Towards precise predictions for $p_\perp$ Higgs distributions in BSM physics

Emanuele A. Bagnaschi (DESY Hamburg)

In collaboration with Robert Harlander (U. Wuppertal), Heindrik Mantler (CERN), Marius Wiesemann (U. Zurich) and Alessandro Vicini (U. Milano)

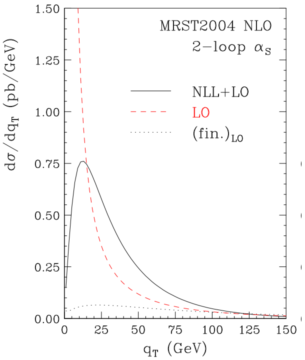
References: hep-ph/1505.00735 and hep-ph/1409.0531.

The 10th Workshop of the LHC Higgs Cross Section Working Group
15 July 2015
CERN

Talk structure

The p_T^H distribution

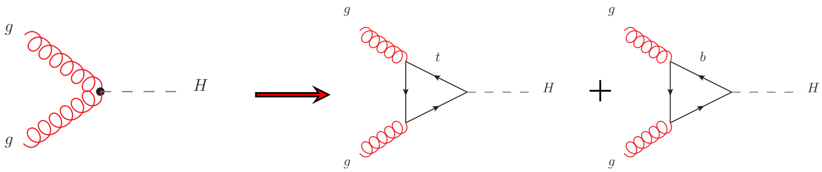
- The Higgs acquires a transverse momentum due to the recoil against QCD radiation.
- At fixed order, the p_T^H distribution diverges in the limit $p_T^H \to 0$.
- The physical behavior is restored by resumming the divergent $\log\left(\frac{p_T^H}{m_H}\right)$ terms, either analytically or numerically (i.e. through a Parton Shower).
- problem: match the resummed and fixed order calculation.
- Uncertainty estimation in this procedure is important for precision phenomenology.



Available resummation frameworks

- **Analytic resummation** (Catani, Grazzini). Dependence on the unphysical resummation scale can be used to probe the missing higher-order terms.
- **NLO+PS,** `MC@NLO` (Frixione, Webber). Variation of the shower scale used to probe the matching uncertainty.
- **NLO+PS,** `POWHEG` (Frixione, Nason, Oleari). The damping factor D_h can control higher-order terms in the matching procedure.

A problem of three scales



- The inclusion of the bottom quark adds a mass scale that is much lower with respect to the others (m_b and m_t).
- We can always rewrite the full amplitude as

$$|\mathcal{M}(t+b)|^2 = |\mathcal{M}(t)|^2 + |\mathcal{M}(b)|^2 + \left[|\mathcal{M}(t+b)|^2 - |\mathcal{M}(t)|^2 - |\mathcal{M}(b)|^2\right].$$

- One should introduce separate resummation scales for the top (Q_t), the bottom (Q_b) and the interference (Q_{int}) contributions and rewrite the formula for the total cross section as

$$\sigma(t+b) = \sigma(t, Q_t) + \sigma(b, Q_b) + [\sigma(t+b, Q_{\text{int}}) - \sigma(t, Q_{\text{int}}) - \sigma(b, Q_{\text{int}})].$$

- We extend the same reasoning to differential distributions.

Description of the Higgs p_T in the 2HDM

A prescription for the choice of the relevant scales is especially important when the bottom is dominant.

Bagnaschi-Vicini (BV)

- Based on the idea that the resummation should be applied when the collinear limit is a good approximation.
- Parton-level analysis of the behavior of the squared matrix elements.

Harlander-Mantler-Wiesemann (HMV)

- Assume that we want to recover the NLO behavior sufficiently fast for $p_T \gtrsim m_H$.
- Hadronic-level analysis (positivity, NLO matching) of the transverse momentum distribution.

