PROGRESS ON e^+e^- LINEAR COLLIDERS

– PHYSICS ISSUES –

1.) INTRODUCTION
- general physics base
- LC physics parameters

2.) ELECTROWEAK SYMMETRY BREAKING
- Higgs mechanism
- alternative: strong elec symmetry breaking

3.) SUPERSYMMETRY
- exp. and phenomenological analyses
- reconstructing fundam. SUSY parameters

4.) EXTRA SPACE DIMENSIONS

5.) HIGH - PRECISION PHYSICS: SM & BEYOND
- top and QCD
- electroweak gauge theories: SM & extended

6.) SUMMARY

1. INTRODUCTION

LINEAR COLLIDER TARGETS:

1. phase: high-precision coverage of energy range above LEP2 up to ~ 1 TeV

2. phase: extending energy up to ~ 5 TeV

PHYSICS GOALS:

- Electroweak symmetry breaking:
  microscop. picture: Higgs physics / dynam. elw SB
- grand / ultimate unification:
  exploring supersymmetry: phenom. + fundam. theory
- Structure of space and time:
  extra space dimensions at low scales //
- high-precision SM analyses:
  top, QCD, $W^{\pm}/Z$ ... q.m. closure of model / new windows

PROGRAM:

- LC complementary to and synergetic with LHC program
- high precision: extrapolation to scales that cannot be accessed directly

- **Energy steps:** … 500 GeV … 1 TeV

  … 3 TeV … 5 TeV

- **Luminosities:** $\mathcal{L} \sim 1.5$ to $3 \times 10^{34}\ cm^{-2}\ sec^{-1}$

  $\int\mathcal{L} = 1\ ab^{-1}$ in several years

  \# SM events $\sim 10^{6}$

  \# beam-Strahlg $\sim$ 4% in first phase } lumi peak

  $>$ 30% in second phase } max E

- **Polarization:** $e^- \approx 90\%$, $e^+ \approx 60\%$ } – supp. bkgd / $e^+e^- \to W^+W^-$ – particle diagnostics

- **Satellite modes:** e^-e^- : $E = 100\%$ $\mathcal{L} \sim 10\%$

  Compton back-scattg of laser light:

  $e\gamma$: $E \approx 90\%$ $\mathcal{L} \sim 30\%$

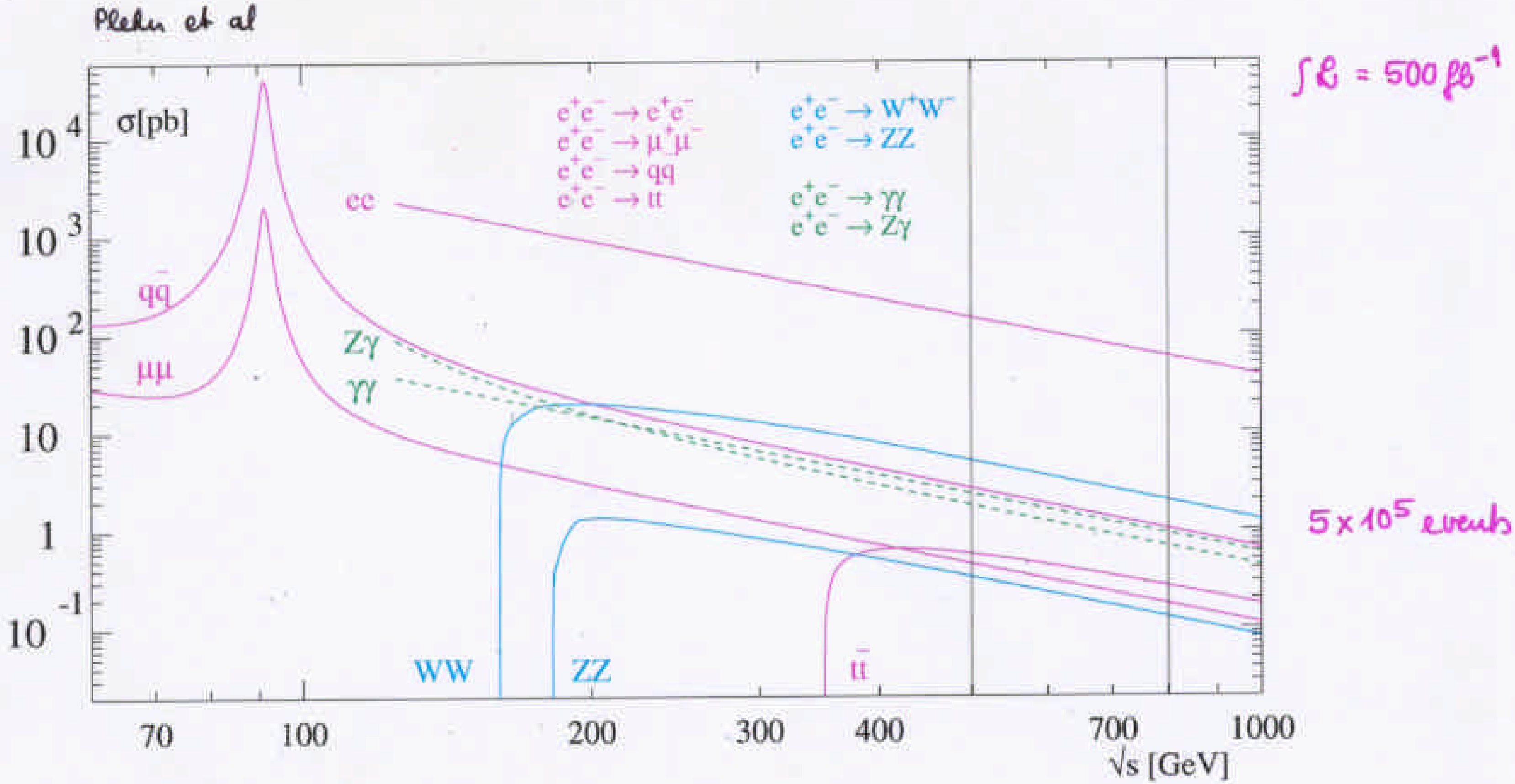
  $\gamma\gamma$: $E \approx 80\%$ $\mathcal{L} \sim 30\%$

  giga Z: $E \sim M_Z$ $\sim 10^9\ Z$

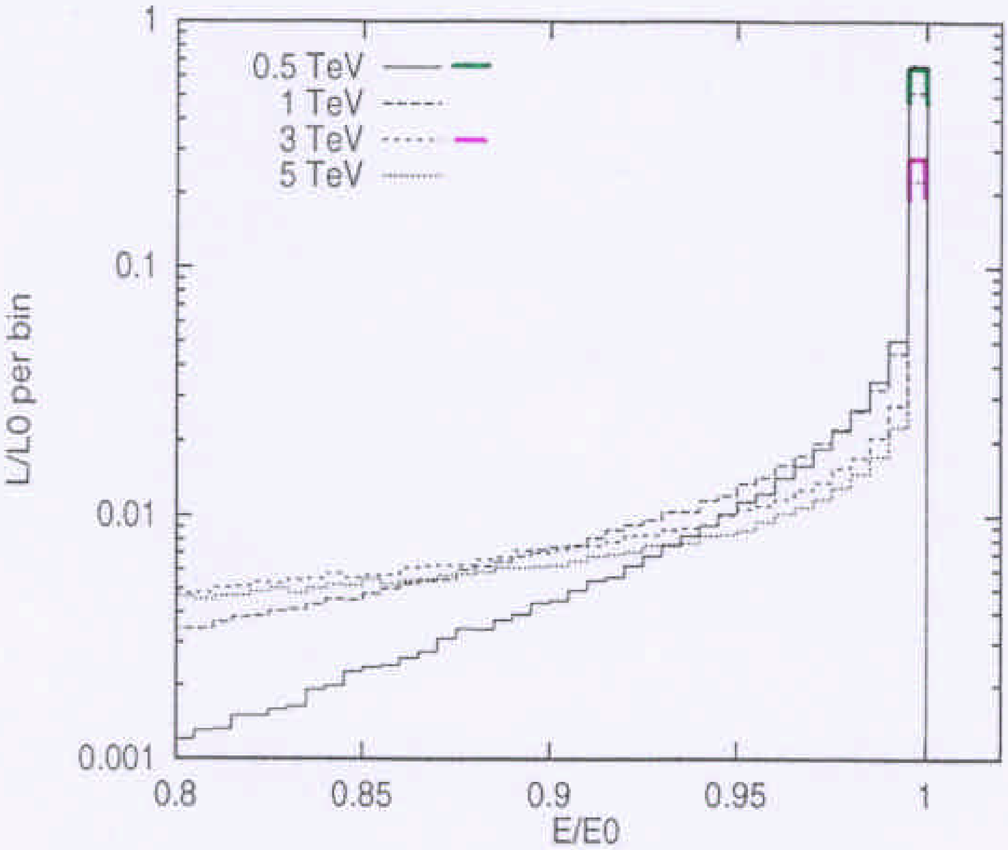
  $\sim 2M_W$ $\sim 10^6\ WW$

DESIGNS: CLIC, JLC, NLC, TESLA ⇐

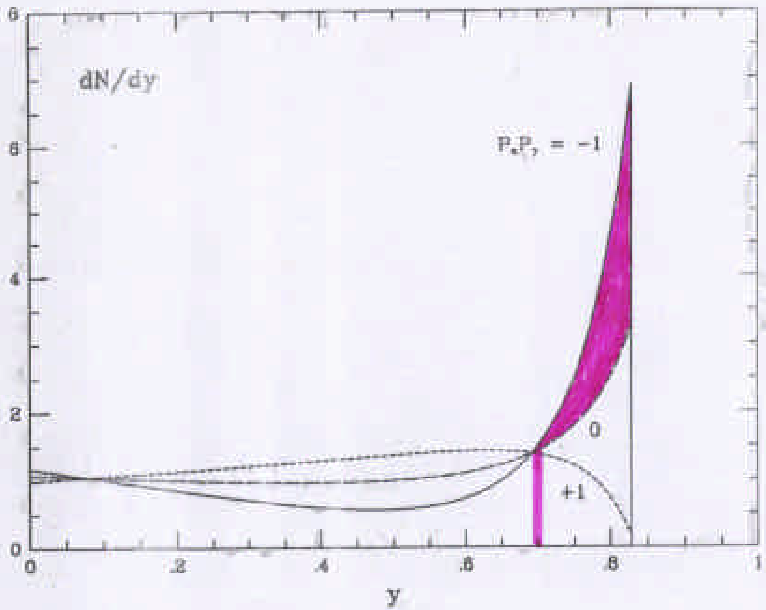
time goal for 1. phase : overlap with LHC } ~ 2012

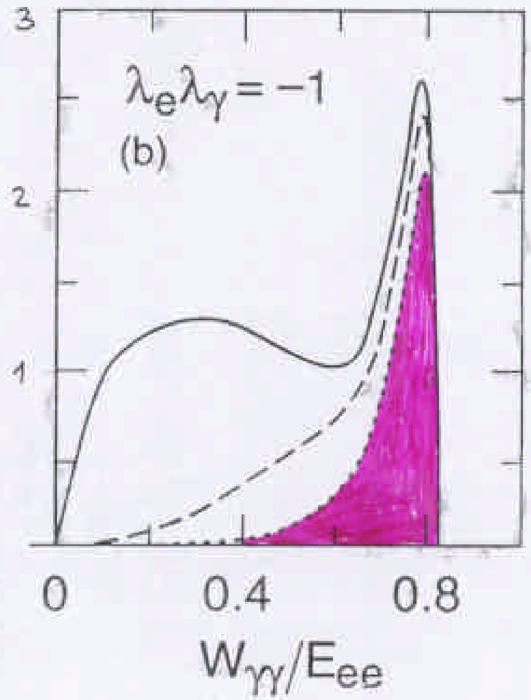


Plehn et al
σ[pb]
10^4
10^3
10^2
10
1
10^-1
qq̄
μμ
ee
Zγ
γγ
WW
ZZ
tt̄
e+e- → e+e-
e+e- → μ+μ-
e+e- → qq
e+e- → tt
e+e- → W+W-
e+e- → ZZ
e+e- → γγ
e+e- → Zγ
70
100
200
300
400
700
1000
√s [GeV]
∫ℒ = 500 fb^-1
5 x 10^5 events



Luminosity distribution with energy.





Ginzburg et al.

LC PHYSICS ISSUES :

Physics with e^+e^- Linear Colliders
E. Accomando et al, ECFA / DESY WG
Phys. Rept. 299 (1998) 1 and hep-ph / 9705442

TESLA TDR: Part 3. Physics at an e^+e^- Linear Collider
J.A. Aguilar - Saavedra et al, ECFA / DESY WG
DESY 01-11 and hep-ph / 0106315

LINEAR COLLIDER Physics Resource Book, SNOWMASS 2001
T. Abe et al, American LC WG
SLAC - 0570 and hep-ex / 0106055 - 058

2.) ELECTROWEAK SYMMETRY BREAKING

<u>key problem</u>: – consistent closure of the Standard Model

– opens windows to new physics domains beyond SM

SCENARIOS: (i) <u>fundamental scalar sector</u> → standard Higgs mechanism / light H boson

(ii) <u>dynamical symmetry breaking</u> → strongly interacting W_L bosons at ~ 1 TeV

(i) HIGGS MECHANISM

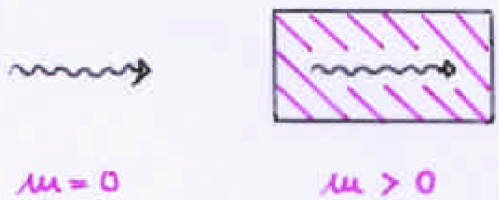
mechanism introducing masses in a consistent way into gauge theories by means of fundamental scalar Higgs field:

a) <u>self-interaction</u>

$V = \lambda\,[\varphi^2 - v^2]^2$

generates gd. state $v \neq 0$

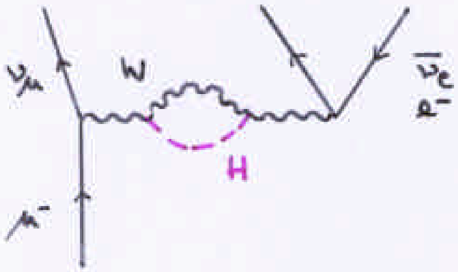
b) interaction energy → <u>mass of particles</u>



Parameters in SM Higgs sector fixed [← mass generation] except:

HIGGS MASS

a) ELW RADIATIVE CORRECTIONS



$G_F, \alpha, M_Z \Rightarrow \log M_H$:

$M_H = 88^{+53}_{-35}$ GeV
< 195 GeV at 95% CL

<u>Note</u>:
estimate can be raised by compensating contributions from physics beyond SM
example: composite Higgs boson $H = [t_L \bar{\chi}_R]$

b) DIRECT SEARCH AT LEP

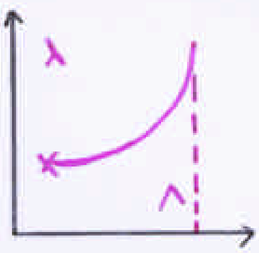
Higgs-strahlung $e^+e^- \to ZH$:

lower limit $M_H > 114.1$ GeV
'tantalizing hint': 115.6 GeV

c) EXTRAPOLATION TO GUT-SCALE

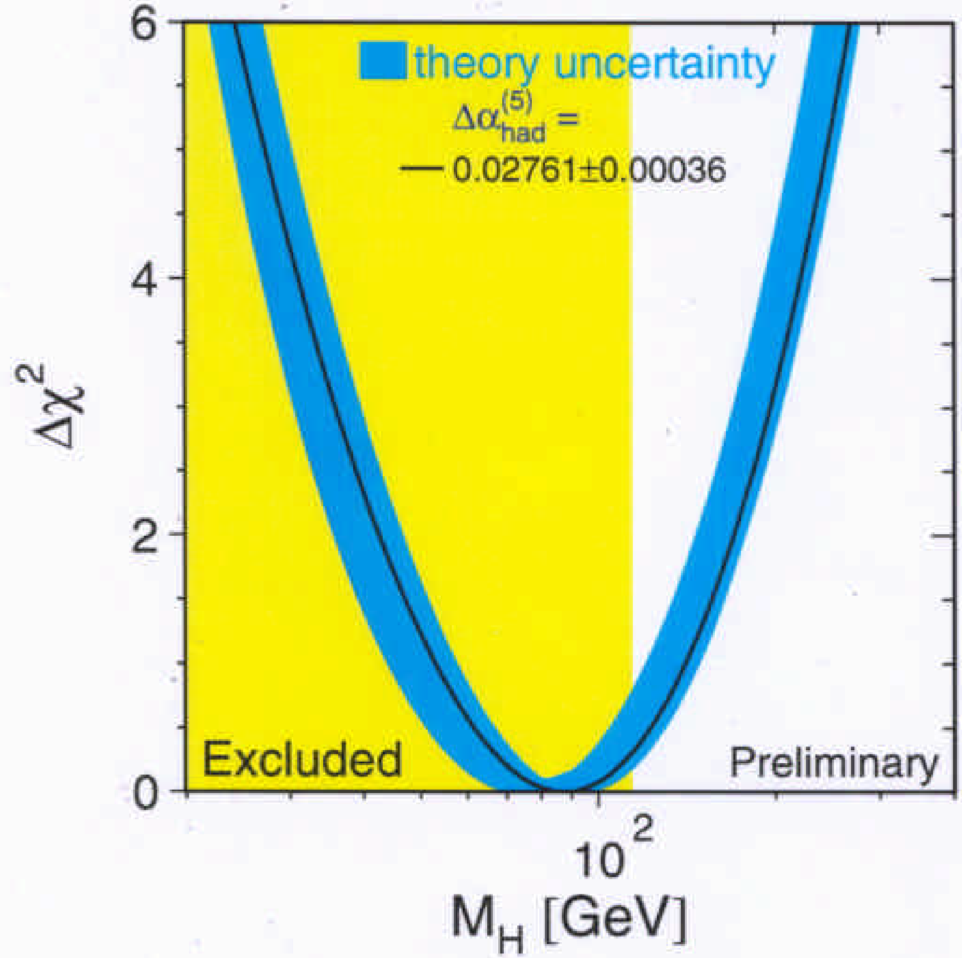
$$V = \lambda[\varphi^2 - v^2]^2$$
$$M_H^2 = 2\lambda v^2$$

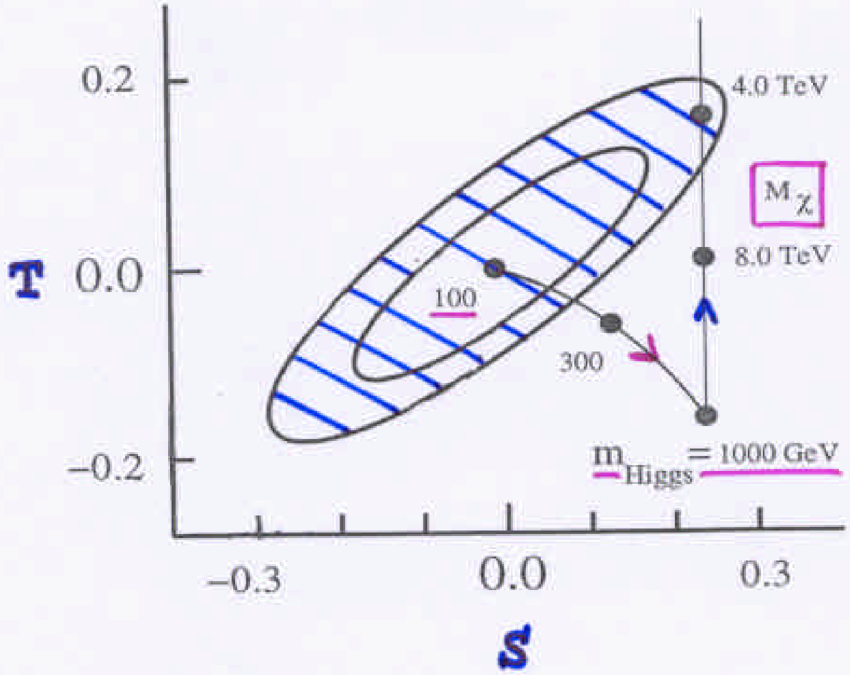
<u>λ rising with scale</u>



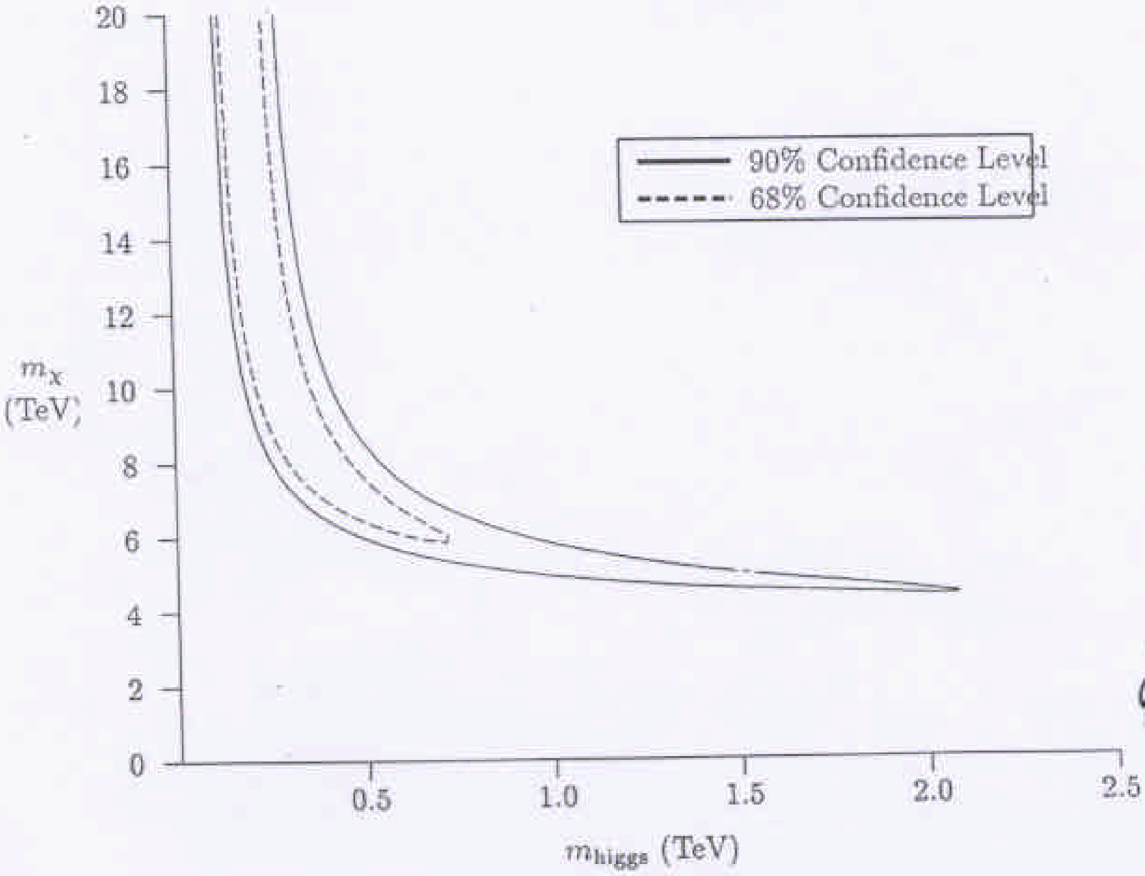
$\lambda < \infty$ for $\Lambda < \Lambda_{GUT}$
↓
$M_H < 200$ GeV

