q_T spectrum for Higgs production via quark annihilation at N^{3}LL$'$+ aN^{3}LO.

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based on work with Pedro Cal, Matthew Lim, Frank Tackmann
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Outline.

Why is $q\bar{q} \to H$ interesting?

- Access Yukawa coupling in production
- Channel separation

$q\bar{q}H$ @ N^{3}LL$'$+aN^{3}LO

- Difference between Drell-Yan and $q\bar{q}H$
- Resummation at N^{3}LL$'$
- Matching to fixed-order and N^{3}LO approximation
- Results

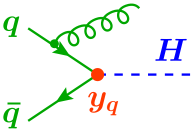
Summary and Outlook

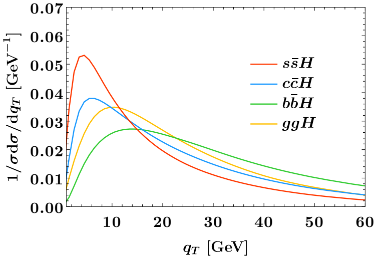
Intro.

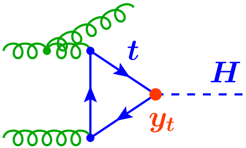
Motivation.

Why $q\bar{q} \to H$?

- Allows to access the Yukawa from the initial side
  - Complementary to measuring it from the final state
- Allows initial state discrimination [Ebert et al. '16, Bishara et al. '16]
  - The q_T spectra of $s\bar{s}H$, $c\bar{c}H$, $b\bar{b}H$, and ggH have different shapes
- Precise prediction for $q\bar{q} \to H$ allows Yukawa fit from initial state







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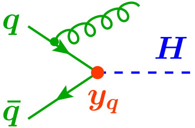
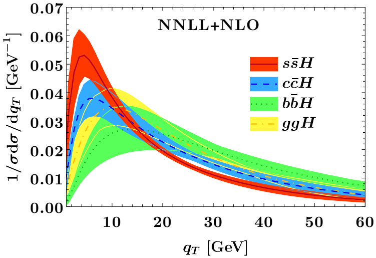
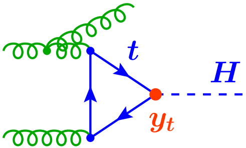


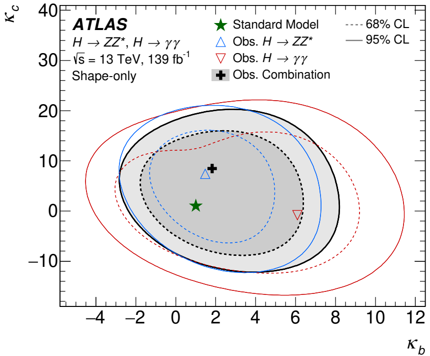




Motivation.

ATLAS measurement [ATLAS, '22]

- Combined fit of the $H \to ZZ$ and $H \to \gamma\gamma$ q_T spectrum
- ggH : N^{3}LL′ prediction from `SCETlib`
- $b\bar{b}H$ and $c\bar{c}H$: only from `MadGraph5_aMC@NLO`



$q\bar{q}H$ @ $\mathrm{N^3LL'}$+a$\mathrm{N^3LO}$.

Factorization and Resummation.

Factorization

- SCET factorization separates the scales at cross section level

$$\frac{d\sigma}{dq_T} = \boxed{H(\mu_H)} \times \boxed{B(\mu_B)} \otimes \boxed{B(\mu_B)} \otimes \boxed{S(\mu_S)} \left[1 + \mathcal{O}\left(\frac{q_T^2}{m_H^2}\right)\right]$$

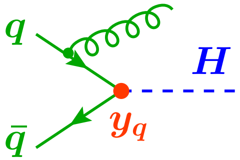
Resummation @ N^{3}LL$'$:

- Resummation with `SCETlib` in b_T space [Billis, Ebert, Michel, Tackmann]
- ingredients for N^{3}LL$'$ resummation:
  - Hard function $\boxed{H(\mu_H)}$ @ N^{3}LO [Gehrmann, Kara '14; Ebert, Michel, Tackmann '17]
  - Beam function $\boxed{B(\mu_B)}$ @ N^{3}LO [Luo, Yang, Zhu, Zhu '19; Ebert, Mistlberger, Vita '20]
  - Soft function $\boxed{S(\mu_S)}$ @ N^{3}LO [Li, Zhu, Neill '16; Li, Zhu, '16]
  - 4-loop cusp and 3-loop non-cusp anom. dim. [Henn, Korchemsky, Mistlberger '20; v. Manteuffel, Panzer, Schabinger '20] [Li, Zhu, '16; Vladimirov '16]
- For $q_T \sim m_H$ use hybrid profiles to turn off resummation

