Higgs p_T in gluon fusion beyond the Standard Model

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hep-ph/1111.2854 hep-ph/1409.0531

Higgs (N)NLO MC and Tools Workshop for LHC RUN-2
17 December 2014
CERN

Talk structure

Matching fixed and all-order results

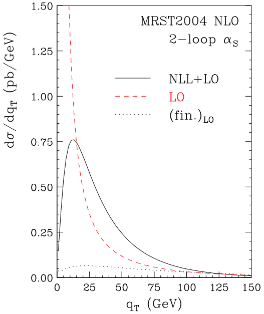
Matching scales determination in gluon fusion
- Partonic collinear-analysis (Bagnaschi and Vicini)
- High-p_T matching (Harlander, Mantler and Wiesemann)

Analytic resummation vs POWHEG vs MC@NLO in the 2HDM **Preliminary**
- Light Higgs
- Heavy Higgs
- Pseudoscalar Higgs

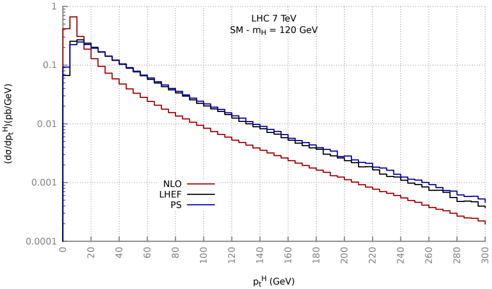
Conclusions

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



(a) HqT (Bozzi Catani De Florian Grazzini,arXiv:hep-ph/0508068)



(b) POWHEG (EAB,Degrassi,Slavich,Vicini, arXiv:hep-ph/1111.2854)

Resummation frameworks

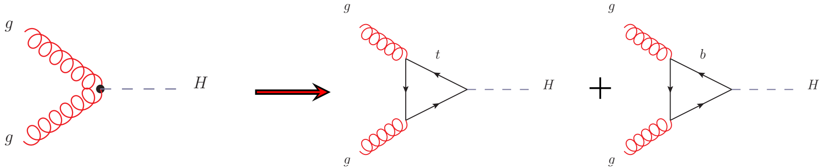
Analytic resummation (Catani, Grazzini)

- 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.

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_h and m_t).
- We can always rewrite the full amplitude as

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

- One should introduce separate resummation scales for the top (Q_t) and the bottom (Q_b) contribution and rewrite the formula for the total cross section as

$$\sigma(t+b) = \sigma(t, Q_t) + [\sigma(t+b, Q_b) - \sigma(t, Q_b)]$$

- We can extend the same reasoning to differential distributions.
- See H. Sargsyan (U. Zurich) talk for a detailed description of the SM case.

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).
- If the bottom quark coupling to the Higgs is enhanced, the bottom annihilation process can be the dominant one.
  See the talk of M. Wiesemann (U. Zürich) on Friday for a discussion of this process.

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.
- Hadronic-level analysis (positivity, NLO matching) of the transverse momentum distribution.

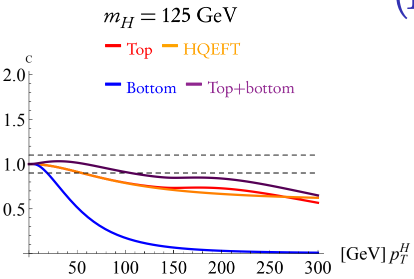
Analytic Resummation

- `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).

Collinear behavior of the $gg \to Hg$ amplitudes (BV)

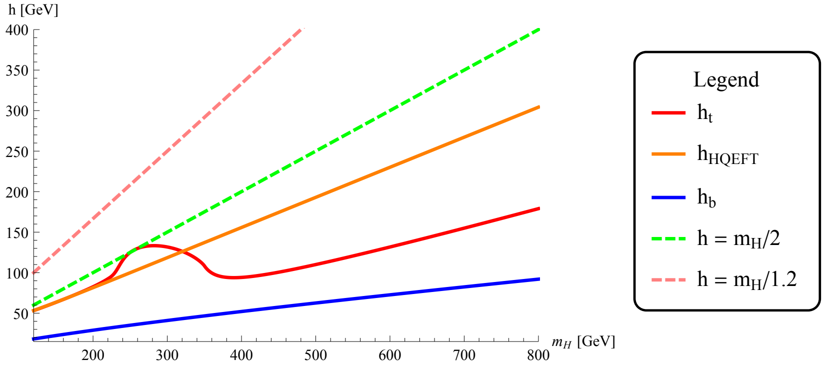


$$C \equiv \frac{|\mathcal{M}_{gg\to Hg}(s,p_T^H,m_Q)|^2}{\left|\mathcal{M}^{div}_{gg\to Hg}(s,p_T^H,m_Q)/p_T^H\right|^2}$$

Relative deviation from the collinear limit.