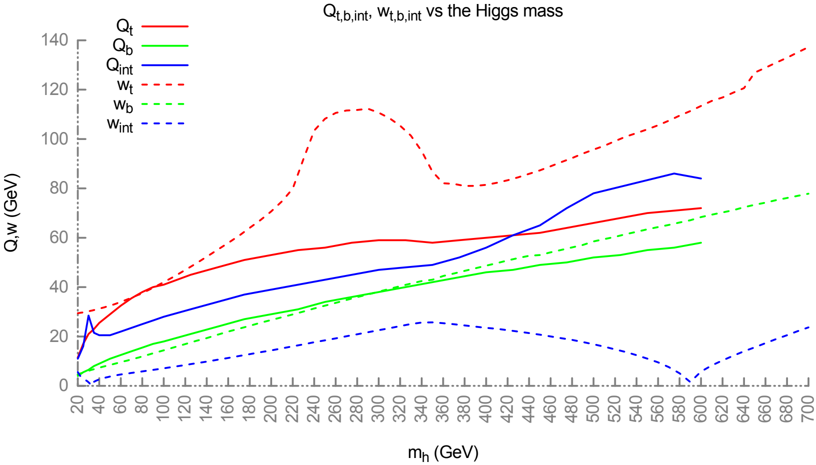
Analytic Resummation

- `MoRe-SusHi` by Harlander et al.

Monte Carlo event generators

- The `POWHEG-BOX` `gg_H_2HDM` generator (Bagnaschi et al).
- The `MadGraph5_aMC@NLO` generator based on `SusHi` (M. Wiesemann).

Comparison of the scale sets



- Similar behavior for the bottom scale.
- Different behavior (especially around the two-top threshold), though compatible, for the top quark contribution.
- Opposite behavior for the interference scale when the interference terms goes to zero.

Comparison of the hadronic predictions

We show the comparison of the results obtained with

Analytic resummation (NLO+NLL),

NLO+PS POWHEG (NLO+LL),

NLO+PS MC@NLO (NLO+LL).

- 2HDM scenario B (hep-ph/1312.5571):

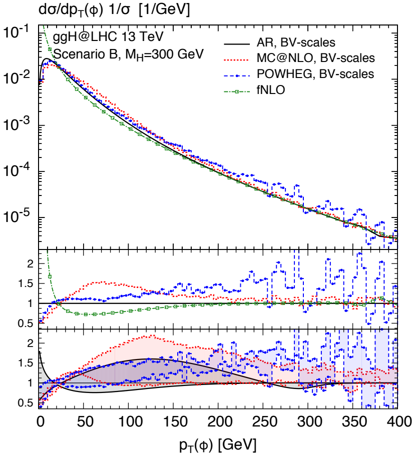
  $$\tan\beta = 50,\ \sin(\beta-\alpha) = 0.999,\ m_h = 125\ \text{GeV},\ m_H = 300\ \text{GeV},\ m_A = 270\ \text{GeV}.$$

- 2HDM large-top scenario

  $$\tan\beta = 1,\ \sin(\beta-\alpha) = 0.999,\ m_h = 125\ \text{GeV},\ m_H = 300\ \text{GeV},\ m_A = 270\ \text{GeV}.$$

- We have considered the shape of the distribution (i.e. $1/\sigma\, d\sigma/dp_T$) for h, H and A production.
- Uncertainty band computed by varying **only** the matching scale using the rescaling-factor combination $\{Q_t/2,\ Q_t,\ 2\cdot Q_t\} \times \{Q_b/2,\ Q_b,\ 2\cdot Q_b\} \times \{Q_i/2,\ Q_b,\ 2\cdot Q_i\}$ and then taking the envelope of the results.
- A more complete study, considering also different scenarios, is underway.

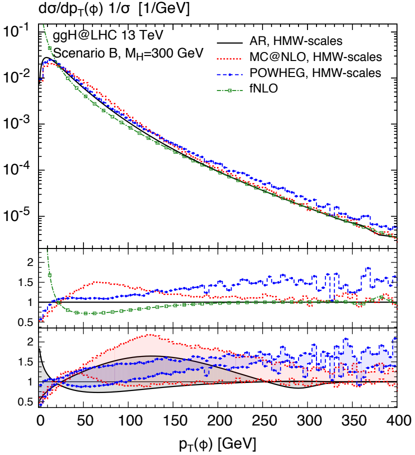
Scenario B – Matching uncertainty



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	111	Q_t	59
w_b	38	Q_b	38
w_{int}	23	Q_{int}	47

- Bottom dominated scenario.
- Comparison at fixed scales (**BV**) of the different tools.
- Same behavior of the MCs up to 25 GeV. In the intermediate region POWHEG is flatter, then the two curves cross at $p_T \simeq 150$ GeV.
- Overlap of the uncertainty bands.
- Different shape of the POWHEG vs MC@NLO band understood to be due to the very different distribution of the shower scale.

