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Potentials of Linear Colliders in Stoponium Searchs

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- Stoponiums could exist. Two scenaria in MSSM with stoponium.
- Stoponium search at PLC. Stoponium factory in case of 2nd scenario.
- Some prospects to observe stoponium at e^+e^- collider.
- Stoponium at muon collider: excelent possibilities to study couplings.

Stop could be light:

- RG ↘ A_t
- large $\tilde{t}_L - \tilde{t}_R$ mixing

could be in SUGRA, GMSB, ...

ALEPH (moriond'2000) $m_{\tilde{t}_1} > 90$ GeV

if $m_{\tilde{\nu}} > 45$ GeV or $m_{\tilde{\chi}} > 50$ GeV

CDF (Moriond'2000) $m_{\tilde{t}_1} > 130$ GeV if $m_{\tilde{\nu}} < 45$ GeV

If $m_{\tilde{t}} \sim m_{\tilde{\chi}} \Rightarrow m_{\tilde{t}_1} > 60$ GeV (ALEPH)

Like a quarkonium $(\tilde{t}\bar{\tilde{t}})$ system can be treated as a quasistationary system with masses

$$M_n = 2m_{\tilde{t}} + E_n \qquad (E_n < 0)$$

for $m_{\tilde{t}} = 100 - 300$ GeV $\quad E_n \sim 1$ GeV

Hagiwara et al 90'

(S)

Stoponium exists if the formation process (time scale $\sim \frac{1}{|E_n|}$) is faster than destroying processes

Possible destroying processes:

i) single stop decays

$\tilde{t} \to t + LSP$, $\tilde{t} \to b +$ chargino, $\tilde{t} \to c +$ neutralino

ii) annihilation decays

$S \to gg$, $S \to hh$, $S \to \gamma\gamma$, ...

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i) $\tilde{t} \to c +$ neutralino

~~FCNC~~ $\Rightarrow$ 1-loop diagrams
suppression factor $\sim 10^{-7}$
Hikasa & Kobayashi '87

GMSB, $LSP = \tilde{G}$
$\tilde{t} \to t + \tilde{G}$

suppressed by SUSY breaking scale

Gravity mediation, LSP = neutralino

$\Gamma(\tilde{t} \to t +$ neutralino$)$, $\Gamma(\tilde{t} \to b +$ chargino$) \sim \alpha\, m_{\tilde{t}}$

if $\exists$ no stoponium

but: if chargino $\simeq \tilde{W}$ and $\tilde{t}_1 \simeq \tilde{t}_R$
then $\tilde{t} \to b +$ chargino chanel is damped
and stoponium exists if

$m_{\tilde{t}} < m_t + m_{LSP}$

$\Downarrow$

Some other possibilities

Drees & Nojiri '94

ii) Drees & Nojiri '94 found two scenaria with S:

I. dominant decay channel $S \to gg$ $\quad \Gamma_S \sim 1$ MeV

II. dominant decay channel $S \to hh$ $\quad \Gamma_S \sim 5\text{-}10$ MeV

In both scenaria S exists as a qusistationary system for $M_S \lesssim 600$ GeV (< 300 GeV if chargino and neutralino ~ higgsino)

We discuss mass range $M_S = 200 - 400$ GeV

if exists this resonance is an object to be observe/study at first stages of LC operating ($\sqrt{s_{ee}} \lesssim 500$ GeV)

Stoponium was studied in

M. J. Herrero, A. Mendoz and T. G. Rizzo PL B200 (1988)

V. Barger and W.-Y. Keung PL B 211 (1988)

H. Inazawa and T. Morii PRL 70 (1993)

M. Drees and M. M. Nojiri PRL 72 (1993)

• M. Drees and M. M. Nojiri PR D49 (1994) 4595

$$A = \frac{2 A_t}{m_{\tilde t_L} + m_{\tilde t_R}}, \quad m_{\tilde t_R} = m_{\tilde t_L}$$

$\tan\beta = 3$ $\mu = 500$ GeV $M_A = 1$ TeV

Drees & Nojiri '94

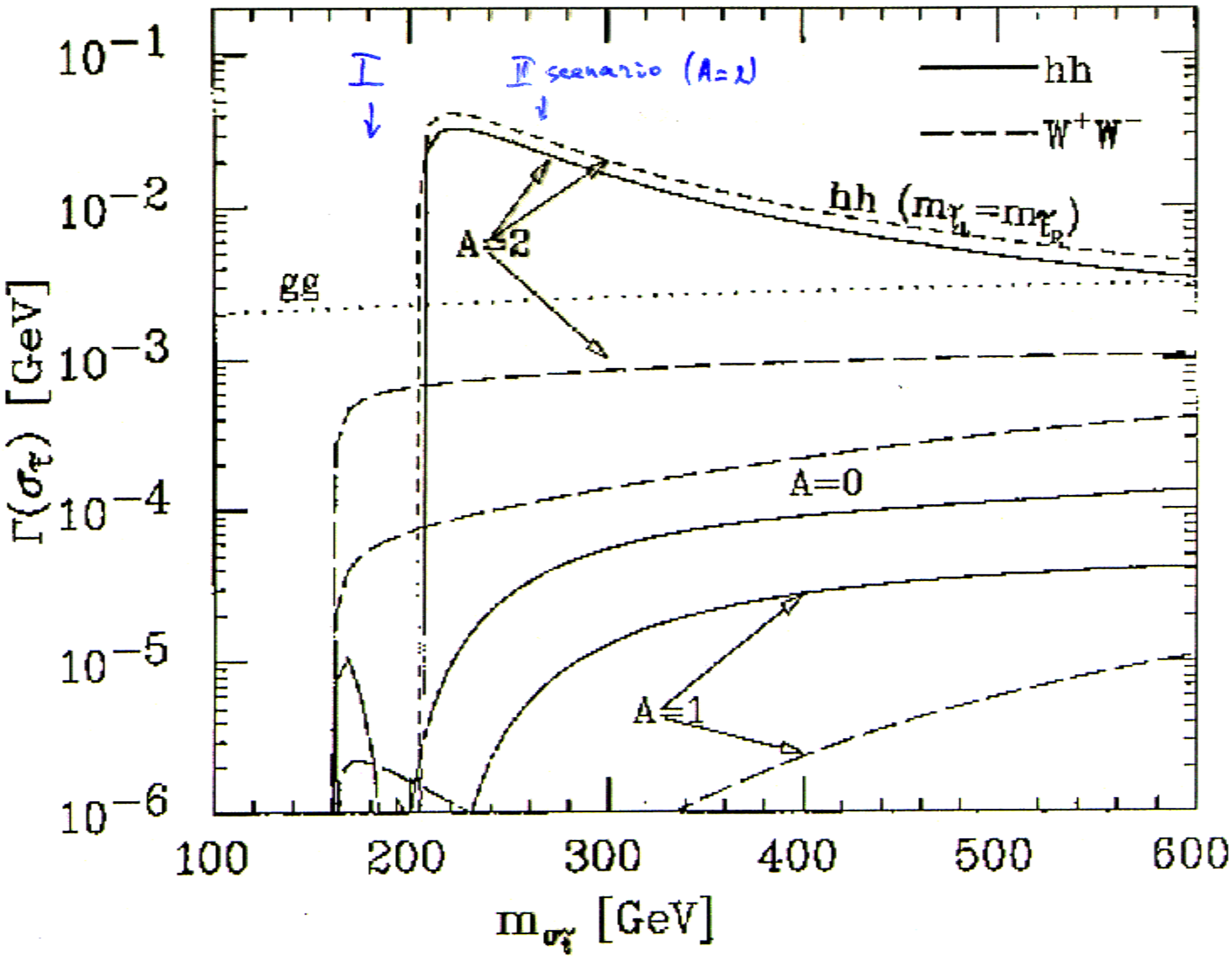


Fig. 5

LC: $\mathcal{L}^{year}_{e^+e^-} = 300\ fb^{-1}$

PLC: $E^{max}_{\gamma\gamma} \sim 0.8\ E_{e^+e^-}$

for 15% $\sqrt{s_{\gamma\gamma}}$ interval below $E^{max}_{\gamma\gamma}$

$$\mathcal{L}^{year}_{\gamma\gamma} \simeq \frac{1}{5}\,\mathcal{L}^{year}_{e^+e^-} \sim 60\ fb^{-1}$$ "canonical"

