Mass effects in the Higgs q_T spectrum

Rebecca von Kuk

DESY

SCET workshop 2024 Salamanca

Based on work with Johannes Michel, Iain Stewart, Zhiquan Sun and Frank Tackmann

HELMHOLTZ

European Research Council

Established by the European Commission

Outline.

Introduction

- motivation: measurement of the quark Yukawa coupling
- state of the literature

Results

- review of different hierarchies for k_T, m_b and m_H
- endpoint divergences for soft and collinear emissions

Summary

Introduction.

Motivation.

Higgs q_T spectrum

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

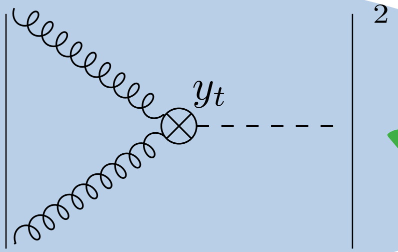
Motivation.

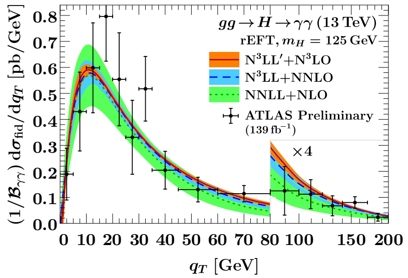
Higgs q_T spectrum

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

$gg \to H$

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





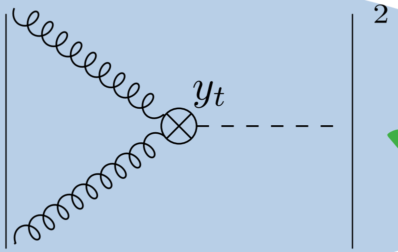
$$\frac{\mathrm{d}\sigma(pp \to H)}{\mathrm{d}q_T} = y_t^2 \frac{\mathrm{d}\sigma_{tt}}{\mathrm{d}q_T} + y_t y_b \frac{\mathrm{d}\sigma_{tb}}{\mathrm{d}q_T} + y_b^2 \frac{\mathrm{d}\sigma_{bb}}{\mathrm{d}q_T} + (y_b \to y_c)$$

Motivation.

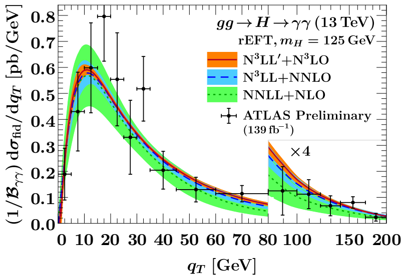
Higgs q_T spectrum

$gg \to H$

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



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

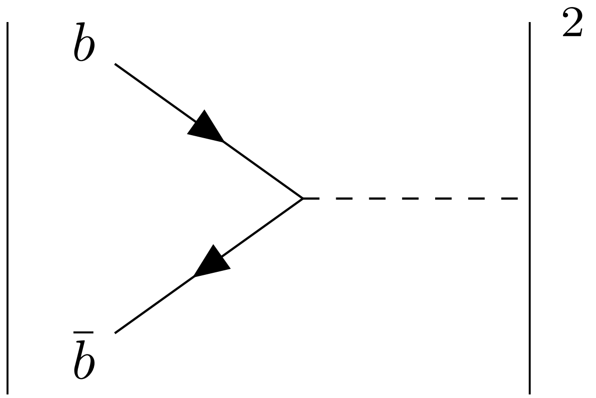


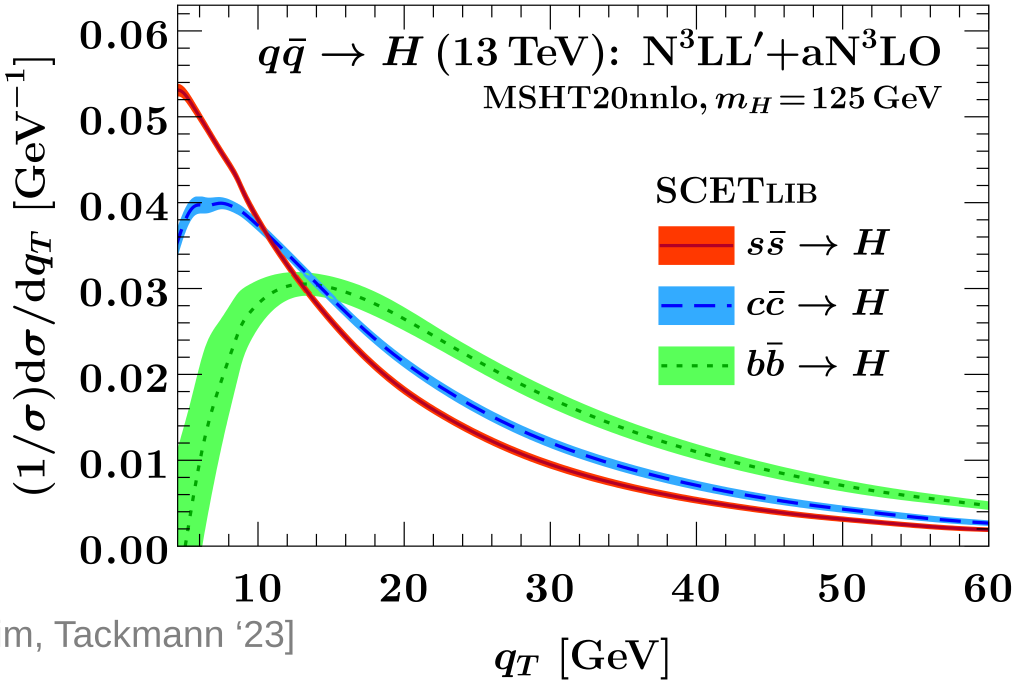
$$\boxed{\frac{\mathrm{d}\sigma(pp \to H)}{\mathrm{d}q_T} = y_t^2 \frac{\mathrm{d}\sigma_{tt}}{\mathrm{d}q_T} + y_t y_b \frac{\mathrm{d}\sigma_{tb}}{\mathrm{d}q_T} + y_b^2 \frac{\mathrm{d}\sigma_{bb}}{\mathrm{d}q_T} + (y_b \to y_c)}$$