Fixed order prediction at large q_T

$q\bar{q}H + j$ fixed order predictions:

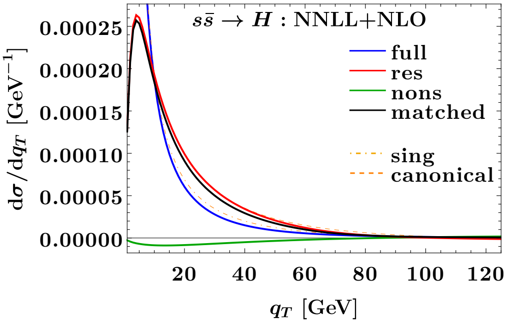
- LO_1: analytic expression implemented in `SCETlib`
- NLO_1: implemented $q\bar{q}H$ process in `Geneva`[Alioli et al.]
  - Use `OpenLoops` matrix elements [Buccioni et al. '19]
- aNNLO_1: approximate something that could be NNLO_1



Matching to fixed-order.

$s\bar{s}H$ vs. $b\bar{b}H$

- $s\bar{s}H$: looks very similar to DY
- $b\bar{b}H$: large nonsingular, very sensitive matching procedure



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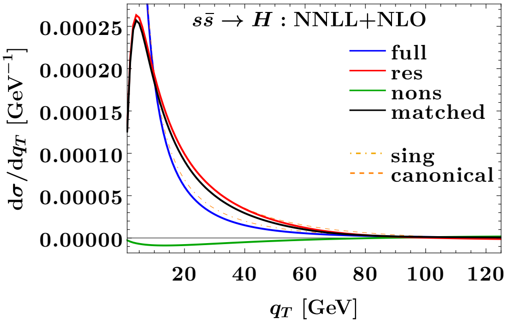
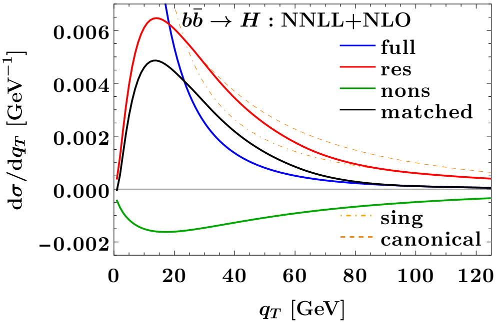




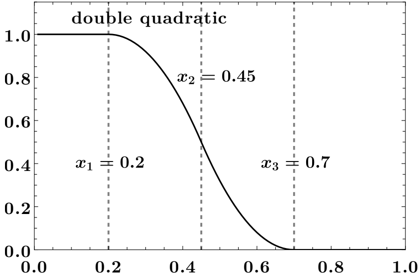
Hybrid profile scales

Use hybrid profile scales to turn off resummation

- Scales depend on q_T and b_T, and transition from the canonical scales to the fixed order scale:

$$\mu(b_T, q_T) \sim 1/b_T \quad \text{for } q_T \ll m_H$$
$$\mu(b_T, q_T) \to \mu_H = \mu_{FO} \quad \text{for } q_T \sim m_H$$

- Governed by double quadratic with transition points (x_1, x_2, x_3) for smooth transition
  - $q_T \leq x_1 m_H$: canonical scales
  - $x_1 m_H \leq q_T \leq x_3 m_H$: transition
  - $q_T \geq x_3 m_H$: resummation fully turned off

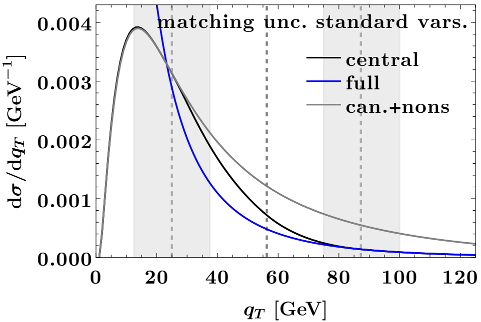


Matching to fixed-order.

