On the PB Sudakov:

NNLL coefficient, CS kernel and intrinsic-kt

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Universiteit Antwerpen

Research Foundation Flanders
Opening new horizons

Soft gluon resummation

Different methods developed to deal with soft gluons

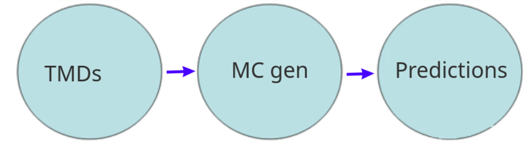
- In Monte Carlos: **Parton Showers (PS)**
- **Transverse Momentum Dependent (TMD)** factorization theorems
  baseline: low $q_{\perp}$ Collins-Soper-Sterman (**CSS**)
- SCET-based factorization
- small-x
- more recent **TMD Parton Branching (PB)**

Different approaches have different origin, assumptions, motivations, application, mathematical formalism, successes and failures etc, ...
Connections and differences between them have to be understood

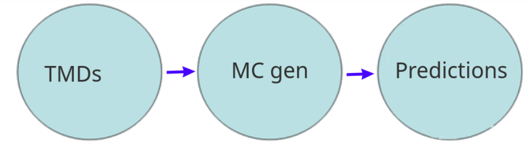
This talk:

TMD PB, especially **PB Sudakov** form factor and its relation to **Sudakov of CSS**

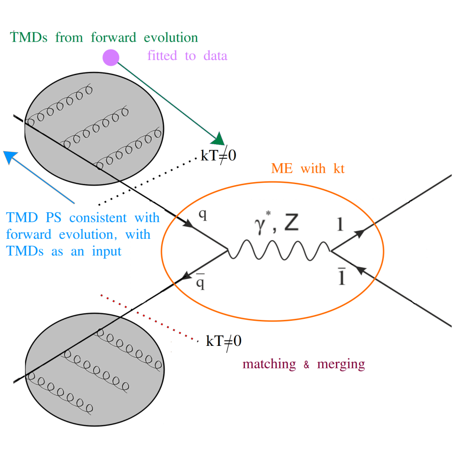
What is the TMD Parton Branching method?



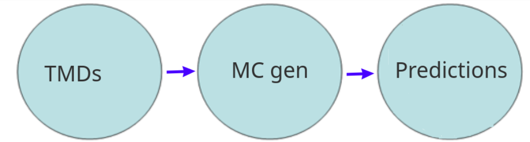
What is the TMD Parton Branching method?



Building blocks:



What is the TMD Parton Branching method?



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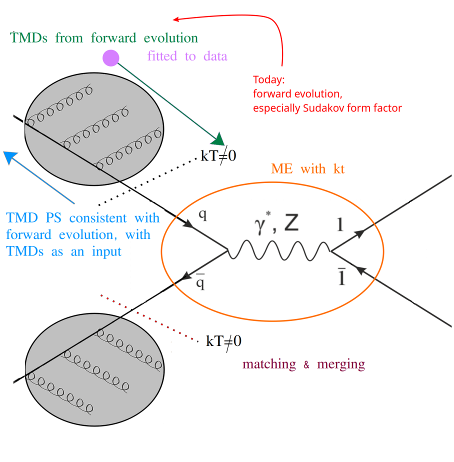
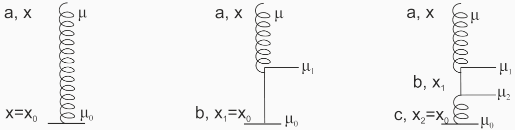


