Mass effects in the Higgs q_T spectrum

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DESY

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HELMHOLTZ

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Outline.

Introduction

- q_T factorization and resummation in SCET
- Higgs q_T spectrum
- measurement of the Yukawa coupling

Quark initiated Higgs production

- N^{3}LL$'$ + aN^{3}LO prediction for $\bar{b}bH$, $\bar{c}cH$ and $\bar{s}sH$

$y_b\, y_t$ interference in gluon fusion

- state of the literature
- different regimes
- cancellation of endpoint divergences

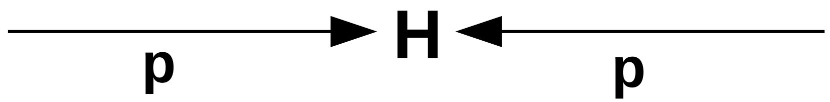
Summary

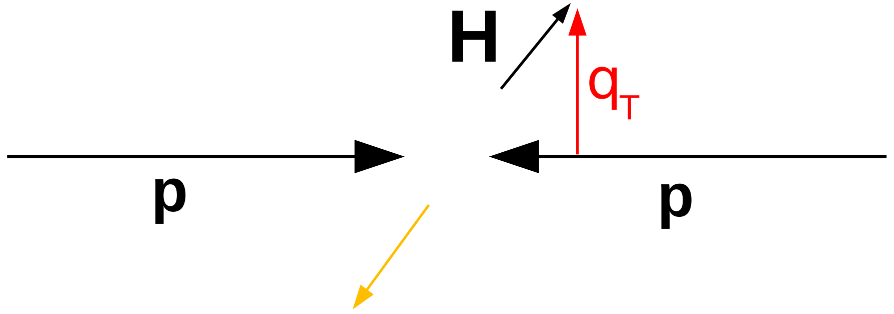
Introduction.

Introduction.

Kinematic distributions

- kinematic distributions and differential cross sections are particularly interesting
- for Higgs production: most Higgs bosons are produced with small transverse momentum q_T
- in this kinematic region the fixed-order perturbative expansion is no longer valid
- **cross section diverges and needs to be resummed!**





Introduction.

Large logs

- consider cross section for $q_T \ll Q = m_H$

$$\sigma(q_T) \sim 1 + \frac{\alpha_s}{4\pi}\left[c_{12}\ln^2_{q_T/Q} + c_{11}\ln_{q_T/Q} + c_{10}\right]$$

NLO

$$+ \left(\frac{\alpha_s}{4\pi}\right)^2 \left[c_{24}\ln^4_{q_T/Q} + c_{23}\ln^3_{q_T/Q} + c_{22}\ln^2_{q_T/Q} + \ldots\right]$$

NNLO

$$+ \left(\frac{\alpha_s}{4\pi}\right)^3 \left[c_{36}\ln^6_{q_T/Q} + c_{35}\ln^5_{q_T/Q} + c_{34}\ln^4_{q_T/Q} + \ldots\right]$$

N^3LO

- for $q_T \to 0$ logs become large $\alpha_s \log^2(q_T/Q) \approx 1$
- switch from fixed-order to logarithmic counting

Introduction.

Large logs

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LL NLL NNLL

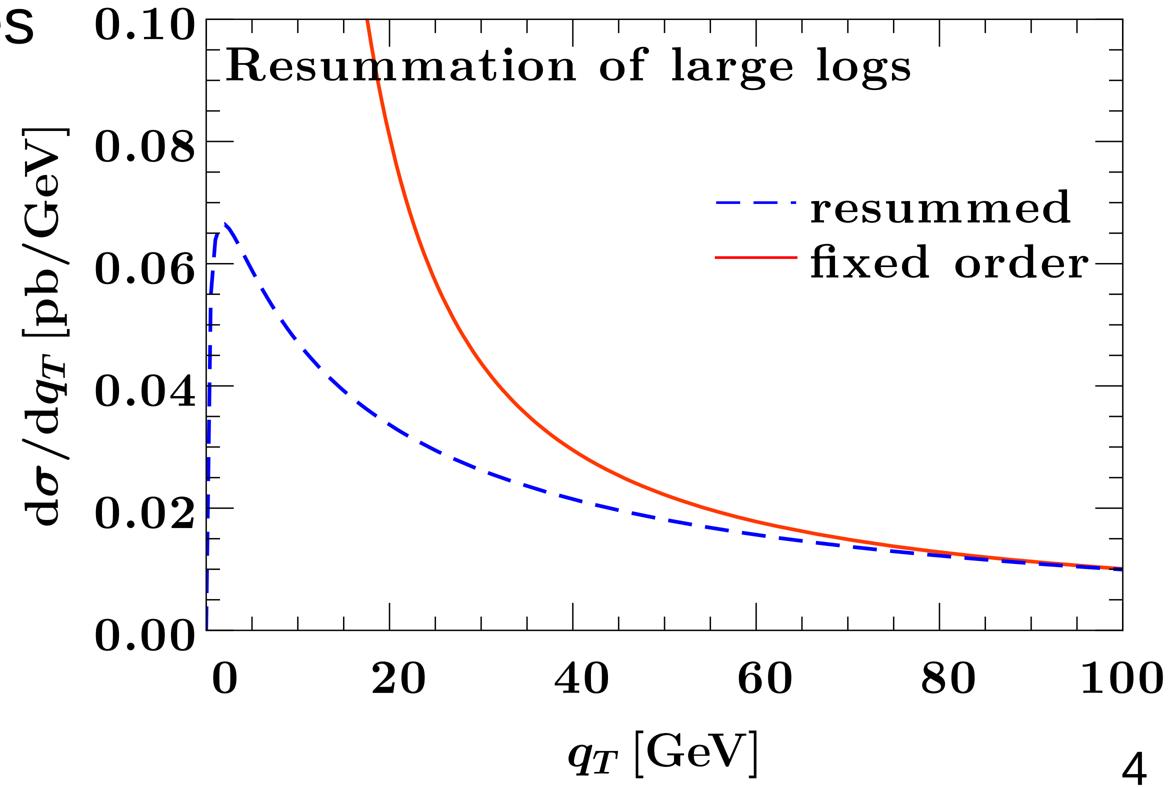
- switch from fixed-order to logarithmic counting

Introduction.

Large logs

- large logs appear and spoil convergence of perturbative series
- **resum logs to all orders to restore convergence!**
- EFTs factorizes dynamics at different scales
- introduce scale μ:

$$\log \frac{q_T}{Q} = \log \frac{q_T}{\mu} + \log \frac{\mu}{Q}$$



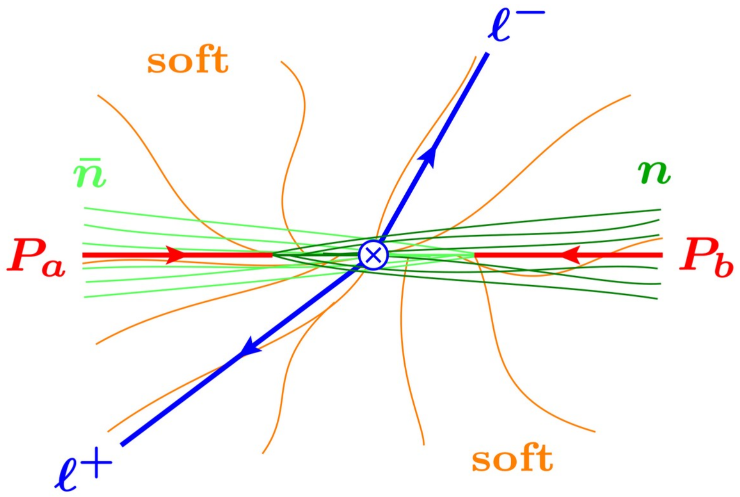
Introduction.

q_T factorization

- SCET factorization theorem separates scales at cross section level

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

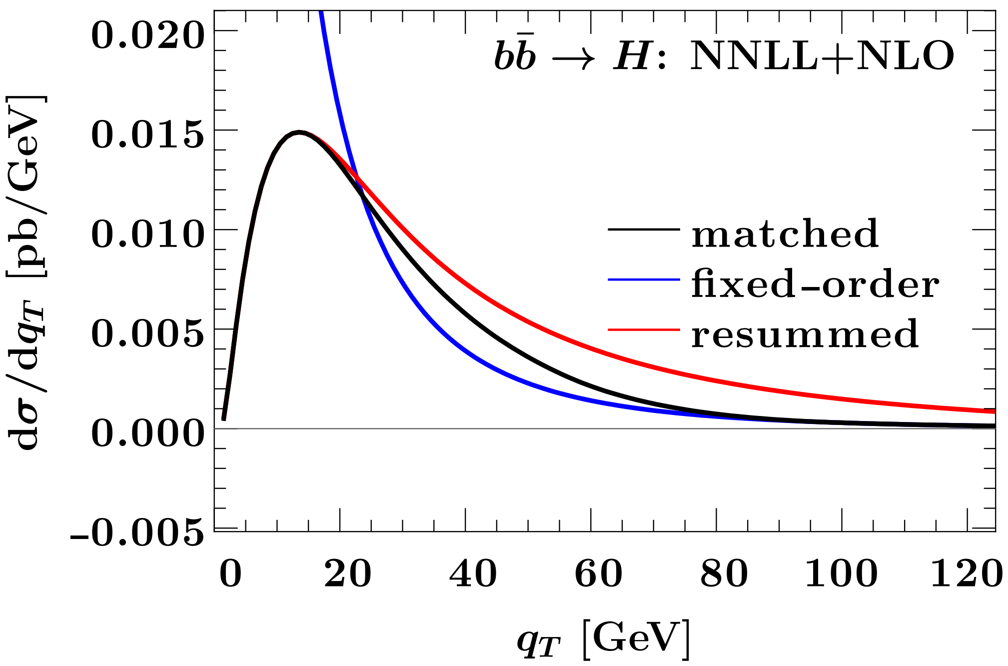
- Hard function: virtual contributions on hard scale
- Beam function: collinear radiation
- Soft function: soft, isotropic radiation



Introduction.

Resummed cross section

- solve RGE for $H(\mu_H), B(\mu_B)$ and $S(\mu_S)$ to resum logs
- resummation generates Sudakov peak for $q_T \ll Q$
- for $q_T \sim Q$ the fixed-order prediction is sufficient
- transition connects fixed-order and resummed prediction



Motivation.

Higgs q_T spectrum

- allows to access quark Yukawa couplings from Higgs production
  - complementary to measuring it from the final state
- initial state discrimination [Ebert et al. ‘16, Bishara at al. ‘16]
  - the q_T spectra of gluon fusion and quark-initiated Higgs productions have different shapes
- **goal: combine different prediction and fit the Yukawa coupling**

$$\frac{\mathrm{d}\sigma(pp \to H)}{\mathrm{d}q_T} = y_t^2 \frac{\mathrm{d}\sigma_{tt}}{\mathrm{d}q_T} + y_t y_b \frac{\mathrm{d}\sigma_{tb}}{\mathrm{d}q_T} + y_b^2 \frac{\mathrm{d}\sigma_{bb}}{\mathrm{d}q_T} + (y_b \to y_c)$$

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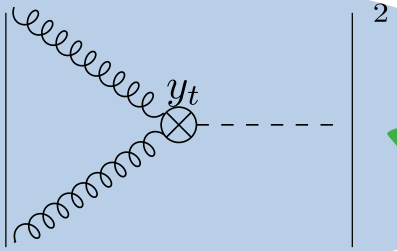
Motivation.

