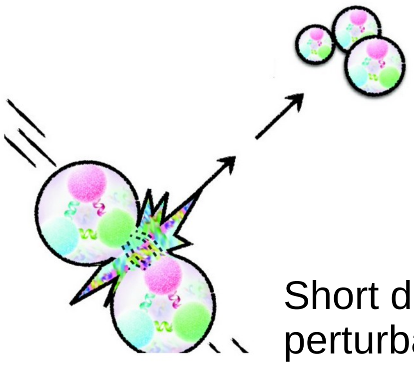
Quantum tomography of nucleons

M. Boglione

In collaboration with O. Gonzalez and A. Simonelli

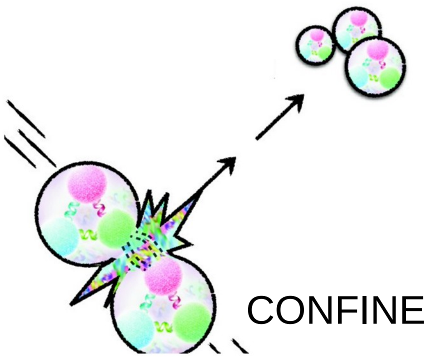
QCD

QCD
- Asymptotic Freedom
- Confinement



QCD
- Perturbative regime (computable but process dependent terms)
- Non perturbative regime (non computable but universal terms)

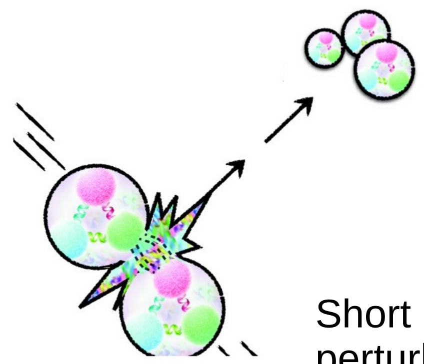
Strong interactions:
hadron structure is
a playground for
studying QCD



Factorization and QCD predictive power

QCD

- Perturbative regime (computable but process dependent terms)
- Non perturbative regime (non computable but universal terms)



Long distance physics, non-perturbative structure functions.

Short distance effects, perturbative QCD

- The interplay between **perturbative** and **non-perturbative** regimes is currently one of the most challenging aspects in phenomenology.
- **Factorization** allows to separate the perturbative content of an observable from its non-perturbative content. At large Q and small m, the non-perturbative contributions are separated out from anything that can be computed by using perturbative techniques, and identified with universal quantities (structure functions).
- **Factorization** restores the predictive power of QCD

Factorization: region classification

J. Collins, Foundations of perturbative QCD (Cambridge University Press, 2011)

Particles are classified according to how they propagate in space,
i.e. according to their virtuality.

Momentum regions:

HARD
$k \sim (Q,\, Q,\, Q)$

Short-distance contributions → Large virtuality

Long-distance contributions → Low virtuality

SOFT
$k \sim (\lambda_S,\, \lambda_S,\, \lambda_S)$

$$\lambda_S = \lambda^2/Q$$

COLLINEAR
$k \sim (Q,\, \lambda^2/Q,\, \lambda)$

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Momentum regions:

HARD
$k \sim (Q,\, Q,\, Q)$

Computable in pQCD

Short-distance contributions $\longrightarrow$ Large virtuality

Long-distance contributions $\longrightarrow$ Low virtuality

Encodes the *correlation* among collinear parts

SOFT
$k \sim (\lambda_S,\, \lambda_S,\, \lambda_S)$

$\lambda_S = \lambda^2/Q$

COLLINEAR
$k \sim (Q,\, \lambda^2/Q,\, \lambda)$

Encodes the essence of the TMD

Factorization theorem

General structure of a generic factorization theorem:

$$\mathcal{O} = H \times \boxed{S \times \prod_j C_j} + p.s.$$

IR-safe hard contribution

Soft and collinear contributions, accounting for non-perturbative effects

Power suppressed terms

- Each term is equipped with proper subtractions.
- The soft factor S encodes the *correlation* among the various collinear parts.
- While H can be computed in pQCD, S and C have to be determined using non perturbative methods. For instance they can be modeled and extracted from experimental data, or computed in lattice QCD

Soft factor and soft/collinear subtraction

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

TMDs are defined through the **factorization definition**:

$$D(z,\, b_T,\, y_1) = \lim_{\hat{y}\to-\infty} \frac{D^{\rm uns.}(z,\, b_T,\, y_P - \hat{y})}{S(b_T,\, y_1 - \hat{y})}$$

From quark-quark correlation matrix

Subtraction of soft-collinear overlapping

The soft factor (included the subtraction term) is defined as:

$$S(b_T,\, y_1 - y_2) = \frac{\rm Tr}{N_C} \langle 0 | W^\dagger_{n_2}[\vec{b_T}/2, \infty]\, W_{n_1}[\vec{b_T}/2, \infty] \times W_{n_2}[-\vec{b_T}/2, \infty]\, W^\dagger_{n_1}[-\vec{b_T}/2, \infty] | 0 \rangle$$

The soft factor of the process and the soft factor of subtractions are the same function!

Square root definition of TMDs

S. M. Aybat and T. C. Rogers, Phys.Rev. D83, 114042 (2011)

sqrt.

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

sqrt.

Recasting terms

Parton model-like

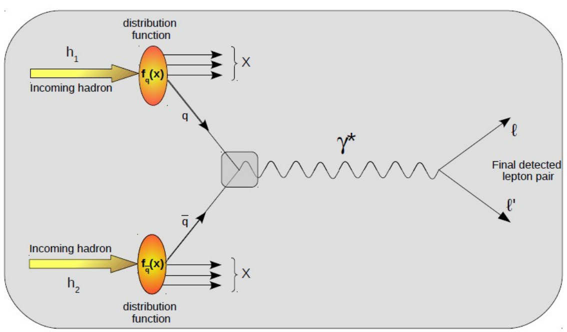
$$= \mathcal{H}_{\rm proc.} \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}_T}\, F^{\rm sqrt}(b_T)\, D^{\rm sqrt}(b_T)$$

Square-root definition of the TMD:

$$D^{\rm sqrt}(z,\, b_T,\, y_n) = \lim_{\substack{\widehat{y}_1\to+\infty \\ \widehat{y}_2\to-\infty}} D^{\rm uns.}(z,\, b_T,\, y_P - \widehat{y}_2)\sqrt{\frac{S(b_T,\, \widehat{y}_1 - y_n)}{S(b_T,\, \widehat{y}_1 - \widehat{y}_2)\, S(b_T,\, y_n - \widehat{y}_2)}}$$

Where do we learn about TMDs?

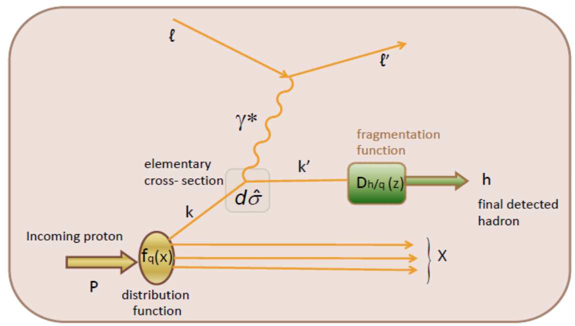
Unpolarized and Polarized Drell-Yan scattering



$$\sigma_{Drell-Yan} = f_q(x,k_\perp)\otimes f_{\bar{q}}(x,k_\perp)\otimes\hat{\sigma}^{q\bar{q}\to\ell\ell'}$$