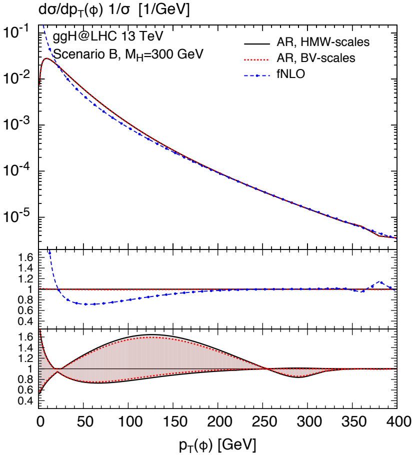
Scenario B – Matching uncertainty



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	111	Q_t	59
w_b	38	Q_b	38
w_{int}	23	Q_{int}	47

- Bottom dominated scenario.
- Comparison at fixed scales (**HMW**) of the different tools.
- Same behavior of the MCs up to 25 GeV. In the intermediate region POWHEG is flatter, then the two curves cross at $p_T \simeq 150$ GeV.
- Overlap of the uncertainty bands.
- Different shape of the POWHEG vs MC@NLO band understood to be due to the very different distribution of the shower scale.

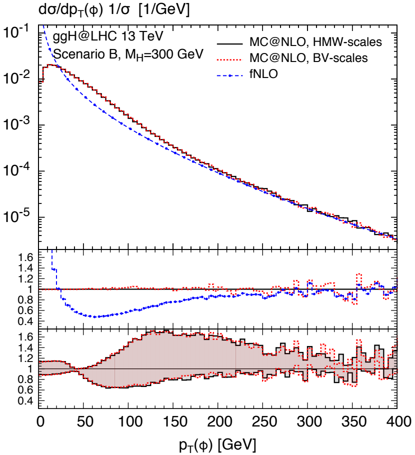
Scenario B – Scale sensitivity



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	111	Q_t	59
w_b	38	Q_b	38
w_{int}	23	Q_{int}	47

- Bottom dominated scenario.
- Fixed tool (**AR**), all scales compared.
- Same scale for the bottom quark.
- Scenario is bottom dominated, the bands are practically identical.

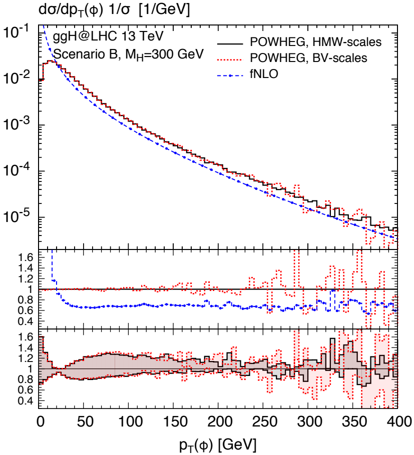
Scenario B – Scale sensitivity



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	111	Q_t	59
w_b	38	Q_b	38
w_{int}	23	Q_{int}	47

- Bottom dominated scenario.
- Fixed tool (MC@NLO), all scales compared.
- Same scale for the bottom quark.
- Scenario is bottom dominated, the bands are practically identical.

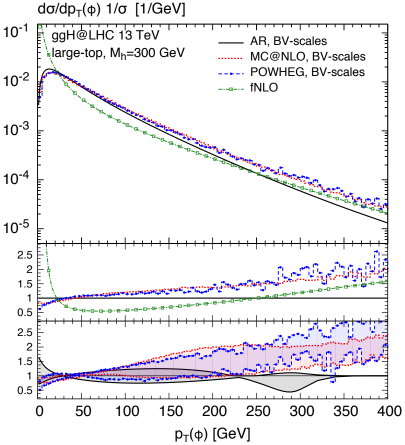
Scenario B – Scale sensitivity



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	111	Q_t	59
w_b	38	Q_b	38
w_{int}	23	Q_{int}	47

- Bottom dominated scenario.
- Fixed tool (POWHEG), all scales compared.
- Same scale for the bottom quark.
- Scenario is bottom dominated, the bands are practically identical.

