PAUL SCHERRER INSTITUT

HIGGS BOSON DECAY AND PRODUCTION AT HADRON COLLIDERS

Michael Spira (PSI)

I Introduction

II Higgs Boson Decays

III Higgs Boson Production

IV Conclusions

I *INTRODUCTION*

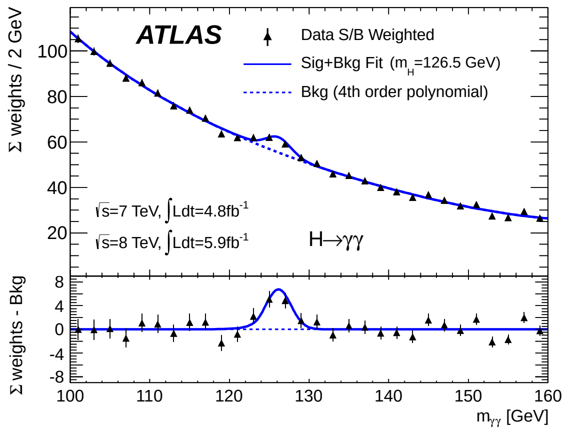
- SM very successful $\longleftarrow$ precision data [LEP, Tevatron, LHC]

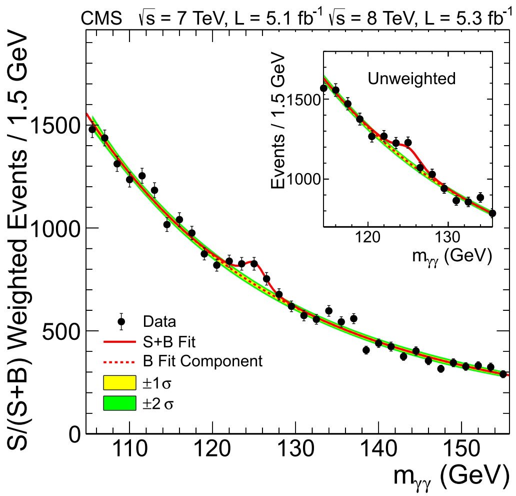
- open problems: – mechanism of electroweak symmetry breaking
  – unification of forces
  – space-time structure @ short distances

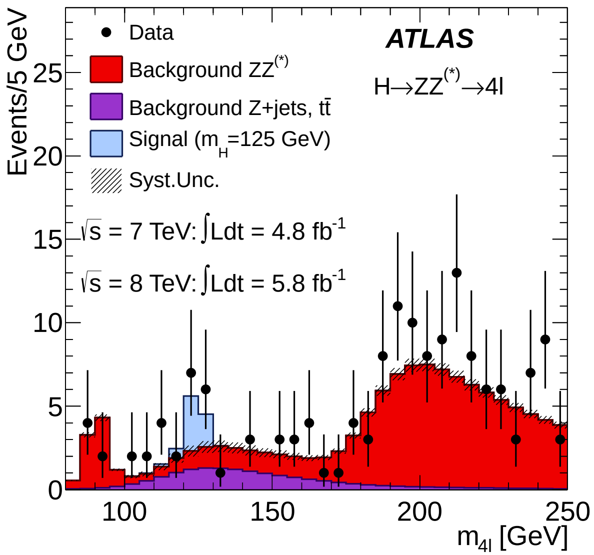
- LHC: fundamental discoveries: Higgs boson(s?)
  Supersymmetry ?
  Extra space dimensions ?

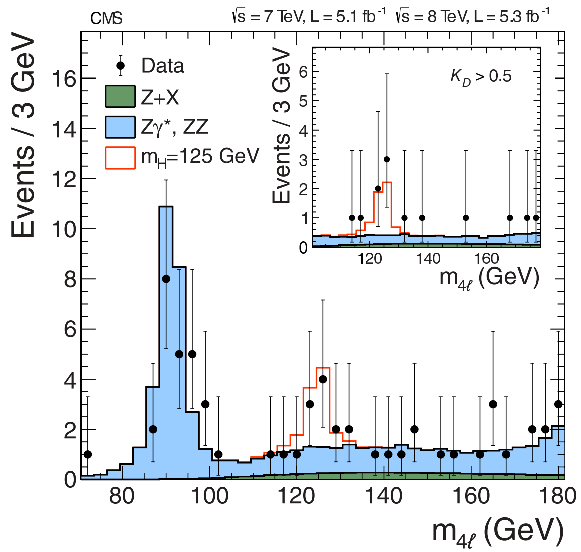
- electroweak symmetry breaking: two classes of realization:
  – standard Higgs mechanism [SM, SUSY,. . .]
  – strong elw. symmetry breaking [TC, LH, Higgsless, ED,. . .]

- we have found the Higgs: $M_H \sim 125$ GeV
- $gg \rightarrow H$ dominant

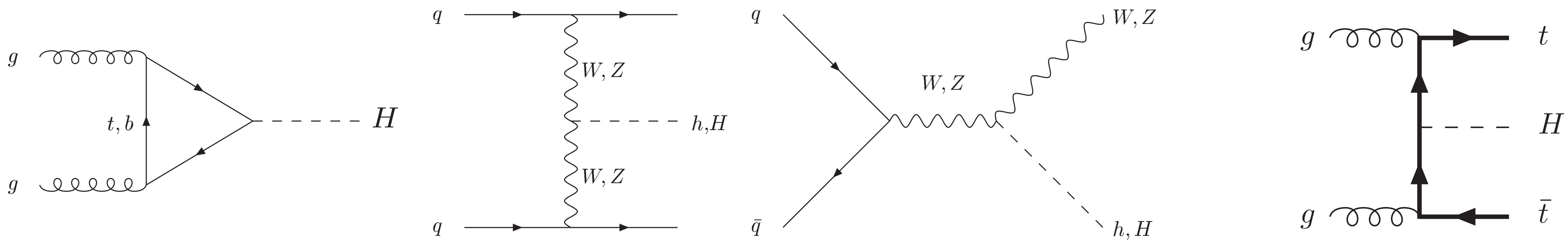


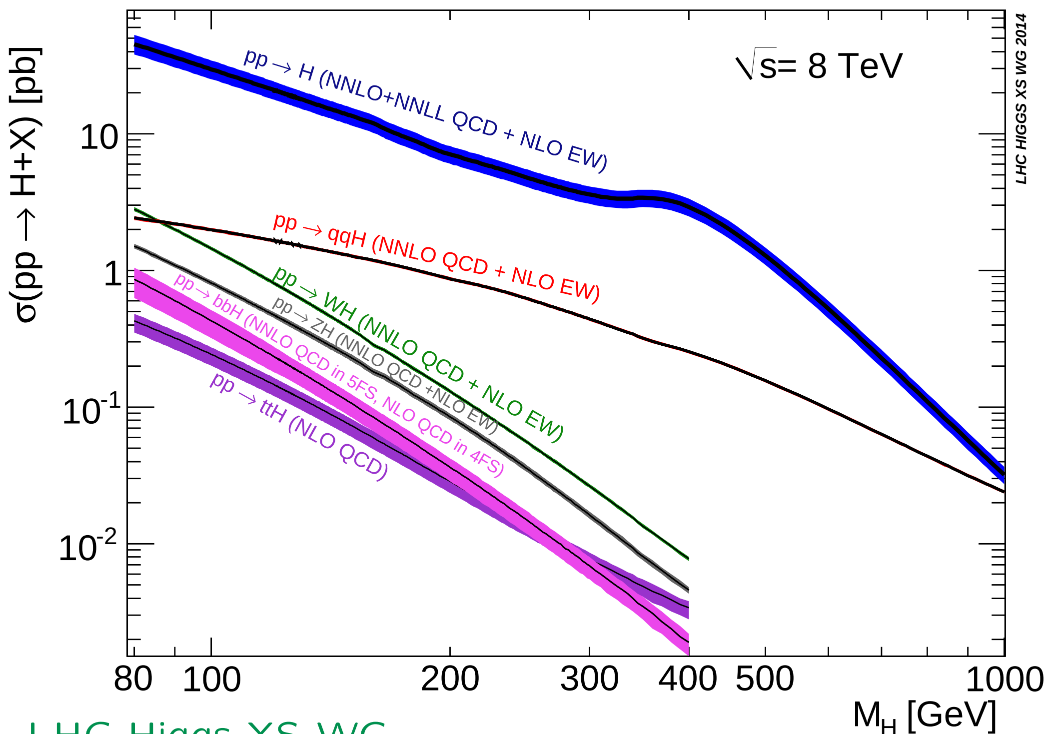




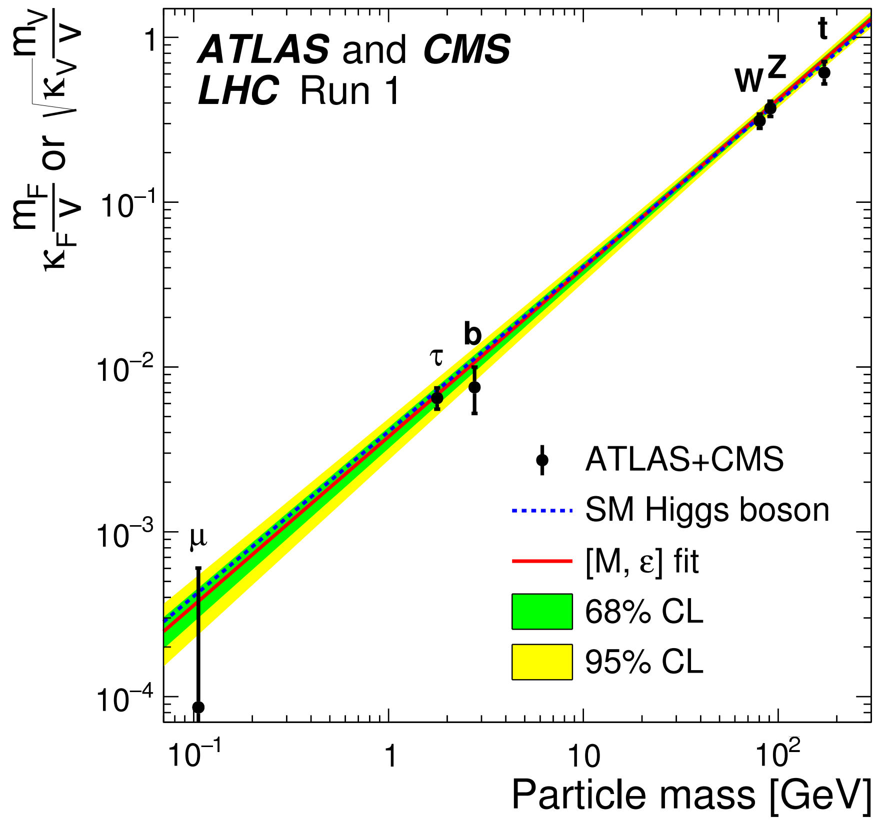


- Higgs Boson Production





LHC Higgs XS WG



- Discovery: LHC [Tevatron]

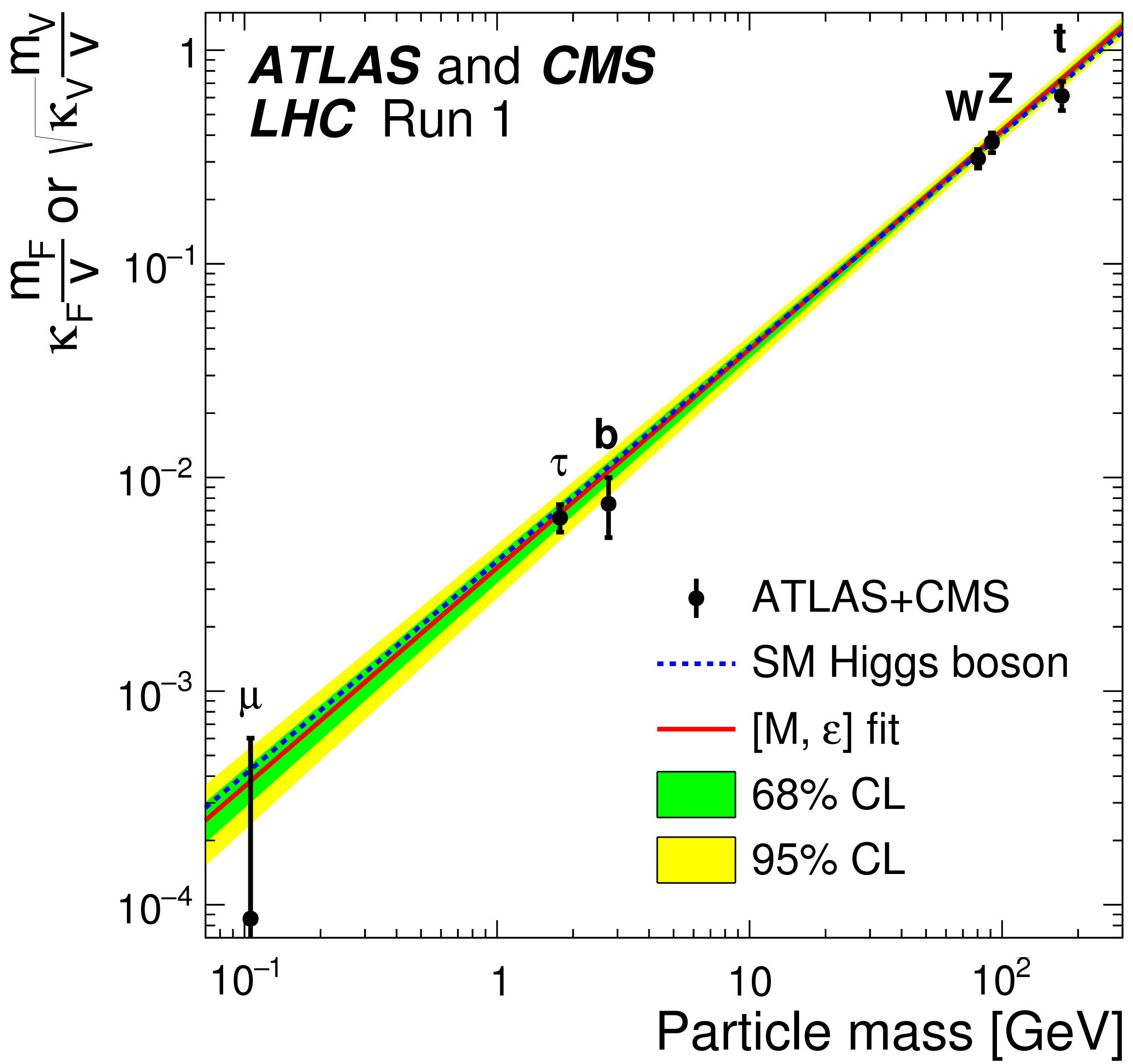
  → Higgs mass

  couplings

  spin

  $\mathcal{CP}$

  λ ?