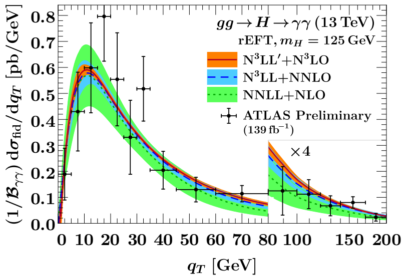
[Billis,Dehnadi, Ebert, Michel, Tackmann ‘21]

Higgs q_T spectrum

$gg \to H$

$\mathrm{N^3LL'} + \mathrm{N^3LO}$





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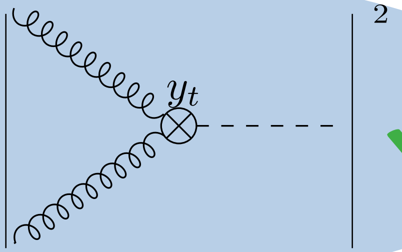

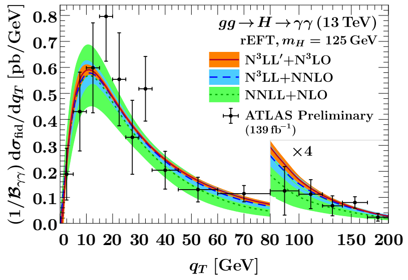

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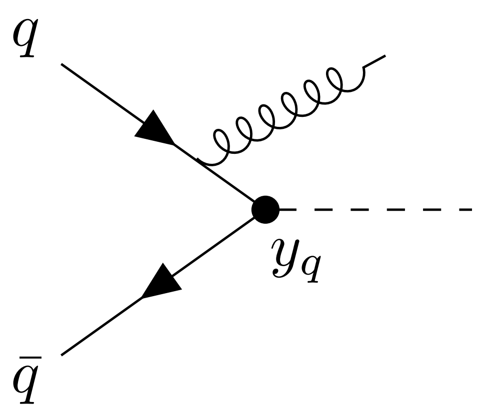
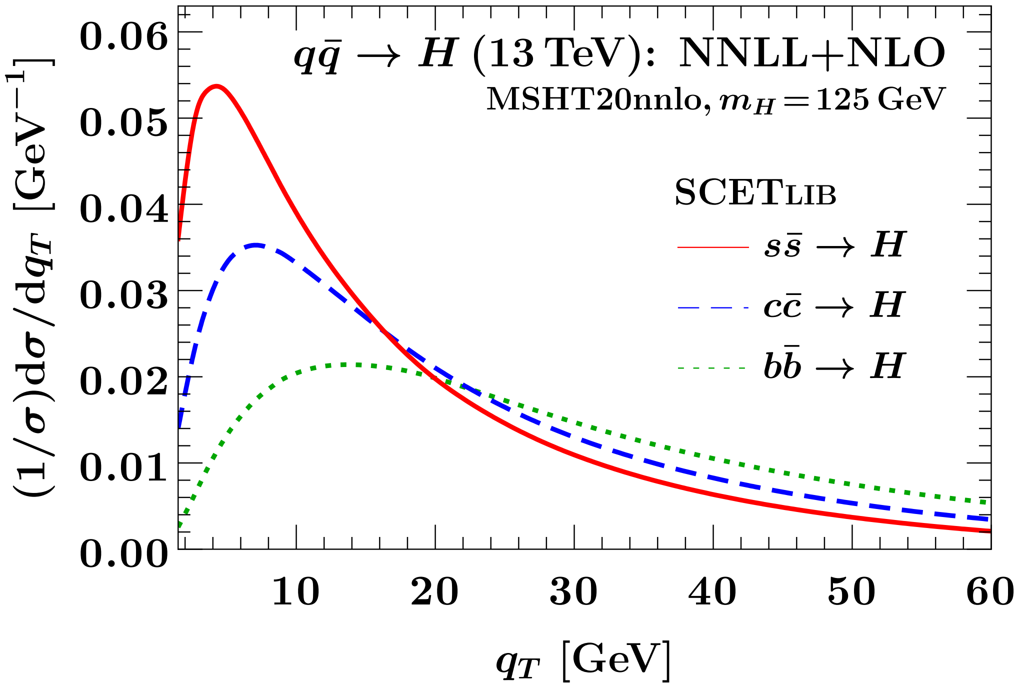
The q_T spectrum for quark initiated Higgs production.

Motivation.

measurement of y_b

- the q_T spectra of $\bar{b}bH, \bar{c}cH$ and $\bar{s}sH$ have different shapes
- precise prediction for $q\bar{q} \to H$ allows for Yukawa fit from the initial state for the quark induced channels
- for NNLL+NLO the uncertainties overlap!
  - Insufficient precision to distinguish them
- **goal: N^{3}LL$'$ + aN^{3}LO prediction**





Motivation.

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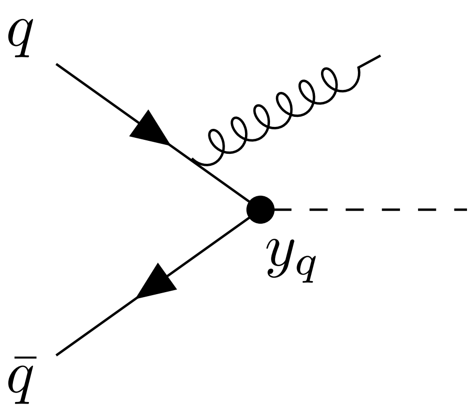
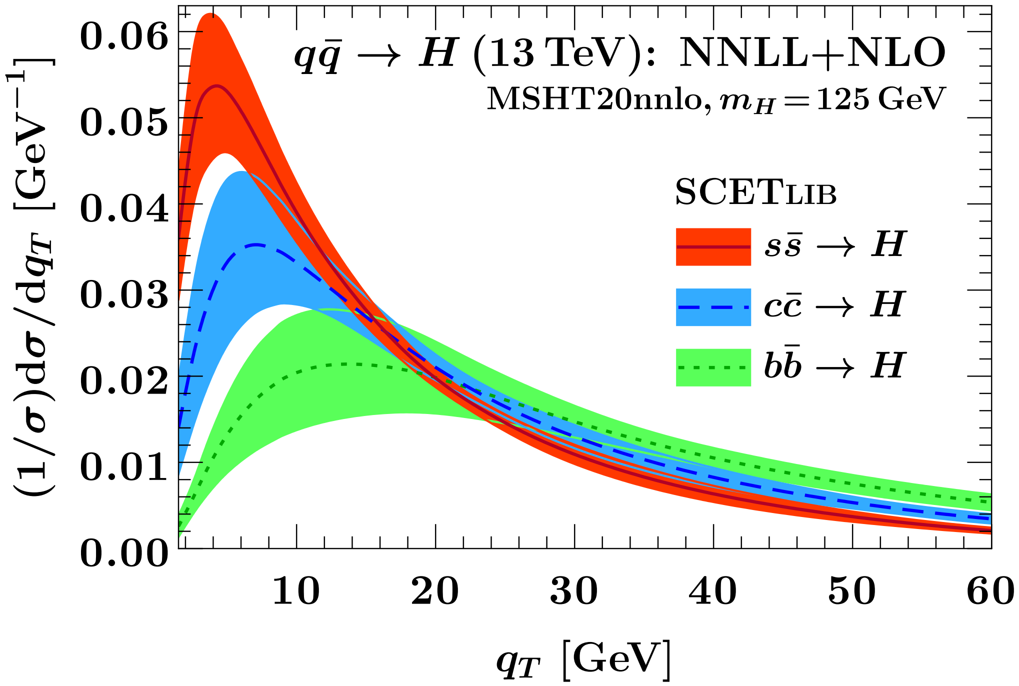




Resummation.

Resummation at N³LL′

- resummation with `SCETlib` in b_T space [Billis, Ebert, Michel, Tackmann]
- ingredients for N³LL' resummation
  - Hard function at N³LO [Gehrmann, Kara`14, Ebert, Michel, Tackmann `17]
  - Beam function at N³LO [Luo,Yang, Zhu, Zhu`19, Ebert, Mistelberger, Vita `20]
  - Soft function at N³LO [Liu, Zhu, Neill`16, Li, Zhu `16]
  - 4-loop cusp and 3-loop non-cusp anom. dim.

    [Henn, Korchemsiky, Mistelberger `20, v. Manteuffel, Panzer , Schabinger`20] [Li, Zhu `16, Valdimirov`16]
- for $q_T \sim m_H$ use hybrid profile scales to turn off resummation

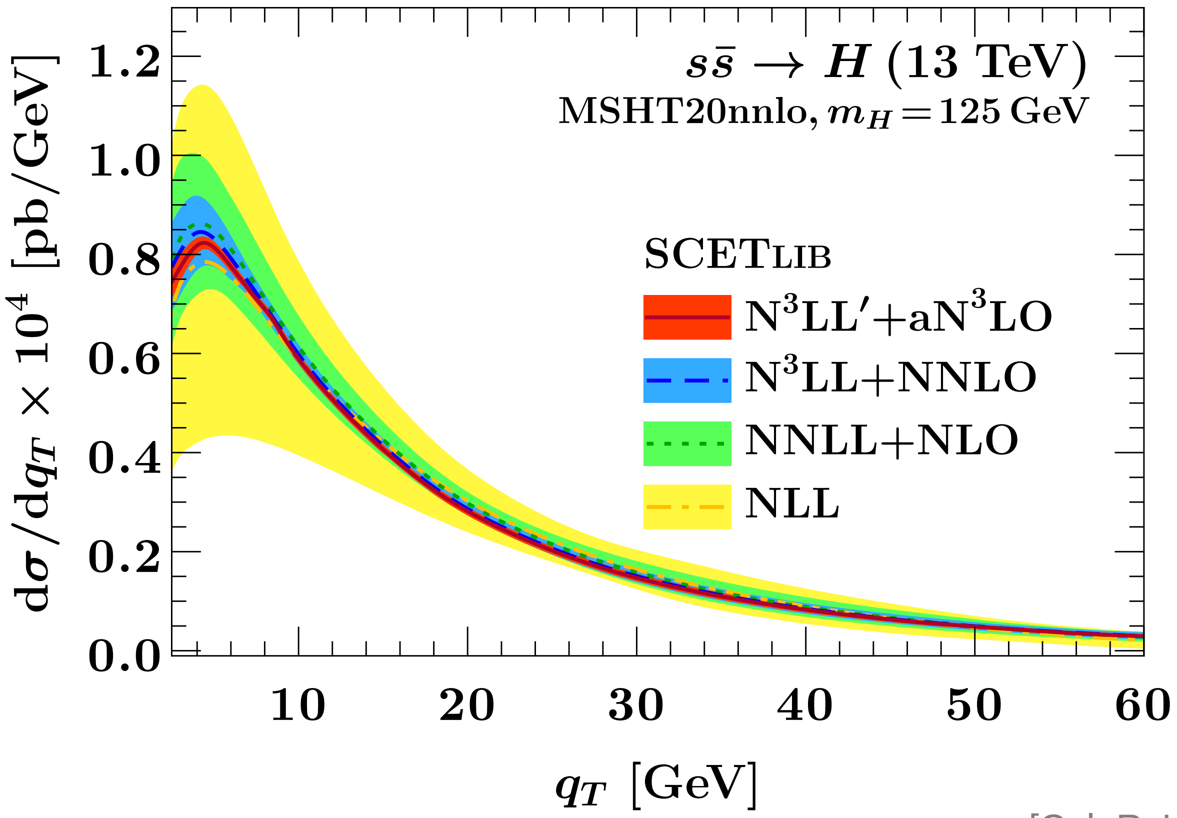
Fixed order prediction.

