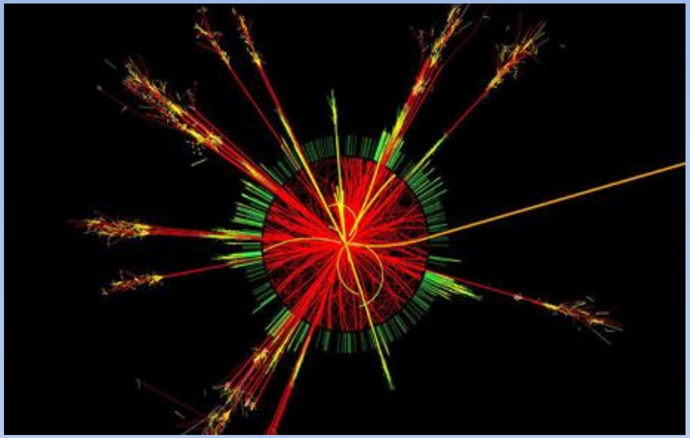

Associated H+W production in NMSSM

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Based on:

R. Enberg, RP, O. Stål,
PRD85, 075016 (2012)

Charged Higgs 2012, Uppsala
October 10th, 2012

I will talk about...

- Higgs sector in Next-to-MSSM
- Leading-order associated H+W production
- Improved Born Approximation
- Parton level results
- Hadron level results
- Conclusions

Motivation to go for Next-to-MSSM

1. **NMSSM provides an elegant solution to the μ-problem of the MSSM via the introduction of a singlet superfield**

$$W_{\text{NMSSM}} = W_{\text{MSSM}} + \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{\kappa}{3}\hat{S}^3 \qquad \mu_{\text{eff}} = \lambda s \qquad s = \langle S \rangle \qquad \tan\beta = v_u/v_d$$

2. **It also resolves the fine-tuning, little hierarchy, electroweak baryogenesis problems of MSSM**

3. **The electroweak scale originates from the SUSY breaking scale only**

4. **NMSSM preserves all the advantages of the MSSM (DM, unification, EWSB due to the Renormalisation Group evolution etc)**

Soft SUSY breaking terms:

$$V_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + \left[\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + \text{h.c.}\right]$$

U. Ellwanger, C. Hugonie, and A. M. Teixeira, Phys. Rept. **496**, 1 (2010)

Higgs sector in the NMSSM

1. **Higgs sector parameters:**

$$\lambda, \kappa, A_\lambda, A_\kappa, s, \quad \textbf{and} \quad \tan\beta$$

2. **Singlet field is complex: two additional Higgs bosons!**

$$\text{CP-even neutral states } H_1, H_2, H_3$$
$$\text{CP-odd neutral states } A_1 \text{ and } A_2$$

Lightest!

and two charged Higgses: $H^\pm$

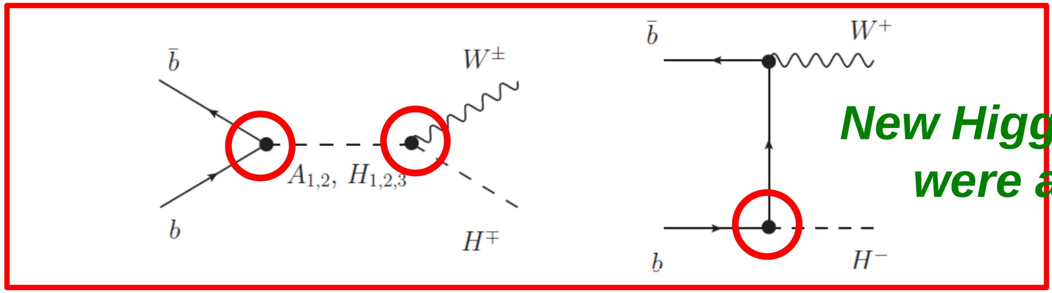
3. **Tree-level charged Higgs masses:**

NMSSM: $m^2_{H^\pm} = \dfrac{2\mu_{\text{eff}}}{\sin 2\beta}(A_\lambda + \kappa s) + m^2_W - \lambda^2 v^2$ MSSM: $m^2_{H^\pm} = m^2_A + m^2_W$

For higher order corrections to Higgs masses, couplings, mixing and decay widths NMSSMTools (v 2.3.5) was used!

