Toward a better understanding of the nucleon's 3D structure through kinematic power corrections (KPCs)

Based on S.Piloñeta and A.Vladimirov JHEP12(2024)059 and 2510.14496

IV IPARCOS CONGRESS

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The study of hadron structure

- What do I do? I am interested in studying the structure of nucleons

Work with inelastic particle collisions involving hadrons 

Factorization theorems → Cross-sections factorized into different blocks

$$\frac{d\sigma}{d\,[\ldots]} \sim \int \boxed{\text{Perturbative}} \times \boxed{\text{Non-perturbative}}$$

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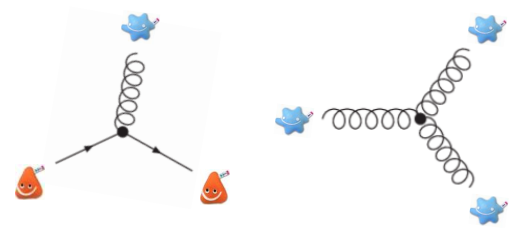
↓

Perturbation theory and Feynman diagrams



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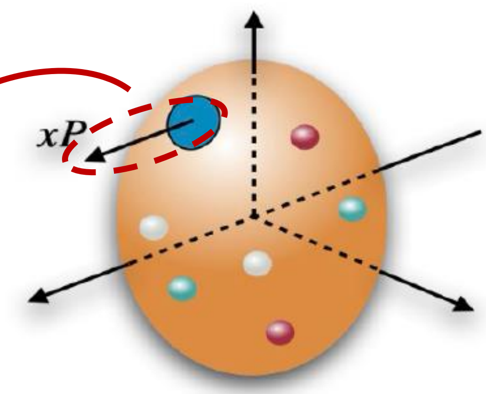

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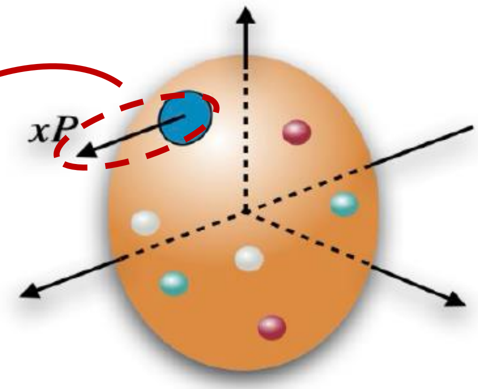

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Transverse Momentum Dependent Distributions (TMDs)

- Generalization of Parton Distributions Functions (PDFs)
  - Incorporate the and transverse momentum
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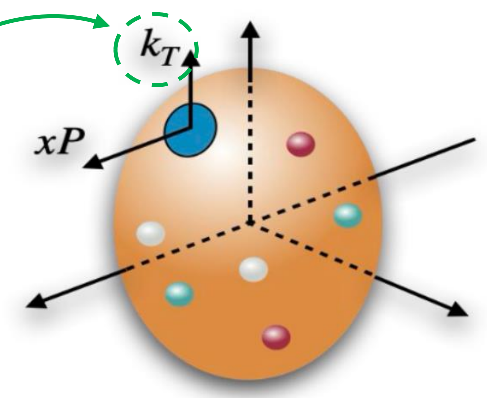

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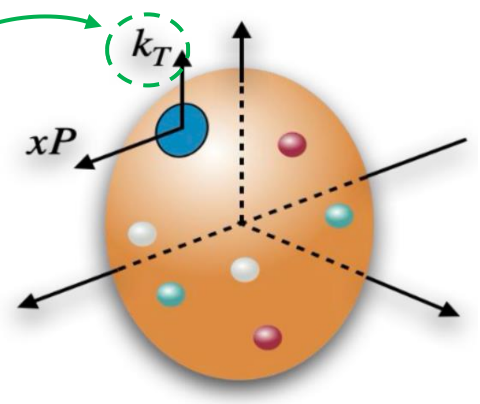
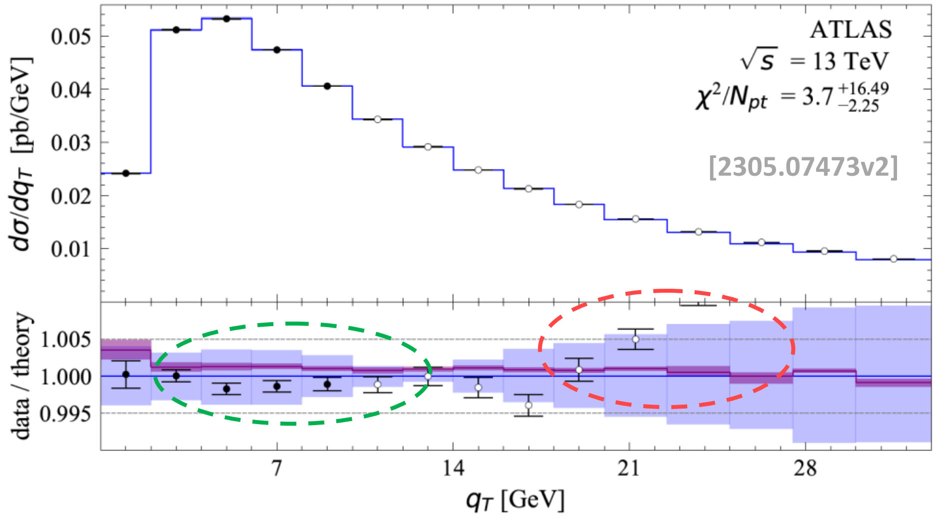
- Extracted from the experimental data through global analyses
  - TMD factorization theorem → Great predictive power



The need for power corrections

- Although it is a very powerful tool, the current form of the TMD factorization has limitations

Z-boson production ATLAS measurement comparison



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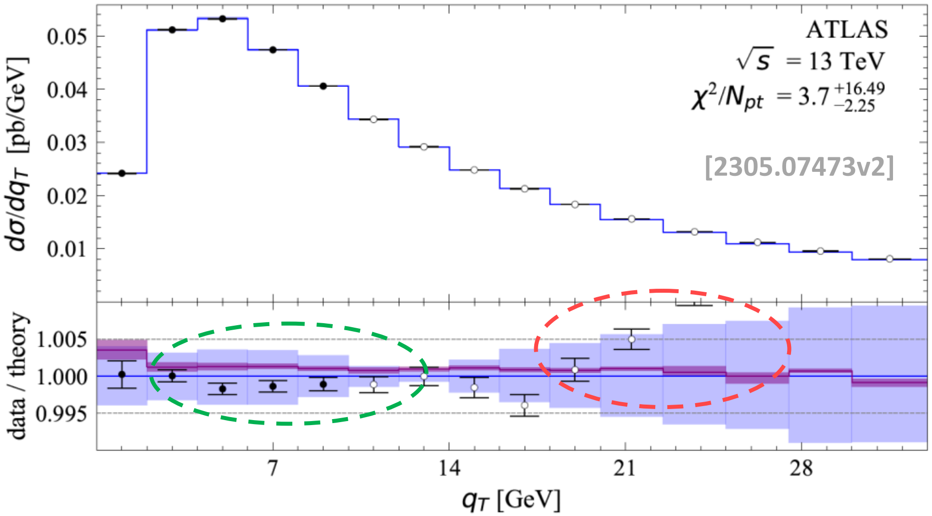

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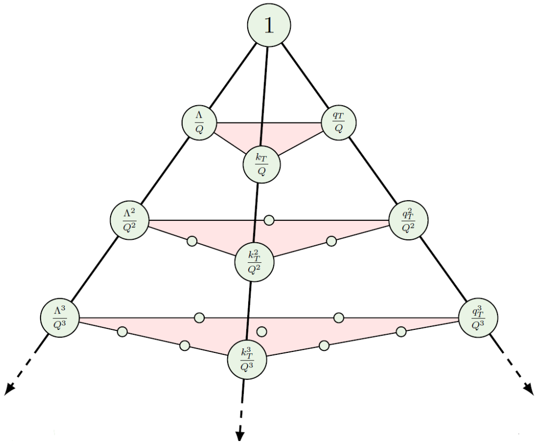