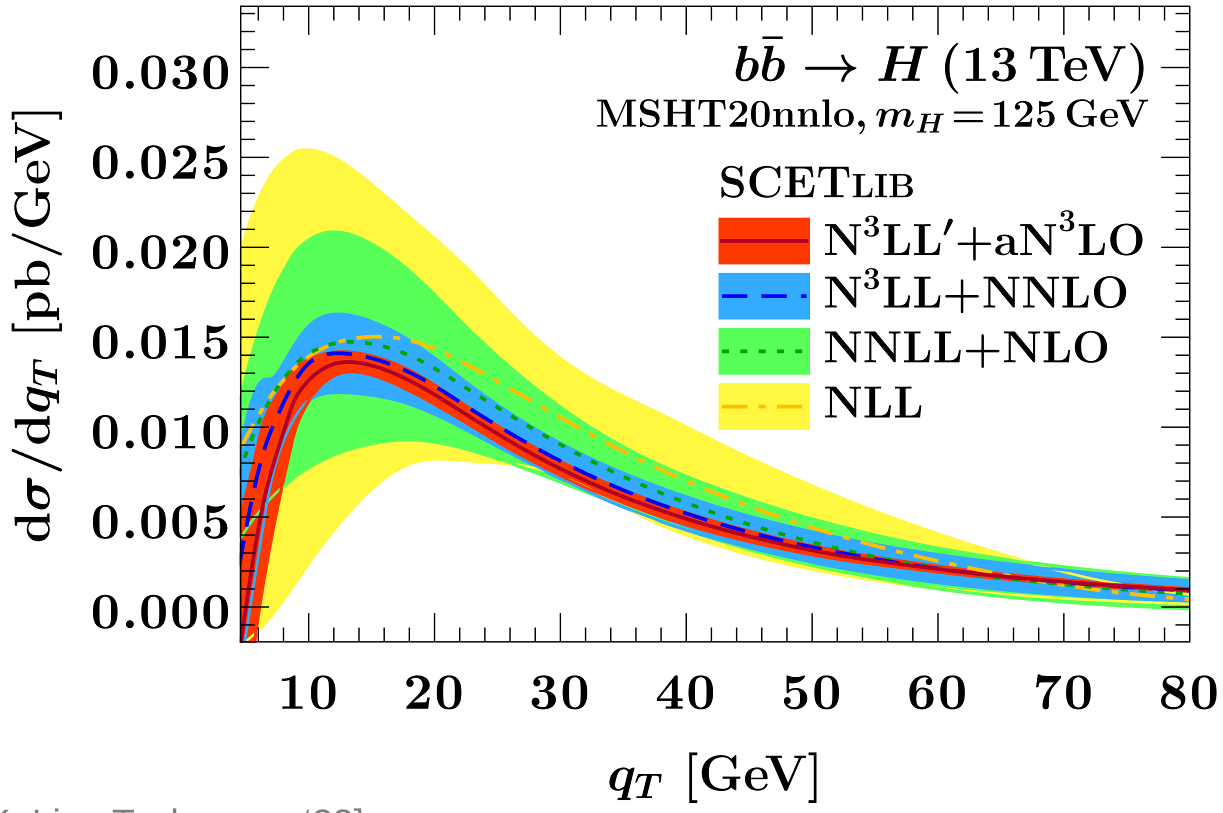
$qqH+$ jet prediction

- LO_1 analytic expression implemented in `SCETlib`
- NLO_1 implemented qqH in MC event generator `Geneva` [Alioli et al. ‘14]
  - Use OpenLoops matrix elements [Bucciconi et al. ‘19]
- aNNLO_1: approximate something that could be NNLO_1

Results.

$\mathrm{N^3LL'}$ + $\mathrm{aN^3LO}$ prediction for $\bar{q}qH$



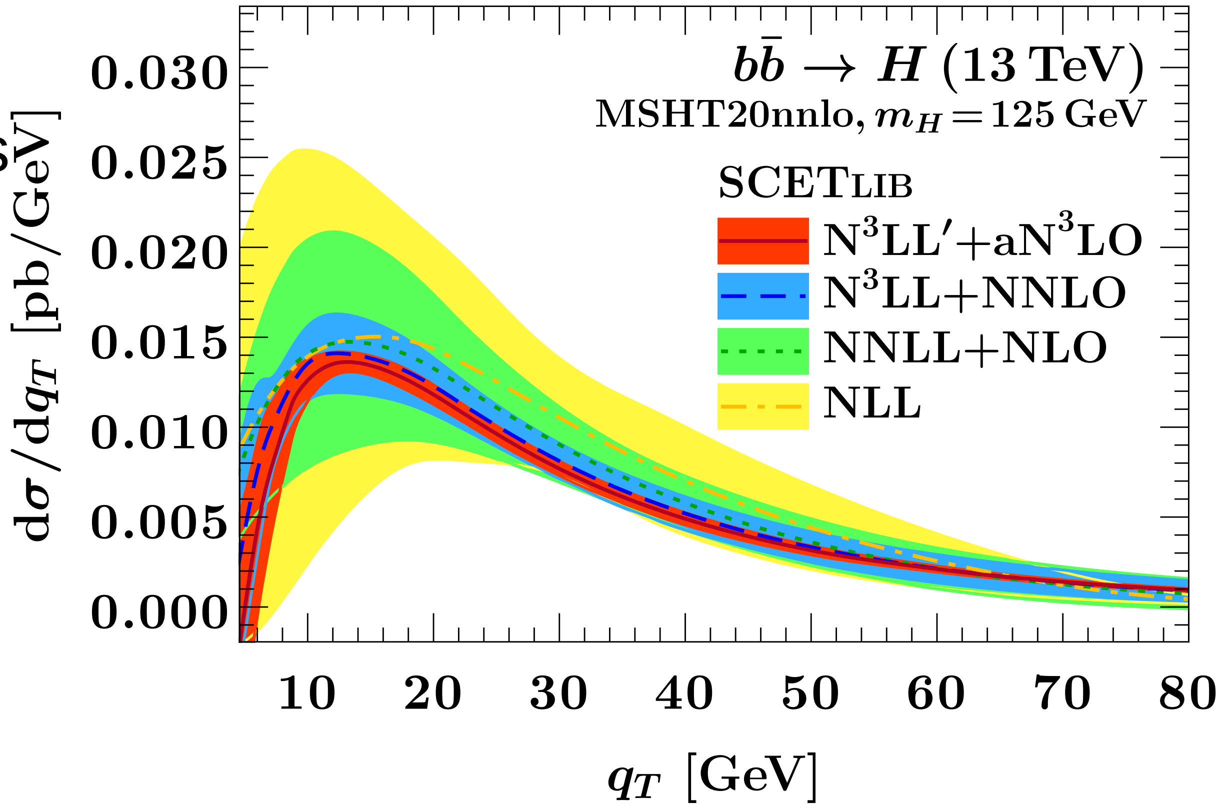


[Cal, RvK, Lim, Tackmann. ‘23]

Results.

N^{3}LL$'$ + aN^{3}LO prediction for $\bar{q}qH$

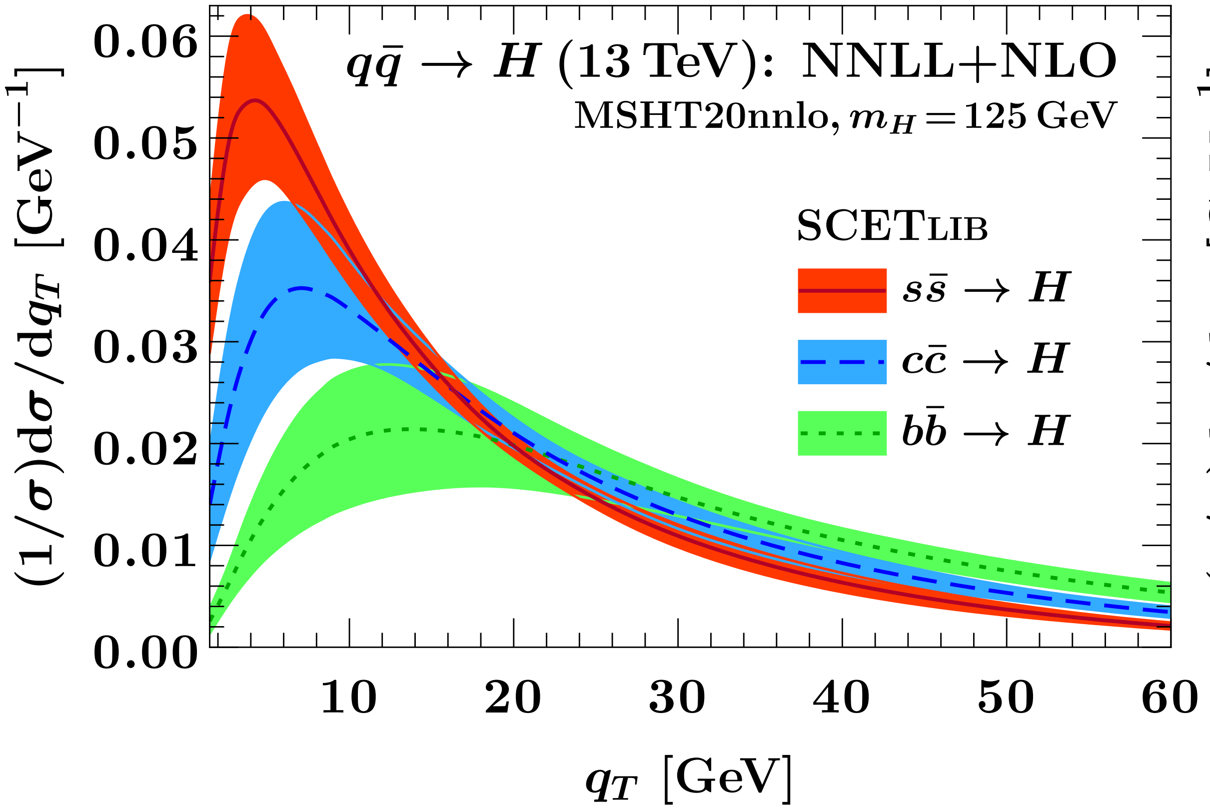
- note: plot is cut at 5 GeV
- using factorization theorem for massless quarks
  - b-quark mass effects become relevant
  - need to include mass effects!
- not an issue for c and s because they are much lighter

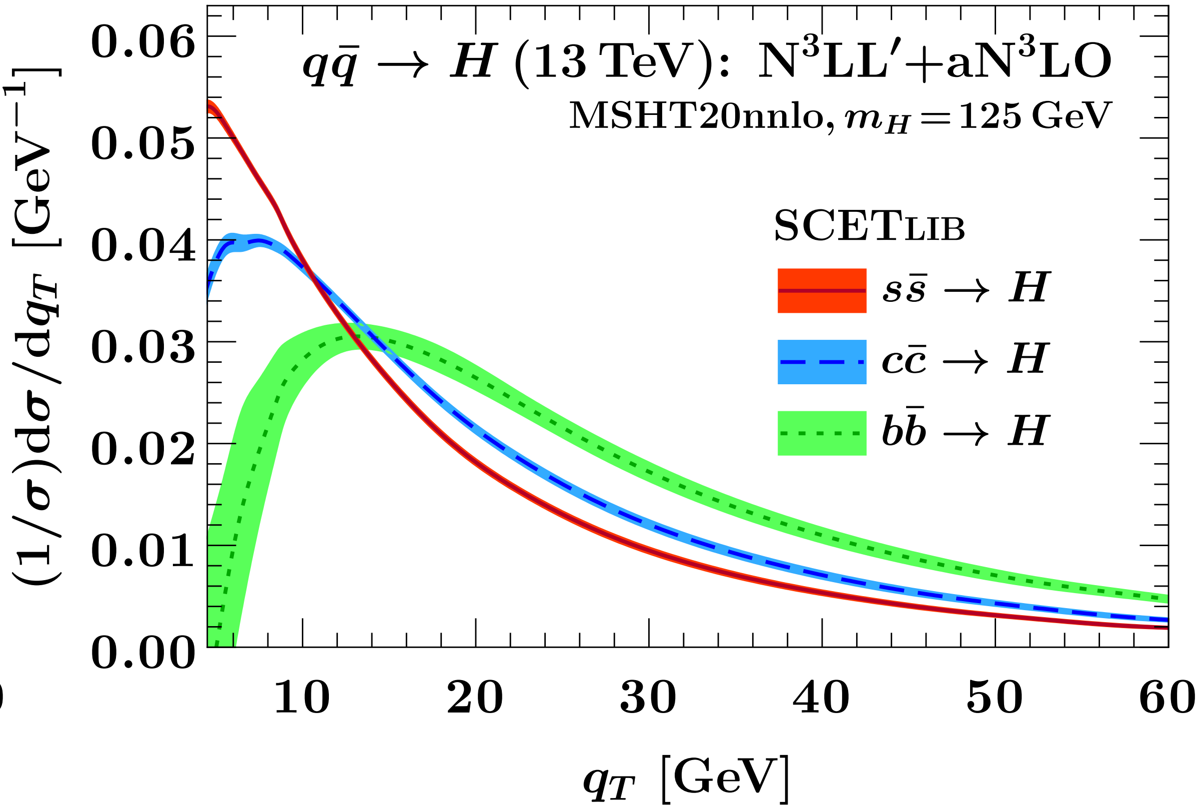


Results.

