Differential Higgs production at small-x

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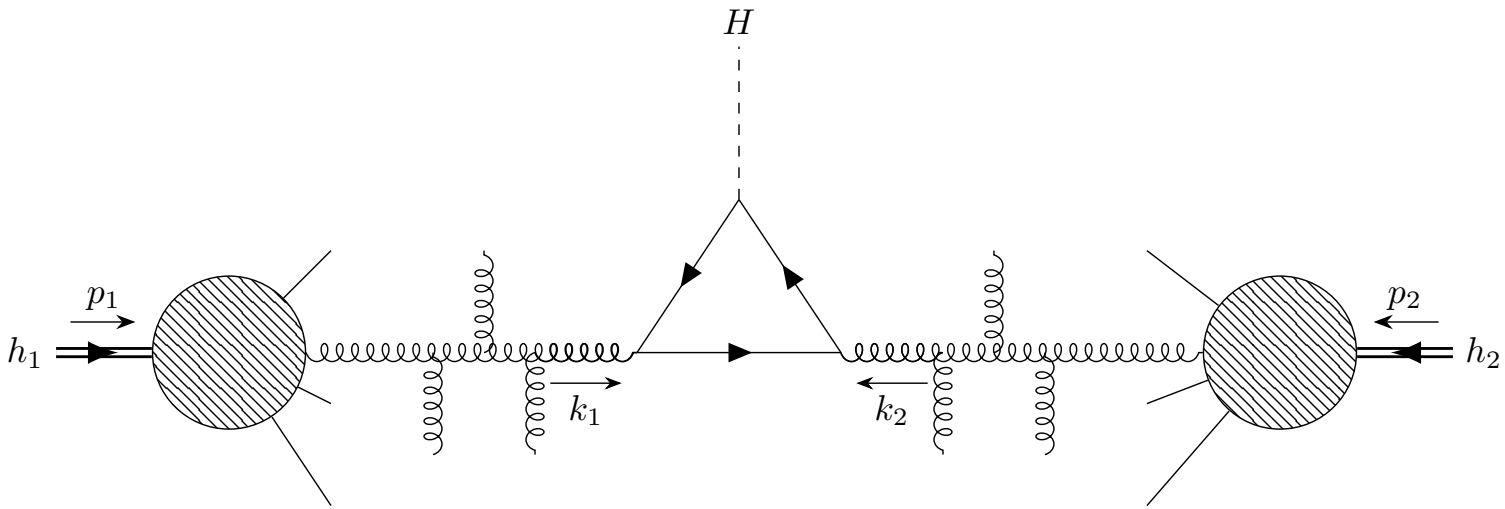
Motivation: Higgs production at small-x

Higgs production at hadron colliders is dominated by gluon fusion $gg \to H$:



Inclusive cross section in the collinear factorization

$$\sigma(\tau, m_H^2) = \sigma_0(m_H^2) \sum_{ij=q,g} \int_\tau^1 \frac{dx_1}{x_1} \int_{\tau/x_1}^1 \frac{dx_2}{x_2} C_{ij}\left(\frac{\tau}{x_1 x_2}, \alpha_s, \frac{m_H^2}{\mu_F^2}\right) f_i\left(x_1, \mu_F^2\right) f_j\left(x_2, \mu_F^2\right).$$

