Higgs p_T in the Standard Model

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Outline

- Introduction
- p_T spectrum at large transverse momenta
- Heavy quark mass effects at fixed order
- p_T spectrum in the low p_T region
- p_T-resummation
- Heavy quark mass effects in the resummed spectrum
- The boosted Higgs

Introduction

Gluon fusion is the dominant production channel of the Higgs boson at the LHC. There was an enormous activity going on in the last 15 years.

- Total cross section up to NNLO

  R. Harlander, W. B. Kilgore (2002), C. Anastasiou, K. Melnikov (2002), V. Ravindran, J. Smith, W. L. Van Neerven (2003).

- EW corrections

  U. Aglietti et al. (2004), G. Degrassi, F. Maltoni (2004), G. Passarino et al. (2008).

- NNLO beyond large-m_{top} approximation

  S.Marzani et al. (2008), R.Harlander et al. (2009, 2010), M.Steinhauser et al. (2009).

- Partial NNNLO and approximations

  Anastasiou et al. (2014), de Florian et al (2014), S.Forte et al (2013, 2014).

- Threshold resummations

  S.Catani, D. de Florian, P. Nason, M. Grazzini (2003), M.Neubert et al. (2011), M.Bonvini, S.Marzani (2014).

- Fully exclusive NNLO calculations

  FEHIPro C. Anastasiou et al. (2005, 2009), HNNLO S. Catani, M. Grazzini (2007), M. Grazzini,(2008).

Transverse-momentum spectrum

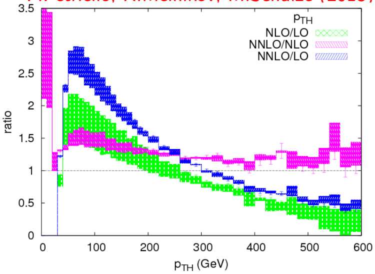
At hadron colliders the production of an (on shell) Higgs boson is characterized by its transverse momentum (p_T) and rapidity (y)

- Shape of rapidity spectrum is mainly driven by PDFs
  → mildly sensitive to radiative corrections
- Effect of QCD radiation is mainly encoded in p_T spectrum
- When $p_T \sim m_H$ the QCD radiative corrections can be evaluated through the standard fixed-order expansion
- When $p_T \ll m_H$ large logarithmic terms appear
  → spoil the perturbative expansion

The $p_T \sim m_H$ region

In order to have $p_T \neq 0$ Higgs boson has to recoil against at least one parton.

- The exact result at LO has been computed long ago
  R. K. Ellis, I. Hinchliffe et al. (1988), U. Baur and E.W.N.Glover (1990)
- The NLO corrections are known only in the large m_{top} limit
  D. de Florian, Z. Kunszt, M. Grazzini (1999), V. Ravindran, J. Smith, V. Van Neerven (2002), C. Glosser, C. Schmidt (2002)
- Recently the NNLO corrections in the gg channel have been evaluated X. Chen, T. Gehrmann, E.W.N. Glover, M. Jaquier (2014), R.Boughezal, F.Petriello, K.Melnikov, M.Schulze (2013)



Large quantitative effect!

Heavy-quark mass effects at fixed order

The heavy-quark mass dependence is known up to NLO

- One loop real corrections

  R. K. Ellis, I. Hinchliffe, M. Soldate, J. van der Bij (1988)

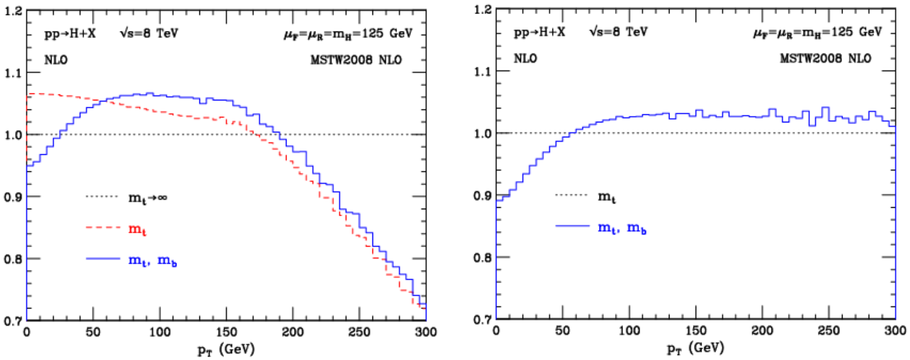
- Two loop virtual corrections

  M. Spira et al. (1991, 1995), R. Harlander, P. Kant (2005), U.Aglietti, R.Bonciani, G. Degrassi, A.Vicini (2006)

The heavy-quark mass dependence has been implemented in the fully exclusive calculation in HNNLO M. Grazzini, HS (2013)

