Higgs Factory Physics

CP conserving part

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Outline

- Introduction
- h_{SM} and h^0 resonances
  - resonance cross section
  - high precision measurements
  - radiative corrections
  - beam polarization
- Heavy scalar resonances (H^0 and A^0)
  - widths and branching ratios
  - telling H^0 from A^0
  - overlapping resonances
- Charged Higgs bosons
- Conclusions

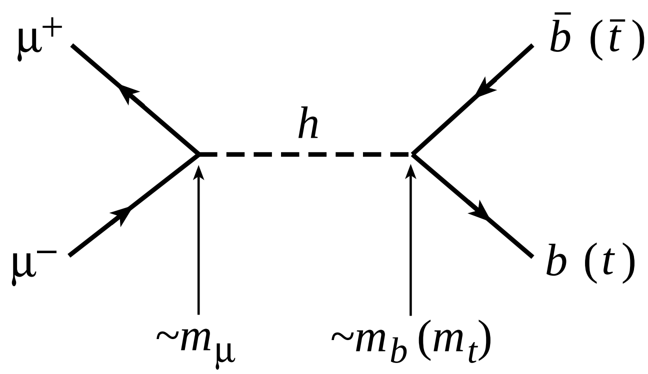
Motivation

One of the key issues of future HEP experiments will be to pin down the exact mechanism of EWSM.

If the Higgs mechanism is Nature's choice one will want to determine masses, couplings, branching ratios, spin–0 character, CP–nature etc of (all) the Higgs boson(s) with high precision.

If there is more than one Higgs one needs to disentangle all the mass eigenstates and determine their properties.

A $\mu^+\mu^-$ collider can essentially do all the physics that an e^+e^- collider of the same energy and luminosity can do. In addition:



Unique feature of the μC:
Higgs production in the s–channel!

The SM and MSSM Higgs bosons

SM: 1 Higgs doublett $\to$ 1 physical Higgs boson

If $m_h < 2\,m_W$ then $\Gamma^{\rm tot} \lesssim 10$ MeV and the dominant decay mode is $h_{SM} \to b\bar{b}$

MSSM: 2 doubletts $\to$ 5 physical Higgs bosons

2 CP–even neutral scalars	h^0, H^0
1 CP–odd neutral scalar	A^0
2 charged scalars	$H^\pm$

Parameters: $\tan\beta$ and m_A

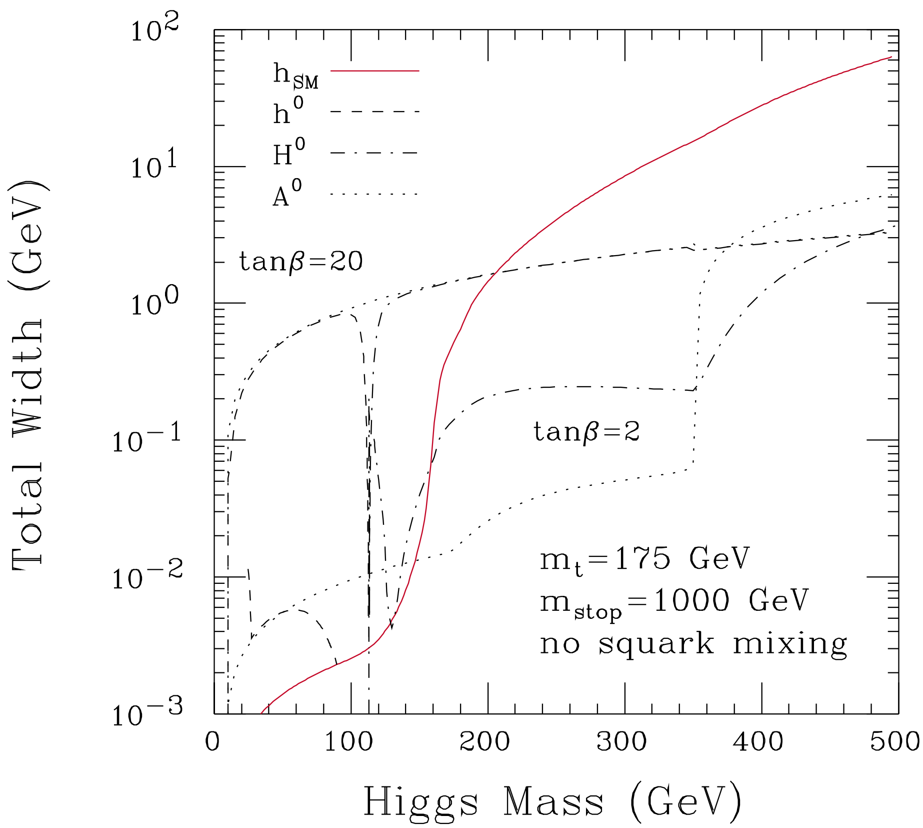
$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$$

	t	b, τ	W, Z
h^0	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
H^0	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
A^0	$-i\gamma_5\cot\beta$	$-i\gamma_5\tan\beta$	0

Theoretical bound: $m_{h^0} \lesssim 135$ GeV

For small $\tan\beta$ and large m_A, h^0 is SM–like.
For large $\tan\beta$, A^0 and H^0 are degenerate.

Higgs Total Widths



Total width versus mass of the SM and MSSM Higgs bosons. SUSY decays are assumed to be absent.

Note that $\Gamma^{\rm tot} \lesssim 10$ MeV for a SM–like Higgs with $m_h < 2\, m_W$.