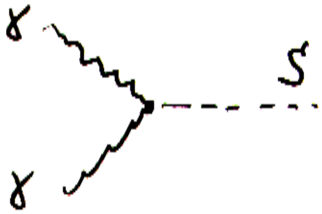
proposals to decrease of horizontal beam emittance at damping ring and increase of repetition rate at low beam energies

⇓

$$\mathcal{L}^{year}_{\gamma\gamma} \simeq 3.2 \cdot \mathcal{L}^{year}_{e^+e^-} \sim 1000\ fb^{-1}$$ "optimistic"

S at PLC

direct resonance production



eff. vertex through

$$\Gamma_{S\to\gamma\gamma} = \sigma(\tilde{t}_1 \bar{\tilde{t}}_1 \to \gamma\gamma)\Big|_{v=0} \cdot v \cdot |\Psi(0)|^2$$

$$\Psi(x) = \frac{1}{\sqrt{\pi}} \left(\frac{\alpha M_S}{4}\right)^{3/2} e^{-\frac{\alpha}{4} x M_S}$$

monochromatic beams:

$$\hat{\sigma}_{\gamma\gamma\to S\to f}(\hat{s}) = 8\pi \frac{\Gamma_{\gamma\gamma} \cdot \Gamma_f}{(\hat{s} - M_S^2)^2 + \Gamma_{tot}^2 \cdot M_S^2}$$

"15%" beam spectrum:

$$\sigma \sim \sigma^{res} \cdot \frac{2\Gamma_{tot}}{0.15 \cdot E_{\gamma\gamma}^{max}}$$

$$\Downarrow$$

$$\sigma_f \simeq 140\,fb \cdot \left(\frac{Br_{\gamma\gamma}}{4 \cdot 10^{-3}}\right) \cdot Br_f \cdot \left(\frac{\Gamma_{tot}}{1\,MeV}\right) \cdot \left(\frac{200\,GeV}{M_S}\right)^3$$

(factor 2 included assuming 100% polarized γ beams)

PLC I scenario

$S \to gg$ dominates $\Gamma_{tot} \sim 1$ MeV $Br_{\gamma\gamma} \sim 4 \cdot 10^{-3}$

$\sigma_{\gamma\gamma \to S} \sim 140$ fb $\sim 8 \cdot 10^3$ stoponiums/year
for $\mathcal{L}_{\gamma\gamma}^{year} = 60$ fb^{-1}

Final states:

gg $\sigma^B_{\gamma\gamma \to q\bar{q}} \sim 50$ pb $(\theta_j > 5°)$

for $M_S = 200$ GeV $\frac{S}{B} \sim \frac{1}{200}$, $\frac{S}{\sqrt{B}} \sim 4$ (60 fb^{-1})

for $\mathcal{L}_{\gamma\gamma}^{year} = 1000$ fb^{-1} $\frac{S}{\sqrt{B}} > 5$ for $M_S = 200-400$ GeV

$\gamma\gamma$ $\sigma^S = 0.5 - 0.2$ fb for $M_S = 200 - 300$ GeV

$\sigma^B_{\gamma\gamma \to \gamma\gamma}(200 \pm 1.4\text{ GeV}) \sim 1$ fb

↑ CMS like ECAL

$\frac{S}{\sqrt{B}} = 4 - 1.5$ 60 fb^{-1}

ZZ $Br_{ZZ} \sim 4 \cdot 10^{-2}$ for $M_S = 250 - 400$ GeV

$\sigma^S \sim 2.8$ fb for $M_S = 250$ GeV

$\sigma^B_{\gamma\gamma \to ZZ} \sim 50$ fb Gounaris et al '99

$\frac{S}{\sqrt{B}} \sim 2.5$ 60 fb^{-1}

PLC I scenario (cont.)

hh open if $M_S > 2 m_h$ $\quad Br_{hh} \gtrsim 2 \cdot 10^{-2}$

$\sigma^S \sim 1.5\,fb$ for $M_S = 250$ GeV

$\sigma^B_{\gamma\gamma \to hh} \sim 0.2\,fb$ (SM Jikia '94)

$\sigma^B_{\gamma\gamma \to bbbb} \sim 0.1\,fb$

$60\,fb^{-1}$: ~ 100 signal events

$\frac{S}{B} \sim 5$ $\qquad \frac{S}{\sqrt{B}} \simeq 20$

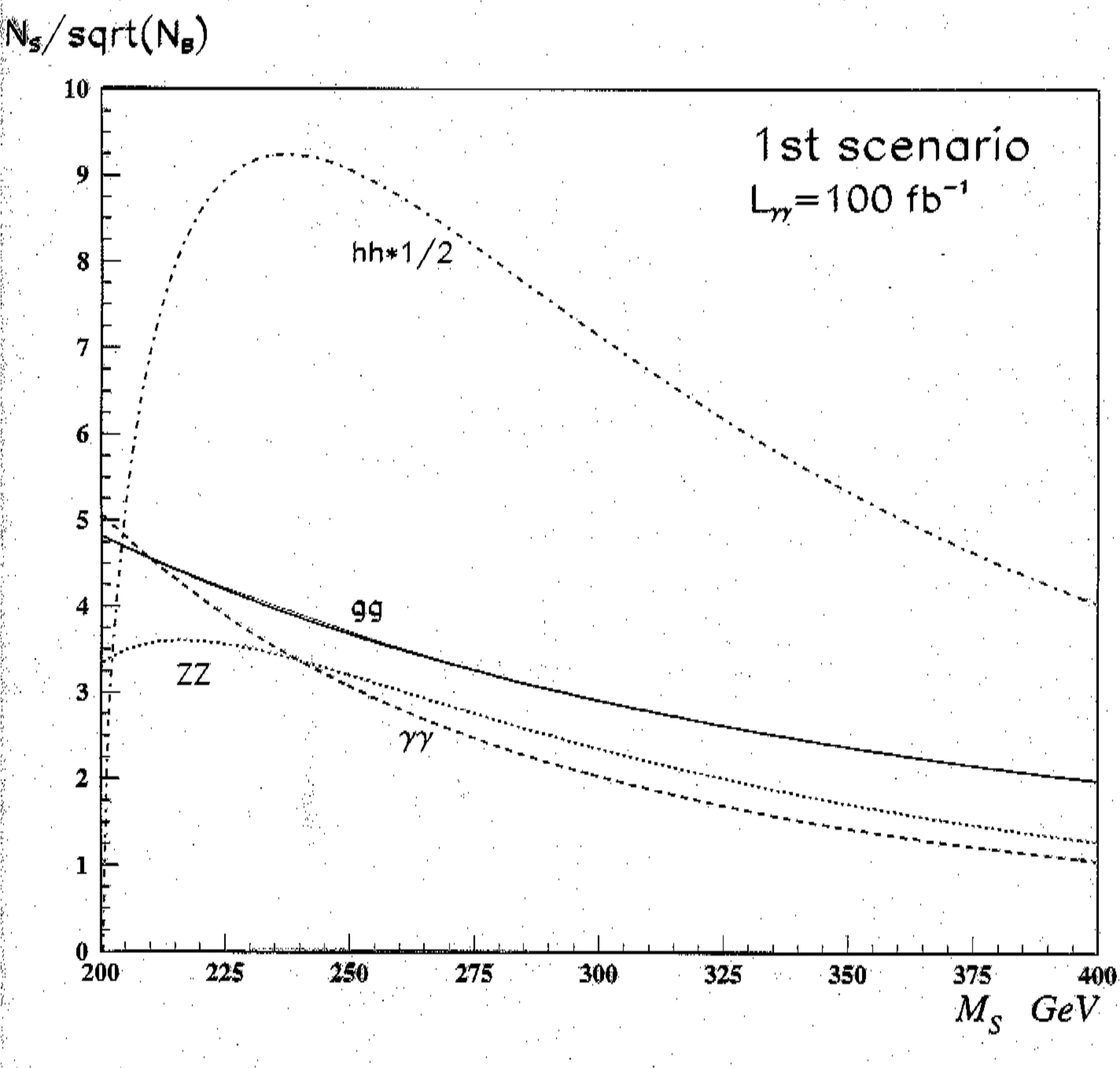
(without threshold suppression ↘ 14)

