



STRONG
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TMD Jet distributions at next-to-leading power

I. Scimemi in collaboration with R. Fernandez del Castillo, M. Jaarsma, W. Waalewijn arXiv:230Y.XXXX

TMD Jet distributions at next-to-leading power

We would like to understand better the NLP TMD expansion:

- ❖ How big NLP effects are?
- ❖ How controllable are they?
- ❖ Do we have a new phenomenology?



TMD Jet distributions at next-to-leading power

The strategy for new effect search has often one basic rule:

Look where you do not expect any



Di-jet production in e^+e^-

This case has several appealing features:

- ◆ The kinematics is simple
- ◆ We can start studying very symmetric final state configurations
- ◆ **We can calculate all perturbatively! (Full control!)**



RECALL PREVIOUS STUDIES ON TMD FACTORIZATION AND JETS ...

Based on :

- D. Gutierrez-Reyes, I.S., W. Waalewijn, L. Zoppi PRL **121**, 162001(2018)
- D. Gutierrez-Reyes, I.S., W. Waalewijn, L. Zoppi JHEP **1910** (2019) 031
- D. Gutierrez-Reyes, Y. Makris, I.S., V. Vaidya, L. Zoppi JHEP **1908** (2019) 161

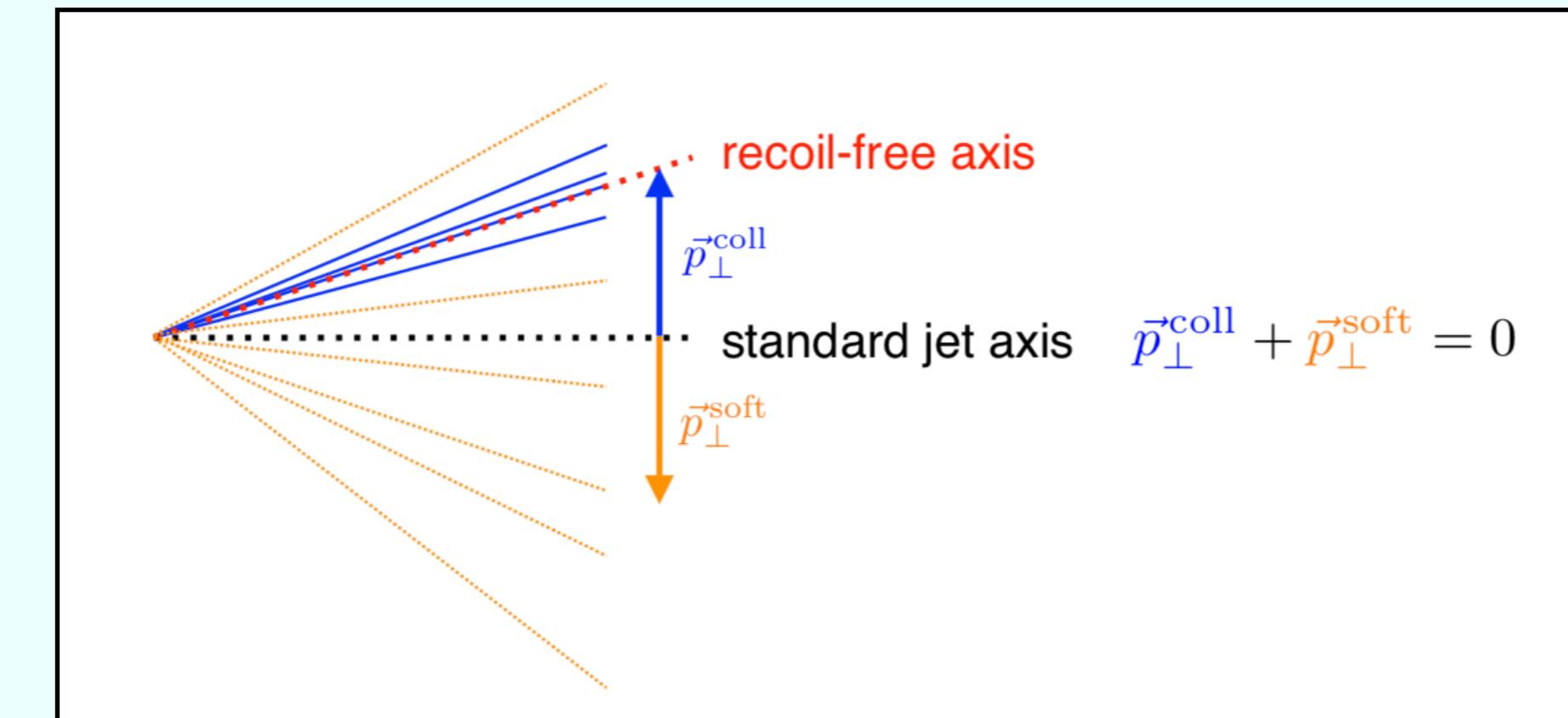
Standard jet axis (SJA)