- The p_T^H at which the deviation reach $\overline{C} = 0.9/1.1$ gives us our preferred value for the factor h.
- 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.
- Results shown for the gg channel. Study of qg underway.

The scales vs the Higgs mass (BV)



- Manifest effect of the top threshold.
- Monotonous line for HQEFT and the bottom since no relevant scales are crossed.
- For heavy Higgs masses, our scales lower than the extrapolation of the "canonical" ones ($m_H/2$, $m_H/1.2$), currently used for a light Higgs.

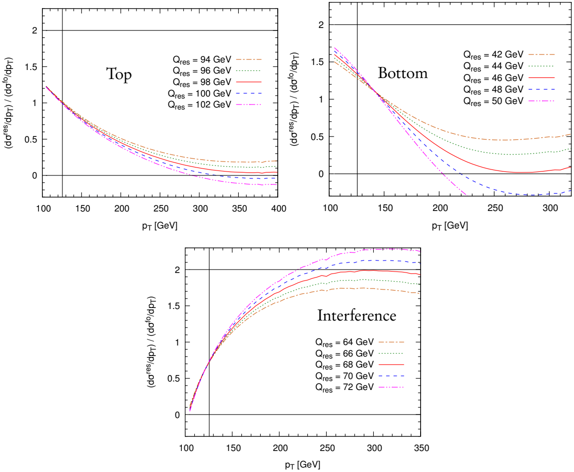
High-p_T matching (HMW)

- Starts from the consideration that we want to recover the NLO 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 $m_h = 300$ 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 case by case).
- For Higgs mass larger than 800 GeV, 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.
- $Q_0 = Q^{max}/2$, while the uncertainty interval is given by $[Q_0/2, 2Q_0]$.

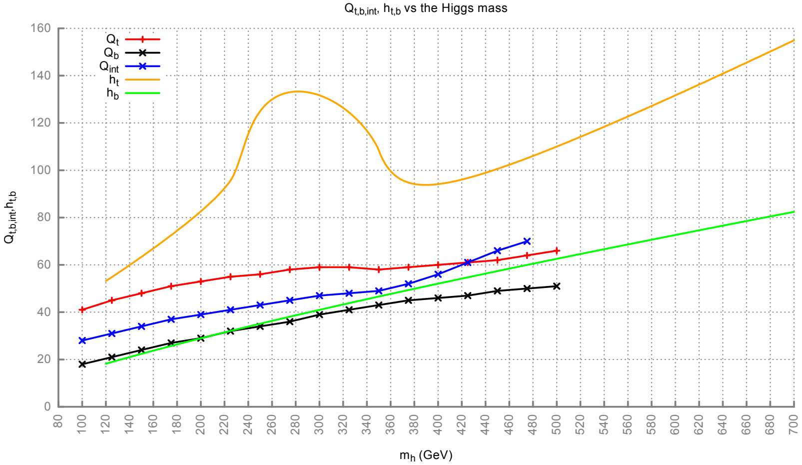
Example for $m_h = 125$ GeV (HMW)

- Decomposition of the cross section in three contributions:

$$\sigma(t+b) = \sigma(t, Q_t) + \sigma(b, Q_b) + \sigma(\text{interference}, Q_{int})$$



Comparison between the approaches



- Similar for the bottom scale.
- Different behavior for the top quark contribution.

