Joint Higgs and jet transverse-momentum resummation in direct space

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Mainly based on
`Monni, Re, PT, 1604.02191`
`Bizon, Monni, Re, Rottoli, PT, 1705.09127`
`Monni, Rottoli, PT, 1909.04704`

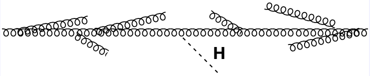
Multi-differential Higgs spectra

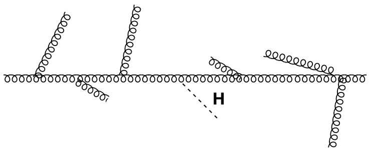
- Kinematic distributions of Higgs and QCD radiation in gluon fusion sensitive to potential BSM effects.
- For instance: Higgs transverse momentum may be used to constrain models with heavy states such as top partners [Banfi, Martin, Sanz, 1308.4771], modifications to light Yukawa couplings [Bishara, et al., 1606.09253], ...
- Higgs events experimentally categorised in jet bins: prospects for precise measurements of kinematic Higgs distributions in different jet bins
- Need good theoretical control of Higgs spectra at the multi-differential level, over the entire phase space: focus on Higgs transverse momentum with a veto on accompanying jets.

Direct-space resummation

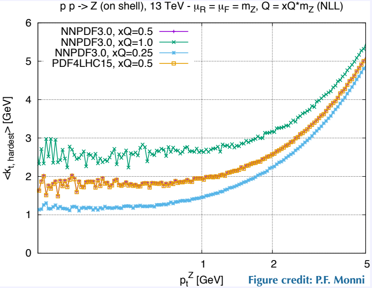
- Multiple soft/collinear QCD emissions require resummation, to accurately describe the low-p_t end of the spectrum
- Tackling resummation of observable V in direct (i.e. momentum) space, as opposed to conjugate space, allows
  * clearer interpretation of dominant dynamics of the $V \to 0$ limit
  * access to exclusive kinematic information on radiation
- Avoiding conjugate space possible if V recursively IRC (rIRC) safe [Banfi, Salam, Zanderighi, 0112156, 0304148, 0407286], allowing exponentiation of leading logarithms.
  CAESAR/ARES method [Banfi et al., 1412.2126, 1607.03111, 1807.11487] $\longrightarrow$ Andrea Banfi's talk
- CAESAR/ARES not including observables with azimuthal cancellations, like Higgs p_t in gluon fusion $\longrightarrow$ RadISH.

Higgs in gluon fusion at small p_t

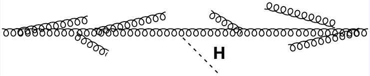


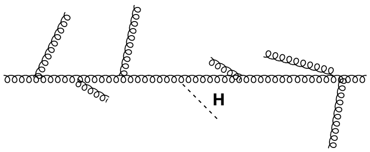


- Left. Commensurate emissions' transverse momenta k_{ti}: $m_H \gg \max(k_{ti}) \equiv k_{t1} \sim p_t^{\mathrm{H}}$.
  Exponential Sudakov suppression of $\Sigma(p_t^{\mathrm{H}} < p_t^{\mathrm{HV}})$ at small p_t^{HV}.
- Right. Large azimuthal cancellations: $m_H \gg k_{t1} \gg p_t^{\mathrm{H}}$.
  Power law $\Sigma(p_t^{\mathrm{H}} < p_t^{\mathrm{HV}}) \sim (p_t^{\mathrm{HV}})^2$ at small p_t^{HV} [Parisi, Petronzio, 1979] dominates over Sudakov.



Higgs production at small p_t





- Left. Commensurate emissions' transverse momenta k_{ti}: $m_H \gg \max(k_{ti}) \equiv k_{t1} \sim p_t^{\mathrm{H}}$. Exponential Sudakov suppression of $\Sigma(p_t^{\mathrm{H}} < p_t^{\mathrm{HV}})$ at small p_t^{HV}.
- Right. Large azimuthal cancellations: $m_H \gg k_{t1} \gg p_t^{\mathrm{H}}$. Power law $\Sigma(p_t^{\mathrm{H}} < p_t^{\mathrm{HV}}) \sim (p_t^{\mathrm{HV}})^2$ at small p_t^{HV} [Parisi, Petronzio, 1979] dominates over Sudakov.
- All configurations accounted for in direct space in the RadISH approach [Monni, Re, PT, 1604.02191], [Bizon, et al., 1705.09127]: p_t^{H} up to N^{3}LL.
- Method applicable to generic colour singlet, not only Higgs, [Bizon et al., 1805.05916, 1905.05171] and all transverse observables (p_t^{J}, ϕ_η^*, E_t, ...), and extendible to more complicated ones.

RadISH resummation in one slide

$$\Sigma(V < \nu) = \int d\Phi_B \, \mathcal{V}(\Phi_B) \sum_{n=0}^{\infty} \int \prod_{i=1}^{n} [dk_i] |M(k_1, \ldots, k_n)|^2 \, \Theta(\nu - V(k_1, \ldots, k_n))$$

- Introduce a slicing parameter ϵk_{t1}.
  Emissions categorised as unresolved (or resolved) if $k_{ti} < \epsilon k_{t1}$ (or $k_{ti} > \epsilon k_{t1}$).

- Unresolved contribute negligibly to V (rIRC safety), exponentiate and regularise the virtual form factor $\mathcal{V}(\Phi_B)$ $\implies$ Sudakov radiator $R(\epsilon k_{t1})$

$$\mathcal{V}(\Phi_B) \sum_{n=0}^{\infty} \int \prod_{i=2}^{n} [dk_i] |M(k_1, \ldots, k_n)|^2 \Theta(\epsilon k_{t1} - k_{ti}) \propto e^{-R(\epsilon k_{t1})},$$

$$-R(k_t) = \underbrace{L_t \, g_1(\alpha_S L_t)}_{LL} + \underbrace{g_2(\alpha_S L_t)}_{NLL} + \underbrace{\frac{\alpha_S}{\pi} g_3(\alpha_S L_t)}_{NNLL} + \ldots, \qquad L_t = \ln(Q/k_t).$$

- Resolved emissions parametrised in terms of $R'(k_{ti}) = dR/d\ln(Q/k_{ti})$.
  Expand ϵk_{t1} and k_{ti} around k_{t1} to eliminate subleading effects.
  Retain subleading terms only for 0, 1, 2, ... emissions at NLL, NNLL, N^{3}LL, ...