$N^3LL' +$ aN^3LO prediction for $\bar{q}qH$

[Cal, RvK, Lim, Tackmann. '23]



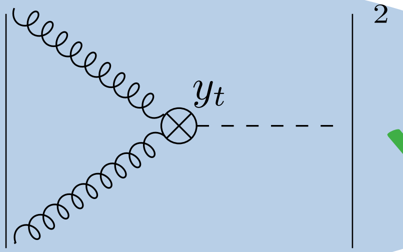


- **theory precision high enough uncertainties to allow clear distinction!**

Higgs q_T spectrum

$gg \to H$

$\mathrm{N^3LL'} + \mathrm{N^3LO}$



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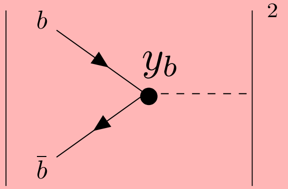
$b\bar{b} \to H$

$\mathrm{N^3LL'} + \mathrm{aN^3LO}$



Motivation.

Higgs q_T spectrum

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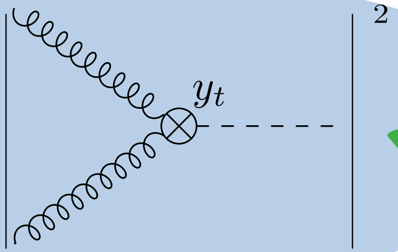
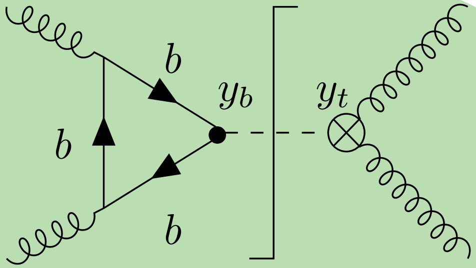
$\mathrm{N^3LL' + N^3LO}$





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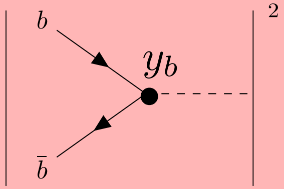

Motivation.

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$gg \to H$

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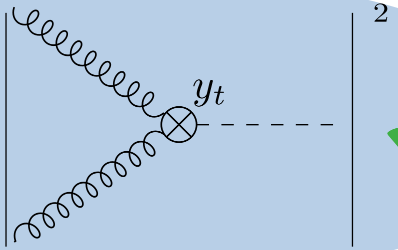
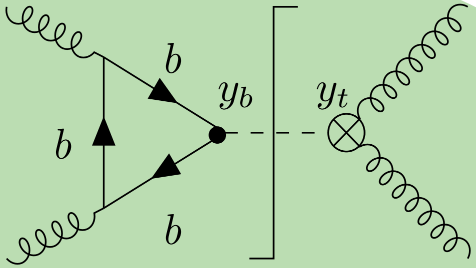
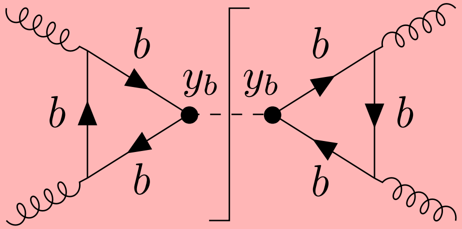


$$\frac{d\sigma(pp \to H)}{dq_T} = y_t^2 \frac{d\sigma_{tt}}{dq_T} + y_t y_b \frac{d\sigma_{tb}}{dq_T} + y_b^2 \frac{d\sigma_{bb}}{dq_T} + (y_b \to y_c)$$





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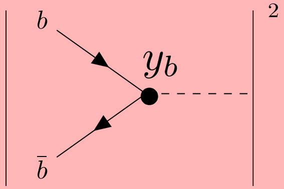
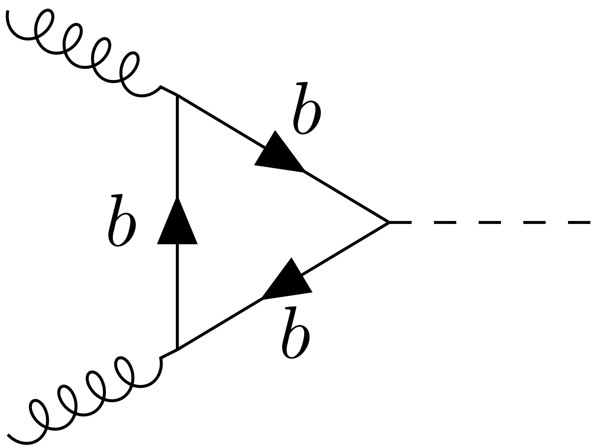


bottom-mass effects in $gg \to H$.

Motivation.

bottom mass effects in gluon fusion

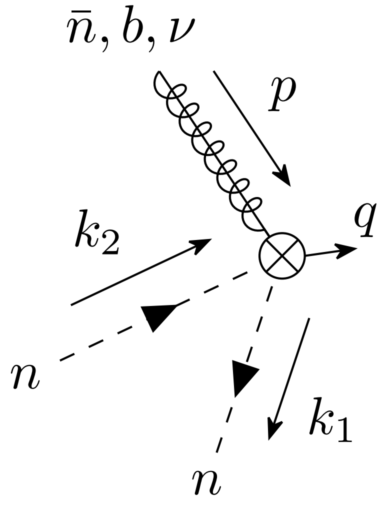
- **now:** consider $gg \to H$ with massive bottom-quark loop
- usually consider top-quark loop since $m_t \gg m_q$
- bottom loop gives $\mathcal{O}(5-10\%)$ contribution from interference with top-quark
- lighter quarks only make up for a few percent of the Higgs cross section



Notation and conventions.

Lightcone momenta

- use lightcone coordinates $p = (p^+, p^-, p_\perp)$
- power-counting: small parameter $\lambda = m_b / m_H \ll 1$
  - collinear $p^\mu \sim (\lambda^2, 1, \lambda)$
  - anti-collinear $p^\mu \sim (1, \lambda^2, \lambda)$
  - soft $p^\mu \sim (\lambda, \lambda, \lambda)$
- Higgs minus momentum $q^- = \omega_n$
- fraction of total minus momentum: $\xi = k_2^- / \omega_n$



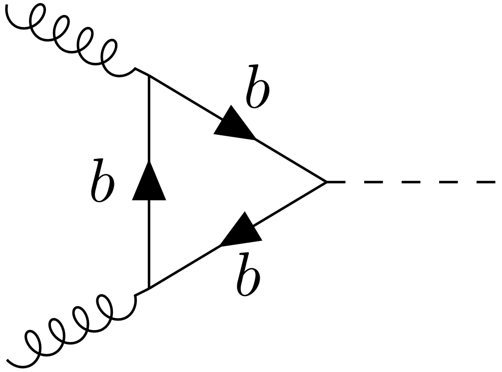
$$n^\mu = (1,0,0,1), \quad \bar{n}^\mu = (1,0,0,-1), \quad p^\mu = \frac{n^\mu}{2} p^- + \frac{\bar{n}^\mu}{2} p^+ + p_\perp^\mu, \quad p^- = \bar{n} \cdot p, \quad p^+ = n \cdot p$$

Mass effects in $gg \to H$.

so far: form factor $F(m_b, m_H)$

- subleading power factorization and resummation of form factor for $m_q \ll Q$

[Liu, Neubert '19,Liu, Mecaj, Neubert, Wang '20, Liu, Neubert, Schnubel, Wang '22]

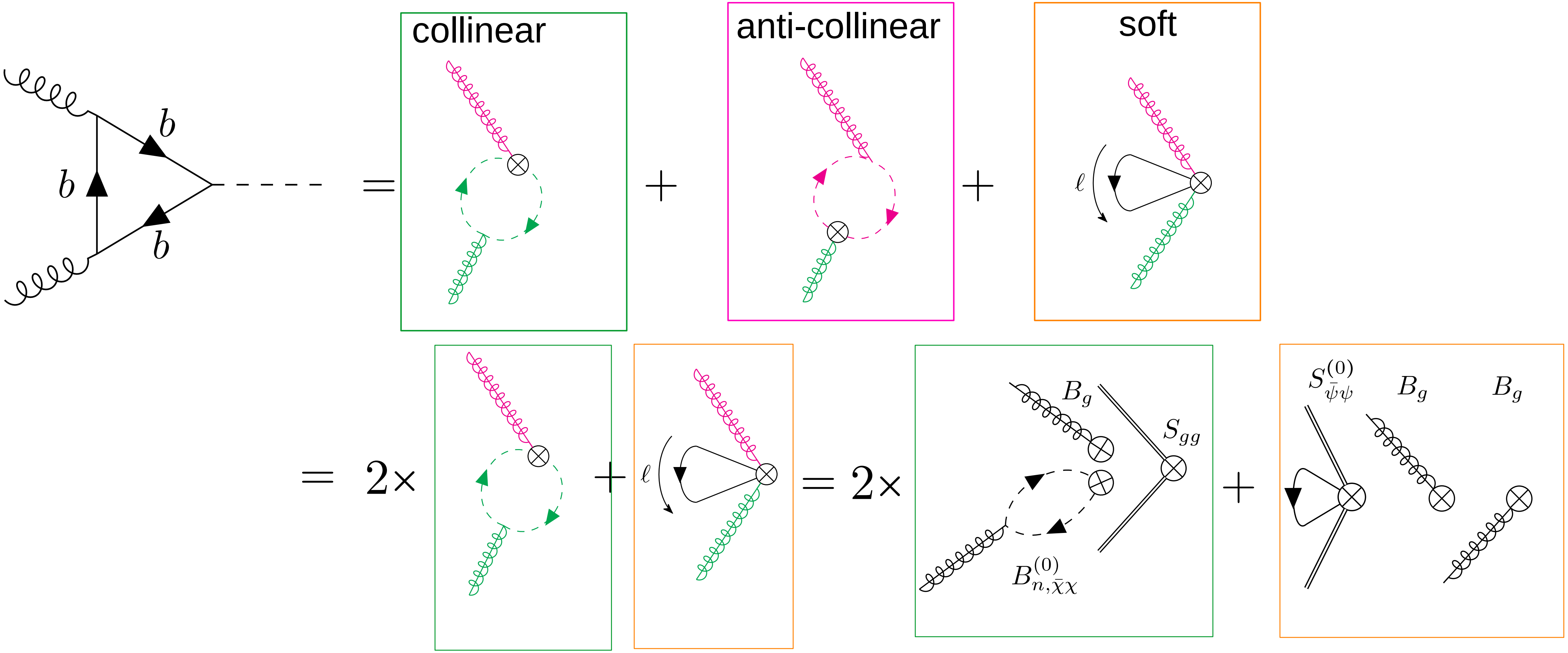


- $F(m_b, m_H)$ depends on two scales
- renormalization and treatment of endpoint divergences is active field of research

[Beneke, Ji, Wang '24]

Mass effects in $gg \to H$.

Notation LO NLP diagram

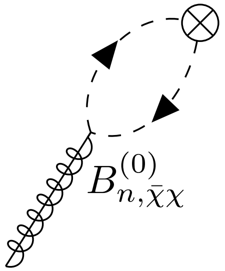


Endpoint divergences at LO.

- regulate endpoint divergences just like rapidity divergences
- example: LO NLP collinear contribution:

$$C^{(0)}_{bbg}(\xi) = \frac{1}{\xi} + \frac{1}{1-\xi}$$

$$\to \int \mathrm{d}\xi \left(\frac{1}{\xi} \left| \frac{\xi}{\nu} \right|^{-\eta} + \frac{1}{1-\xi} \left| \frac{1-\xi}{\nu} \right|^{-\eta} \right)$$



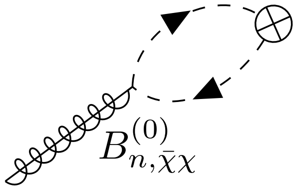
$$\propto \frac{1}{\eta} + \mathcal{O}(\eta^0)$$

- $\frac{1}{\eta}$ is **not** a rapidity divergence!
- the “true” rapidity divergence (related to q_T spectrum) comes later from the phase space integral over k!

