Andrea Simonelli,
Università degli Studi di Torino

In collaboration with M. Boglione, O. Gonzalez

Jets and TMD Fragmentation Functions in $e^+ e^-$ processes

SAR WorS 2021 Sardinian Workshop on Spin

TMD factorization: three benchmark processes

Until the end of 2018, TMD factorization was known to be proved for:

1. $e^+e^- \to h_1\, h_2\, X$ with the two hadrons back-to-back,
2. Semi Inclusive DIS (SIDIS) for small values of momentum transfer $\longleftrightarrow$ $q_T \ll Q$
3. Drell-Yan scattering with the lepton pair generated back-to-back

Same factorized cross-section structure:

$$\frac{d\sigma}{dq_T} = \mathcal{H}_{\text{proc.}} \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}_T}\, \underbrace{F(b_T)}_{\text{First Hadron}}\, \underbrace{S(b_T)}_{\text{No direct experimental probe}}\, \underbrace{D(b_T)}_{\text{Second Hadron}}$$

Here the TMDs F and D are defined by the
Factorization Definition

TMD factorization: three benchmark processes

Until the end of 2018, TMD factorization was known to be proved for:

1. $e^+e^- \to h_1\, h_2\, X$ with the two hadrons back-to-back,
2. Semi Inclusive DIS (SIDIS) for small values of momentum transfer $\longleftrightarrow$ $q_T \ll Q$
3. Drell-Yan scattering with the lepton pair generated back-to-back

Same cross-section structure:

sqrt.

$$\frac{d\sigma}{dq_T} = \mathcal{H}_{\text{proc.}} \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}_T}\, F(b_T)\, \cancel{S(b_T)}\, D(b_T)$$

sqrt.

TMD factorization: three benchmark processes

Until the end of 2018, TMD factorization was known to be proved for:

1. $e^+e^- \rightarrow h_1\, h_2\, X$ with the two hadrons back-to-back,
2. Semi Inclusive DIS (SIDIS) for small values of momentum transfer $\longleftrightarrow$ $q_T \ll Q$
3. Drell-Yan scattering with the lepton pair generated back-to-back

Same cross-section structure:

$$\frac{d\sigma}{dq_T} = \mathcal{H}_{\text{proc.}} \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}_T}\, \underbrace{F^{\text{sqrt}}(b_T)}_{\text{First Hadron}}\, \underbrace{D^{\text{sqrt}}(b_T)}_{\text{Second Hadron}}$$

Square Root definition of TMDs $\Rightarrow$ Past ~10 years of phenomenology

Beyond the benchmark processes: motivations

- The three benchmark processes offer very rich information about many spin effects,
- In principle, they allow to access all the (quark) TMDs.

Enormous efforts into developing more and more competitive **models**, **codes**...

… So why do we have to extend TMD factorization outside the benchmark processes?

- A practical reason: the cross section structure presents a convolution of **two** TMDs, not easy to be disentagled

$$\frac{d\sigma}{dq_T} = \mathcal{H}_{\text{proc.}} \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{q}_T \cdot \vec{b}_T} \, F^{\text{sqrt}}(b_T) \, D^{\text{sqrt}}(b_T)$$

Are there TMD processes that present a **single** TMD parton density? $\dashrightarrow$ $e^+e^- \to h\,X$

- We have to keep up with experiments! EIC…

- Many theoretical reasons, for instance:
  - Gluon TMDs investigation
  - Some aspect of confinement /hadronization may be unaccessible due to the benchmark cross section structure

Beyond the benchmark processes: complications

1) The benchmark processes involve **two reference hadrons**

Universality-breaking effects in e^+e^- hadronic production processes, M. Boglione, A. Simonelli, **Eur.Phys.J.C 81 (2021) 1, 96**

→ Soft radiation is represented by a 2-h soft factor $\mathbb{S}_{2\text{-h}}$

Soft radiation contribution depends on the number $\mathrm{N_h}$ of the reference hadrons
$\mathrm{N_h}$-Universality

$N_h \neq 2$ → Different Soft Factor → **Sqrt Def**. of TMDs cannot be extended straightforwardly

Better use **Factorization Def.** of TMDs for extension beyond the benchmarks

2) Any dependence on rapidity cut-offs disappears in the cross section structure of benchmarks:

$$\frac{\partial}{\partial y_{1,2}} F(b_T,\, y_2)\, \mathbb{S}_{2\text{-h}}(b_T,\, y_1 - y_2)\, D(b_T,\, y_1) = 0$$

