The resummed transverse momentum distribution of the Higgs in gluon fusion

Hendrik Mantler

Theory Division, CERN

in collaboration with Emanuele Bagnaschi, Robert Harlander, Stefan Liebler, Alessandro Vicini and Marius Wiesemann

Radcor-Loopfest

at the

University of California,

Los Angeles

June 15-19, 2015

Different models

- SM
- 2HDM
- MSSM
- NMSSM

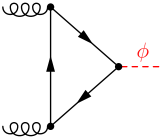
The resummation of logarithms $\log(p_T/m_\Phi)$ is necessary to obtain reliable result for small p_T

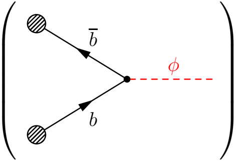
Different approaches

- Analytic resummation
- MC@NLO
- POWHEG

Different processes

- Gluon fusion
- (Bottom quark annihilation)





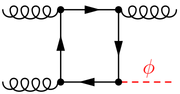
Gluon fusion

Resummed p_T distribution

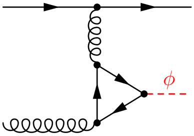
- with exact quark mass dependence
  [Bagnaschi, Degrassi, Slavich, Vicini '12; HM, Wiesemann '12; Grazzini, Sargsyan '13; Banfi, Monni, Zanderighi '13]
- and with squark contributions in the MSSM
  [Bagnaschi, Degrassi, Slavich, Vicini '12; HM, Wiesemann '12]

Real emission:

- Quark
  known analytically
  [Spira, Djouadi, Graudenz, Zerwas '95]

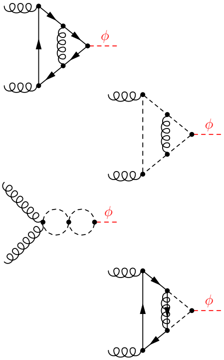


- Squark
  known analytically
  [Mühlleitner, Spira '06; Bonciani, Degrassi, Vicini '07]



Gluon fusion / virtual corrections

- Quark-gluon known analytically (at higher orders)
  [Spira, Djouadi, Graudenz, Zerwas '95; Harlander, Kant '05]
- Squark-gluon/squark known analytically
  [Anastasiou, Beerli, Bucherer, Daleo, Kunszt '06; Aglietti, Bonciani, Degrassi, Vicini '06; Mühlleitner, Spira '06]
- Quark-squark-gluino semi-analytically known, but no public code
  [Anastasiou, Beerli, Daleo '08; Mühlleitner, Rzehak, Spira '10]



- Taylor expansion in the Higgs mass: $m_\phi \ll m_q, m_{\tilde{q}_1}, m_{\tilde{q}_2}, m_{\tilde{g}}$
  [Harlander, Steinhauser '03 '04 + Hofmann '05; Degrassi, Slavich '08]
  $\longrightarrow$ top-stop-gluino
- Expansion in SUSY masses: $m_\phi, m_q \ll m_{\tilde{q}_1}, m_{\tilde{q}_2}, m_{\tilde{g}}$
  [Harlander, Hofmann, HM '10; Degrassi, Slavich '10 + Di Vita '11 '12]
  $\longrightarrow$ bottom-sbottom-gluino
  $\longrightarrow$ top-stop-gluino

Codes for gluon fusion

POWHEG

Implementations in POWHEG-BOX:

gg_H_quark-mass-effects, gg_H_2HDM, gg_H_MSSM
[1111.2854, Bagnaschi, Degrassi, Slavich, Vicini '12]
powhegbox.mib.infn.it

POWHEG-SusHi [HM unpublished]
Amplitudes from SusHi [1212.3249; Harlander, Liebler, HM '12]

MC@NLO

aMCSusHi [1504.06625, HM, Wiesemann '15]
cp3.irmp.ucl.ac.be/projects/madgraph/wiki/aMCSusHi
Script for MadGraph5_aMC@NLO, link to SusHi

Analytic resummation

MoRe-SusHi [1409.0531, Harlander, HM, Wiesemann '14]
Analytically resummed p_T distribution at NLO+NLL
sushi.hepforge.org/moresushi

SM	2HDM	MSSM	NMSSM
✓	✓	✓	
✓	✓	✓	✓
✓	✓	✓	✓
✓	✓	✓	✓

✓ = published, ✓ = only private code

Codes for gluon fusion

POWHEG

Implementations in POWHEG-BOX:

gg_H_quark-mass-effects, gg_H_2HDM, gg_H_MSSM
[1111.2854, Bagnaschi, Degrassi, Slavich, Vicini '12]
powhegbox.mib.infn.it