LEPEWWG
SNOWMASS HIGGS WG



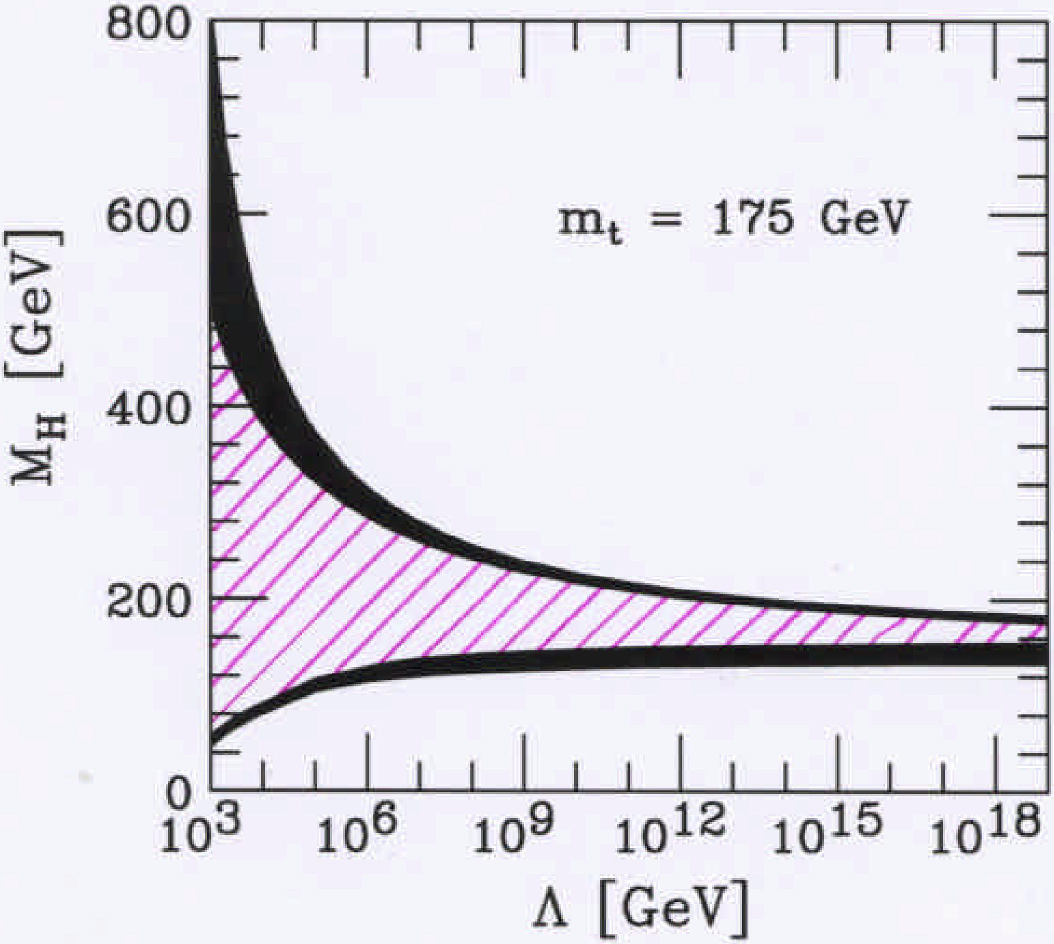


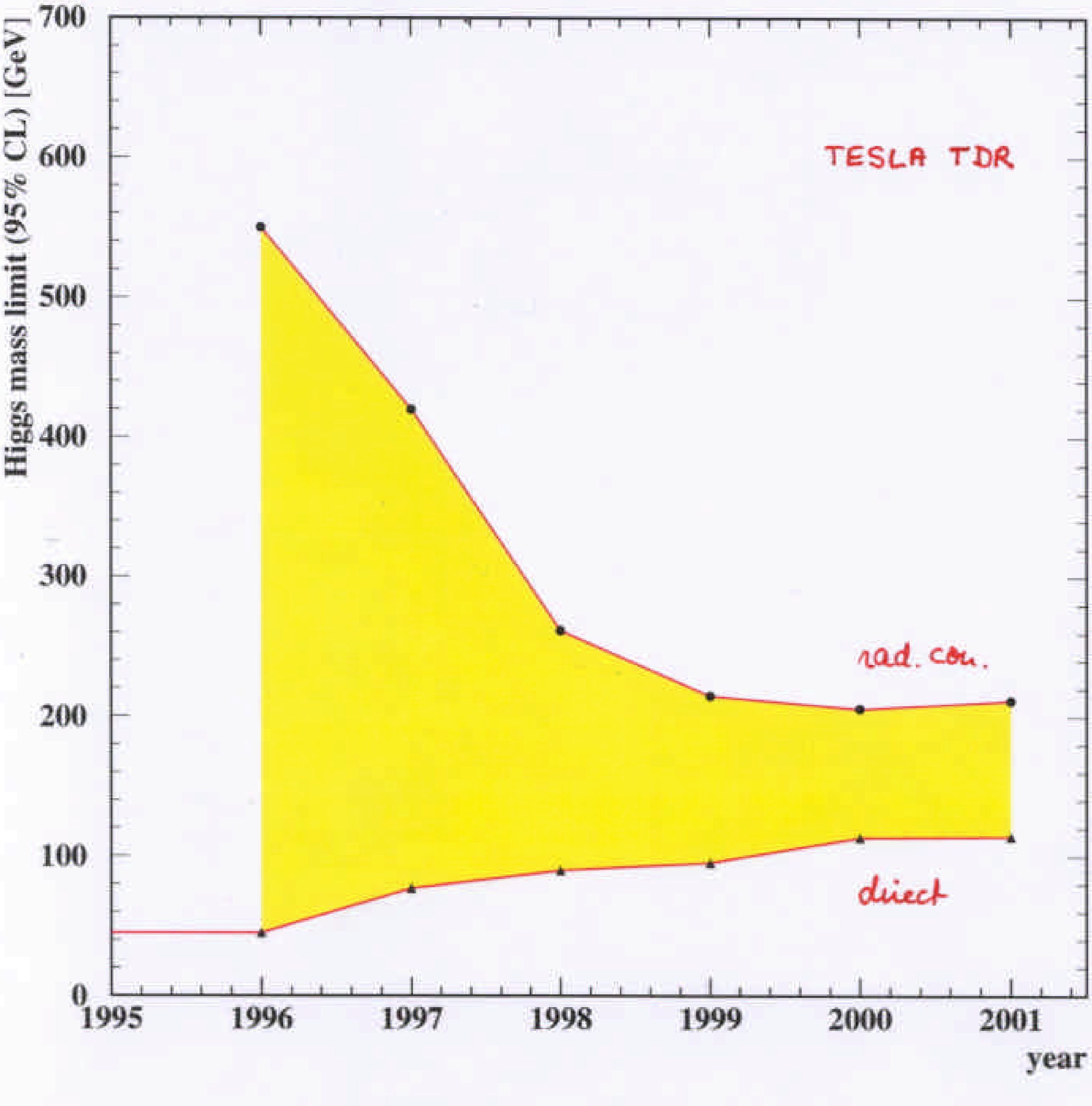
Hill ea



Georgi e

Riesselmann





Higgs mass limit (95% CL) [GeV]
0
100
200
300
400
500
600
700
1995
1996
1997
1998
1999
2000
2001
year
TESLA TDR
rad. cor.
direct

Task: establish Higgs mechanism sui generis for generating masses of fundamental SM particles

Three steps: (1) Higgs boson must be discovered

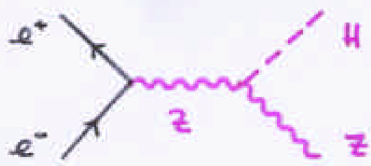
(2) Couplg ~ mass: generatg mass by Higgs interaction

(3) reconstruction of Higgs potential for generating $v \neq 0$ [SSB] by measg self-cplgs

(1) DISCOVERY OF HIGGS BOSON : ↖ decided by LHC

– PRODUCTION MECHANISMS at colliders:

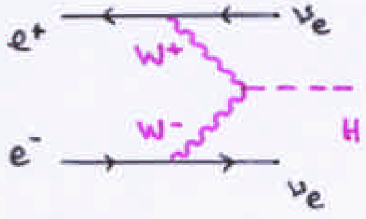
Higgs-strahlung:



$\sigma = \frac{G_F^2 M_Z^4}{96 \pi s}$ 2nd ord scaling

moderate mass

WW-fusion :



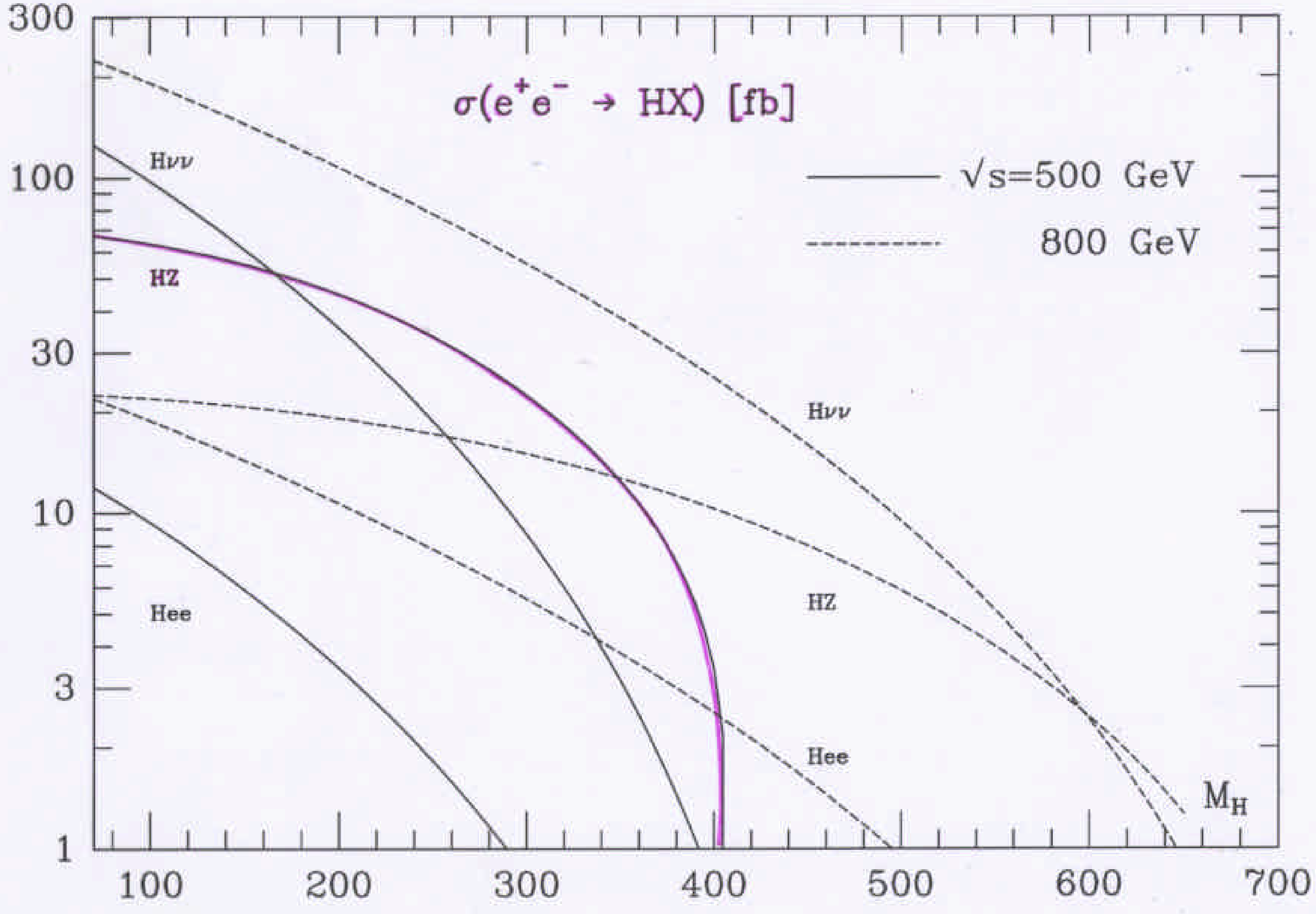
$\sigma = \frac{G_F^3 M_W^4}{4\sqrt{2}\pi^3} \log \frac{s}{M_H^2}$

3rd order
flat in energy

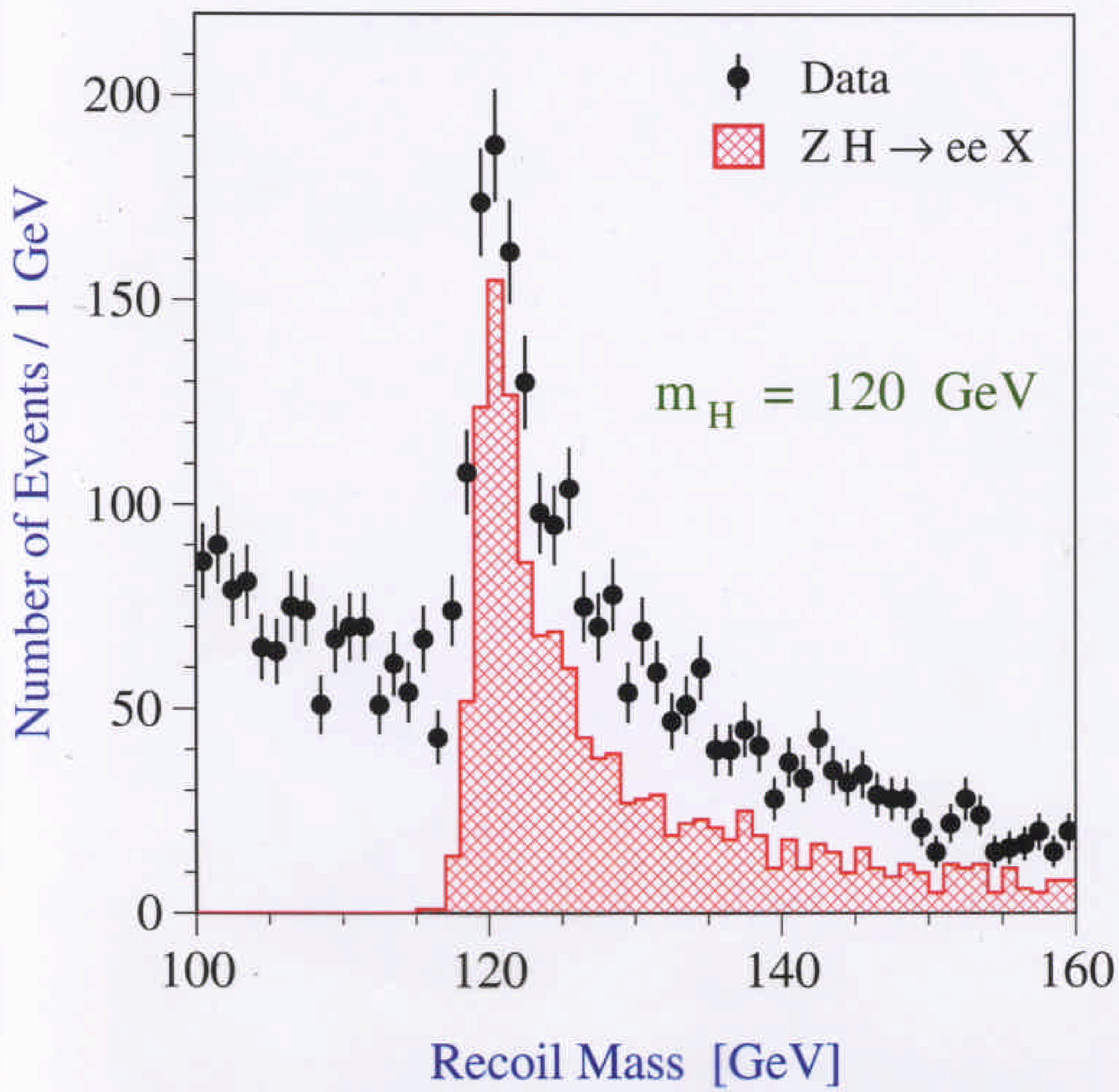
$\sqrt{s} = 300$ GeV / $\int \mathcal{L} = 500\ fb^{-1}$
$M_H \sim$ intermediate mass range

10⁵ Higgs bosons nearly bkgd free

Djouadi ea



σ(e+e- → HX) [fb]
√s=500 GeV
800 GeV
Hνν
HZ
Hee
Hνν
HZ
Hee
M_H
300
100
30
10
3
1
100
200
300
400
500
600
700


Data
Z H → ee X
m H = 120 GeV
Number of Events / 1 GeV
0
50
100
150
200
100
120
140
160
Recoil Mass [GeV]

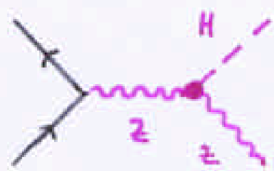
Properties:

- **Mass** : accuracy ≲ 50 MeV in Higgs-strahlung
- **Lifetime** : $\Gamma = \Gamma(H \to WW) / BR(H \to WW)$
  ↑ prodct ↑ decay
  model-independent to ~ 5%
- **Spin-Parity**: $J^P = 0^+$: model-indep. by combining threshold excit ⊕ ang. correl.

(2) MASS GENERATION

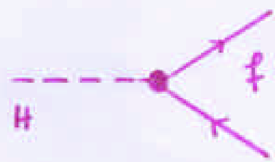
if mass generated by interaction with Higgs field → coupling ~ mass of source

– gauge couplings: HZZ, HWW : Higgs-strahlg - fusion - decay



$\sigma \sim g^2(HZZ)$ ~ 1%

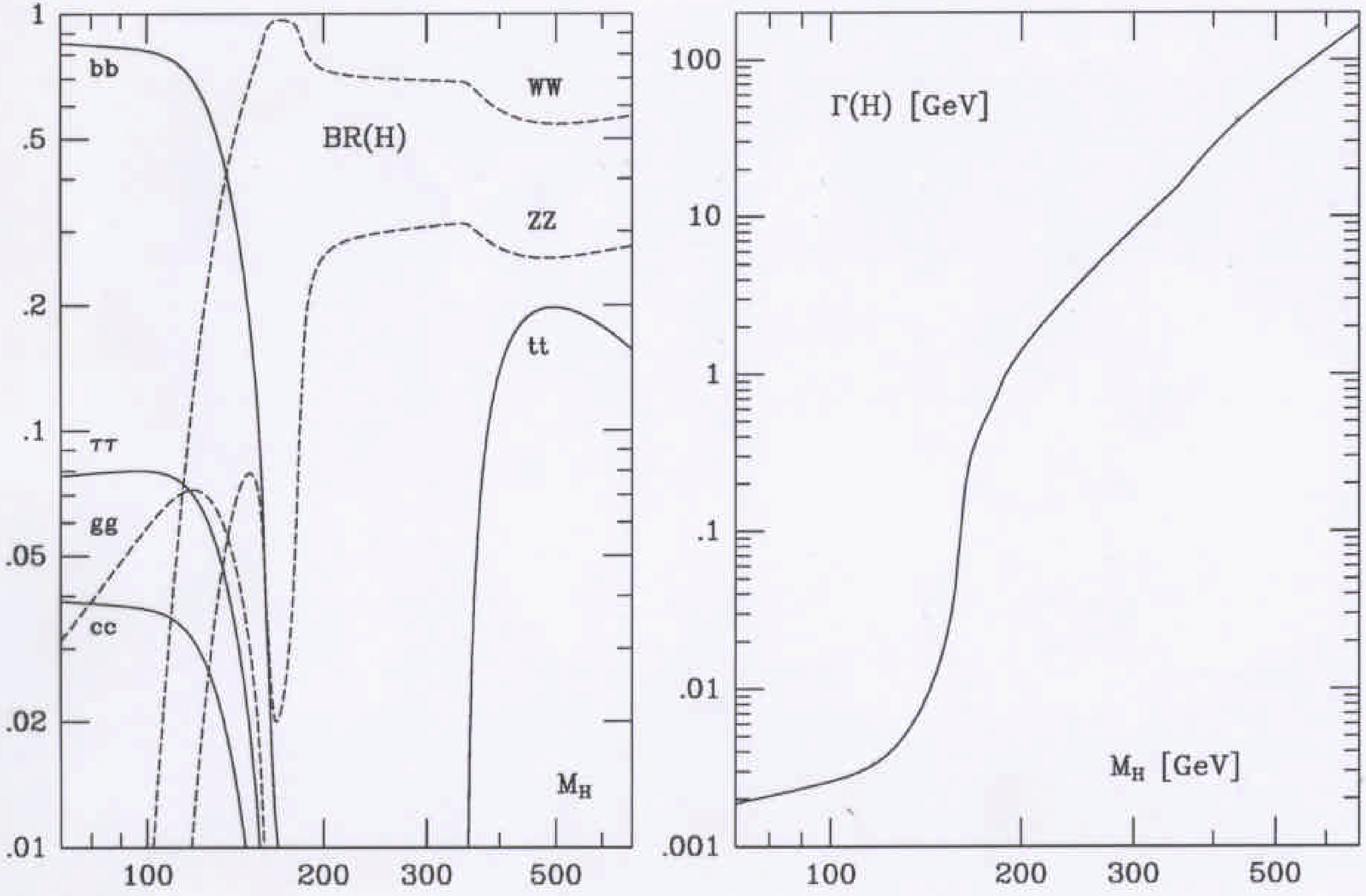
– Yukawa couplings: Hff: $f = b, c, \tau, \mu$: decay branchg ratios



$BR_f \sim M_f^2$

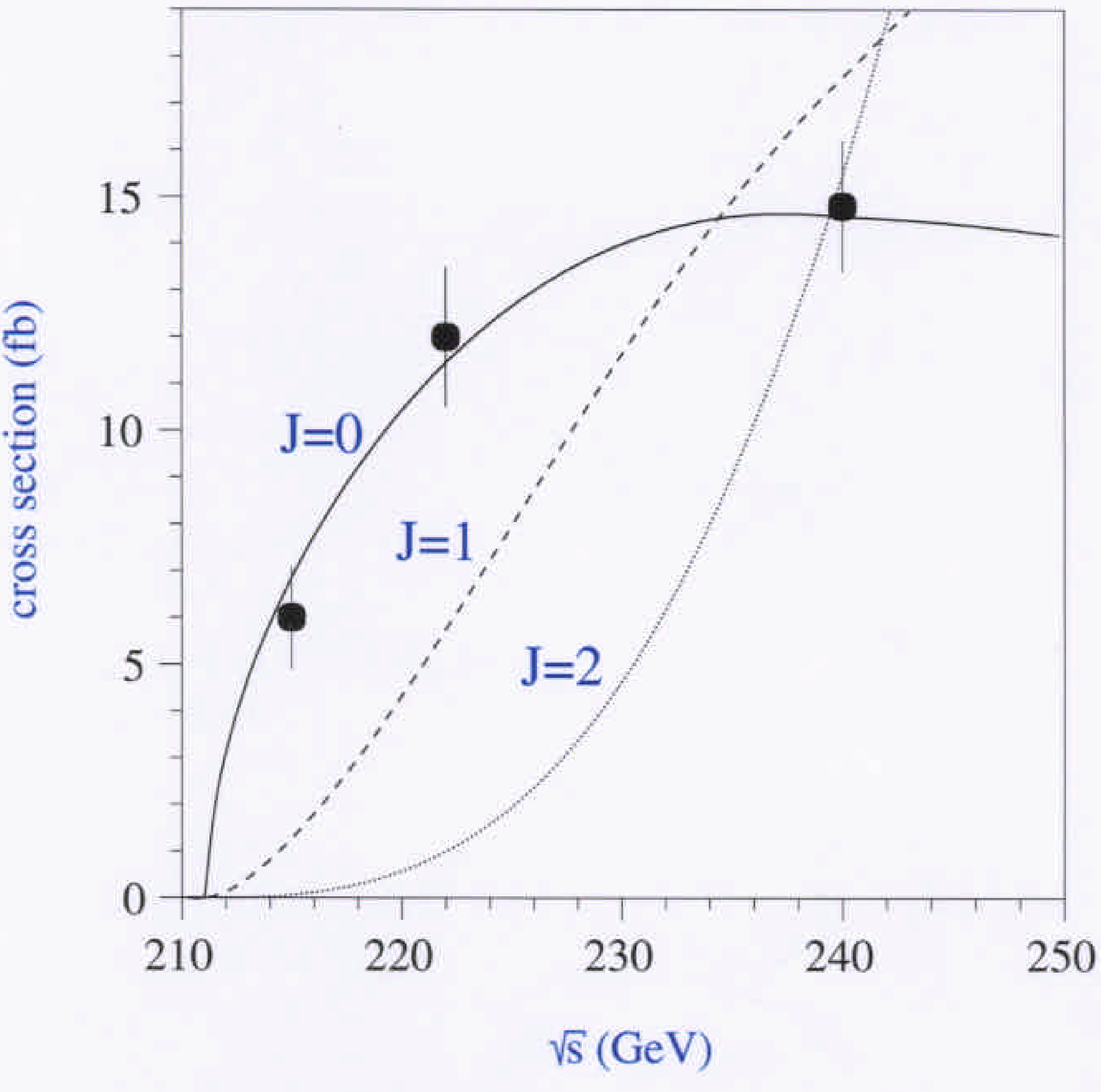
$BR_\tau / BR_b = M_\tau^2 / 3M_b^2$
$\approx 10^{-1}$ for running b

con: gauge ~ fermion
lepton ~ quark
up ~ down



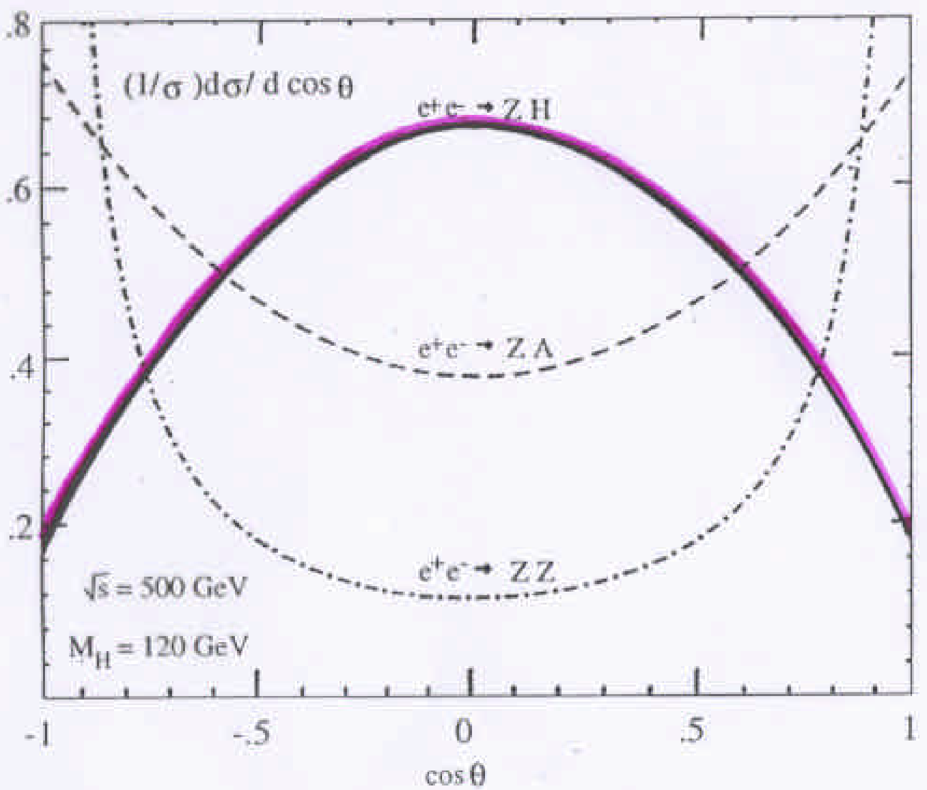
BR(H)
bb
ττ
gg
cc
WW
ZZ
tt
M_H
1
.5
.2
.1
.05
.02
.01
100
200
300
500
Γ(H) [GeV]
M_H [GeV]
100
10
1
.1
.01
.001