Motivation.

measurement of y_b

- last year: q_T spectrum for $q\bar{q} \to H$ at N³LL'+aN³LO
- at sufficiently high order: can resolve initial state quarks
- disadvantage: $q\bar{q} \to H$ minor contribution to Higgs production





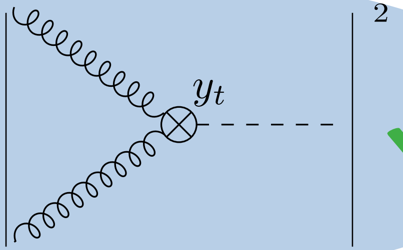
[Cal, RvK, Lim, Tackmann ‘23]

Motivation.

Higgs q_T spectrum

$gg \to H$

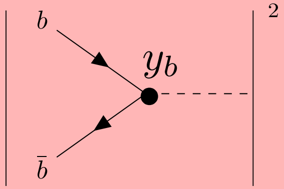
$\mathrm{N^3LL'} + \mathrm{N^3LO}$



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

$b\bar{b} \to H$

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

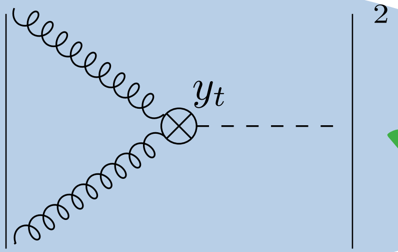


Motivation.

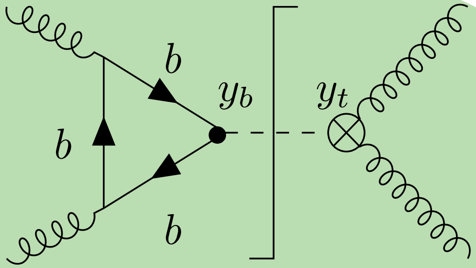
Higgs q_T spectrum

$gg \to H$

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

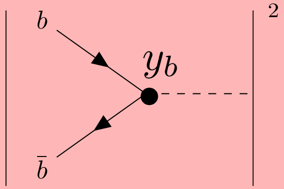


$$\frac{\mathrm{d}\sigma(pp \to H)}{\mathrm{d}q_T} = y_t^2 \frac{\mathrm{d}\sigma_{tt}}{\mathrm{d}q_T} + y_t y_b \frac{\mathrm{d}\sigma_{tb}}{\mathrm{d}q_T} + y_b^2 \frac{\mathrm{d}\sigma_{bb}}{\mathrm{d}q_T} + (y_b \to y_c)$$



$b\bar{b} \to H$

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

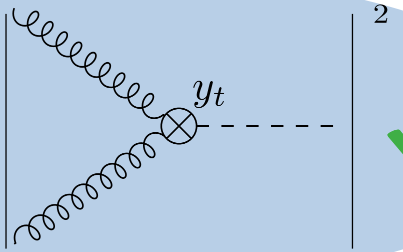


Motivation.

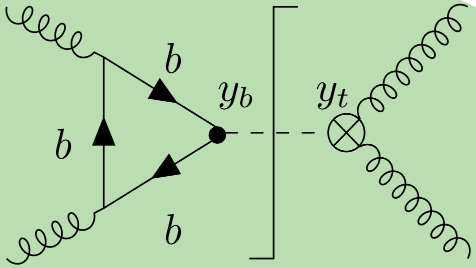
Higgs q_T spectrum

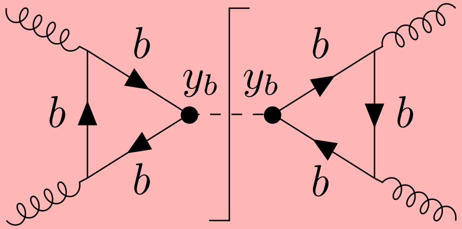
$gg \to H$

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



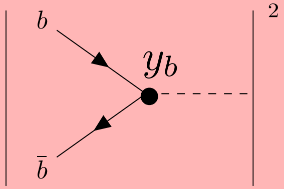
$$\frac{\mathrm{d}\sigma(pp \to H)}{\mathrm{d}q_T} = y_t^2 \frac{\mathrm{d}\sigma_{tt}}{\mathrm{d}q_T} + y_t y_b \frac{\mathrm{d}\sigma_{tb}}{\mathrm{d}q_T} + y_b^2 \frac{\mathrm{d}\sigma_{bb}}{\mathrm{d}q_T} + (y_b \to y_c)$$





$b\bar{b} \to H$

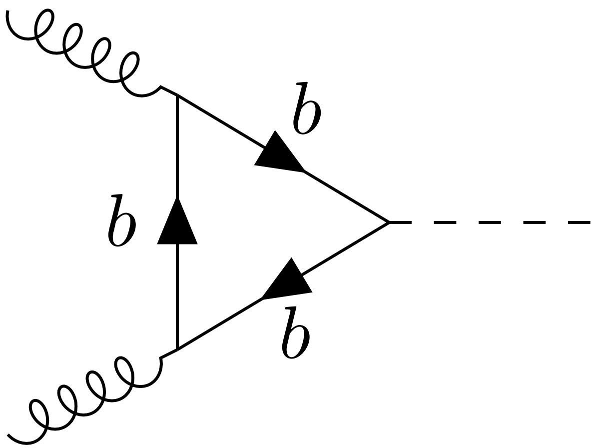
$\mathrm{N^3LL' + aN^3LO}$



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

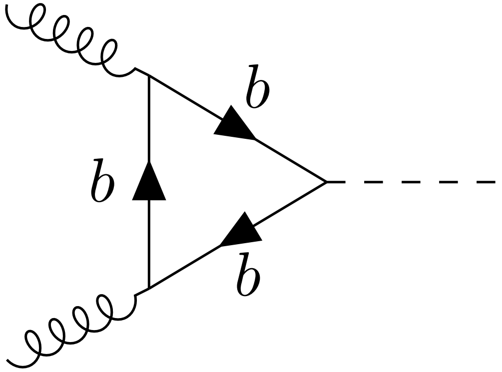


Mass effects in $gg \to H$.