[Barger, Berger, Gunion, Han '96]

Resonant Higgs production

The effective cross section at $\sqrt{s} = m_h$ results from convoluting the standard s-channel Breit–Wigner resonance cross section with a Gaussian energy distribution σ_E :

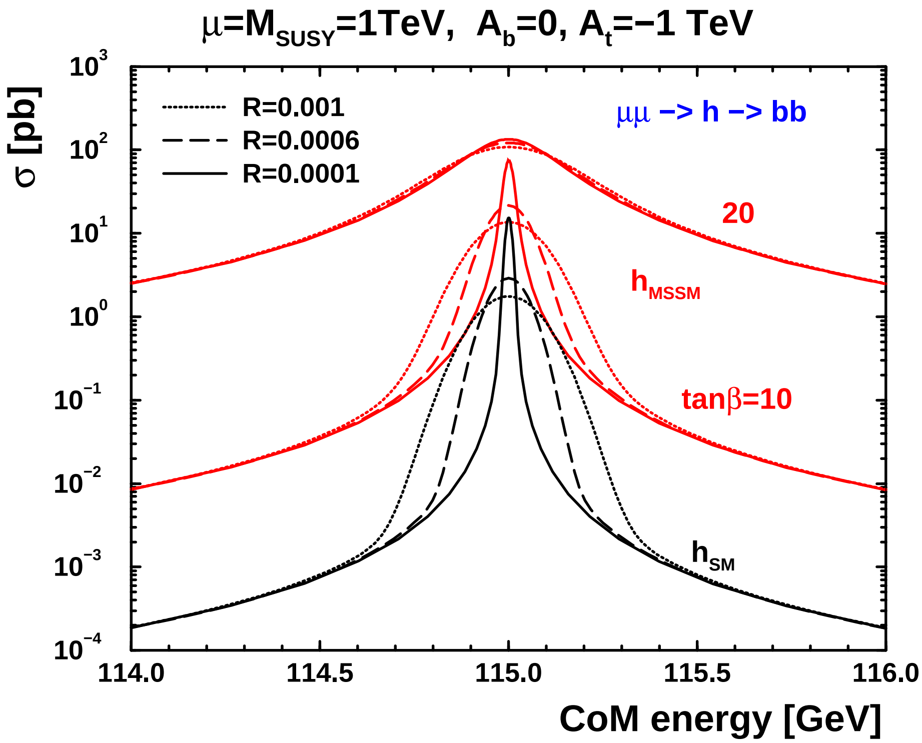
$$\bar{\sigma}_h \simeq \frac{4\pi}{m_h^2} \frac{B(h \to \mu^+\mu^-)\, B(h \to X)}{\left[1 + \frac{8}{\pi}\left(\frac{\sigma_E}{\Gamma_h^{\rm tot}}\right)^2\right]^{1/2}} .$$

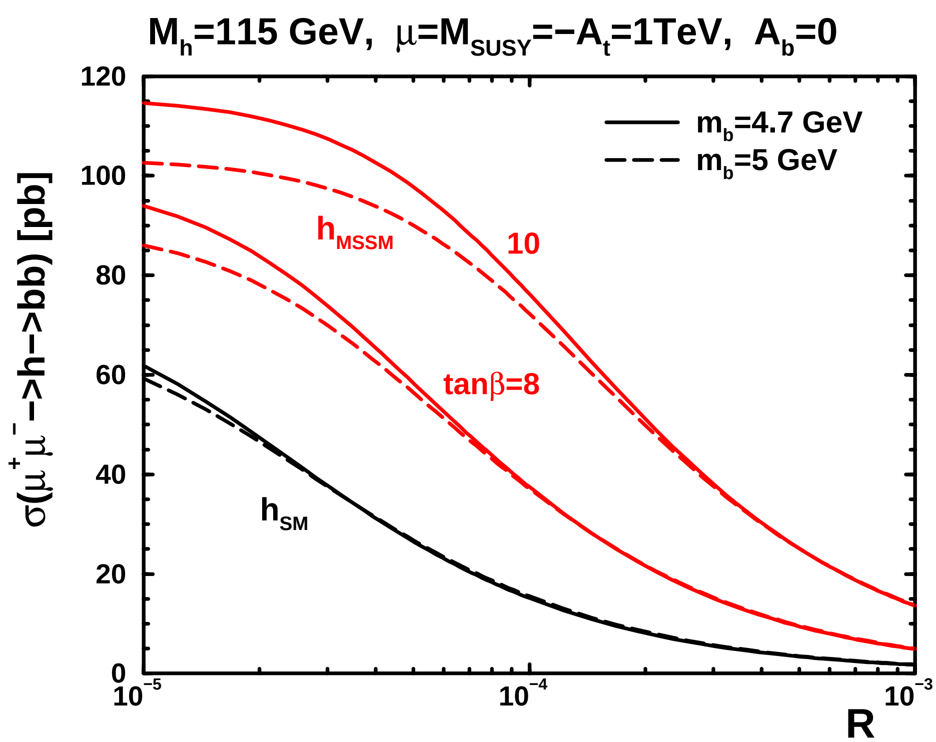
The peak cross section is largest if $\Gamma^{\rm tot}$ is small and $\sigma_E \sim \Gamma^{\rm tot}$. There are two important limits:

$$\sigma_E \ll \Gamma^{\rm tot} \quad \Rightarrow \quad \bar{\sigma}_h = \frac{4\pi\, B(h \to \mu^+\mu^-)\, B(h \to X)}{m_h^2}$$

$$\sigma_E \gg \Gamma^{\rm tot} \quad \Rightarrow \quad \bar{\sigma}_h = \frac{\sqrt{2\pi^3}\, \Gamma(h \to \mu^+\mu^-)\, B(h \to X)}{m_h^2\, \sigma_E}$$

Often the beam energy resolution $R = \sqrt{2}\, \sigma_E / \sqrt{s}$ is used instead of σ_E.


μ=M_SUSY=1TeV, A_b=0, A_t=−1 TeV
σ [pb]
R=0.001
R=0.0006
R=0.0001
μμ −> h −> bb
20
h_MSSM
tanβ=10
h_SM
CoM energy [GeV]


M_h=115 GeV, μ=M_SUSY=−A_t=1TeV, A_b=0
σ(μ+μ− −>h−>bb) [pb]
m_b=4.7 GeV
m_b=5 GeV
h_MSSM
10
tanβ=8
h_SM
R

Determining the properties of the resonance

Once m_h is approximately known, the μC can be run at $\sqrt{s} = m_h$. $\longrightarrow$ Allows to determine $m_h < 2\,m_W$ of a SM–like Higgs to a fraction of MeV.

Scanning: 3–point method

Measuring the ratio of the central peak cross section to the cross sections on the wings of the peak allows to determine $\Gamma_h^{\rm tot}$ to $\mathcal{O}(10\%)$ if $m_h \lesssim 130$ GeV. Requires an excellent energy resolution $(\sigma_E < \Gamma)$.

Varying the beam energy resolution

The ratio of the peak cross sections for two different beam energy resolutions $\sigma_E^{\rm min} \ll \Gamma_h^{\rm tot}$ and $\sigma_E^{\rm max} \gg \Gamma_h^{\rm tot}$ is proportional to $\Gamma_h^{\rm tot}$. Favourable method if $\sigma_E < \Gamma$ leads to loss of $\mathcal{L}$ and/or $m_h \gtrsim 130$ GeV.