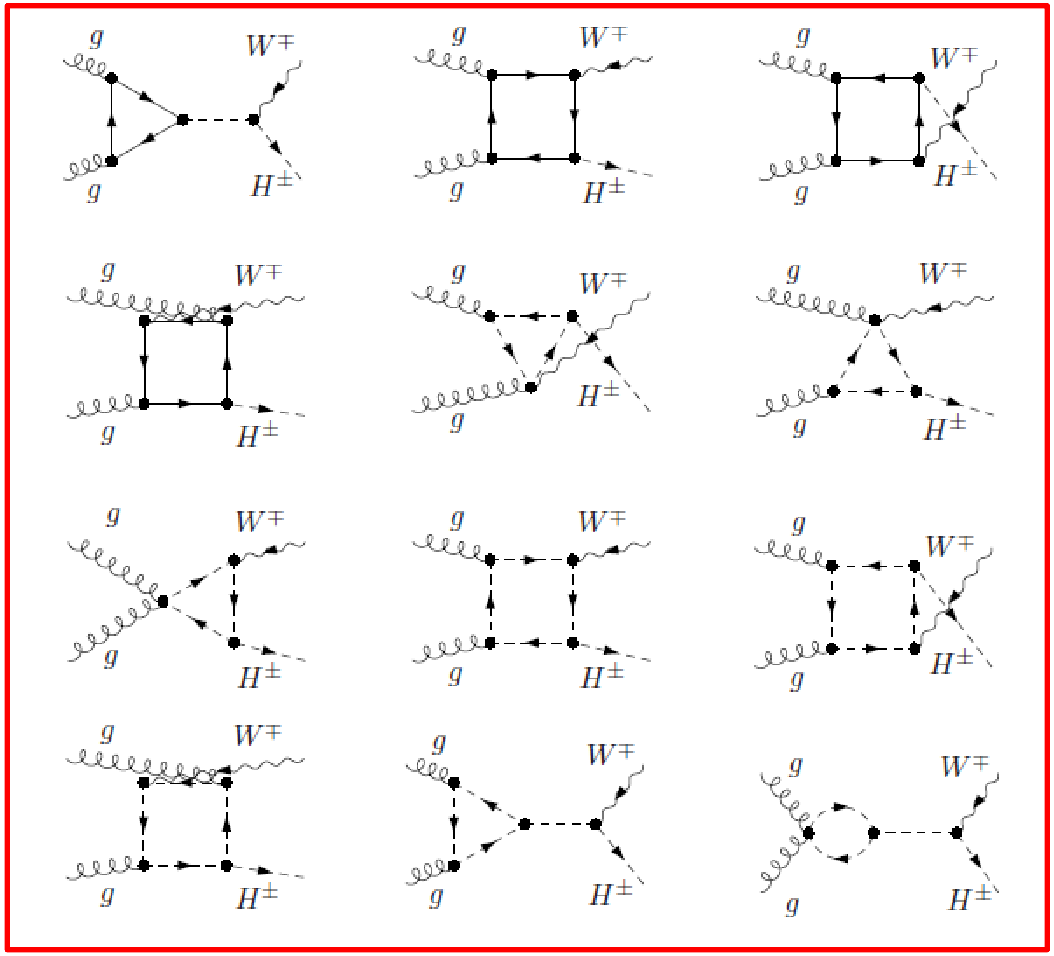
Leading-order H+W production: diagrams

$b\bar{b} \to H^{\pm}W^{\mp}$



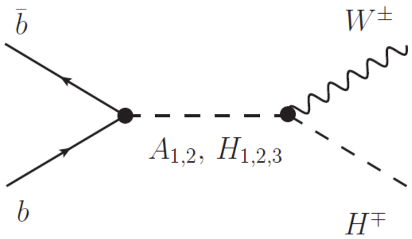
New Higgs fields/couplings were added/modified

$gg \to H^{\pm}W^{\mp}$



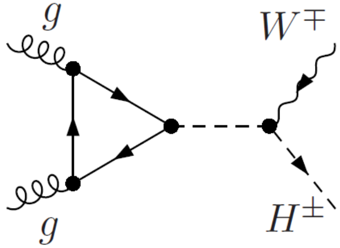
FeynArts, FormCalc, LoopTools were used!