Comparison of hadronic predictions for $d\sigma/dp_T^H$

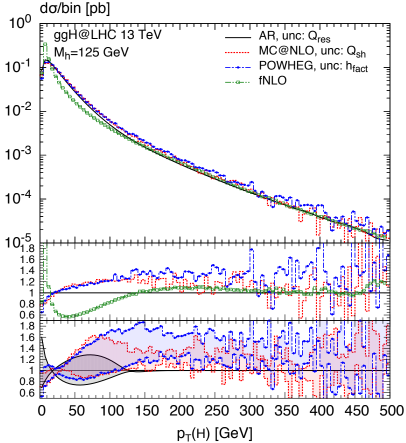
We studied a comparison of

Preliminary

Analytic resummation (NLO+NLL)
POWHEG (NLO+LL)
aMC@NLO(NLO+LL)

- 2HDM scenario B (hep-ph/1312.5571): $\tan\beta = 50$, $m_h = 125$ GeV, $m_H = 300$ GeV, $m_A = 270$ GeV.
- Light Higgs is top dominated; Heavy Higgs and pseudoscalar bottom dominated.
- POWHEG using BV scales
- Analytic resummation and aMC@NLO with the HMW ones.
- Comparison BV vs HMW scales in the same MC.
- We also present a remark on the comparison HQEFT result.
- We consider 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 resummation scale/h factor/shower scale using a factor $[Q_t/2, 2Q_t] \times [Q_b/2, 2Q_b]$.

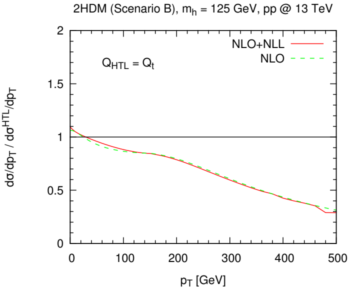
Light Higgs comparison

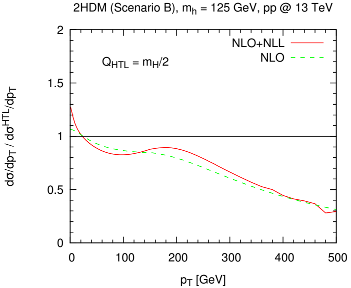


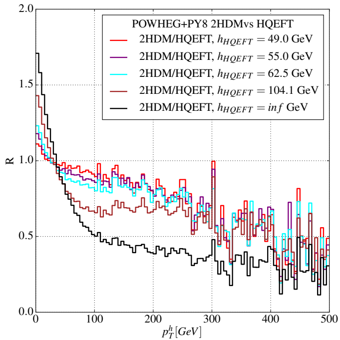
POWHEG		aMC@NLO/MoRe-SusHi	
Scale	Value [GeV]	Scale	Value [GeV]
h_t	55	Q_t	49
h_b	19	Q_b	23
		Q_{inf}	34

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

Comparison with the HQEFT

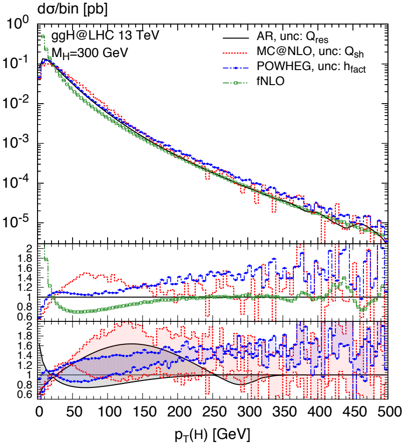






- HQEFT vs 2HDM for h ($m_h = 125$ GeV).
- The plot strongly depends on the scale chosen for the HQEFT.
- Choosing a HQEFT scale equal to the scale of the dominant contribution (i.e. the top one) gives a result close to the NLO one.

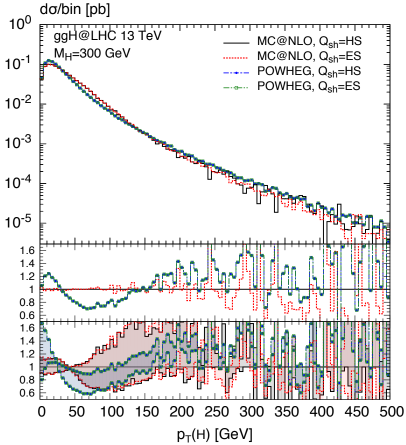
Heavy Higgs comparison



POWHEG		aMC@NLO/MoRe-SusHi	
Scale	Value [GeV]	Scale	Value [GeV]
h_t	132	Q_t	62
h_b	41	Q_b	41
		Q_{inf}	51

- Bottom dominated scenario.
- Scale for the top quark is different between POWHEG and aMC@NLO/MoRe-SusHi.
- 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.