Bremsstrahlung tail

If $\sqrt{s} > m_h$ it is possible to search for a peak in the bremsstrahlung tail. This requires a good reconstruction of $\sqrt{s}_{\rm eff}$ from the final state momenta. Useful if m_h not known and essentially independent of R.

[Barger, Berger, Gunion, Han '96]

[Casalbuoni et al. '99]

High precision measurements of m_h, $\Gamma_h^{\rm tot}$ and σ_{peak}

$\Rightarrow$ distinguish between h_{SM} and h^0 of the MSSM

$\Rightarrow$ determine the partial widths and associated couplings for all channels in which the Higgs can be ovserved: $h \to b\bar{b}, \tau^+\tau^-, WW^*, ZZ^*$

$\Rightarrow$ fit $(\tan\beta, m_A)$ with very good precision

[Janot, CERN 99-02]

Need to know theoretical predictions very precisely. Radiative corrections to the MSSM Higgs sector are important! e.g. [Heinemeier, Weiglein], [Carena, Garcia, Nierste, Wagner]

[Eberl, SK, Majerotto, Yamada]

$\star$ $\sin\alpha_{\rm eff} \to 0$: suppression of $\sigma(\mu^+\mu^- \to h^0)$

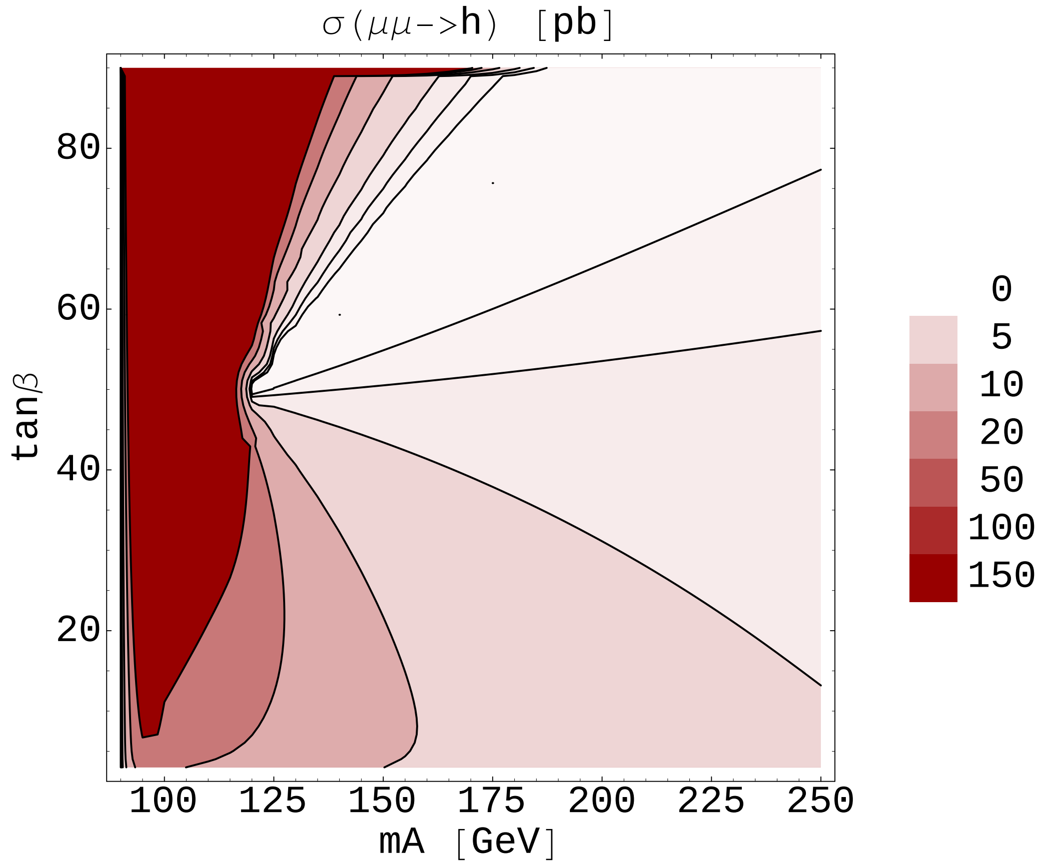
- $\sigma(\mu^+\mu^- \to H^0, A^0)$ $\tan\beta$ enhanced
- $H^0, A^0 \to b\bar{b}, \tau^+\tau^-$ dominate

$\star$ $g_{hbb} \to 0$ due to $\tan\beta$ enhanced SQCD corrections.

- No suppression of $\sigma(\mu^+\mu^- \to h^0)$
- h^0 does not decay into $b\bar{b}$
- $h^0 \to \tau^+\tau^-$ or WW^* observable