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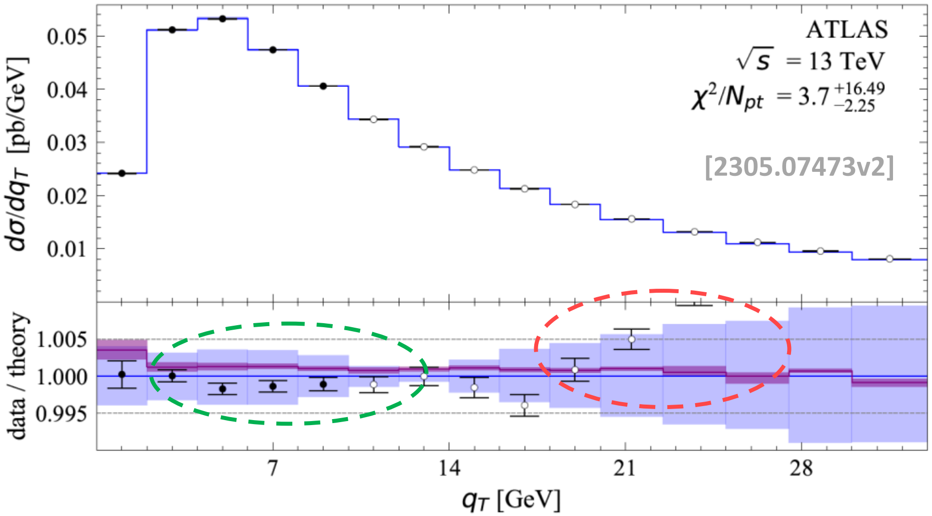

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Develop a theoretical framework including them

For details, see [AV, 2307.13054v2]

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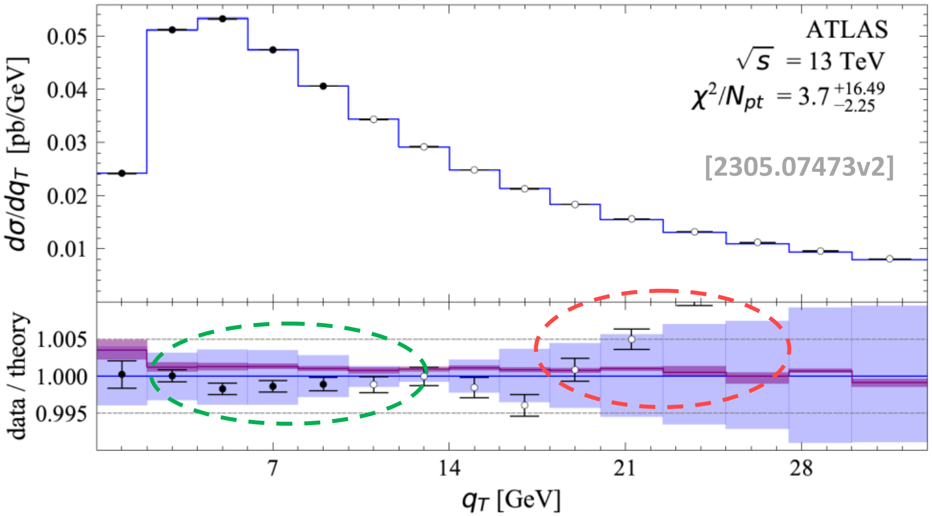

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TMD-with-KPCs factorization theorem

Focus on Kinematic Power Corrections (KPCs)

- We expect that they are the largest in the TMD factorization regime
- Restore EM-gauge invariance and frame invariance

- **Feasibility** of using the **TMD-with-KPCs factorization**

Drell-Yan → Proton ( ) – proton ( ) collision to leptons ( )

→ ***Angular distributions** of Drell-Yan leptons in the TMD factorization approach*

[2407.06277]

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[2407.06277]

Angular decomposition of the cross-section

$$\frac{d\sigma}{d\,[\ldots]} \sim \boxed{\text{Global factor}} \times \sum_i \mathcal{P}_i\, \boxed{A_i}$$

Only four described by usual TMD factorization, while the rest are power-suppressed

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A complete description including KPCs

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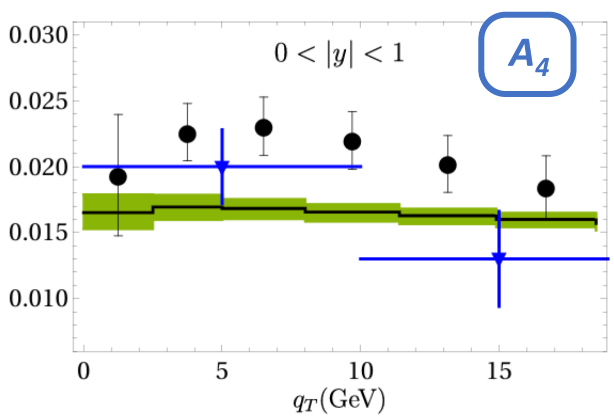
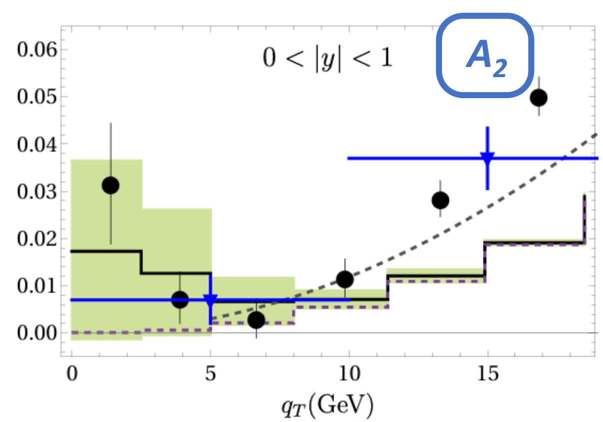
- But… When we **incorporate the summed KPCs**, we can **describe all** of them!





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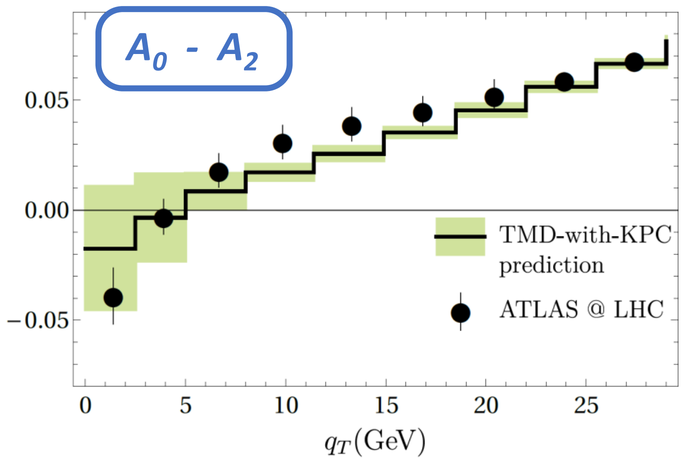
- Satisfactory description for the Lam-Tung relation



KPCs in semi-Inclusive deep inelastic scattering (SIDIS) [I]

- Let's shift our focus to SIDIS → essential process for probing hadron structure

  → Proton () – lepton () collision where 1 hadron is measured

Cross-section decomposition in terms of structure functions

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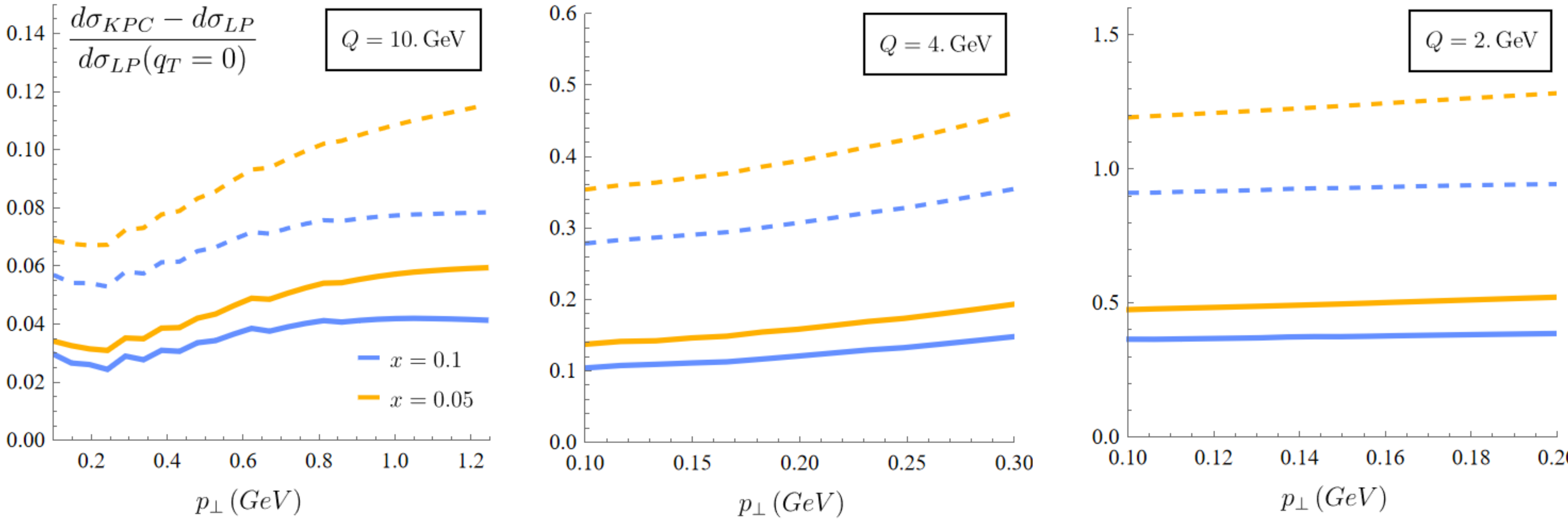
→ **Study the impact of including KPCs on SIDIS observables**

KPCs in semi-Inclusive deep inelastic scattering (SIDIS) [II]



✓ KPCs very important at low energies

Q = 2 GeV → About **40-50%** $\xrightarrow{+F_{UU,L}}$ **Several tens** of percents!