POWHEG-SusHi [HM unpublished]
Amplitudes from SusHi [1212.3249; Harlander, Liebler, HM '12]

MC@NLO

aMCSusHi [1504.06625, HM, Wiesemann '15]
cp3.irmp.ucl.ac.be/projects/madgraph/wiki/aMCSusHi
Script for MadGraph5_aMC@NLO, link to SusHi

Analytic resummation

MoRe-SusHi [1409.0531, Harlander, HM, Wiesemann '14]
Analytically resummed p_T distribution at NLO+NLL
sushi.hepforge.org/moresushi

matching scale

hfact

---

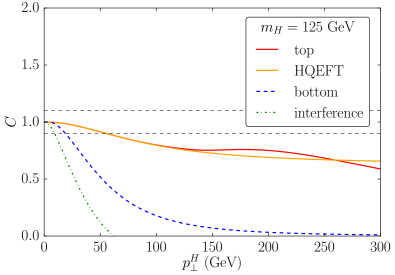
shower scale

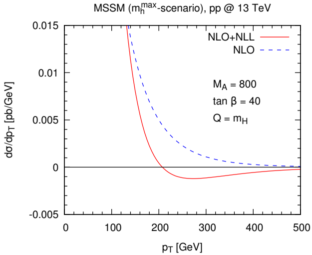
---

resummation scale

BV method	HMW method
[Bagnaschi, Vicini]	[Harlander, HM, Wiesemann]

Restrict resummation to region in which the collinear approximation is valid $\rightarrow$ deviation between matrix element and collinear approximation should be smaller than 10%





p_T distribution can be negative!

Too large Q overemphasizes the Sudakov contribution
$\Rightarrow$ large cross section at small p_T

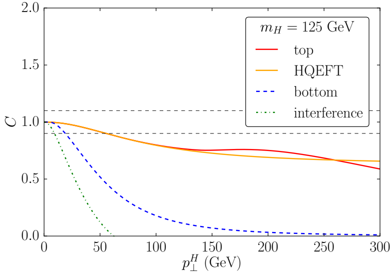
unitarity constraint:

$$\int \left(\frac{d\sigma}{dp_T}\right)^{NLO+NLL} dp_T = \sigma^{NLO}$$

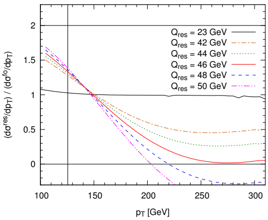
$\Rightarrow$ compensation at large p_T

BV method	HMW method
[Bagnaschi, Vicini]	[Harlander, HM, Wiesemann]

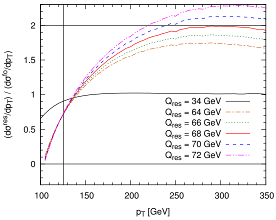
Restrict resummation to region in which the collinear approximation is valid $\rightarrow$ deviation between matrix element and collinear approximation should be smaller than 10%



bottom

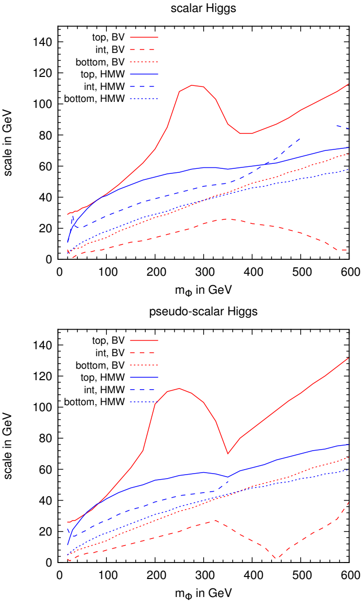


top bottom interference



BV vs. HMW

Preliminary



Both methods do not dependent on the scenario!
Only dependence: Higgs mass m_Φ

Top

- Large threshold effect for BV, much less pronounced for HMW
- Agreement up to a factor of two

Bottom

- Differences are below 20%
- Bottom scales smaller than the top scales, but larger than m_b

