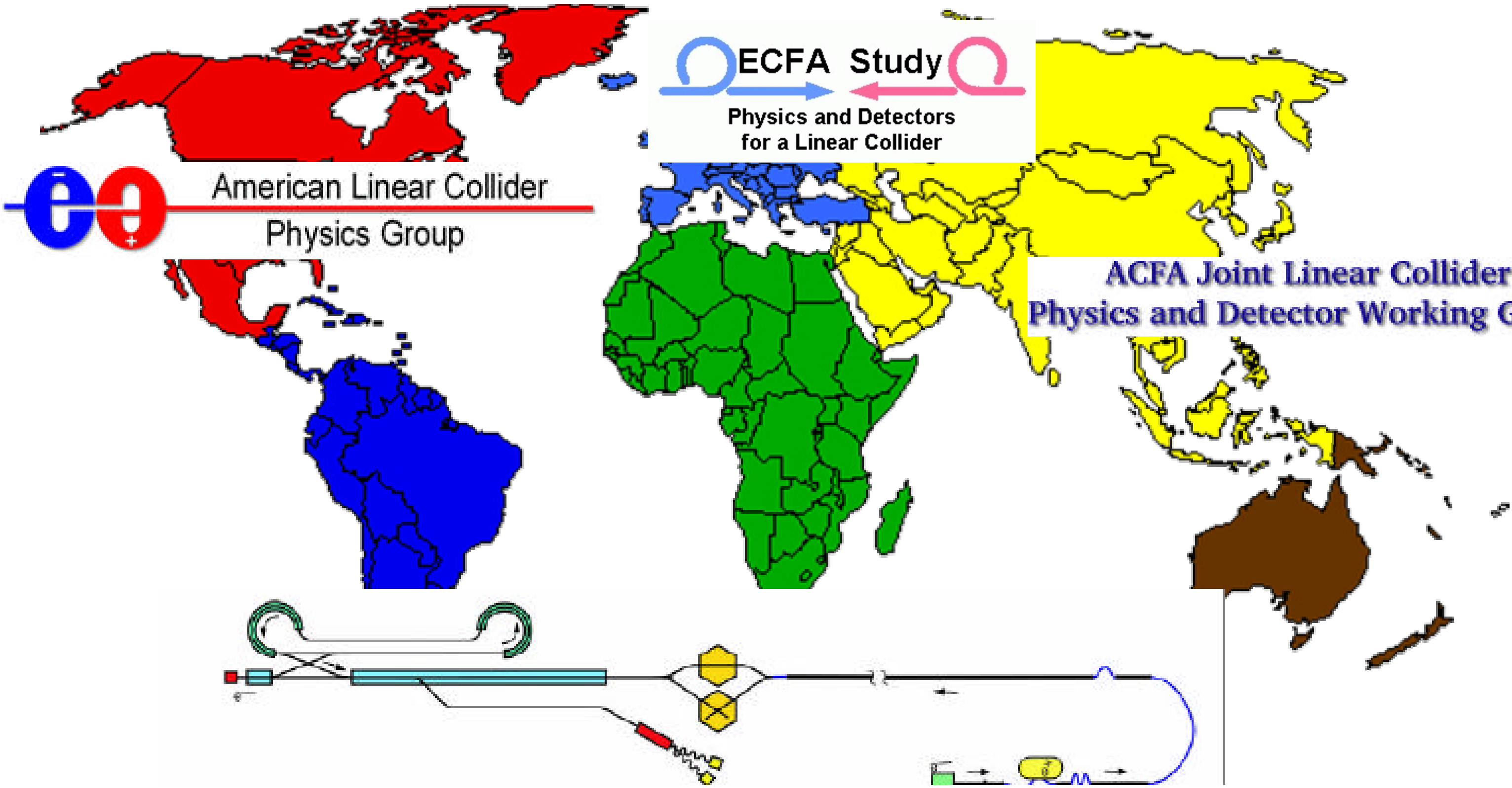
Physics of the Linear Collider

F. Richard LAL/Orsay



Outline

- Which machine ?
- Which detector ?
- For which physics ? Possible scenarios

Origin of mass EWSB — Main emphasis

Hierarchy of masses — SUSY

Input to Cosmology

↴ Major ongoing effort in Americas, Asia, Europe

↴ Apologies: incomplete picture in 30' + personal biases

Machine

- The baseline is an e+e- LC operating from M_Z to 500 GeV with polarized e- (80 %) and collecting 500 fb-1 in the 1st 4 years of running
- Upgradeable to ~ 1 TeV 500fb-1 /year

Options :

- e+ polarization (60%) needed at GigaZ and with transverse polarization
- e-e- ~ easy
- ?? ?e more involved

~Le+e-/3 ?s??~0.8?s

High pol. xssing angle

Detector

In many instances LC analyses will be systematics limited -> Aim at a ~perfect detector

3 outstanding improvements/LEP-SLD can be fulfilled with LC detectors:

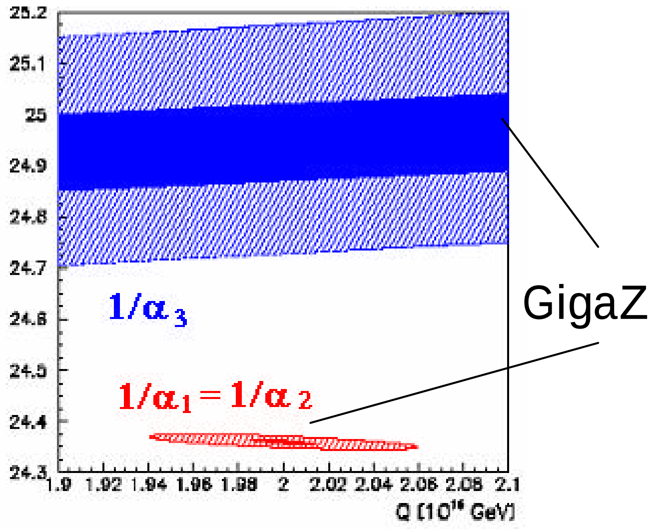
- Improved vertexing : c (?=70% >80% pure),tau tagging
- ?E/E~1/2 LEP 6/8 jets reconstruction

  WW/ZZ separation (+ ??)
- ?p/p²~1/10 LEP down to 100 mrad

  Also:
- Hermeticity on energetic ?/e down to 5 mrad
- *L*, Polarization, ?s very precise (Z physics)

  -> Machine Detector interface activity

Which Scenario for EWSB?



