The Higgs transverse momentum in gluon fusion as a multiscale problem: ambiguities and predictions in different pt-resummation frameworks

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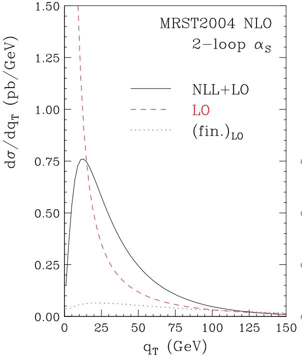
Talk structure

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

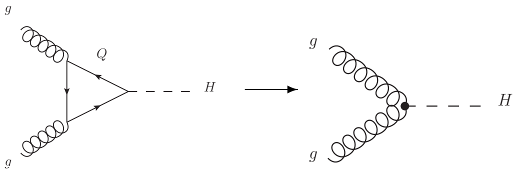
- **Analytic resummation** (Catani, Grazzini). Dependence on the unphysical resummation scale can be used to probe the missing higher-order terms.
- **NLO+PS,** `MC@NLO` (Frixione, Webber). Variation of the shower scale used to probe the matching uncertainty.
- **NLO+PS,** `POWHEG` (Frixione, Nason,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

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

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

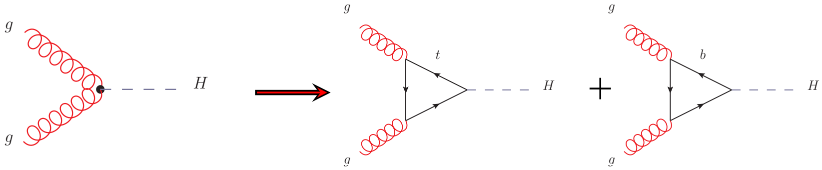
In this theory the heavy quark loop shrinks to a point vertex, simplifying the calculations



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 $\tan\beta$)

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.

Matching in an analytic resummation framework

The master formula for the analytic matching is given by

$$\frac{d\sigma}{dp_\perp^2} = \int \frac{d\Phi_B}{dp_\perp^2}(B+\hat{V}_{\text{fin}})\mathscr{F}_{\text{NLL}}(Q_{\text{res}}) + \int \frac{d\Phi}{dp_\perp^2} R\otimes\Gamma - \int \frac{d\Phi_B}{dp_\perp^2} B\,\mathscr{F}_{\text{NLO}}(Q_{\text{res}}),$$

with

$$\mathscr{F}_{\text{NLL}}(Q_{\text{res}},p_\perp) = \frac{m_\phi^2}{S}\int_0^\infty db\,\frac{b}{2}J_0(bp_\perp)\mathscr{S}(\alpha_s,\tilde{L})$$
$$\times\sum_{i,j}\int dz_1\,dz_2\left[\delta_{z_1}\delta_{z_2} + \frac{\alpha_s(b_0/b)}{\pi}C_{gi}^{(1)}(z_1)\delta_{z_2} + \frac{\alpha_s(b_0/b)}{\pi}\delta_{z_1}C_{gj}^{(1)}(z_2)\right]\Gamma_{ij}(b_0/b,z_1,z_2),$$

with $\mathscr{S}(\alpha_s,\tilde{L}) = \exp\left\{\tilde{L}g^{(1)}(\alpha_s\tilde{L}) + g^{(2)}(\alpha_s\tilde{L})\right\}$,

- Additive matching. Remove explicitly the terms that are double counted.
- $\tilde{L} = \ln(b^2Q_{\text{res}}^2/b_0^2+1)$
- The scale Q_{res} determines the $p_\perp$-range where the resummation is applied.

Matching in an NLO+PS framework

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

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

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

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.

SM and 2HDM phenomenology

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

Bagnaschi-Vicini

- 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

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

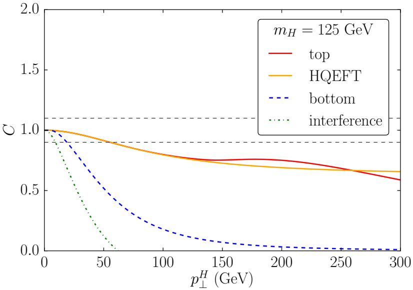
Analytic Resummation

- `HRes` by Grazzini et al.
- `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