Introduces soft-sensitivity to axis definition. In TMD factorization works for small R

Winner-take-all (WTA)

Larkoski, Neill, Thaler JHEP 04 (2014) 017

Recoil invariant. It is not sensitive to soft radiation. In TMD factorization works for all R



AND RECENT RECOIL FREE JET RECOMBINATION SCHEMES..

Y.-T. Chien, R. Rahn, D.Y. Shao, W. Waalewijn, B. Wu JHEP 02 (2023) 256

$$\hat{n} = \frac{p_{T,i}^m \hat{n}_i + p_{T,j}^m \hat{n}_j}{p_{T,i}^m + p_{T,j}^m} \quad \text{WTA for } m \rightarrow \infty$$

AND HADRON JET CORRELATORS THAT APPEAR IN EE-CORRELATIONS

I. Moult, H.-X, Zhu JHEP 08 (2018) 160

$$J_{EEC}(b) = \sum_i \int_0^1 dz z \mathbb{C}_{q \leftarrow i} \left(\frac{b}{z}, z \right)$$

Outline of working steps

- Start from the NLP operator basis of (MSV basis: V.Moos, I.S., A.Vladimirov JHEP 01 (2022) 110)
- Extract the interesting operator basis and hadronic tensor with jets
- Perform the necessary jet calculations

Notation basics

The field units include are **collinear or anti-collinear fields** and include **Wilson lines**

$$U_{1,\bar{n}}(y^-, b) = [L_n + b, y^- n + b] \xi_{\bar{n}}(y^- n + b)$$

$$U_{2,\bar{n}}^\mu(\{y_1^-, y_2^-\}, b) = g [L_n + b, y_2^- n + b] F_{\bar{n}}^{\mu+}(y_2^- n + b) [y_2^- n + b, y_1^- n + b] \xi_{\bar{n}}(y_1^- n + b)$$

4 LP operators (open Dirac indices)

$$\mathcal{O}_{11,\bar{n}}^{li}(y^-, y_T) = [\bar{U}_{1,\bar{n}}^{(-)}(y^-, y_T)]^l [U_{1,\bar{n}}^{(+)}(0,0)]^i, \dots$$

8 NLP operators (open Dirac indices)

$$\mathbb{O}_{21,\bar{n}}^{ji}(y^-, y_T) = [\bar{\xi}_{\bar{n}}^{(-)} A_{\bar{n},T}^{(-)}(y^- n + y_T)]^i [\xi_{\bar{n}}^{(+)}(0)]^j,$$

$$\mathbb{O}_{12,\bar{n}}^{ji}(y^-, y_T) = [\bar{\xi}_{\bar{n}}^{(-)}(y^- n + y_T)]^i [A_{\bar{n},T}^{(+)} \xi_{\bar{n}}^{(+)}(0)]^j, \dots$$

Warning: Only some operators are shown here

Hadronic Tensor for fermionic operators

We have a consistent expansion and a general way to write the hadronic tensor

$$\mathcal{J}^{\mu\nu} = \mathcal{J}_{\text{LP}}^{\mu\nu} + \mathcal{J}_{\text{NLP}}^{\mu\nu} = \mathcal{J}_{\text{LP}}^{\mu\nu} + \mathcal{J}_{\text{NLP-kin}}^{\mu\nu} + \mathcal{J}_{\text{NLP-hto}}^{\mu\nu}$$

$$\mathcal{J}_{\text{LP}}^{\mu\nu}(y) = \frac{\gamma_{T,ij}^\mu \gamma_{T,kl}^\nu}{N_c} \left(\mathcal{O}_{11,\bar{n}}^{li}(y^-, y_T) \overline{\mathcal{O}}_{11,n}^{jk}(y^+, y_T) + \overline{\mathcal{O}}_{11,\bar{n}}^{jk}(y^-, y_T) \mathcal{O}_{11,n}^{li}(y^+, y_T) \right)$$