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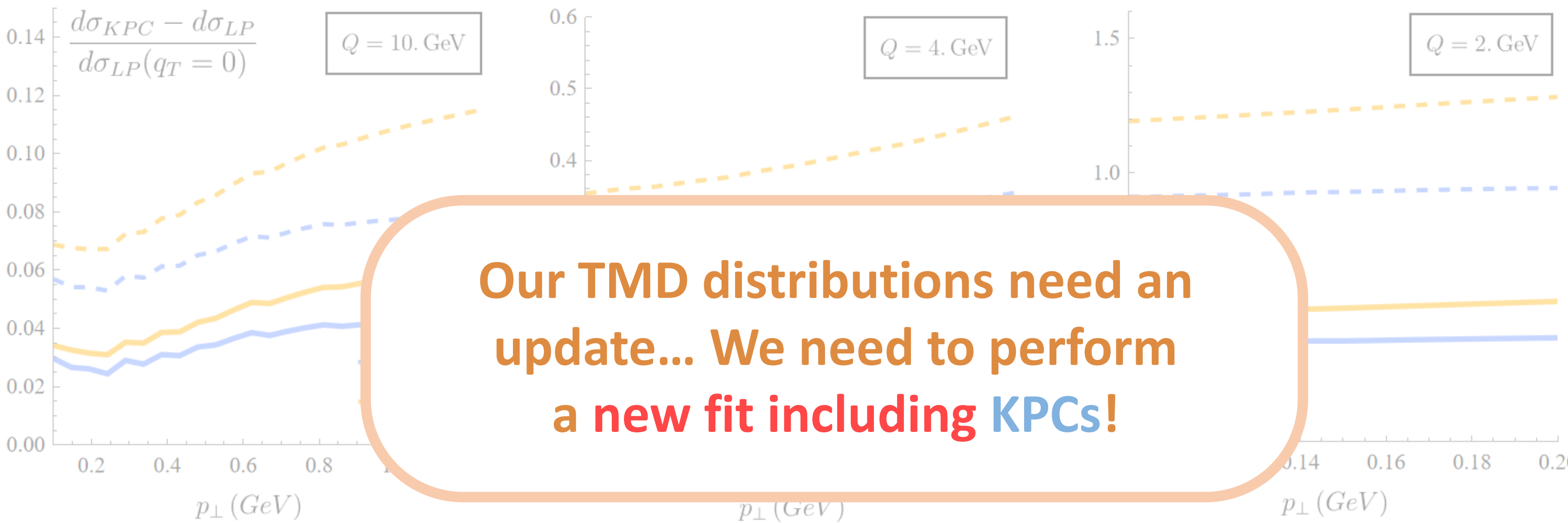

Our TMD distributions need an update… We need to perform a new fit including KPCs!

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Take home messages and future work

- The TMD-with-KPCs factorization theorem [2307.13054v2] has been tested
  - Angular distributions of Drell-Yan leptons can be satisfactorily described [2407.06277]
  - SIDIS structure functions have been computed using it [2510.14496]
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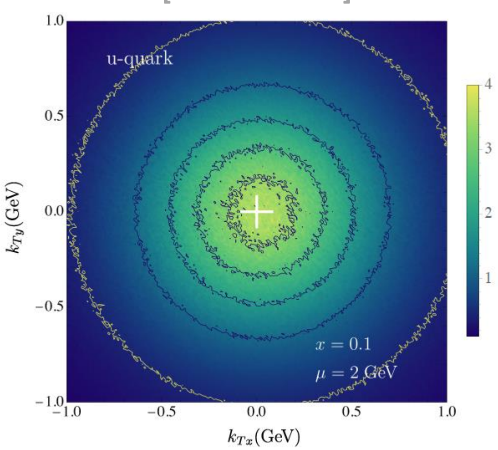
- What comes next?
  - Incorporate these corrections into Drell-Yan and SIDIS fits
    - Extract TMDs including KPCs

Improve tomographic picture of the nucleon

[2103.0327v1]



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Thank you for your attention! ☺

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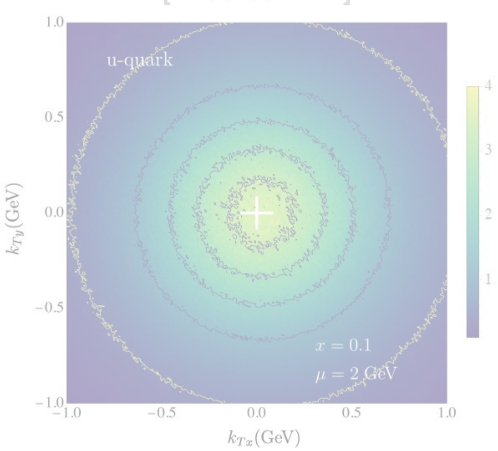


BACKUP

Power corrections

The four types

- **Corrections** to the **LP term** → **suppressed by** powers of $Q\,(\sim q^+ \sim q^-)$ **large scale**
- The power corrections can be categorized into **four** conceptual **types**
  - ❑ **Target-mass** corrections $\sim M/Q$ → hadron mass
  - ❑ ***Higher-twist*** power corrections $\sim (\Lambda/Q)^{n-2}$ → TMDs of larger **twist** ***(n = D − S)***
  - ❑ q_T/Q power corrections