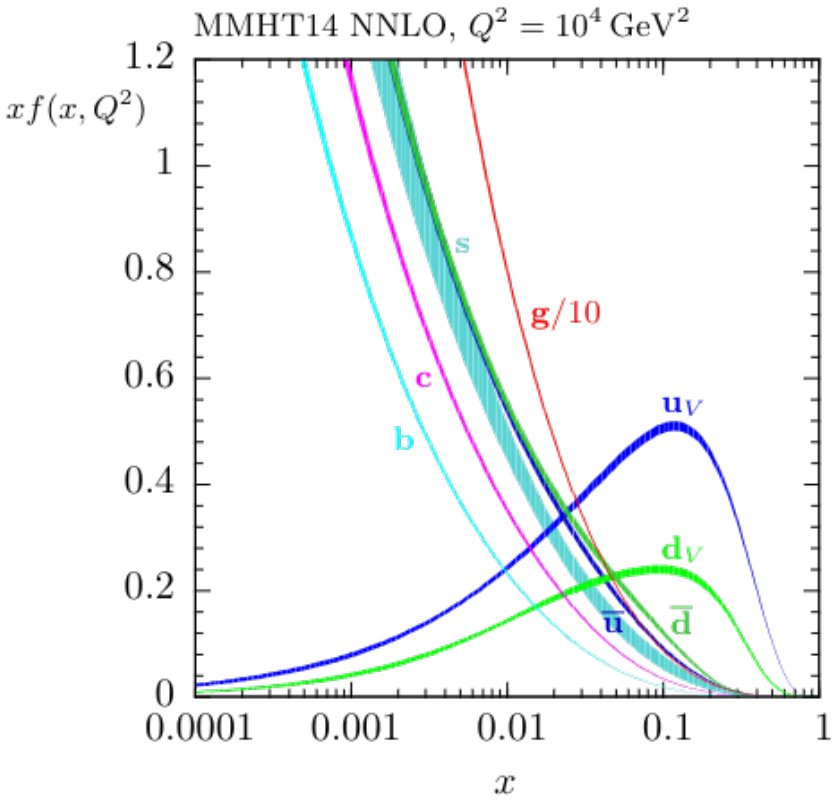
With

$$\tau = \frac{m_H^2}{s}; \quad \sqrt{s} = \text{collider energy}; \quad x = \frac{\tau}{x_1 x_2};$$
$$k_i^\mu = x_i p^\mu; \quad p^\mu = P(1,0,0,1)$$

- Higher $\sqrt{s} \Longrightarrow$smaller $x_{1,2}$ and x;
- Small-x logs $\alpha_s^n \log^n(1/x)$ grow and must be resummed.

Gluon PDFs at small-x

Increasing collider energies allow precision measurements to probe progressively smaller values of x.



- The gluon PDF rises steeply at small-x;
- Higgs production becomes increasingly sensitive to this region;
- Large logarithms spoil fixed-order perturbation theory

$$\alpha_s^n \log^n \frac{1}{x},$$

- These logarithms must be resummed to all orders.

Small-x resummation

$$\sigma(\tau, m_H^2) = \sigma_0(m_H^2) \sum_{ij=q,g} \int_\tau^1 \frac{dx_1}{x_1} \int_{\tau/x_1}^1 \frac{dx_2}{x_2} C_{ij}\left(\frac{\tau}{x_1 x_2}, \alpha_s, \frac{m_H^2}{\mu_F^2}\right) f_i\left(x_1, \mu_F^2\right) f_j\left(x_2, \mu_F^2\right).$$

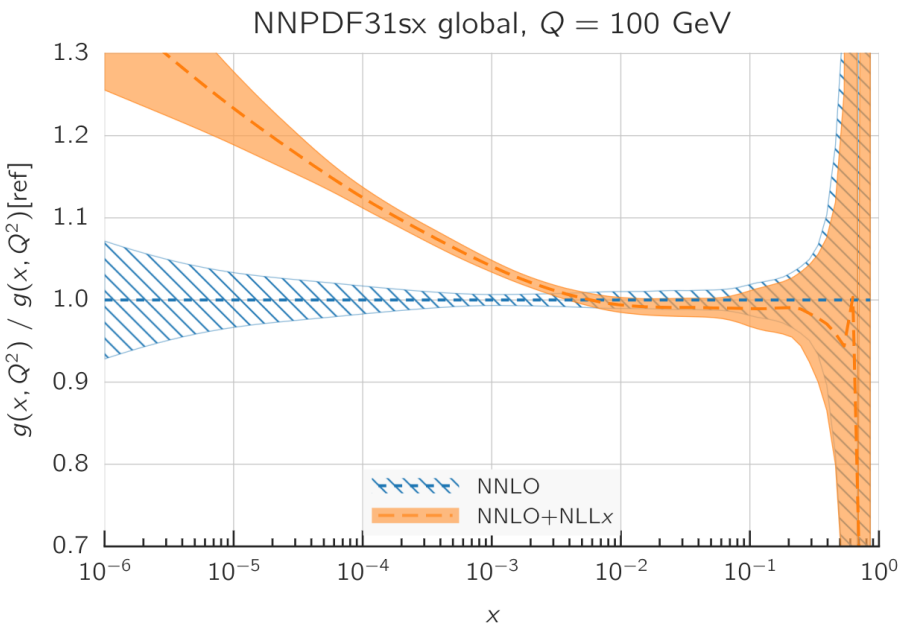
Two separate terms:

- **Coefficient-function resummation**: via high-energy factorization;
- **PDF resummation**: obtained by fitting PDFs with resummed anomalous dimensions γ_{ij} and DIS coefficient functions.

Both are required to obtain a consistent small-x prediction.