Standard procedure:

- Pick x_1 and x_3 and set $x_2 = (x_1 + x_3)/2$
- Vary x_i to get matching uncertainty estimate

▶ **Disadvantage: one-sided matching uncertainty $\to$ unphysical!**



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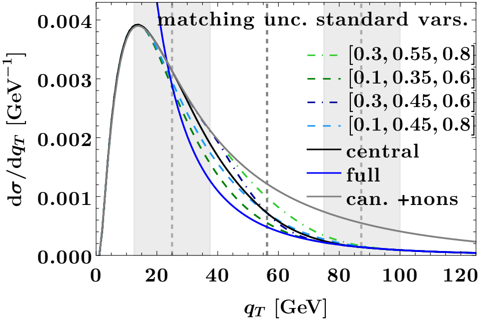
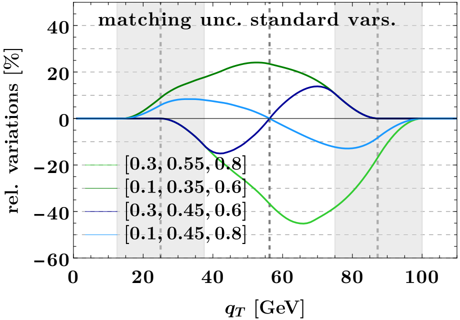




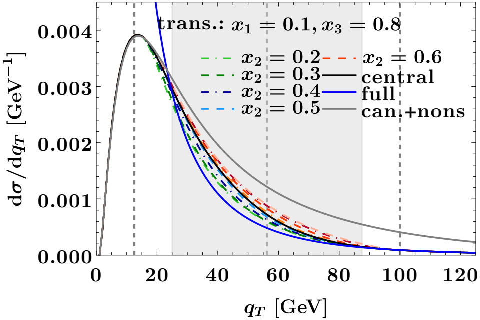
Matching.

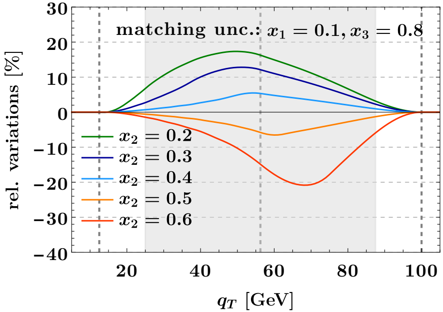
New approach:

- Take previous min. x_1 and max. x_3 and vary only x_2

▶ **Advantage: avoids one-sided uncertainties!**

- Bonus: single parameter to parameterize uncertainty (avoids enveloping)





Matching to N^{3}LL$'$

- Consistent matching requires NNLO$_1$ to match to N^{3}LL$'$
- NNLO$_1$: implemented in MCFM, but not publicly available

Approximation for NNLO$_1$

- Write $\mathrm{d}\sigma^{\text{nons}}$ in terms of coefficients c_i

$$\mathrm{d}\sigma^{\text{nons}} = |y_b|^2 \left[\alpha_s c_1 + \alpha_s^2 c_2 + {\alpha_s}^3 c_3\right]$$

  - Want to come up with an approximation for c_3

Decorrelation.

- Problem: $\mathrm{d}\sigma^{\text{sing}}$ and $\mathrm{d}\sigma^{\text{nons}}$ are strongly correlated at large q_T
  - Need to ensure proper cancellation between $\mathrm{d}\sigma^{\text{nons}}$ and $\mathrm{d}\sigma^{\text{sing}}$ to recover correct $\mathrm{d}\sigma^{\text{full}}$
- **Decorrelation**: add and subtract a term $\mathrm{d}\sigma^{\text{corr}}$, which is as of yet unspecified:

$$\begin{aligned}\mathrm{d}\sigma^{\text{match}} &= \mathrm{d}\sigma^{\text{res}} + \mathrm{d}\sigma^{\text{nons}} \\ &= \underbrace{\mathrm{d}\sigma^{\text{res}} + \mathrm{d}\sigma^{\text{corr}}}_{\mathrm{d}\tilde{\sigma}^{\text{res}}} + \underbrace{\mathrm{d}\sigma^{\text{nons}} - \mathrm{d}\sigma^{\text{corr}}}_{\mathrm{d}\tilde{\sigma}^{\text{nons}}} \equiv \mathrm{d}\tilde{\sigma}^{\text{res}} + \mathrm{d}\tilde{\sigma}^{\text{nons}}\end{aligned}$$