Allows extraction of distribution functions

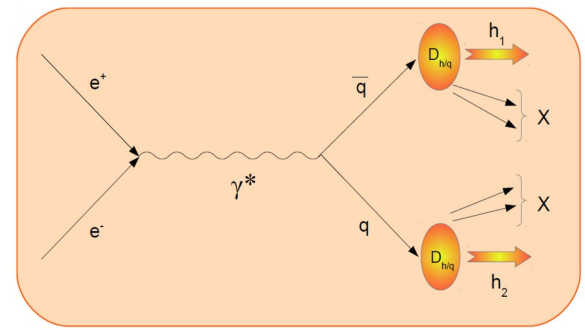
Unpolarized and Polarized SIDIS scattering



$$\sigma_{SIDIS} = f_q(x)\otimes\hat{\sigma}\otimes D_{h/q}(z)$$

Allows extraction of distribution and fragmentation functions

$e^+ e^- \to h_1\, h_2\, X$

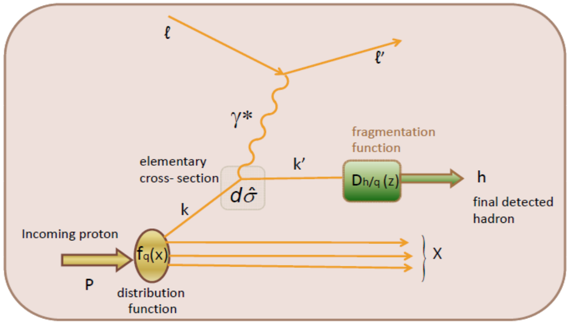


$$\sigma_{h1\,h2}\propto D(z_1)\otimes D(z_2)\otimes\hat{\sigma}$$

Allows extraction of fragmentation functions

Where do we learn about TMDs?

Unpolarized and Polarized SIDIS scattering



$$\sigma_{SIDIS} = f_q(x) \otimes \hat{\sigma} \otimes D_{h/q}(z)$$

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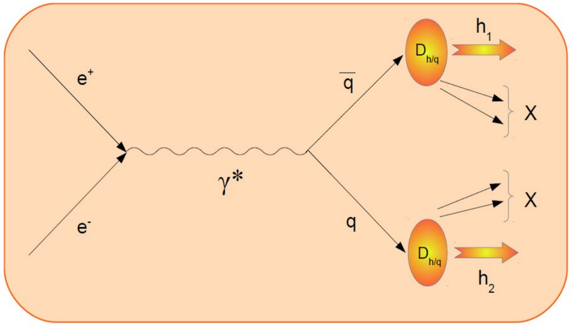
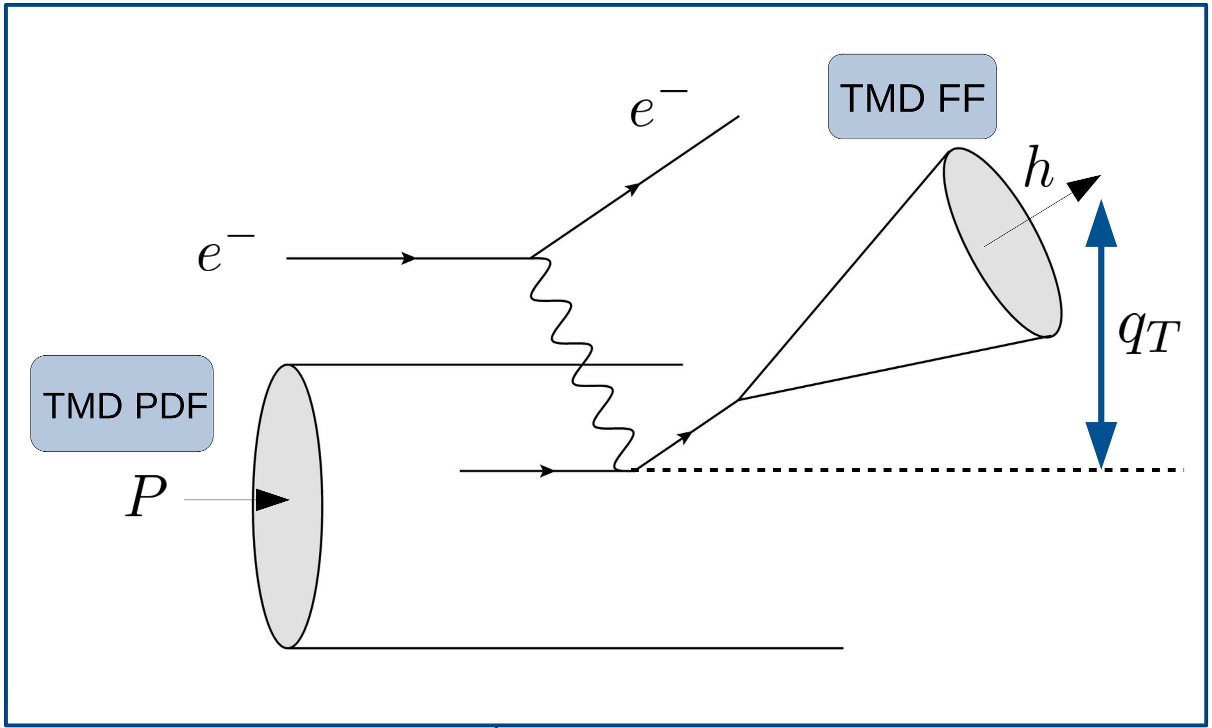


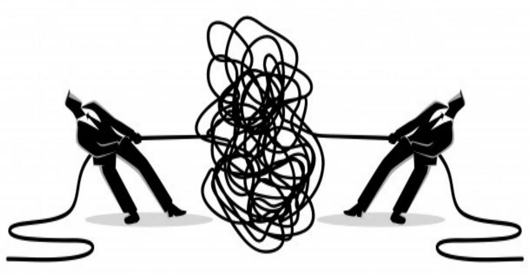
$$\sigma_{h1h2} \propto D(z_1) \otimes D(z_2) \otimes \hat{\sigma}$$

Allows extraction of fragmentation functions

SIDIS: $e\,p \to h\,X$



In e^+e^- cross sections, distribution and fragmentation TMDs are convoluted.
How can they be disentangled?

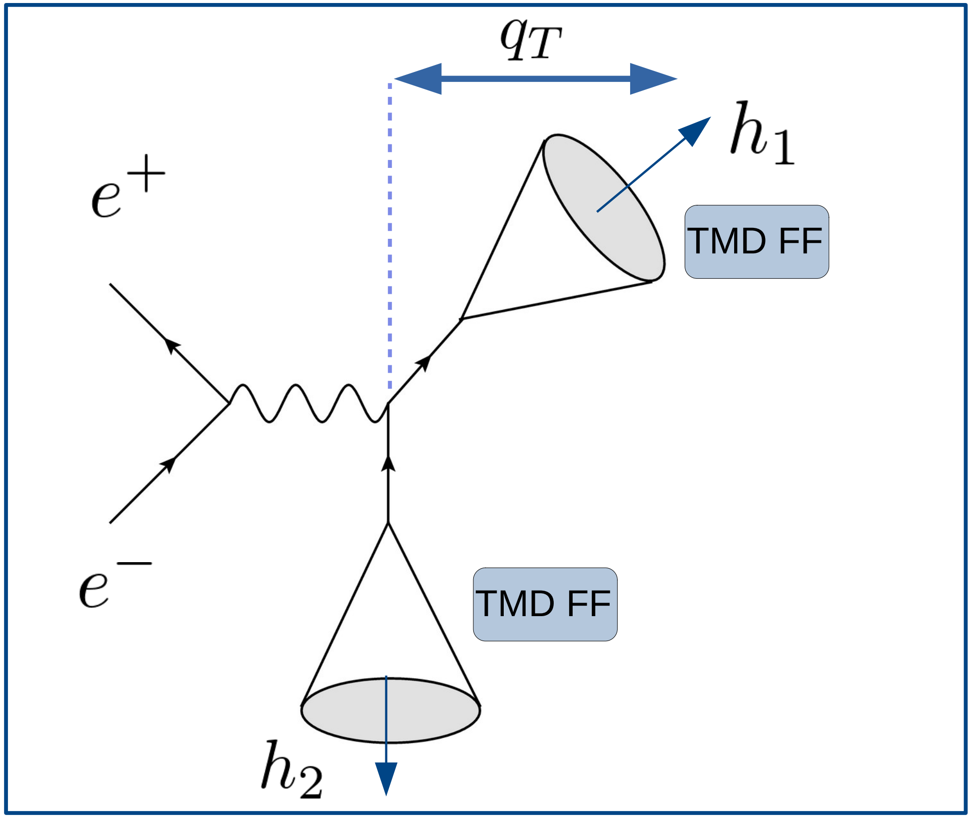


$$\frac{d\sigma}{dq_T} = \mathcal{H}_{\rm sidis} \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}_T} \, F(b_T)\, D(b_T)$$