TMD evolution equation

Evolution in the TMD PB method

Hautmann, Jung, Lelek, Radescu, Zlebcik, Phys.Lett.B 772 (2017) 446 & JHEP 01 (2018) 070



$$\widetilde{A}_a\left(x, k_\perp^2, \mu^2\right) = \Delta_a\left(\mu^2, \mu_0^2\right)\widetilde{A}_a\left(x, k_\perp^2, \mu_0^2\right) + \sum_b \int \frac{\mathrm{d}^2\mu_{\perp 1}}{\pi \mu_{\perp 1}^2}\Theta\left(\mu_{\perp 1}^2 - \mu_0^2\right)\Theta\left(\mu^2 - \mu_{\perp 1}^2\right)$$

$$\times \Delta_a\left(\mu^2, \mu_{\perp 1}^2\right)\int_x^{z_M} \mathrm{d}z P_{ab}^R\left(z, \mu_{\perp 1}^2\right)\widetilde{A}_b\left(\frac{x}{z}, |k_{\perp 1}|^2, \mu_{\perp 0}^2\right)\Delta_b\left(\mu_{\perp 1}^2, \mu_{\perp 0}^2\right) + \ldots$$

Intuitive **probabilistic interpretation** $\Longleftrightarrow$ easy to **solve by Monte Carlo** (MC) :

- Sudakov form factor

$$\Delta_a\left(\mu^2, \mu_0^2\right) = \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{\mathrm{d}\mu'^2}{\mu'^2}\int_0^{z_M} \mathrm{d}z\ z P_{ba}^R\left(z, \mu'^2\right)\right)$$

$$\approx \exp\left(-\int_{\mu_0^2}^{\mu^2} \frac{\mathrm{d}\mu'^2}{\mu'^2}\left(\int_0^{z_M} k_a(\alpha_s)\frac{1}{1-z}\mathrm{d}z - d_a(\alpha_s)\right)\right)$$

probability of an evolution without resorvable branchings between μ_0^2 and μ^2

- Splitting function $P_{ab}^R(z, \mu^2)$ - probability of $b \to a$

P_{qq}^R & P_{gg}^R- **divergent** for $z \to 1 \Leftrightarrow$ **soft gluons**: z_M defines **resolvable and non-resolvable** branchings

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$\widetilde{A} = xA$, z- splitting variable, $x = zx_1$, $z \in (0, 1)$

Transverse momentum in PB

- **starting distribution** at μ_0^2:

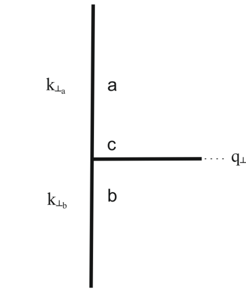
  $$\widetilde{A}_{a,0}(x, k_{\perp 0}^2, \mu_0^2) = \widetilde{f}_{a,0}(x, \mu_0^2) \frac{1}{\pi q_s^2} \exp\left(\frac{-k_{\perp 0}^2}{q_s^2}\right)$$

- Initial distribution $\widetilde{f}_{a,0}(x, \mu_0^2)$ obtained from **fits to inclusive DIS data**
- Intrinsic transverse momentum $k_{\perp 0}$ constraint from DY data
- transverse momentum **k calculated at each branching**

  $\mathbf{k}_a = \mathbf{k}_b - \mathbf{q}_c$,

  k of the propagating parton is a sum of intrinsic transverse momentum and all emitted transverse momenta

  $\mathbf{k} = \mathbf{k}_0 - \sum_i \mathbf{q}_i \rightarrow$ **TMD from parton branching**



How to relate $q_\perp$ and the evolution scale μ' ?
$\rightarrow$ Ordering condition: **Angular Ordering** (AO) of S. Catani, G. Marchesini, B. Webber (CMW)
scale associated with the rescaled transverse momentum

$q_\perp = (1 - z)\mu'$

AO assures PB TMDs do not have IR singularities
Moreover:

$\alpha_s(q_\perp)$

AO picture

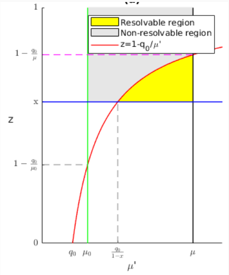
$$\Delta_a\left(\mu^2,\mu_0^2\right) \approx \exp\left(-\int_{\mu_0^2}^{\mu^2}\frac{\mathrm{d}\mu'^2}{\mu'^2}\left(\int_0^{z_M} k_a(\alpha_s)\frac{1}{1-z}\mathrm{d}z - d_a(\alpha_s)\right)\right)$$