This may be not verified for different structures of factorized cross sections

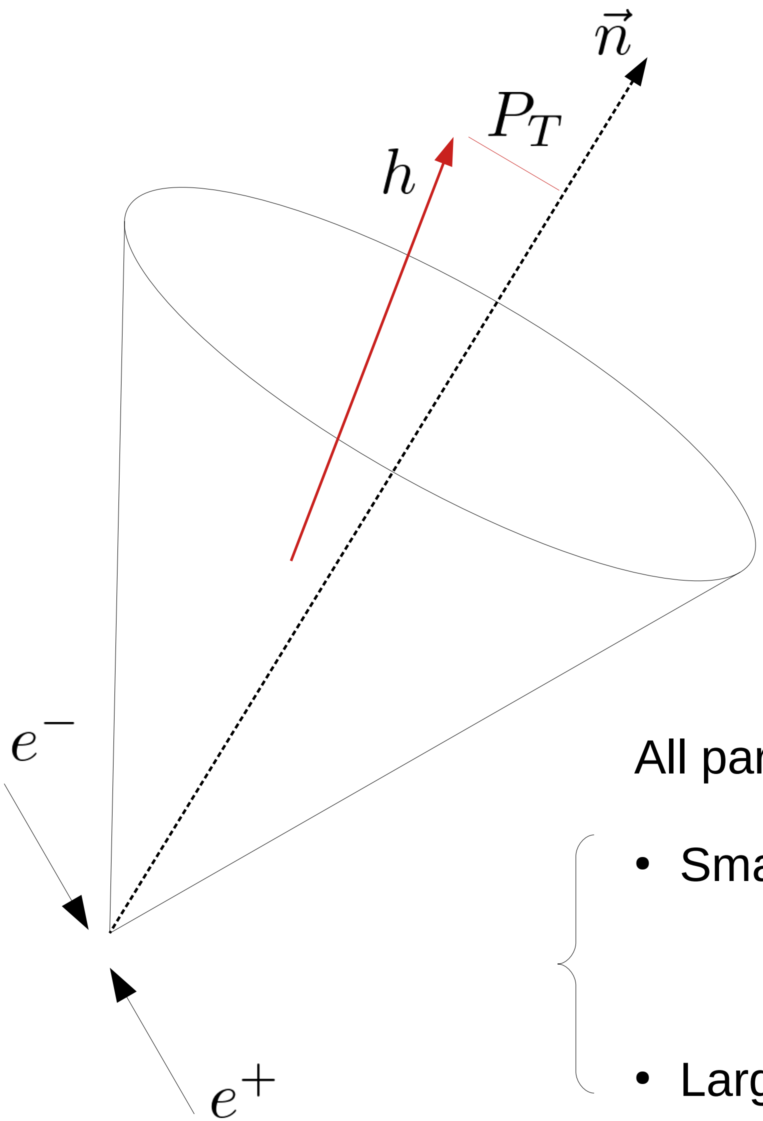
The process $e^+ e^- \to h\, X$ (thrust)

The cross section is differential in: $z_h = \dfrac{E}{Q/2}$, $\underbrace{T = \dfrac{\sum_i |\vec{P}_{(\mathrm{c.m.}),\, i} \cdot \hat{n}|}{\sum_i |\vec{P}_{(\mathrm{c.m.}),\, i}|}}$, P_T w.r.t $\vec{n}$

$0.5 \leq T \leq 1$

Spherical distribution ⟵ ⟶ 2-jet limit

2-jet final state is the most probable topology configuration



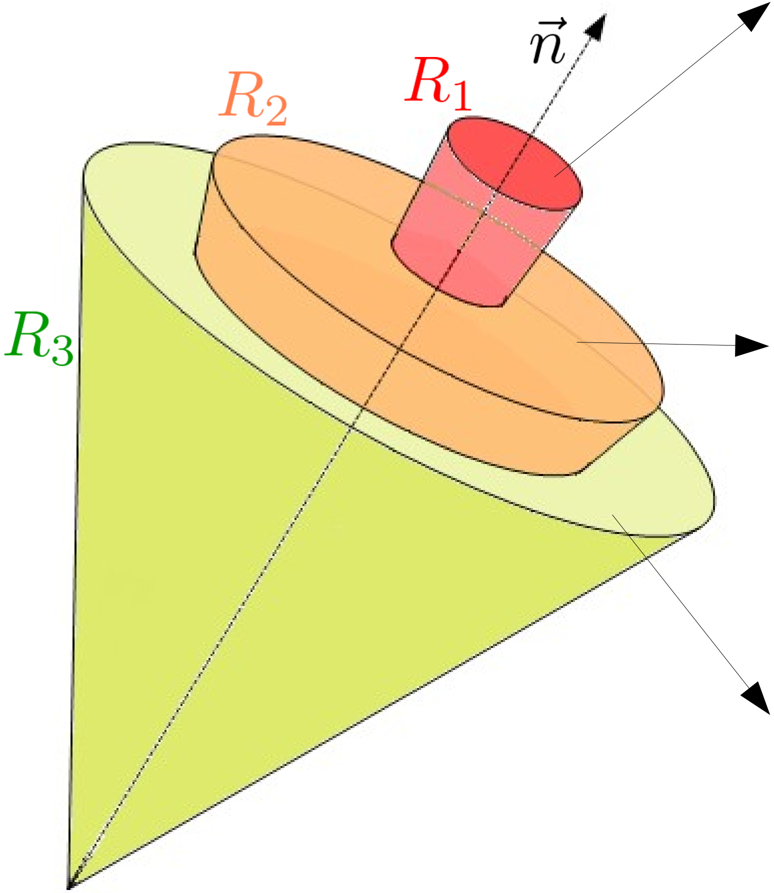
All particles inside the jet in which h is detected must have:

- Small transverse momentum $P_T \ll P^+ = z_h \dfrac{Q}{\sqrt{2}}$
- Large rapidity $y_P = \dfrac{1}{2} \log \dfrac{2(P^+)^2}{P_T^2 + M_h^2} \gg 0$

Kinematic regions of $e^+ e^- \to h\, X$ (thrust)

Depending on where the hadron is located within the jet the underlying kinematics can be remarkably different, resulting in different factorization theorems

Three Regions:



Kinematic Regions in $e^+e^- \to h\, X$ process in a 2-jet topology, M. Boglione, A. Simonelli, **arxiv:2109.xxyy (in preparation)**

The hadron is detected very close to the axis of the jet:

- Extremely small P_T
- Soft radiation affects significantly the transverse deflection of the hadron from the thrust axis

TMD FF + non-pert. SOFT contribution

The hadron is detected in the central region of the jet:

- Most common scenario
- Majority of experimental data fall into this case

TMD FF

The hadron is detected near the boundary of the jet:

- Moderately small P_T
- The hadron P_T causes the spread of the jet affecting the topology of the final state (i.e. the value of thrust)

Generazlized FJF

Identify the regions: kinematic requirements

We are primarily interested into the central region R_2 where the hadron is detected. It corresponds to the region where the following requirements hold true:

- **(H1)** not too close to the jet boundary, hence its transverse momentum P_T should be small compared to the maximum transverse spreading of the jet.
- **(H2)** not too close to the thrust axis, hence its transverse momentum P_T should not be considerably small. The hadron belongs to the jet mostly because it has a very large rapidity rather than because of the small size of its transverse deviation from the thrust axis.