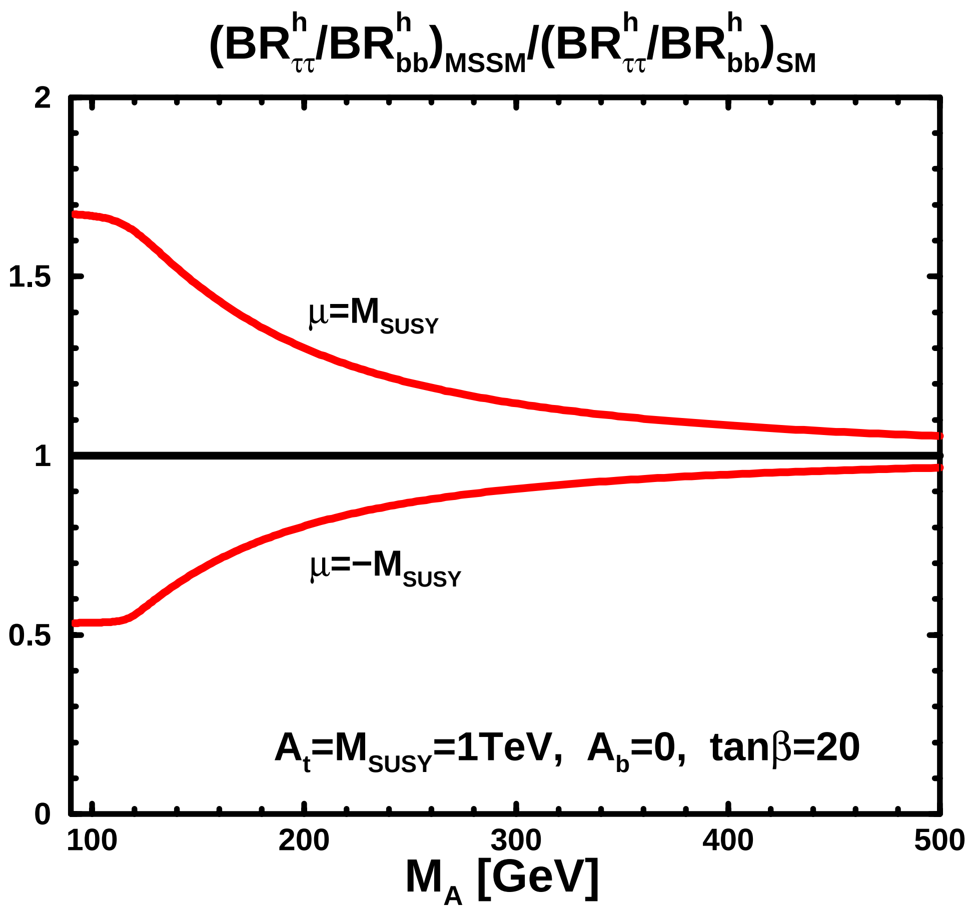
[Carena, Garcia, SK, Wagner, this WS]

[Talk by D. Gracia, 9 May 2000]



$$R = 10^{-4},\ -A_t = \mu = M_{SUSY} = 1\ \text{TeV}$$

[talk by D. Gracia, 9 May 2000]



[talk by D. Gracia, 9 May 2000]

The $\tau^+\tau^-$ signal

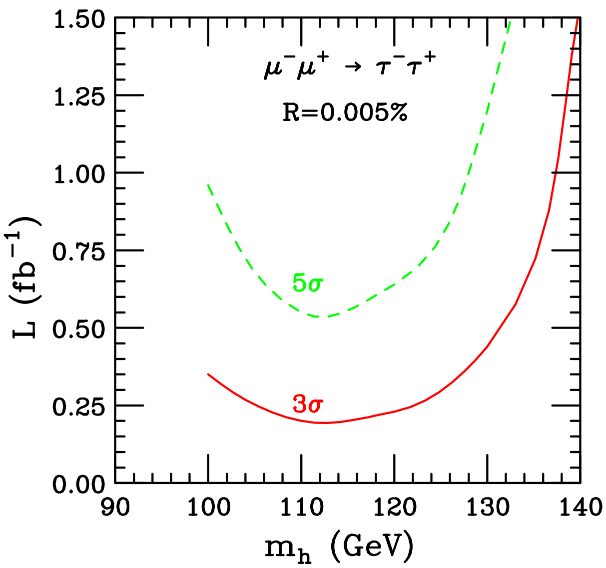
Allows to determine the the relative b and τ Yukawa couplings and to test $b-\tau$ unification of SUSY GUT theories.

Higgs vs. γ/Z exchange

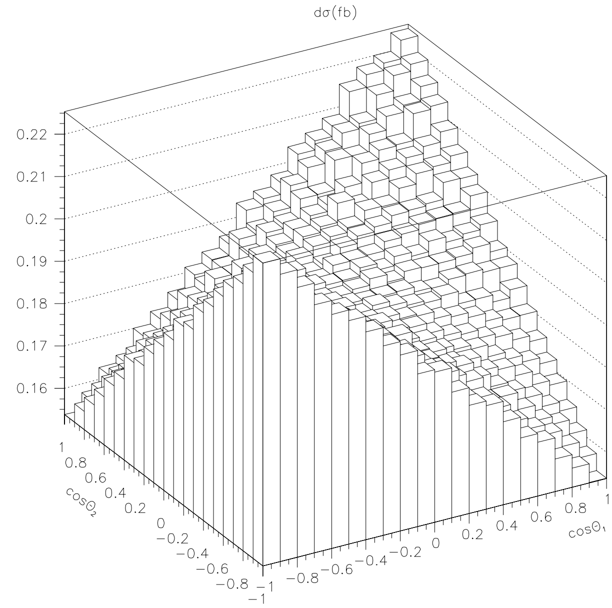
The Higgs exchange populates LL and RR helicity states of $\mu^+\mu^-$ which lead to LL and RR combinations of $\tau^+\tau^-$. The differential cross section is isotropic in phase–space.

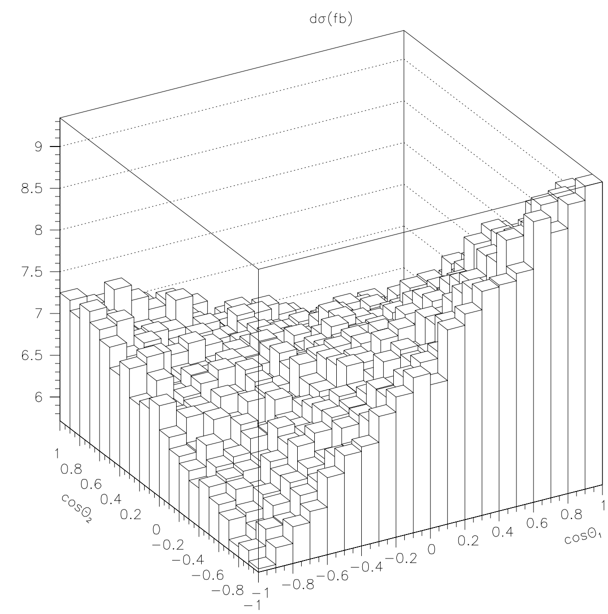
The SM background yields LR and RL combinations of $\tau^+\tau^-$. It shows a characteristic FB asymmetry in the scattering angle and a LR asymetry in beam polarization.

Better beam energy resolution: significant enhancement of the signal for a narrow resonance, negligible effect on background.



[Barger, Han, Zhou '00]





Double differential distributions for $\mu^+\mu^- \rightarrow \tau^+\tau^- \rightarrow \rho^-\nu_\tau\rho^+\bar{\nu}_\tau$. via Higgs exchange (upper fig.) and γ/Z exchange (lower fig.) for $\sqrt{s} = m_h = 120$ GeV and $R = 0.05\%$. Initial $\mu^\mp$ beam polarizations are $P_- = P_+ = 0.25$.