LHC^{high} $\sim$ PLC

$pp \to S \to \gamma\gamma$ $\qquad \gamma\gamma \to S \to hh$

Drees & Nojiri '94

$\lambda_{ggS}, \lambda_{\gamma\gamma S}$ $\qquad + \lambda_{Shh}$



Ns/sqrt(NB)
1st scenario
Lγγ=100 fb-1
hh*1/2
gg
ZZ
γγ
0
1
2
3
4
5
6
7
8
9
10
200
225
250
275
300
325
350
375
400
MS GeV

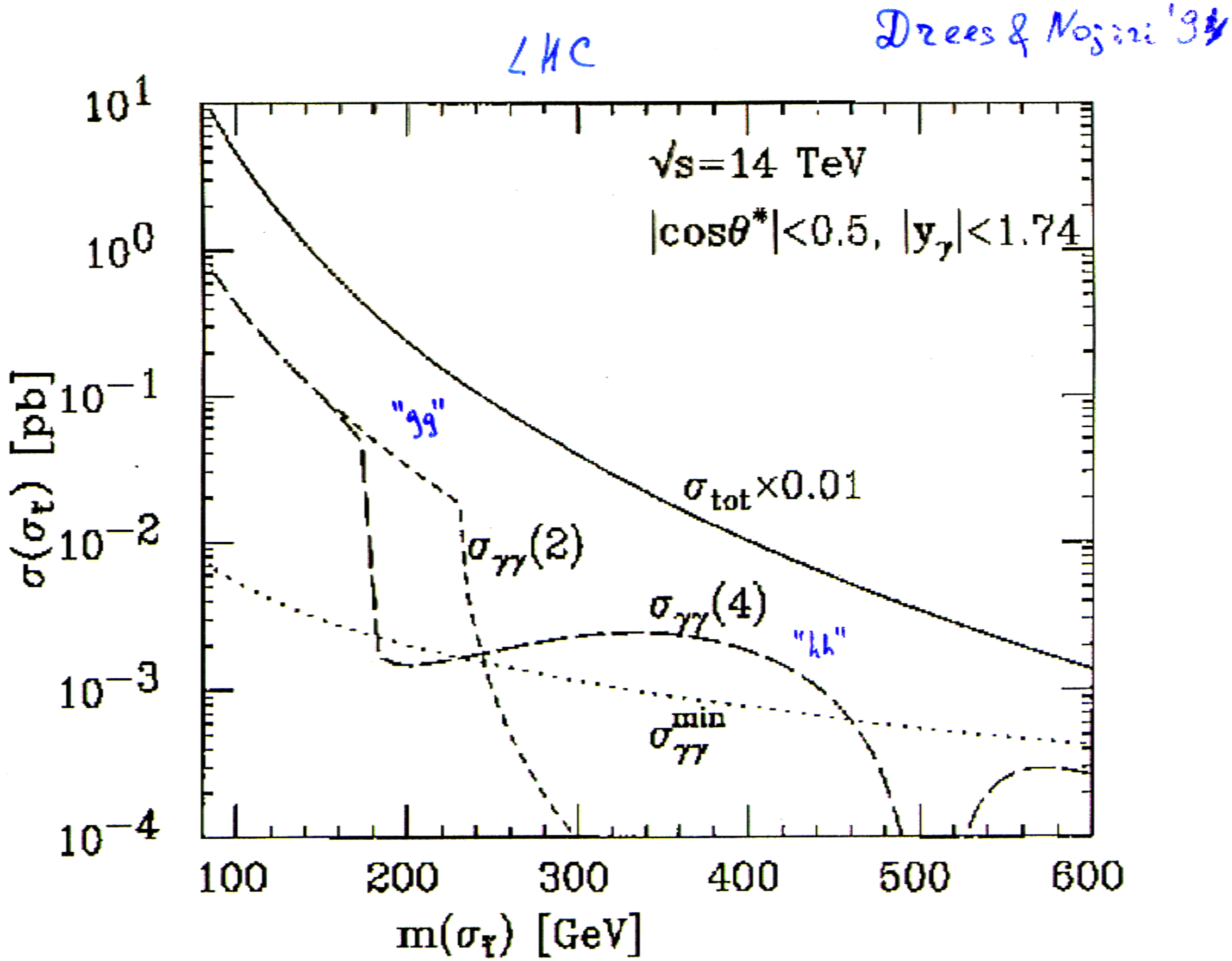

LHC
Drees & Nojiri '93
√s=14 TeV
|cosθ*|<0.5, |y_γ|<1.74
σ_tot ×0.01
σ_γγ(2)
σ_γγ(4)
σ_γγ^min
"gg"
"hh"
σ(σ_t) [pb]
m(σ_t) [GeV]
10^1
10^0
10^-1
10^-2
10^-3
10^-4
100
200
300
400
500
600

Fig. 7

PLC II scenario

$S \to hh$ dominates $\quad \Gamma_{tot} \gtrsim 10\ \mathrm{MeV} \quad B_{\gamma\gamma} \sim (2\text{-}4)\cdot 10^{-4}$

$$\sigma^{S}_{\gamma\gamma \to S \to hh} \sim 70 - 140\ \mathrm{fb}$$

$$\sigma^{B}_{\substack{\gamma\gamma \to hh \\ \gamma\gamma \to b\bar{b}b\bar{b}}} \sim 0.3\ \mathrm{fb}$$