Spiia et al

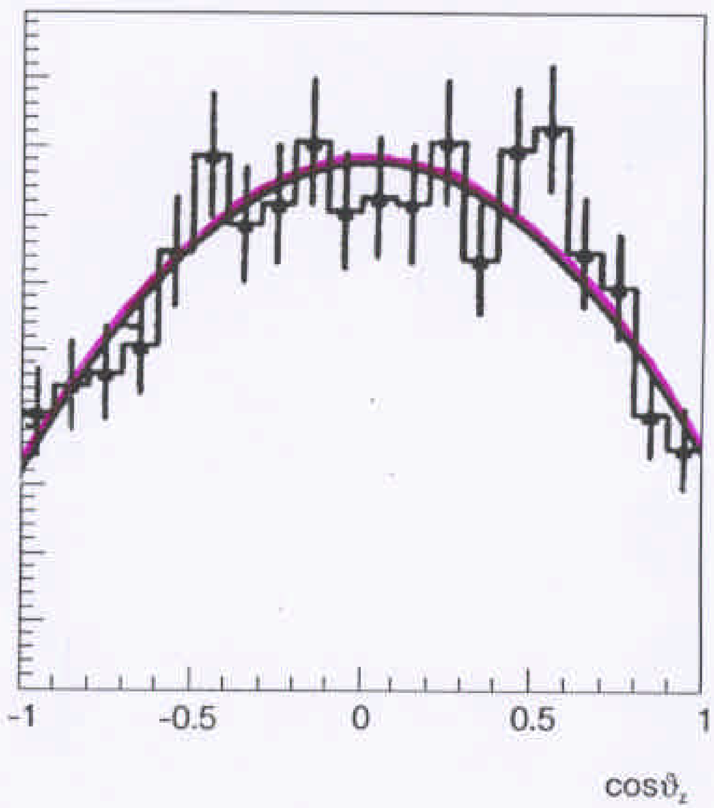


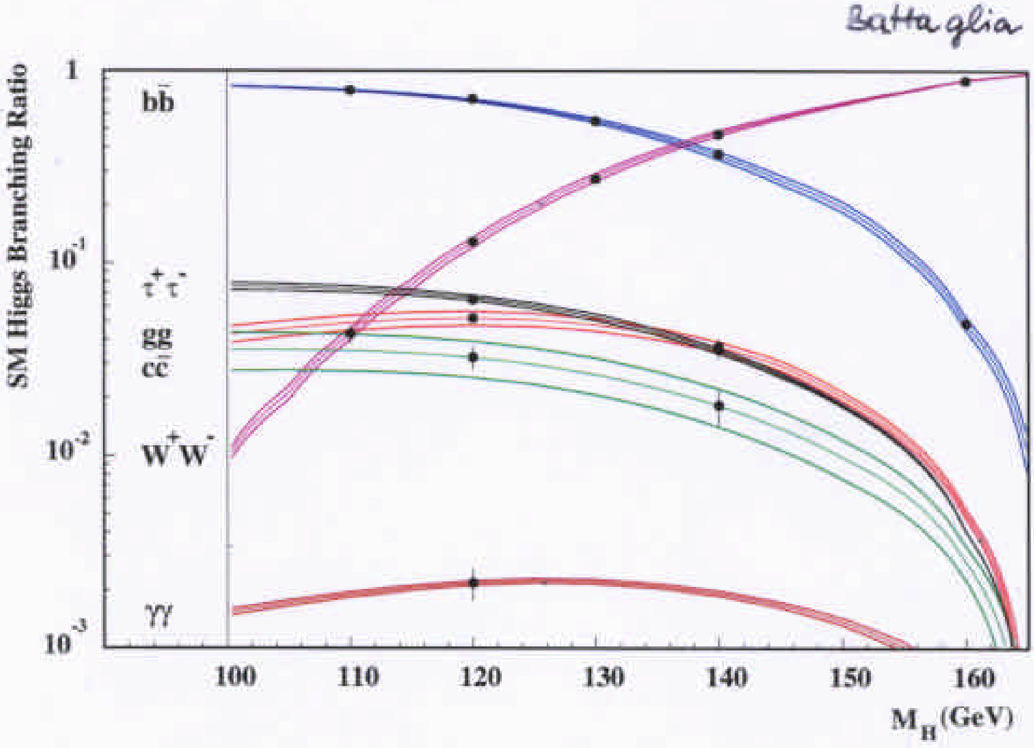
cross section (fb)
15
10
5
0
210
220
230
240
250
√s (GeV)
J=0
J=1
J=2

Kniehl et al



JLC



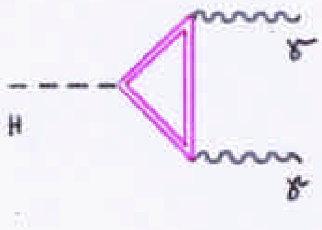

Battaglia
SM Higgs Branching Ratio
1
10^{-1}
10^{-2}
10^{-3}
$b\bar{b}$
$\tau^+\tau^-$
gg
$c\bar{c}$
W^+W^-
$\gamma\gamma$
100
110
120
130
140
150
160
M_H(GeV)

- top Yukawa cplg: bremsstrahlung

  for light Higgs ~ 5%

Remarks:

- $H\gamma\gamma$:



affected by virtual charged particles

precision measurem. ~ 2% in $\gamma\gamma \to H$

analogous: Hgg color-charged loops

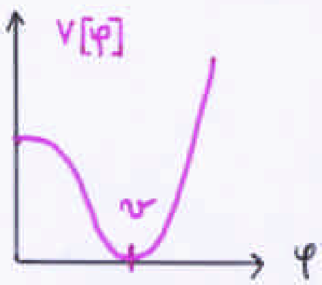
- Higgs may mix with other fields [← radion for extra space]: precision measurements can provide information on BYSM

(3) HIGGS POTENTIAL

shape of scalar Higgs potential → $v \neq 0$ in ground state

$$V = \lambda\left[\varphi^2 - v^2\right]^2$$

$$= \frac{M_H^2}{2} H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

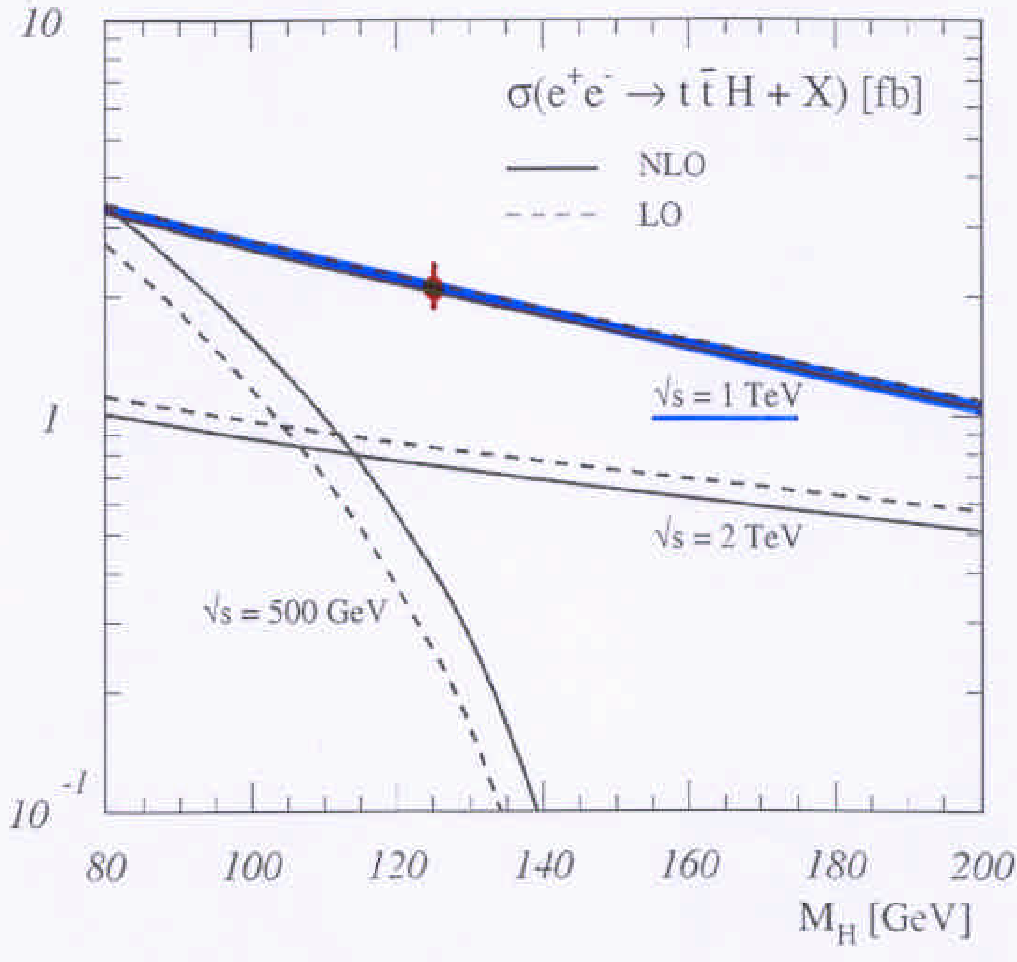


$\varphi \sim v + H$ expansion: bilinear ~ Higgs mass

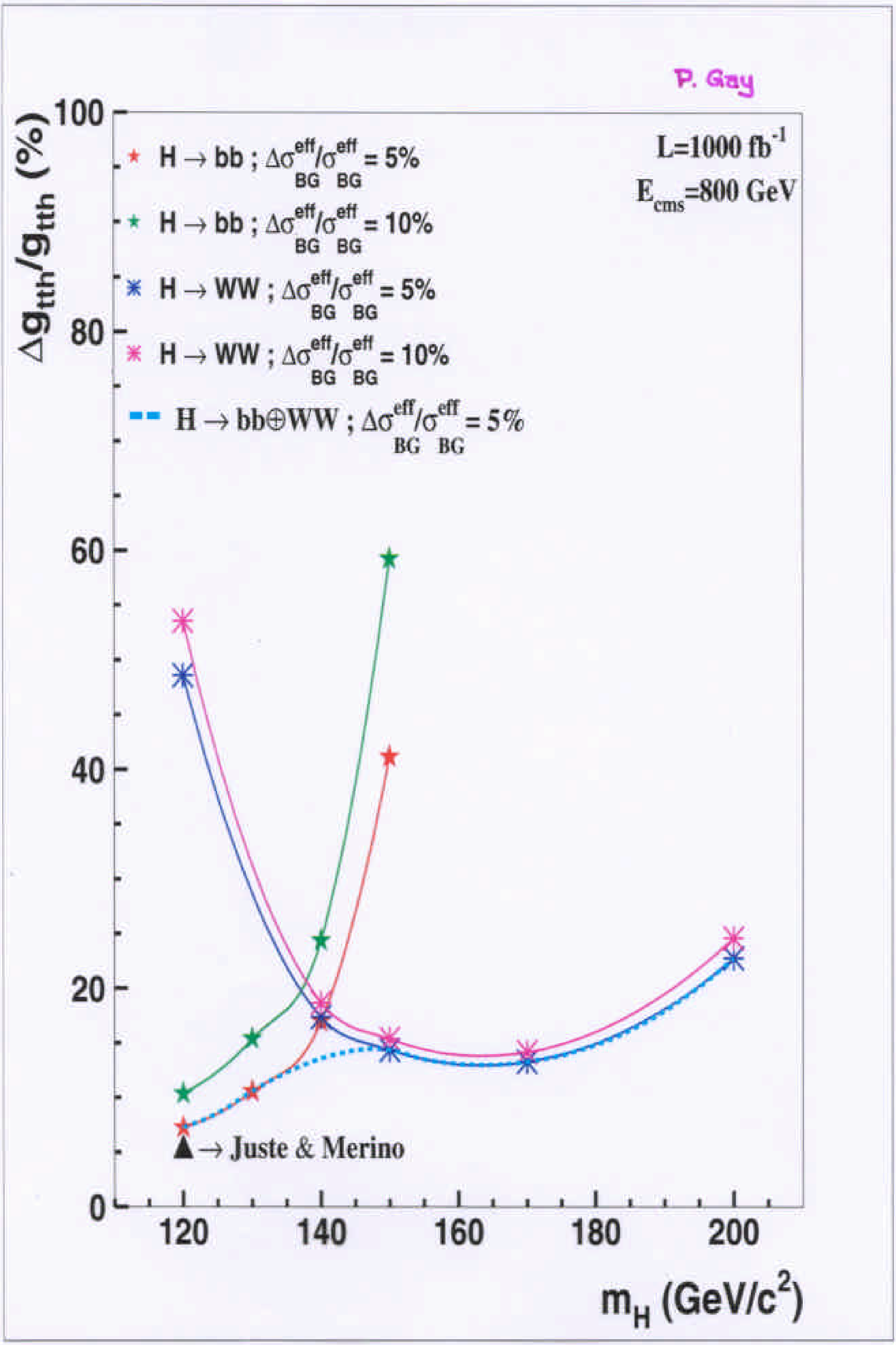
<u>trilinear interaction</u> ←

quadrilinear interaction ← SM

Dittmaier
Krämer et al

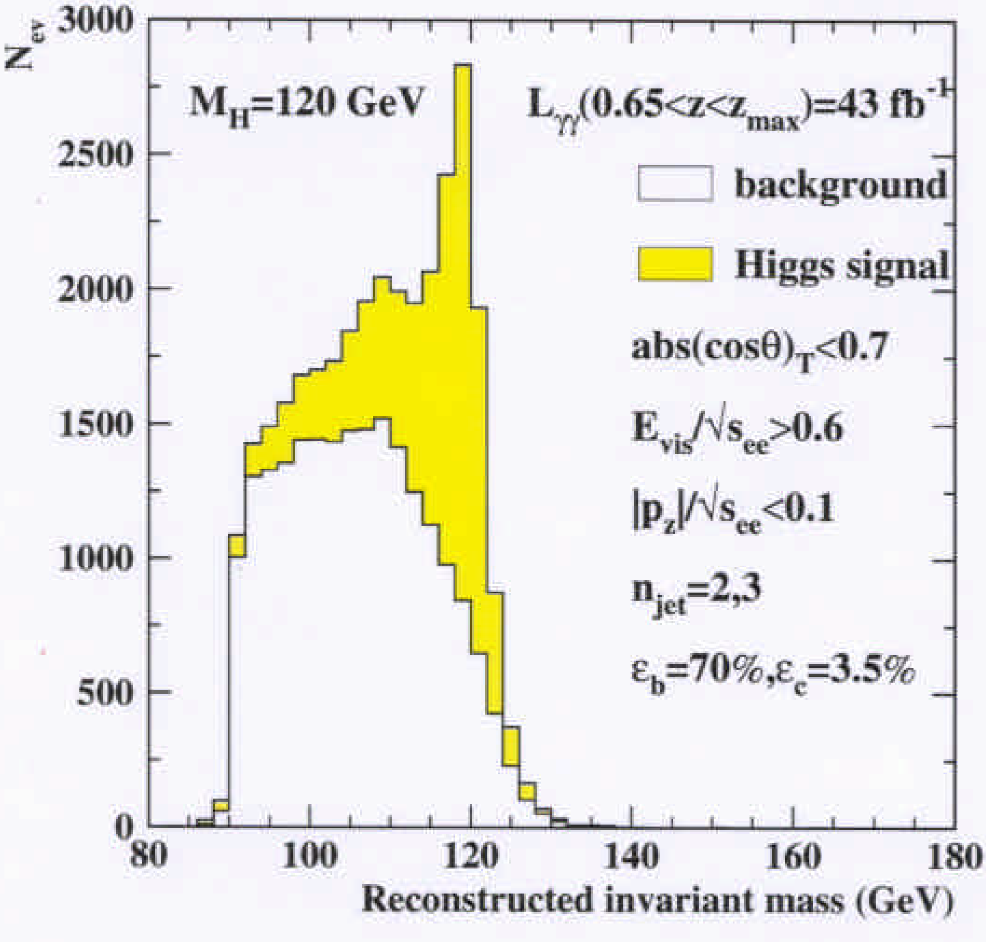


Results



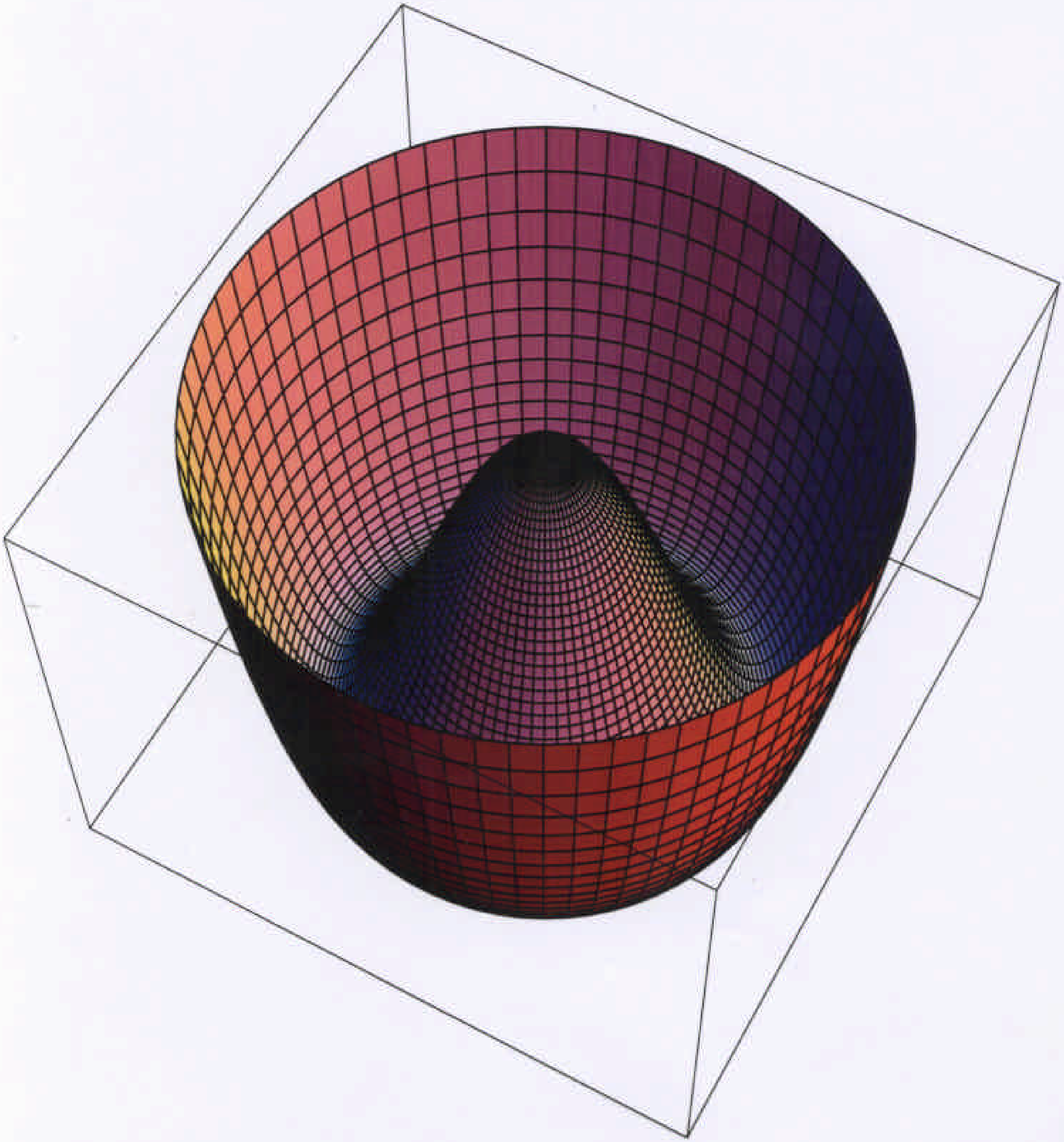
P. Gay
L=1000 fb^-1
E_cms=800 GeV
H → bb ; Δσ^eff_BG/σ^eff_BG = 5%
H → bb ; Δσ^eff_BG/σ^eff_BG = 10%
H → WW ; Δσ^eff_BG/σ^eff_BG = 5%
H → WW ; Δσ^eff_BG/σ^eff_BG = 10%
H → bb⊕WW ; Δσ^eff_BG/σ^eff_BG = 5%
▲ → Juste & Merino
Δg_tth/g_tth (%)
m_H (GeV/c^2)
0
20
40
60
80
100
120
140
160
180
200

Zikia ea

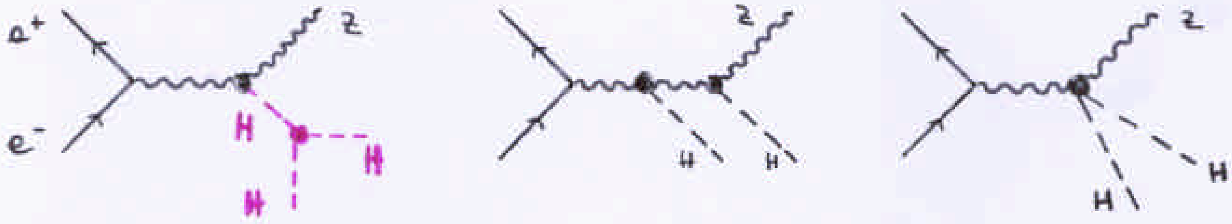


N_{ev}
M_H=120 GeV
$L_{\gamma\gamma}(0.65<z<z_{max})=43\ fb^{-1}$
background
Higgs signal
$abs(\cos\theta)_T<0.7$
$E_{vis}/\sqrt{s_{ee}}>0.6$
$|p_z|/\sqrt{s_{ee}}<0.1$
$n_{jet}=2,3$
$\varepsilon_b=70\%,\varepsilon_c=3.5\%$
0
500
1000
1500
2000
2500
3000
80
100
120
140
160
180
Reconstructed invariant mass (GeV)

Higgs Potential



<u>double Higgs-strhlg</u> → trilinear couplg : $e^+e^- \to ZHH$



final states: $e^+e^- \to Z(b\bar{b})(b\bar{b})$
$\to Z(W^+W^-)(W^+W^-)$

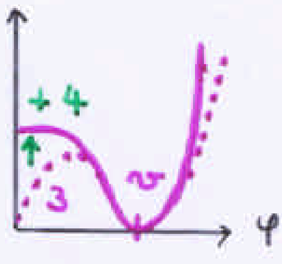
$\sigma \simeq$ a few 10^{-1} fb
sensitiv. $\Delta\lambda/\lambda \simeq 18\%$

high luminosity needed :
⊕ WW fusion : $\approx 8\%$

<u>quatrolin. cplg</u> : $\sigma[e^+e^- \to ZHHH] \sim ab$ [very difficult]

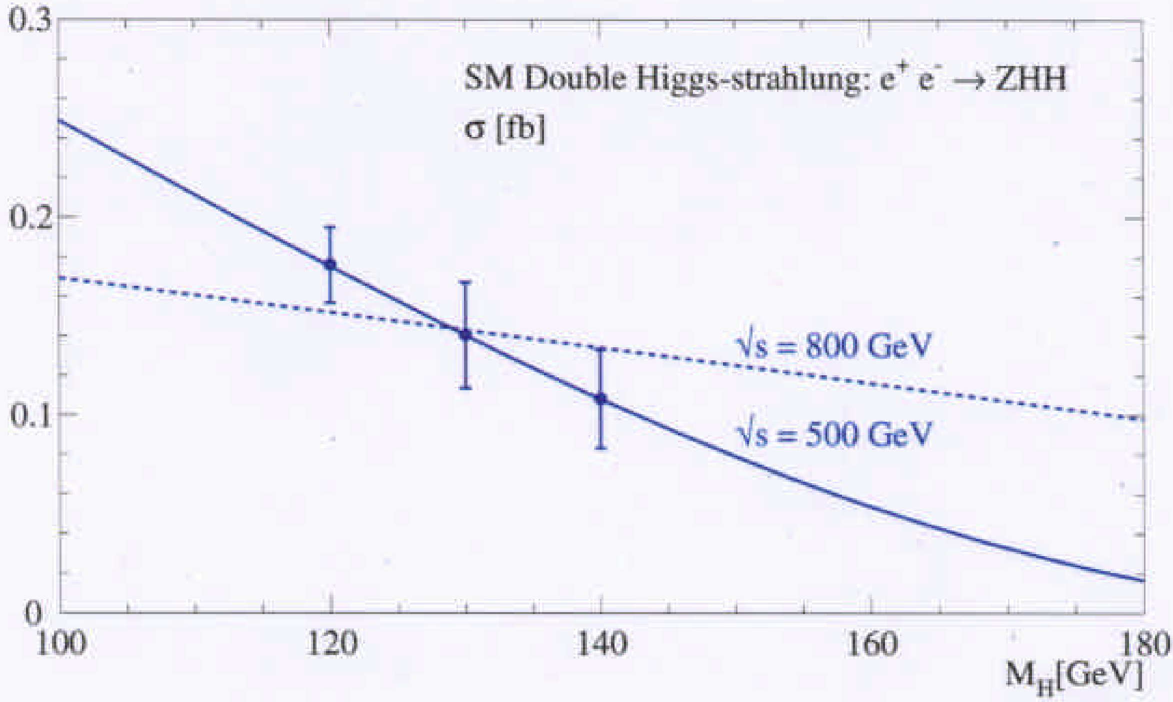
<u>SHIFT $v \neq 0$</u> : follows from

trilin. cplg + posit $[H^4]$



essential elements of the Higgs mechanism can experimentally be established at high lumi LC

Mühlleitner,
Kilian, Z
gay ea



(i') HIGGS MECHANISM [SUSY]

a) min SUSY = MSSM :

2 Higgs doublets → 5 physical states :

h^0	CP even	}
H^0	CP even	}
A^0	CP odd	
$H^\pm$	charged	

params : mass M_A, $tg\beta = v_2 / v_1$ }

characteristic : quartic coupling $\sim g^2$ →

mass hierarchy : $M_{h^0} < M_Z + RC \lesssim 135\,GeV$

$M_{H^0} \sim M_{A^0} \sim M_{H^\pm} \sim v \ldots 1\,TeV$

decays : standard decays $h^0 \to b\bar{b}$ ...

cascades $A^0 \to Z h^0$ ...

SUSY decays $A^0 \to \tilde{f}\bar{\tilde{f}}$ ...