kin= kinematic NLP terms; they appear as derivation of LP terms

hto=higher twist operators with no derivatives on transverse variables

Hadronic Tensor for fermionic operators

$$\begin{aligned}
 \mathcal{J}_{\text{NLP-kin}}^{\mu\nu} &= -\frac{n^\mu \gamma_{T,ij}^\rho \gamma_{T,kl}^\nu + n^\nu \gamma_{T,ij}^\mu \gamma_{T,kl}^\rho}{N_c} \left(\frac{\partial_\rho}{\partial_+} \mathcal{O}_{11,\bar{n}}^{li} \bar{\mathcal{O}}_{11,n}^{jk} + \frac{\partial_\rho}{\partial_+} \bar{\mathcal{O}}_{11,\bar{n}}^{jk} \mathcal{O}_{11,n}^{li} \right) + \dots \\
 \mathcal{J}_{\text{NLP-hto}}^{\mu\nu} &= +ig \frac{\mathbb{I}_{ij} \gamma_{T,kl}^\nu}{N_c} \left\{ \mathbb{O}_{21,\bar{n}}^{li} \left(\frac{\bar{n}^\mu}{\overrightarrow{\partial_-}} - \frac{n^\mu}{\overleftarrow{\partial_+}} \right) \bar{\mathcal{O}}_{11,n}^{jk} - \bar{\mathbb{O}}_{21,\bar{n}}^{jk} \left(\frac{\bar{n}^\mu}{\overrightarrow{\partial_-}} - \frac{n^\mu}{\overleftarrow{\partial_+}} \right) \mathcal{O}_{11,n}^{li} \right. \\
 &\quad \left. + \mathcal{O}_{11,\bar{n}}^{li} \left(\frac{\bar{n}^\mu}{\overrightarrow{\partial_-}} - \frac{n^\mu}{\overleftarrow{\partial_+}} \right) \bar{\mathbb{O}}_{21,n}^{jk} - \bar{\mathcal{O}}_{11,\bar{n}}^{jk} \left(\frac{\bar{n}^\mu}{\overrightarrow{\partial_-}} - \frac{n^\mu}{\overleftarrow{\partial_+}} \right) \mathbb{O}_{21,n}^{li} \right\} + \dots
 \end{aligned}$$

In principle we have a basis with fundamental operators, but some algebra must be done to arrive at a useful form

Jets at LP

At LP the jet definition is simple because there is no polarization

$$J_{11,\bar{n}}^{\textcolor{red}{q}}(b) = \int \frac{dy^-}{2\pi} e^{iy^- q^+} \text{tr} \left[\gamma^+ | \langle 0 | U_{1,\bar{n}}(y^-, b) | J_{\text{alg}}^{\bar{n}} X \rangle \langle J_{\text{alg}}^{\bar{n}} X | \bar{U}_{1,\bar{n}}(0,0) | 0 \rangle \right]$$

plus $(q, n) \rightarrow (\bar{q}, n)$ and $(q, \bar{n}) \rightarrow (\bar{q}, \bar{n})$