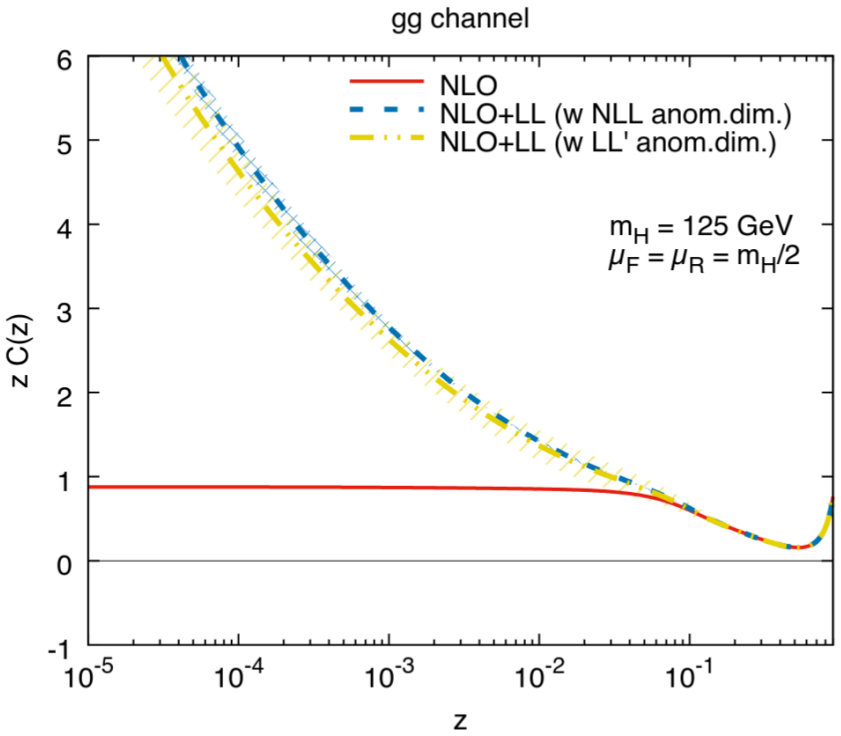
Small-x resummation ingredients

- PDF resummation $\hookrightarrow$
- C_{ij} resummation: resummation of the partonic coefficient functions $\hookrightarrow$
  - Resummation enhances the gluon PDF $g(x, Q^2)$ at very small-x;
  - The effect becomes sizeable already for
    $$x \lesssim 10^{-3};$$
  - Important impact already at LHC, much larger at FCC-hh.



Small-x resummation ingredients

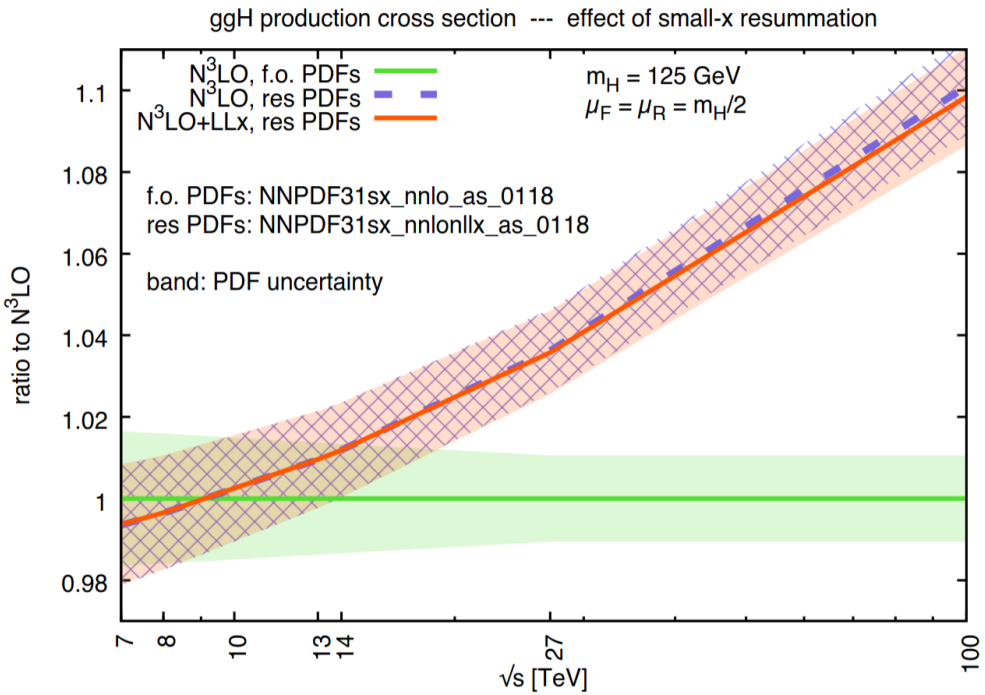
- PDF resummation ↪
- C_{ij} resummation: resummation of the partonic coefficient functions ↪
  - Computed in high-energy, k_t-factorization;
  - Incoming gluons carry transverse momentum (off-shell);
  - Resums LLx logs to all orders at partonic level.