(ii) MSSM

- 2 Higgs doubletts $\stackrel{\text{ESB}}{\longrightarrow}$ 5 Higgs bosons: $h, H, A, H^\pm$

- LO: 2 input parameters: $M_A, \mathrm{tg}\beta = \frac{v_2}{v_1}$

- radiative corrections $\propto m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$ $\longrightarrow$ $\boxed{M_h \lesssim 135 \text{ GeV}}$

Haber
Carena,. . .
Heinemeyer,. . .
Zhang
Slavich,. . .
. . .

- modified couplings:

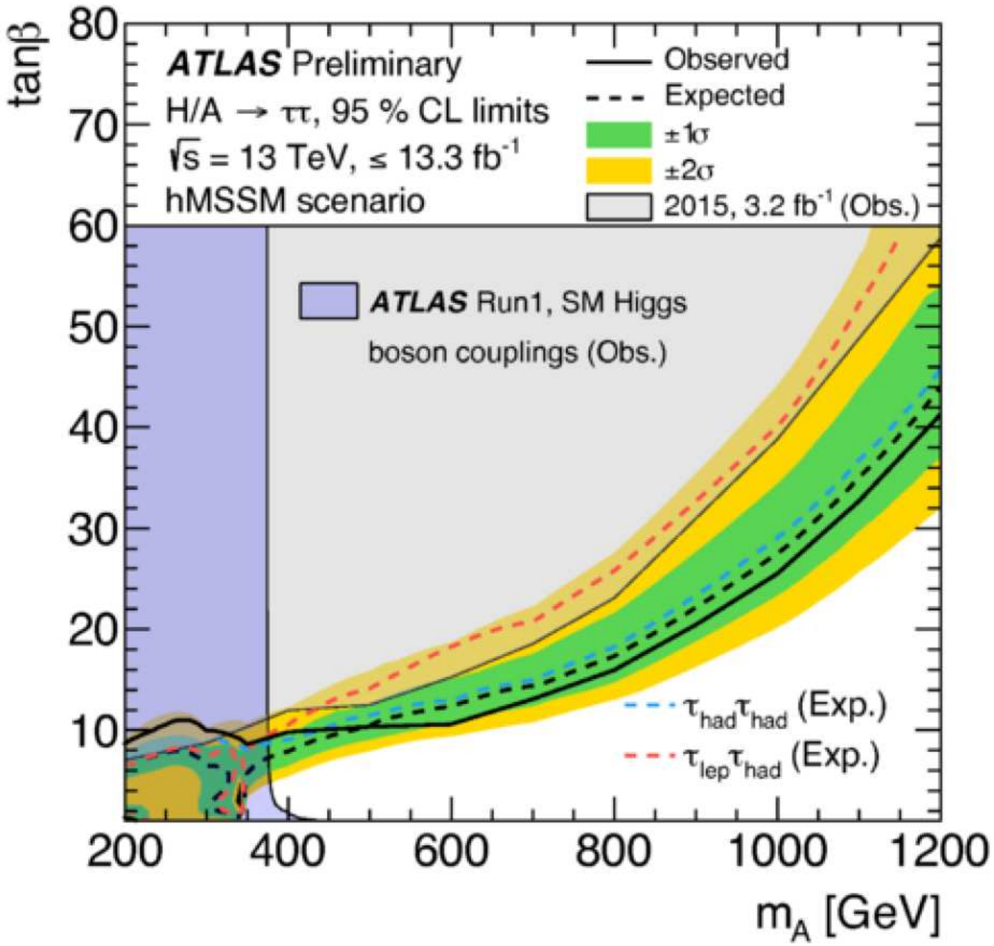
ϕ	g_u^ϕ	g_d^ϕ	g_V^ϕ
h	c_α/s_β	$-s_\alpha/c_\beta$	$s_{\beta-\alpha}$
H	s_α/s_β	c_α/c_β	$c_{\beta-\alpha}$
A	$\mathrm{ctg}\beta$	$\mathrm{tg}\beta$	0

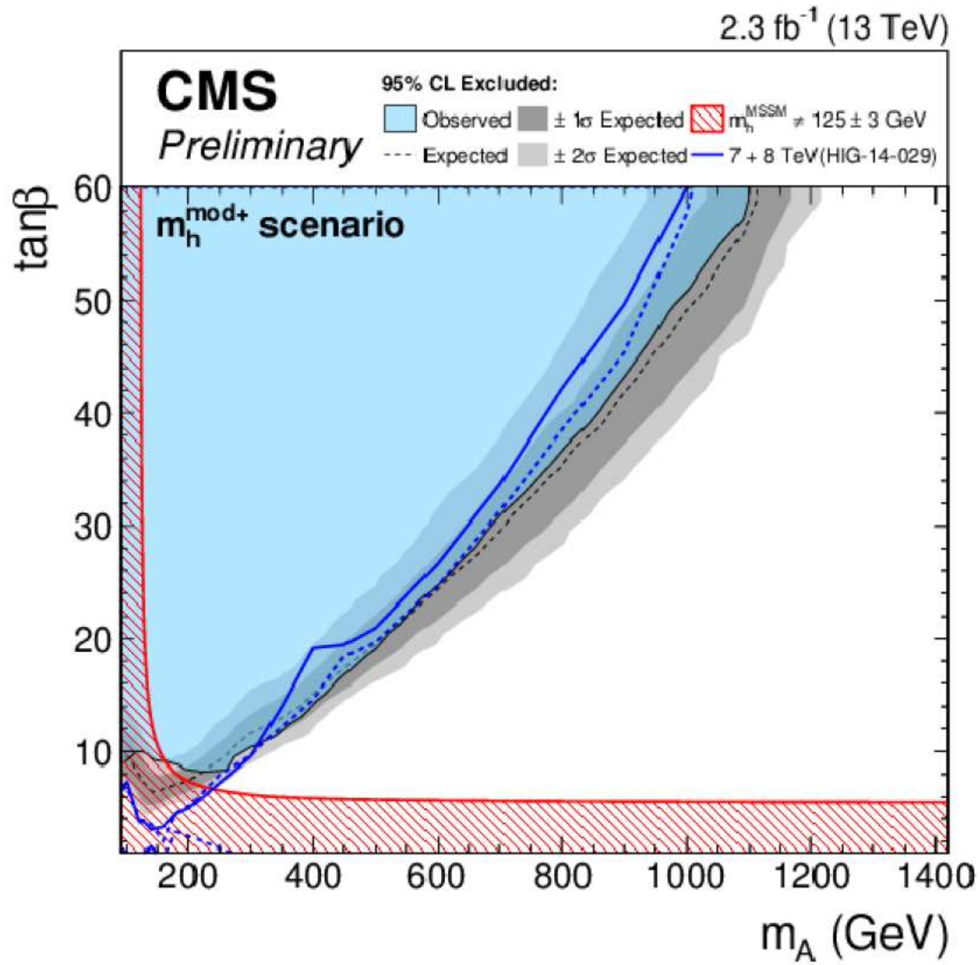
- Yukawa couplings: $\mathrm{tg}\beta\uparrow$ $\Rightarrow$ $g_u^\phi\downarrow$ $g_d^\phi\uparrow$ $g_V^\phi\downarrow$

- LHC: $gg \to \phi$ dominant for $\mathrm{tg}\beta \lesssim 10$
  $gg \to \phi b\bar{b}$ dominant for $\mathrm{tg}\beta \gtrsim 10$

$gg \to b\bar{b}\phi^0, \; gg \to \phi^0 \qquad \phi^0 \to \tau^+\tau^-$

↓ ↓





II *HIGGS BOSON DECAYS*

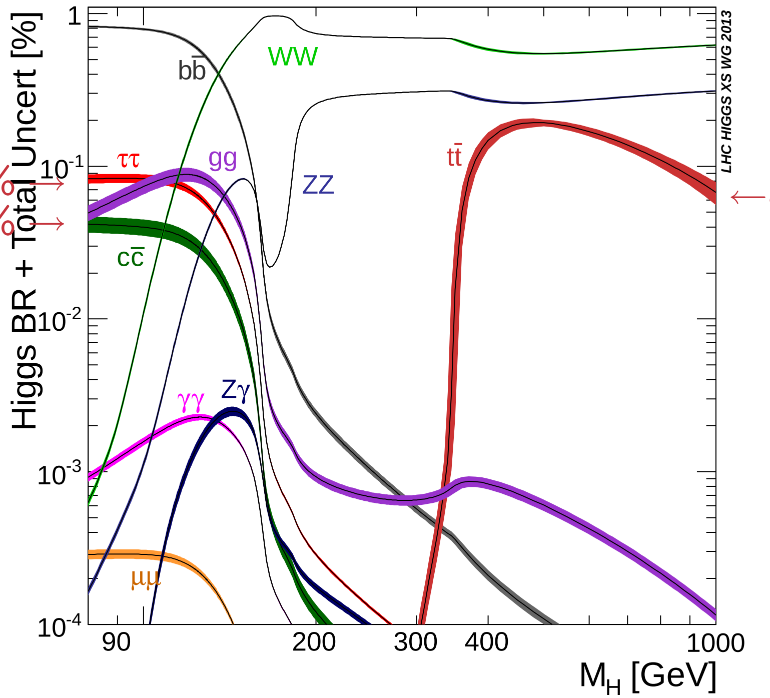
Partial Width	QCD	Electroweak	Total	on-shell Higgs
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$ for $M_H \lesssim 500$GeV	$\sim 0.5\%$	NNNNLO / NLO
		$\sim 0.1(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	~ 0.5–10%	
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim 0.5\%$ for $M_H \lesssim 500$GeV	$\sim 0.5\%$	NLO
		$\sim 0.1(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	~ 0.5–10%	
$H \to t\bar{t}$	$\lesssim 5\%$	$\lesssim 0.5\%$ for $M_H < 500$GeV	$\sim 5\%$	(NNN)NLO / LO
		$\sim 0.1(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	~ 5–10%	
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$	NNNLO approx. / NLO
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	NLO / NLO
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$	(N)LO / LO
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500$GeV	$\sim 0.5\%$	(N)NLO
		$\sim 0.17(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	~ 0.5–15%	

- QCD: variation of Higgs widths for scale by factor 2 and 1/2
  elw: missing HO estimated from known structure at NLO
  $M_H \gtrsim 500$ GeV: Higgs self-interactions dominate error
  different uncertainties added linearly for each channel
- parametric uncertainties:
  $m_t = 172.5 \pm 1$ GeV $\qquad \alpha_s(M_Z) = 0.118 \pm 0.0015$
  $m_b(m_b) = 4.18 \pm 0.03$ GeV $\qquad m_c(3\text{GeV}) = 0.986 \pm 0.025$ GeV
  different uncertainties added quadratically for each channel
- total uncertainties: parametric & theor. uncertainties added linearly

HDECAY & Prophecy4f

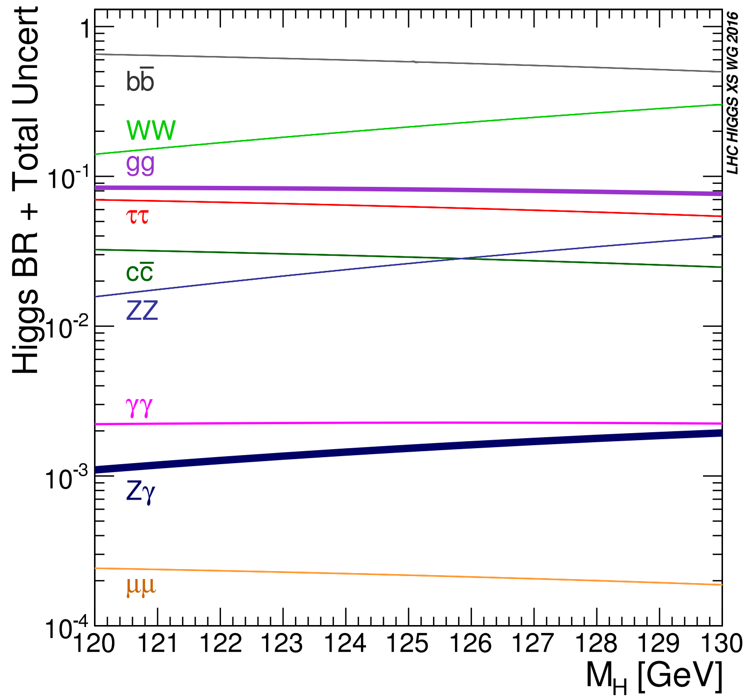
$\sim 10\% \rightarrow$

$\sim 10\% \rightarrow$



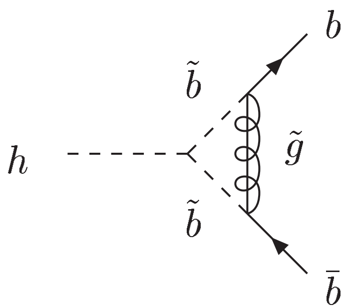
$\leftarrow\sim 20\%$

$\longrightarrow$



Denner, Heinemeyer, Puljak, Rebuzzi, S.