LEP/SLD/Tevatron legacy:

- SM/MSSM compatible with PM
- MSUSY 1-10 TeV ~GUT with some small but interesting discrepancy

-> A light Higgs is expected <250 GeV

However:

- A^b_{FB} (NuTeV) not understood Th/exp
- Could be a fake (Peskin-Wells) if there are extra contributions as in alternate schemes to SM/MSSM

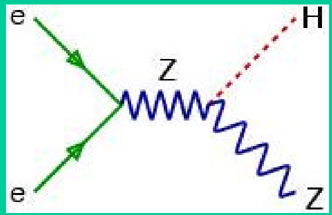
3 EWSB scenarios for LC:

MSSM	PM on Higgs couplings with ~10^5 HZ
mH > 200 GeV	Direct/Indirect signals of new physics
S.I. no Higgs	PM at TeV primarily with WW final states

-> Can LC can provide sufficient observables, with proper accuracy, to cope with these 3 scenarios (including GigaZ/W)

Scenario 1
Is this the MSSM Higgs ?

- Quantum numbers: spin with scan
- CP from ZH angles



? ff and $g_{ZZ/WWH}$ at %

? ???? 20 % at % with ???coll

g_{ttH} 7-15% mH 120-200 GeV

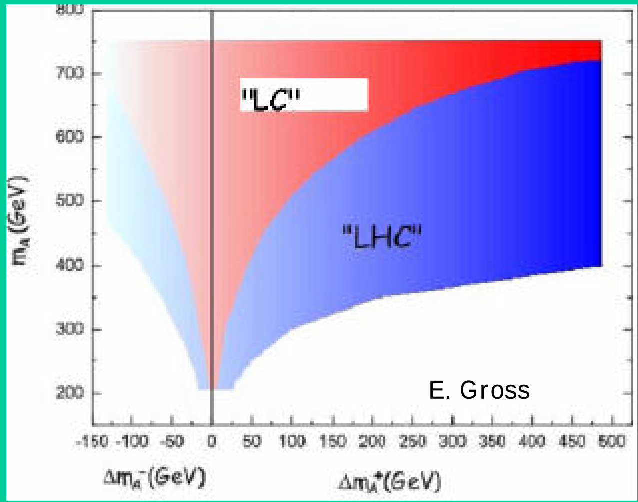
$?_{HHH}$~20%(10%) ?s 500(800)GeV

- Within MSSM: mA from bb/WW
- Beyond MSSM: NMSSM, CP violation

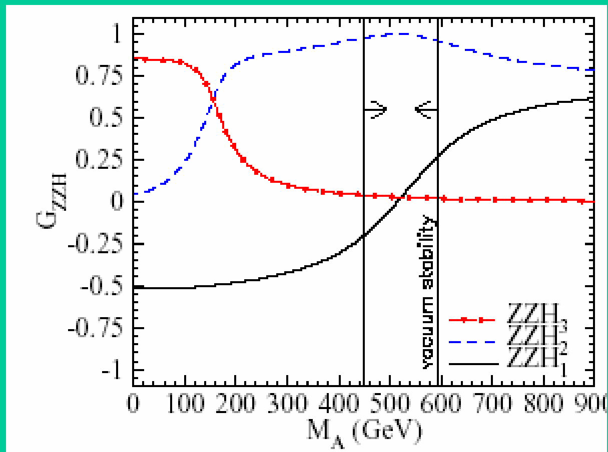
-> Measurable changes on g_{ZZH}, in some cases serious reduction of $?_{HZ}$

Robustness of LC:

can stand ~SM/100



NMSSM/SM



D.J. Miller et al.

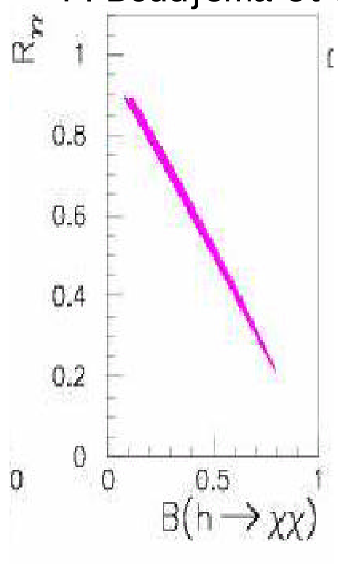
Scenario 1

Beyond MSSM (suite)

- Detection does not depend on final state BR
  Example Invisible decays:
  Long list of channels:
  - h-> ? ? ? with non-universal gaugino masses
  - ? $\tilde{G}$ within GMSB
  - Gravitons GG, Graviscalar mixing
  - Majorons JJ, ADD ?L ?RKK....

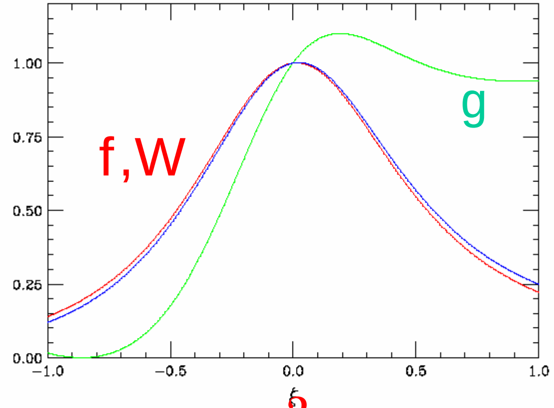
  -> High sensitivity 5? BR_{inv}=2%

F. Boudjema et al



- Mixing with an other scalar field
  Radion ?$_{gg}$ at 5%

Rad/SM J. Hewett et al



Quantum level consistency

M_HDirect=M_H Indirect ?