AO of Catani-Marchesini-Webber (CMW): $q_\perp = (1-z)\mu'$

If we assume minimum $q_0 \to z_M = z_{\rm dyn} = 1 - q_0/\mu'$
Let's use $z_{\rm dyn}$ as an intermediate scale, to divide the phase space:

- Perturbative: $z < z_{\rm dyn}$, where $|q_\perp| > q_0$ (resolvable)
- NP: $z_{\rm dyn} < z < z_M$ ($z_M = 1 - \epsilon$ with $0 \simeq \epsilon \ll 1$), where $|q_\perp| < q_0$ (non-resolvable)

$$\Delta_a(\mu^2,\mu_0^2) = \exp\left(-\int_{\mu_0^2}^{\mu^2}\frac{d\mu'^2}{\mu'^2}\left[\int_0^{z_{\rm dyn}(\mu')} dz\frac{k_q(\alpha_s)}{1-z} - d_q(\alpha_s)\right]\right) \times\exp\left(-\int_{\mu_0^2}^{\mu^2}\frac{d\mu'^2}{\mu'^2}\int_{z_{\rm dyn}(\mu')}^{z_M\approx 1} dz\frac{k_q(\alpha_s)}{1-z}\right).$$



Nucl.Phys.B 949 (2019) 114795

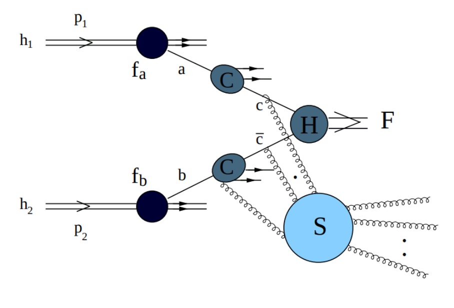
I.e.:

$$\Delta_a(\mu^2,\mu_0^2) = \Delta_a^{(\mathrm{P})}\left(\mu^2,\mu_0^2,q_0\right)\cdot\Delta_a^{(\mathrm{NP})}\left(\mu^2,\mu_0^2,\epsilon,q_0^2\right).$$

Using dynamical $z_M = 1 - \frac{q_0}{\mu'}$ i.e. skipping the non-perturbative Sudakov in the evolution has interesting consequences

CSS Sudakov form factor

Collins-Soper-Sterman (CSS)



$$\frac{d\sigma}{dq_\perp} \sim \int d^2b \exp(ib \cdot q_\perp) \int dz_1 dz_2 H(Q^2)$$
$$F_1(z_1, b, \text{scales}) F_2(z_2, b, \text{scales}) + Y$$

where the TMD: $F = f \otimes C \otimes \sqrt{\Delta}$

and the Sudakov Δ divided in perturbative and non-perturbative parts:

$\Delta = \Delta^{(P)} \Delta^{(NP)}$

CSS Sudakov: CSS1

$$\Delta_a^{\mathrm{CSS1}}(Q, Q_0, b, x_a, x_{\widetilde{a}}, b_{\max}, C_1, C_2) =$$
$$\exp\left\{-\int_{\mu_{b*}^2}^{\mu_Q^2} \frac{\mathrm{d}\mu'^2}{\mu'^2}\left(A_a(\alpha_s)\ln\left(\frac{\mu_Q^2}{\mu'^2}\right) + B_a(\alpha_s)\right)\right\}$$
$$\times\exp\left\{-g_{a/A}(x_a, b, b_{\max}) - g_{\widetilde{a}/B}(x_{\widetilde{a}}, b, b_{\max}) - g_{K,a}(b, b_{\max})\ln\frac{Q^2}{Q_0^2}\right\}$$

$A_a(\alpha_s)$ and $B_a(\alpha_s)$ have series expansions: $\mathcal{R}_a = \sum_n (\alpha_s/2\pi)^n \mathcal{R}_a^{(n)}$.