- MSSM: large SUSY–QCD corrections to $\phi^0 \rightarrow b\bar{b}$



$$\propto \frac{\alpha_s}{\pi}\,\frac{m_{\tilde{g}}\mu\,\mathrm{tg}\beta}{M_{SUSY}^2} \sim \Delta_b$$

Hall, . . .
Carena, . . .
Nierste, . . .
Häfliger, . . .
Noth, S.
Mihaila, Reisser
etc.

SUSY-QCD Corrections to $b\bar{b}\phi^0$ [$\Delta \lesssim 1\%$]

$$\mathcal{L}_{eff} = -\lambda_b \overline{b_R}\left[\phi_1^0 + \frac{\Delta_b}{\mathrm{tg}\beta}\phi_2^{0*}\right] b_L + h.c. \quad \text{valid to all orders in } \Delta_b$$

$$= -m_b \bar{b}\left[1 + i\gamma_5 \frac{G^0}{v}\right] b - \frac{m_b/v}{1+\Delta_b}\bar{b}\left[g_b^h\left(1 - \frac{\Delta_b}{\mathrm{tg}\alpha\ \mathrm{tg}\beta}\right) h + g_b^H\left(1 + \Delta_b \frac{\mathrm{tg}\alpha}{\mathrm{tg}\beta}\right) H - g_b^A\left(1 - \frac{\Delta_b}{\mathrm{tg}^2\beta}\right) i\gamma_5 A\right] b$$

$$\Delta_b = \Delta_b^{QCD(1)} + \Delta_b^{elw(1)}$$

$$\Delta_b^{QCD(1)} = \frac{2}{3}\frac{\alpha_s(\mu_R)}{\pi} M_{\tilde{g}}\ \mu\ \mathrm{tg}\beta\ I(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, M_{\tilde{g}}^2)$$

$$\Delta_b^{elw(1)} = \frac{\lambda_t^2(\mu_R)}{(4\pi)^2}\ \mu\ A_t\ \mathrm{tg}\beta\ I(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2)$$

$$I(a,b,c) = -\frac{ab\log\frac{a}{b} + bc\log\frac{b}{c} + ca\log\frac{c}{a}}{(a-b)(b-c)(c-a)}$$

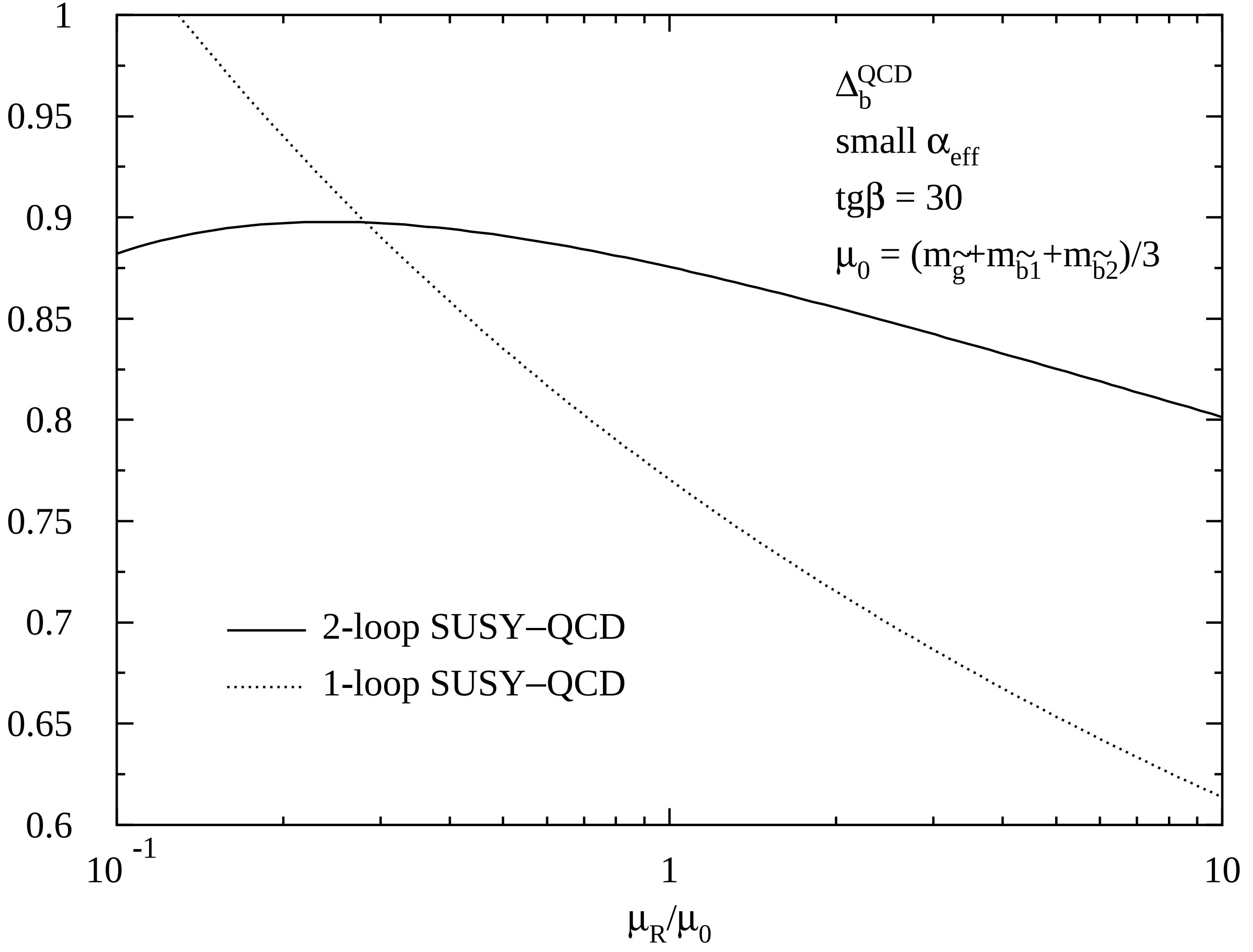
$\Rightarrow$ resummed Yukawa couplings $\tilde{g}_b^\Phi$

Carena, Garcia, Nierste, Wagner
Guasch, Häfliger, S.

small α_{eff} scenario [modified]

$$
\begin{aligned}
\mathrm{tg}\beta &= 30 \\
M_{\tilde{Q}} &= 800 \text{ GeV} \\
M_{\tilde{g}} &= 1000 \text{ GeV} \qquad \longleftarrow \\
M_2 &= 500 \text{ GeV} \\
A_b = A_t &= -1.133 \text{ TeV} \\
\mu &= 2 \text{ TeV}
\end{aligned}
$$

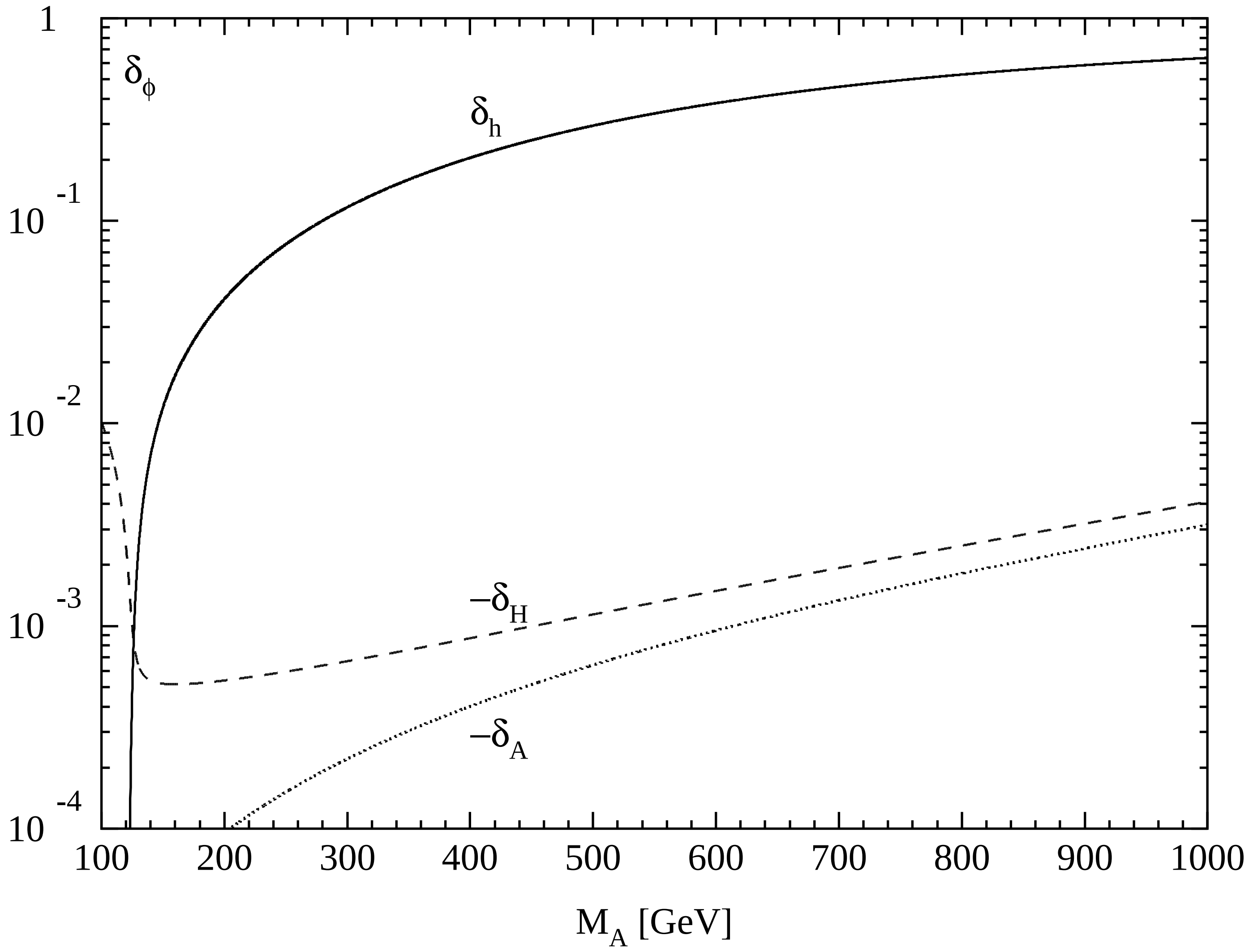
$$
\begin{aligned}
m_{\tilde{t}_1} &= 679 \text{ GeV} \qquad m_{\tilde{t}_2} = 935 \text{ GeV} \\
m_{\tilde{b}_1} &= 601 \text{ GeV} \qquad m_{\tilde{b}_2} = 961 \text{ GeV}
\end{aligned}
$$



Noth, S.
(Mihaila, Reisser)