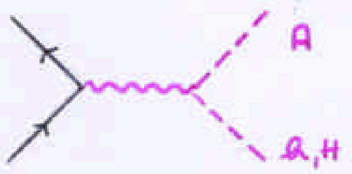
e^+e^- PRODUCTION :

Higgs-strahlung :

$\sigma[Zh] = \sin^2\alpha' \cdot \sigma_{SM}$

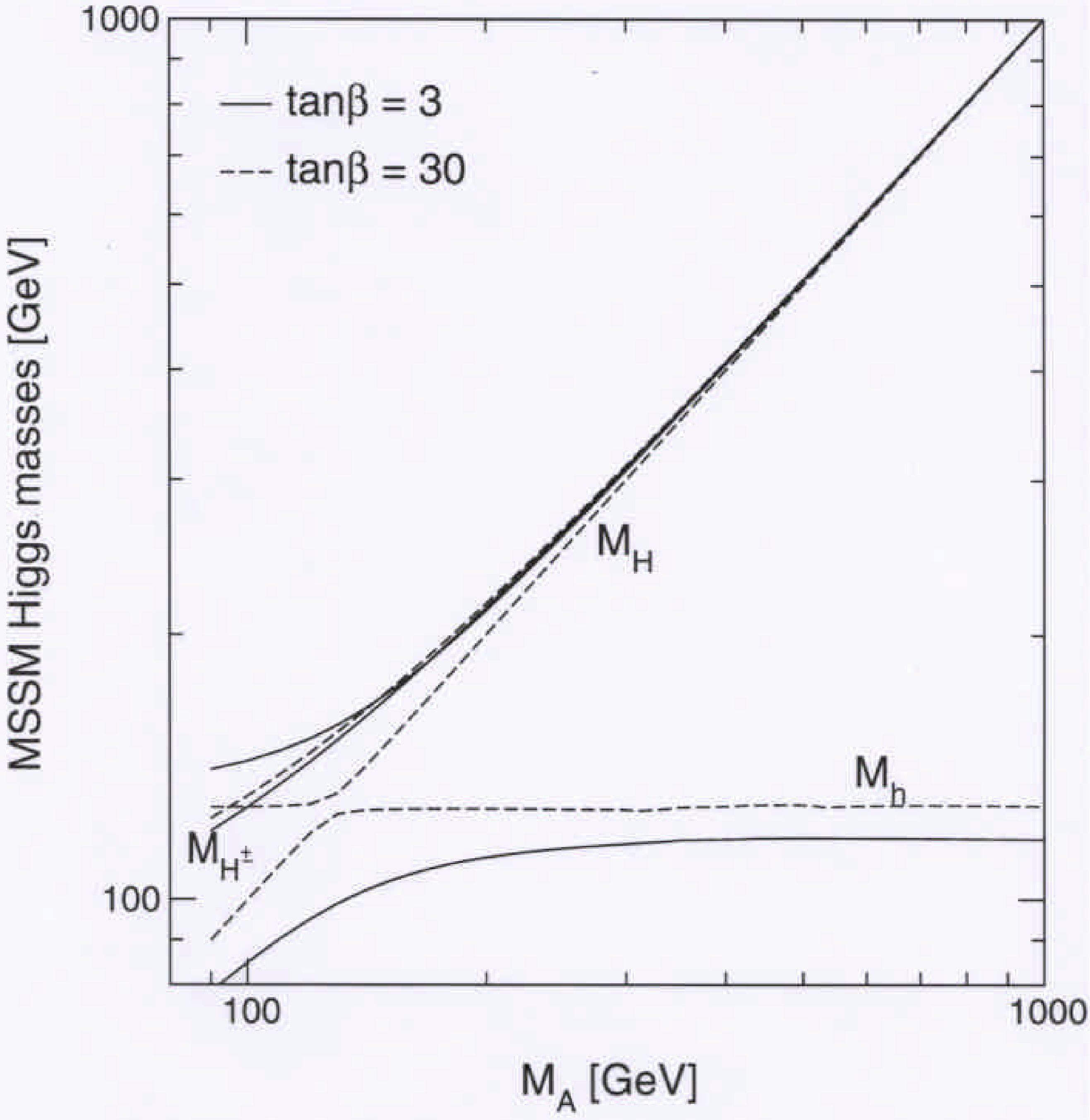
$\sigma[ZH] = \cos^2\alpha' \cdot \sigma_{SM}$

pair production :

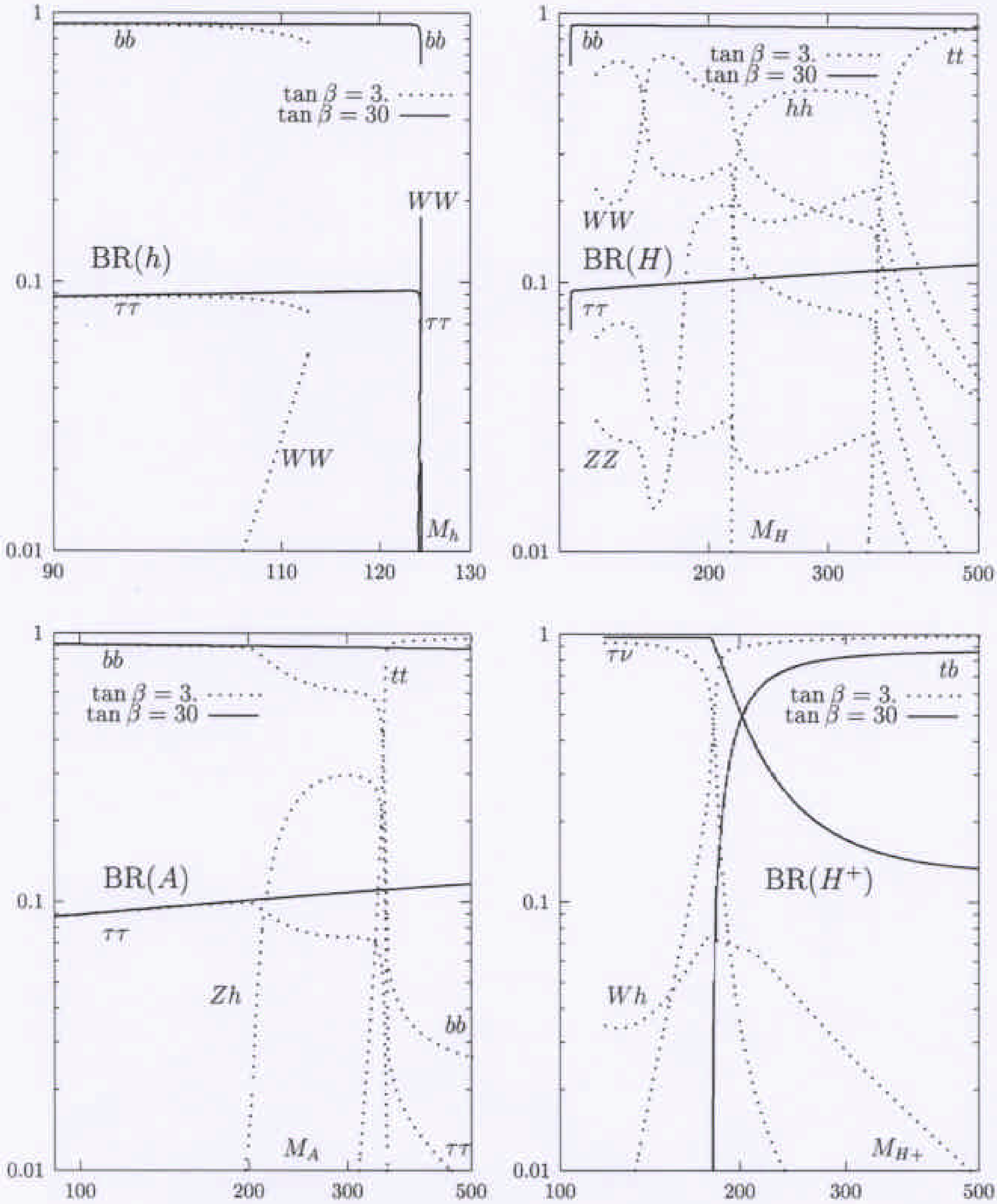


$\sigma[Ah] = \cos^2\alpha' \cdot \lambda\,\sigma_{SM}$

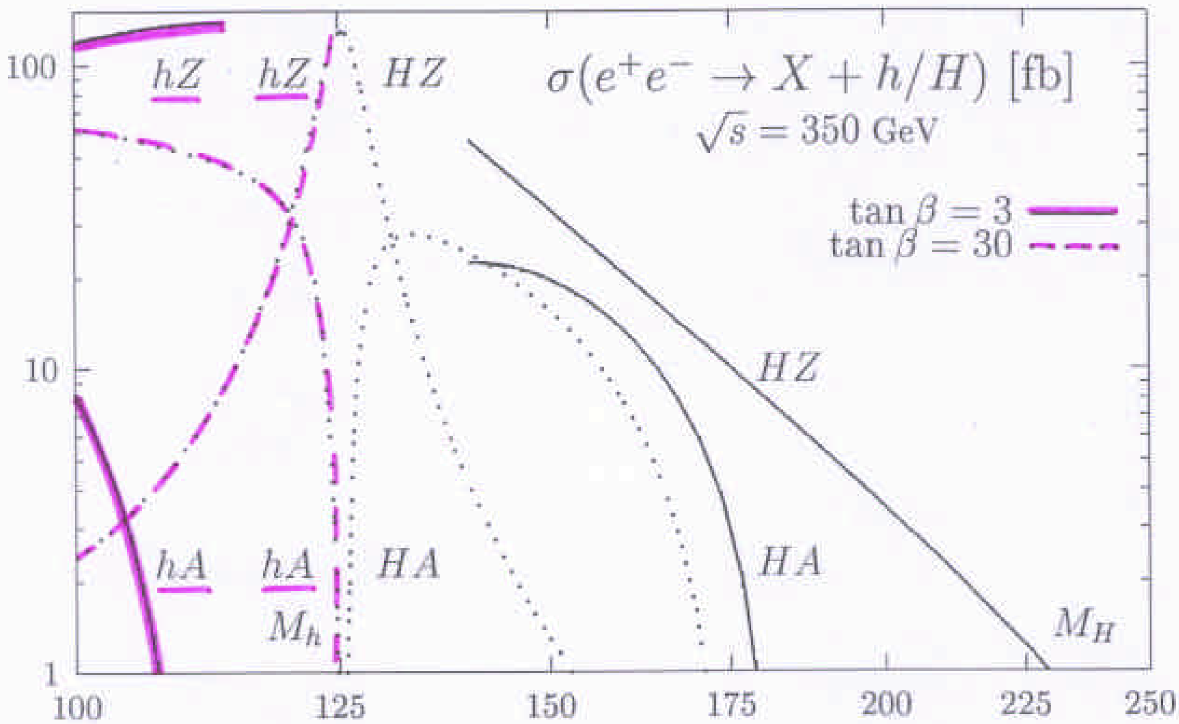
$\sigma[AH] = \sin^2\alpha' \cdot \lambda\,\sigma_{SM}$



tanβ = 3
tanβ = 30
MSSM Higgs masses [GeV]
1000
100
M_H
M_h
M_H±
100
1000
M_A [GeV]



BR(h)
tan β = 3.
tan β = 30
bb
WW
ττ
M_h
BR(H)
tt
hh
ZZ
M_H
BR(A)
Zh
M_A
BR(H+)
τν
tb
Wh
M_H+



σ(e⁺e⁻ → X + h/H) [fb]
√s = 350 GeV
tan β = 3
tan β = 30
hZ
hZ
HZ
HZ
hA
hA
HA
HA
M_h
M_H
100
10
1
100
125
150
175
200
225
250

general rule: mutual $\sin^2 / \cos^2$ dependence
$\cos^2$ large ~ $M_{H,A,H^\pm}$ small [!] not gen. 2Hd

⇒ no-lose theorem: one particle found

⇒ in Higgs-strahlg: indep. of decay mode

decouplg rule: if $M_A \gtrsim 200$ GeV: $e^+e^- \to Z h^0$ large ~ SM
$e^+e^- \to A^0 H^0$ large

many scenarios: h^0 ~ SM properties
$H^0, A^0, H^\pm$ pair produced

REMARKS

a) H, A "blind wedge" at LHC : $M_A \gtrsim 200$ GeV, $tg\beta$ moderate

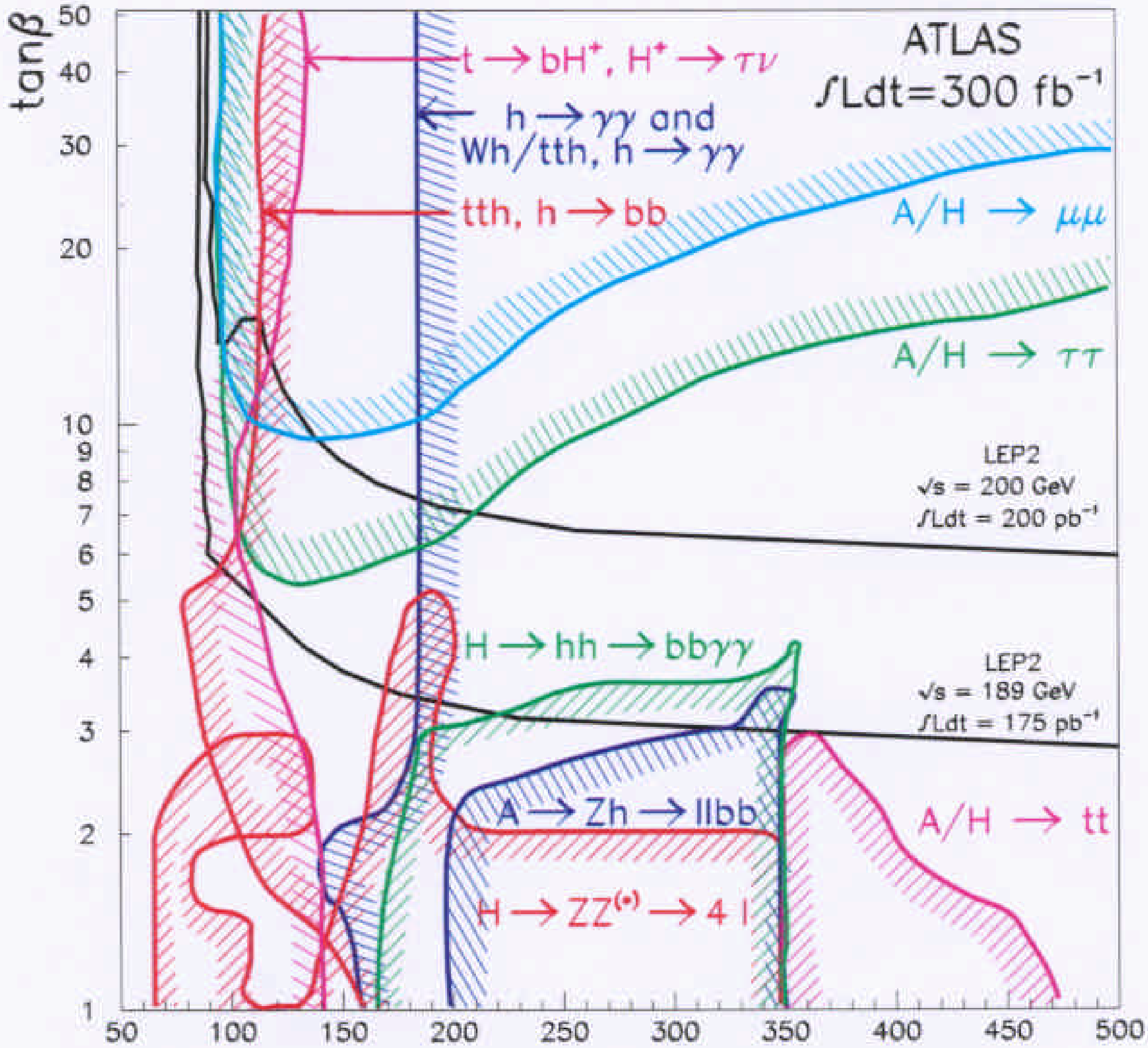
H,A pair produced in $e^+e^- \to HA$: $M_{H,A} \lesssim \sqrt{s}/2$

TESLA, ... 1st phase $\lesssim$ 250 .. 400 GeV
CLIC 2nd phase $\lesssim$ 2.5 TeV ⇐

H,A produced singly in Compton collider:

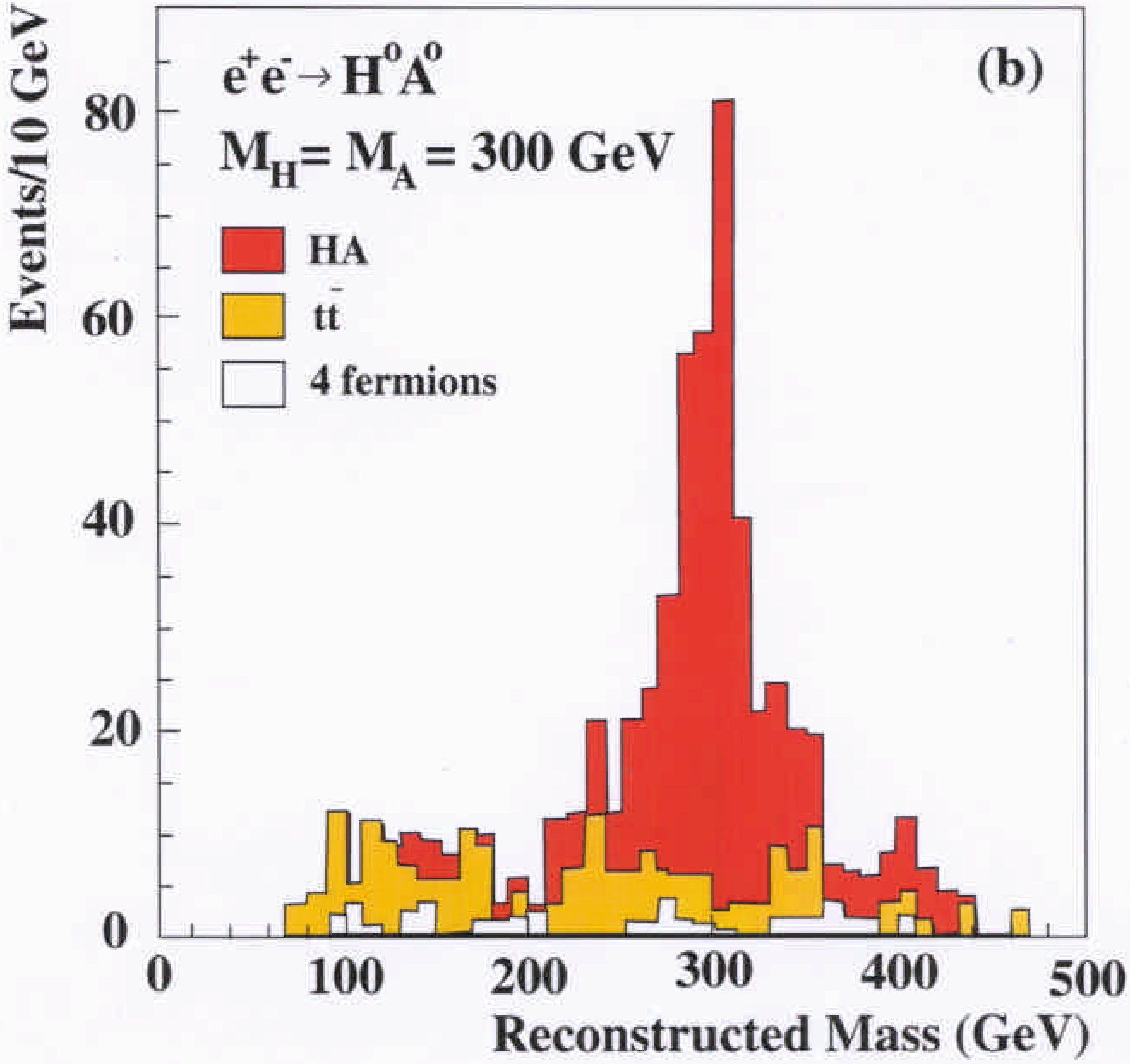
$\gamma\gamma \to H$ and A with $M_{H,A} \lesssim$ 60 to 70% of $\sqrt{s_{ee}}$

b) Parity: linear polarization: $\gamma\gamma_\parallel \to H$ parallel
$\gamma\gamma_\perp \to A$ perpend.

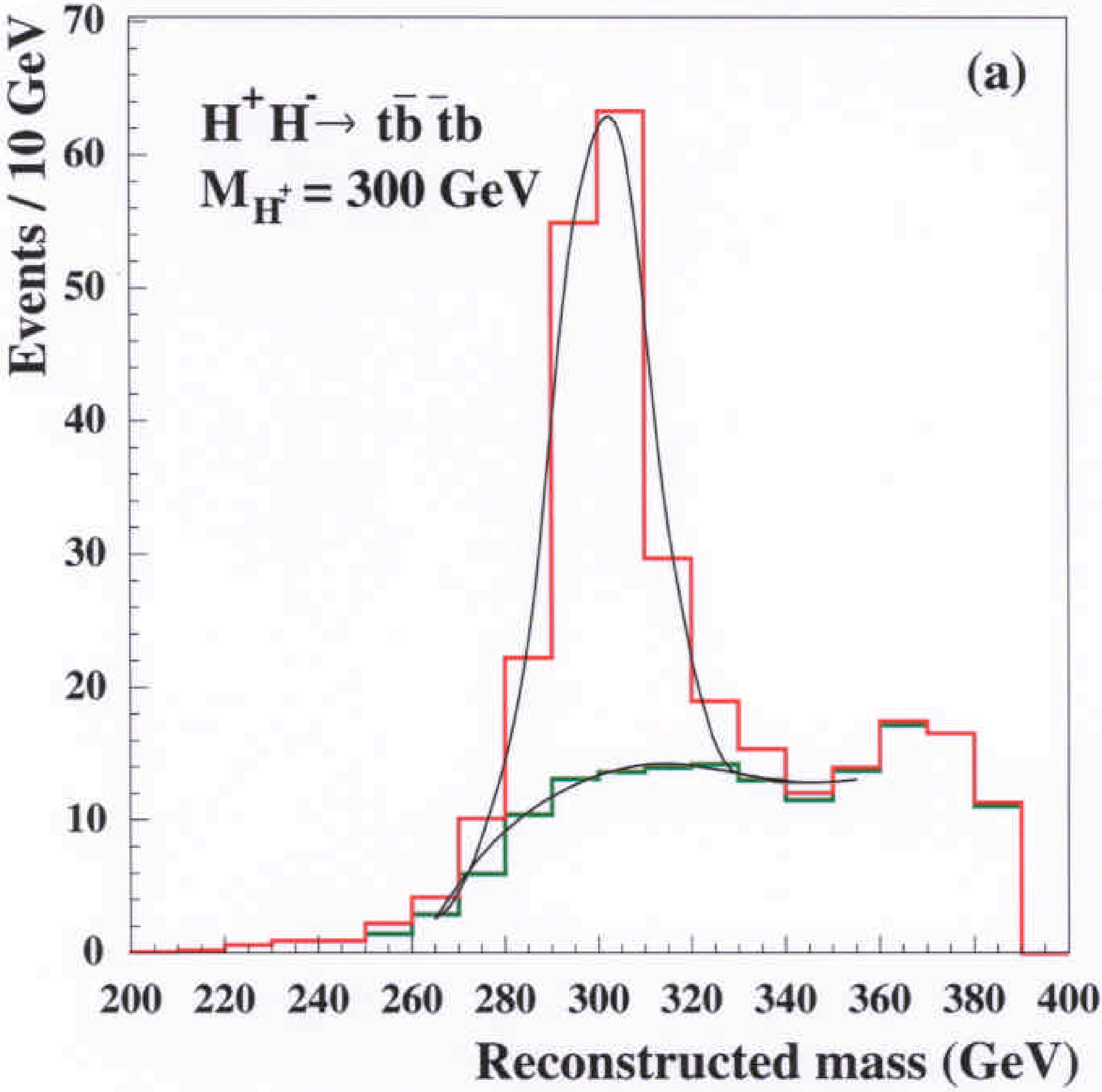


ATLAS
∫Ldt=300 fb⁻¹
t → bH⁺, H⁺ → τν
h → γγ and
Wh/tth, h → γγ
tth, h → bb
A/H → μμ
A/H → ττ
LEP2
√s = 200 GeV
∫Ldt = 200 pb⁻¹
H → hh → bbγγ
LEP2
√s = 189 GeV
∫Ldt = 175 pb⁻¹
A → Zh → llbb
A/H → tt
H → ZZ(*) → 4 l
tanβ
m_A (GeV)

TESLA TDR

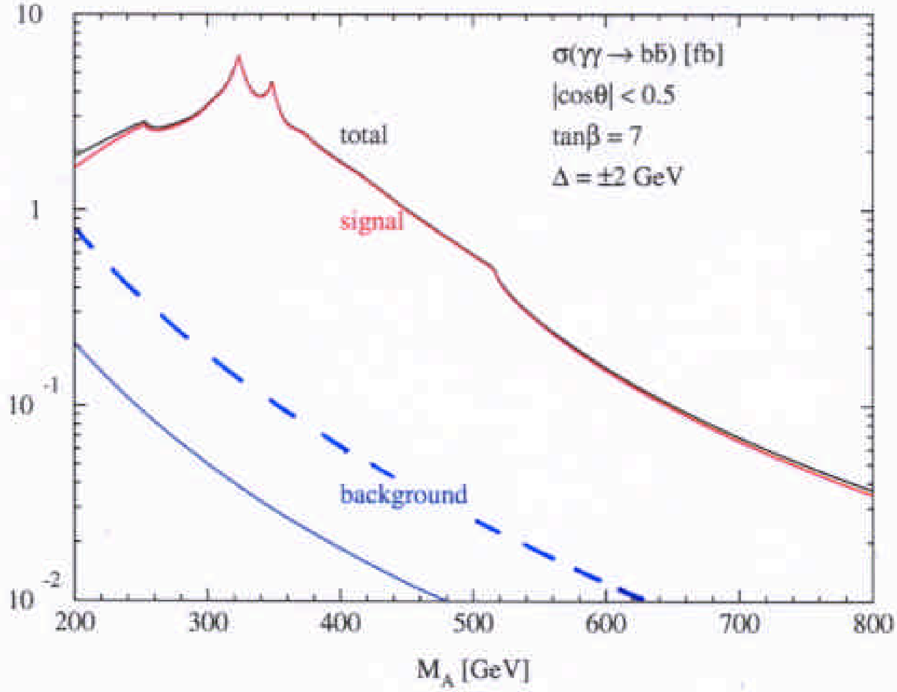


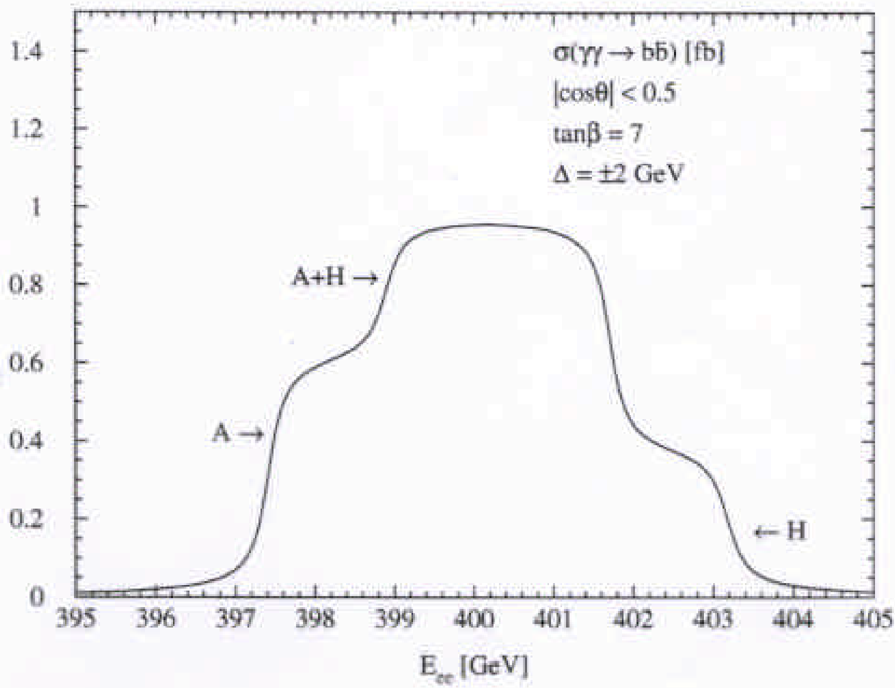
$e^+e^- \to H^oA^o$
(b)
$M_H = M_A = 300$ GeV
HA
$t\bar{t}$
4 fermions
Events/10 GeV
0
20
40
60
80
0
100
200
300
400
500
Reconstructed Mass (GeV)