3D-picture of partons inside the target hadron

3D-picture of partons hadronizing into the detected hadron

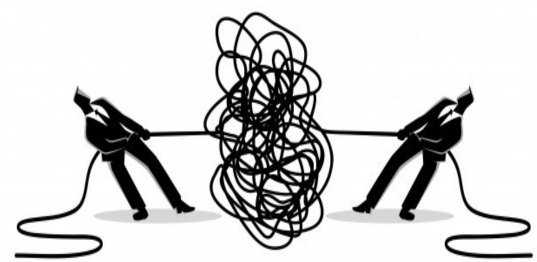
e⁺e⁻ annihilations in two hadrons: $e^+ e^- \to h_1 h_2 X$



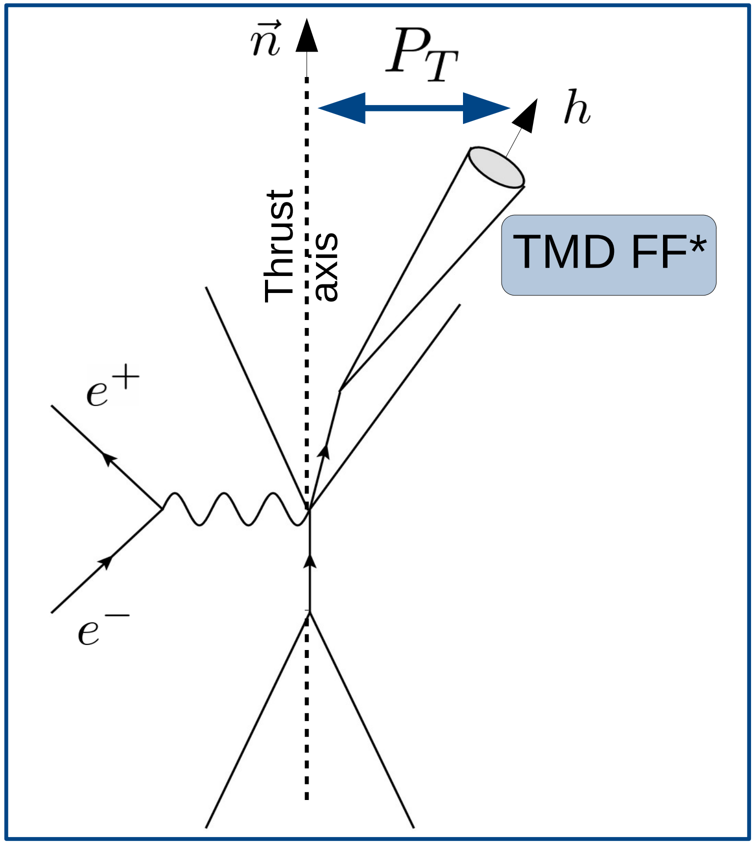
$$\frac{d\sigma}{dq_T} = \mathcal{H}_{\text{2-h}} \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}_T} D_1(b_T)\, D_2(b_T)$$

3D-picture of the **hadronization** of partons into hadrons

In e⁺e⁻ cross sections, distribution and fragmentation TMDs are convoluted.
How can they be disentangled?



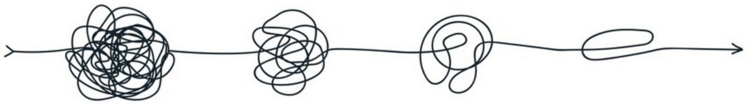
e+e- annihilations in one hadron: $e^+ e^- \to h\, X$



$$\frac{d\sigma}{dP_T} = d\hat{\sigma} \otimes D^\star(P_T)$$

3D-picture of the **hadronization** of partons into hadrons

In $e^+ e^- \to h\, X$ cross sections, only one fragmentation TMD appears



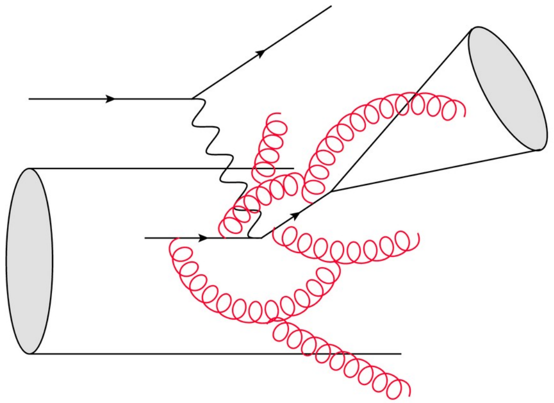
One of the cleanest ways to access TMD Fragmentation Functions***...**

BUT

$D^*(P_T)$ is not the same as $D(P_T)$!!!

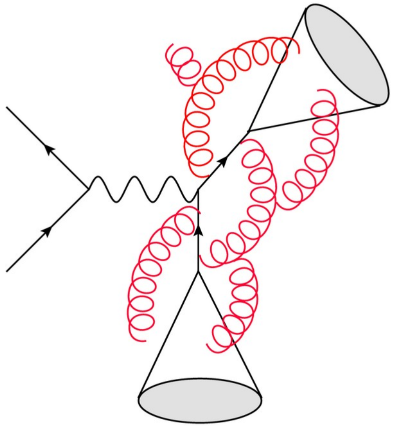
Soft Gluon contribution

SIDIS



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

Double hadron production



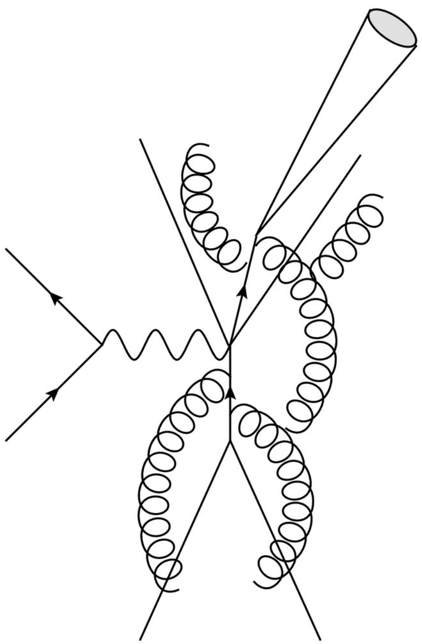
$$\frac{d\sigma}{dq_T} = \mathcal{H}_{\text{2-h}} \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}_T}\, D_1(b_T)\, D_2(b_T)$$

Soft Gluon Factor:
- Non-Perturbative contribution
- Evenly shared by the TMDs

Soft Gluons

M. Boglione, A. Simonelli, Eur. Phys. J. C 81 (2021)

$$e^+e^- \to hX$$



$$\frac{d\sigma}{dP_T} = d\hat{\sigma} \otimes D^\star(P_T)$$

Soft Gluon Factor:

- Perturbative contribution
- The TMD FF***** is **free** from any soft gluon contributions

D(P_T) and D*(P_T) are different,
BUT
the relation between D and D* is known!

We can perform combined analyses and disentangle non-perturbative terms.

Relation between FF and FF*

M. Boglione, A. Simonelli, Eur. Phys. J. C 81 (2021)

$$D = D^{\star}\sqrt{M_S}$$

SQUARE ROOT DEFINITION

Usual definition of TMDs.
Soft Gluon Factor contributing to the cross section are included in the two TMDS and equally shared between them.

FACTORIZATION DEFINITION

Purely collinear TMD, totally free from any soft gluon contribution.

