

# Single and Double Higgs Production in GENEVA

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Istituto Nazionale di Fisica Nucleare



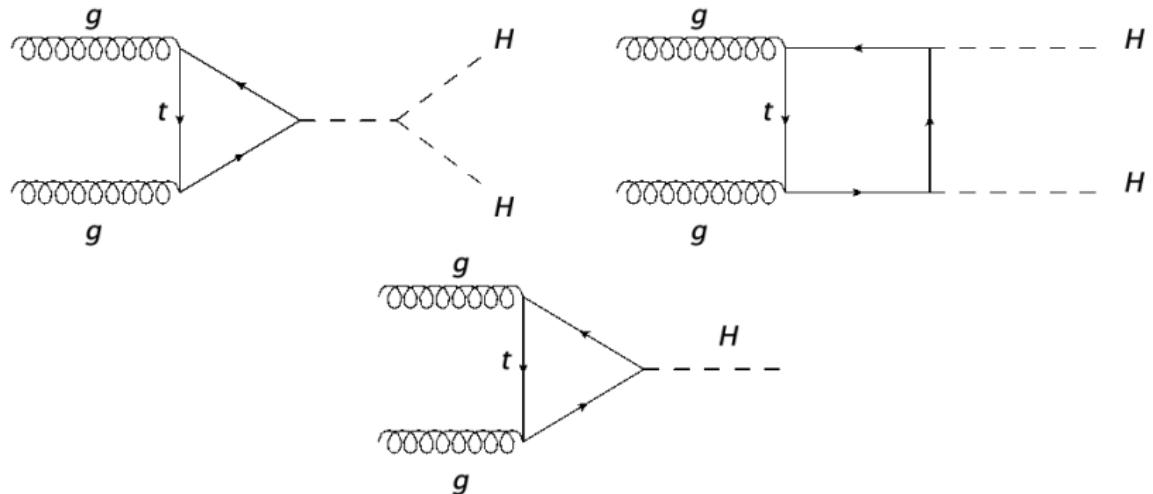
# Outline

- ▶ Single and Double Higgs production
- ▶ GENEVA features used
- ▶ Phenomenological results



# Single and Double Higgs production

- ▶ gluon fusion  $\Rightarrow p\ p \rightarrow g\ g \rightarrow HX/HHX$  in HTL,  $m_t \rightarrow \infty$



# Single Higgs production

## State of the art

- ▶ **Full  $m_t$  NNLO:** Czakon, Harlander et al. [2105.04436];
- ▶ **Incl. N<sup>3</sup>LO HTL:** Anastasiou, Duhr et al. [1503.06056, 1602.00695], Mistlberger, Dulat, et al. [1802.00833, 1802.00827] ;
- ▶ **Diff. N<sup>3</sup>LO HTL:** Dulat, Lionetti et al. [1704.08220], Dulat, Mistlberger et al. [1710.03016, 1810.09462]  
Cieri, Chen et al. [1807.11501]  
Chen, Gehrmann et al. [2102.07607];
- ▶ **NNLO + N3LL in  $p_T$ :** Chen, Gehrmann et al. [1805.00736], Bizon, Chen et al. [1805.05916];
- ▶ **NNLO + N3LL' in  $p_T$ :** Billis, Dehnadi et al. [2102.08039], Re, Rottoli et al. [2104.07509];
- ▶ **Mixed QCD-EW:** Bonetti, Melnikov et al. [1801.10403], Anastasiou, Del Duca et al. [1811.11211], Becchetti, Bonciani et al. [2010.09451];

# Double Higgs production

## State of the art

- ▶ **Full  $m_t$  NLO:** Borowka, Greiner et al. [1604.06447, 1608.04798],  
Baglio, Campanario et al. [1811.05692]
- ▶ **NNLO HTL:** de Florian, Grazzini et al. [1606.09519];
- ▶ **N3LO HTL:** Chen, Li et al. [1909.06808, 1912.13001] ;
- ▶ **NNLO+NNLL':** de Florian, Mazzitelli [1807.03704] ;
- ▶ **Full  $m_t$  NLO+NLL  $p_T$ :** Ferrera, Pires [1609.01691] ;
- ▶ **Monte Carlo full  $m_t$  NLO:** Heinrich, Jones et al. [1703.09252]  
Jones, Kuttimalai [1711.03319];
- ▶ **EFT full  $m_t$  NLO:** Buchalla, Capozi et al. [1806.05162];
- ▶ **EFT NNLO HTL:** de Florian, Fabre, Mazzitelli [1704.05700];
- ▶ **EFT approx. QCD NNLO:** de Florian, Fabre et al. [2106.14050].