Endpoint divergences.

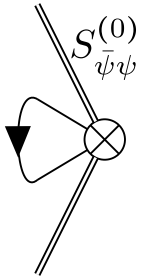
LO NLP contribution

$$\int \mathrm{d}\xi \left(\frac{1}{\xi} \left| \frac{\xi}{\nu} \right|^{-\eta} + \frac{1}{1-\xi} \left| \frac{1-\xi}{\nu} \right|^{-\eta} \right)$$



$\times 2$

$$+ \int \mathrm{d}\ell^+ \mathrm{d}\ell^- \frac{1}{\ell^+\ell^-} \left| \frac{\ell^+\ell^-}{\nu} \right|^{-\frac{\eta}{2}} \left| \sinh y_\ell \right|^{-\eta}$$



$= \mathcal{O}(\eta^0)$

- all endpoint divergences cancel between soft and collinear contributions!

Mass effects in $gg \to H$.

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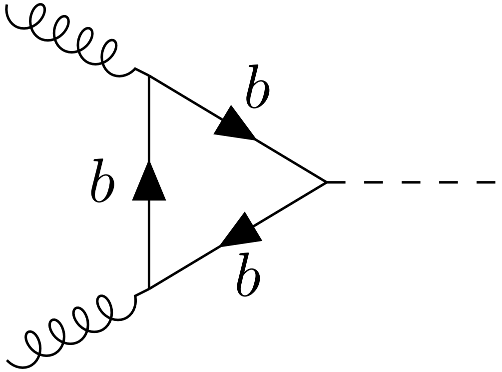

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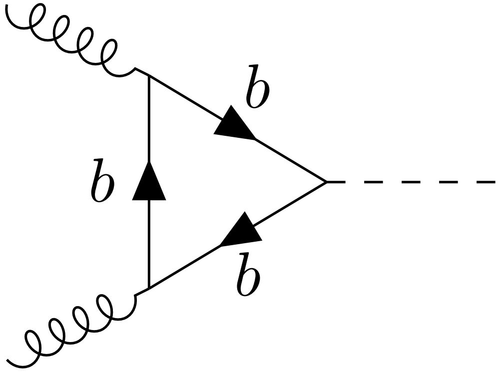

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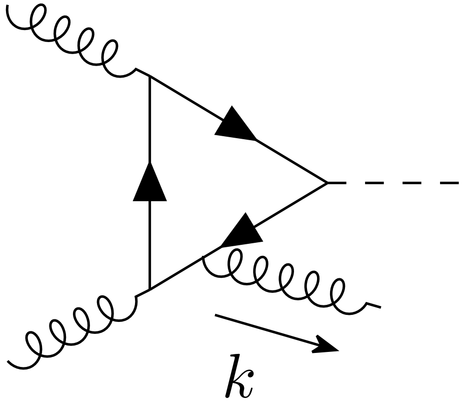
[Beneke, Ji, Wang '24]

now: q_T spectrum $d\sigma(q_T, m_b, m_H)$

- q_T measurment adds additional scale

➡ three scale problem!



- add emission $k_T \sim q_T$
- still have $m_q \ll Q$, but k_T can have different scalings

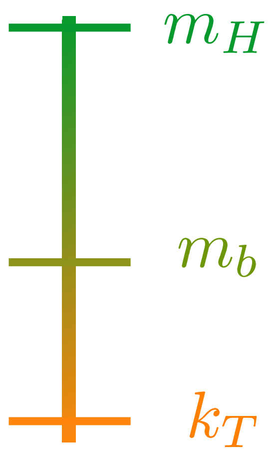
Different regimes.

consider different scalings of k_T

- emission k_T introduces additional scale to the calculation

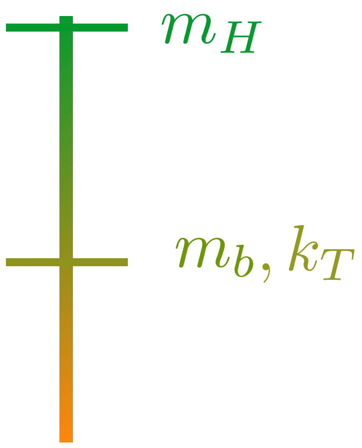
I

$$k_T \ll m_b \ll m_H$$



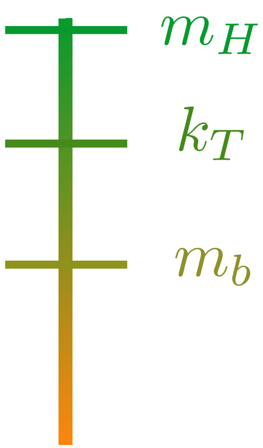
II

$$k_T \sim m_b \ll m_H$$



III

$$m_b \ll k_T \ll m_H$$



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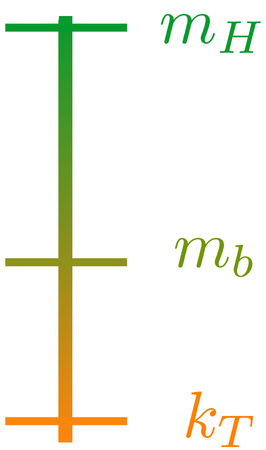

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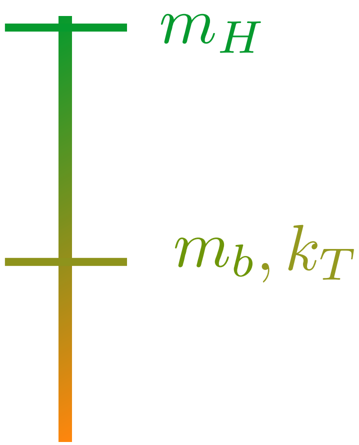


III

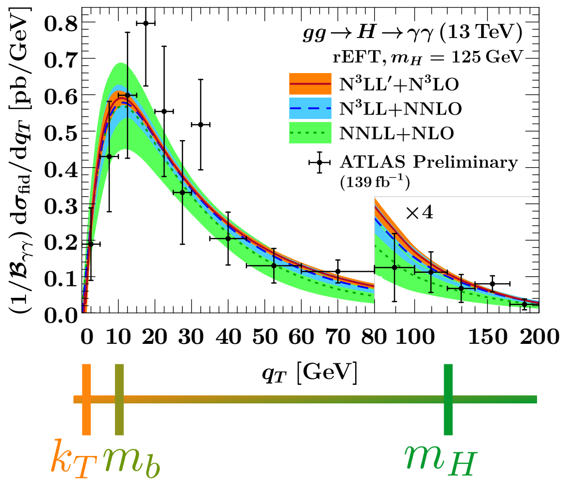
$$m_b \ll k_T \ll m_H$$

Regime I.

Factorization theorem

- only valid in a very small region of the q_T spectrum
- use standard factorization for q_T resummation with $n_f = 4$ massless flavors

$$\frac{\mathrm{d}\sigma_{y_t y_b}}{\mathrm{d}q_T} = 2\mathrm{Re}[C^*_{ggt}(m_H)\, C_{ggb}(m_b, m_H)]\, B_g(q_T) \otimes B_g(q_T) \otimes S_{gg}(q_T)$$



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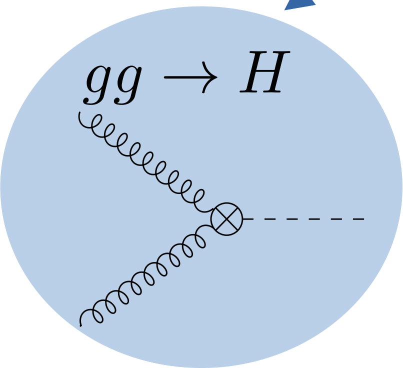

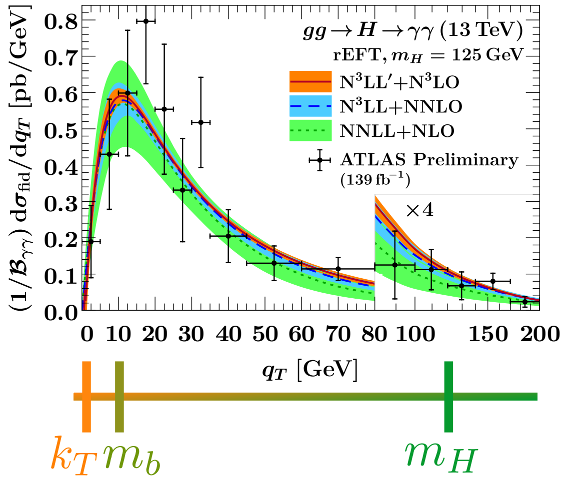

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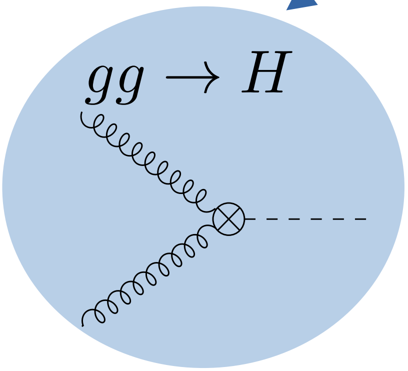

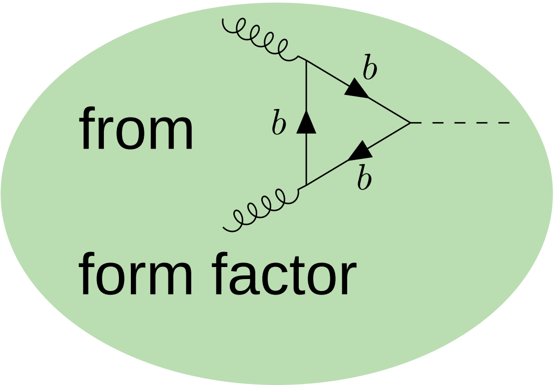

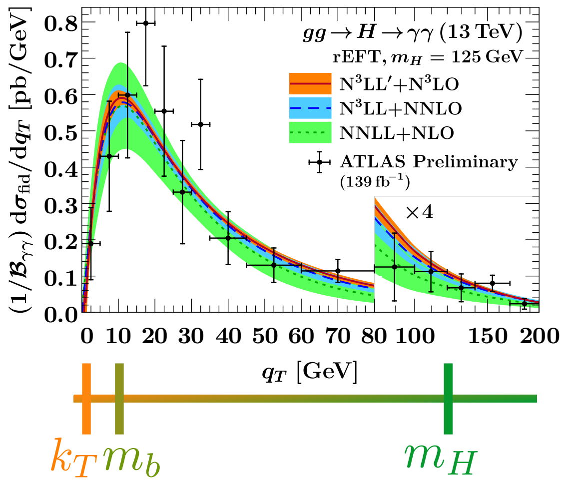

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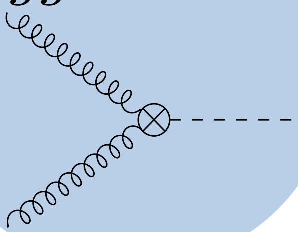
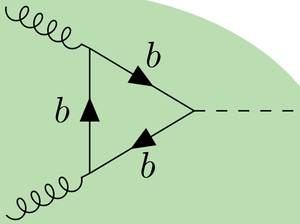
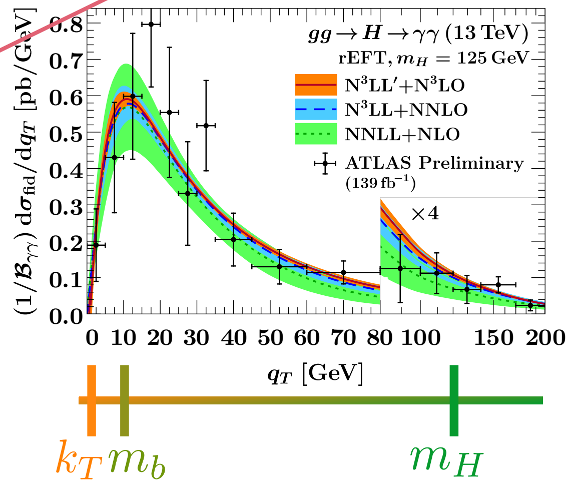
$gg \to H$