- Need to satisfy conditions:

$$\begin{aligned}\mathrm{d}\tilde{\sigma}^{\text{nons}} &\to \mathrm{d}\sigma^{\text{full}} \quad \text{for} \quad q_T \sim m_H \\ \mathrm{d}\tilde{\sigma}^{\text{nons}} &\sim q_T^2/m_H^2 \quad \text{for} \quad q_T \ll m_H\end{aligned}$$

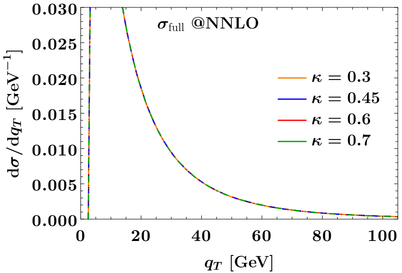
- Choose function that freezes at κm_H :

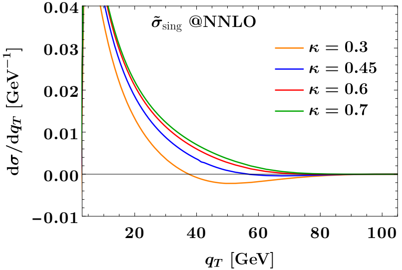
$$\begin{aligned}\mathrm{d}\sigma^{\text{corr}}(q_T) &= -\mathrm{d}\sigma^{\text{sing}}(q_T) \quad \text{for} \quad q_T \sim m_H \\ \mathrm{d}\sigma^{\text{corr}}(q_T) &= -\mathrm{d}\sigma^{\text{sing}}(\kappa m_H) = \text{const.} \quad \text{for} \quad q_T \ll m_H\end{aligned}$$

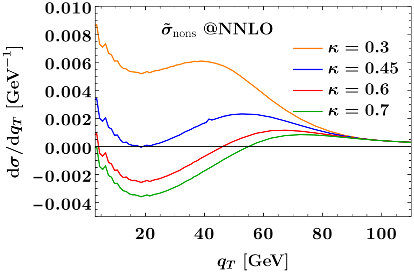
Decorrelation.

at NNLO:

- $\mathrm{d}\tilde{\sigma}^{\text{sing}}$ and $\mathrm{d}\tilde{\sigma}^{\text{nons}}$ do depend on κ
- κ-dependence cancels exactly in $\mathrm{d}\sigma^{\text{full}} = \mathrm{d}\tilde{\sigma}^{\text{sing}} + \mathrm{d}\tilde{\sigma}^{\text{nons}}$







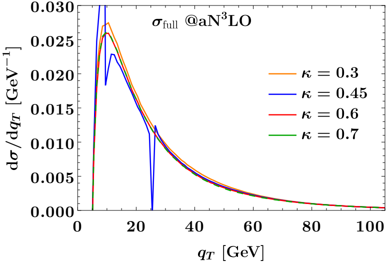
Approximation for $\mathrm{d}\tilde{\sigma}_{\text{nons}}$ at N^{3}LO:

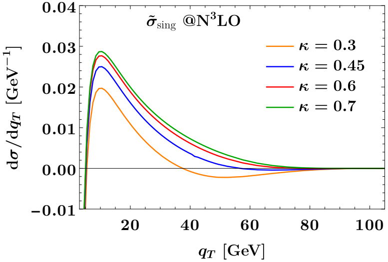
$$\mathrm{d}\tilde{\sigma}_{\text{nons}} = |y_b(\mu_R)|^2 \left[\alpha_s(\mu_R)\tilde{c}_1 + \alpha_s^2(\mu_R)\left(\tilde{c}_2 + \#\log\frac{\mu_R}{m_H}\right)\right.$$
$$\left. + \alpha_s^3(\mu_R)\left(\boxed{\tilde{c}_3} + \#\log\frac{\mu_R}{m_H} + \#\log^2\frac{\mu_R}{m_H}\right)\right]$$

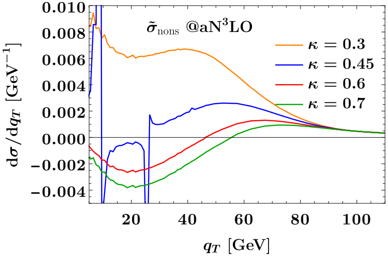
- Use naive Pade approximation for $\boxed{\tilde{c}_3 = K\frac{\tilde{c}_2^2}{\tilde{c}_1}}$
  - Correct power of logs
  - Pick K factor from existing NNLO$_1$ results at large q_T
- Implement correct μ_R dependence
- μ_F-dependence: repeat procedure for μ_F variation

at aN^{3}LO:

- No strong κ-dependence in $\mathrm{d}\tilde{\sigma}^{\text{full}}$
- Need to choose κ such that they are no singularities



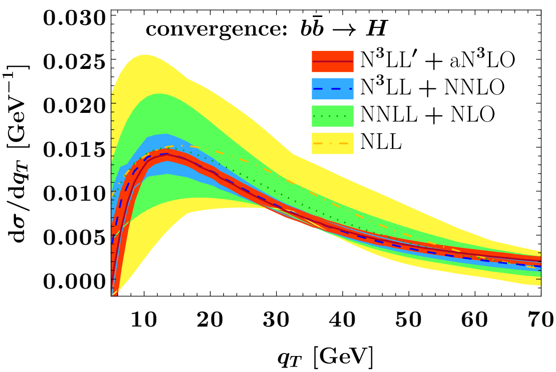


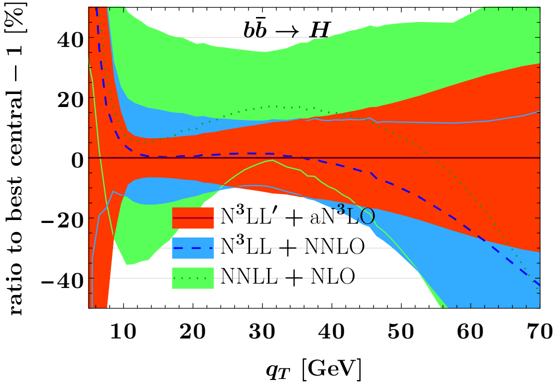


Results.

Convergence:

- Good convergence for higher orders

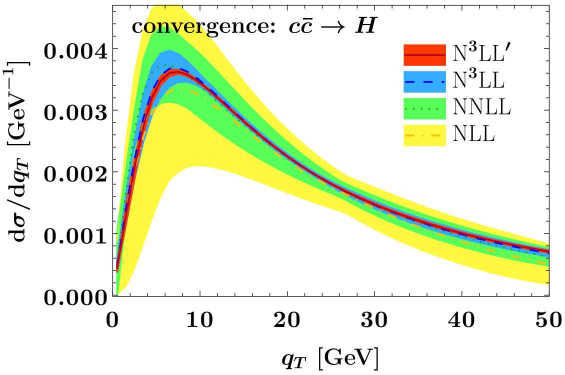


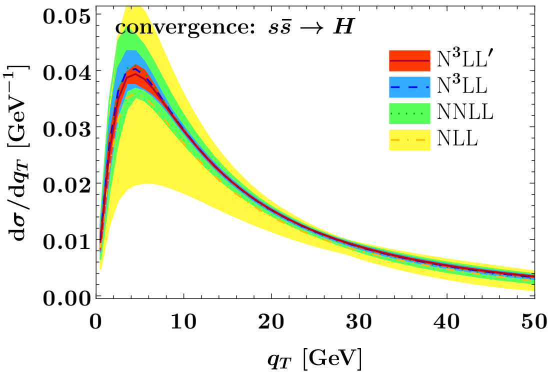


Results.

Convergence:

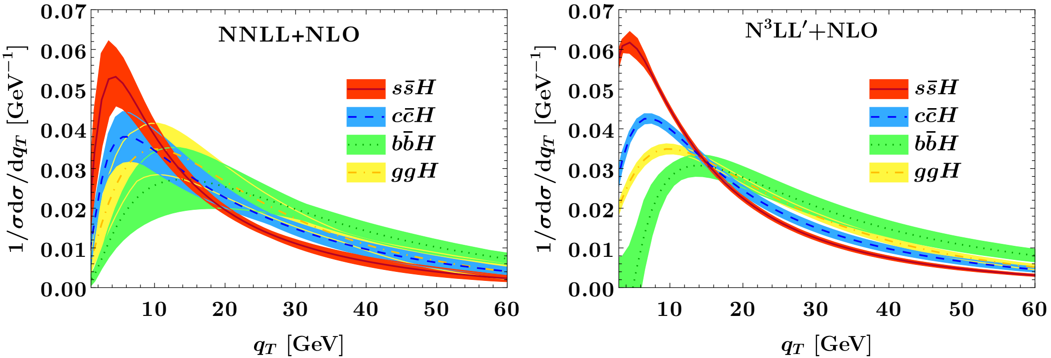
- Good convergence for higher orders
- Uncertainties for $c\bar{c}H$ and $s\bar{s}H$ are in general smaller





Separating initial states.