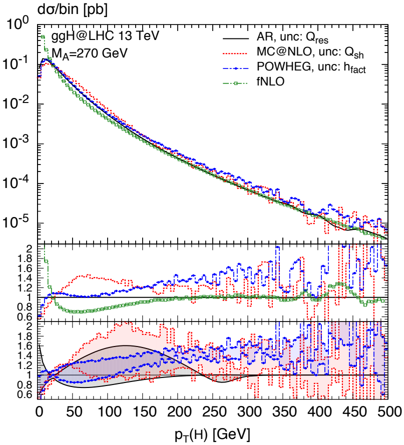
BV vs HMW comparison



POWHEG		aMC@NLO/MoRe-SusHi	
Scale	Value [GeV]	Scale	Value [GeV]
h_t	132	Q_t	62
h_b	41	Q_b	41
		Q_{inf}	51

- We now run both MCs with the two sets of scale choice.
- Not great variations since here the dominant contribution is the bottom one for which the scale is very close.

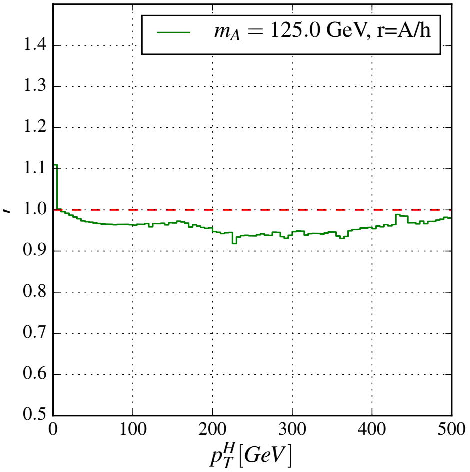
Pseudoscalar Higgs comparison



POWHEG		aMC@NLO/MoRe-SusHi	
Scale	Value [GeV]	Scale	Value [GeV]
h_t	132	Q_t	61
h_b	37	Q_b	40
		Q_{inf}	48

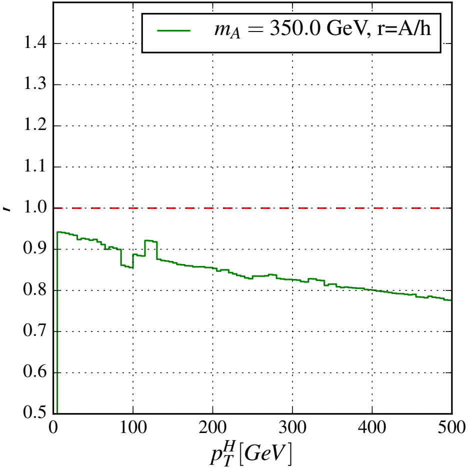
- Similar to the heavy Higgs.
- The p_T spectrum of the pseudoscalar is different from the one of a scalar of equal mass.
- This could be interesting to consider for CP studies.

H vs A @ NLO as a function of the Higgs mass



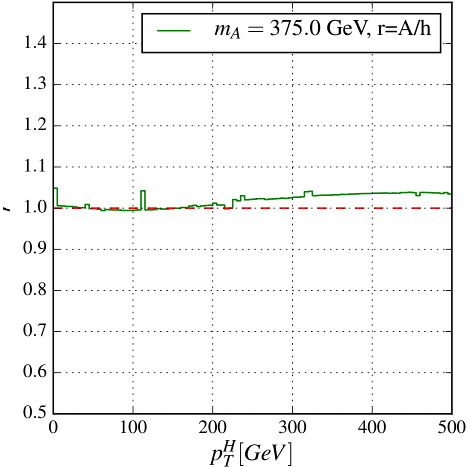
- Shape ratio between a scalar and a pseudoscalar of equal mass.

H vs A @ NLO as a function of the Higgs mass



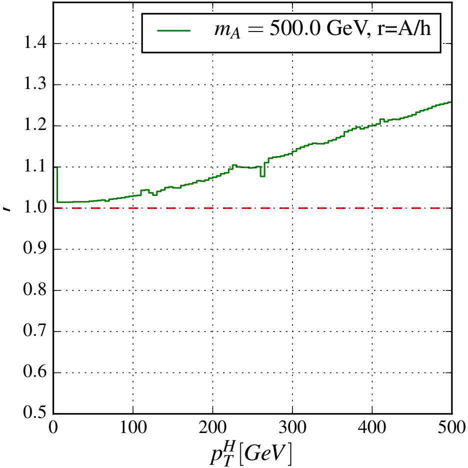
- Shape ratio between a scalar and a pseudoscalar of equal mass.

