LEPTRE - 2001

Muon colliders: the physics program

Roberto Casalbuoni

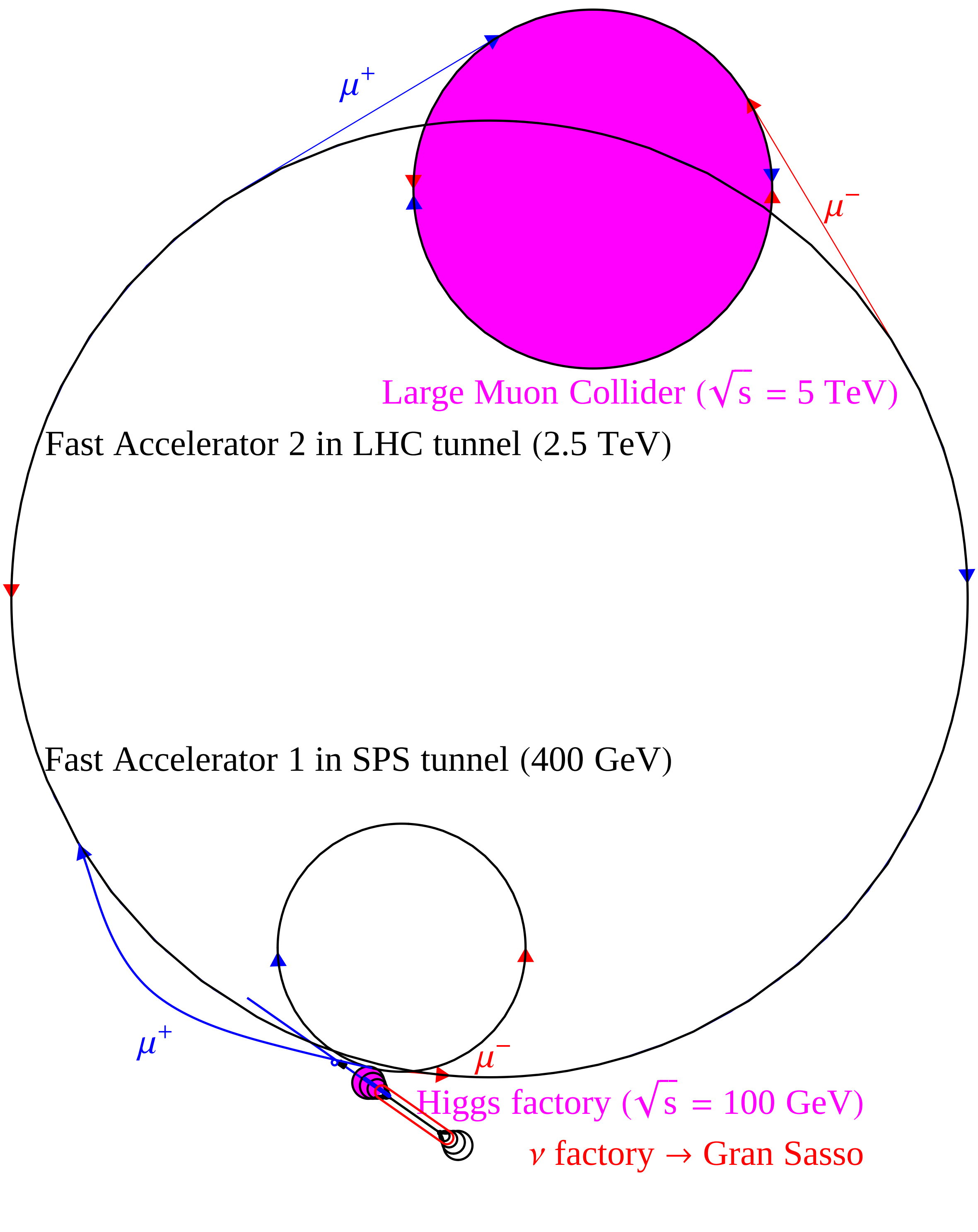
University of Florence and INFN

Rome, June 19, 2001

- Talk based on CERN Workshop Prospective study of muon storage rings at CERN (1999)

- Discussion about peculiar aspects of μC: **s-channel production of narrow resonances**

- ★ Main features of μC
- ★ Narrow resonances
- ★ SM-like Higgs and SUSY implications
- ★ SUSY H^0 and A^0
- ★ PNG bosons
- ★ Conclusions


μ^+
μ^-
Large Muon Collider ($\sqrt{s}$ = 5 TeV)
Fast Accelerator 2 in LHC tunnel (2.5 TeV)
Fast Accelerator 1 in SPS tunnel (400 GeV)
μ^+
μ^-
Higgs factory ($\sqrt{s}$ = 100 GeV)
ν factory → Gran Sasso

Baseline parameters for high- and low-energy muon colliders.

Higgs/year assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width

$\Gamma = 2.7$ MeV; 1 year $= 10^7$ s.

CoM energy	TeV	3	0.4		0.1	
p energy	GeV	16	16		16	
p's/bunch		2.5×10^{13}	2.5×10^{13}		5×10^{13}	
Bunches/fill		4	4		2	
Rep. rate	Hz	15	15		15	
p power	MW	4	4		4	
μ/bunch		2×10^{12}	2×10^{12}		4×10^{12}	
μ power	MW	28	4		1	
Wall power	MW	204	120		81	
Collider circum.	m	6000	1000		350	
Ave bending field	T	5.2	4.7		3	
Rms $\Delta p/p$	%	0.16	0.14	0.12	0.01	0.003
6-D $\epsilon_{6,N}$	$(\pi m)^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
Rms ϵ_n	π mm-mrad	50	50	85	195	290
β^*	cm	0.3	2.6	4.1	9.4	14.1
σ_z	cm	0.3	2.6	4.1	9.4	14.1
σ_r spot	μm	3.2	26	86	196	294
σ_θ IP	mrad	1.1	1.0	2.1	2.1	2.1
Tune shift		0.044	0.044	0.051	0.022	0.015
n_{turns} (effective)		785	700	450	450	450
Luminosity	$\text{cm}^{-2}\text{s}^{-1}$	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/year				1.9×10^3	4×10^3	3.9×10^3

Technical motivations

★ As for electrons, effective energy bigger than for hadronic machines

★ Since muons have negligible synchrotron radiation, possible circular machines much smaller than for electrons

★ Lack of beamstrahlung allows energy spread as low as 3×10^{-5}. Very difficult to monitor at the NLC's

★ The natural polarization of muons makes possible energy determination with accuracy of 10^{-6} or better

★ Luminosity $\mathcal{L}$ scales with $\Delta E_{\rm beam}/E_{\rm beam} = 0.01 R(\%)$ as

$$\mathcal{L} \approx (\sqrt{s})^{11/7} (R)^{4/7}$$

In particular

$R(\%)$	0.12	0.01	0.003
$\mathrm{L_{year}(fb^{-1})}$	1	0.22	0.1

Improving R by 2 means a 33% loss in $\mathcal{L}$

These features make muon colliders (μC) ideal machines for studying thresholds and very narrow resonances in the s channels. Among these is the Higgs where

$$\sigma_{\ell^+\ell^- \to H} \propto m_\ell^2$$

with a gain of 4×10^4 to the electrons.

▶ Possibility of measuring mass and couplings of the Higgs with great precision

▶ Muons belong to a different generation w.r.t. electrons. They would couple to different particles if these existed

Narrow resonances

- Assume Breit-Wigner shape for a spin-j resonance produced in the s-channel with decay $R \to F$

  $$\sigma^F(E) = 4\pi(2j+1)\frac{\Gamma(R \to \ell^+\ell^-)\Gamma(R \to F)}{(E^2 - M^2)^2 + M^2\Gamma^2}$$

  with $E = \sqrt{s}$. We assume $\Gamma \ll M$ and neglect the running of Γ

- The total production cross-section is

  $$\sigma(E) = 4\pi(2j+1)\frac{\Gamma(R \to \ell^+\ell^-)\Gamma}{(E^2 - M^2)^2 + M^2\Gamma^2}$$

- Ignoring bremsstrahlung, assume a Gaussian shape for the beam with a beam energy spread

$$\Delta E_{\text{beam}}/E_{\text{beam}} = 0.01R(\%)$$

giving a c.o.m. spread

$$\sigma_E = \frac{0.01R(\%)}{\sqrt{2}}E \approx 0.007R(\%)E$$

The energy distribution can be written as

$$f(E) = \frac{1}{\sigma_E} g\left(\frac{E - E_0}{\sigma_E}\right), \quad \int f(E)dE = 1$$

- Convoluting σ^F with $f(E)$

$$\sigma_c^F(E) = 4\pi(2j+1)\Gamma_{R\to\ell^+\ell^-}\Gamma_{R\to F}\, h(\Gamma, \sigma_E, E)$$

$$h(\Gamma, \sigma_E, E) = \int \frac{f(E - E')}{(E'^2 - M^2)^2 + M^2\Gamma^2} dE'$$

- $\boxed{\Gamma \gg \sigma_M}$ (and also w.r.t. the brem energy spread)

$$\sigma_c(E) = \frac{4\pi(2j+1)B_{\ell^+\ell^-}}{M^2} \frac{\Gamma^2 M^2}{(E^2 - M^2)^2 + \Gamma^2 M^2}$$

From $\sigma_c(M) \longmapsto B_{\ell^+\ell^-}$. Then Γ from the scan of the resonance

- $\boxed{\Gamma \ll \sigma_M}$ (assuming a gaussian for $f(E)$)