- Gluon and quark induced processes can be distinguished by the shape of the q_T spectrum
- $b\bar{b}H$ vs. $c\bar{c}H$ vs. $s\bar{s}H$: also differences in the shape of the q_T spectrum
- uncertainties for the channels overlap $\rightarrow$ more precise predictions needed to cleanly distinguish channels
- Optimistic that channels can be distinguished with N^{3}LL′+aN^{3}LO



Summary.

Relevance of $q\bar{q}H$

- Initial state discrimination
- Possibility to measure the Yukawa coupling

Matching

- Modify matching uncertainties to avoid one-sided uncertainties
- Much easier to use in experimental fits

aN^{3}LO

- Need NNLO$_1$ for consistent matching with N^{3}LL$'$
- Problem: $\mathrm{d}\sigma^{\text{nons}}$ and $\mathrm{d}\sigma^{\text{sing}}$ are strongly correlated $\rightarrow$ decorrelation

Outlook:

- Soon: N^{3}LL$'$+ aN^{3}LO predictions for $b\bar{b}H$, $c\bar{c}H$ and $s\bar{s}H$
- Theory nuisance parameters to account for correlations between channels

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European Research Council

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Hybrid profile scales

$$\mu_H = \nu_B = \mu_{\mathrm{FO}}, \tag{1}$$

$$\mu_B = \mu_S = \nu_S = \mu_{\mathrm{FO}} f_{\mathrm{run}}\left(\frac{q_T}{m_H}, \frac{b_0}{b_T m_H}\right) \tag{2}$$

with

$$f_{\mathrm{run}}(x, y) = 1 + g_{\mathrm{run}}(x)(y-1)\,,$$

and

$$g_{\mathrm{run}}(x) = \begin{cases} 1 & 0 < x \le x_1\,, \\ 1 - \frac{(x-x_1)^2}{(x_2-x_1)(x_3-x_1)} & x_1 < x \le x_2\,, \\ \frac{(x-x_3)^2}{(x_3-x_1)(x_3-x_2)} & x_2 < x \le x_3\,, \\ 0 & x_3 \le x\,. \end{cases} \tag{3}$$

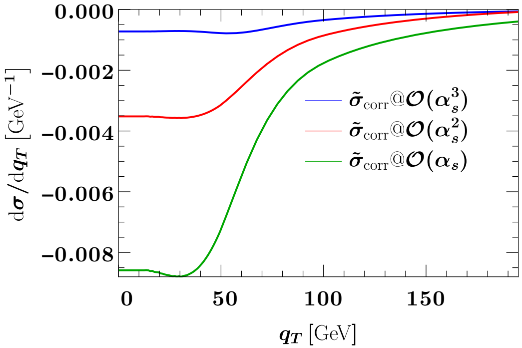
Backup.

Decorrelation:

- choose function that freezes at $\mathrm{d}\sigma^{\text{sing}}(\kappa m_H)$:

$$\mathrm{d}\sigma^{\text{corr}}(q_T) = -\mathrm{d}\sigma^{\text{sing}}(\tilde{q}_T)\,,$$

- $\tilde{q}_T$ is itself a function of q_T, κ is a constant of our choice



Decorrelation:

$$\tilde{q}_T(q_T) = \kappa\, g_{\mathrm{run}}(q_T) + q_T[1 - g_{\mathrm{run}}(q_T)]\,,$$

κ is a constant of our choice and $g_{\mathrm{run}}(q_T)$ is (again) double quadratic

$$g_{\mathrm{run}}(x) = \begin{cases} 1 & 0 < x \le x_1\,, \\ 1 - \frac{(x-x_1)^2}{(x_2-x_1)(x_3-x_1)} & x_1 < x \le x_2\,, \\ \frac{(x-x_3)^2}{(x_3-x_1)(x_3-x_2)} & x_2 < x \le x_3\,, \\ 0 & x_3 \le x\,. \end{cases} \tag{4}$$

How to choose κ?

- prefer higher values of κ (= freeze earlier)
  - decorrelate resummation and singular region
- make sure not to introduce artificial divergences