GigaZ ?sin²?$_W$~10^{-5} with Pe+

WW$_{th}$?M$_W$~6MeV E from Z at 5$10^{-5}$

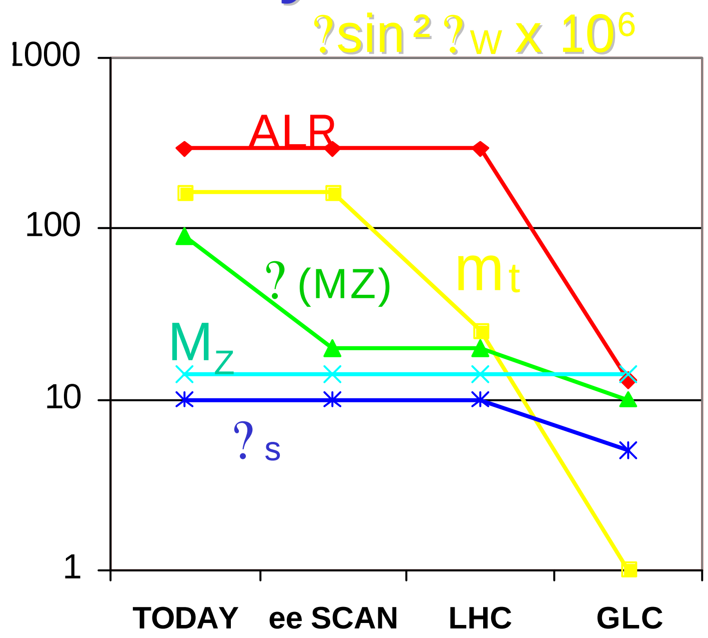
Improved experimental inputs

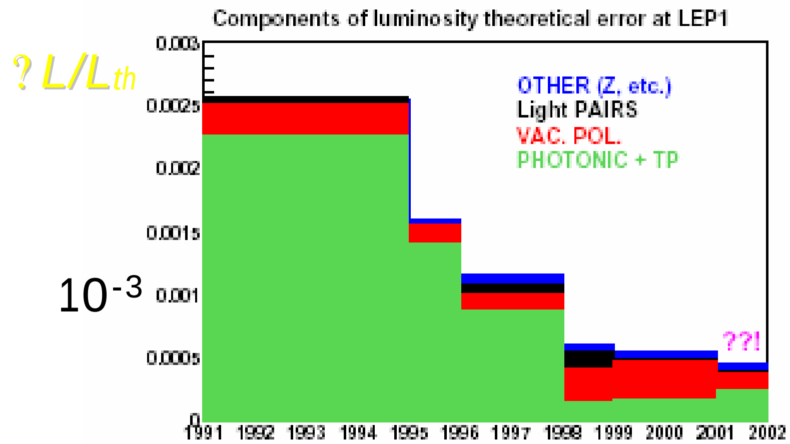
Improved theory (Loopverein)

?M$_H$ Indirect~5% (~50 % at LEP/SLD)

(WW$_{th}$ gives ?M$_H$ ~10%)

Recall that LEP/SLD did much better than anticipated





S. Jadach

Scenario 2
mH > 200 GeV

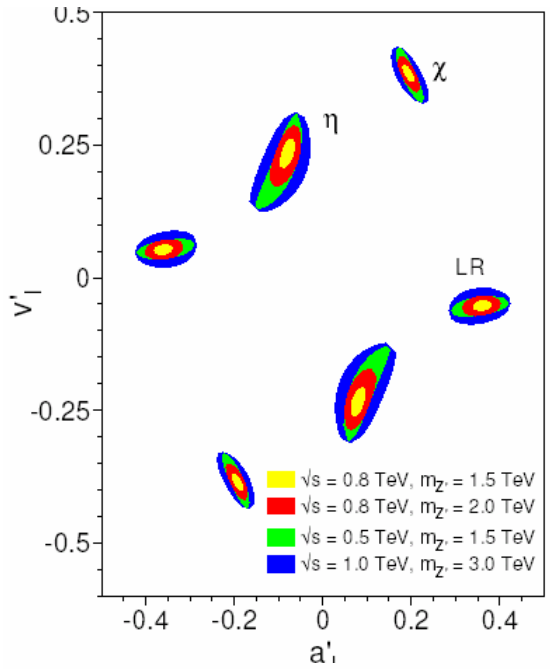
mH inconsistent with SM/MSSM

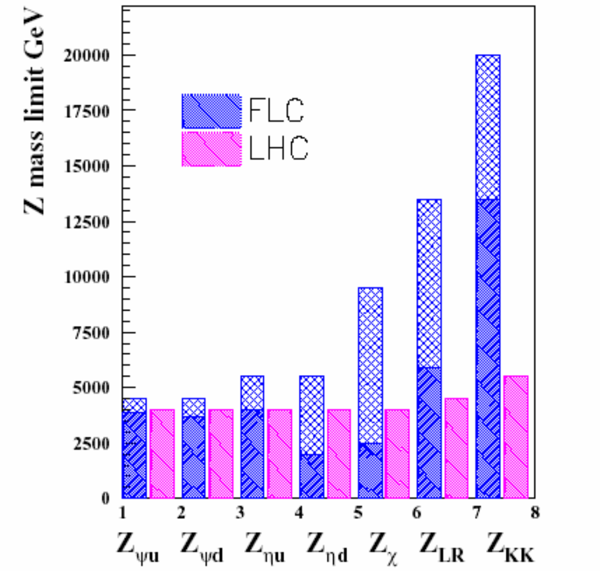
-> find the 'guilty part'

- With direct evidence at LHC : e.g. Z'

  -> Decipher the message, Z-Z' mixing at GigaZ, interference at high ?s
- Many scenarios, well separated if Z' mass given by LHC
- In UED no Z' f f coupling, isospin violation seen with ? at GigaZ
- If no evidence at LHC

  -> Use LC to estimate the new scale
- Also possible within SUSY ('Fat Higgs')





Little Higgs with mH>200 GeV

-> From LEP/SLD Most Z' scenarios do not favor mH>200 GeV
What about Little Higgs ?

A viable alternative (hierarchy) to SUSY:

H ~ PG boson of a broken symmetry (several groups possible), perturbative theory up to 10-100 TeV

- Cancellation of quadratic divergences on mH^2

  -> New objects: B' W' t' H'...

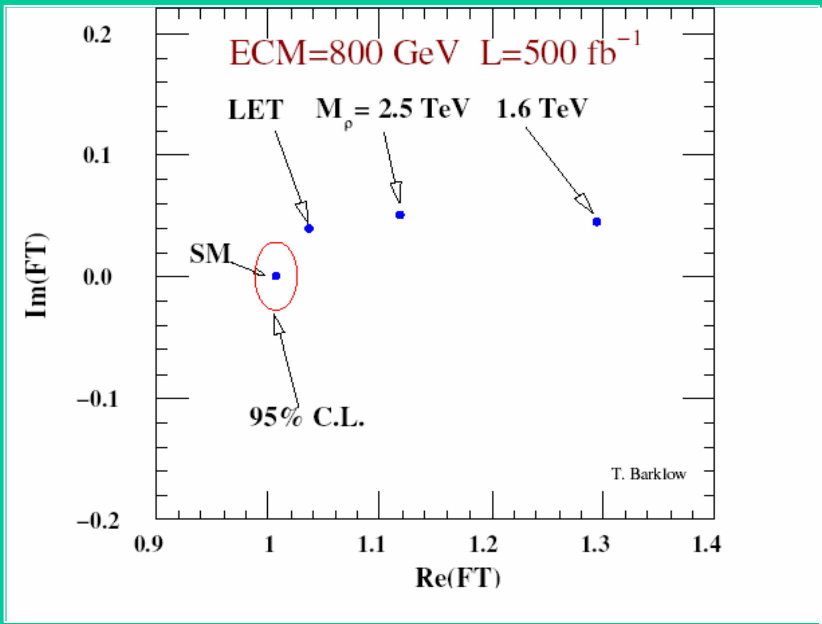
- B' can contribute to ? and can 'hide' a heavy Higgs
- mH>200 GeV possible given $\sin^2 ?_{eff}$ + M_W from LEP/SLD with mB' > 2 TeV and adjusting $g'_B/g'_{SM} < 1$
- If LHC finds e.g. B' -> LC to identify the LH scheme
- If not, LC can predict mB' and indicate upgrade *L*/?s needed at LHC (or at future colliders)