Position space

$$\sim \frac{1}{bQ}$$

↔

Momentum space

$$\sim \frac{q_T}{Q}$$

  - ❑ k_T/Q power corrections → **Kinematic Power Corrections (KPCs)**

Position space

$$\sim F_1(x_1, b)\,\frac{\partial}{\partial b^\mu}\,F_2(x_2, b)$$

↔

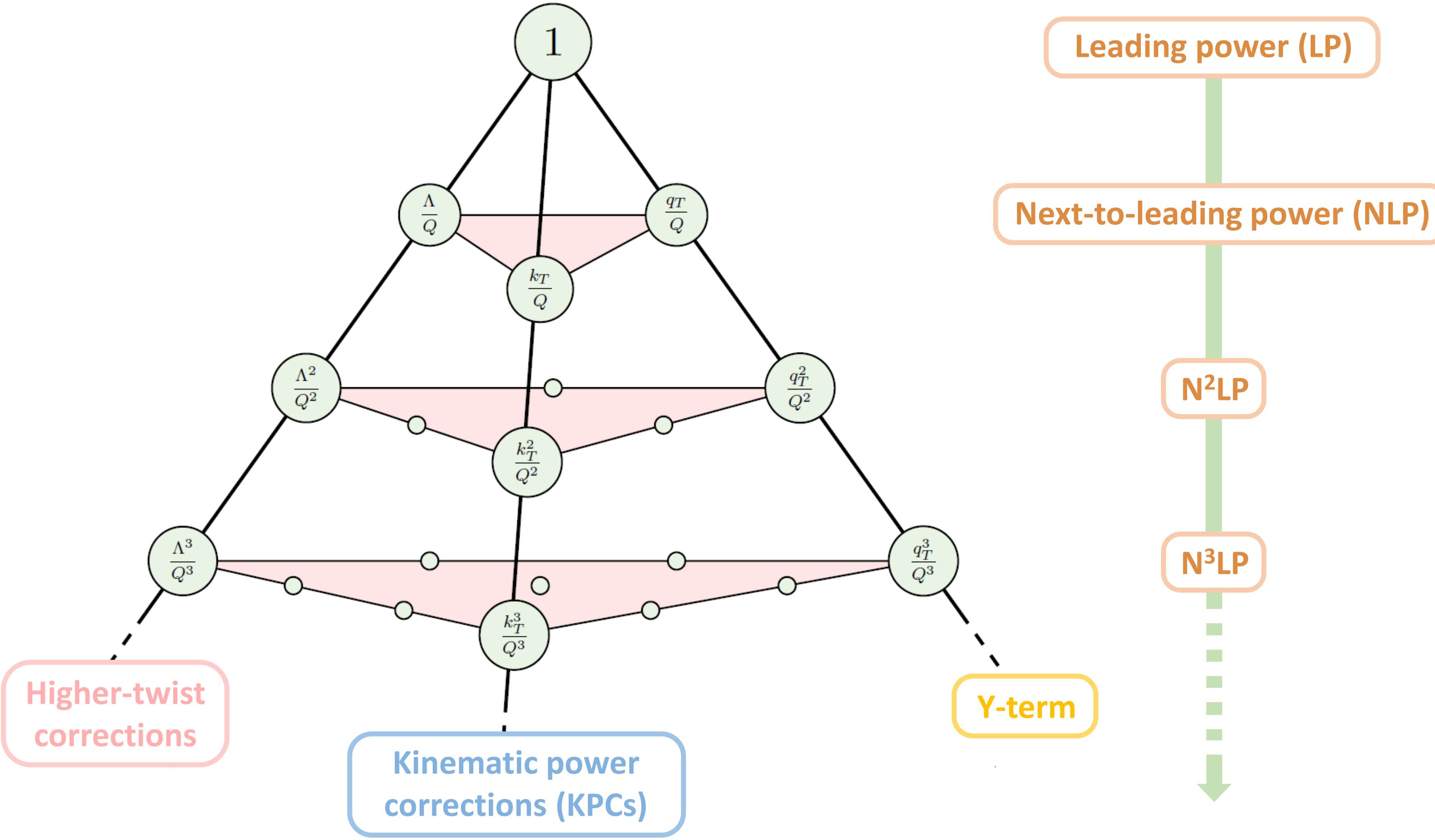
Momentum space

$$\sim \frac{k_{2T}^\mu}{Q} F_1(x_1, k_{1T}) F_2(x_2, k_{2T})$$

→ **Transverse derivatives** of TMD distributions

The hierarchy of the TMD factorization theorem

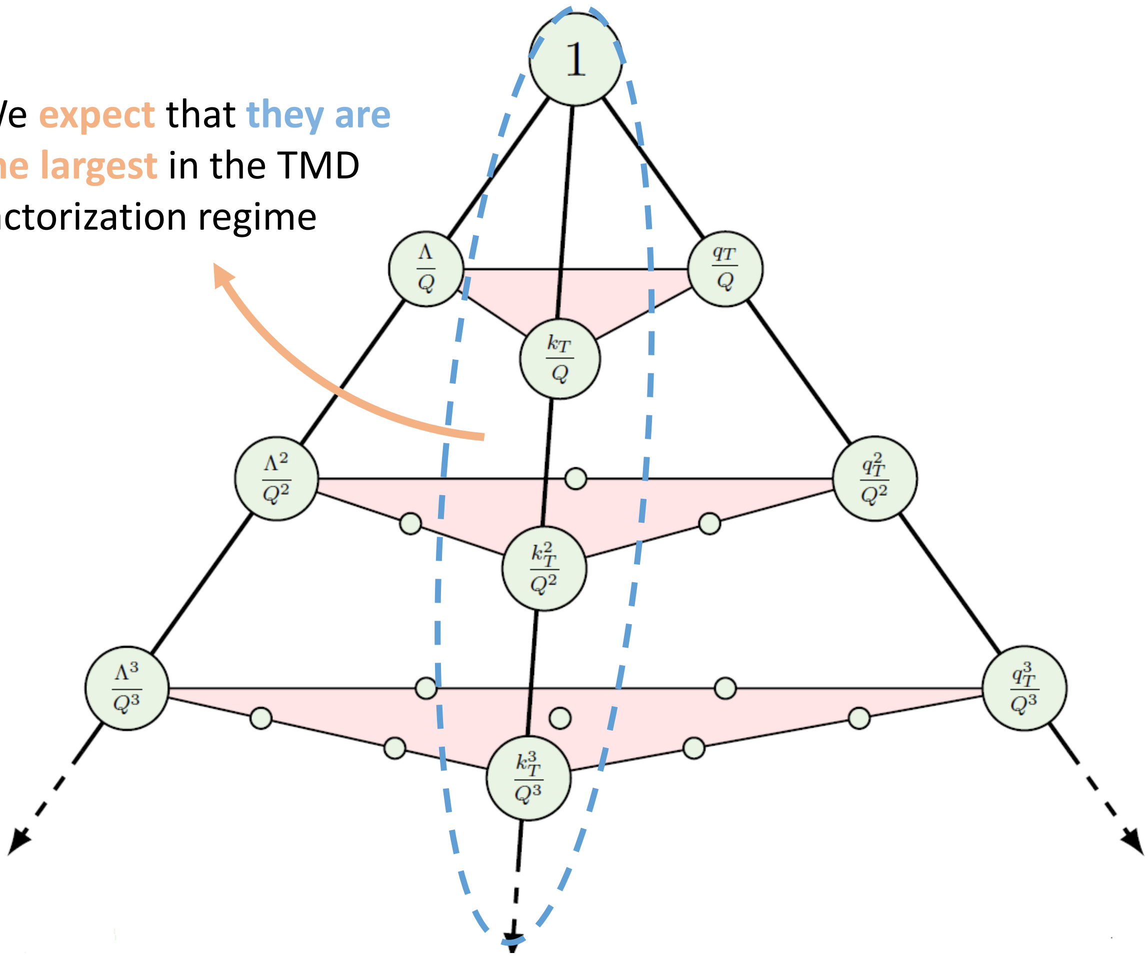
- There is a whole “pyramid” of power corrections



The TMD-with-KPCs factorization theorem

- We focus on the kinematic power corrections (KPCs) that follow the LP term

We expect that they are the largest in the TMD factorization regime



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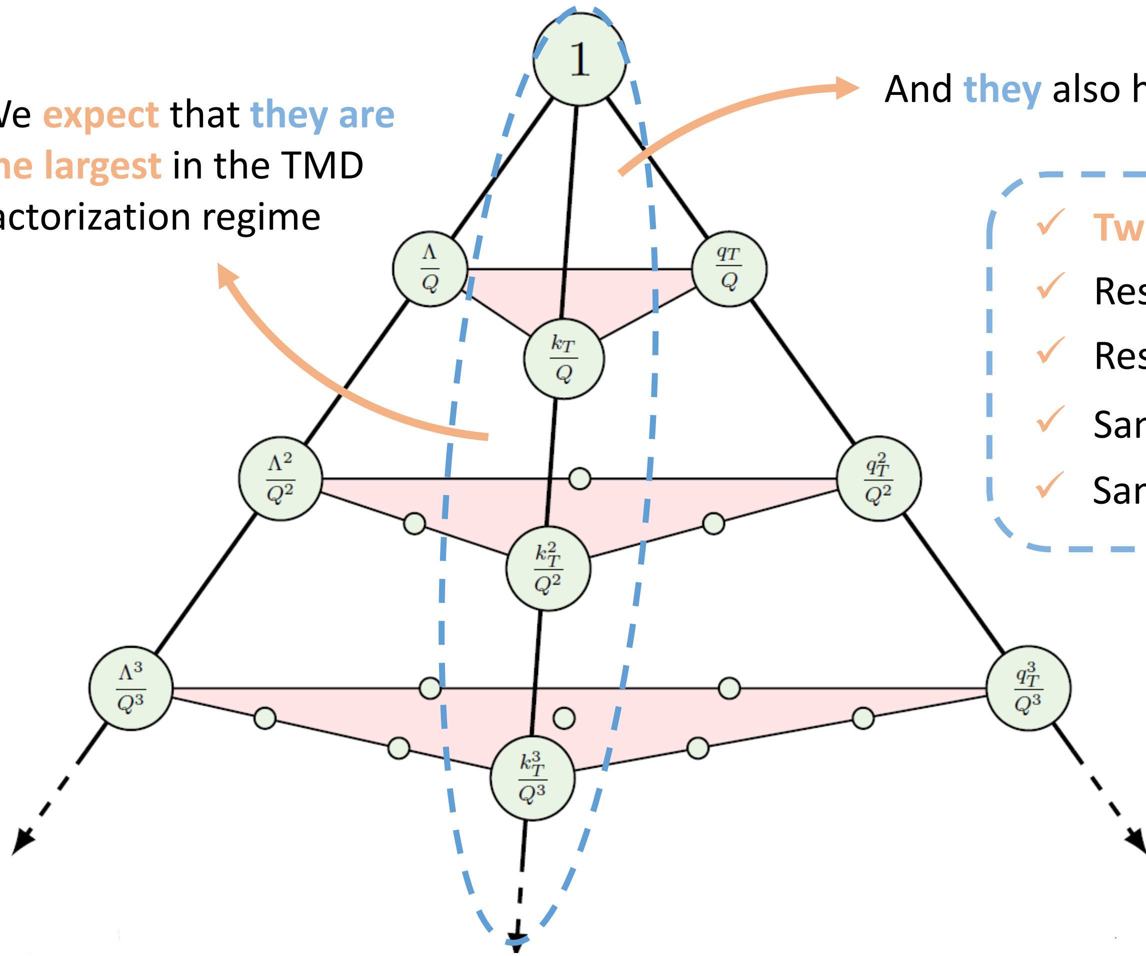

And they also have nice properties!