Events / 10 GeV
(a)
$H^+H^- \rightarrow t\bar{b}\,\bar{t}b$
M_{H^+} = 300 GeV
0
10
20
30
40
50
60
70
200
220
240
260
280
300
320
340
360
380
400
Reconstructed mass (GeV)

Mühlleitner
Krämer, Spira, Z





b) non-min SUSY → (M+1) SSM :

superstring motivated E_6 : additional isoscalar Higgs field

7 physical states : A_1, A_2 CP odd
H_1, H_2, H_3 CP even
$H^\pm$ charged

spectrum : H_1 remains light [if theory extd to GUT]
H_2 also light [expected]
A_1 " "
$H_3, A_2, H^\pm$ heavy ~ MSSM characteristics

no-lose theorem : if lightest state decouples –
theorem applies again to reduced system
...
↘ rules as in MSSM

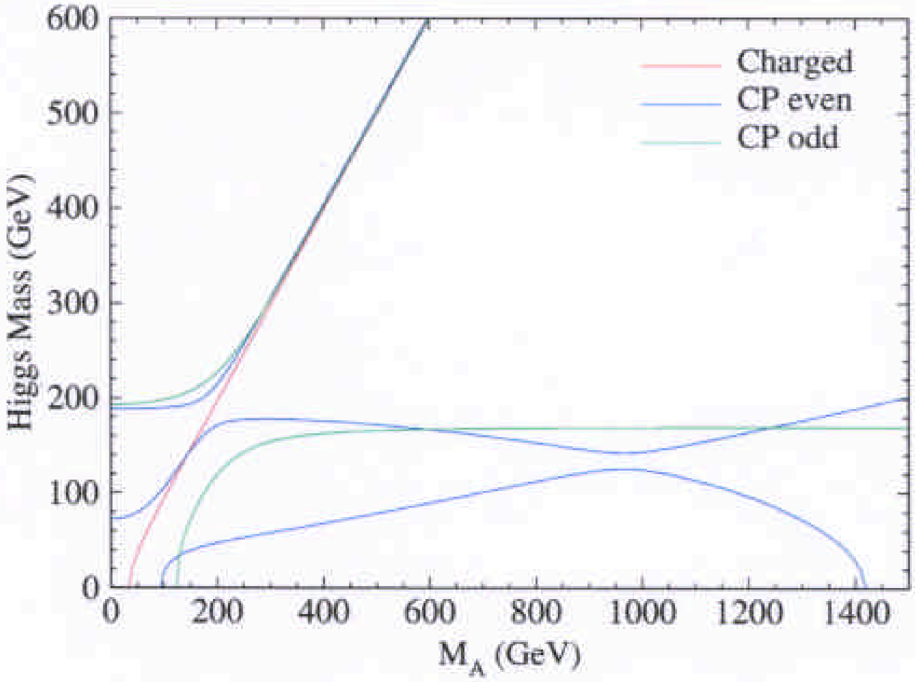
CONCLUSION :

sum rules for couplings : not all cplgs small at same time

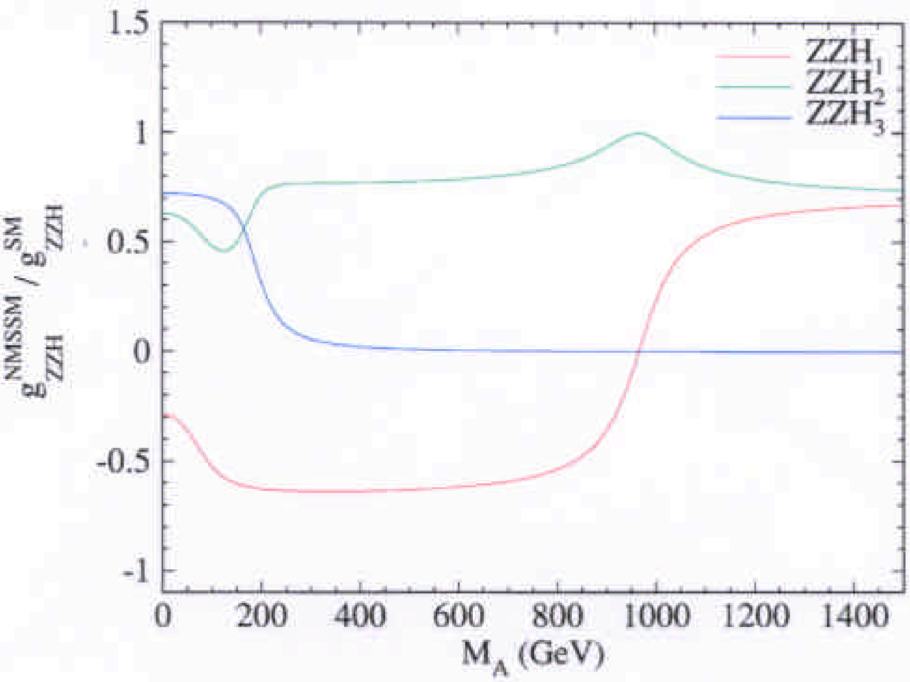
- mutual production mechanisms
- temporary escape if states too heavy : indirect effects in large regions of parameter space on precision observables
- closure of Higgs system up to ≳ 3 TeV at CLIC

$\lambda = 0.5,\ \kappa = 0.4,\ \mu = 100$ GeV,
$\tan\beta = 10,\ A_\kappa = -100$ GeV

One loop Higgs boson masses:



CP even couplings:



(ii) DYNAMICAL ELW SYMMETRY BREAKING

picture: fundam. Higgs field replaced by composite field

realizations: techni-color schemes
top-color schemes ... }

complicated constructs needed to be compatible with existing data [FCNC; M_t]

unitarity theorem: no light Higgs bosons realized → strong W interactions at $\sqrt{s} \gtrsim 1.2$ TeV

signatures: (a) WW scattering amplitudes differ from SM prediction by new SI effects:

$\Delta \simeq s/\Lambda_*^2$ scale: $\Lambda_* \simeq 4\pi v \simeq 3$ TeV

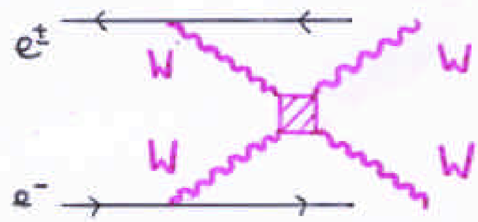
(b) light Goldstone bosons in $e^+e^- \to \gamma + P$
$\gamma\gamma \to P$

(c) new resonances in WW scattering:

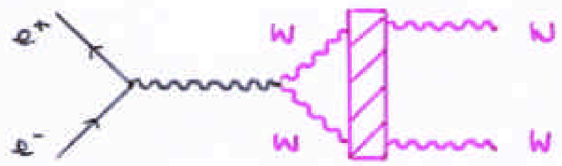
masses $M_* \lesssim \Lambda_* \simeq 3$ TeV

note: W's can be reconstructed in e^+e^- environment
→ complete reconstruction of resonance spectrum

- WW scattering :



- WW rescattering :



1. phase : sensitivity to new strong interactions through

TESLA

threshold region $\Lambda_* \lesssim 3$ TeV

2. phase : resonance production in $WW \to R_* \to WW$

CLIC

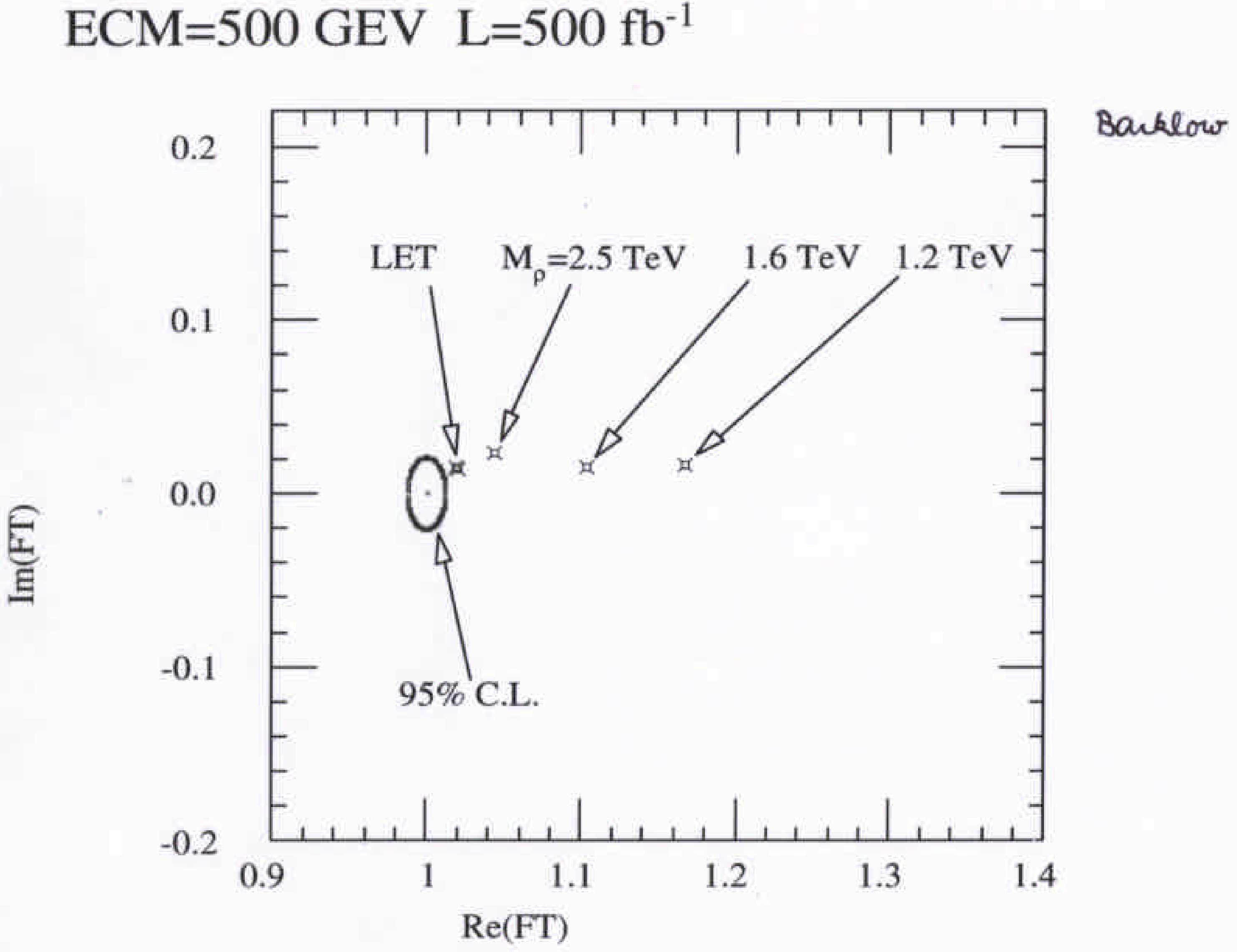
rescattering production in $e^+e^- \to WW \to R^* \to WW$

new resonance region $\Lambda_* \sim 3$ TeV

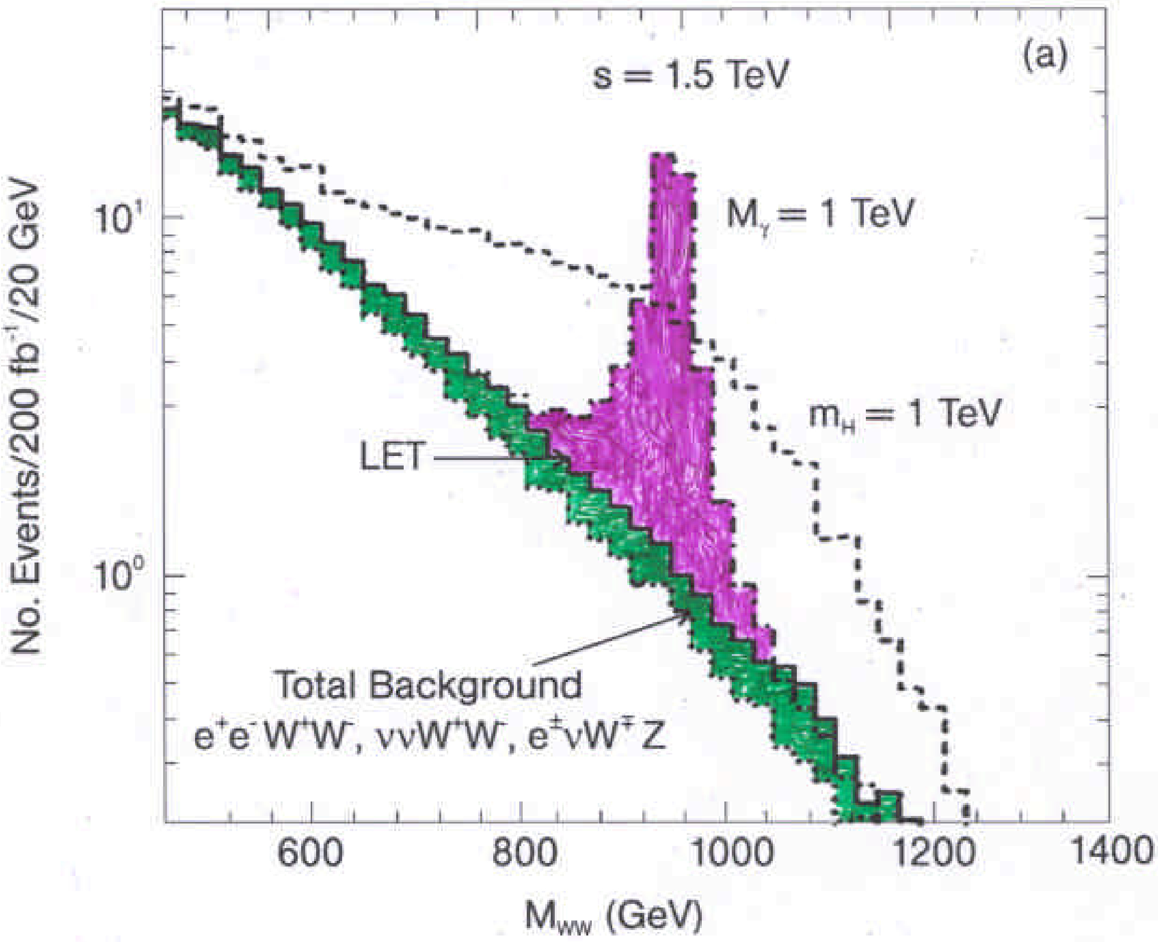
TeV collider provides first SI scale Λ_* information ;

multi-TeV collider needed to fully explore new interactions

new constituents ? VLHC ?


ECM=500 GEV L=500 fb-1
LET
Mρ=2.5 TeV
1.6 TeV
1.2 TeV
95% C.L.
0.2
0.1
0.0
-0.1
-0.2
0.9
1
1.1
1.2
1.3
1.4
Re(FT)
Im(FT)
Barklow

Banger...



(a)
s = 1.5 TeV
$M_\gamma = 1$ TeV
$m_H = 1$ TeV
LET
Total Background
$e^+e^-W^+W^-$, $\nu\nu W^+W^-$, $e^\pm\nu W^\mp Z$
No. Events/200 fb^{-1}/20 GeV
10^1
10^0
600
800
1000
1200
1400
M_{WW} (GeV)

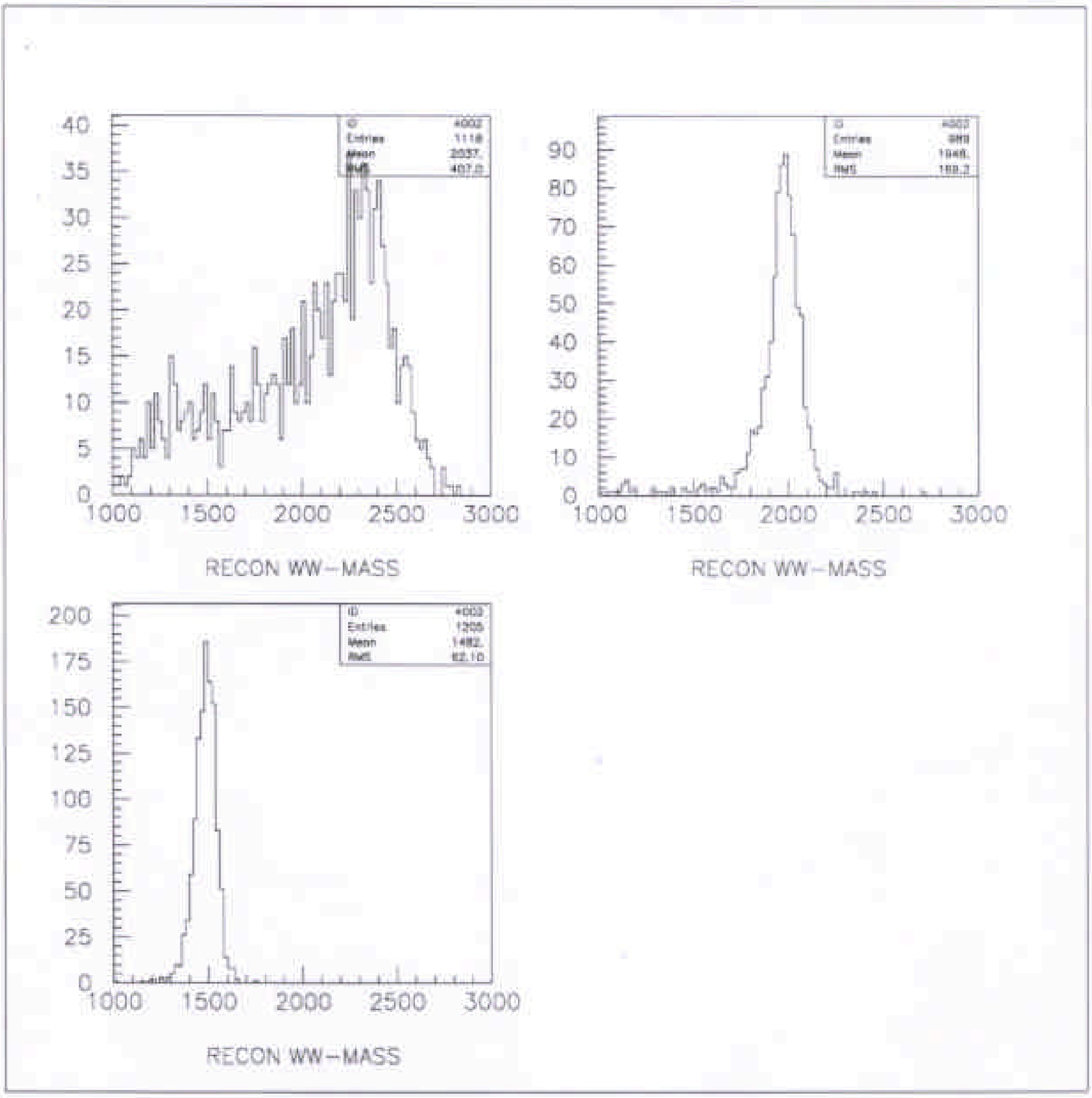
RECONSTRUCTED MASS

$M_{WW} = 1.5$ TeV, $\Gamma = 35$ GeV

$M_{WW} = 2$ TeV, $\Gamma = 85$ GeV

$M_{WW} = 2.5$ TeV, $\Gamma = 250$ GeV

deRoeck



3.) SUPERSYMMETRY

SUSY:
- bridging gap between elw and GUT/PL scales
- local realization: rationale for gravity

$\Leftarrow$ related to grand/ultimate unification of interactions

tasks:
1.) discovery of SUSY particles $\leftarrow$ Tevatron, LHC
2.) reconstruction of fundamental theory and SUSY breaking mechanism

demands: highest possible accuracy to allow stable extrapolations to high scales ~ GUT/PL scale

strategy:

1) precision meas. of masses / mixings / couplings ...

$\Downarrow$

2.) extractg basic LE params: gaugino masses scalar masses ..

$\Downarrow$

3.) reconstructg fundam. theory/SUSY breakg at high scale by means of RG evolution

SPECTRUM

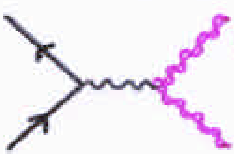
MSSM

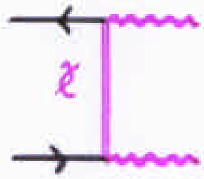
SM Particles		SUSY Particles		
Leptons ℓ	F	Sleptons $\tilde{\ell}$	B	
Quarks q	F	Squarks $\tilde{q}$	B	
Photon γ	B	Photino $\tilde{\gamma}$	F	* $\chi^{\pm}_{1,2}$
W, Z Bosons	B	Wino, Zino $\tilde{W}\tilde{Z}$	F	* $\chi^{0}_{1,2,3,4}$
Gluon g	B	Gluino $\tilde{g}$	F	
Higgs H	B	Higgsino $\tilde{H}$	F	*

'typical' mass values: charginos / neutralinos : ~ few 100 GeV
↓ sleptons : ~ few 100 GeV
Snowmass points squarks / gluinos : ~ sev. 100 GeV

1.) EXP. ANALYSIS / non-colored particles

- charginos / neutralinos :
- sleptons :



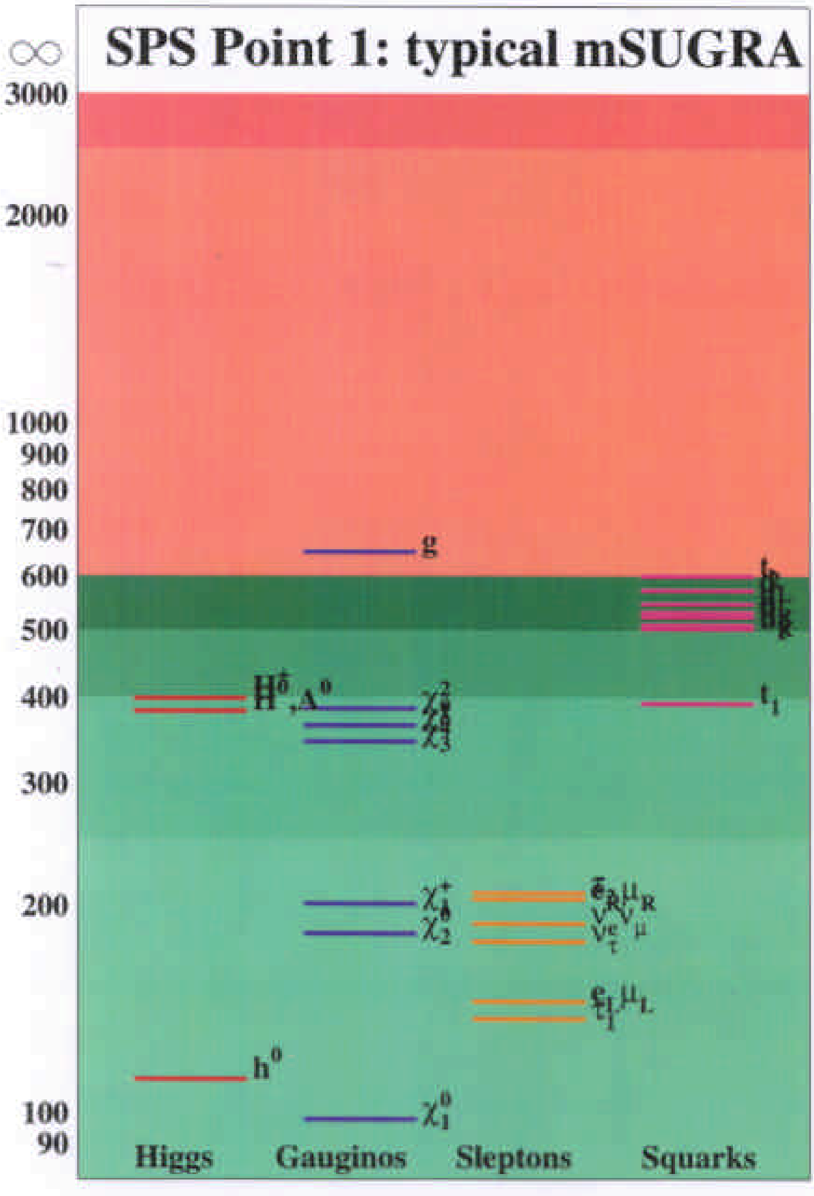


masses:

reconstruction

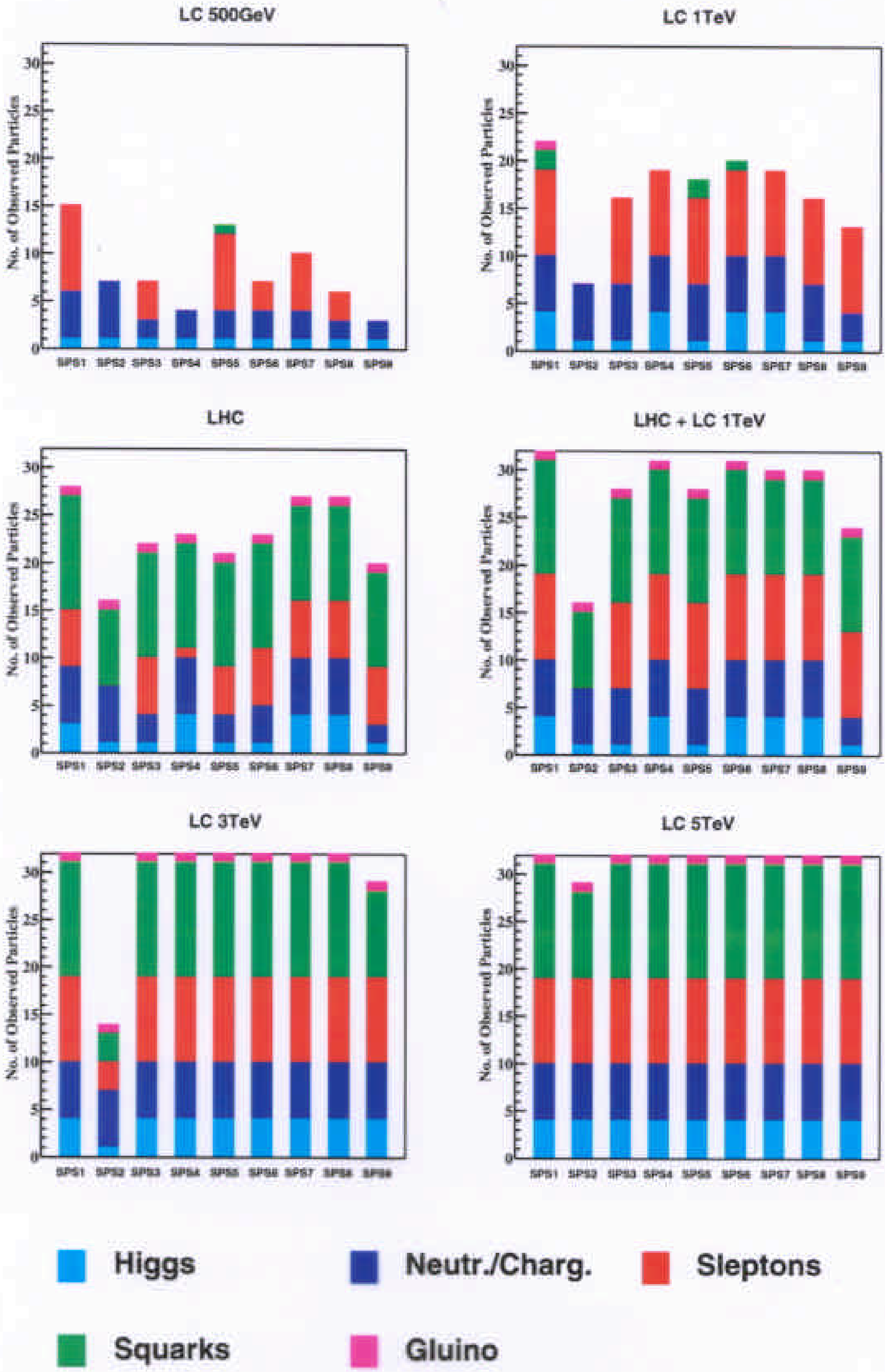
threshold: $\tilde{\chi} \sim \beta$
$\tilde{\ell} \sim \beta^3$

	final state	threshold
$\tilde{\chi}$	200 - 300 MeV	30 - 300 MeV
$\tilde{\ell}$	200 - 300 MeV	70 - 500 MeV