Resonant contributions: analytics



$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}(b\bar{b} \to H^+W^-) = \frac{G_F^2}{24\pi\hat{s}}\frac{m_b^2}{2}\lambda(\hat{s}, m_W^2, m_{H^\pm}^2)\left(|\mathcal{S}_b(\hat{s})|^2 + |\mathcal{P}_b(\hat{s})|^2\right)$$

…suppressed, but can be noticeable!



$$\frac{\mathrm{d}\hat{\sigma}^{\Delta}}{\mathrm{d}\hat{t}}(gg \to H^+W^-) = \frac{\alpha_s^2(\mu_R)G_F^2}{2048\pi^3}\lambda(\hat{s}, m_W^2, m_{H^\pm}^2)\left(|\Sigma(\hat{s})|^2 + |\Pi(\hat{s})|^2\right)$$

A. Barrientos Bendezu and B. A. Kniehl, Phys. Rev. D **59**, 015009 (1999)

$$\Sigma(\hat{s}) = \sum_q \mathcal{S}_q(\hat{s}) S\left(\frac{\hat{s} + \mathrm{i}\epsilon}{4m_q^2}\right)$$

$$\Pi(\hat{s}) = \sum_q \mathcal{P}_q(\hat{s}) P\left(\frac{\hat{s} + \mathrm{i}\epsilon}{4m_q^2}\right)$$

Modifications MSSM → NMSSM

$$H_j^{\mathrm{weak}} = (\mathrm{Re}\, H_d,\ \mathrm{Re}\, H_u,\ \mathrm{Re}\, S)$$

$$H_i^{\mathrm{mass}} = S_{ij} H_j^{weak}$$

$$A_j^{\mathrm{weak}} = (\mathrm{Im}\, H_d,\ \mathrm{Im}\, H_u,\ \mathrm{Im}\, S)$$

$$A_i^{\mathrm{mass}} = P_{ij} A_j^{\mathrm{weak}}$$

$$\mathcal{S}_t(\hat{s}) = \frac{1}{\sin\beta}\sum_{i=1,2,3}\frac{S_{i2}\left(S_{i2}\cos\beta - S_{i1}\sin\beta\right)}{\hat{s} - m_{H_i}^2 + \mathrm{i}m_{H_i}\Gamma_{H_i}},$$

$$\mathcal{S}_b(\hat{s}) = \frac{1}{\cos\beta}\sum_{i=1,2,3}\frac{S_{i1}\left(S_{i2}\cos\beta - S_{i1}\sin\beta\right)}{\hat{s} - m_{H_i}^2 + \mathrm{i}m_{H_i}\Gamma_{H_i}},$$

$$\mathcal{P}_t(\hat{s}) = \frac{1}{\sin\beta}\sum_{i=1,2}\frac{P_{i2}\left(P_{i2}\cos\beta - P_{i1}\sin\beta\right)}{\hat{s} - m_{A_i}^2 + \mathrm{i}m_{A_i}\Gamma_{A_i}},$$

$$\mathcal{P}_b(\hat{s}) = -\frac{1}{\cos\beta}\sum_{i=1,2}\frac{P_{i1}\left(P_{i2}\cos\beta - P_{i1}\sin\beta\right)}{\hat{s} - m_{A_i}^2 + \mathrm{i}m_{A_i}\Gamma_{A_i}},$$

