Precision phenomenology for the Higgs sector in the SM and beyond

Emanuele A. Bagnaschi (DESY Hamburg)

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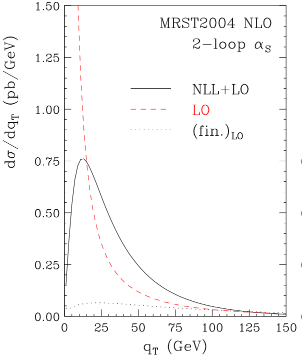
Talk structure

The Higgs transverse momentum in gluon fusion

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

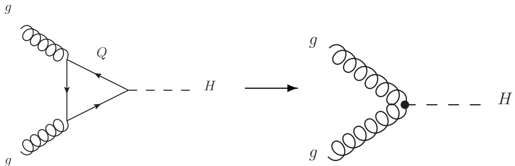
- **Analytic resummation** (Catani, Grazzini). Dependence on the unphysical resummation scale can be used to probe the missing higher-order terms.
- **NLO+PS,** `MC@NLO` (Frixione, Webber). Variation of the shower scale used to probe the matching uncertainty.
- **NLO+PS,** `POWHEG` (Frixione, Nason,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

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

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

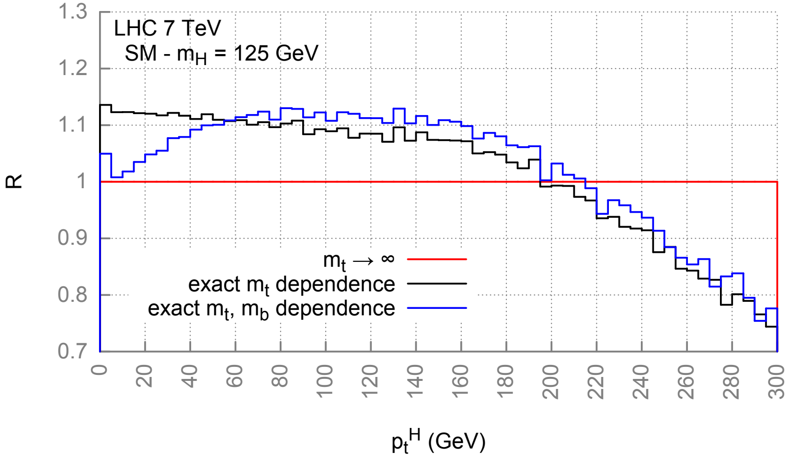
In this theory the heavy quark loop shrinks to a point vertex, simplifying the calculations



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 THDM/MSSM for large $\tan\beta$)

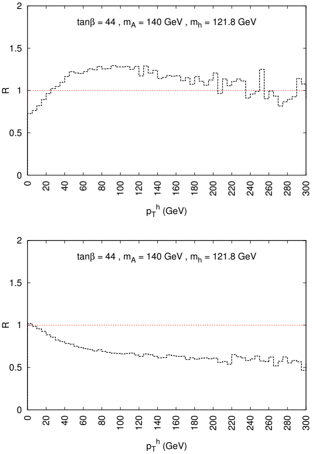
Shape distorsion: SM vs HQEFT



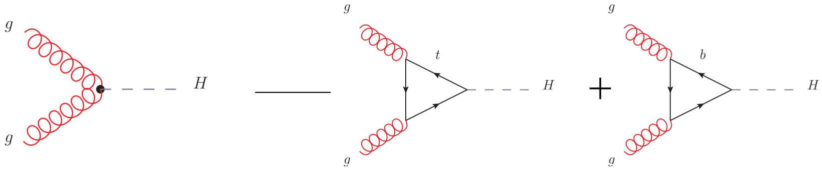
- High-p_T region inaccurate if HQEFT used.
- Top-mass effect sizable, quickly greater than 50% suppression as soon as $p_T > m_t$.
- H+1@NLO not available in the SM, H+2 jets tree level.

Shape distorsion: SM vs MSSM

- Exactly as one can have an effect on total rates due to the presence of additional BSM particles in the gluon fusion loops, one can have effects on the shape of the p_T^h distribution.
- Change in the relative weight of the Yukawa couplings to top and bottom can affect the shape too (e.g. 2HDM).
- High-p_T^h events probe relatively large mass scales.