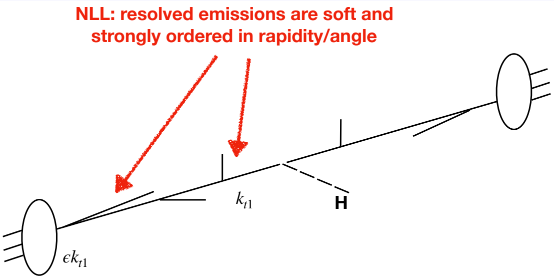
Higgs p_t at NLL

- Resummed cross section for Higgs transverse momentum p_t^{H} below a certain value p_t^{HV}.

- $L_{t1} = \ln(m_H/k_{t1})$, $\mathcal{L}_{NLL}$ = NLL luminosity, $p_t^{\mathrm{H}}(\{k_j\}) = |\sum_j \vec{k}_{tj}|$.

$$\begin{aligned}\Sigma_{NLL}(p_t^{\mathrm{H}} < p_t^{\mathrm{HV}}) &= \int_0^\infty \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \frac{d}{dL_{t1}} \left[- e^{-R_{NLL}(L_{t1})} \mathcal{L}_{NLL}(L_{t1}) \right] \times \\ &\quad \times \underbrace{\epsilon^{R'_{LL}(L_{t1})} \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_{\epsilon k_{t1}}^{k_{t1}} \frac{dk_{ti}}{k_{ti}} \frac{d\phi_i}{2\pi} R'_{LL}(L_{t1})}_{\equiv \int d\mathcal{Z}} \Theta\Big(p_t^{\mathrm{HV}} - |\sum_{j=1}^{n+1} \vec{k}_{tj}|\Big)\end{aligned}$$

- Generated as a k_t-ordered (semi-inclusive) parton shower.



Higgs p_t at NNLL

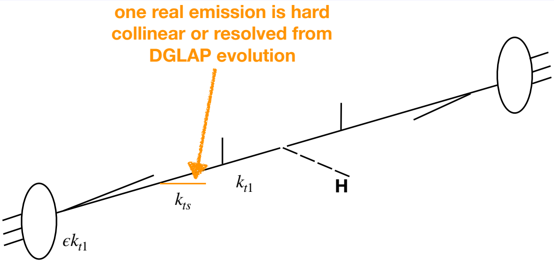
$$\Sigma_{NNLL}(p_t^{\rm H} < p_t^{\rm HV}) \;=\; \int_0^\infty \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z} \left\{ \frac{d}{dL_{t1}} \left[-e^{-R_{NNLL}(L_{t1})} \mathcal{L}_{NNLL}\,(L_{t1}) \right] \Theta\left(p_t^{\rm HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj}| \right) \right\}$$

- Luminosity $\mathcal{L}_{NNLL}$ with $O(\alpha_{\rm S})$ coefficient functions, radiator R_{NNLL} with $O(\alpha_{\rm S}^n L_{t1}^{n-1})$ terms.

Higgs p_t at NNLL

$$\Sigma_{NNLL}(p_t^{H} < p_t^{HV}) = \int_0^\infty \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z} \Bigg\{ \frac{d}{dL_{t1}} \left[-e^{-R_{NNLL}(L_{t1})} \mathcal{L}_{NNLL}(L_{t1}) \right] \Theta\Big(p_t^{HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj}|\Big)$$
$$+ e^{-R_{NLL}(L_{t1})} R'_{LL}(k_{t1}) \int_0^{k_{t1}} \frac{dk_{ts}}{k_{ts}} \frac{d\phi_s}{2\pi} \left[\left(\delta R'(k_{t1}) + R''_{LL}(k_{t1}) \ln \frac{k_{t1}}{k_{ts}} - \frac{d}{dL_{t1}} \right) \mathcal{L}_{NLL}(L_{t1}) \right]$$
$$\times \left[\Theta\Big(p_t^{HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj} + \vec{k}_{ts}|\Big) - \Theta\Big(p_t^{HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj}|\Big) \right] \Bigg\}$$

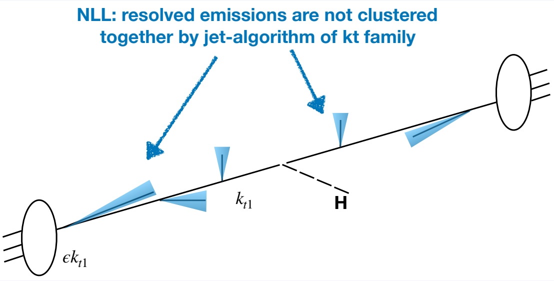
- Correction of one emission k_s (only one at NNLL) in the resolved ensemble (finite in $d = 4$)



Hardest jet p_t at NLL

- Observables $p_t^{\rm J}(\{k_j\}) = \max(k_{tj})$ and $p_t^{\rm H}(\{k_j\}) = |\sum_j \vec{k}_{tj}|$ have the same radiator R.
- At NLL the (anti)-k_t jet algorithm does not cluster emissions together.
  Same NLL resummation as $p_t^{\rm H}$ but for the measurement function.

$$
\begin{aligned}
\Sigma_{NLL}(p_t^{\rm J} < p_t^{\rm JV}) \quad = \quad & \int_0^\infty \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \frac{d}{dL_{t1}} \left[- e^{-R_{NLL}(L_{t1})} \mathcal{L}_{NLL}(L_{t1}) \right] \times \\
& \times \epsilon^{R'_{LL}(L_{t1})} \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_{\epsilon k_{t1}}^{k_{t1}} \frac{dk_{ti}}{k_{ti}} \frac{d\phi_i}{2\pi} R'_{LL}(L_{t1})\, \Theta(p_t^{\rm JV} - k_{t1})
\end{aligned}
$$



Hardest jet p_t at NNLL

$$\Sigma_{NNLL}(p_t^{\mathrm{J}} < p_t^{\mathrm{JV}}) = \int_0^{\infty} \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z} \left\{ \frac{d}{dL_{t1}} \left[-e^{-R_{NNLL}(L_{t1})} \mathcal{L}_{NNLL}(L_{t1}) \right] \Theta\left(p_t^{\mathrm{JV}} - k_{t1}\right) \right\}$$

- Luminosity $\mathcal{L}_{NNLL}$ with $O(\alpha_S)$ coefficient functions, radiator R_{NNLL} with $O(\alpha_S^n L_{t1}^{n-1})$ terms.