(H1)	**(H2)**	reg.
True	False	R_1
True	True	R_2
False	True	R_3

How can these requirements be used into the proof of factorization theorems?

TMD relevance

Consider 2-jet final state topology $\longrightarrow$ **Two hemispheres** defined by the thrust axis

- S_A (forward radiation)
- S_B (backward radiation)

Not all the contributions singled out by the factorization procedure are relevant for the study of TMD effects.

TMD-relevant contributions

$$\int d^{D-2}\vec{k}_T \, e^{-i\,\vec{k}_T \cdot \vec{b}_T}$$

E.g. A-coll radiation

TMD-irrelevant contributions

$$\int d^{D-2}\vec{k}_T$$

E.g. all radiation flowing into S_B

This is particularly relevant for soft and soft-collinear S_A radiation

	soft	soft-coll	coll
R_1	Relevant	Relevant	Relevant
R_2	Irrelevant	Relevant	Relevant
R_3	Irrelevant	Irrelevant	Relevant

"Bottom-up" Factorization Proof

TMD relevance is an "easy" way to implement the kinematic requirements and **(H1)** and **(H2)** into perturbative computations.

"**BOTTOM-UP**" approach to factorization
Proceeding order by order in pQCD and then deducing the all-orders cross section

ADVANTAGES:

- Easy way to approach the problem, one should simply apply the factorization procedure (power counting, approximators…)
- the steps of the factorization proof are much clearer, as the various contributions can be readily disentangled and made more explicit transparent

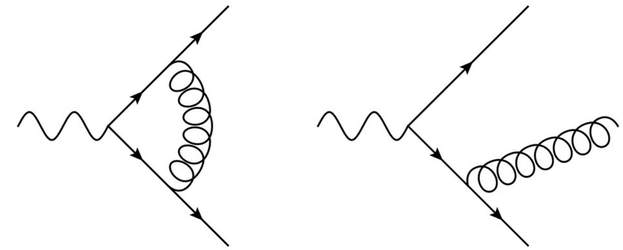
COMPLICATIONS:

- Explicit pQCD computations may be potentially very difficult. In this case:
  - Non-trivial implementation of 2-jet limit in b_T-space
  - Non-standard mathematical tools required to compute some of the integrals, e.g.

$$\left(\frac{1}{\tau}\right)_+ \quad \left(\frac{1}{1-z}\right)_+ \quad {}_0F_1\left(1-\varepsilon;\, -\tau\frac{1-z}{z}\frac{b^2}{4}\right) \qquad\qquad I(a,\,r) = \int_0^1 dx\,\frac{x^{\varepsilon/2}}{x-r}\,J_{-\varepsilon}\left(\frac{a}{\sqrt{x}}\right)$$

- Blindness to effects arising at higher orders

Region 2 at 1-loop



$+h.c.$

Virtual gluon

$$\frac{1}{\sigma_B}\frac{d\sigma^{[1]}_{R_2}}{dz\,db_T\,d\tau} = \\ = N_C\left[\delta(1-z)\left(\delta(\tau)\,V(\varepsilon) + \underbrace{J^{[1]}(\varepsilon;\tau) + S^{[1]}_{-}(\varepsilon;\,\tau)} + \underbrace{\mathcal{S}^{[1]}_{+}(\varepsilon;\tau,\,y_1)\right) + \delta(\tau)\,z\,\widetilde{D}^{[1],\,(0)}_{q/q}(\varepsilon;\,z,\,b_T,\,y_1)}\right]$$

Backward gluon:

- Jet Thrust Function $J^{[1]}(\varepsilon,\,\tau)$ (from B-collinear approximator)
- Soft Thrust Function in the S_B-hem. $S^{[1]}_{-}(\varepsilon;\,\tau)$ (from combination of soft and softcollinear approximators)

Forward gluon:

NEW!

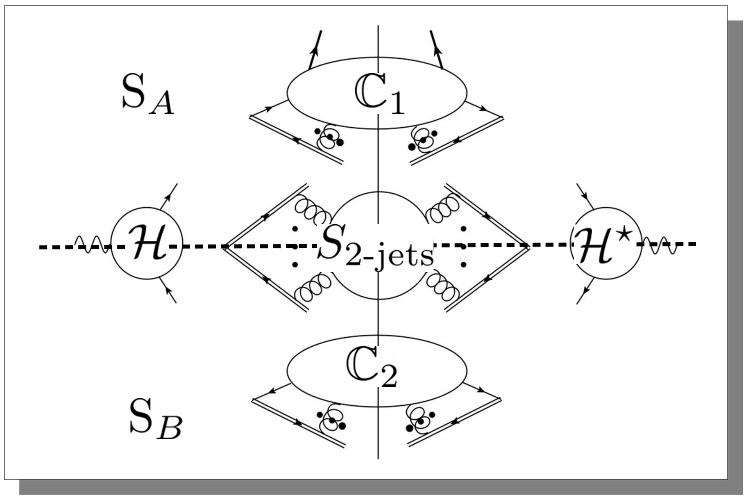
- Generalized Soft Thrust Function $\mathcal{S}^{[1]}_{+}(\varepsilon;\tau,\,y_1)$(from soft approximator)
- q-from.q (bare) TMD FF $\widetilde{D}^{[1],\,(0)}_{q/q}(\varepsilon;\,z,\,b_T,\,y_1)$ in **factorization definition** (from combination of soft and softcollinear approximators)

✔ Finite (no poles in ε)
✔ RG-invariant $(\mu = Q)$
✗ Not CS-invariant $\longrightarrow$ The final result depends explicitly on y_1