The jets here are initiated a quark or an antiquark

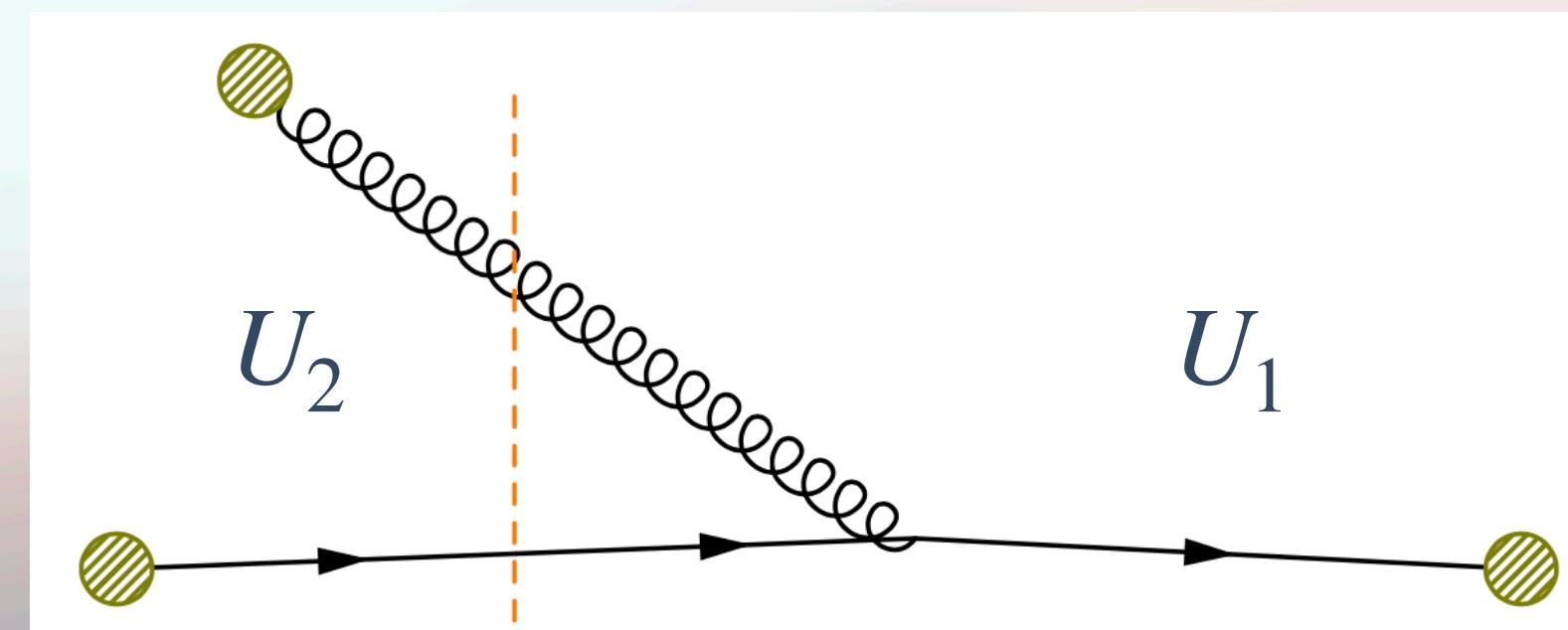
Jets at NLP

The NLP for jets comes considering the jet-algorithm

$$J_{21,\bar{n}}^{\rho,\textcolor{red}{q}}(x,b) = \frac{1}{\bar{x} - is\delta^+} \int \frac{dy_1^-}{2\pi} \frac{dy_2^-}{2\pi} e^{+i(xy_1^- + \bar{x}y_2^-)q^+} \text{tr} \left[\gamma^+ \langle 0 | U_{2,\bar{n}}^\rho(\{y_1^-, y_2^-\}, b) | J_{\text{alg}}^{\bar{n}} X \rangle \langle J_{\text{alg}}^{\bar{n}} X | \bar{U}_{1,\bar{n}}(0,0) | 0 \rangle \right],$$

Plus all possible combinations of antiquark, collinear directions, order of operators, ...

The jets here are initiated a quark or an antiquark and a gluon!



Jets at NLP*

$$J_{21,\bar{n}}^{\rho,\Delta q}(x,b) = \frac{1}{\bar{x} - is\delta^+} \int \frac{dy_1^-}{2\pi} \frac{dy_2^-}{2\pi} e^{+i(xy_1^- + \bar{x}y_2^-)q^+} \text{tr} \left[\gamma^+ \gamma^5 \langle 0 | U_{2,\bar{n}}^\rho(\{y_1^-, y_2^-\}, b) | J_{\text{alg}}^{\bar{n}} X \rangle \langle J_{\text{alg}}^{\bar{n}} X | \bar{U}_{1,\bar{n}}(0,0) | 0 \rangle \right],$$

Plus all possible combinations of antiquark, collinear directions, order of operators, ...

The helicity distributions do not vanish. This is because the γ^5 Dirac structure only probes the helicity of the quark, while the jet is initiated by both the quark and the gluon.
Tensor structures are null.

Symmetries of the jet..