$\Delta^{(P)}$: Perturbative resummation
LL: $A_a^{(1)}$
NLL: $A_a^{(2)}$ and $B_a^{(1)}$,
NNLL by $A_a^{(3)}$ and $B_a^{(2)}$ etc.

Perturbative Sudakov

After change of integration variables ($\mu' \to q_\perp = (1-z)\mu'_\perp$)

$$\Delta_a^{(\mathrm{P})}(\mu^2, q_0^2) = \exp\left(-\int_{q_0^2}^{\mu^2} \frac{dq_\perp^2}{q_\perp^2}\left[\frac{1}{2}k_a(\alpha_s)\ln\left(\frac{\mu^2}{q_\perp^2}\right) - d_a(\alpha_s)\right]\right)$$

the perturbative PB Sudakov coincides, in its overall structure, with the perturbative CSS1 Sudakov form factor

$$\Delta_a^{\mathrm{CSS1\ (P)}}(\mu^2, \mu_{b*}^2) = \exp\left(-\int_{\mu_{b*}^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2}\left[A_a(\alpha_s)\ln\left(\frac{\mu^2}{\mu'^2}\right) + B_a(\alpha_s)\right]\right)$$

One can **try to compare the exact forms of the PB coefficients with that of CSS1 to determine the logarithmic accuracy** achieved by the PB Sudakov form factor.

Perturbative Sudakov

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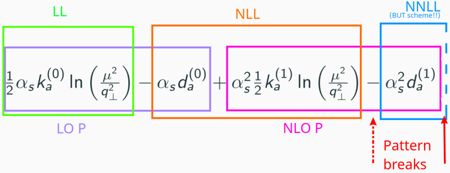
One can **try to compare the exact forms of the PB coefficients with that of CSS1 to determine the logarithmic accuracy** achieved by the PB Sudakov form factor.

- LO P and LL: $k_a^{(0)} = A_a^{(1)} = \frac{1}{2}\gamma_{k,a}^{(1)}$
- LO P and NLL: $d_a^{(0)} = -\frac{1}{2}B^{(1)} = \frac{1}{2}\gamma_a^{(1)}$
- NLO P and NLL: $k_a^{(1)} = A_a^{(2)} = \frac{1}{2}\gamma_{k,a}^{(2)}$
  Here however this simple pattern breaks !



Renormalization group mix the B, C, and H of the CSS formalism
$d_a^{(1)} = -\frac{1}{2}B^{(2)\bar{MS}}$
Difference between PB and CSS literature:
$B_q^{(2)\mathrm{DY}} - (-2)\cdot d_q^{(1)} = 16C_F\pi\beta_0\left(\zeta_2 - 1\right)$ and $B_g^{(2)\mathrm{H}} - (-2)\cdot d_g^{(1)} = 16C_A\pi\beta_0\left(\zeta_2 + \frac{11}{24}\right)$

Double logarithmic coefficient at NNLL

Phys.Lett.B 868 (2025) 139762, A. Lelek et al.

Collinear anomaly: Becher & Neubert, Eur.Phys.J.C 71 (2011) 1665

the NNLL resummation coefficient $A_a^{(3)}$ differs from the NNLO DGLAP coefficient $k_a^{(2)}$.
The difference is:

$$A_a^{(3)} - k_a^{(2)} = C_a \pi \beta_0 \left[C_A \left(\frac{808}{27} - 28\zeta_3 \right) - \frac{112}{27} N_f \right]$$

One obtains this result by differentiating the CS kernel with respect to $\ln b_\star^2$:

$$A_a - k_a = -\frac{\mathrm{d}\widetilde{K}_a(b_\star, \mu_{b_\star})}{\mathrm{d} \ln b_\star^2}$$

The **NNLL accuracy can be achieved by the usage of physical soft-gluon coupling**

Catani et al., Eur.Phys.J.C 79 (2019) 8, 685

Banfi et al., JHEP 01 (2019) 083

$$\alpha_s^{\mathrm{NNLL}} = \alpha_s \left(1 + \mathcal{K}^{(2)} \left(\frac{\alpha_s}{2\pi} \right)^2 \right)$$