Region 2: Factorized Cross Section

$$\frac{d\sigma_{R_2}}{dz_h\, dP_T^2\, dT} = \sigma_B\, \pi N_C \int d\tau_{S_+}\, d\tau_{S_-}\, d\tau_B\, \delta(\tau - \tau_{S_+} - \tau_{S_-} - \tau_B) \int \frac{d^2\vec{b}_T}{(2\pi)^2}\, e^{i\,\frac{\vec{P}_T}{z_h}\cdot\vec{b}_T} \sum_f e_f^2 \times$$

$$\times \underbrace{V}_{\text{Virtual radiation}}\, \underbrace{J(\tau_B)\, S_-(\tau_{S_-})}_{\text{Backward radiation}} \underbrace{\mathcal{S}_+\left(\tau_{S_+},\, y_1\right)\;\; \widetilde{D}_{h/f}\left(z_h,\, b_T,\, y_1\right)}_{\text{Forward radiation}}$$



The *same* result can be obtained adopting a "**top-down**" approach to factorization

$$W_h^{\mu\,\nu}(z_h, \vec{P}_T, T) = \sum_{j_1} \int \frac{d^D k_1}{(2\pi)^D}\, \delta\left(\vec{P}_T\left[1 + \mathcal{O}\left(\frac{P_T^2}{Q^2}\right)\right] + \frac{P^+}{k_1^+}\vec{k}_{1,T}\right) \sum_{j_2} \int \frac{d^D k_2}{(2\pi)^D}$$

$$\times\, \mathrm{Tr}_D \left\{ \mathrm{P}_1 \mathbb{C}_1(k_1,\, P)_{j_1} \overline{\mathrm{P}}_1 \mathcal{H}^{\mu}_{j_1\, j_2}(\widehat{k}_1, \widehat{k}_2)\, \mathrm{P}_2 \mathbb{C}_2(k_2)_{j_2} \overline{\mathrm{P}}_2 \left(\mathcal{H}^\dagger\right)^{\nu}_{j_1\, j_2}(\widehat{k}_1, \widehat{k}_2) \right\}$$

$$\times \int \frac{d^D k_S}{(2\pi)^D} S_{2_{\text{jets}};\, j_1\, j_2}(k_S)\, \underbrace{\delta(q - k_1 - k_2 - k_S)}_{\text{(H2)}}\, \underbrace{\delta\left(T - T_{\text{def.}}(k_1,\, k_2,\, k_S)\right)}_{\text{(H1)}}$$

Region 2: **Collinear-TMD Factorization**

NEW!

$$\frac{d\sigma_{R_2}}{dz_h\, dP_T^2\, dT} = \sigma_B\, \pi N_C \int d\tau_{S_+}\, d\tau_{S_-}\, d\tau_B\, \delta(\tau - \tau_{S_+} - \tau_{S_-} - \tau_B) \int \frac{d^2\vec{b}_T}{(2\pi)^2}\, e^{i\,\frac{\vec{P}_T}{z_h}\cdot\vec{b}_T} \sum_f e_f^2 \times$$

$$\times \boxed{V\, J(\tau_B)\, S_-(\tau_{S_-})\mathcal{S}_+\left(\tau_{S_+},\, y_1\right)}\; \widetilde{D}_{h/f}\left(z_h,\, b_T,\, y_1\right) =$$

Fully perturbative!

Re-organization into a partonic cross-section

$$= \pi \sum_f \int_{z_h}^1 \frac{d\widehat{z}}{\widehat{z}}\, \frac{d\widehat{\sigma}_f(y_1)}{d(z_h/\widehat{z})\, dT} \int \frac{d^2\vec{b}_T}{(2\pi)^2}\, e^{i\,\frac{\vec{P}_T}{\widehat{z}}\cdot\vec{b}_T}\, \widetilde{D}_{f,\,h}(\widehat{z},\, b_T,\, y_1)$$

$$\sim \sum_f \widehat{\sigma}_f(T,\, y_1) \otimes \widetilde{D}_{f,\,h}(b_T,\, y_1)$$

A new kind of factorization theorem (never encountered before in literature)

- Same structure of collinear factorized cross sections
- The convolution involves TMDs, in **Factorization Definition**

Hybrid nature between collinear and TMD factorization

- Non-trivial role of rapidity cut-off

Region 2: **Collinear-TMD Factorization**

Universality-breaking effects in e^+e^- hadronic production processes, M. Boglione, A. Simonelli, **Eur.Phys.J.C 81 (2021) 1, 96**

- The convolution involves TMDs, in **Factorization Definition**
  How to match with usual sqrt. definition of TMDs?

$$\widetilde{D}^{\text{sqrt}}_{h/f}(z_h, b_T, \ldots) = \widetilde{D}_{h/f}(z_h, b_T, \ldots)\sqrt{M_S(b_T)}$$

Which means:

$$M^{\text{sqrt}}_D(z_h, b_T, \ldots) = M_D(z_h, b_T, \ldots)\sqrt{M_S(b_T)}$$

NEW!

SOFT MODEL
Non-Perturbative function describing the long-distance behavior of 2-h soft factor.
It depends ONLY on b_T.

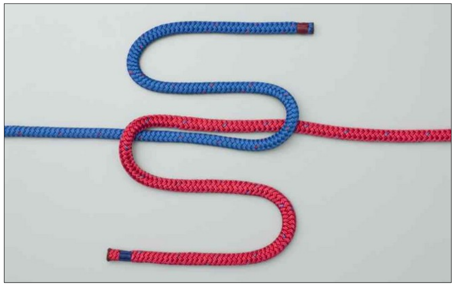
This highlights a strategy for extracting TMDs:

1. Extract M_D from $e^+e^- \to h\,X$ in Region 2

   See talk by O. Gonzalez

2. Compare with M^{sqrt}_D (benchmark SIDIS, $e^+e^- \to h_1\,h_2\,X$) to obtain the soft model as the ratio $M_S = D^{\text{sqrt}}/D$.