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

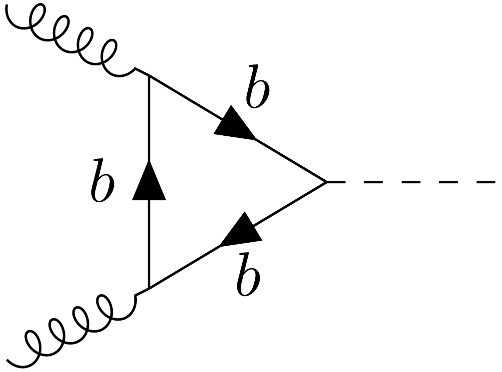
[Beneke, Ji, Wang '24, see also M. Beneke's talk]

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]



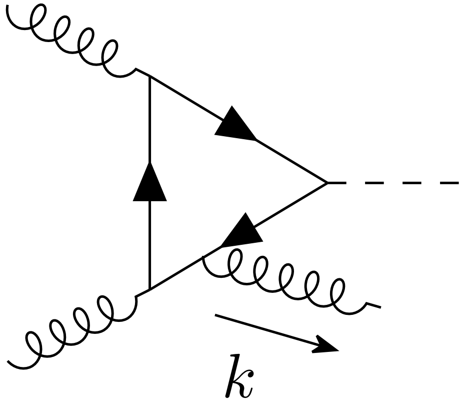
- $F(m_b, m_H)$ depends on two scales
- renormalization and treatment of endpoint divergences is active field of research

[Beneke, Ji, Wang '24, see also M. Beneke's talk]

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

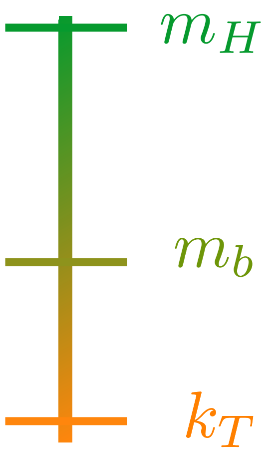
q_T spectrum for $gg \to H$

consider different scalings of k_T

- emission k_T introduces additional scale to the calculation

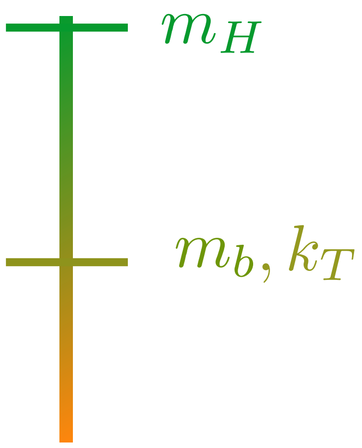
I

$$k_T \ll m_b \ll m_H$$



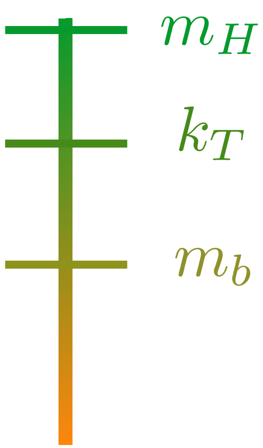
II

$$k_T \sim m_b \ll m_H$$



III

$$m_b \ll k_T \ll m_H$$



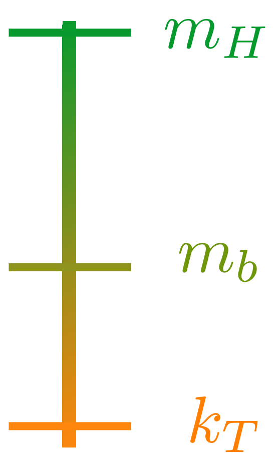
Different regimes.