[Barger, Han, Zhou '00]

H^0 and A^0

Prediction of m_A from high precision measurements at $\sqrt{s} = m_{h^0} \longrightarrow$ scan for the H^0 and A^0 resonances.

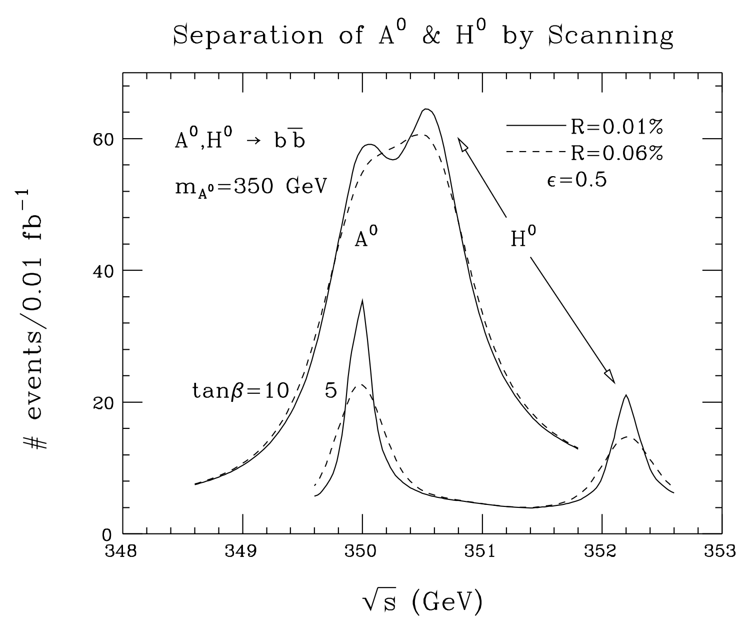
Once centered at $\sqrt{s} = m_{H,A}$
$\longrightarrow$ precision measurements of the H^0 and A^0 properties.

For large $\tan\beta$ and/or large m_A, H^0 and A^0 are (almost) degenerate and the two resonances (partly) overlap.

The high sensitivity on $\tan\beta$ allows to determine $\tan\beta$ with outstanding accuracy.

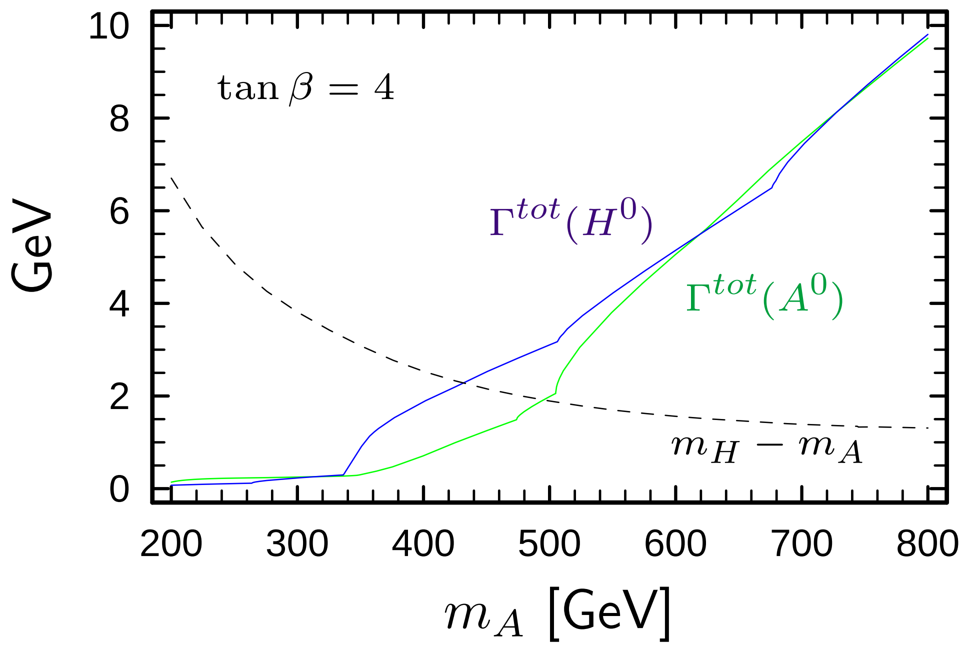
[Janot, CERN 99-02]

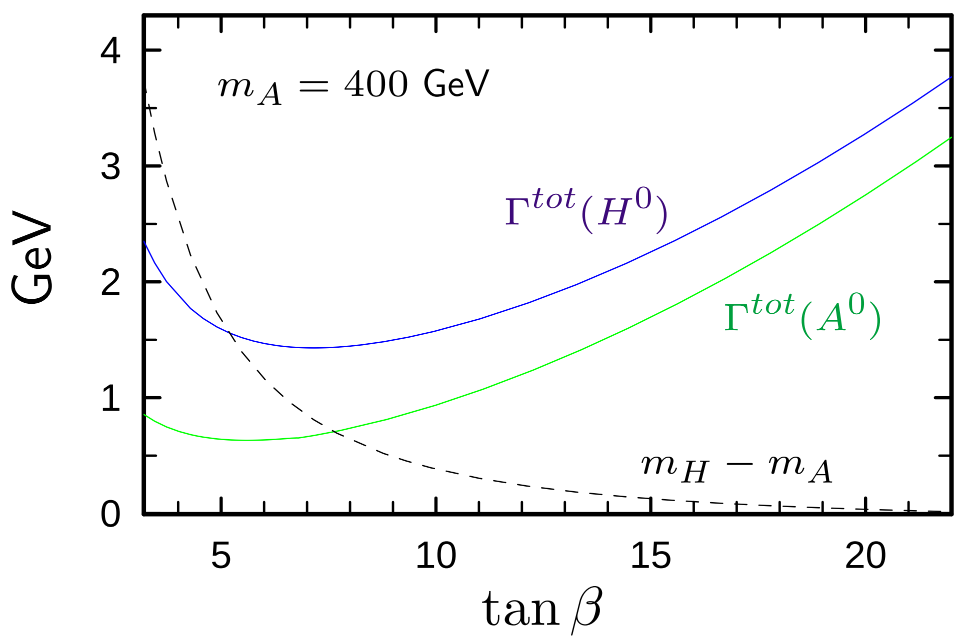
Stringent test of the model!