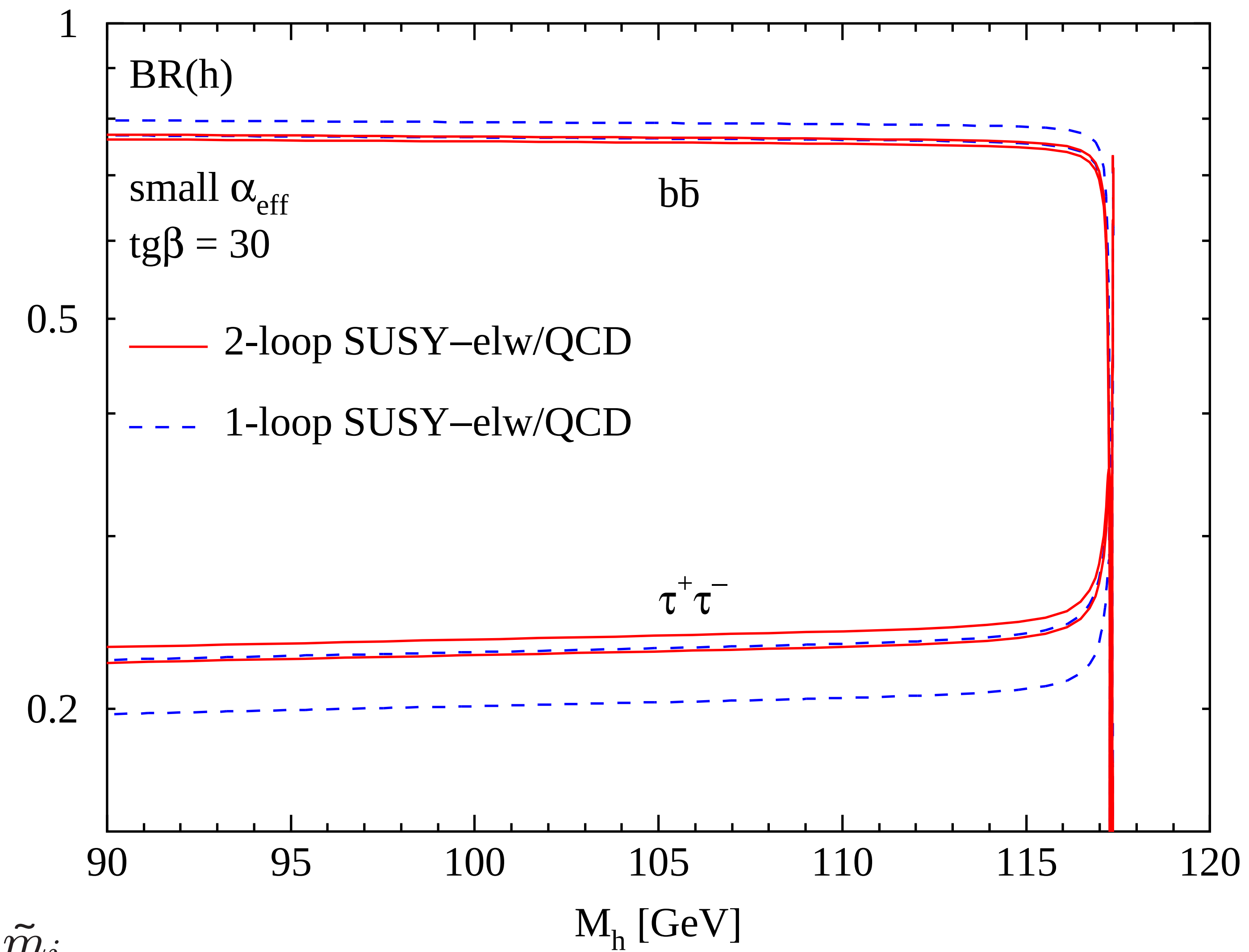
$$\Gamma[\Phi \to b\bar{b}] = \frac{3G_F M_\Phi}{4\sqrt{2}\pi}\overline{m}_b^2(M_\Phi)\ \Delta_{\rm QCD}\ \tilde{g}_b^\Phi\left[\tilde{g}_b^\Phi + g_b^\Phi \delta_{rem}\right]$$

$$M_A^2 \gg M_Z^2 : {\rm tg}\alpha \to -\frac{1}{{\rm tg}\beta} \quad \Rightarrow \quad \tilde{g}_b^h \to \frac{1}{1+\Delta_b}\left(1 - \frac{\Delta_b}{{\rm tg}\alpha\ {\rm tg}\beta}\right) \to 1$$



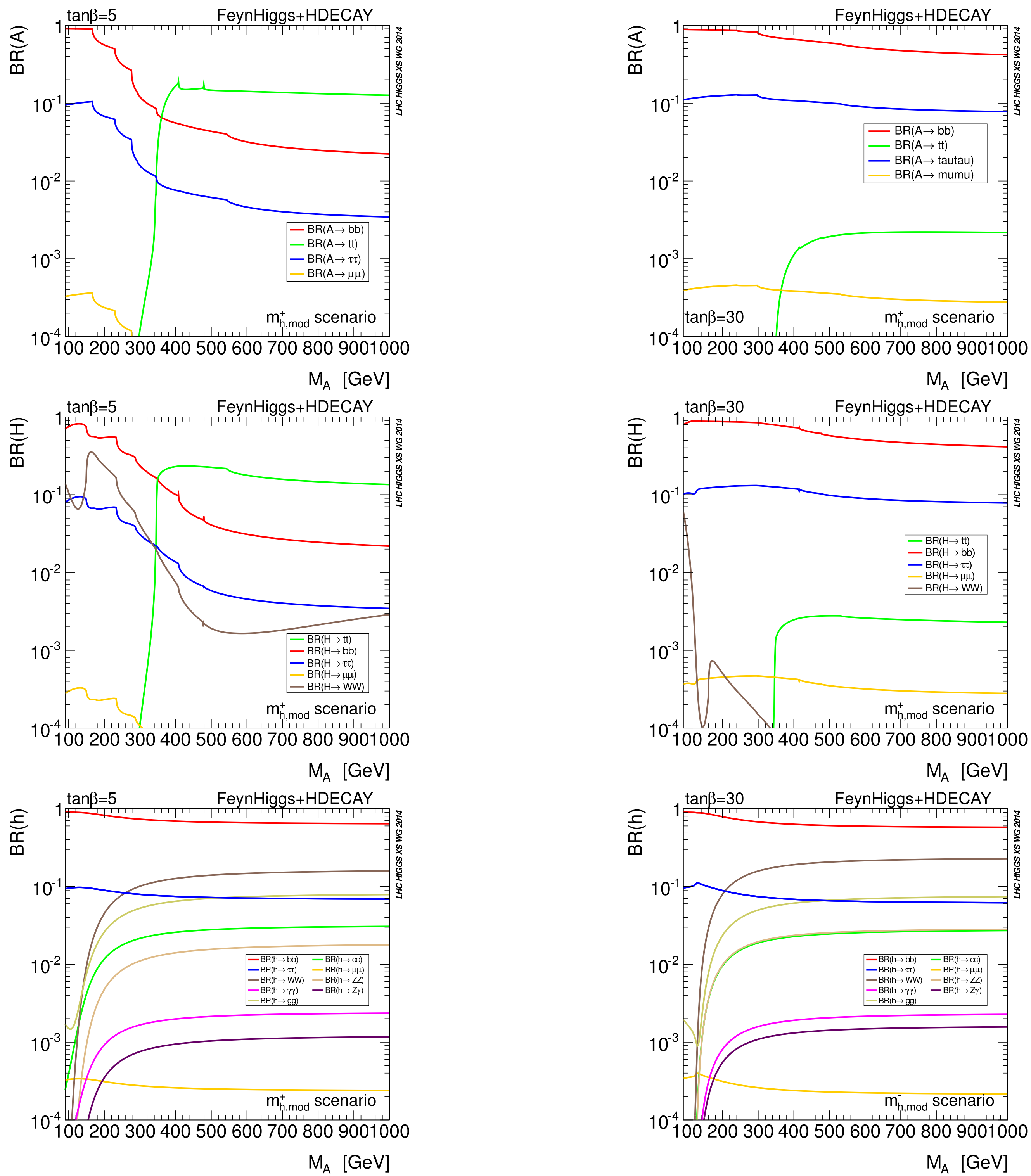
$$\delta_\phi = \frac{\delta_{rem}}{\delta_{SQCD}}$$

Guasch, Häfliger, S.



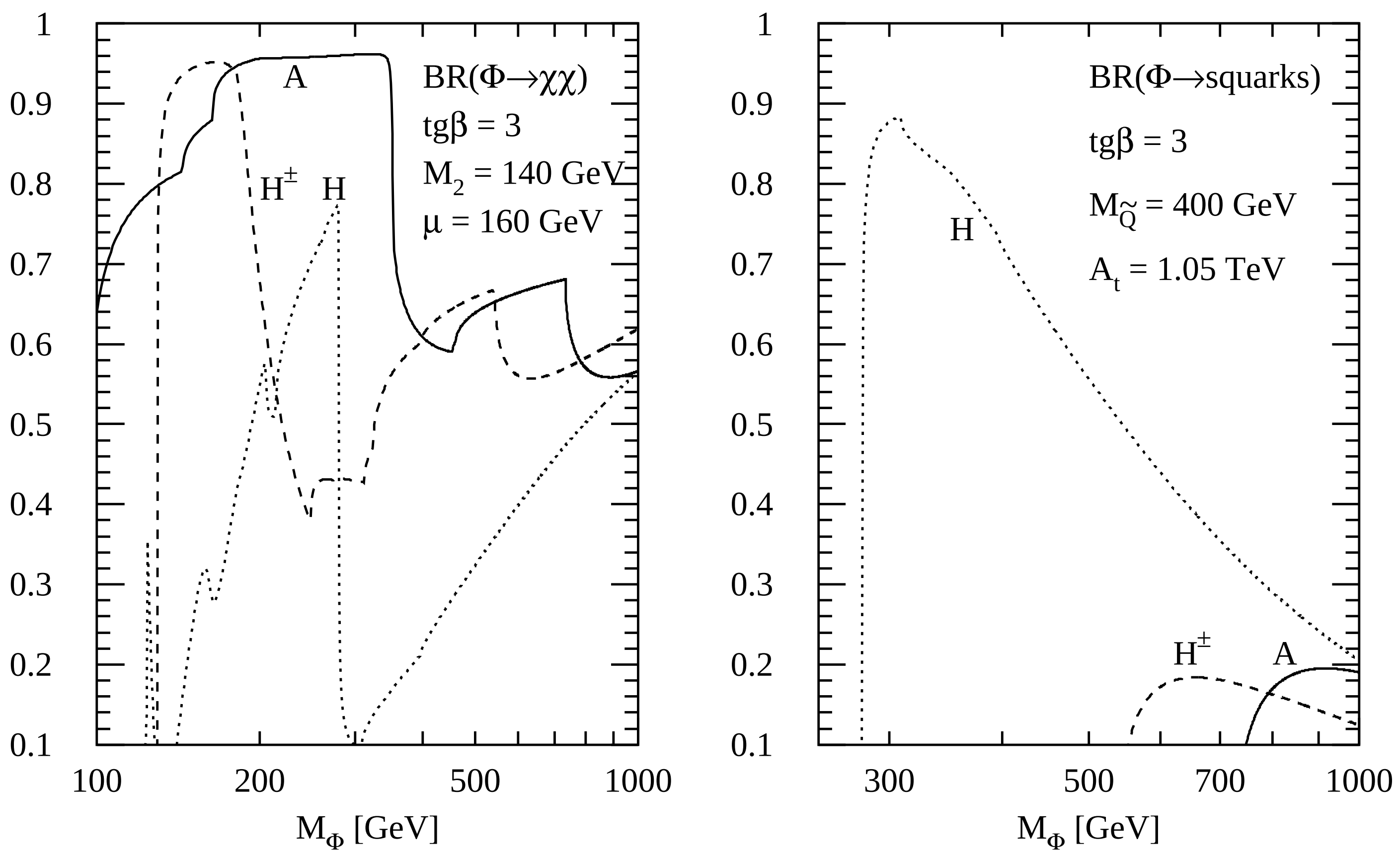
$$\mu_R = \frac{1}{3}\sum \tilde{m}_i$$

Noth, S. → HDECAY



+ charged Higgs decays

SUSY Decays

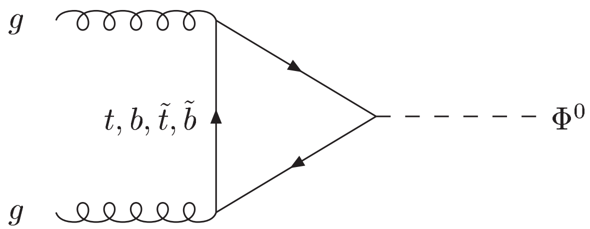


HDECAY

- if kinematically possible → important

III *HIGGS BOSON PRODUCTION*

(i) $gg \to h/H/A$



Georgi,. . .

Gamberini,. . .

