2HDM THEORY RECOMMENDATIONS

Michael Spira (PSI)

I INTRODUCTION

2HDM

- minimal extension: 2 Higgs doublets

ESB $\rightarrow$ 5 Higgs bosons:

h, H	neutral, $\mathcal{CP}$ even
A	neutral, $\mathcal{CP}$ odd
$H^{\pm}$	charged

- modified couplings:

2HDM type II [I]

ϕ	g_u^ϕ	g_d^ϕ	g_V^ϕ
h	c_α/s_β	$-s_\alpha/c_\beta$ $[c_\alpha/s_\beta]$	$s_{\beta-\alpha}$
H	s_α/s_β	c_α/c_β $[s_\alpha/s_\beta]$	$c_{\beta-\alpha}$
A	ctgβ	tgβ $[-\text{ctg}\beta]$	0

II *HIGGS BOSON DECAYS*

Two codes for type I–IV 2HDM:

- 2HDMC: calculation of 2HDM Higgs sector including perturbativity/vac. stability and exp. constraints [→ HiggsBounds] Eriksson, Rathsman, Stål
- HDECAY: extension to BRs of 2HDM Djouadi, Kalinowski, Mühlleitner, S.

- both codes include higher-order (QCD) corrections in a sufficient way [small differences] → ongoing work...

- successful comparison!

- recommendation: use both codes [most up-to-date 2HDM tools]

- scenarios for comparison [arbitrary!]

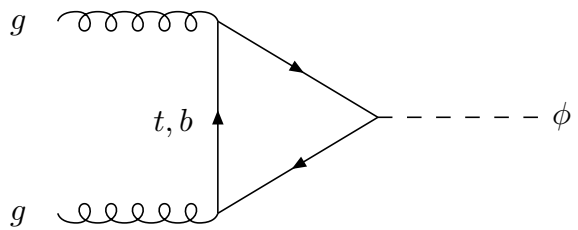
Parameter	Scenario A	Scenario B	Scenario C
Common parameters			
Type	I	II	II
M_h (GeV)	125	125	125
M_H (GeV)	300	300	400
M_A (GeV)	330	270	500
$M_{H^\pm}$ (GeV)	230	335	550
M_{12}^2 (GeV^2)	25600	1798	15800
$\tan\beta$	1.5	50	10
2HDMC			
$\sin(\beta-\alpha)$	0.901314	0.999001	0.999
λ_6	0	0	0
λ_7	0	0	0
HDECAY			
α	-0.14	0.0247	-0.0549436