consider different scalings of k_T

- emission k_T introduces additional scale to the calculation

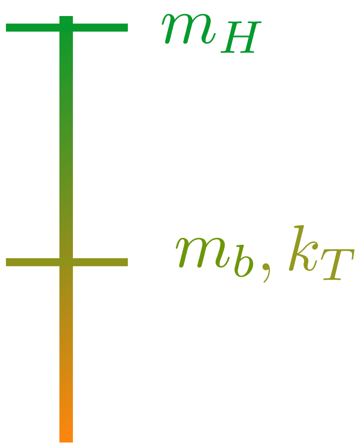
I

$$k_T \ll m_b \ll m_H$$



II

$$k_T \sim m_b \ll m_H$$



III

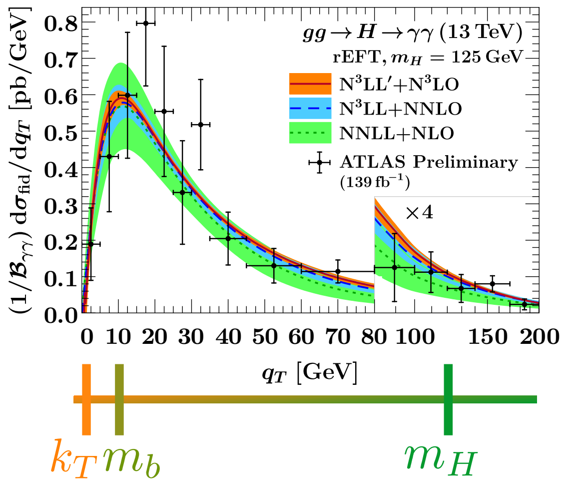
$$m_b \ll k_T \ll m_H$$

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

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

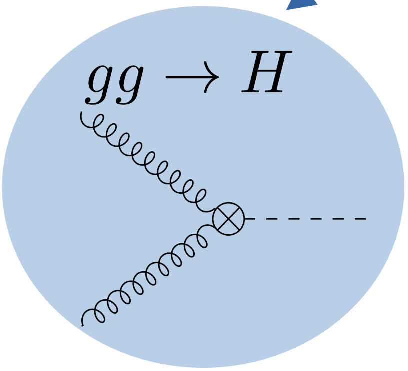


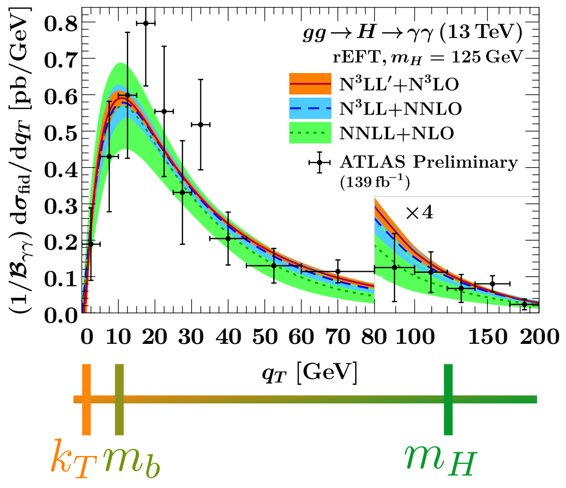
Regime I.

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

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



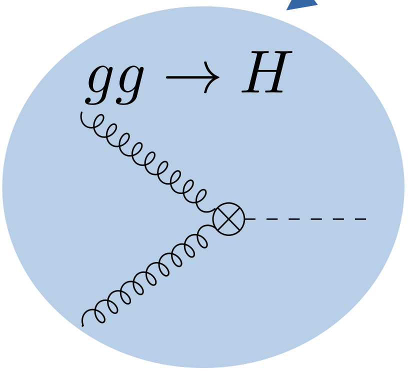


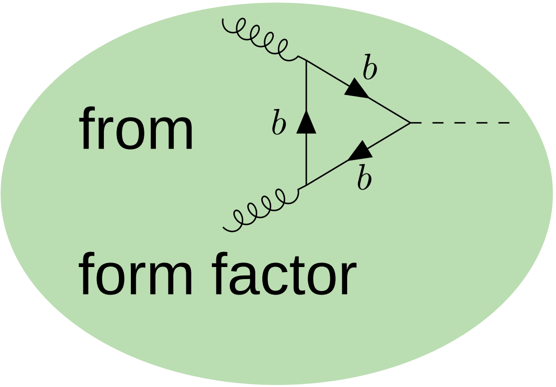
Regime I.

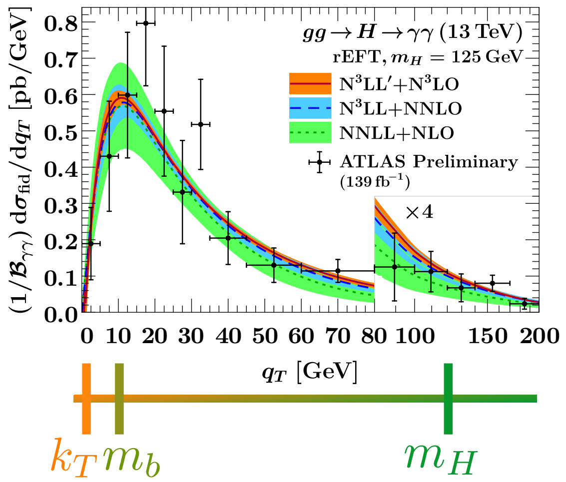
factorization theorem

- 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

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







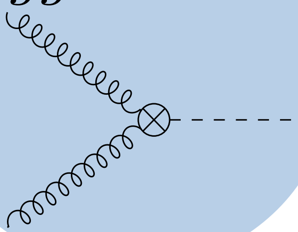
Regime I.

factorization theorem

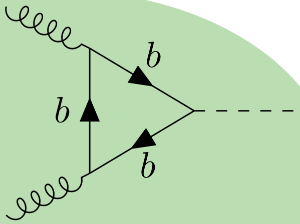
- Only valid in a very small region of the q_T spectrum
- use standard factorization for q_T resummation with $n_f = 4$ massless flavors

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

$gg \to H$

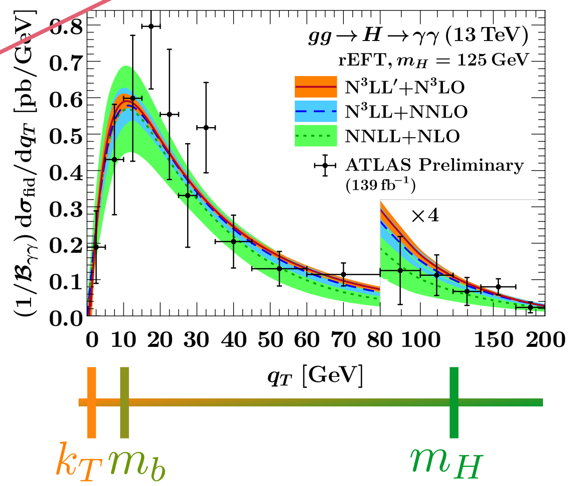


from



form factor

q_T resummation



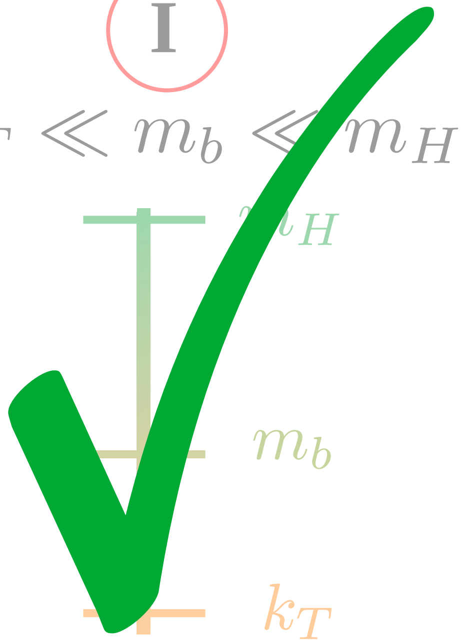
Different regimes.