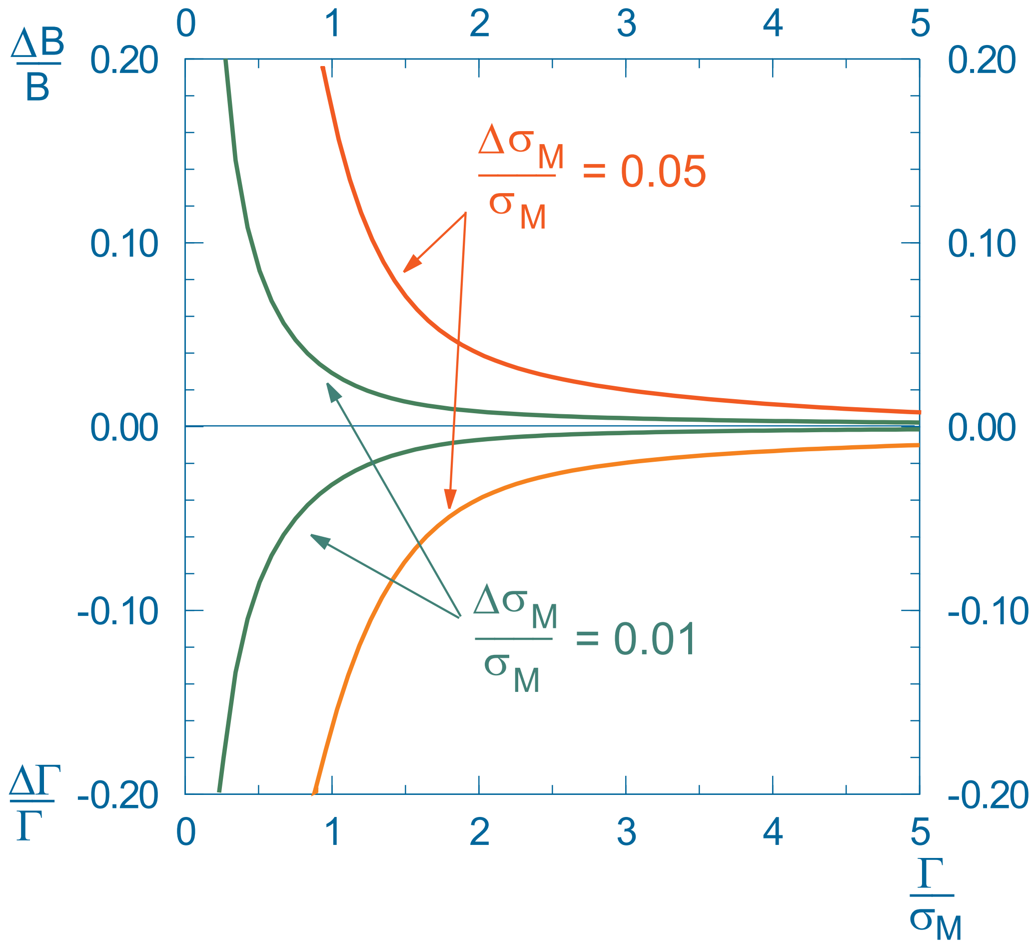
$$\sigma_c(E) = \frac{4\pi(2j+1)B_{\ell^+\ell^-}}{M^2} \underbrace{\frac{1}{2}\sqrt{\frac{\pi}{2}}}_{\approx 0.63} \frac{\Gamma}{\sigma_M}$$

$$\times \exp\left[-\frac{(E-M)^2}{2\sigma_M^2}\right]$$

Provided σ_M is known we get $B_{\ell^+\ell^-} \times \Gamma$. σ_M from $\sigma_c(E)$ with $E \neq M$, BUT poor statistical accuracy (Γ/σ_M)

Cross-section large and systematics induced by σ_M small, for $\sigma_M \ll \Gamma$. Often $\Gamma \approx \sigma_M$. Then the σ_M-induced errors get enhanced

σ_M-induced errors on B and Γ for scanning at $E = M$, $E = M \pm 2\Gamma$



Errors $2.5 \div 3.5$ times $\Delta\sigma_M/\sigma_M$ for $\Gamma \approx \sigma_M$, down to $0.3 \div 0.5$ times $\Delta\sigma_M/\sigma_M$ for $\Gamma \approx 3\sigma_M$

3-points scan in symmetrical positions as 2-points. In asymmetric position, intermediate results.

(R.C., D. Dominici, S. De Curtis, A. Deandrea, R. Gatto and J.F. Gunion, JHEP 081999011)

Brem does not change results significantly

$\Delta\sigma_M/\sigma_M = \pm 0.05$. No-brem. Brem and $R = 0.003\%$.

$R = 0.03\%$. $R = 0.1\%$

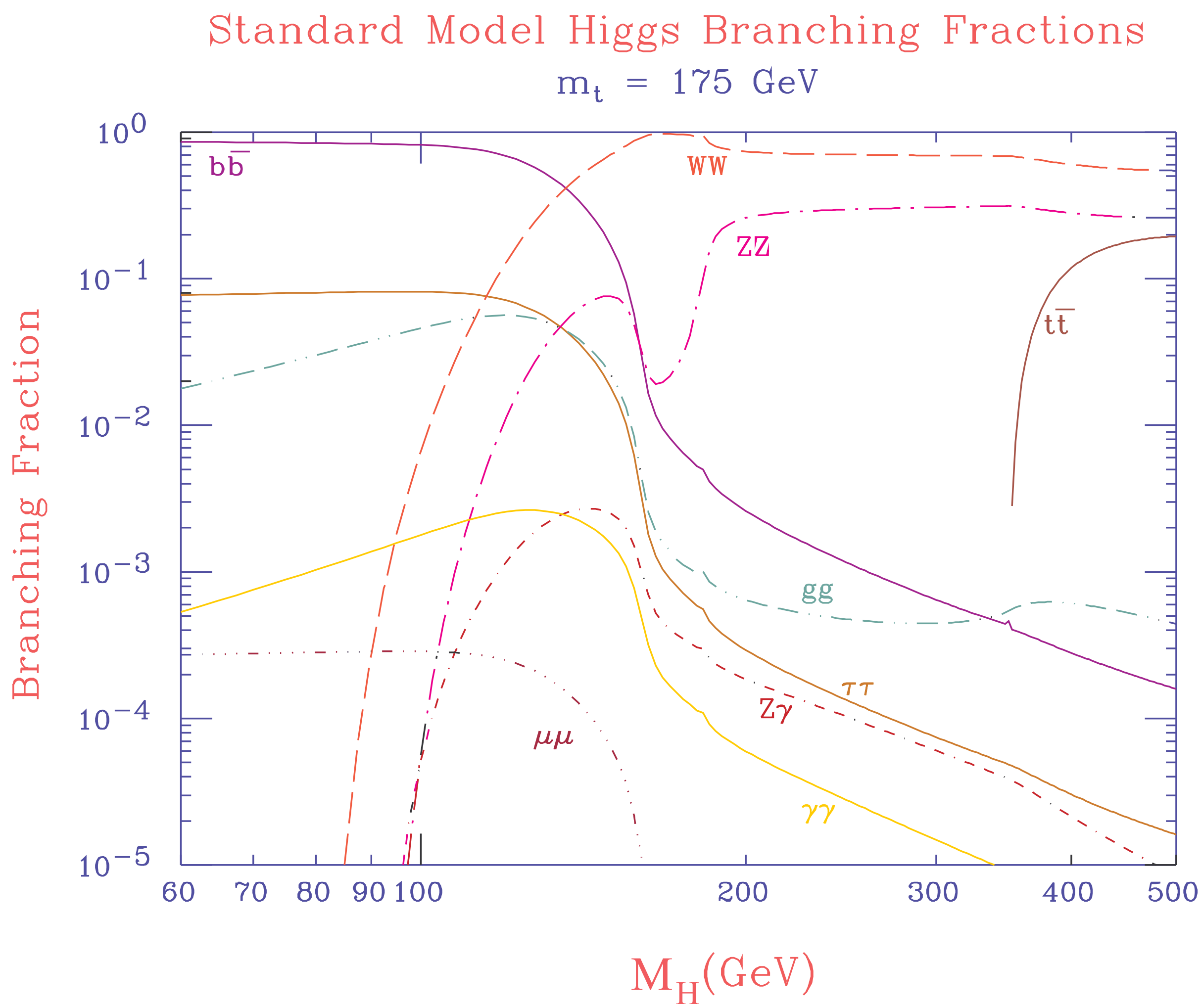
Γ/σ_M	1Γ $\Delta B/B$	1Γ $\Delta\Gamma/\Gamma$	2Γ $\Delta B/B$	2Γ $\Delta\Gamma/\Gamma$	3Γ $\Delta B/B$	3Γ $\Delta\Gamma/\Gamma$
1	+0.22	−0.21	+0.17	−0.16	+0.11	−0.10
	+0.22	−0.21	+0.18	−0.16	+0.12	−0.11
	+0.22	−0.21	+0.18	−0.16	+0.12	−0.11
	+0.22	−0.21	+0.18	−0.16	+0.12	−0.11
2	+0.065	−0.075	+0.043	−0.037	+0.035	−0.023
	+0.067	−0.078	+0.046	−0.044	+0.040	−0.032
	+0.065	−0.075	+0.044	−0.041	+0.037	−0.029
	+0.067	−0.077	+0.045	−0.042	+0.039	−0.031
3	+0.031	−0.036	+0.023	−0.017	+0.022	−0.013
	+0.031	−0.035	+0.024	−0.020	+0.023	−0.017
	+0.031	−0.037	+0.024	−0.020	+0.023	−0.017
	+0.031	−0.038	+0.024	−0.021	+0.022	−0.016
4	+0.018	−0.020	+0.016	−0.011	+0.015	−0.009
	+0.019	−0.022	+0.017	−0.013	+0.015	−0.011
	+0.018	−0.021	+0.016	−0.012	+0.015	−0.011
	+0.018	−0.020	+0.015	−0.012	+0.015	−0.011

One could discuss optimization of σ_M w.r.t. Γ in order to minimize the net statistical + systematic errors. In practice need a priori knowledge of Γ, therefore plan to operate at the smallest possible value of R ($R(\%) \approx 0.003$) if dealing with Higgs or PNGB's. Better possibilities in other cases.

