Andrea Simonelli

In collaboration with M. Boglione

Disentangling Soft Effects from TMD Fragmentation Functions

Old Dominion University

Jefferson Lab

DIS2024

XXXI International Workshop on Deep Inelastic Scattering

8-12 April 2024, Grenoble, France

A. Simonelli

TMD Factorization

- Drell-Yan $pp \to e^+ e^- X$
- Semi-Inclusive DIS $e^- p \to e^- h X$
- Double-Inclusive Annihilation $e^+ e^- \to h_1 h_2 X$

"STANDARD" PROCESSES

$$d\sigma = |H|^2 \int \frac{d\vec{b}_T}{(2\pi)^2} e^{-i\,\vec{q}_T \cdot \vec{b}_T}\, D_A(z_A, b_T, y_A - y_n)\, D_B(z_B, b_T, y_n - y_B)$$

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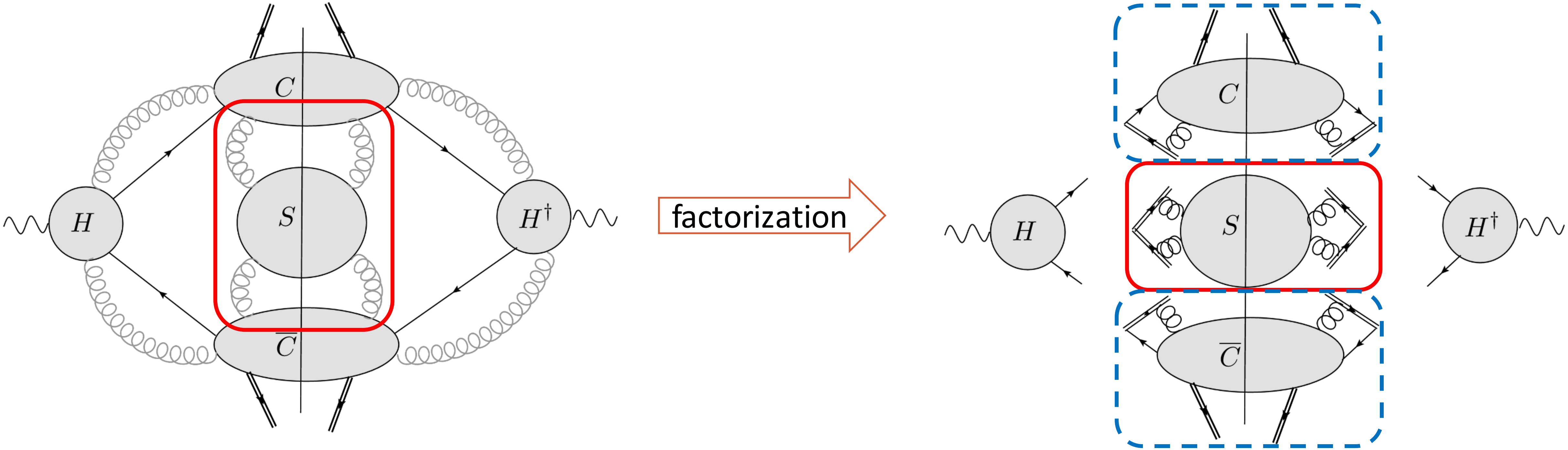
Such cross section actually comes from the **re-arranging** of:

$$d\sigma = |H|^2 \int \frac{d\vec{b}_T}{(2\pi)^2} e^{-i\,\vec{q}_T\cdot\vec{b}_T} D^\star_A(z_A, b_T, y_A - y_1)\, S(b_T, y_1 - y_2)\, D^\star_B(z_B, b_T, y_2 - y_B)$$



"Hidden" and **not directly accessible** soft factor correlating the two collinear groups

$$d\sigma = |H|^2 \int \frac{d\vec{b}_T}{(2\pi)^2} e^{-i\,\vec{q}_T \cdot \vec{b}_T}$$

$$\frac{D_A^{\text{uns.}}(z_A, b_T, y_A - (-\infty))}{S(b_T, y_1 - (-\infty))} S(b_T, y_1 - y_2) \frac{D_B^{\text{uns.}}(z_B, b_T, \infty - y_B)}{S(b_T, \infty - y_2)}$$

$$D_A^{\star}(z_A, b_T, y_A - y_1) \qquad D_B^{\star}(z_A, b_T, y_2 - y_B)$$

Where:

$$D^{\text{uns}}(z, b_T, y_{\text{had}} - (-\infty)) = \frac{\text{Tr}_c}{N_c} \frac{\text{Tr}_D}{4} \sum_X \frac{1}{z} \int \frac{dx^-}{2\pi} e^{ik^+ x^-} \qquad x = \left(0, x^-, \vec{b}_T/2\right)$$

$$\langle 0|\gamma^+ W_- \left(x/2 \to \infty\right) |P;X\rangle\langle P;X| W_-^\dagger \left(-x/2 \to \infty\right) |0\rangle$$

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$$d\sigma = |H|^2 \int \frac{d\vec{b}_T}{(2\pi)^2} e^{-i\,\vec{q}_T\cdot\vec{b}_T} \frac{D_A^{\rm uns.}(z_A, b_T, y_A - (-\infty))}{S(b_T, y_1 - (-\infty))} S(b_T, y_1 - y_2) \frac{D_B^{\rm uns.}(z_B, b_T, \infty - y_B)}{S(b_T, \infty - y_2)}$$

TMD Parton Distribution and Fragmentation Functions with QCD Evolution

S.Mert Aybat (NIKHEF, Amsterdam and Vrije U., Amsterdam), Ted C. Rogers (Vrije U., Amsterdam) (Jan, 2011)

Published in: *Phys.Rev.D* 83 (2011) 114042 • e-Print: 1101.5057 [hep-ph]

Same functional form!

Magic of
2-hadron processes

$$D(z, b_T, y_{\rm had} - y_1) = D^{\rm uns}(z, b_T, y_{\rm had} - (-\infty)) \sqrt{\frac{S(b_T, \infty - y_1)}{S(b_T, \infty - (-\infty))\, S(b_T, y_1 - (-\infty))}}$$

- Light-cone limit $\begin{cases} y_1 \to \infty \\ y_2 \to -\infty \end{cases}$
- Soft Evolution $S(y_A - y_B) \propto S(y_A - y_C)\, S(y_C - y_B)$

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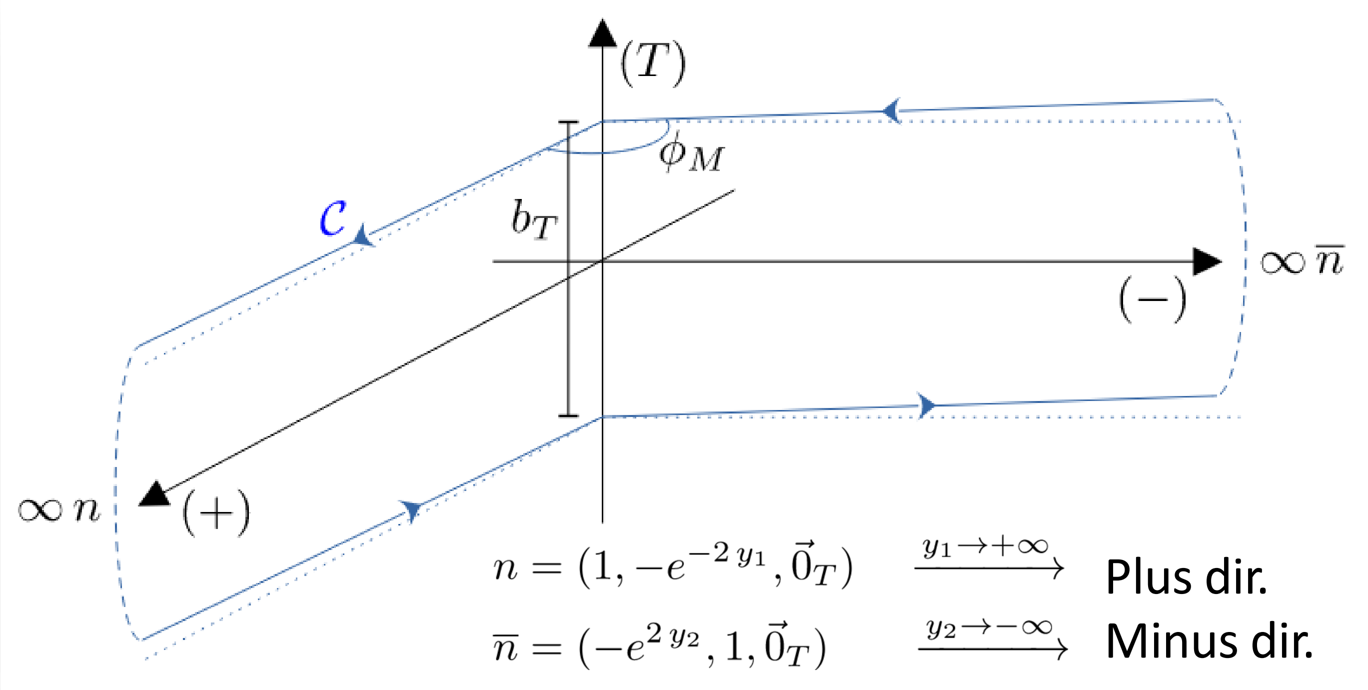
Soft Factor



