soft Collinear Effective Theory)

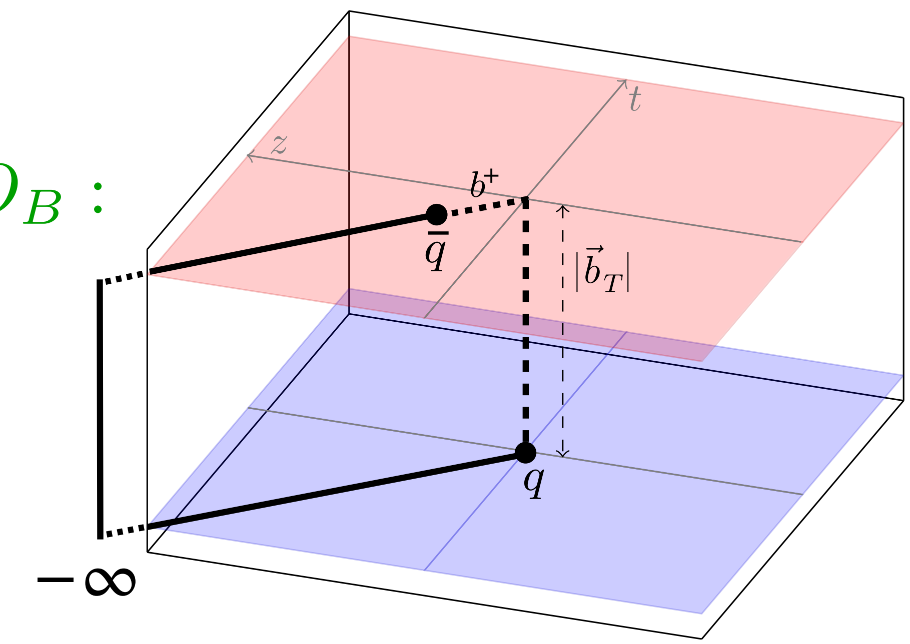
- **TMD Definitions** (constructions & schemes)

→ full understanding now available

$$f_q(x,\vec{b}_T,\mu,\zeta) \sim Z_{\rm uv}\langle p|O_B|p\rangle \Big/ \sqrt{\langle 0|O_S|0\rangle}$$

→ tractable methods with **Lattice QCD**

O_B :



- **Universality** same TMDs in DY, SIDIS, e^+e^-

<u>but</u> with sign flip for Sivers and Boer-Mulders:

$$f_{1T}^{\perp\,\rm SIDIS} = -f_{1T}^{\perp\,\rm DY}$$

$$h_1^{\perp\,\rm SIDIS} = -h_1^{\perp\,\rm DY}$$

Brodsky-Huang-Schmidt; Collins, …

directly probes final/initial state interactions with "spectator" partons in the proton!

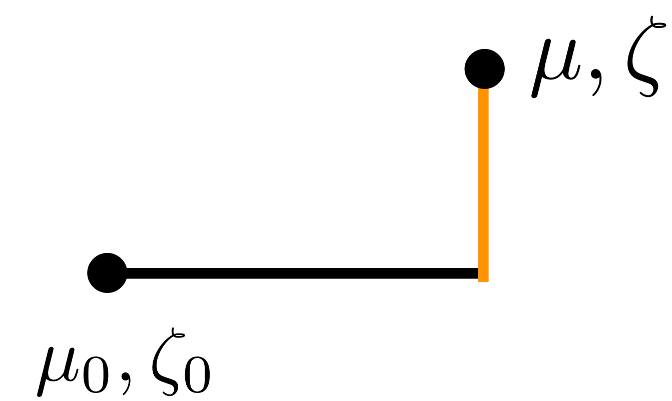
Field Theory

- **Evolution**

$$\color{red}{f_q(x, \vec{b}_T, \mu, \zeta)} = \exp\Big[\int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'} \gamma_\mu^q(\mu', \zeta_0)\Big] \exp\Big[\frac{1}{2}\color{orange}{\gamma_\zeta^q(\mu, b_T)} \ln\frac{\zeta}{\zeta_0}\Big] \; \color{blue}{f_q(x, \vec{b}_T, \mu_0, \zeta_0)}$$

CS kernel   Boundary condition

Sum large logarithms: $\ln(Q^2 b_T^2) \sim \ln\dfrac{Q^2}{q_T^2}$



Perturbative γ_i^q : Leading Log (LL) → Next-to-leading log (NLL) → NNLL → N^{3}LL → N^{4}LL

Nonperturbative γ_ζ^q : fit to data using models, or calculate with Lattice QCD

Field Theory

- **Evolution**

$$f_q(x,\vec{b}_T,\mu,\zeta) = \exp\left[\int_{\mu_0}^{\mu}\frac{d\mu'}{\mu'}\gamma_\mu^q(\mu',\zeta_0)\right]\exp\left[\frac{1}{2}\gamma_\zeta^q(\mu,b_T)\ln\frac{\zeta}{\zeta_0}\right] f_q(x,\vec{b}_T,\mu_0,\zeta_0)$$

CS kernel — Boundary condition

Perturbative γ_i^q : Leading Log (LL) → Next-to-leading log (NLL) → NNLL → N^3LL → N^4LL

Nonperturbative γ_ζ^q : fit to data using models, or calculate with Lattice QCD

- **Operator Product Expansion and (non)perturbative inputs**

$$f_{i/h}(x,b_T,\mu,\zeta) = f_{i/h}^{\rm pert}(x,b^*(b_T),\mu,\zeta)\, f_{i/h}^{\rm NP}(x,b_T)$$

perturbative: $b_T^{-1} \sim q_T \gg \Lambda_{\rm QCD}$

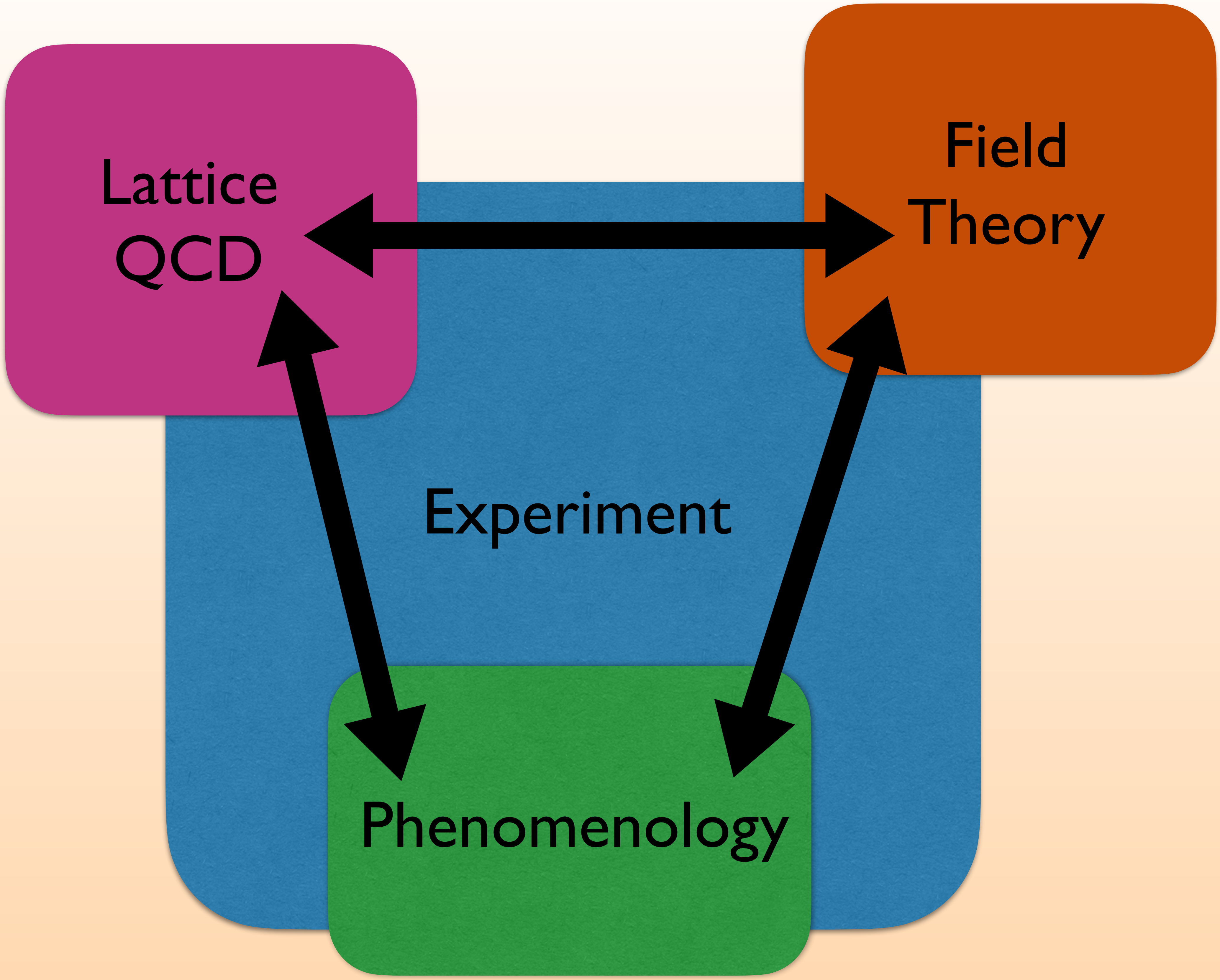
nonperturbative (models, lattice): $b_T^{-1} \sim q_T \sim \Lambda_{\rm QCD}$

OPE: $$f_{i/h}^{\rm pert}(x,b_T,\mu,\zeta) = \sum_j \int \frac{dy}{y} C_{ij}(x/y,b_T,\mu,\zeta) f_{j/h}(y,\mu)$$

longitudinal PDFs

LO (α_s^0) → NLO (α_s) → NNLO (α_s^2) → N^3LO (α_s^3)

TMDs



TMD Handbook

A modern introduction to the physics of
Transverse Momentum Dependent distributions

April 6, 2023

Renaud Boussarie
Matthias Burkardt
Martha Constantinou
William Detmold
Markus Ebert
Michael Engelhardt
Sean Fleming
Leonard Gamberg
Xiangdong Ji
Zhong-Bo Kang
Christopher Lee
Keh-Fei Liu
Simonetta Liuti
Thomas Mehen *
Andreas Metz
John Negele
Daniel Pitonyak
Alexei Prokudin
Jian-Wei Qiu
Abha Rajan
Marc Schlegel
Phiala Shanahan
Peter Schweitzer
Iain W. Stewart *
Andrey Tarasov
Raju Venugopalan
Ivan Vitev
Feng Yuan
Yong Zhao

* - Editors

TMD Collaboration

U.S. DEPARTMENT OF ENERGY | Office of Science

12 chapters
471 pages
arXiv:2304.03302

1. Introduction
2. Definitions of TMDs
3. Factorization Theorems
4. Evolution and Resummation
5. Phenomenology and Extraction of TMDs
6. Lattice Calculations of TMDs
7. Models
8. Small-x TMDs
9. Jet Fragmentation
10. Subleading TMDs
11. Generalized TMDs & Wigner Space Distn.
12. Summary and Outlook

(Selected) Recent TMD Results

- **Precision TMDs (Multi-loop, Global fits)**
- **Lattice QCD for TMDs**
- **TMDs in Heavy Hadrons**
- **New observables:** q_*
  Jets
  EECs

Not covered:

Subleading TMDs (study of QGQ correlators)
TMDs in Nuclei
Proton Spin decomposition
Small-x & Saturation
Nucleon Energy Correlators
…

} See Shohini Bhattacharya's Wed. review talk

Precision TMDs

Multi-loop results

TMD physics with state-of-the-art precision

Key new ingredients:

- OPE for TMD PDFs and FFs to 3-loops (all channels)
  Ebert, Mistlberger, Vita (2020)
  Luo, Yang, Zhu, Zhu (2020)

$$f^{\rm pert}_{i/h}(x, b_T, \mu, \zeta) = \sum_j \int \frac{dy}{y} C_{ij}(x/y, b_T, \mu, \zeta) f_{j/h}(y, \mu)$$

- CS kernel to 4-loops
  Duhr, Mistlberger, Vita (2022)
  Moult, Zhu, Zhu (2022)

$$\gamma^q_\zeta[\alpha_s] = \alpha_s\, \gamma^{q(1)}_\zeta + \alpha_s^2\, \gamma^{q(2)}_\zeta + \alpha_s^3\, \gamma^{q(3)}_\zeta + \alpha_s^4\, \gamma^{q(4)}_\zeta + \dots$$

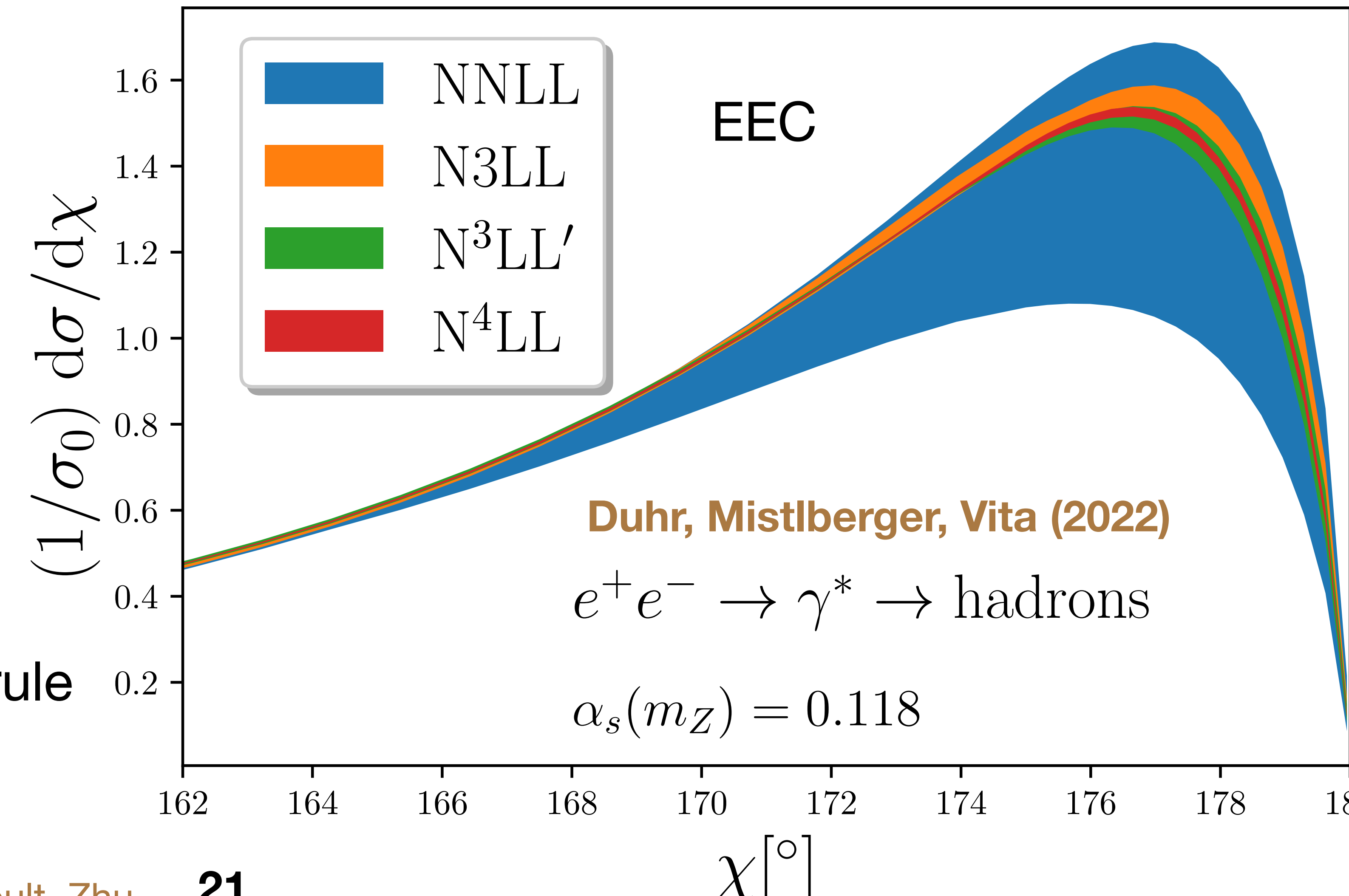
(3-loop result: Li, Zhu 2016; Vladimirov 2016)

- large angle EEC = TMD FF sum rule

$$J(b_T) = \sum_h \int dz\, z\, \tilde{D}_{h/q}(z, b_T)$$

Collins, Soper; Kodaira, Trentadue; Moult, Zhu

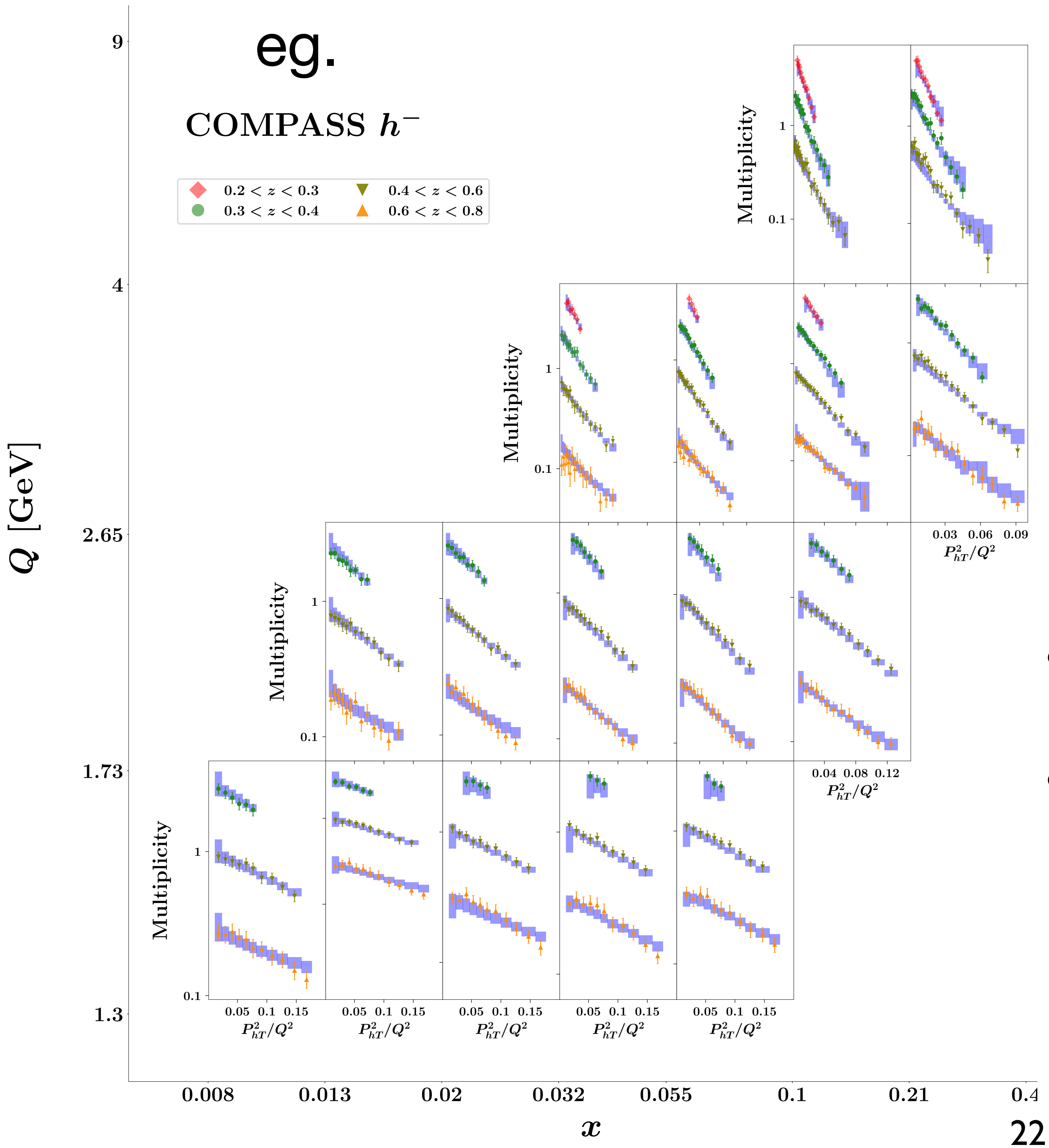
Accuracy	H, $\mathcal{J}$	$\Gamma_{\rm cusp}(\alpha_s)$	$\gamma^q_H(\alpha_s)$	$\gamma^q_r(\alpha_s)$	$\beta(\alpha_s)$
LL	Tree level	1-loop	–	–	1-loop
NLL	Tree level	2-loop	1-loop	1-loop	2-loop
NLL′	1-loop	2-loop	1-loop	1-loop	2-loop
NNLL	1-loop	3-loop	2-loop	2-loop	3-loop
NNLL′	2-loop	3-loop	2-loop	2-loop	3-loop
N^3LL	2-loop	4-loop	3-loop	3-loop	4-loop
N^3LL′	3-loop	4-loop	3-loop	3-loop	4-loop
N^4LL	3-loop	5-loop	4-loop	4-loop	5-loop
N^4LL′	4-loop	5-loop	4-loop	4-loop	5-loop