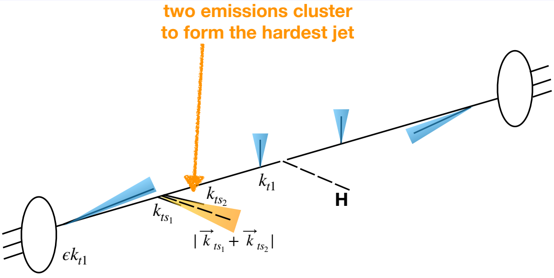
Hardest jet p_t at NNLL

$$\Sigma_{NNLL}(p_t^{\rm J} < p_t^{\rm JV}) = \int_0^\infty \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z} \Bigg\{ \frac{d}{dL_{t1}} \left[-e^{-R_{NNLL}(L_{t1})} \mathcal{L}_{NNLL}(L_{t1}) \right] \Theta\left(p_t^{\rm JV} - k_{t1}\right)$$

$$+ \frac{1}{2!} \mathcal{L}_{NLL}(L_{t1})\, e^{-R_{NLL}(L_{t1})} \left(R'_{LL}(k_{t1})\right)^2 \int_0^{k_{t1}} \frac{dk_{ts_1}}{k_{ts_1}} \frac{dk_{ts_2}}{k_{ts_2}} \int d\Delta\eta_{s_1 s_2} \frac{d\phi_{s_1}}{2\pi} \frac{d\Delta\phi_{s_1 s_2}}{2\pi} \left(2 C_A \frac{\alpha_s(k_{t1})}{\pi}\right)$$

$$\times \; J_R(s_1, s_2) \left[\Theta\left(p_t^{\rm JV} - |\vec{k}_{ts_1} + \vec{k}_{ts_2}|\right) - \Theta\left(p_t^{\rm JV} - \max(k_{ts_1}, k_{ts_2})\right) \right] \Theta\left(p_t^{\rm JV} - k_{t1}\right) + \dots \Bigg\}$$

- Clustering correction, [Banfi, et al., 1206.4998], with $J_R(s_1, s_2) \equiv \Theta\left(R^2 - \Delta\eta^2_{s_1 s_2} - \Delta\phi^2_{s_1 s_2}\right)$: at NNLL the jet algorithm may cluster two emissions to form the hardest jet (ellipses: $s_{1,2} \to 1$).



Hardest jet p_t at NNLL

$$
\begin{aligned}
\Sigma_{NNLL}(p_t^{J} < p_t^{JV}) \;=\; & \int_0^{\infty} \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z} \Bigg\{ \frac{d}{dL_{t1}} \left[-e^{-R_{NNLL}(L_{t1})} \mathcal{L}_{NNLL}(L_{t1}) \right] \Theta\left(p_t^{JV} - k_{t1}\right) \\
& + \frac{1}{2!} \mathcal{L}_{NLL}(L_{t1})\, e^{-R_{NLL}(L_{t1})} \left(R'_{LL}(k_{t1})\right)^2 \int_0^{k_{t1}} \frac{dk_{ts_1}}{k_{ts_1}} \frac{dk_{ts_2}}{k_{ts_2}} \int d\Delta\eta_{s_1 s_2} \frac{d\phi_{s_1}}{2\pi} \frac{d\Delta\phi_{s_1 s_2}}{2\pi} \left(2C_A \frac{\alpha_S(k_{t1})}{\pi}\right) \\
& \times \Bigg[J_R(s_1, s_2) \left[\Theta\left(p_t^{JV} - |\vec{k}_{ts_1} + \vec{k}_{ts_2}|\right) - \Theta\left(p_t^{JV} - \max(k_{ts_1}, k_{ts_2})\right) \right] \Theta\left(p_t^{JV} - k_{t1}\right) \\
& + \mathcal{C}(s_1, s_2) \left[1 - J_R(s_1, s_2)\right] \left[\Theta\left(p_t^{JV} - \max(k_{ts_1}, k_{ts_2})\right) - \Theta\left(p_t^{JV} - |\vec{k}_{ts_1} + \vec{k}_{ts_2}|\right) \right] \Bigg] + \ldots \Bigg\}
\end{aligned}
$$

- Correlated correction, [Banfi, et al., 1206.4998], with $\mathcal{C}(a,b) = \frac{|\tilde{M}(k_a,k_b)|^2}{|M(k_a)|^2 |M(k_b)|^2}$, and $|\tilde{M}(k_a,k_b)|^2$ is the non-factorisable part of the double-soft matrix element.
- $|\tilde{M}(k_a,k_b)|^2$ appears in $R_{NLL}(k_{t1})$, resulting in the CMW coupling [Catani, Marchesini, Webber, 1991]. Integrated inclusively there, and veto constraint applied on $|\vec{k}_{ta} + \vec{k}_{tb}|$: need to correct for configurations where the two correlated emissions are not clustered together.

Joint Higgs and jet p_t resummation at NNLL

- From contributions detailed above just need to combine measurement functions!

'inclusive' contribution **with ptH and ptj measurement functions**

$$
\begin{aligned}
&\Sigma_{NNLL}(p_t^{\rm H} < p_t^{\rm HV}, p_t^{\rm J} < p_t^{\rm JV}) \; = \\
&\int_0^\infty \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z} \Bigg\{ \frac{d}{dL_{t1}} \left[-e^{-R_{NNLL}(L_{t1})} \mathcal{L}_{NNLL}(L_{t1}) \right] \Theta\Big(p_t^{\rm HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj}|\Big) \Theta\Big(p_t^{\rm JV} - k_{t1}\Big) \\
&+ e^{-R_{NLL}(L_{t1})} R'_{LL}(k_{t1}) \int_0^{k_{t1}} \frac{dk_{ts}}{k_{ts}} \frac{d\phi_s}{2\pi} \left[\left(\delta R'(k_{t1}) + R''_{LL}(k_{t1}) \ln \frac{k_{t1}}{k_{ts}} - \frac{d}{dL_{t1}} \right) \mathcal{L}_{NLL}(L_{t1}) \right] \\
&\quad \times \left[\Theta\Big(p_t^{\rm HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj} + \vec{k}_{ts}|\Big) - \Theta\Big(p_t^{\rm HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj}|\Big) \right] \Theta\Big(p_t^{\rm JV} - k_{t1}\Big) \\
&+ \frac{1}{2!} \mathcal{L}_{NLL}(L_{t1}) \, e^{-R_{NLL}(L_{t1})} \Big(R'_{LL}(k_{t1})\Big)^2 \int_0^{k_{t1}} \frac{dk_{ts_1}}{k_{ts_1}} \frac{dk_{ts_2}}{k_{ts_2}} \int d\Delta\eta_{s_1 s_2} \frac{d\phi_{s_1}}{2\pi} \frac{d\Delta\phi_{s_1 s_2}}{2\pi} \left(2C_A \frac{\alpha_S(k_{t1})}{\pi} \right) \\
&\quad \times \Theta\Big(p_t^{\rm HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj} + \vec{k}_{ts_1} + \vec{k}_{ts_2}|\Big) \Bigg[J_R(s_1, s_2) \Big(\Theta\Big(p_t^{\rm JV} - |\vec{k}_{ts_1} + \vec{k}_{ts_2}|\Big) - \Theta\Big(p_t^{\rm JV} - \max(k_{ts_1}, k_{ts_2})\Big) \Big) \\
&\quad + \mathcal{C}(s_1, s_2) \Big[1 - J_R(s_1, s_2) \Big] \Big(\Theta\Big(p_t^{\rm JV} - \max(k_{ts_1}, k_{ts_2})\Big) - \Theta\Big(p_t^{\rm JV} - |\vec{k}_{ts_1} + \vec{k}_{ts_2}|\Big) \Big) \Bigg] \Theta\Big(p_t^{\rm JV} - k_{t1}\Big) + \ldots \Bigg\}
\end{aligned}
$$