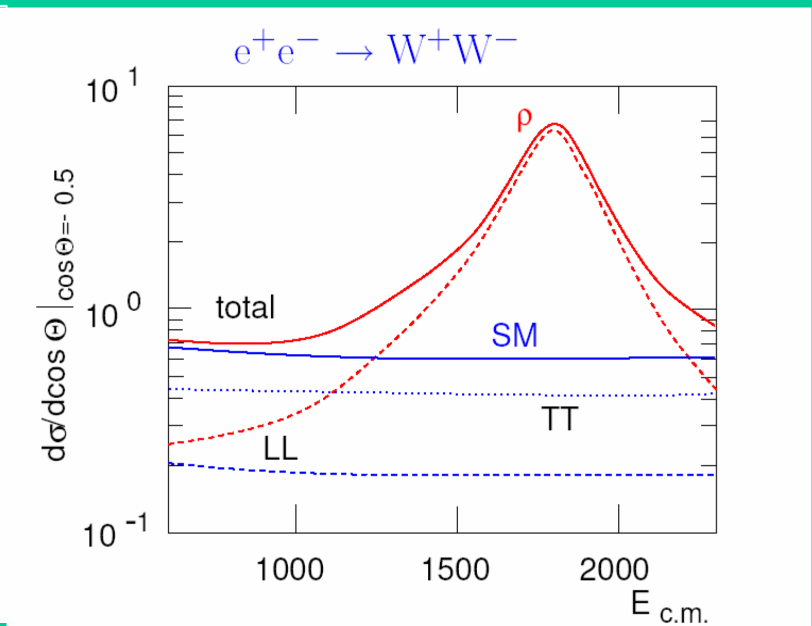
  -> Strong LHC/LC synergy

Scenario 3
No Higgs

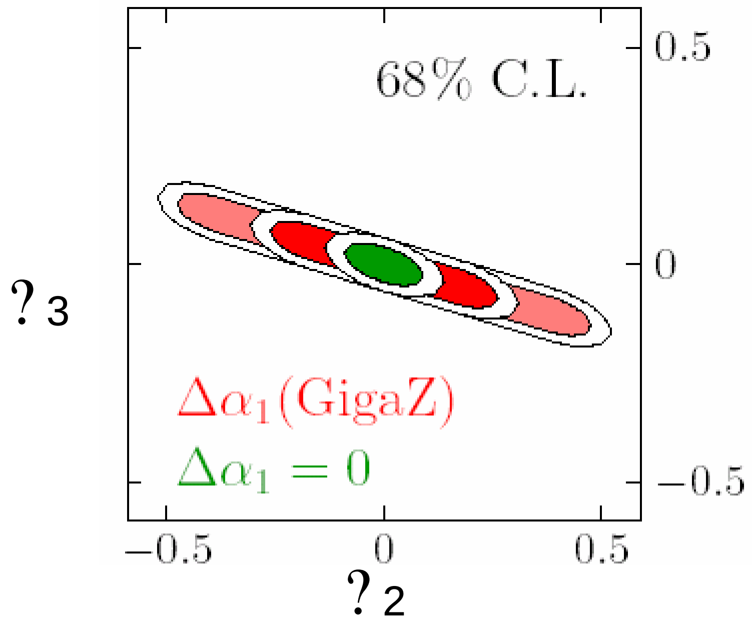
$W_L W_L$ will strongly interact resulting in:

- Production of a resonance ?-type in e+e✍W+W-
- M? < ? $_{EWSB}$=4?v=3 TeV
- Without a resonance LET still observable





	?s GeV	L fb⁻¹	M? 1.6TeV	LET
LC	0.5	300	16?	3?
LC	0.8	500	38?	6?
LC	1.5	200	204?	5?
LHC	14	100	6?	5?



if J=0,2 I=0,2 resonances

-> use e+e-✍??W^+W^-

also ?? ✍W^+W^-

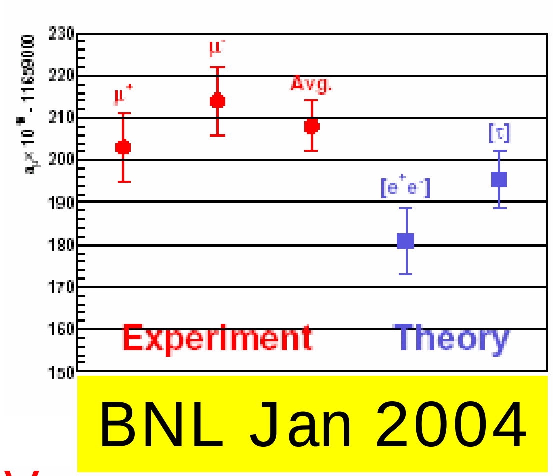
5 TGC conserving P, $SU(2)_{Cust}$
- 3 with WW+ GigaZ
- 2 with ??WW