SPS Point 1: typical mSUGRA
3000
2000
1000
900
800
700
600
500
400
300
200
100
90
g
h0
Higgs
Gauginos
Sleptons
Squarks

Snowmass Points and Slopes (SPS)

SUSY Particles at LC + LHC



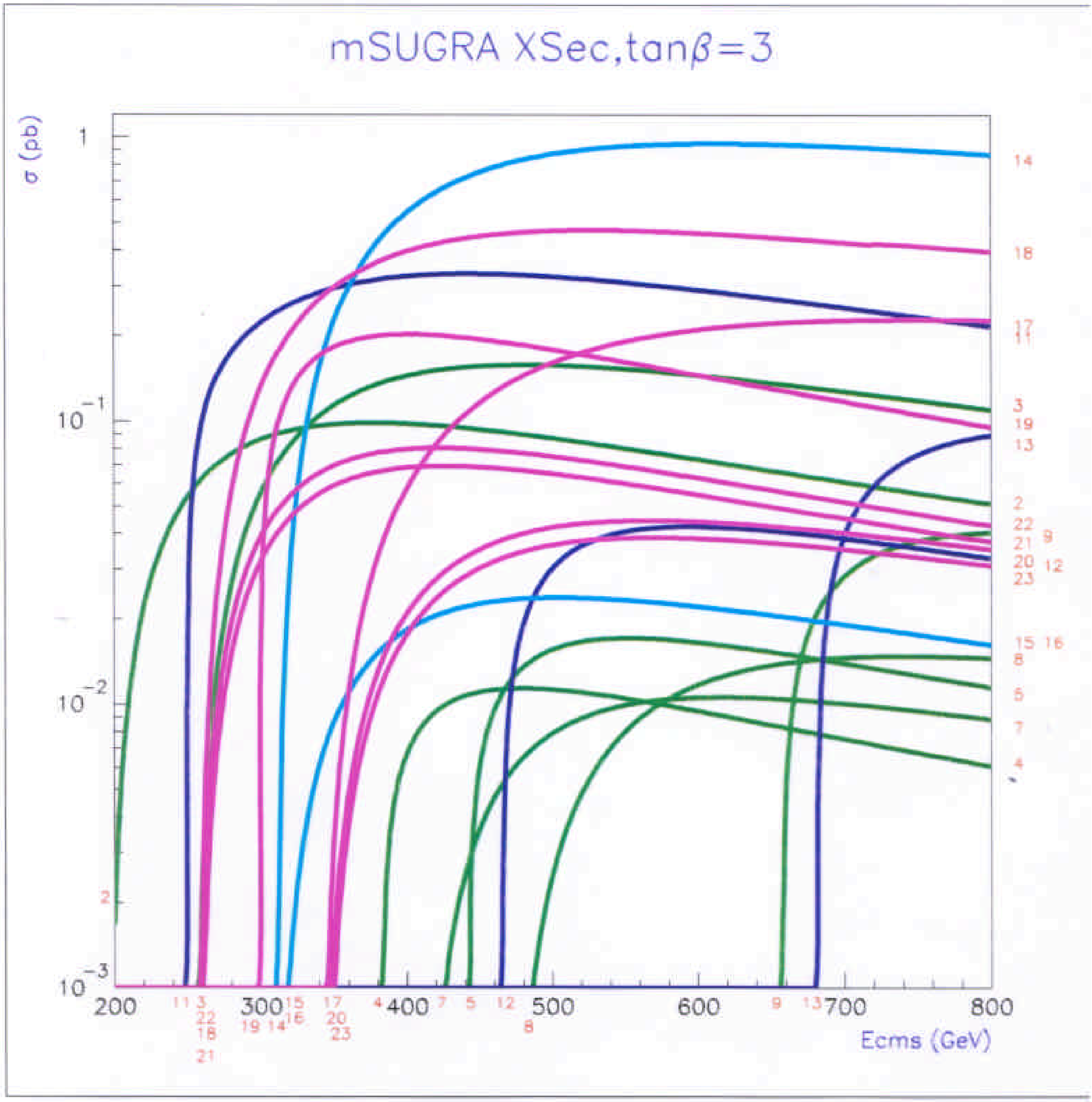
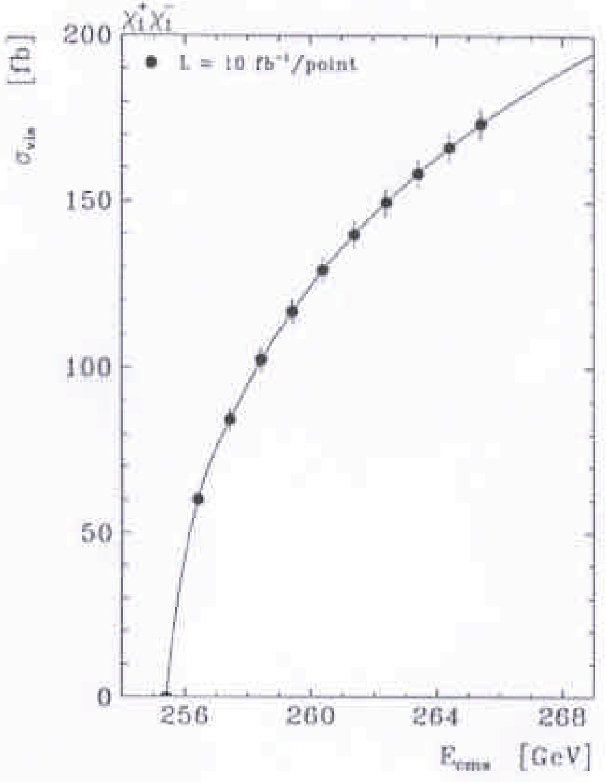


Figure 1: Cross sections of processes for $\tan\beta=3$. The process numbers shown in red correspond to those of SUSYGEN and are listed in the table

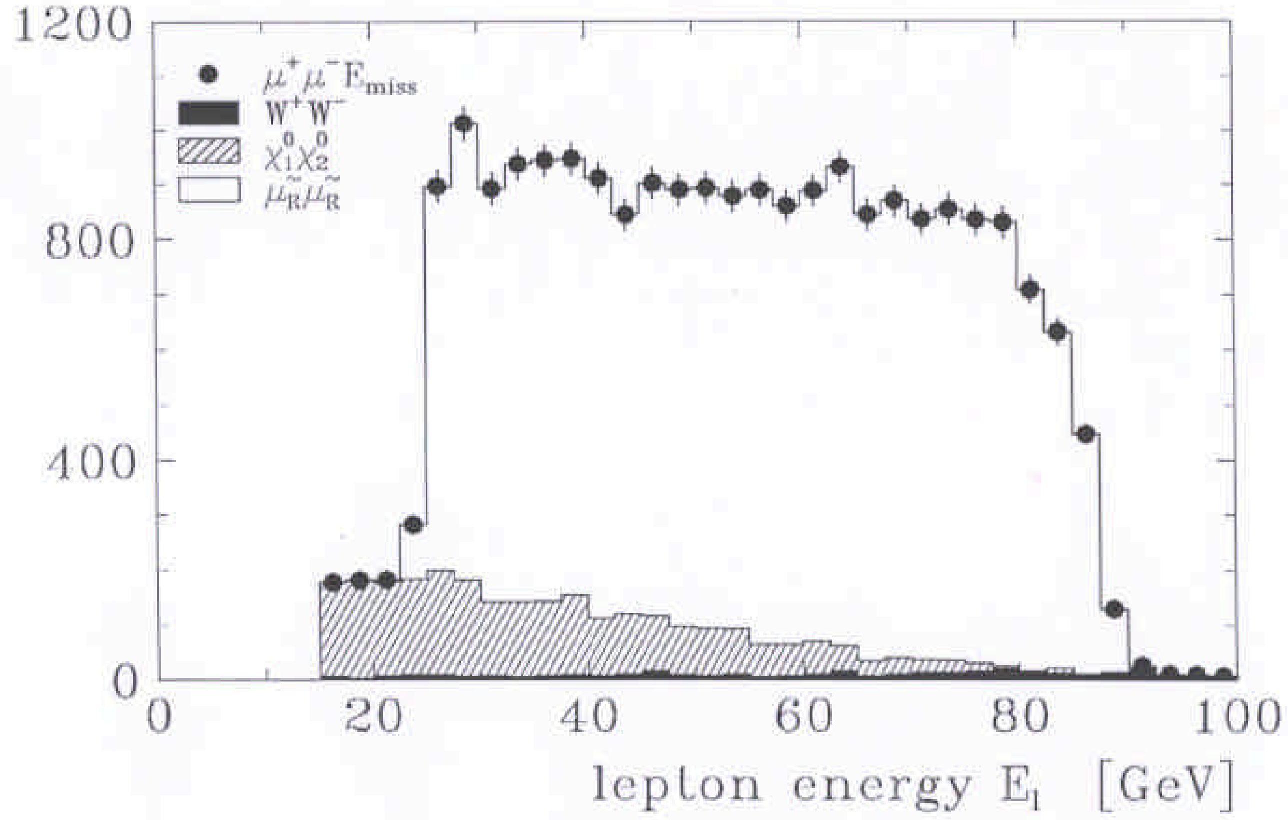
$e_L^- e_R^+ \to \chi_1^- \chi_1^+$



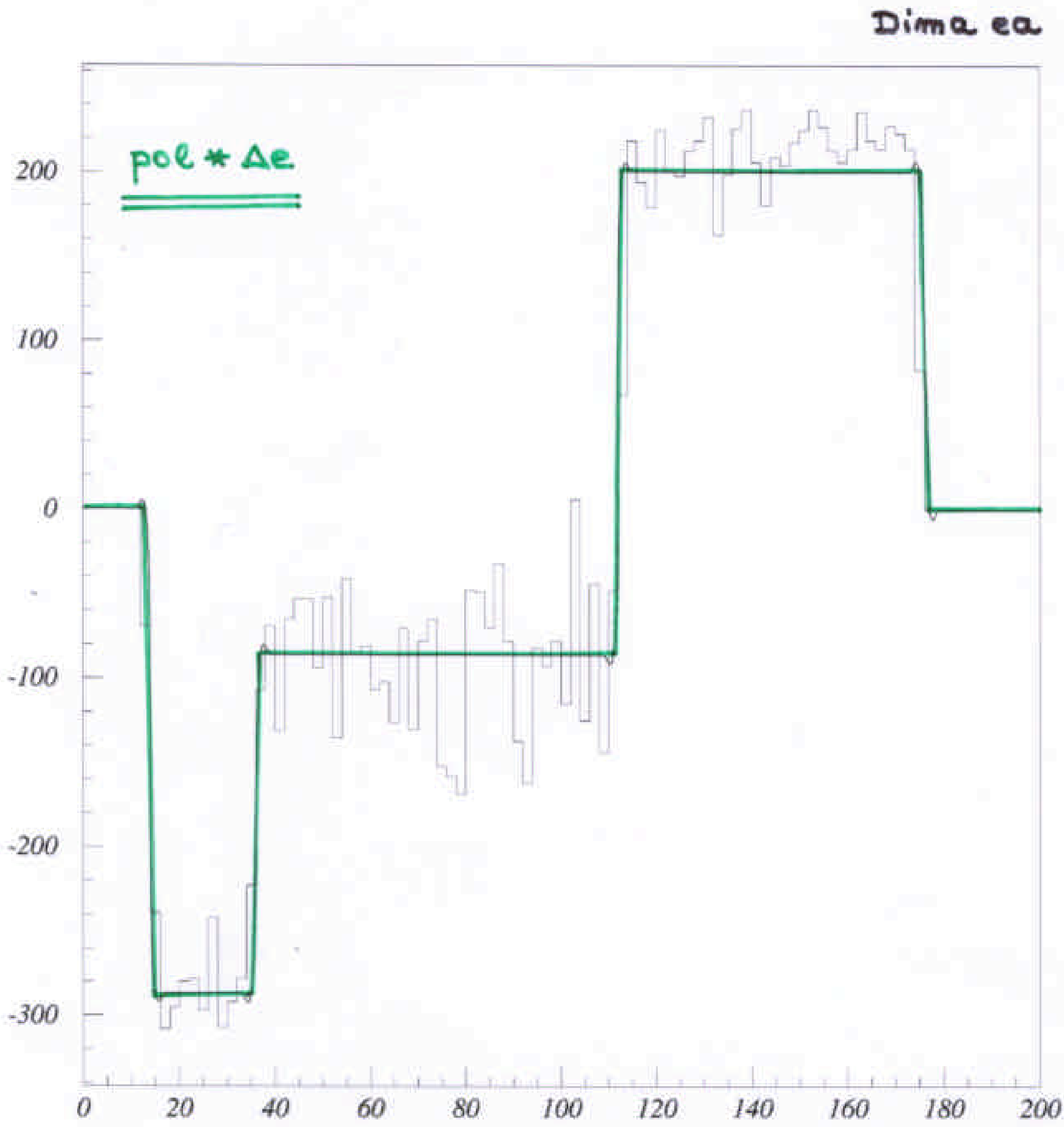
$m_{\chi_1^\pm} = 127.7 \pm 0.04$ GeV

$e^+e^- \to \tilde{\mu}_R^+ \tilde{\mu}_R^-$

Martyn



$m_{\tilde{\mu}_R} = 132.0 \pm 0.3$ GeV $m_{\chi_1^0} = 71.9 \pm 0.2$ GeV



Dima ea
pol * Δe
200
100
0
-100
-200
-300
0
20
40
60
80
100
120
140
160
180
200

mixings: $\tilde{\chi}^-_{1L} = \cos\phi_L \tilde{W}^-_L + \sin\phi_L \tilde{H}^-_L$

$\tilde{\chi}^-_{2L} = -\sin\phi_L \tilde{W}^-_L + \cos\phi_L \tilde{H}^-_L$ and $L \to R$

mixing parameters uniquely determined in production with L,R polarized beams

analogous analysis for mixed $\tilde{t}$ squarks

note: accuracy deteriorates for heavy squarks:
non-zero width effect in β^3 }
beamstrahlung } ‰ → %

2.) EXTRACTING BASIC PARAMETERS

M_2, M_1	gaugino mass parameters	
μ	higgsino mass parameter	
$tg\beta$		

$M_2 = 158 \pm 1.8$ GeV
$M_1 = 72 \pm 3.2$ GeV
$\mu = 316 \pm 0.9$ GeV
$tg\beta = 3.0 \pm 0.7$

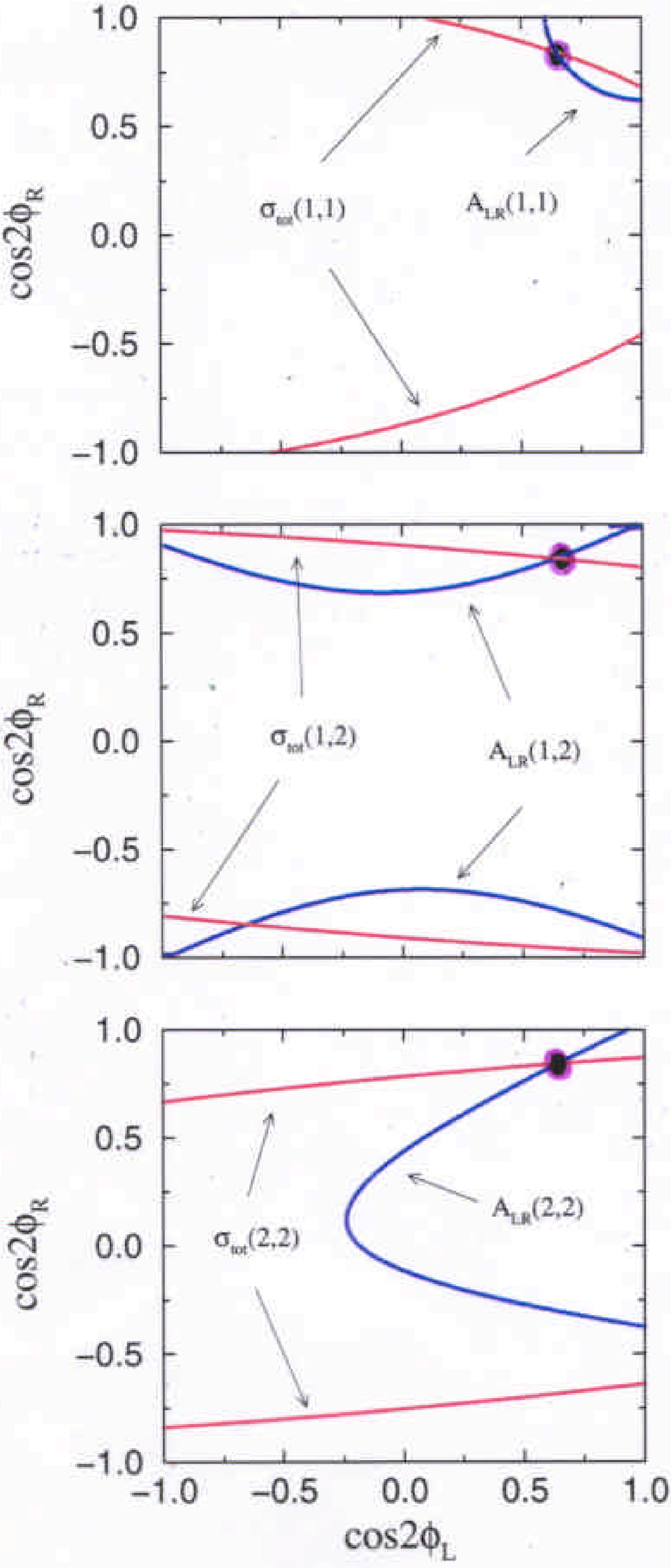
$$M_2/|\mu| = \frac{1}{2}\left[2(\chi_2^\pm + \chi_1^\pm - 2W) \mp (\chi_2^\pm - \chi_1^\pm)(\cos 2\phi_R + \cos 2\phi_L)\right]^{1/2}$$

$$M_1^2 = \Sigma \chi_i^0 - M_2^2 - \mu^2 - 2Z$$

$$tg\beta = \left[4W + (\chi_2^\pm - \chi_1^\pm)(\cos 2\phi_R - \cos 2\phi_L)\right]^{1/2} / [-]^{1/2}$$

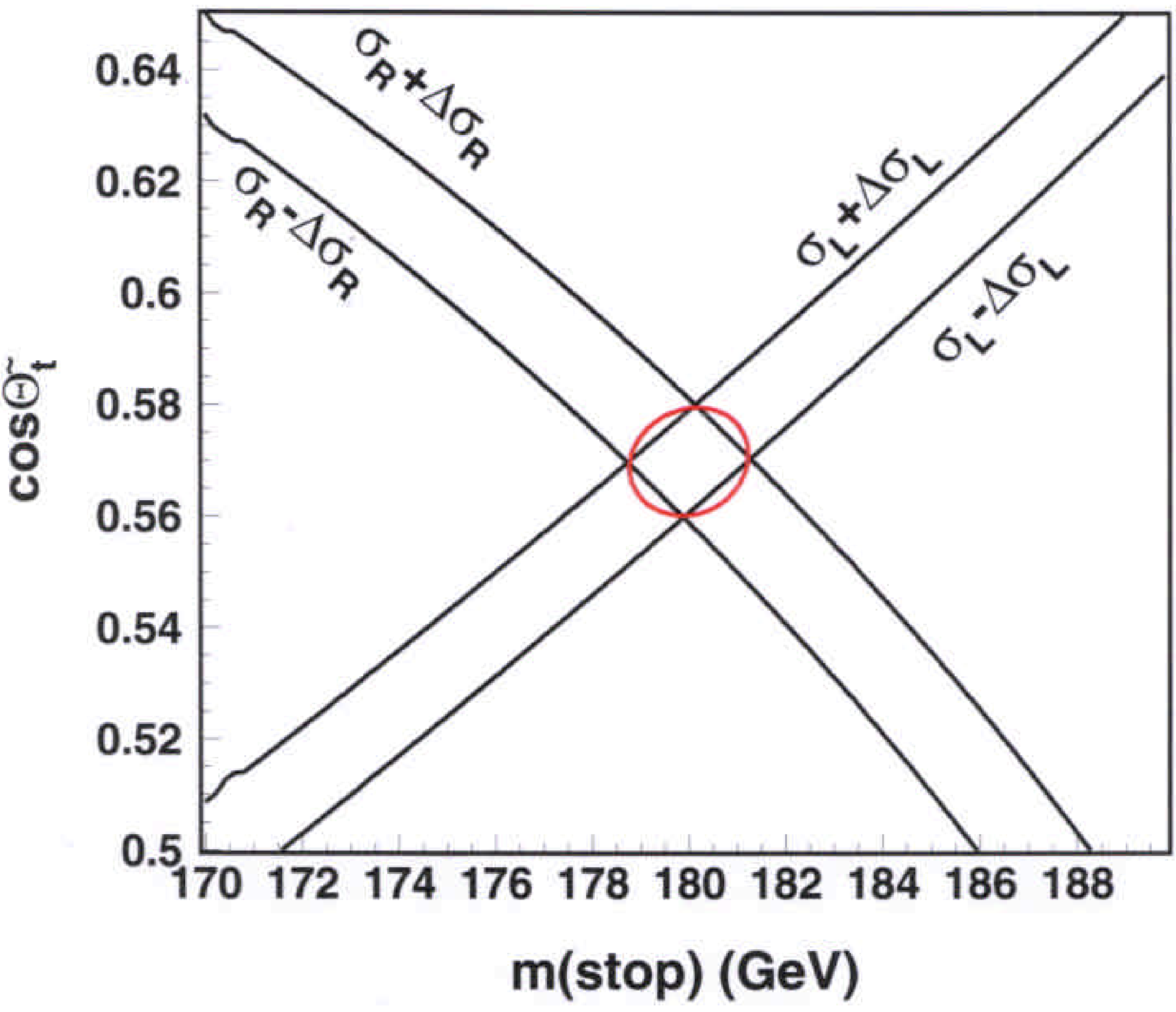
note: large $tg\beta$ ← $\tilde{\tau} \to \tau$ polarization effects
Higgs analyses

Choi, Song, Djouadi, Z.