[Barger, Berger, Gunion, Han]

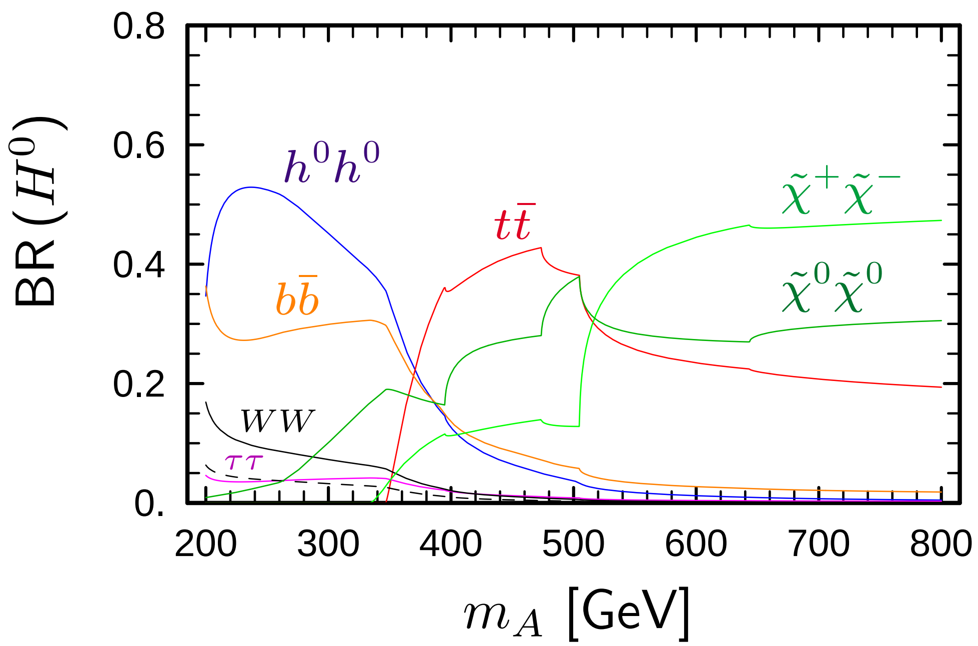
H^0 and A^0 total widths

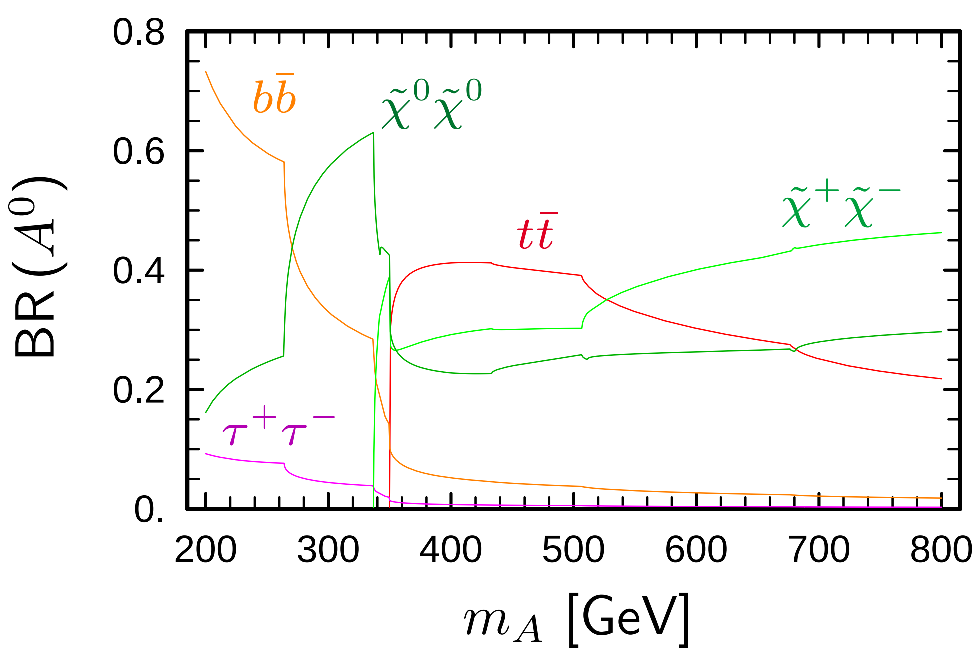




for $M_2 = 200$ GeV, $\mu = 300$ GeV, $m_{\tilde{q}} \sim m_{\tilde{\ell}} \sim 800$ GeV