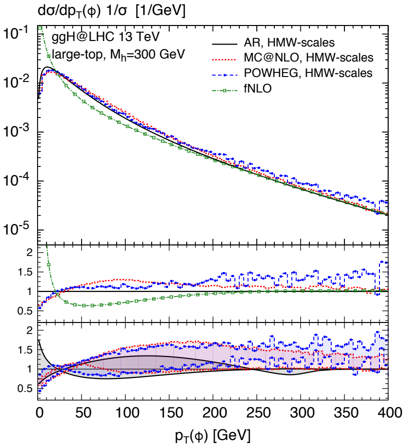
H, large t scenario – Matching uncertainty



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	111	Q_t	59
w_b	38	Q_b	38
w_{int}	23	Q_{int}	47

- Bottom dominated scenario.
- Comparison at fixed scales (**BV**) of the different tools.
- Same behavior of the MCs up to 25 GeV. In the intermediate region POWHEG is flatter, then the two curves cross at $p_T \simeq 150$ GeV.
- Overlap of the uncertainty bands.
- Very similar shape of the uncertainty band for the MCs.

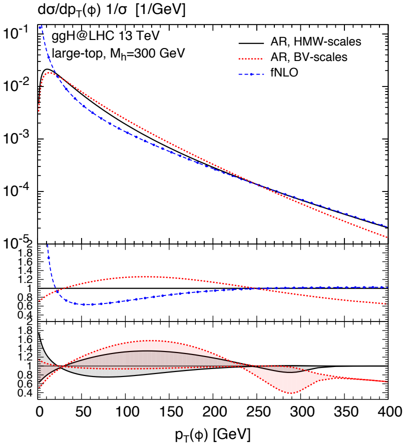
H, large t scenario – Matching uncertainty



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	111	Q_t	59
w_b	38	Q_b	38
w_{int}	23	Q_{int}	47

- Bottom dominated scenario.
- Comparison at fixed scales (**HMW**) of the different tools.
- Same behavior of the MCs up to 25 GeV. In the intermediate region POWHEG is flatter, then the two curves cross at $p_T \simeq 150$ GeV.
- Overlap of the uncertainty bands.
- Very similar shape of the uncertainty band for the MCs.

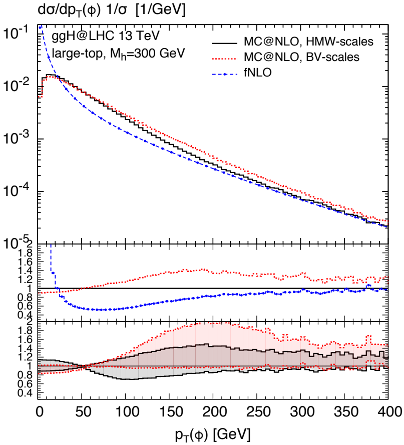
H, large t – Scale sensitivity



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	111	Q_t	59
w_b	38	Q_b	38
w_{int}	23	Q_{int}	47

- Top dominated scenario.
- Fixed tool (**AR**), all scales compared.
- Different scales for the top quark.
- Deviation of the central value predictions.

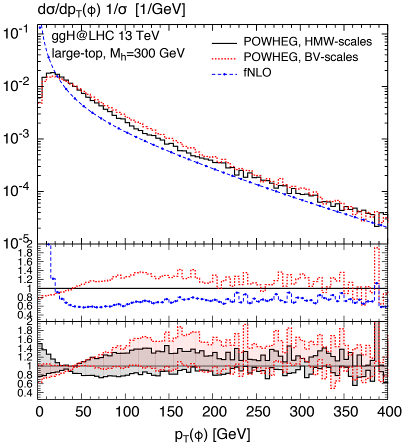
H, large t – Scale sensitivity



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	111	Q_t	59
w_b	38	Q_b	38
w_{int}	23	Q_{int}	47

- Top dominated scenario.
- Fixed tool (MC@NLO), all scales compared.
- Different scales for the top quark.
- Deviation of the central value predictions.

H, large t – Scale sensitivity



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	111	Q_t	59
w_b	38	Q_b	38
$w_{\rm int}$	23	$Q_{\rm int}$	47

- Top dominated scenario.
- Fixed tool (POWHEG), all scales compared.
- Different scales for the top quark.
- Deviation of the central value predictions.