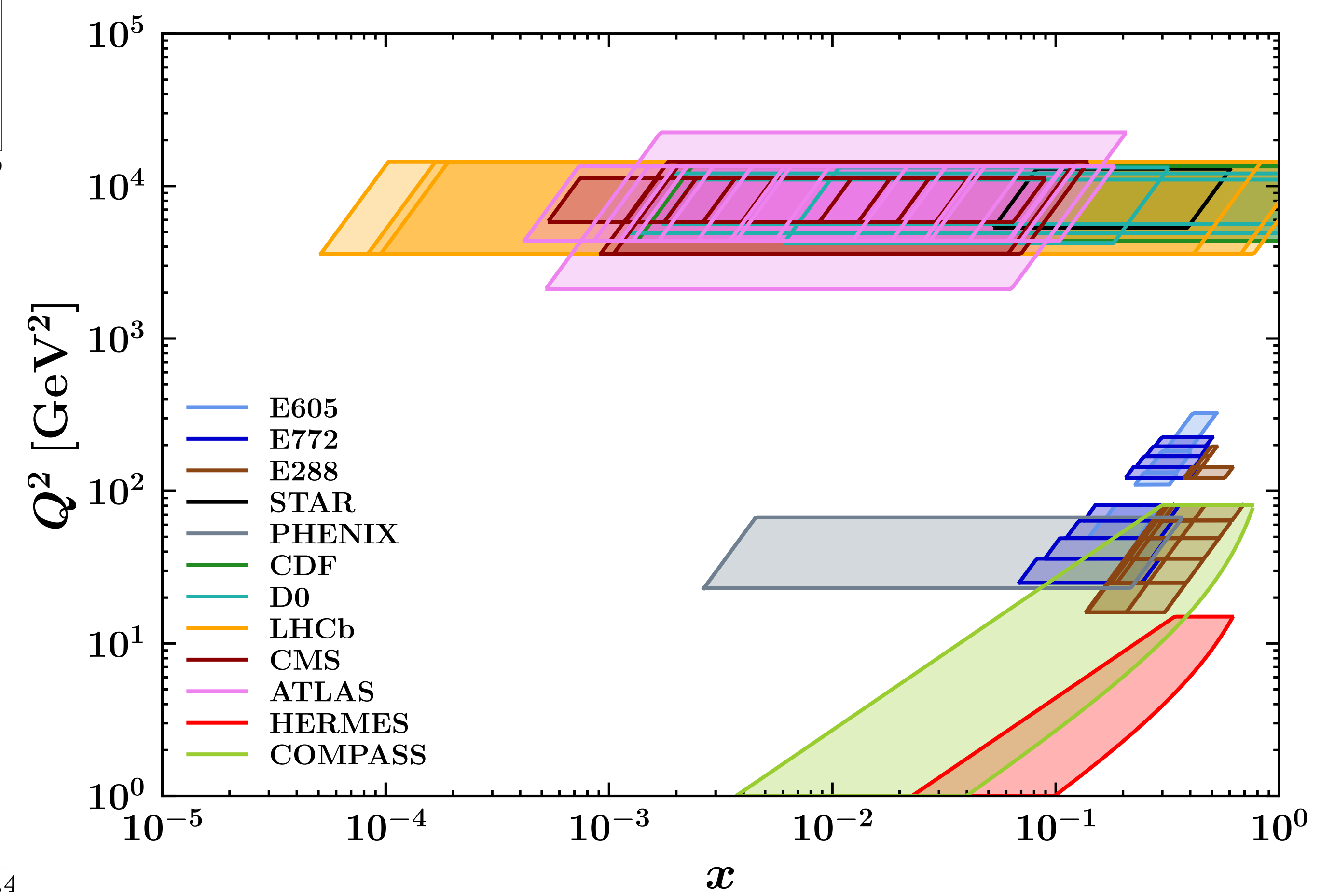


MAP Bacchetta, Bertone, Bissolotti, Bozzi, Cerutti, Delcarro, Radici, Rossi, Signori (2405.13833)

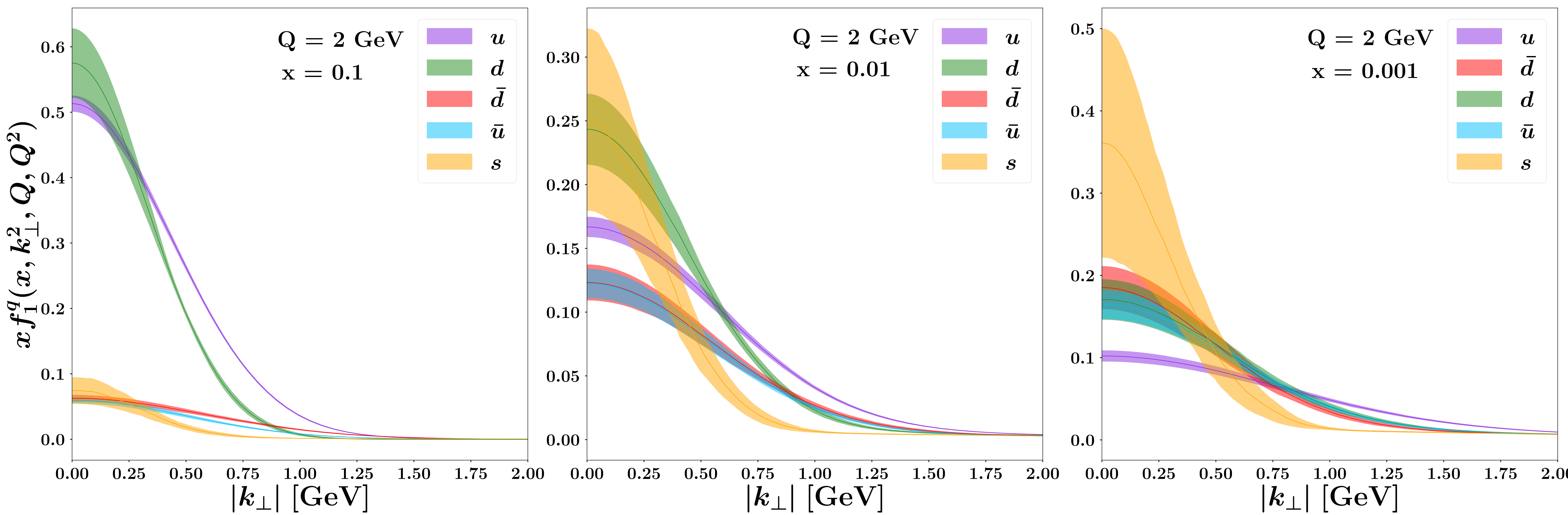
Drell-Yan + SIDIS Global Fit at N^3LL & flavor dependent NP-TMDs

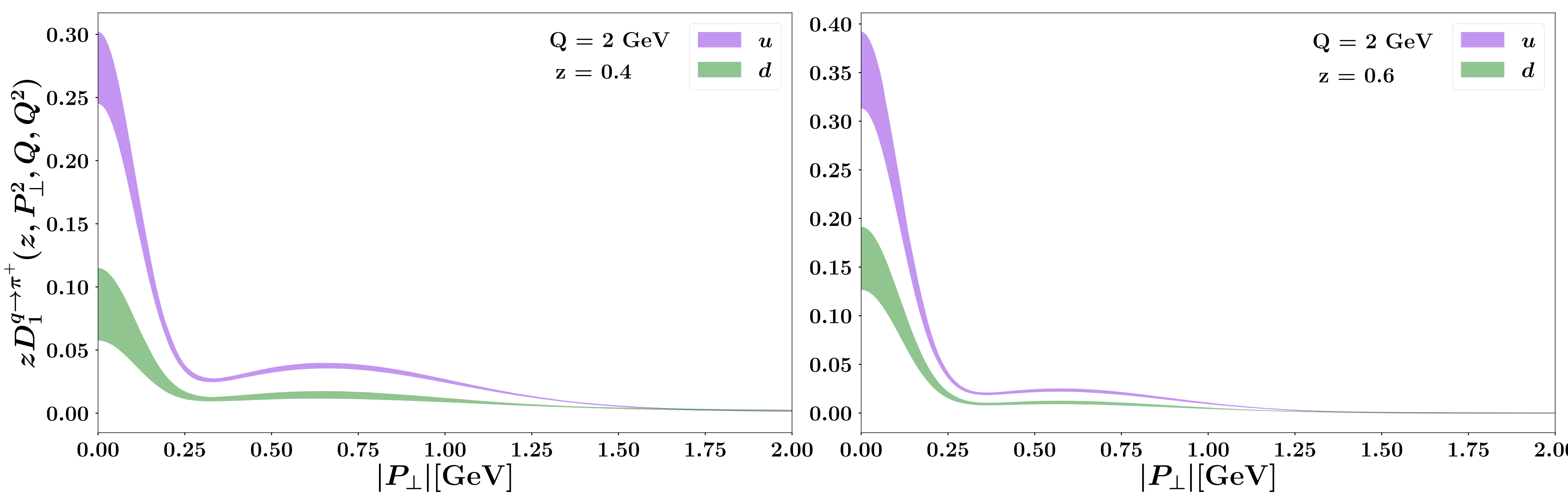
eg.





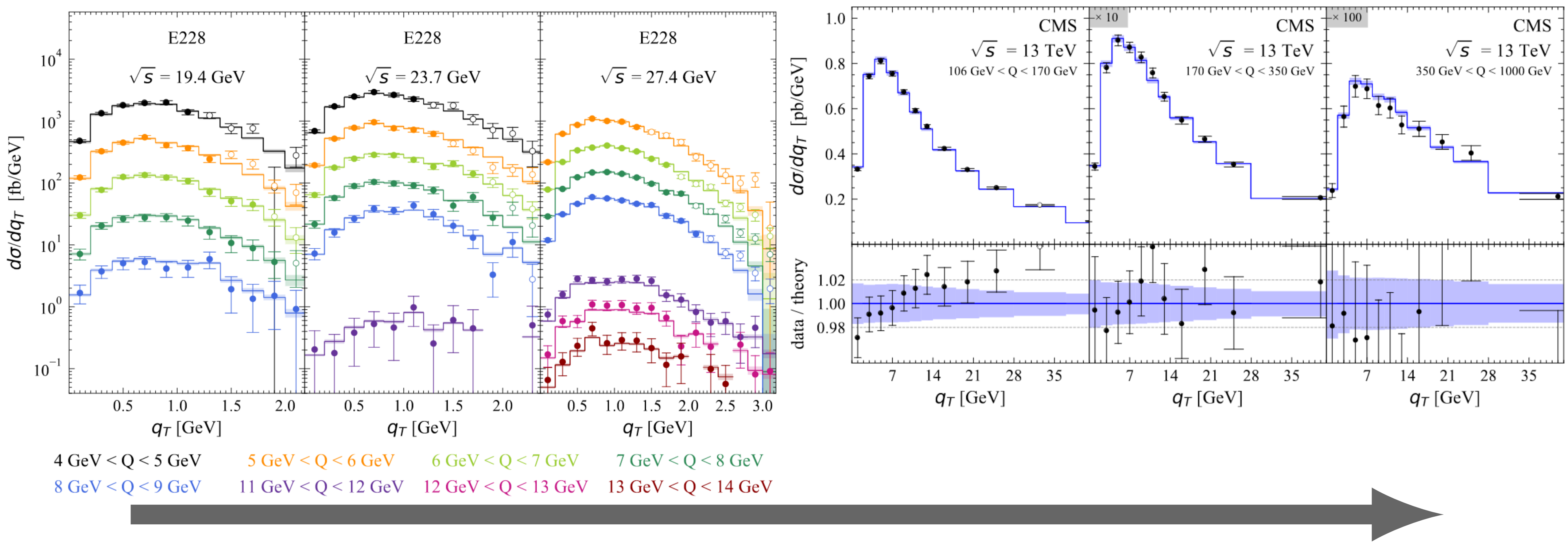
Drell-Yan + SIDIS Global Fit at N^3LL & flavor dependent NP-TMDs





ART23 Moos, Scimemi, Vladimirov, Zurita (2305.07473)

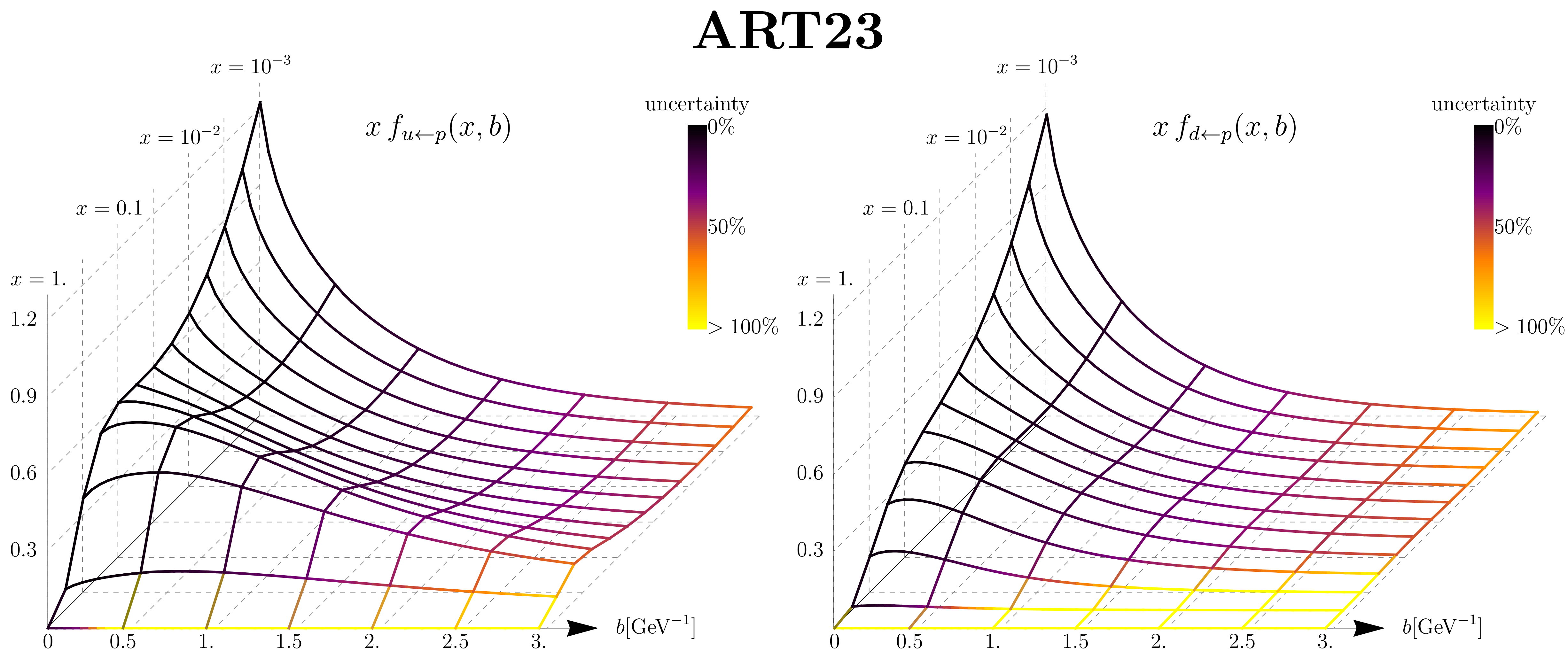
Drell-Yan Global Fit at N^4LL & flavor dependent NP-TMDs



4GeV 1000GeV

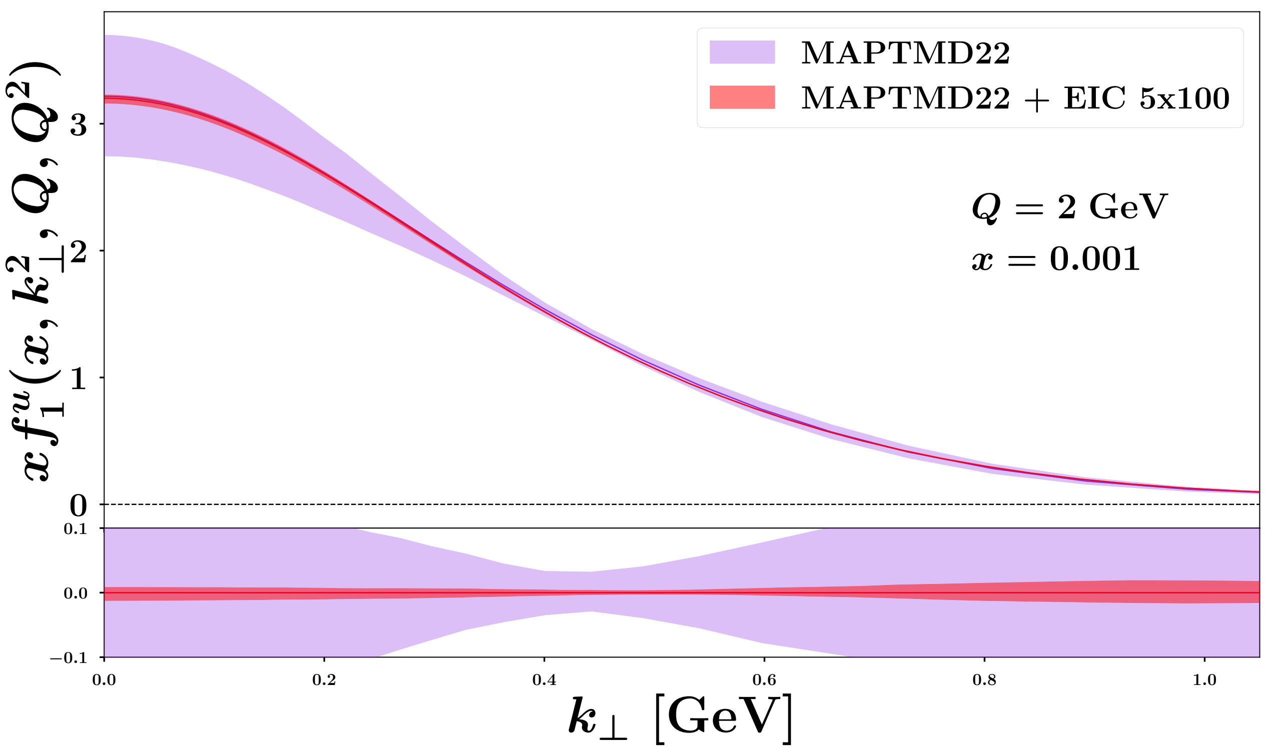
ART23 Moos, Scimemi, Vladimirov, Zurita (2305.07473)