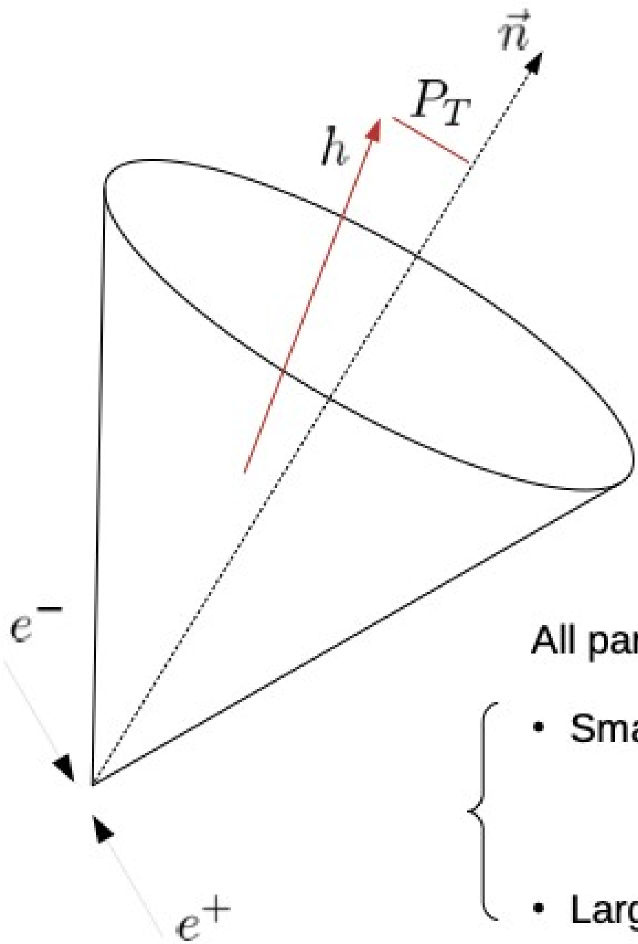
SOFT MODEL

The Soft Gluon Factor appearing in the cross section (process dependent) is **not** included in the TMD

- Same for Drell-Yan, SIDIS and 2-hadron production. (2-h class universality).
- Non-perturbative function (phenomenology).

The $e^+e^- \to hX$ process

The cross section is differential in: $z_h = \dfrac{E}{Q/2}$, $T = \dfrac{\sum_i |\vec{P}_{(\mathrm{c.m.}),\, i} \cdot \hat{n}|}{\sum_i |\vec{P}_{(\mathrm{c.m.}),\, i}|}$, 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 $y_P = \dfrac{1}{2} \log \dfrac{2(P^+)^2}{P_T^2 + M_h^2} \gg 0$

Rapidity divergencies and thrust in Region 2

ISSUES FROM TREATMENT OF RAPIDITY DIVERGENCES

- Peculiar interplay between soft and collinear contributions $\Rightarrow$ some of the rapidity divergences are naturally regulated by the thrust, T, but those associated to strictly TMD parts of the cross section need an extra artificial regulator, which is a rapidity cut- off.
- This induces a redundancy, which generates an additional relation between the regulator, the transverse momentum and thrust.
- This relation inevitably spoils the picture in which the cross section factorizes into the convolution of a partonic cross section (encoding the whole T dependence) with a TMD FF (which encapsulates the whole P_T dependence).
- Thrust resummation is intertwined with the transverse momentum dependence, making the treatment of the large T behavior highly non-trivial.
- A proper phenomenological analysis of Region 2 must rely on a factorized cross section where the regularization of rapidity divergences is properly taken into account. All difficulties encountered in the theoretical treatment get magnified in the phenomenological applications.
- In this analysis we adopt some approximations, in order to simplify the structure of the factorization theorem without altering its main architecture.

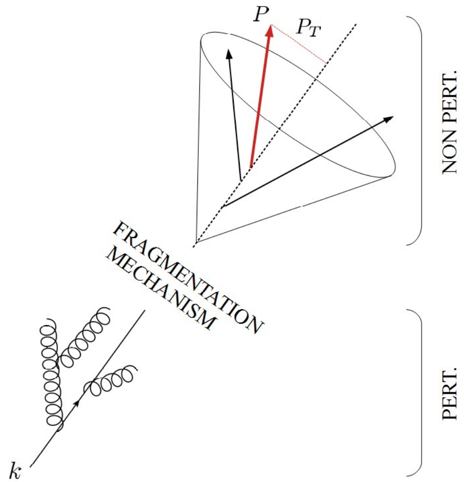
$e^+e^- \to hX$ cross section

M. Boglione, A. Simonelli, JHEP 02 (2021) 076

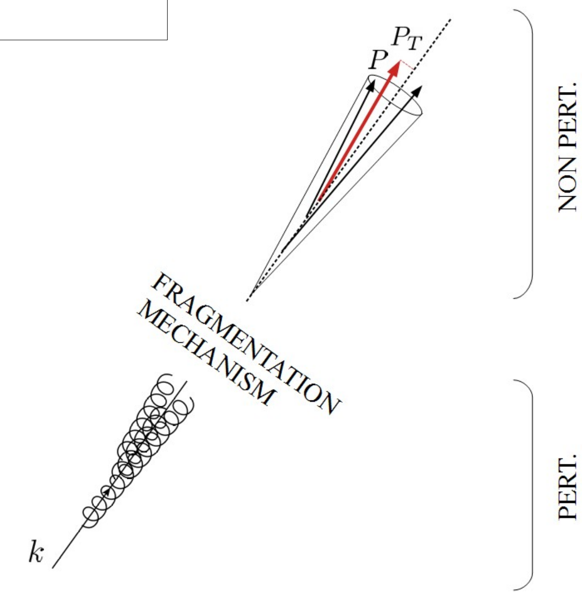
The hadronic cross section is written as a convolution of a partonic cross section with a TMD FF

$$\boxed{\frac{d\sigma}{dz_h\,dT\,dP_T^2} = \pi \sum_f \int_{z_h}^1 \frac{dz}{z}\,\frac{d\widehat{\sigma}_f}{dz_h/z\,dT}\,D_{1,\,\pi^\pm/f}(z,\,P_T,\,Q,\,(1-T)\,Q^2)}$$

The TMD FF acquires a dependence on thrust through its rapidity cut-off.



$$\xrightarrow[T \to 1]{\text{2-jet limit}}$$



Partonic cross section (NLO)

M. Boglione, A. Simonelli, JHEP 02 (2021) 076

$$\frac{d\sigma}{dz_h\, dT\, dP_T^2} = \pi \sum_f \int_{z_h}^1 \underbrace{\frac{dz}{z}\, \frac{d\widehat{\sigma}_f}{dz_h/z\, dT}} D_{1,\,\pi^\pm/f}(z,\, P_T,\, Q,\, (1-T)\, Q^2)$$

$$\boxed{\frac{d\widehat{\sigma}_f}{dz\, dT} = \left[-\sigma_B e_f^2 N_C \frac{\alpha_S(Q)}{4\pi} C_F \delta(1-z) \left[\frac{3+8\log\tau}{\tau}\right] + \mathcal{O}\left(\alpha_S(Q)^2\right)\right] e^{-\frac{\alpha_S(Q)}{4\pi}\, 3C_F (\log\tau)^2 + \mathcal{O}\left(\alpha_S(Q)^2\right)}}$$

TMD Fragmentation Function

$$\frac{d\sigma}{dz_h\, dT\, dP_T^2} = \pi \sum_f \int_{z_h}^1 \frac{dz}{z} \frac{d\widehat{\sigma}_f}{dz_h/z\, dT} D_{1,\,\pi^\pm/f}(z,\, P_T,\, Q,\, (1-T)\,Q^2)$$

Fourier Transform of:

Collinear FFs

$$\widetilde{D}_{1,\,\pi^\pm/f}(z,\, b_T;\, Q,\, \tau Q^2) = \frac{1}{z^2} \sum_k \left[\boxed{d_{\pi^\pm/k}} \otimes \mathcal{C}_{k/f}\right](\mu_b) \times$$

$$\times \exp\left\{\frac{1}{4}\widetilde{K}\,\log\frac{\tau Q^2}{\mu_b^2} + \int_{\mu_b}^{Q}\frac{d\mu'}{\mu'}\left[\gamma_D - \frac{1}{4}\gamma_K\,\log\frac{\tau Q^2}{\mu'^2}\right]\right\} \times$$

$$\times \underbrace{(M_D)_{f,\,\pi^\pm}(z,\, b_T)} \exp\left\{-\frac{1}{4}\underbrace{g_K(b_T)}\log\left(\tau\frac{Q^2}{M_H^2}\right)\right\}$$

Perturbative part (NLL)

Non-Perturbative part Phenomenological Model

Embeds the non-perturbative, long-range behavior of the TMD FF

Universal, independent of the TMD definition used

Phenomenological parametrization: M_D

M. Boglione, J.O. Gonzalez-Hernandez, A. Simonelli, 2206.08876 [hep-ph]

$$M_D = \underbrace{\frac{2^{2-p}(b_T M)^{p-1}}{\Gamma(p-1)} K_{p-1}(b_T M)}_{\text{Power-law model}} \times \underbrace{F(b_T, z_h)}_{\text{Multiplicative function modulating the z dependece}}$$

Power-law model

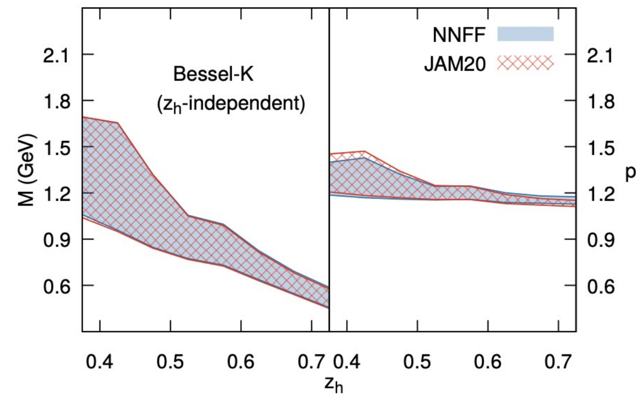
Multiplicative function modulating the z dependece

$\mathcal{FT}\{M_D\}$ reminiscent of a propagator in k_T space $\left.\right\} \dfrac{1}{(k_T^2 + M^2)^p}$

Exponential behaviour at $b_T \to \infty$

Preliminary fits at fixed z show that

- the M and p parameters are VERY strongly correlated
- M requires some z-dependence while p does not vary much with z



Phenomenological parametrization: M_D

M. Boglione, J.O. Gonzalez-Hernandez, A. Simonelli, 2206.08876 [hep-ph]

$$M_{\mathrm{D}} = \underbrace{\frac{2^{2-p}(b_{\mathrm{T}} M_0)^{p-1}}{\Gamma(p-1)} K_{p-1}(b_{\mathrm{T}} M_0)}_{\text{BK parameters do not depend on z}} \times F(b_{\mathrm{T}}, z_h)$$

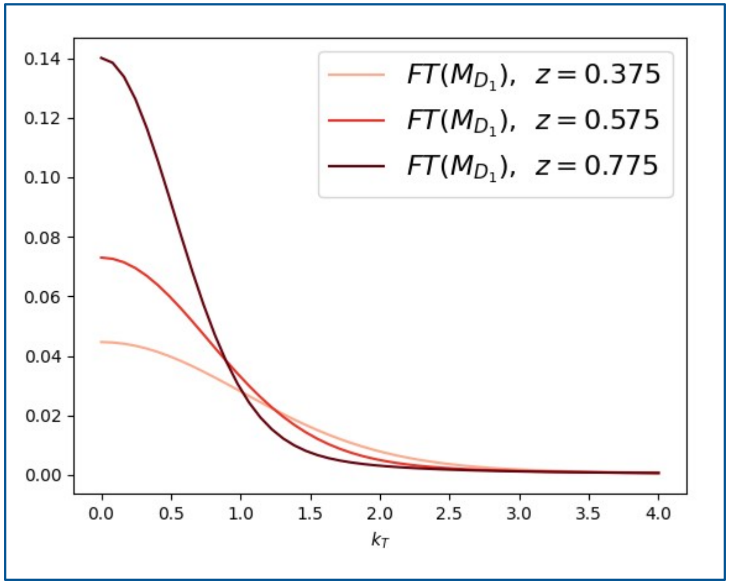
BK parameters do not depend on z

M_D MODEL 1

ID	M_{D} model
I	$F = \left(\frac{1 + \log\left(1 + (b_{\mathrm{T}} M_z)^2\right)}{1 + (b_{\mathrm{T}} M_z)^2} \right)^q$ $M_z = -M_1 \log(z_h)$

z-dependence controlled by the function F, through M_z

z-dependence controlled by F



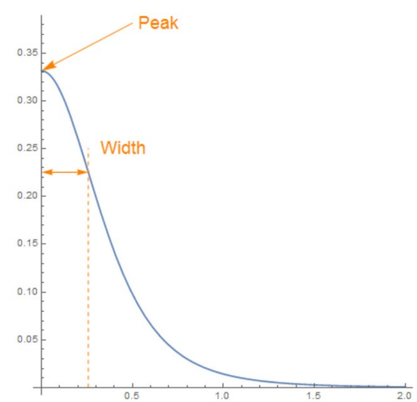
Phenomenological parametrization: M_D

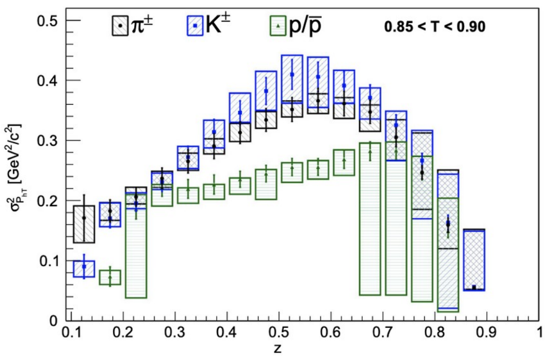
$$M_D = \underbrace{\frac{2^{2-p_z}(b_T M_z)^{p_z-1}}{\Gamma(p_z-1)} K_{p_z-1}(b_T M_z)}_{\text{BK parameters depend on z}} \times \underbrace{F(b_T, z_h)}_{F\,=\,1}$$

M_D MODEL 2

II	$F = 1$
	$M_z = M_h \dfrac{1}{z\, f(z)^2} \sqrt{\dfrac{3}{1-f(z)}}$
	$p_z = 1 + \dfrac{3}{2} \dfrac{f(z)}{1-f(z)}$
	$f(z) = 1 - (1-z)^{\beta}, \quad \beta = \frac{1-z_0}{z_0}$

The z behaviour of M_D is constrained by requiring that the theory lines appropriately reproduce the peak and the width of the measured cross sections, at each value of z.





