# $q_T$ resummation for Higgs production via quark annihilation.

Rebecca von Kuk

Deutsches Elektronen-Synchrotron

German Conference of Women in Physics 2022

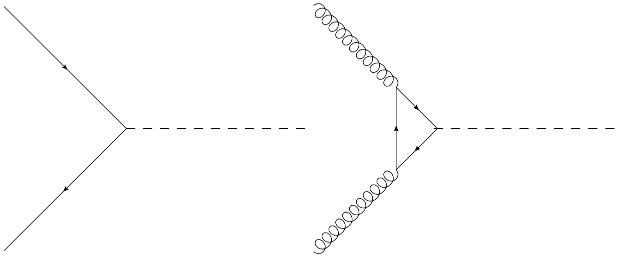
European Research Council

Established by the European Commission

# Motivation.

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

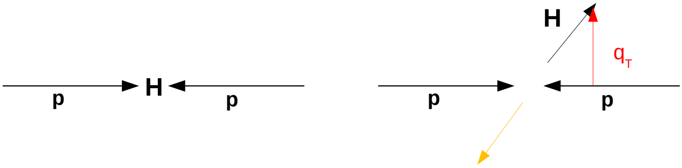
- Currently: $q\bar{q} \to H$ and $gg \to H$ are very hard to distinguish
- Very challenging to measure the Yukawa coupling for charm and lighter quarks
- Precise prediction for $q\bar{q} \to H$ allows Yukawa fit from initial state



## Kinematic distributions

- Kinematic distributions and differential cross sections are particularly interesting
- 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- In this kinematic region the fixed order perturbative expansion is no longer valid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!**



# Large logs.

## Divergent cross section due to large logs:

- Consider cross section for $q_T \ll Q = m_H$:

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

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

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

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

# Large logs.

**Divergent cross section due to large logs:**

- Consider cross section for $q_T \ll Q = m_H$:

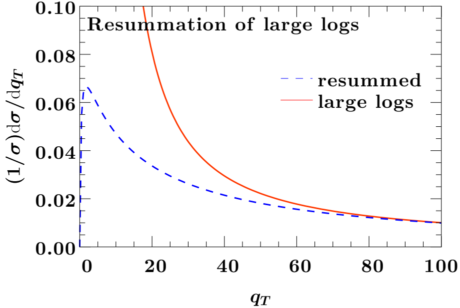
$$\sigma(q_T) \sim 1 + \frac{\alpha_s}{4\pi}\left[c_{12}\ln^2_{q_T/Q} + c_{11}\ln_{q_T/Q} + c_{10}\right]$$
$$+ \left(\frac{\alpha_s}{4\pi}\right)^2\left[c_{24}\ln^4_{q_T/Q} + c_{23}\ln^3_{q_T/Q} + c_{22}\ln^2_{q_T/Q} + \dots\right]$$
$$+ \left(\frac{\alpha_s}{4\pi}\right)^3\left[c_{36}\ln^6_{q_T/Q} + c_{35}\ln^5_{q_T/Q} + c_{34}\ln^4_{q_T/Q} + \dots\right]$$

LL NLL NNLL

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

# Large logs.

## Divergent cross section due to large logs:



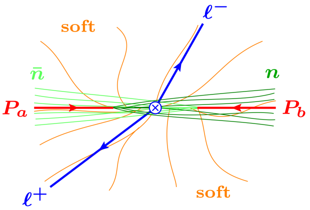

- large logs appear and spoil the convergence of the perturbative series
- **Resum logs to all orders to restore convergence!**

# Factorization in EFTs.

- EFTs factorize the dynamics of the hard scale $Q$ and the soft scale $q_T$
- Introduce scale: $\log(\frac{q_T}{Q}) = \log(\frac{\mu}{Q}) + \log(\frac{q_T}{\mu})$
- Soft-Collinear Effective Field Theory (SCET) separates the scales at cross section level

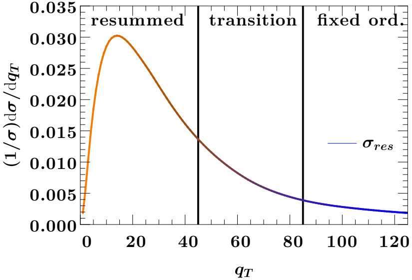
$$\frac{d\sigma}{dq_T} = \boxed{H(\mu_H)} \times \boxed{B(\mu_B)} \otimes \boxed{B(\mu_B)} \otimes \boxed{S(\mu_S)} \left[1 + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)\right]$$

- Hard function: virtual contributions at scale $Q$
- Beam function: collinear radiation
- Soft function: soft, isotropic radiation



