Higgs boson pair production at NLO in the POWHEG approach and the top quark mass uncertainties

Emanuele A. Bagnaschi (INFN LNF/CERN)

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

20 October 2023

Discussion on Monte Carlo at NLO QCD

Zoom

emanuele.bagnaschi@cern.ch

Introduction

Double Higgs production at the LHC

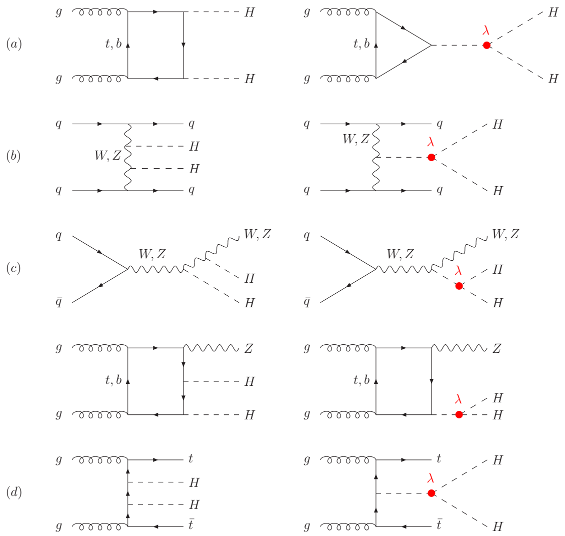
Production processes

(a) gluon fusion

(b) VBF

(c) double-Higgs strahlung

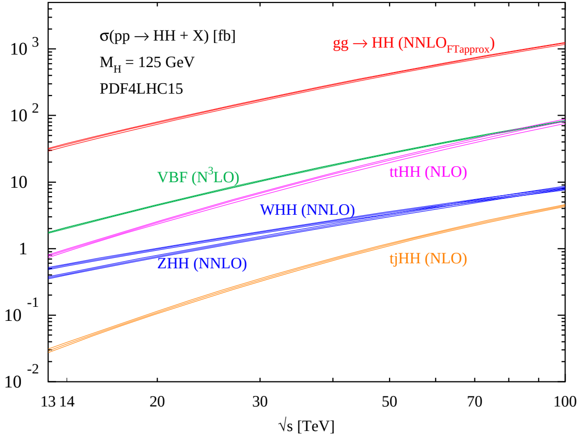
(d) top quark associated production



[Di Micco et al., Rev.Phys. 5 (2020) 100045]

Production channels

- Gluon fusion is the dominant production process



[Di Micco et al., Rev.Phys. 5 (2020) 100045]

Theoretical status of $ggHH$ calculations

Available results

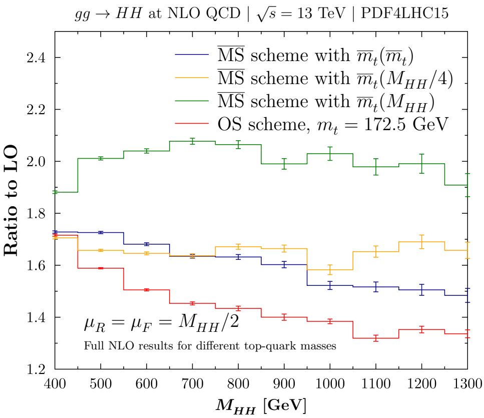
- NLO in the $m_t \to \infty$ limit [Dawson et al. PRD58 (1998) 115012]
- Full NLO [Borowka et al., PRL17 (2016) 012001; Baglio et al., EPJC79 (2019) 6, 459; Baglio et al., JHEP 04 (2020) 181]
- NNLO in the $m_t \to \infty$ limit [de Florian et al, PRL111 (2013) 201801]
- NNLL in in the $m_t \to \infty$ [Shao et al., JHEP07 (2013) 169; de Florian et al, JHEP09 (2015) 053]
- NNLO FTa [Grazzini et al, JHEP05 (2018) 059]
- Differential NNLO in the $m_t \to \infty$ [De Florian et al., JHEP09 (2016) 151]
- Approximate NNLO QCD[JHEP 09 (2021) 161]
- Virtual corrections for NNLO in the $m_t \to \infty$ limit [De Florian et al., PLBB724 (2013) 306; Grigo et al., NPB888 (2014) 17]
- 2-loop matrix elements using HE expansion [Davies et al., JHEP 03 (2018) 048; Davies et al.,JHEP 01 (2019) 176]
- 2-loop matrix elements using p_T expansion, combination with HE expansion [Bonciani et al., PRL121 (2018), 16200; Bellafronte et al., JHEP 07 (2022) 069]
- 2-loop matrix elements using small mass expansion [Xu et al., JHEP 01 (2019) 211; Want et al., , PRD104 no. 5, (2021)]
- Monte Carlo full NLO [Heinrich et al., JHEP08 (2017) 088; Jones et al., JHEP02 (2018) 176; Heinrich et al., JHEP10 (2020) 021]
- Top scheme uncertainties [Baglio et al., PRD 103 (2021) 5, 056002]