Joint Higgs and jet p_t resummation at NNLL

- From contributions detailed above just need to combine measurement functions!

NNLL correction to ptH

with ptj measurement function

$$
\Sigma_{NNLL}(p_t^{\rm H} < p_t^{\rm HV}, p_t^{\rm J} < p_t^{\rm JV}) =
$$

$$
\int_0^\infty \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z} \Bigg\{ \frac{d}{dL_{t1}} \left[-e^{-R_{NNLL}(L_{t1})} \mathcal{L}_{NNLL}(L_{t1}) \right] \Theta\Big(p_t^{\rm HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj}|\Big) \Theta\Big(p_t^{\rm JV} - k_{t1}\Big)
$$

$$
+ e^{-R_{NLL}(L_{t1})} R'_{LL}(k_{t1}) \int_0^{k_{t1}} \frac{dk_{ts}}{k_{ts}} \frac{d\phi_s}{2\pi} \left[\left(\delta R'(k_{t1}) + R''_{LL}(k_{t1}) \ln \frac{k_{t1}}{k_{ts}} - \frac{d}{dL_{t1}} \right) \mathcal{L}_{NLL}(L_{t1}) \right]
$$

$$
\times \left[\Theta\Big(p_t^{\rm HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj} + \vec{k}_{ts}|\Big) - \Theta\Big(p_t^{\rm HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj}|\Big) \right] \Theta\Big(p_t^{\rm JV} - k_{t1}\Big)
$$

$$
+ \frac{1}{2!} \mathcal{L}_{NLL}(L_{t1}) e^{-R_{NLL}(L_{t1})} \Big(R'_{LL}(k_{t1})\Big)^2 \int_0^{k_{t1}} \frac{dk_{ts_1}}{k_{ts_1}} \frac{dk_{ts_2}}{k_{ts_2}} \int d\Delta\eta_{s_1 s_2} \frac{d\phi_{s_1}}{2\pi} \frac{d\Delta\phi_{s_1 s_2}}{2\pi} \left(2C_A \frac{\alpha_S(k_{t1})}{\pi} \right)
$$

$$
\times \Theta\Big(p_t^{\rm HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj} + \vec{k}_{ts_1} + \vec{k}_{ts_2}|\Big) \Bigg[J_R(s_1, s_2) \Big(\Theta\Big(p_t^{\rm JV} - |\vec{k}_{ts_1} + \vec{k}_{ts_2}|\Big) - \Theta\Big(p_t^{\rm JV} - \max(k_{ts_1}, k_{ts_2})\Big) \Big)
$$

$$
+ \mathcal{C}(s_1, s_2) \Big[1 - J_R(s_1, s_2) \Big] \Big(\Theta\Big(p_t^{\rm JV} - \max(k_{ts_1}, k_{ts_2})\Big) - \Theta\Big(p_t^{\rm JV} - |\vec{k}_{ts_1} + \vec{k}_{ts_2}|\Big) \Big) \Bigg] \Theta\Big(p_t^{\rm JV} - k_{t1}\Big) + \ldots \Bigg\}
$$

Joint Higgs and jet p_t resummation at NNLL

- From contributions detailed above just need to combine measurement functions!

clustering and correlated NNLL ptj corrections

with ptH measurement function

$$
\begin{aligned}
&\Sigma_{NNLL}(p_t^{\rm H} < p_t^{\rm HV}, p_t^{\rm J} < p_t^{\rm JV}) = \\
&\int_0^\infty \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z} \Bigg\{ \frac{d}{dL_{t1}} \left[-e^{-R_{NNLL}(L_{t1})} \mathcal{L}_{NNLL}(L_{t1}) \right] \Theta\Big(p_t^{\rm HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj}|\Big) \Theta\Big(p_t^{\rm JV} - k_{t1}\Big) \\
&+ e^{-R_{NLL}(L_{t1})} R'_{LL}(k_{t1}) \int_0^{k_{t1}} \frac{dk_{ts}}{k_{ts}} \frac{d\phi_s}{2\pi} \left[\left(\delta R'(k_{t1}) + R''_{LL}(k_{t1}) \ln \frac{k_{t1}}{k_{ts}} - \frac{d}{dL_{t1}} \right) \mathcal{L}_{NLL}(L_{t1}) \right] \\
&\quad \times \left[\Theta\Big(p_t^{\rm HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj} + \vec{k}_{ts}|\Big) - \Theta\Big(p_t^{\rm HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj}|\Big) \right] \Theta\Big(p_t^{\rm JV} - k_{t1}\Big) \\
&+ \frac{1}{2!} \mathcal{L}_{NLL}(L_{t1}) e^{-R_{NLL}(L_{t1})} \Big(R'_{LL}(k_{t1})\Big)^2 \int_0^{k_{t1}} \frac{dk_{ts_1}}{k_{ts_1}} \frac{dk_{ts_2}}{k_{ts_2}} \int d\Delta\eta_{s_1 s_2} \frac{d\phi_{s_1}}{2\pi} \frac{d\Delta\phi_{s_1 s_2}}{2\pi} \left(2C_A \frac{\alpha_s(k_{t1})}{\pi} \right) \\
&\quad \times \Theta\Big(p_t^{\rm HV} - |\sum_{j=1}^{n+1} \vec{k}_{tj} + \vec{k}_{ts_1} + \vec{k}_{ts_2}|\Big) \Big[J_R(s_1, s_2) \Big(\Theta\Big(p_t^{\rm JV} - |\vec{k}_{ts_1} + \vec{k}_{ts_2}|\Big) - \Theta\Big(p_t^{\rm JV} - \max(k_{ts_1}, k_{ts_2})\Big) \Big) \\
&\quad + \mathcal{C}(s_1, s_2) \big[1 - J_R(s_1, s_2) \big] \Big(\Theta\Big(p_t^{\rm JV} - \max(k_{ts_1}, k_{ts_2})\Big) - \Theta\Big(p_t^{\rm JV} - |\vec{k}_{ts_1} + \vec{k}_{ts_2}|\Big) \Big) \Big] \Theta\Big(p_t^{\rm JV} - k_{t1}\Big) + \ldots \Bigg\}
\end{aligned}
$$