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

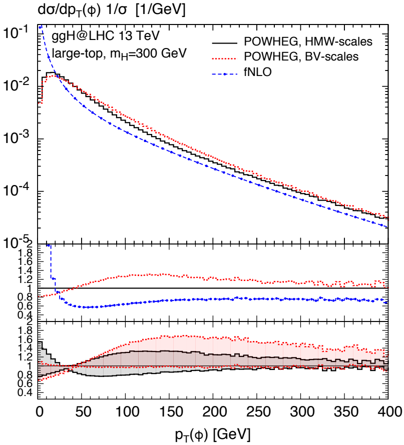
$$|\mathcal{M}(t+b)|^2 = |\mathcal{M}(t)|^2 + |\mathcal{M}(b)|^2 + \left[|\mathcal{M}(t+b)|^2 - |\mathcal{M}(t)|^2 - |\mathcal{M}(b)|^2\right].$$

- 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

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

- We extend the same reasoning to differential distributions.

H production at low tan β



	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 (POWHEG), all scales compared.
- Different scales for the top quark.
- Deviation of the central value predictions.

Theoretical uncertainty estimation in a Bayesian framework

Perturbative QCD and MHOUs

Baseline

- The perturbative expansion of an observable known up to order k is

$$O_k(Q,\mu) = \sum_{n=l}^{k} \alpha_s^n(\mu) c_n(Q,\mu) \quad \text{(known)}$$

- Q is the hard scale of the process, μ represents the unphysical scale(s) (e.g. the renormalization scale) from which the truncated perturbative expansion depends. We assume it set at the value Q
- The remainder of the series expansion is unknown and it is our MHOU

$$\Delta_k = \sum_{n=k+1}^{\infty} \alpha_s^n(Q) c_n(Q) \simeq \alpha_s^{k+1} c_{k+1} = \,?$$

Scale variation

Procedure

- Vary the unphysical scale(s) μ around the central scale Q by an **arbitrary** factor r
- Different prescriptions used in the literature. We will use the following ones:
  1. **Scan**: vary μ between Q/r and $r \times Q$ and use the maximum/minimum value of the observable to define the uncertainty
  2. **Extrema**: Use the maximum/minimum of the value of the observable obtained for $\mu = r \times Q, Q/r$
- **Caveat**: the factor r is arbitrary and the interval obtained has **no** statistical meaning

The CH model

Bayesian framework

- Suppose there is an upper bound on the coefficients magnitude and call it $\bar{c}$
- The priors for the model are then given by

$$f_\epsilon(\ln \bar{c}) = \frac{1}{2|\ln \epsilon|} \chi_{|\ln \bar{c}| \leq |\ln \epsilon|}$$

$$f(c_n|\bar{c}) = \frac{1}{2\bar{c}} \begin{cases} 1 & \text{if } |c_n| \leq \bar{c} \\ 0 & \text{if } |c_n| > \bar{c} \end{cases}$$

$$f(\{c_i, i \in I\}|\bar{c}) = \prod_{i \in I} f(c_i|\bar{c})$$

- Bayesian inference gives then the uncertainty interval posterior

$$f(\Delta_k|c_l, \ldots, c_k) \simeq \left(\frac{n_c}{n_c+1}\right) \frac{1}{2\alpha_s^{k+1}\bar{c}_k} \begin{cases} 1 & \text{if } |\Delta_k| \leq \alpha_s^{k+1}\bar{c}_k \\ \frac{1}{(|\Delta_k|/(\alpha_s^{k+1}\bar{c}_k)^{n_c+1}} & \text{if } |\Delta_k| > \alpha_s^{k+1}\bar{c}_k \end{cases}$$

  where $n_c = k - l + 1$ and $\bar{c}_k = \max(c_l, \ldots, c_k)$
- Intervals have a statistical meaning in term of Degree of Belief (DoB)

The $\overline{\text{CH}}$ model

Recent developments

- **Issue:** the uncertainty estimate **depends** on the expansion parameter of the series
- **Approach:** rewrite the observable as