Telling H^0 from A^0: branching ratios

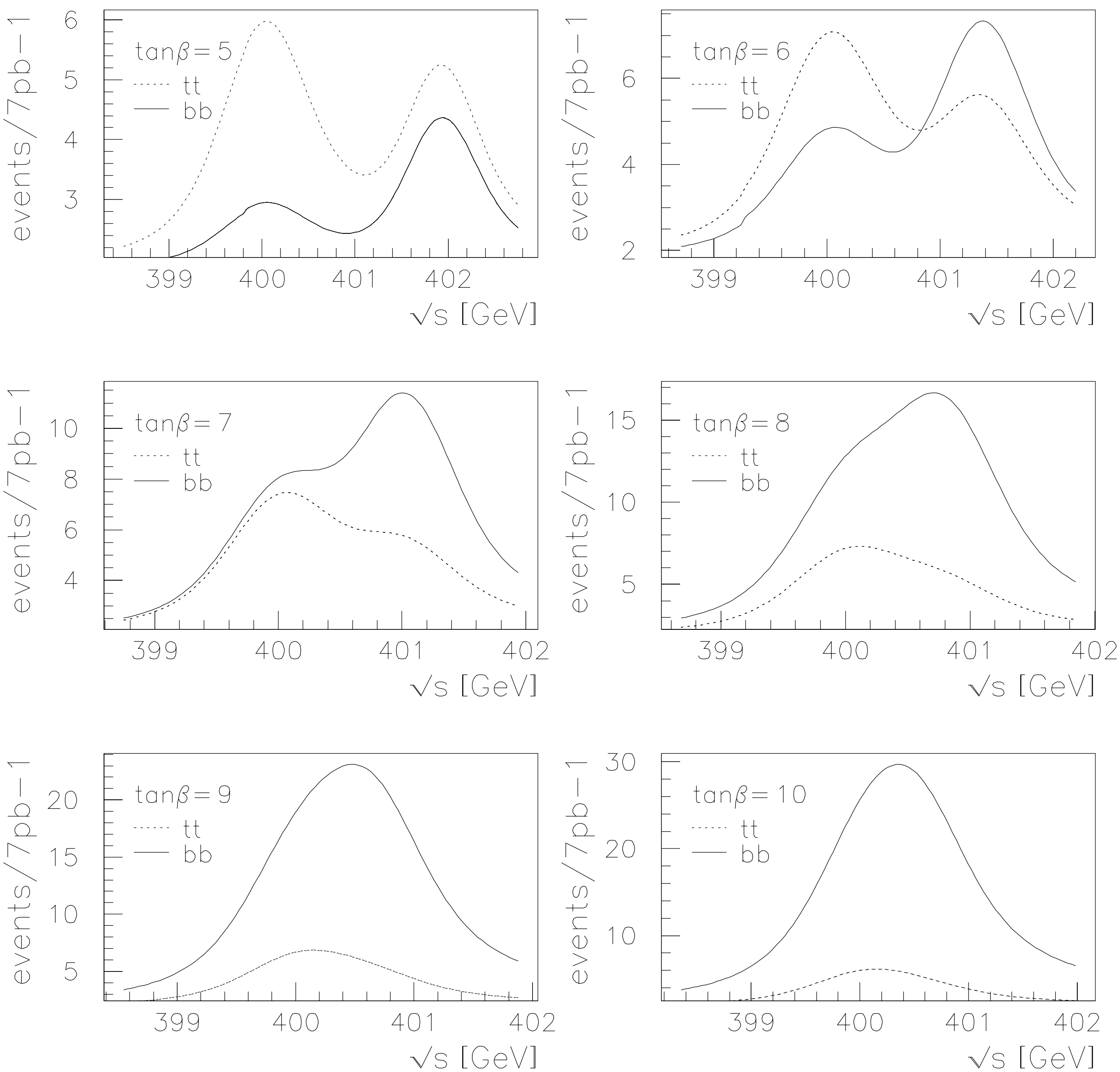




for $\tan\beta = 4$, $M_2 = 200$ GeV, $\mu = 300$ GeV,
$m_{\tilde{q}} \sim m_{\tilde{\ell}} \sim 800$ GeV

Telling H^0 from A^0:

$\mu^+\mu^- \to H^0/A^0 \to b\bar{b},\ t\bar{t}$



Number of $b\bar{b}$ (solid) and $t\bar{t}$ (dashed) events per $\mathcal{L} = 7\,\mathrm{pb}^{-1}$ coming from $\mu^+\mu^- \to H^0 + A^0$ for $m_A = 400$ GeV, $m_{\tilde{q}} = 1$ TeV, and no squark mixing.

[Grzadkowski, Gunion, Pliszka '00]

$H^0 - A^0$ interference effects

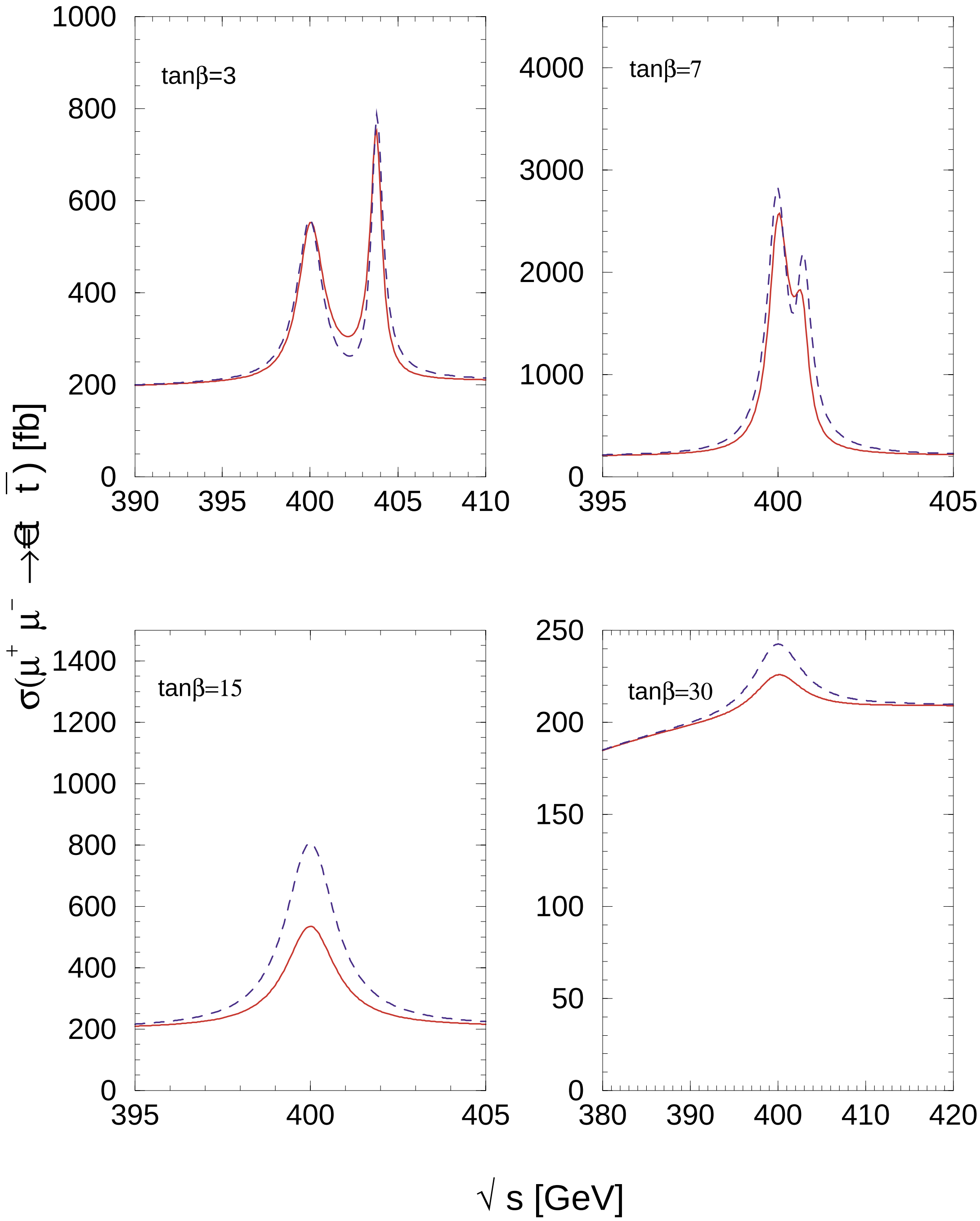
If the helicities of the initial and final state particles are fixed and $m_H - m_A \lesssim \Gamma_{H,A}$, the amplitudes of the H^0 and A^0 exchanges can sizably interfere. The asymmetry