NLL joint resummation in b space

- Differential control in momentum space provides guidance to an analytic formula for joint resummation in impact-parameter space
- NLL $p_t^{\rm H}$ differential cross section (toy model with scale-independent PDFs for the sake of the argument): $p_t^{\rm H}$ measurement function completely factorises (by construction)

$$\frac{d\sigma}{d^2 \vec{p}_t^{\rm H}} = \sigma_B \int \frac{d^2 \vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_t^{\rm H}} \sum_{n=0}^{\infty} \frac{1}{n!} \int [dk_i] |M(k_i)|^2 \left(e^{i\vec{b}\cdot\vec{k}_{ti}} - 1 \right)$$

- Factorisation implies a factor $e^{i\vec{b}\cdot\vec{k}_{ti}}$ per emission: jet-veto constraints on k_{ti} can be applied at the level of b-space integrand!
- Jet veto on real radiation at NLL: $\Theta(p_t^{\rm JV} - \max(k_{t1}, ..., k_{tn})) = \prod_{i=1}^{n} \Theta(p_t^{\rm JV} - k_{ti})$
- Joint resummation at NLL in b space

$$\begin{aligned} \frac{d\sigma(p_t^{\rm J} < p_t^{\rm JV})}{d^2 \vec{p}_t^{\rm H}} &= \sigma_B \int \frac{d^2 \vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_t^{\rm H}} \sum_{n=0}^{\infty} \frac{1}{n!} \int [dk_i] |M(k_i)|^2 \left(e^{i\vec{b}\cdot\vec{k}_{ti}} \Theta(p_t^{\rm JV} - k_{ti}) - 1 \right) \\ &= \sigma_B \int \frac{d^2 \vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_t^{\rm H}} e^{-\int [dk] |M(k)|^2 \left(1 - e^{i\vec{b}\cdot\vec{k}_t} \Theta(p_t^{\rm JV} - k_t)\right)} \end{aligned}$$

NNLL joint resummation in b space

- NNLL clustering/correlated corrections in the b-space integrand.

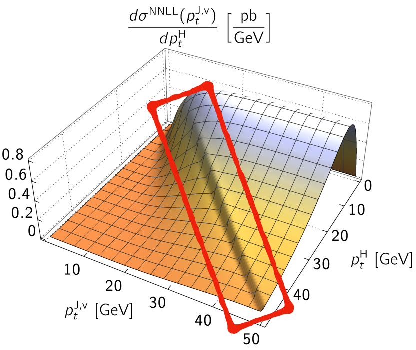
$$\mathcal{F}_{\rm clust} = \frac{1}{2!}\int [dk_a][dk_b]|M(k_a)|^2|M(k_b)|^2 J_R(a,b)\, e^{i\vec{b}\cdot(\vec{k_{ta}}+\vec{k_{tb}})} \times \left[\Theta(p_t^{\rm JV}-|\vec{k}_{ta}+\vec{k}_{tb}|)-\Theta(p_t^{\rm JV}-\max\{k_{ta},k_{tb}\})\right]$$

$$\mathcal{F}_{\rm correl} = \frac{1}{2!}\int [dk_a][dk_b]|\tilde{M}(k_a,k_b)|^2 \left[1-J_R(a,b)\right] e^{i\vec{b}\cdot(\vec{k_{ta}}+\vec{k_{tb}})} \times \left[\Theta(p_t^{\rm JV}-\max\{k_{ta},k_{tb}\})-\Theta(p_t^{\rm JV}-|\vec{k}_{ta}+\vec{k}_{tb}|)\right]$$

- Joint resummation at NNLL in b space

$$\frac{d\sigma(p_t^{\rm J,v})}{dy^{\rm H}d^2\vec{p}_t^{\,\rm H}} = M^2_{\rm gg\to H}\,\mathcal{H}(\alpha_s(m_{\rm H}))\int_{\mathcal{C}_1}\frac{d\nu_1}{2\pi i}\int_{\mathcal{C}_2}\frac{d\nu_2}{2\pi i}x_1^{-\nu_1}\,x_2^{-\nu_2}\int\frac{d^2\vec{b}}{4\pi^2}e^{-i\vec{b}\cdot\vec{p}_t^{\,\rm H}}\,e^{-S_{\rm NNLL}}\left(1+\mathcal{F}_{\rm clust}+\mathcal{F}_{\rm correl}\right)$$
$$\times f_{\nu_1,a_1}(b_0/b)\,f_{\nu_2,a_2}(b_0/b)\left[\mathcal{P}\,e^{-\int_{p_t^{\rm J,v}}^{m_{\rm H}}\frac{d\mu}{\mu}\mathbf{\Gamma}_{\nu_1}(\alpha_s(\mu))J_0(b\mu)}\right]_{c_1a_1}\left[\mathcal{P}\,e^{-\int_{p_t^{\rm J,v}}^{m_{\rm H}}\frac{d\mu}{\mu}\mathbf{\Gamma}_{\nu_2}(\alpha_s(\mu))J_0(b\mu)}\right]_{c_2a_2}$$
$$\times C_{\nu_1,gb_1}(\alpha_s(b_0/b))\,C_{\nu_2,gb_2}(\alpha_s(b_0/b))\left[\mathcal{P}\,e^{-\int_{p_t^{\rm J,v}}^{m_{\rm H}}\frac{d\mu}{\mu}\mathbf{\Gamma}^{(C)}_{\nu_1}(\alpha_s(\mu))J_0(b\mu)}\right]_{c_1b_1}\left[\mathcal{P}\,e^{-\int_{p_t^{\rm J,v}}^{m_{\rm H}}\frac{d\mu}{\mu}\mathbf{\Gamma}^{(C)}_{\nu_2}(\alpha_s(\mu))J_0(b\mu)}\right]_{c_2b_2},$$

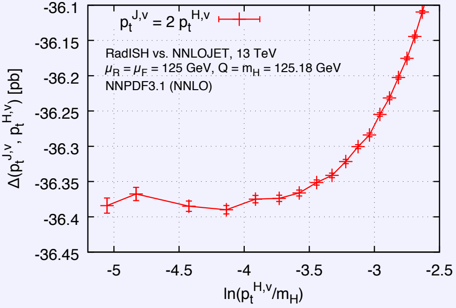
NNLL cross section differential in p_t^{H}, cumulative in $p_t^{\mathrm{J}} < p_t^{\mathrm{JV}}$