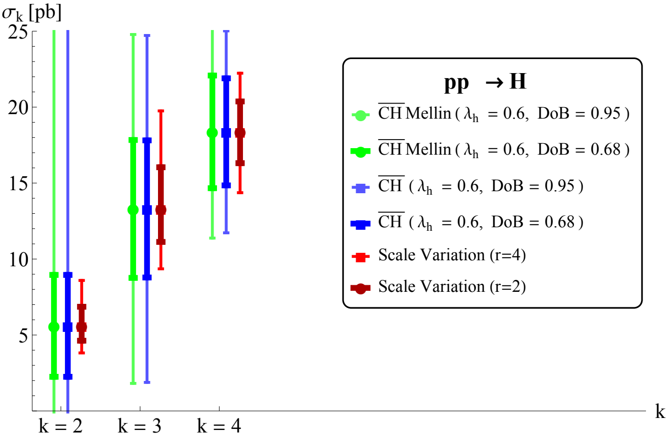
$$O_k(Q) = \sum_{n=l}^{k} \left(\frac{\alpha_s(Q)}{\lambda} \right)^n (n-1)!\, b_n(Q)$$

- Apply the same prior to b_n
- The $(n-1)!$ factor is suggested by renormalon based analysis
- λ estimated empirically from the performance of the model

Uncertainty on the total cross section in the SM

$pp(gg) \to H$ at the LHC 8 TeV (Mellin)

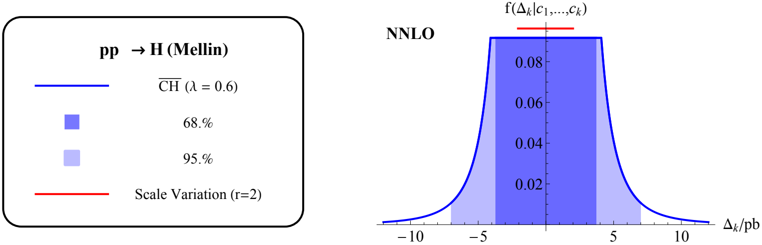
Error bars: $\overline{\text{CH}}$ vs scale variation



Benchmarks

$pp(gg) \to h$ at the LHC 8 TeV (Mellin)

Density profile for the posterior distribution at NNLO



Higgs mass prediction in Supersymmetry

At the EW scale	Much above the EW scale

Single scale SUSY

Chiral supermultiplets

Name	Symbol	spin 0	spin 1/2	$(SU(3)_C, SU(2)_L, U(1)_Y)$
squarks,quarks	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(×3 families)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons,leptons	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgses, Higgsinos	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

Gauge supermultiplets

Name	spin 1/2	spin 1	$(SU(3)_C, SU(2)_L, U(1)_Y)$
gluino,gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^\pm \quad \widetilde{W}^0$	$W^\pm \quad W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

At the EW scale | Much above the EW scale

Split SUSY

Chiral supermultiplets

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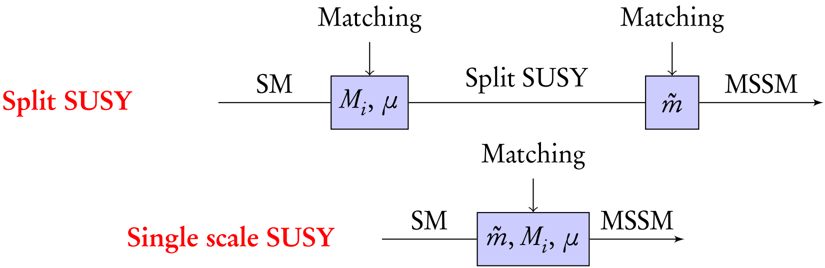
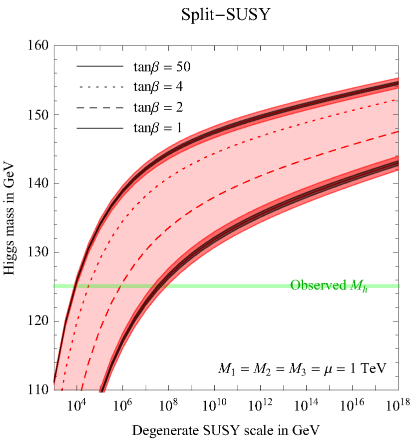
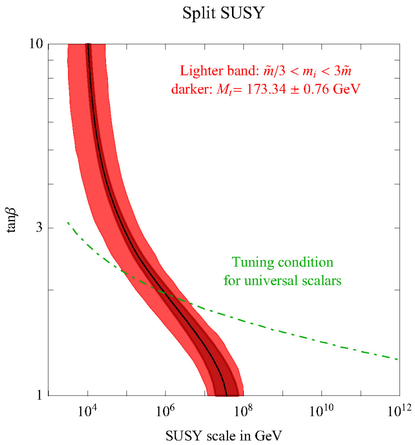
A tower of effective theories