- Top and bottom quark mass dependence is taken into account up to NLO
- at NNLO we consider only the top quark contribution and we rescale it with $\sigma_{\mathrm{LO}}(m_{\mathrm{t}})/\sigma_{\mathrm{LO}}(m_{\mathrm{t}} \to \infty)$

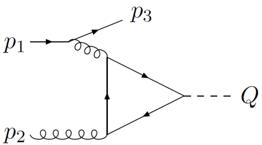
Heavy-quark mass effects at fixed order

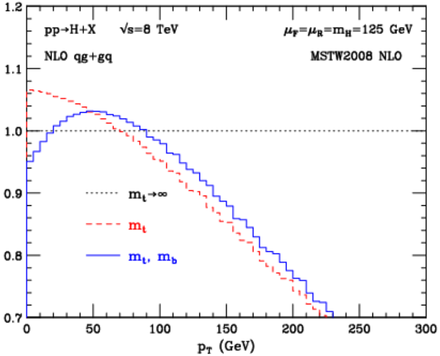


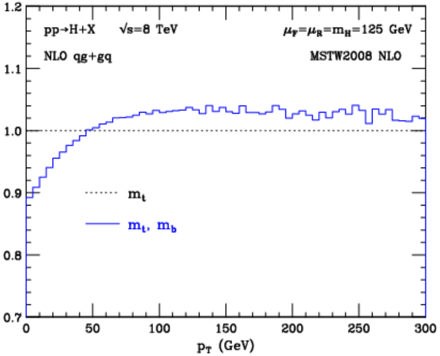
- At large p_T the top quark contribution dominates and reduces the cross section with respect to the result in the large-m_t limit
- At small p_T the bottom contribution is significant and changes the shape of the spectrum

The bottom quark loop

Consider the amplitude of the Higgs production in the $qg \to Hq$ channel







Similar effect as for the full calculation: The bottom-induced contribution does not factorize naively

Checked also analytically !

The low p_T region

- When $p_T^2 \ll M_{\rm H}^2$ large logarithms of the form $\alpha_S^n \log(M_{\rm H}^2/p_T^2)$ appear, due to soft and collinear gluon emissions. Effective expansion variable is the $\alpha_S^n \log(M_{\rm H}^2/q_T^2)$, which can be ~ 1 even for small α_S. These large logarithms need to be resummed to all orders in α_S, in order to get reliable predictions over the whole range of the transverse momenta.
- Such resummation is effectively performed by standard MC generators

p_T-resummation

S. Catani, D. de Florian, M. Grazzini(2000)

G. Bozzi, S. Catani, D. de Florian, M. Grazzini(2005)

$$\frac{d\hat{\sigma}_{a_1 a_2}}{dp_T^2} = \frac{d\hat{\sigma}^{(\mathrm{res.})}_{a_1 a_2}}{dp_T^2} + \frac{d\hat{\sigma}^{(\mathrm{fin.})}_{a_1 a_2}}{dp_T^2}$$

$$\left[\frac{d\hat{\sigma}^{(\mathrm{fin.})}_{a_1 a_2}}{dp_T^2}\right]_{\mathrm{f.o.}} = \left[\frac{d\hat{\sigma}_{a_1 a_2}}{dp_T^2}\right]_{\mathrm{f.o.}} - \left[\frac{d\hat{\sigma}^{(\mathrm{res.})}_{a_1 a_2}}{dp_T^2}\right]_{\mathrm{f.o.}}$$

- The resummed component is obtained by working in impact parameter b space

$$\frac{d\hat{\sigma}^{(\mathrm{res.})}_{a_1 a_2}}{dp_T^2} = \int_0^\infty db \frac{b}{2} J_0(bp_T) \mathcal{W}_{a_1 a_2}(b, M; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2)$$