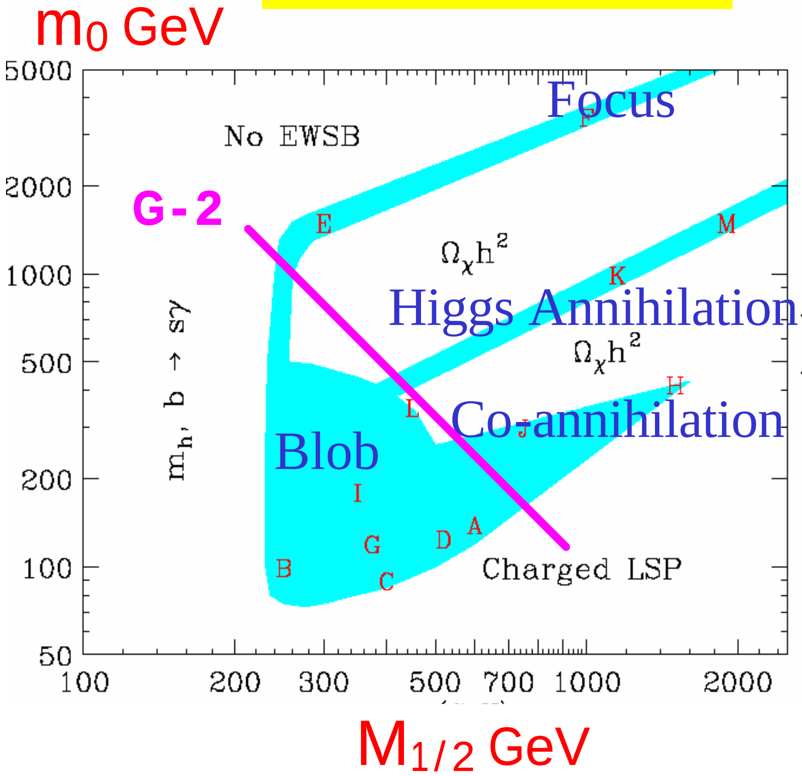
???(?$_{EWSB}$/?)^2

- All LC limits reach ? > ?$_{EWSB}$

The SUSY scenario

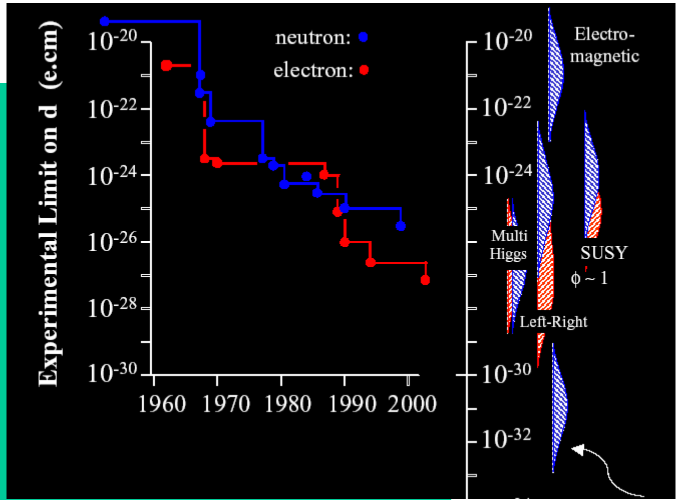
- SUSY is the leading theory:
  - compatible with PM (light H)
  - mass hierarchies up to M_{Planck}
  - compatible with GUT
  - link to cosmology (e.g. DM)
- No unique SSB mechanism
- Essential goals of LC after SUSY discovery by LHC:
  - to understand SSB
  - to determine mass and couplings of the LSP for cosmology
- Using mSUGRA, for pedagogy, 4 regions consistent with DM





Caveat: Flavor constraints

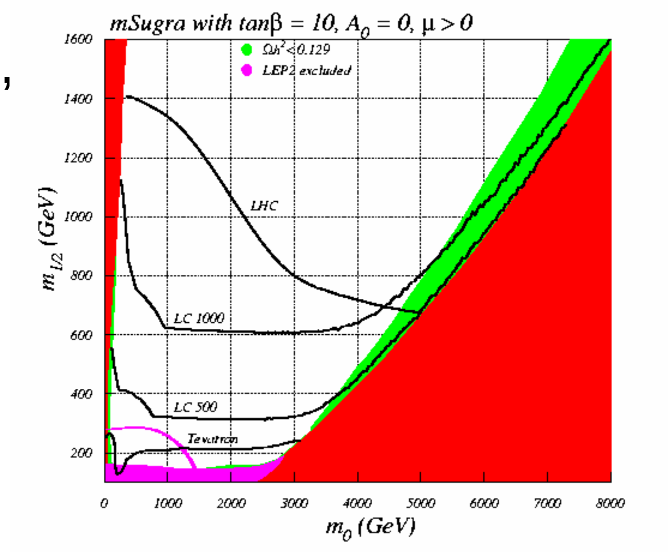
B.E. Sauer



- Flavor : FCNC CP ?K EDM ?p
  -> Heavy sfermions (1st 2 generations)
  -> For CP, hidden symmetry (LR) avoiding phases or cancellation (?) of phases
- 3 possible scenarios:
  - All scalars very heavy h and possibly ? ?' ?? and $\tilde{g}$ accessible at LHC/LC
    DM -> ? Wino(M2<M1)/Higgsino (low µ) ? ?' ?? ~ mass degen.
  - $\tilde{?}$ $\tilde{t}$ $\tilde{b}$ scalars could also be observed
    DM -> co-annihilation ? Bino and $\tilde{?}$ ~ mass degen. < 500 GeV
  - Phases ~0 most sparticles could be accessible ('blob') at LC/LHC

DM at LC

H. Baer et al



- LC will accurately measure m? and couplings, i.e. Higgsino/Wino/Bino content (polar.)
  -> Essential input to cosmology
  -> Input for non-accelerator searches
- In the 'blob' (B) mSugra scenario, LC accuracy on m? ~0.1 GeV, m?̃ ~0.6 GeV
  -> Prediction of ? DMh ² with an accuracy ~ CMB anisotropies
  -> A mismatch would reveal different sources of DM (Axions, Axinos...)
  Also access to mẽL, mẽR, m?̃ up to ~TeV
- Less precise, but still possible (cf. LEP2) in a mass degenerate scenario

'WMAP'	7 %
LHC	~15 %
'Planck'	~2 %
LC	~3 %

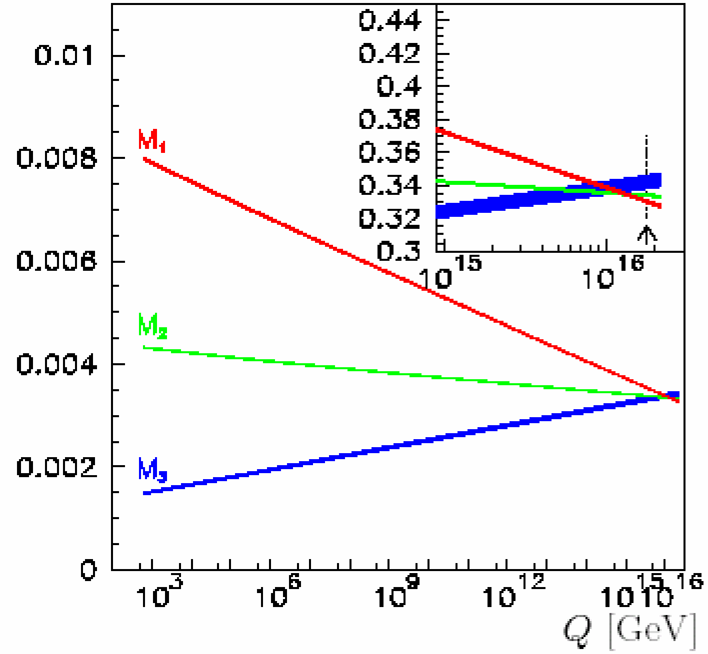
MicrOMEGAs Pt B

LC and SSB

- Model independence (large set of observables LC+LHC) High accuracy SUSY needed to to access to the underlying SSB mechanism
- Lesson from LEP/SLD on GUT
- Subtle differences (loops) expected on Mi at unification
- LHC M_3 error (gluino), due to correlations -> with m? from LC ? M_3 improved by a large factor

-> Reconstruct fundamental param of an effective string theory

$-1/M_i$ GeV^{-1} G. Blair et al



Summary: Why do we need a LC ?