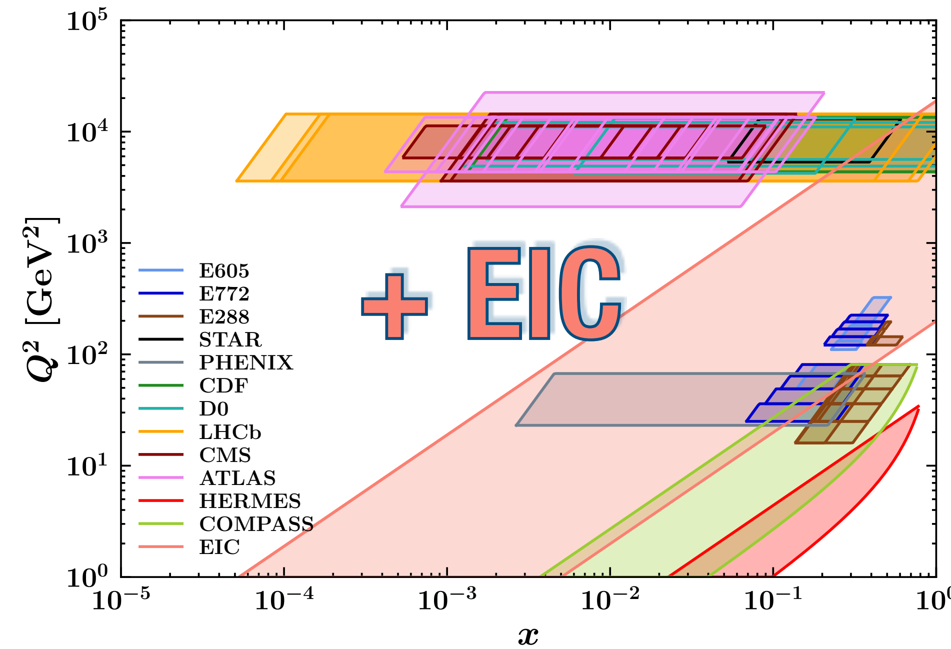
Drell-Yan Global Fit at N^{4}LL & flavor dependent NP-TMDs

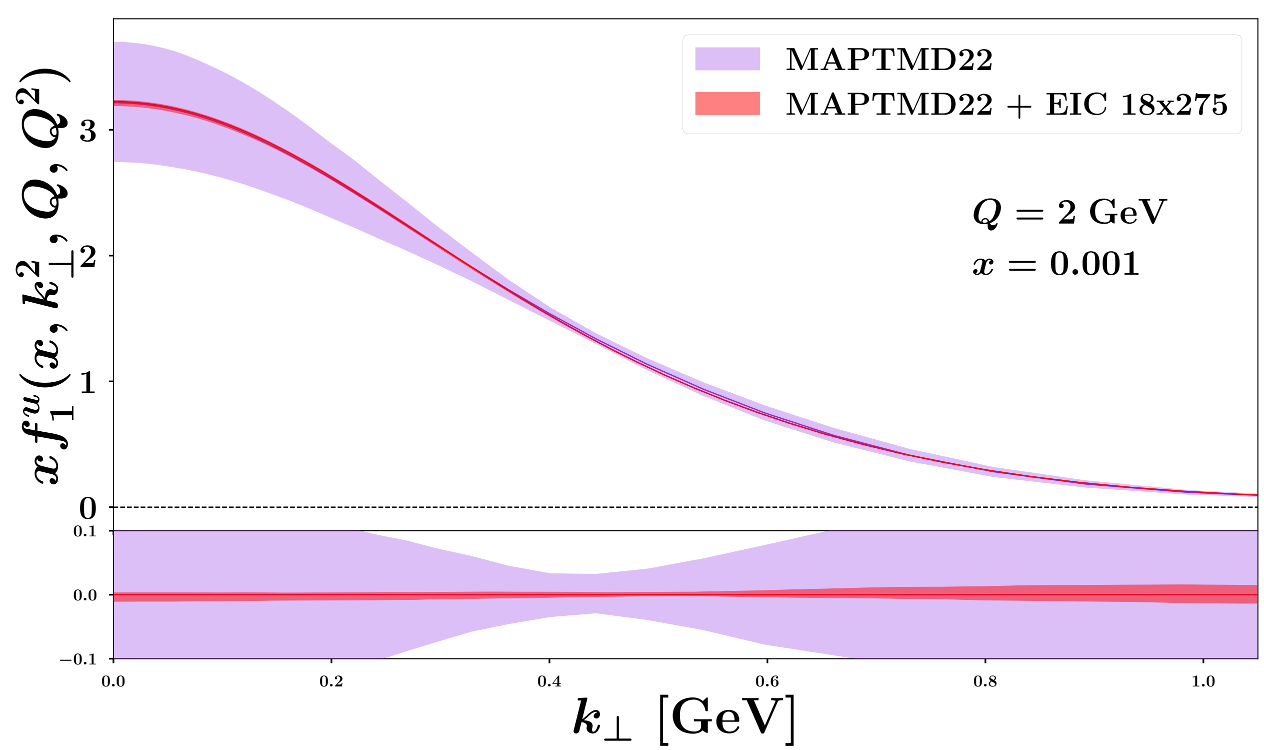


Slide from Chiara Bissolotti (MAP22)

Impact studies - EIC





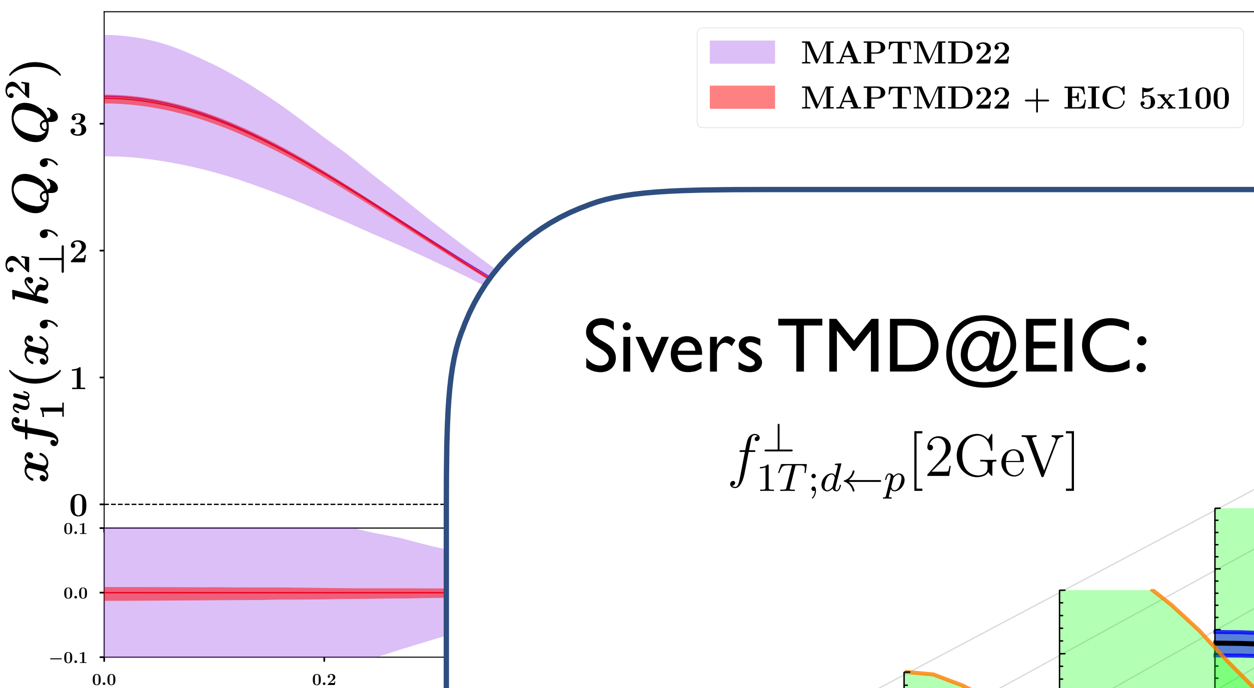


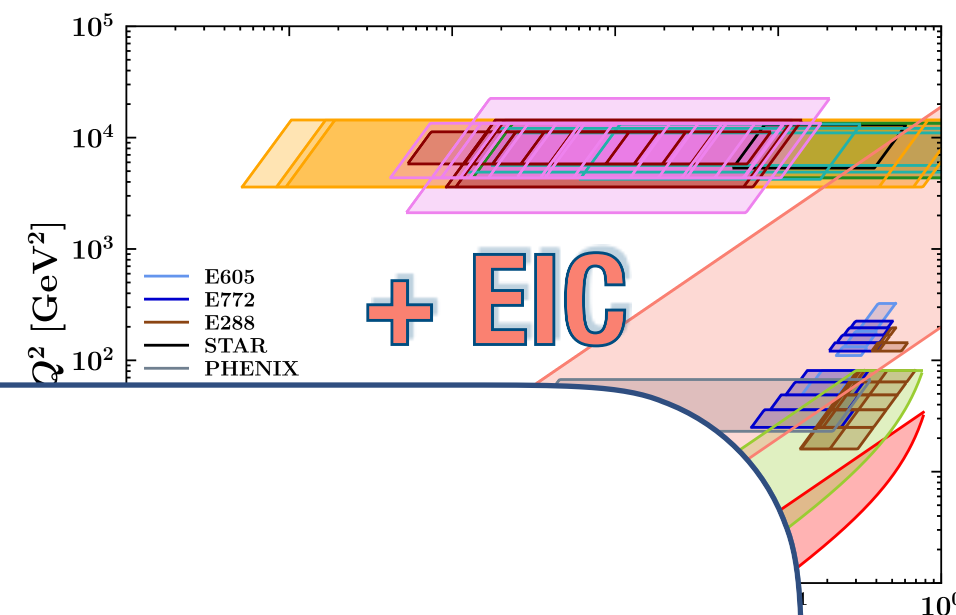
- general reduction of the bands

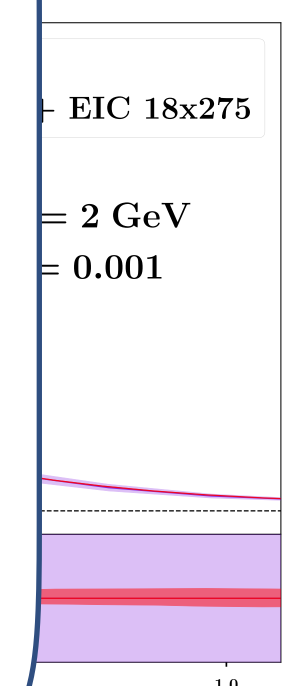
18

Slide from Chiara Bissolotti (MAP22)

Impact studies - EIC

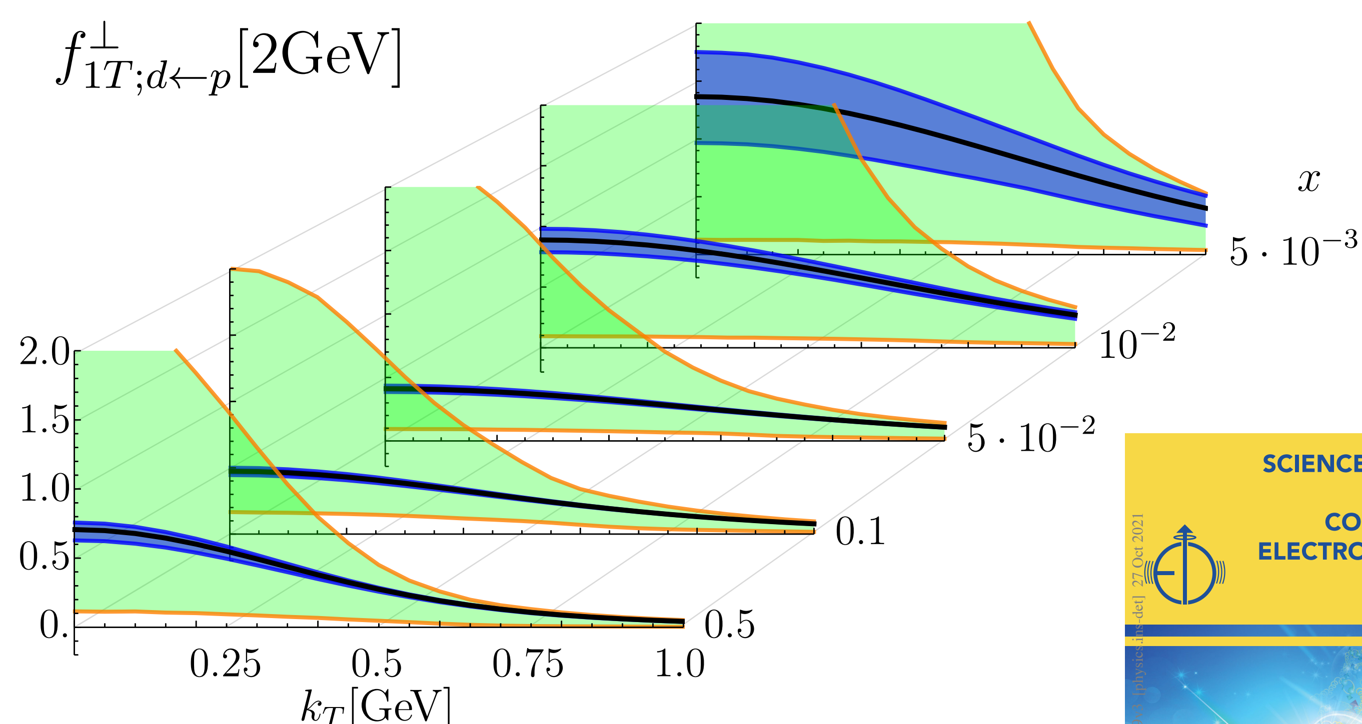


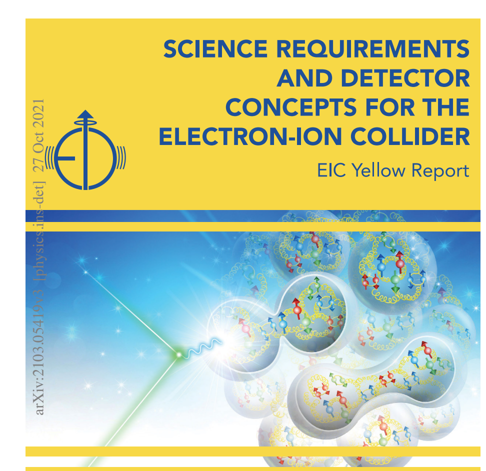




general r

Sivers TMD@EIC:





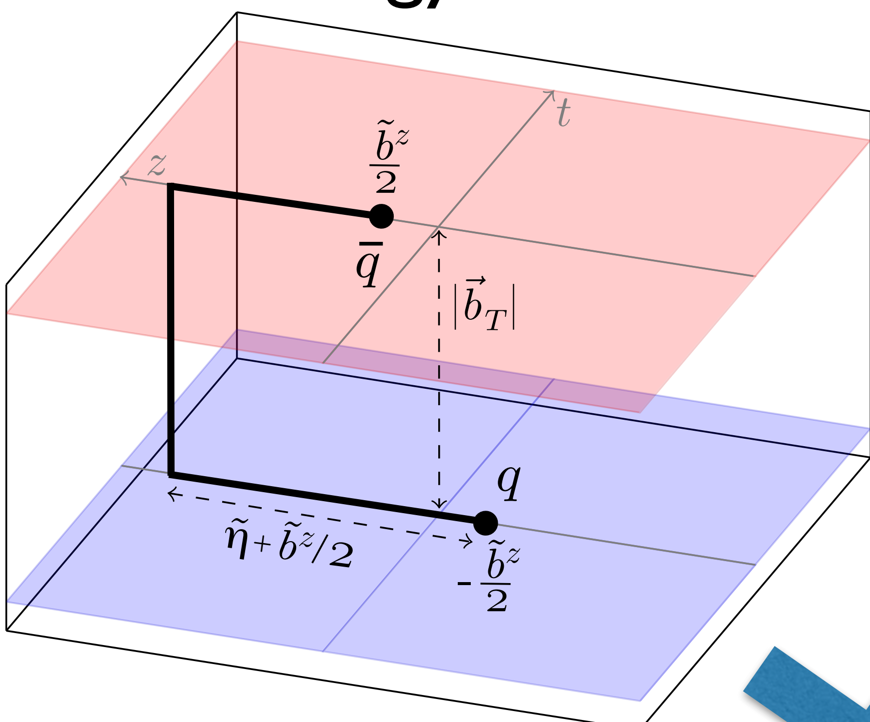
18

Lattice TMDs

Lattice Calculations for TMDs

Lattice QCD

- Basic issue: lattice is Euclidean and TMDs involve the light-cone
- Strategy:



lattice “quasi-TMDs”

Musch, Hägler, Engelhardt, Negele, Schäfer ('10, '11, '15)

Ji, Sun, Xiong, Yuan ('14); Ji, Link, Yuan, Zhang, Zhao ('18)