from form factor



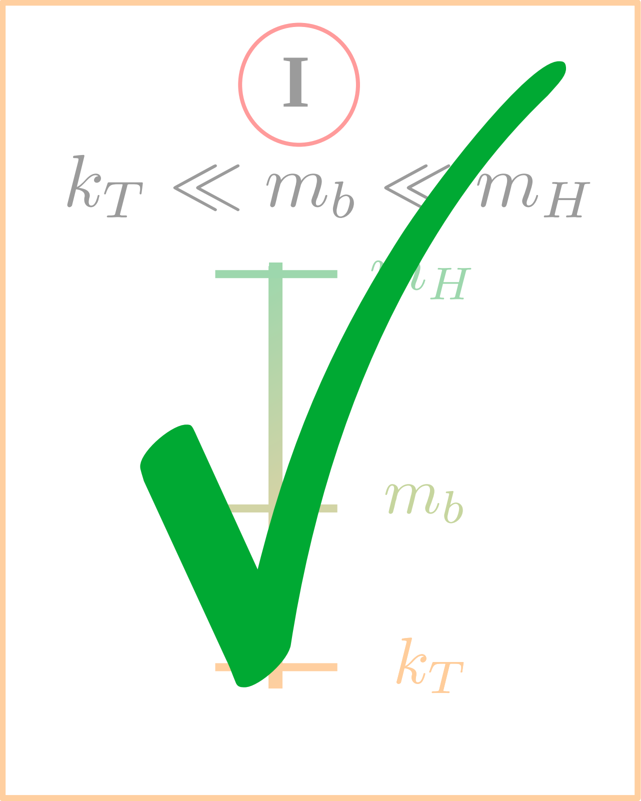
q_T resummation

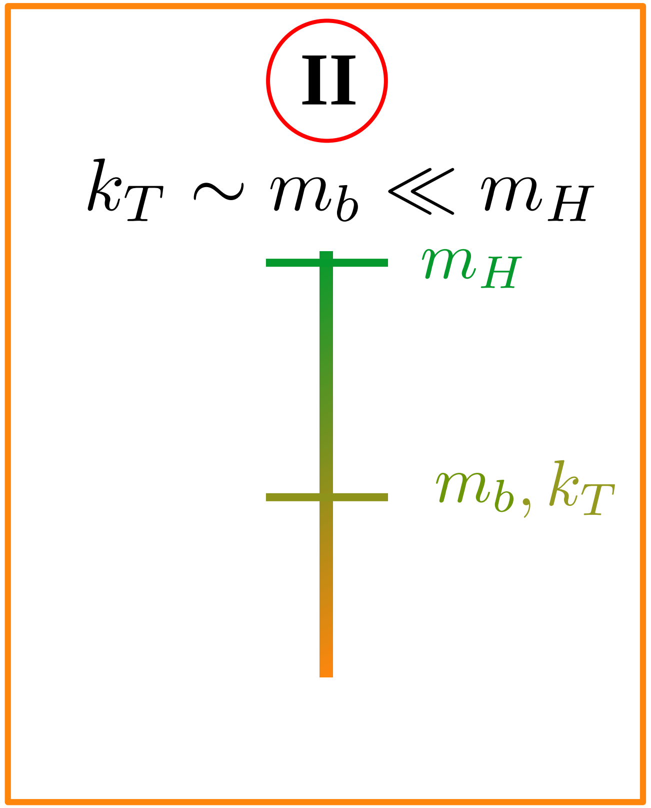


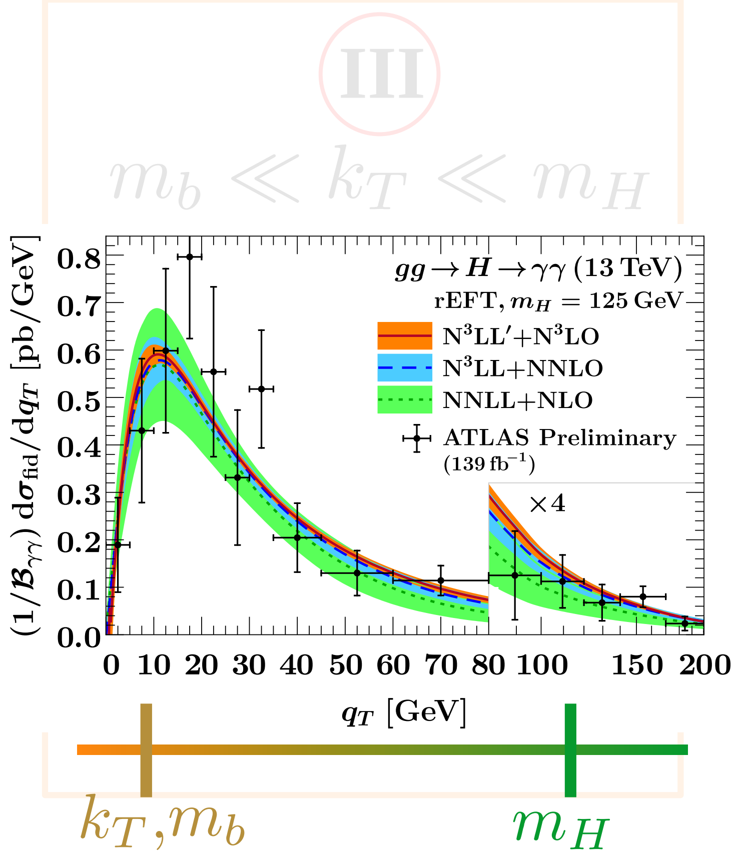
Different regimes.

Consider different scalings of k_T

- emission k_T introduces additional scale to the calculation







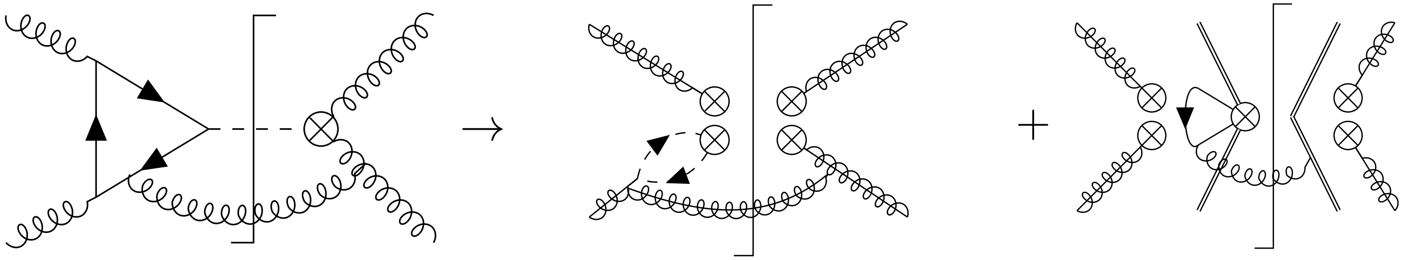
Regime II.

Bare factorization theorem $k_T \sim m_b \ll m_H$

$$\frac{\mathrm{d}\sigma_{y_t y_b}}{\mathrm{d}q_T} = H_{gg}(m)\, B_g(q_T) \otimes B_g(q_T) \otimes S_{gg}(q_T)$$

$$+ \int \mathrm{d}\xi H_{bbg}(\xi) \left[B_{n,\bar{\chi}\chi}(\xi, q_T, m) \otimes B_g(q_T) \otimes S_{gg}(q_T) + B_g(q_T) \otimes B_{\bar{n},\bar{\chi}\chi}(\xi, q_T, m) \otimes S_{gg}(q_T)\right]$$

$$+ \int \mathrm{d}\ell^+ \mathrm{d}\ell^- H_{bbgg} \mathcal{J}(\ell^+) \mathcal{J}(\ell^-)\, B_g(q_T) \otimes B_g(q_T) \otimes S_{\bar{\psi}\psi}(\ell^+, \ell^-, q_T, m)$$



operators: [M. Stahlhofen's SCET talk ' 15, Liu, Neubert '19]

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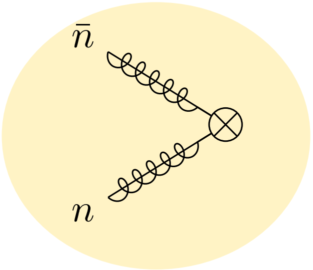
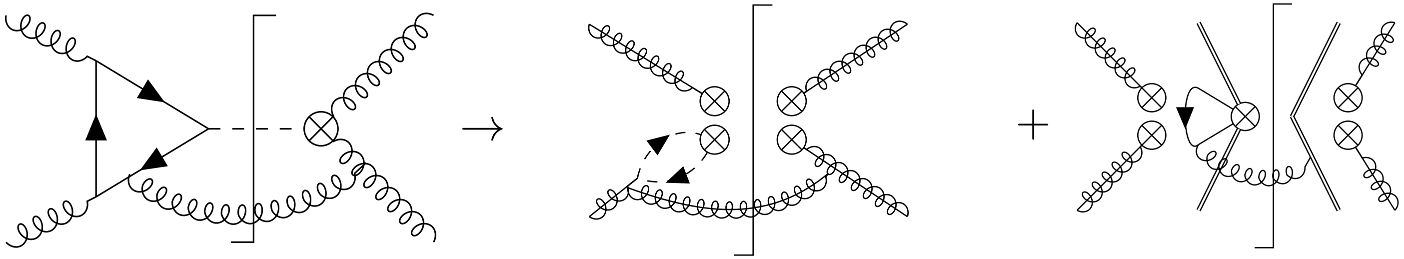


$$\frac{d\sigma_{y_t y_b}}{dq_T} = H_{gg}(m)\, B_g(q_T) \otimes B_g(q_T) \otimes S_{gg}(q_T)$$
$$+ \int d\xi H_{bbg}(\xi)\, [B_{n,\bar{\chi}\chi}(\xi, q_T, m) \otimes B_g(q_T) \otimes S_{gg}(q_T)$$
$$+ B_g(q_T) \otimes B_{\bar{n},\bar{\chi}\chi}(\xi, q_T, m) \otimes S_{gg}(q_T)]$$
$$+ \int d\ell^+ d\ell^- H_{bbgg} \mathcal{J}(\ell^+) \mathcal{J}(\ell^-)\, B_g(q_T) \otimes B_g(q_T) \otimes S_{\bar{\psi}\psi}(\ell^+, \ell^-, q_T, m)$$



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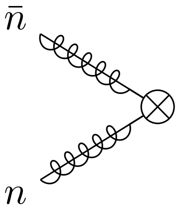

$$\frac{d\sigma_{y_t y_b}}{dq_T} = H_{gg}(m)\, B_g(q_T) \otimes B_g(q_T) \otimes S_{gg}(q_T)$$
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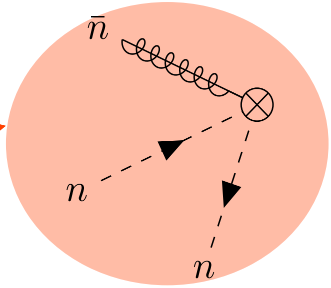