- To provide the full picture on an SM/MSSM Higgs
- To provide an answer on EWSB with difficult or unexpected scenarios : heavy Higgs, reduced Higgs x-section
- To access to the SSB mechanism with LC+LHC measurements
- To predict precisely, within SUSY, $?_{DM}h^2$
- To interpret unambiguously an unexpected discovery at LHC, e.g. a Z' or a KK ?
- To estimate mass scales beyond LC/LHC reach (~LEP/SLD):

  - Deviations on PM on Higgs couplings translated into, e.g. mA or Z' mass

  - Test of the theory at the quantum level which can reveal new mass scales (e.g. LEP/SLD and the Higgs mass)

-> New frontier: improved LHC or future colliders CLIC VLHC

Apologies

- Physics with CLIC
- SUSY and the neutrino sector
- Xtra dimensions: various schemes alternate or combined with SUSY
- Non-commutative effects
- Transverse polarization for Gravity induced effects
- SUSY and CP violation
- e-e-, ?? and ?e physics
- QCD
- ...

Neutrinos:
Conclusions of A. Yu. Smirnov at LP03

Enormous progress in determination of the neutrino masses and mixings, studies of properties of mass matrix. Still large freedom in possible structures exists which leads to very different interpretations.

Main open question: what is behind obtained results? Preference? Probably seesaw, and probably associated with Grand Unification. Although other mechanisms are not excluded and can give important or sub-leading contributions.

How to check our ideas about neutrinos? Future experiments will perform precision measurements of neutrino parameters. Apart from that we will need results from non-neutrino experiments:

- from astrophysics and cosmology
- from searches for proton decay and rare decays
- from future high energy colliders.

Neutrino Sector and the LC

- RP violation could be the answer but then loosing the neutralino solution for DM (Alternates: Axion, Axino, Gravitino…)
- The seesaw mechanism is the favored explanation but seems very hard/impossible (M>10[10] GeV) to test with colliders (?????Mee not too small??? ?oscillation if ?$_{13}$ finite)
- It could have very interesting cosmological implications (Baryogenesis, inflation)
- Experimental consequences are parameter dependent (mass of heavy neutrino, phases) but there could be observable signals:

- Rare decays ???e? ?PSI) ???????LHC, super Bfactory)

- Flavour violation e+e- ??????????

e+e- ???????????

F. Deppisch[1,2*], H. Päs[1†], A. Redelbach[1‡], R. Rückl[1§], Y. Shimizu[3¶]

1O fb

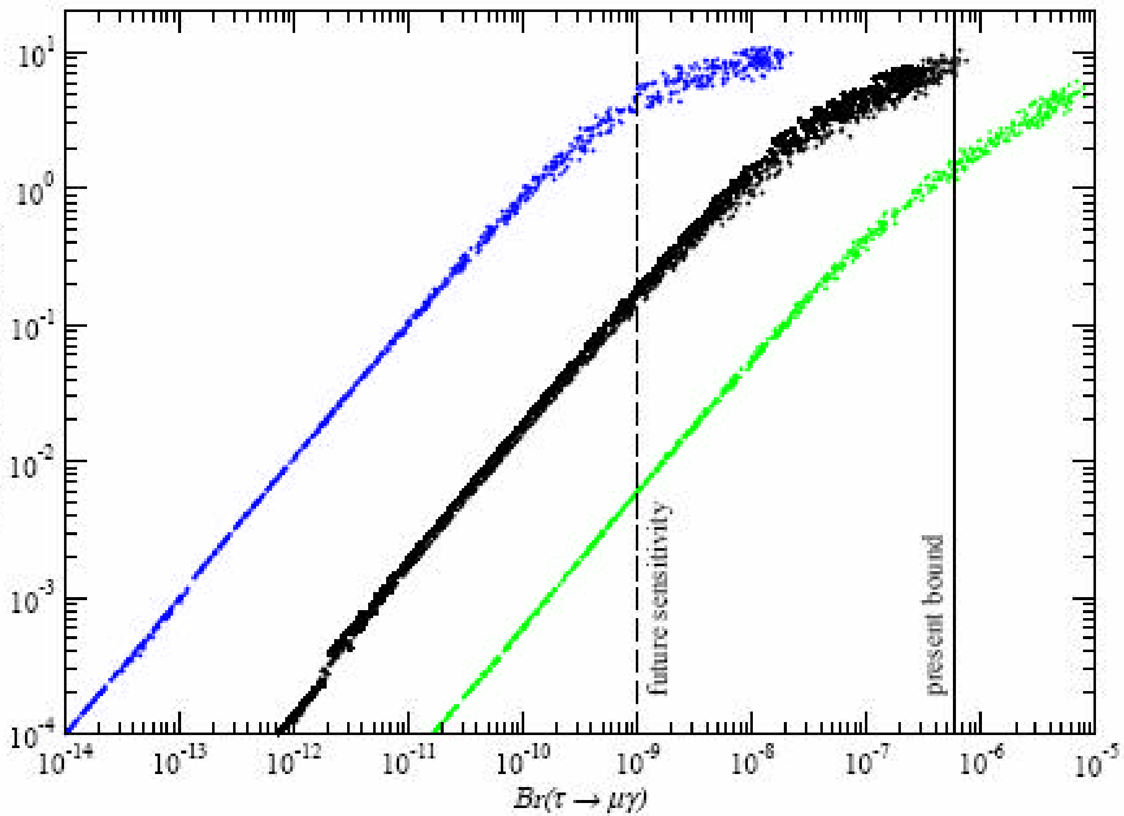


Figure 6: Correlation of $\sigma(e^+e^- \to \tau^+\mu^- + 2\tilde{\chi}_1^0)$ at $\sqrt{s} = 800$ GeV with $Br(\tau \to \mu\gamma)$ in scenario (from left to right) C, G (open circles), B and I for the case of very light neutrinos.