...

Impact of the choice of the top mass scheme

Top scheme uncertainty

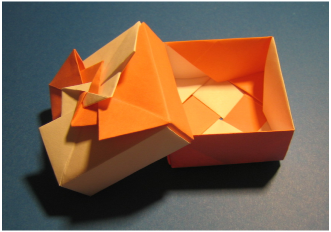
- Uncertainty due to the renormalization scheme choice of the top Yukawa
- First shown in [Baglio et al., EPJC79 (2019) 6, 459]
- More in depth studied in [Baglio et al., PRD 103 (2021) 5, 056002]



Yet another Monte Carlo

Our goal

- Currently available Monte Carlo event generator in the `POWHEG-BOX` is based around the 2-loop results of Borowka et al., PRL17 (2016) 012001, which are implemented using a series of interpolation grids (to account for modified trilinears etc.) matched with the HE expansion
- Fixed values of the input parameters; no possibility of changing the top mass scheme;
- Develop a new MC event generator based around the p_T and HE expansions
- Allow to vary the input parameters; implement renormalization scheme dependence



The 2-loop amplitudes: transverse momentum expansions

- The $gg \to HH$ amplitude can be written as

$$A^{\mu\nu} = \frac{G_\mu}{\sqrt{2}} \frac{\alpha_S(\mu_R)}{2\pi} \delta_{ab}\, T_F\, \hat{s}\, [A_1^{\mu\nu}\, F_1 + A_2^{\mu\nu}\, F_2]$$

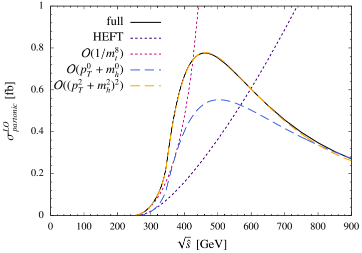
- The transverse momentum can be written in terms of Mandelstam variables

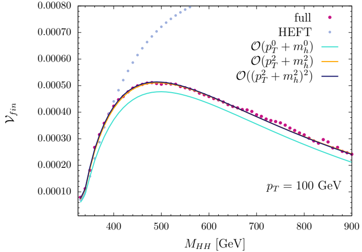
$$(p_T^H)^2 = \frac{\hat{t}\hat{u} - m_h^4}{\hat{s}}$$

- Rewritten as

$$(p_T^H)^2 = \frac{\hat{t}\hat{u} - m_h^4}{\hat{s}}$$

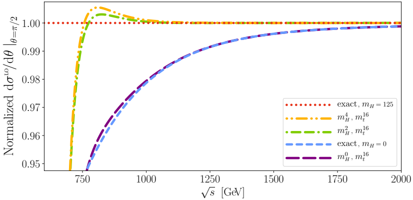
- Expand in $p_\perp^2/s' \ll 1$ and $m_h^2/s' \ll 1$ where $s' = \hat{s}/2$
- Very good description up to $\hat{s} < 750$ GeV.

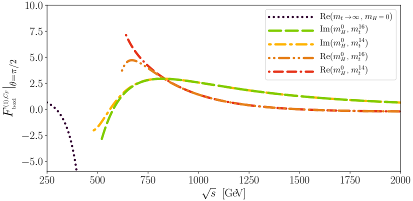




[Bonciani et al., PRL121 (2018), 16200]

- High-energy expansion of the two loop form factors
- Valid down to around 700 GeV
- Complementary range with respect to the p_T^H expansion