Improved Born approximation

1. **Largest SUSY [QCD + EW] corrections to the bottom Yukawa:**

$$\lambda^{\rm eff}_{b\bar{b}H_i} = -{\rm i}\frac{m_b^{\overline{\rm DR}}}{\sqrt{2}\,v\cos\beta}\frac{S_{i1}}{1+\Delta_b}\left(1+\Delta_b\frac{S_{i2}}{S_{i1}\tan\beta}\right), \quad i=1,2,3$$

$$\lambda^{\rm eff}_{b\bar{b}A_k} = \frac{m_b^{\overline{\rm DR}}}{\sqrt{2}\,v\cos\beta}\frac{P_{k1}}{1+\Delta_b}\left(1+\Delta_b\frac{P_{i2}}{P_{i1}\tan\beta}\right), \quad k=1,2$$

$$m_b^{\overline{\rm DR}}(\mu_R) = m_b^{\overline{\rm MS}}(\mu_R)\left[1-\frac{\alpha_s}{3\pi}-\frac{\alpha_s^2}{144\pi^2}(73-3n)\right]$$

running (two-loop) b-mass

Generalization of MSSM results

$$\Delta_b = \Delta_b^{\rm SQCD} + \Delta_b^{\rm SEW} \qquad \Delta_b^{\rm SEW} \simeq \Delta_b^{\tilde{H}\tilde{t}}$$

$$\Delta_b^{\rm SQCD} = \frac{2\alpha_s(Q)}{3\pi} m_{\tilde{g}}\,\mu_{\rm eff}\tan\beta\, I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}}), \quad Q=(m_{\tilde{b}_1}+m_{\tilde{b}_2}+m_{\tilde{g}})/3,$$

$$\Delta_b^{\tilde{H}\tilde{t}} = \frac{m_t^2}{16\pi^2 v^2\sin^2\beta} A_t\,\mu_{\rm eff}\tan\beta\, I(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}, |\mu_{\rm eff}|^2),$$

$$I(a,b,c) = -\frac{1}{(a-b)(b-c)(c-a)}\left(ab\ln\frac{a}{b}+bc\ln\frac{b}{c}+ca\ln\frac{c}{a}\right)$$

2. **+ HO corrections to the Higgs masses, widths, running b-mass**

M. S. Carena, S. Mrenna, and C. Wagner, Phys. Rev. D **60**, 075010 (1999)

Parameters set-up: benchmark scenarios

"Maximal mixing" benchmark (analogous to MSSM):

$$M_{SUSY} = 1\ \text{TeV}, \quad X_t^{\overline{DR}} \equiv A_t - \mu_{eff} \cot\beta = \sqrt{6} M_{SUSY}, \quad A_b = A_\tau = A_t$$
$$\mu_{eff} = 250\ \text{GeV}, \quad M_1 = 100\ \text{GeV}, \quad M_2 = 200\ \text{GeV}, \quad M_3 = 1\ \text{TeV}$$

so we vary only Higgs sector parameters!