- ✓ Twist-2 terms at $q_T \ll Q$
- ✓ Restore EM-gauge invariance
- ✓ Restore frame-invariance
- ✓ Same TMD distributions as LP
- ✓ Same coefficient function as LP

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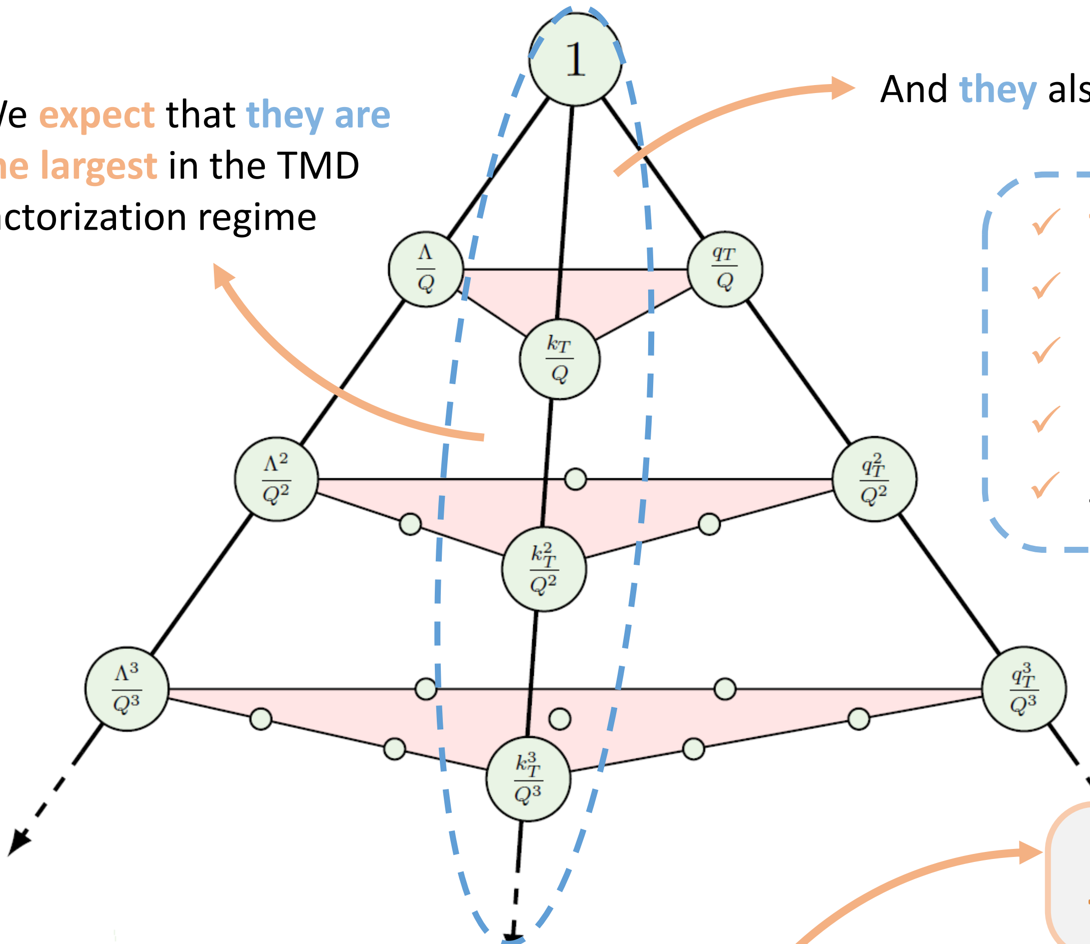

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TMD-with-KPCs factorization theorem

Theoretical framework including them

For details, see [AV, 2307.13054v2]

The hierarchy of the TMD factorization theorem

- General structure of the TMD factorization theorem

$$
\begin{aligned}
W^{\mu\nu} = \frac{1}{N_c}\int \frac{d^2b}{(2\pi)^2}\, e^{-i(bq_T)} \Big\{ & \\
& \boxed{\Phi_2 \times \Phi_2 \quad \text{LP}} \\
& + \frac{1}{Q}\boxed{\Big(D\;\; \Phi_2 \times \Phi_2 + \quad \Phi_2 \times \Phi_3\Big) \;\text{NLP}} \\
& + \frac{1}{Q^2}\boxed{\Big(D^2\, \Phi_2 \times \Phi_2 + D\;\; \Phi_2 \times \Phi_3 + \quad \Phi_3 \times \Phi_3 + \quad \Phi_2 \times \Phi_4 + \frac{\Phi_2 \times \Phi_2}{b^2}\Big) \;\text{NNLP}} \\
& + \frac{1}{Q^3}\Big(D^3\, \Phi_2 \times \Phi_2 + D^2\, \Phi_2 \times \Phi_3 + D\;\; \Phi_3 \times \Phi_3 + D\;\; \Phi_2 + \Phi_4 + D\frac{\Phi_2 \times \Phi_2}{b^2} + \dots\Big) \\
& + \frac{1}{Q^4}\Big(D^4\, \Phi_2 \times \Phi_2 + \dots\Big) \\
& + \;\dots \Big\}^{\mu\nu}
\end{aligned}
$$

Notation

Φ_n → TMD of twist-n

$\times$ → Integral convolution

$D \sim \frac{\partial}{\partial b^\mu}$ → transverse derivative

The hierarchy of the TMD factorization theorem

- **General structure** of the **TMD factorization theorem**

$$
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&+ \frac{1}{Q^2}\Big(D^2\,\Phi_2 \times \Phi_2 + D\ \Phi_2 \times \Phi_3 + \Phi_3 \times \Phi_3 + \Phi_2 \times \Phi_4 + \frac{\Phi_2 \times \Phi_2}{b^2}\Big) \\
&+ \frac{1}{Q^3}\Big(D^3\,\Phi_2 \times \Phi_2 + D^2\,\Phi_2 \times \Phi_3 + D\ \Phi_3 \times \Phi_3 + D\ \Phi_2 + \Phi_4 + D\frac{\Phi_2 \times \Phi_2}{b^2} + \dots\Big) \\
&+ \frac{1}{Q^4}\Big(D^4\,\Phi_2 \times \Phi_2 + \dots\Big) \\
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Each **column**
- Series of KPCs to the first term
- Unique non-perturbative content
- Independent contributions

The hierarchy of the TMD factorization theorem

- **General structure** of the **TMD factorization theorem**

$$W^{\mu\nu} = \frac{1}{N_c}\int \frac{d^2b}{(2\pi)^2}\, e^{-i(bq_T)} \Bigg\{ \Phi_2 \times \Phi_2$$

k_T/Q

$$+\frac{1}{Q}\Big(D\ \Phi_2\times\Phi_2 + \Phi_2\times\Phi_3\Big)$$

k^2_T/Q^2

$$+\frac{1}{Q^2}\Big(D^2\,\Phi_2\times\Phi_2 + D\ \Phi_2\times\Phi_3 + \Phi_3\times\Phi_3 + \Phi_2\times\Phi_4 + \frac{\Phi_2\times\Phi_2}{b^2}\Big)$$

k^3_T/Q^3

$$+\frac{1}{Q^3}\Big(D^3\,\Phi_2\times\Phi_2 + D^2\,\Phi_2\times\Phi_3 + D\ \Phi_3\times\Phi_3 + D\ \Phi_2 + \Phi_4 + D\frac{\Phi_2\times\Phi_2}{b^2} + \ldots\Big)$$

k^4_T/Q^4

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$$+\ \ldots\ \Bigg\}^{\mu\nu}$$

Notation

- Φ_n → TMD of twist-n
- $\times$ → Integral convolution
- $D \sim \frac{\partial}{\partial b^\mu}$ → transverse derivative

KPCs following the **LP term**

- Same TMDs and perturbative part as LP
- All power-suppressed terms containing twist-2 TMDs
- Restoration of gauge and frame invariance

Angular distributions of Drell-Yan leptons

- Feasibility of using the TMD-with-KPCs factorization → unpolarized Drell-Yan as a starting point