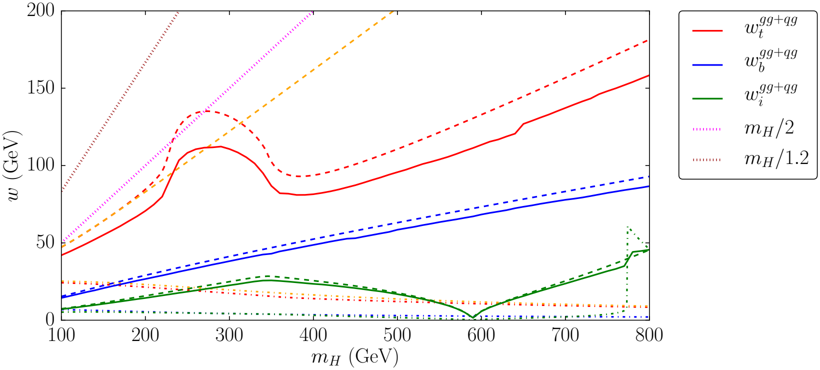


$$C \equiv \frac{|\mathcal{M}_{gg\to Hg}(s, p_T^H, m_Q)|^2}{\left|\mathcal{M}^{div}_{gg\to Hg}(s, p_T^H, m_Q)/p_T^H\right|^2}$$

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.
- Analogous study for the qg channel yields much lower scales.

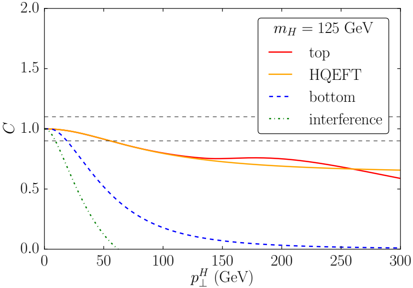
The scales vs the Higgs mass

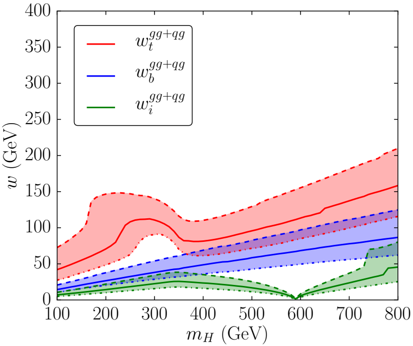


- Combination of the two channels using a differential weights.
- Manifest effect of the top threshold.
- Monotonous line for HQEFT and the bottom since no relevant scales are crossed.
- For heavy Higgs masses, our scales lower than the extrapolation of the “canonical” ones ($m_H/2$, $m_H/1.2$), currently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

Dependence on the auxiliary parameters

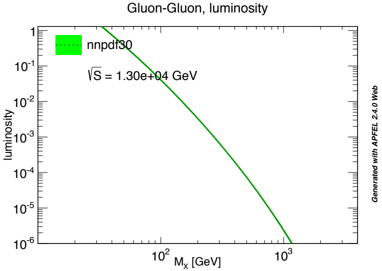
- Sensitivity to the choice of $\overline{C}$.
- It represents how much we allow collinear factorization to be broken.
- Band width comparable with the standard variation interval $[w_i/2, 2\,w_i]$.

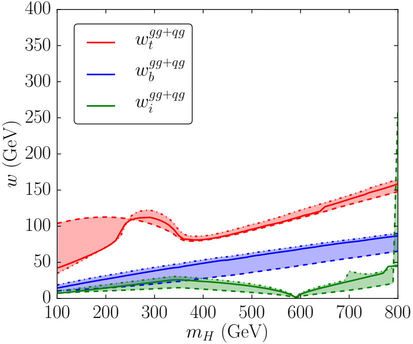




Dependence on the auxiliary parameters

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





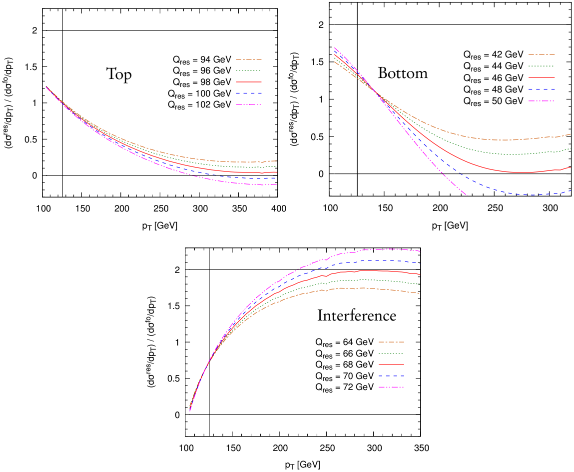
High-p_T matching

- 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 $[Q_0/2, 2Q_0]$.

