

# MSSM Higgs-boson production in bottom-quark fusion: electroweak radiative corrections

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*in collaboration with*

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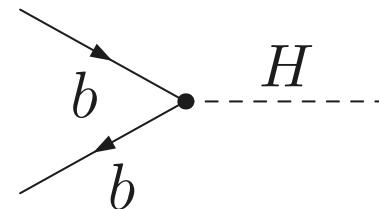
see: hep-ph/0611353

# Outline

- Why Higgs-production from b-quark fusion?
- organizing the calculation: 4FNS and 5FNS
- status of the predictions
- electroweak MSSM corrections

# Bottom Yukawa Coupling

Higgs bosons from **b** quarks:

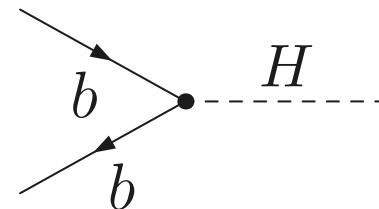


- SM:  $\lambda_b^{\text{SM}} = \frac{m_b}{v} = \frac{e m_b}{2 s_W M_W}$

⇒ not competitive with **gluon fusion**

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⇒ let's have a look at the **MSSM**

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MSSM Higgs sector:

- two Higgs doublets  $H_u, H_d$  with VEVs  $v_u, v_d$
- 5 physical Higgs particles:  $h^0, H^0, A^0, H^\pm$
- Higgs mixing:  $h^0 = c_\alpha H_u^0 - s_\alpha H_d^0$

$$t_{2\alpha} = \frac{M_{A^0}^2 + M_Z^2}{M_{A^0}^2 - M_Z^2} \quad t_{2\beta} \quad \text{with} \quad s_{2\alpha} < 0$$

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but:  $s_\alpha/c_\beta \sim \mathcal{O}(1)$  for large  $M_A$

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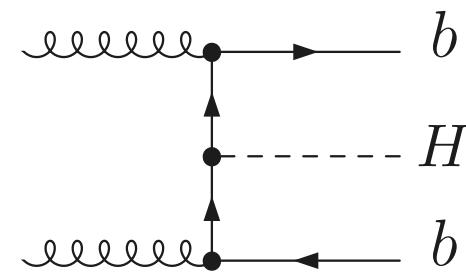
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$\Rightarrow$  dominates total  $H^0$  and  $A^0$  production for large  $\tan \beta$

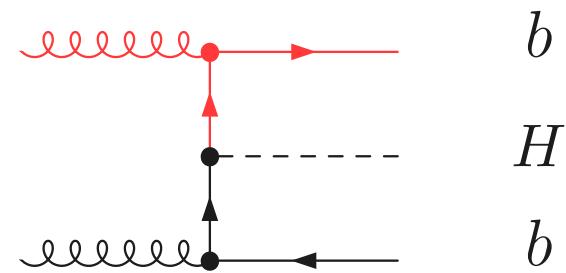
# Basic Process

basic process at gluon collider:



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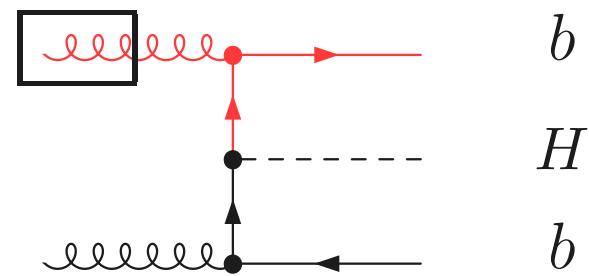


gluon splitting: large logs from collinear  $b$  quarks

⇒ expansion in  $\log \frac{\mu_F}{m_b} \alpha_s$

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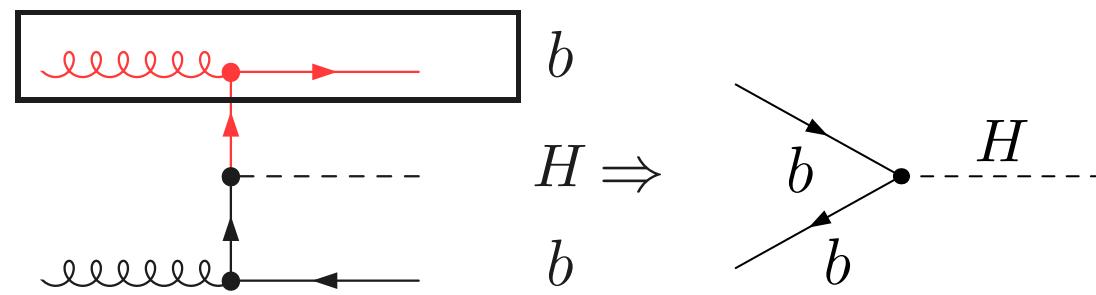
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gluon splitting in short range matrix element?

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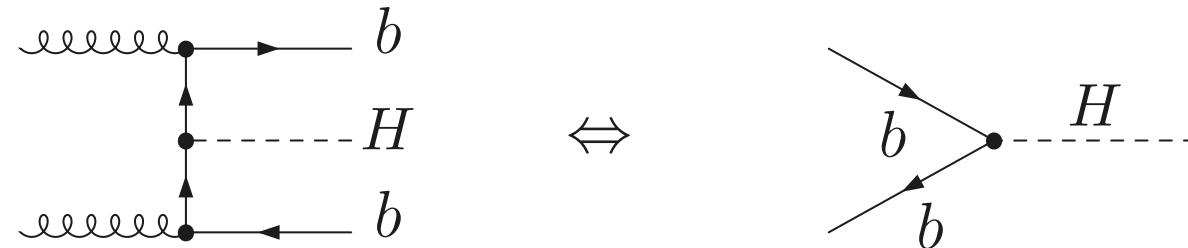
possible resummation:

introduce PDF for  $b$  quarks in the proton

massless approximation  $m_b \rightarrow 0$  ( $\log \frac{\mu_F}{m_b} \rightarrow 1/\epsilon$ )

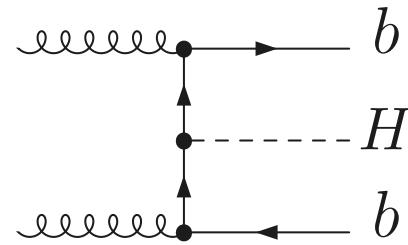
collinear  $1/\epsilon$  poles absorbed in PDF

# 4FNS and 5FNS

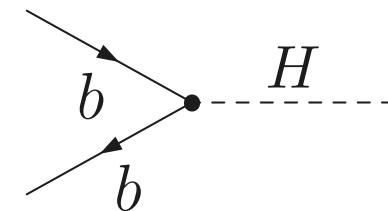


4 flavors in proton       $\Leftrightarrow$       5 flavors in proton

# 4FNS and 5FNS



$\Leftrightarrow$

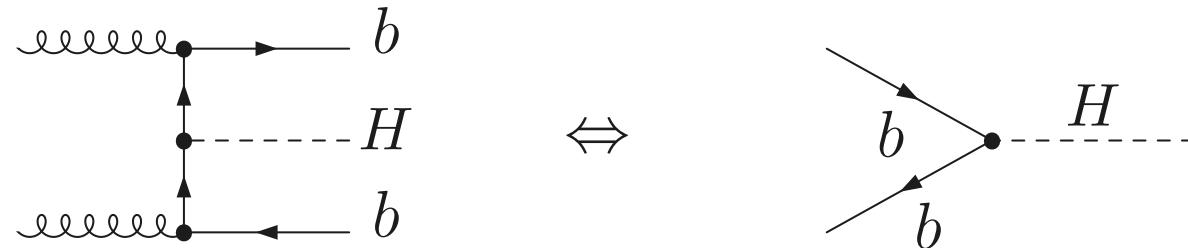


4 Flavor  
Number Scheme

$\Leftrightarrow$

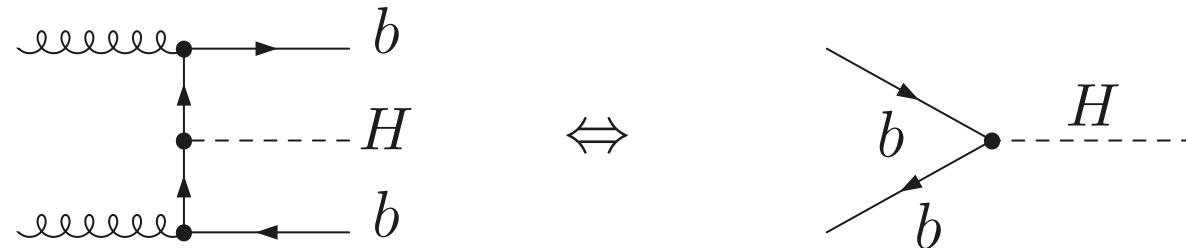
5 Flavor  
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# 4FNS and 5FNS