I. e. We modify

$$\Delta_a^{(\mathrm{P})}(\mu^2, q_0^2) = \exp \left(- \int_{q_0^2}^{\mu^2} \frac{dq_\perp^2}{q_\perp^2} \left[\frac{1}{2} k_a(\alpha_s^{\mathrm{NNLL}}) \ln \left(\frac{\mu^2}{q_\perp^2} \right) - d_a(\alpha_s^{\mathrm{NNLL}}) \right] \right)$$

NNLL in PB

Phys.Lett.B 868 (2025) 139762, A. Lelek et al.

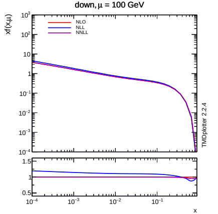
With NLO P

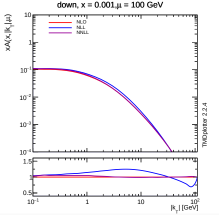
$$
\begin{aligned}
\ln(\Delta_a^{(\mathrm{P})}(\mu^2, q_0^2)) &= -\int_{q_0^2}^{\mu^2} \frac{dq_\perp^2}{q_\perp^2} \frac{\alpha_s^{\mathrm{phys}}}{2\pi} \left(\ln \frac{\mu^2}{q_\perp^2} \left(k_a^{(0)} + \frac{\alpha_s^{\mathrm{phys}}}{2\pi} k_a^{(1)} \right) - d_a^{(0)} - \frac{\alpha_s^{\mathrm{phys}}}{2\pi} d_a^{(1)} \right) \\
&= -\int_{q_0^2}^{\mu^2} \frac{dq_\perp^2}{q_\perp^2} \frac{\alpha_s}{2\pi} \left(\ln \frac{\mu^2}{q_\perp^2} \left(k_a^{(0)} + \frac{\alpha_s}{2\pi} k_a^{(1)} \right) - d_a^{(0)} - \frac{\alpha_s}{2\pi} d_a^{(1)} \right. \\
&+ \left. \frac{\alpha_s^2}{(2\pi)^2} \mathcal{K}^{(2)} k_a^{(0)} \frac{1}{2} \ln \frac{\mu^2}{q_\perp^2} + \ldots \right)
\end{aligned}
$$

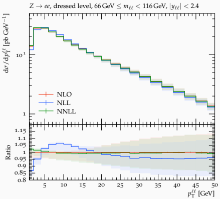
where $\mathcal{K}^{(2)} \cdot k_a^{(0)} = A_a^3$.

All Sudakov coefficients at NNLL, i.e. $A_a^{(1)}$, $A_a^{(2)}$, $A_a^{(3)}$, $B_a^{(1)}$ and $B_a^{(2,\overline{MS})}$, are **included in the PB**

The middle row: standard NLO PB evolution







Non-perturbative Sudakov

CSS Sudakov: CSS2

$$\Delta_a^{\mathrm{CSS2}}(Q, Q_0, b, x_a, x_{\tilde{a}}, b_{\max}, C_1, C_2) =$$
$$\exp\left\{-\int_{\mu_{b*}}^{\mu_Q} \frac{\mathrm{d}\mu'}{\mu'}\left(\gamma_{k,a}(\alpha_s)\ln\left(\frac{Q^2}{\mu'^2}\right) - 2\gamma_a(\alpha_s)\right)\right\}$$
$$\times\exp\left(-g_{a/A}(x_a, b, b_{\max}) - g_{\tilde{a}/B}(x_{\tilde{a}}, b, b_{\max}) - g_{K,a}(b, b_{\max})\ln\frac{Q^2}{Q_0^2}\right)$$
$$\times\exp\left(\widetilde{K}_a(b_*, \mu_{b*})\ln\frac{Q^2}{\mu_{b*}^2}\right)$$