- Peaked structure at small p_t^{H}; Sudakov suppression at small p_t^{J}.
- Sudakov shoulder [Catani, Webber, 9710333]: integrable singularity at $p_t^{\mathrm{H}} \sim p_t^{\mathrm{JV}}$.
- Logarithms associated with the shoulder are resummed in the region $p_t^{\mathrm{H}} \sim p_t^{\mathrm{JV}} \ll m_H$ (absence of the integrable singularity there)

Accuracy check

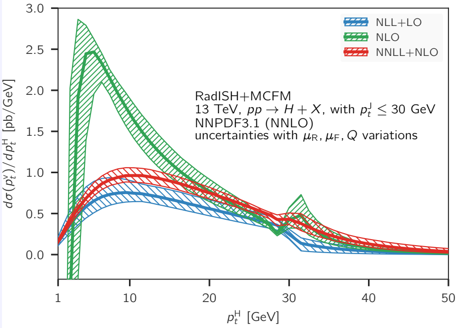
Difference between $\Sigma_{NNLL}(p_t^{\mathrm{H}} < p_t^{\mathrm{HV}}, p_t^{\mathrm{J}} < p_t^{\mathrm{JV}})$ expanded at $\mathcal{O}(\alpha_s^2)$ and fixed order at $\mathcal{O}(\alpha_s^2)$



- Difference tends to an $\mathcal{O}(\alpha_s^2)$ constant (i.e. N^{3}LL) at very small p_t^{HV} in the region of the shoulder, $p_t^{\mathrm{JV}} = 2\, p_t^{\mathrm{HV}}$.
- Very strong check: control of logarithms associated to the shoulder when $p_t^{\mathrm{J}} \sim p_t^{\mathrm{H}} \ll m_H$.
- Analogously for $p_t^{\mathrm{H}} \ll p_t^{\mathrm{J}}$ or $p_t^{\mathrm{H}} \gg p_t^{\mathrm{J}}$.
  Logarithms correctly accounted for regardless of hierarchy between p_t^{H} and p_t^{J} (if $\ll m_H$).

LHC results: Higgs p_t with a jet veto

Multiplicative matching with fixed order (NLO $H + j$ from MCFM, [Campbell, Ellis, Giele, 1503.06182])



- Resummed results display good perturbative convergence below 10 GeV. Above, effects from the large Higgs K factor.
- NNLL+NLO has less than 10% uncertainty for $p_t^{\mathrm{H}} < p_t^{\mathrm{JV}}$.
- Much reduced sensitivity to the shoulder at 30 GeV with respect to fixed order.

Outlook

- Theoretical control of multi-differential information to exploit LHC potential in the Higgs sector (and much more!).
- First double-differential resummation for observable defined through a jet algorithm in hadronic collisions.
- Formulation in direct space (RadISH) provides guidance to compact analytic formulation in b space.
- Logarithms of p_t^{H}/m_H and p_t^{J}/m_H controlled at NNLL when transverse momenta $\ll m_H$.
- This does not rely on hierarchy between p_t^{H} and p_t^{J}. Sudakov shoulder $p_t^{\mathrm{H}} \sim p_t^{\mathrm{J}}$ resummed in the small-p_t region.

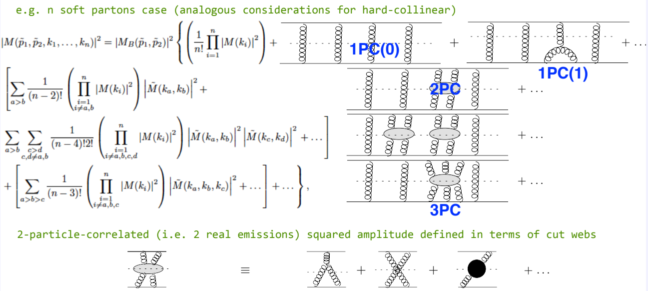
Thank you for your attention

Backup

RadISH resummation: organisation into correlated matrix elements

$$\Sigma(V < \nu) = \int d\Phi_B \, \mathcal{V}(\Phi_B) \sum_{n=0}^{\infty} \int \prod_{i=1}^{n} [dk_i] |M(k_1, ..., k_n)|^2 \, \Theta(\nu - V(k_1, ..., k_n))$$

- $\mathcal{V}(\Phi_B)$ = all-order virtual form factor (see [Dixon, Magnea, Sterman, 0805.3515]).
- Multiple emission matrix element $|M(k_1, ..., k_n)|^2$ organised into *n*-particle-correlated (*n*PC) blocks $|\tilde{M}(k_1, ..., k_n)|^2$.



- Higher-orders in α_s at fixed n, or larger n $\Longrightarrow$ logarithmically suppressed

p_t^{H} resummation: finiteness in four dimensions, NLL case

$$\frac{d\Sigma_{\mathrm{NLL}}(p_t)}{d\Phi_B} = \int_0^M \frac{dk_{t1}}{k_{t1}} \int_0^{2\pi} \frac{d\phi_1}{2\pi} k_{t1} \frac{\partial}{\partial k_{t1}} \left(-e^{-R(k_{t1})} \mathcal{L}_{\mathrm{NLL}}(k_{t1}) \right) \times$$
$$\times \underbrace{\epsilon^{R'(k_{t1})} \sum_{n=0}^{\infty} \frac{1}{n!} \left(\prod_{i=2}^{n+1} \int_{\epsilon k_{t1}}^{k_{t1}} \frac{dk_{ti}}{k_{ti}} \int_0^{2\pi} \frac{d\phi_i}{2\pi} R'(k_{t1}) \right)}_{\equiv \int d\mathcal{Z}[\{R', k_i\}]} \Theta(p_t - |\vec{k}_{t1} + \ldots + \vec{k}_{t(n+1)}|).$$