- The resummation can be organized in an exponential form using N-moments

$$\mathcal{W}_N(b, M; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2) = \mathcal{H}_N(M, \alpha_S(\mu_R^2); M^2/\mu_R^2, M^2/\mu_F^2, M^2/Q^2) \times exp\left\{\mathcal{G}_N(\alpha_S(\mu_R^2), \tilde{L}; M^2/\mu_R^2, M^2/Q^2)\right\}$$

resummation scale

$$\tilde{L} = ln\left(\frac{Q^2 b^2}{b_0^2} + 1\right)$$

p_T-resummation

- The process dependent hard-virtual factor $\mathcal{H}_N$ is computable order by order in perturbation theory

$$\mathcal{H}_N(M,\alpha_S) = \sigma^{(0)}(\alpha_S, M)\left[1 + \sum_1^\infty \left(\frac{\alpha_S}{\pi}\right)^n \mathcal{H}_N^{(n)}\right]$$

- The universal exponential factor can be organized in the following way

LL → $\tilde{L} g^{(1)}(\alpha_S \tilde{L})$, NLL → $g_N^{(2)}(\alpha_S \tilde{L})$, NNLL → $\frac{\alpha_S}{\pi}\tilde{L} g_N^{(3)}(\alpha_S \tilde{L})$

$$\mathcal{G}_N(\alpha_S, \tilde{L}) = \tilde{L} g^{(1)}(\alpha_S \tilde{L}) + g_N^{(2)}(\alpha_S \tilde{L}) + \frac{\alpha_S}{\pi}\tilde{L} g_N^{(3)}(\alpha_S \tilde{L}) + \sum_4^\infty \left(\frac{\alpha_S}{\pi}\right)^{n-2} \tilde{L} g_N^{(n)}(\alpha_S \tilde{L})$$

- All the perturbative coefficients are known up to NNLO

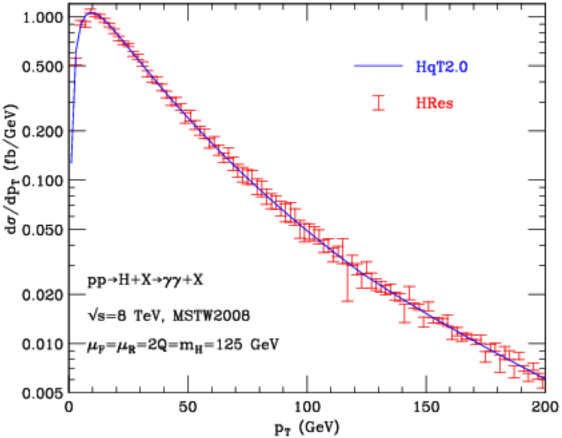
  ⟹ NNLL+NNLO is the highest accuracy available at the moment

  ⟹ Implemented in HqT

HRes

D. de Florian, G. Ferrera, D. Tommasini, M. Grazzini (2011)

- HRes combines the NNLO calculation in HNNLO with the small p_T-resummation implemented in HqT
- Three decay channels of the Higgs boson implemented: $H \to \gamma\gamma$, $H \to WW \to l\nu l\nu$ and $H \to 4l$



Mass effects in the resummed spectrum

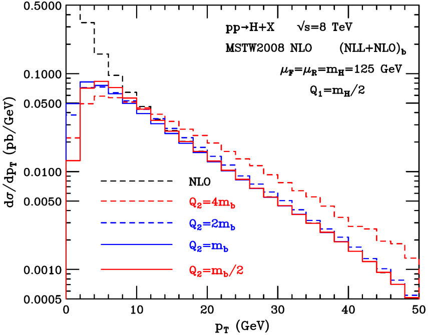
- Since $m_t \sim m_H$, as far as only the top quark is considered we have only 2 physical scales m_H and p_T
- The inclusion of the bottom quark introduces the third physical scale m_b

  Studying the analytic behaviour of the QCD matrix elements we find that, for the bottom quark contribution the collinear factorization is a good approximation only when $p_T \ll 2m_b$

  → the standard resummation procedure cannot be straightforwardly applied to the bottom quark contribution
- Our resummation formalism introduces an unphysical scale Q (resummation scale) which sets the scale up to which the resummation is effective
- the top quark gives the dominant contribution to the p_T cross section and we treat it as usual with a resummation scale $Q_1 \sim m_H/2$
- the bottom contributions (and the top-bottom interference) are controlled by an additional resummation scale Q_2 that we choose of the order of m_b

Mass effects in the resummed spectrum

We have implemented the exact heavy-quark mass dependence in a new version of the numerical program HRes