consider different scalings of k_T

- emission k_T introduces additional scale to the calculation

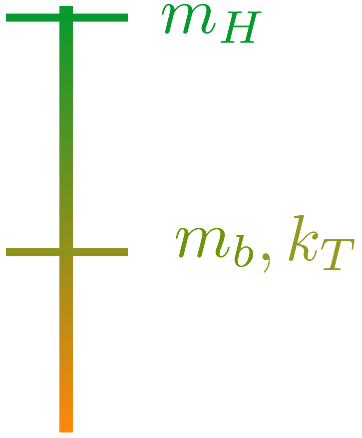
I

$k_T \ll m_b \ll m_H$



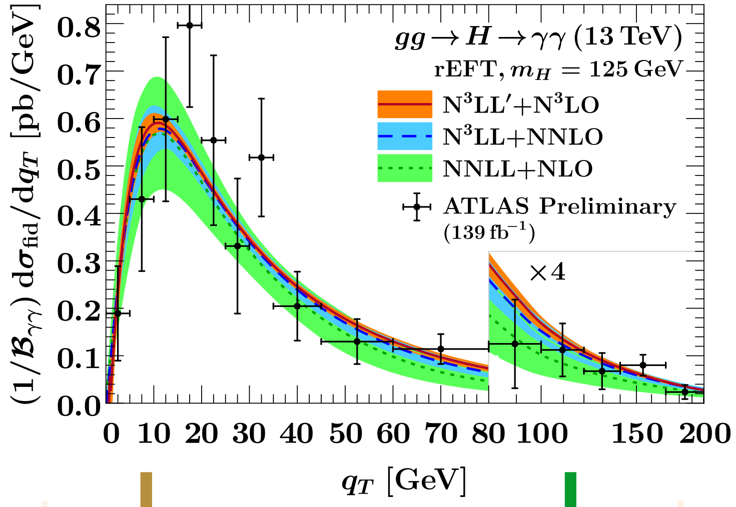
II

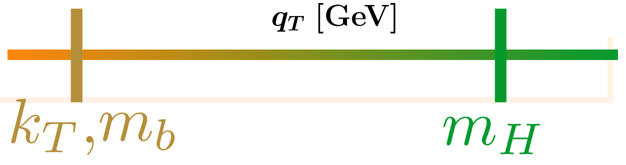
$k_T \sim m_b \ll m_H$



III

$m_b \ll k_T \ll m_H$

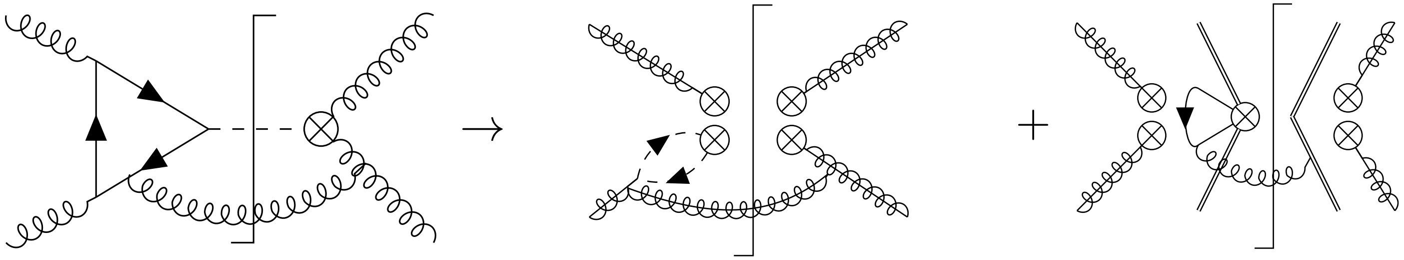




Regime II.

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

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

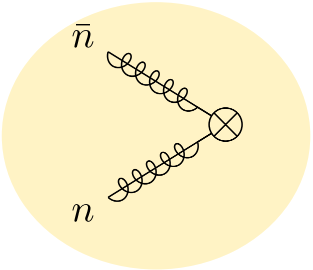


operators: [M. Stahlhofen's SCET talk ' 15, Liu, Neubert '19]

Regime II.

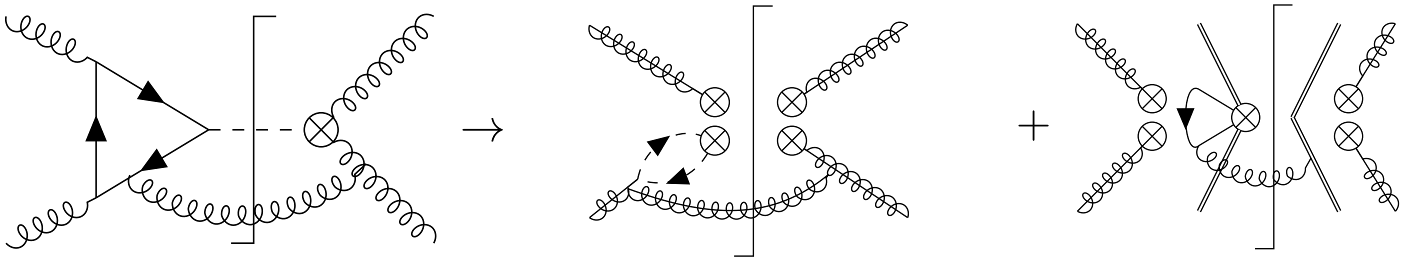
bare factorization theorem $k_T \sim m_b \ll m_H$