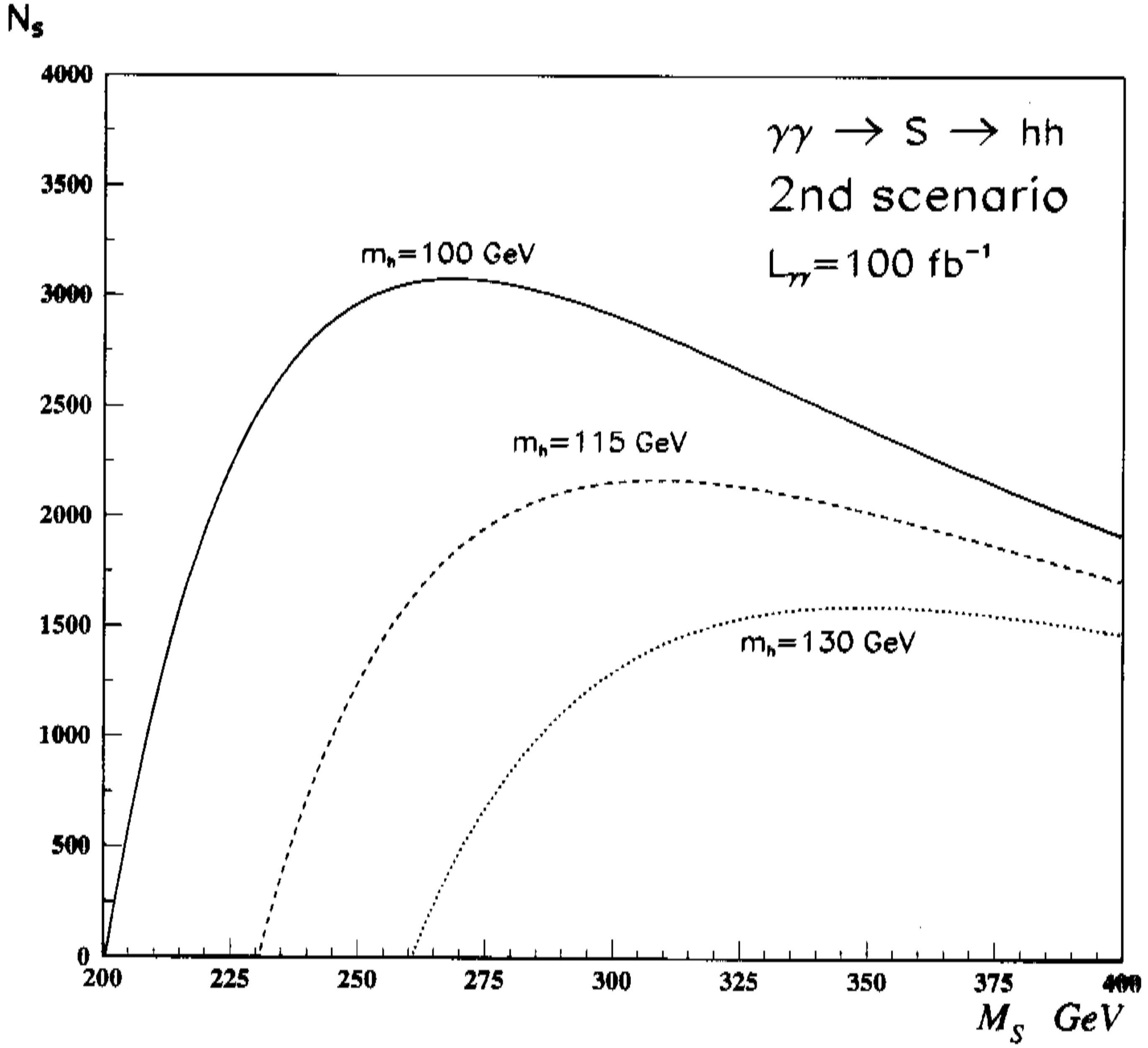
thousands of stoponiums / year $\quad 60\ \mathrm{fb}^{-1}$

practically free of background

PLC as a S-factory

LHC: few years at $\mathcal{L}^{high}$

Drees & Nojiri '94



N_s
4000
3500
3000
2500
2000
1500
1000
500
0
200
225
250
275
300
325
350
375
400
M_S GeV
$\gamma\gamma \rightarrow S \rightarrow hh$
2nd scenario
$L_{\gamma\gamma}=100\ fb^{-1}$
m_h=100 GeV
m_h=115 GeV
m_h=130 GeV

e^+e^-

1). $e^+e^- \to S$ in P-state of $e^\pm$

$$\sigma^{res} = \frac{12\pi}{M_S^2} \frac{\Gamma(S\to e^+e^-)}{\Gamma_{tot}}, \quad \Gamma(S\to e^+e^-) = \frac{32}{3}\alpha^2 \frac{|R_P'(0)|^2}{M_S^4}$$

Beamstrahlung + ISR $\Rightarrow$ effective width of the collision energy spread

$w_{eff} \sim \mathcal{O}(10\ \text{GeV})$

$$\sigma_{e^+e^-\to S} \sim \sigma^{res} \cdot \frac{2\Gamma_{tot}}{w_{eff}}$$

$$\frac{|R_P'(0)|^2}{M_S^4} = 5\cdot 10^{-5}\ \text{GeV}$$ Hagiwara et al '90

so $\sigma_{e^+e^-\to S} \sim 4\ \text{fb} \left(\frac{200\ \text{GeV}}{M_S}\right)^2$

$$\frac{\sigma_{e^+e^-}}{\sigma_{PLC}} \sim \frac{1}{30} - \frac{1}{17} \quad M_S = 200-400\ \text{GeV}$$

$300\ \text{fb}^{-1}$ $N_S \sim 1000 \left(\frac{200\ \text{GeV}}{M_S}\right)^2$

I scenario: B $e^+e^- \to 2j$ $\sigma \sim 10\ \text{pb}$ for $\sqrt{s} = 200\ \text{GeV}$

$$\frac{S}{\sqrt{B}} \sim 0.5$$

hh $N_S \sim \mathcal{O}(10)$ /year

II scenario:

hh hundreds stoponiums /year
free of background

e^+e^- (cont.)

2). $e^+e^- \to Z S$ $\sigma \simeq 0.03$ fb (no mixing in stop sector, $M_{\tilde{t}} = 1$ TeV)

~10 signal events/year

only 2nd scenario could be visible...

B $e^+e^- \to Z hh$

$\sigma^B \sim 0.2 - 0.5$ fb $\quad tg\beta = 3 - 50$

$$\frac{S}{\sqrt{B}} < 1$$

$e^+e^- \to \nu\bar{\nu} S$ (W-fusion) $\quad \sigma < 10^{-3}$ fb

Muon collider

I. $\sqrt{s}_{\mu^+\mu^-} = 100$ GeV $\qquad \mathcal{L}^{year} = 1.2\ fb^{-1} \left(\frac{\varepsilon}{0.12\%}\right)^{0.67}$