- One could reduce the σ_M-induced errors by using different methods as measuring the on-peak cross-section for different σ_M (R.C., S. De Curtis, A. Deandrea, D. Dominici, R. Gatto and J. Gunion, Phys. Rev. Lett. **83** (1999) 1525, and JHEP 081999011), since one has for $\sigma_M^{\rm min} \ll \Gamma$, $\sigma_M^{\rm max} \gg \Gamma$

$$\frac{\sigma_c(\sigma_M^{\rm min})}{\sigma_c(\sigma_M^{\rm max})} = \frac{2\sqrt{2}\sigma_M^{\rm max}}{\sqrt{\pi}\Gamma} \rightarrow \frac{\Delta\Gamma}{\Gamma} = \frac{\Delta\sigma_M^{\rm max}}{\sigma_M^{\rm max}}$$

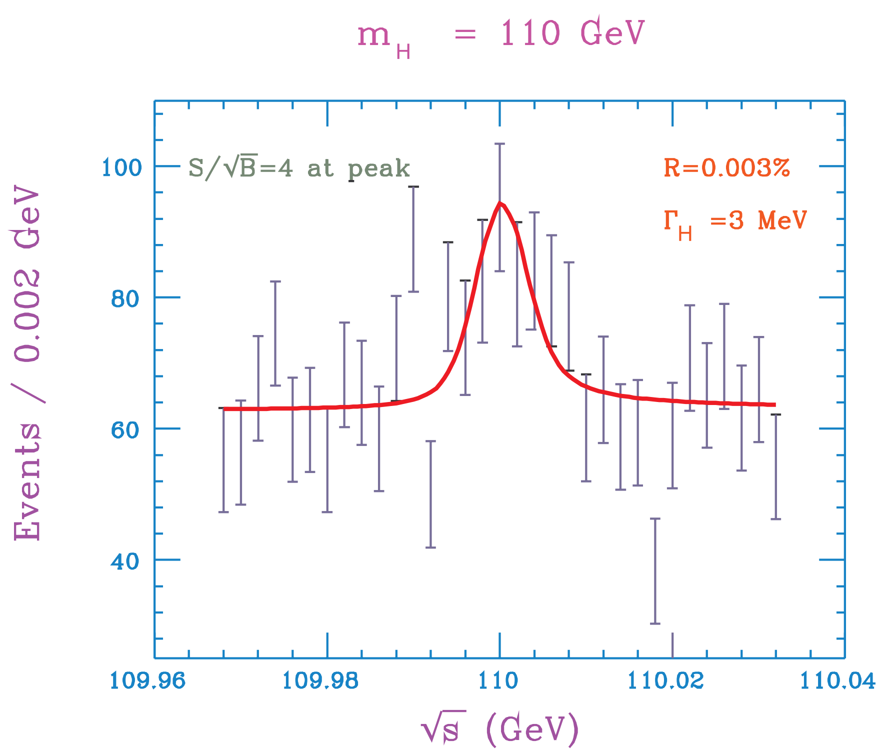
Standard Model-Like Higgs



For $M_H \lesssim 130\ GeV$ $BR(H \to b\bar{b})$ is about $0.8 \div 0.9$. When the modes WW^* and ZZ^* turn on ($M_H \gtrsim 2m_W$), H becomes broad and $BR(H \to b\bar{b})$ declines rapidly.

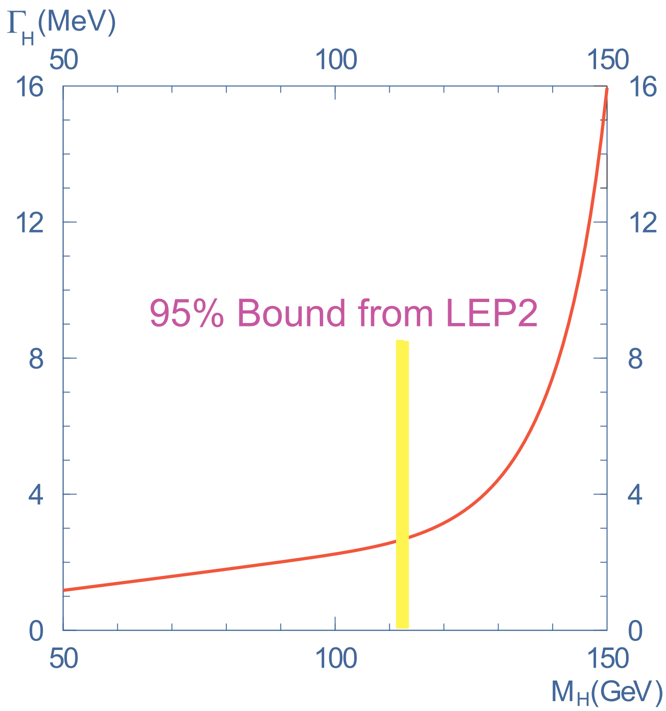
- Since $\sigma_c(M) \propto B_{\mu^+\mu^-}$ we need $M_H \lesssim 2m_W$ for a good s-channel cross section.

- Strategy: From LHC (2γ-mode) or NLC ($e^+e^- \to hZ$ using recoil mass technique) $\Delta M_H \approx 100$ MeV (or less). Center on $\sqrt{s} \approx M_H$ via rough scan ($L \approx 0.1$ fb^{-1})



■ Measuring:

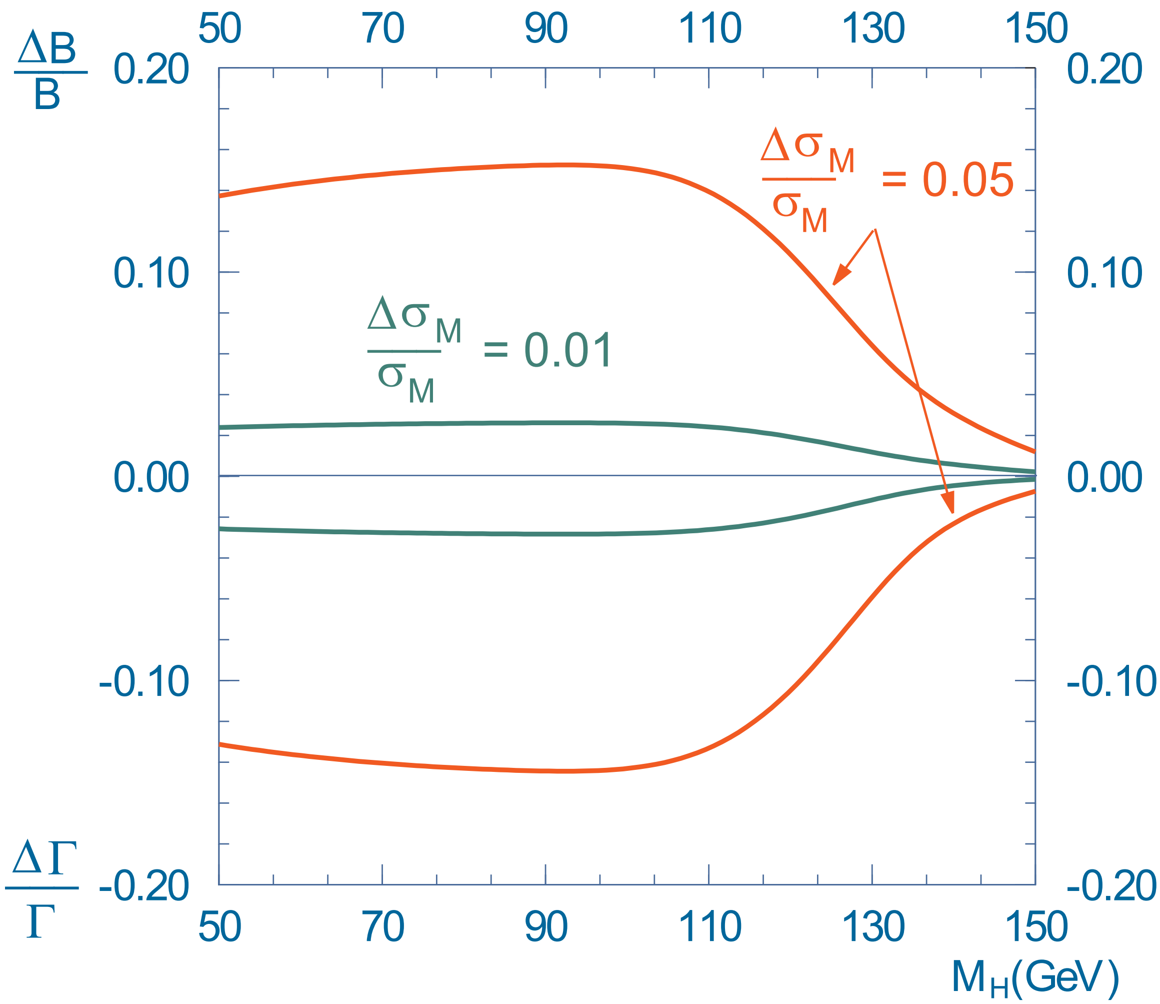
- The Higgs width: $\Gamma_H \approx 1 \div 10\ MeV$ with $M_H \leq 140\ GeV$



- σ_c^F with $F = b\bar{b},\ WW^*,\ ZZ^*,\ c\bar{c},\ \tau^+\tau^-$

■ In this energy range $\Gamma_H \approx \sigma_M$ and we need to run at the minimum value of R, i.e. $R(\%) = 0.003$. From the 3-points scan:

Errors in B and Γ for scanning at $E = M$, $E = M \pm 2\Gamma$, $R = 0.003\%$



Up to 130 GeV we need the smallest R. Taking $R(\%) = 0.01$ implies $\Gamma/\sigma_M \approx 0.5$ with errors about 10% for $\Delta\sigma_M/\sigma_M = 0.01$

- Assuming a total accumulated luminosity of $L = 0.4$ fb^{-1} (meaning about 4 years of running) the statistical errors for a 3-scan points and for the ratio-technique are given in the Table. The two methods look complementary for Γ_H. To avoid contamination from the systematics induced by σ_M we need $\Delta\sigma_M/\sigma_M < 5\%$

- TESLA with 500 fb^{-1}/yr is more than competitive (see Table). **In 1 year TESLA does better than muon collider in 4 years (ignoring systematics)**. Muon collider needs increase the luminosity at $R = 0.003\%$ at least of a factor 10 in order to compete with TESLA

Quantity	Errors for the scan procedure					
Mass (GeV)	**100**	**110**	**120**	**130**	**140**	**150**
$\sigma_c B(b\bar{b})$	4%	3%	3%	5%	9%	28%
$\sigma_c B(WW^\star)$	32%	15%	10%	8%	7%	9%
$\sigma_c B(ZZ^\star)$	–	190%	50%	30%	26%	34%
Γ_H	30%	16%	16%	18%	29%	105%

Quantity	Errors for the $\bar{r}$-ratio procedure					
Mass (GeV)	**100**	**110**	**120**	**130**	**140**	**150**
$\sigma_c B(b\bar{b})$	3.8%	2.8%	2.8%	4.4%	7.6%	21%
$\sigma_c B(WW^\star)$	26%	12%	7.7%	5.7%	5.0%	5.6%
$\sigma_c B(ZZ^\star)$	–	190%	46%	25%	20%	22%
Γ_H	45%	25%	20%	19%	17%	18%

Quantity	Errors		
Mass (GeV)	**120**	**140**	**150**
$\Gamma(ZZ)$	2.5%	2.7%	3%
$B(b\bar{b})$	2.4%	2.6%	6.5%
$B(c\bar{c})$	8.3%	19%	–
$B(\tau^+\tau^-)$	5.0%	8.0%	–
$B(WW^\star)$	5.1%	2.5%	2.1%
$B(ZZ^\star)$	–	–	16.9%
$B(\gamma\gamma)$	16%	–	–
$\Gamma_h^{\rm tot} = \frac{\Gamma(WW\to h)}{B(WW^*)}$	6.1%	4.5%	13.4%
$\Gamma_h^{\rm tot} = \frac{\Gamma(WW)=\Gamma(ZZ)}{B(WW^*)}$	5.6%	3.7%	3.6%
$\Gamma_h^{\rm tot} = \frac{\Gamma(WW)=\Gamma(ZZ)}{B(WW^*)}$	23%	–	–

Two questions are in order

1) - Does the accuracy of the μC allow stringent tests of the SM?

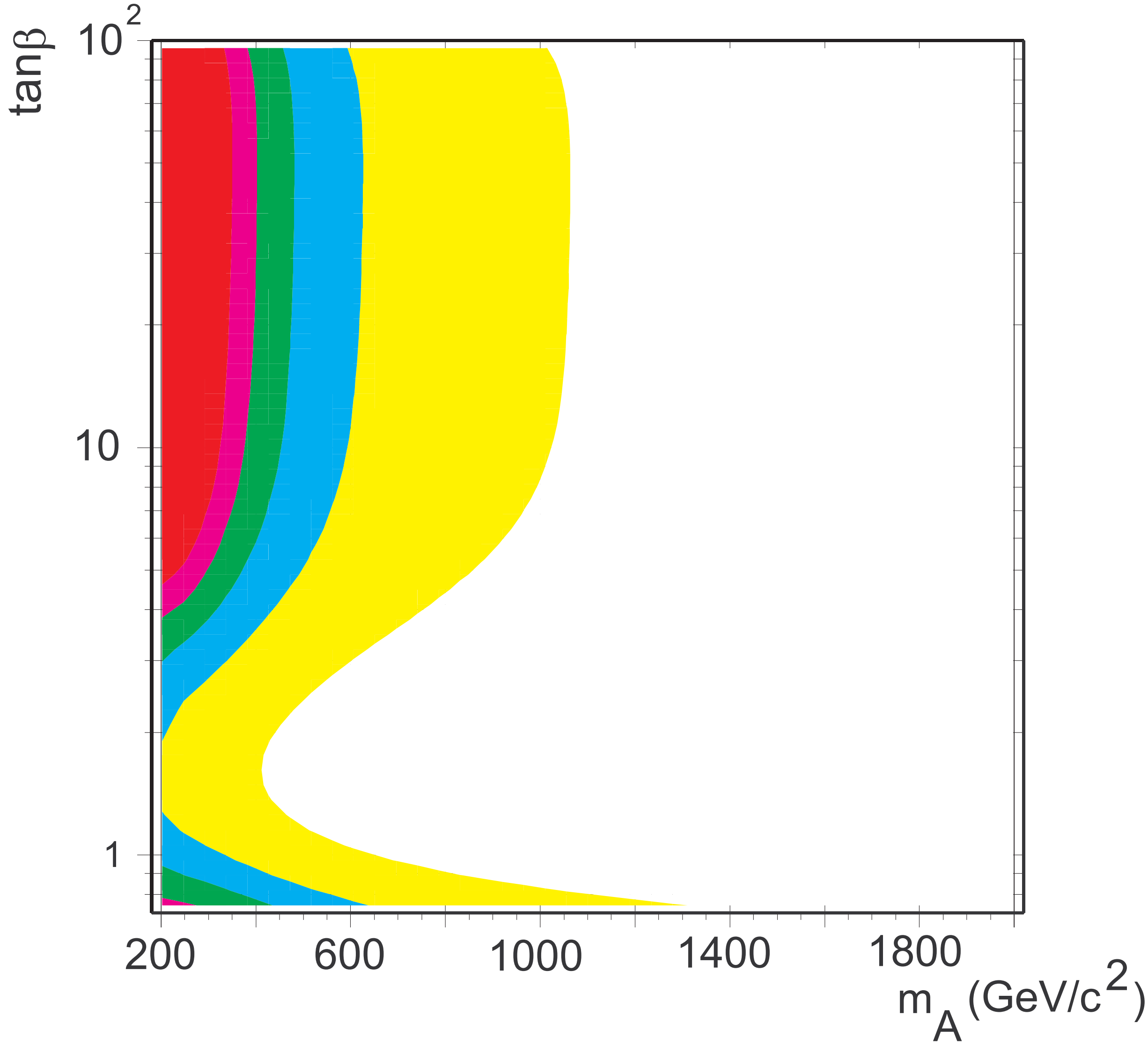
2) - Is the μC helpful to understand the underlying theory?

- Notice that the possible great precision in M_H is not crucial since $\Delta M_H = 100\ MeV$ translates in 0.25% in cross-section (recall $\Delta\Gamma_H/\Gamma_H \approx 20\%$)

- Assume that LHC (via $H \to \gamma\gamma$) or the NLC (via $e^+e^- \to H$ with $H \to b\bar{b}$) have discovered the Higgs in the mass range $110 \leq M_H \leq 140\ GeV$ with accuracy $\Delta M_H = 100\ MeV$, 20% on $\sigma(gg \to H)B(H \to \gamma\gamma)$ and 2.5% on $\sigma(e^+e^- \to HZ)B(H \to b\bar{b})$, dominated by the gluon structure functions and by the b-quark pole mass respectively

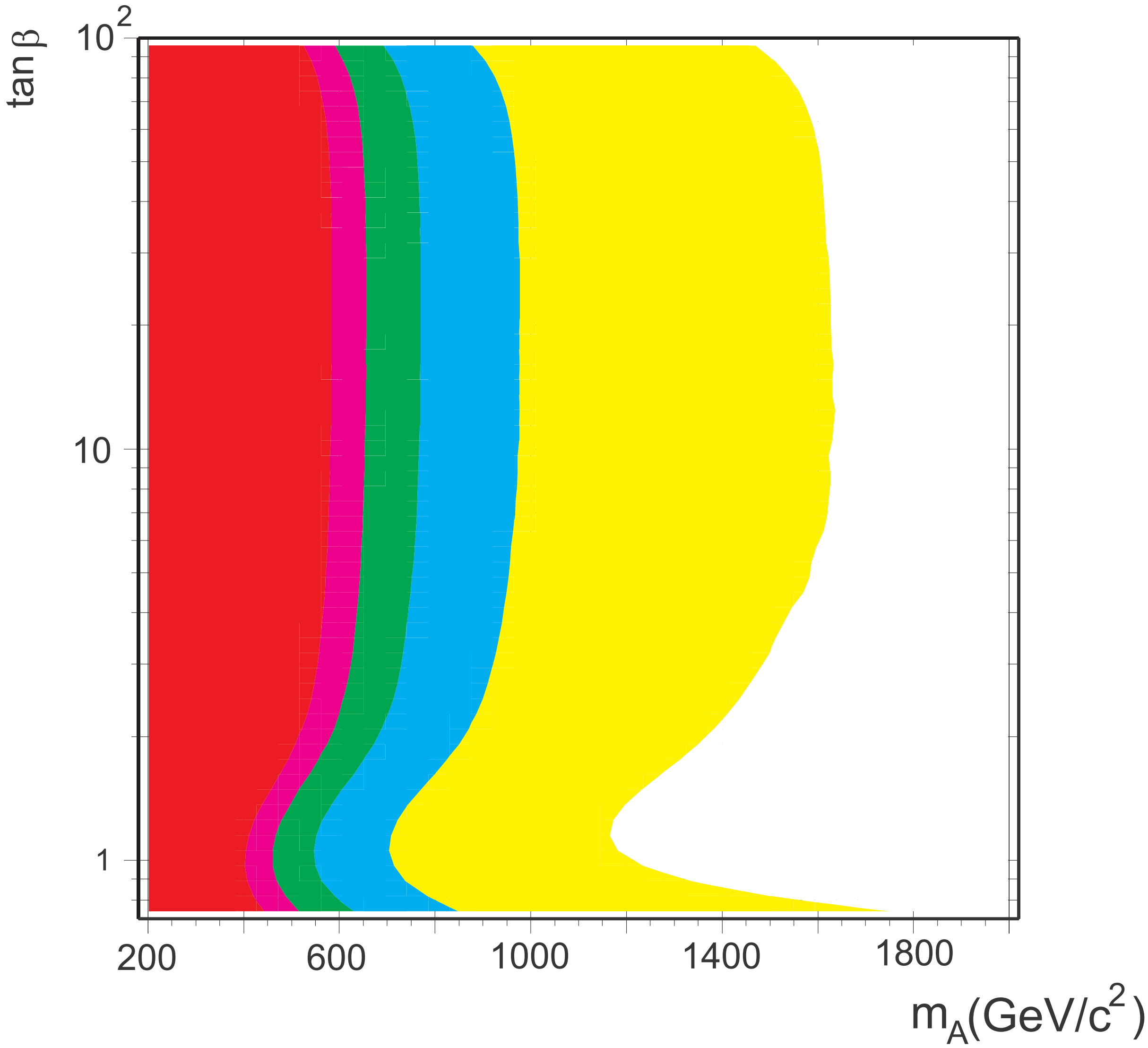
- Assume now MSSM. At tree level the Higgs sector is determined by m_A and $\tan\beta$. We can compare LHC and NLC measurements for the lighter CP-even Higgs boson with the SM predictions in the plan (m_A, $\tan\beta$) (see Figures)