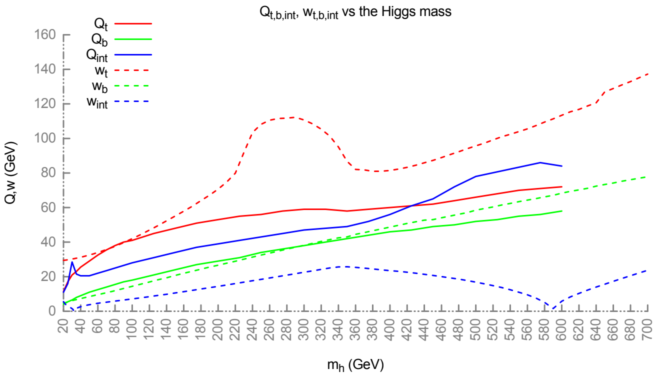
Example for $m_h = 125$ GeV

- Decomposition of the cross section in three contributions:

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

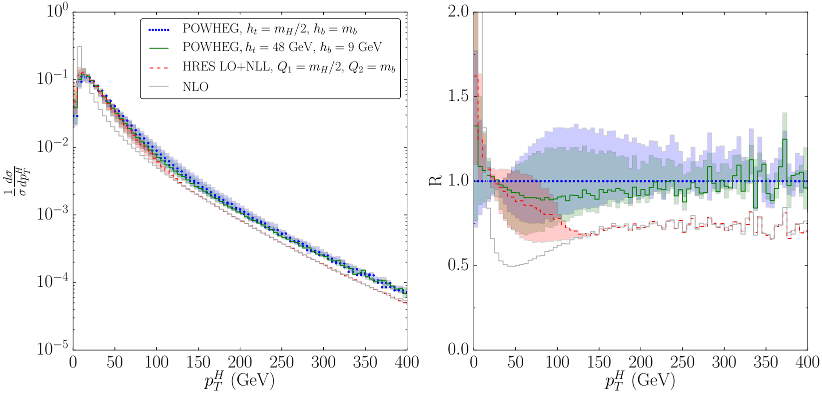


Comparison of the scale sets



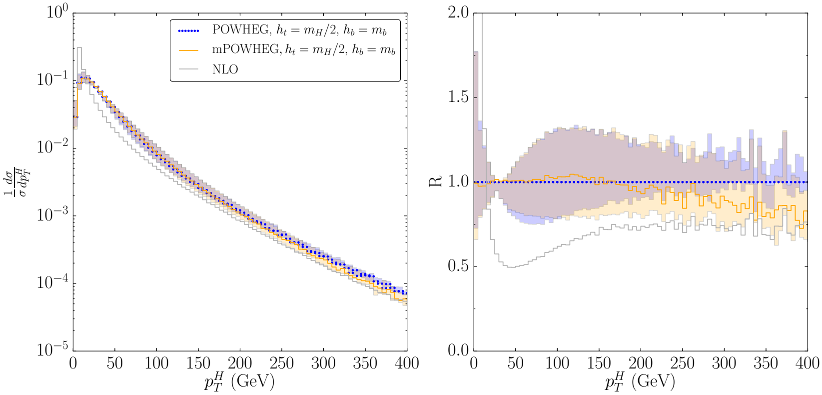
- Similar behavior for the bottom scale.
- Different behavior (especially around the two-top threshold), though compatible, for the top quark contribution.
- Opposite behavior for the interference scale when the interference terms goes to zero.

The SM



- `HRes` recovers the fixed order distribution at $\mathcal{O}(m_b)$ with a forced matching.
- Difference in the intermediate region due to different matching and possibly due to the structure of the `POWHEG` Sudakov form factor.

POWHEG high-p_T tail



- Change the default shower scale choice in `POWHEG`, by capping it at the same value used for h.
- Tail of the distribution goes over the fixed order results.

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.

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):

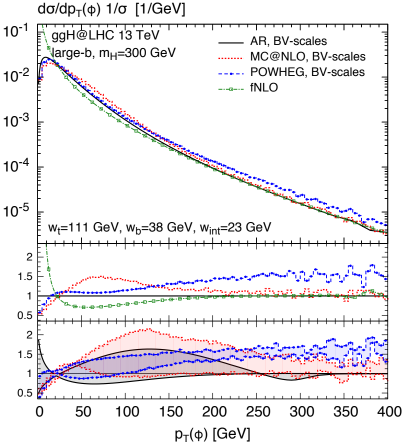
  $\tan\beta = 50$, $\sin(\beta-\alpha) = 0.999$, $m_h = 125$ GeV, $m_H = 300$ GeV, $m_A = 270$ GeV.

- 2HDM large-top scenario

  $\tan\beta = 1$, $\sin(\beta-\alpha) = 0.999$, $m_h = 125$ GeV, $m_H = 300$ GeV, $m_A = 270$ 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 available in `hep-ph/1510.08850`

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.