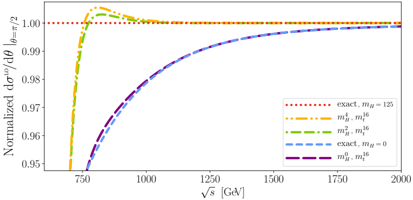


Cross-check at LO

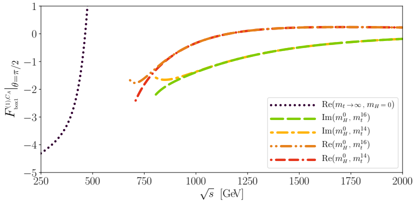
[Davies et al., JHEP 03 (2018) 048; Davies et al.,JHEP 01 (2019) 176];

The 2-loop amplitudes: high-energy expansion

- High-energy expansion of the two loop form factors
- Valid down to around 700 GeV
- Complementary range with respect to the p_T^H expansion



Cross-check at LO



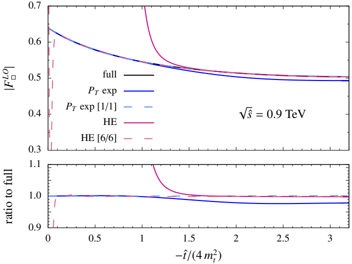
[Davies et al., JHEP 03 (2018) 048; Davies et al.,JHEP 01 (2019) 176];

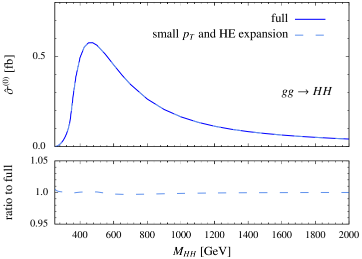
The 2-loop amplitudes: combining the two expansions

- The two expansions work well in complementary kinematic range
- Build a combined result that therefore reproduces very well the full top mass dependence all across the phase space
- Padé approximant

$$[m/n](x) = \frac{p_0 + p_1 x + \cdots + p_m x^m}{1 + q_1 x + \ldots q_n x^n}$$

- [1/1] for the p_T^H expansion, [6/6] for the HE expansion sufficient to have a good behavior across all the $\sqrt{\hat{s}}$ range



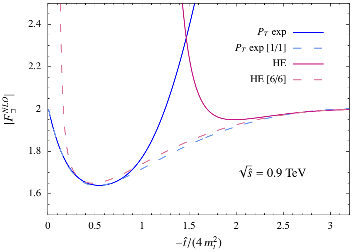


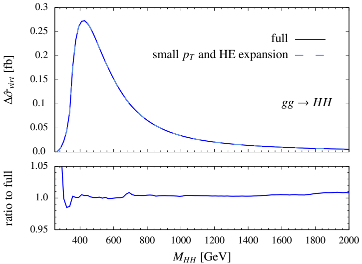
The 2-loop amplitudes: combining the two expansions

- The two expansions work well in complementary kinematic range
- Build a combined result that therefore reproduces very well the full top mass dependence all across the phase space
- Padé approximant

$$[m/n](x) = \frac{p_0 + p_1 x + \cdots + p_m x^m}{1 + q_1 x + \ldots q_n x^n}$$

- [1/1] for the p_T^H expansion, [6/6] for the HE expansion sufficient to have a good behavior across all the $\sqrt{\hat{s}}$ range





The Monte Carlo

The MC framework

- We implement a MC in the **POWHEG-BOX** framework that uses the Padé-combined expansions as the two-loop matrix elements
- The real matrix elements is obtained with **MadLoop**

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}O}\right)_{\texttt{POWHEG}} = \sum_{n\geq 1}\int \Bigg[\bar{B}^s\,\mathrm{d}\Phi_B\left\{\Delta^s_{t_{\min}} + \Delta^s_t\,\frac{R^s_{\texttt{POWHEG}}}{B}\mathrm{d}\Phi_r\right\}$$

$$+R^f_{\texttt{POWHEG}}\otimes\Gamma\,\mathrm{d}\Phi \;+ R_{\mathrm{reg}}\otimes\Gamma\,\mathrm{d}\Phi\,\Bigg]\frac{\mathrm{d}\Phi^{MC}_{n-1}}{\mathrm{d}O}\mathcal{I}_{n-1}(t_1\equiv p^{\mathrm{rad}}_{\perp})$$

$$\overline{B}^S = B(\Phi_b) + \left[V(\Phi_b) + \int \mathrm{d}\Phi_{R|B}\hat{R}^S_{\texttt{POWHEG}}(\Phi_{R|B})\right]$$

$$\Delta^s_t(\bar{\Phi}_B, p_T) = \exp\left\{-\int d\Phi_{\mathrm{rad}}\,\frac{R^S_{\texttt{POWHEG}}(\bar{\Phi}_B,\Phi_{\mathrm{rad}})}{B(\Phi_1)}\theta(k_T - p_T)\right\}$$

$$R^S_{\texttt{POWHEG}} = \frac{h^2}{h^2+p_T^2}R \quad , \quad R^f_{\texttt{POWHEG}} = \frac{p_T^2}{h^2+p_T^2}R$$