From P. Janot "Prospective study of muon storage rings at CERN", CERN 99-02"



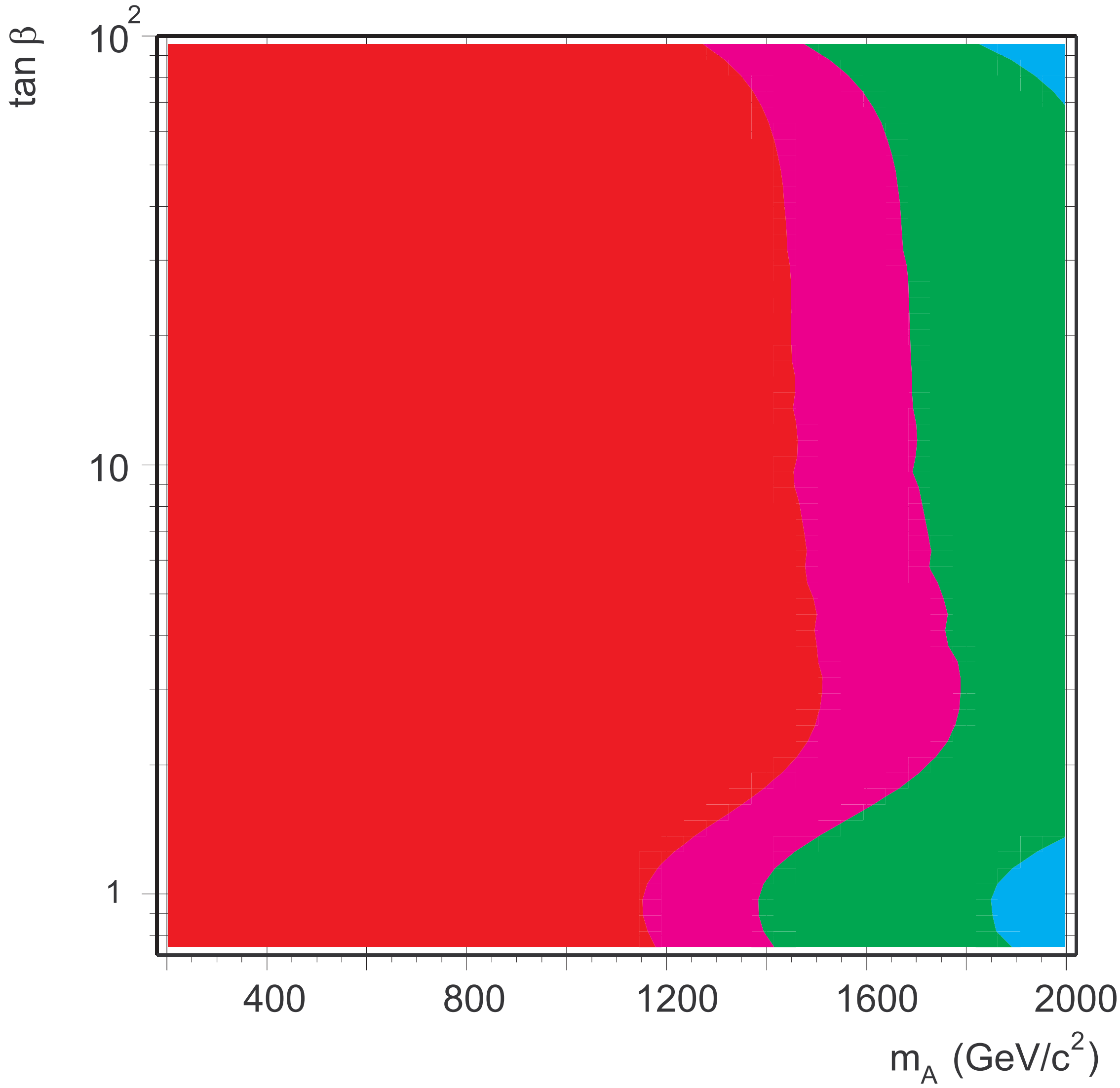
Bound about 400 GeV on m_A.
From TESLA TDR, the bound at 95% CL on m_A is about 600 GeV.
(ignoring systematics in interpretation)

From P. Janot "Prospective study of muon storage rings at CERN", CERN 99-02"



$L = 0.2$ fb^{-1} (1 yr with $\mathcal{L} = 2 \cdot 10^{31}$ cm^{-2} sec^{-1}) at the μC. SUSY scale = 1 TeV, maximal stop mixing. 3-σ bound on m_A about 600 GeV

From P. Janot "Prospective study of muon storage rings at CERN", CERN 99-02"



$L = 10$ fb^{-1} (5 yr with $\mathcal{L} = 2 \cdot 10^{32}$ cm^{-2} sec^{-1}) at the μC. SUSY scale = 1 TeV, maximal stop mixing. 3-σ bound on m_A about 2 TeV

Answers about underlying theory need specific choices. Also needed clean theoretical interpretation. In the MSSM case many uncertainties from SUSY decays, radiative corrections, etc.

- A clean way, using μC and NLC results, is to measure $\Gamma(H \to \mu^+\mu^-)$

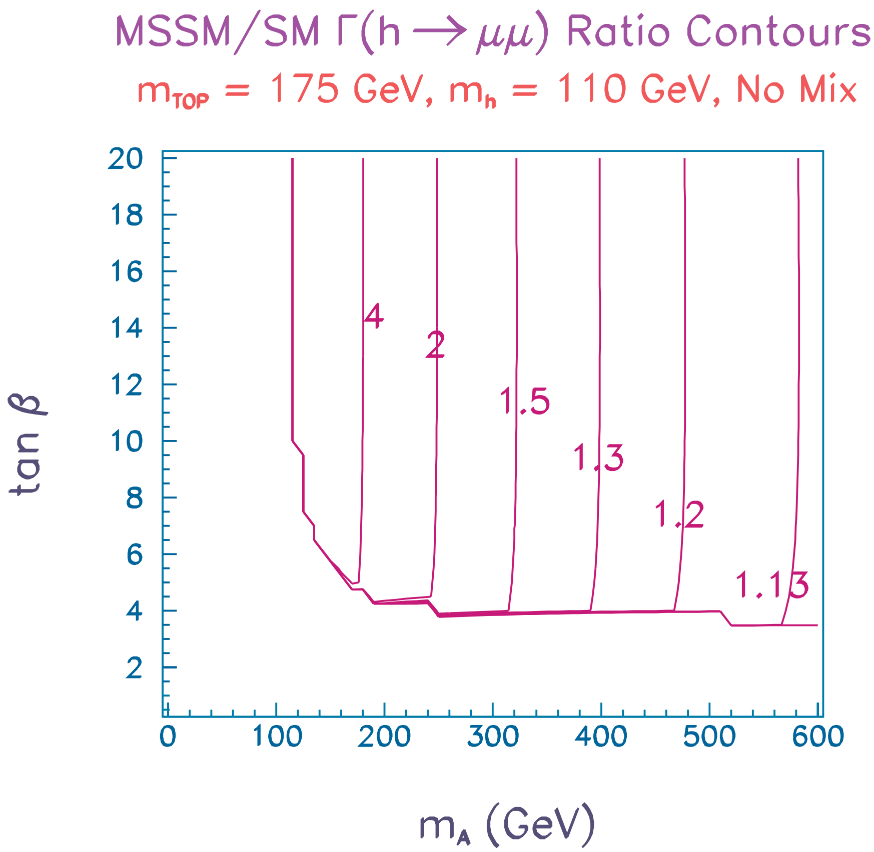
  - $\Gamma(H \to \mu^+\mu^-) = \frac{\left[\Gamma(H \to \mu^+\mu^-) \cdot B(H \to b\bar{b})\right]_{\mu\text{C}}}{\left[B(H \to b\bar{b})\right]_{\text{NLC}}}$