# GENEVA framework: GENerate EVents Analytically

Fully differential fixed order calculations

up to NNLO through  $N$ -jettiness  $\mathcal{T}_N$  subtraction

$$\mathcal{T}_N = \sum_k \min\{q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, \dots, q_N \cdot p_k\}$$

beam  $q_{a,b}$  and jet  $q_{1,\dots,N}$  directions

Higher-logarithmic resummation

up to NNLL' through SCET

Parton showering, hadronization and MPI

currently using standard Pythia8 shower and new Dire shower.

## GENEVA features: beam, soft and hard functions

$$\begin{aligned}\frac{d\sigma^{\text{SCET}}}{d\Phi_0}(\mathcal{T}_0^{\text{cut}}) = & \int_0^{\mathcal{T}_0^{\text{cut}}} \sum_{i,j} \frac{d\sigma_{ij}^B}{d\Phi_0} \textcolor{blue}{H}_{ij}(Q^2, \mu_H) U_H(\mu_H, \mu) \\ & \times [\textcolor{brown}{B}_i(x_a, \mu_B) \otimes U_B(\mu_B, \mu)] \\ & \times [\textcolor{brown}{B}_j(x_b, \mu_B) \otimes U_B(\mu_B, \mu)] \\ & \otimes \textcolor{red}{S}(\mu_S) \otimes U_S(\mu_S, \mu)\end{aligned}$$

$U_H$ ,  $U_B$  and  $U_S$  renormalization group evolution factors;  
 $H$ ,  $\textcolor{brown}{B}_{a,b}$  and  $\textcolor{red}{S}$  respectively **hard**, **beams** and **soft** functions.

- ▶ Gluon beam function  $\Rightarrow$  taken from **SCETlib**;
- ▶ Hard function  $\Rightarrow$  taken from **SCETlib** for single Higgs prod.,  
for double Higgs prod. two-loop virtual  
corrections calculation [[arXiv:1305.5206](#), [1408.2422](#)];
- ▶ Soft function  $\Rightarrow$  taken from [arXiv:1012.4480](#).

## GENEVA features: splitting function on-the-fly

$$P_{N \rightarrow N+1}(\Phi_{N+1}) = \frac{f_{kj}(\Phi_N, \mathcal{T}_N, z, \phi)}{\sum_{kj} \int_{z_{\min}(\mathcal{T}_N)}^{z_{\max}(\mathcal{T}_N)} f_{kj}(\Phi_N, \mathcal{T}_N, z, \phi) J(\Phi_N, \mathcal{T}_N, z) dz d\phi}$$
$$J(\Phi_N, \mathcal{T}_N, z) = \frac{d\Phi_{N+1}}{d\Phi_N d\mathcal{T}_N dz d\phi}$$

$f_{kj}$  based on the Altarelli-Parisi splitting functions,  
integral computed for every  $\Phi_{N+1}$  configuration generated.

- Assuming that the jacobian does not depend on  $\phi$  for  $1 \rightarrow 0$  and  $2 \rightarrow 1$  mappings;
- Used both in single and double Higgs production.