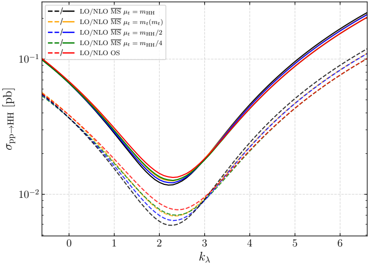
Results

Setup and input parameters

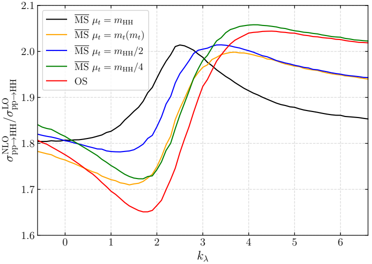
Setup

- LHC, $\sqrt{S} = 13.6$ TeV
- `NNPDF31_as_0118_NLO`
- $\mu_R = \mu_F = M_{HH}/2$
- $M_H = 125$ GeV, $M_T = 172.5$ GeV
- Consider both OS M_T and $\overline{MS}$ m_t ($\mu_t = m_t(m_t), m_{HH}/2, m_{HH}/4, m_{HH}$)

Inclusive cross sections and k-factors



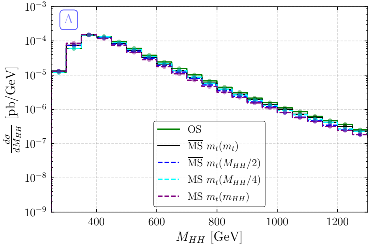
- Total inclusive cross section at LO and NLO for different values of k_λ and different choices of the top mass renormalization scheme

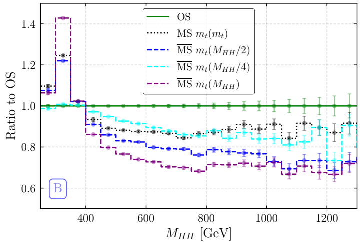


- K-factors for different top mass scheme choices

- Minimum of the cross section depends on the top scheme
- As expected, the difference between the schemes is smaller at NLO
- We have found some disagreement with existing calculations, currently under investigation $\to$ see Gudrun's talk for an update of the existing `POWHEG-BOX` Monte Carlo

SM top scheme dependence: M_{HH}



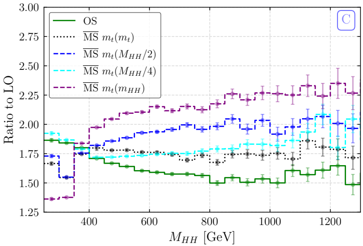


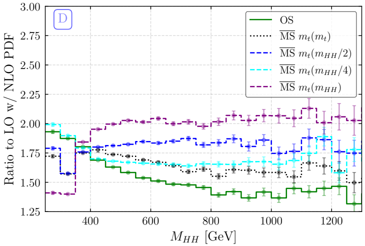
- Absolute distributions for different top mass schemes

- Ratio to the OS prediction at NLO

- Different top mass scheme $\longrightarrow$ tilt of the distribution around the peak
- Largest effect for $m_t(M_{HH})$

SM top scheme dependence: M_{HH}



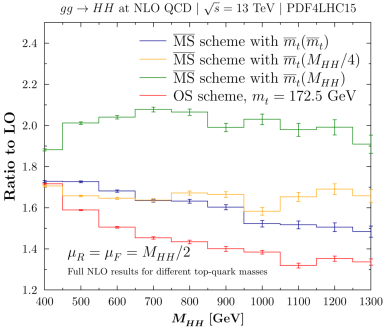


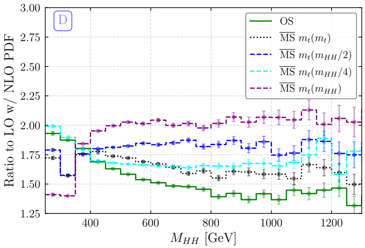
- K-factor for various scheme choices

- Ratio to LO while using the same PDFs and $\alpha_s \rightarrow$ highlight the difference in the ME (cfr. 2008.11626)