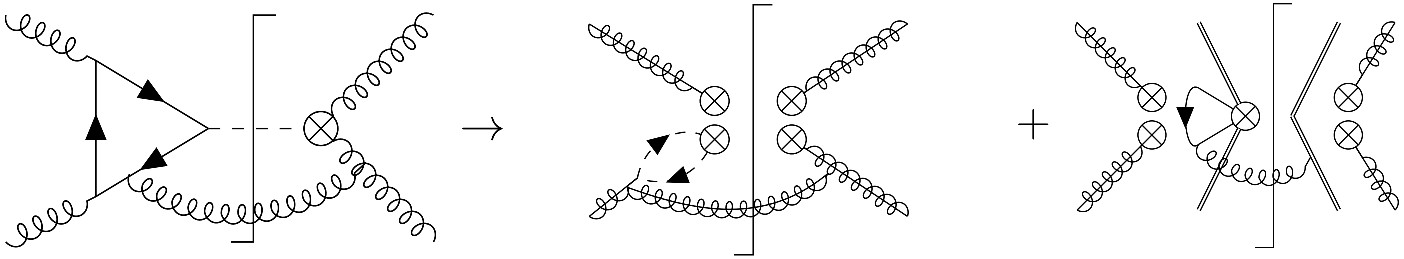

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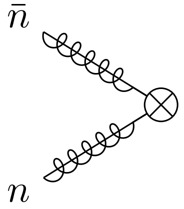
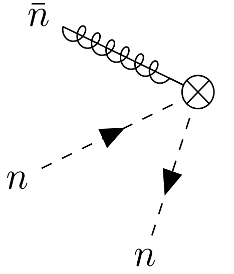
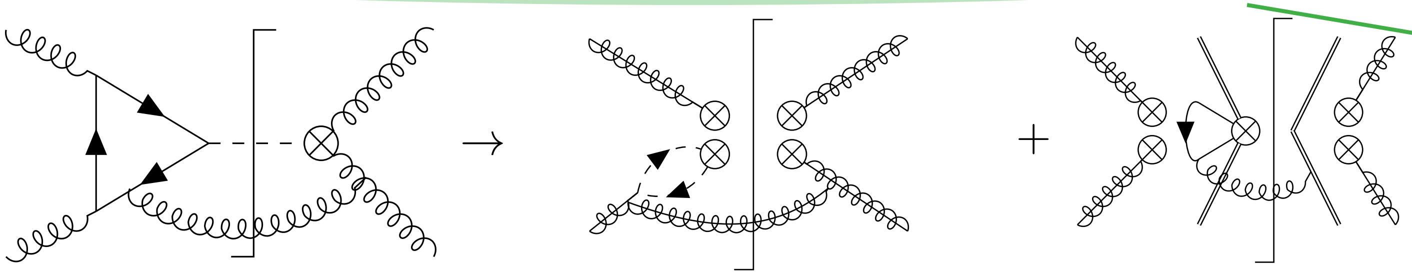
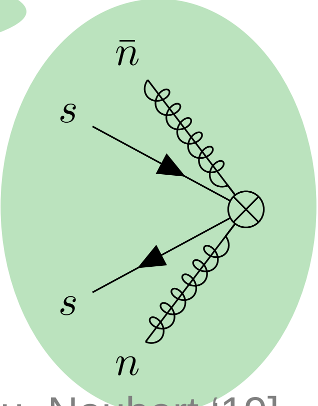


$$
\begin{aligned}
\frac{\mathrm{d}\sigma_{y_t y_b}}{\mathrm{d}q_T} &= H_{gg}(m)\, B_g(q_T) \otimes B_g(q_T) \otimes S_{gg}(q_T) \\
&+ \int \mathrm{d}\xi H_{bbg}(\xi)\, [B_{n,\bar{\chi}\chi}(\xi, q_T, m) \otimes B_g(q_T) \otimes S_{gg}(q_T) \\
&\qquad + B_g(q_T) \otimes B_{\bar{n},\bar{\chi}\chi}(\xi, q_T, m) \otimes S_{gg}(q_T)] \\
&+ \int \mathrm{d}\ell^+ \mathrm{d}\ell^- H_{bbgg} \mathcal{J}(\ell^+) \mathcal{J}(\ell^-)\, B_g(q_T) \otimes B_g(q_T) \otimes S_{\bar{\psi}\psi}(\ell^+, \ell^-, q_T, m)
\end{aligned}
$$







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$$+ B_g(q_T) \otimes B_{\bar{n},\bar{\chi}\chi}(\xi, q_T, m) \otimes S_{gg}(q_T)\big]$$
$$+ \int \mathrm{d}\ell^+ \mathrm{d}\ell^-\, H_{bbgg}\, \mathcal{J}(\ell^+) \mathcal{J}(\ell^-)\, B_g(q_T) \otimes B_g(q_T) \otimes S_{\bar{\psi}\psi}(\ell^+, \ell^-, q_T, m)$$

$$\frac{1}{\xi} + \frac{1}{1-\xi}$$

$$\frac{1}{\ell^+ \ell^-}$$

lead to endpoint divergences! (just as for form factor)

operators: [M. Stahlhofen's SCET talk ' 15, Liu, Neubert '19]

Endpoint divergences.

- expect endpoint divergences in soft and collinear contribution
- form factor $F(m_b, m_H)$ depends on two scales
- the spectrum introduces an additional scale k_T

$$\frac{1}{\xi} f_n\left(\frac{m}{k_T}\right) \longleftrightarrow \frac{1}{\ell^+\ell^-} f_s\left(\frac{m}{k_T}\right)$$

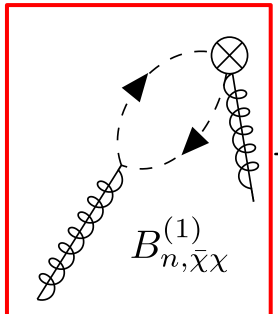
- **how does the additional scale affect the structure of the endpoint divergences?**
- in general $f_n(m/k_T)$ and $f_s(m/k_T)$ can be non-trivial functions of m/k_T

Endpoint divergences.

collinear NLP one-gluon contribution

- Now: add emission k_T to contribution from collinear loop

$$\int \mathrm{d}\xi \left(\frac{1}{\xi}\left|\frac{\xi}{\nu}\right|^{-\eta} + \frac{1}{1-\xi}\left|\frac{1-\xi}{\nu}\right|^{-\eta}\right)\Bigg(\ \ \Bigg)$$



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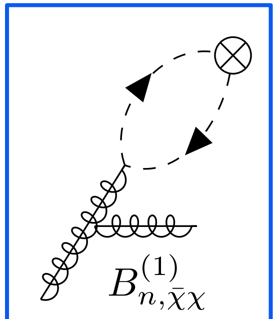

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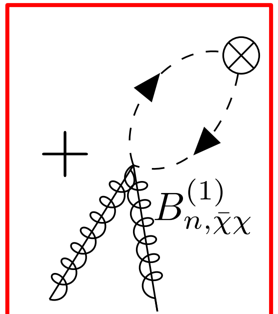

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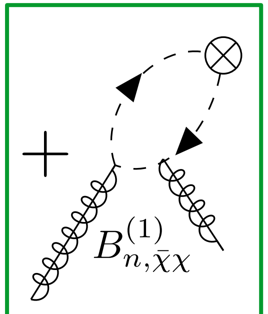

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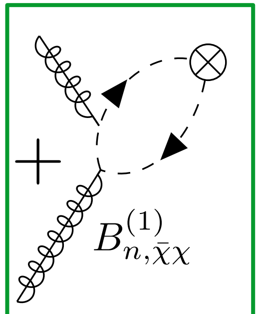


$$= -\frac{A(k^-)}{4\eta\epsilon} - \frac{B(k^-)}{2\eta\epsilon} - \frac{A(k^-)}{4\eta\epsilon} \underbrace{- \frac{C(k^-)}{2\eta\epsilon} + \frac{C(k^-)}{2\eta\epsilon}}_{=\,\mathcal{O}(\eta^0)}$$

$$= -\frac{A(k^-)}{2\eta\epsilon} - \frac{B(k^-)}{2\eta\epsilon}$$

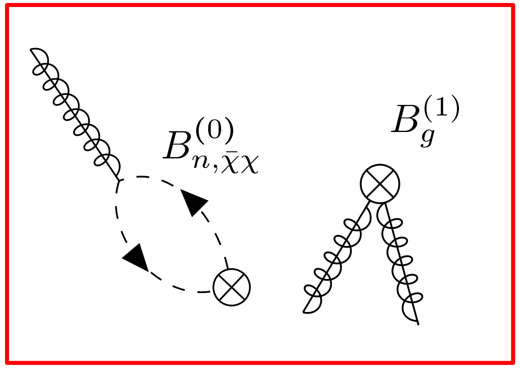
- endpoint divergences partially cancel within the beam function but there are left-over poles

Endpoint divergences.

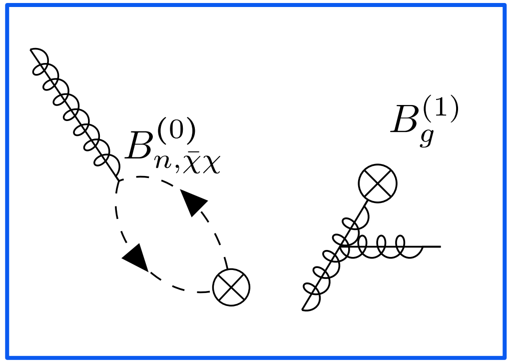
collinear LP one-gluon contribution

- contribution from anti-collinear loop can have LP gluon emission

$$\int \mathrm{d}\xi \left(\frac{1}{\xi} \left| \frac{\xi}{\nu} \right|^{-\eta} + \frac{1}{1-\xi} \left| \frac{1-\xi}{\nu} \right|^{-\eta} \right) \Bigg($$



$$+$$



$$\Bigg)$$

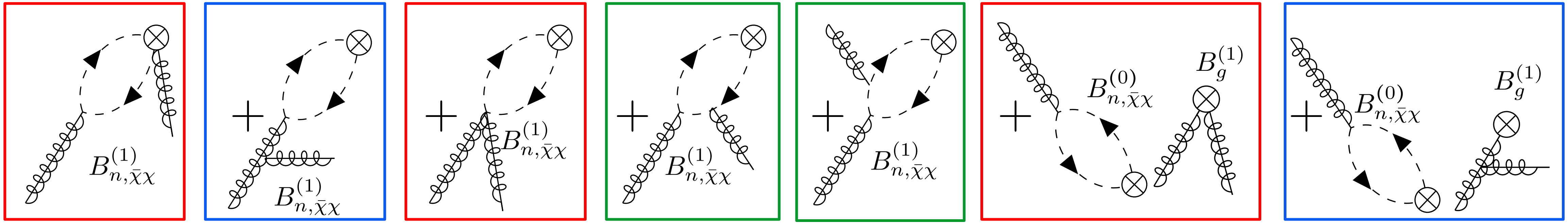
$$= -\frac{A(k^-)}{2\eta\epsilon} - \frac{B(k^-)}{2\eta\epsilon}$$

- endpoint divergences have the same sign as NLP collinear emission

Endpoint divergences.

collinear NLP and LP emissions

$\int \mathrm{d}\xi \Big($



$\Big)$

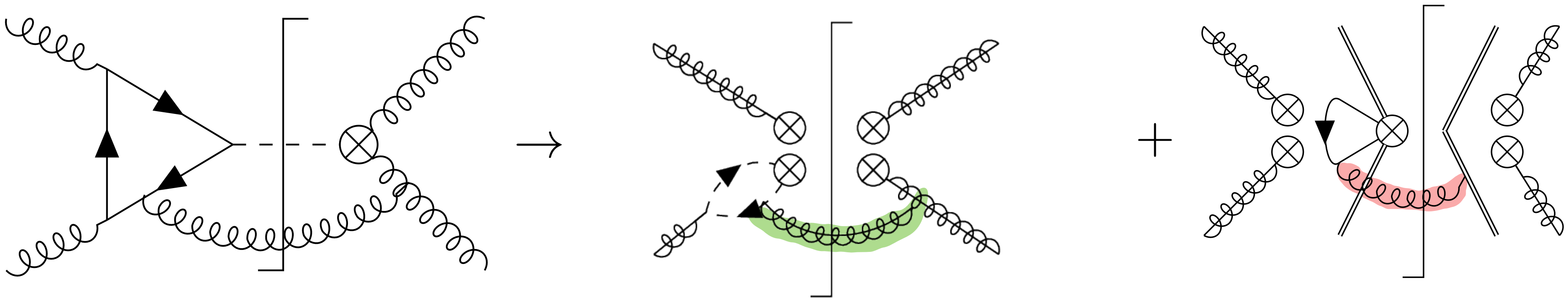
$$= -\frac{A(k^-)}{\eta\epsilon} - \frac{B(k^-)}{\eta\epsilon}$$

- **uncanceled endpoint divergences for collinear and anti-collinear loops!**

Emission k_T.

soft vs. collinear emission

- emitted gluon can be soft or collinear
- endpoint divergences **have to cancel** within the same sector
- consider both sectors separately

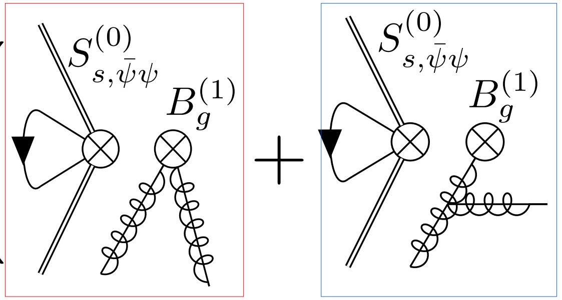


Endpoint divergences.