## GENEVA features: timelike resummation

Timelike processes:  $q^2 = Q^2 > 0$

$$H(q^2, \mu) \propto L \equiv \ln \left( \frac{-q^2 - i0}{\mu^2} \right) = 2 \ln \left( \frac{-iQ}{\mu} \right) = -i\pi + 2 \ln \left( \frac{Q}{\mu} \right)$$

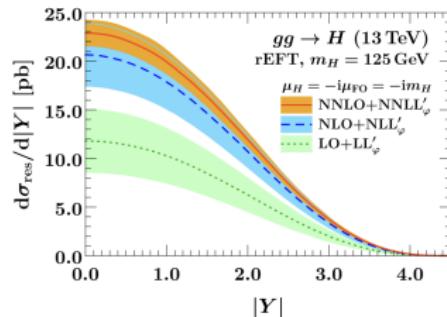
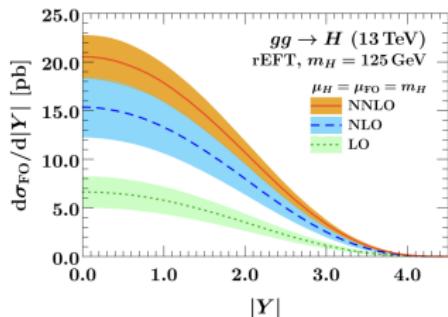
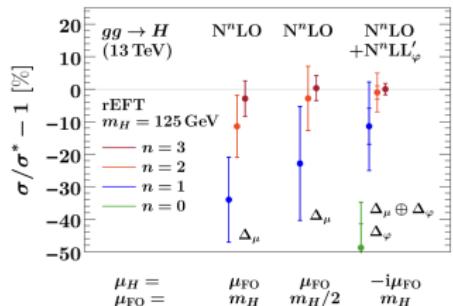
$$\mu = Q \quad \text{classical choice}$$

$$\mu = -iQ = Q e^{-i\varphi} \quad \text{timelike resummation}$$

- $\varphi = 0$  central value of FO prediction (no resummation);
- $\varphi = \frac{\pi}{2}$  central value of resummed prediction;
- $\varphi \in \left[ \frac{\pi}{4}, \frac{3\pi}{4} \right]$  phase variation of  $\pm \frac{\pi}{4}$ .

GENEVA  $\Rightarrow$  **SCETlib** interface for complex  $\alpha_S$  and scales.  
Timelike resummation implemented only in single Higgs production.

# GENEVA features: timelike resummation



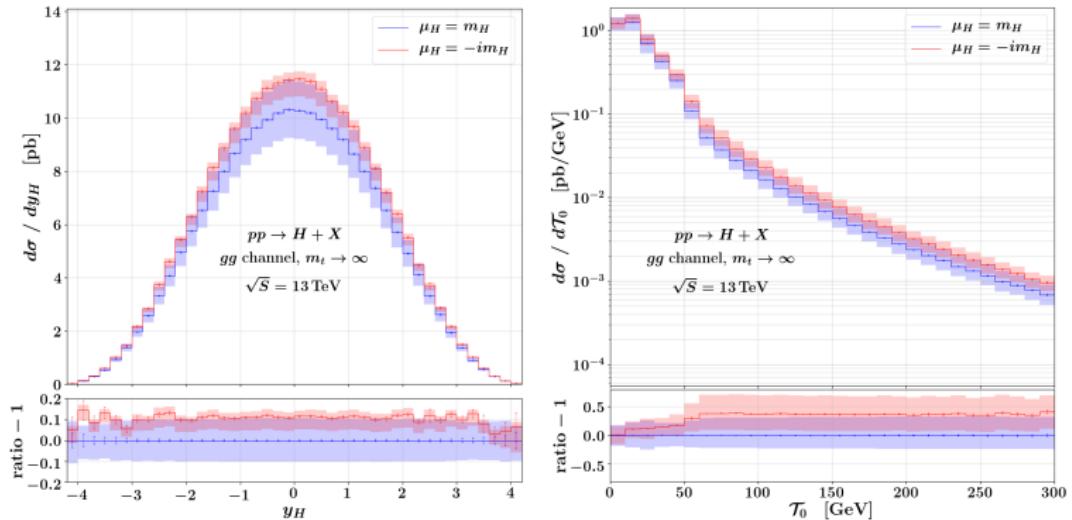
$\Delta_\mu$  fixed-order uncertainty;  
 $\Delta_\varphi$  resummation uncertainty;  
 $\Delta_\mu \oplus \Delta_\varphi = \sqrt{\Delta_\mu^2 + \Delta_\varphi^2}$ .