$\delta(\sqrt{s}_{\mu\mu}) = 0.01\ \varepsilon$

$0.003 < \varepsilon < 0.12$

I a) $\sqrt{s}_{\mu\mu} = 200 - 300$ GeV

$\mathcal{L}^{year} = 0.1\ fb^{-1} \qquad \varepsilon = 0.003$

I b) $\sqrt{s}_{\mu\mu} = 200 - 300$ GeV

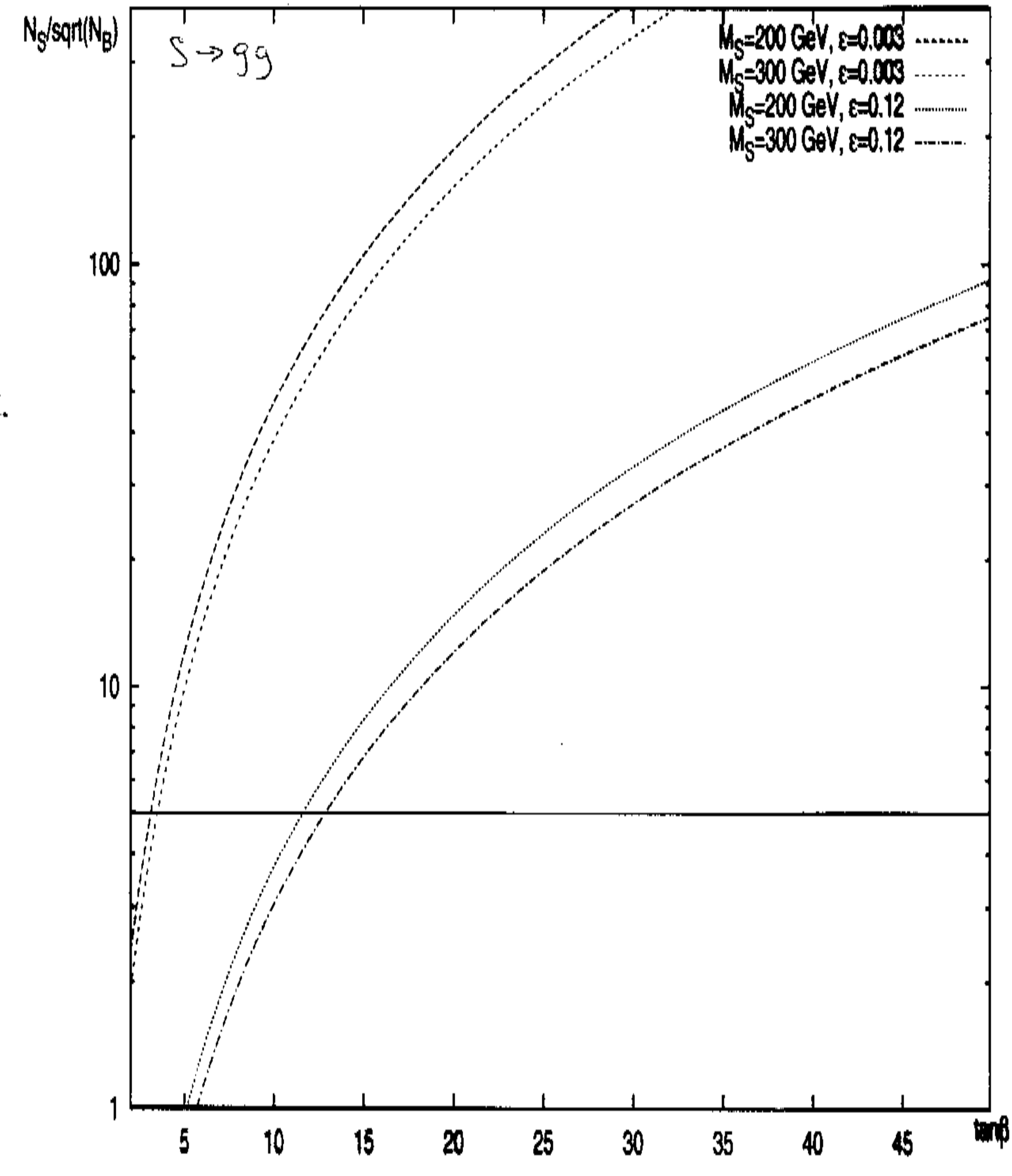
$\mathcal{L}^{year} = 1\ fb^{-1} \qquad \varepsilon = 0.12$

II $\sqrt{s}_{\mu\mu} = 300 - 600$ GeV

$\mathcal{L}^{year} = 10\ fb^{-1} \qquad \varepsilon = 0.14$

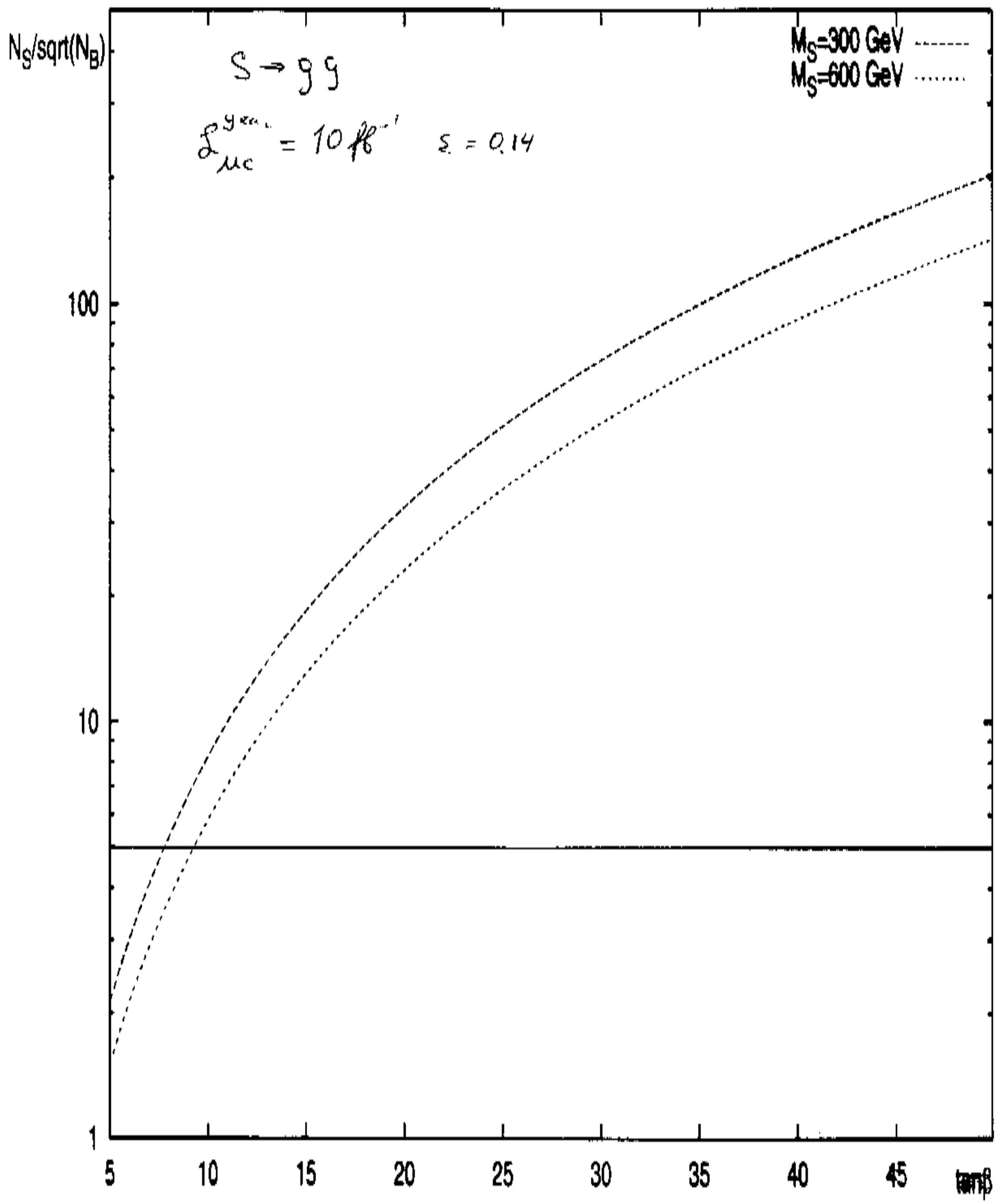
$$\sigma_{\mu^+\mu^- \to S \to f} \approx 7\,fb\ (1 + tg^2\beta) \cdot Br_f \cdot \left(\frac{200\ GeV}{\mu_S}\right)^{1/2} \cdot \left(\frac{0.1\%}{\varepsilon}\right)$$