BELLE Phys. Rev. D99 (2019) 11 112006

Phenomenological parametrization: g_K

M. Boglione, J.O. Gonzalez-Hernandez, A. Simonelli, 2206.08876 [hep-ph]

In this analysis we consider two different hypothesis for g_K for which, asymptotically, we have $g_K = o(b_T)$

J. Collins, T. Rogers, Phys. Rev. D 91, 074020 (2015)
C. Aidala et al., Phys.Rev. D89, 094002 (2014)
A.. Vladimirov Phys. Rev. Lett. 125, 192002 (2020).

g_{K} model		
A	$g_{\mathrm{K}} = \log\left(1 + (b_{\mathrm{T}} M_{\mathrm{K}})^{p_{\mathrm{K}}}\right)$	$M_{\mathrm{K}},\ p_{\mathrm{K}}^*$
B	$g_{\mathrm{K}} = M_{\mathrm{K}} b_{\mathrm{T}}^{(1-2p_{\mathrm{K}})}$	$M_{\mathrm{K}},\ p_{\mathrm{K}}^*$

Testing different b_T behaviors of g_K
allows us to give a reliable estimate
of the uncertainties affecting our analysis

Phenomenological results – correlations

M. Boglione, J.O. Gonzalez-Hernandez, A. Simonelli, 2206.08876 [hep-ph]

Model I

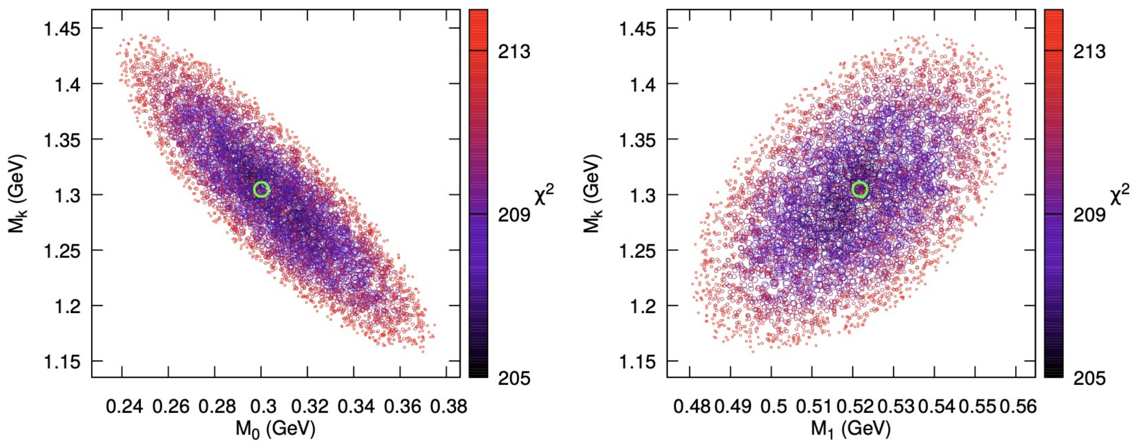
3 parameter fit

$q_{\mathrm{T}}/Q < 0.15$ (pts = 168)		
	IA	IB
$\chi^2_{\mathrm{d.o.f.}}$	1.25	1.19
$M_0(\mathrm{GeV})$	$0.300^{+0.075}_{-0.062}$	$0.003^{+0.089}_{-0.003}$
$M_1(\mathrm{GeV})$	$0.522^{+0.037}_{-0.041}$	$0.520^{+0.027}_{-0.040}$
p^*	1.51	1.51
q^*	8	8
$M_{\mathrm{K}}(\mathrm{GeV})$	$1.305^{+0.139}_{-0.146}$	$0.904^{+0.037}_{-0.086}$
p^*_{K}	0.609	0.229

Data selection

$$0.375 \leq z_h \leq 0.725\,, \qquad 0.750 \leq T \leq 0.875\,,$$

$$q_{\mathrm{T}}/Q \leq 0.15$$



Phenomenological results – correlations

M. Boglione, J.O. Gonzalez-Hernandez, A. Simonelli, 2206.08876 [hep-ph]

Model II

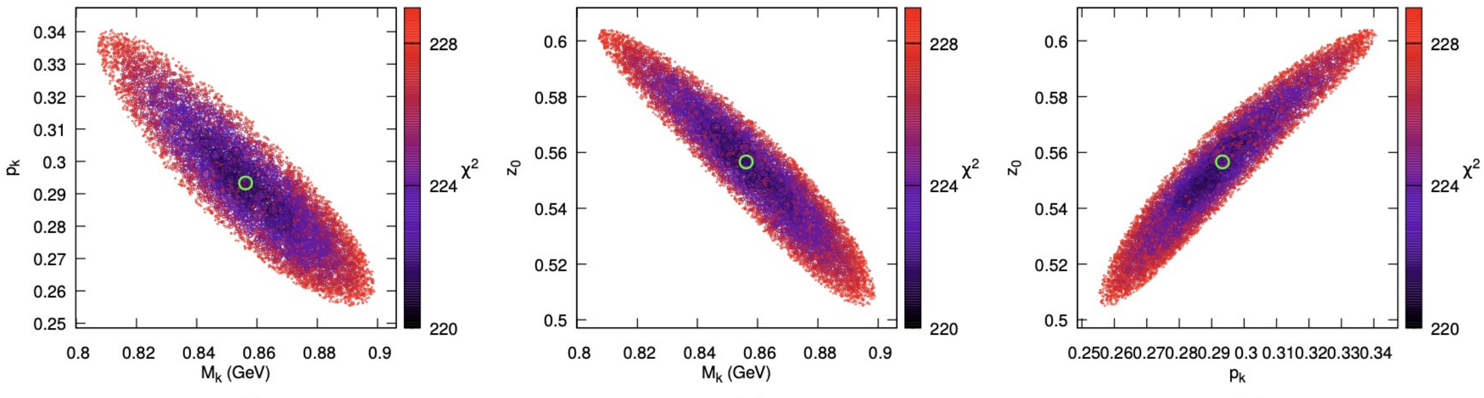
3 parameter fit

$q_T/Q < 0.15$ (pts = 168)		
	IIA	IIB
$\chi^2_{\mathrm{d.o.f.}}$	1.35	1.33
z_0	$0.574^{+0.039}_{-0.041}$	$0.556^{+0.047}_{-0.051}$
M_K(GeV)	$1.633^{+0.103}_{-0.105}$	$0.687^{+0.114}_{-0.171}$
p_k	$0.588^{+0.127}_{-0.141}$	$0.293^{+0.047}_{-0.038}$

Data selection

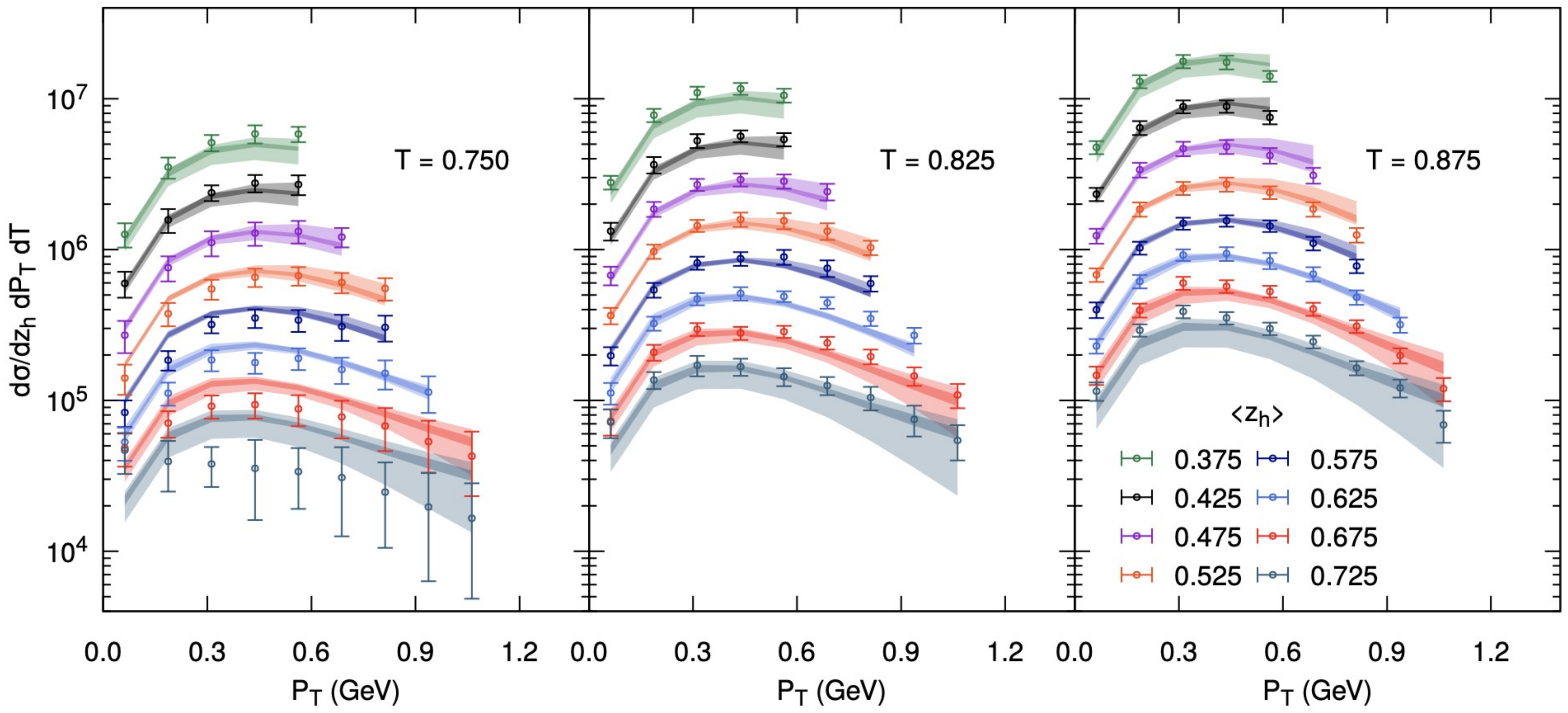
$$0.375 \le z_h \le 0.725\,, \qquad 0.750 \le T \le 0.875\,,$$