- Luminosity $\mathcal{L}_{\mathrm{NLL}}(k_{t1}) = \sum_{a,b} \frac{d|M_B|^2_{ab}}{d\Phi_B} f_a(x_1, k_{t1}) f_b(x_2, k_{t1})$.
- $\int d\mathcal{Z}[\{R', k_i\}]\Theta$ finite as $\epsilon \to 0$:

$$\epsilon^{R'(k_{t1})} = 1 - R'(k_{t1}) \ln(1/\epsilon) + \ldots = 1 - \int_0^{2\pi} \frac{d\phi}{2\pi} \int_{\epsilon k_{t1}}^{k_{t1}} \frac{dk_t}{k_t} R'(k_{t1}) + \ldots,$$

$$\int d\mathcal{Z}[\{R', k_i\}]\Theta = \left[1 - \int_0^{2\pi} \frac{d\phi}{2\pi} \int_{\epsilon k_{t1}}^{k_{t1}} \frac{dk_t}{k_t} R'(k_{t1}) + \ldots\right] \left[\Theta(p_t - |\vec{k}_{t1}|) + \int_0^{2\pi} \frac{d\phi_2}{2\pi} \int_{\epsilon k_{t1}}^{k_{t1}} \frac{dk_{t2}}{k_{t2}} R'(k_{t1}) \Theta(p_t - |\vec{k}_{t1} + \vec{k}_{t2}|) + \ldots\right]$$
$$= \Theta(p_t - |\vec{k}_{t1}|) + \int_0^{2\pi} \frac{d\phi_2}{2\pi} \underbrace{\int_0^{k_{t1}}}_{\epsilon \to 0} \frac{dk_{t2}}{k_{t2}} R'(k_{t1}) \underbrace{\left[\Theta(p_t - |\vec{k}_{t1} + \vec{k}_{t2}|) - \Theta(p_t - |\vec{k}_{t1}|)\right]}_{\text{finite: real-virtual cancellation}} + \ldots$$

Small-p_t^{H} behaviour at NLL

$$\frac{d^2\Sigma(p_t)}{d^2\vec{p}_t d\Phi_B} \propto \int \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} e^{-R(k_{t1})} R'(k_{t1}) \int d\mathcal{Z}[\{R', k_i\}] \delta^{(2)} \left(\vec{p}_t - \left(\vec{k}_{t1} + \cdots + \vec{k}_{t(n+1)}\right)\right).$$

- Fourier transform of the delta: $\delta^{(2)}\left(\vec{p}_t - |\sum_i \vec{k}_{ti}|\right) = \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_t} \prod_{i=1}^{n+1} e^{i\vec{b}\cdot\vec{k}_{ti}}.$
- Integrate over azimuthal direction of all $\vec{k}_{ti}$ and of $\vec{p}_t$:

$$\begin{aligned} \frac{d^2\Sigma(v)}{dp_t d\Phi_B} &= \sigma^{(0)}(\Phi_B)\, p_t \int b\, db J_0(p_t b) \int \frac{dk_{t1}}{k_{t1}} e^{-R(k_{t1})} R'(k_{t1}) J_0(bk_{t1}) \\ &\quad \times \exp\left\{-R'(k_{t1}) \int_0^{k_{t1}} \frac{dk_t}{k_t}(1 - J_0(bk_t))\right\}. \end{aligned}$$

- In the limit where $M \gg k_{t1} \gg p_t$ this gives

$$\int b\, db J_0(p_t b) J_0(bk_{t1}) \exp\left\{-R'(k_{t1}) \int_0^{k_{t1}} \frac{dk_t}{k_t}(1 - J_0(bk_t))\right\} \simeq 4 \frac{k_{t1}^{-2}}{R'(k_{t1})}$$

$$\implies \frac{d^2\Sigma(v)}{dp_t d\Phi_B} = 4\, \sigma^{(0)}(\Phi_B)\, p_t \int_{\Lambda_{\mathrm{QCD}}}^{M} \frac{dk_{t1}}{k_{t1}^3} e^{-R(k_{t1})}.$$

Treatment of Landau pole

- Landau singularity in the radiator and in the coupling:

$$\alpha_S(\mu_R)\beta_0 \ln(Q/k_{t1}) = \frac{1}{2} \quad \Longrightarrow \quad k_{t1} \sim 0.1\ GeV \quad \textit{for} \quad \mu_R \sim Q \sim m_H$$

- Perturbative prediction is cut off below this scale, by setting probabilities to 0.

- This cutoff is not a problem: low p_t^H dominated by k_{ti}'s above the GeV

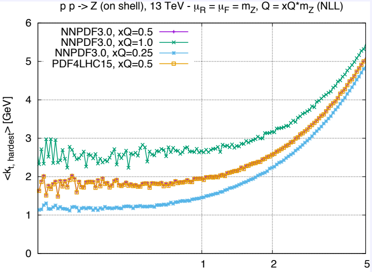


Figure credit: P.F. Monni

- This does not imply absence of non-perturbative corrections (not studied here) at scales of a GeV

Equivalence of direct-space p_t^{H} resummation with b space

- Take direct-space formula for $d\Sigma/d\vec{p}_t$, Fourier-transform the $\delta^{(2)}(p_t - |\sum_i \vec{k}_{ti}|)$, and get

$$
\begin{aligned}
\frac{d}{dp_t}\hat{\Sigma}^{c_1 c_2}_{N_1,N_2}(p_t) &= \mathbf{C}^{c_1;T}_{N_1}(\alpha_s(M))H(M)\mathbf{C}^{c_2}_{N_2}(\alpha_s(M))\, p_t \int b\, db J_0(p_t b) \int_0^M \frac{dk_{t1}}{k_{t1}} \\
&\times \sum_{\ell_1=1}^{2}\left(\mathbf{R}'_{\ell_1}(k_{t1}) + \frac{\alpha_s(k_{t1})}{\pi}\Gamma_{N_{\ell_1}}(\alpha_s(k_{t1})) + \Gamma^{(C)}_{N_{\ell_1}}(\alpha_s(k_{t1}))\right) J_0(bk_{t1}) \\
&\times \exp\left\{-\sum_{\ell=1}^{2}\int_{k_{t1}}^{M}\frac{dk_t}{k_t}\left(\mathbf{R}'_{\ell}(k_t) + \frac{\alpha_s(k_t)}{\pi}\Gamma_{N_\ell}(\alpha_s(k_t)) + \Gamma^{(C)}_{N_\ell}(\alpha_s(k_t))\right) J_0(bk_t)\right\} \\
&\times \exp\left\{-\sum_{\ell=1}^{2}\int_{\epsilon k_{t1}}^{M}\frac{dk_t}{k_t}\left(\mathbf{R}'_{\ell}(k_t) + \frac{\alpha_s(k_t)}{\pi}\Gamma_{N_\ell}(\alpha_s(k_t)) + \Gamma^{(C)}_{N_\ell}(\alpha_s(k_t))\right) (1 - J_0(bk_t))\right\}.
\end{aligned}
$$