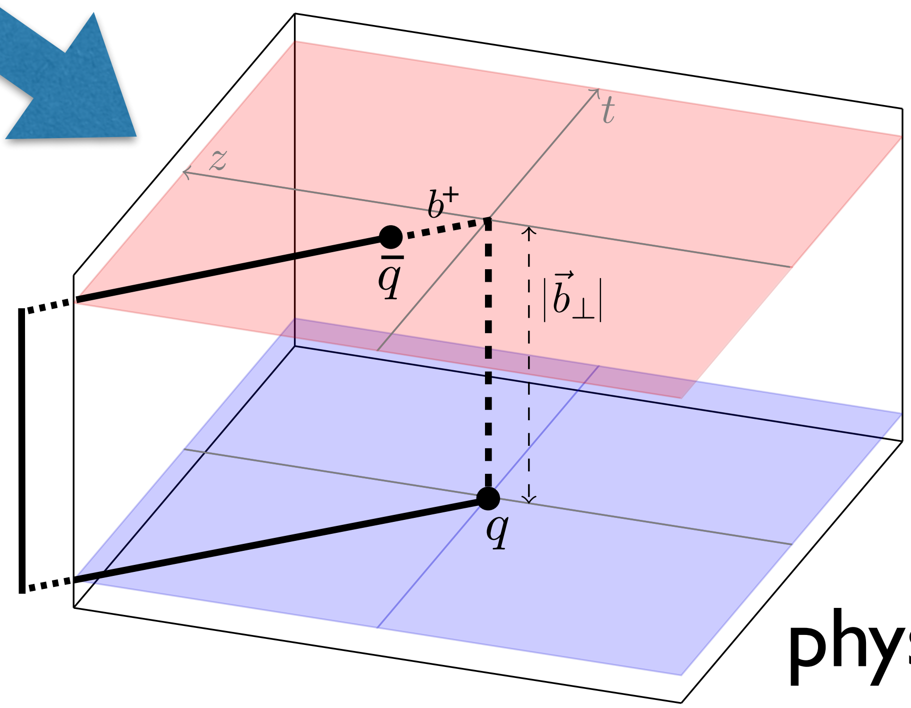
Ebert, IS, Zhao ('18, '19, '19); Ji, Liu, Liu ('19, '19)

Shanahan, Wagman, Zhao ('19, '20, '21)

Vladimirov, Schäfer ('20);

...

same infrared physics



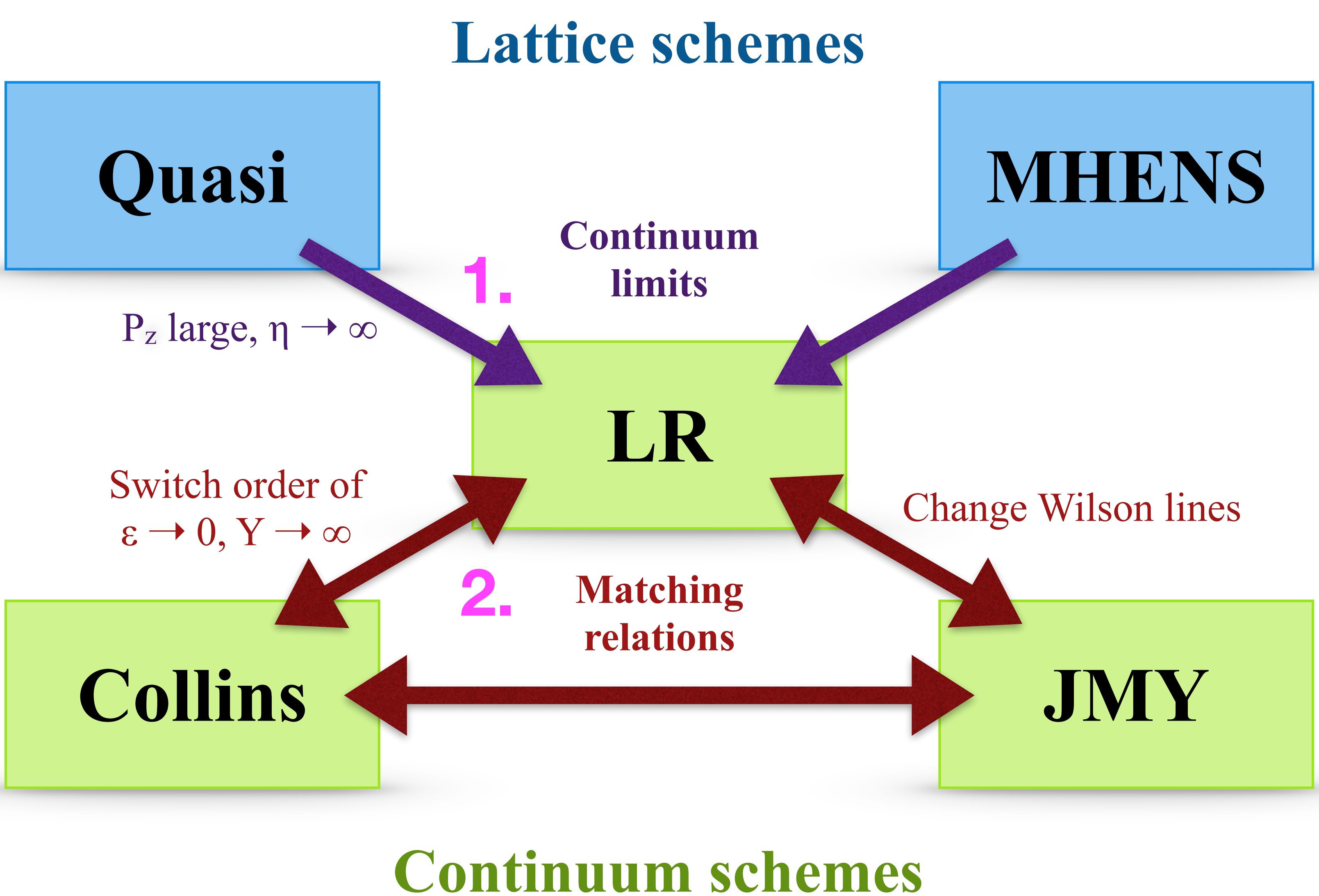
physical TMDs

Factorization relation between lattice TMDs and physical TMDs

perturbative coefficient

$$\lim_{\tilde{\eta}\to\infty} \tilde{f}_{i/h}(x, \vec{b}_T, \mu, \zeta, x\tilde{P}^z, \tilde{\eta}) = C_i(x\tilde{P}^z, \mu)\, f^C_{i/h}(x, \vec{b}_T, \mu, \zeta)$$

$$\times \left\{ 1 + \mathcal{O}\left[\frac{b_T}{\tilde{\eta}}, \frac{1}{\tilde{x}P^z\tilde{\eta}}, \frac{1}{(x\tilde{P}^z b_T)^2}, \frac{\Lambda^2_{\rm QCD}}{(x\tilde{P}^z)^2} \right] \right\}$$



- Ji, Sun, Xiong and Yuan, PRD91 (2015);
- Ji, Jin, Yuan, Zhang and YZ, PRD99 (2019);
- Ebert, Stewart, YZ, PRD99 (2019), JHEP09 (2019) 037;
- Ji, Liu and Liu, NPB 955 (2020), PLB 811 (2020);
- Ebert, Schindler, Stewart and YZ, JHEP 09 (2020);
- Vladimirov and Schäfer, PRD 101 (2020);
- Ji, Liu, Schäfer and Yuan, PRD 103 (2021);
- Ebert, Schindler, Stewart and YZ, JHEP 04, 178 (2022).

Ebert, Schindler, IS, Zhao (2201.08401)

30

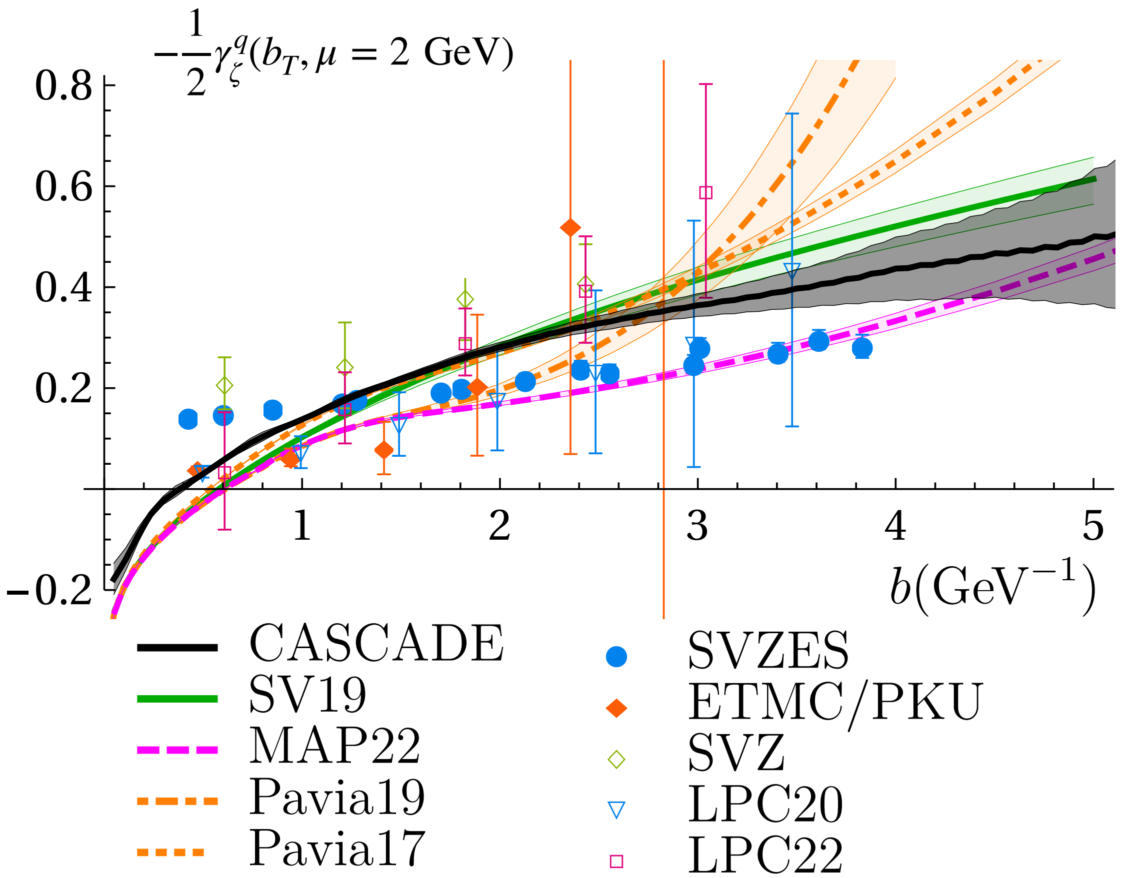
CS Kernel: Nonperturbative determinations with Lattice QCD

(slide from Yong Zhao)

Current status for the Collins-Soper kernel

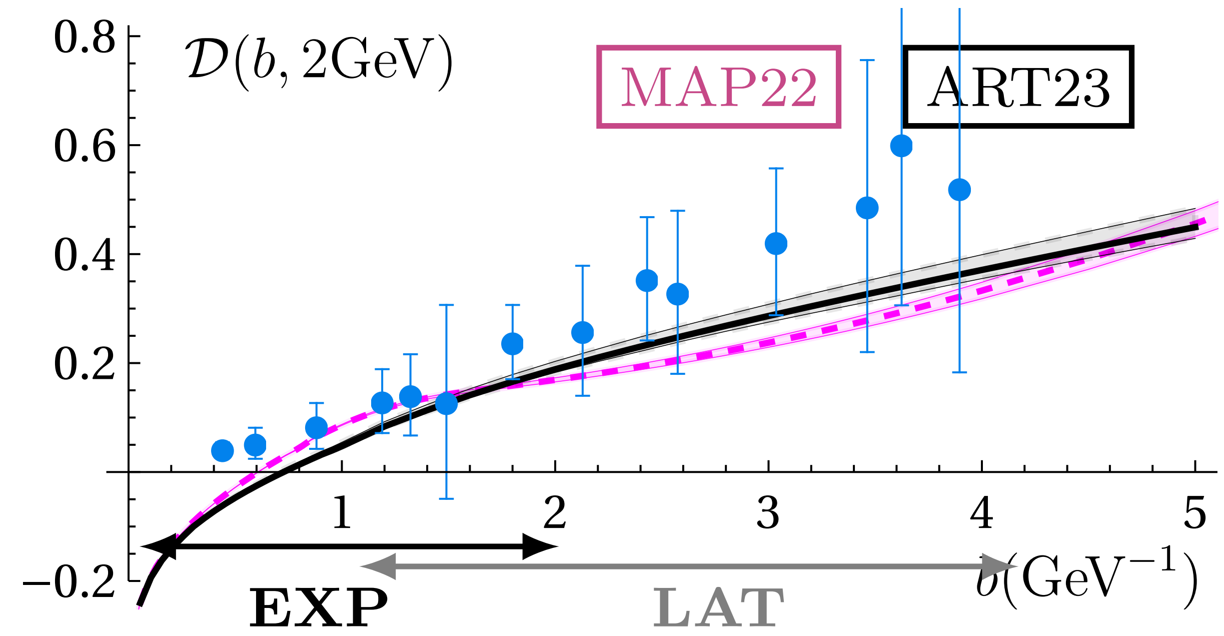
	Pion mass	Renormalization	Operator mixing	Fourier transform	Matching	*x*-plateau search
SWZ20 PRD 102 (2020) Quenched	$m_\pi = 1.2$ GeV	Yes	Yes	Yes	LO	Yes
LPC20 PRL 125 (2020)	$m_\pi = 547$ MeV	N/A	No	N/A	LO	N/A
SVZES JHEP08 (2021), 2302.06502	$m_\pi = 422$ MeV	N/A	No	N/A	NLO	N/A
PKU/ETMC 21 PRL 128 (2022)	$m_\pi = 827$ MeV	N/A	No	N/A	LO	N/A
SWZ21 PRD 106 (2022)	$m_\pi = 580$ MeV	Yes	Yes	Yes	NLO	Yes
LPC22 PRD 106 (2022)	$m_\pi = 670$ MeV	Yes	No	Yes	NLO	Yes
LPC23 JHEP 08 (2023)	$m_\pi = 220$ MeV	Yes	No	Yes	NLO	Yes
ASWZ23 2307.12359	$m_\pi = 148.8$ MeV	Yes	Yes	Yes	NNLL	Yes

Results as of 2022

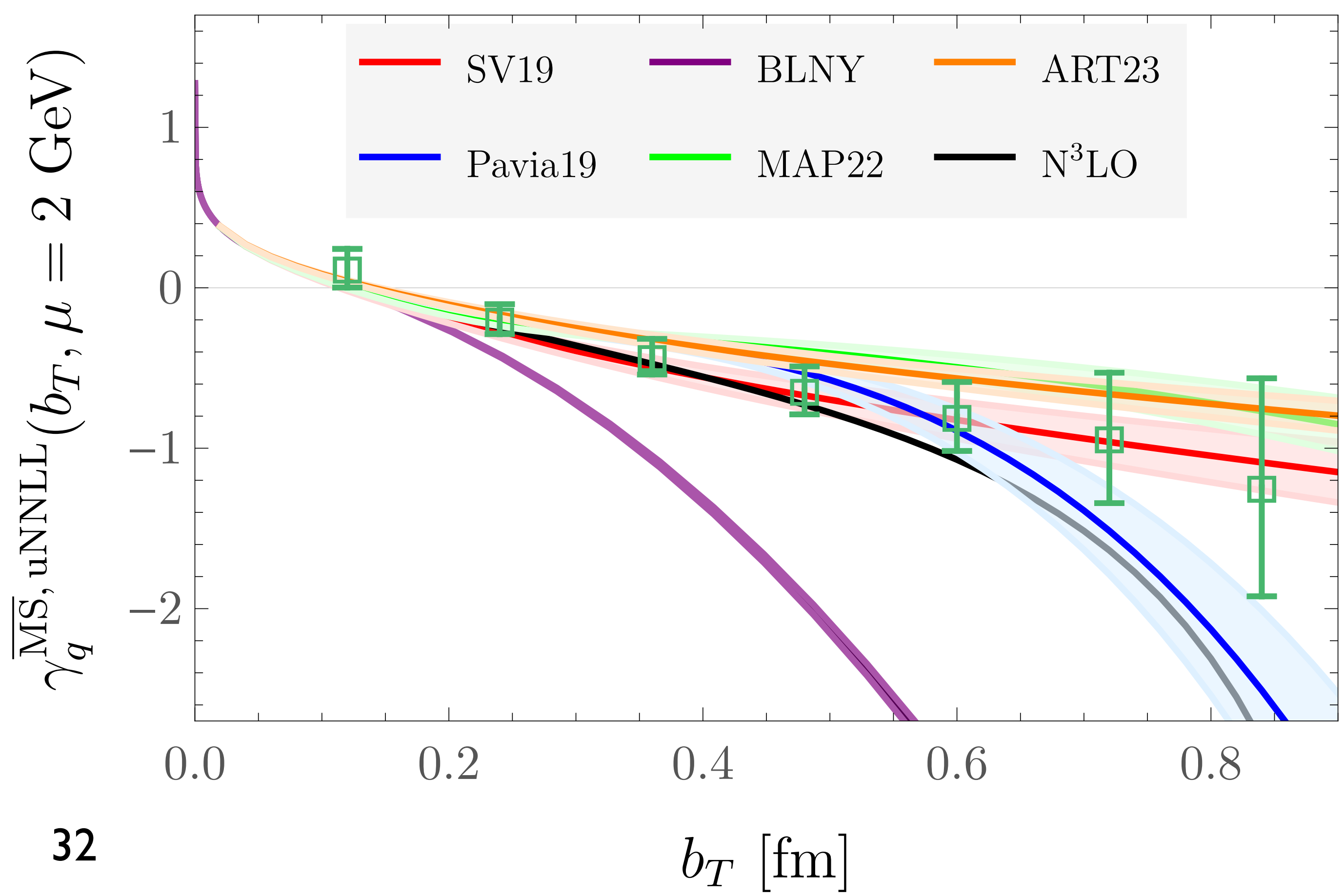


MAP22: Baccheta, Bertone, Bissolotti, et al., JHEP **10** (2022)
SV19: I. Scimemi and A. Vladimirov, JHEP **06** (2020)
Pavia19: A. Bacchetta et al., JHEP **07** (2020)
Pavia 17: A. Bacchetta et al., JHEP **06** (2017)
CASCADE: Martinez and Vladimirov, PRD **106** (2022)