Conclusions

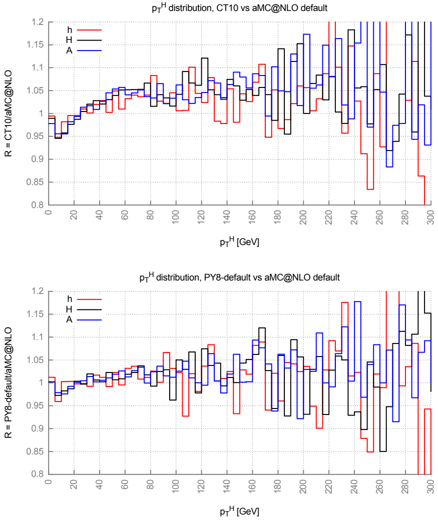
- We compared three different tools available to compute the transverse momentum spectrum in the 2HDM (POWHEG gg_H_2HDM, aMC@NLO and MoRe-SusHi).
- Two prescriptions available to determine the scales for a proper description of the p_T spectrum of the Higgs boson.
- Especially for a heavy Higgs, significant difference with the standard prescription $m_h/2$ (or $m_h/1.2$).
- Even with different scale choices the MCs uncertainty bands overlap.
- Our analysis can be used as a guide for MSSM analysis, if no light squarks are present in the particle spectrum.

Backup slides

Simulation parameters

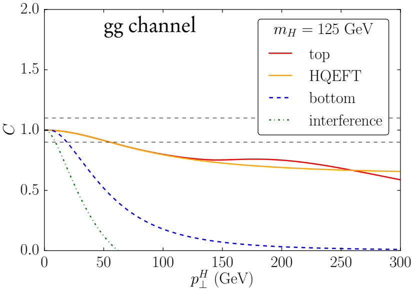
Simulation setup		2HDM	
Parameter	**Value**	**Parameter**	**Value**
$\sqrt{s}$	13 TeV	$M_h[GeV]$	125
PDF	MSTW2008nlo68cl	$M_H[GeV]$	300
m_t [GeV]	172.5	$M_A[GeV]$	270
m_b [GeV]	4.74	$M_{H^\pm}[GeV]$	335
μ_r	m_ϕ	$M_{12}^2[GeV^2]$	1798
μ_f	m_ϕ	$\tan\beta$	50
Shower	Pythia 8	$\sin(\beta-\alpha)$	0.999001
Tune	`aMC@NLO` default	λ_6	0
Number of events	1000000	λ_7	0
		α	0.0247

Pythia 8 tune sensitivity



- Compared Pythia8 default, CT10 tune and the default tune of aMC@NLO.
- The distortion in the shape is independent of the Higgs type.
- At most ±5%.

Collinear behavior of the amplitudes (BV)



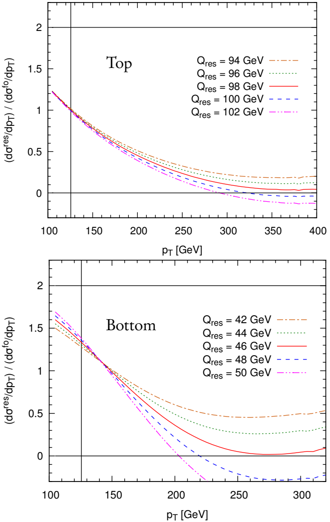
$$C \equiv \frac{|\mathcal{M}_{gg\to Hg}(s, p_T^H, m_Q)|^2}{\left|\mathcal{M}^{div}_{gg\to Hg}(s, p_T^H, m_Q)/p_T^H\right|^2}$$

Relative deviation from the collinear limit.

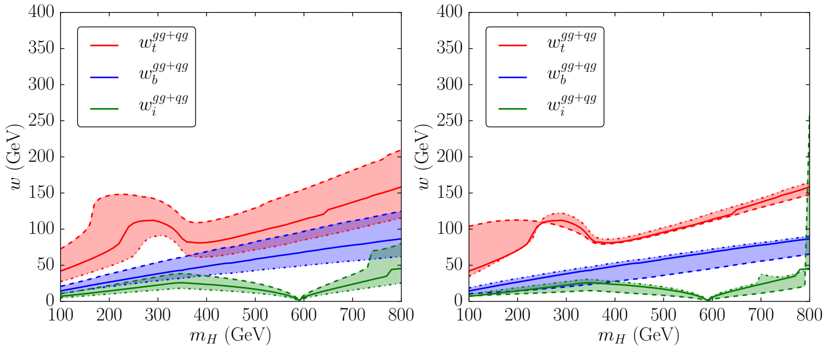
- The p_T^H at which the deviation reach $\overline{C} = 0.9/1.1$ gives us our ”collinear deviation“ scale.
- We choose a value of $s = s_{\text{min}} + s_{\text{soft}}$ close to the production threshold. Larger values should be PDF suppressed.
- $s_{\text{min}} = m_H^2 + 2(p_T^H)^2 + 2p_T^H\sqrt{(p_T^H)^2 + m_H^2}$. s_{soft} is used to move away from the soft divergence.
- The qg channel has a different behavior that yields smaller scales.
- The scales from the two channels are averaged using a weight based on their relative importance, bin by bin in p_T.