Impact of small-x resummation

Inclusive cross section of $gg \longrightarrow H$

Impact of the resummation in the cross section:



- At FCC-hh:

$$\Delta\sigma \approx 10\%$$

  from small-x resummation;
- At the LHC the effect is smaller;
- The dominant contribution originates from PDF resummation

$\Longrightarrow$ Differential distributions can isolate kinematic regions where coefficient-function resummation becomes important.

Differential small-x resummation

Collinear factorization:

$$\frac{d\sigma}{dY\,dq_t^2} = \tau \sum_{ij} \int_\tau^1 \frac{dx}{x} \int dy \frac{dC_{ij}}{dy dq_t^2} \left(x, y, m_H^2, q_t^2, \alpha_s, \frac{m_H^2}{\mu_F^2} \right)$$
$$\times f_i \left(\sqrt{\frac{\tau}{x}} e^{Y-y}, \mu_F^2 \right) f_j \left(\sqrt{\frac{\tau}{x}} e^{-(Y-y)}, \mu_F^2 \right).$$

$$x_{1,2} = \sqrt{\frac{\tau}{x}} e^{\pm(Y-y)} \rightarrow \frac{\tau}{x} = x_1 x_2.$$

k_t-factorization:

$$\frac{d\sigma}{dY\,dq_t^2} = \tau \int_\tau^1 \frac{dz}{z} \int d\eta \int_0^\infty dk_{t1}^2 \int_0^\infty dk_{t2}^2 \frac{d\mathcal{C}}{d\eta dq_t^2}(z, \eta, k_{t1}^2, k_{t2}^2, m_H^2, q_t^2)$$
$$\times \mathcal{F}_g \left(\sqrt{\frac{\tau}{z}} e^{Y-\eta}, k_{t1}^2 \right) \mathcal{F}_g \left(\sqrt{\frac{\tau}{z}} e^{-(Y-\eta)}, k_{t2}^2 \right).$$

Off-shell gluons allow LL_x resummation of partonic coefficient functions with $k_i^\mu = x_i p^\mu + k_{ti}$.

Differential small-x resummation: the HELL approach

The k_t-dependent gluon PDF can be related to the collinear PDFs through the introduction of the DGLAP evolutor:

$$\mathcal{F}_g(x, k_t^2) = \int_x^1 \frac{dz}{z} U'_{gg}(z, k_t^2, \mu_F^2) f_g\left(\frac{x}{z}, \mu_F^2\right).$$

The DGLAP evolutor

$$\int_0^\infty dz z^{N-1} U_{gg}(z, k_t^2, \mu_F^2) = \exp \int_{\mu_F^2}^{k_t^2} \frac{d\mu^2}{\mu^2} \gamma_{gg}(N, \alpha_s(\mu^2)).$$