→ *Angular distributions of Drell-Yan leptons in the TMD factorization approach*

→ First practical application of this framework [S. Piloñeta, AV, 2407.06277]

Angular decomposition of the cross-section

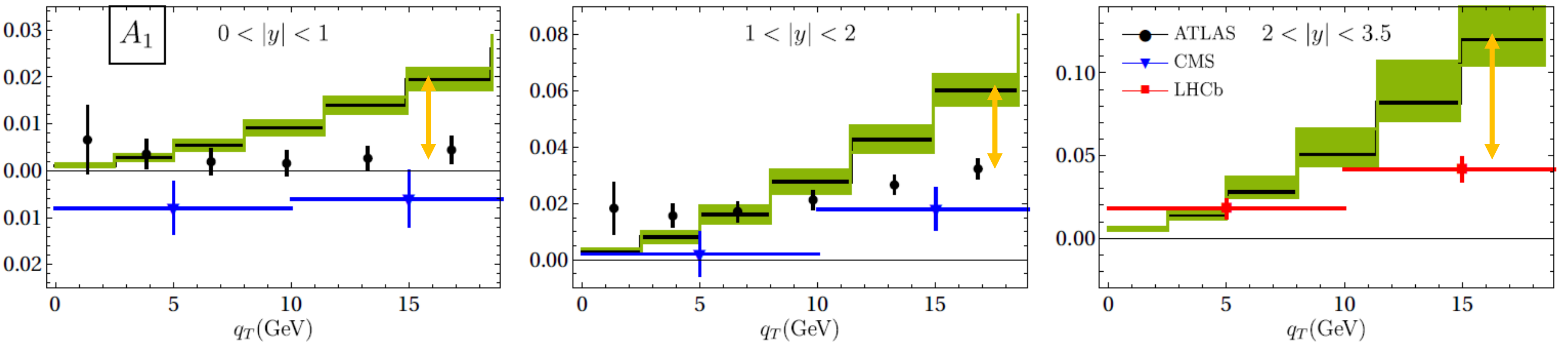
$$\frac{d\sigma}{dp_T dy dQ d\Omega} = \frac{3}{16\pi} \boxed{\frac{d\sigma^{U+L}}{dp_T dy dQ}} \Big[(1+\cos^2\theta) + \frac{1-3\cos^2\theta}{2} A_0 + \sin 2\theta \cos\phi A_1 + \frac{\sin^2\theta\cos 2\phi}{2} A_2 + \sin\theta\cos\phi A_3 + \cos\theta A_4 + \sin^2\theta \sin 2\phi A_5 + \sin 2\theta \sin\phi A_6 + \sin\theta\sin\phi A_7 \Big]$$

A_U → Unpolarized angle-integrated cross-section

$A_{0,\dots,7}$ → Only four at LP $\{A_U, A_2, A_4, A_5\}$

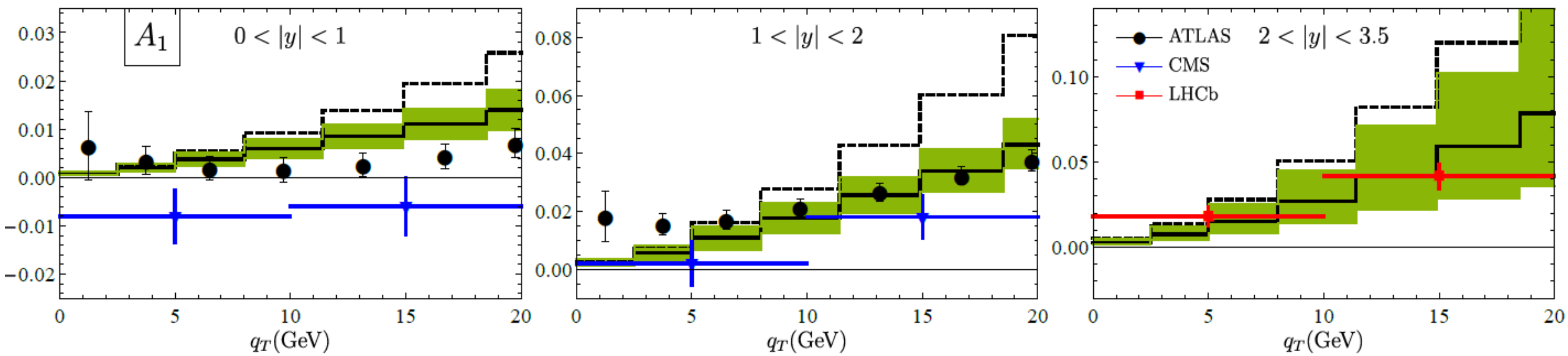
→ The rest are power-suppressed

Angular distribution A_1



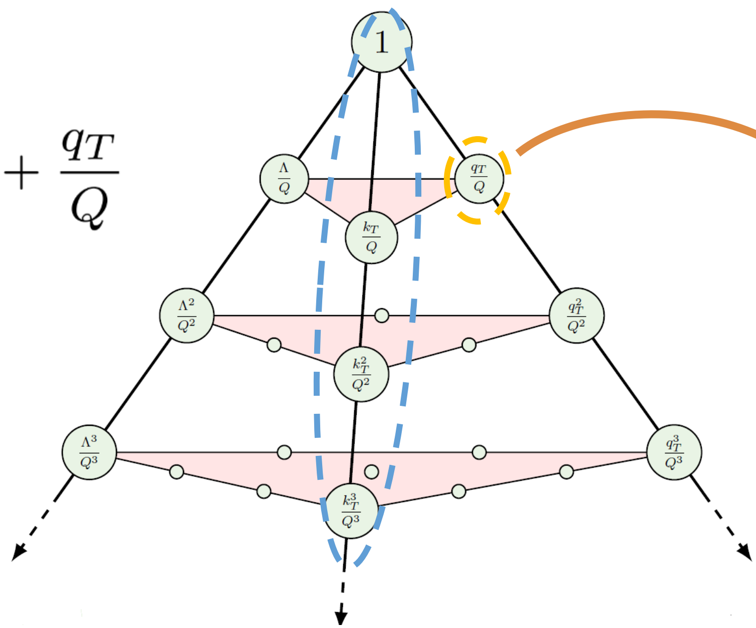
- Problems with the A_1 data description at larger values of q_T

Angular distribution A_1



- **Problems** with the A_1 data description at **larger values of q_T**

KPCs $+ \dfrac{q_T}{Q}$



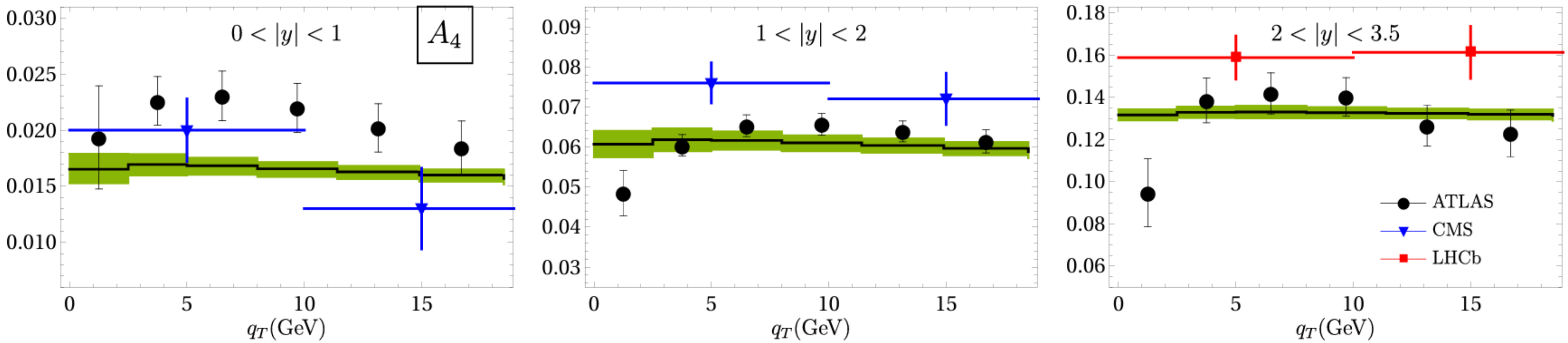
Including the computation of the **leading q_T/Q correction** fixes the jump!