High-p_T fixed-order matching (HMW)

- Based on the consideration that we want to recover the fixed-order description in the high-p_T region.
- The resummation scale Q is then the maximum scale such that this expectation is true.
- For Higgs masses up to $m_h = 600$ GeV, Q is the maximum scale for which the p_T-distribution is within $[0, 2]\, d\sigma/dp_T^2$ in the range $[m_\phi, p_T^{max}]$ (p_T^{max} is chosen on a case by case basis).
- For large Higgs masses, due to numerical instabilities, the criteria is changed to requiring that $|[d\sigma^{res}/dp_T^2]/d\sigma/dp_T^2] - 1| = 1/2$ at $p_T = 700$ GeV.
- $Q_0 = Q^{max}/2$.

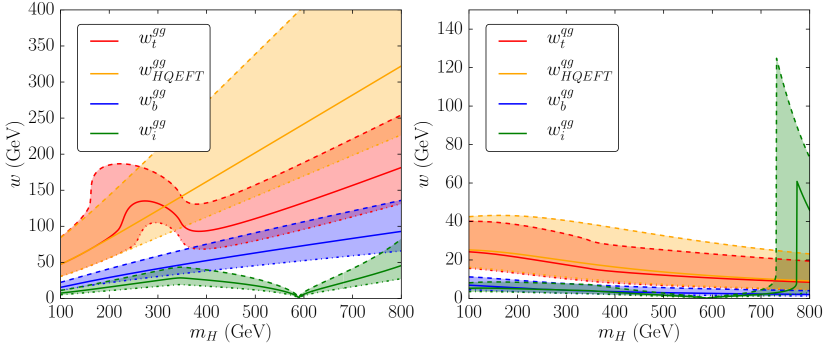


Dependence on the auxiliary parameters



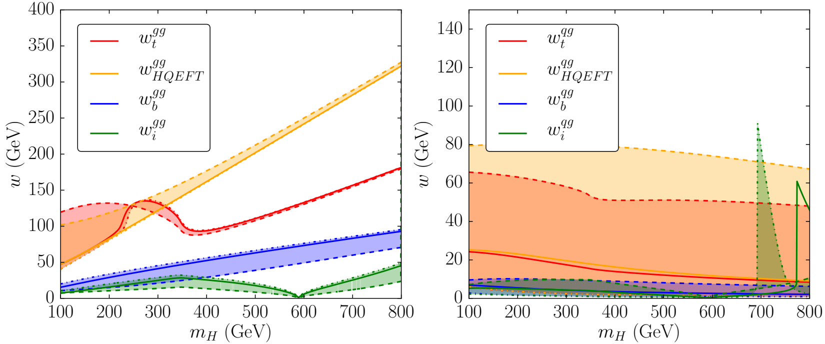
- Sensitivity to the choice of $\overline{C}$ (left) and s_{soft} (right).
- Results obtained after the merging of the gg and the qg channel.
- Band width comparable with the standard variation interval $[h_i/2, 2\,h_i]$.

Dependence on the auxiliary parameters



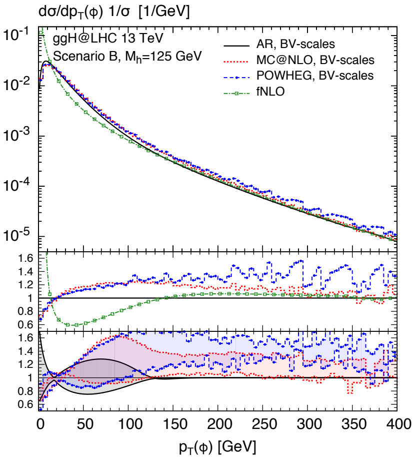
- Sensitivity to the choice of $\overline{C}$.
- On the left *gg* channel, on the right *qg* channel.
- Band width comparable with the standard variation interval $[w_i/2, 2\, w_i]$, $i = \{t, b, \text{int}\}$.

Dependence on the auxiliary parameters



- Sensitivity to the value of s_{soft}.
- On the left *gg* channel, on the right *qg* channel.
- Less dependence than on $\overline{C}$. Smaller than the standard uncertainty width.