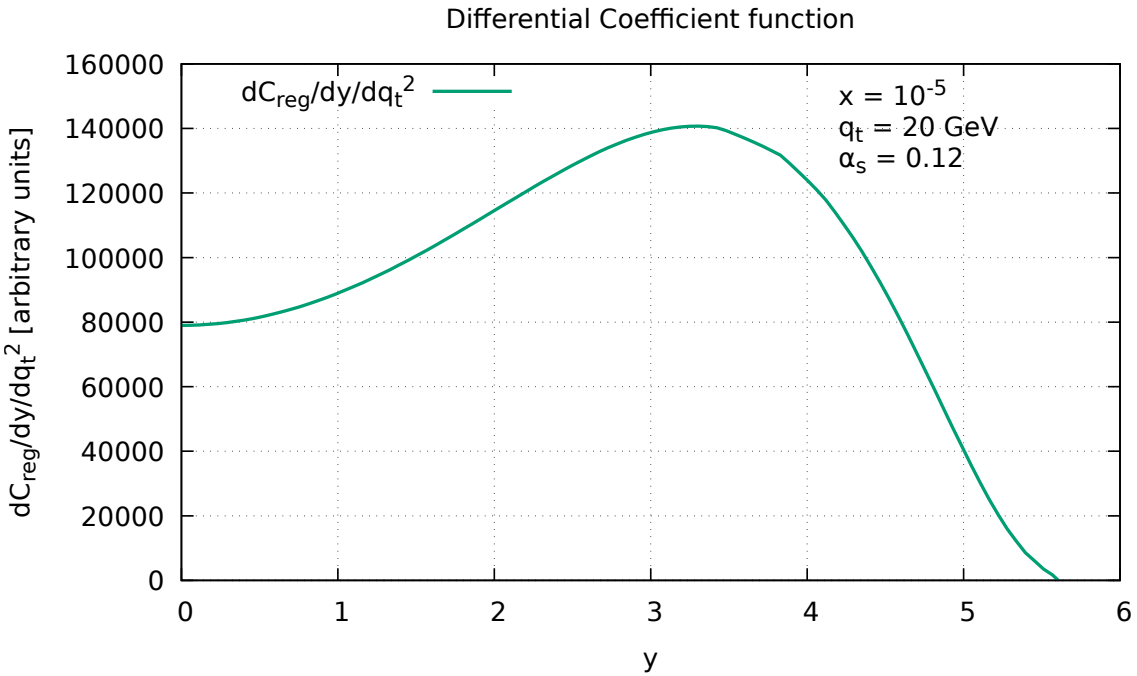
The resummed anomalous dimension γ_{gg} encodes all small-x logarithms.

Resummation for differential coefficient-functions

$$\frac{dC_{gg}}{dy dq_t^2}\left(x, y, m_H^2, q_t^2, \alpha_s, \frac{m_H^2}{\mu_F^2}\right) = \int_0^\infty dk_{t1}^2 \int_0^\infty dk_{t2}^2 \int_x^1 \frac{dz}{z} \int d\bar{\eta}$$

$$\times \frac{d\mathcal{C}}{d\eta dq_t^2}(z, y - \bar{\eta}, k_{t1}^2, k_{t2}^2, m_H^2, q_t^2) U'_{gg}\left(\sqrt{\frac{x}{z}} e^{\bar{\eta}}, k_{t1}^2, \mu_F^2\right) U'_{gg}\left(\sqrt{\frac{x}{z}} e^{-\bar{\eta}}, k_{t2}^2, \mu_F^2\right)$$