S., Djouadi, Graudenz, Zerwas
Dawson, Kauffman

- NLO QCD corrections: $\sim 10 \ldots 100\%$

- NNLO calculated for $m_t \gg M_\phi \Rightarrow$ further increase by 20–30%
  [mass effects small]

Harlander, Kilgore
Anastasiou, Melnikov
Ravindran, Smith, van Neerven

Marzani, Ball, Del Duca, Forte, Vicini
Harlander, Ozeren
Pak, Rogal, Steinhauser

- N^{3}LO for $m_t \gg M_\phi$ $\Rightarrow$ scale stabilization
scale dependence: $\Delta \lesssim 5\%$

Moch, Vogt
Ravindran
de Florian, Mazzitelli, Moch, Vogt
Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger
Ball, Bonvini, Forte, Marzani, Ridolfi

- N^{3}LL soft gluon resummation: $\lesssim 2\%$

Catani, de Florian, Grazzini, Nason
Ravindran
Ahrens, Becher, Neubert, Yang
Ball, Bonvini, Forte, Marzani, Ridolfi
Bonvini, Marzani
Schmidt, S.

- elw. corrections: $\sim 5\%$

Aglietti,. . .
Degrassi, Maltoni
Actis, Passarino, Sturm, Uccirati

- QCD corrections to squark loops: 10–100%

Mühlleitner, S.
Bonciani, Degrassi, Vicini

- genuine SUSY–QCD corrections: 10–100%
  [$\leftarrow \Delta_b$ @ large tgβ]

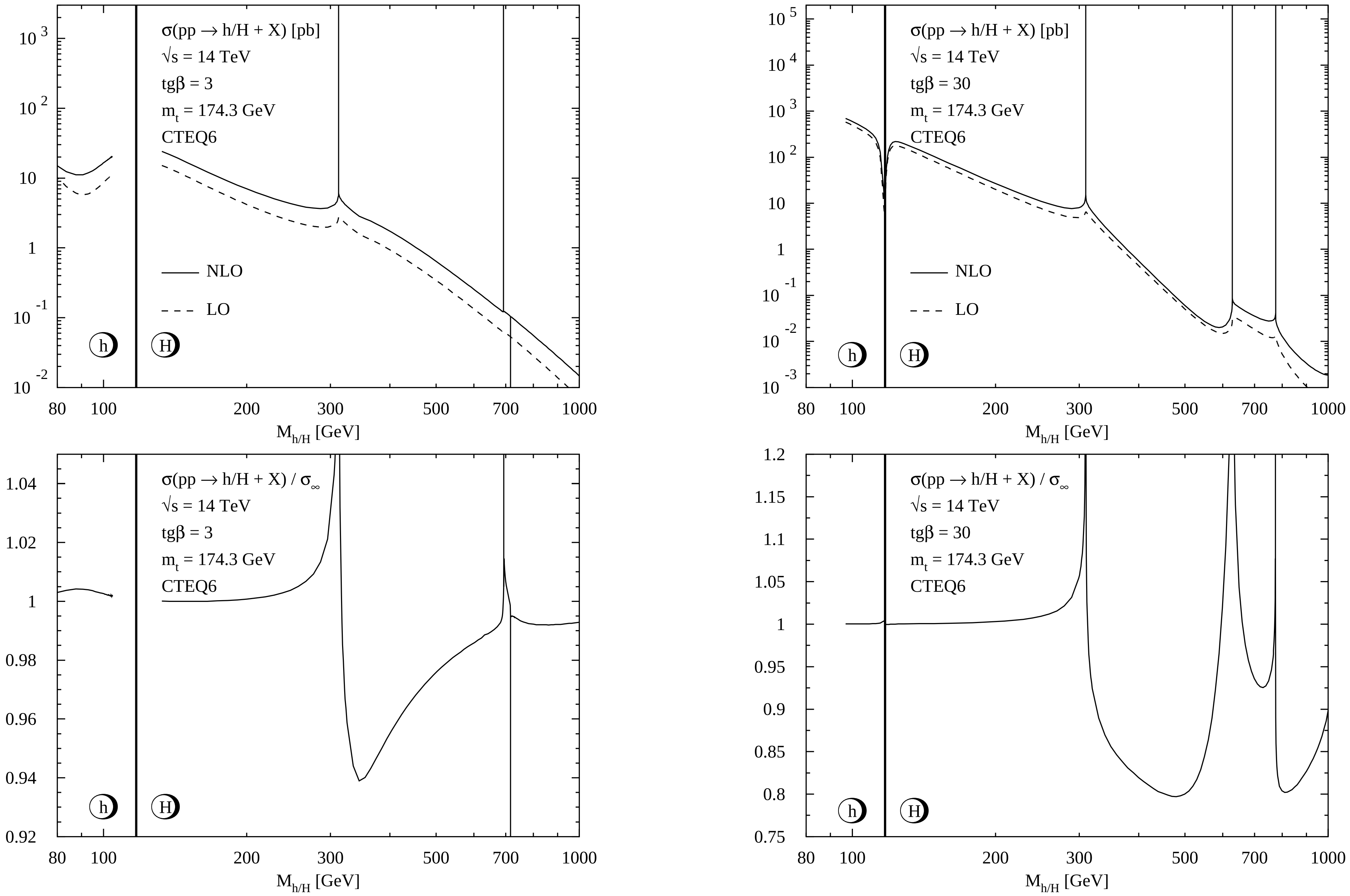
Harlander, Steinhauser, Hofmann
Degrassi, Slavich
Anastasiou, Beerli, Daleo
Mühlleitner, Rzehak, S.

- SUSY-elw. corrections unknown

- impl. of $gg \to \phi$ in POWHEG including mass effects @ NLO

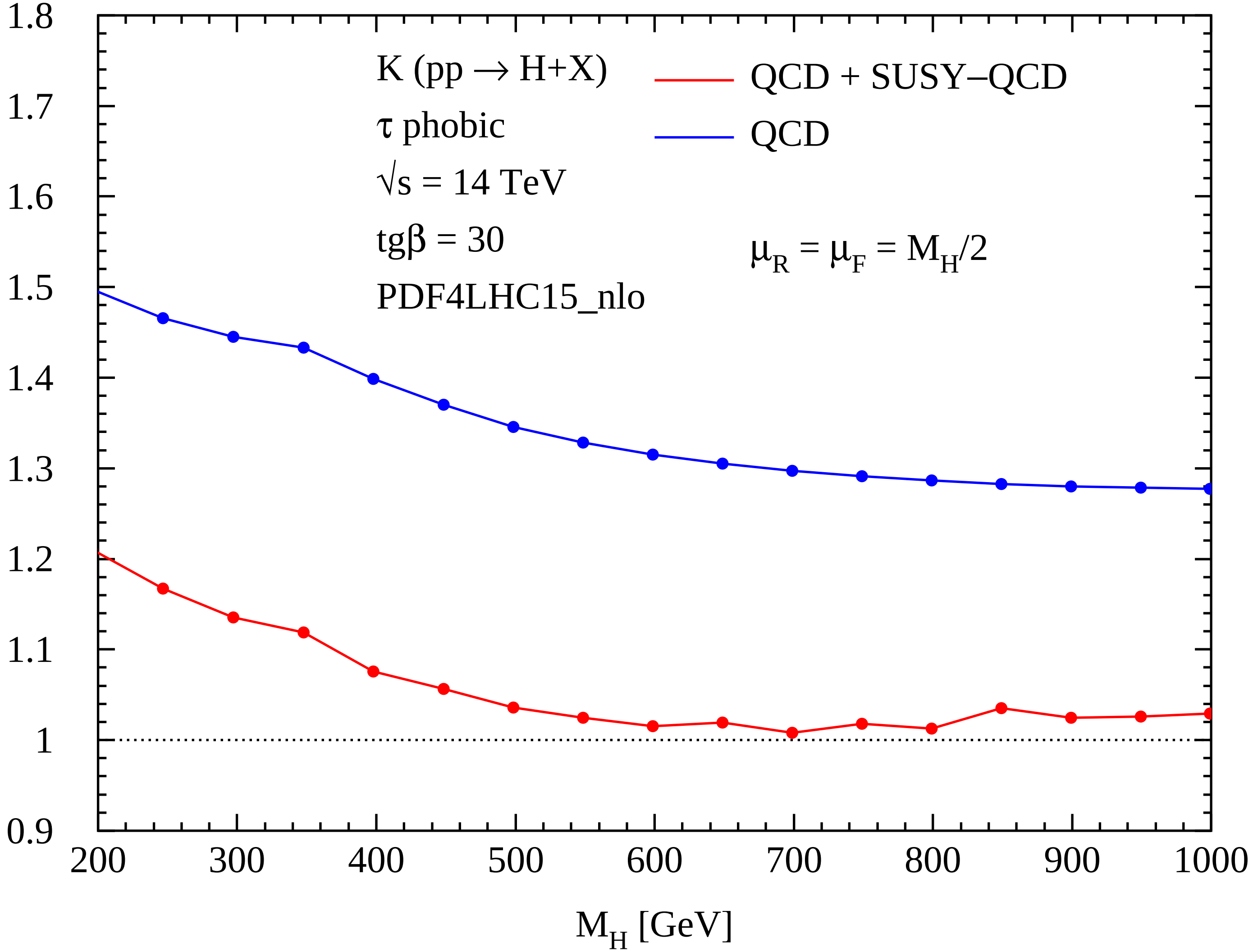
Bagnaschi, Degrassi, Slavich, Vicini

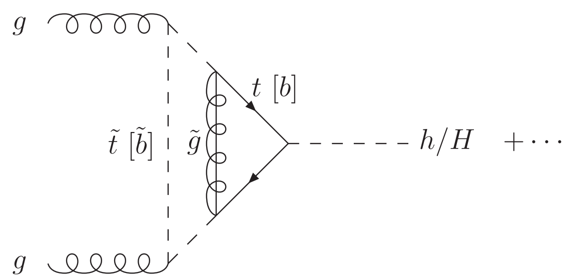
• QCD corrections to squark loops: Mühlleitner, S.



$$\sigma(gg \to \Phi) = \sigma_{LO}(g_t^\Phi, \tilde{g}_b^\Phi) \left[1 + \delta_{QCD} + \delta_{SQCD}\right]$$

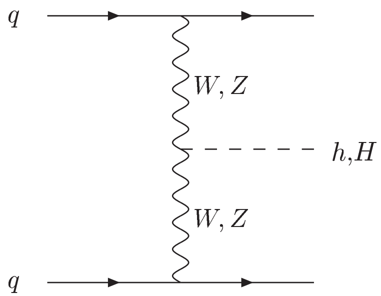
PRELIMINARY





Mühlleitner, Rzehak, S.

(ii) W/Z fusion: $pp \to W^*W^*/Z^*Z^* \to h/H$



Cahn, Dawson
Hikasa
Atarelli, Mele, Pitolli

Han, Valencia, Willenbrock
Figy, Oleari, Zeppenfeld
Berger, Campbell

- QCD corrections ← DIS: $\sim$ 10%

  [approx] 2–loop: $\lesssim$ 1% — Bolzano, Maltoni, Moch, Zaro; Cacciari, Dreyer, Karlberg, Salam, Zanderighi

  [approx] 3–loop: $\lesssim$ 0.3% — Dreyer, Karlberg

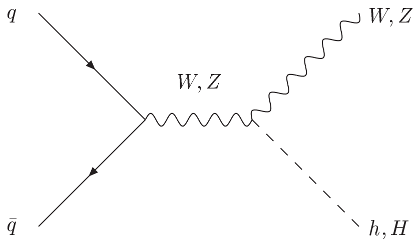
- elw. corrections: $\sim$ 10% — Ciccolini, Denner, Dittmaier

- genuine SUSY-QCD corrections small — Djouadi, S.

- genuine SUSY-elw. corrections: $\lesssim$ 5% — Hollik, Rzehak, Plehn, Rauch; Figy, Palmer, Weiglein

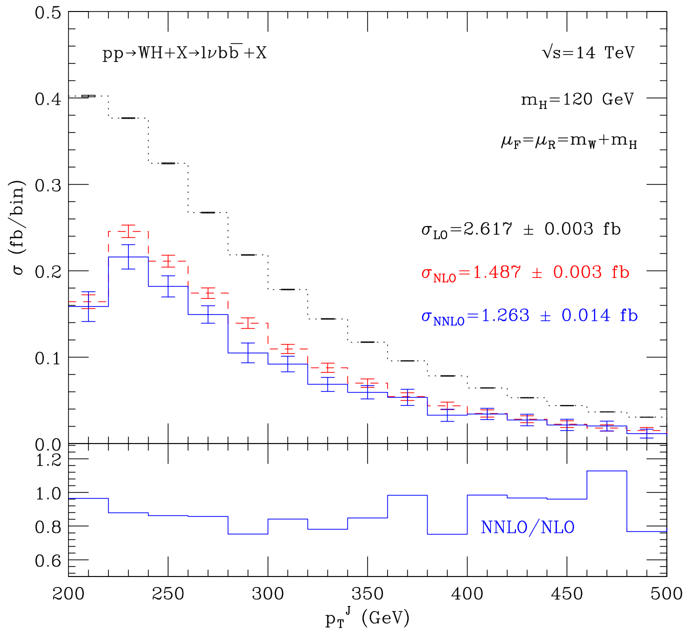
  [implemented in VBFNLO]

(iii) Higgs–strahlung: $pp \to W^*/Z^* \to W/Z + h/H$

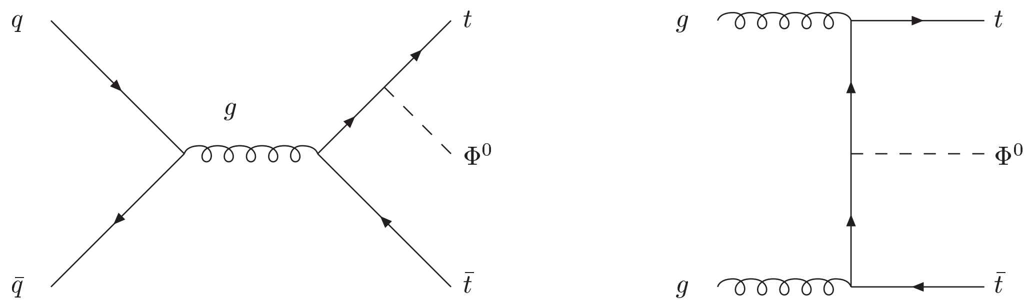


Glashow,...
Kunszt,...