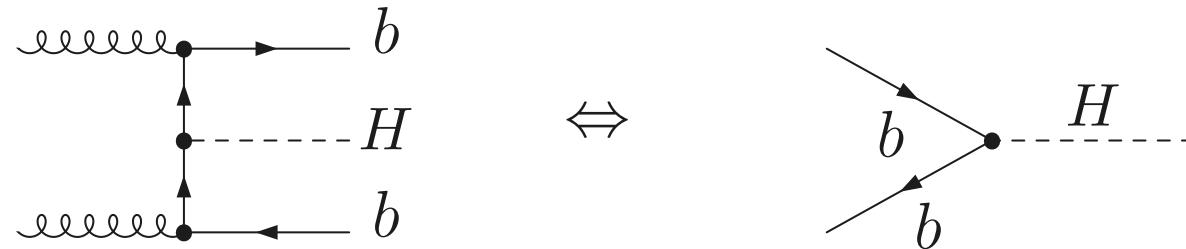
- no summation
  - exact  $g \rightarrow b\bar{b}$ -splitting
  - full kinematics  
(final state  $b$  jets)
- summation of  $\log \frac{\mu_F}{m_b}$
  - LL approx. to  $g \rightarrow b\bar{b}$
  - massless  $b$  approx.

# 4FNS and 5FNS



- no summation
- exact  $g \rightarrow b\bar{b}$ -splitting
- full kinematics  
(final state b jets)
- same physics
- agree at all orders
- different organization of the perturbation series

# 4FNS and 5FNS



4FNS: exclusive  $b\bar{b}H$  final state

known to **NLO** (Dittmaier, Krämer, and Spira  
Phys. Rev. D70 (2004) 074010  
Dawson, Jackson, Reina, and Wackerlo  
Phys. Rev. Lett. 94 (2005) 031802)

5FNS: resummed logs

known to **NNLO** (Harlander and Kilgore  
Phys. Rev. D68 (2003) 013001)

The two approaches **agree** for small Higgs masses.

(within their respective errors, for  $\mu_F \sim M_H/4$ )

# Status of the calculation

uncertainties (from QCD):

- $\sim 10\%$  from **scale** dependence ( $\mu_F, \mu_R$ )
- $\sim 10\%$  from **PDFs**

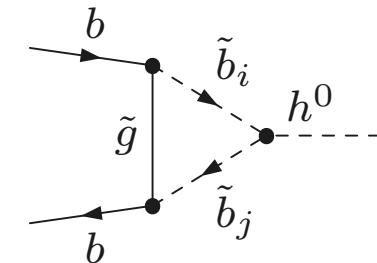
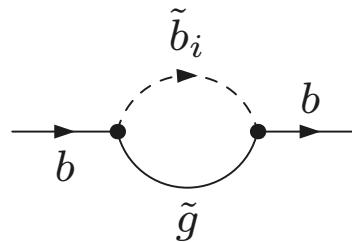
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improved born approximation for EW :

- $\tan \beta$  enhanced:  
(SUSY-QCD and EW)



$$\Rightarrow \lambda_b^{h^0} = -\lambda_b^{\text{SM}} \frac{1}{1+\Delta_b} \left( \frac{s_\alpha}{c_\beta} - \Delta_b \frac{c_\alpha}{s_\beta} \right) \quad \text{with } \Delta_b \propto \tan \beta$$

(Carena, Garcia, Nierste, Wagner, ...)

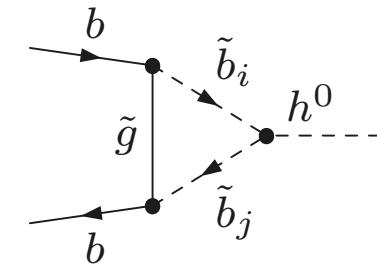
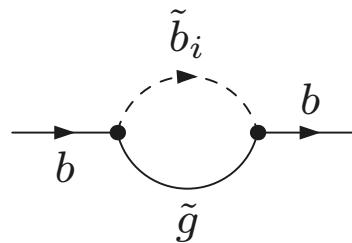
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- Higgs mixing:  $\alpha \rightarrow \alpha_{\text{eff}}$  (including self-energy corrections)

# MSSM cross section

improved born approximation:

$$\hat{\sigma}_{\text{IBA}} = \frac{\sqrt{2}\pi G_\mu \bar{m}_b(\mu_R)^2}{6M_{\phi^0}^2} \delta(1-\tau) \left\{ \begin{array}{l} \frac{s_{\alpha_{\text{eff}}}^2}{c_\beta^2} \left( \frac{1 - \Delta_b/(t_\beta t_{\alpha_{\text{eff}}})}{1 + \Delta_b} \right)^2 \\ \frac{c_{\alpha_{\text{eff}}}^2}{c_\beta^2} \left( \frac{1 + \Delta_b t_{\alpha_{\text{eff}}}/t_\beta}{1 + \Delta_b} \right)^2 \\ t_\beta^2 \left( \frac{1 - \Delta_b/t_\beta^2}{1 + \Delta_b} \right)^2 \end{array} \right.$$

for  $h^0$ ,  $H^0$ , and  $A^0$  production

all additional one-loop corrections relative to  $\sigma_{\text{IBA}}$

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known for the decay (Dabelstein)

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renormalization:

- no simple on-shell renormalization (SM:  $\delta Z_H = -\Sigma'_H(M_H^2)$ )
- $t_\beta$ -renormalization (DCPR- and  $\overline{DR}$ -schemes)

• DCPR-scheme:  $\hat{\Sigma}_{A^0Z}(M_{A^0}^2) = 0$

$$\Rightarrow \delta t_\beta / t_\beta = \Sigma_{A^0Z}(M_{A^0}^2) / (s_{2\beta} M_Z)$$

(Dabelstein, Chankowski, Pokorski, Rosiek)

•  $\overline{DR}$ -scheme:  $\delta t_\beta$  pure divergence

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many vertices and diagrams:

- tools for the 1-loop calculation  
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Higgs mixing and masses:

- potentially large effects:  $s_\alpha \rightarrow s_{\alpha_{\text{eff}}}$

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$$(k^2 - m_{h^0}^2 + \hat{\Sigma}_{h^0}(k^2)) (k^2 - m_{H^0}^2 + \hat{\Sigma}_{H^0}(k^2)) - \hat{\Sigma}_{H^0 h^0}^2(k^2) = 0$$

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- renormalized self-energies:

$$\hat{\Sigma}_{h^0}(k^2) = \Sigma_{h^0}(k^2) + k^2 (\delta Z_{H_u} c_\alpha^2 + \delta Z_{H_d} s_\alpha^2) - \delta m_{h^0}^2$$

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- Higgs mass counterterms:

$$\delta m_{h^0}^2 = c_{\beta-\alpha}^2 \Sigma_{A^0}(M_{A^0}^2) + s_{\beta+\alpha}^2 \Sigma_Z(M_Z^2) - \frac{e s_{\beta-\alpha}^2 c_{\beta-\alpha}}{2 M_Z s_W c_W} T_{H^0} + \frac{e s_{\beta-\alpha} (1 + c_{\beta-\alpha}^2)}{2 M_Z s_W c_W} T_{h^0}$$

$$- (M_{A^0}^2 c_{\beta-\alpha}^2 + M_Z^2 s_{\beta+\alpha}^2) \Sigma'_{A^0}(M_{A^0}^2) + M_Z \frac{c_{2\alpha} - c_{2\beta}}{s_{2\beta}} \Sigma_{A^0 Z}(M_{A^0}^2)$$

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- leading two-loop SE corrections from FeynHiggs

(Hahn, Heinemeyer, Hollik, Weiglein)

# results for SPS 4

- $t_\beta = 50$ ,  $M_{h^0} = 115.66 \text{ GeV}$ ,  $M_{H^0} = 397.72 \text{ GeV}$ ,  $M_{A^0} = 397.67 \text{ GeV}$

	h <sup>0</sup>		H <sup>0</sup>		A <sup>0</sup>	
	$m_b[\text{GeV}]$	$\sigma[\text{pb}]$	$m_b[\text{GeV}]$	$\sigma[\text{pb}]$	$m_b[\text{GeV}]$	$\sigma[\text{pb}]$
QCD	2.80	0.97	2.55	24.12	2.55	24.13
+QED	2.80	0.97	2.55	24.07	2.55	24.09
$+\Delta_b^{\tilde{g}}$	2.72	0.92	1.95	14.14	1.95	14.15
$+\Delta_b^{\text{weak}}$	2.75	0.94	2.24	18.66	2.24	18.67
$+\sin(\alpha_{\text{eff}})$	2.75	0.88	2.24	18.66	2.24	18.67
full calculation	2.75	0.87	2.24	18.43	2.24	18.44