$$\cosh\phi_M = \frac{n\cdot\overline{n}}{\sqrt{n^2\,\overline{n}^2}} \equiv \cosh(y_1 - y_2)$$

$\phi_M = y_1 - y_2$ Minkowskian angle

$\phi_M \to \infty$ TMD Factorization

$\phi_M \to 0$ Bremsstrahlung function

$\phi_M \to i\pi$ quark-antiquark potential

$$\mathcal{S}(b_T, \phi_M) = \frac{\mathrm{Tr}}{N}\langle 0|W_{\mathcal{C}}(b_T,\phi_M)|0\rangle = \frac{\mathrm{Tr}}{N}\mathcal{P}\,Z_S\,\langle 0|e^{-ig_0\oint_{\mathcal{C}} dx^\mu A_\mu^{(0),\,a}(x)\,t_a}|0\rangle$$

QCD cusp anomalous dimension: current status

Andrey Grozin (Novosibirsk, IYF) (Dec 10, 2022)

e-Print: 2212.05290 [hep-ph]

$$
\begin{aligned}
\Gamma = {} & 4C_R \frac{\alpha_s}{4\pi} \Big\{ \varphi \coth\varphi - 1 + \frac{\alpha_s}{4\pi} \Big[C_A \Big[\frac{2}{3}\pi^2 - \frac{49}{9} + 2\varphi^2 \\
& + \coth\varphi \left(2\,\mathrm{Li}_2(e^{-2\varphi}) - 4\varphi \log(1 - e^{-2\varphi}) - \frac{\pi^2}{3} - \frac{2}{3}\pi^2\varphi + \frac{67}{9}\varphi - 2\varphi^2 - \frac{2}{3}\varphi^3 \right) \\
& + \coth^2\varphi \left(2\,\mathrm{Li}_3(e^{-2\varphi}) + 2\varphi\,\mathrm{Li}_2(e^{-2\varphi}) - 2\zeta_3 + \frac{\pi^2}{3}\varphi + \frac{2}{3}\varphi^3 \right) \Big] \\
& - \frac{20}{9} T_F n_f (\varphi \coth\varphi - 1) \Big] + \mathcal{O}(\alpha_s^2) \Big\} \\
= {} & 4C_R \frac{\alpha_s}{4\pi} \Big\{ \varphi \coth\varphi - 1 \\
& + \frac{\alpha_s}{4\pi} \Big[C_A \Big[2\left(1 + \frac{2}{3}\varphi^2\right) - \frac{1}{3}(\varphi\coth\varphi - 1)\left(2\pi^2 - \frac{67}{3} + 2\varphi^2\right) \\
& + \coth\varphi(\varphi\coth\varphi + 1)\big(\mathrm{Li}_2(1 - e^{2\varphi}) - \mathrm{Li}_2(1 - e^{-2\varphi})\big) \\
& - 2\coth^2\varphi\big(\mathrm{Li}_3(1 - e^{2\varphi}) + \mathrm{Li}_3(1 - e^{-2\varphi})\big) \Big] \\
& - \frac{20}{9} T_F n_f (\varphi\coth\varphi - 1) \Big] + \mathcal{O}(\alpha_s^2) \Big\} \qquad (4.2)
\end{aligned}
$$

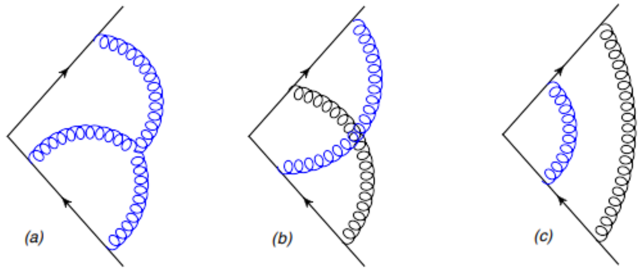
Non-Abelian Exponentiation Theorem

See works by E. Gardi, E. Leanen, L. Magnea, C. White etc...

Webs in multiparton scattering using the replica trick

Einan Gardi (Edinburgh U.), Eric Laenen (Amsterdam U. and Utrecht U. and NIKHEF, Amsterdam), Ge Stavenga (Fermilab), Chris D. White (Glasgow U. and Durham U., IPPP and Durham U.) (Aug, 2010)

Published in: *JHEP* 11 (2010) 155 • e-Print: 1008.0098 [hep-ph]



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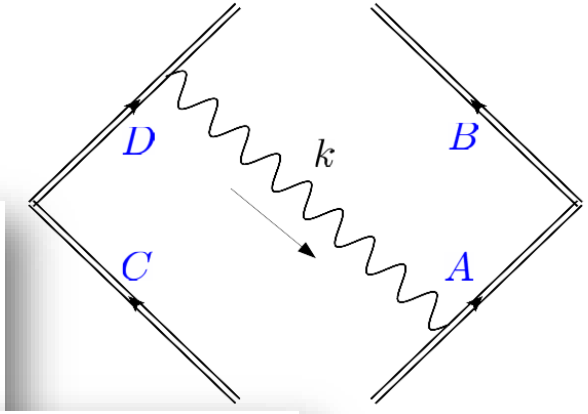
In the light-cone limit:

$\phi_M \to \infty$

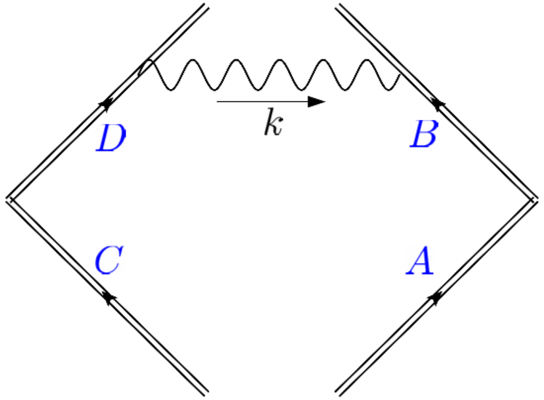
$$S(b_T;\phi_M) = e^{\phi_M K(b_T) + P(b_T)}$$

Studied a lot in TMD factorization...