Charge conjugation simplifies even more the structure of the states

$$J_{21,\bar{n}}^{\rho,\bar{q}}(x, b) = - J_{21,\bar{n}}^{\rho,q}(x, b)$$

$$J_{21,n}^{\rho,\bar{q}}(x, b) = - J_{21,n}^{\rho,q}(x, b)$$

$$J_{21,\bar{n}}^{\rho,\Delta\bar{q}}(x, b) = J_{21,\bar{n}}^{\rho,\Delta q}(x, b) \equiv J_{21,\bar{n}}^{\rho,\Delta}(x, b)$$

$$J_{21,n}^{\rho,\Delta\bar{q}}(x, b) = J_{21,n}^{\rho,\Delta q}(x, b) \equiv J_{21,n}^{\rho,\Delta}(x, b)$$

And we can also remove an index

$$J_{21,\bar{n}}^{\rho,q}(x, b) = \frac{b^\rho}{b^2} J_{21,\bar{n}}^q(x, b), \quad J_{21,\bar{n}}^{\rho,\Delta}(x, b) = + i\epsilon_T^{\rho\sigma} \frac{b_\sigma}{b^2} J_{21,\bar{n}}^\Delta(x, b), \dots$$

Hadronic tensor for SIA..

$$W_{\text{NLP-kin}}^{\mu\nu}(q) = + \frac{2i |C_1(q^+q^-, \mu^2)|^2}{4N_c} \int \frac{d^2 b}{(2\pi)^2} e^{+ib \cdot q_T} \left(\frac{1}{q^+} [n^\mu g_T^{\nu\rho} + n^\nu g_T^{\mu\rho}] [\partial_\rho J_{11,\bar{n}}(b) J_{11,n}(b)] + n \leftrightarrow \bar{n} \right)$$

$$W_{\text{NLP-hto}}^{\mu\nu}(q) = + \frac{2g}{4N_c} i \int \frac{d^2 b}{(2\pi)^2} e^{+ib \cdot q_T} \int dx C_1(q^+q^-, \mu^2) C_2^*(x, q^+q^-, \mu^2) \left[\frac{n^\mu}{q^+} - \frac{\bar{n}^\mu}{q^-} \right]$$

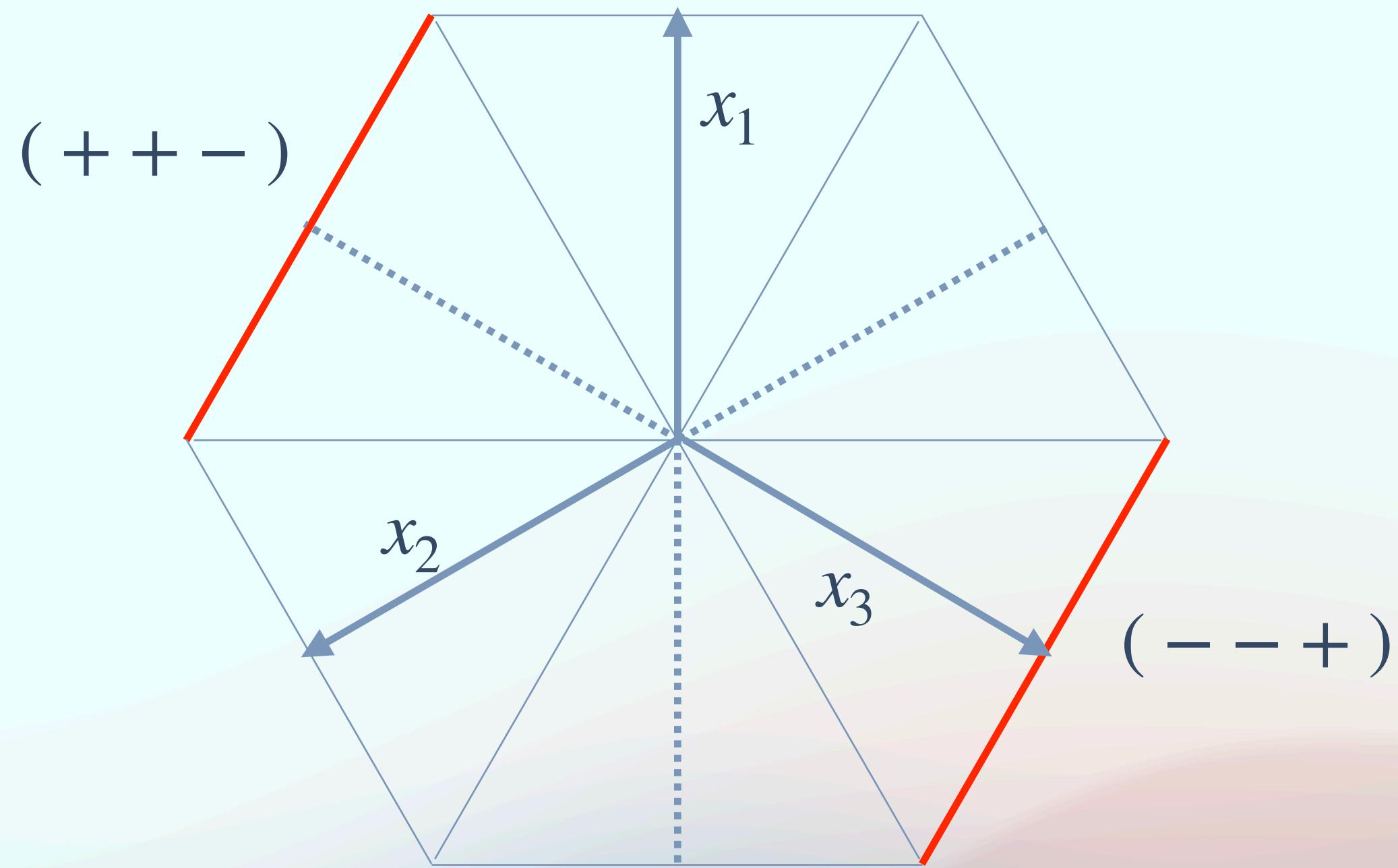
$$\times \frac{b^\nu}{b^2} \left\{ [-J_{21,\bar{n}}^\Delta(x, b) + J_{21,\bar{n}}^q(x, b)] J_{11,n}(b) - J_{11,\bar{n}}(b) [-J_{21,n}^\Delta(x, b) + J_{21,n}^q(x, b)] \right\} + \text{h.c.}$$