[arXiv:1702.00794]

Ebert, Michel and Tackmann

# Phenomenological results single Higgs production

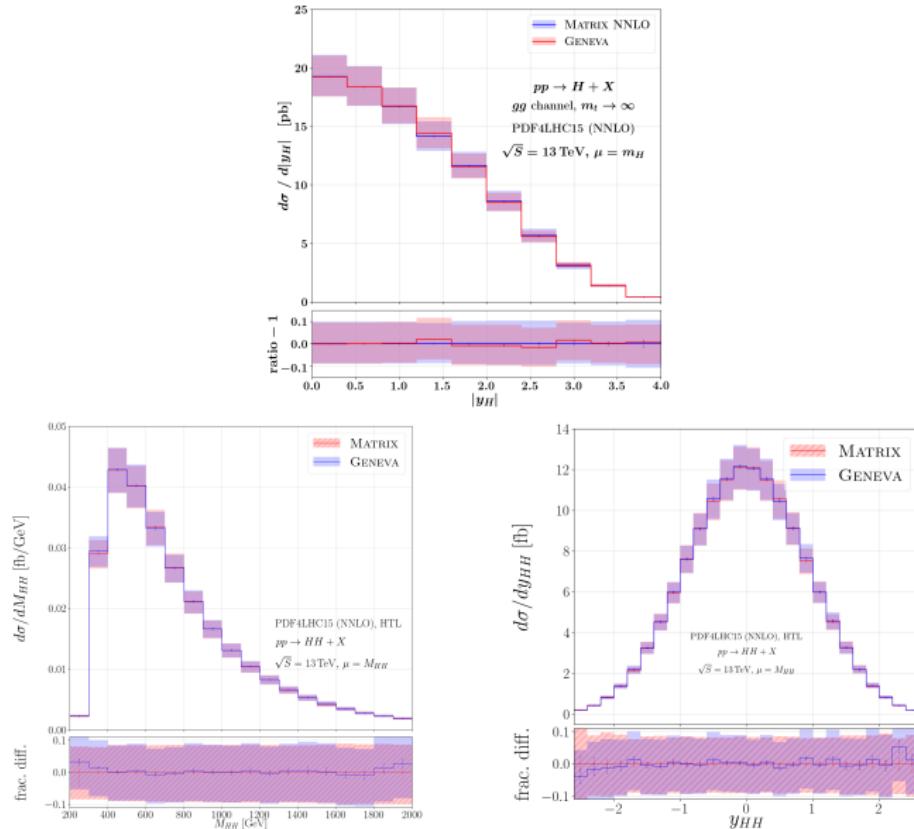
Effects of the timelike resummation:



7-points scale variations

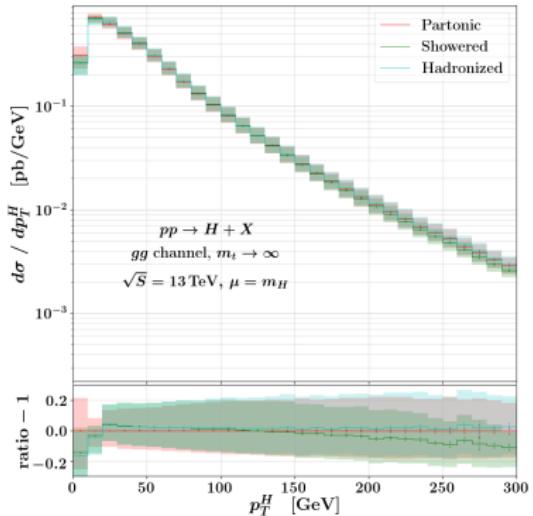
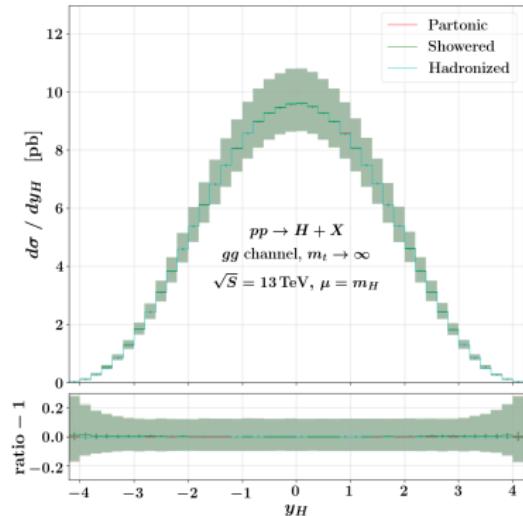
# Phenomenological results