- numbers for scenario B

		2HDMC		HDECAY		
		BR	Γ (GeV)	BR	Γ (GeV)	Γ_{2H}/Γ_{HD}
$h \to$	$b\bar{b}$	0.6794	4.018×10^{-3}	0.6809	4.051×10^{-3}	0.992
	$\tau^+\tau^-$	6.672×10^{-2}	3.946×10^{-4}	6.633×10^{-2}	3.947×10^{-4}	1.000
	$\mu^+\mu^-$	2.362×10^{-4}	1.397×10^{-6}	2.348×10^{-4}	1.397×10^{-6}	1.000
	$s\bar{s}$	2.384×10^{-4}	1.410×10^{-6}	2.402×10^{-6}	1.429×10^{-6}	0.987
	$c\bar{c}$	2.031×10^{-2}	1.201×10^{-4}	1.975×10^{-2}	1.175×10^{-4}	1.022
	gg	7.043×10^{-2}	4.166×10^{-4}	7.089×10^{-2}	4.218×10^{-4}	0.988
	$\gamma\gamma$	1.391×10^{-3}	8.229×10^{-6}	1.375×10^{-3}	8.181×10^{-6}	1.006
	$Z\gamma$	1.013×10^{-3}	5.994×10^{-6}	1.003×10^{-3}	5.968×10^{-6}	1.004
	W^+W^-	0.1425	8.427×10^{-4}	0.1416	8.425×10^{-4}	1.000
	ZZ	1.780×10^{-2}	1.053×10^{-4}	1.769×10^{-2}	1.053×10^{-4}	1.000
Total width			$\mathbf{5.915 \times 10^{-3}}$		$\mathbf{5.950 \times 10^{-3}}$	**0.994**
$H \to$	$b\bar{b}$	0.8947	13.52	0.8950	13.58	0.996
	$\tau^+\tau^-$	0.1028	1.553	0.1024	1.553	1.000
	$\mu^+\mu^-$	3.635×10^{-4}	5.494×10^{-3}	3.621×10^{-4}	5.494×10^{-3}	1.000
	$s\bar{s}$	3.172×10^{-4}	4.795×10^{-3}	3.208×10^{-4}	4.867×10^{-3}	0.985
	$c\bar{c}$	9.829×10^{-9}	1.486×10^{-7}	9.590×10^{-9}	1.455×10^{-7}	1.021
	gg	4.477×10^{-4}	6.676×10^{-3}	4.604×10^{-4}	6.985×10^{-3}	0.969
	$\gamma\gamma$	1.044×10^{-7}	1.578×10^{-6}	1.075×10^{-7}	1.631×10^{-6}	0.968
	$Z\gamma$	1.034×10^{-7}	1.562×10^{-6}	1.027×10^{-7}	1.558×10^{-6}	1.003
	W^+W^-	7.474×10^{-4}	1.130×10^{-2}	7.447×10^{-4}	1.130×10^{-2}	1.000
	ZZ	3.317×10^{-4}	5.014×10^{-3}	3.305×10^{-4}	5.014×10^{-3}	1.000
	hh	3.493×10^{-4}	5.280×10^{-3}	3.481×10^{-7}	5.281×10^{-3}	1.000
	ZA	7.891×10^{-7}	1.193×10^{-5}	7.869×10^{-7}	1.194×10^{-5}	0.999
Total width			**15.12**		**15.17**	**0.996**
$A \to$	$b\bar{b}$	0.8975	12.42	0.8979	12.47	0.996
	$\tau^+\tau^-$	0.1010	1.399	0.1007	1.399	1.000
	$\mu^+\mu^-$	3.573×10^{-4}	4.946×10^{-3}	3.561×10^{-4}	4.946×10^{-3}	1.000
	$s\bar{s}$	3.179×10^{-4}	4.401×10^{-3}	3.217×10^{-4}	4.468×10^{-3}	0.985
	$c\bar{c}$	6.514×10^{-9}	9.018×10^{-8}	6.358×10^{-9}	8.830×10^{-8}	1.021
	gg	5.648×10^{-4}	7.818×10^{-3}	5.741×10^{-4}	7.973×10^{-3}	0.981
	$\gamma\gamma$	1.126×10^{-7}	1.559×10^{-6}	1.089×10^{-7}	1.512×10^{-6}	1.031
	$Z\gamma$	5.261×10^{-8}	7.283×10^{-7}	5.238×10^{-8}	7.275×10^{-7}	1.001
	Zh	1.957×10^{-4}	2.710×10^{-3}	1.951×10^{-4}	2.710×10^{-3}	1.000
Total width			**13.84**		**13.89**	**0.997**

III NEUTRAL HIGGS BOSON PRODUCTION

(i) $gg \to \phi$



Georgi,. . .

Gamberini,. . .

$$\sigma(pp \to \phi^0) = \sigma_0^\phi \tau_\phi \frac{d\mathcal{L}^{gg}}{d\tau_\phi}$$

$$\sigma_0^{h/H} = \frac{G_F \alpha_s^2}{288\sqrt{2}\pi} \left| \sum_Q g_Q^{h/H} A_Q^{h/H}(\tau_Q) \right|^2 \qquad \sigma_0^A = \frac{G_F \alpha_s^2}{128\sqrt{2}\pi} \left| \sum_Q g_Q^A A_Q^A(\tau_Q) \right|^2$$

$$A_Q^{h/H}(\tau_Q) = \frac{3}{2}\tau_Q \left[1 + (1-\tau_Q) f(\tau_Q)\right] \qquad A_Q^A(\tau_Q) = \tau_Q f(\tau_Q)$$

$$f(\tau) = \begin{cases} \arcsin^2 \dfrac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\dfrac{1}{4}\left[\log \dfrac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \end{cases}$$