Bartl ea
Nowak ea

stop into c neutralino 80/60 pol



3.) FUNDAMENTAL THEORY / SUSY BREAKING

realizations: mSUGRA
GMSB
...

method: realization of GUT reflected in identical gauge couplings after extrapol. to high scale
↓
regularities of SUSY mass parameters if extrapolated to high scale

⇐ exploring physics near GUT/PL scale

mSUGRA : SUSY transmitted from hidden world by gravity

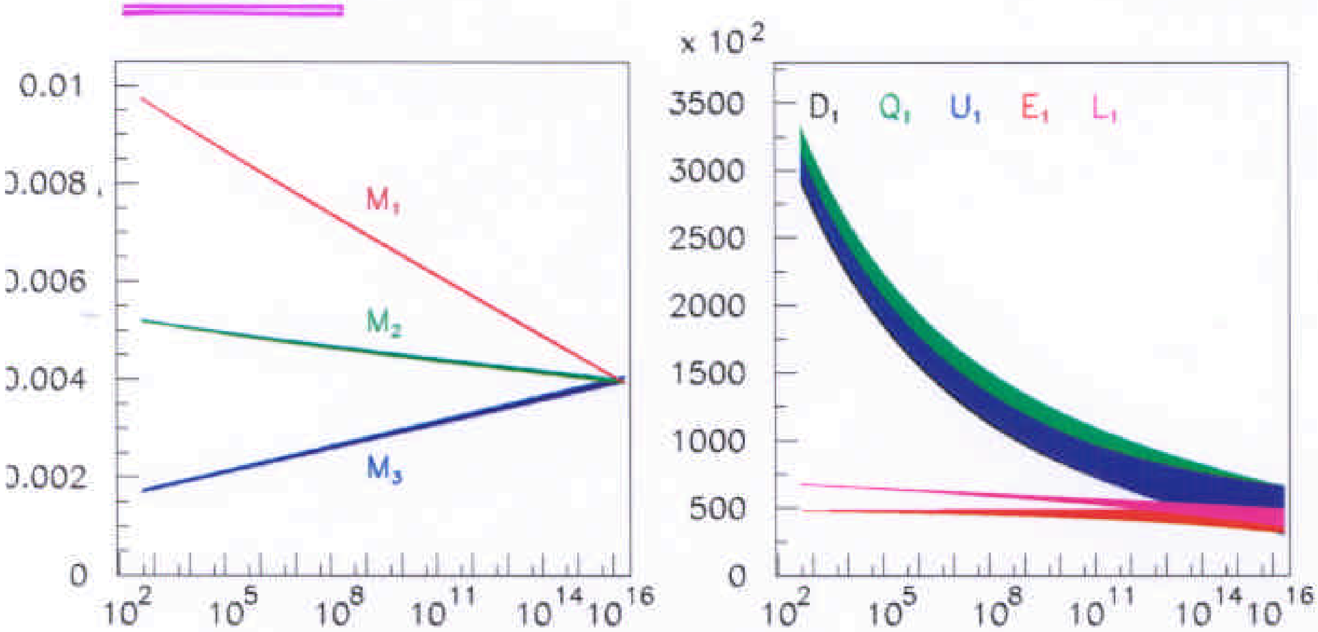
breaking flavor univ.: masses, decay, production } 5 parameters: $m_0, M_{1/2}, A_0, tg\beta, sgn\,\mu$

universality emerging in extrapolation of measured parameters by means of RG near Λ_{GUT}:

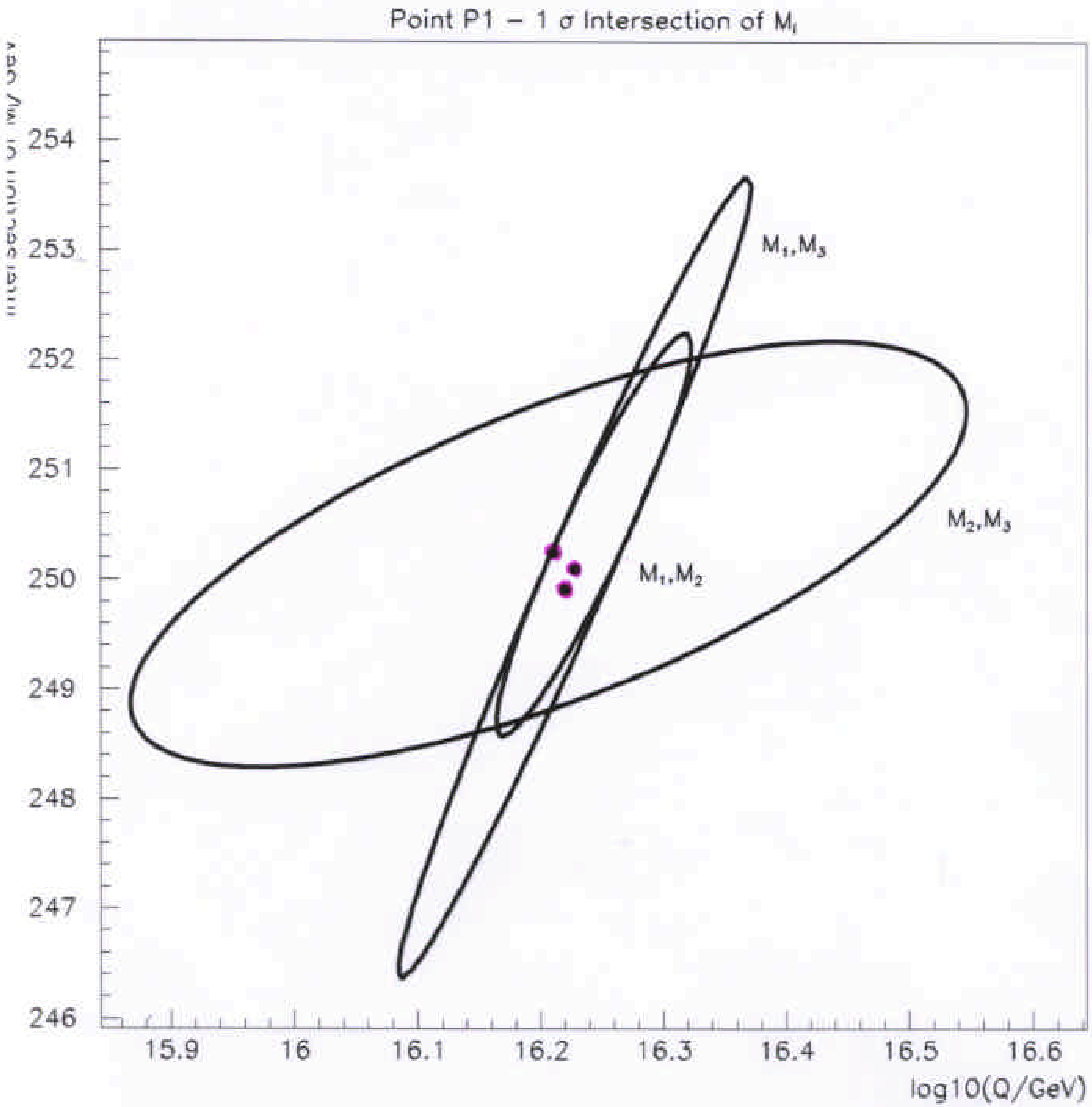
$M_i \to M_{1/2}$
$\tilde{m}_f \to m_0$ }

Blair
Porod, Z

mSUGRA



mSUGRA



Point P1 – 1 σ Intersection of M_i
254
253
252
251
250
249
248
247
246
15.9
16
16.1
16.2
16.3
16.4
16.5
16.6
log10(Q/GeV)
M_1, M_3
M_2, M_3
M_1, M_2

ex:

sgn μ = +		theor. values	meas./extrap.
scalar mass	m_0	160 GeV	159.9 ± 0.1 GeV
gaugino mass	$M_{1/2}$	200 GeV	200.0 ± 0.1 GeV
trilin. cplg	A_0	600 GeV	599.0 ± 2.0 GeV
	$tg\beta$	30	30.01 ± 0.01

GMSB : SUSY transmitted through messenger sector [~ 10 and 10^3 TeV] by gauge fields

→ no universality in scalar sector at GUT scale

→ regularity at intermediate scale: $\tilde{m}$ univ. for ident. quantum numbers }

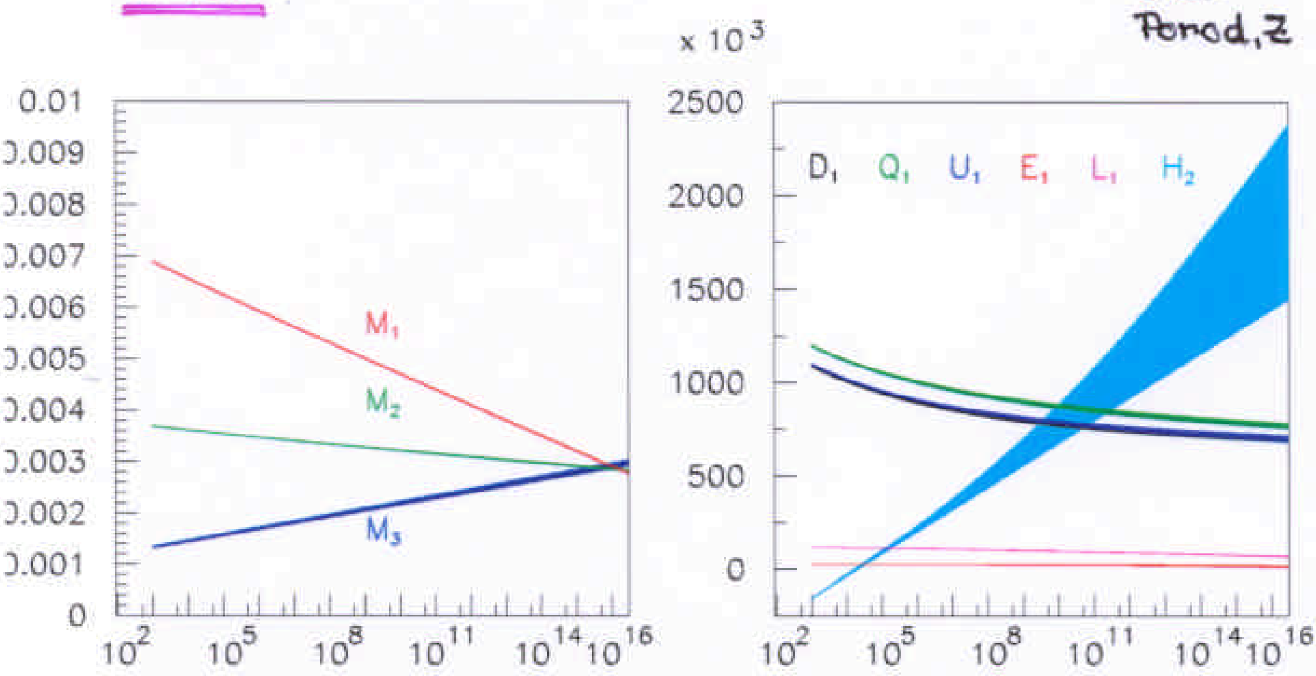
[direct exp. signature: LSP = gravitino : $\tilde{\chi}^0_1 \to \gamma + \tilde{G}$
$\tilde{\tau}_1 \to \tau + \tilde{G}$]

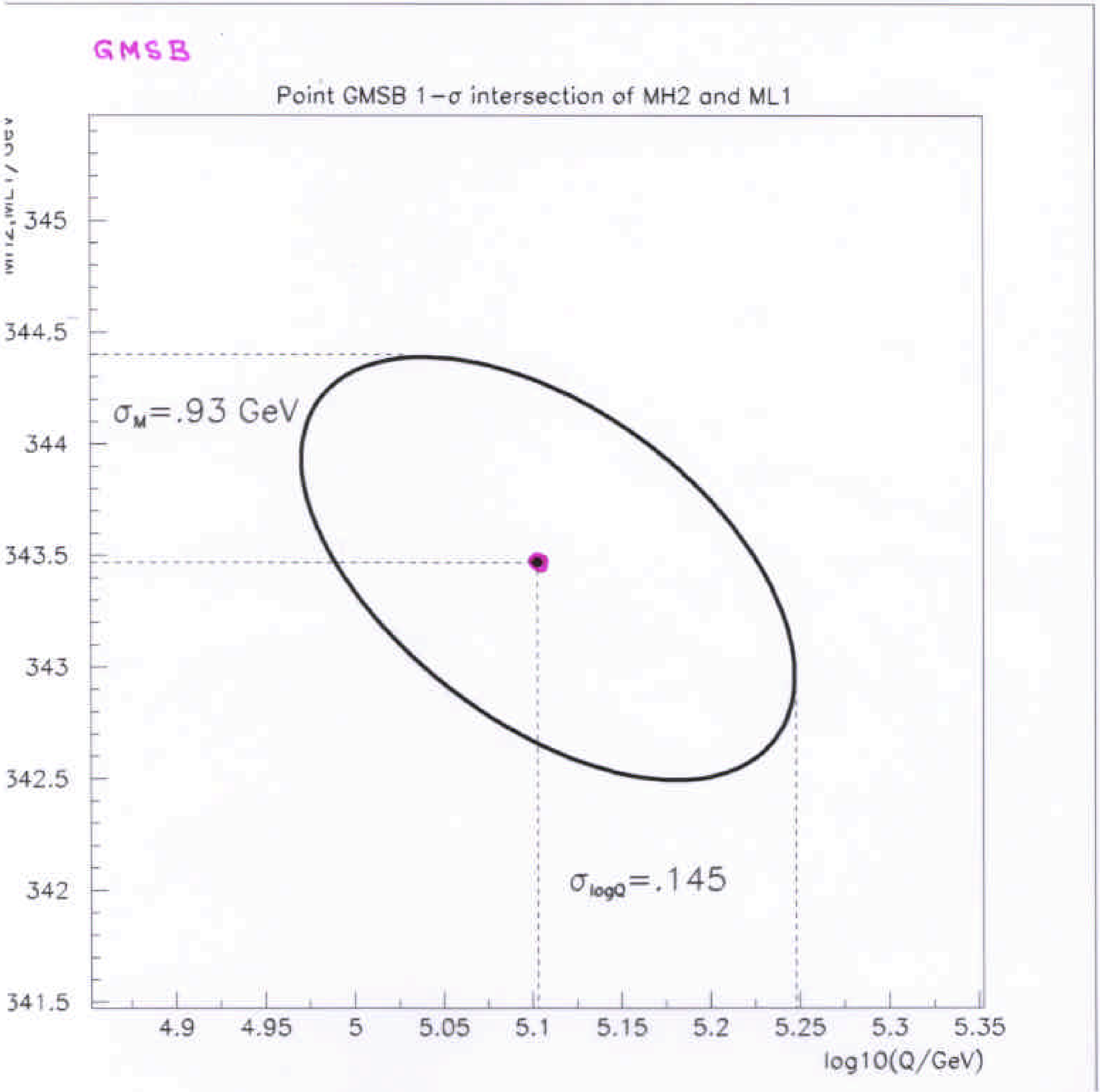
ex:

FUNDAMENTAL PARAMETERS		theor.	exp. error
mass scale	Λ	76 TeV	76.01 ± 0.08 TeV
mess. multiplicity	N_5	1	0.9994 ± 0.0009
messenger scale	M_m	160 TeV	161 ± 2 TeV
SUSY brkg parameter	$\sqrt{F}$	60 to 5×10^3 TeV	± 5%
mix	$tg\beta$	3.50	3.50 ± 0.03

GMSB

Blair
Porod, Z




GMSB
Point GMSB 1−σ intersection of MH2 and ML1
MH2,ML1 / GeV
σ_M=.93 GeV
σ_{logQ}=.145
345
344.5
344
343.5
343
342.5
342
341.5
4.9
4.95
5
5.05
5.1
5.15
5.2
5.25
5.3
5.35
log10(Q/GeV)

SUSY at LC: 1.) comprehensive and robust determination of basic SUSY parameters

2.) high accuracy allows reconstruction of fundamental SUSY theory / SUSY breaking parameters

LC may provide, through SUSY sector, essential information on physics near GUT/PL scale ~ grand/ultimate unification

4.) EXTRA SPACE DIMENSIONS

alternative: gravity scale [TeV] ~ ELW scale

reconciled with observations if weak gravity in dim = 4 only projection of strong gravity in dim > 4

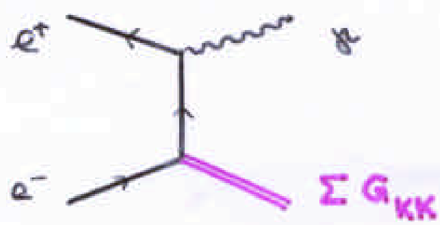
(a) ADD: volume effect: adding n compactified dimensions

$$M_*^{n+2} R_*^{n} \sim G_N^{-1}$$

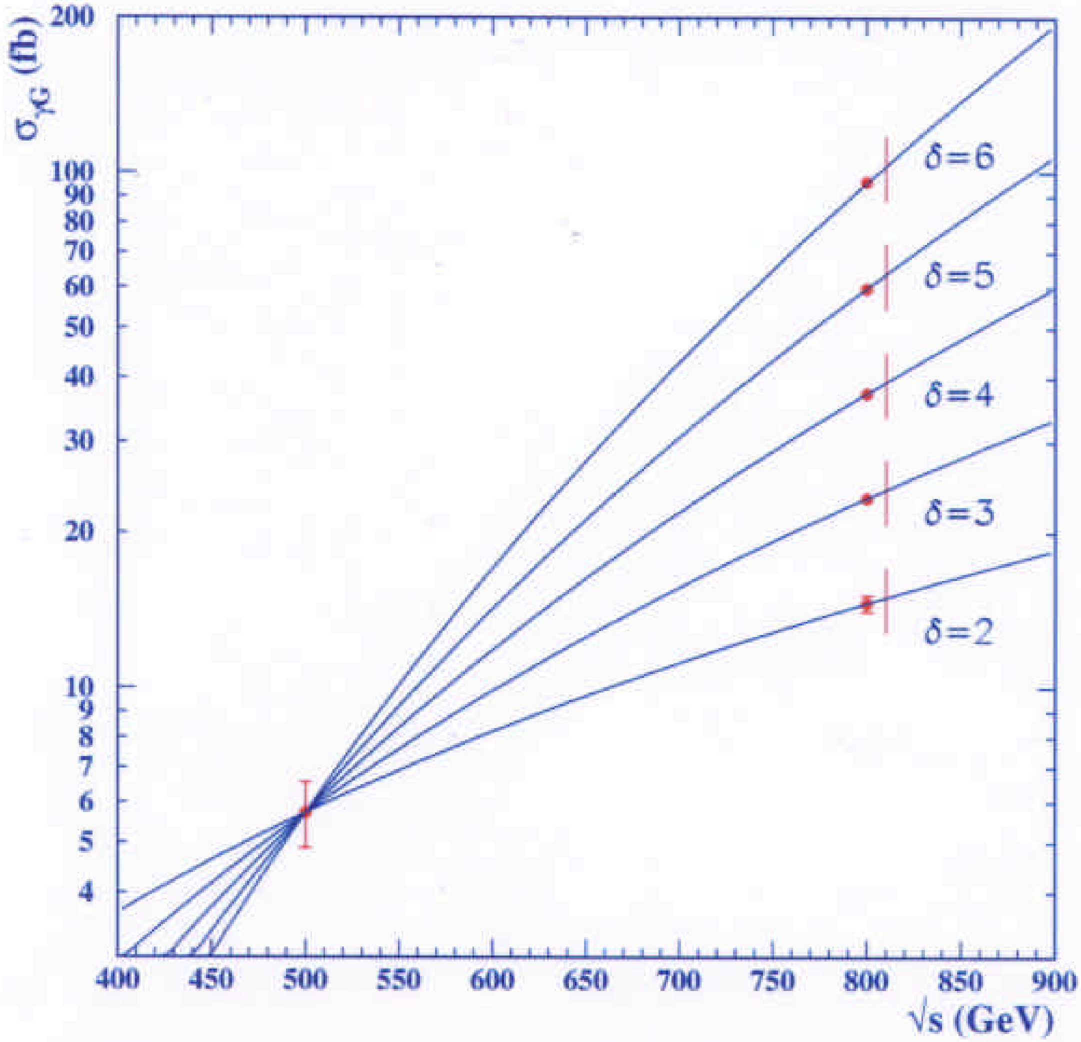
⇒ emission of graviton KK towers:

$$e^+e^- \to \gamma + \Sigma G_{KK}$$
$$\to \gamma + \not{E}$$

$$\sigma = F[M_*, n]_s$$



Wilson



$\sigma_{\gamma G}$ (fb)
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
$\delta=6$
$\delta=5$
$\delta=4$
$\delta=3$
$\delta=2$
400
450
500
550
600
650
700
750
800
850
900
$\sqrt{s}$ (GeV)

→ spin-2 contact interactions:

ee → ee:

$J = 2$ ang. distr.

$\sqrt{s} \sim 0.8$ TeV :

sensitivity
$M_* \simeq 8$ TeV

(b) RS : exponential damping by warp factor } G brane $\xrightarrow[\text{exp}]{}$ SM brane

KK resonances : non-uniform Bessel spacing

$e^+e^- \to f\bar{f}$ $\quad M_{KK} \sim$ TeV

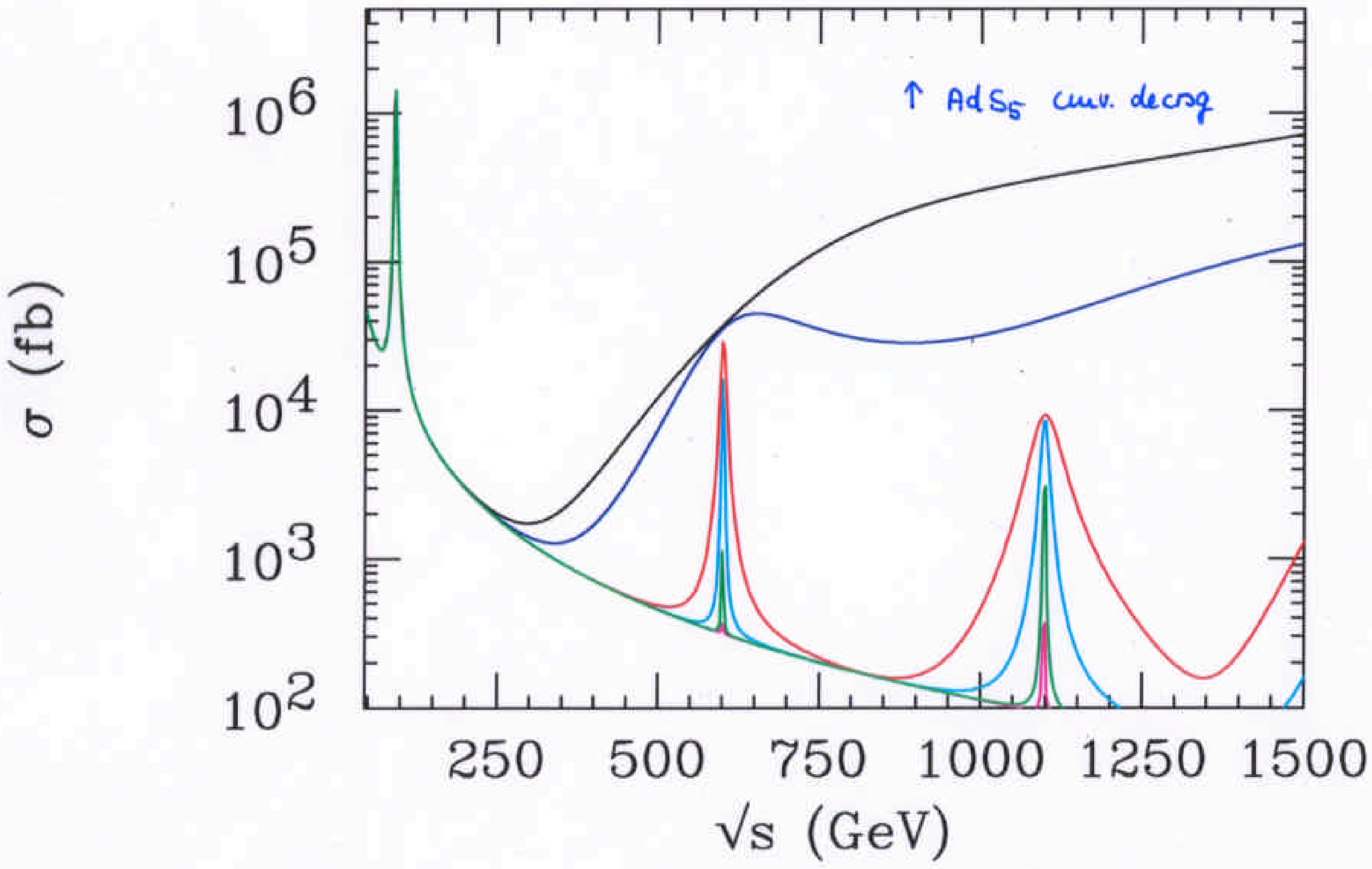
5.) HIGH-PRECISION ANALYSES: SM & BEYOND

a) TOP QUARK

high-precision measurements of t properties:

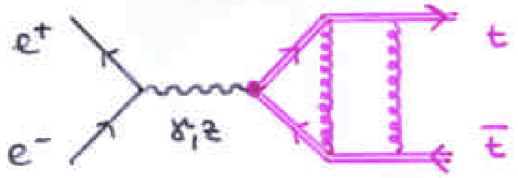
- test of elw sym brkg at qu level: $M_t, M_Z, s_W^2 \to M_H$
- maximal coupling to Higgs field
- max mass: key rôle in flavor sector: $M_t \to M_e, M_\nu, \ldots$

Hewett ea



↑ AdS5 curv. decrsg
10^6
10^5
10^4
10^3
10^2
σ (fb)
250
500
750
1000
1250
1500
√s (GeV)

M_t max. precision: $e^+e^- \to t\bar{t}$ excitation curve near threshold



$\sigma_{t\bar{t}} \sim \beta_t \sim \sqrt{s - 4M_t^2}$

$\ominus$ Γ_t smearing

$\oplus$ 1s remnant

consistent M_t schemes: (a) short-distance definition

(b) stability for pred. of cross sections includg log v resummations

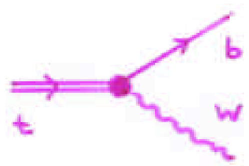
<u>Results</u>:

$\Delta M_t \lesssim 200$ MeV
$\Delta M_t / M_t \lesssim 1‰$

most precise determination of mass in quark sector

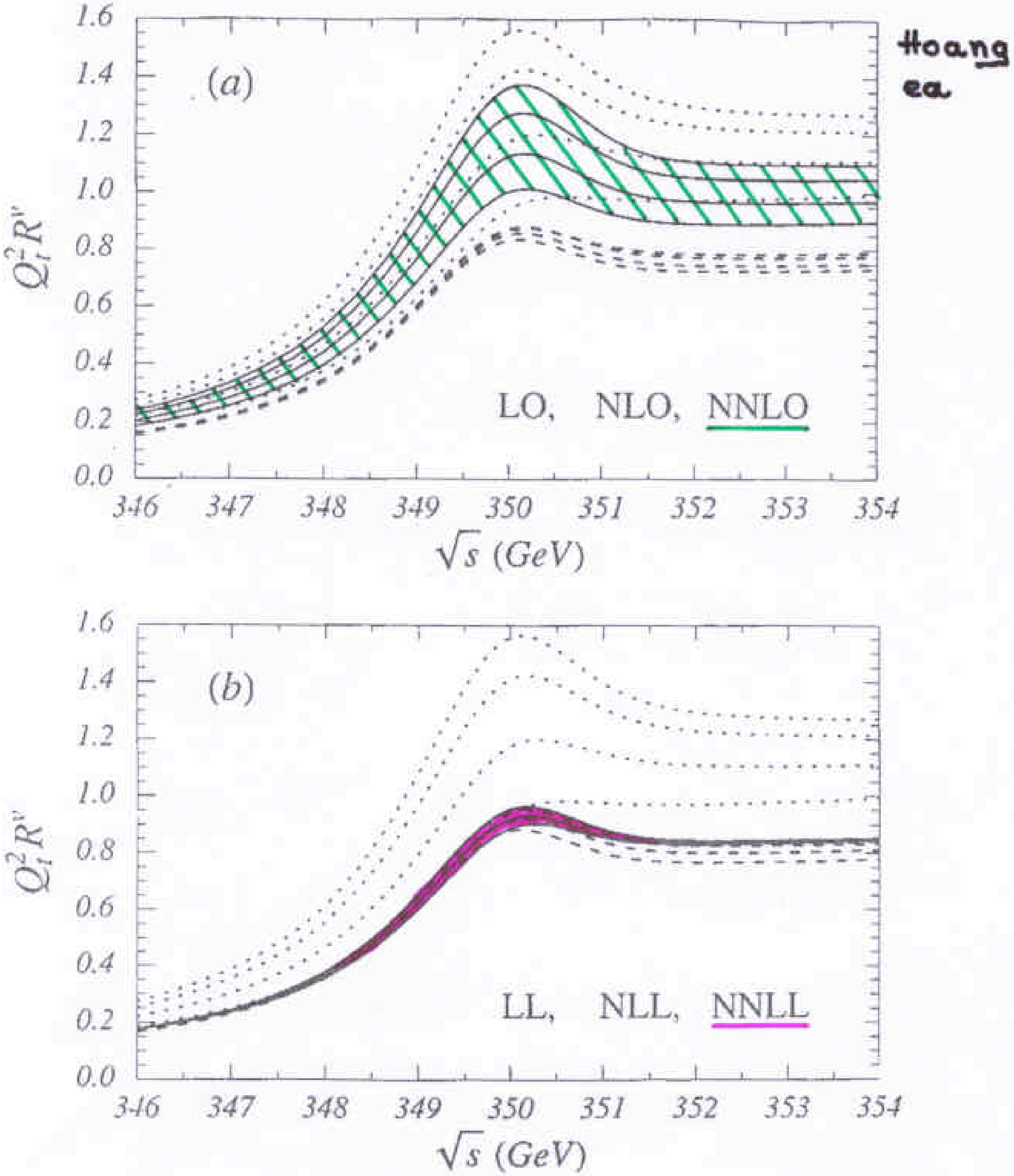
ELW

<u>stat. param.</u>: charges
magn. / el dipole mom.