Differential coefficient function resummation



$$x = 10^{-5}$$

$$q_t = 20\,\mathrm{GeV}$$

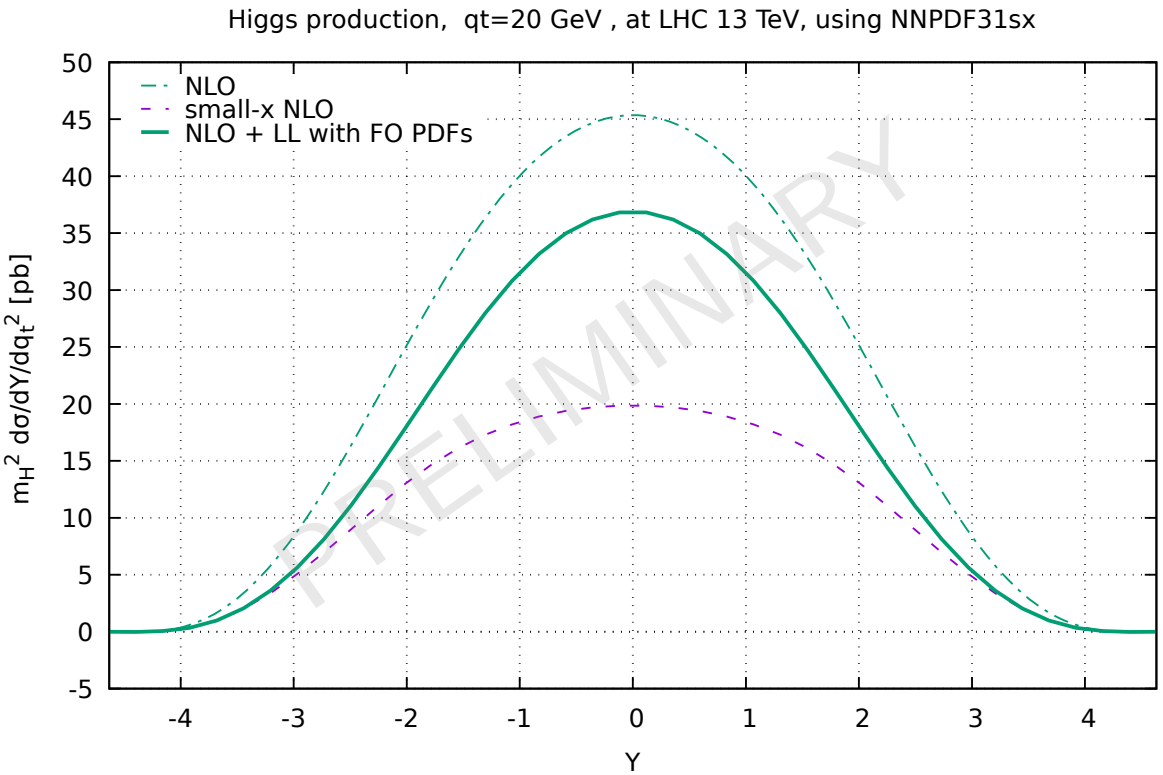
$$\alpha_s = 0.12$$

Compute $\frac{dC_{gg}}{dydq_t^2}$ for each value of x and y.

Convolution with PDFs gives the resummed differential distribution.

Result for NLO+LL$_x$ resummation

Double differential Higgs cross section as a function of the hadronic rapidity Y, for fixed $q_t = 20$ GeV.

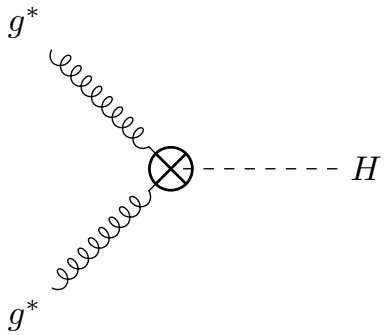


- LO is proportional to $\delta(q_t)$;
- Resummation effect is a reduction to the fixed order cross section;
- At this q_t, the resummed contribution is numerically sizeable, reaching almost half the fixed-order.

Finite quark-mass effects

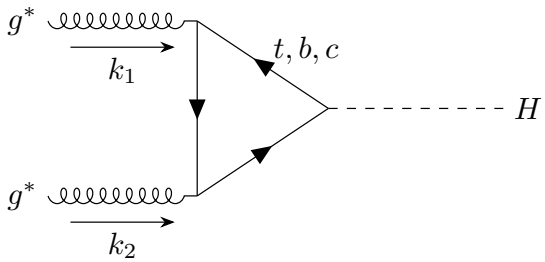
The higgs production cross section (both inclusive and differential) computation is known up to N^{3}LO in the heavy-top EFT;

- The EFT corresponds to:



$m_t \to \infty$;
And the EFT does not reproduce the correct high-energy behavior;

- Small-x resummation therefore requires finite quark-mass dependence:



Important

The small-x limit and the heavy-top EFT limit do not commute.

Here the quark-mass dependence is retained in the partonic amplitude before resummation.

Where larger small-x effects are expected?

The Higgs distribution

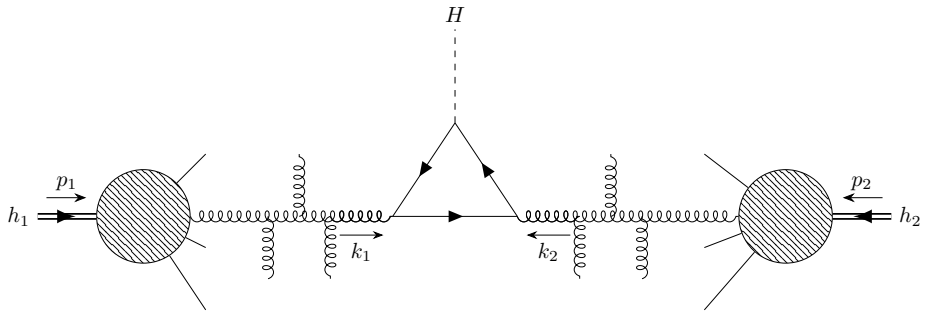
$$\frac{d\sigma}{dY dq_t^2}(\tau, m_H^2, Y, q_t^2) = \tau \sum_{ij} \int_\tau^1 \frac{dx}{x} \int dy \frac{dC_{ij}}{dy dq_t^2}(x, y) f_i\left(\sqrt{\frac{\tau}{x}} e^{Y-y}\right) f_j\left(\sqrt{\frac{\tau}{x}} e^{-(Y-y)}\right)$$

$$x_{1,2} = \sqrt{\frac{\tau}{x}} e^{\pm(Y-y)}.$$

Unlike inclusive kinematics, the coefficient function has non-trivial phase-space constraints from the $2 \to 1$ physics. In particular the integral in x gets an upper limit:

$$x < x_{\max} = \frac{1}{1 + (\frac{q_t}{m_H})^2}.$$

.