$\widetilde{K}_a$ perturbative CS kernel

$g_{K,a}$ the non-perturbative part of the CS kernel

$g_{a/A}$, $g_{\tilde{a}/B}$ and $g_{K,a}$ the same as in the CSS1

A_a and B_a and $\gamma_{k,a}$ and γ_a do not coincide at all orders but they are related with each other.

$$\Delta_a^{\mathrm{CSS2}}(Q, Q_0, b, x_a, x_{\widetilde{a}}, b_{\max}, C_1, C_2) =$$
$$\exp\left\{-\int_{\mu_{b*}}^{\mu_Q} \frac{\mathrm{d}\mu'}{\mu'}\left(\gamma_{k,a}(\alpha_s)\ln\left(\frac{Q^2}{\mu'^2}\right) - 2\gamma_a(\alpha_s)\right)\right\}$$
$$\times\exp\left(-g_{a/A}(x_a, b, b_{\max}) - g_{\widetilde{a}/B}(x_{\widetilde{a}}, b, b_{\max}) - g_{K,a}(b, b_{\max})\ln\frac{Q^2}{Q_0^2}\right)$$
$$\times\exp\left(\widetilde{K}_a(b_*, \mu_{b*})\ln\frac{Q^2}{\mu_{b*}^2}\right)$$

CS kernel

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CSS Sudakov: CSS2

$$\Delta_a^{\mathrm{CSS2}}(Q, Q_0, b, x_a, x_{\tilde{a}}, b_{\max}, C_1, C_2) =$$
$$\exp\left\{-\int_{\mu_{b*}}^{\mu_Q}\frac{\mathrm{d}\mu'}{\mu'}\left(\gamma_{k,a}(\alpha_s)\ln\left(\frac{Q^2}{\mu'^2}\right) - 2\gamma_a(\alpha_s)\right)\right\}$$
$$\times\exp\left(-g_{a/A}(x_a, b, b_{\max}) - g_{\tilde{a}/B}(x_{\tilde{a}}, b, b_{\max}) - g_{K,a}(b, b_{\max})\ln\frac{Q^2}{Q_0^2}\right)$$
$$\times\exp\left(\widetilde{K}_a(b_*, \mu_{b*})\ln\frac{Q^2}{\mu_{b*}^2}\right)$$

In CSS formalism:

$$\frac{\partial \ln f_{f/H}(x, b_t, \zeta, \mu)}{\partial \ln\sqrt{\zeta}} = \mathcal{K}(b_t, \mu)$$

CS kernel:

- governs the rapidity evolution
- contains non-perturbative information
- can be extracted from measurements
- is the only QCD function which is largely unknown

$\widetilde{K}_a$ perturbative CS kernel

$g_{K,a}$ the non-perturbative part of the (

$g_{a/A}$, $g_{\tilde{a}/B}$ and $g_{K,a}$ the same as in the

A_a and B_a and $\gamma_{k,a}$ and γ_a do not coi

each other.

Non-perturbative PB Sudakov

Non-resolvable region:
$z_{\rm dyn} < z < z_M$ ($z_M = 1 - \epsilon$ with $0 \simeq \epsilon \ll 1$), for which $|q_\perp| < q_0$
In PB, $\alpha_s = \alpha_s(q_\perp) \to$ **freeze at $\alpha_s(q_{\rm cut})$**

$$\Delta_a^{(\rm NP)}(\mu^2, \mu_0^2, \epsilon, q_0) = \exp\left(-\int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_{1-q_0\mu'}^{1-\epsilon} dz \frac{k_a(\alpha_s)}{1-z} \right) = \exp\left(-\frac{k_a(\alpha_s)}{2} \ln\left(\frac{\mu^2}{\mu_0^2}\right) \ln\left(\frac{q_0^2}{\epsilon^2 \mu_0 \mu}\right)\right)$$

$\ln \mu^2/\mu_0^2$ resembles the structure of the NP CS kernel $g_{K,a}(b, b_{\rm max}) \ln \frac{Q^2}{Q_0^2} \to$ **rapidity evolution**