I scenario



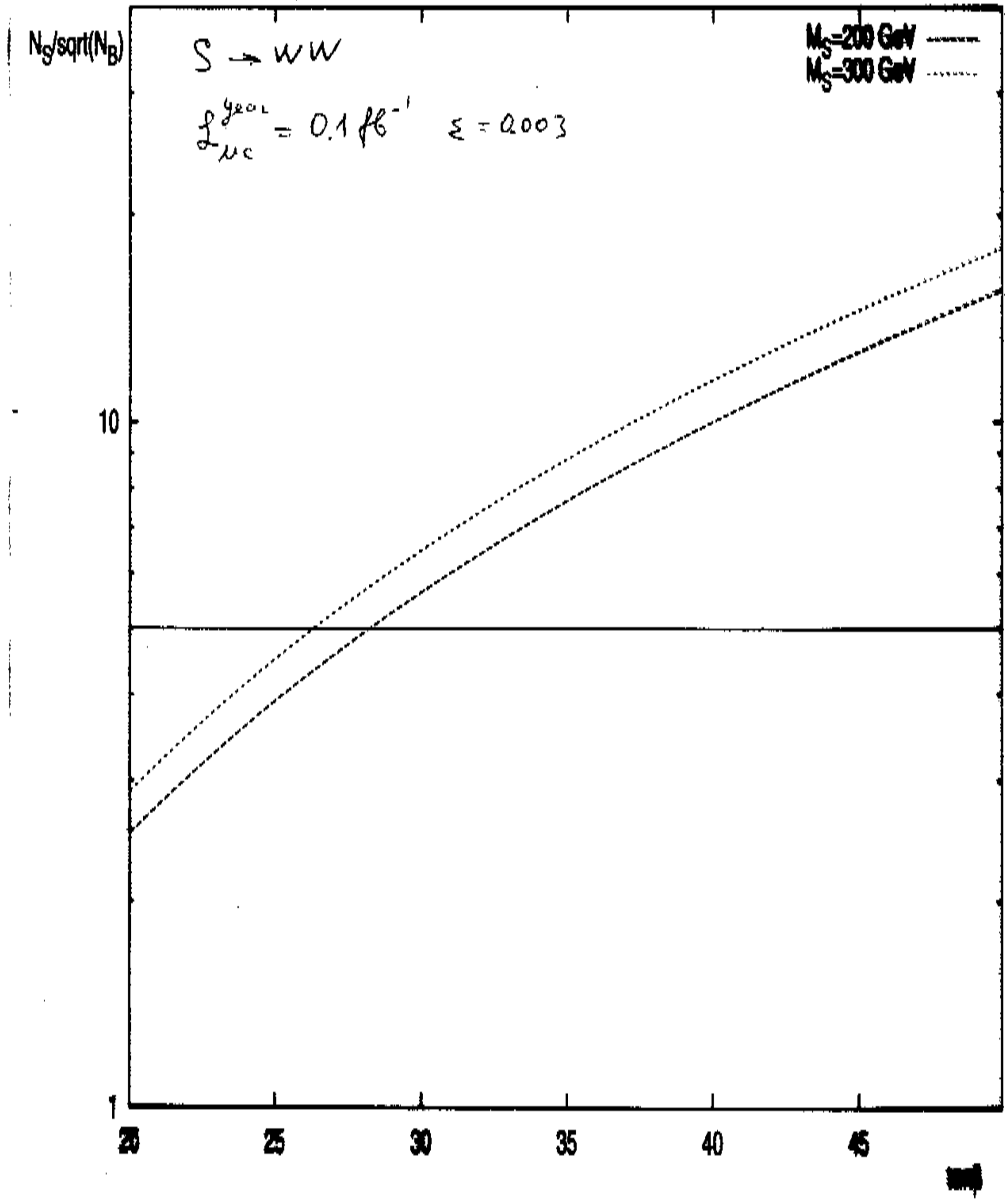
N_S/sqrt(N_B)
S→gg
M_S=200 GeV, ε=0.003
M_S=300 GeV, ε=0.003
M_S=200 GeV, ε=0.12
M_S=300 GeV, ε=0.12
100
10
1
5
10
15
20
25
30
35
40
45
tanβ