At small q_t

- $x_{\max} \sim 1$: integration probes all x;
- also accesses configurations with small $x_{1,2}$;
- the dominant effect originates from the resummed PDFs.

At large q_t:

- integral probes only small partonic x;
- off-shell dynamics enhanced;
- coefficient-function resummation becomes visible.

Conclusions

Results

- Small-x resummation in the `HELL` language extended to fully differential Higgs production;
- Higgs production probes gluon dynamics at very small-x;
- Differential observables highlight where resummation is most relevant

Outlook

- Identify quantitatively the regions dominated by PDF vs coefficient-function resummation.
- Combine with NNLO finite-mass differential predictions as they become available.

Thank you for your attention!

Backup slides

Small-x resummation-backup

Impact of resummation, defining $x = \frac{Q^2}{s}$, with s the energy of the collider squared and Q^2 the invariant mass of the different production cases.

x	Higgs	Z,W	Drell-Yan	$c\bar{c}$
LHC($13TeV$)	10^{-4}	5×10^{-5}	$\sim 10^{-6}$	$\sim 10^{-7}$
FCC-hh ($100TeV$)	1.5×10^{-6}	8×10^{-7}	$\sim 10^{-8}$	$\sim 10^{-9}$

In the case of Higgs production $\alpha_s \log(1/x) = 1.1$.

Small-x resummation in HELL code is done via the definition

UGD in HELL

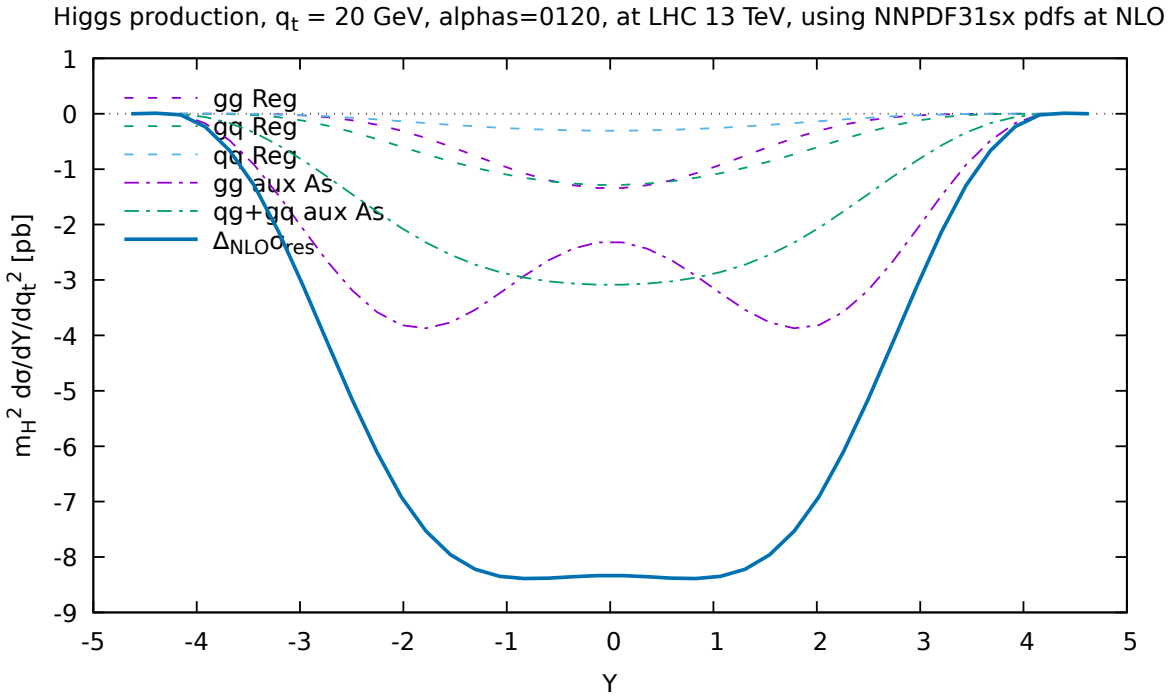
$$\mathcal{F}_g(N, k_t^2) = (U'_{\text{reg}}(N, k_t^2, \mu_F^2) + \delta(k_t^2)) f_g(\mu_F^2) + \frac{C_F}{C_A} U'_{\text{reg}}(N, k_t^2, \mu_F^2) f_q(\mu_F^2).$$