- QCD corrections $\leftarrow$ DY: $\sim 30\%$ — Han, Willenbrock
  2–loop: $\lesssim 5\%$ — Brein, Djouadi, Harlander
- SUSY-QCD corrections small — Djouadi, S.
- electroweak corrections: $\sim -10\%$ — Ciccolini, Dittmaier, Krämer
- $W/Z + H$: fully exclusive @ NNLO QCD — Ferrera, Grazzini, Tramantano



(iv) Bremsstrahlung: $pp \to t\bar{t} + h/H/A$



Kunszt
Gunion
Marciano, Paige

dominant

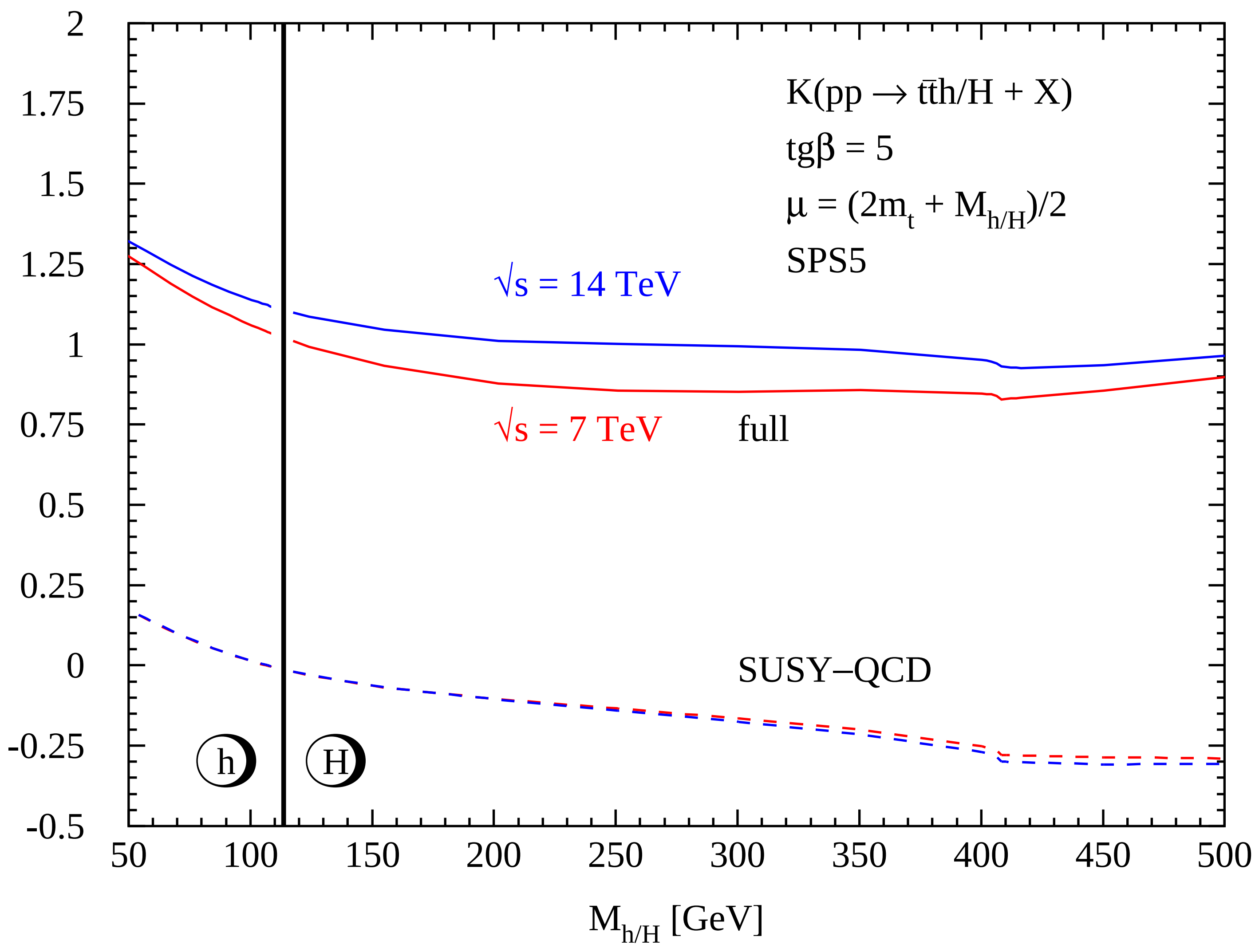
- $t\bar{t}h \to t\bar{t}b\bar{b}$ important @ LHC → top Yukawa cplg.

- QCD corrections [SM]: $\sim 20\%$ [threshold suppressed: $\sigma_{LO} \sim \beta^4$]
  Beenakker, Dittmaier, Krämer, Plümper, S., Zerwas
  Dawson, Orr, Reina, Wackeroth
  Broggio, Ferroglia, Pecjak, Signer, Yang

- SUSY-QCD corrections: moderate
  Dittmaier, Häfliger, Krämer, S., Walser

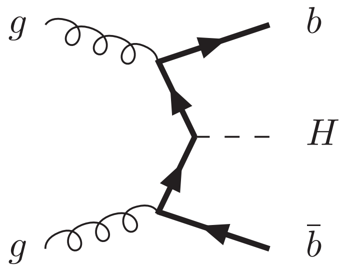
- link to parton showers: aMC@NLO, PowHel
  Frederix et al.
  Garzelli, Kardos, Papadopoulos, Trócsányi

- important work on backgrounds $t\bar{t}b\bar{b}, t\bar{t}jj$, etc.
  Bredenstein, Denner, Dittmaier, Pozzorini
  Bevilacqua, Czakon, Papadopoulos, Pittau, Worek
  Cascioli, Maierhofer, Pozzorini

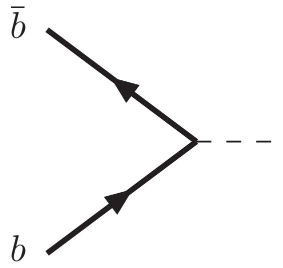


Dittmaier, Häfliger, Krämer, S., Walser

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



NLO



$[\leftarrow \Delta_b]$

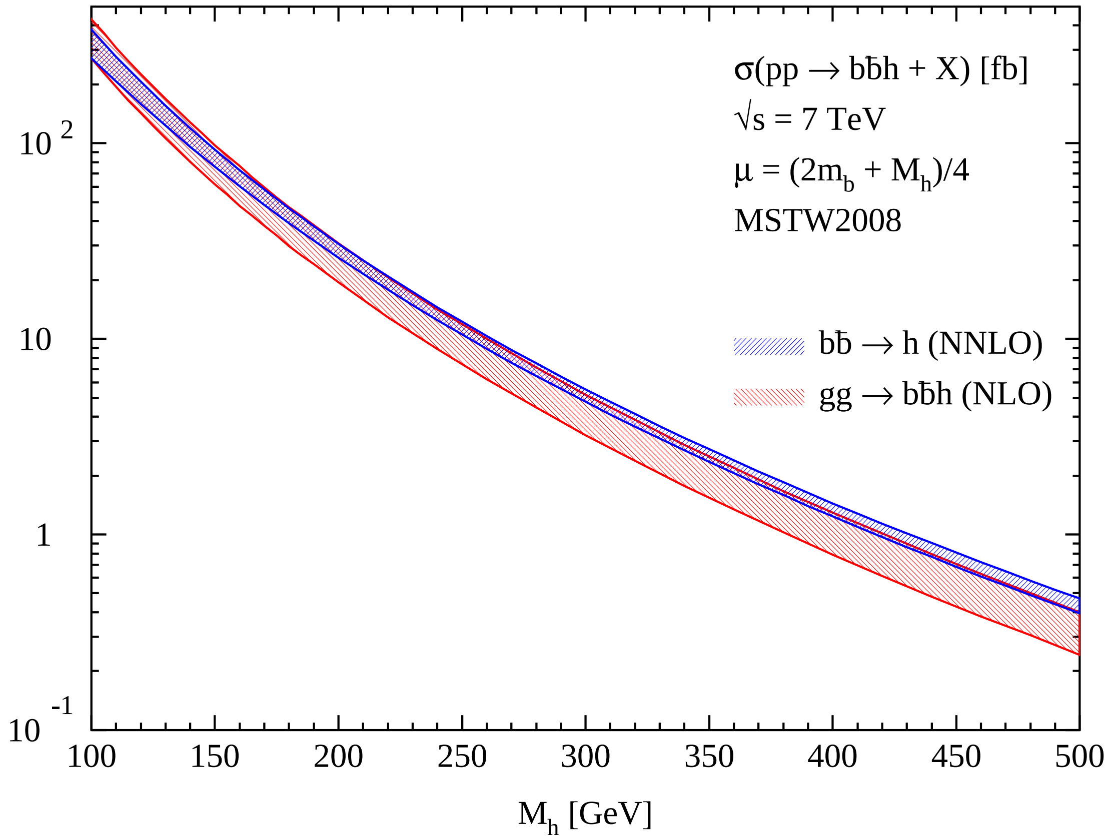
NNLO

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:

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

$$w = \log\frac{M_H}{m_b} - 2$$

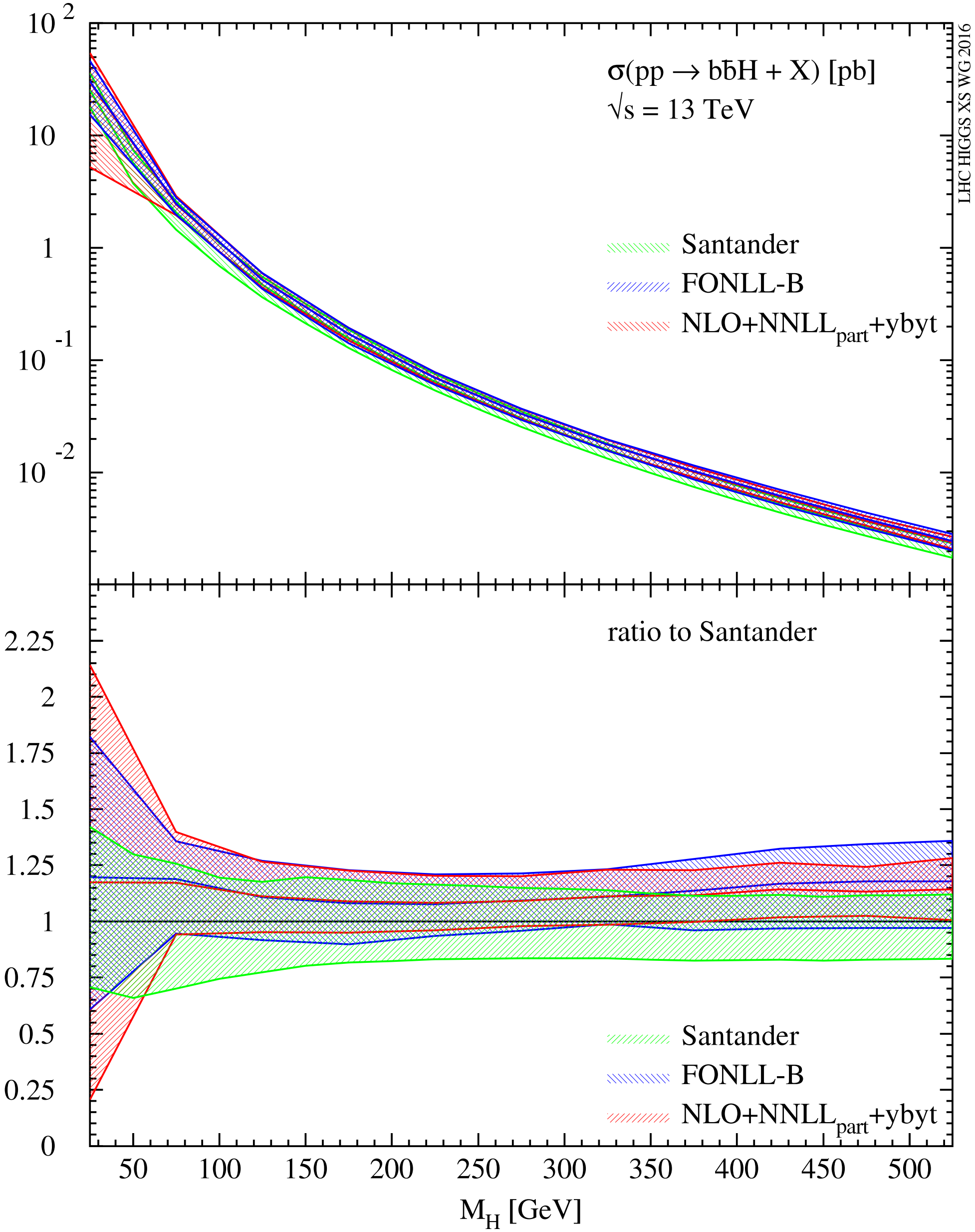
Harlander, Krämer, Schumacher

Dittmaier, Krämer, S.