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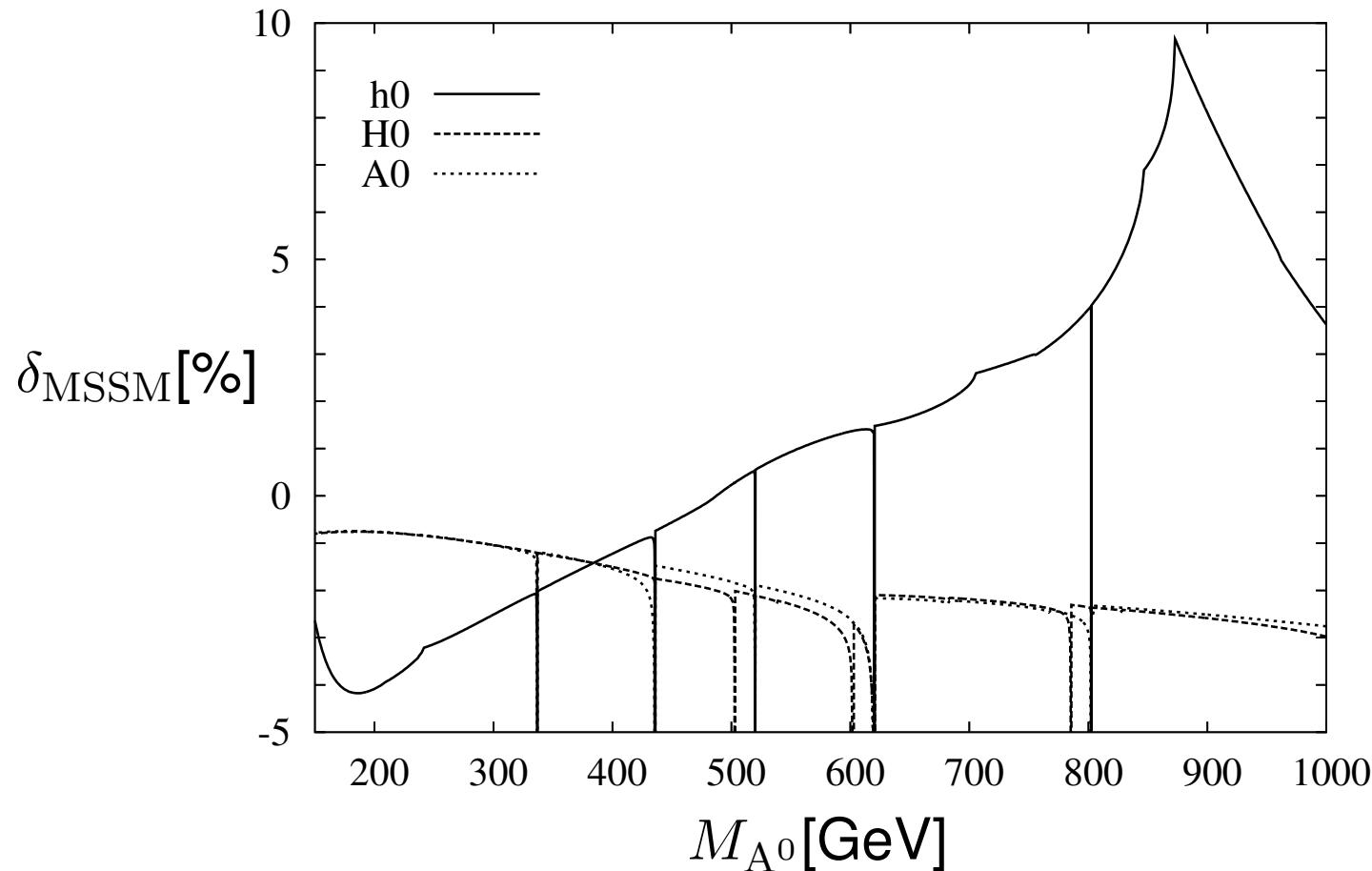
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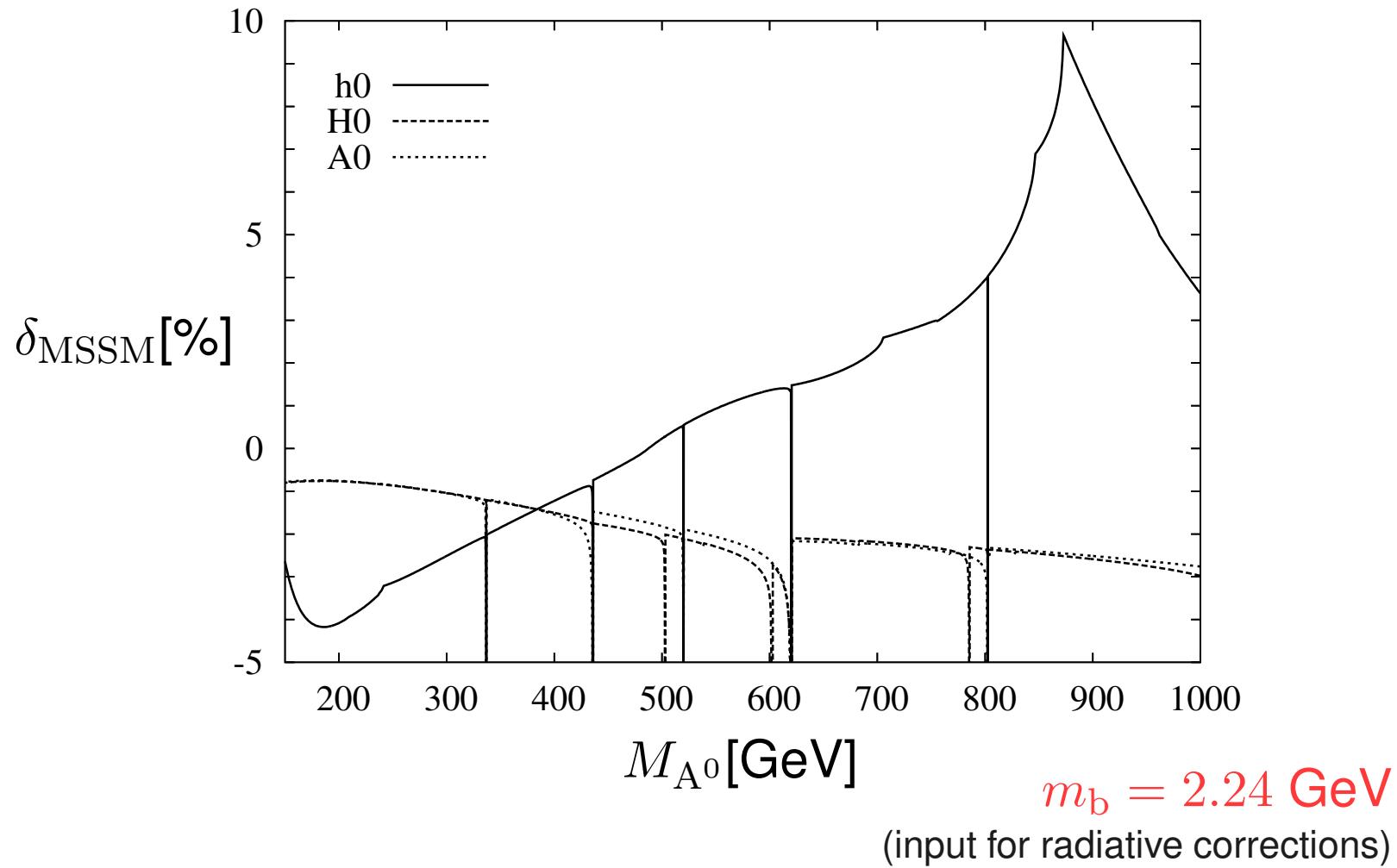
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- correction  $\delta_{\text{MSSM}}$  beyond improved born approximation