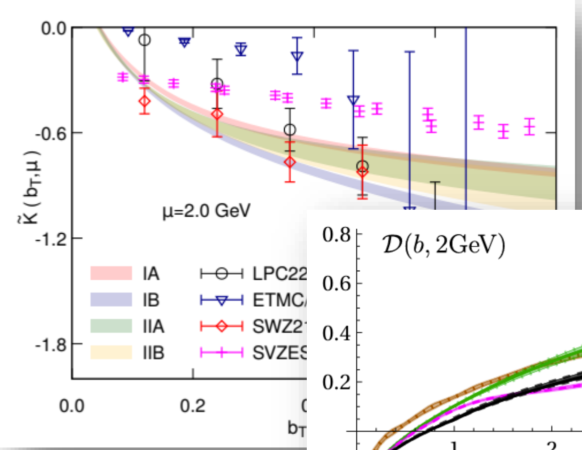
Collins-Soper kernel

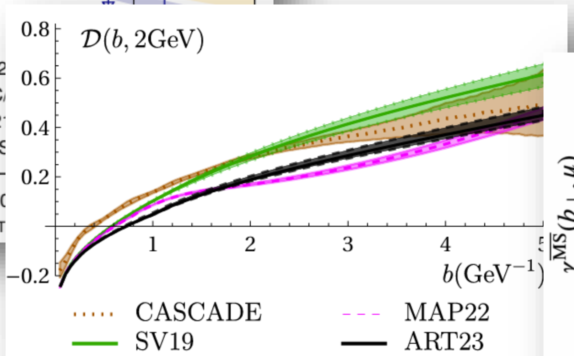


"Constant" P-term



2206.08076 [hep-lat]





2305.07473 [hep-lat]

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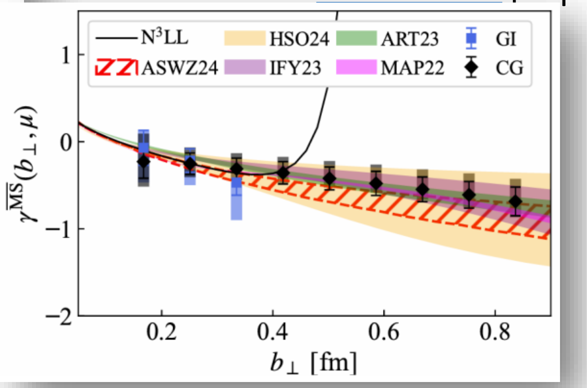

Where is it and **how** can we access it?

The P-terms **disappear** in the standard TMD factorization...

$$\frac{\mathcal{D}_A^{\text{uns.}}(z_A, b_T; y_A - (-\infty))}{\mathcal{S}(b_T; y_1 - (-\infty))} \times \mathcal{S}(b_T; y_1 - y_2) \times \frac{\mathcal{D}_B^{\text{uns.}}(z_B, b_T; \infty - y_B)}{\mathcal{S}(b_T; \infty - y_2)}$$

$$= \frac{\mathcal{D}_A^{\text{uns.}}(z_A, b_T; y_A - (-\infty))}{e^{(y_1-(-\infty))K + \cancel{\frac{1}{2}P}}} \times e^{(y_1-y_2)K+\cancel{P}} \times \frac{\mathcal{D}_B^{\text{uns.}}(z_B, b_T; \infty - y_B)}{e^{(\infty-y_2)K+\cancel{\frac{1}{2}P}}}$$

...as well as in the standard TMD definition:

$$D(y_{\text{had}} - y_1) = D^{\text{uns.}}(y_{\text{had}} - (-\infty))\sqrt{\frac{\mathcal{S}(\infty - y_1)}{\mathcal{S}(\infty - (-\infty))\,\mathcal{S}(y_1 - (-\infty))}}$$

$$= D^{\text{uns.}}(y_{\text{had}} - (-\infty))\sqrt{\frac{e^{(\infty-y_1)K+\cancel{\frac{1}{2}P}}}{e^{(\infty-(-\infty))K}\, e^{(y_1-(-\infty))K+\cancel{\frac{1}{2}P}}}}$$

The standard definition is optimal for standard TMD factorization.

We can forget about the existence of the P-term **in the standard cases.**

This is a naïve proof! Actual proof requires to modify also the unsubtracted TMDs

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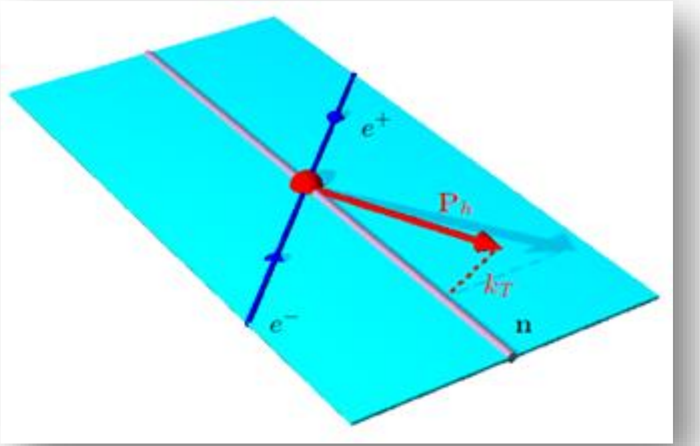
A non-standard case

Single-Inclusive Annihilation (SIA) with thrust $e^+e^- \to h\,X$



The transverse momentum of the detected hadron is measured w.r.t. the thrust axis

$$z_h = \frac{E}{Q/2}, \quad T = \frac{\sum_i |\vec{P}_{(\mathrm{c.m.}),\,i} \cdot \hat{n}|}{\sum_i |\vec{P}_{(\mathrm{c.m.}),\,i}|}, \quad P_T \text{ w.r.t } \vec{n}$$

Data available since 2019

Transverse momentum dependent production cross sections of charged pions, kaons and protons produced in inclusive e^+e^- annihilation at $\sqrt{s} =$ 10.58 GeV #11

Belle Collaboration • R. Seidl (RIKEN BNL) et al. (Feb 5, 2019)

Published in: *Phys.Rev.D* 99 (2019) 11, 112006 • e-Print: 1902.01552 [hep-ex]

pdf DOI cite claim reference search 34 citations

Complete theoretical treatment and first phenomenology is now available

Full treatment of the thrust distribution in single inclusive $e^+e^- \to h\,X$ processes #1

M. Boglione (Turin U. and INFN, Turin), A. Simonelli (Old Dominion U. and Jefferson Lab) (Jun 5, 2023)

Published in: *JHEP* 09 (2023) 006 • e-Print: 2306.02937 [hep-ph]

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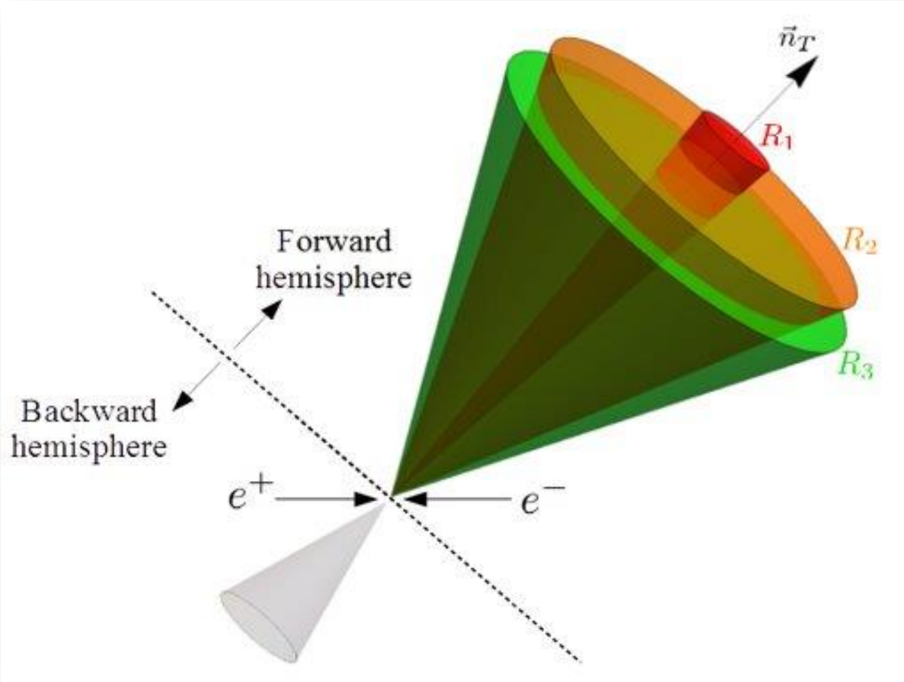

The hadron is detected very close to the **axis** of the jet.
- Extremely small P_T
- Soft radiation affects significantly the transverse deflection of the hadron from the thrust axis

The hadron is detected in the **central region** of the jet.
- Most common scenario
- Majority of experimental data expected to fall into this case