Remarks:
In the CSS literature: NP CS kernel modelled and fitted to data
In PB: Modelling of the NP Sudakov probes the AO picture (i.e. $z_{\rm dyn}$), & depends on α_s modelling (freezing)

b and μ are related to each other:

- b is Fourier transform of $k_\perp$
- $k_\perp$ contains the whole evolution history, ($k_\perp = k_{\perp 0} - \sum_i q_{\perp,i}$)
- $q_{\perp,i}$ is related to the branching scales by the AO condition, i.e. $q_{\perp,i} = (1 - z_i)\mu'_{\perp,i}$)

Next slides: **extract the CS kernel from the PB approach**

Models for numerical studies

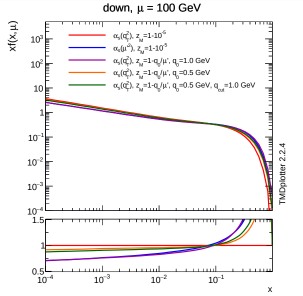
We study 5 PB models which **differ in the amount of (soft) radiation**.
Amount of radiation **modelled in terms of α_s and z_M**

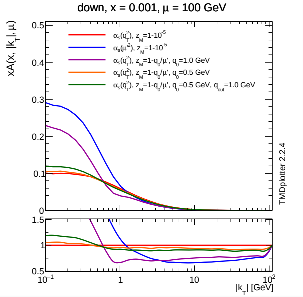
Models with fixed $z_M \approx 1$:

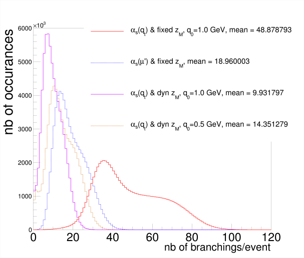
- $\alpha_s(q_\perp^2)$, $\alpha_s = \alpha_s(\max(q_0^2, q_\perp^2))$, $q_0 = 1.0$ GeV (red)
- $\alpha_s(\mu'^2)$ (blue)

Models with $\alpha_s(q_\perp^2)$ and dynamical $z_M = 1 - q_0/\mu'$ (i.e. no non-perturbative Sudakov):

- $q_0 = 1.0$ GeV (purple)
- $q_0 = 0.5$ GeV (orange)
- $q_0 = 0.5$ GeV and $qcut = 1$ GeV (green)



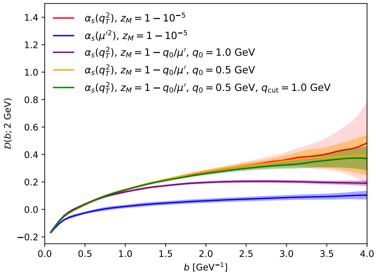




CS kernel

Phys.Lett.B 868 (2025) 139762, A. Lelek et al.

CS kernels extracted from PB DY predictions



$$\mathcal{D}(b, \mu_0) = \frac{\ln(\Sigma_1(b)/\Sigma_2(b)) - \ln Z(Q_1, Q_2) - 2\Delta_R(Q_1, Q_2; \mu_0)}{4\ln(Q_2/Q_1)} - 1$$

Σ_1 and Σ_2 - Hankel transformed DY cross sections

$$\Delta_R(Q_1, Q_2; \mu_0) = \int_{Q_2}^{Q_1} \frac{d\mu}{\mu} \gamma_F(\mu, Q_1) - 2\ln\frac{Q_1}{Q_2} \int_{\mu_0}^{Q_2} \frac{d\mu}{\mu} \gamma_k(\mu)$$

$$Z(Q_1, Q_2) = \frac{\alpha_{em}^2(Q_1)|C_V(Q_1, \mu_{Q_1})|^2}{\alpha_{em}^2(Q_2)|C_V(Q_2, \mu_{Q_2})|^2}$$

where C_V is the hard coefficient function.