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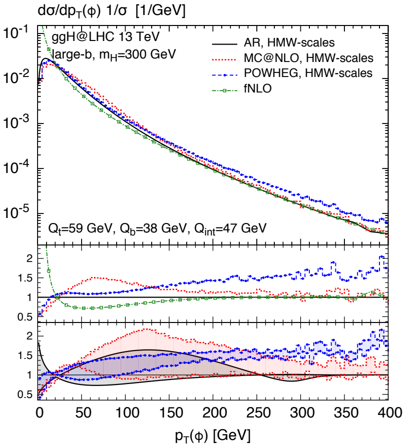

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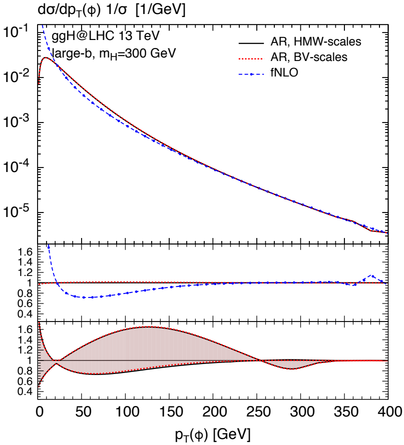
Scenario B – Scale sensitivity



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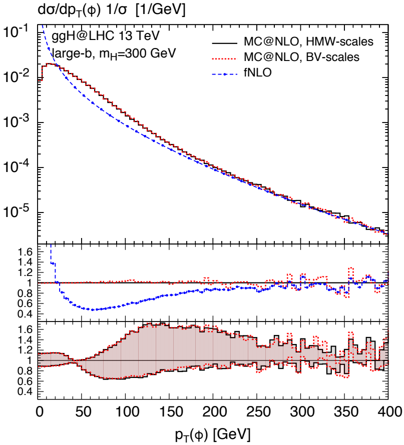

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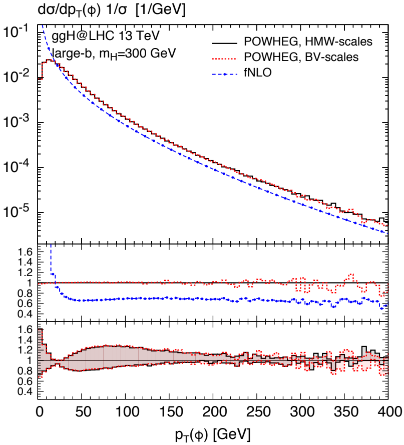

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- Fixed tool (POWHEG), all scales compared.
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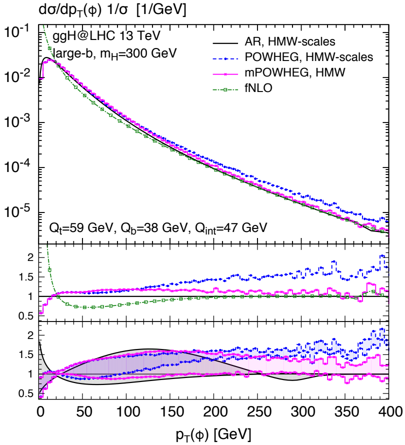
Understanding the high-p_T tail in POWHEG

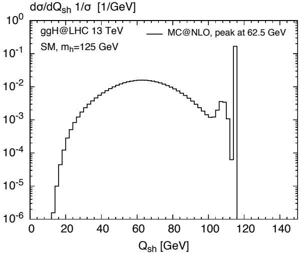
- High-pt tail behavior enhanced in the case of bottom dominated models.
- Changing the default prescription for the shower scale (mPOWHEG) allow for the recovery of the fixed order at high-pt.

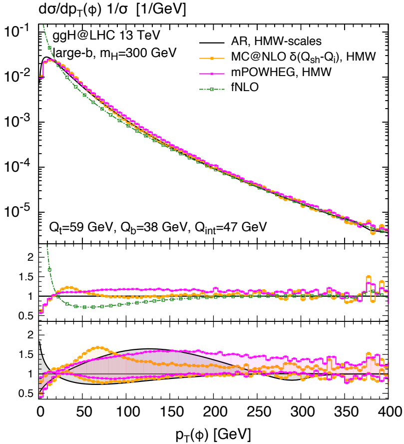


Sensitivity to the shower scale choice in aMC@NLO

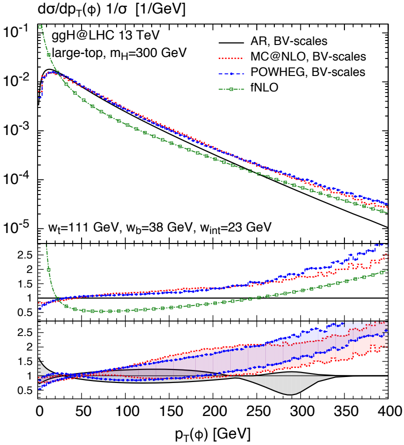
In the default aMC@NLO implementation, the shower scale is chosen as