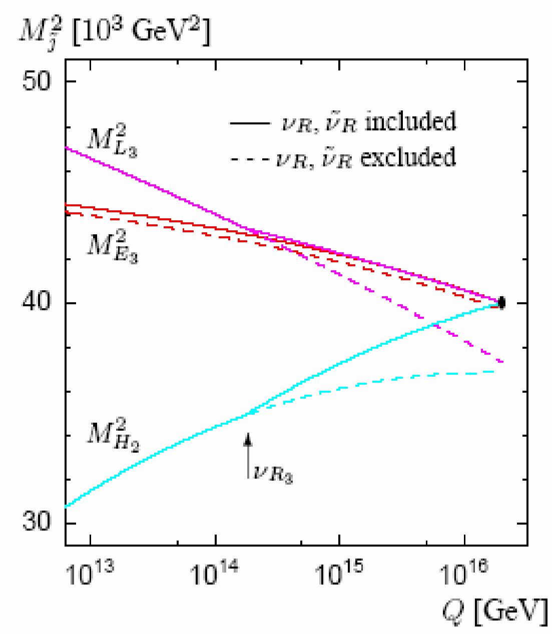
GUT scale effects

• SUSY-GUT assumes that there is a 'desert' from ~1 TeV up to the GUT scale

• The see-saw mechanism suggest that there could be a new scale > 10^{10} GeV but below the GUT scale

-> The slepton masses would not unify anymore in an mSUGRA scheme as can be seen in the example of a LR SUGRA scenario

• PM of slepton masses at a LC could provide a window on this new scale and even lead to its measurement



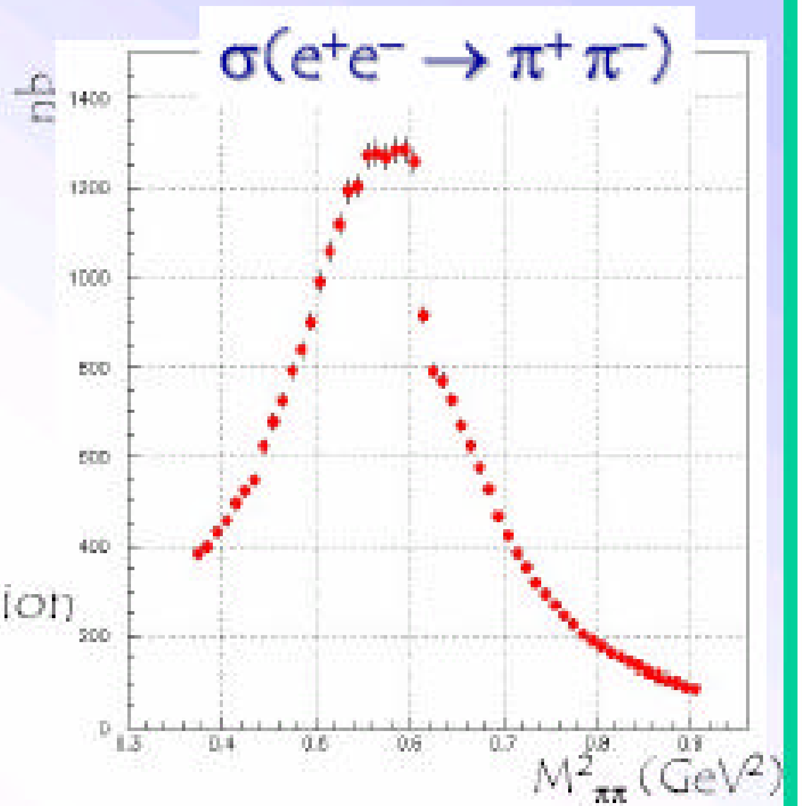
P.M. Zerwas et al
Hep-ph/0211076

Results for a_μ^{had}

$$a_\mu^{\pi\pi} \propto \int ds\, \sigma(e^+e^- \to \pi^+\pi^-)\, K(s)$$

bare cross section integrated in the region

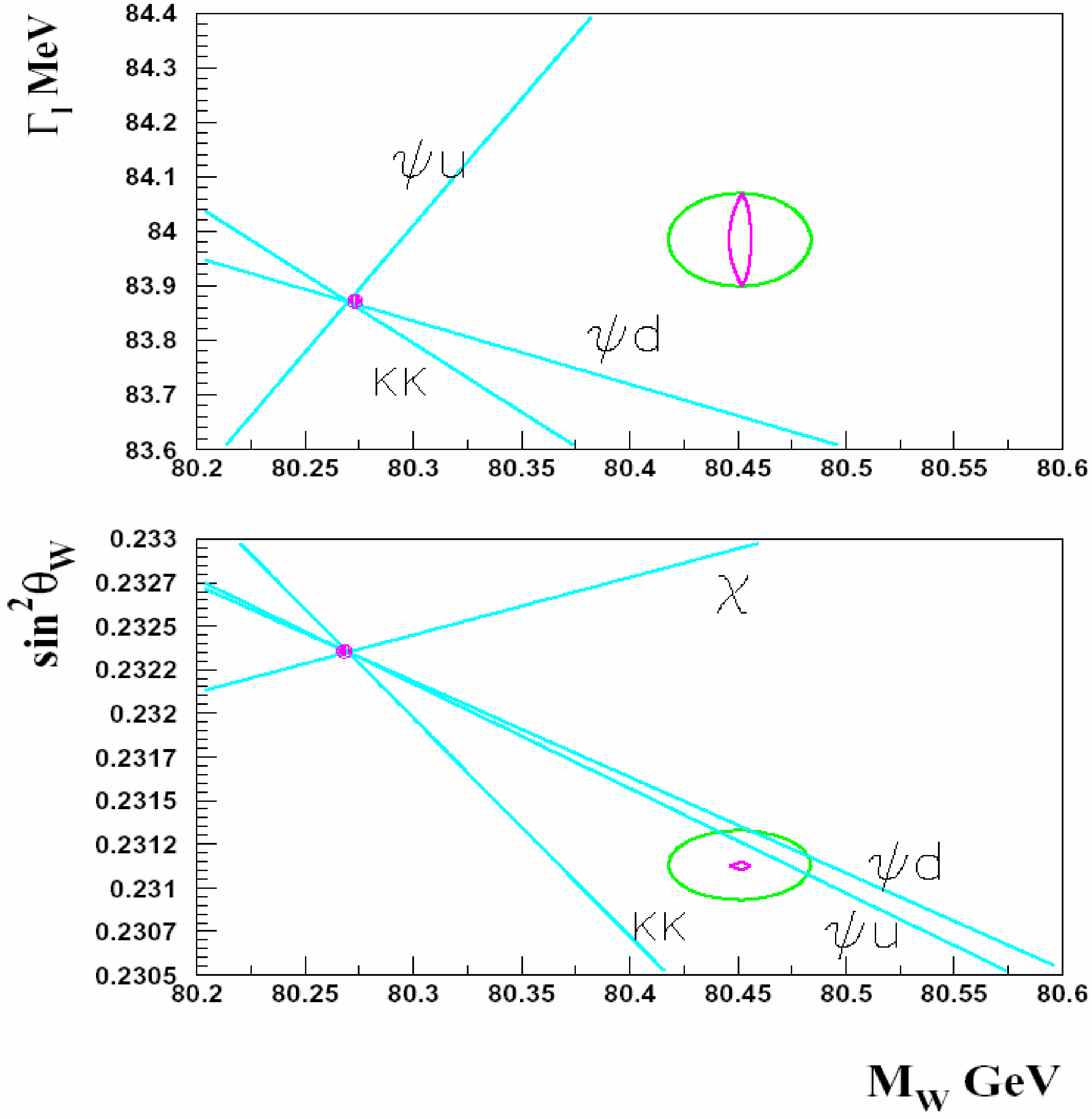
$0.37\ GeV^2 < M^2_{\pi\pi} < 0.93\ GeV^2$