$$A = \frac{\sigma^{RRRR} + \sigma^{LLLL} - \sigma^{RRLL} - \sigma^{LLRR}}{\sigma^{RRRR} + \sigma^{LLLL} + \sigma^{RRLL} + \sigma^{LLRR}} = \frac{2Re[\mathcal{M}_H \cdot \mathcal{M}_A^*]}{|\mathcal{M}_H|^2 + |\mathcal{M}_A|^2}$$

is a measure of the interference effect.

$A \neq 0$ means that two Higgs bosons with different CP–parities contribute to the resonance.

[Asakawa, Sugamoto, Watanabe '00]



Effecitve cross sections for $\mu^+\mu^- \longrightarrow t\bar{t}$ for $\tan\beta = 3, 7, 10, 30$, $m_A = 400$ GeV and 60% beam polarization.

Red: $\sigma(\mu_L^+\mu_L^- \longrightarrow t_L\bar{t}_L)$ or $\sigma(\mu_R^+\mu_R^- \longrightarrow t_R\bar{t}_R)$,

Blue: $\sigma(\mu_L^+\mu_L^- \longrightarrow t_R\bar{t}_R)$ or $\sigma(\mu_R^+\mu_R^- \longrightarrow t_L\bar{t}_L)$

[Asakawa, Sugamoto, Watanabe '00]

Charged Higgs

Pair production

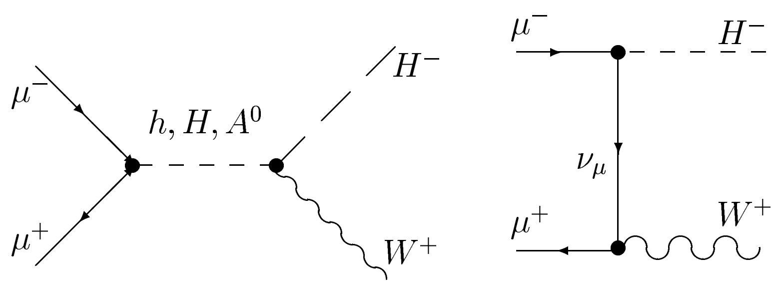
In the MSSM, H^0, A^0 and $H^\pm$ are roughly degenerate if $m_A > 200$ GeV.

$\Rightarrow$ main mechanism is $\mu^+\mu^- \to \gamma/Z \to H^+H^-$

$\Rightarrow$ can probe up to $m_{H^+} \lesssim \sqrt{s}/2$ identical to e^+e^-

Single production

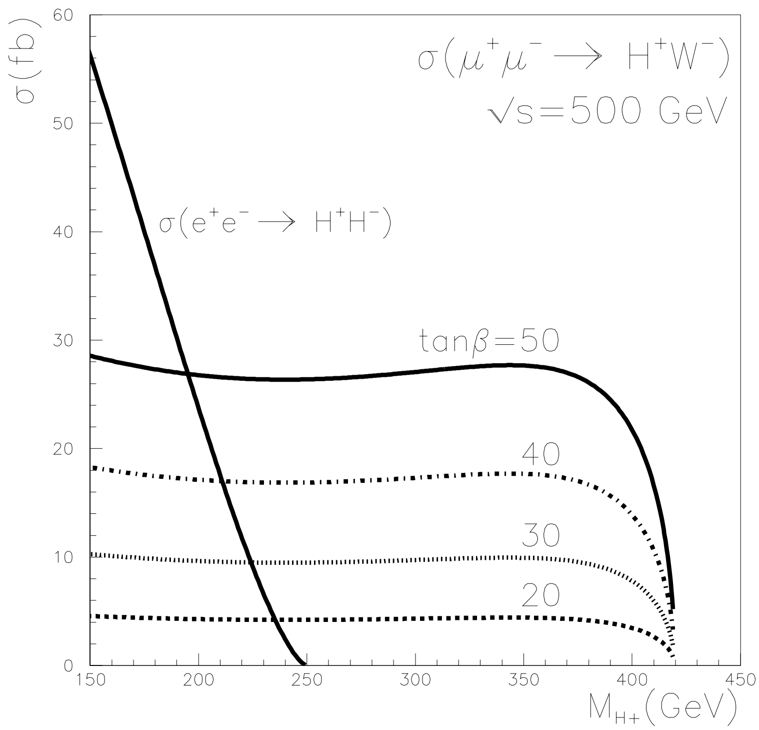
$\mu^+\mu^- \to H^\pm W^\mp$ proceeds via s-channel Higgs and t-channel neutrino exchange.



$\Rightarrow$ sensitive to the $H^\pm\mu^\mp\nu_\mu$ Yukawa coupling

$\Rightarrow$ t-channel contribution can be large for large $\tan\beta$

$\Rightarrow$ kinematical reach up to $m_{H^+} \lesssim \sqrt{s} - m_W$



[Akeroyd, Arhrib, Dove '99]

Conclusions

- At the μC the properties of the Higgs boson(s) h_{SM} (h^0, H^0, A^0), i.e. mass, total and partial widths, spin, CP nature ...., may be determined with outstanding accuracy.

  e.g. for a SM–like Higgs boson with $m_h < 2m_W$: m_h, Γ_h to fractions of MeV!

- This allows to determine $\tan\beta$ with high precision, even for high $\tan\beta$.

- Precise theoretical predictions are necessary (radiative corrections to $h^0 \to b\bar{b}$ etc)

- Possibility for scanning and excellent beam energy resolution are essential.

- Beam polarization may be helpful to disentangle overlapping H^0 and A^0 resonances.

- A charged Higgs may be observed through $\mu^+\mu^- \to H^\pm W^\mp$ with a kinematic reach of $m_{H^+} \lesssim \sqrt{s} - m_W$.