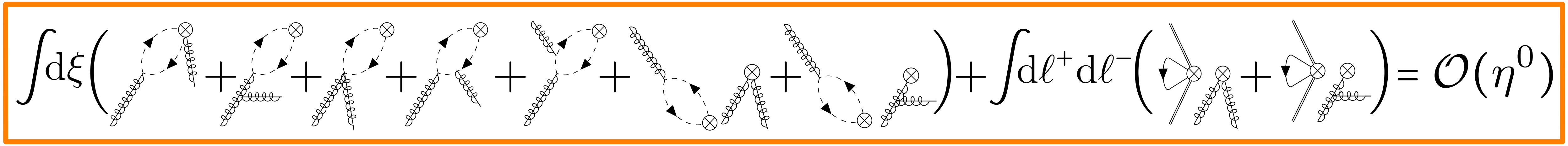
collinear emission

- has to be canceled by collinear LP emission and soft LO NLP!

$$\int \mathrm{d}\ell^+ \mathrm{d}\ell^- \left|\frac{\ell^+\ell^-}{\nu}\right|^{-\frac{\eta}{2}} |\sinh y_\ell|^{-\eta} \Big(\ldots \Big) = +\frac{A(k^-)}{\eta\epsilon} + \frac{B(k^-)}{\eta\epsilon}$$



- endpoint divergences cancel between diagrams with collinear emission!



- **divergences cancel against LP collinear emission!**
- **mass and k_T dependence are factorized!**

Endpoint divergences.

soft emission

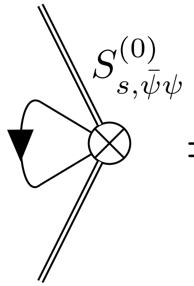
- sum of diagrams with collinear emission is finite

→ **sum of diagrams with soft emission has to be finite as well!**

→ free to choose regulator to regulate endpoint divergences in this subset of diagrams!

- LO NLP example for pure rapidity regulator [Ebert, Moult, Stewart,Tackmann, Vita, Zhu ‘18]

$$\int \mathrm{d}\ell^+ \mathrm{d}\ell^- \left(\frac{\ell^+}{\ell^-}\right)^{-\eta}$$



$$= 0$$

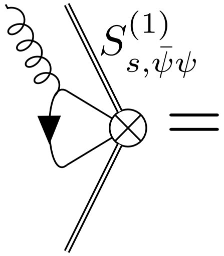
(scaleless)

Endpoint divergences.

soft emission

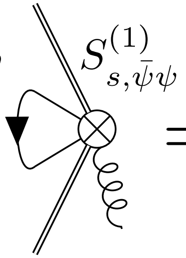
- use the pure rapidity regulator for NLP soft diagram

$$\int \mathrm{d}\ell^+ \mathrm{d}\ell^- \left(\frac{\ell^+}{\ell^-}\right)^{-\eta}$$



$$= \mathcal{O}(\eta^0)$$

$$\int \mathrm{d}\ell^+ \mathrm{d}\ell^- \left(\frac{\ell^+}{\ell^-}\right)^{-\eta}$$



$$= \mathcal{O}(\eta^0)$$

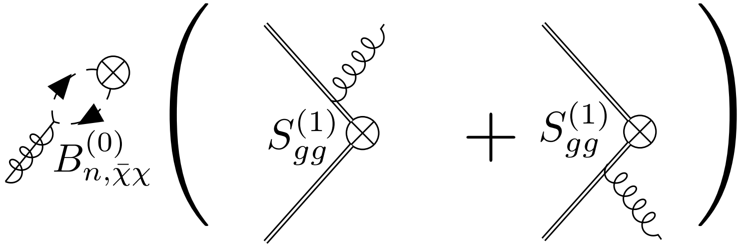
- **both contributions are individually finite!**

Endpoint divergences.

soft emission

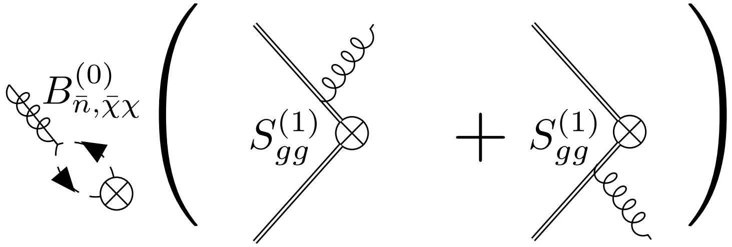
- what about the collinear LO NLP $\times$ soft LP emission?

$$\int \mathrm{d}\xi \left(\frac{1}{\xi} + \frac{1}{1-\xi}\right) \xi^{-\eta}(1-\xi)^{-\eta}$$



$$= \frac{D(k^-)}{\eta}$$

$$\int \mathrm{d}\xi \left(\frac{1}{\xi} + \frac{1}{1-\xi}\right) \xi^{-\eta}(1-\xi)^{-\eta}$$

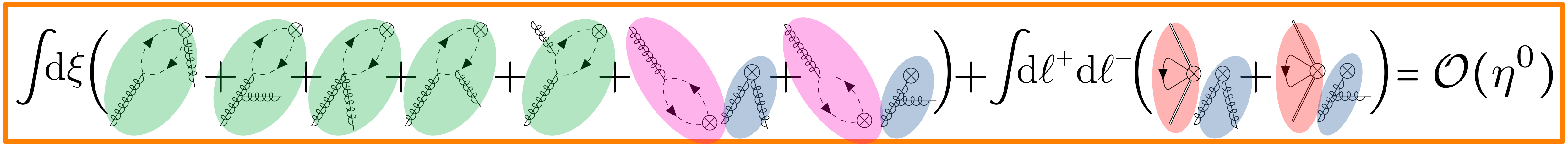


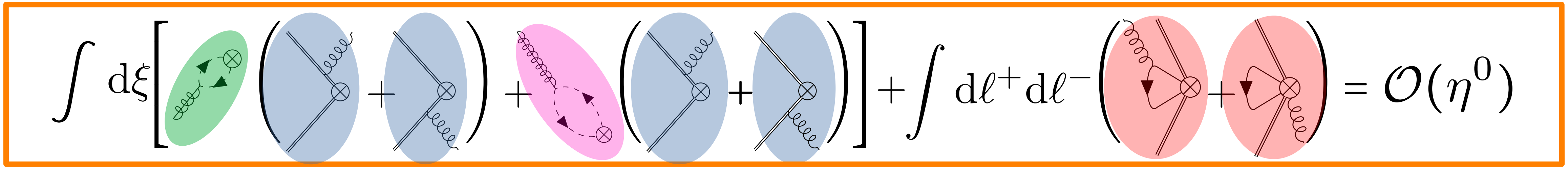
$$= -\frac{D(k^-)}{\eta}$$

- **endpoint divergences from n- and $\bar{n}$- collinear sector cancel!**

Endpoint divergences.

Summary





- **all endpoint divergences cancel!**
- m **and** k_T **dependence factorizes!**

Mass effects in ggH.

Next steps

- endpoint divergences cancel ✓
- calculate finite parts of the integrals ✓
- compare against full QCD amplitude in respective limit [Bauer, Glover 1989]
- phase space integral over emission k
- write paper!

Outlook and summary.

Outlook.

Yukawa fits

- include finite mass effects for qqH
- combine qqH and bottom-mass effects in gluon fusion

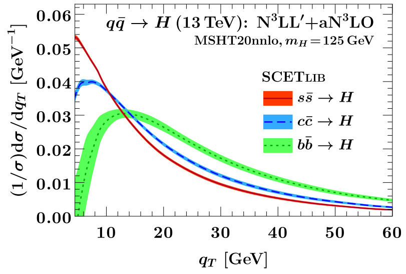
$$\frac{\mathrm{d}\sigma(pp \to H)}{\mathrm{d}q_T} = y_t^2 \frac{\mathrm{d}\sigma_{tt}}{\mathrm{d}q_T} \checkmark + y_t y_b \frac{\mathrm{d}\sigma_{tb}}{\mathrm{d}q_T} \checkmark + y_b^2 \frac{\mathrm{d}\sigma_{bb}}{\mathrm{d}q_T} \checkmark + (y_b \to y_c)$$

- fit the bottom and charm Yukawa couplings from Higgs production!

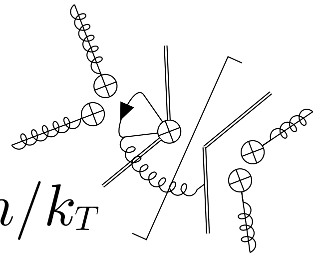
Summary.

$N^3LL' + aN^3LO$ prediction for qqH

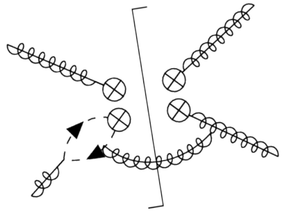
- new prediction for quark initiated Higgs production
- at $N^3LL' + aN^3LO$: uncertainties no longer overlap!



m_b effects in gluon fusion



- the emission k_T adds an extra scale to the problem
- coefficient functions of endpoint divergences could be non- trivial functions of m/k_T
- m and k_T dependence factorizes!
- endpoint divergences from soft and collinear emissions cancel separately



Outlook

- put everything together and fit the Yukawa coupling

Thank you!

Acknowledgments.

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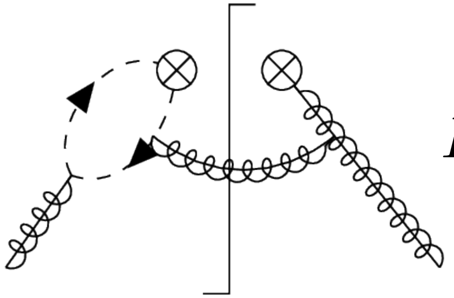
Back up.

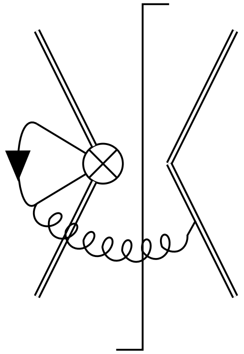
Matrix element definition.

Beam function



$$B_{n,\chi\bar{\chi}}\left(x = \frac{\omega}{P_N^-}\right) = \sum\!\!\!\!\!\!\!\int \langle N|\,\mathcal{B}_\perp^{a,\mu}\,\delta^2(k_\perp - P_{X,\perp})\,|X\rangle\langle X|\,\bar{\chi}_{n,\omega z}T^a\gamma_{\perp\mu}\chi_{n,\omega(1-z)}\,|N\rangle$$

Soft function



$$\mathcal{O}^{ab}_{S,\bar{\psi}\psi}(\ell^+\ell^-) = \frac{1}{\ell^+\ell^-}[\bar{\psi}S_n\delta(\ell^+ - n\cdot\mathcal{P}])[\gamma_{\perp,\mu}T^a\frac{\bar{\not{n}}\not{n}}{4}S_n^\dagger S_{\bar{n}}\gamma_\perp^\mu T^b][S_{\bar{n}}^\dagger\psi\delta(\ell^- - \bar{n}\cdot\mathcal{P}])$$

$$S_{\bar{\psi}\psi}(\ell^+, \ell^-, k_T, m) = \sum\!\!\!\!\!\!\!\int \frac{1}{N_c^2 - 1}\langle 0|\,\mathcal{O}_s^{(0)\,ab}\,\delta^2(k_\perp - P_{X,\perp})\,|X\rangle\langle X|\,\mathcal{O}^{ba}_{s,\bar{\psi}\psi}\,|0\rangle$$