Interference

- Large differences

Running the codes

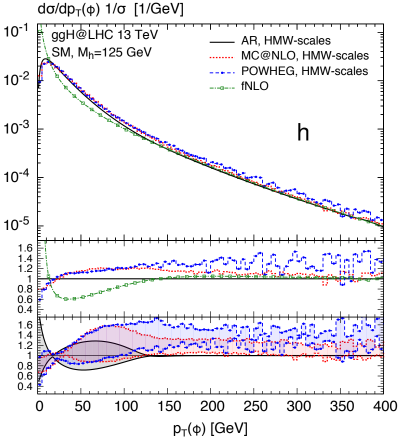
3 different matching scales $\Rightarrow$ 5 runs of the code:

$$\sigma_t(Q_t) + \sigma_b(Q_b) + [\sigma_{b+t}(Q_{int}) - \sigma_t(Q_{int}) - \sigma_b(Q_{int})]$$

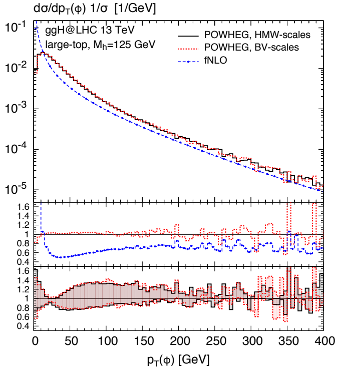
SusHi-related codes:
Input file in the SLHA format, similar to a SusHi input file:

```
Block MORESUSHI
  1     50000    # Number of integrations
Block DISTRIB2
  1     1.d0     # Minimal Higgs pT in GeV
  2     100.d0   # Maximal Higgs pT in GeV
  5     1.d0     # Stepsize of Higgs pT in GeV
Block MORESUSHIKEYS
  1     1        # gluon-gluon channel: 0=off, 1=on
  2     1        # gluon-quark channel: 0=off, 1=on
  3     1        # quark-quark channel: 0=off, 1=on
 11     0        # heavy-top approximation: 0=off, 1=on
Block SCALES
  4     68.d0    # Resummation scale Qres in GeV
Block SUSHI
  1     0        # Chosen model: 0=SM, 1=MSSM, 2=2HDM
  2     11       # 11=scalar, 21=pseudo-scalar
  3     0        # Particle collider: 0=pp, 1=ppbar
  4     13000.d0 # center-of-mass energy in GeV
...
```

Preliminary

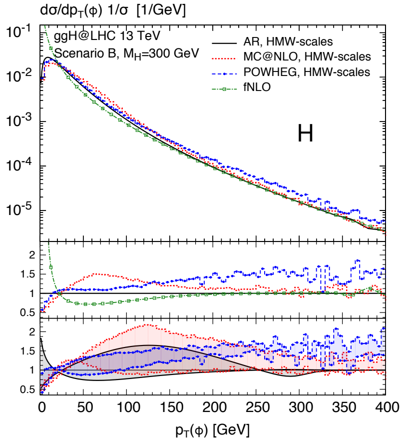


Approach	Method
POWHEG	HMW
MC@NLO	HMW
analytic resummation	HMW

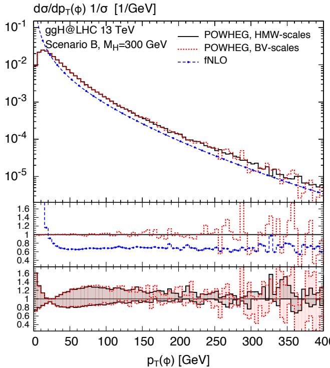


Top contribution is dominant

Preliminary



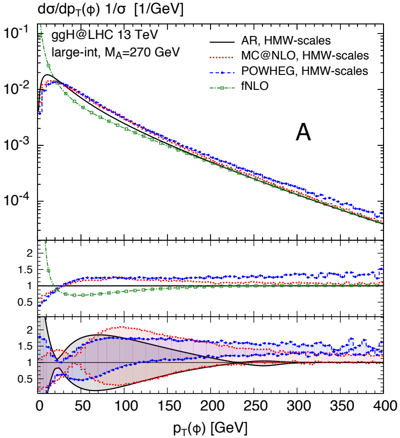
Approach	Method
POWHEG	HMW
MC@NLO	HMW
analytic resummation	HMW



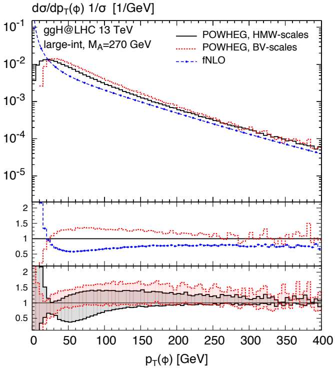
Scenario B from [1312.5571, Harlander, Mühlleitner, Rathsman, Spira, Stål '13]