$$\tau_Q = 4\frac{m_Q^2}{M_\phi^2} \qquad \tau_\phi = \frac{M_\phi^2}{s}$$

- third generation dominant

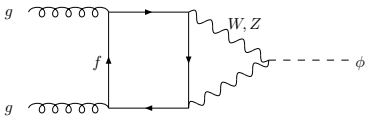
- QCD corrections large

S., Djouadi, Graudenz, Zerwas
Dawson, Kauffman
Harlander, Kilgore
Anastasiou, Melnikov
Ravindran, Smith, van Neerven

$$\sigma^{2HDM}(gg \to \phi) = \left(\frac{g_t^{2HDM}}{g_t^{SM}}\right)^2 \sigma_{tt}(gg \to \phi) + \left(\frac{g_b^{2HDM}}{g_b^{SM}}\right)^2 \sigma_{bb}(gg \to \phi) + \frac{g_t^{2HDM}}{g_t^{SM}} \frac{g_b^{2HDM}}{g_b^{SM}} \sigma_{tb}(gg \to \phi)$$

$$\Delta\sigma_{tt}^{NNLO}(gg \to \phi) = \Delta K_{NNLO}\, \sigma_{tt}^{LO}(gg \to \phi)$$

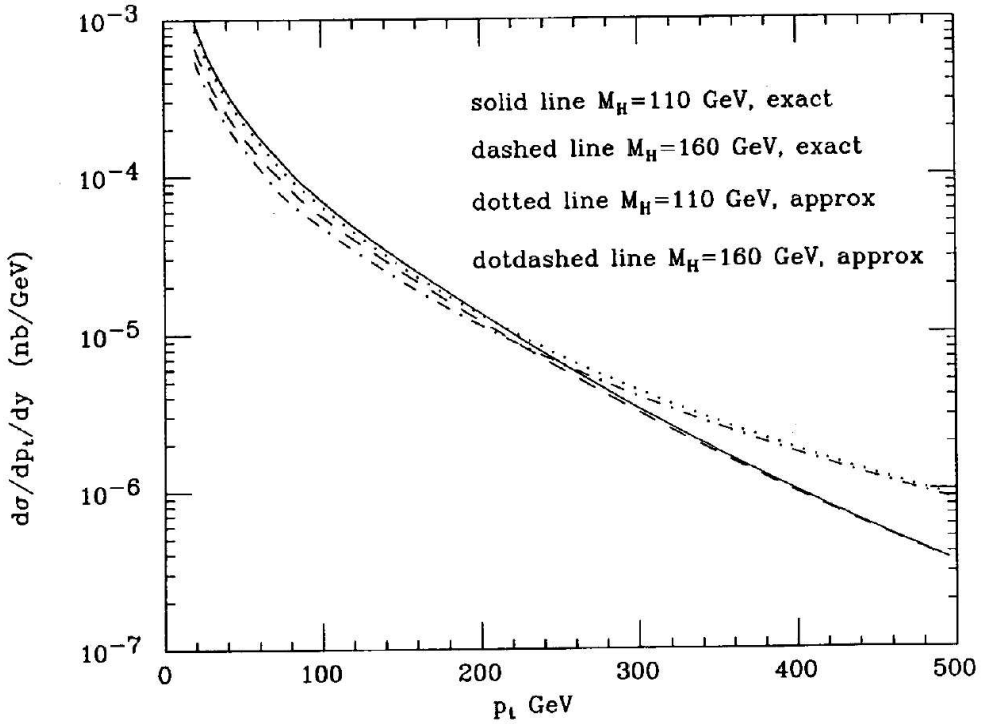
$$\Delta K_{NNLO} = \frac{\sigma^0_{NNLO} - \sigma^0_{NLO}}{\sigma^0_{LO}}$$

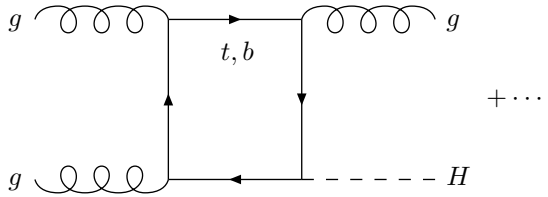


- cross sections: HIGLU & SusHi — Spira; Harlander eal
- large g_b^ϕ: b-loops dominant $\rightarrow$ NLO
- full elw. corrections unknown $\rightarrow$ light-fermion contributions universal
- SusHi: $gg \to \phi$ with NNLO QCD corrections + elw. light fermion
  $b\bar{b} \to \phi$ @ NNLO [5FS] — Harlander, Liebler, Mantler
- HIGLU: $gg \to \phi$ with NNLO QCD corrections — Spira
- impl. of $gg \to \phi$ into POWHEG including mass effects @ NLO