## FO comparison against Matrix:



# Phenomenological single Higgs production

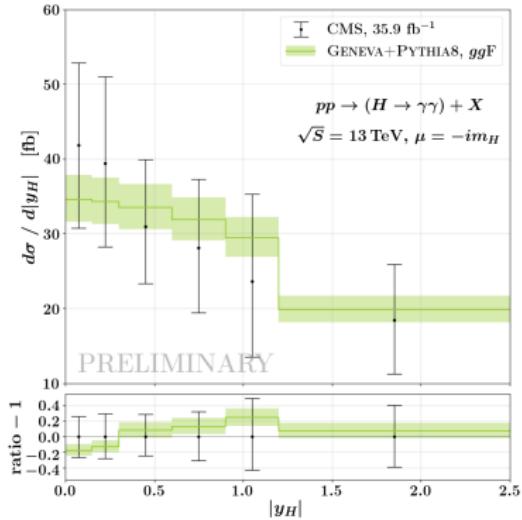
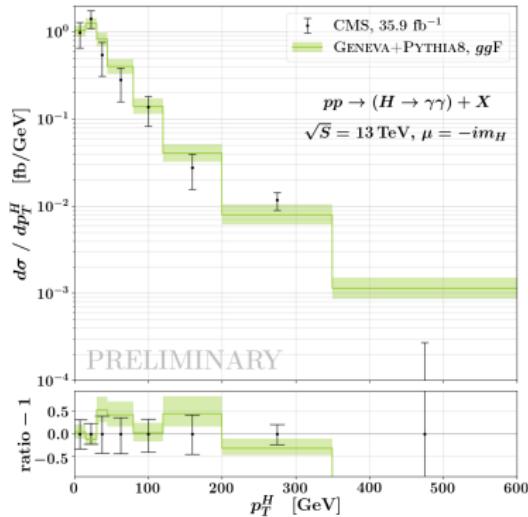
## Parton Shower and Hadronization: Higgs rapidity and $p_T$



Pythia8 Simple shower

# Phenomenological results single Higgs production

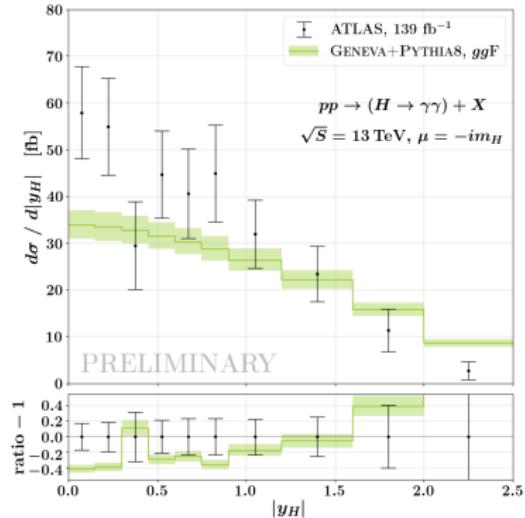
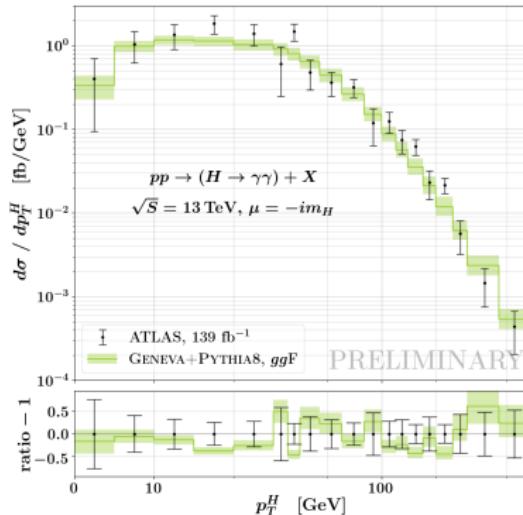
## Preliminary data comparison with CMS:



GENEVA timelike resummed, 7-points scale variations

# Phenomenological results single Higgs production

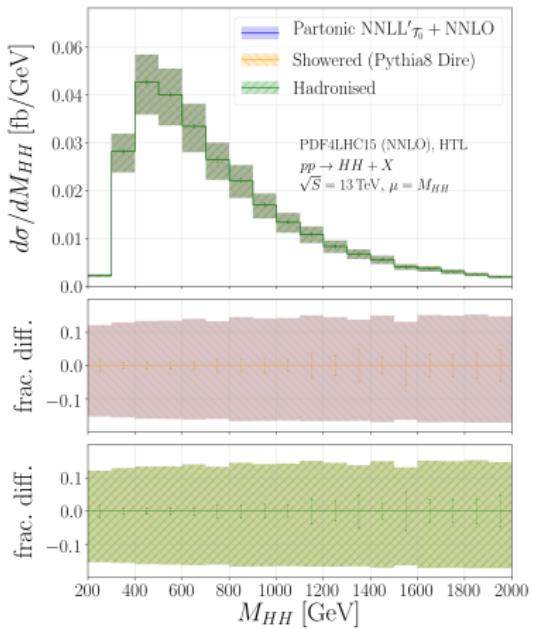
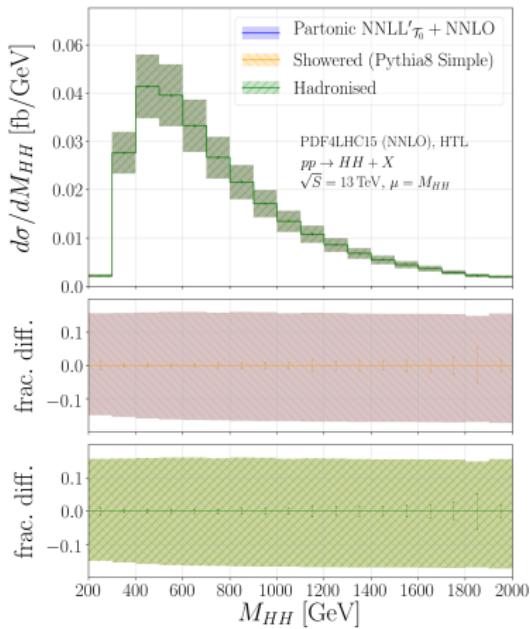
## Preliminary data comparison with ATLAS:



GENEVA timelike resummed, 7-points scale variations

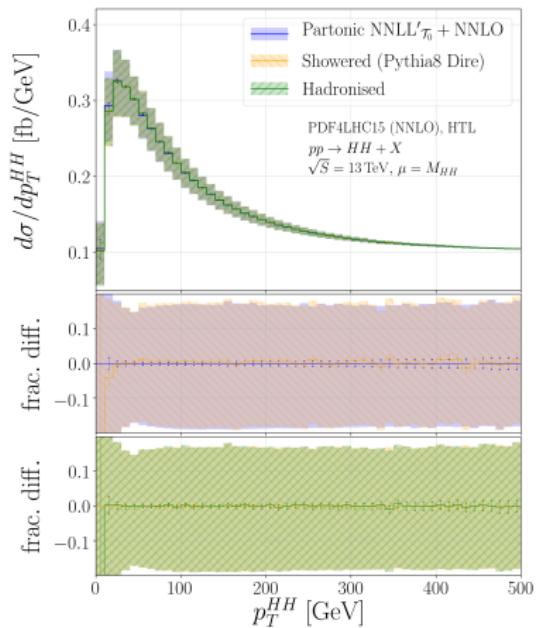
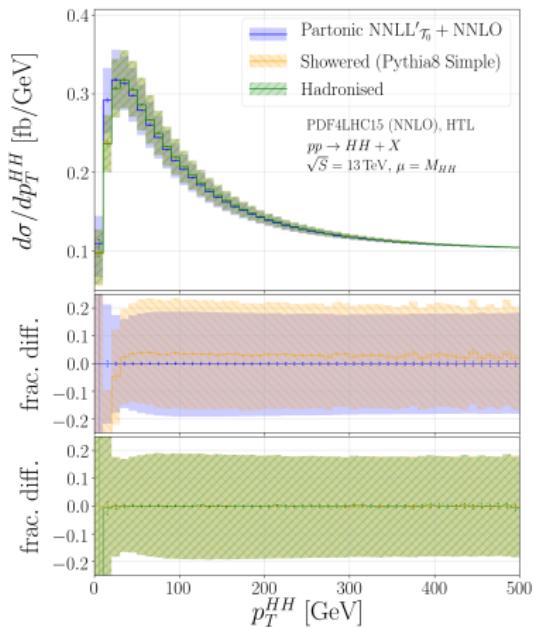
# Phenomenological results double Higgs production