H vs A @ NLO as a function of the Higgs mass



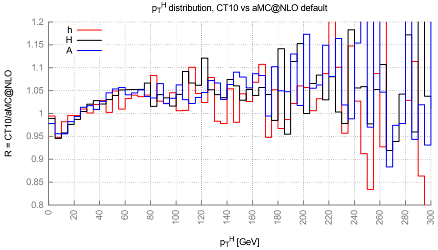
- Shape ratio between a scalar and a pseudoscalar of equal mass.

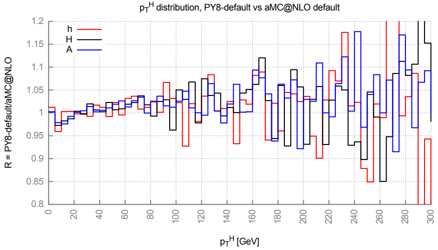
H vs A @ NLO as a function of the Higgs mass



- Shape ratio between a scalar and a pseudoscalar of equal mass.

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%.

Conclusions

- Several 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 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.
- The picture in the MSSM should be the same as in the 2HDM if no light squarks are present.

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

Matching in an NLO+PS framework

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

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

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

MC@NLO

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

- 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.

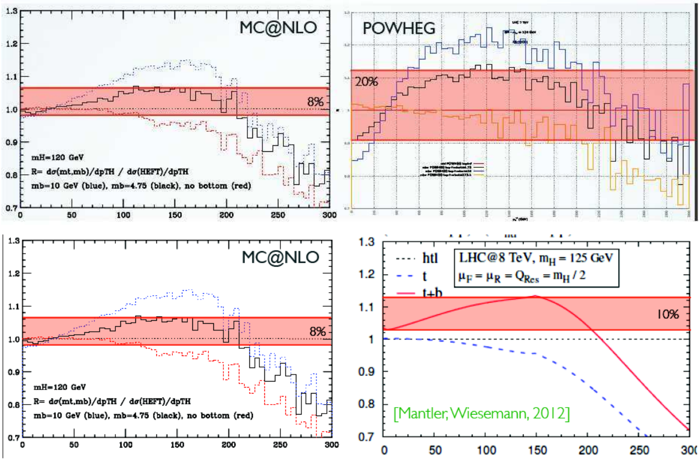
POWHEG

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

- 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.

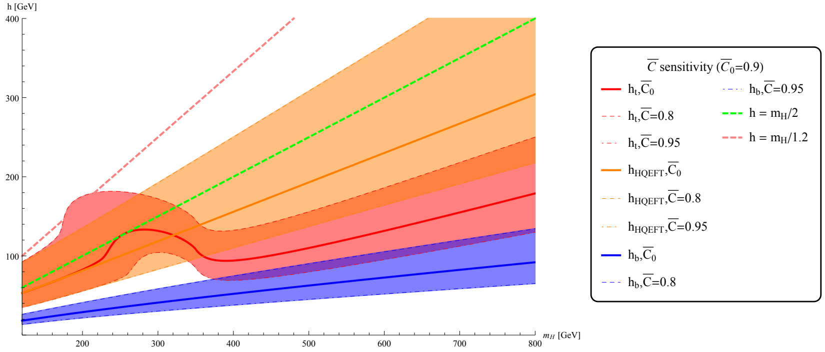
Description of the Higgs p_T in the SM



See H. Sargsyan (U. Zurich) talk for a detailed description of the SM case.

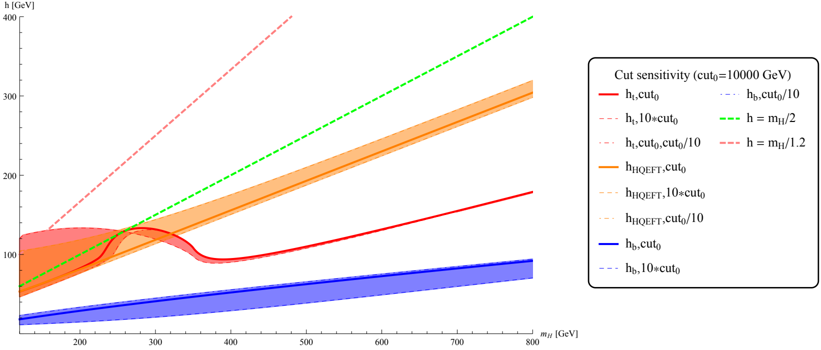
Figure courtesy of S. Frixione.