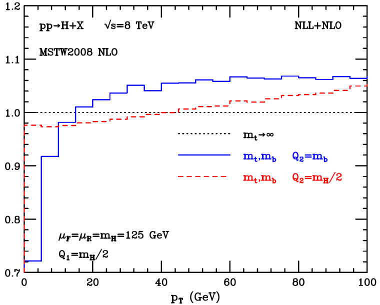
We focus on the bottom contribution
The p_T spectra for $Q_2 = m_b/2$, $Q_2 = m_b$ and $Q_2 = 2m_b$ agree well with the fixed order spectrum, while for $Q_2 = 4m_b$ the resummed and fixed order spectra do not match

→ We choose $Q_2 = m_b$ as a central value of the second resummation scale

Mass effects in the resummed spectrum

The naive implementation of the the bottom quark mass leads to a result very similar to MC@NLO
Good agreement with independent calculation by Wiesmann, Mantler (2012)

The inclusion of the second resummation scale increases the effect of the bottom quark in the low p_T region



➡ result is more similar to the POWHEG result, though in our case the effects of the bottom quark are confined to smaller values of p_T

But in order to judge the relevance of this effect we should compare with the perturbative uncertainties affecting the NLL+NLO calculation (which are large)

Mass effects in the resummed spectrum

Recently the choice of the central value of the second resummation scale and the range of variation of it for getting a reliable estimation of the scale uncertainties has been a matter of discussion

- For a related quantity - the cross section with a jet veto, it was argued that the factorisation breaking terms are moderate and can be treated as a finite remainder

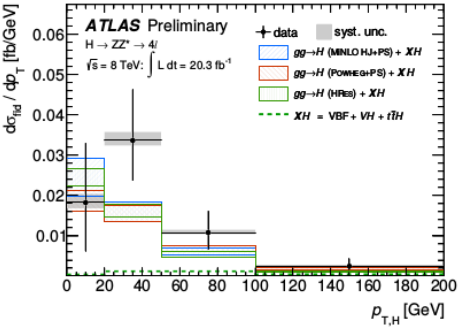
  A. Banfi, P. F. Monni, G. Zanderighi (2013)
- In the work by Harlander et al. it was suggested to choose the second resummation scale on the case-by-case basis, with a requirement of the resummed cross section to agree reasonably well ($\pm 100\,\%$) with the fixed order spectrum for the large transverse momenta

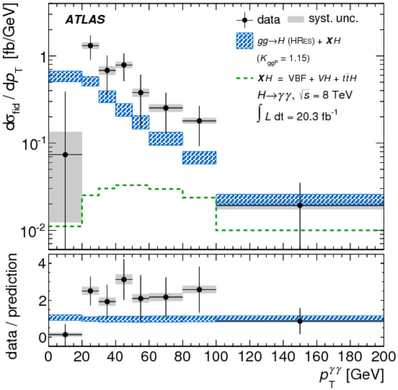
  R. Harlander, R. Mantler,M. Wiesemann (2014)

  In this way they get Q_2 larger than what was proposed in our work, but still smaller than Q_1

  Taking into account these new observations maybe one has to vary the second resummation scale Q_2 in a broader range

The data





The observed spectrum seems to be harder than the theory prediction, however the uncertainties are still large !

Boosted Higgs

In generic BSM scenarios the effective gluon-gluon-Higgs vertex will receive contributions from dimension-6 operators
Droping away the CP-violating operators the effective Lagrangian can be parametrised as

$$\mathcal{L} = -\kappa_t \frac{m_{\rm top}}{v} \bar{t} t h + \kappa_g \frac{\alpha_S}{12\pi} \frac{h}{v} G^a_{\mu\nu} G^{\mu\nu\, a} \,, \quad \mathrm{SM:} \;\; \kappa_t = 1\,, \quad \kappa_g = 0\,.$$

due to the Higgs low energy theorem $\sigma_{\rm incl}(\kappa_t, \kappa_g) \simeq (\kappa_t + \kappa_g)^2 \sigma_{\rm incl}^{\rm SM}$

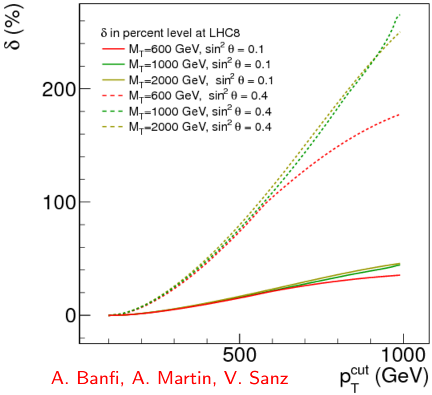
→ impossible to disentangle short- and long-distance contribution