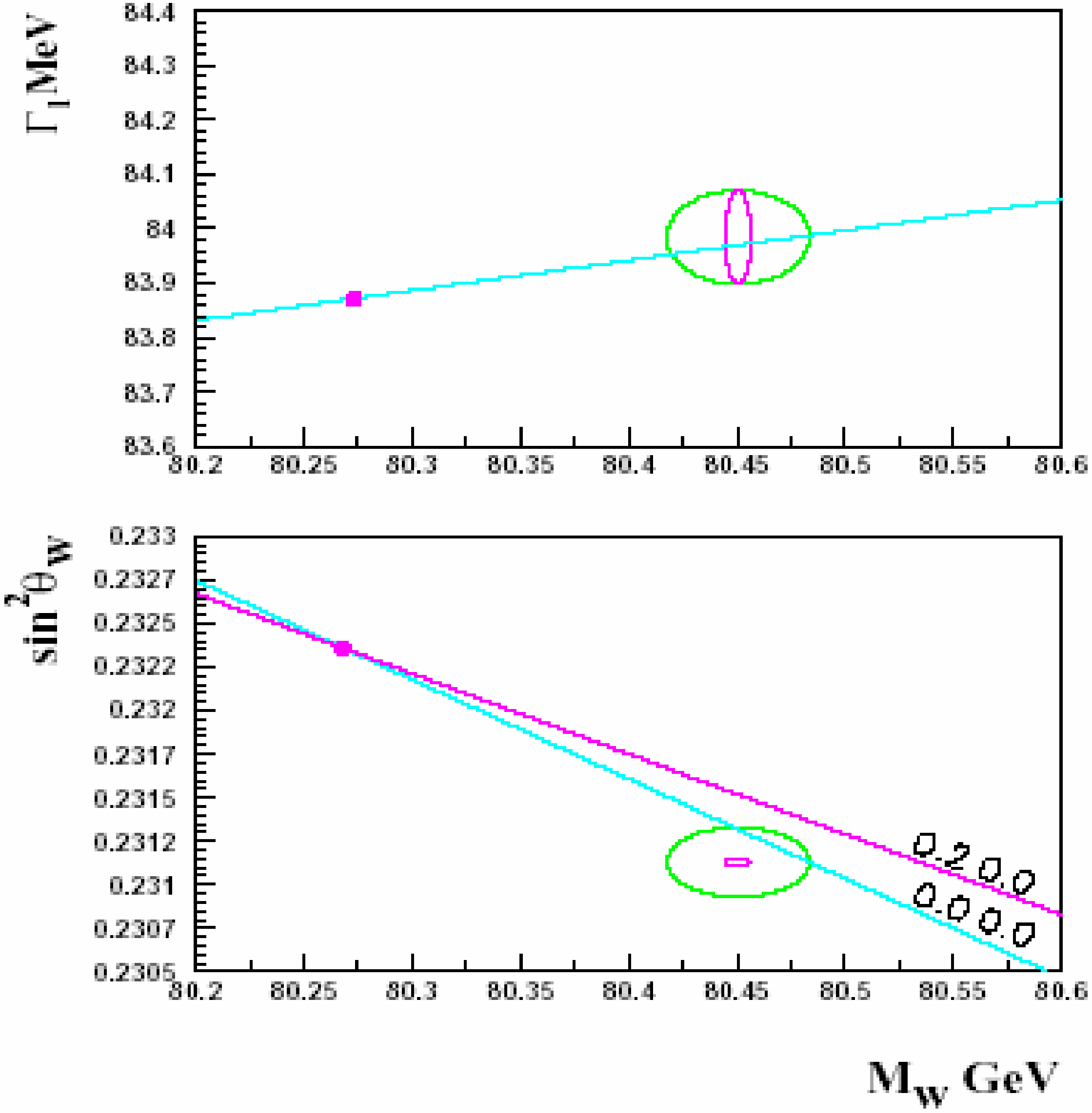
KLOE result: $a_\mu^{\pi\pi}(0.37\text{-}0.93) = 378.4 \pm 0.8_{stat} \pm 4.9_{syst} \pm 3.0_{theo} \pm 3.8_{FSR}$

	0.2%	1.2 %	0.8%	1%
It will go to →	0.2%	1.0%	0.8%	

Published CMD-2 result: $a_\mu^{\pi\pi}(0.37\text{-}0.93) = 378.6 \pm 2.7_{stat} \pm 2.3_{syst+theo}$



Γl MeV
84.4
84.3
84.2
84.1
84
83.9
83.8
83.7
83.6
ψu
ψd
KK
80.2
80.25
80.3
80.35
80.4
80.45
80.5
80.55
80.6
sin²θW
0.233
0.2327
0.2325
0.2322
0.232
0.2317
0.2315
0.2312
0.231
0.2307
0.2305
χ
ψd
ψu
KK
80.2
80.25
80.3
80.35
80.4
80.45
80.5
80.55
80.6
MW GeV



Γ_l MeV
84.4
84.3
84.2
84.1
84
83.9
83.8
83.7
83.6
80.2
80.25
80.3
80.35
80.4
80.45
80.5
80.55
80.6
$\sin^2\theta_W$
0.233
0.2327
0.2325
0.2322
0.232
0.2317
0.2315
0.2312
0.231
0.2307
0.2305
0.200
0.000
M_W GeV