   In this scheme the Soft Factor acquires a central and active role in phenomenological analyses.



3. The only remaining unknowns are the models of TMD PDFs, (benchmark SIDIS, Drell-Yan)

Region 2: **Collinear-TMD Factorization**

- Non-trivial role of rapidity cut-off $$\frac{\partial}{\partial y_1} \sum_f \widehat{\sigma}_f(y_1) \otimes \widetilde{D}_{f,h}(b_T, y_1) \neq 0$$

  The rapidity cut-off is *intimately* related to the value of thrust:

$$y_P = \frac{1}{2} \log \frac{P^+}{P^-} = \log \frac{z_h\, Q}{\sqrt{P_T^2 + M_h^2}} \geq -\frac{1}{2} \log(1-T) + \mathcal{O}\left(\frac{M_h^2}{P_T^2}\right),$$

- Since y_1 is related to a measured quantity, it cannot be just a mere computational tool and **it must acquire a real physical meaning**.

- However, in Collins factorization formalism the exact relation between rapidity cut-off and thrust cannot be made explicit: a **new** way of regularizing rapidity divergences is required.

- Without an explicit relation between y_1 and thrust, the resummation on T is compromised. A shortcut to circumvent this issue is:
  - Neglect all the T-divergent terms
  - Fix the rapidity cut-off according to the kinematic argument above: $y_1 = -\frac{1}{2} \log(1-T)$

Factorization of $e^+e^- \to h\, X$ cross section, differential in z_h, P_T and thrust, in the 2-jet limit, M. Boglione, A. Simonelli, **JHEP 02 (2021) 076**

In Region 2 the TMD Ffs depend on thrust through their rapidity cut-off

Region 1: **TMD Factorization**

$$\frac{d\sigma_{R_1}}{dz_h\, dP_T^2\, dT} = \sigma_B\, \pi N_C \int d\tau_S\, d\tau_B\, \delta(\tau - \tau_S - \tau_B) \int \frac{d^2\vec{b}_T}{(2\pi)^2}\, e^{i\,\frac{\vec{P}_T}{z_h}\cdot\vec{b}_T} \sum_f e_f^2 \times$$
$$\times\, V\, J(\tau_B)\, S_-(\tau_S)\, \widetilde{\mathbb{S}}_{\text{2-h},+}(b_T,\, y_1)\; \widetilde{D}_{h/f}(z_h,\, b_T,\, y_1)$$

A TMD factorization theorem:

- “half” of the structure present in SIDIS, $e^+e^- \to h_1\, h_2\, X$
- Non-trivial non-perturbative contribution of soft radiation
- CS-invariance
- Possible Non-Global Logs effects should be considered

The combination of non-perturbative functions in the cross section behaves as if the TMD FF was defined by the **square root def.**

$$\widetilde{\mathbb{S}}_{\text{2-h},+}(b_T,\, y_1)\; \widetilde{D}_{h/f}(z_h,\, b_T,\, y_1) \propto \sqrt{M_S(b_T)}\, M_D(b_T, \dots) = M_D^{\text{sqrt}}(b_T, \dots)$$

Region 1: **TMD Factorization**

$$\frac{d\sigma_{R_1}}{dz_h\, dP_T^2\, dT} = \sigma_B\, \pi N_C \int d\tau_S\, d\tau_B\; \delta(\tau - \tau_S - \tau_B) \int \frac{d^2\vec{b}_T}{(2\pi)^2}\, e^{i\,\frac{\vec{P}_T}{z_h}\cdot\vec{b}_T} \sum_f e_f^2 \times$$
$$\times\, V\, J(\tau_B)\, S_-(\tau_S)\, \widetilde{\mathbb{S}}_{\text{2-h},+}(b_T, y_1)\; \widetilde{D}_{h/f}(z_h, b_T, y_1)$$

In the literature (SCET):

- The same cross section is presented in:
  Joint thrust and TMD resummation in electron-positron and electron-proton collisions, Y. Makris, F. Ringer, W.J. Waalewijn **JHEP 02 (2021) 070**

- A similar structure is also presented in:
  QCD resummation on single hadron transverse momentum distribution with the thrust axis, Z. Khang, D. Shao, F. Zhao, **JHEP 12 (2020) 127**.
  However their cross section is integrated over thrust. It can be recovered as:

$$\int_0^1 d\tau\; d\sigma_{R_1} + \text{Contribution of Fragmenting gluons} = \text{Kang's cross section}$$

However, in the literature there is no mention to the different definition of the TMD we must adopt

Region 3: **Generalized Collinear Factorization**

$$\frac{d\sigma_{R_3}}{dz_h\, dP_T^2\, dT} = \sigma_B\, \pi N_C \int d\tau_S\, d\tau_A\, d\tau_B\; \delta(\tau - \tau_S - \tau_A - \tau_B) \sum_f e_f^2 \times$$
$$\times\, V\, J(\tau_B)\, S(\tau_S)\, \Gamma_{h/f}\left(z_h,\, \frac{P_T}{z_h},\, \tau_A\right)$$

Generalized Fragmenting Jet Function

- A lot in common with collinear FFs (e.g. DGLAP) but carries TMD information
- Its non-perturbative part depends EXPLICITLY on the thrust (invariant mass of the jet)