$tan\beta = 40 \Rightarrow$ Bottom is dominant

Preliminary



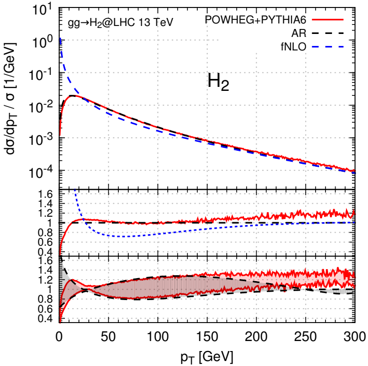
Approach	Method
POWHEG	HMW
MC@NLO	HMW
analytic resummation	HMW

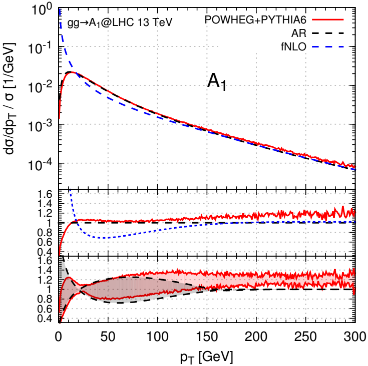


Scenario with a large interference term

Comparison in the NMSSM

Preliminary





HMW-scales for all approaches

Parameters:

$\tan\beta = 2$, $A_\kappa = -20$ GeV, $\lambda = 0.62$, $\mu = 200$ GeV, $m_{H^\pm} = 400$ GeV,
$m_{\tilde{t}_1} = 544.7$ GeV, $m_{\tilde{t}_1} = 941.2$ GeV, $m_{\tilde{b}_1} = 749.4$ GeV, $m_{\tilde{b}_1} = 757.4$ GeV,
$M_3 = 1.5$ TeV, $\kappa = 0.5$, $m_{H_2} = 297.5$ GeV, $m_{A_1} = 166.5$ GeV

Conclusion

- Codes for three different approaches (POWHEG, MC@NLO and analytic resummation)
- Two independent methods (BV and HMW) to determine the matching scales
- Study of the 2HDM including a comparison between the different approaches and methods ongoing
- New codes for the NMSSM will be available soon
- What about the squark contributions?

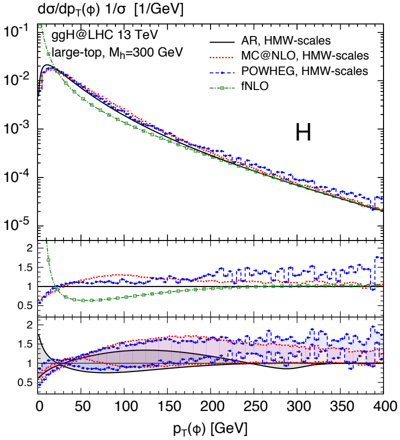
- Codes for three different approaches (POWHEG, MC@NLO and analytic resummation)
- Two independent methods (BV and HMW) to determine the matching scales
- Study of the 2HDM including a comparison between the different approaches and methods ongoing
- New codes for the NMSSM will be available soon
- What about the squark contributions?

Thanks for your attention!

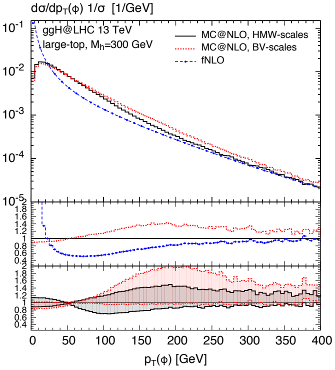
Backup

Model (page)	m_Φ [GeV]	HMW [GeV]			BV [GeV]		
		Q_t	Q_b	Q_{int}	w_t	w_b	w_{int}
SM (10)	125	45	21	31	48	18	9
2HDM (11+17)	300	59	39	47	111	38	23
2HDM (12+18)	270	57	37	44	110	35	22
NMSSM (13,left)	297.5	59	39	47	-	-	-
NMSSM (13,right)	166.5	49	27	35	-	-	-