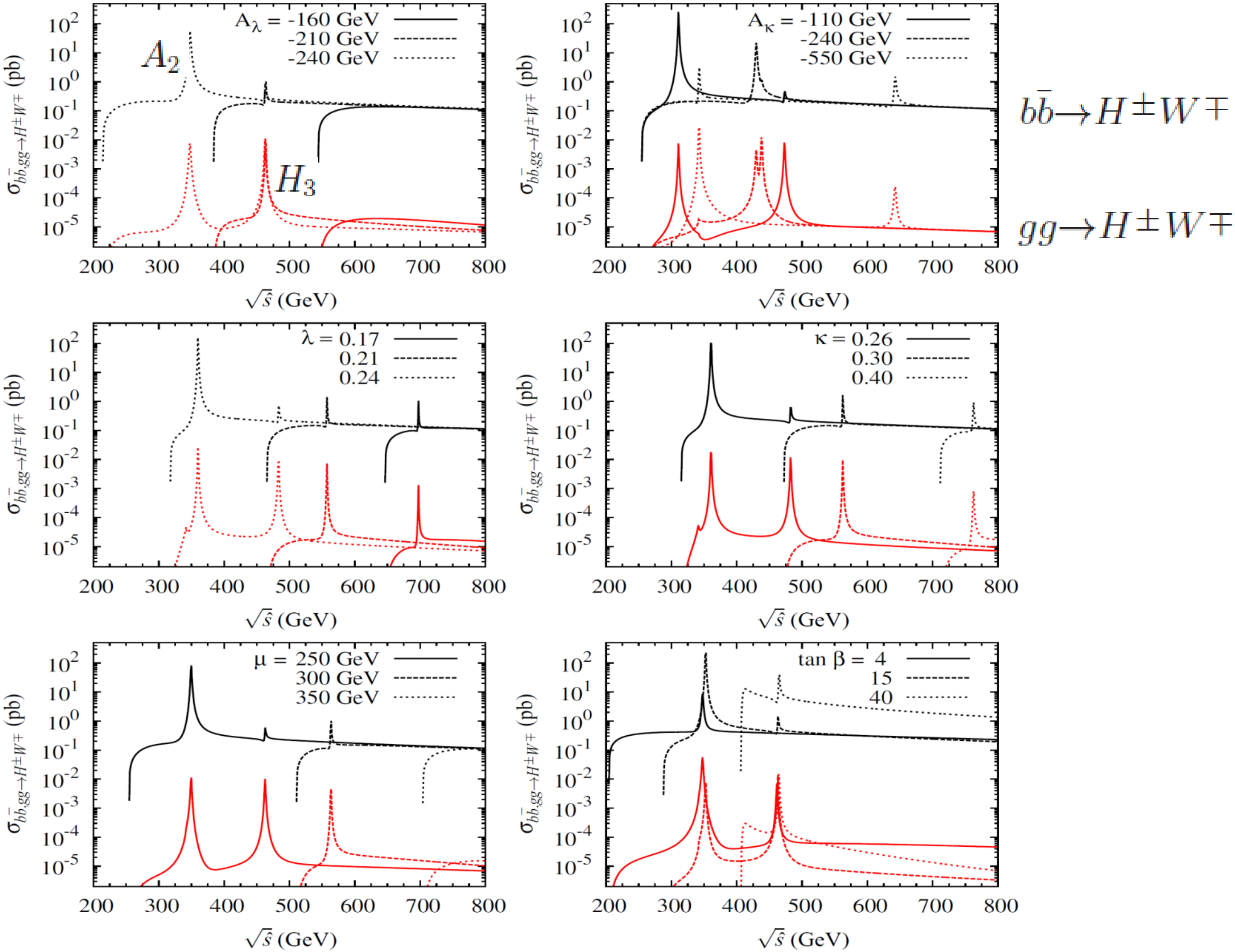
Five different benchmark scenarios:

Parameter	Scenario A	B	C	D	E
A_λ (GeV)	−235	−235	−235	−185	−243
A_κ (GeV)	−150	−250	−400	−150	−150
λ	0.25	0.25	0.25	0.5	0.25
κ	0.25	0.25	0.25	0.5	0.25
$\tan\beta$	10	10	10	2.2	40
Higgs mass spectrum (GeV)					
$m_{H^\pm}$	174.3	174.3	174.3	195.3	171.7
m_{H_1}	118.4	117.4	115.0	114.6	120.3
m_{H_2}	173.5	174.1	174.3	203.6	246.0
m_{H_3}	462.6	435.3	391.1	459.6	463.3
m_{A_1}	139.0	156.4	165.4	92.0	213.2
m_{A_2}	349.3	438.2	549.2	383.4	355.7