- S-events: it uses a probability density distribution, which depends on the kinematic of the event, and that results in relatively low scales.
- H-events: the scale is taken equal to the maximum of the distribution for the S-events.
- Probe the sensitivity to these choices by using instead a δ-function distribution.





H, large t scenario – Matching uncertainty



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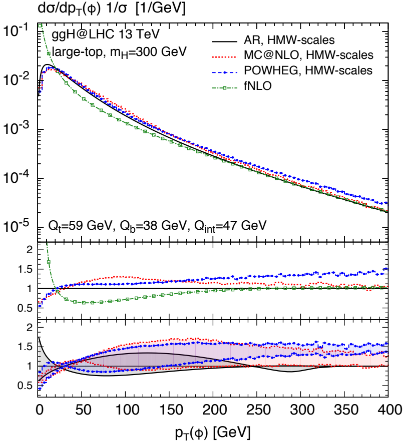

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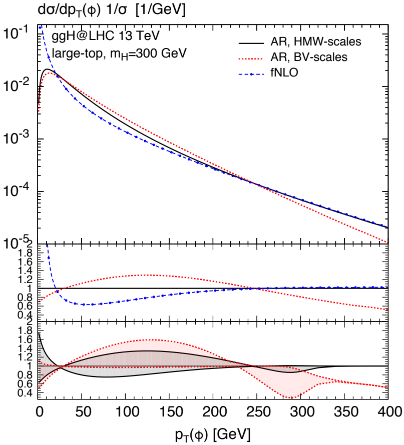

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- Fixed tool (**AR**), all scales compared.
- Different scales for the top quark.
- Deviation of the central value predictions.

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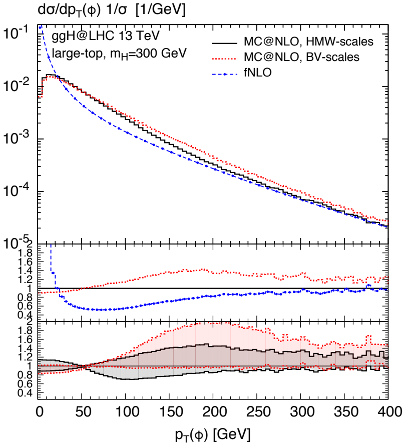

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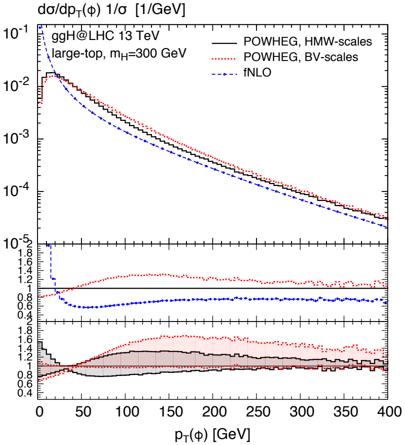

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- Fixed tool (POWHEG), all scales compared.
- Different scales for the top quark.
- Deviation of the central value predictions.

Conclusions

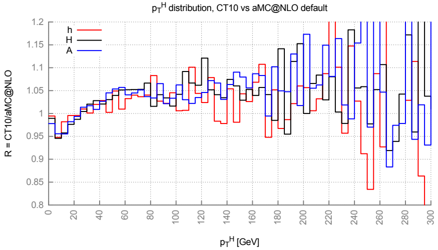
- We compared three different tools available to compute the transverse momentum spectrum in the 2HDM (`POWHEG gg_H_2HDM`, `aMC@NLO` and `MoRe-SusHi`).
- Two prescriptions available to determine the scales for a proper description of the p_T spectrum of the Higgs boson.
- Especially for a heavy Higgs, 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.

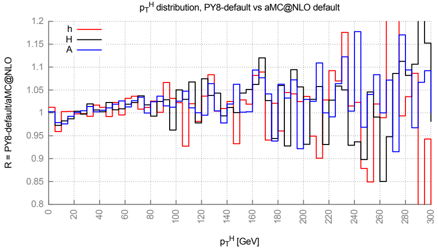
Backup slides

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%.