- Problem: mass gap in the physical spectrum makes large logs of the ratio $m_{\text{ew}}/\tilde{m}$ appears in the perturbative expressions.
- Solution: For a proper computation these logs have to be resummed.
- Method: define a tower of effective field theories, where the heavy particles are integrated out, and match them at a proper scale. Use RGE to resum the large logarithms.



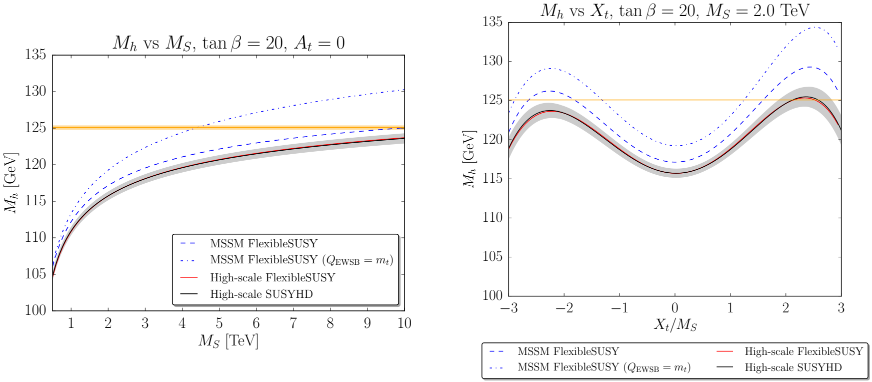
Split-SUSY





- $M_1 = M_2 = M_3 = \mu = 1$ TeV.
- All scalars degenerate at scale $\tilde{m}$.
- $A_t = 0$ (In Split-SUSY $A_t/\tilde{m} \ll 1$).

Uncertainty in the Higgs mass prediction



- Different region of applicability for the two approaches (low SUSY vs large SUSY masses).
- Uncertainty estimation in the intermediate, phenomenologically interesting region, not trivial.

Overview

p_T-distribution of the Higgs in gluon fusion

- Study of the effects of the complete top and bottom contribution in the SM.
- Shape-distorsion in BSM models due to modified Yukawa coupling or new degrees freedoms.
- validity of the collinear approximation
- Matching of the MSSM with a THDM at the low scale; study of the vacuum stability.

[1111.2854,1505.00735,1510.08850]

Theoretical uncertainty estimation

- Study of the statistical performance of scale variation on a wide set of observable.
- Study of the extension of the CH model to hadronic observables.
- Extensive study of uncertainty for the MSSM total inclusive production rates.

[1404.0327,1409.5036]

Matched MC event generator

- Work in progress on new processes both in the SM and in the MSSM.

Overview

Higgs mass in SUSY

- Computation in the MSSM with heavy SUSY and a single Higgs doublet at the low scale.
- Uncertainty estimation and comparison with the prediction in the full model.
- Computation of new radiative correction to the matching conditions.
- Matching of the MSSM with a THDM at the low scale; study of the vacuum stability.

[1407.4081,1512.07761]

Global fit of SUSY models

- Global fit of the pMSSM10.
- Analysis of dark matter annihilation mechanism in the CMSSM/NUHM1/NUHM2 and the pMSSM10.
- Extension to other scenarios under way.

[1504.03260,1508.01173]

XHSWG

- Collaboration with the Higgs Cross Section Working Group – WG3.

[1201.3084,1307.1347,LHCHXSWG-2015-002]

Backup slides