Hadronic tensor for SIA..

$$\begin{aligned}
W_{\text{NLP-kin}}^{\mu\nu}(q) &= + \frac{2i |C_1(q^+q^-, \mu^2)|^2}{4N_c} \int \frac{d^2 b}{(2\pi)^2} e^{+ib \cdot q_T} \left(\frac{1}{q^+} [n^\mu g_T^{\nu\rho} + n^\nu g_T^{\mu\rho}] [\partial_\rho J_{11,\bar{n}}(b) J_{11,n}(b)] + n \leftrightarrow \bar{n} \right) \\
W_{\text{NLP-hfo}}^{\mu\nu}(q) &= + \frac{2g}{4N_c} i \int \frac{d^2 b}{(2\pi)^2} e^{+ib \cdot q_T} \int dx C_1(q^+q^-, \mu^2) C_2^*(x, q^+q^-, \mu^2) \left[\frac{n^\mu}{q^+} - \frac{\bar{n}^\mu}{q^-} \right] \\
&\quad \times \frac{b^\nu}{b^2} \left\{ [-J_{21,\bar{n}}^\Delta(x, b) + J_{21,\bar{n}}^q(x, b)] J_{11,n}(b) - J_{11,\bar{n}}(b) [-J_{21,n}^\Delta(x, b) + J_{21,n}^q(x, b)] \right\} + \text{h.c.}
\end{aligned}$$

All NLP tensor cancels unless we break the $n \leftrightarrow \bar{n}$ symmetry!!

Evolution (check in progress)



The evolution is a limit case of the one treated in S. Rodini A. Vladimirov JHEP 08 (2022) 031

Evolution (check in progress)