## Parton Shower and Hadronization: Higgs pair invariant mass



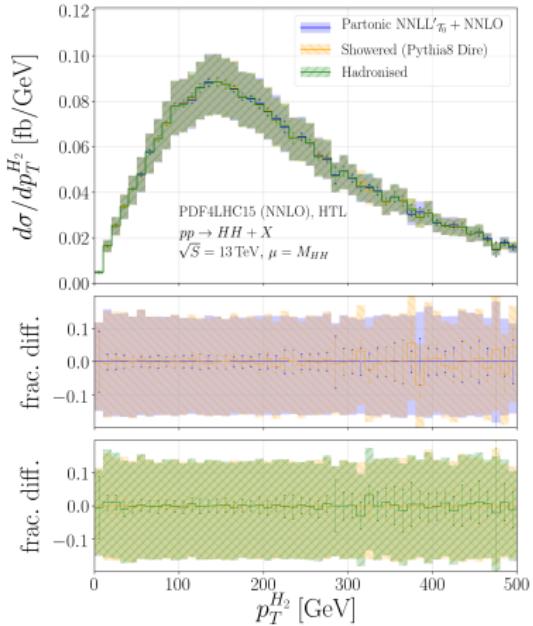
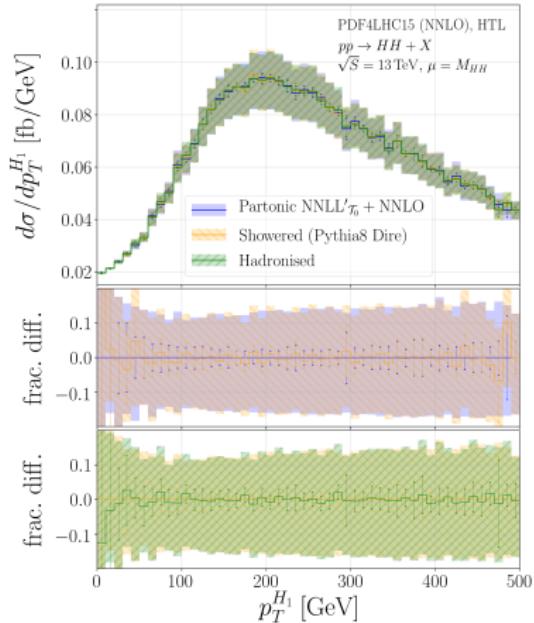
# Phenomenological results

## Parton Shower and Hadronization: Higgs pair $p_T$



# Phenomenological results

Parton Shower and Hadronization: Hardest( $H_1$ ) and softest ( $H_2$ )  
Higgs  $p_T$



**THANKS FOR YOUR ATTENTION!**

# Backup Slides

Timelike resummation:

$$H(q^2, \mu) = |\textcolor{orange}{C}(q^2, \mu)|^2 = 1 + H^{(1)}(q^2, \mu) + H^{(2)}(q^2, \mu) + \dots$$

$$H(q^2, \mu) = H(q^2, \mu_H) \textcolor{red}{U}_H(\mu_H, \mu)$$

$C(q^2, \mu)$  Wilson coefficients,  $U_H(\mu_H, \mu)$  matching coefficients.