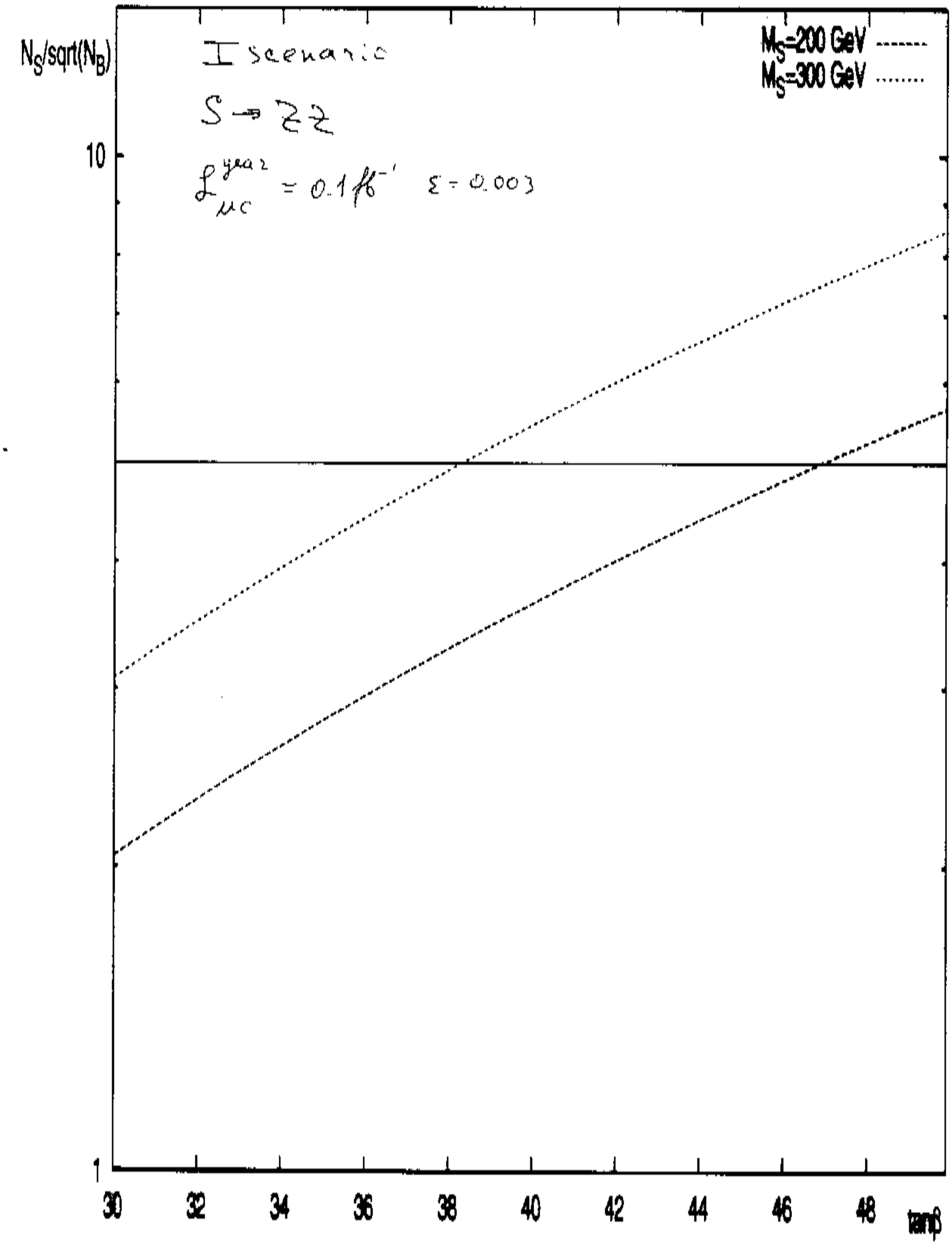
I scenario



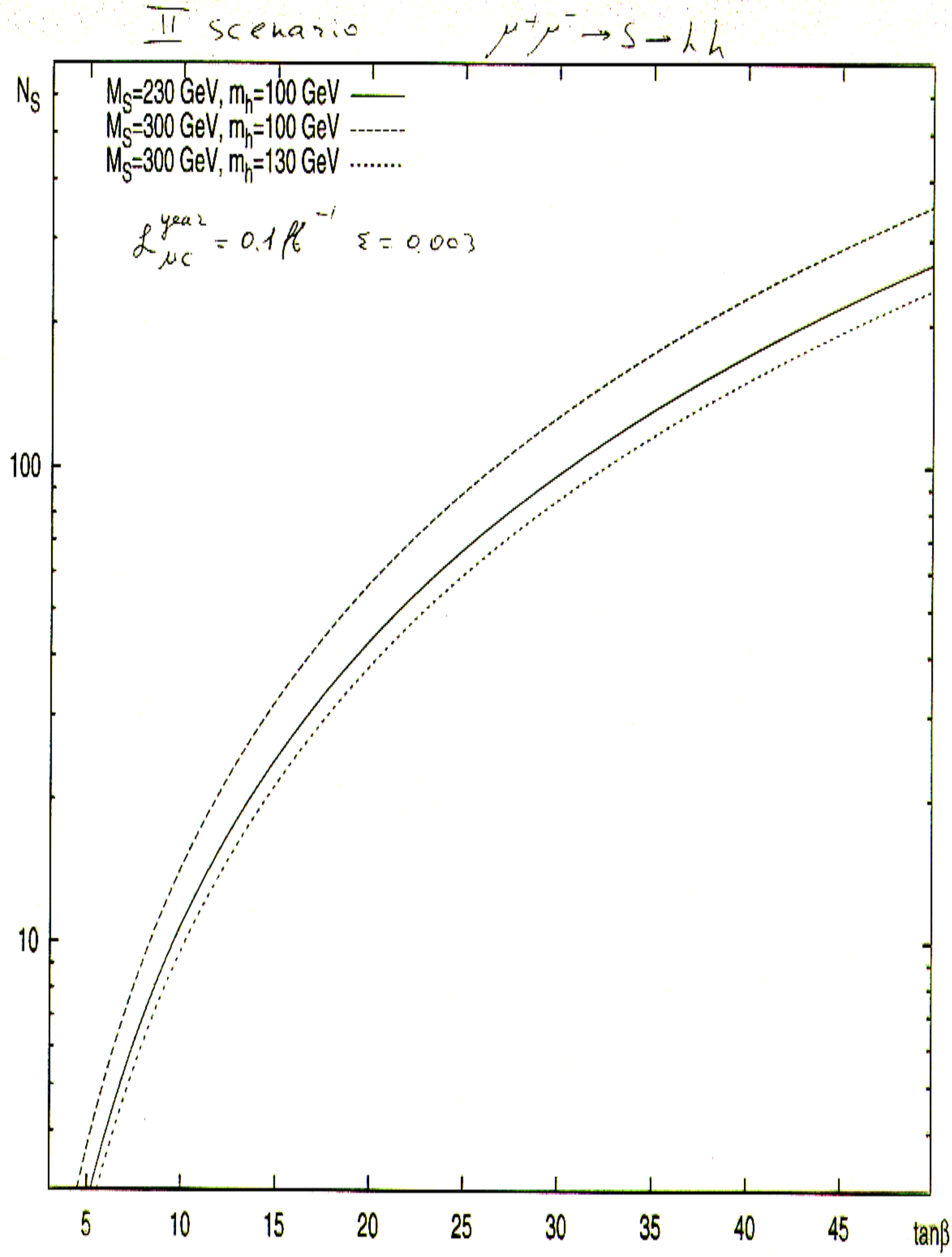
N_S/sqrt(N_B)
$S \to gg$
$\mathcal{L}_{\mu c}^{year} = 10\ fb^{-1}$ $\delta = 0.14$
M_S=300 GeV
M_S=600 GeV
100
10
1
5
10
15
20
25
30
35
40
45
tanβ