The hadron is detected near the **boundary** of the jet.
- Moderately small P_T
- The hadron transverse momentum affects the topology of the final state directly

Different kinematics leads to different factorized cross sections

Factorization works in the same way for all the three regions, but it produces different results depending on the underlying kinematics

	soft	soft-collinear	collinear
R_1	TMD-relevant	TMD-relevant	TMD-relevant
R_2	TMD-irrelevant	TMD-relevant	TMD-relevant
R_3	TMD-irrelevant	TMD-irrelevant	TMD-relevant

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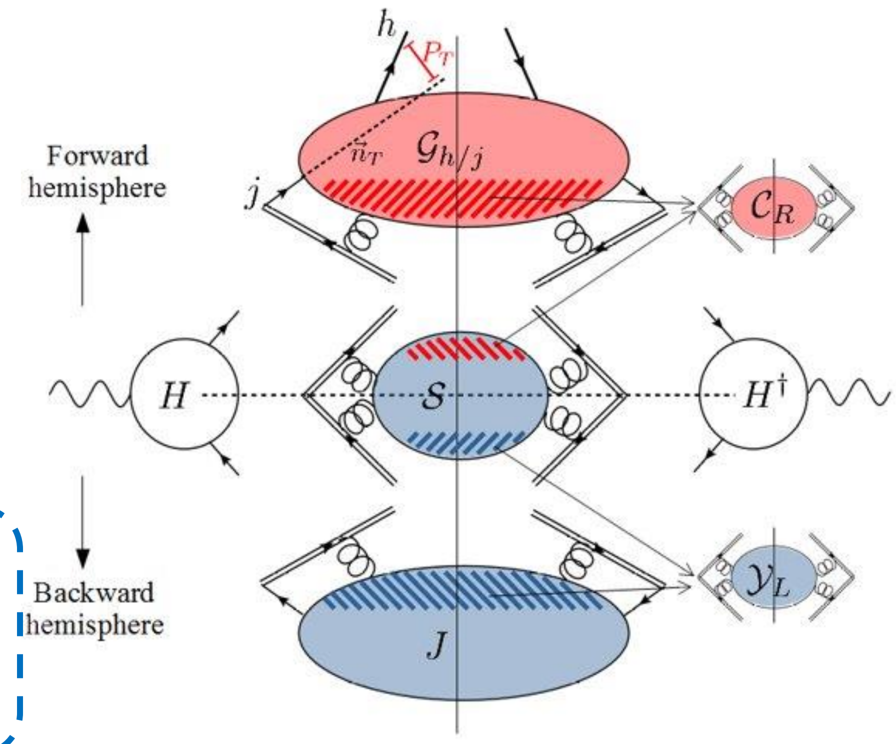
$$d\sigma_{R_2} = |H|^2 \int \frac{du}{2\,i\,\pi} e^{u\tau} \int \frac{d\vec{b}_T}{(2\pi)^2} e^{iz\vec{P}_T\cdot\vec{b}_T}$$

$$J(u, \infty - y_j) \frac{\widehat{S}(u, y_1 - y_2)}{\widehat{S}(u, \infty - y_2)} D^\star(z, b_T, y_{\mathrm{had}-y_1})$$

$$\frac{D^{\mathrm{uns}}(z, b_T, y_{\mathrm{had}} - (-\infty))}{S(b_T, y_1 - (-\infty))}$$

Not same functional form!

No magic this time...



Red blobs are TMD-relevant

Blue blobs are TMD-irrelevant

We are forced to use the definition*.
There are disadvantages but also...

- More universal (no soft contamination)
- Inclusion of P-term effects (new physics!)

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Accessing the P-term

From comparing **operators**:

$$D(z, b_T, y_{\rm had} - y_1) = D^\star(z, b_T, y_{\rm had} - y_1) e^{-\frac{1}{2}P(b_T)}$$

Hidden soft effects

TMD extraction from standard process

TMD extraction from beyond standard process (SIA R_2)

Oss: $\frac{dP(b_T, \mu)}{d \log \mu} = -\gamma_P(a_S(\mu))$

$$\frac{\partial \log D^\star(z, b_T; \mu, y_1)}{\partial y_1} = -K(b_T, \mu)$$

$$\frac{\partial \log D^\star(z, b_T; \mu, y_1)}{\partial \log \mu} = \gamma_d(a_S(\mu)) + \frac{1}{2}\gamma_P(a_S(\mu)) - \gamma_K(a_S(\mu)) \log \frac{Qe^{-y_1}}{\mu}$$

→ D* has different evolution equations

$$R = \frac{\text{TMD extraction from beyond standard process}}{\text{TMD extraction from standard process}} = e^{-\frac{1}{2}P(b_T,\mu)}$$

This relation is *exact,* provided that:

1. Both extractions are performed @ same perturbative accuracy

2. Both extractions use the same model for the non-perturbative behavior of the CS-kernel

... in practice, given the extractions available today, none of the assumptions above are satisfied at the same time.

Also, the comparison is cleaner if both extractions use the same prescription for separating out the non-perturbative effects in b_T-space (CSS b*, HSO...)

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Simplifications at the numerator:

Neglecting orders $\mathcal{O}\left(\frac{1}{y_1}\right)$ as in

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pdf DOI cite claim reference search 1 citation

$$d\sigma_{R_2} \propto e^{I_R(u,y_1,\mu)-\frac{1}{2}P(b_T,\mu)} \approx e^{\frac{1}{2}g_P(b_T)}$$

P-terms for thrust and TMD sector

CSS b*-prescription

$$P(b_T,\mu) = P(a_S(\mu_b^\star)) - \int_{\mu_b^\star}^{\mu} \frac{d\mu'}{\mu'}\gamma_P(a_S(\mu')) - g_P(b_T)$$

The function g_P for the P-term is the counterpart of g_K for the CS-kernel.

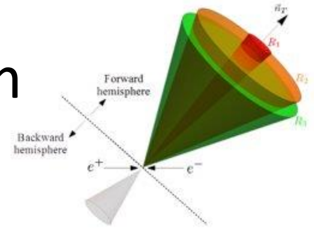
Then, effectively:

$$D^\star_{i/h}(z,b_T,\mu,y_1) = \frac{1}{z^2}C_{i/j}\otimes d_{j/h}(z,\mu_b)$$

$$e^{\frac{1}{2}K(a_S(\mu_b^\star))\log\frac{Qe^{-y_1}}{\mu_b^\star}+\int_{\mu_b^\star}^{\mu}\frac{d\mu'}{\mu'}\gamma_D\left(a_S(\mu'),\log\frac{Qe^{-y_1}}{\mu'}\right)}$$

$$M_D(z,b_T)e^{\frac{1}{2}g_P(b_T)}e^{-\frac{1}{2}g_K(b_T)\log\frac{Qe^{-y_1}}{M_{\rm had}}}$$

Effective combination extracted from



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Ideally:

BS23 (NP-model)

Full treatment of the thrust distribution in single inclusive $e^+e^- \to h\,X$ processes #1

M. Boglione (Turin U. and INFN, Turin), A. Simonelli (Old Dominion U. and Jefferson Lab) (Jun 5, 2023)

Published in: *JHEP* 09 (2023) 006 • e-Print: 2306.02937 [hep-ph]

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$$R = \frac{\text{BS23}}{\text{SV19 OR MAP22}} = e^{\frac{1}{2} g_P(b_T)}$$

SV19 (NP-model)

Non-perturbative structure of semi-inclusive deep-inelastic and Drell-Yan scattering at small transverse momentum #

Ignazio Scimemi (Madrid U.), Alexey Vladimirov (Regensburg U.) (Dec 13, 2019)

Published in: *JHEP* 06 (2020) 137 • e-Print: 1912.06532 [hep-ph]

pdf DOI cite claim reference search 138 citation

OR

MAP22 (NP-model)

Unpolarized transverse momentum distributions from a global fit of Drell-Yan and semi-inclusive deep-inelastic scattering data #4

MAP (Multi-dimensional Analyses of Partonic distributions) Collaboration • Alessandro Bacchetta (Pavia U. and INFN, Pavia) et al. (Jun 15, 2022)

Published in: *JHEP* 10 (2022) 127 • e-Print: 2206.07598 [hep-ph]

pdf DOI cite claim reference search 50 citations

The plan is:

- ❑ Check z-independence of R (insensitive to collinear physics)
- ❑ Infer information on g_P

Beware! This would be an extraction of an extraction!