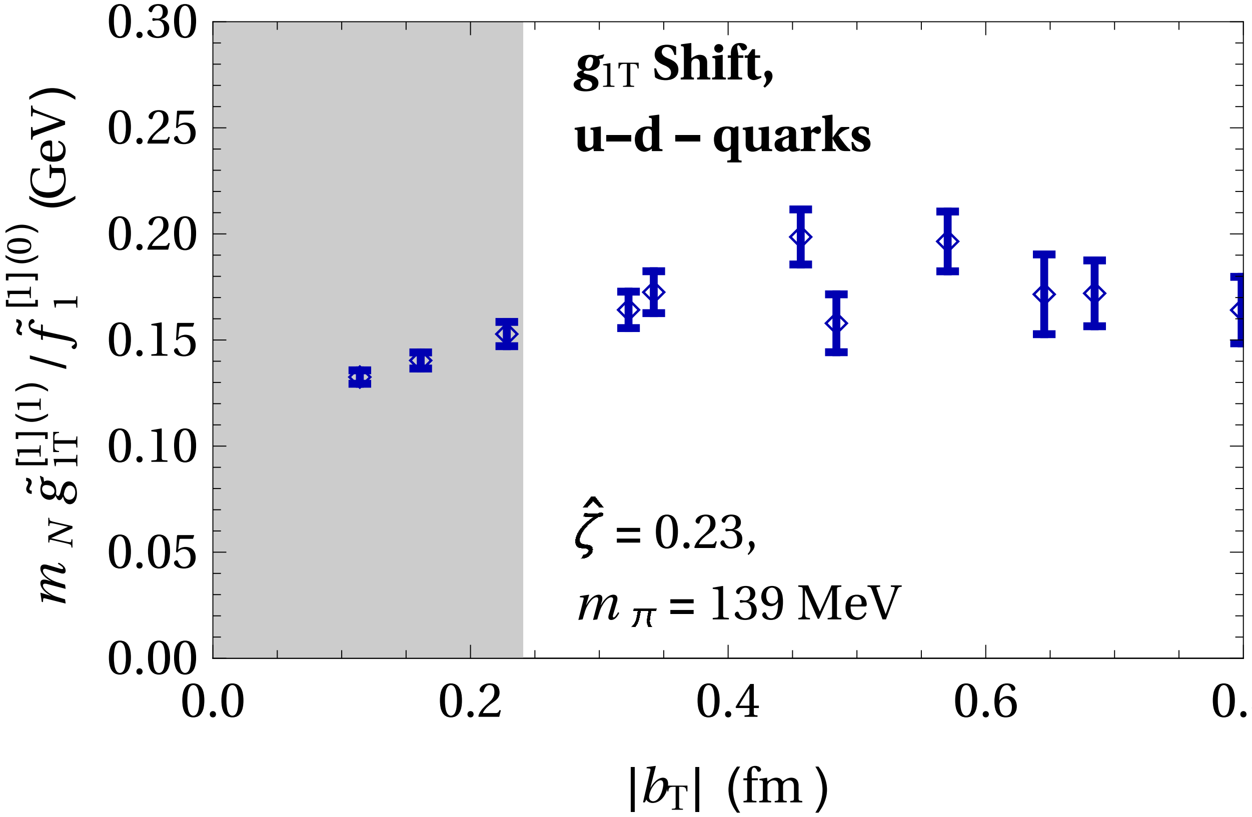
June 2023 lattice avg. by A.Vladamirov



ASWZ23 results

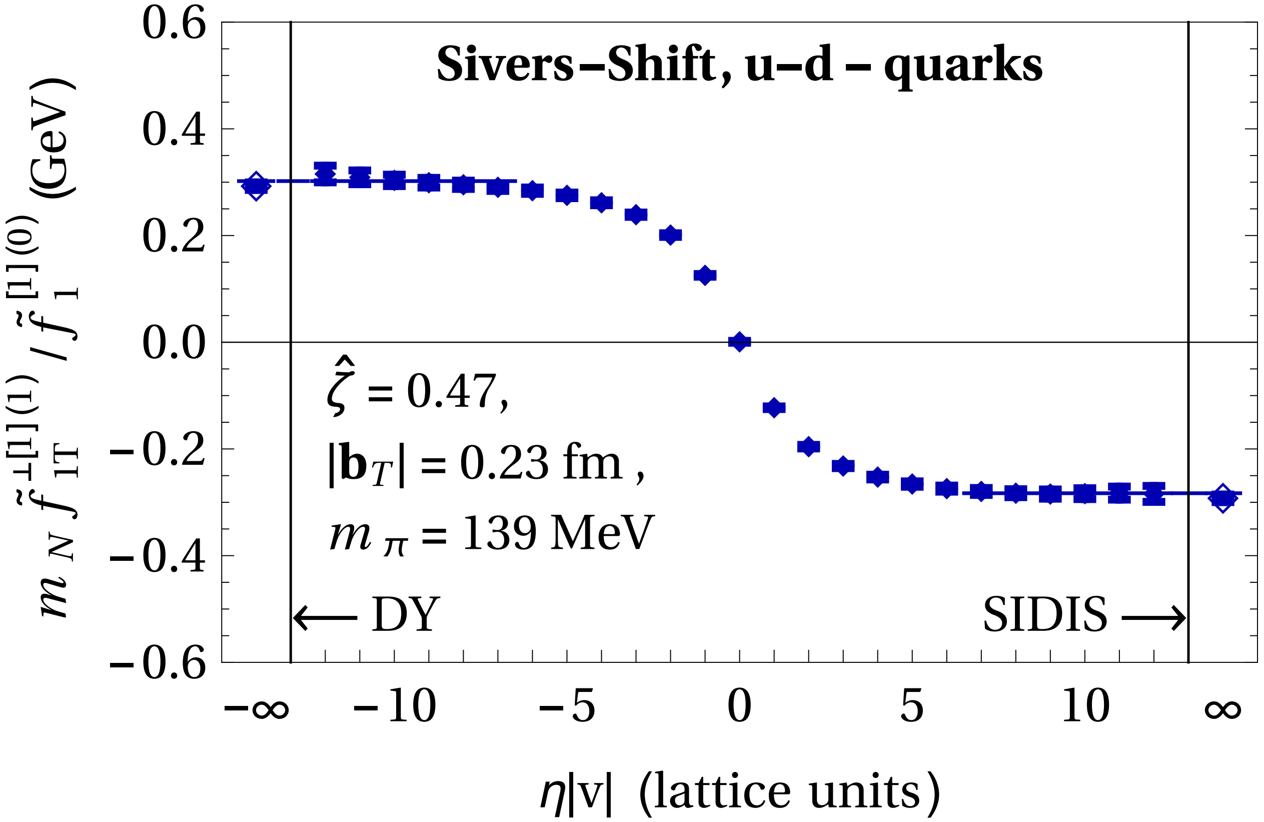


$$\frac{m_N \tilde{g}_{1T}^{[1](1)}(b_T)}{\tilde{f}_1^{[1](0)}(b_T)}$$



M. Engelhardt, et al., *PoS* LATTICE2022 (2023)

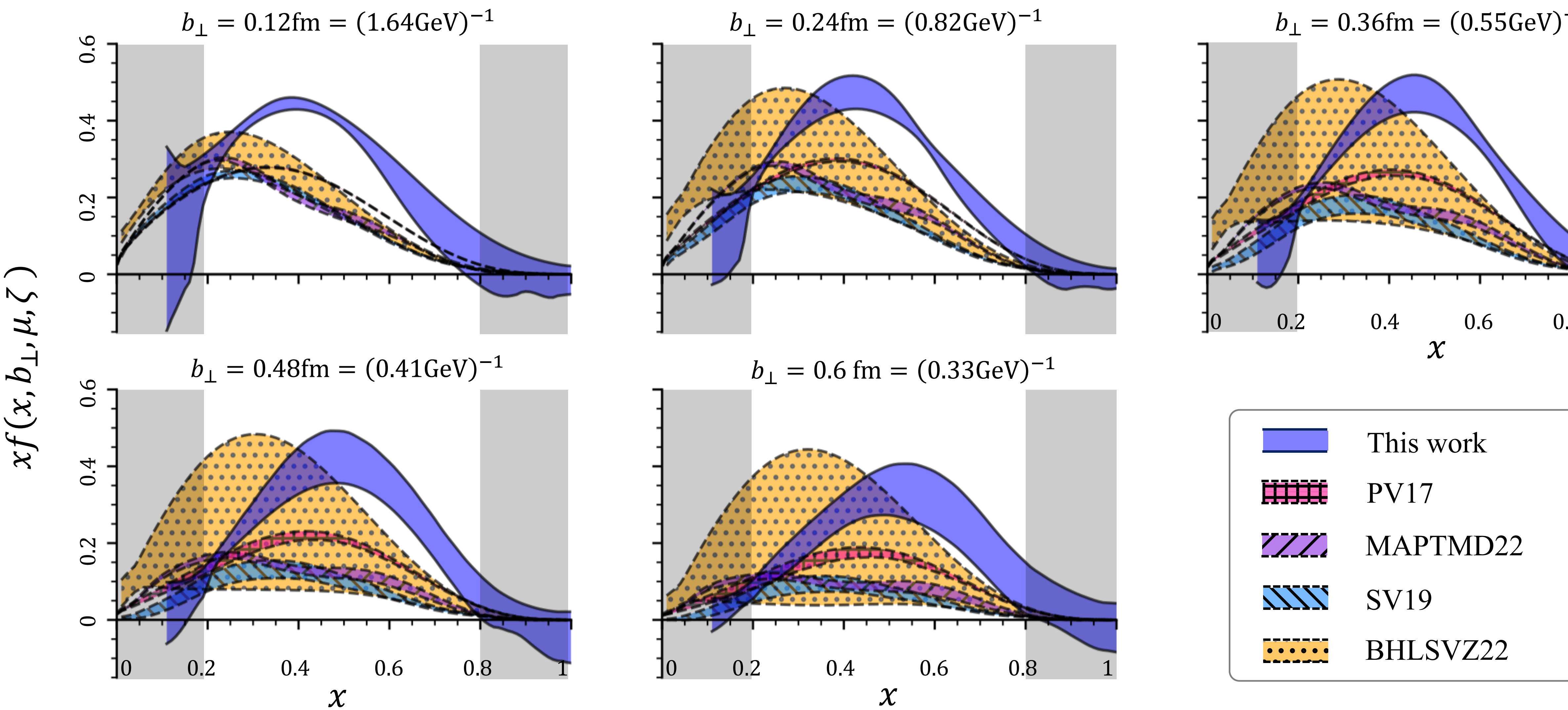
$$\frac{m_N \tilde{f}_{1T}^{\perp[1](1)}(b_T)}{\tilde{f}_1^{[1](0)}(b_T)}$$



M. Engelhardt, et al., TMD Handbook, 2304.03302.

(x, b_T) dependence of the unpolarized proton TMD

J.-C. He, M.-H. Chu, J. Hua et al., (LPC), arXiv: 2211.02340.



$a = 0.12$ fm, $m_\pi = \{310, 220\}$ MeV, $P^z_{max} = 2.58$ GeV

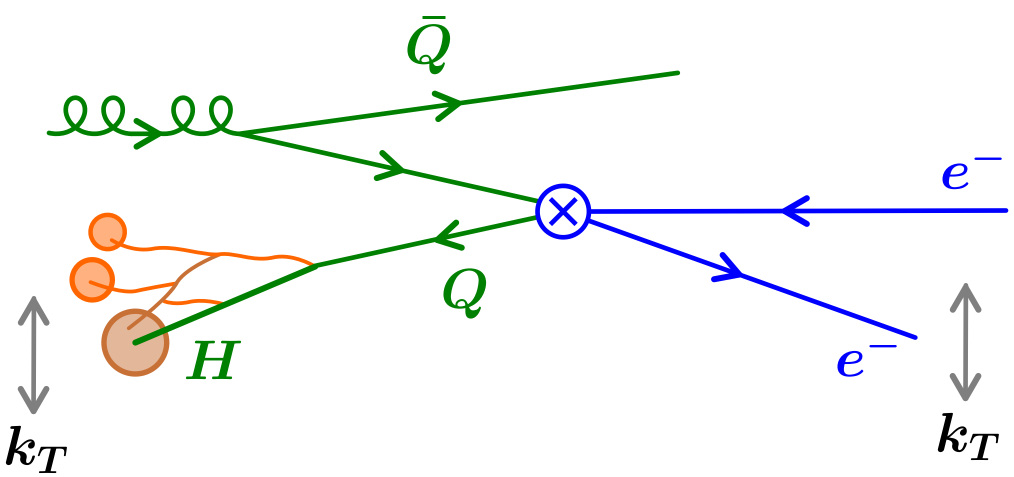
SV19: Scimemi and Vladimirov, JHEP **06** (2020)
Pavia19: Bacchetta et al., JHEP **07** (2020).
MAPTMD22: Bacchetta et al., JHEP **10** (2022).
BHLSVZ22: Bury et al., JHEP **10** (2022).

Heavy Hadron TMDs

Heavy Hadron TMD FFs

von Kuk, Michel, Sun (2305.5461)

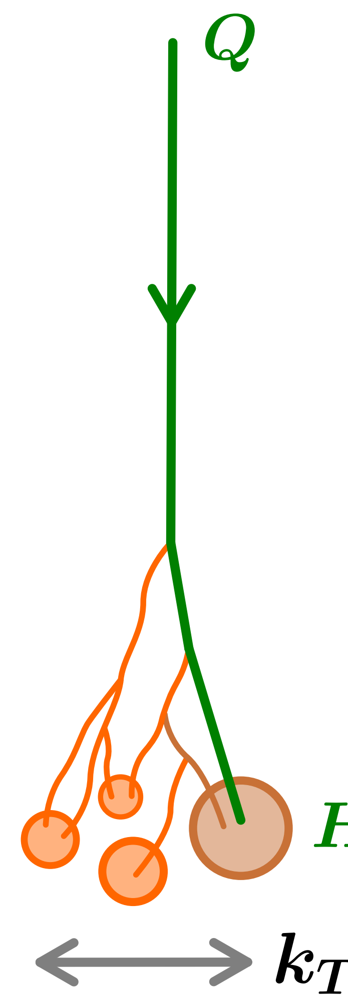
$$eN \to HX$$



$$d\sigma_{\text{unpol}} \propto H\, f_{1\,Q/N} \otimes D_{1\,H/Q}$$

$$A_{\sin(2\phi_H)} \propto H\, h_{1L\,Q/N}^{\perp} \otimes D_{1\,H/Q}^{\perp}$$

Heavy Quark Spin Symmetry relations



Unpolarized:

e.g.: $s_\ell = \frac{1}{2}$: $\quad \chi_{1,D}(b_T,\mu,\zeta) = \frac{1}{4}\chi_{1,\ell}(b_T,\mu,\zeta)\,, \qquad \chi_{1,D^*}(b_T,\mu,\zeta) = \frac{3}{4}\chi_{1,\ell}(b_T,\mu,\zeta)$

$$\chi_1(b_T) \equiv \sum_H \chi_{1,H}(b_T) = \frac{1}{N_c}\,\mathrm{Tr}\,\langle 0|\big[W^\dagger Y_v\big](b_\perp)\,\big[Y_v^\dagger\, W\big](0)|0\rangle$$

fragmentation probed by pure Wilson line object

Polarized (Collins):

e.g.: $H_{1\,D/c}^{\perp} = -H_{1\,D^*/c}^{\perp} \qquad A_{UL^{\sin(2\phi_H)}} \propto \dfrac{h_{1L}^{\perp} \otimes H_1^{\perp}}{f_1 \otimes D_1}$

Clean probe of sign of Heavy Quark Collins function

q_* : TMDs from angles

Key challenge for probing hadronization and confinement at EIC is ability to accurately reconstruct final $\vec{\ell}\,'$, and thus $\vec{P}_{hT}$

$$e^-(\ell) + N(P) \to e^-(\ell') + h(P_h) + X$$

Gao, Michel, Sun, IS (2209.11211)

eg. $Q = 20\,\text{GeV}, \Delta\ell' = 0.5\,\text{GeV}$ $\Longrightarrow$ 50% uncertainty on $P_{hT}/z = 1\,\text{GeV}$

Solve by replacing $\vec{P}_{hT}$ by observable q_* we can measure with EIC lab frame angles

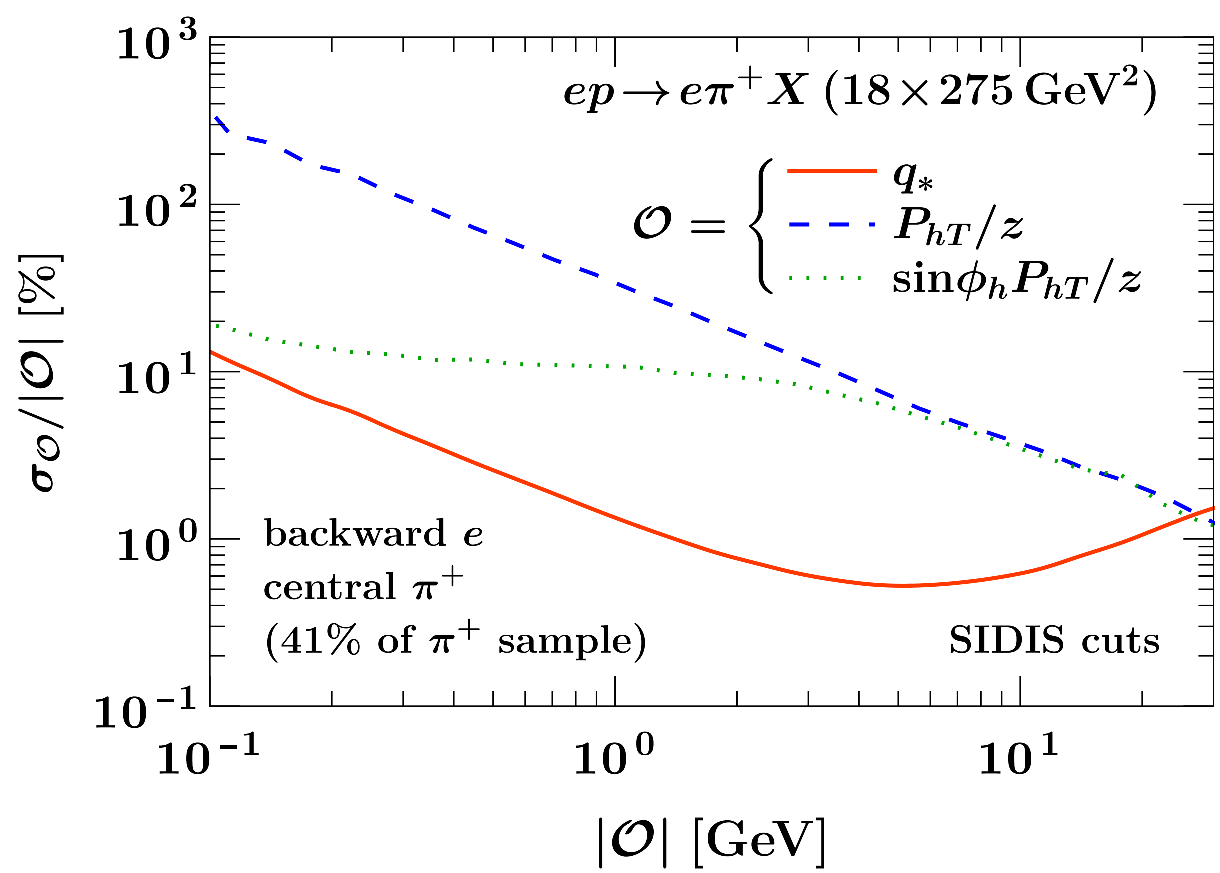
$$q_* \equiv 2P^0_{\text{EIC}} \frac{e^{\eta_h}}{1+e^{(\eta_h-\eta_{\ell'})}} \tan\phi^{\text{EIC}}_{\text{acop}}$$

$P_{hT} \ll Qz$: $\quad q_* = -\sin\phi_h \dfrac{P_{hT}}{z} + \ldots$

→ **measure same TMDs**

expected event-level resolution for these TMD observables:

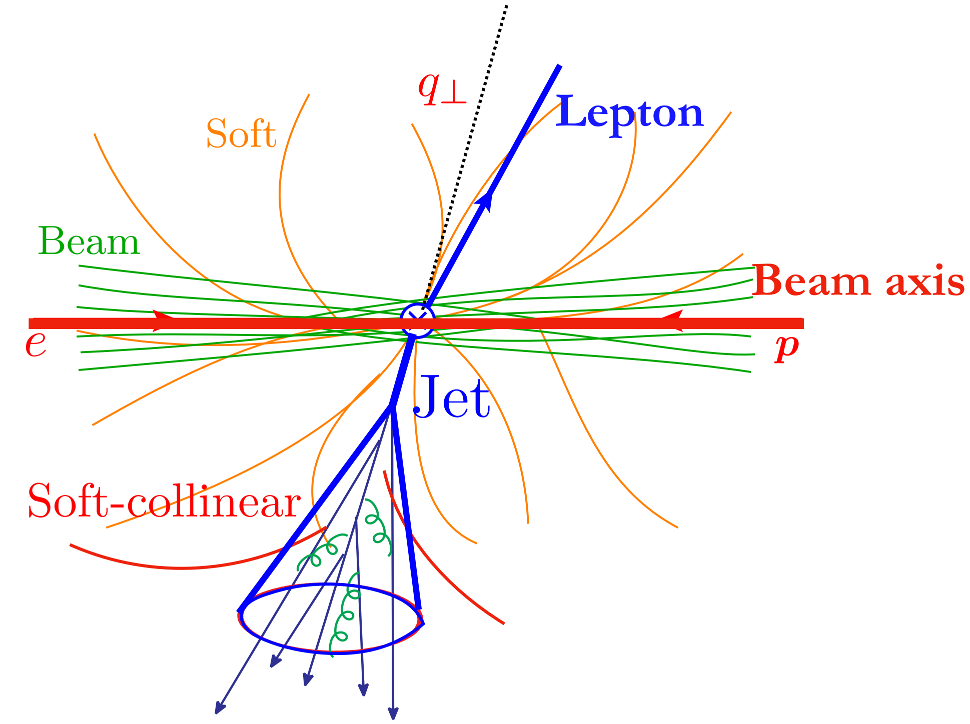
q_* **gives an order of magnitude improvement!**



TMDs from Jets

TMDs from Jets

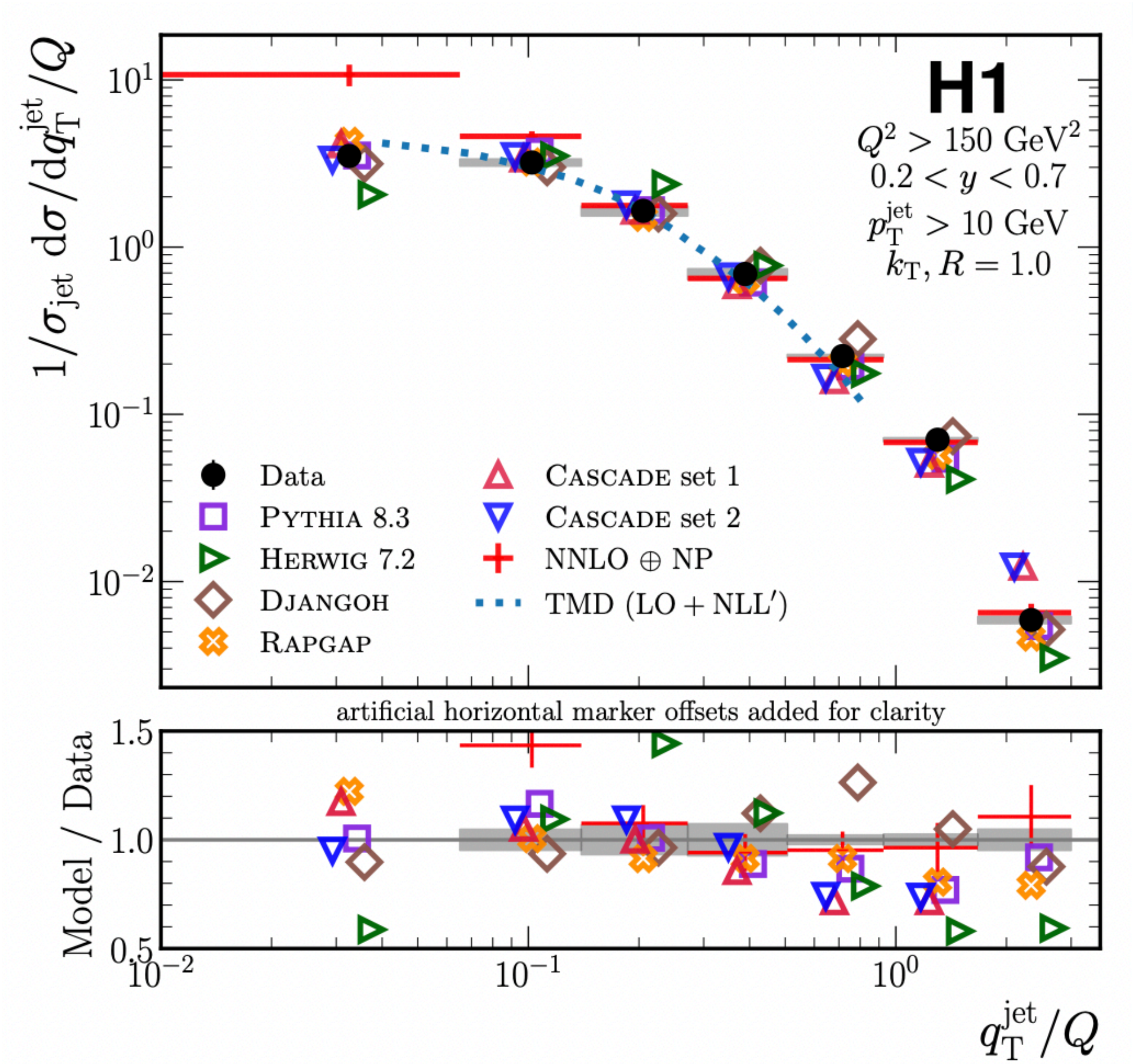
Standard processes ~ two TMDs,
while with jets ~ one TMD



1) Lepton + jet imbalance

TMDPDFs $eP \to e + J + X$

$$\frac{d\sigma_{eP\to e+\mathrm{jet}}}{dp_\perp dq_\perp} = H(Q) f_a(x, k_\perp) \otimes S^{\mathrm{global}}(k_\perp) \otimes S_{J_c}(k_\perp) J_c$$



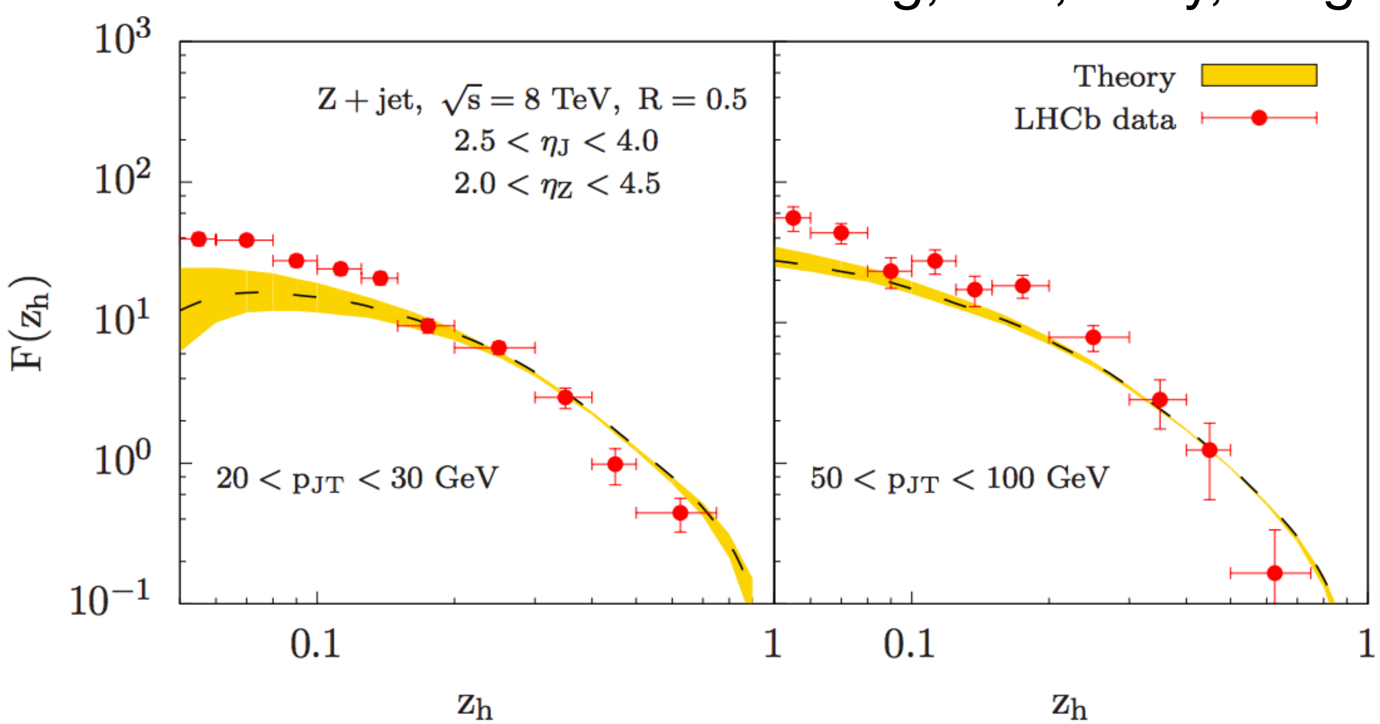
Liu, Ringer, Vogelsang, Yuan `18, `20
Arratia, Kang, Prokudin, Ringer `20
Also, Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi `19, `20

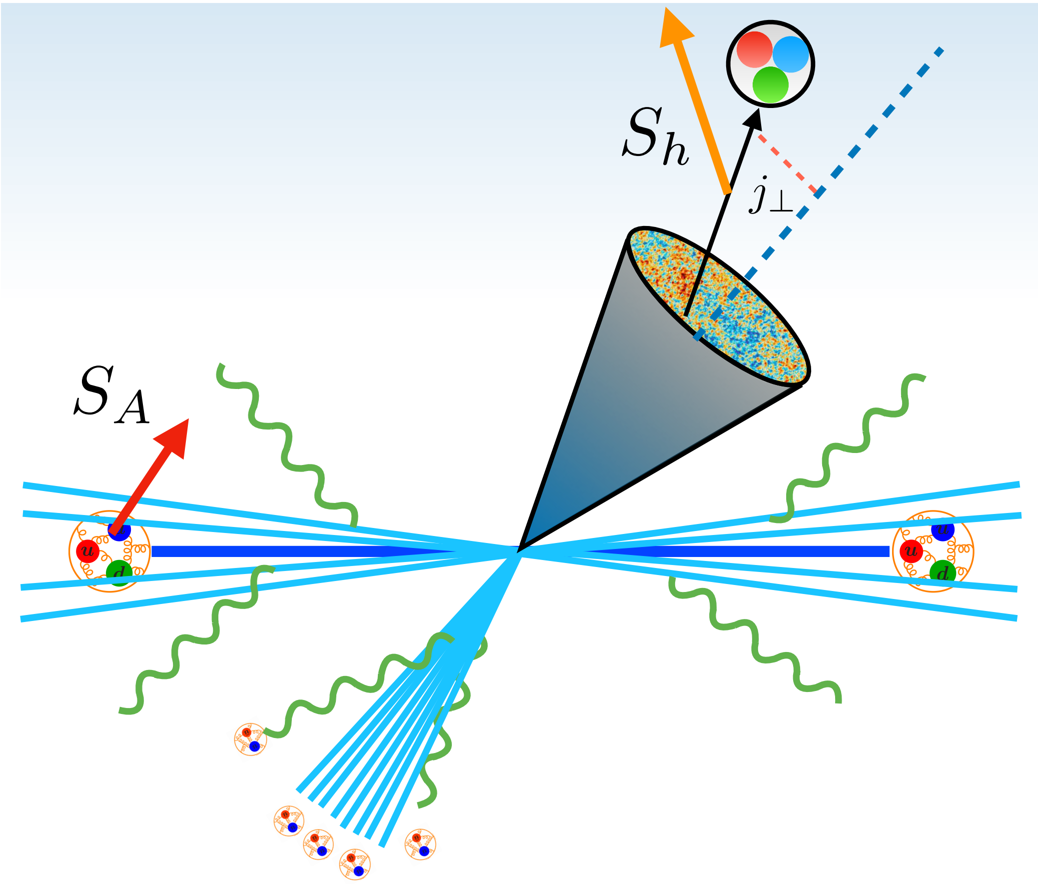
2) Fragmenting Jet Functions

TMDFFs $PP\,/\,e\,P \to J(h) + X$

Z-tagged jets at LHCb

Kang, Lee, Terry, Xing '19

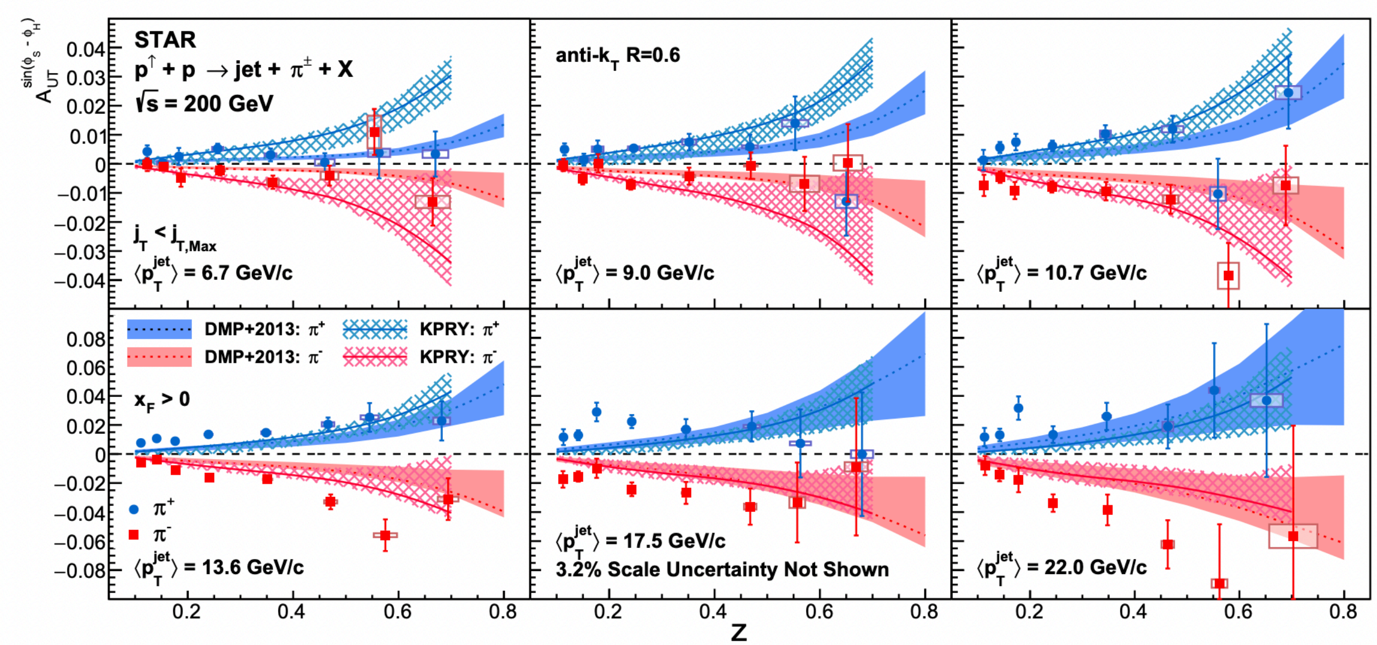




$$\frac{d\sigma^{pp\to \text{jet}(h)X}}{dp_T d\eta dz_h d^2\boldsymbol{j}_\perp} = \sum_{a,b,c} f_{a/A} \otimes f_{b/B} \otimes H^c_{ab} \otimes \mathcal{G}^h_c(z_h, \boldsymbol{j}_\perp)$$

$\Lambda_{\rm QCD}$ $\quad p_T \quad$ $p_T R$, $\Lambda_{\rm QCD}$, $j_\perp$

Collins TMD FJF



Kang, Lee, Zhao '20

STAR Collaboration `22

Procura, Stewart `10
Arleo, Fontannaz, Guillet, Nguyen `14
Kaufmann, Mukherjee, Vogelsang `15
Kang, Ringer, Vitev `16
Dai, Kim, Leibovich `16