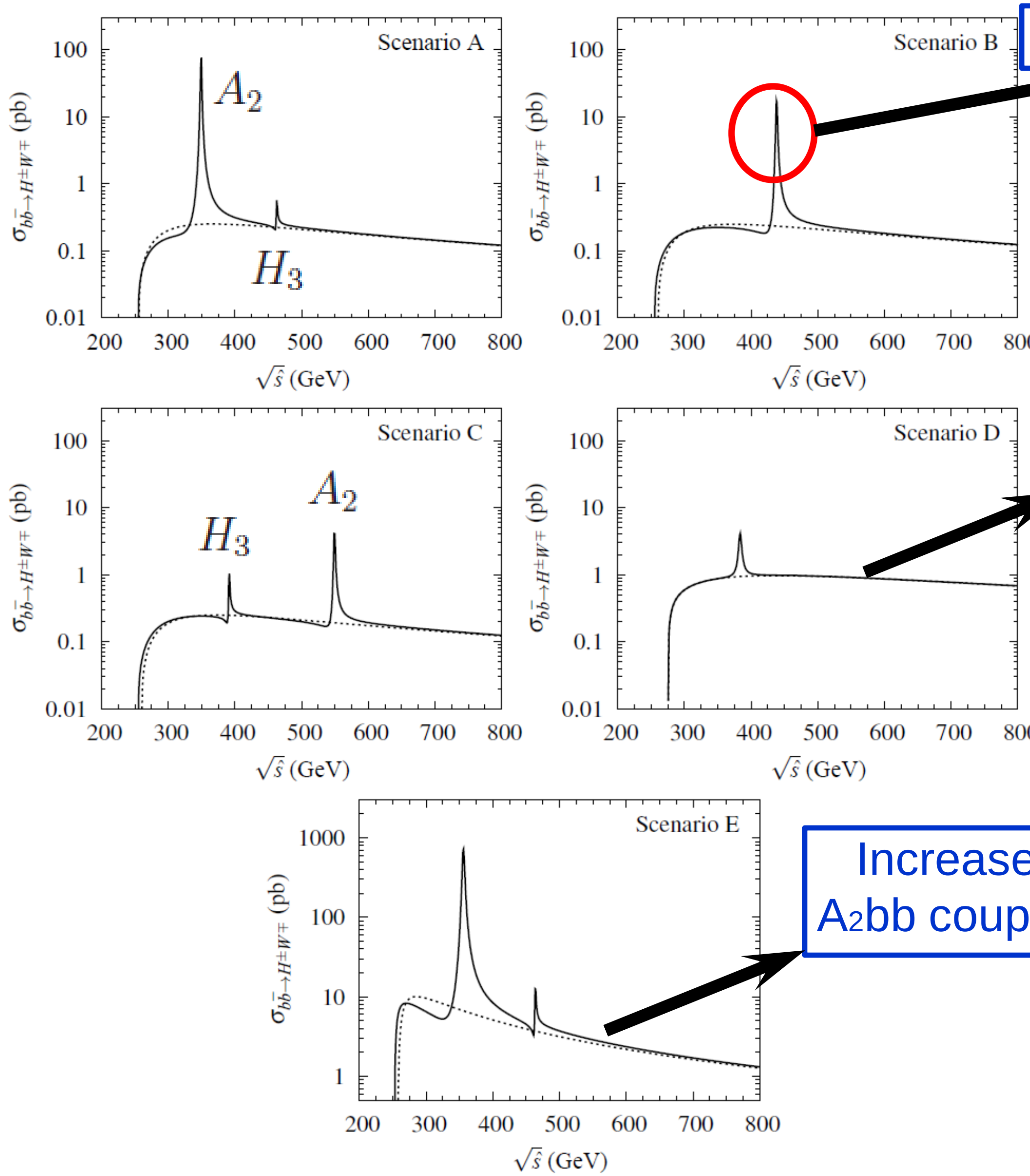
noticeable sensitivity of results to the parameters set-up!

dominated by mixing with singlet field!