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Ratio w.r.t SV19

Full treatment of the thrust distribution in single inclusive $e^+e^- \to h\,X$ processes #1

M. Boglione (Turin U. and INFN, Turin), A. Simonelli (Old Dominion U. and Jefferson Lab) (Jun 5, 2023)

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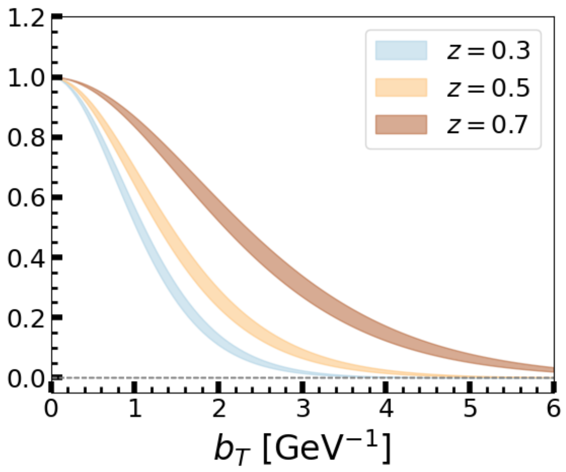
2 free parameters

$$M_D(z,b_T) = \frac{2}{\Gamma(p(z)-1)}\left(\frac{b_T\, m(z)}{2}\right)^{p(z)-1} K_{p(z)-1}\left(b_T\, m(z)\right)$$



Non-perturbative structure of semi-inclusive deep-inelastic and Drell-Yan scattering at small transverse momentum #

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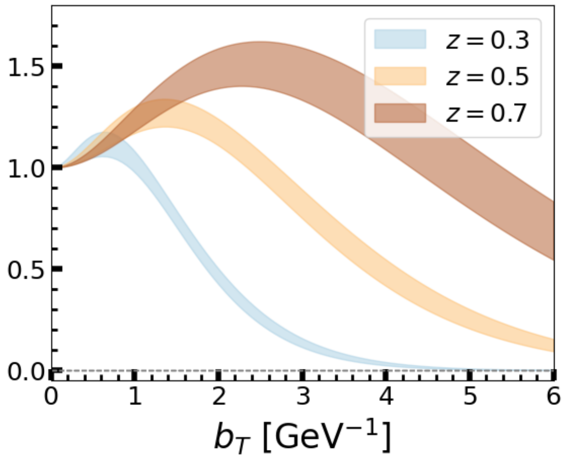
4 free parameters

$$D_{NP}(x,b) = \exp\left(-\frac{\eta_1 z + \eta_2(1-z)}{\sqrt{1+\eta_3(\boldsymbol{b}/z)^2}}\frac{\boldsymbol{b}^2}{z^2}\right)\left(1+\eta_4\frac{\boldsymbol{b}^2}{z^2}\right)$$



Test the ansatz:

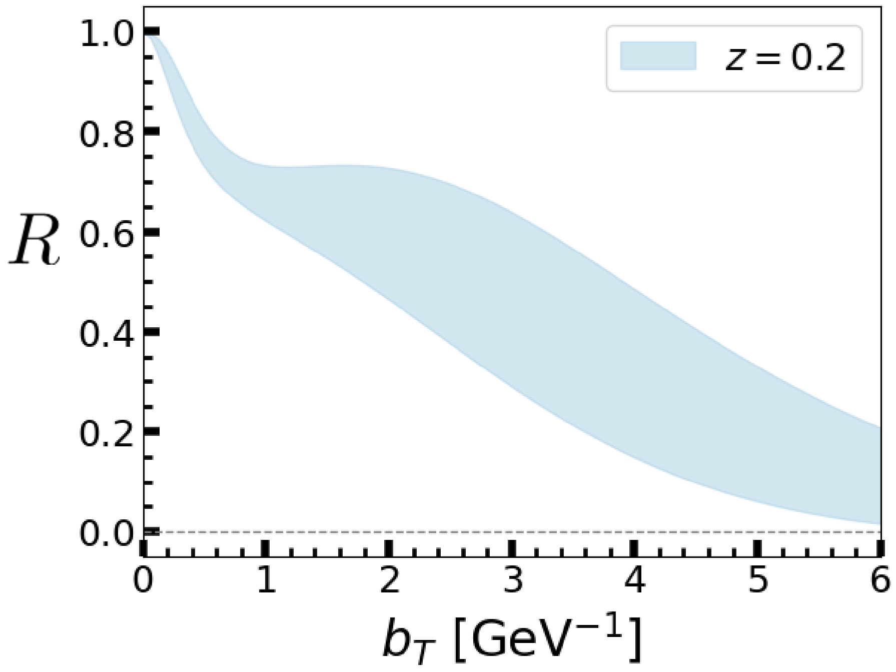
- Extractions @ same perturbative accuracy ✗
- Extractions use the same g_K ✗

BS23	SV19
NLL	N2LL
~ constant	~ linear

→ z-independence affected

→ b_T-dependence affected

Still:



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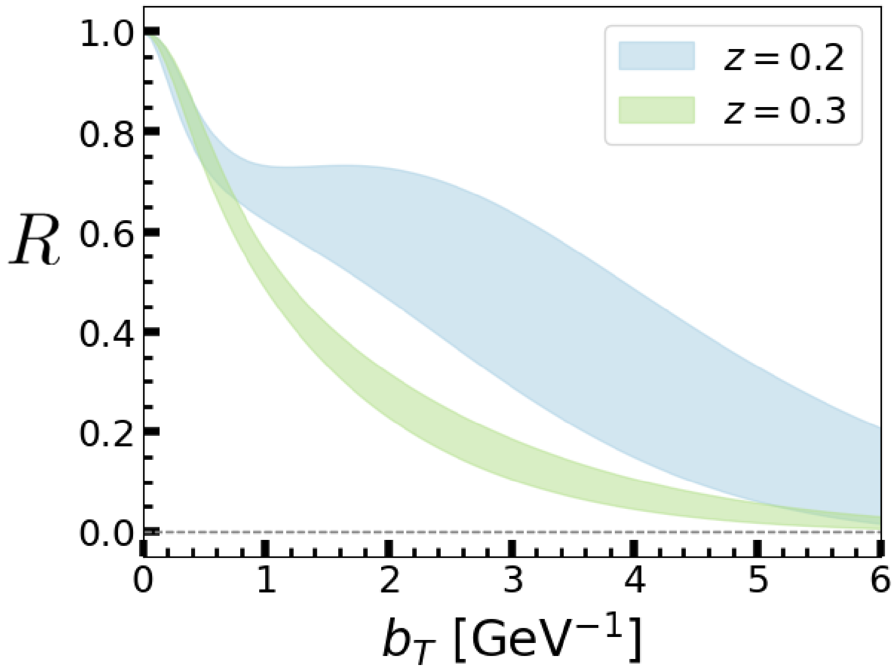
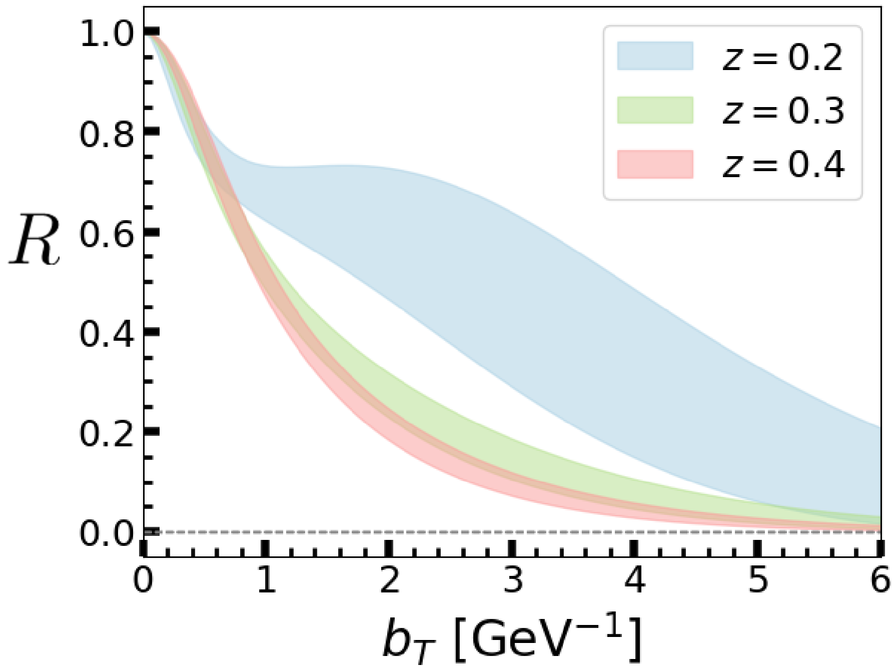