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



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

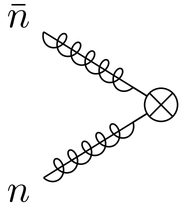
$$+ \int \mathrm{d}\ell^+ \mathrm{d}\ell^- H_{bbgg} \mathcal{J}(\ell^+) \mathcal{J}(\ell^-)\, B_g(q_T) \otimes B_g(q_T) \otimes S_{\bar{\psi}\psi}(\ell^+, \ell^-, q_T, m)$$



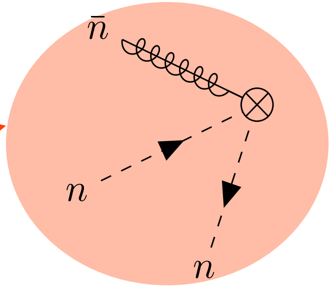
operators: [M. Stahlhofen's SCET talk ' 15, Liu, Neubert '19]

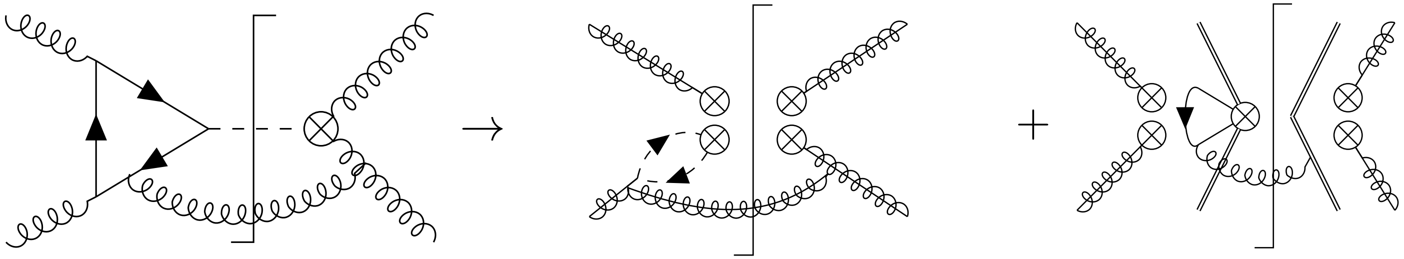
Regime II.

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



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

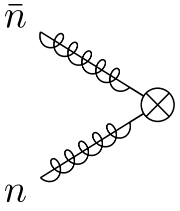




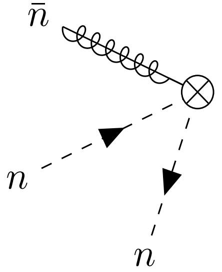
operators: [M. Stahlhofen's SCET talk ' 15, Liu, Neubert '19]

Regime II.

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



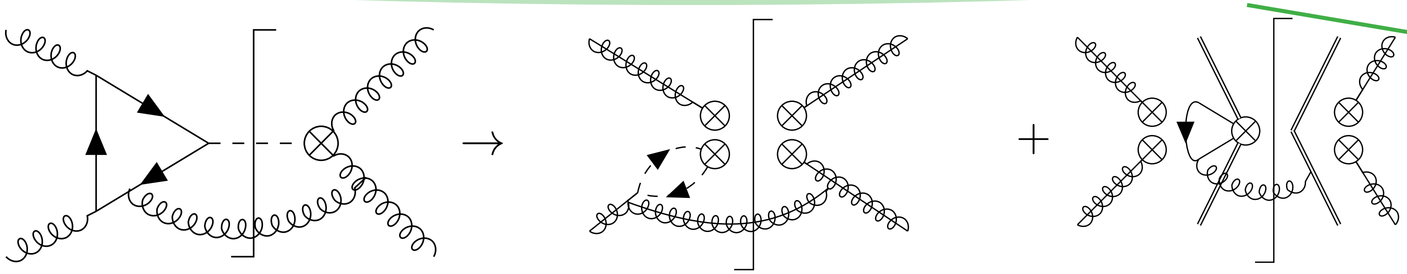
$$\frac{\mathrm{d}\sigma_{y_t y_b}}{\mathrm{d}q_T} = H_{gg}(m)\, B_g(q_T) \otimes B_g(q_T) \otimes S_{gg}(q_T)$$

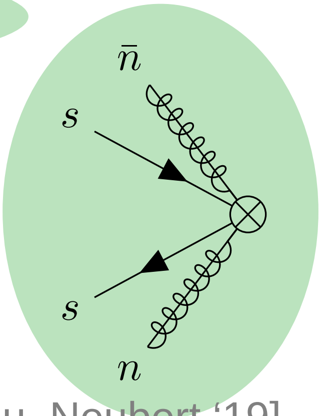


$$+ \int \mathrm{d}z H_{bbg}(z)\, \left[B_{n,\bar{\chi}\chi}(z, q_T, m) \otimes B_g(q_T) \otimes S_{gg}(q_T) \right.$$

$$\left. + B_g(q_T) \otimes B_{\bar{n},\bar{\chi}\chi}(z, q_T, m) \otimes S_{gg}(q_T)\right]$$

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

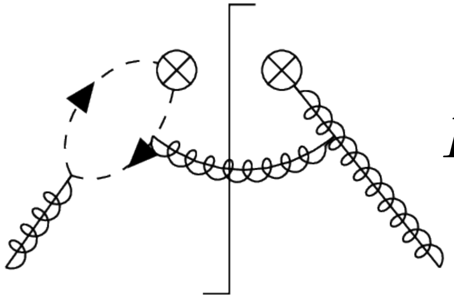




operators: [M. Stahlhofen's SCET talk ' 15, Liu, Neubert '19]

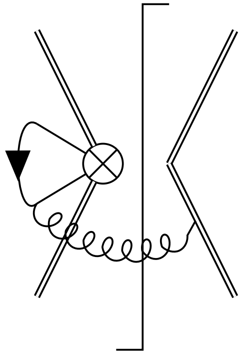
Matrix element definition.