Bagnaschi, Degrassi, Slavich, Vicini

Higgs p_T spectrum: $gg \to Hg$





$m_t = 160$ GeV

Ellis, Hinchliffe, Soldate, van der Bij

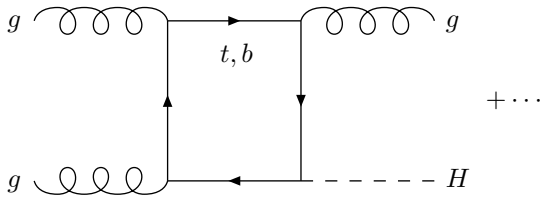
- mass effects important @ large p_T
- NLO corrections: $M_H^2 \ll m_t^2, p_T^2$

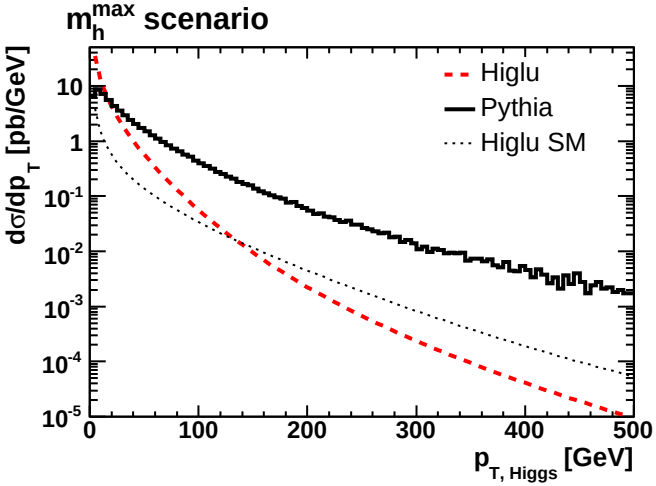
Schmidt
De Florian eal
Ravindran eal
Boughezal eal

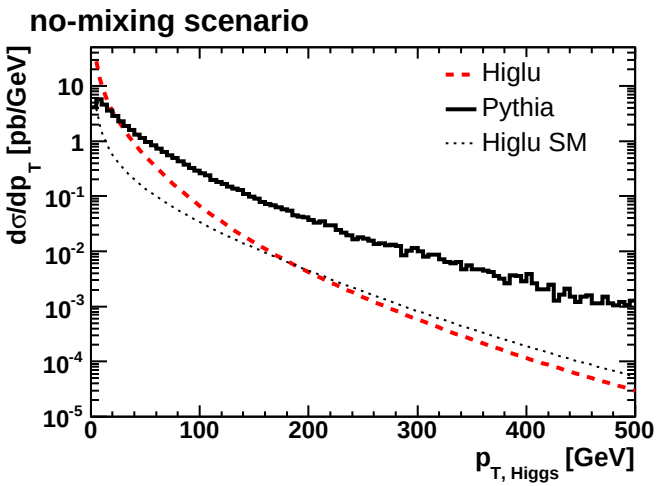
- NLO top mass effects small up to $p_T \sim 300$ GeV