Preliminary



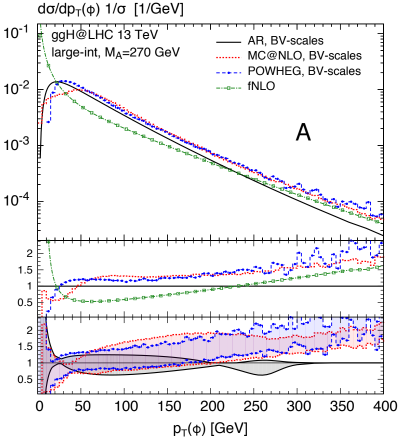
Approach	Method
POWHEG	HMW
MC@NLO	HMW
analytic resummation	HMW



Top contribution is dominant

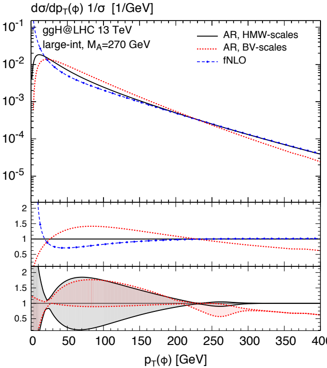
Comparison in the 2HDM

Preliminary



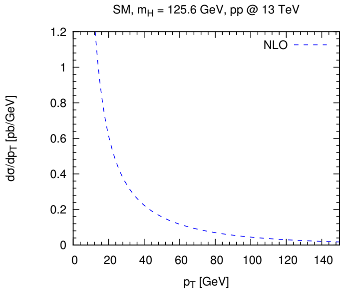
Scenario with a large interference term

Approach	Method
POWHEG	BV
MC@NLO	BV
analytic resummation	BV



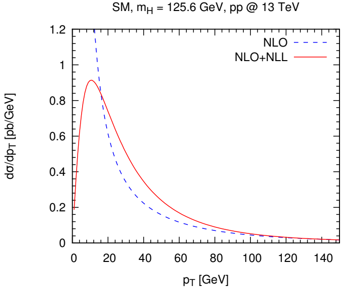
p_T distribution at NLO+NLL:

$$\left(\frac{d\sigma}{dp_T}\right)^{NLO+NLL} = \frac{d\sigma^{\mathrm{NLO}}}{dp_T} - \left[\frac{d\sigma^{\mathrm{logs}}}{dp_T}\right]_{NLO} + \left[\frac{d\sigma^{\mathrm{res}}}{dp_T}\right]_{NLL}$$



p_T distribution at NLO+NLL:

$$\left(\frac{d\sigma}{dp_T}\right)^{NLO+NLL} = \frac{d\sigma^{\mathrm{NLO}}}{dp_T} - \left[\frac{d\sigma^{\mathrm{logs}}}{dp_T}\right]_{NLO} + \left[\frac{d\sigma^{\mathrm{res}}}{dp_T}\right]_{NLL}$$



p_T distribution at NLO+NLL:

$$\left(\frac{d\sigma}{dp_T}\right)^{NLO+NLL} = \frac{d\sigma^{\text{NLO}}}{dp_T} - \left[\frac{d\sigma^{\text{logs}}}{dp_T}\right]_{NLO} + \left[\frac{d\sigma^{\text{res}}}{dp_T}\right]_{NLL}$$

unitarity constraint:

$$\int \left(\frac{d\sigma}{dp_T}\right)^{NLO+NLL} dp_T = \sigma^{NLO}$$

p_T distribution at NLO+NLL:

$$\left(\frac{d\sigma}{dp_T}\right)^{NLO+NLL} = \frac{d\sigma^{\text{NLO}}}{dp_T} - \left[\frac{d\sigma^{\text{logs}}}{dp_T}\right]_{NLO} + \left[\frac{d\sigma^{\text{res}}}{dp_T}\right]_{NLL}$$

unitarity constraint:

$$\int \left(\frac{d\sigma}{dp_T}\right)^{NLO+NLL} dp_T = \sigma^{NLO}$$

new unphysical scale:

resummation scale Q

Suppression of the error bands for large p_T:

$$d(p_T) = \{1 + \exp[\alpha\,(p_T - m_\Phi)]\}^{-1}, \quad \alpha = 0.1\,\mathrm{GeV}^{-1}$$

$$\left(\frac{d\sigma}{dO}\right)_{\text{MC@NLO}} = \int d\Phi_n \left[B + V + \int d\Phi_1^{\text{MC}}\, K^{\text{MC}}\right] \mathcal{I}_B^{\text{MC}}(O)$$
$$+ \int \left[d\Phi_{n+1} R - d\Phi_{n+1}^{\text{MC}} K^{\text{MC}}\right] \mathcal{I}^{\text{MC}}(O)$$