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



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

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

Regime II.

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

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

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

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

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

$$\boxed{\frac{1}{z} f_n\left(\frac{m}{k_T}\right) \Longleftrightarrow \frac{1}{\ell^+ \ell^-} f_s\left(\frac{m}{k_T}\right)}$$

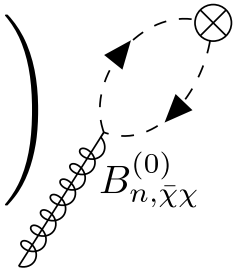
- **how does the additional scale affect the structure of the endpoint divergences?**
- in general $f_n(m/k_T)$ and $f_s(m/k_T)$ can be non-trivial functions of m/k_T

Endpoint divergences.

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

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

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



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

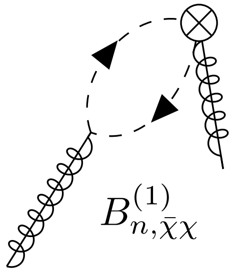
- $\frac{1}{\eta}$ is **not** a rapidity divergence!
- the “true” rapidity divergence (related to q_T spectrum) comes later from the phase space integral over k!

Endpoint divergences.

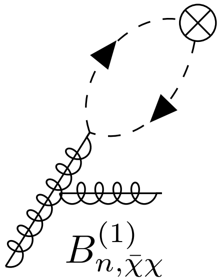
collinear NLP one-gluon contribution

- consider collinear NLP with emission k_T

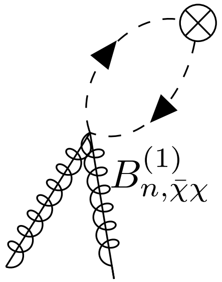
$$\int \mathrm{d}z \left(\frac{1}{z}\left|\frac{z}{\nu}\right|^{-\eta} + \frac{1}{1-z}\left|\frac{1-z}{\nu}\right|^{-\eta}\right)\Bigg($$



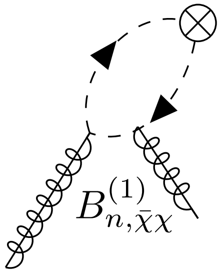
$+$



$+$



$+$



$$\Bigg)$$

$$= \boxed{-\frac{A(k^-)}{4\eta\epsilon} - \frac{C(k^-)}{4\eta\epsilon}} \quad \boxed{-\frac{B(k^-)}{4\eta\epsilon}} \quad \boxed{-\frac{C(k^-)}{4\eta\epsilon}} \quad \boxed{+\frac{C(k^-)}{2\eta\epsilon}}$$

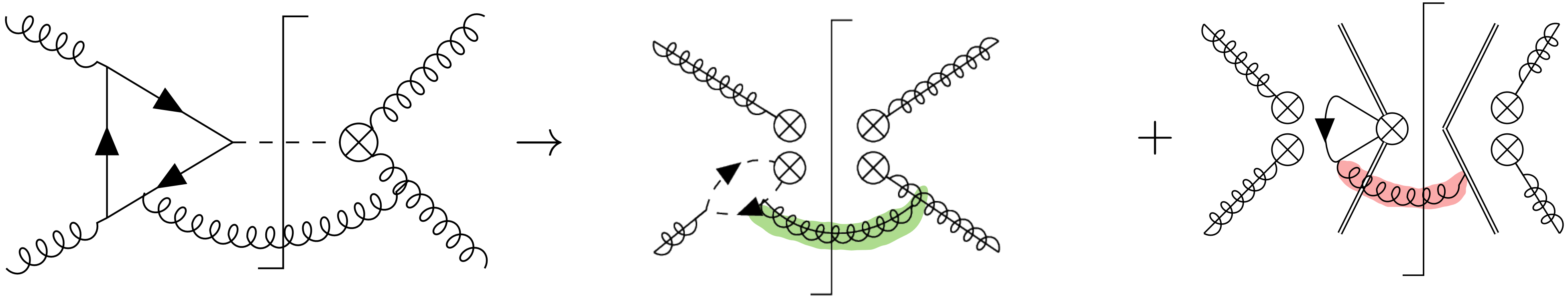
$$= -\frac{A(k^-)}{4\eta\epsilon} - \frac{B(k^-)}{4\eta\epsilon}$$

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

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

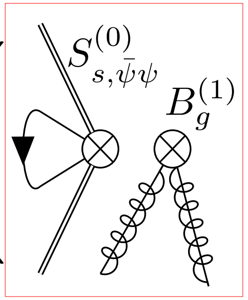


Endpoint divergences.

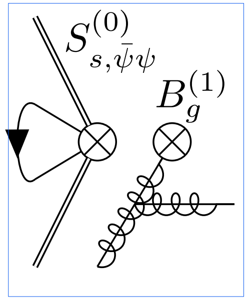
collinear emission

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

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



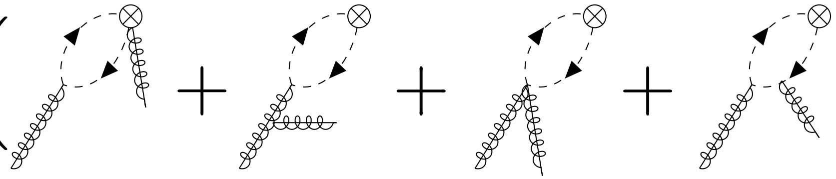
$$+$$



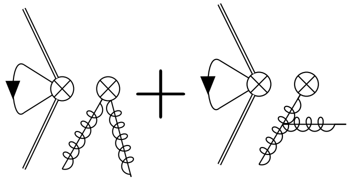
$$\Bigg) = +\frac{A(k^-)}{4\eta\epsilon} + \frac{B(k^-)}{4\eta\epsilon}$$