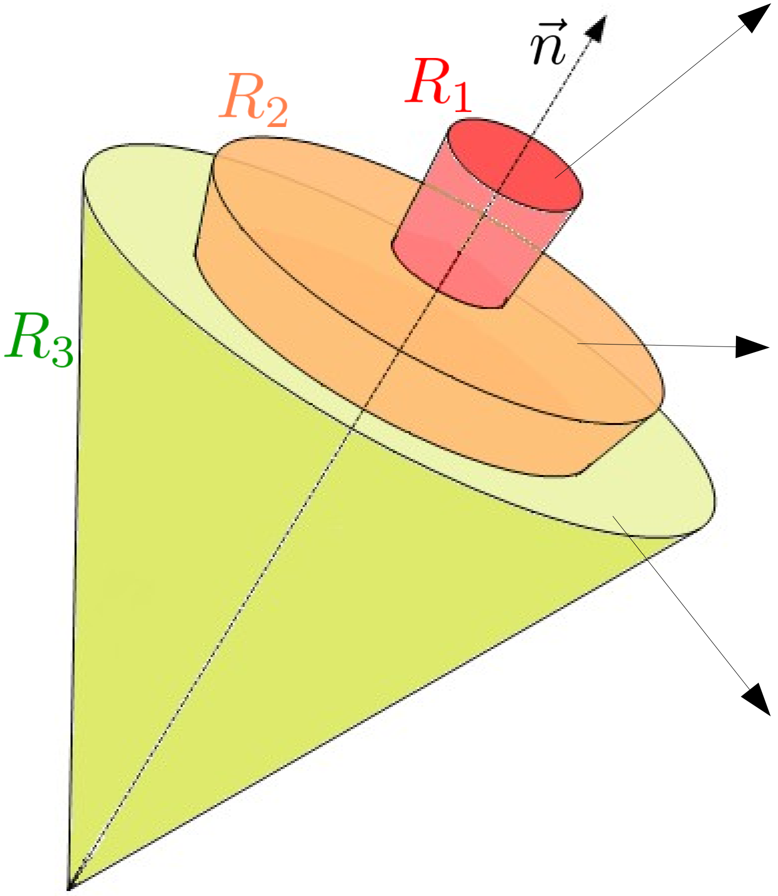
A generalized collinear factorization theorem:

- None of the functions in the cross section depend on a rapidity cut-off
- "Clean" way to access GFJFs

In the literature (SCET):

- The same cross section is presented in:
  Joint thrust and TMD resummation in electron-positron and electron-proton collisions, Y. Makris, F. Ringer, W.J. Waalewijn **JHEP 02 (2021) 070**

Three distinct factorization theorems



Kinematic Regions in $e^+e^- \to h\,X$ process in a 2-jet topology, M. Boglione, A. Simonelli, **arxiv:2109.xxyy (in preparation)**

TMD Factorization (similar to benchmarks).

TMD FFs are contamined by soft radiation as in the **square root definition**. Access to:

$$M_S, \quad M_D, \quad g_K$$

collinear-TMD Factorization

NEW!

TMD FFs are pure collinear objects, defined through the **factorization definition**. Access to:

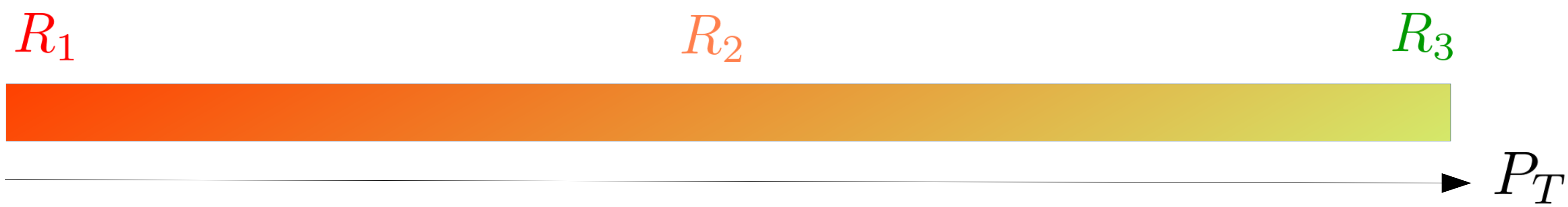
$$M_D, \quad g_K$$

Generalized collinear Factorization

The hadronization is described by GFJFs, which depend explicitly on thrust.

How to distinguish between the regions

- The transverse momentum of the detected hadron increases as we move from Region 1 to Region 3.



- Three variables to take into account $z_h,\, T,\, P_T$

- The boundaries of the three regions are not sharply defined, making the description of data difficult, especially in the overlapping regions.

Problem of matching
(c.f. e.g. SIDIS benchmark cases)

- TMDs (and GFJFs) are well defined only where $P_T \ll P^+$

We need an ALGORITHM

Kinematic Regions in $e^+e^- \to h\,X$ process in a 2-jet topology, M. Boglione, A. Simonelli, **arxiv:2109.xxyy (in preparation)**