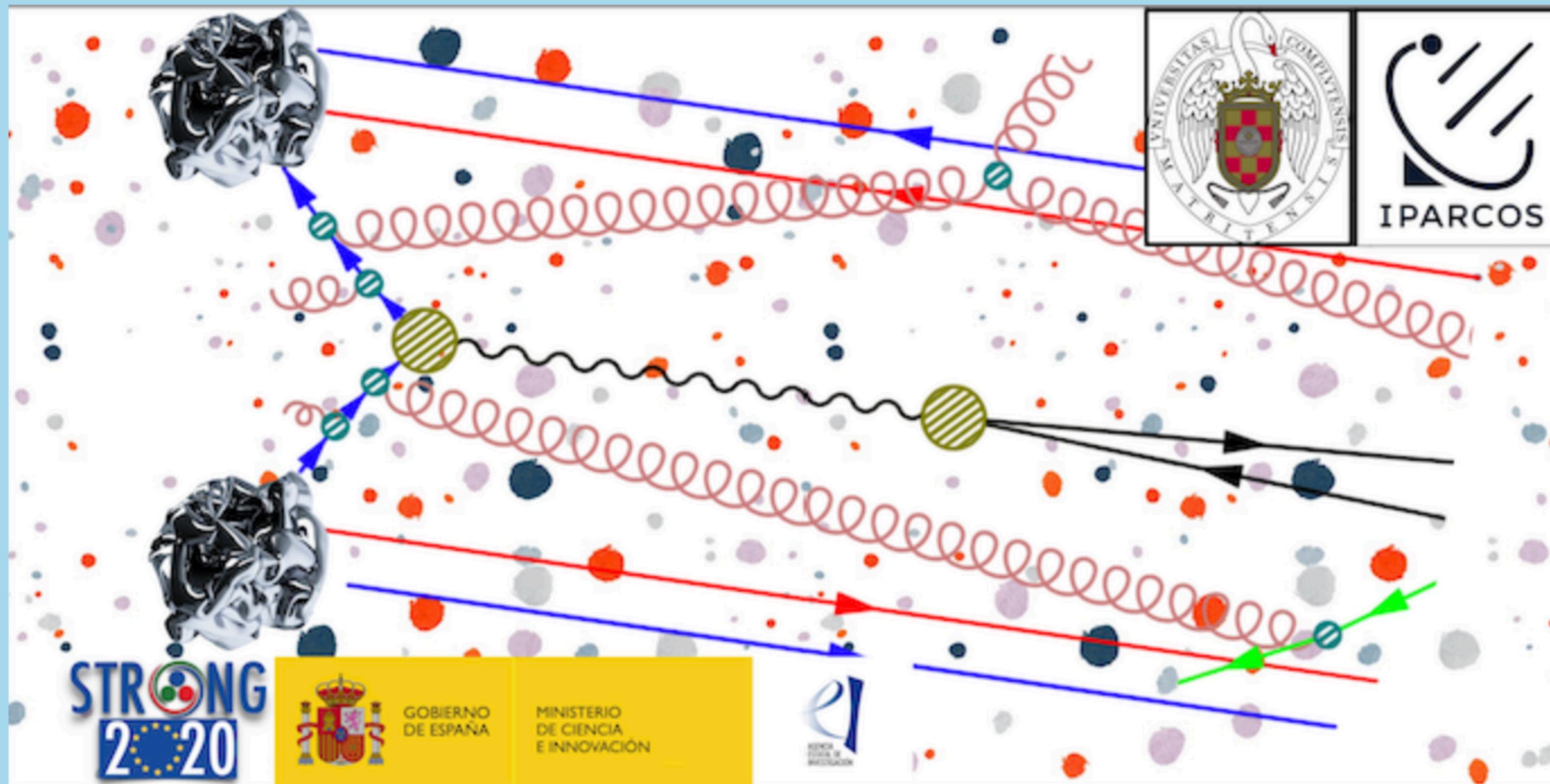
Finally we have only a possible definition of jet operator structure. Different jets can differ only by specific algorithms or operator independent elements

$$J_{\text{ht},\bar{n}}^\rho = \frac{b^\rho}{b^2} [-J_{21,\bar{n}}^\Delta(x, b) + J_{21,\bar{n}}^q(x, b)]$$

$$\mu^2 \frac{dJ_{\text{ht},\bar{n}}^\rho}{d\mu^2} = \left(\frac{\Gamma_{\text{cusp}}}{2} \ln \frac{\mu^2}{\zeta} + \Upsilon_{x,\bar{x},-1} \right) J_{\text{ht},\bar{n}}^\rho + 2\mathbb{P}_{\bar{x}x}^A \otimes J_{\text{ht},\bar{n}}^\rho$$

Conclusions

- ➊ We can work out a new phenomenology combining our knowledge of higher powers in hadronic tensors with jets.
- ➋ Jets allow a controllable framework to simplify the theory and to test it also in this new case
- ➌ We expect to extend this analysis to the SIDIS case



Resummation, Evolution, Factorization 2023 (REF2023)

23-27 octubre 2023
Facultad de Físicas
Europe/Madrid timezone

<https://indico.fis.ucm.es/event/19/>