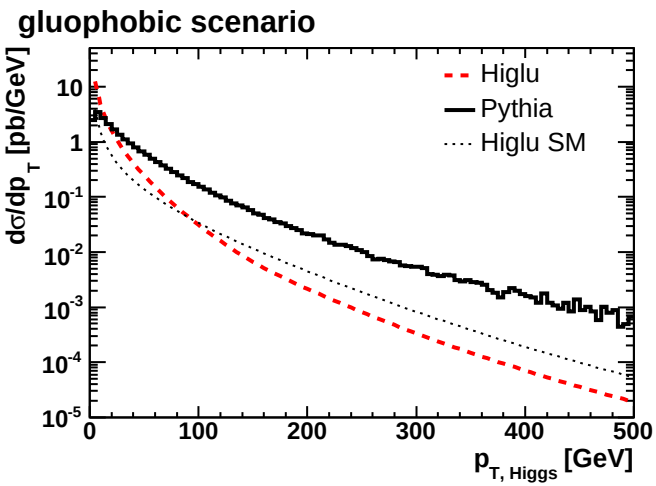
Harlander eal

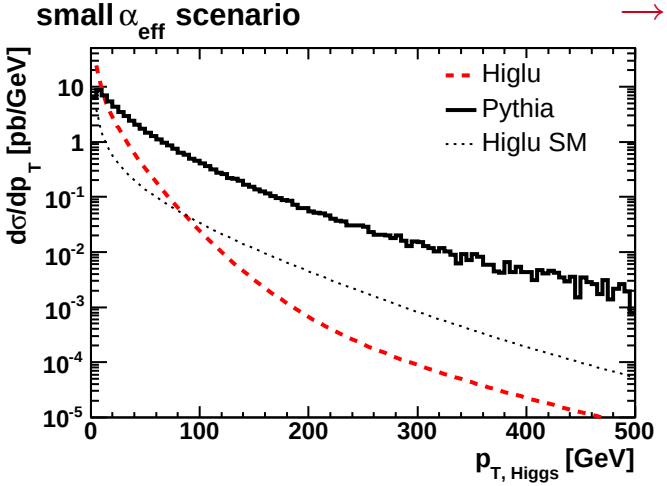
Higgs p_T spectrum: $gg \to Hg$







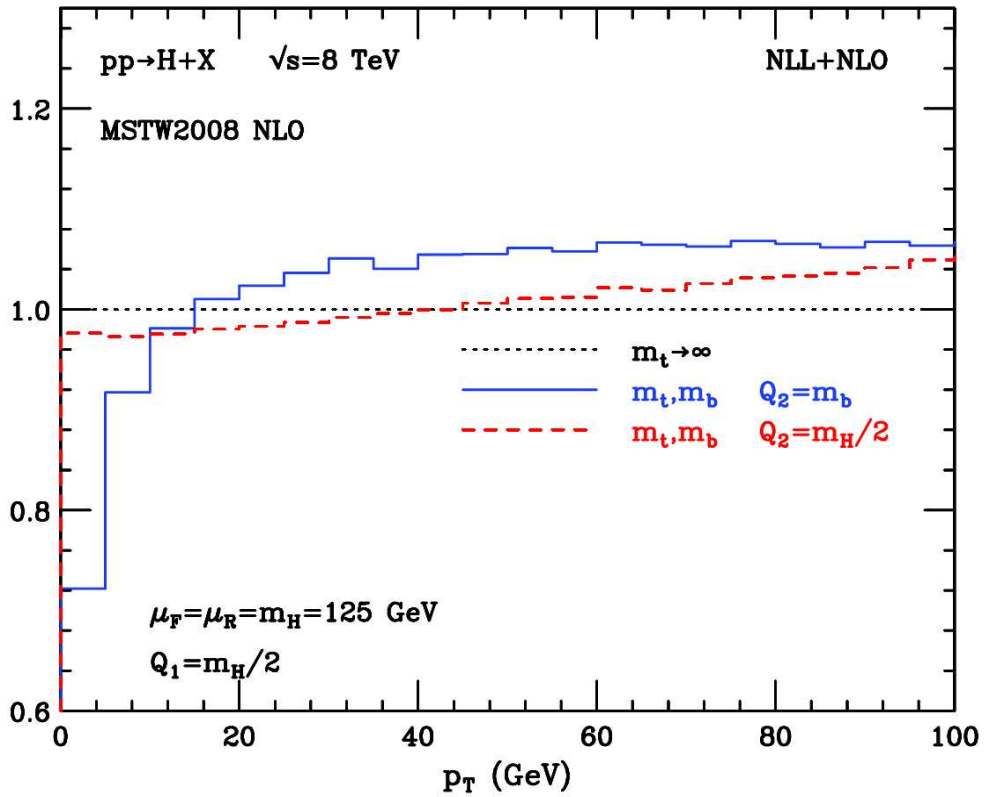




→LO @ large $p_T/M_\phi/g_b^\phi$!