$$\sigma(X) = H(Q^2, \mu_{\text{FO}}) \times R(X, \mu_{\text{FO}})$$

$$\begin{aligned} \sigma_{\text{res}} &= H(\mu_H) U_H(\mu_H, \mu_{\text{FO}}) R(\mu_{\text{FO}}) \\ &= U_H(\mu_H, \mu_{\text{FO}}) \sigma^{(0)} [1 + H^{(1)}(\mu_H) + R^{(1)}(\mu_{\text{FO}}) \\ &\quad + H^{(2)}(\mu_H) + R^{(2)}(\mu_{\text{FO}}) + H^{(1)}(\mu_H) R^{(1)}(\mu_{\text{FO}}) + \dots] \\ &= U_H(\mu_H, \mu_{\text{FO}}) \left[ \frac{H(\mu_H)}{H(\mu_{\text{FO}})} \sigma_{\text{FO}} \right]_{\text{FO}} \end{aligned}$$

$R(\mu_{\text{FO}})$  the remainder,  $[.]_{\text{FO}}$  fixed-order expansion in  $\alpha_S(\mu_{\text{FO}})$  and  $\alpha_S(\mu_H)$ ,  $\sigma_{\text{FO}}$  fixed-order cross section expanded in  $\alpha_S(\mu_{\text{FO}})$ .

# Backup Slides

CMS analysis:  $H \rightarrow \gamma\gamma$

- ▶  $\frac{p_T^{\gamma_1}}{m_{\gamma\gamma}} \geq \frac{1}{3}$  or  $\frac{p_T^{\gamma_2}}{m_{\gamma\gamma}} \geq \frac{1}{4}$ ;
- ▶ for each photon candidate the sum of the  $p_T$  of stable particles (contained in a cone of radius  $\Delta R = 0.3$ ) must be less than 10 GeV;
- ▶ charged leptons with  $p_T > 10$  GeV and  $|\eta| < 2.5$  are vetoed;
- ▶ events with missing  $p_T > 140$  GeV are vetoed.

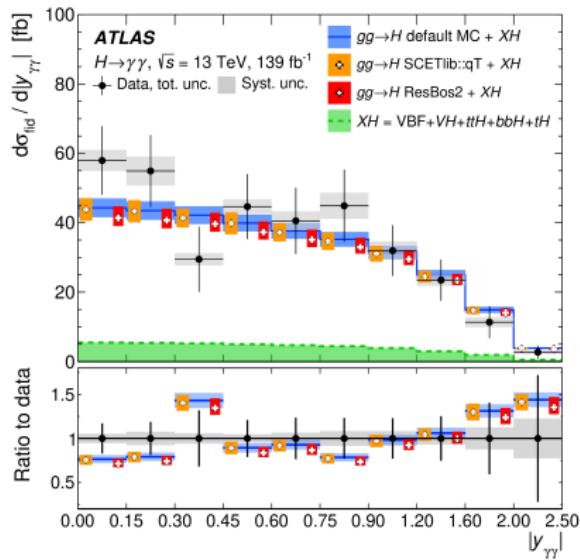
# Backup Slides

ATLAS analysis:  $H \rightarrow \gamma\gamma$

- ▶  $m_{\gamma\gamma} \geq 105$  GeV or  $m_{\gamma\gamma} \leq 160$  GeV;
- ▶  $\frac{p_T^{\gamma_1}}{m_{\gamma\gamma}} \geq 0.35$  or  $\frac{p_T^{\gamma_2}}{m_{\gamma\gamma}} \geq 0.25$ ;
- ▶  $|\eta_{1,2}| < 1.37$  or  $1.52 < |\eta_{1,2}| < 2.37$  (detector acceptance);
- ▶ for each photon candidate the sum of the  $p_T$  of tracks (contained in a cone of radius  $\Delta R = 0.2$ ) must be greater than 1 GeV;
- ▶ the sum of the  $p_T$  of tracks has to be less than  $5\% p_T^\gamma$ .

# Backup Slides

Measured differential cross-section probing the Higgs kinematic variable  $|y_{\gamma\gamma}|$ :



taken from [arXiv:2202.00487](https://arxiv.org/abs/2202.00487).