NMSSM parameter dependence



NMSSM vs MSSM: bottom contribution

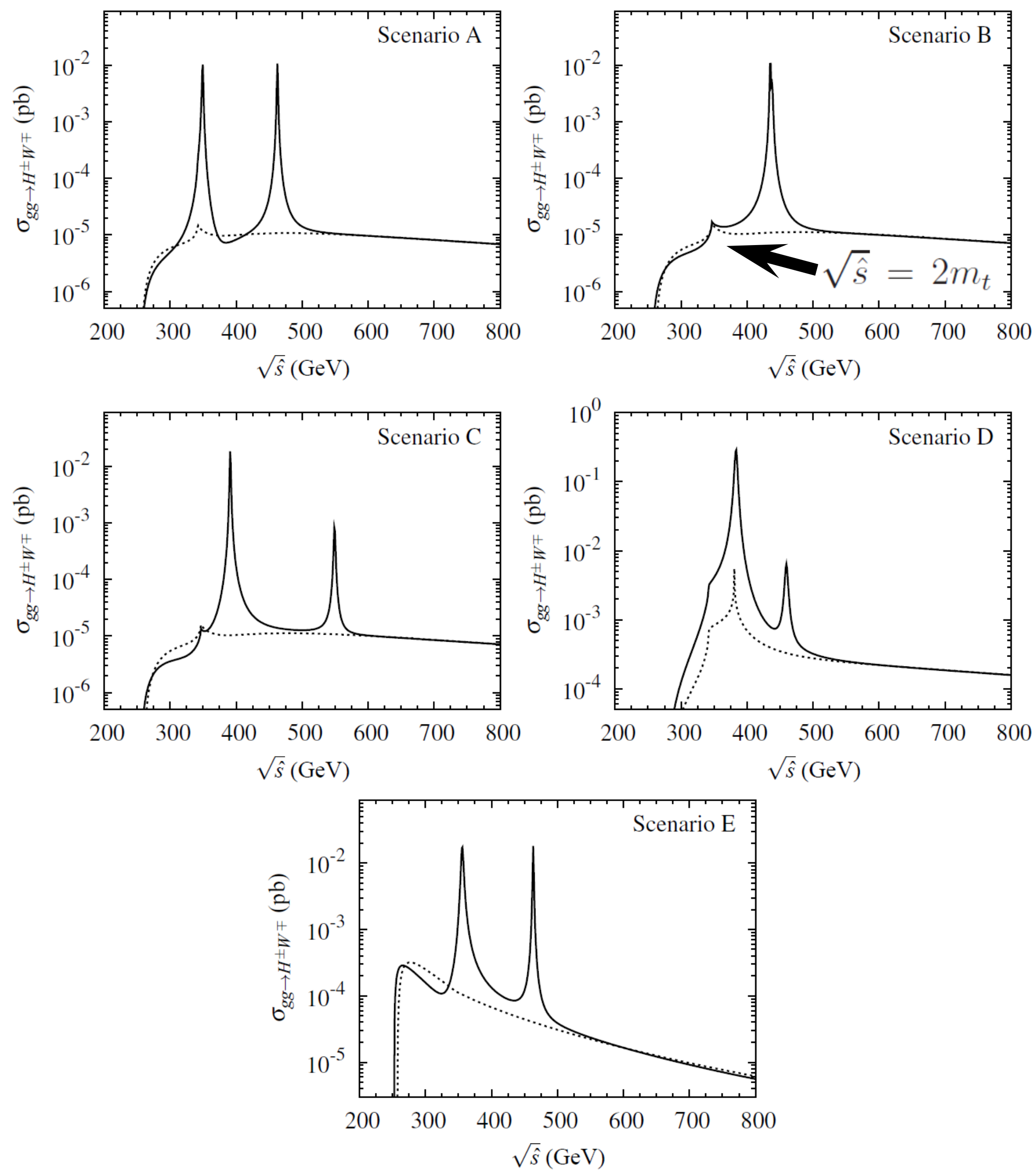


two peaks collided!