Test the ansatz:

	BS23	SV19
○ Extractions @ same perturbative accuracy ✕	NLL	N2LL → z-independence affected
○ Extractions use the same g_K ✕	~ constant	~ linear → b_T-dependence affected

Still:

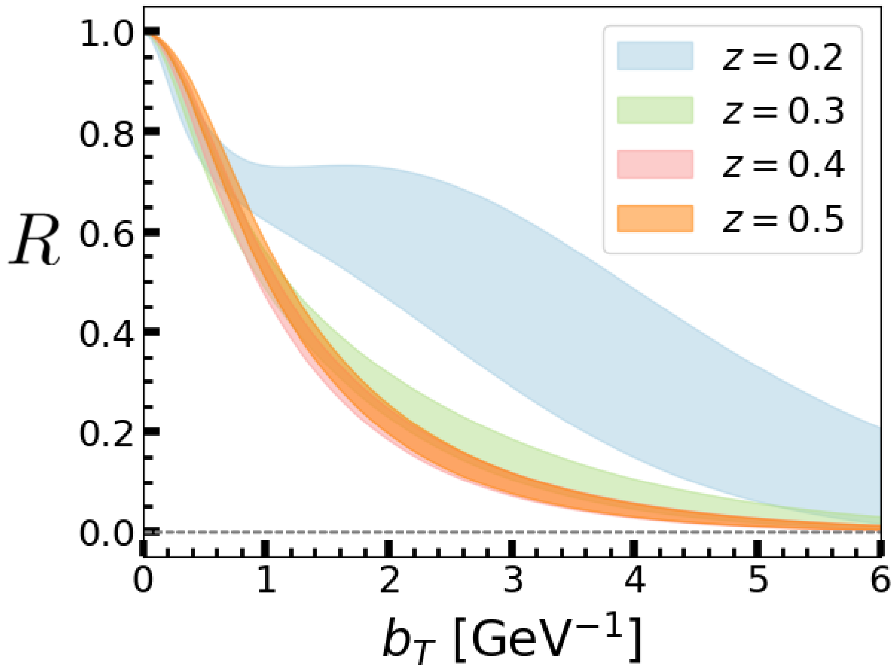


Test the ansatz:

- Extractions @ same perturbative accuracy ✗
- Extractions use the same g_K ✗

	BS23	**SV19**	
Extractions @ same perturbative accuracy	NLL	N2LL	→ z-independence affected
Extractions use the same g_K	~ constant	~ linear	→ b_T-dependence affected

Still:



Test the ansatz:

- Extractions @ same perturbative accuracy ✗
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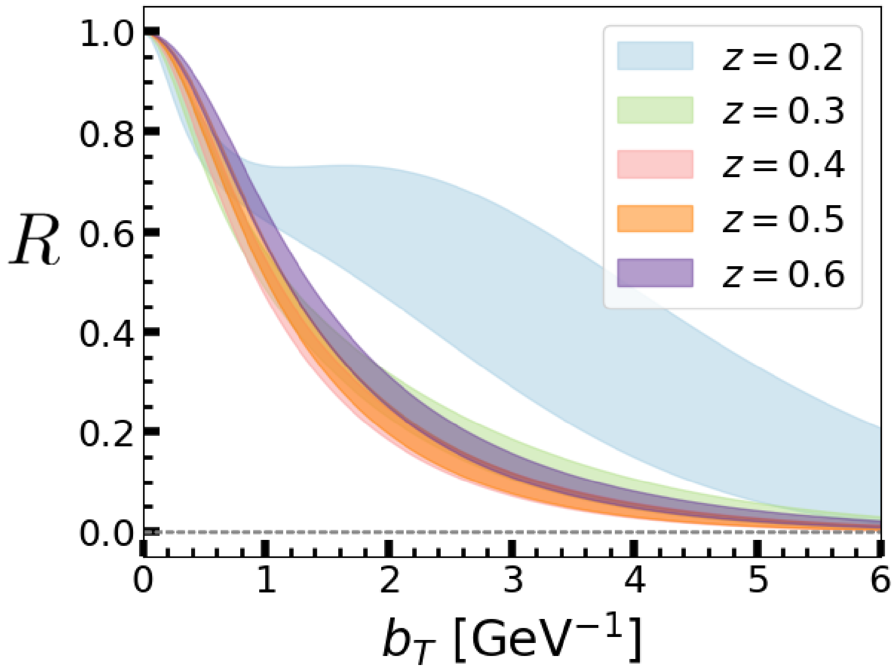
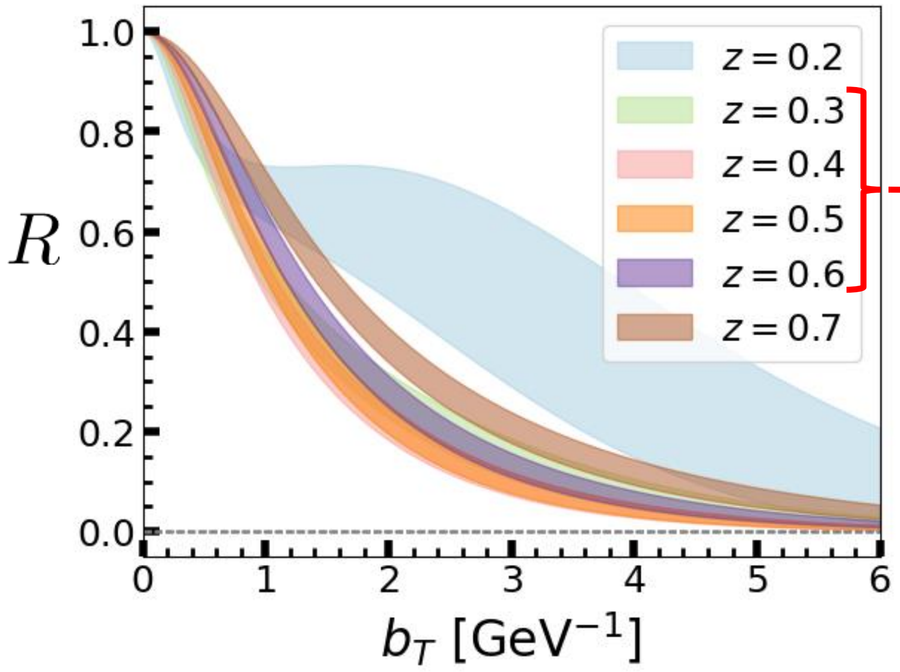


Test the ansatz:

- Extractions @ same perturbative accuracy ✕
- Extractions use the same g_K ✕

BS23	SV19	
NLL	N2LL	→ z-independence affected
~ constant	~ linear	→ b_T-dependence affected

Still:



→ Quite not dependent on z

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BS23 (BELLE data $e^+e^- \to \pi^\pm X$ with thrust)