<u>decay char.</u>: Michel analysis → RH/LH couplings

The profile of the top quark can be reconstructed with high accuracy at the level 10^{-2} to 10^{-3}



Hoang ea
(a)
LO, NLO, NNLO
$Q_t^2 R^v$
$\sqrt{s}$ (GeV)
(b)
LL, NLL, NNLL
$Q_t^2 R^v$
$\sqrt{s}$ (GeV)

Form factor	SM value	$\sqrt{s} = 500\,\mathrm{GeV}$		$\sqrt{s} = 800\,\mathrm{GeV}$	
		$p = 0$	$p = -0.8$	$p = 0$	$p = -0.8$
F_{1V}^{Z}	1		0.019		
F_{1A}^{Z}	1		0.016		
$F_{2V}^{\gamma,Z} = (g-2)^{\gamma,Z}{}_t$	0	0.015	0.011	0.011	0.008
$\mathrm{Re}\,F_{2A}^{\gamma}$	0	0.035	0.007	0.015	0.004
$\mathrm{Re}\,d_t^{\gamma}$ [10^{-19} e cm]	0	20	4	8	2
$\mathrm{Re}\,F_{2A}^{Z}$	0	0.012	0.008	0.008	0.007
$\mathrm{Re}\,d_t^{Z}$ [10^{-19} e cm]	0	7	5	5	4
$\mathrm{Im}\,F_{2A}^{\gamma}$	0	0.010	0.008	0.006	0.005
$\mathrm{Im}\,F_{2A}^{Z}$	0	0.055	0.010	0.037	0.007
F_{1R}^{W}	0	0.030	0.012		
$\mathrm{Im}F_{2R}^{W}$	0	0.025	0.010		

Table 5.3.1: *1 s.d. statistical sensitivities to some (non) SM form factors in $t\bar{t}$ production [57, 95, 96] and in t decay to Wb [57, 88]. The second column contains the respective SM value to lowest order, p denotes the polarisation of the electron beam. For the c.m. energy $\sqrt{s} = 500\,GeV (800\,GeV)$ an integrated luminosity of 300 fb^{-1} (500 fb^{-1}) was used. F_{1R}^{W} measures $(V + A)/(V - A)$.*

b) ELECTROWEAK GAUGE BOSONS

- increase precision on basic <u>electroweak parameters</u>
- establish <u>non-abelian gauge symmetry</u> of elw interactions, one of the most fundamental symmetries in Nature, at the highest accuracy possible
- open window to <u>new elw gauge bosons and fermions</u> as inspired by GUT scenarios

(i) ELW MIXING ANGLE $\sin^2\vartheta_W$ and M_W :

– LR pol asymmetry : $A_{L,R} = \dfrac{2(1-4s_\ell^2)}{1+(1-4s_\ell^2)^2}$
$[P_\pm \neq 0]$

– WW threshold excitation : W mass

1 giga Z:
$\delta \sin^2\vartheta_\ell \approx 1\cdot 10^{-5}$
$\delta M_W \approx 6$ MeV

HIGGS TEST

$[G_F, \alpha(M_Z), \sin^2\vartheta_\ell, M_t] \to M_H$: confront with direct measurem
field-th consistency ~ new scal
in loops

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha(M_Z^2)}{M_Z^2 s_\ell^2 c_\ell^2}\,\frac{1}{1-\Delta_\ell} \; : \quad \Delta_\ell^t = -\frac{3G_F M_t^2}{8\sqrt{2}\,\pi^2}\left[1-\frac{2M_Z^2}{9M_t^2}\log\frac{M_t^2}{M_W^2}\right]$$

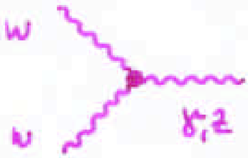
$$\Delta_\ell^H = +\frac{G_F M_W^2}{8\sqrt{2}\,\pi^2}\,\frac{1+9s_W^2}{3c_W^2}\left[\log\frac{M_H^2}{M_W^2}-\frac{5}{6}\right]$$

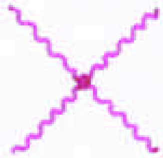
	ΔM_t	$\Delta \sin^2\vartheta_{\rm eff}$	ΔM_W	$\Delta M_H / M_H$
LHC	1 GeV	2×10^{-4}	15 MeV	0.37 / 0.31
LC	200 MeV	1×10^{-5}		0.06

(ii) GAUGE FIELD COUPLINGS :

SM : $SU_3 \times SU_2 \times U_1$: non-Abelian symmetry ← self-interaction

couplings ←
(i) gauge invariance
(ii) renormalizibility





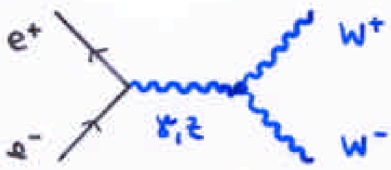
general parametrization :

charge : $g_1 = 1 + \Delta g_1$ — SM: $g_1 = 1$

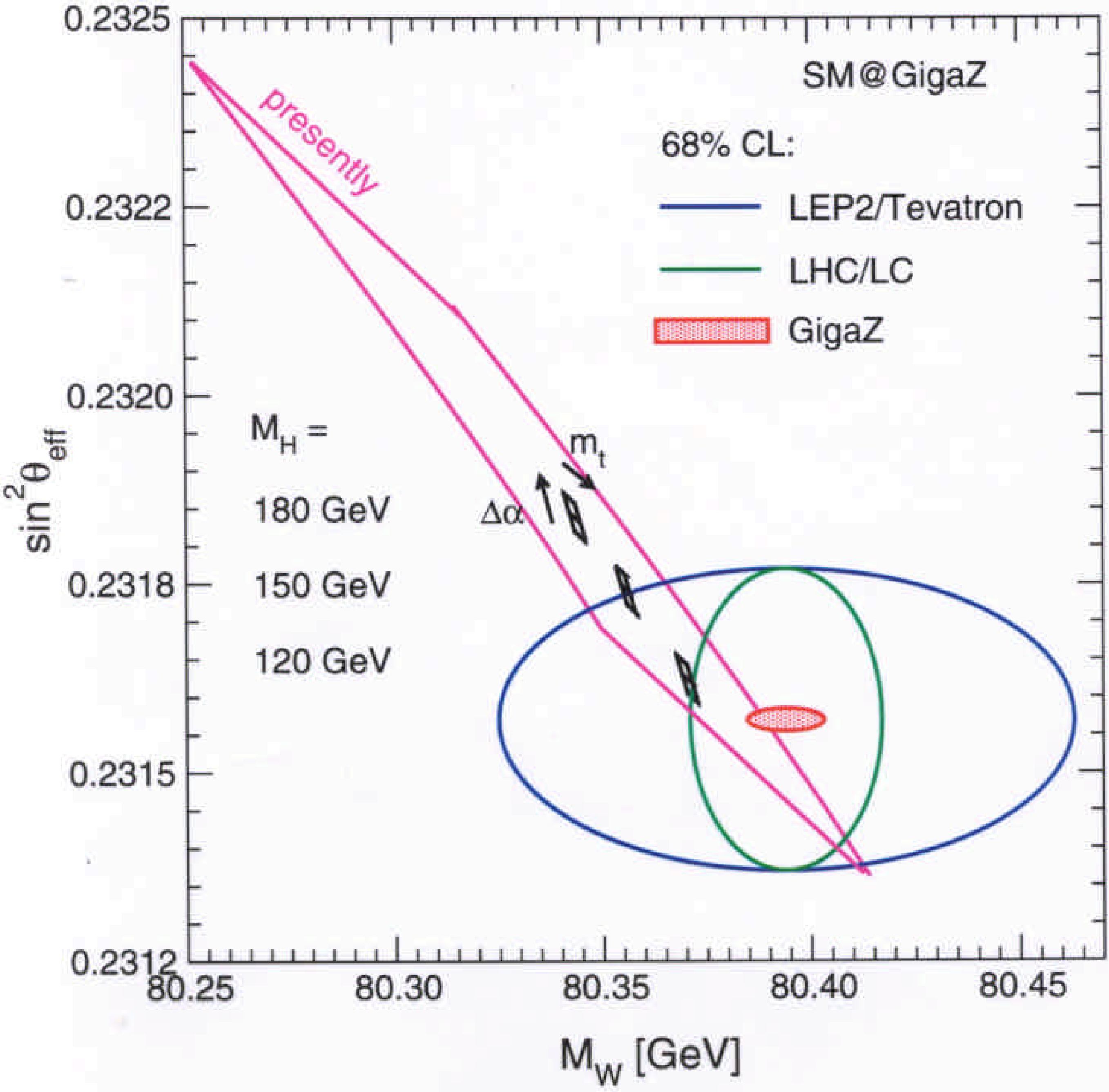
magn. dip. mom. : $\mu = \frac{e}{2M_W}\left[2 + \Delta g_1 + \Delta\kappa + \lambda\right]$ — $\kappa = 1$

elec. quad. mom. : $Q = -\frac{e}{M_W^2}\left[1 + \Delta\kappa - \lambda\right]$ — $\lambda = 0$

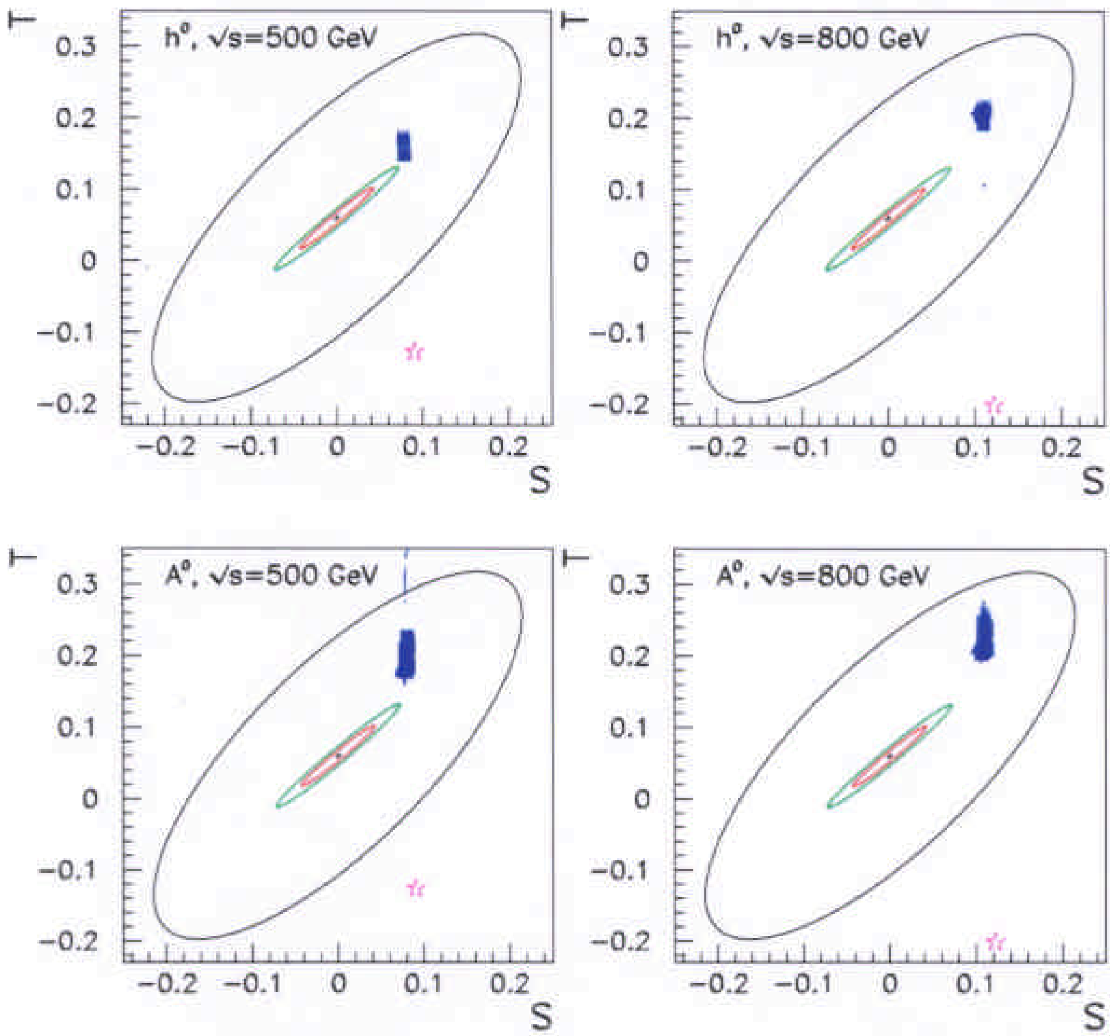
experiment : $e^+e^- \to W^+W^-$
- $W \to \ell\nu$
- $W \to q\bar{q}'$



Eiler et al



SM@GigaZ
68% CL:
LEP2/Tevatron
LHC/LC
GigaZ
presently
M_H =
180 GeV
150 GeV
120 GeV
m_t
$\Delta\alpha$
0.2325
0.2322
0.2320
0.2318
0.2315
0.2312
80.25
80.30
80.35
80.40
80.45
$\sin^2\theta_{eff}$
M_W [GeV]


h°, √s=500 GeV
h°, √s=800 GeV
A°, √s=500 GeV
A°, √s=800 GeV
T
S
0.3
0.2
0.1
0
−0.1
−0.2
0.1
0.2

orthod. appr.:

dev ~ SM signl

[ℓ in Higgs rep]

$$\lambda_\gamma = \lambda_Z \lesssim 1\cdot 10^{-3}$$
$$\Delta\kappa_\gamma \lesssim 2\cdot 10^{-3}$$
$$\Delta\kappa_Z \lesssim 3\cdot 10^{-3}$$

precision of order 10^{-3} reached at LC 500 for first time

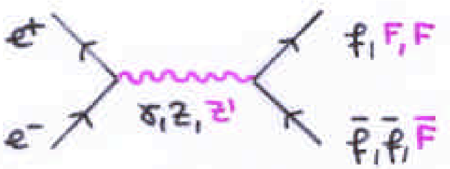
ADDENDUM: QCD cplg $\alpha_s(M_Z)$ at GigaZ: $\Delta\alpha_s = 0.001$

(iii) EXTENDED GAUGE SYMMETRIES

{ LR inspired
{ superstring

SO(10) : W_R, Z_R : ν_R

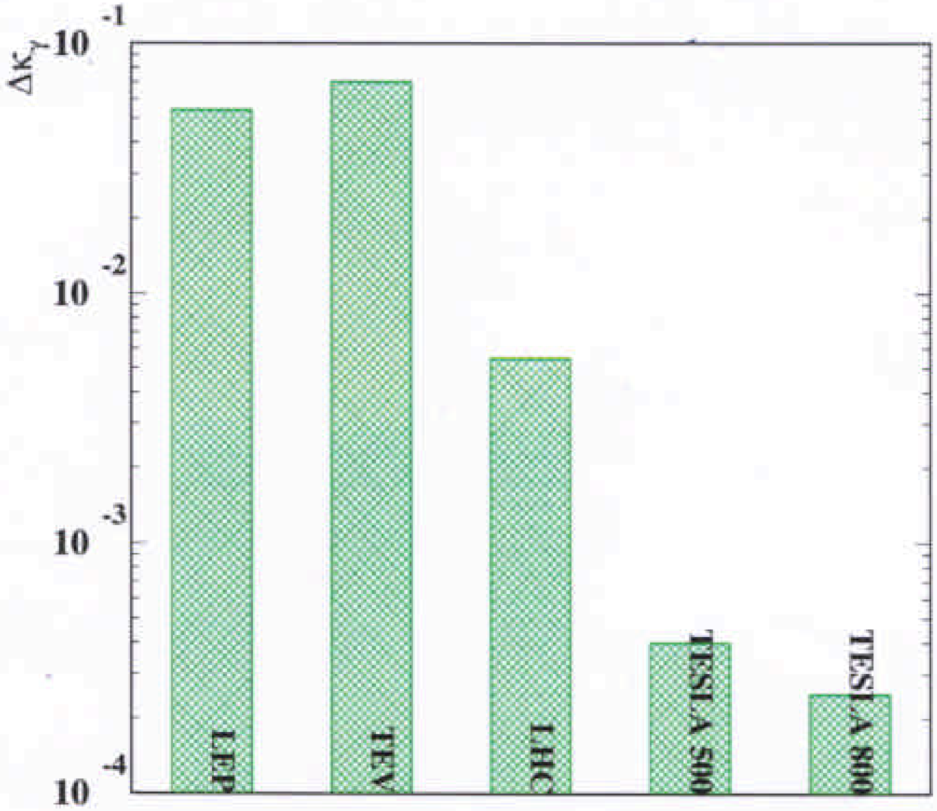
E(6) : Z' : ν_R $\begin{bmatrix} N \\ E \end{bmatrix}_L$ $\begin{bmatrix} N \\ E \end{bmatrix}_R$ n_R D_L D_R



√s	SO(10)	E(6)
500 GeV 1,000 GeV	7 TeV 10 TeV	4 – 6 TeV 6 – 9 TeV
5 TeV	22 TeV	13 – 20 TeV

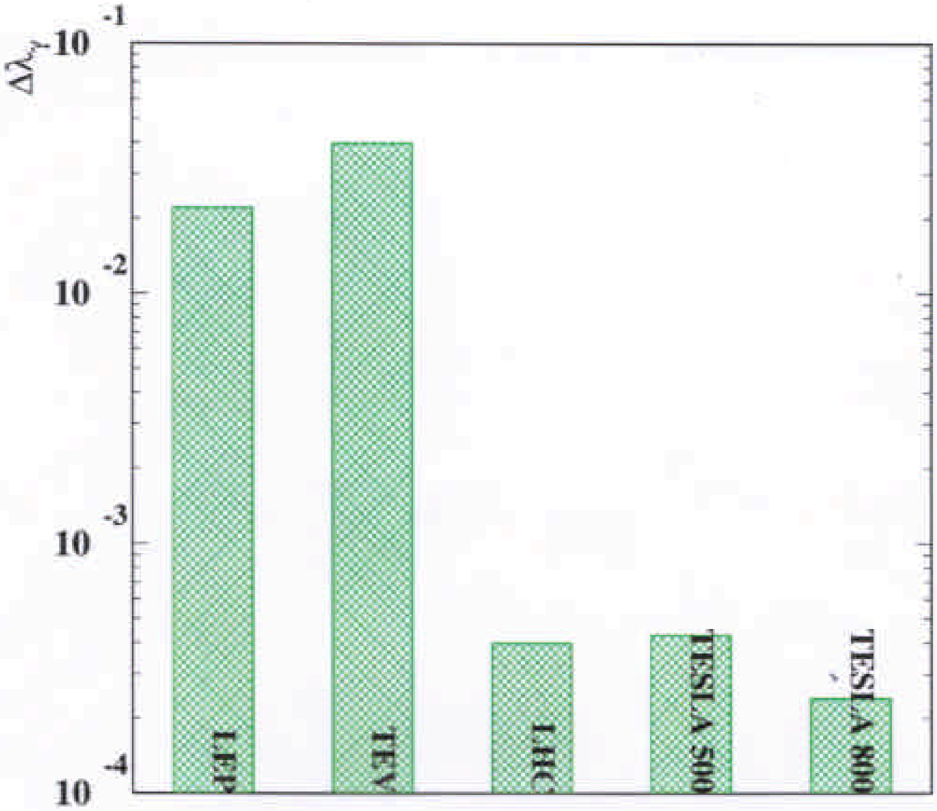
LHC: $M(Z') \sim 5$ TeV

- new gauge bosons: windows beyond LHC
- new leptons: windows up to $M \lesssim \frac{1}{2}\sqrt{s}$ ... $\sqrt{s}$
- precision analysis of old / new fermion couplings

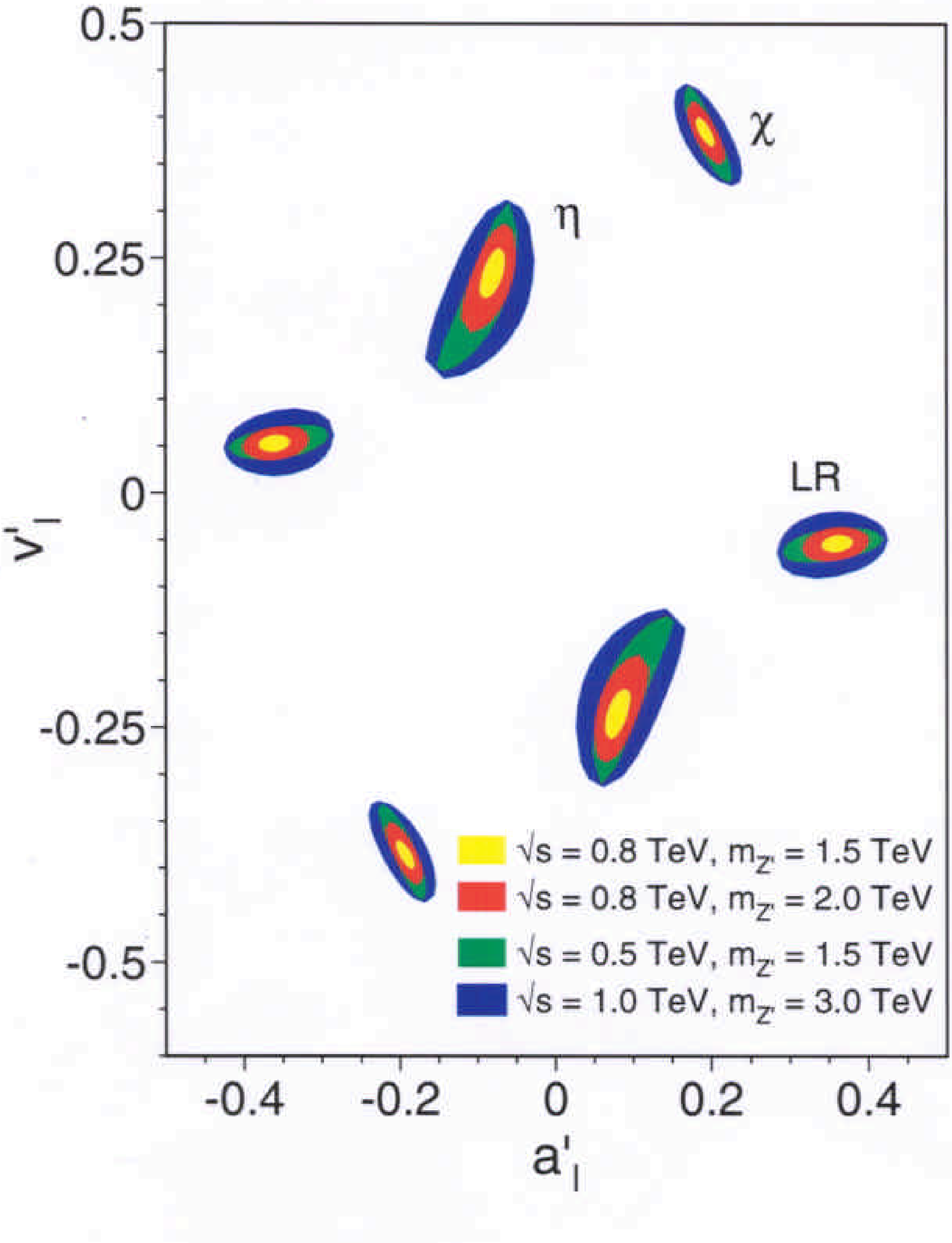


$\Delta\kappa_\gamma$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
LEP
TEV
LHC
TESLA 500
TESLA 800

Mönig ea



$\Delta\lambda_\gamma$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
LEP
TEV
LHC
TESLA 500
TESLA 800



χ
η
LR
√s = 0.8 TeV, m_Z' = 1.5 TeV
√s = 0.8 TeV, m_Z' = 2.0 TeV
√s = 0.5 TeV, m_Z' = 1.5 TeV
√s = 1.0 TeV, m_Z' = 3.0 TeV
v'_l
a'_l
0.5
0.25
0
-0.25
-0.5
-0.4
-0.2
0
0.2
0.4

6.) SUMMARY

Experiments at e^+e^- linear colliders can advance the understanding of Nature in the TeV / multi-TeV range in a significant way:

a) microscopic picture of electroweak symmetry breaking:

Higgs mechanism / dynamical SB

b) Supersymmetry: if realized in Nature, this sector can be studied in a comprehensive and very precise form

⇒ explore: grand / ultimate unification scheme

c) structure of space-time: if extra space dimensions accessible at TeV scale, scale and dimension determined

Together with LHC results, a coherent picture can be developed for a crucial energy range of [particle] physics.