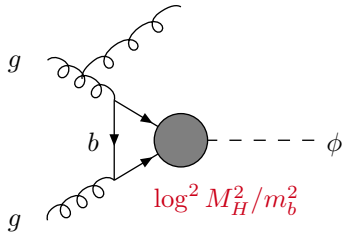
Langenegger, S., Starodunov, Trüb

- factorization: $p_T \ll 2m_b \to Q \sim m_b$ [← POWHEG, MC@NLO]

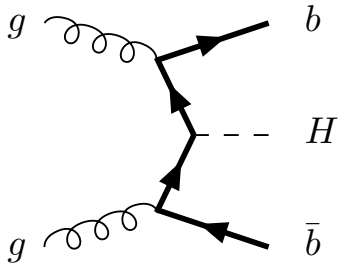


Grazzini, Sargsyan

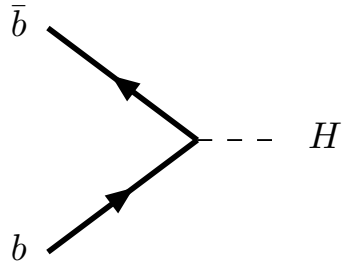
- Sudakov form factor → unresummed logs



(ii) $b\bar{b}$+Higgs production



NLO



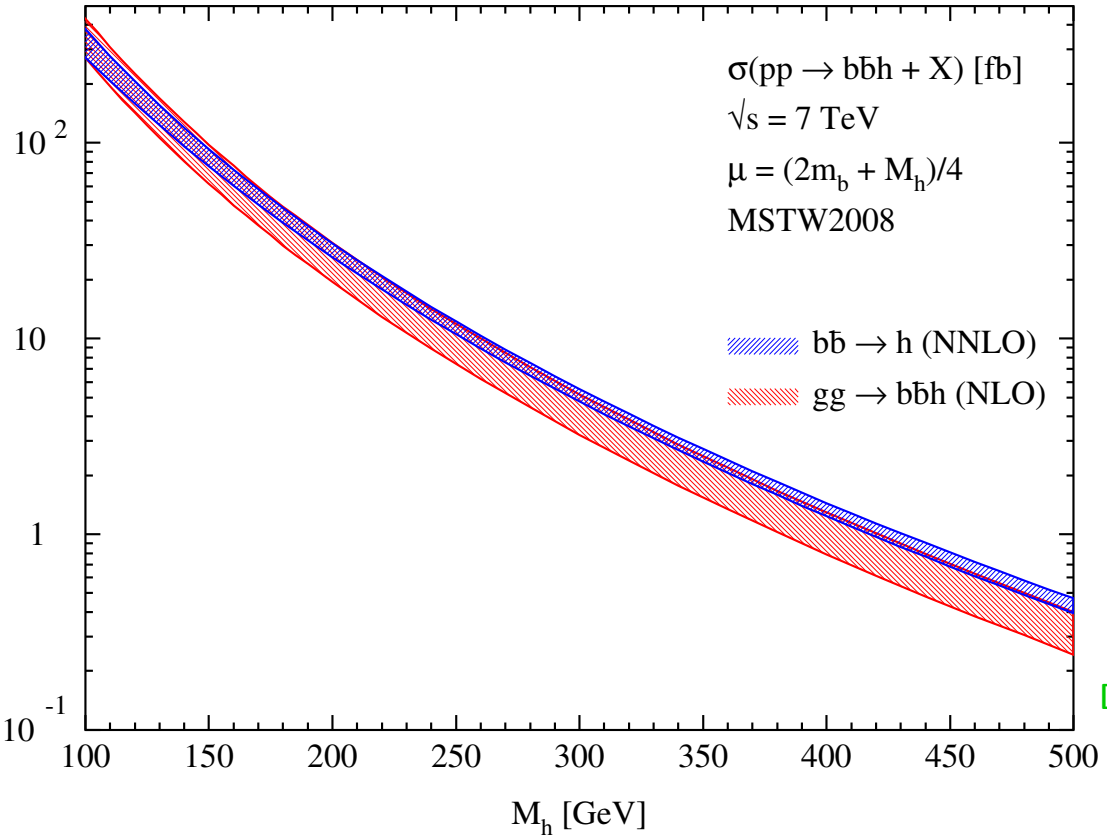
NNLO

exact $g \to b\bar{b}$ splitting & mass/off-shell effects

no resummation of log M_H^2/m_b^2 terms

massless/on-shell b's, no p_{Tb}

resummation of log M_H^2/m_b^2 terms



Santander matching:

$$\sigma = \frac{\sigma^{4FS} + w\sigma^{5FS}}{1+w}$$

$$w = \log\frac{M_H}{m_b} - 1$$

Harlander, Krämer, Schumacher

Dittmaier, Krämer, S.
Dawson, Jackson, Reina, Wackeroth
Harlander, Kilgore

- $gg \to \phi$

$\sqrt{s}$	$\sigma(gg \to h)$ SusHi	$\sigma(gg \to h)$ HIGLU	$\sigma(gg \to H)$ SusHi	$\sigma(gg \to H)$ HIGLU	$\sigma(gg \to A)$ SusHi	$\sigma(gg \to A)$ HIGLU
7	17.90	17.23	2.027	2.025	3.982	3.981
8	22.73	21.89	2.760	2.758	5.358	5.358
13	51.32	49.45	7.660	7.655	14.35	14.34
14	57.73	55.62	8.845	8.837	16.49	16.49

- $gg, q\bar{q} \to b\bar{b}\phi$

$\sqrt{s}$	$\sigma(b\bar{b} \to h)$ 5FS	$\sigma(b\bar{b} \to h)$ 4FS	$\sigma(b\bar{b} \to H)$ 5FS	$\sigma(b\bar{b} \to H)$ 4FS	$\sigma(b\bar{b} \to A)$ 5FS	$\sigma(b\bar{b} \to A)$ 4FS
7	0.2528	0.2383	12.73	10.47	20.31	16.96
8	0.3295	0.3144	18.16	15.05	28.55	24.16
13	0.8008	0.7835	57.85	49.54	87.32	76.50
14	0.9088	0.8849	67.99	59.39	102.1	89.93

IV *RECOMMENDATIONS*

- 2HDM Higgs decays: 2HDMC and HDECAY

- $gg \to \phi$: SusHi [elw. light fermion] and HIGLU

- $b\bar{b}\phi$ production: SusHi [5FS] and MSSM grid [4FS]
$\to$ Santander matching

- SusHi linked to 2HDMC

- HIGLU linked to HDECAY

- approach of S. Thomas invalid

$$\sigma^{approx}_{2HDM} = \frac{\sigma^{NNLO}_{SM}}{\sigma^{LO}_{SM}} \left\{ g_t^2 \sigma^{LO}_{tt} + g_t g_b \sigma^{LO}_{tb} + g_b^2 \sigma^{LO}_{bb} \right\} ,$$

- $\sqrt{s} = 8$ TeV: $K_{tt} \sim 2.0,\ K_{bb} \sim 1.2 - 1.3$

M_H [GeV]	σ_{tt} [pb]	σ_{tb} [pb]	σ_{bb} [pb]	σ_{tot} [pb]
	(LO)	(LO)	(LO)	(LO)
125.0	10.32	-1.242	0.1131	9.188
125.5	10.23	-1.226	0.1108	9.116
126.0	10.15	-1.210	0.1085	9.044
150.0	7.012	-0.6770	0.04330	6.379
200.0	3.788	-0.2465	0.009013	3.551
250.0	2.395	-0.1093	0.002540	2.288
300.0	1.748	-0.05662	0.0008719	1.692
	(NLO)	(NLO)	(NLO)	(NLO)
125.0	17.32	-1.207	0.1357	16.25
125.5	17.18	-1.192	0.1330	16.12
126.0	17.04	-1.178	0.1303	15.99
150.0	11.90	-0.692	0.05293	11.26
200.0	6.518	-0.270	0.01133	6.260
250.0	4.159	-0.1251	0.003257	4.037
300.0	3.061	-0.0671	0.001135	2.995
	(NNLO)	(NLO)	(NLO)	(mixed)
125.0	20.19	-1.207	0.1357	19.12
125.5	20.03	-1.192	0.1330	18.97
126.0	19.86	-1.178	0.1303	18.81
150.0	13.79	-0.692	0.05293	13.15
200.0	7.493	-0.270	0.01133	7.235
250.0	4.757	-0.1251	0.003257	4.635
300.0	3.486	-0.06705	0.001135	3.420