  - $\Gamma(H \to \mu^+\mu^-) = \frac{\left[\Gamma(H \to \mu^+\mu^-) \cdot B(H \to WW^*)\right]_{\mu\text{C}}}{[B(H \to WW^*)]_{\text{NLC}}}$

  - We can get two other determinations via

$$B(H \to F)_{\text{NLC}} \to \frac{[\Gamma(H \to F)]_{\text{NLC}}}{[\Gamma_H]_{\mu\text{C}}}$$

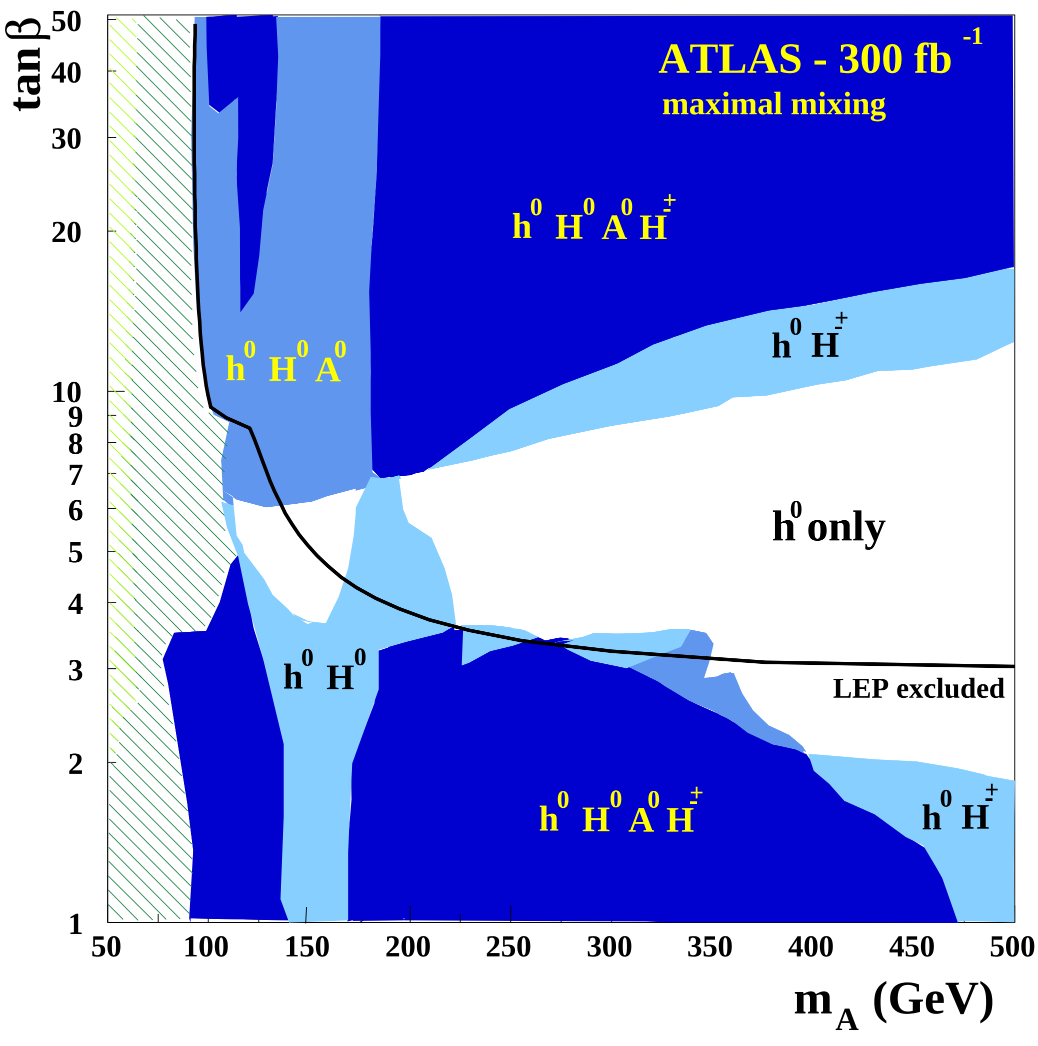
★ Using $L = 0.4$ fb^{-1} for the μC and 200 fb^{-1} for the NLC (500 GeV) one gets (J.F. Gunion talk at the UCLA Higgs factory March 2001) 4% error giving 3-σ sensitivity for $m_A \leq$ 600 GeV $(M_H < 2M_W)$. **No systematics as for $\mathrm{b\bar{b}}$**



★ **μC is the only probe for H-couplings to muons**

SUSY H^0 and A^0

- Possibility of discovering H^0 and A^0 are limited at the LHC and the NLC
  - At the LHC not accessible region



- At the NLC $e^+e^- \to H^0A^0$ pair production is limited to about $m_{H^0} \approx m_{A^0} \approx 230 \div 240\ GeV$

- At the $\gamma\gamma$ collider one could probe up about $400\ GeV$ with $L \gtrsim 150 \div 200$ fb^{-1}

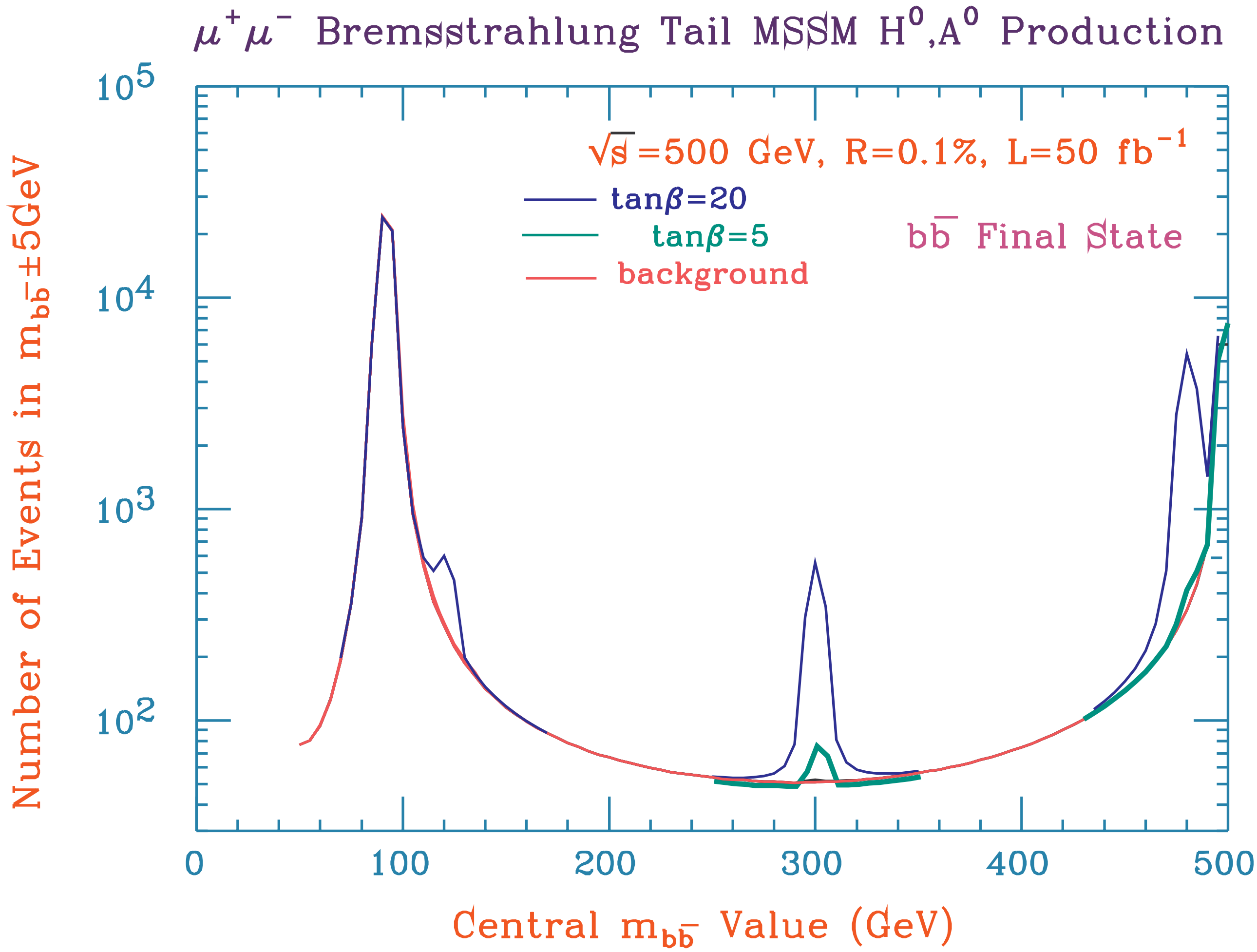
- μC allows to study $m_{A^0} \approx m_{H^0} \lesssim \sqrt{s}$ via s-channel production using $L = 50$ fb^{-1} (5 yrs of running at $\mathcal{L} = 10^{33}$ cm^{-2} sec^{-1} as possible for $R \gtrsim 0.1\%$ at $\sqrt{s} \approx 300 \div 500\ GeV$)

  - **with preknowledge** on m_{A^0} (from LHC or NLC) possible to study $\mu^+\mu^- \to A^0$ for all $\tan\beta \gtrsim 1$

  - **without preknowledge**, discovery by scanning $\mu^+\mu^- \to H^0, A^0$ (e.g. $m_{A^0} \gtrsim 250\ GeV$ and $4 \lesssim \tan\beta \lesssim 10$)

  - running at high-energy discovery possible through the brem tail, if good $b\bar{b}$ mass resolution and large $\tan\beta$ (V. Barger, M.S. Berger, J.F. Gunion and T. Han, Phys. Rep. **286** (1997), hep-ph/9602415)