Dependence on the auxiliary parameters



- Sensitivity to the choice of $\overline{C}$.
- Band width comparable with the standard variation interval $[h_i/2, 2\, h_i]$.

Dependence on the auxiliary parameters



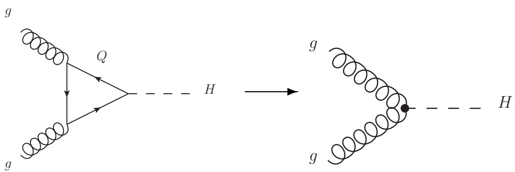
- Sensitivity to the value of s_{soft}.
- Less dependence than on $\overline{C}$. Smaller than the standard uncertainty width.

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

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

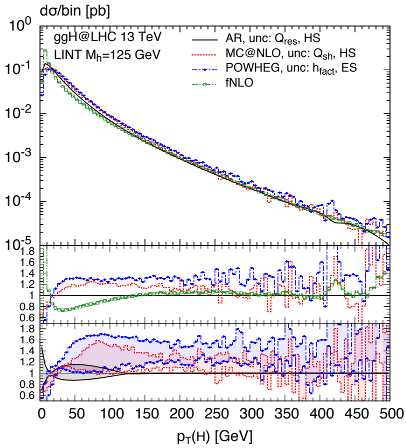
In this theory the heavy quark loop shrinks to a point vertex, simplifying the calculations



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 $\tan\beta$)

Light Higgs comparison (large-int)

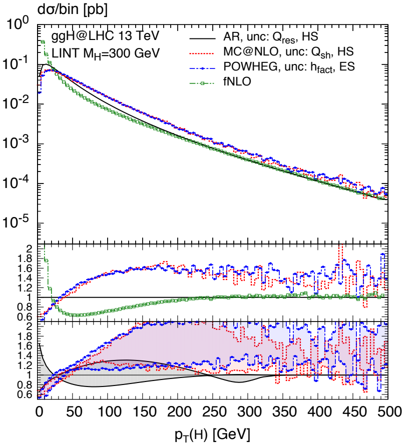


tan β	α	interference@LO
3.2	5.053	-135%

POWHEG		aMC@NLO/MoRe-SusHi	
Scale	Value [GeV]	Scale	Value [GeV]
h_t	55	Q_t	49
h_b	19	Q_b	23
		Q_{inf}	34

- MCs almost overlap completely across all the range.
- Very different behavior from analytic resummation.

Heavy Higgs comparison (large-int)



tan β	α	interference@LO
1.8	0.528	-11%

POWHEG		**aMC@NLO/MoRe-SusHi**	
Scale	Value [GeV]	Scale	Value [GeV]
h_t	132	Q_t	62
h_b	41	Q_b	41
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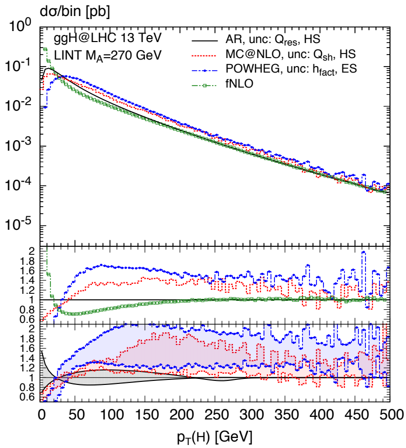
- Very different behavior from analytic resummation.

Pseudoscalar Higgs comparison (large-int)



$\tan\beta$	α	interference@LO
7.1	1.694	273%

POWHEG		**aMC@NLO/MoRe-SusHi**	
Scale	Value [GeV]	Scale	Value [GeV]
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h_b	37	Q_b	40
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- Bottom dominated scenario.
- Scale for the top quark is different between POWHEG and aMC@NLO/MoRe-SusHi.
- 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.