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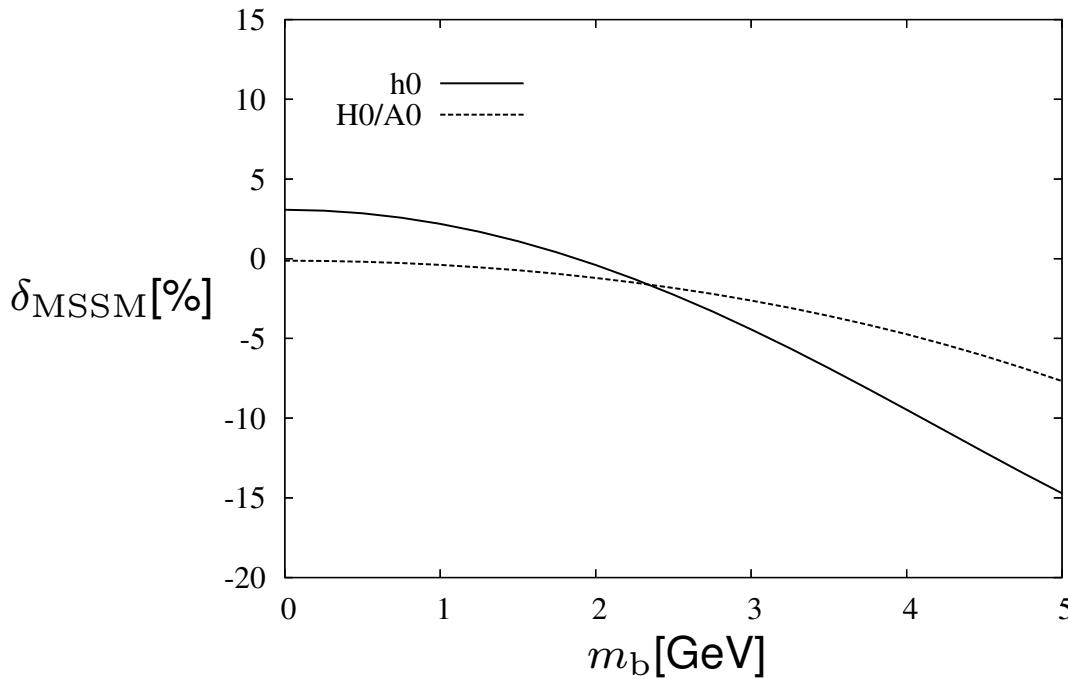
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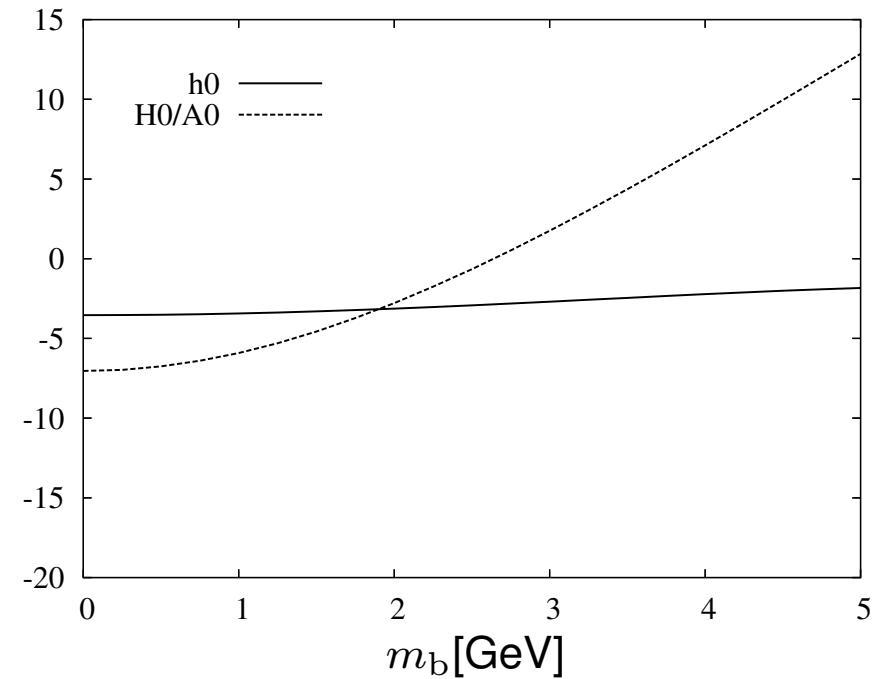
# $m_b$ input

- large dependence on input value of b mass  
(large Yukawa coupling)
- massless (QCD) approx. inadequate for EW corrections

$\overline{\text{DR}}$  scheme:



DCPR scheme:



# SPS results

cross section  $\sigma$  (full calculation) and relative correction  $\delta$  w.r.t.  
the improved born approximation  $\sigma_{IBA}$  for the SPS points:

	$\sigma[\text{pb}]$			$\delta[\%]$		
	$h^0$	$H^0$	$A^0$	$h^0$	$H^0$	$A^0$
SPS 1a	1.03	0.91	0.92	2.29	-0.21	0.15
SPS 1b	0.81	2.23	2.23	1.96	-0.20	-0.21
SPS 2	0.77	0.00	0.00	3.11	-1.35	-1.35
SPS 3	0.84	0.18	0.18	4.17	0.02	0.00
SPS 4	0.87	18.44	18.44	-0.92	-1.24	-1.27
SPS 5	0.95	0.02	0.02	-4.08	0.26	-1.10
SPS 6	0.95	0.47	0.47	3.06	-0.12	0.19
SPS 7	1.09	2.45	2.46	4.62	1.59	1.61
SPS 8	0.92	0.67	0.67	5.86	0.96	1.25
SPS 9	0.83	0.02	0.02	3.36	-0.87	-0.81

# Summary

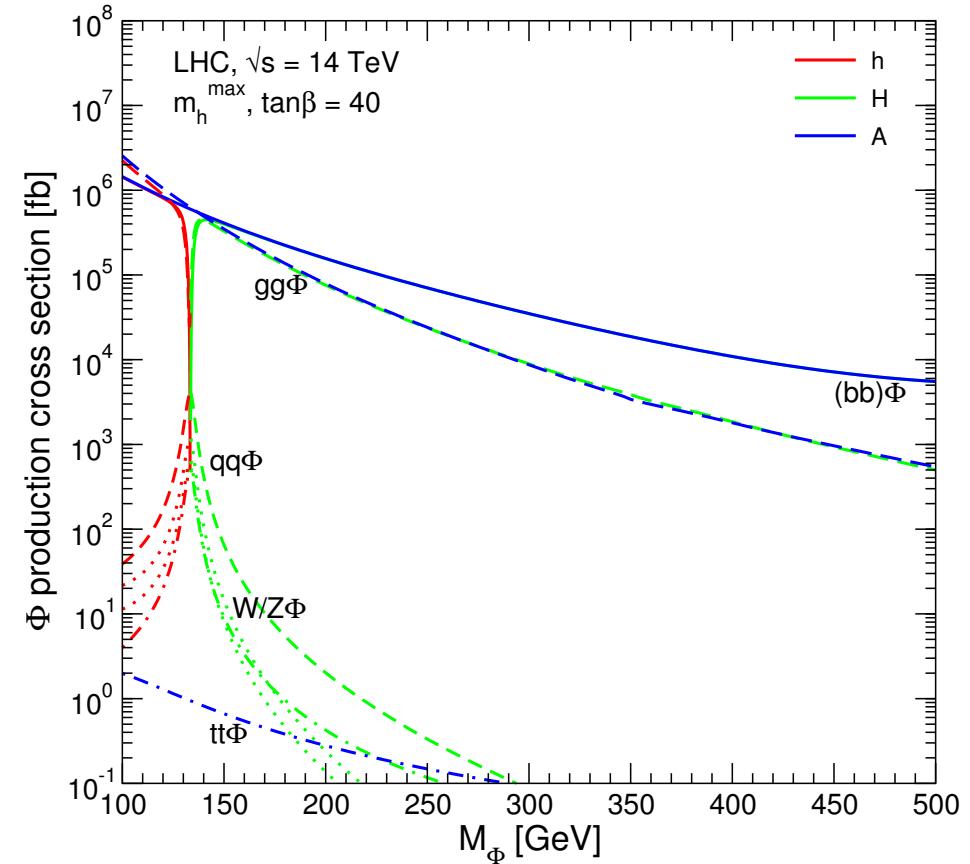
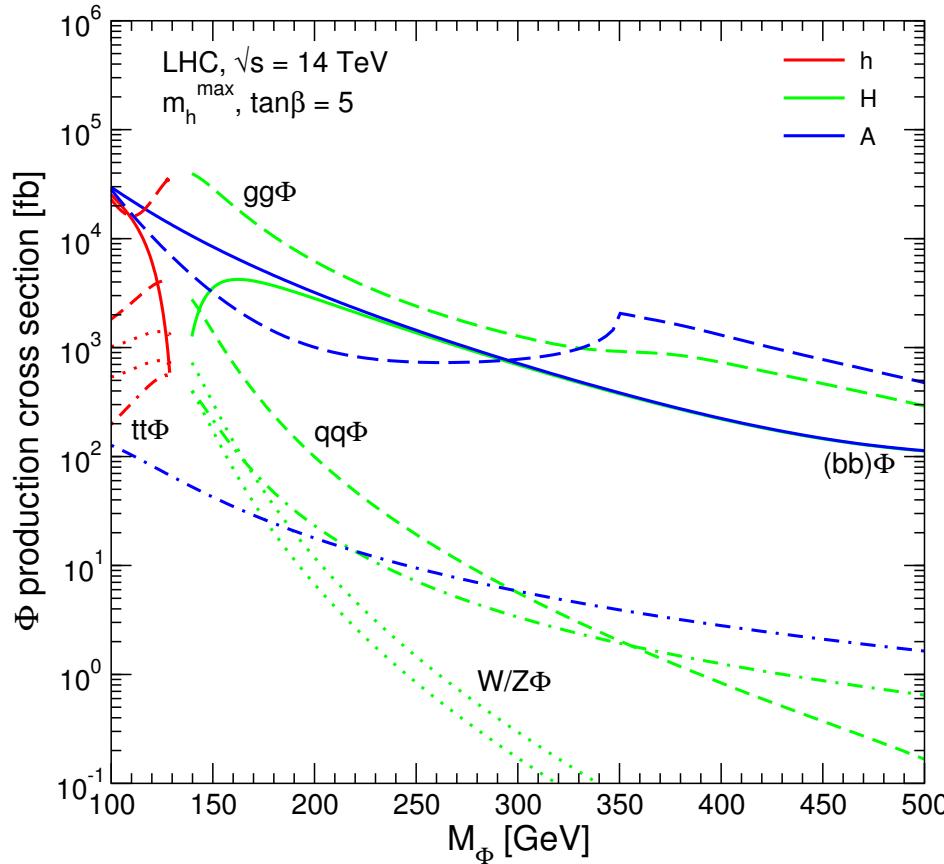
## Higgs production from $b$ quarks:

- important production channel for large  $\tan \beta$
- under good theoretical control
  - different schemes agree ( $4\text{FNS} \Leftrightarrow 5\text{FNS}$ )
  - scale and pdf uncertainties  $\sim 10\text{-}20\%$
  - known  $\tan \beta$  enhanced corrections
- full 1-loop EW MSSM corrections
  - a few percent
  - depending on  $m_b$  input

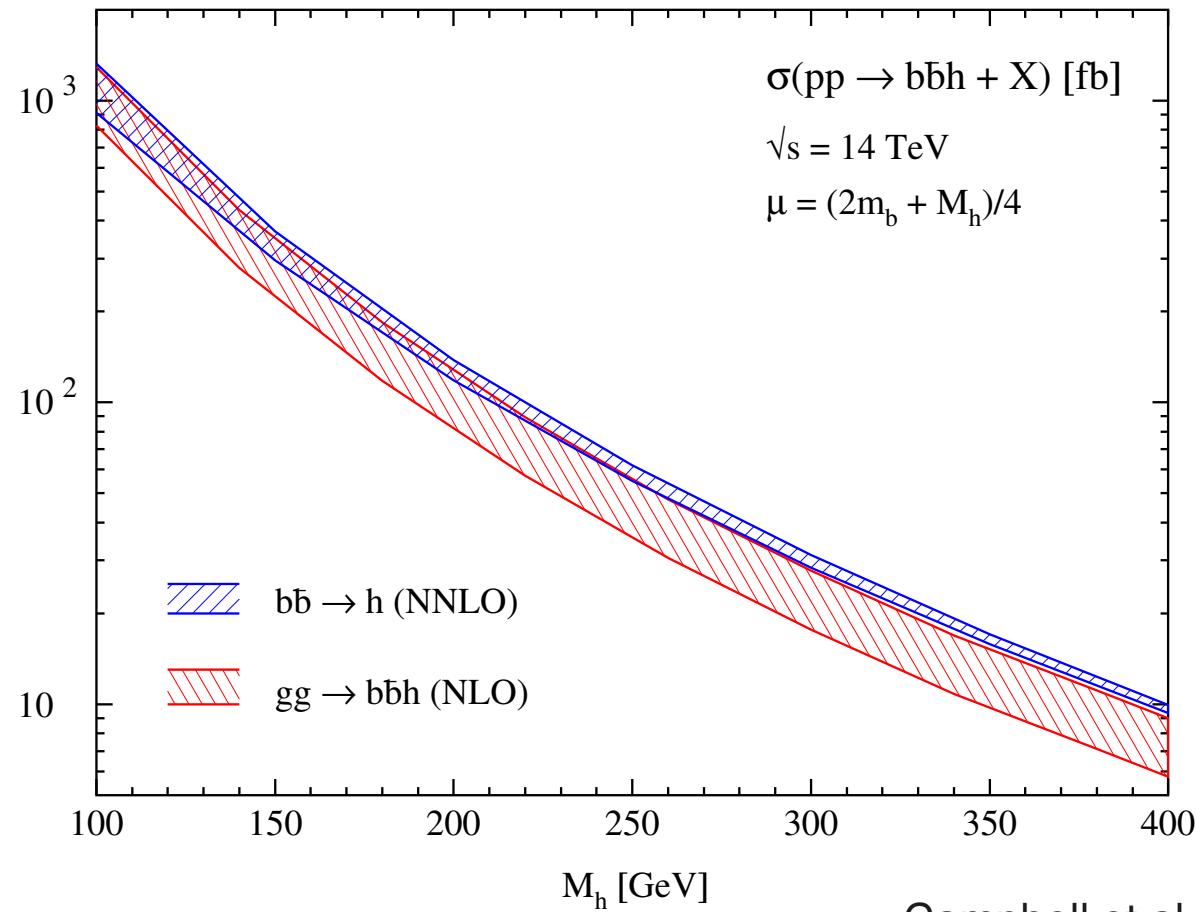
# Back-up slides

# MSSM cross section

<http://maltoni.home.cern.ch/maltoni/TeV4LHC/MSSM.html>



# 4FNS and 5FNS



the two approaches agree for a light Higgs and  $\mu_F \sim M_H/4$   
(scale choice: Spira; Maltoni,Sullivan,Willenbrock; Boos, Plehn)

# Status of the calculation

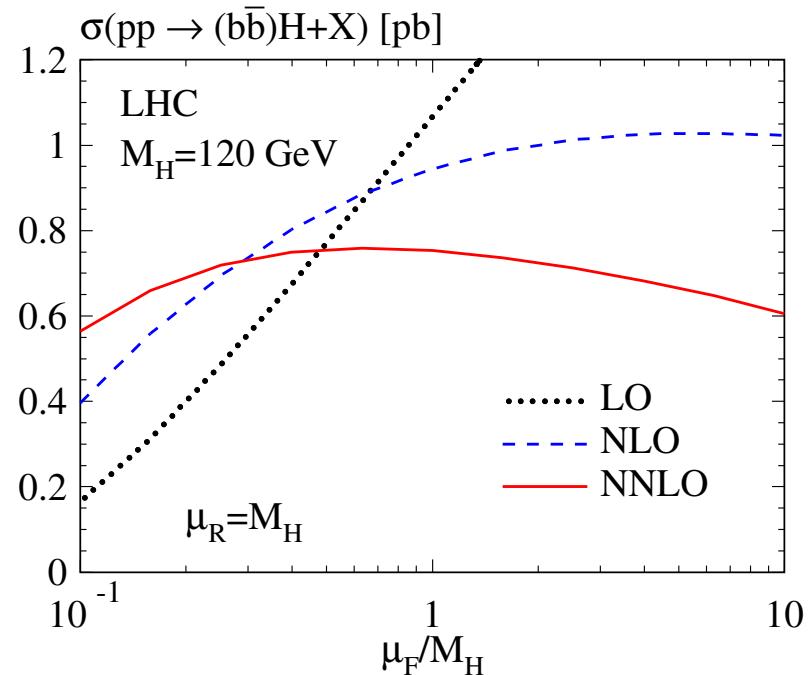
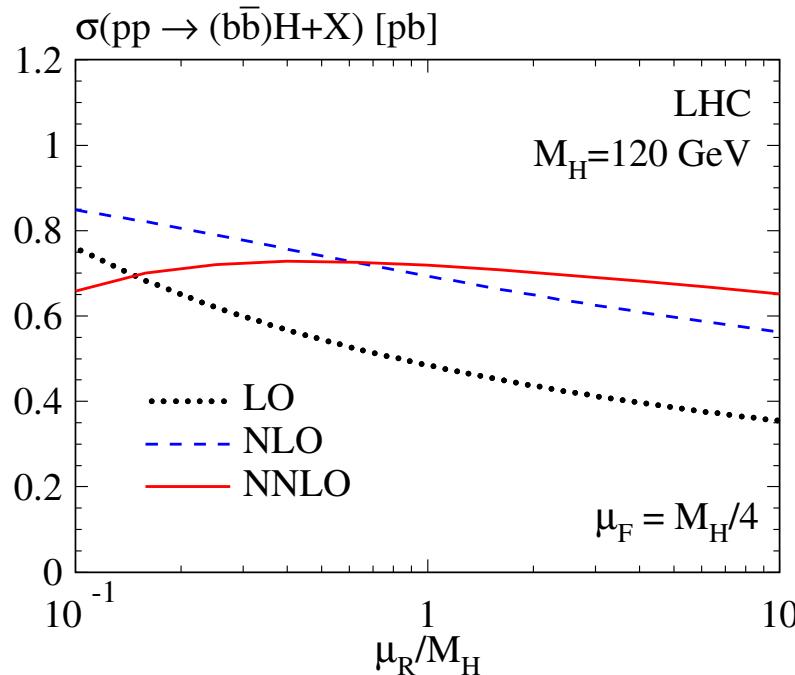
Scale Dependence:

- fact. scale  $\mu_F$  dependence of PDFs
- ren. scale  $\mu_R$  dependence of running  $m_b$  and  $\alpha_s$

# Status of the calculation

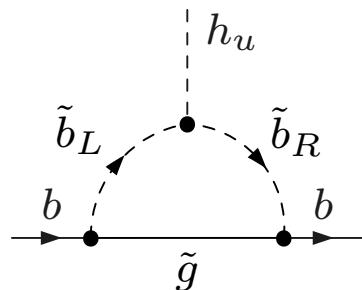
Scale Dependence:

- fact. scale  $\mu_F$  dependence of PDFs
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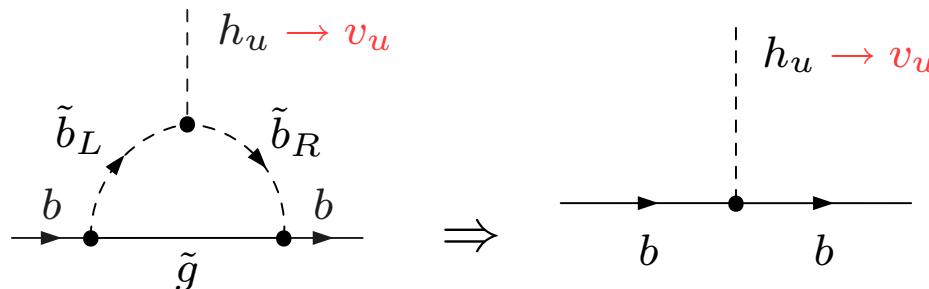


Harlander and Kilgore, Phys.Rev. D68 (2003) 013001

effective  $b\bar{b}H_u$  coupling:

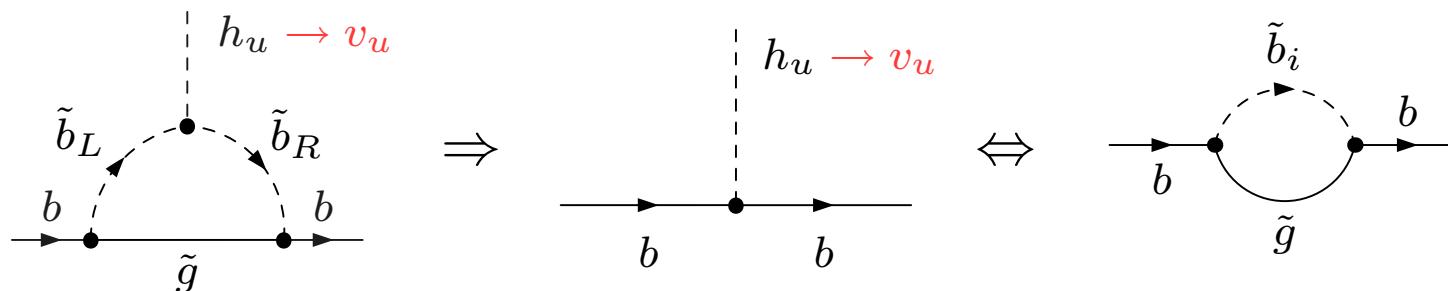


effective  $b\bar{b}H_u$  coupling:



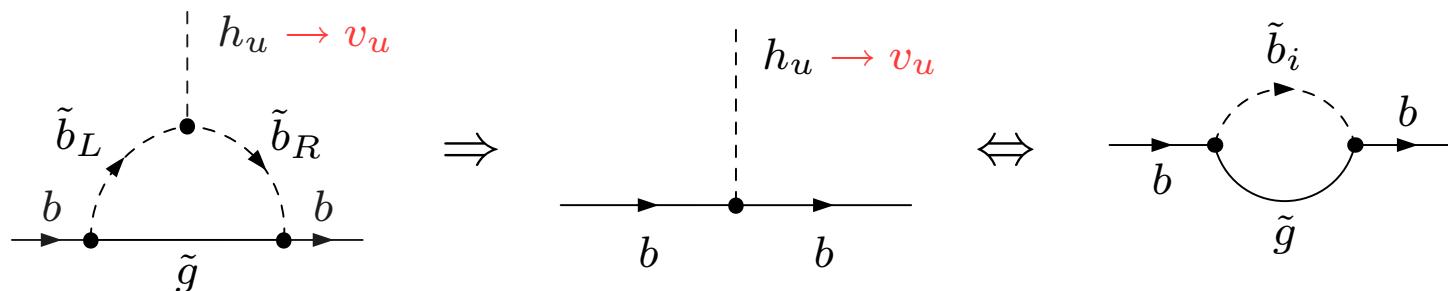
effective field theory:  $m_b \rightarrow m_b(1 + \Delta_b)$   
with  $\Delta_b \propto \tan \beta$

effective  $b\bar{b}H_u$  coupling:



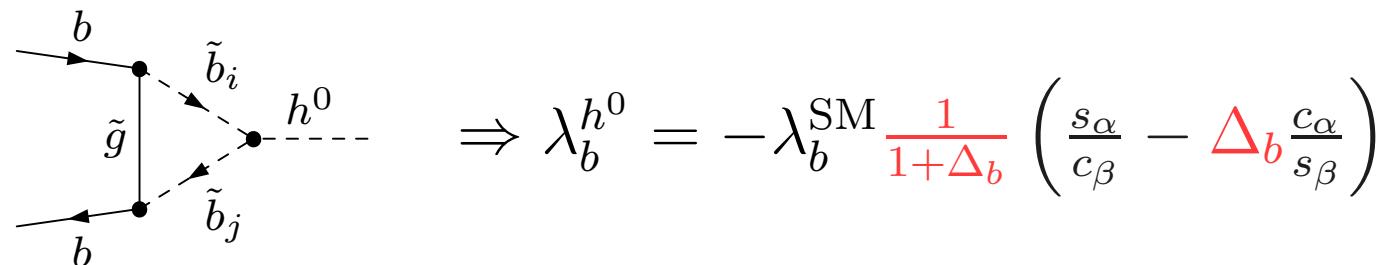
effective field theory:  $m_b \rightarrow m_b(1 + \Delta_b)$

effective  $b\bar{b}H_u$  coupling:



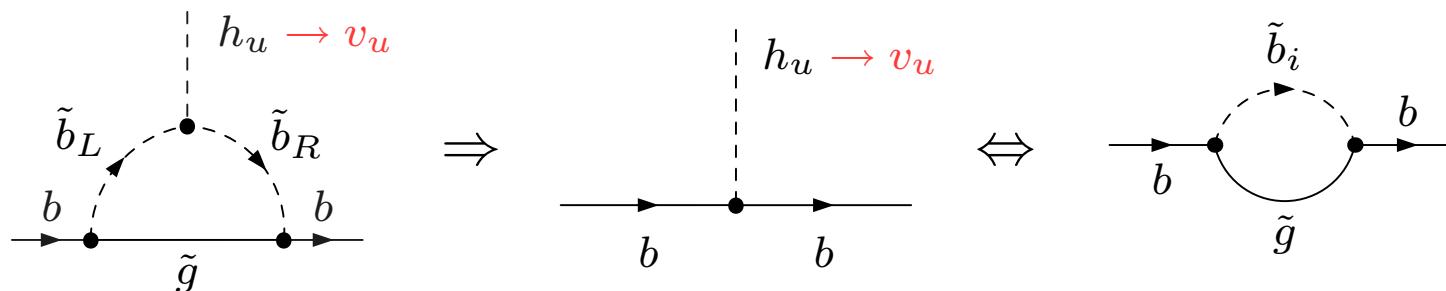
effective field theory:  $m_b \rightarrow m_b(1 + \Delta_b)$

effective vertex correction:



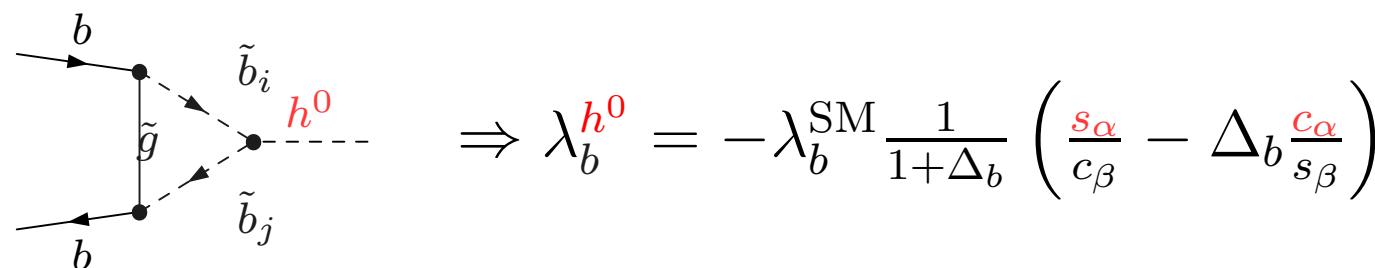
$\Leftarrow | \longleftrightarrow | \Rightarrow$

effective  $b\bar{b}H_u$  coupling:



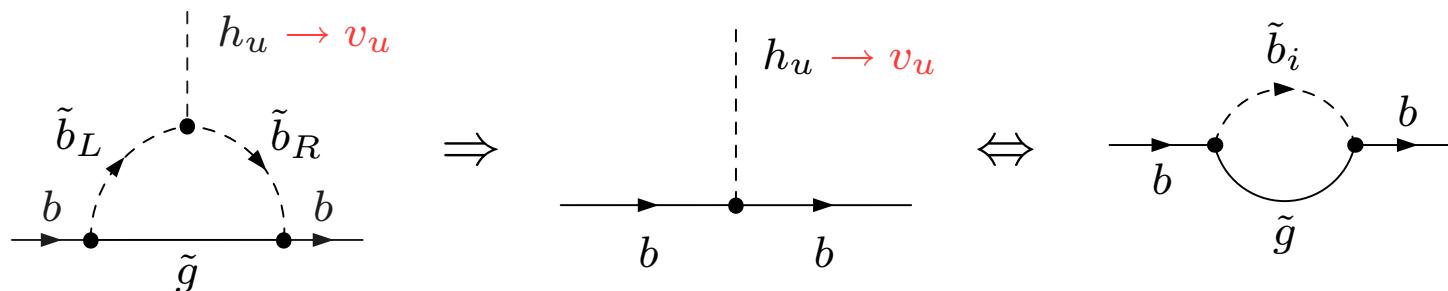
effective field theory:  $m_b \rightarrow m_b(1 + \Delta_b)$

effective vertex correction:



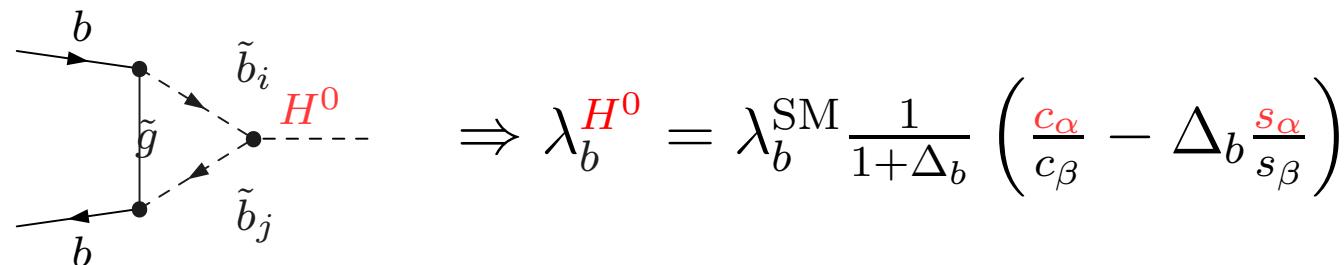
$\Leftarrow | \longleftrightarrow | \Rightarrow$

effective  $b\bar{b}H_u$  coupling:



effective field theory:  $m_b \rightarrow m_b(1 + \Delta_b)$

effective vertex correction:



$\Leftarrow | \longleftrightarrow | \Rightarrow$

# effective mixing angle

definition:  $\alpha_{\text{eff}} = \alpha + \delta\alpha$

$$\begin{pmatrix} m_{h^0}^2 - \hat{\Sigma}_{h^0}(m_{h^0}^2) & -\hat{\Sigma}_{h^0 H^0}((m_{h^0}^2 + m_{H^0}^2)/2) \\ -\hat{\Sigma}_{h^0 H^0}((m_{h^0}^2 + m_{H^0}^2)/2) & m_{H^0}^2 - \hat{\Sigma}_{H^0}(m_{H^0}^2) \end{pmatrix} \xrightarrow{\delta\alpha} \begin{pmatrix} M_{h^0}^2 & 0 \\ 0 & M_{H^0}^2 \end{pmatrix}$$

alternative definition:

$$\begin{pmatrix} m_{h^0}^2 - \hat{\Sigma}_{h^0}(p^2 = 0) & -\hat{\Sigma}_{h^0 H^0}(p^2 = 0) \\ -\hat{\Sigma}_{h^0 H^0}(p^2 = 0) & m_{H^0}^2 - \hat{\Sigma}_{H^0}(p^2 = 0) \end{pmatrix} \xrightarrow{\delta\alpha} \begin{pmatrix} M_{h^0}^2 & 0 \\ 0 & M_{H^0}^2 \end{pmatrix}$$

# results for SPS 1b

- $t_\beta = 30$ ,  $M_{h^0} = 117.67 \text{ GeV}$ ,  $M_{H^0} = 525.69 \text{ GeV}$ ,  $M_{A^0} = 525.66 \text{ GeV}$

	$h^0$		$H^0$		$A^0$	
	$m_b[\text{GeV}]$	$\sigma[\text{pb}]$	$m_b[\text{GeV}]$	$\sigma[\text{pb}]$	$m_b[\text{GeV}]$	$\sigma[\text{pb}]$
QCD	2.79	0.85	2.50	2.64	2.50	2.64
+QED	2.79	0.84	2.50	2.63	2.50	2.63
$+\Delta_b^{\tilde{g}}$	2.76	0.83	2.08	1.82	2.08	1.82
$+\Delta_b^{\text{weak}}$	2.77	0.83	2.30	2.24	2.30	2.24
$+\sin(\alpha_{eff})$	2.77	0.80	2.30	2.24	2.30	2.24
full calculation	2.77	0.81	2.30	2.23	2.30	2.23

# results for SPS 1b

- $t_\beta = 30$ ,  $M_{h^0} = 117.67 \text{ GeV}$ ,  $M_{H^0} = 525.69 \text{ GeV}$ ,  $M_{A^0} = 525.66 \text{ GeV}$

	h <sup>0</sup>		H <sup>0</sup>		A <sup>0</sup>	
	$m_b[\text{GeV}]$	$\sigma[\text{pb}]$	$m_b[\text{GeV}]$	$\sigma[\text{pb}]$	$m_b[\text{GeV}]$	$\sigma[\text{pb}]$
QCD	2.79	0.85	2.50	2.64	2.50	2.64
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full calculation	2.77	0.81	2.30	2.23	2.30	2.23