Energy Correlators

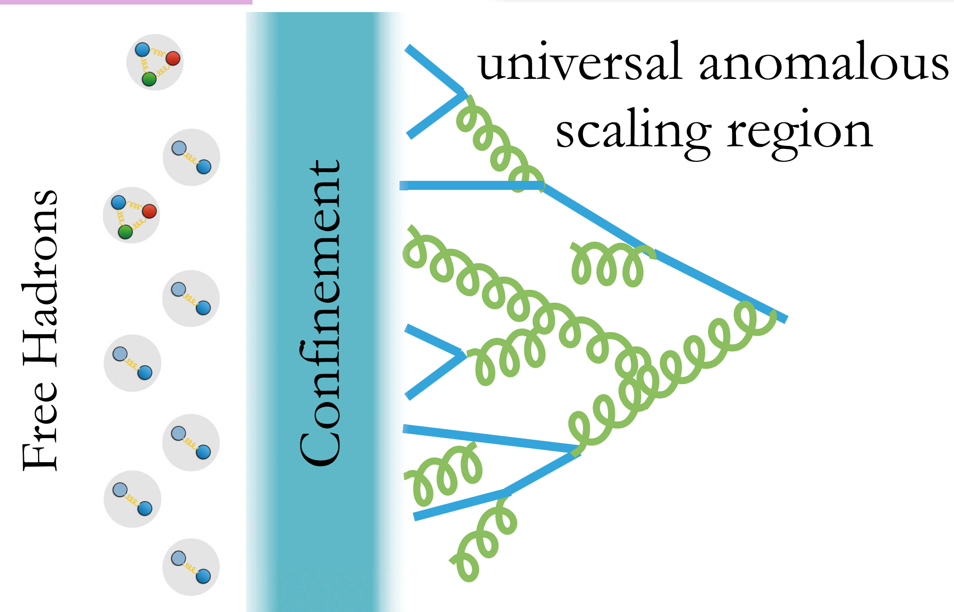
Energy Correlators

Direct probe of the confinement transition

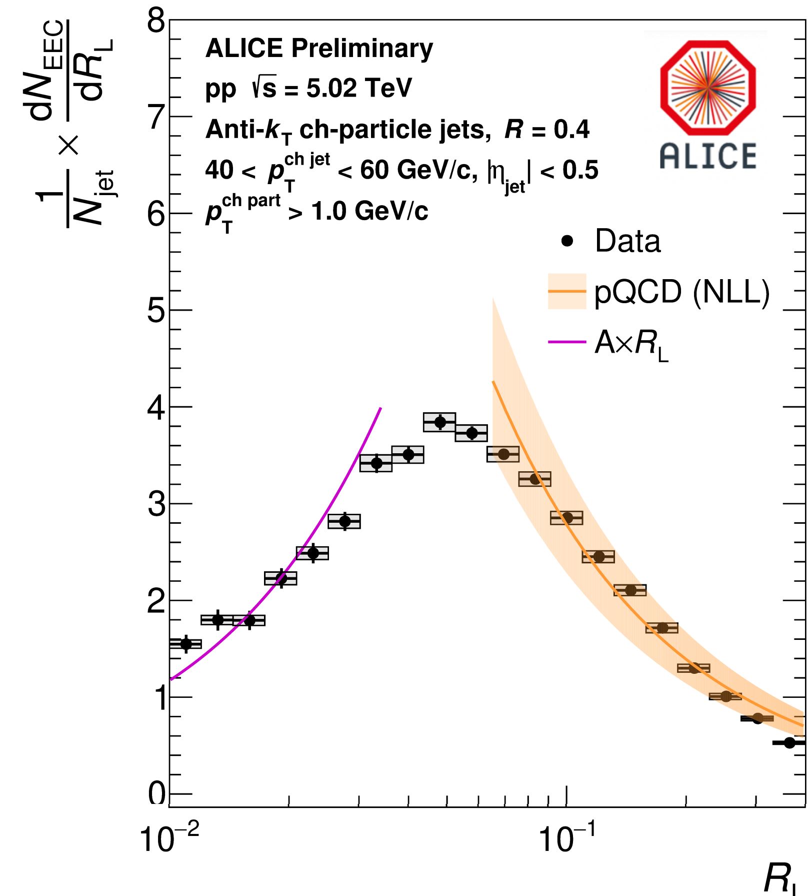
$\theta = R_L \ll 1$ region

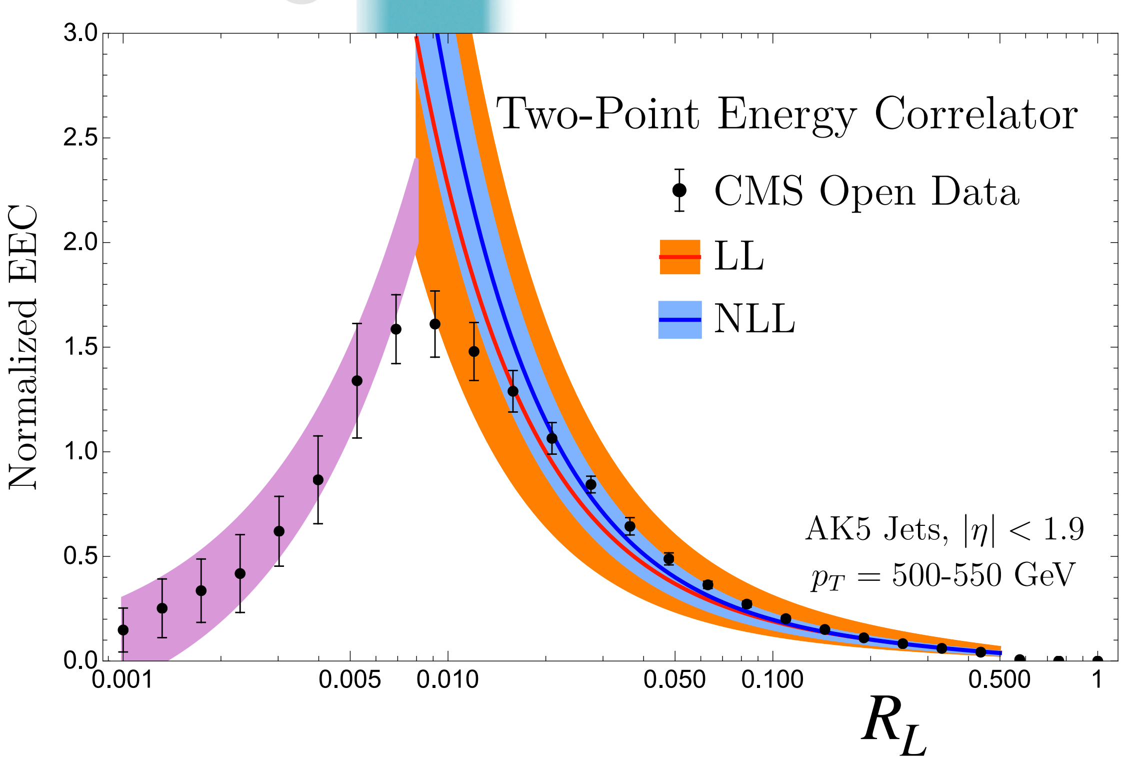
$$\frac{d\sigma}{d\theta} = \text{const} \times 2\theta$$

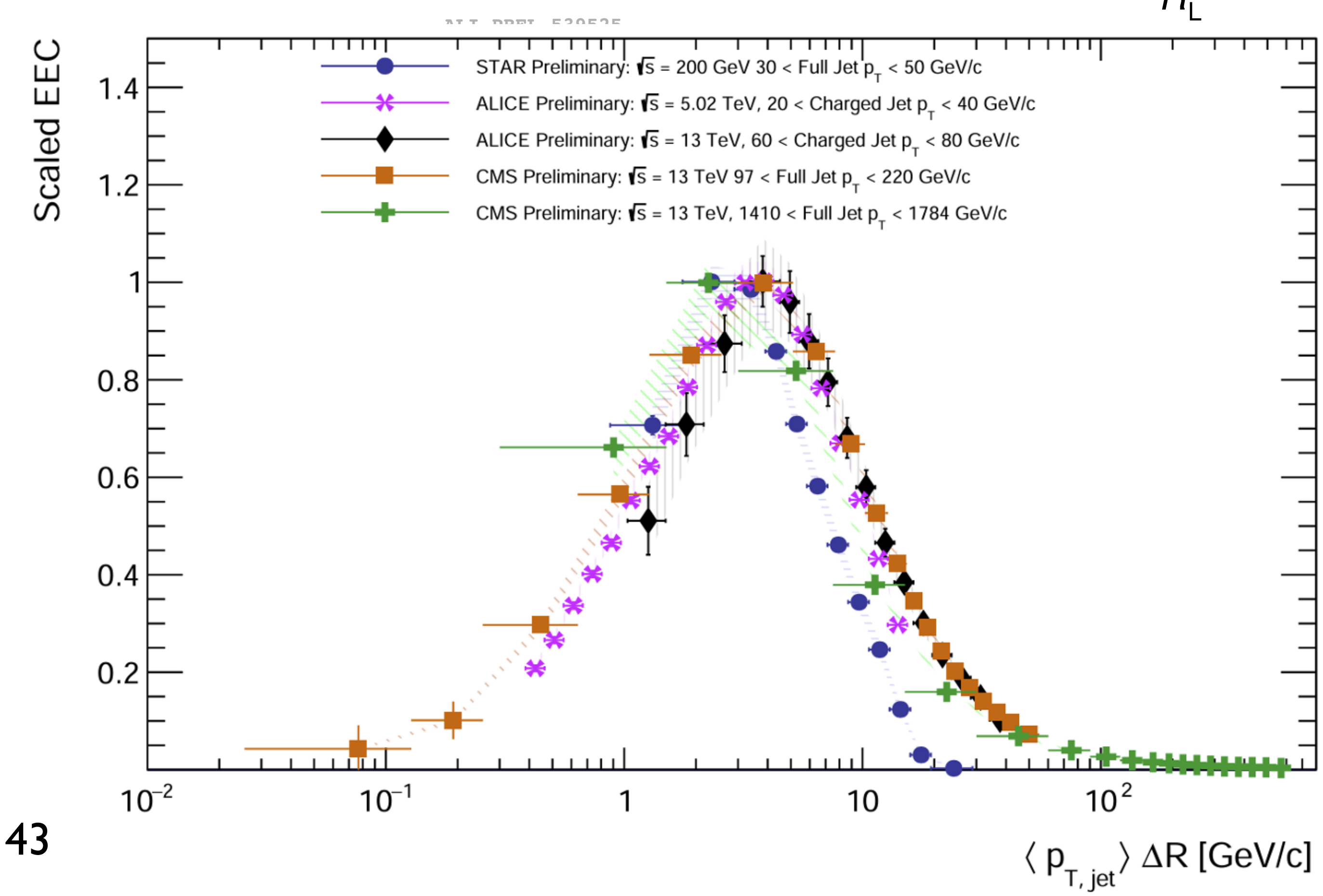
$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\gamma(3)-2}\mathbb{O}_i(\hat{n}_1)$$



ALICE `23







KL, Meçaj, Moult `22

Komiske, Moult, Thaler, Zhu `22

e^+e^- for $\theta \ll 1$ exhibits same universal scaling as hadron colliders

$\gamma_{q,g}(N)$ scaling $\qquad x_L = (1-\cos\theta_L)/2$

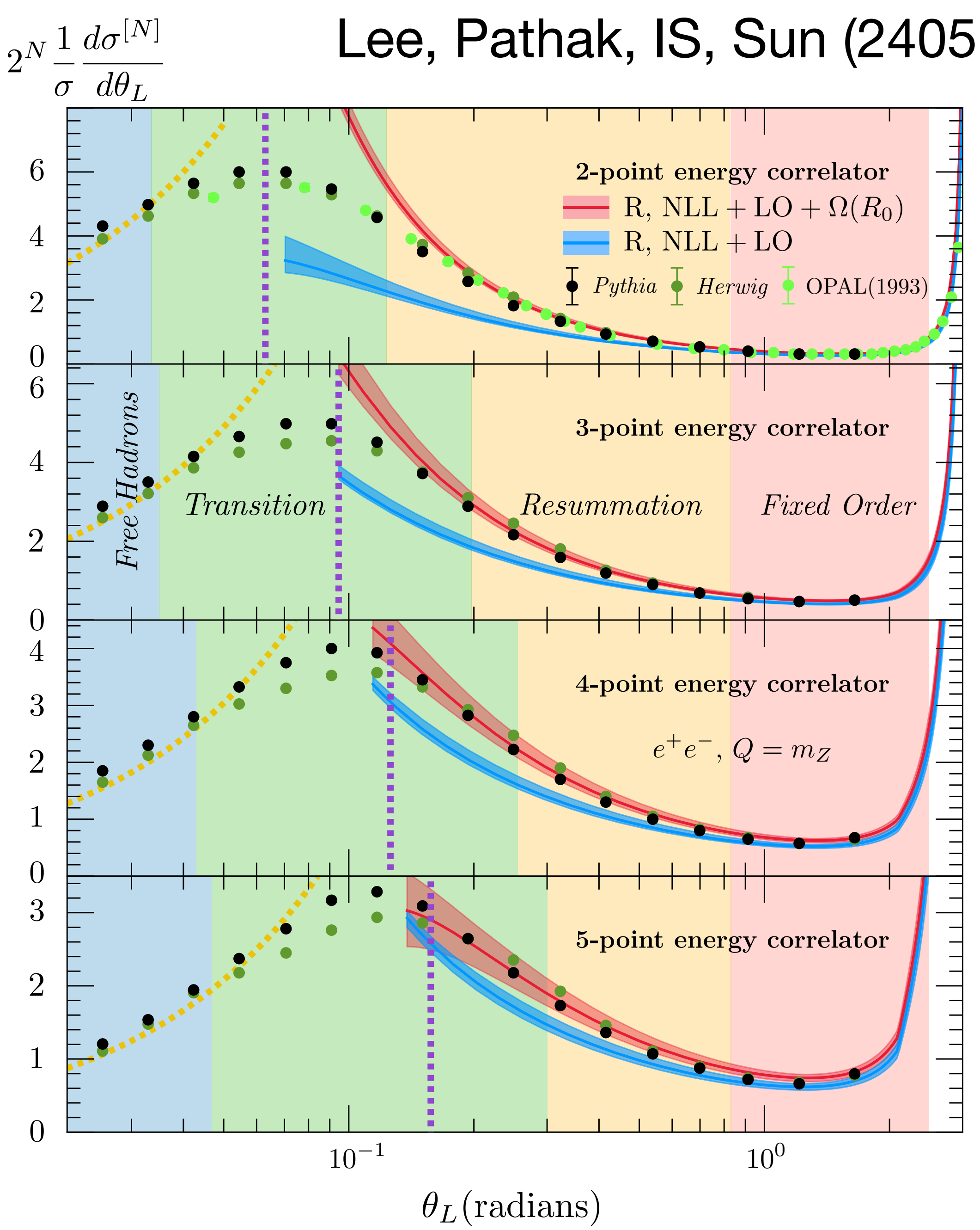
$$\frac{1}{\sigma}\frac{d\sigma^{[N]}}{dx_L} = \boxed{\frac{1}{\sigma}\frac{d\hat{\sigma}^{[N]}}{dx_L}} + \boxed{\frac{N}{2^N}\frac{\bar{\Omega}_{1q}}{Q\left(x_L\left(1-x_L\right)\right)^{3/2}}}$$

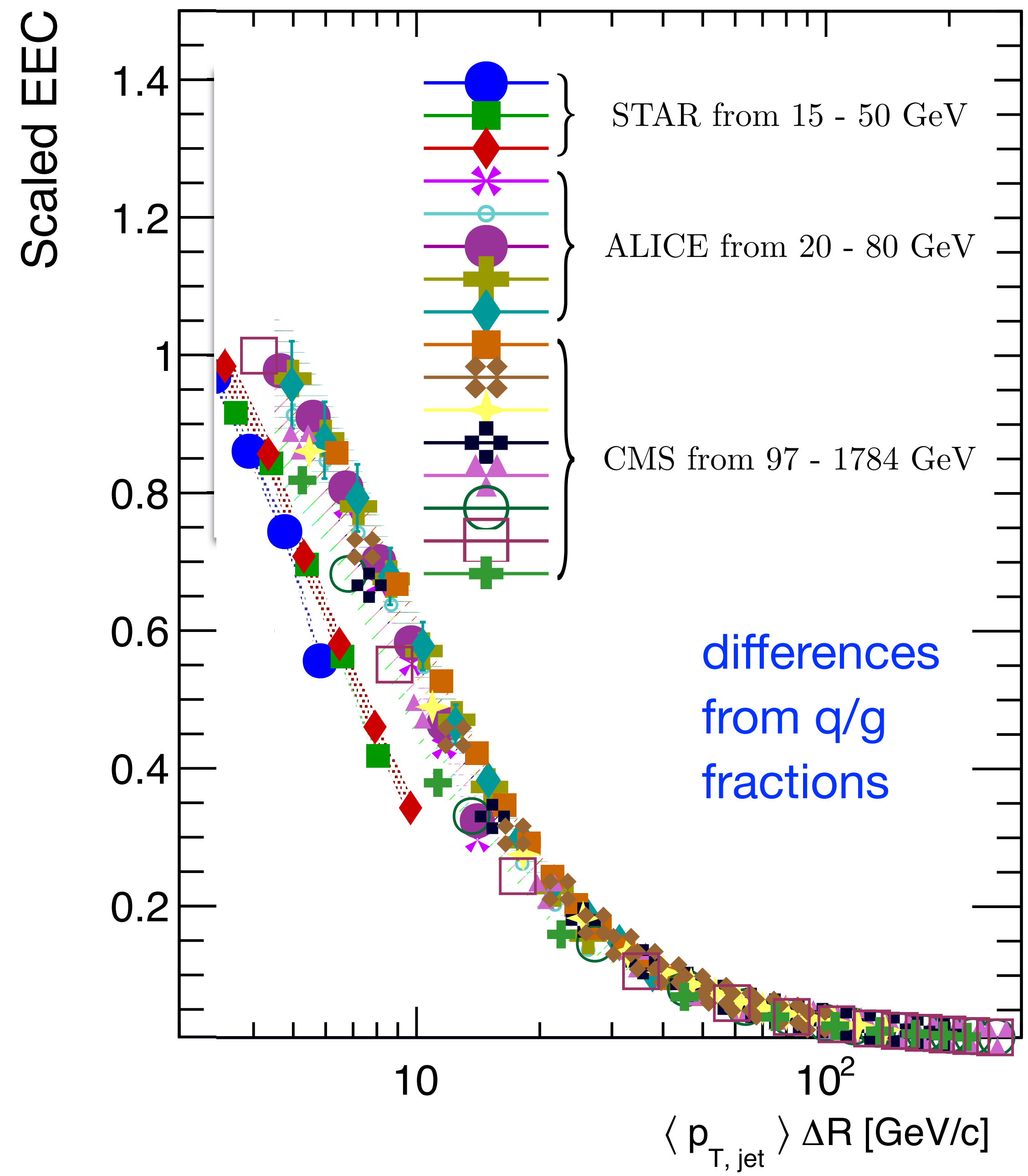
Universal Power Corrections

including leading hadronization corrections!