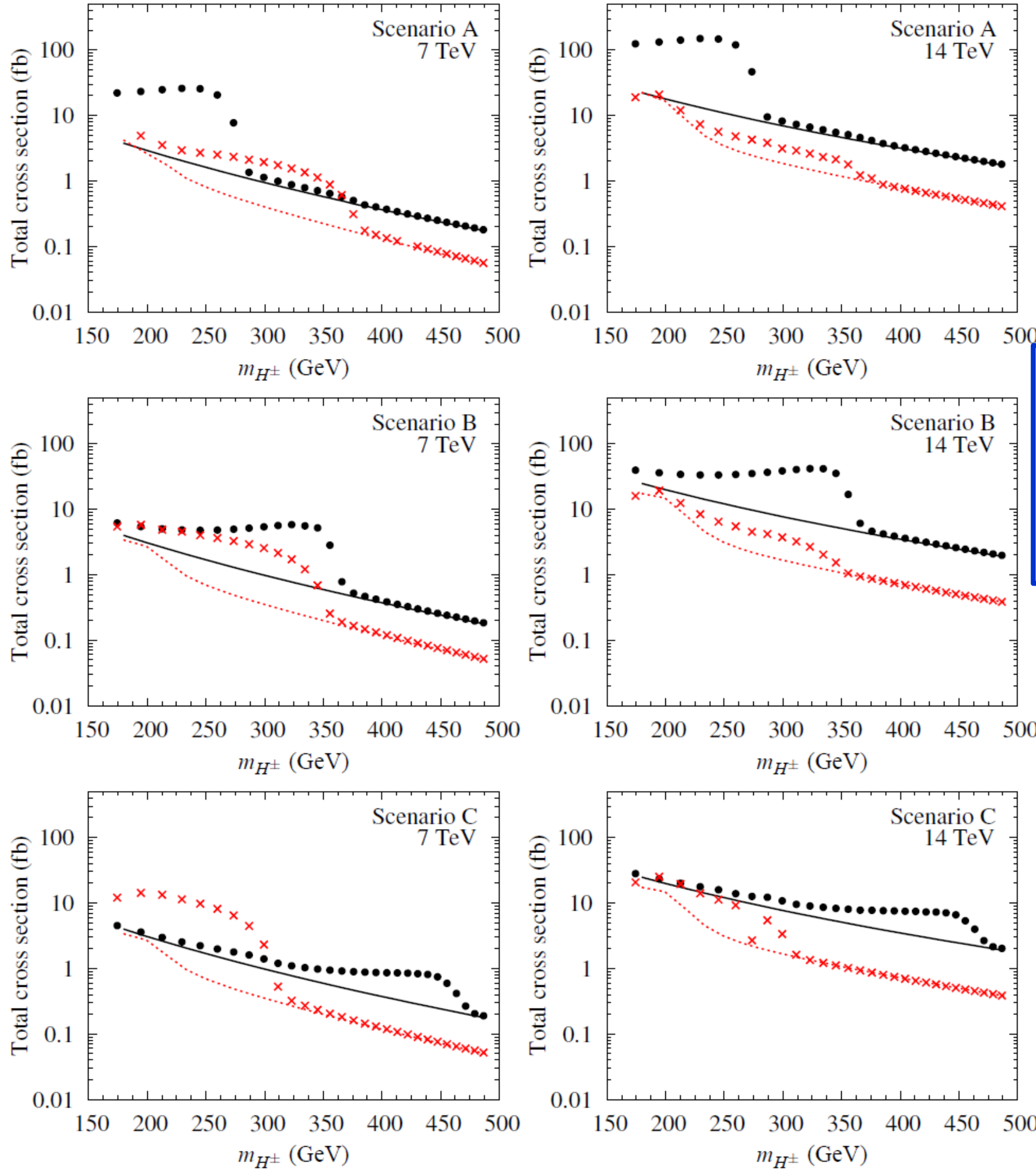
Increased t-channel non-resonant part (at low tanb)

Increased due to larger A_2bb coupling at large tanb

NMSSM vs MSSM: gluon contribution



Collider phenomenology: hadronic CS



interference effects between resonant and non-resonant (boxes) are important!

Conclusions and Outlook

- We studied associated (heavy, $m_{H^\pm} > m_t$) charged Higgs production at the LHC in a general NMSSM setting.
- Complete LO (bb + gg) results in an improved Born approximation for five different scenarios were obtained.
- We found a significant (up to an order of magnitude) resonant enhancement of the cross section due to the presence of new heavy singlet-dominated Higgs bosons compared to MSSM results.
- This analysis provides a significant discrimination power between MSSM and NMSSM
- More detailed Monte-Carlo study with exact decay kinematics and parton showers which gives a noticeable impact on interplay between resonant and non-resonant contributions and is strongly needed.