$B \equiv$ Born
$V \equiv$ virtual corrections
$R \equiv$ real emission
$K^{\text{MC}} \equiv$ subtraction term
$\mathcal{I}_{(B)}^{\text{MC}}(O) \equiv$ shower

Shower scale corresponds to the starting scale of the shower choosen event by event from a distribution

$$d\sigma = \bar{B}^s\left(\Phi_B\right) d\Phi_B \left\{ \Delta^s_{t_0} + \Delta^s_t \frac{R^s\left(\Phi\right)}{B\left(\Phi_B\right)} d\Phi_\mathrm{r} \right\} + R^f d\Phi + R_{reg} d\Phi$$

$\bar{B}^s(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int d\Phi_r\, R^s(\Phi_r)$

$B \equiv$ Born
$V \equiv$ virtual corrections
$R = R_{reg} + R_{div} \equiv$ real emission

The real emission can be split into channels that are regular (R_{reg}) and divergent (R_{div}) in the limit of collinear emission

$R_{div} = R^s + R^f$

$R^s \equiv$ singular part of R_{div}
$R^f \equiv$ finite part of R_{div}

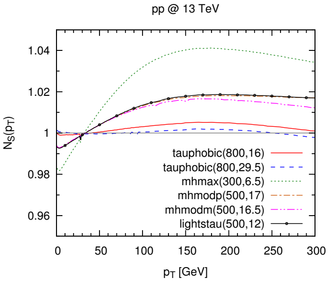
Damping factor $D(h) = \frac{h^2}{h^2 + p_T^2}$
$R^s = D \cdot R_{div}, \quad R^f = (1 - D) \cdot R_{div}$

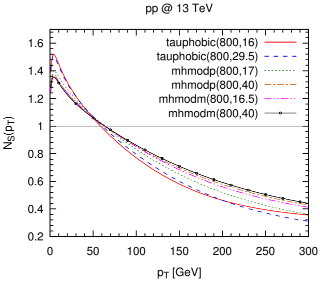
[1409.0531, Harlander, HM, Wiesemann '14]

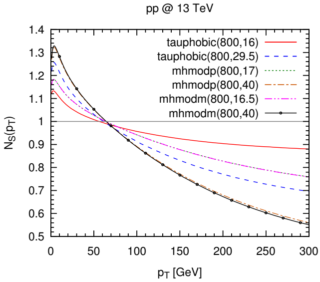
Scenario(M_A, $\tan\beta$)

$$\frac{d\bar{\sigma}}{dp_T} = \frac{1}{\sigma}\frac{d\sigma}{dp_T}$$

$$N_{\mathcal{S}}(p_T) = \frac{d\bar{\sigma}_{\mathcal{S}}/dp_T}{d\bar{\sigma}_{\text{SM}}/dp_T}$$



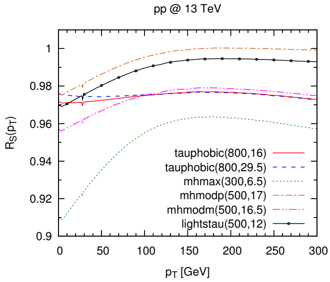


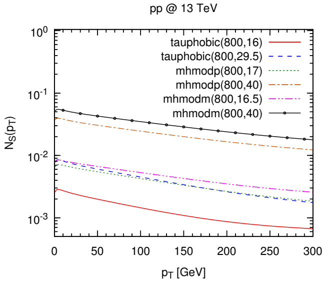


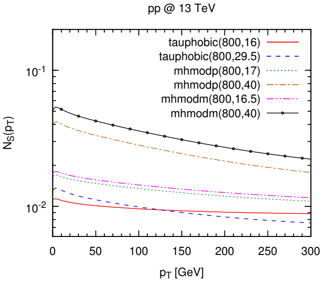
[1409.0531, Harlander, HM, Wiesemann '14]

Scenario(M_A, $\tan\beta$)

$$R_S(p_T) = \frac{\mathrm{d}\sigma_S/\mathrm{d}p_T}{\mathrm{d}\sigma_{\mathrm{SM}}/\mathrm{d}p_T}$$







Shapes

The p_T-shape for the bottom-quark (red, solid) and the top-bottom interference contribution (green, dotted), normalized to the top-contribution (black, dash-double dotted):