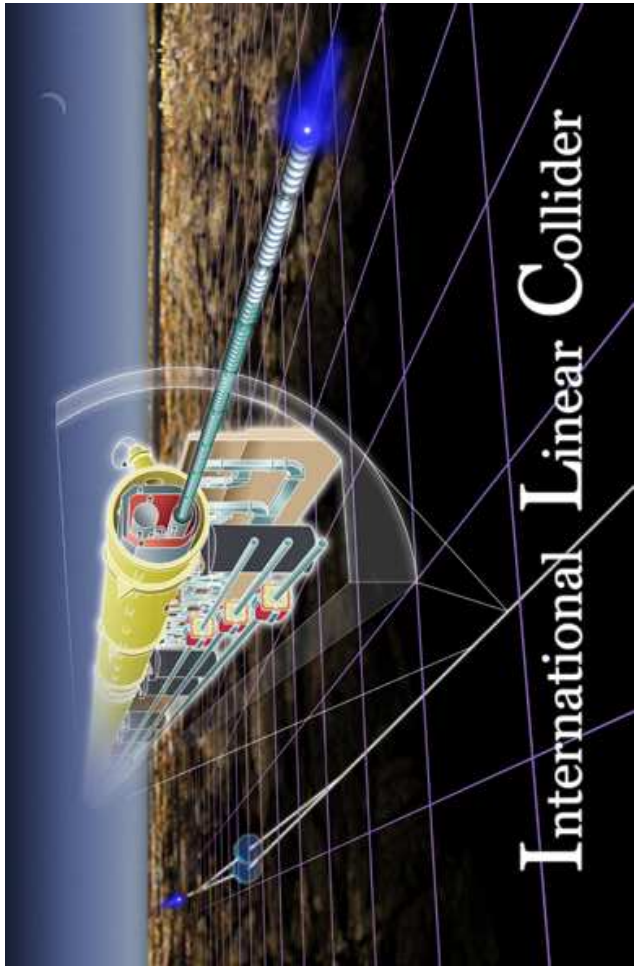


THE ILC PHYSICS CASE

1. Introduction

- Physics base and perspectives

2. ILC Physics Targets in Micro-Universe

- Electroweak Symmetry Breaking
- Ultimate Unification / Supersymmetry
- Extra Space Dimensions

3. Cosmology Connection

4. Conclusions

1. INTRODUCTION

Basic laws of Nature $\sim 10^{-15}$ cm : Standard Model of particle physics

$\oplus$ Gravity

Central problems in micro-Universe ...

- Mechanism of electroweak symmetry breaking $\Leftarrow$ Higgs or alternative ?
- Unification of forces - including gravity $\Leftarrow$ Supersymmetry ?
- Space-time structure at short distances $\Leftarrow$ Dimensions > 4 ?

... and macro-Universe

- Connection with cosmology $\Leftarrow$ Cold Dark Matter?

  $\Leftarrow$ Baryon Asymmetry?

  $\Leftarrow$ ...

TARGETS $\Leftarrow$ LHC and ILC

break-through and high-resolution picture of Terascale scenario $\Rightarrow$

unification of matter and interactions

canonical path: Standard Model | Supersymmetry | $\Rightarrow$ GUT/Planck Scenario

alternative: Standard Model $\Rightarrow$ TeV Planck Scenario

CHARGE OF TALK :

... high-lighting central physics targets of ILC : $\sqrt{s} = 500$ GeV | upgrade $= 1$ TeV
$e^-[e^+]$ polarization
e^-e^- | $e\gamma/\gamma\gamma$ | GigaZ

in line with Physics Chapter of DCR

A.Djouadi, J.Lykken, K.Mönig,
Y.Okada, M.Oreglia, S.Yamashita

... leaving LHC and ILC/LHC to special presentation by K.Desch
... and general collider hep to A.Masiero

2A. ELECTROWEAK SYMMETRY BREAKING

– *missing keystone of Standard Model : generating mass of fundamental particles*

– *indicator of physics landscape beyond SM*

realizations: standard Higgs mechanism [SM, SUSY, ...]

$\Downarrow$

strong elw symmetry breaking [Little Higgs, higgsless, ...]