I Scenario

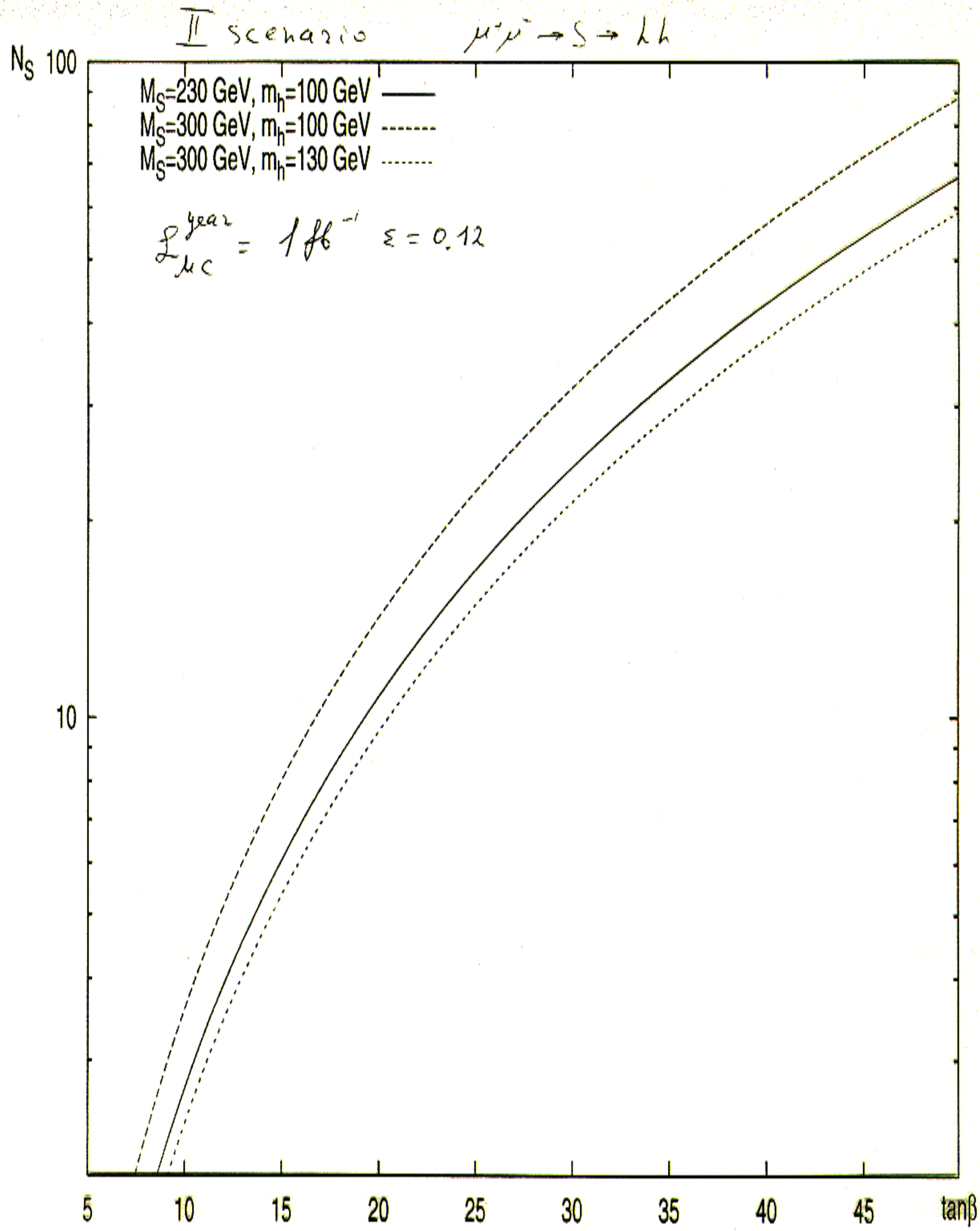

N_S/sqrt(N_B)
S → WW
$\mathcal{L}_{\mu c}^{year} = 0.1\ fb^{-1}$ $\varepsilon = 0.003$
M_S=200 GeV
M_S=300 GeV
10
1
20
25
30
35
40
45



N_S/sqrt(N_B)
I scenario
S → ZZ
$\mathcal{L}_{\mu C}^{year} = 0.1 fb^{-1}$ ε = 0.003
M_S=200 GeV
M_S=300 GeV
10
1
30
32
34
36
38
40
42
44
46
48
tanβ

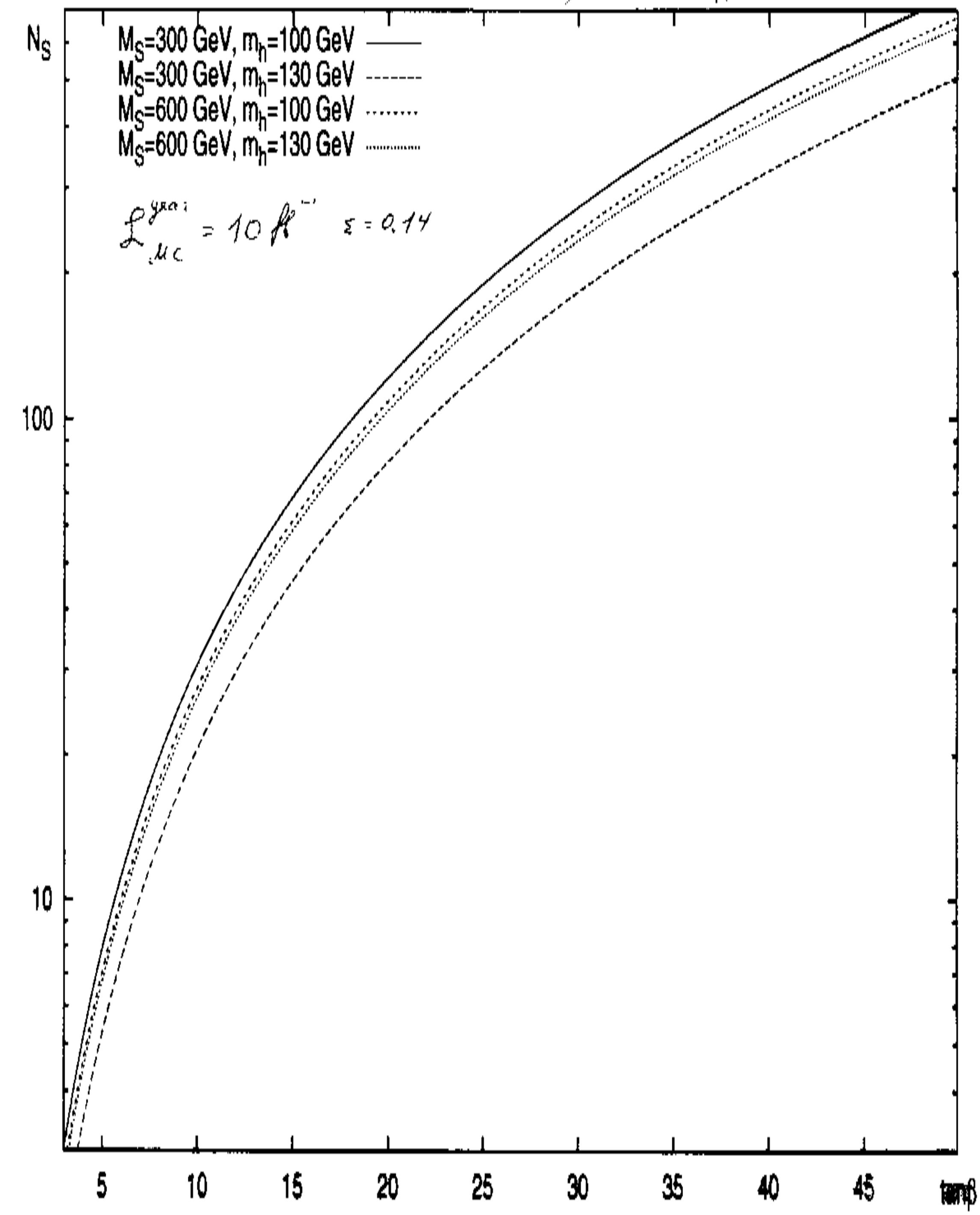


II scenario
$\mu^+\mu^- \to S \to hh$
N_S
M_S=230 GeV, m_h=100 GeV
M_S=300 GeV, m_h=100 GeV
M_S=300 GeV, m_h=130 GeV
$\mathcal{L}_{\mu c}^{year} = 0.1 fb^{-1}$ $\varepsilon = 0.003$
100
10
5
10
15
20
25
30
35
40
45
tanβ



II scenario $\mu^+\mu^- \to S \to hh$
N_S
100
10
M_S=230 GeV, m_h=100 GeV
M_S=300 GeV, m_h=100 GeV
M_S=300 GeV, m_h=130 GeV
$\mathcal{L}^{year}_{\mu C} = 1 fb^{-1}$ $\varepsilon = 0.12$
5
10
15
20
25
30
35
40
45
tanβ

2nd scenario $\mu^+\mu^- \to S \to hh$



Conclusions

Stoponium exist in some MSSM scenaria
with $M_S = 200 - 400\ (600)$ GeV
and can be observed / studied at:

LHC $pp \to S \to \gamma\gamma$

I scenario $\frac{S}{\sqrt{B}} \simeq \mathcal{O}(10)$

II scenario few years at $\mathcal{L}^{high}$

PLC $60\,fb^{-1}$ $1000\,fb^{-1}$

I scenario

$\gamma\gamma \to S \to hh$ $\frac{S}{\sqrt{B}} \simeq \mathcal{O}(10)$

$\gamma\gamma \to S \to gg$ $\frac{S}{\sqrt{B}} \sim 4-2$

$\gamma\gamma \to S \to \gamma\gamma,\ ZZ$ $\frac{S}{\sqrt{B}} \sim 3-1$

II scenario $\gamma\gamma \to S \to hh$ $10^4 - 10^3$ stoponiums / year
no background
S-factory

$\gamma\gamma \to S \to gg,\ \gamma\gamma,\ ZZ$ $\frac{S}{\sqrt{B}} \sim$ few

e^+e^- II scenario only $e^+e^- \to S \to hh$ $\mathcal{O}(10^2)$ stoponiums/year
free of background

MC excelent possibilities to measure effective couplings
$S\gamma\gamma$, Shh, Sgg, SWW, SZZ, ...