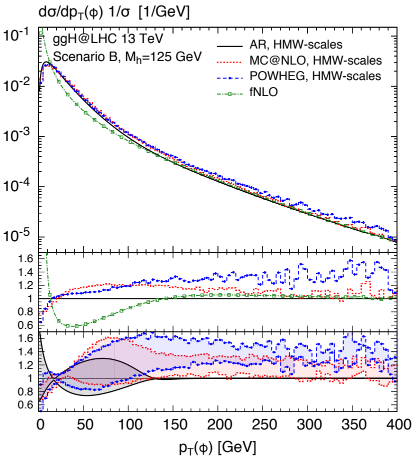
Light Higgs – Matching uncertainty



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	48	Q_t	45
w_b	18	Q_b	21
w_{int}	9	Q_{int}	31

- Comparison at fixed scales (**BV**) of the different tools.
- Top-dominated SM-like Higgs, aside from the opposite sign of bottom Yukawa (change the sign of the interference term).
- Very good agreement in the low-p_T region. Bands overlap throughout all the range.
- Analytic resummation reaches the NLO faster than the MCs.

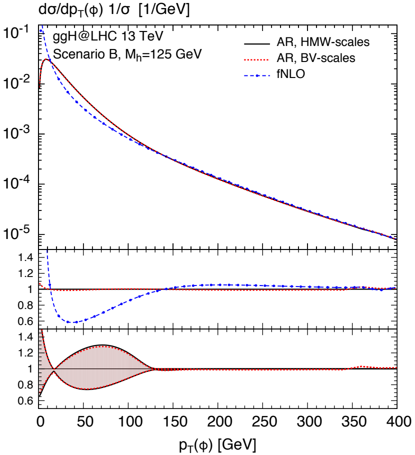
Light Higgs – Matching uncertainty



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	48	Q_t	45
w_b	18	Q_b	21
w_{int}	9	Q_{int}	31

- Comparison at fixed scales (**HMW**) of the different tools.
- Top-dominated SM-like Higgs, aside from the opposite sign of bottom Yukawa (change the sign of the interference term).
- Very good agreement in the low-p_T region. Bands overlap throughout all the range.
- Analytic resummation reaches the NLO faster than the MCs.

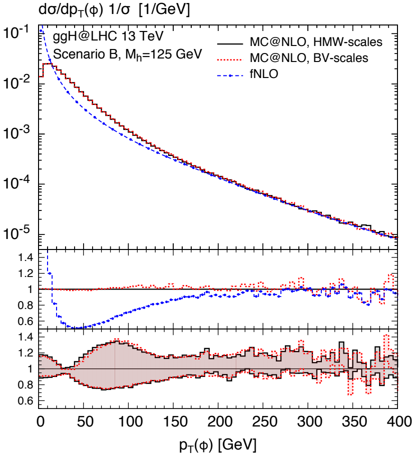
Light Higgs – Scale sensitivity



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	48	Q_t	45
w_b	18	Q_b	21
w_{int}	9	Q_{int}	31

- Fixed tool (**AR**), all scales compared.
- Top-dominated SM-like Higgs, aside from the opposite sign of bottom Yukawa (change the sign of the interference term).
- Similar scales, very small dependence on the scale set chosen.

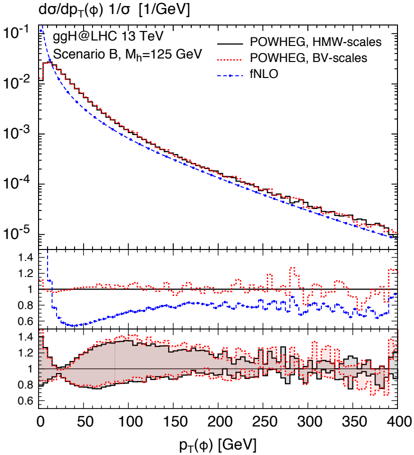
Light Higgs – Scale sensitivity



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	48	Q_t	45
w_b	18	Q_b	21
w_{int}	9	Q_{int}	31

- Fixed tool (MC@NLO), all scales compared.
- Top-dominated SM-like Higgs, aside from the opposite sign of bottom Yukawa (change the sign of the interference term).
- Similar scales, very small dependence on the scale set chosen.