[A.Arroyo, I.Scimemi, AV, 2503.24336]

Angular distribution A_4

- **Leading power**
- Proportional to the **difference between quark and anti-quark** distributions (**anti-symmetric flavor**)
- **Inclusion** in standard f_1 **extractions**

➢ Comparison as a **function** of q_T with **ATLAS**, **CMS** and **LHCb** measurements

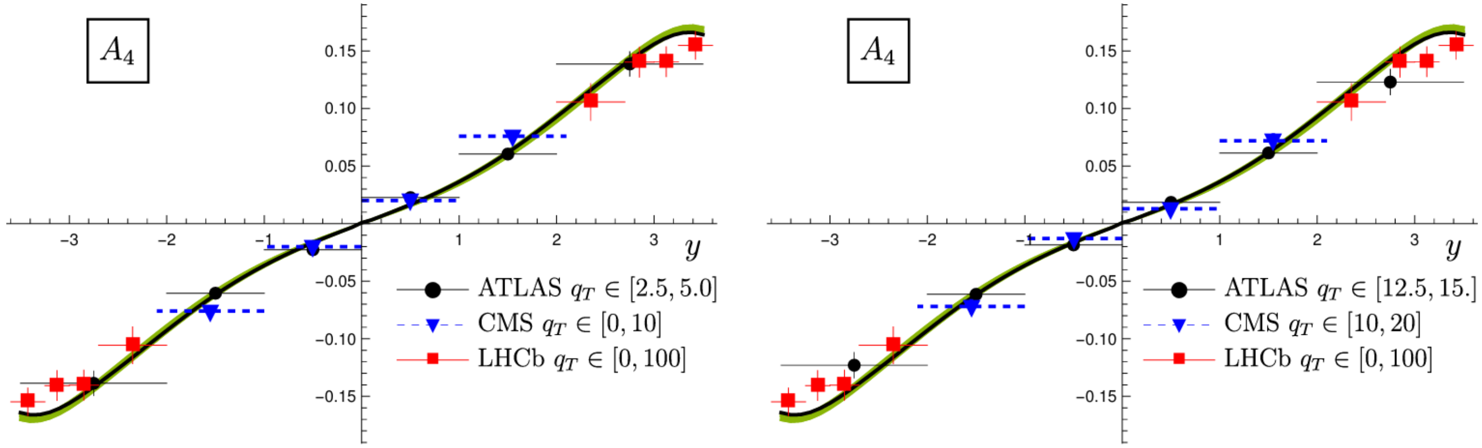


- Theory **prediction agrees** very well **with the measurements**

Angular distribution A_4

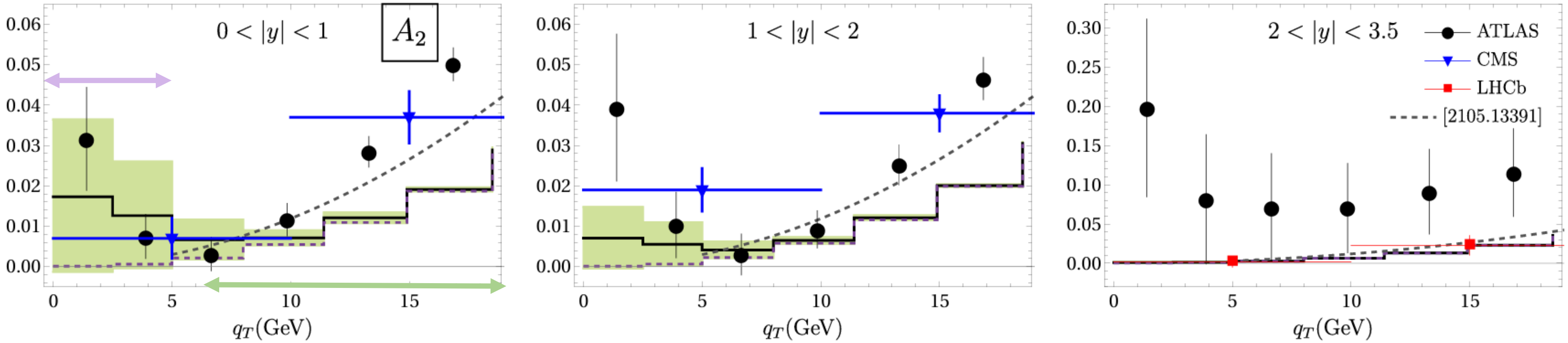
- Leading power
- Proportional to the difference between quark and anti-quark distributions (anti-symmetric flavor)
- Inclusion in standard f_1 extractions

➢ Comparison as a function of y with **ATLAS**, CMS and LHCb measurements



- The agreement is even more transparent

Angular distribution A_2



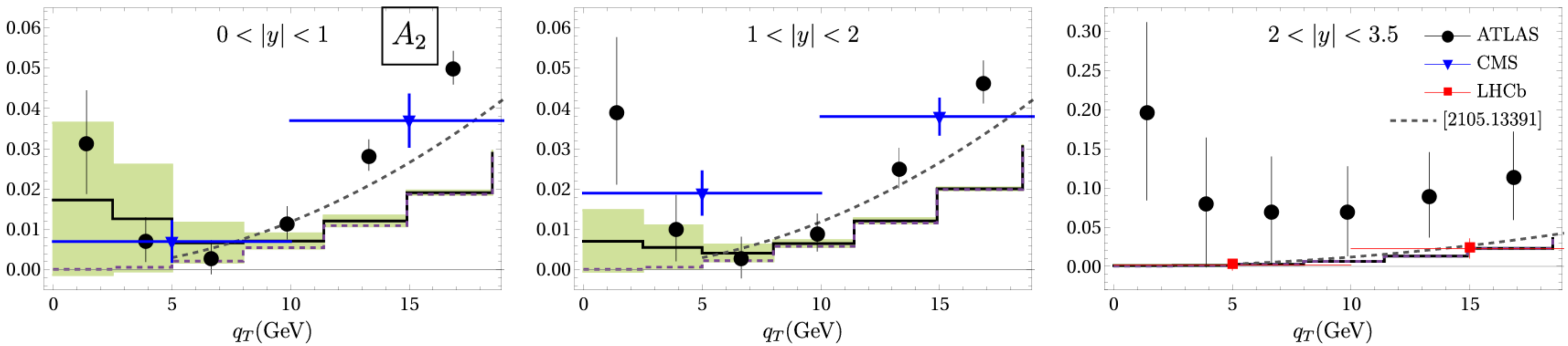
$$A_2 \sim \left[(v^2 - a^2)_q \frac{h_1^\perp h_1^\perp}{M^2} + (v^2 + a^2)_q \frac{f_1 f_1}{Q^2}\right]$$

Dominant at larger q_T

Dominant at $q_T \to 0$

- Contains both Boer-Mulders and unpolarized distributions

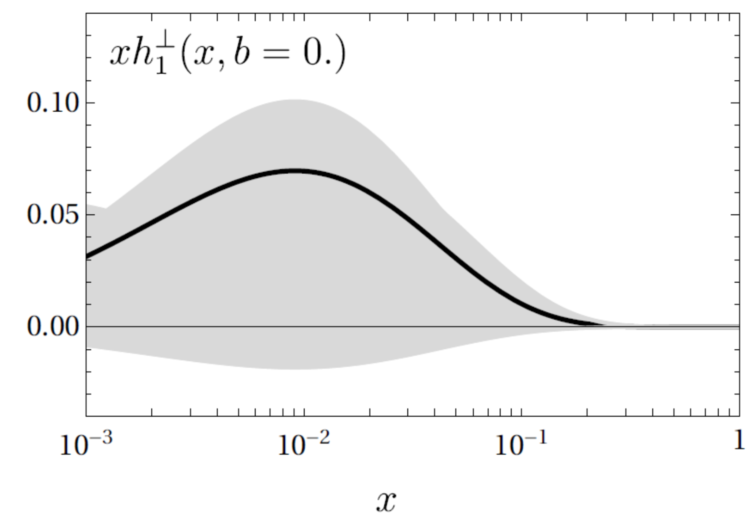
Angular distribution A_2



$$A_2 \sim \left[(v^2 - a^2)_q \frac{h_1^\perp h_1^\perp}{M^2} + (v^2 + a^2)_q \frac{f_1 f_1}{Q^2}\right]$$

- Boer-Mulders distribution extraction from A_2
  - Very primitive model
    - New fit is required
  - First evidence (?) of twist-3 effects at LHC

$x|E(-x,0,x)|$



Lam-Tung relation ($A_0 - A_2$) description

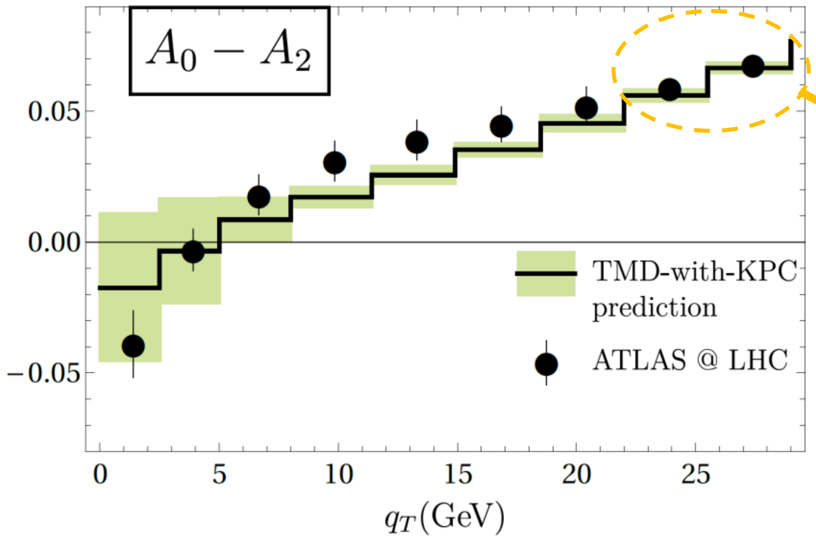
- At leading power, the TMD factorization theorem can not describe it

$$(A_0 - A_2)_{LP} \sim \boldsymbol{k}^2/M^2\, h_1^\perp h_1^\perp$$

The Boer-Mulders is very small!