Since $\mathcal{U}_{gg}(N, k_t^2, \mu_F^2)$ is not a regular function is preferred to use $U'_{\text{reg}}(N, k_t^2, \mu_F^2)$. Then one can separate the different contributions to C_{gg} introducing the definition of auxiliary and regular functions

$$C_{\text{reg}}\left(N, \alpha_s, \frac{\mu_F^2}{m_H^2}\right) = \int d^2k_{t1} d^2k_{t2} \mathcal{C}\left(N, \frac{k_{t1}^2}{m_H^2}, \frac{k_{t2}^2}{m_H^2}, \alpha_s\right) U'_{\text{reg}}(N, k_{t1}^2, \mu_F^2) U'_{\text{reg}}(N, k_{t2}^2, \mu_F^2);$$

$$C_{\text{aux}}\left(N, \alpha_s, \frac{\mu_F^2}{m_H^2}\right) = \int d^2k_{t1} \mathcal{C}\left(N, \frac{k_{t1}^2}{m_H^2}, 0, \alpha_s\right) U'_{\text{reg}}(N, k_{t1}^2, \mu_F^2).$$

Differential results in Higgs production



The breakdown of the individual contributions to the resummed distribution at NLO differential in rapidity and transverse momentum squared at $q_t = 20GeV$

Where larger small-x resummation effects are expected?

The Higgs distribution

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$$x_{1,2} = \sqrt{\frac{\tau}{x}} e^{\pm(Y-y)}.$$

Detail on the rapidity dependence

At **central rapidity** Y

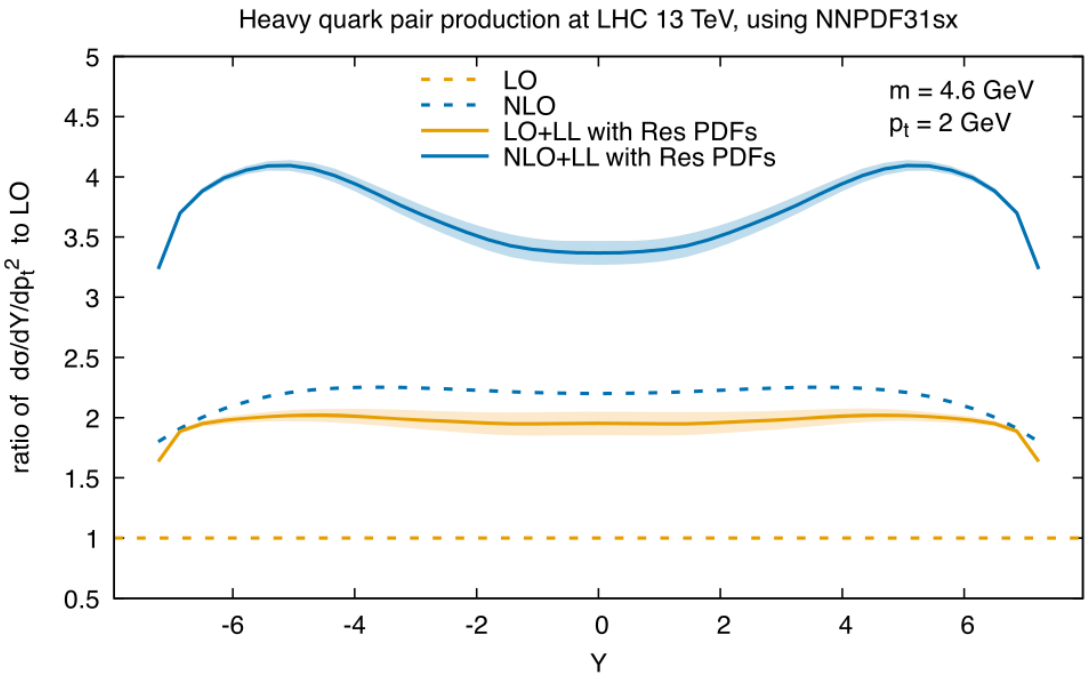
- The incoming momentum fractions are approximately symmetric:

$$x_1 \sim x_2.$$

At **large rapidity** $|Y|$

- Configurations where one incoming gluon carries very small-x.
- Small-x enhancement competes with suppression of the opposite large-x leg.

Resummation effect



[Silvetti,Bonvini 2211.10142]