Dawson, Jackson, Reina, Wackeroth

Harlander, Kilgore

matching



Bonvini, Papanastasiou, Tackmann

Forte, Napoletano, Ubiali

	M_A	M_H [GeV]	δ^A_{QCD}	δ^A_{SUSY}	$\delta^A_{SUSY rem}$	δ^H_{QCD}	δ^H_{SUSY}	$\delta^H_{SUSY rem}$
7 TeV	100	113.9	0.23	−0.30	0.4×10^{-4}	0.27	−0.38	0.3×10^{-4}
	200	200	0.38	−0.30	2.9×10^{-4}	0.39	−0.30	5.8×10^{-4}
	300	300	0.46	−0.30	6.7×10^{-4}	0.47	−0.30	9.3×10^{-4}
	400	400	0.53	−0.30	1.3×10^{-3}	0.53	−0.30	1.5×10^{-3}
	500	500	0.57	−0.30	2.0×10^{-3}	0.59	−0.30	2.2×10^{-3}
14 TeV	100	113.9	0.14	−0.30	0.4×10^{-4}	0.17	−0.38	0.5×10^{-4}
	200	200	0.28	−0.30	2.7×10^{-4}	0.29	−0.30	5.7×10^{-4}
	300	300	0.37	−0.30	6.5×10^{-4}	0.39	−0.30	9.3×10^{-4}
	400	400	0.45	−0.30	1.2×10^{-3}	0.45	−0.30	1.5×10^{-3}
	500	500	0.50	−0.30	2.1×10^{-3}	0.49	−0.30	2.3×10^{-3}

	tgβ	M_A	M_H [GeV]	δ^A_{SUSY}	$\delta^A_{SUSY rem}$	δ^H_{SUSY}	$\delta^H_{SUSY rem}$
7 TeV	3	200	209.7	−0.04	2.1×10^{-4}	−0.04	5.7×10^{-4}
	5	200	204.0	−0.06	2.4×10^{-4}	−0.06	5.3×10^{-4}
	7	200	202.1	−0.08	2.5×10^{-4}	−0.09	3.9×10^{-4}
	10	200	200.9	−0.12	2.5×10^{-4}	−0.12	3.8×10^{-4}
	20	200	200.1	−0.21	2.6×10^{-4}	−0.21	4.4×10^{-4}
	30	200	200.0	−0.30	2.9×10^{-4}	−0.30	5.8×10^{-4}
14 TeV	3	200	209.7	−0.04	2.0×10^{-4}	−0.04	7.2×10^{-4}
	5	200	204.0	−0.06	2.2×10^{-4}	−0.06	5.0×10^{-4}
	7	200	202.1	−0.08	2.4×10^{-4}	−0.09	4.4×10^{-4}
	10	200	200.9	−0.12	2.5×10^{-4}	−0.12	4.1×10^{-4}
	20	200	200.1	−0.21	2.7×10^{-4}	−0.21	4.4×10^{-4}
	30	200	200.0	−0.30	2.7×10^{-4}	−0.30	5.7×10^{-4}

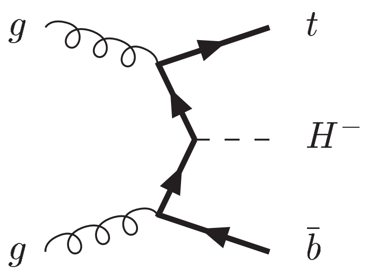
Dittmaier, Häfliger, Krämer, S., Walser

(vi) $pp \to t\bar{b}H^- + X$

- $M_{H^\pm} < m_t - m_b$: $\sigma_{t\bar{b}H^-} = \sigma_{t\bar{t}} \times BR(\bar{t} \to \bar{b}H^-)$
- $M_{H^\pm} \sim m_t - m_b$: new NLO calculation

Degrande, Frederix, Wiesemann, Zaro

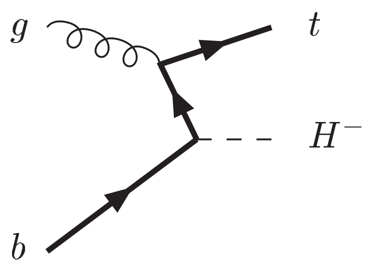
- $M_{H^\pm} > m_t - m_b$:



NLO

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

no resummation of $\log M_{H^\pm}^2/m_b^2$ terms



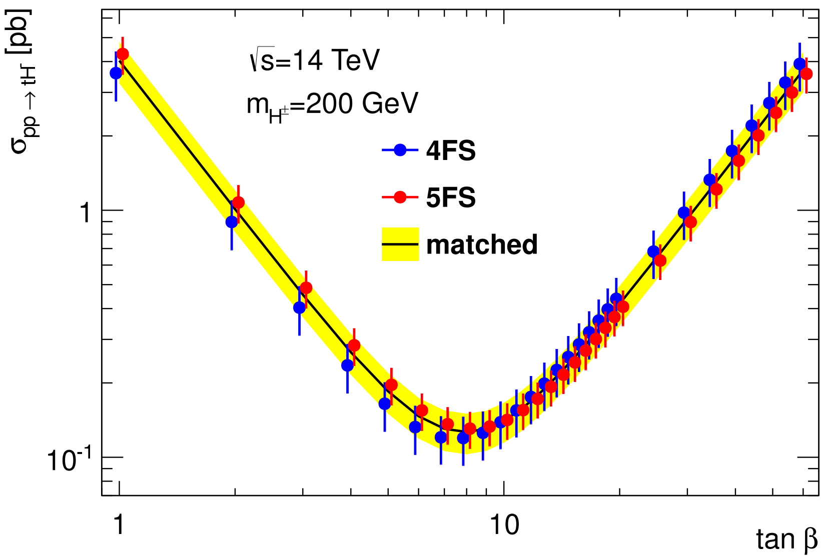
NLO

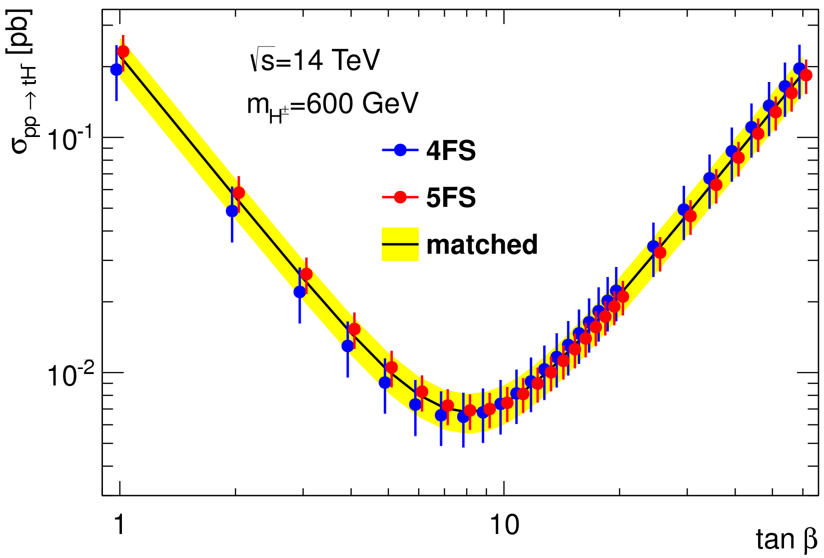
massless/on-shell b's, no p_{Tb}

resummation of $\log M_{H^\pm}^2/m_b^2$ terms

- Santander matching

minimum: $\text{tg}\beta \sim \sqrt{\frac{m_t}{\overline{m}_b}} \sim 8$





Dittmaier, Krämer, S., Walser
Plehn
Flechl, Klees, Krämer, Spira, Ubiali

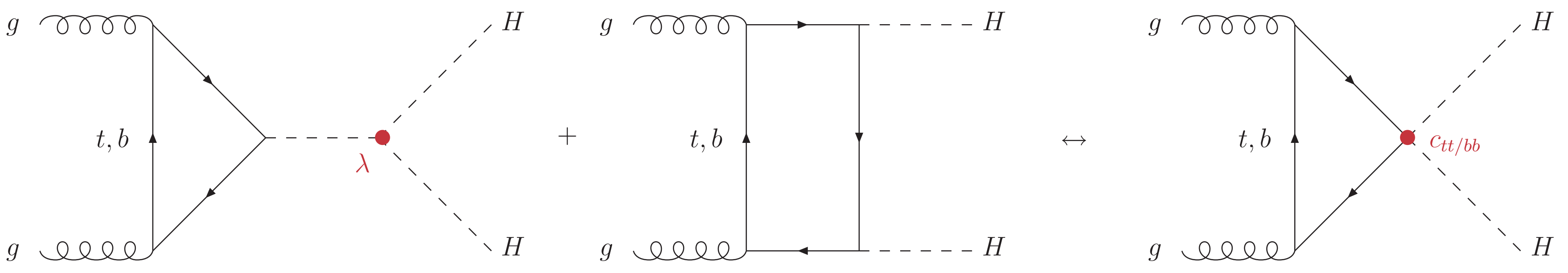
- analogous for charged Higgs: $\tilde{g}_b^{H^\pm} = \frac{\mathrm{tg}\beta}{1+\Delta_b}\left(1 - \frac{\Delta_b}{\mathrm{tg}^2\beta}\right)$

$$\sigma_{NLO} = \sigma_{LO}\big|_{g_b^{H^\pm} \to \tilde{g}_b^{H^\pm}} \times \left\{1 + \delta_{QCD} + \delta_{SQCD}^{rem}\right\}$$

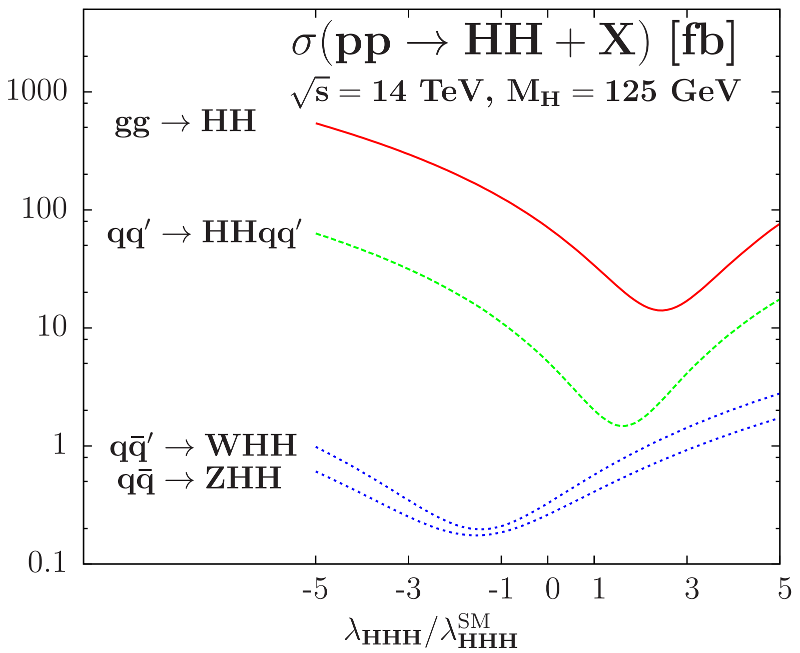
$\mathrm{tg}\beta$	δ_{SUSY}^{rem} [%]
3	-5.7%
5	-7.9%
10	-4.8%
30	-0.13%

Dittmaier, Krämer, S., Walser

$gg \to HH$



- threshold region: sensitive to λ
  large M_{HH}: sensitive to $c_{tt/bb}$ [e.g. boosted Higgs pairs]



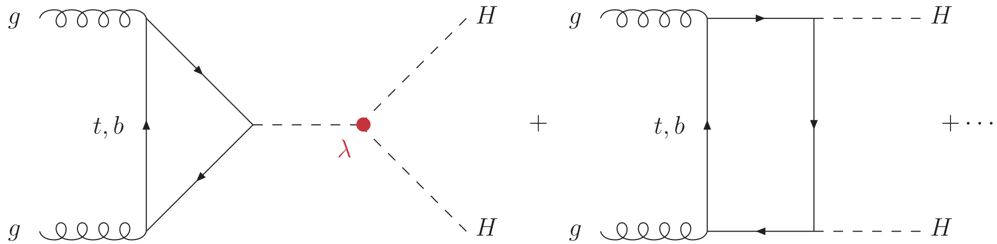
$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

[decreasing with M_{HH}^2]

Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, S.