Power-counting algorithm

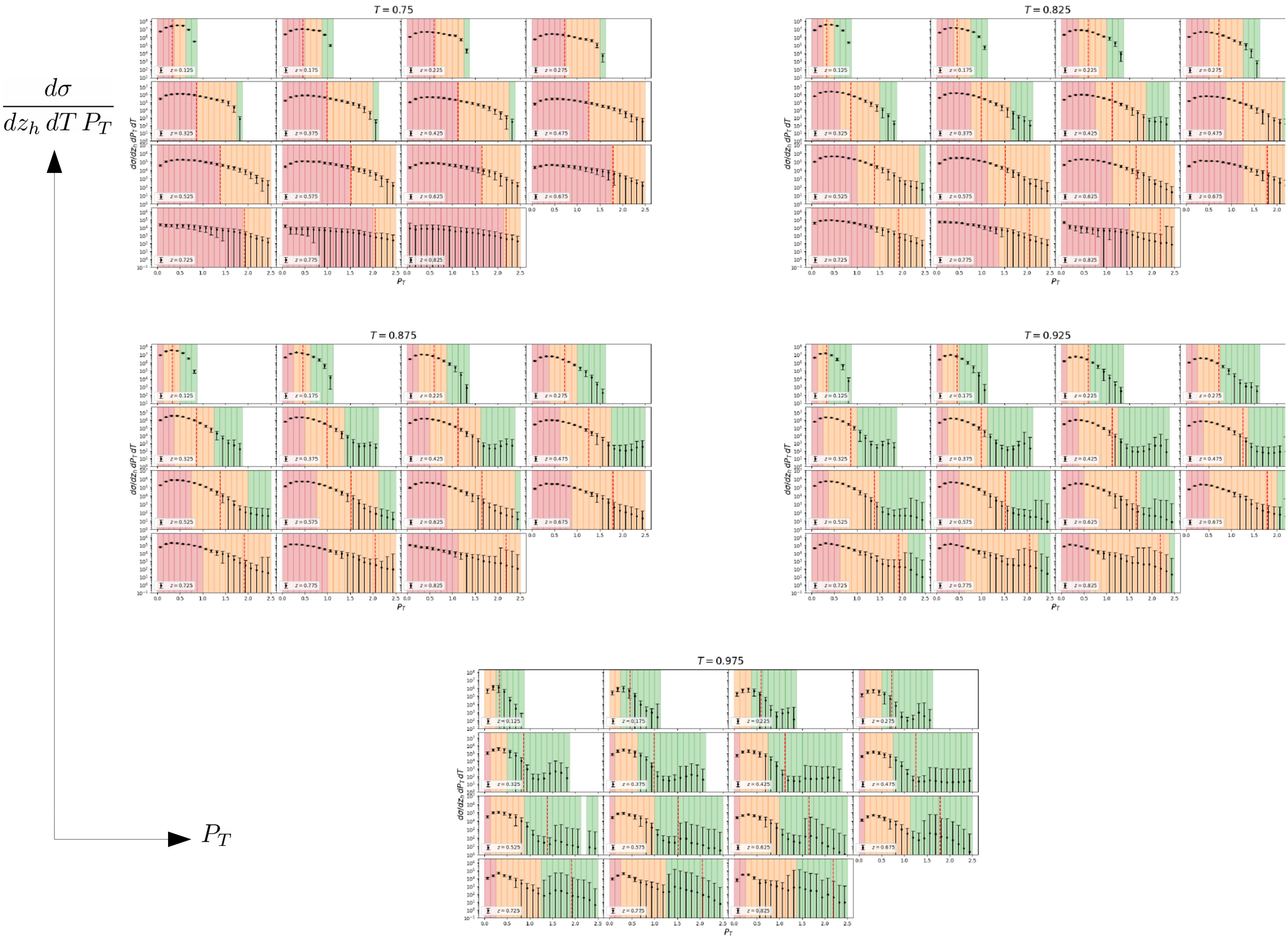
The easiest algorithm is entirely based on power counting:

R_1	R_2	R_3
$\frac{P_T}{z_h} < \tau Q$	$\tau Q < \frac{P_T}{z_h} < \sqrt{\tau} Q$	$\frac{P_T}{z_h} \sim \sqrt{\tau} Q$

Proposed in Y. Makris, F. Ringer, W.J. Waalewijn JHEP 02 (2021) 070

- Based on very general assumptions
- Very simple implementation
- The rapidity of the hadron is not taken into account → Difficult distintion between R_1 and R_2
- Region 1 is overestimated
- Phenomenology cannot be performed without a well defined matching procedure (many bins are **multicolor**)

Power-counting algorithm



Ratios algorithm

- Based on the comparison of ratios that describe the kinematics of each region. Such ratios are inspired by 1-loop explicit computation.