$m_{A^0} = 120,\ 300,\ 480$

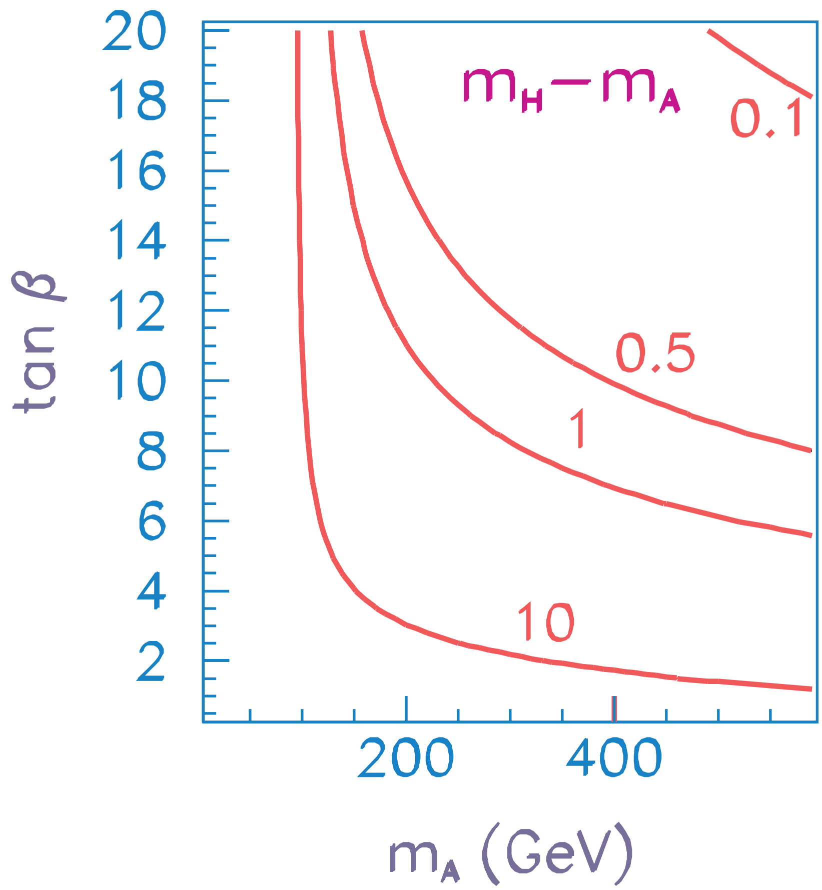


Number of $b\bar{b}$ events in the interval $m_b \pm 5\ GeV$ vs. the central $m_{b\bar{b}}$ value from the low $\sqrt{\hat{s}}$ brem tail. Two loop/RGE-improved radiative corrections included. $m_t = 175\ GeV$, $m_{\tilde{t}} = 1\ TeV$, no squark-mixing

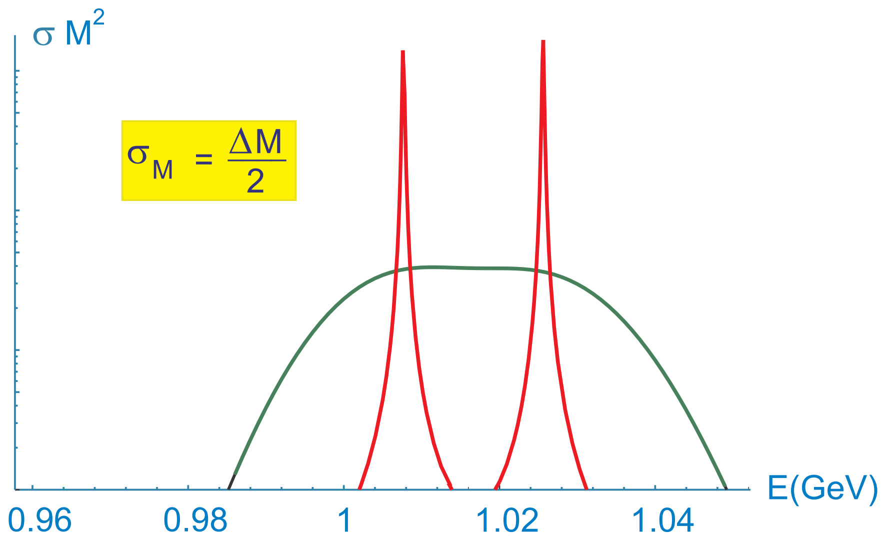
For large m_{A^0} and $\tan\beta$, H^0 and A^0 becomes nearly degenerate in mass

Mass Difference Contours

m_{TOP} = 175 GeV, m_{STOP} = 1 TeV

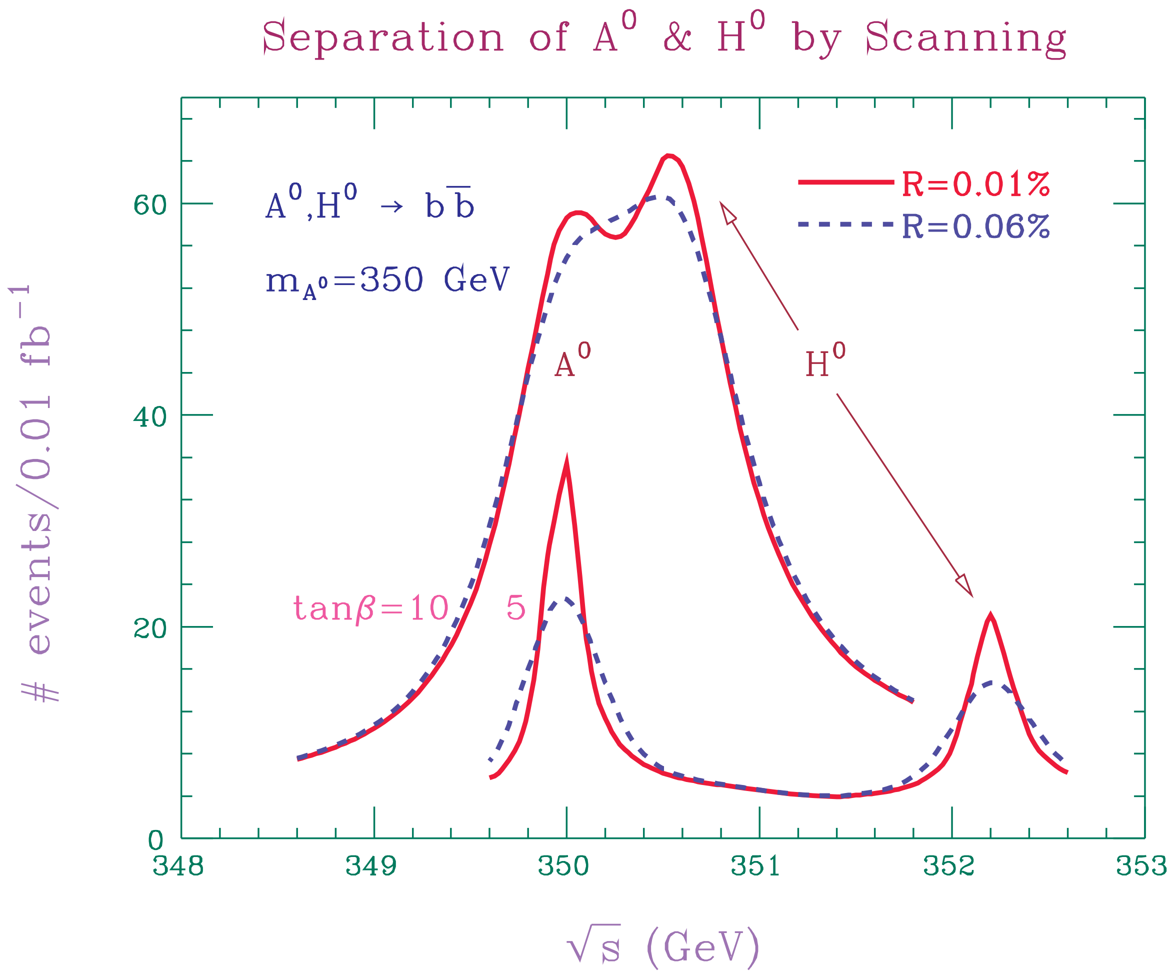


★ To discriminate nearly degenerate resonances require $\sigma_M \lesssim \Delta M$. The choice of σ_M depends on the ratio of the peak cross-sections. For equal values



★ H^0 and A^0 have comparable peak cross-section. For $m_{A^0} = 350\ GeV$ and $\tan\beta = 10$ (not observable at LHC), one has for $R = 0.06\%$, $\sigma_M/\Delta M \approx 1/3$. **At the NLC, with typical $\mathrm{R} = 0.1\%$, the separation is not possible**. The result is in Figure

Channel isolation efficiency $\epsilon = 0.5$, $m_t = 175\ GeV$, two-loop/RGE-improved radiative corrections. $m_{\tilde{t}} = 1\ TeV$, no squark mixing. No SUSY decays allowed