All terms except Σ_1/Σ_2 are perturbative and known up to up to N^{3}LO

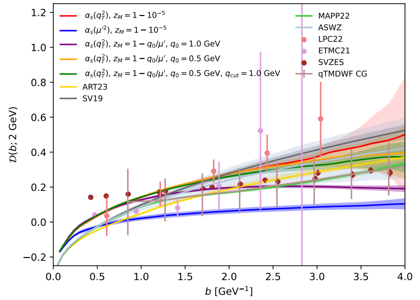
The method of A. Bermudez Martinez and A. Vladimirov, Phys.Rev.D 106 (2022) 9, L091501

- different modelling of radiation can lead to a very different kernel behaviour, including different slopes.
- the results probe the AO picture, through α_s and resolution scale z_M
- the curves with $\alpha_s(q_\perp)$ are close to one another at small b
- instead, the curve with $\alpha_s(\mu')$ is already very different at small b
- note flattening behavior at large b in curve with $q0 = 1$ GeV

CS kernel

Phys.Lett.B 868 (2025) 139762, A. Lelek et al.

CS kernels extracted from PB DY predictions



- different modelling of radiation can lead to a very different kernel behaviour, including different slopes.
- the results probe the AO picture, through α_s and resolution scale z_M
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- instead, the curve with $\alpha_s(\mu')$ is already very different at small b
- note flattening behavior at large b in curve with $q0 = 1$ GeV
- The curves spread over a wide range, covering extractions from other groups

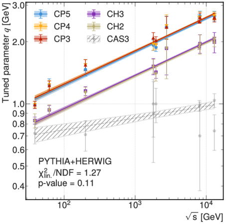
Interplay of non-perturbative Sudakov and Intrinsic-kt

Intrinsic kt vs center-of-mass energy & DY mass

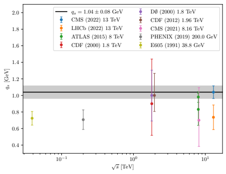
Pythia, Herwig: the intrinsic $k_\perp$ is center-of-mass dependent

T. Sjostrand, Peter Z. Skands, JHEP 03 (2004) 053

Stefan Gieseke, Michael H. Seymour, Andrzej Siodmok, JHEP 06 (2008) 001



Phys.Rev.D 111 (2025) 7, 072003

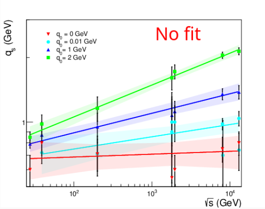


Eur.Phys.J.C 84 (2024) 2, 154

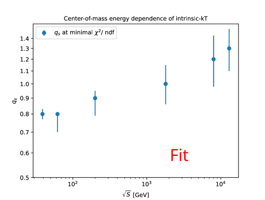
Method:

- replicas of PB-NLO-HERAI+II-2018-set2 created with q_s scanned scanned between $q_s = 0.1$ and $q_s = 2.0$ GeV with a step of 0.1 GeV;
- prediction for each DY measurement obtained with each replica;
- for each measurement, the q_s providing the best χ^2 was extracted.

In PB, the $\sqrt{s}$ dependence of intrinsic-kt much weaker than in other MCs



Eur.Phys.J.C 85 (2025) 3, 278



JHEP 06 (2025) 192

The center-of-mass **dependence of the intrinsic kt** comes from the treatment of **soft gluons**

When q_0 $O(1\,\mathrm{GeV})$ is used, intrinsic kt depends on center-of-mass energy

The **slope increases with increasing q_0**

The **non-perturbative Sudakov** ($z_M \to 1$) & $\alpha_s(q_\perp)$ **crucial for intrinsic kt independent of $\sqrt{s}$**

Summary

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We discussed PB Sudakov form factor

- AO-driven division of the phase space allows to get the Perturbative and model the Non-Perturbative Sudakov
- P: logarithmic resummation (new: NNLL $A^{(3)}$ included, in addition to single-log NNLL $B^{(2)}$)
- NP: rapidity evolution (new: extractions of CS kernel from TMD PB, both with fixed and dynamical zmax)

PB approach contains the Sudakov form factor (both perturbative and non-perturbative) exactly corresponding to the Sudakov of CSS formulation.

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Thank you