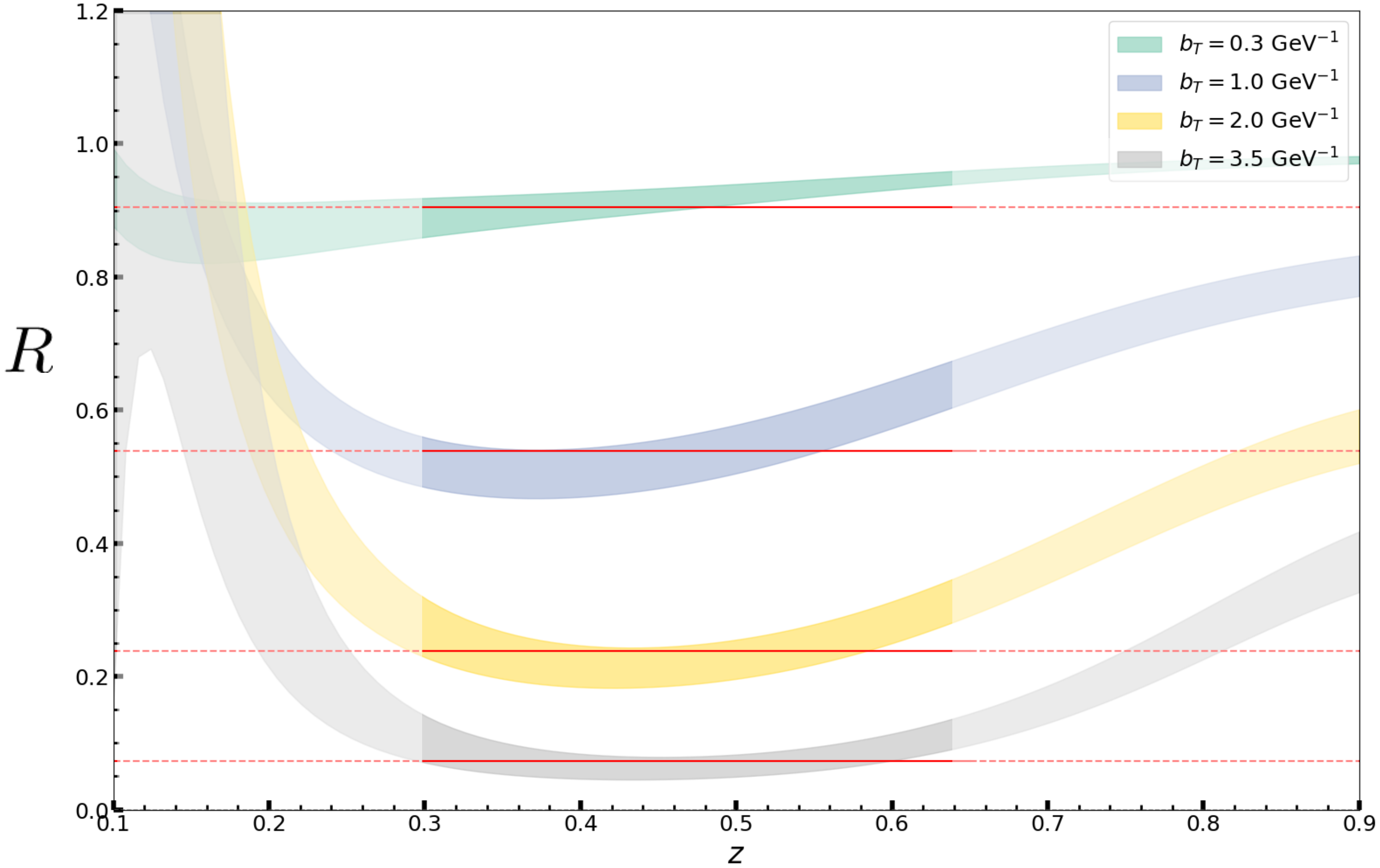
T	z												P_T/z max	N
	0.20 – 0.25	0.25 – 0.30	0.30 – 0.35	0.35 – 0.40	0.40 – 0.45	0.45 – 0.50	0.50 – 0.55	0.55 – 0.60	0.60 – 0.65	0.65 – 0.70	0.70 – 0.75	0.75 – 0.80		
0.80 – 0.85													$0.16\,Q$	57
0.85 – 0.90													$0.15\,Q$	60
0.90 – 0.95													$0.14\,Q$	61
0.95 – 1.00													$0.13\,Q$	52

SV19

Experiment	Reaction	ref.	Kinematics	N_{pt} after cuts
HERMES	$p \to \pi^+$	[66]	0.023<x<0.6 (6 bins) 0.2<z<0.8 (6 bins) 1.0<Q<$\sqrt{20}$GeV $W^2 > 10\text{GeV}^2$ 0.1<y<0.85	24
	$p \to \pi^-$			24
	$p \to K^+$			24
	$p \to K^-$			24
	$D \to \pi^+$			24
	$D \to \pi^-$			24
	$D \to K^+$			24
	$D \to K^-$			24
COMPASS	$d \to h^+$	[67]	0.003<x<0.4 (8 bins) 0.2<z<0.8 (4 bins) 1.0<Q$\simeq$ 9GeV (5 bins)	195
	$d \to h^-$			195
Total				582

The two extractions overlapping core is

$$0.3 \lesssim z \lesssim 0.7$$

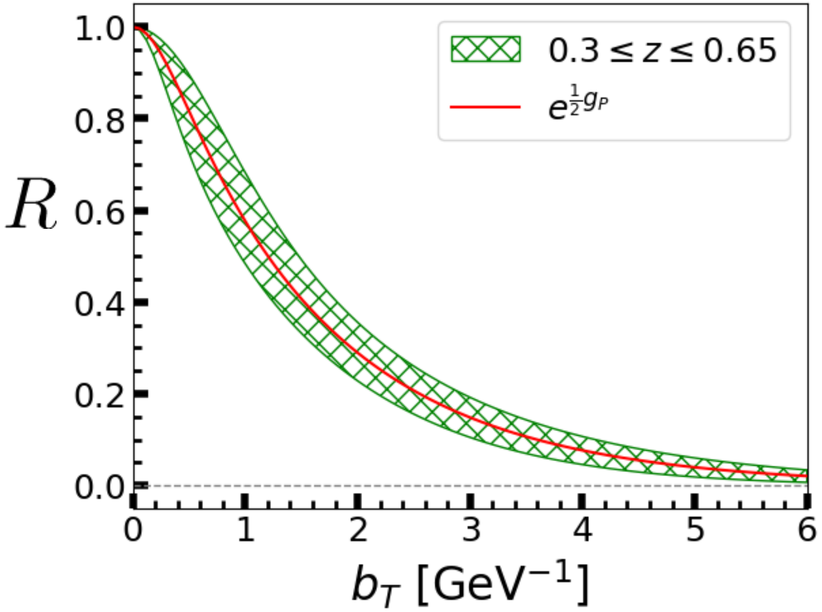


z-independence ✓

Keep in mind that:

- Very different functional forms at numerator and denominator
- Extractions from completely different data sets (BELLE vs SIDIS/DY)

Spread of error bands can be used to constraint the "extraction" of g_P



Asymptotically linear

$$g_P = -\frac{b_T^2}{\alpha\sqrt{1+\frac{b_T^2}{\beta^2}}}$$

$\alpha = 0.48 \pm 0.15\ \mathrm{GeV}^{-2}$

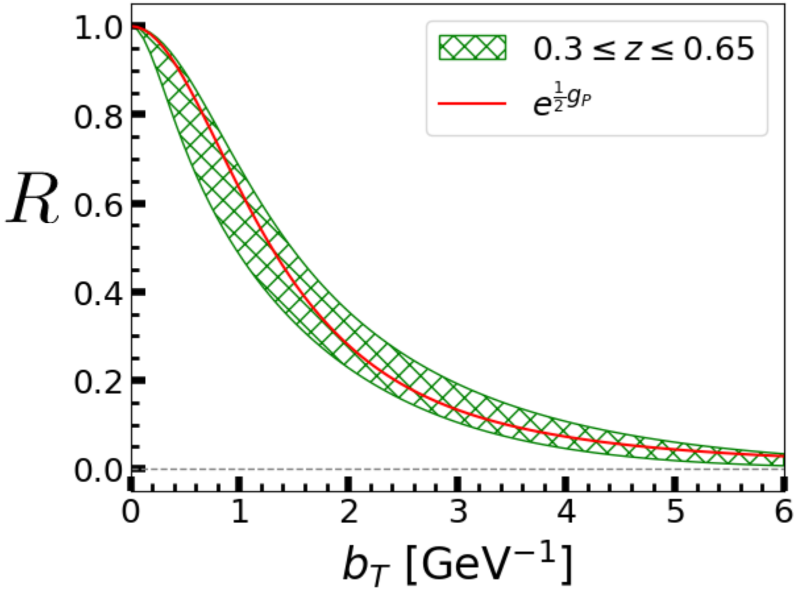
$\beta = 0.65 \pm 0.21\ \mathrm{GeV}^{-1}$