Once separation is done many SUSY tests are possible

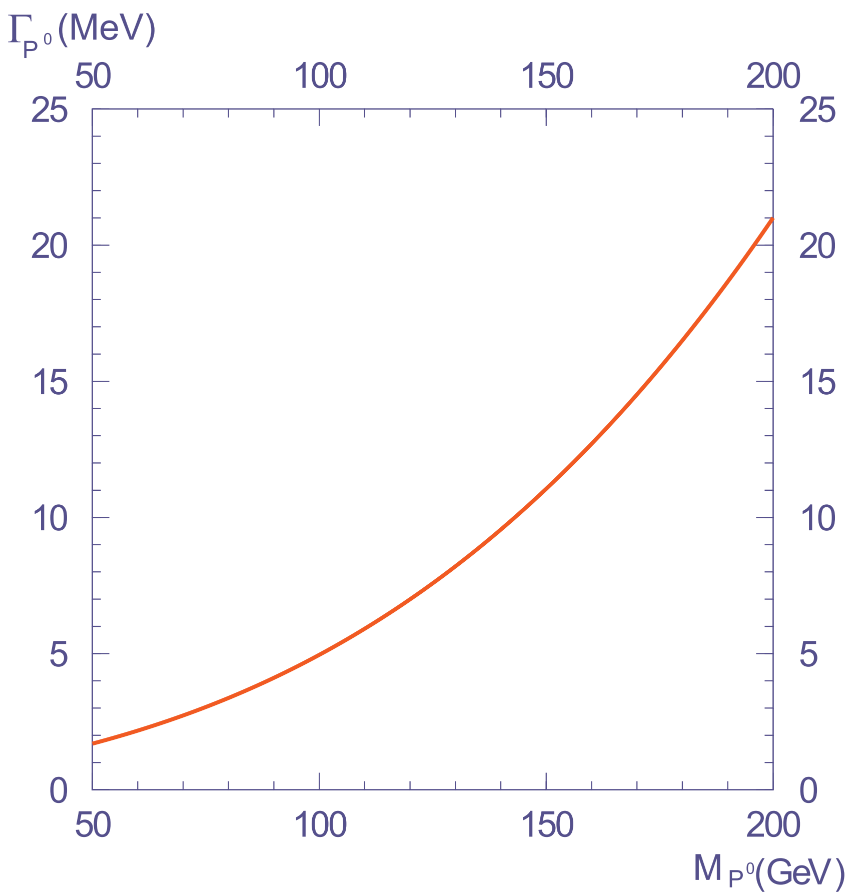
(V. Barger, M.S. Berger, J.F. Gunion and T. Han, Phys. Rep. **286** (1997), hep-ph/9602415)

PNG bosons

★ Any DSB theory with a symmetry larger than $SU(2)_L \otimes SU(2)_R$ contains PNGB's

★ In many models the lightest PNGB, P^0, is the colorless, neutral, $T_3 = -1/2$ mass eigenstate. Its mass is proportional to m_b (R.C. et al., JHEP 081999011)

★ P^0 couples to $\mu^+\mu^- \propto m_\mu/v$. It is almost as narrow as the Higgs. Typically $2 \le \Gamma_{P^0} \le 20\ MeV$ for $50 \le m_{P^0} \le 200\ GeV$



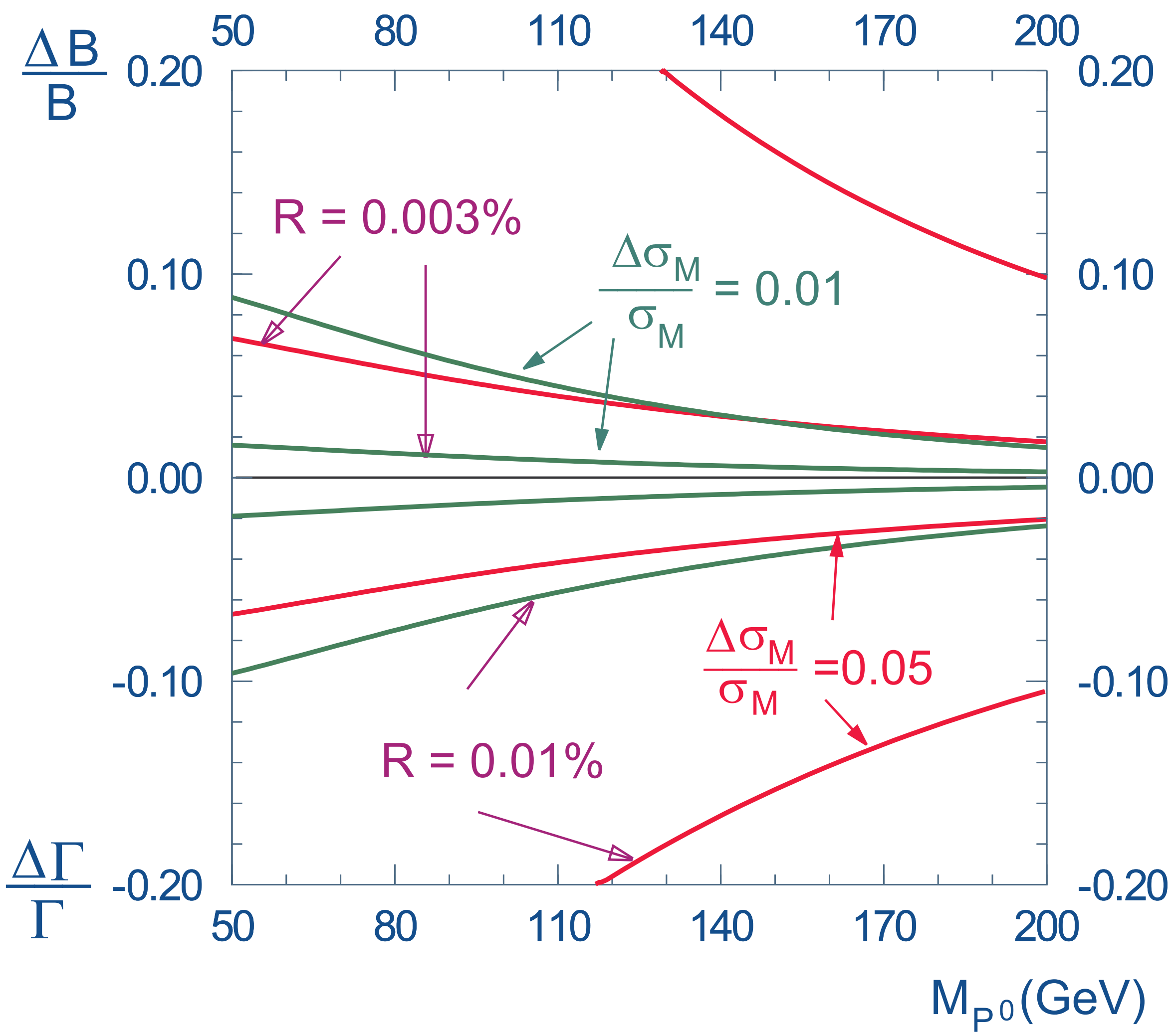
- ★ No constraints on P^0 from LEP, LEP2, Tevatron Run I. Some possibilities at Run II (via $gg \to P^0 \to \gamma\gamma$, $m_{P^0} > 60\ GeV$). Perhaps at the LHC, $30 \le m_{P^0} \le 200\ GeV$, with uncertainties on the lower bound due to γ-j discrimination (requires detailed study)

- ★ Not easy at the NLC since no tree-level couplings ZZP^0 (only via $e^+e^- \to \gamma P^0$). At the $\gamma\gamma$ option, $\gamma\gamma \to P^0 \to b\bar{b}$ robust, other final states uncertain

- ★ **Only μC has the potential to study the P^0 in detail**

- ★ **Strategy:** **Possibility of scanning in about 1 year the case $\mathrm{m_{P^0}} < 80\ \mathrm{GeV}$. Above this mass LHC may discover it with $\approx 100\ \mathrm{MeV}$ uncertainty. If not too close to $\mathrm{m_Z}$, μC can scan and center on the particle in less than 1 year**

★ Once centered good measurements of rates in $b\bar{b}$, $\tau^+\tau^-$, $c\bar{c}$ and gg final states, and of the total width. Systematics from errors on $\Delta\sigma_M$ under control using $R = 0.003\%$



★ The statistical fractional errors for the combined the channel rates and Γ_{P0}, are given in the next Table. The luminosity is 0.4 fb^{-1}. Scan and the $\bar{r}$-ratio techniques are compared. In the latter case one run $2f$ yrs at $R = 0.003\%$ and $(4 - 2f)$ yrs at $R = 0.03\%$. For the scanning $R = 0.003\%$

Quantity	Errors for the scan procedure					
Mass (GeV)	**60**	**80**	M_Z	**110**	**150**	**200**
$\sigma_c B$	0.0029	0.0054	0.043	0.0093	0.012	0.018
Γ_{P0}	0.014	0.029	0.25	0.042	0.052	0.10
Quantity	Errors for the r_c-ratio procedure					
Mass (GeV)	**60**	**80**	M_Z	**110**	**150**	**200**
f	0.8	0.7	0.6	0.8	0.9	1.0
$\sigma_c B$	0.0029	0.0062	0.055	0.010	0.011	0.016
Γ_{P0}	0.014	0.028	0.24	0.041	0.039	0.053

►►► **If PNGB's exist no substitute for μC**

Conclusions

Compare LHC, ≤ 2 TeV NLC, ≤ 4 TeV μC

X = inaccessible, Y = accessible, F = μ flavor helps, P = polarization helps (NLC), R = μC energy resolution helps, E = high energy helps

Physics	LHC	NLC	μC
Narrow Resonances			
Higgs	Y	Y	Y: F, R
PNGB's	Y	?: $\gamma\gamma$	Y: F,R
Supersymmetry			
Heavy H^0, A^0	X?	Y?: $\gamma\gamma$?	Y: E,F,R
Sfermions	$\tilde{q}$, $\tilde{\ell}$?	$\tilde{q}$, $\tilde{\ell}$?	$\tilde{q}$, $\tilde{\ell}$: E,F
Charginos	Y?	Y: P	Y: F,R,E
R violation	$\bar{q}$ decays	λ_{1i1}	λ_{2i2}: F,R,E
SUSY breaking	good	better	superb: F,R,E
Strong WW, TC			
Continuum	$\leq 1.5\ TeV$	$\leq 1.5\ TeV$	$\leq 2.5\ TeV$: E
Resonances	Y	Y	Y: R,E
Extra Dimensions			
$\not{E}_T$	Y	Y	Y: E, R?
Resonances	q^*, g^*	γ^*, Z^*, e^*	γ^*, Z^*, μ^*: R, E