- Direct access to the top Yukawa coupling is through the $pp \to t\bar{t}h$ process, but small rate, high threshold, complicated final state
- Looking at high-p_T events allows us to break this degeneracy

Boosted Higgs

$$\delta(p_T^{\rm cut}, M_T, \sin\theta) = \frac{\sigma_{t+T}(p_T > p_T^{\rm cut}) - \sigma_t(p_T > p_T^{\rm cut})}{\sigma_t(p_T > p_T^{\rm cut})}\,.$$

$$\sigma(p_T > p_T^{\rm cut}) = \int_{p_T^{\rm cut}} dp_T \frac{d\sigma}{dp_T}\,.$$

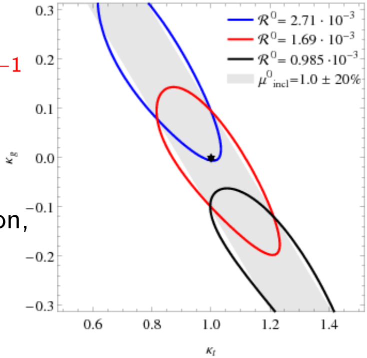


A. Banfi, A. Martin, V. Sanz

- Relative effect of top partners on high-p_T cross section can be very large

Boosted Higgs

Recent study by Grojean et al. in $H \to \tau\tau$
High luminocity LHC at 14 TeV with $3\,\mathrm{ab}^{-1}$
$10\,\%$ systematics
Conider the ratio $\frac{\sigma(p_T > 650\,\mathrm{GeV})}{\sigma(p_T > 150\,\mathrm{GeV})}$
Include NLO K-factors in the EFT
Even if the inclusive rate shows no deviation,
a $20\,\%$ deviation of the $t\bar{t}h$ coupling
can be resolved



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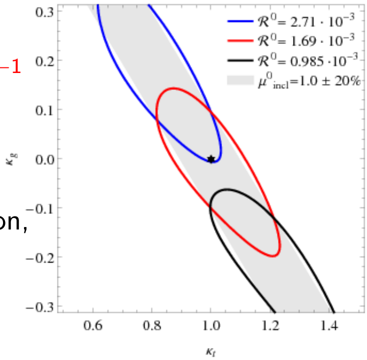


Exact m_{top} dependence needed for the $H + \mathrm{jet}$ production at NLO for better analyses!

Summary

- The p_T distribution of the Higgs is one of the most important observables at hadron colliders
- The first data suggests somewhat harder spectrum, but the uncertainties are still large
- The heavy quark mass effects are included in the fixed order and resummed calculations up to NLO and NLO+NLL accuracy and implemented in the numerical programs HNNLO and HRes
- At NNLO we consider only the top-quark contribution and we rescale it with $\sigma_{\rm LO}(m_{\rm t})/\sigma_{\rm LO}(m_{\rm t} \to \infty)$

Summary

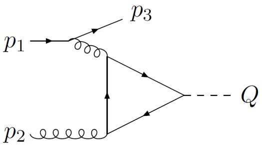
- The bottom quark plays an important role and leads to relatively large differences in the shape of the p_T spectrum
- The inclusion of the latter beyond fixed order introduces a third scale in the calculation, reducing the range of applicability of the transverse momentum resummation
- We deal with this problem by controlling the resummed bottom-quark contribution through an additional resummation scale $Q_2 \sim m_b$
- Other works on this issue propose larger values for Q_2, but still smaller than Q_1
- High-p_T Higgs events offer the possibility to explore BSM scenarios in which large deviations appear that are not visible in the inclusive rate
- The case of models with top partners is a clear example

Backup slides

The bottom quark loop

Consider the amplitude of the Higgs production in the $qg \to Hq$ channel

$$s = (p_1 + p_2)^2$$
$$t = (p_1 - p_3)^2$$
$$u = (p_2 - p_3)^2$$



$$|\mathcal{M}_{qg\to Hq}(s,t,u)|^2 = \alpha_W \alpha_S^3 C_F C_A \frac{u^2+s^2}{-tM_W^2} \frac{m_H^4}{(u+s)^2} |A_5(t,s,u)|^2$$

$$s + u + t = m_H^2, \quad ut = sp_T^2$$

$$A_5(t,s,u) = \sum_{f=b,t} \frac{m_f^2}{m_H^2} \Big[4 + \frac{4t}{u+s}\left[W_1(t) - W_1(m_H^2)\right] + \left[1 - \frac{4m_f^2}{u+s}\right]\left[W_2(t) - W_2(m_H^2)\right]\Big],$$