Asymptotically sub-linear

$$g_P = -\alpha \log\left(1 + \beta\, b_T^2\right)$$

$\alpha = 2.51 \pm 0.21$

$\beta = 0.43 \pm 0.07\ \mathrm{GeV}^2$



A. Simonelli

Ratio w.r.t MAP22

Full treatment of the thrust distribution in single inclusive $e^+e^- \to h\,X$ processes #1

M. Boglione (Turin U. and INFN, Turin), A. Simonelli (Old Dominion U. and Jefferson Lab) (Jun 5, 2023)

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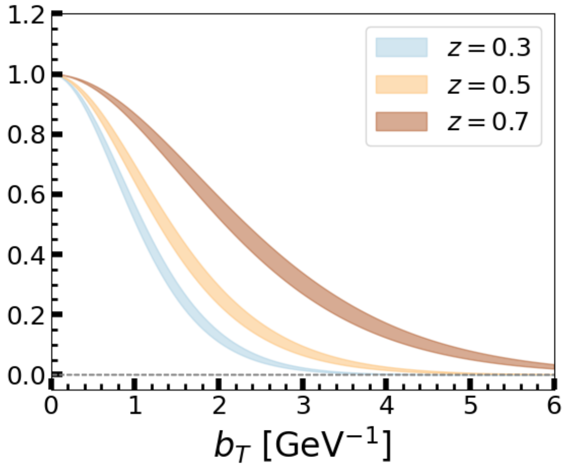
2 free parameters

$$M_D(z,b_T) = \frac{2}{\Gamma(p(z)-1)}\left(\frac{b_T\,m(z)}{2}\right)^{p(z)-1} K_{p(z)-1}\left(b_T\,m(z)\right)$$



Unpolarized transverse momentum distributions from a global fit of Drell-Yan and semi-inclusive deep-inelastic scattering data #4

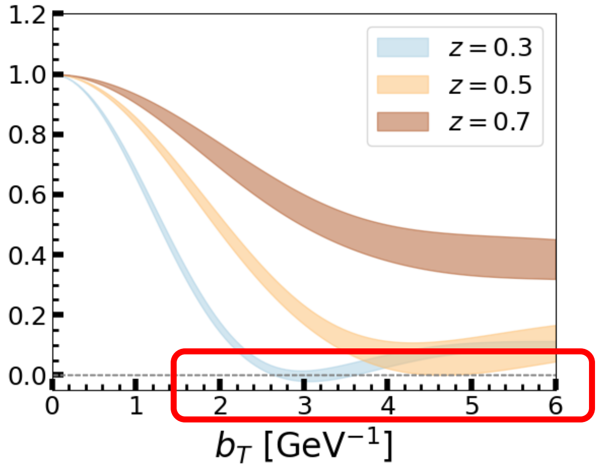
MAP (Multi-dimensional Analyses of Partonic distributions) Collaboration • Alessandro Bacchetta (Pavia U. and INFN, Pavia) et al. (Jun 15, 2022)

Published in: *JHEP* 10 (2022) 127 • e-Print: 2206.07598 [hep-ph]

pdf DOI cite claim reference search 50 citations

9 free parameters

$$D_{1\,NP}(z,b_T^2;\zeta,Q_0) = \frac{g_3(z)\,e^{-g_3(z)\frac{b_T^2}{4z^2}} + \frac{\lambda_F}{z^2}\,g_{3B}^2(z)\left[1 - g_{3B}(z)\frac{b_T^2}{4z^2}\right]e^{-g_{3B}(z)\frac{b_T^2}{4z^2}}}{g_3(z) + \frac{\lambda_F}{z^2}\,g_{3B}^2(z)}$$

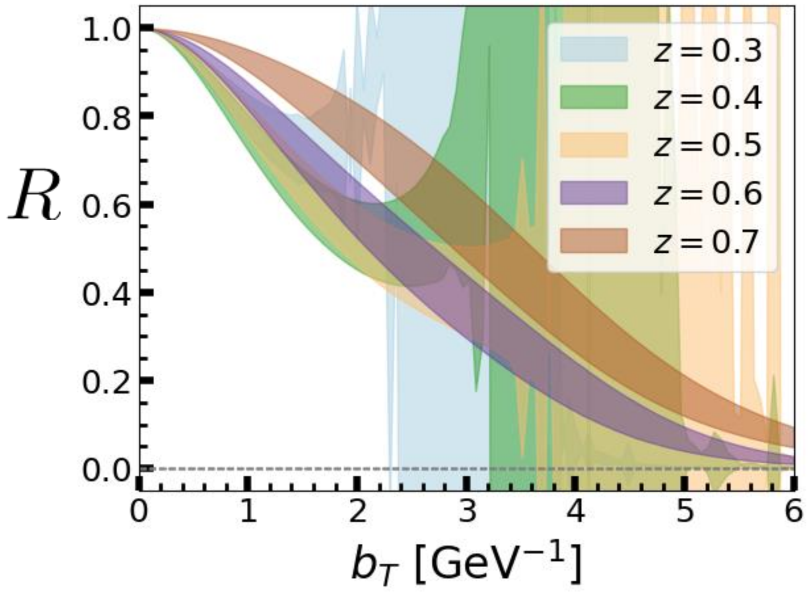


Test the ansatz:

- Extractions @ same perturbative accuracy ✓
- Extractions use the same g_K ✗

BS23	MAP22	
NLL	NLL	→ z-independence not affected
~ constant	~ quadratic	→ b_T-dependence affected

However:



z-independence ?

Not satisfied, or, at least, not constrained.

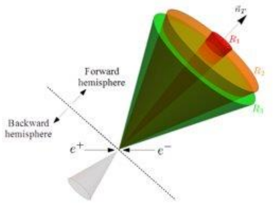
Conclusions

- Hidden soft effects, that cancel out in standard cross sections

$$S(b_T;\phi_M) = e^{\phi_M\, K(b_T) + P(b_T)}$$

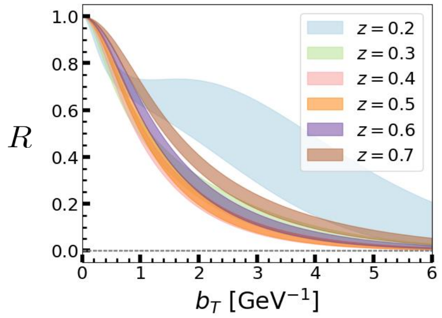
- Need to go **beyond** standard processes to have sensitivity on P-term

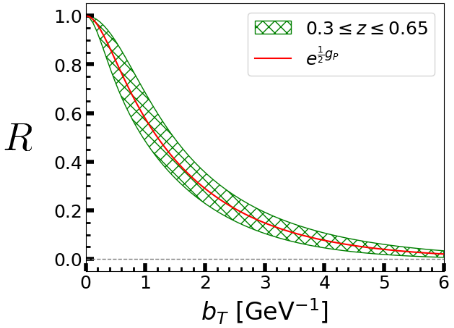
$$d\sigma_{R_2} \propto e^{I_R(u,y_1,\mu) - \frac{1}{2}P(b_T,\mu)} \approx e^{\frac{1}{2}g_P(b_T)}$$



- The relevant quantity is the **ratio**:

$$R = \frac{\text{TMD extraction from beyond standard process}}{\text{TMD extraction from standard process}} = e^{-\frac{1}{2}P(b_T,\mu)}$$





- Lattice applications

Thank You!