Korchemsky, Sterman `06
Schindler, IS, Sun `23
Lee, Pathak, IS, Sun `24
Chen, Monni, Xu, Zhu `24

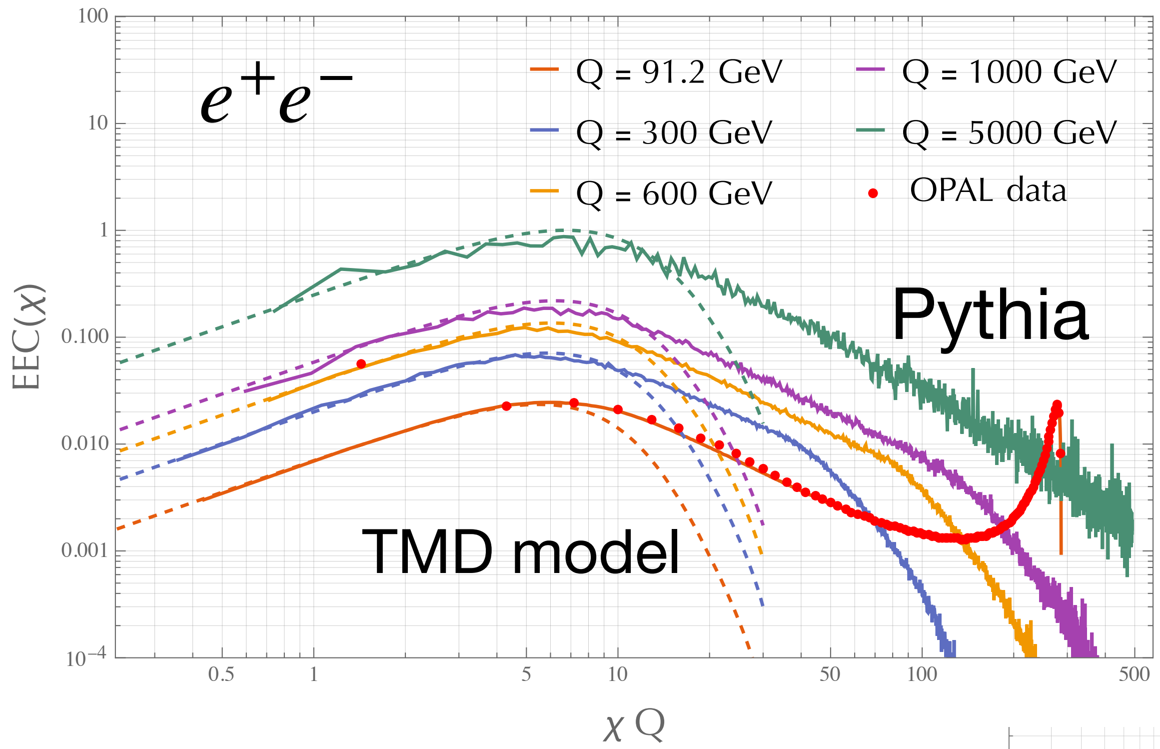
Lee, Pathak, IS, Sun (2405.19396)



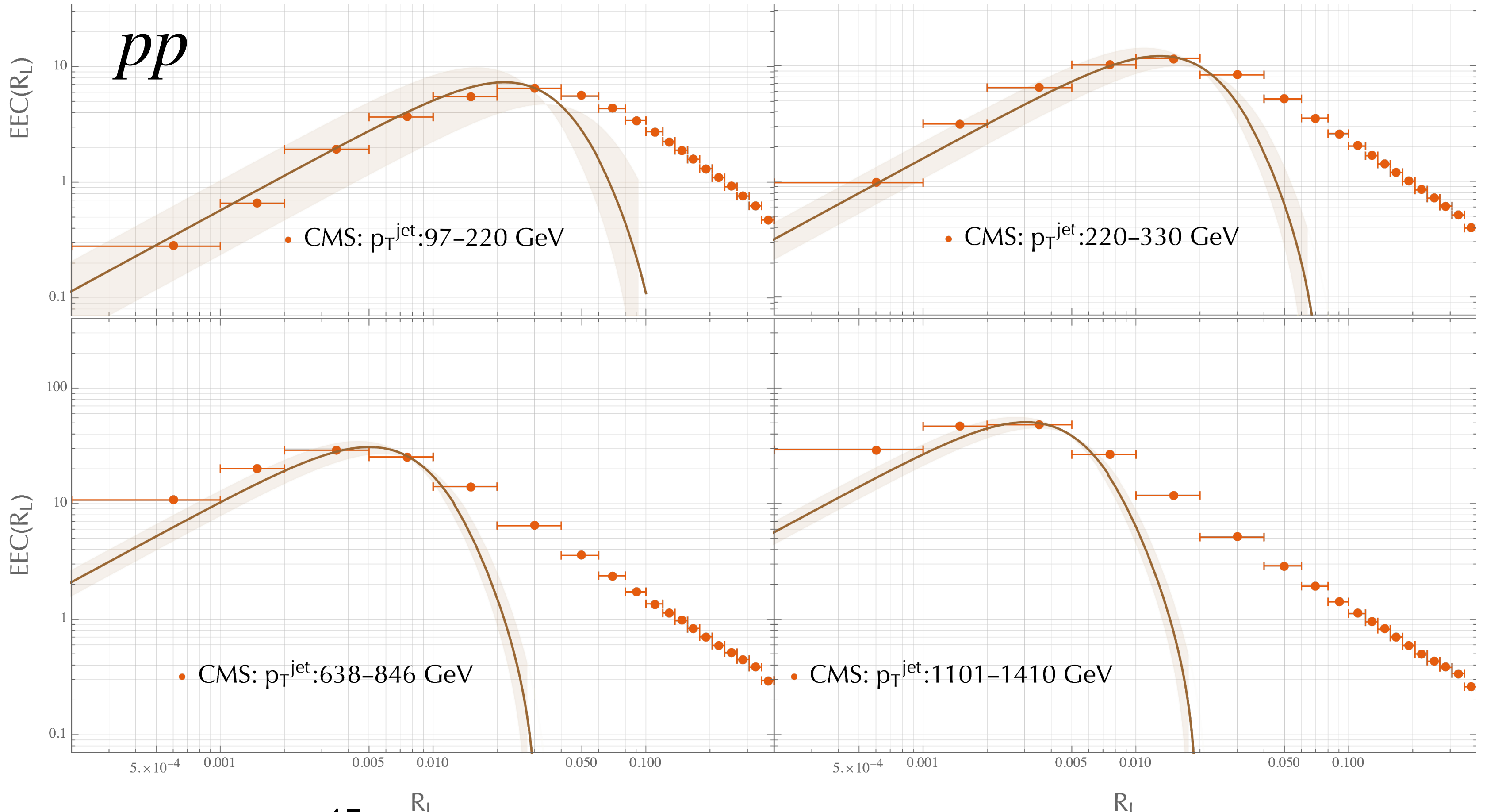


Full QFT based description of the transition is an open problem

Recent progress from free hadron side based on TMD FF models!



1) Liu, Vogelsang, Yuan, Zhu (2410.16371)



Full QFT based description of the transition is an open problem

Recent progress from free hadron side based on TMD FF type models!

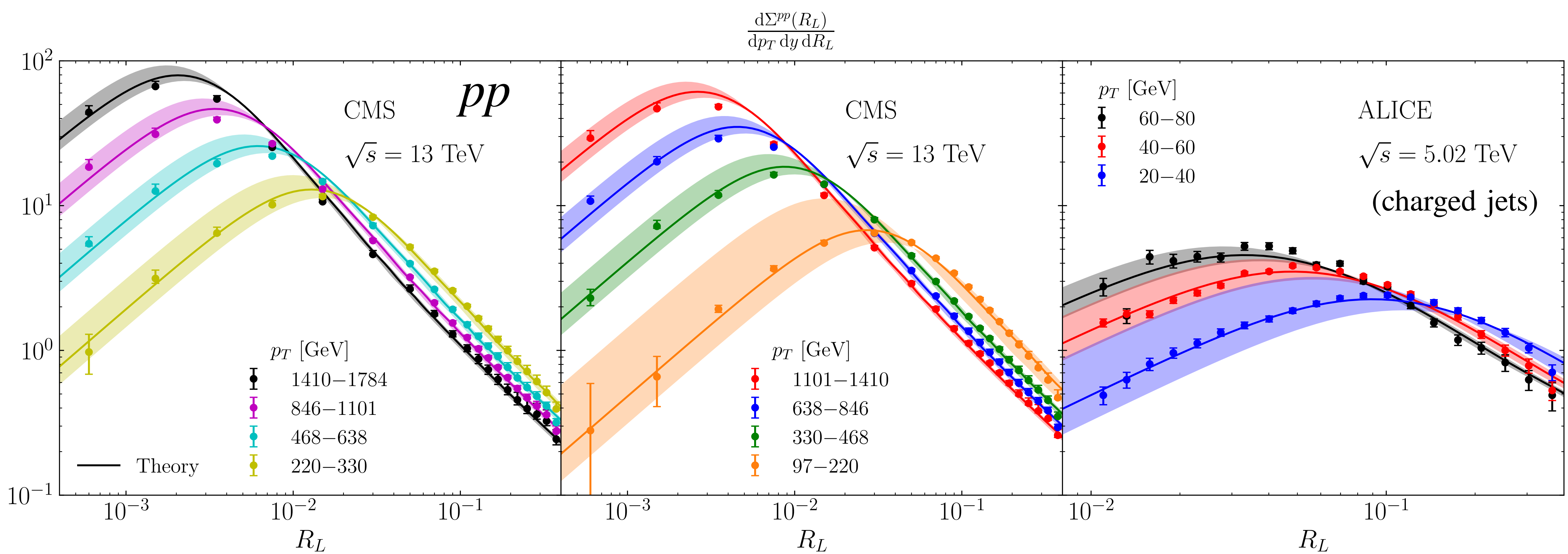
2) Barata, Kang, López, Penttala (2411.11782)

$$\frac{\mathrm{d}\Sigma^{pp}}{\mathrm{d}p_T\,\mathrm{d}y\,\mathrm{d}R_L} = R_L p_T^2 \int_0^\infty \mathrm{d}b\, b\, J_0(R_L p_T b)\, j_{\rm np}(b)\, \widetilde{\Sigma}(b)$$

LL scaling

$$j_{\rm np}(b) = \exp(-a_0 b)$$

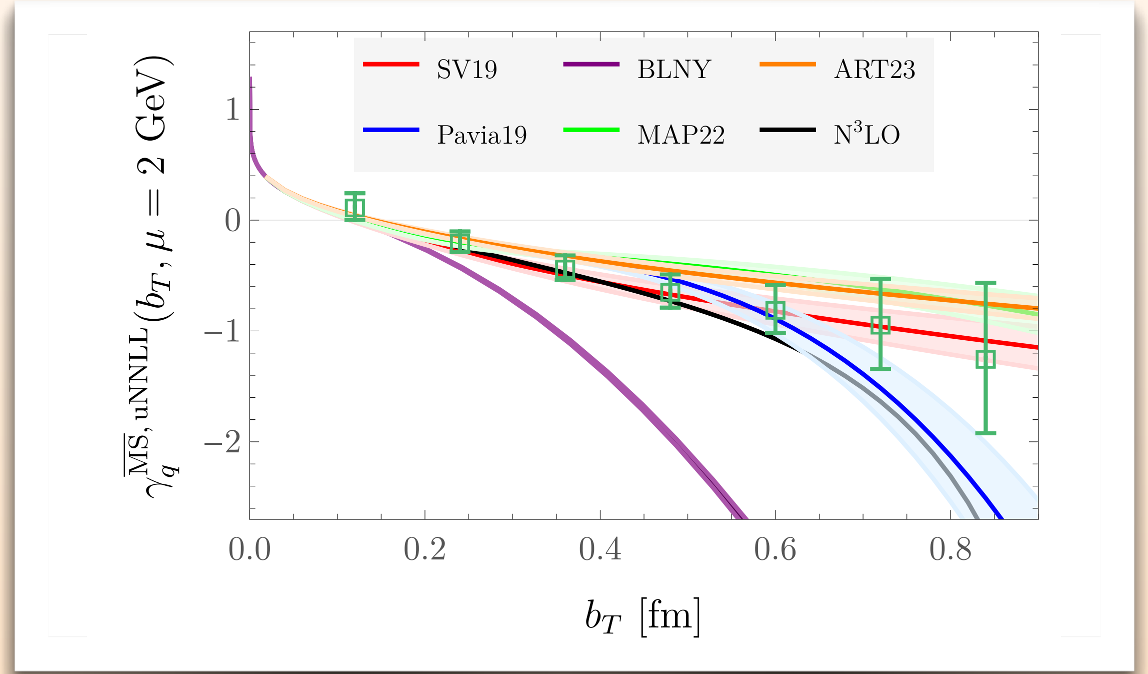
K-factors 0.9 (CMS), 0.75 (ALICE)



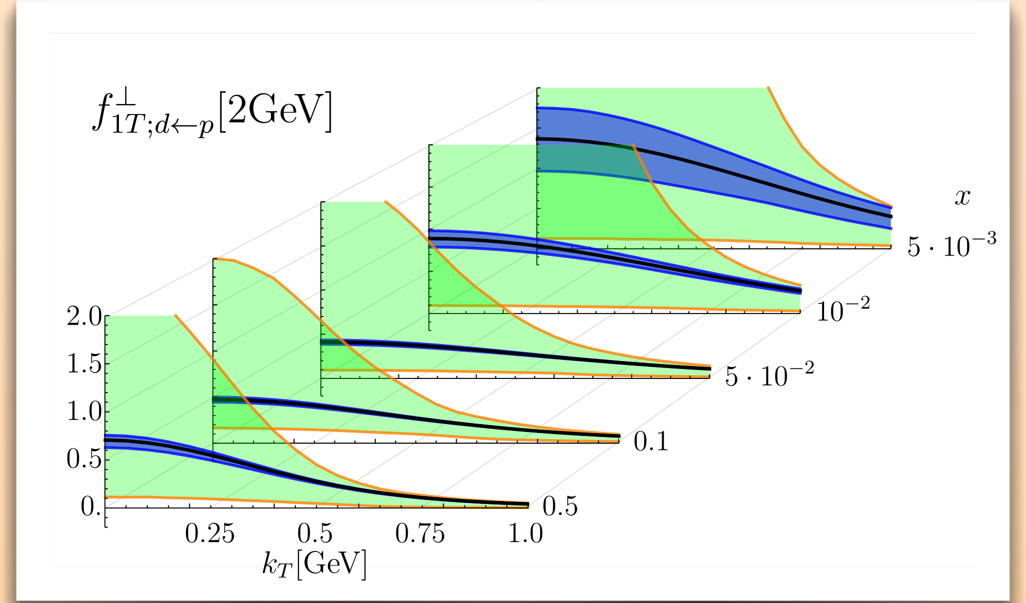
Summary

- TMDs provide new dimensions to probe mysteries of hadronic structure

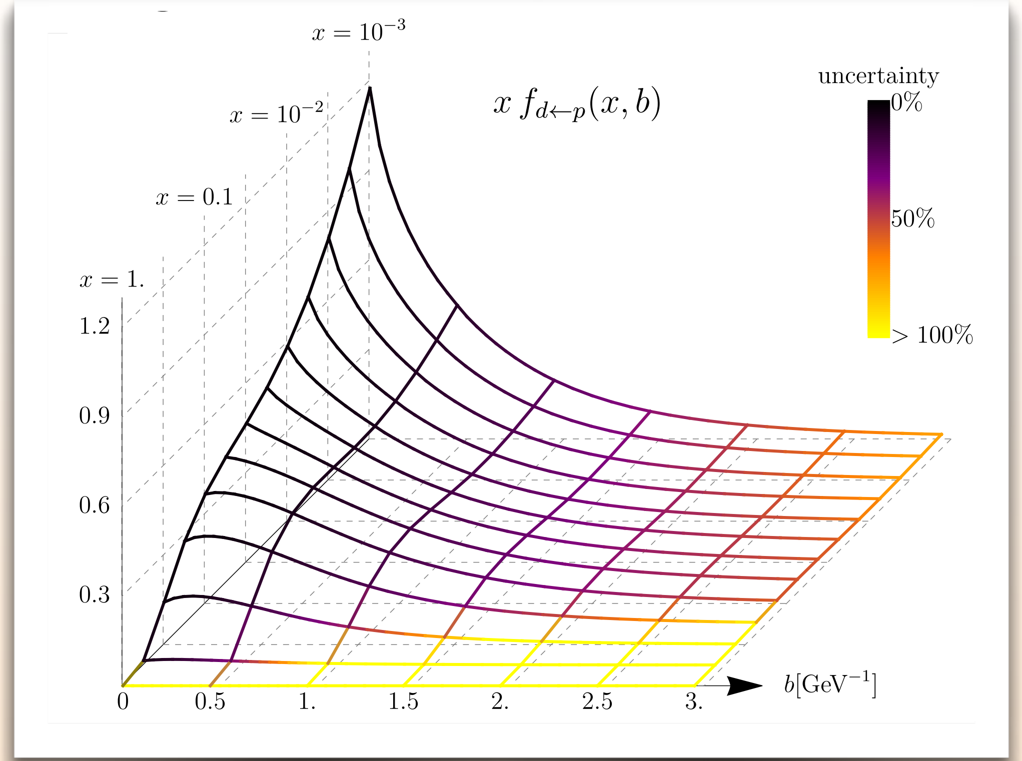
- New Lattice QCD calculations



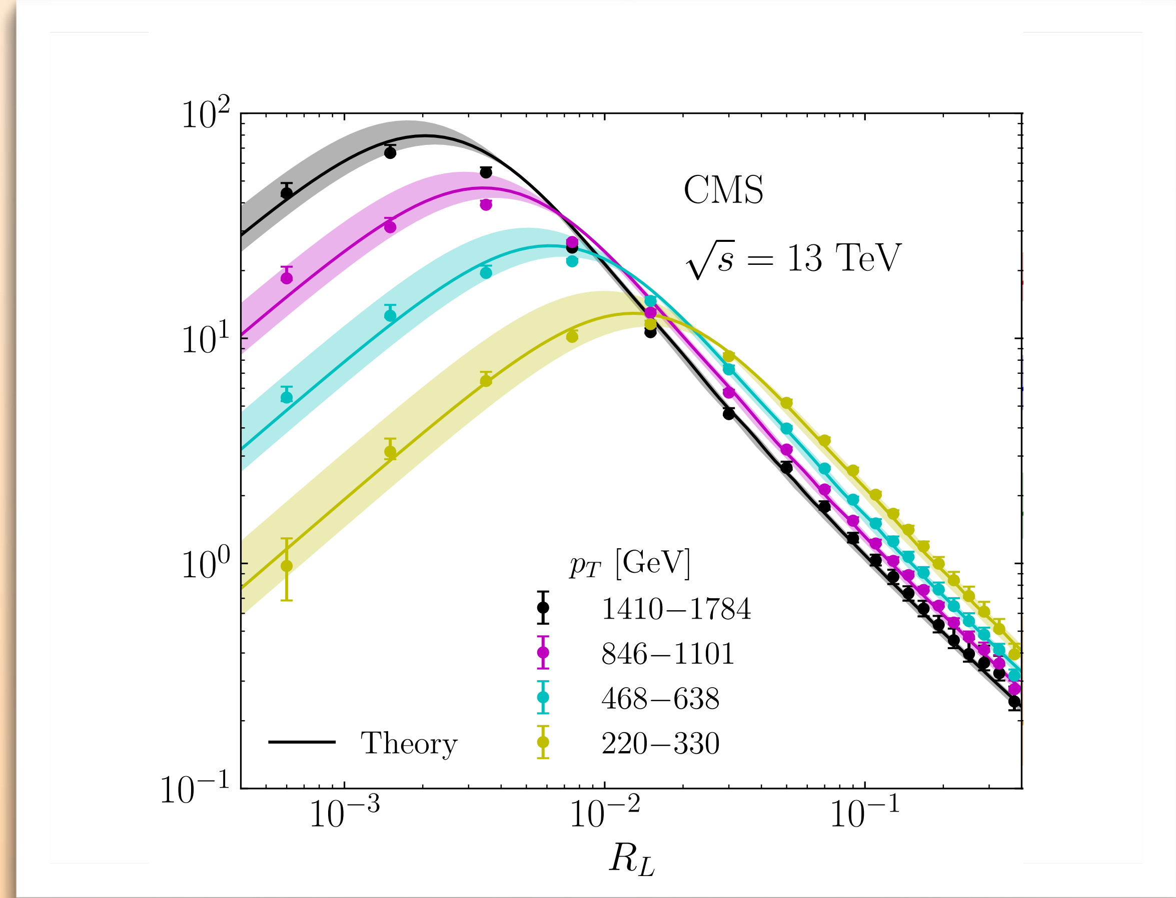
- Many Targets for EIC



- Precision & Global fits



- New insights into hadronization



Backup

TMD Factorization (Drell Yan)

CSS (Collins, Soper, Sterman)

SCET (Soft Collinear Effective Theory)

$$\frac{d\sigma}{dQ\,dY\,dq_T^2} = H(Q,\mu) \int d^2\vec{b}_T\, e^{i\vec{q}_T\cdot\vec{b}_T}\, f_q(x_a,\vec{b}_T,\mu,\zeta_a)\, f_q(x_b,\vec{b}_T,\mu,\zeta_b) \Big[1 + \mathcal{O}\Big(\frac{q_T^2}{Q^2}\Big)\Big]$$

Hard virtual corrections

TMDs

two cutoff parameters

$$\zeta = 2\big(xP^+e^{-y_n}\big)^2$$

$$f_q(x,\vec{b}_T,\mu,\zeta) \sim Z_{\rm uv} B_q / \sqrt{S_q}$$

← complications