- endpoint divergences cancel between diagrams with collinear emission!

$$\int \mathrm{d}z \Bigg($$



$$\Bigg) + \int \mathrm{d}\ell^+ \mathrm{d}\ell^- \Bigg($$



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

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

Endpoint divergences.

soft emission

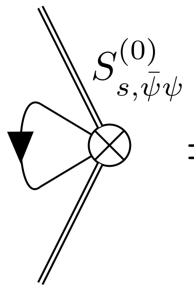
- sum of diagrams with collinear emission is finite

➔ **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]

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



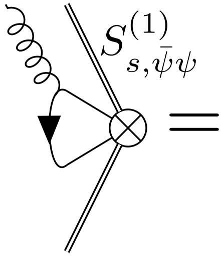
$$= 0$$ (scaleless)

Endpoint divergences.

soft emission

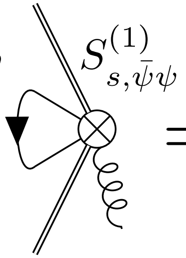
- use the pure rapidity regulator for NLP soft diagram

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



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

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



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

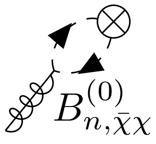
- **both contributions are individually finite!**

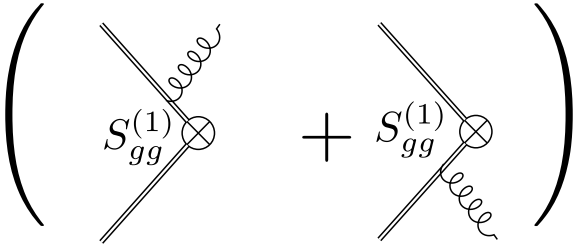
Endpoint divergences.

soft emission

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

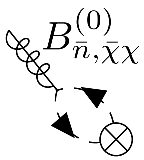
$$\int \mathrm{d}z \left(\frac{1}{z}+\frac{1}{1-z}\right) z^{-\eta}(1-z)^{-\eta}$$

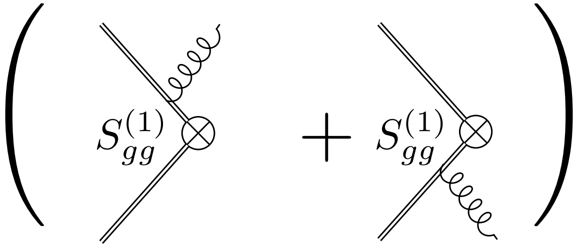




$$= \frac{D(k^-)}{\eta}$$

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





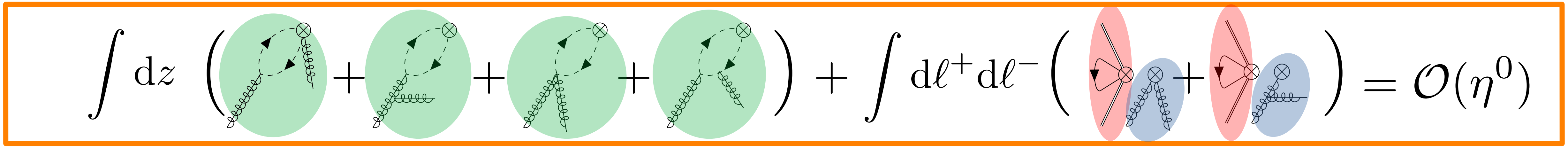
$$= -\frac{D(k^-)}{\eta}$$

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

Endpoint divergences.

bare factorization theorem

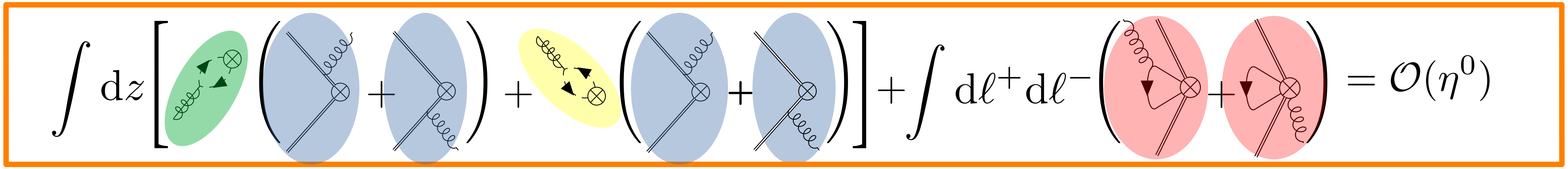
$$
\begin{aligned}
\frac{\mathrm{d}\sigma_{y_t y_b}}{\mathrm{d}q_T} = {} & H_{gg}(m)\, B_g(q_T) \otimes B_g(q_T) \otimes S_{gg}(q_T) \\
& + \int \mathrm{d}z H_{bbg}(z)\, \big[B_{n,\bar{\chi}\chi}(z, q_T, m) \otimes B_g(q_T) \otimes S_{gg}(q_T) \\
& \qquad + B_g(q_T) \otimes B_{\bar{n},\bar{\chi}\chi}(z,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



Endpoint divergences.

bare factorization theorem

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



Summary.

Summary.

$y_b y_t$ interference in gluon fusion

- interference term contributes $5\text{–}10\%$ to the cross section
- important contribution to measure the Yukawa coupling

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
- collinear endpoint divergences cancel against LP collinear emssion

  ➡ m and k_T dependence factorizes!
- endpoint divergences from soft and collinear emissions cancel separately

next steps

- compare to fixed order amplitudes
- integrate over phase space

Thank you!

Acknowledgments.

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program (Grant agreement No. 101002090 COLORFREE).

erc

European Research Council

Established by the European Commission