- If we include KPCs the theoretical expression also contains the unpolarized f_1

This allows us to make a prediction for the Lam-Tung relation



Y-term suppressed by an extra α_S factor

Excellent agreement up to $q_T \sim 30\,\text{GeV}$!

Good description only possible due to KPCs inclusion!

Moving to SIDIS: structure functions computation using KPCs

- Now, let's shift our focus to SIDIS → essential process for probing hadron structure

Cross-section decomposition in terms of structure functions

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,d\boldsymbol{p}_\perp^2} = \frac{\alpha_{\rm em}^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h} + \ldots$$

We want to compute them including KPCs

$$\Big\{ F_{UU,T} + \ldots \Big\} = \frac{x}{4z}\frac{1-\varepsilon}{Q^2} L_{\mu\nu} \underbrace{W^{\mu\nu}}_{2}$$

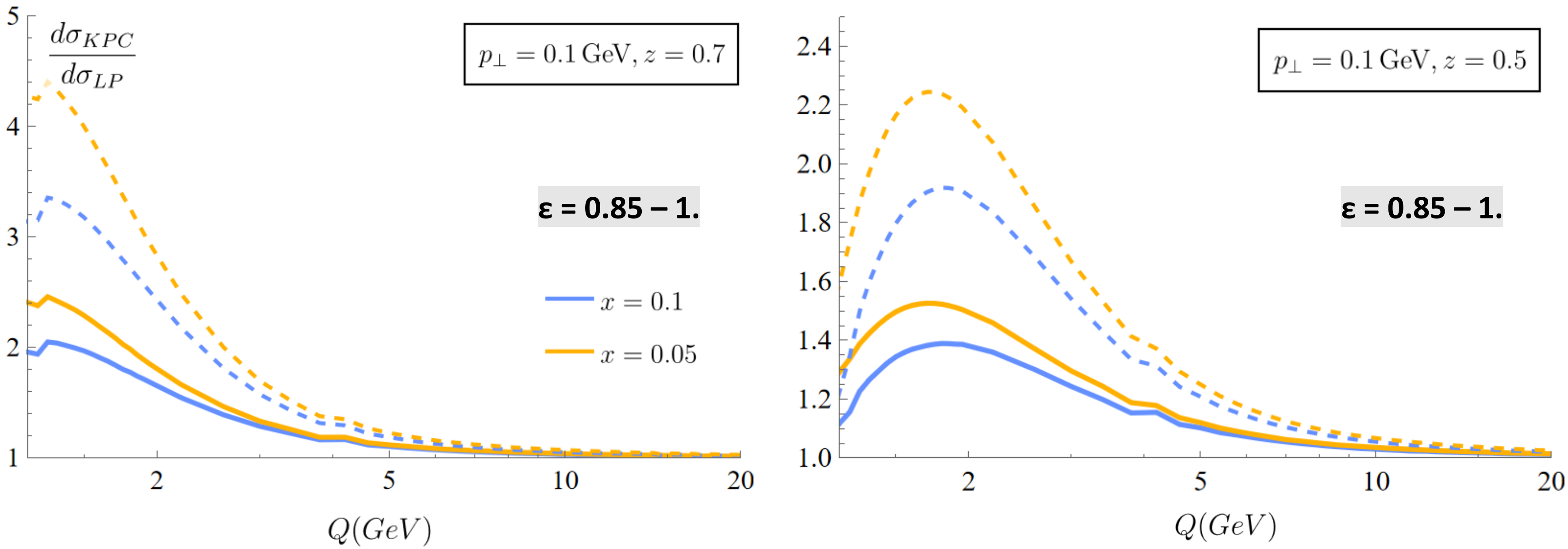
2 Hadron tensor computed using the TMD-with-KPCs factorization theorem

- Same coefficient function as LP $\quad \boxed{q_\mu W^{\mu\nu} = 0}$
- Main difference with LP → Convolution integral $\mathcal{C}_{KPC}$

Ratio of KPCs-summed to LP cross-sections

- I study the ratio $d\sigma_{KPC}/d\sigma_{LP}$ in two different scenarios

(i) $d\sigma_{KPC} \sim F_{UU,T}$ (ii) $d\sigma_{KPC} \sim F_{UU,T} + \varepsilon F_{UU,L}$

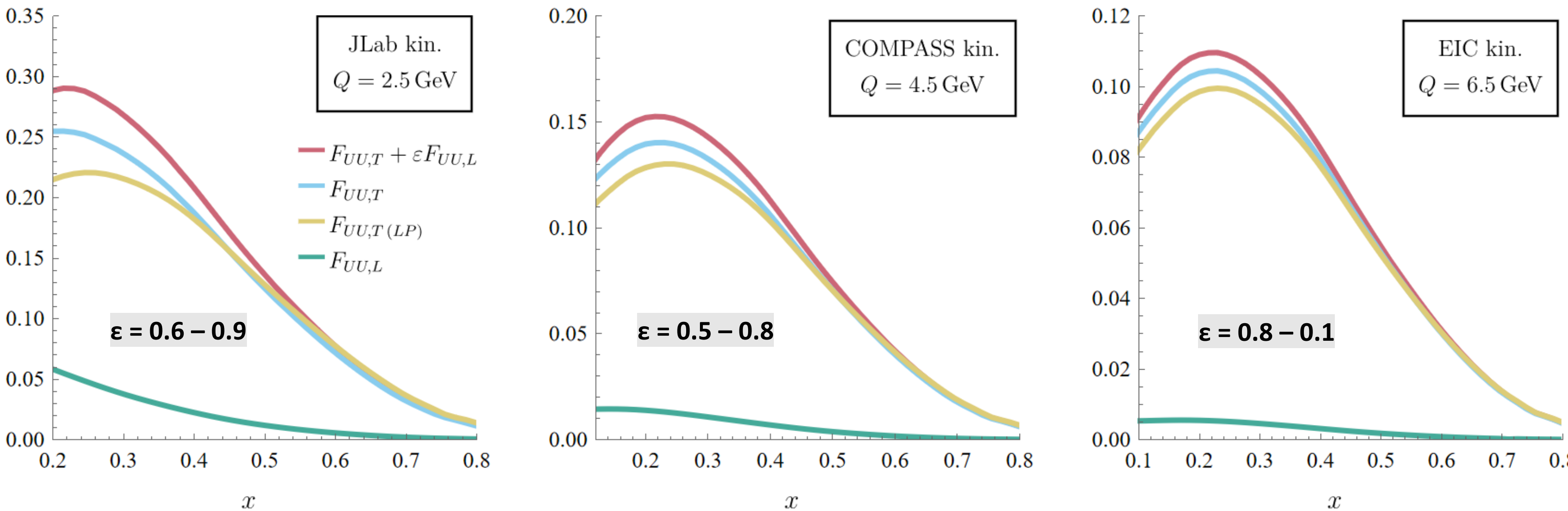


Q = 2 GeV → Corrections comparable to $(F_{UU,T})_{LP}$ both for $F_{UU,T}$ and $F_{UU,L}$

As Q grows the corrections become smaller and $\lim_{Q\to\infty} d\sigma_{KPC} = d\sigma_{LP}$

Longitudinal photons effects in different kinematics

- What about the contribution of longitudinal photons ($F_{UU,L}$) for different experiments?



✓ At low energies, the $F_{UU,L}$ contribution is clearly not negligible

JLab → significant difference between $(F_{UU,T})_{LP}$ and $F_{UU,T} + \varepsilon F_{UU,L}$

✓ Less important at higher energies → EIC → smaller but still visible