$$q_T/Q \le 0.15$$



Phenomenological results – T dependence

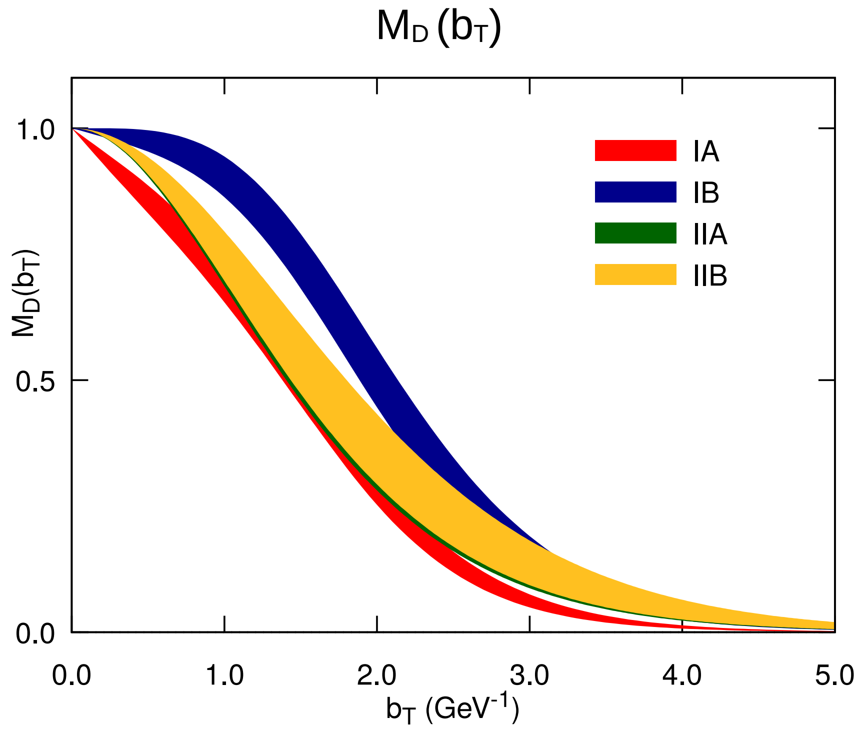
M. Boglione, J.O. Gonzalez-Hernandez, A. Simonelli, 2206.08876 [hep-ph]

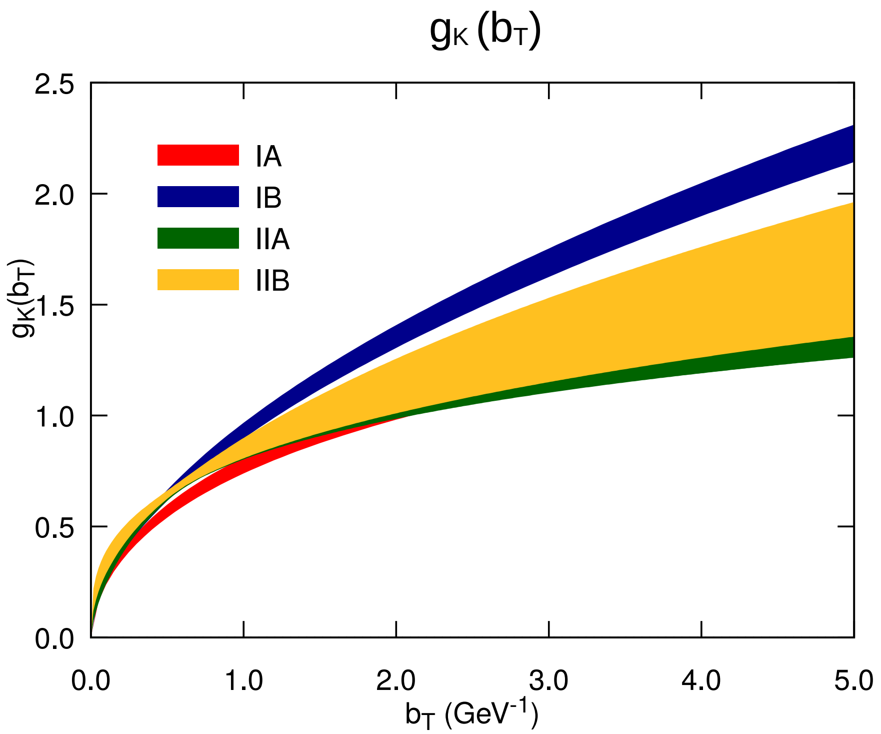


BELLE Collaboration, R. Seidl et al.,Phys. Rev. D99 (2019), no. 11 112006

Phenomenological results

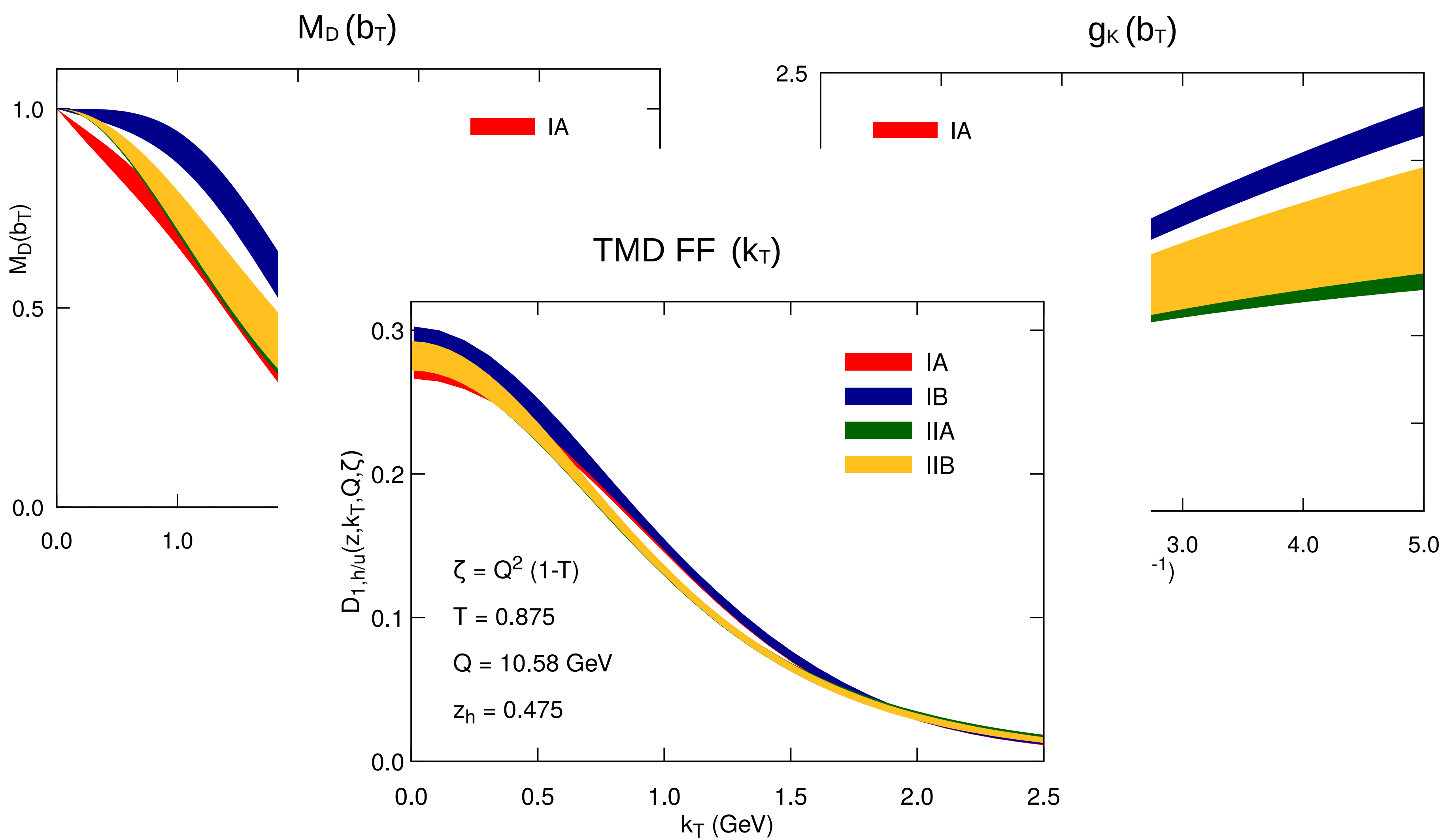
M. Boglione, J.O. Gonzalez-Hernandez, A. Simonelli, 2206.08876 [hep-ph]