R.K. Ellis, I. Hinchliffe, M. Soldate, J. van der Bij (1988)

In the small p_T region we have $t \to 0$ and $u \to -s(1-z)$, $z = m_H^2/s$

The bottom quark loop

In the limit $p_T \to 0$ (naive collinear factorization)

$$|\mathcal{M}_{qg\to Hq}(s,t,u)|^2 = \alpha_W \alpha_S^3 C_F C_A \frac{1+(1-z)^2}{z^2} \frac{m_H^4}{M_W^2} \frac{1}{-t} |A_1(m_H^2)|^2,$$

where $A_1(m_H^2)$ is the Born $gg \to H$ amplitude

$$A_1(m_H^2) = \sum_{f=b,t} \frac{m_f^2}{m_H^2} \left[4 - W_2(m_H^2) \left(1 - \frac{4m_f^2}{m_H^2} \right) \right]$$

$$A_{5b}(t,s,u) = \frac{m_b^2}{m_H^2} \left[4 - \left(W_2(m_H^2) - W_2(t) \right) \left(1 - \frac{4m_b^2}{m_H^2} \right) \right]$$

$$W_2(t) = 4 \left(\mathrm{arcsinh} \left(\frac{\sqrt{-t}}{2m_b} \right) \right)^2$$

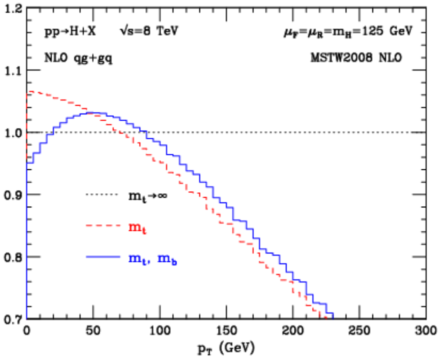
$$A_{5b} \xrightarrow{p_T \to 0} A_{1b}$$

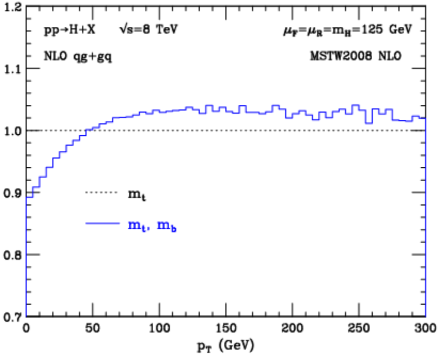
The bottom quark loop

This does not hold when $p_T \sim m_b$

$$|t| \sim 4m_b^2 \;\Longrightarrow\; W_2(t) \sim 1$$

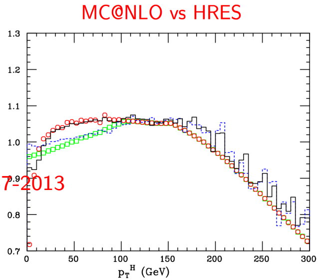
- The naive collinear factorization, which would lead us to recover the Born result, does not hold here
- $W_2(t)$ is an increasing function of $-t$, and hence, of p_T, thus explaining the steep behaviour in p_T distribution





Indeed, also in this channel the bottom contribution distorts the spectrum at low p_T

MC@NLO vs HRes



23-7-2013

S. Frixione, Higgs XS WG Meeting,

histograms: MC@NLO symbols: HRes

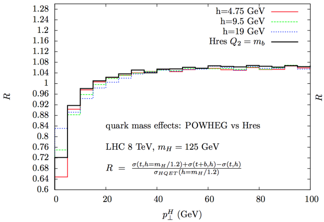
solid and circles: $Q_2 = \mathcal{O}(m_b)$ dashed and boxes: $Q_2 = \mathcal{O}(m_H)$

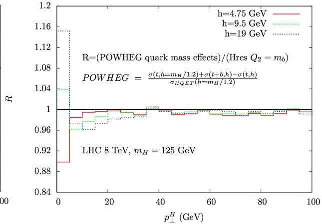
POWHEG vs HRes

A. Vicini, Higgs XS WG Meeting, 23-7-2013

Numerical comparison with Hres

- Hres results (arXiv:1306.4581) kindly provided by M. Grazzini





- Significant suppression due to bottom mass effects in the first two bins, rather flat and positive corrections above 30 GeV