## Resummed cross section:

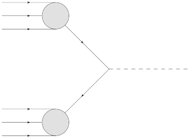
- Solve RGE for $\boxed{H(\mu_H)}$, $\boxed{B(\mu_B)}$ and $\boxed{S(\mu_S)}$ to resum the logs
- Resummation generates Sudakov peak for $q_T \ll Q$
- for $q_T \sim Q$ the fixed order calculation is sufficient
- Transition connects fixed order and resummation region

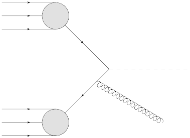


# Higgs production via quark annihilation.

**Current Status:**

- NNLL+NNLO prediction $b\bar{b}H$ for $y_q \neq 0$ and $m_b = 0$ [Harlander, Tripathi, Wiesemann '14]
- prediction for $m_q \neq 0$ to NLO
- $c\bar{c}H$ and $s\bar{s}H$
  - no explicit predictions
  - strongly suppressed due to small Yukawa coupling





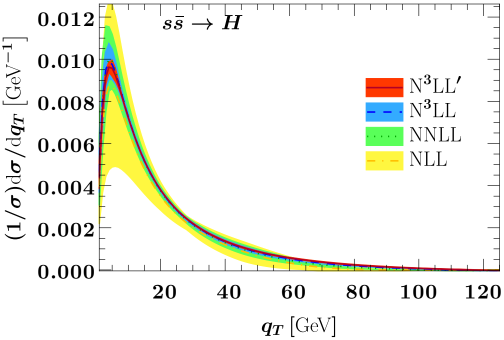
**Goal:**

- N$^3$LL'+N$^3$LO prediction für $b\bar{b}H$ , $c\bar{c}H$ , $s\bar{s}H$
- prediction including full mass effects $m_q \neq 0$

# Convergence.

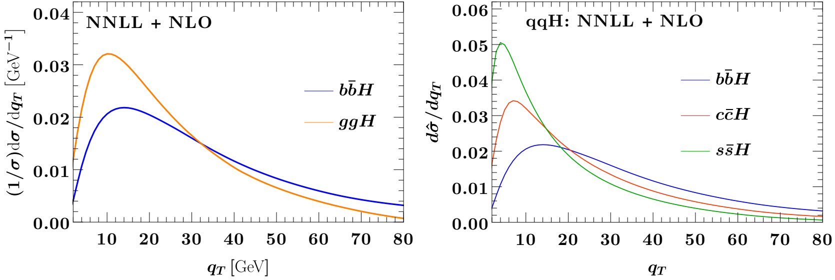
## Why do we need higher orders?

- uncertainties are obtained by varying resummation scales $\mu_H, \mu_B$ and $\mu_S$
- the uncertainty bands shrink for each additional order



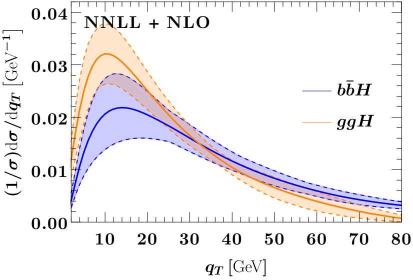
# Yukawa Fit.

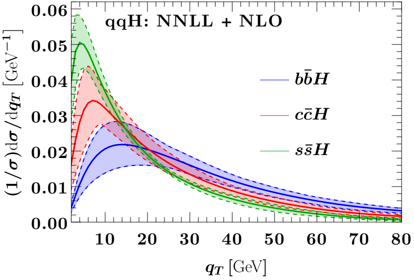
- Gluon and quark induced processes can be distinguished by the shape of the $q_T$ spectrum
- $b\bar{b}H$ vs. $c\bar{c}H$ vs. $s\bar{s}H$ : also differences in the shape of the $q_T$ spectrum, but a bit more subtle
  - uncertainties for the channels overlap $\rightarrow$ more precise predictions needed to cleanly distinguish channels
  - **more precise predictions needed**



# Yukawa Fit.

- 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, but a bit more subtle
  - uncertainties for the channels overlap $\rightarrow$ more precise predictions needed to cleanly distinguish channels
  - **more precise predictions needed**



# Summary.

## Resumation

## Resummation

- kin. distributions diverge for small values of $q_T$ due to large logs
- spectra have to be resummed to obtain a meaningful prediction

## Higgs production via quark annihilation

- Gluon fusion and quark annihilation show different shapes in the $q_T$ spectrum
  - Application: Yukawa fit for charm and lighter quarks
- At NNLL+NLO the theory unc. are too large to clearly separate channels
  - more precise predictions needed!