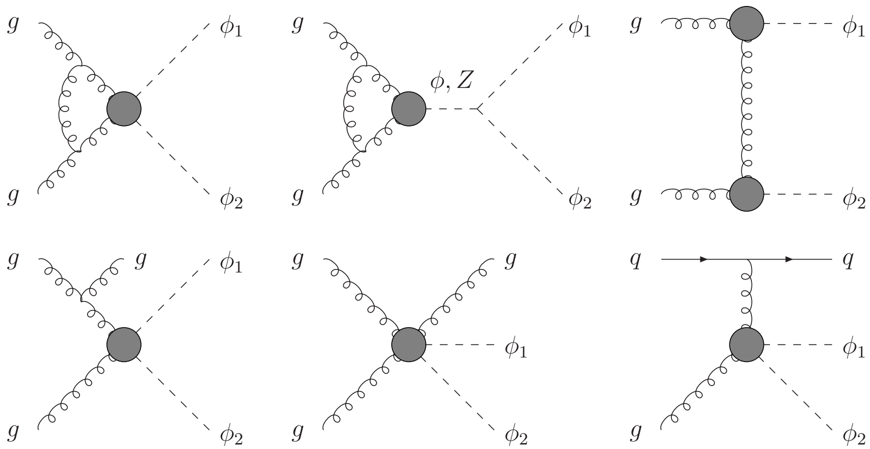
$gg \to HH$

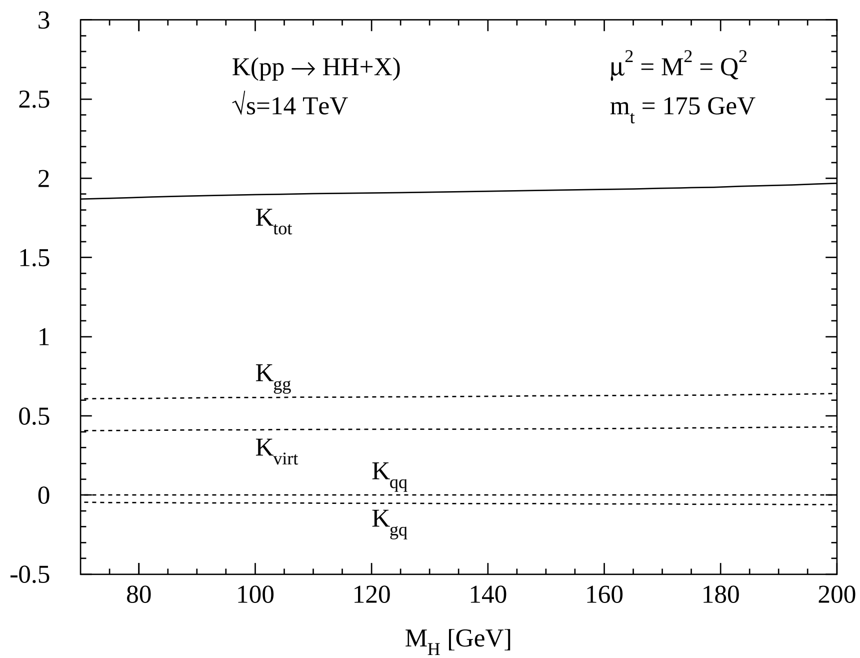
SM



- third generation dominant $\to t, b$

- 2-loop QCD corrections: $\sim 90 - 100\%$
  $[M_H^2 \ll 4m_t^2, \qquad \mu = M_{HH}]$



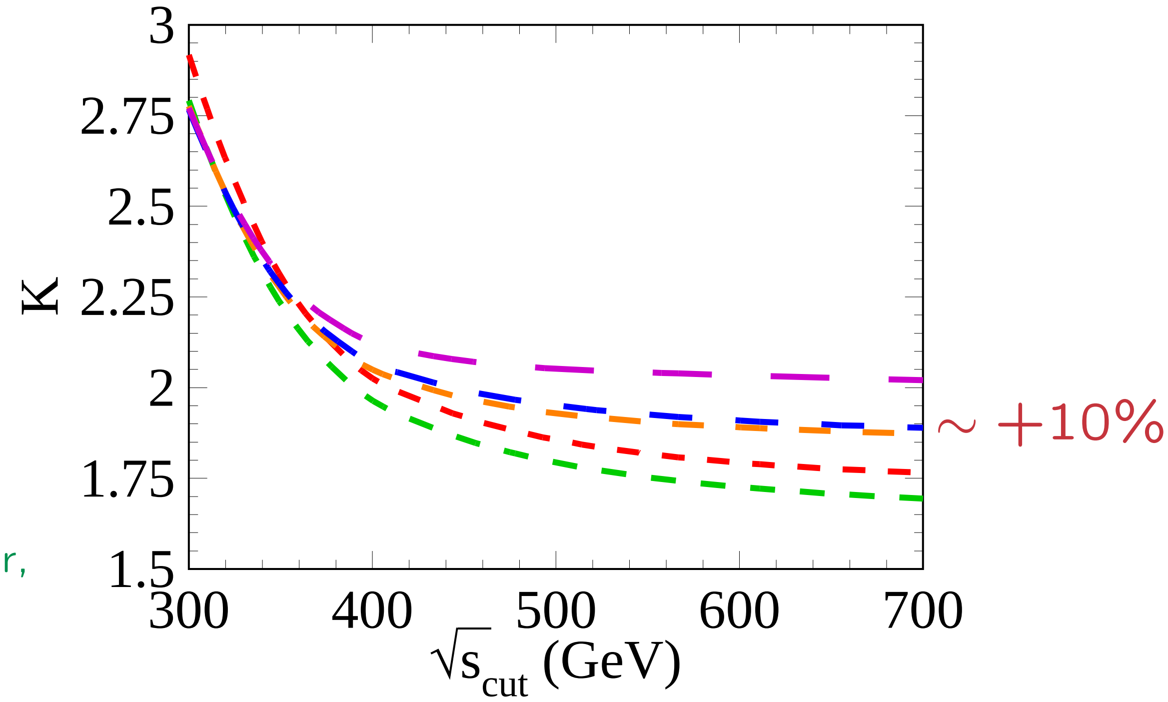


Dawson, Dittmaier, S.

- 2-loop QCD corrections:

$$\sigma = \sigma_0 + \frac{\sigma_1}{m_t^2} + \cdots + \frac{\sigma_4}{m_t^8}$$

Grigo, Hoff, Melnikov, Steinhauser



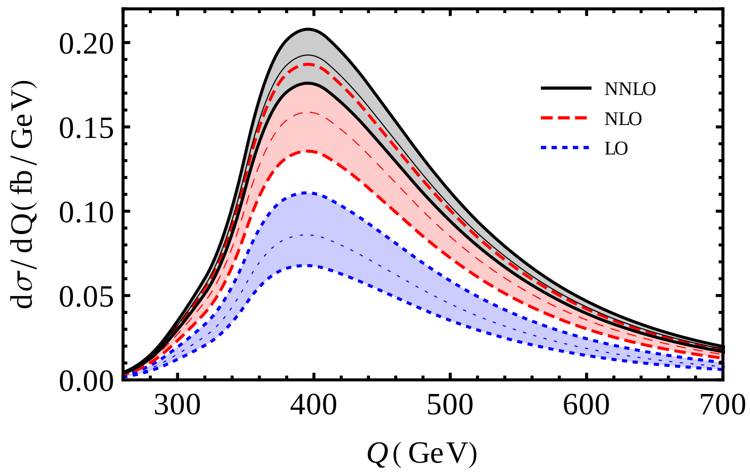
- NLO mass effects @ NLO in real corrections: $\sim -10\%$

  Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro

  $\rightarrow$ sizeable virtual mass effects

- NNLO QCD corrections: $\sim 20\%$ $[M_H^2 \ll 4m_t^2]$

  de Florian, Mazzitelli
  Grigo, Melnikov, Steinhauser



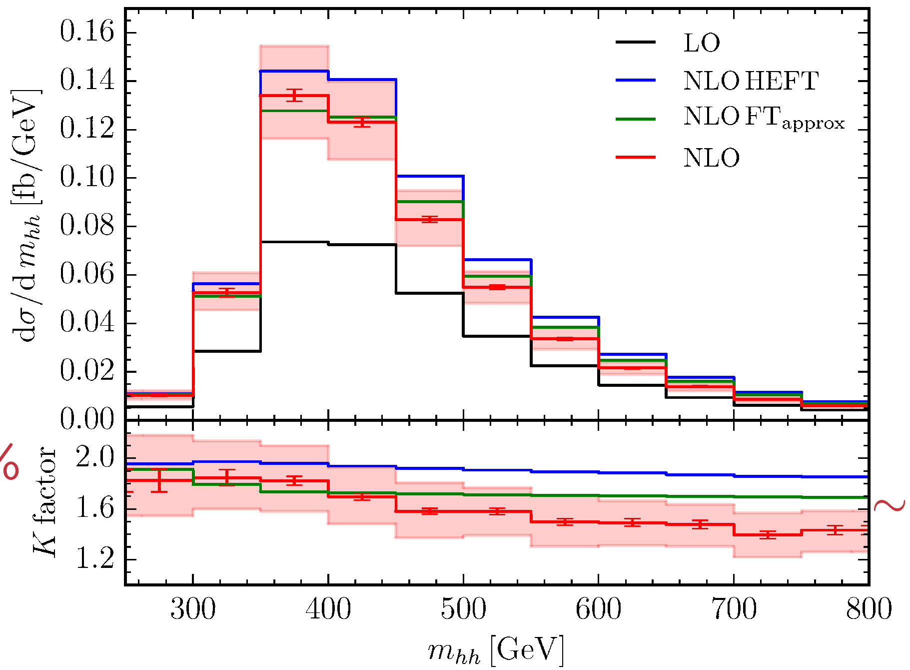
- soft gluon resummation: $\sim 10\%$ $[M_H^2 \ll 4m_t^2]$

Shao, Li, Li, Wang
de Florian, Mazzitelli

Full NLO calculation: top only

Numerical integration, sector decomposition, contour deformation

$\sim -6\%$



$\sim -20\%$

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke

Baglio, Campanario, Glaus, Mühlleitner, S., Streicher (in preparation)

- 13 TeV:

$$\sigma_{NLO} = 27.80(8)^{+13.8\%}_{-12.8\%}\ fb$$

$$\sigma^{HEFT}_{NLO} = 32.22^{+18\%}_{-15\%}\ fb$$

$\Rightarrow$ -13.7% mass effects

IV CONCLUSIONS

- Higgs boson searches/studies at LHC belong to major endeavours

- most (SUSY–)QCD and –elw. corrections known $\rightarrow \Delta \lesssim 10 - 15\%$ @ LHC

- several dedicated HO–tools available for SM, MSSM [NMSSM,. . .]

- important to develop NLO event generators [$\leftarrow$ backgrounds]

BACKUP SLIDES

PAUL SCHERRER INSTITUT PSI

τ-phobic scenario [scale = 1 TeV]

$$
\begin{aligned}
m_t &= 173.2 \text{ GeV} \\
\text{tg}\beta &= 30 \\
M_{\tilde{Q}} &= 1.5 \text{ TeV} \\
M_{\tilde{g}} &= 1.5 \text{ TeV} \\
M_2 &= 200 \text{ GeV} \\
A_b = A_t &= 4.417 \text{ TeV} \qquad [X_t = 2.9\ M_{\tilde{Q}}] \\
\mu &= 2 \text{ TeV} \\
M_{\tilde{\ell}_3} &= 500 \text{ GeV}
\end{aligned}
$$

$$
\begin{aligned}
m_{\tilde{t}_1} &= 1.318 \text{ TeV} \qquad m_{\tilde{t}_2} = 1.726 \text{ TeV} \\
m_{\tilde{b}_1} &= 1.501 \text{ TeV} \qquad m_{\tilde{b}_2} = 1.565 \text{ TeV}
\end{aligned}
$$

SPS 5

$$
\begin{aligned}
\mathrm{tg}\beta &= 5 \\
\mu &= 639.8 \text{ GeV} \\
A_t &= -1671.4 \text{ GeV} \\
A_b &= -905.6 \text{ GeV} \\
m_{\tilde{g}} &= 710.3 \text{ GeV} \\
m_{\tilde{q}_L} &= 535.2 \text{ GeV} \\
m_{\tilde{b}_R} &= 620.5 \text{ GeV} \\
m_{\tilde{t}_R} &= 360.5 \text{ GeV}
\end{aligned}
$$

$$
\longrightarrow m_{\tilde{t}_1} = 204.1 \text{ GeV}, m_{\tilde{t}_2} = 656.1 \text{ GeV}, m_{\tilde{b}_1} = 533.3 \text{ GeV}, m_{\tilde{b}_2} = 625.2 \text{ GeV}
$$