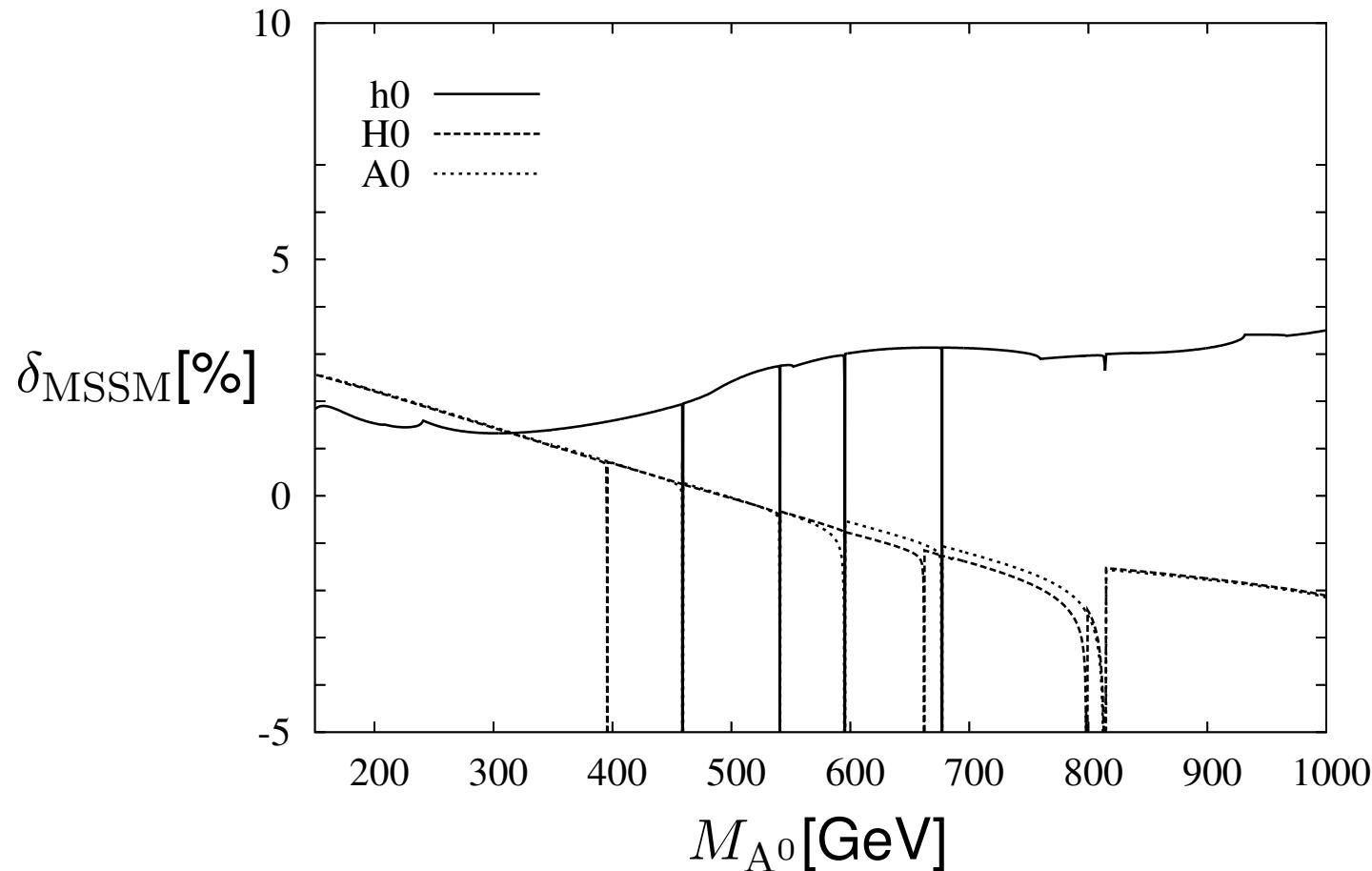
# results for SPS 1b

- $t_\beta = 30$ ,  $M_{h^0} = 117.67 \text{ GeV}$ ,  $M_{H^0} = 525.69 \text{ GeV}$ ,  $M_{A^0} = 525.66 \text{ GeV}$

	h <sup>0</sup>		H <sup>0</sup>		A <sup>0</sup>	
	$m_b[\text{GeV}]$	$\sigma[\text{pb}]$	$m_b[\text{GeV}]$	$\sigma[\text{pb}]$	$m_b[\text{GeV}]$	$\sigma[\text{pb}]$
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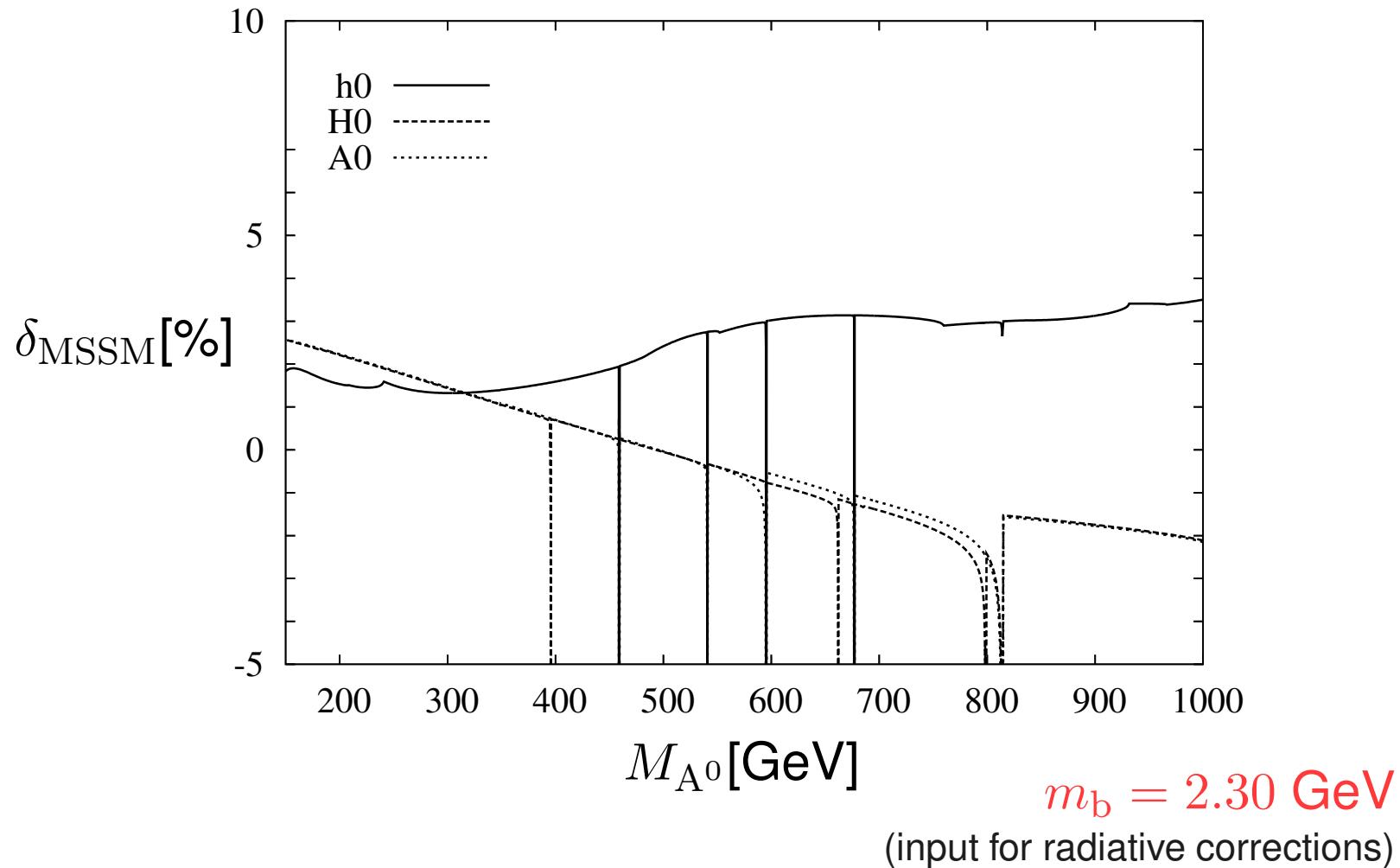
# results for SPS 1b

- correction  $\delta_{\text{MSSM}}$  beyond improved born approximation



# results for SPS 1b

- correction  $\delta_{\text{MSSM}}$  beyond improved born approximation



# results for SPS 4

- correction  $\delta_{\text{MSSM}}$  beyond improved born approximation  
(alternative definition of  $\sin \alpha_{\text{eff}}$ )