## Outlook

- $N^3$LL'+ $N^3$LO predictions for $b\bar{b}H$ , $c\bar{c}H$ and $s\bar{s}H$
- Include full quark mass dependence

# Acknowledgements.

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

erc

European Research Council

Established by the European Commission

# Backup.

## Simplified model:

1. Factorize cross section : $\sigma(Q,p) = H(Q,\mu) \times S(p,\mu)$

   - Split large log with additional scale $\mu$: $\log(\frac{p}{Q}) = \log(\frac{\mu}{Q}) + \log(\frac{p}{\mu})$

2. Find renormalization group $H(Q,\mu)$ [see $\mu \frac{\mathrm{d}\alpha_s(\mu)}{\mathrm{d}\mu} = \beta(\alpha_s)$]

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} H(Q,\mu) = \left[\Gamma(\alpha_s) \log(\frac{\mu}{Q}) + \gamma(\alpha_s)\right] H(Q,\mu)$$

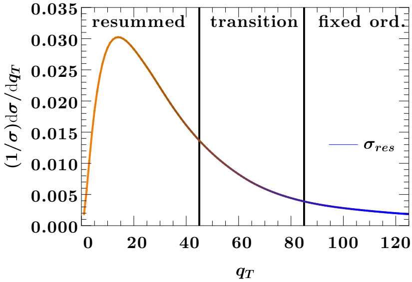
3. Solve RGEs and run $\mu_H = Q$ und softer Skala $\mu_S = p$

$$\sigma_{res}(Q,p) = H(Q,\mu_H) \times \exp\left[\int_{\mu_H}^{\mu_S} \frac{\mathrm{d}}{\mathrm{d}\mu} [...]\right] \times S(p,\mu_S)$$

- cross section is resummed to all orders

## Resumed cross section:

- Solve RGE to resum the logs
- Resummation generates Sudakov peak for $q_T \ll Q$
- for $q_T \sim Q$ the perturbative calculation is sufficient




$$\underbrace{\sigma_{\text{match}}}_{\text{NNLL+ NLO}} = \underbrace{\sigma_{\text{fac}}(\mu_{\text{res}})}_{\text{NNLL}} + \underbrace{(\sigma_{\text{QCD}} - \sigma_{\text{fac}})}_{\text{NLO}}(\mu_{\text{FO}})$$

## Logarithmic accuracy

REG: $\mu \frac{\mathrm{d}H(Q,\mu)}{\mathrm{d}\mu} = \left[\Gamma(\alpha_s)\log(\frac{\mu}{Q}) + \gamma(\alpha_s)\right] \times H(Q,\mu)$

| order | $\Gamma$ | $\gamma$ | $\beta$ | $X$ |
|---|---|---|---|---|
| LL | 1-Loop | - | 1-Loop | LO |
| NLL | 2-Loop | 1-Loop | 2-Loop | LO |
| NLL' | 2-Loop | 1-Loop | 2-Loop | NLO |
| NNLL | 3-Loop | 2-Loop | 3-Loop | NLO |
| NNLL' | 3-Loop | 2-Loop | 3-Loop | NNLO |
| $N^3$LL | 4-Loop | 3-Loop | 4-Loop | NNLO |
| $N^3$LL' | 4-Loop | 3-Loop | 4-Loop | $N^3$LO |

# Backup.

## Theorieunsicherheiten

aktuell:

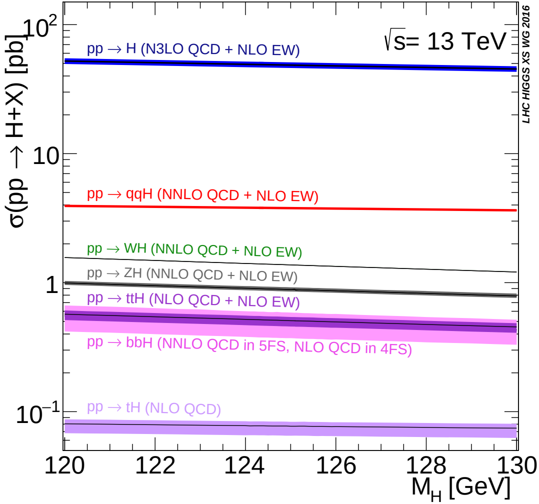
- Skalenvariation: $\mu_F \in \left[\frac{\mu_F}{2}, 2\mu_F\right]$ und $\mu_R \in \left[\frac{\mu_R}{2}, 2\mu_R\right]$
- Matching: Variation des übergangspunkts
- PDF Unsicherheiten
- berechne viele Verteilung und nehme die maximale Abweichung als Unsicherheit
- geringer Aufwand, aber Korrelationen der Unsicherheiten gehen verloren

Theory Nuisance Parameter:

- größerer Rechenaufwand, aber Korrelationen können berücksichtigt werden
- wertvolles Ergebnis für Experimentalphysiker: können auch Theorieunsicherheiten richtig korrelieren

# Higgs production via quark annihilation.

## Higgsproduktion am LHC



## bottom and charm convergence

- convergence not as good as for $s\bar{s}H$
- mass effects are already an issue