Phenomenological results

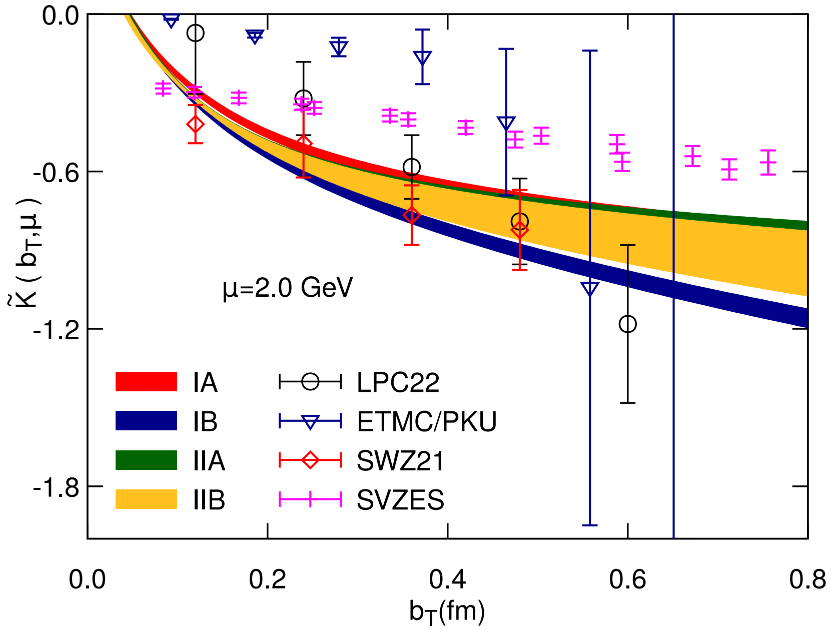
M. Boglione, J.O. Gonzalez-Hernandez, A. Simonelli, 2206.08876 [hep-ph]



Collins-Soper kernel: comparison to other analyses

M. Boglione, J.O. Gonzalez-Hernandez, A. Simonelli, 2206.08876 [hep-ph]

Our extraction of the Collins-Soper Kernel compared to corresponding lattice computations



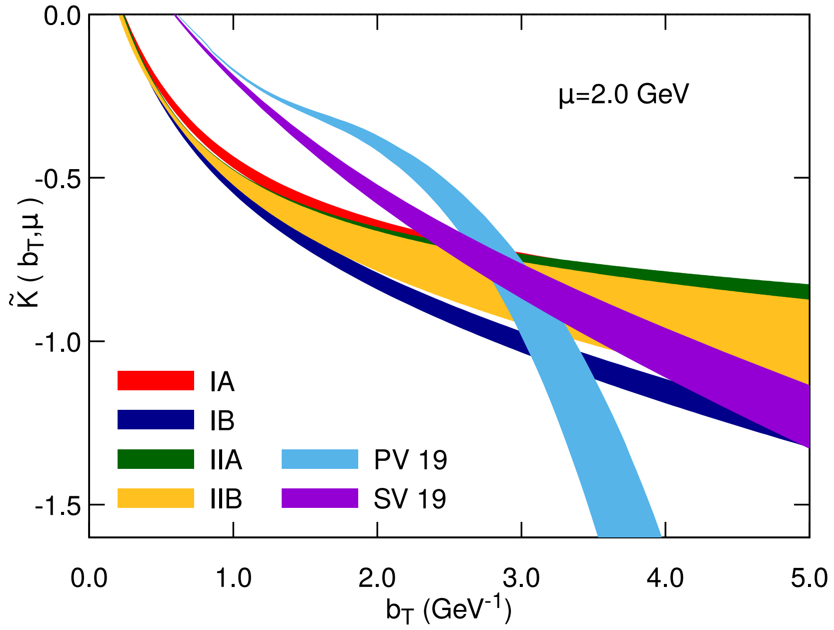
M.-H. Chu et al. (LPC22), arXiv:2204.00200 [hep- lat]

Y. Li et al.,(ETMC/PKU) Phys. Rev. Lett. 128, 062002 (2022),

P. Shanahan et al. (SVZ21) Phys. Rev. D 104, 114502 (2021),

M. Schlemmer et al. (SVZES) JHEP 08, 004 (2021),

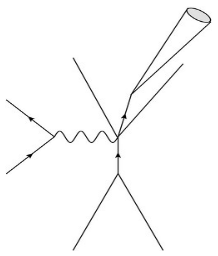
Our extraction of the Collins-Soper Kernel compared to other phenomenological analyses



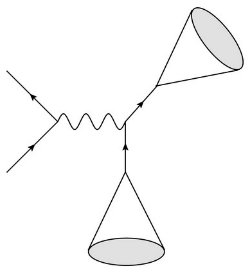
I. Scimemi and A. Vladimirov, (SV19) JHEP 06, 137 (2020)

A. Bacchetta, et al. (PV19) JHEP 07, 117 (2020)

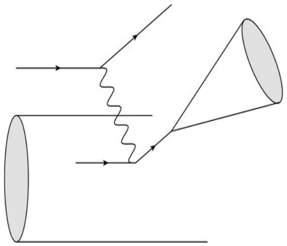
Outlook



1. $e^+ e^- \to h\, X$
   Extraction of the unpolarized TMD FF, D*, for charged pions from BELLE data (using factorization definition)



2. $e^+ e^- \to h_1 h_2\, X$
   Two non-perturbative functions:
   D*, known from step 1
   Soft Model M_s, obtained as ratio: $M_S = D/D^\star$



3. $SIDIS$ (this is where COMPASS, HERMES, JLAB and EIC data play a crucial role!)
   Three non-perturbative functions in the cross section
   D*, known from step 1.
   Soft Model M_S, known from step 2.
   Extraction of the TMD PDF, F* (in the factorization definition, F*≠F).

Conclusions and Outlook

The Soft Factor acquires a central role

The focus of phenomenological analyses moves from the TMDs considered as a whole, to the Soft Factor contribution (which encloses the full process dependent part of the TMD).

The Collins-Soper kernel acquires a central role

The focus of phenomenological analyses moves from the TMDs considered as a whole, to the g_K function (which embeds the non-perturbative essence of the TMD evolution).