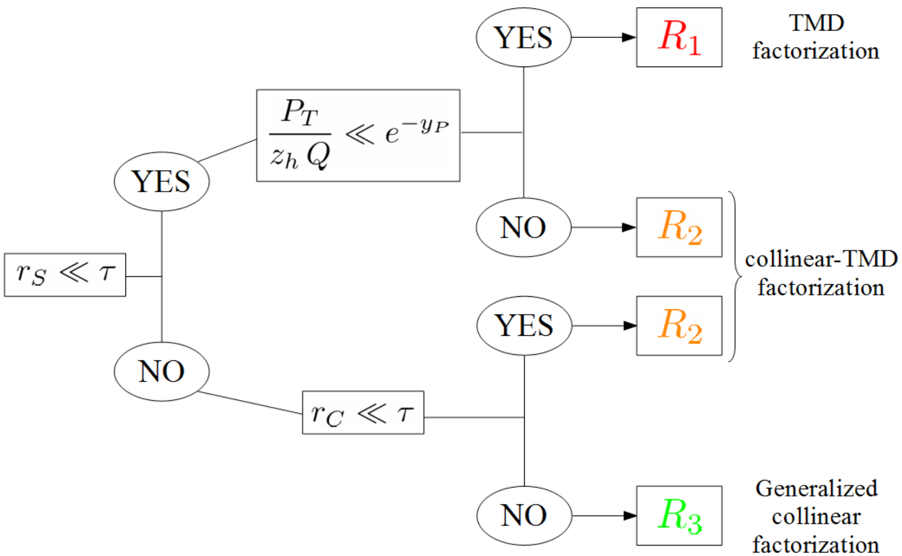
SOFT RATIO

$$r_S = \frac{P_T}{z_h\, Q} e^{-y_P}$$

COLLINEAR RATIO

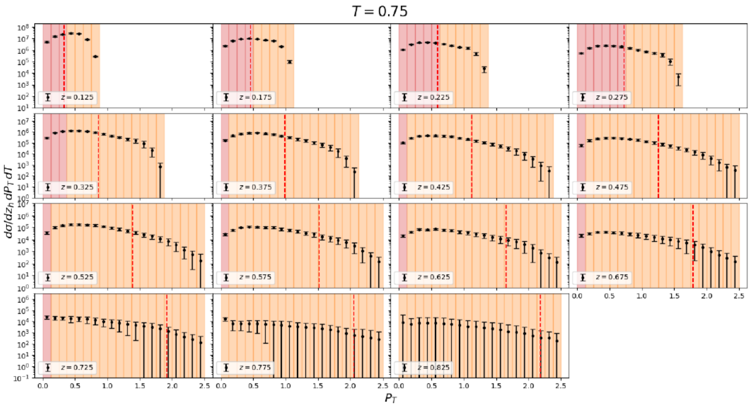
$$r_C = z_h\,(1 - z_h)\, e^{-2\, y_P}$$

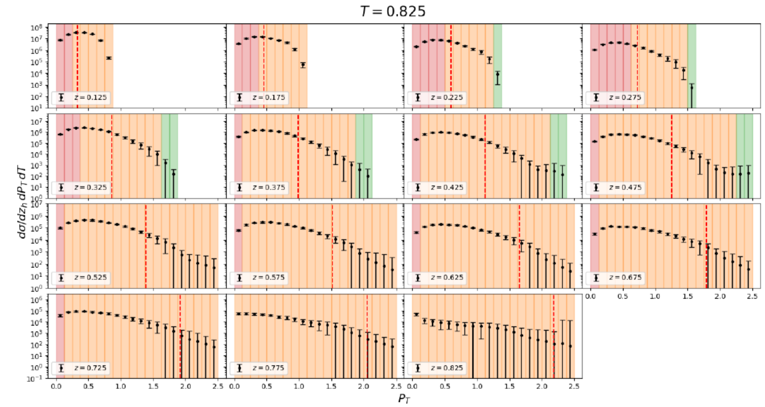
- The rapidity of the hadron is taken explicitly into account
- Region 2 is the widest region as expected
- The problem of the matching is not urgent, as there are many **monocromatic** bins

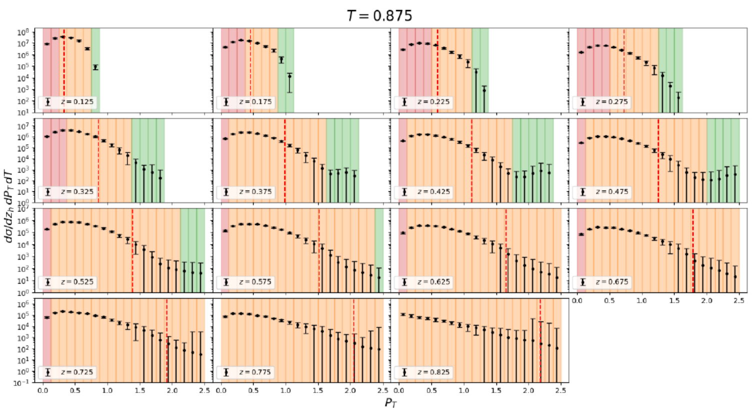


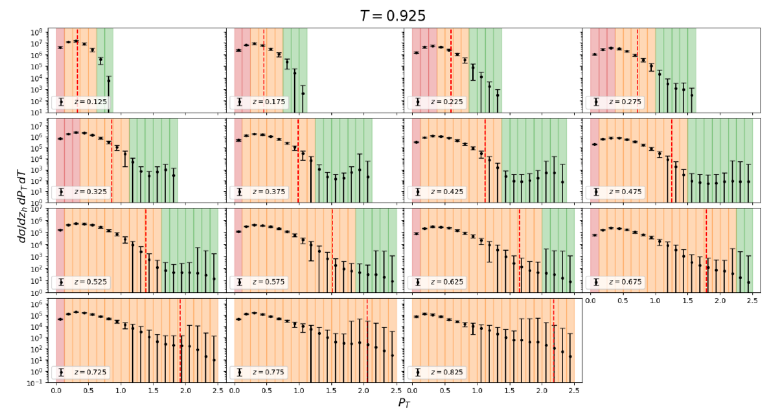
Ratios algorithm

$$\frac{d\sigma}{dz_h\,dT\,P_T}$$

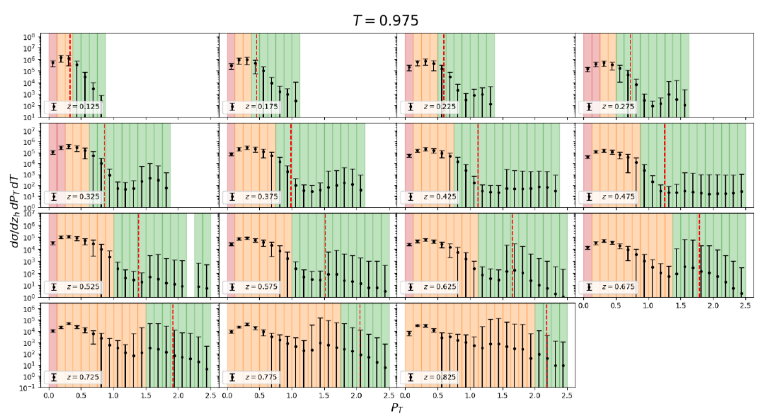








P_T



Conclusions

- The process $e^+e^- \to h\,X$ encodes a lot of incredibly interesting information regarding TMD physics.

- Three distinct factorization theorems, each associated to a different kinematic region.

R_1	R_2	R_3
TMD factorization	collinear-TMD factorization	Generalized collinear factorization

- Collinear-TMD factorized cross sections (R_2) are a new kind of observables, where rapidity cut-offs show their hidden physical meaning.
  This may shed light on on totally new aspects of the hadronization mechanism and on the confinement of partons.

THANK YOU FOR YOUR ATTENTION!