Light Higgs – Scale sensitivity



BV		HMW	
Scale	Value [GeV]	Scale	Value [GeV]
w_t	48	Q_t	45
w_b	18	Q_b	21
w_{int}	9	Q_{int}	31

- Fixed tool (POWHEG), all scales compared.
- Top-dominated SM-like Higgs, aside from the opposite sign of bottom Yukawa (change the sign of the interference term).
- Similar scales, very small dependence on the scale set chosen.

The Two Higgs-doublet model

Coupling	Type I	Type II	Lepton specific	Flipped
λ_u^h	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
λ_d^h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
λ_u^H	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
λ_d^H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
λ_u^A	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
λ_d^A	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$

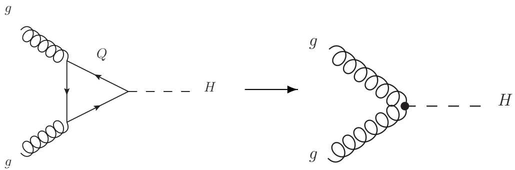
- Two Higgs doublets. Enlarged physical spectrum: $h/H/A$ and $H^{\pm}$.
- Rescaled couplings to quarks. Change in the relative weight of the quarks in the gluon fusion process (e.g. bottom contribution larger than the top).
- The MSSM realizes a Type II 2HDM. We study the latter as a simplified case for the MSSM with heavy scalars.
- Note: if the bottom quark coupling to the Higgs is enhanced, the bottom annihilation process can be the dominant one and must be taken into account for an accurate prediction.

Heavy Quark Effective Field Theory (HQEFT)

In the limit $m_{top} \to \infty$ we can construct an effective Lagrangian for the interaction of the Higgs boson with the gluons

$$\mathcal{L}_{eff} = \frac{\alpha_s}{12\pi} \frac{H}{v} (1+\Delta) \mathrm{Tr}\left[G^a_{\mu\nu} G^a_{\mu\nu} \right]$$

In this theory the heavy quark loop shrinks to a point vertex, simplifying the calculations



Validity conditions

- Total cross section, $m_H < 2m_{top}$
- Kinematic variables, as p_T^H, less than m_{top}
- No strongly coupled light particles running in the loop (e.g. bottom quark in the MSSM for large $\tan\beta$)

Resummation frameworks

Analytic resummation (Catani, Grazzini)

- In parameter space the cross section for multiple emissions factorizes and can be resummed. The factorization is defined at the unphysical resummation scale Q.
- Q is unphysical and the complete result does not depend on it. However, at fixed resummation-accuracy one has a residual dependency on it.
- This dependency can be used to probe the theoretically uncertainty on the resummed spectrum.

Matched NLO+PS (Frixione, Nason)

- Two available approaches: `MC@NLO` and `POWHEG`. Differences due to higher order effects.
- In `MC@NLO`, the shower scale Q determines the effective range of application of the resummation. It is chosen in such a way to recover the NLO behavior in the high-p_T region.
- In `POWHEG` we can use effectively the h parameter (that controls the higher order terms) to recover the NLO behavior in the high-p_T region.

Matching in an NLO+PS framework

$$d\sigma = d\Phi_B \overline{B}^s(\Phi_b)\left[\Delta^s(p_\perp^{\min}) + d\Phi_{R|B}\frac{R^s(\Phi_R)}{B(\Phi_B)}\Delta^s(p_T(\Phi))\right] + d\Phi_R R^f(\Phi_R)$$

$$\overline{B}^s = B(\Phi_b) + \left[V(\Phi_b) + \int d\Phi_{R|B}\hat{R}(\Phi_{R|B})\right]$$

$$\Delta(\bar{\Phi}_1, p_T) = \exp\left\{-\int d\Phi_{\rm rad}\frac{R^s(\bar{\Phi}_1, \Phi_{\rm rad})}{B(\Phi_1)}\theta(k_T - p_T)\right\}$$

MC@NLO

$$R^s \propto \frac{\alpha_s}{t}P_{ij}(z)B(\Phi_B) \;\;,\;\; R^f = R - R^s$$

- The Sudakov form factor is the one from the P.S., i.e. it uses the collinear splitting function in the exponent.
- The full matrix element appears only in the regular contribution.

POWHEG

$$R^s = \frac{h^2}{h^2 + p_T^2}R \;\;,\;\; R^f = \frac{p_T^2}{h^2 + p_T^2}R$$

- hfact controls high order effects
- At low p_T R goes into collinear factorization and the Sudakov regains the splitting function in the exponent.

The two approaches differs by higher order terms.