- Take limit $\epsilon \to 0$. Integrand in k_{t1} is a total derivative and integrates to 1, leaving

$$
\begin{aligned}
\frac{d}{dp_t}\hat{\Sigma}^{c_1 c_2}_{N_1,N_2}(p_t) &= \mathbf{C}^{c_1;T}_{N_1}(\alpha_s(M))H(M)\mathbf{C}^{c_2}_{N_2}(\alpha_s(M))\, p_t \int b\, db J_0(p_t b) \\
&\times \exp\left\{-\sum_{\ell=1}^{2}\int_{0}^{M}\frac{dk_t}{k_t}\left(\mathbf{R}'_{\ell}(k_t) + \frac{\alpha_s(k_t)}{\pi}\Gamma_{N_\ell}(\alpha_s(k_t)) + \Gamma^{(C)}_{N_\ell}(\alpha_s(k_t))\right) (1 - J_0(bk_t))\right\}.
\end{aligned}
$$

- Transform $1 - J_0$ in a Θ up to subleading logarithms, and plug this into the hadronic cross section, to get the traditional b-space formulation.

$$
(1 - J_0(bk_t)) \simeq \Theta(k_t - \frac{b_0}{b}) + \frac{\zeta_3}{12}\frac{\partial^3}{\partial \ln(Mb/b_0)^3}\Theta(k_t - \frac{b_0}{b}) + \dots .
$$

- ζ_3 term starts at N^{3}LL, is resummation-scheme change w.r.t. b space.

Generating secondary radiation as a simplified parton shower

- Secondary radiation:

$$
\begin{aligned}
d\mathcal{Z}[\{R', k_i\}] &= \sum_{n=0}^{\infty} \frac{1}{n!} \left(\prod_{i=2}^{n+1} \int_0^{2\pi} \frac{d\phi_i}{2\pi} \int_{\epsilon k_{t1}}^{k_{t1}} \frac{dk_{ti}}{k_{ti}} R'(k_{t1}) \right) \epsilon^{R'(k_{t1})} \\
&= \sum_{n=0}^{\infty} \left(\prod_{i=2}^{n+1} \int_0^{2\pi} \frac{d\phi_i}{2\pi} \int_{\epsilon k_{t1}}^{k_{t(i-1)}} \frac{dk_{ti}}{k_{ti}} R'(k_{t1}) \right) \epsilon^{R'(k_{t1})}, \\
\epsilon^{R'(k_{t1})} &= e^{-R'(k_{t1}) \ln 1/\epsilon} = \prod_{i=2}^{n+2} e^{-R'(k_{t1}) \ln k_{t(i-1)}/k_{ti}},
\end{aligned}
$$

with $k_{t(n+2)} = \epsilon\, k_{t1}$.

- Each secondary emissions has differential probability

$$
dw_i = \frac{d\phi_i}{2\pi} \frac{dk_{ti}}{k_{ti}} R'(k_{t1}) e^{-R'(k_{t1}) \ln k_{t(i-1)}/k_{ti}} = \frac{d\phi_i}{2\pi} d\left(e^{-R'(k_{t1}) \ln k_{t(i-1)}/k_{ti}} \right).
$$

- $k_{t(i-1)} \geq k_{ti}$. Scale k_{ti} extracted by solving $e^{-R'(k_{t1}) \ln k_{t(i-1)}/k_{ti}} = r$, with r uniform random number in $[0, 1]$.

- Extract ϕ_i randomly in $[0, 2\pi]$.

Modified logarithms

- Ensure resummation does not affect the hard region of the spectrum.
- Supplement logarithms with power-suppressed terms, irrelevant at small k_{t1}, that enforce resummation to vanish at $k_{t1} \gg Q$.
- Modified logarithms

$$\ln\left(\frac{Q}{k_{t1}}\right) \quad \to \quad \tilde{L} = \frac{1}{p}\ln\left(\left(\frac{Q}{k_{t1}}\right)^{p} + 1\right).$$

- Q = resummation scale of $\mathcal{O}(M)$, varied to assess systematics due to higher logarithms.
- p = chosen so that resummation vanishes faster than fixed order in the hard region.
- Checked that variation of p does not induce visible effects.
- Modified logarithms map $k_{t1} = Q$ into $k_{t1} \to \infty$.

Luminosity to NNLL

$$\mathcal{L}_{NNLL}(k_{t1}) = \sum_{c,c'} \frac{d|\mathcal{M}_B|^2_{cc'}}{d\Phi_B} \sum_{i,j} \int_{x_1}^1 \frac{dz_1}{z_1} \int_{x_2}^1 \frac{dz_2}{z_2} f_i\left(\mu_F e^{-L_{t1}}, \frac{x_1}{z_1}\right) f_j\left(\mu_F e^{-L_{t1}}, \frac{x_2}{z_2}\right)$$
$$\times \left\{ \delta_{ci}\delta_{c'j}\delta(1-z_1)\delta(1-z_2)\left(1 + \frac{\alpha_S(\mu_R)}{2\pi} H^{(1)}(\mu_R, x_Q)\right)\right.$$
$$\left. + \frac{\alpha_S(\mu_R)}{2\pi} \frac{1}{1-2\alpha_S(\mu_R)\beta_0 L_{t1}} \left(C_{ci}^{(1)}(z_1, \mu_F, x_Q)\delta(1-z_2)\delta_{c'j} + \{z_1 \leftrightarrow z_2; c, i \leftrightarrow c', j\}\right)\right\}$$

with $L_{t1} = \ln(Q/k_{t1})$.

Sudakov radiator for joint resummation in b space

$$
\begin{aligned}
S_{NNLL} &= \int [dk]|M(k)|^2 \left(1 - e^{i\vec{b}\cdot\vec{k}_t}\Theta(p_t^{\mathrm{JV}} - k_t)\right) \\
&= \int \frac{dk_t}{k_t} R'(k_t)\left(1 - J_0(bk_t)\Theta(p_t^{\mathrm{JV}} - k_t)\right) \\
&= \int \frac{dk_t}{k_t} R'(k_t)\left(1 - J_0(bk_t)\right) + \int \frac{dk_t}{k_t} R'(k_t) J_0(bk_t)\Theta(k_t - p_t^{\mathrm{JV}}) \\
&= -L_b g_1(\alpha_S L_b) - g_2(\alpha_S L_b) - \frac{\alpha_S}{\pi} g_3(\alpha_S L_b) + \int_{p_t^{\mathrm{JV}}}^{m_H} \frac{dk_t}{k_t} R'(k_t) J_0(bk_t)
\end{aligned}
$$

with $L_b = \ln(m_H b/b_0)$, $b_0 = 2e^{-\gamma_E}$.
Analogously for PDFs and coefficient functions.