- Smallest k-factor for the OS above the peak
- Largest k-factor for the $\overline{\text{MS}}$ scheme and $m_t(m_{HH})$

SM top scheme dependence: M_{HH}

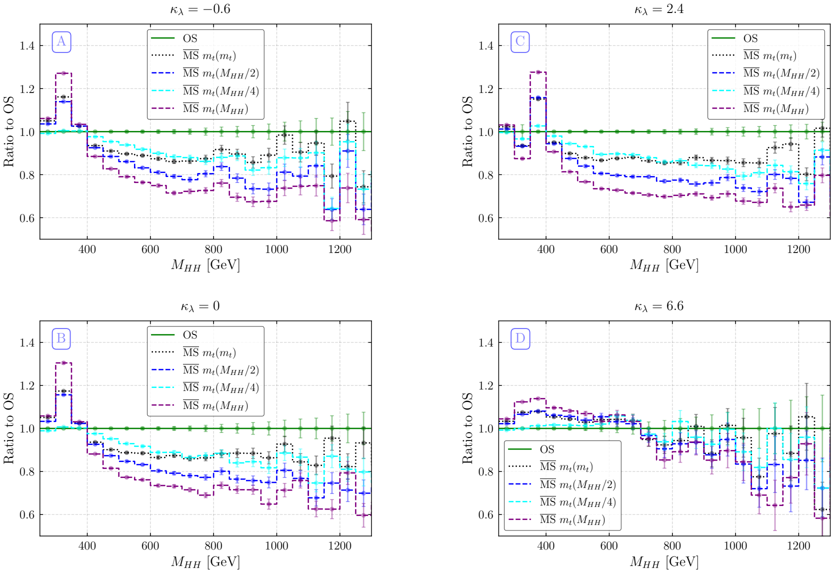




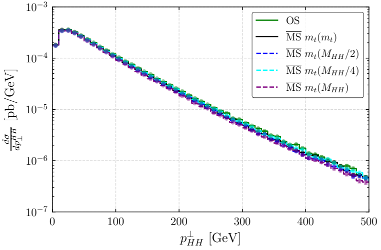
[Baglio et al., PRD 103 (2021) 5, 056002, hep-ph/2008.11626]

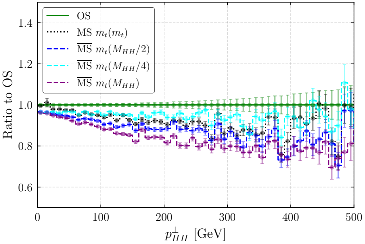
- Very good agreement even if the setup is slightly different

Top scheme dependence with a modified trilinear



Transverse momentum distribution of the Higgs pair

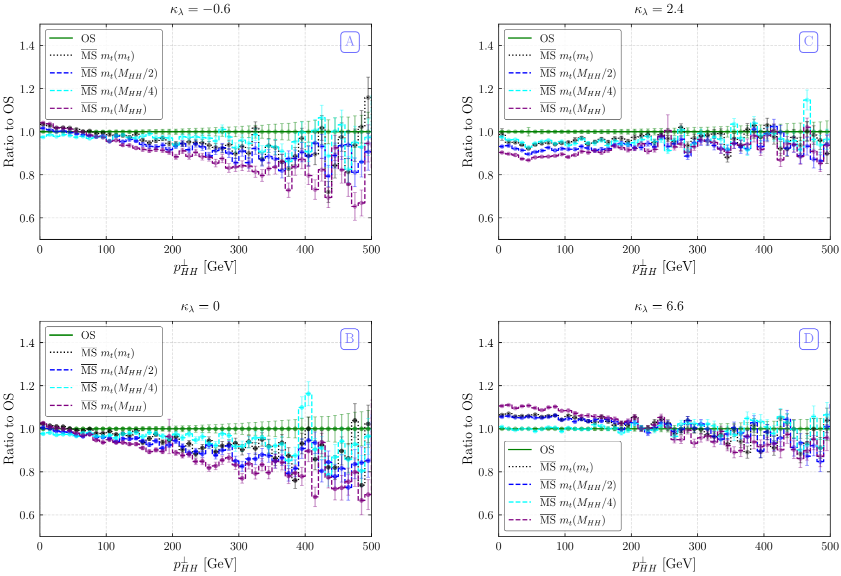




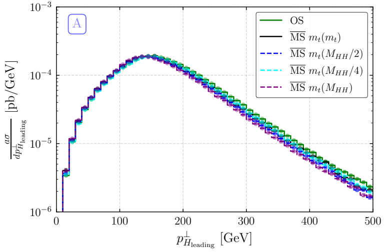
- Absolute distributions for different top mass schemes
- Ratio to the OS prediction at NLO

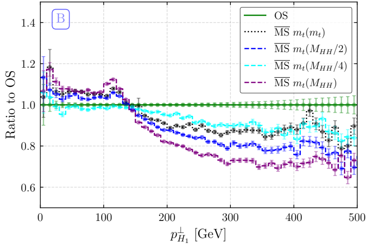
- Different top mass scheme $\rightarrow$ different slope of the p_{HH} distribution
- Largest effect for $m_t(M_{HH})$

Top scheme dependence with a modified trilinear



$p^{\perp}_{H_1}$ in the SM

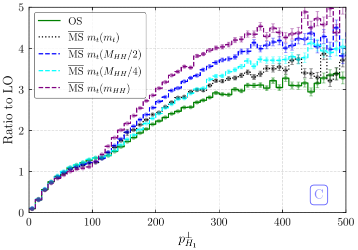


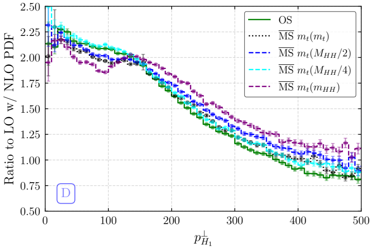


- Absolute distributions for different top mass schemes
- Ratio to the OS prediction at NLO

- Different top mass scheme $\rightarrow$ different slope of the p_{HH} distribution above the treshold
- Largest effect for $m_t(M_{HH})$

$p^{\perp}_{H_1}$ in the SM

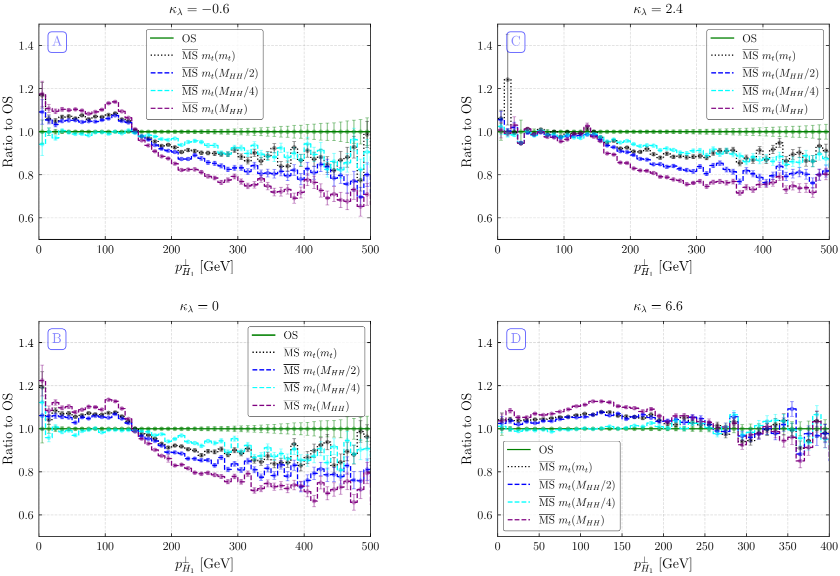




- K-factor for various scheme choices
- Ratio to LO while using the same PDFs and α_S $\rightarrow$ highlight the difference in the ME (cfr. 2008.11626)

- Smallest k-factor for the OS above the peak
- Largest k-factor for the $\overline{\text{MS}}$ scheme and $m_t(m_{HH})$

Top scheme depence for $p^{\perp}_{H_1}$



Outlook

- We have developed a new Monte Carlo event generator in the `POWHEG-BOX` framework that includes the possibility of varying the trilinear coupling of the Higgs and the input parameters
- Gives the possibility of studying the uncertainty from the top mass scheme directly at the analysis level
- It will be made available in the `POWHEG-BOX` svn repository
- Future developments: possibility of rescaling the top Yukawa coupling; production of *HH* via an heavy resonance