$\Downarrow$

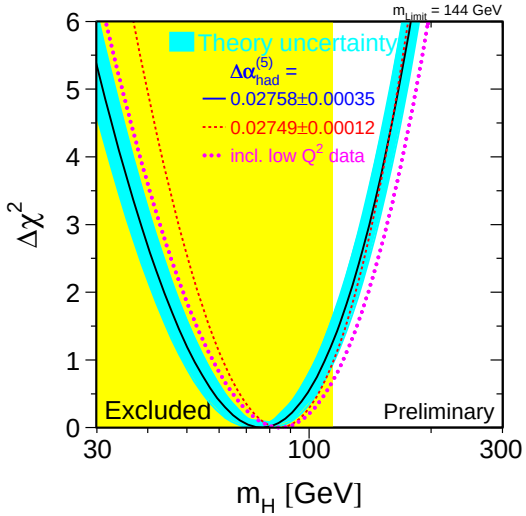
topology extra space dim [$H \sim$ 5th gauge field, BC:higgsless, ...]

a) SM HIGGS MECHANISM

– light Higgs: suggested by precision data [EWWG:

$$M_H = 76^{+33}_{-24}\ \text{GeV} \ \mid \ < 144\ \text{GeV}\ (95\%\ \text{CL})$$

– probability 15.1% : provoking un-$o\rho\theta o\delta o\xi\alpha$



3 central questions

1. *Higgs field filling vacuum* $\Rightarrow$ *scalar field*

$\star$

2. *mass generation by Higgs interaction* $\Rightarrow$ *Higgs coupling prop mass*

$\star$

3. *elw symmetry breaking : Higgs potential* $\Rightarrow$ *non-zero vacuum value*

(a) Higgs = fundamental scalar :

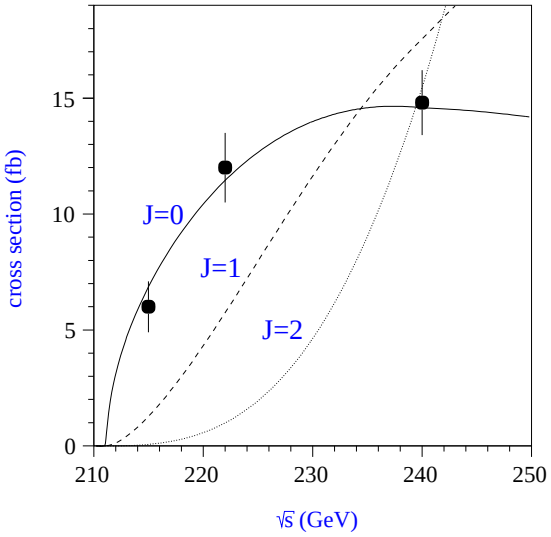
Higgs-strahlung near threshold:

$$\sigma[e^+e^- \to ZH] \sim \sqrt{s-(m_H+m_Z)^2}$$

ruling out : $0^-, 1^-, 2^-, 3^\pm, ...$

$1^+, 2^+$ no TL ang correl

Miller,D.J. ea



Lohmann ea

(b) Higgs couplings to SM particles :

Higgs coupling – mass relation:

$$g(Hpp) = \sqrt{2\sqrt{2}G_F}\, m_p$$

$\Leftarrow$ proving mass generation by interaction with Higgs field

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

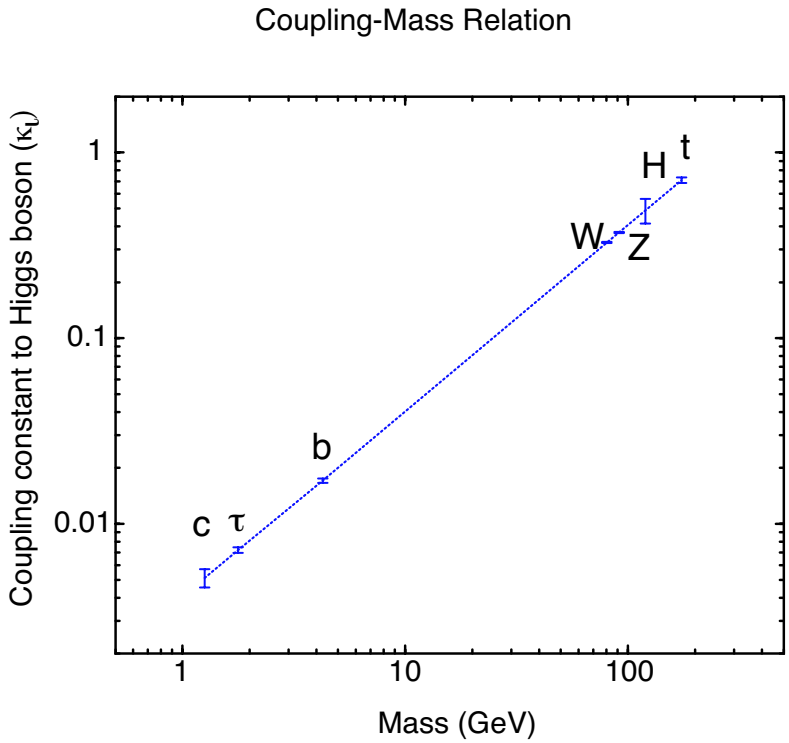
WW fusion : $e^+e^- \to \nu\nu H$

$\Rightarrow$ production cross sections

$\Rightarrow$ decay branching ratios

$\Rightarrow$ Higgs radiation off *top*

Battaglia,Desch



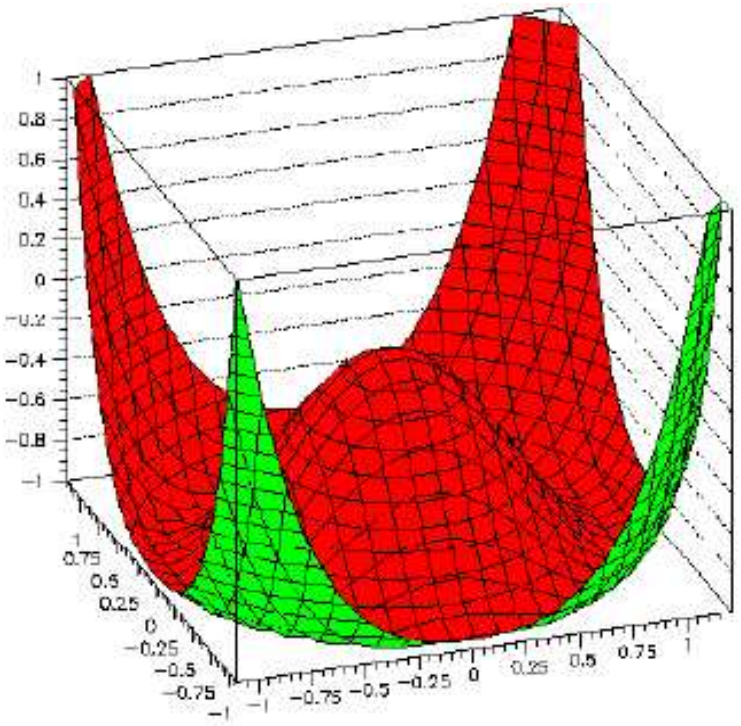
ACFA LC Study

improving on LHC significantly:
precision and model-indep slope
$/Z/W/\tau/b/t/ = /1/1/3/2/2\%$

(c) Higgs potential

elw SB $\Leftarrow$ non-zero Higgs field v
generated by shifted min of potential :

$$V = \lambda[|\phi|^2 - \tfrac{1}{2}v^2]^2$$
$$\phi = (v + H)/\sqrt{2}$$



self-interaction :

$$V = \tfrac{1}{2}M_H^2\, H^2 + \tfrac{1}{2}\frac{M_H^2}{v}\, H^3 + \tfrac{1}{8}\frac{M_H^2}{v^2}\, H^4$$

trilin coupling $\Rightarrow$ bending of potential
$\Rightarrow$ shift of minimum

measurement: $e^+e^- \to ZHH$
$e^+e^- \to \nu\nu HH$

$\sqrt{s} = 500$ GeV : 22%
1 TeV : 12%

LHC $\to$ SLHC for $M_H > 140$ GeV

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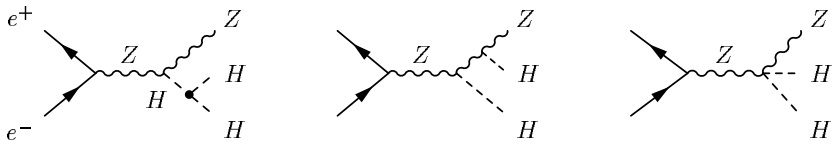
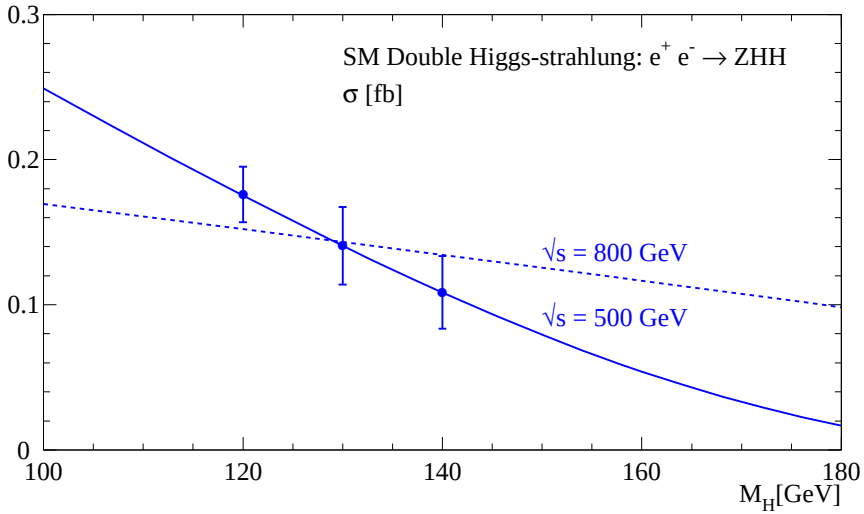




Mühlleitner ea | Gay | Yamashita (ea)

b) SUSY HIGGS BOSONS

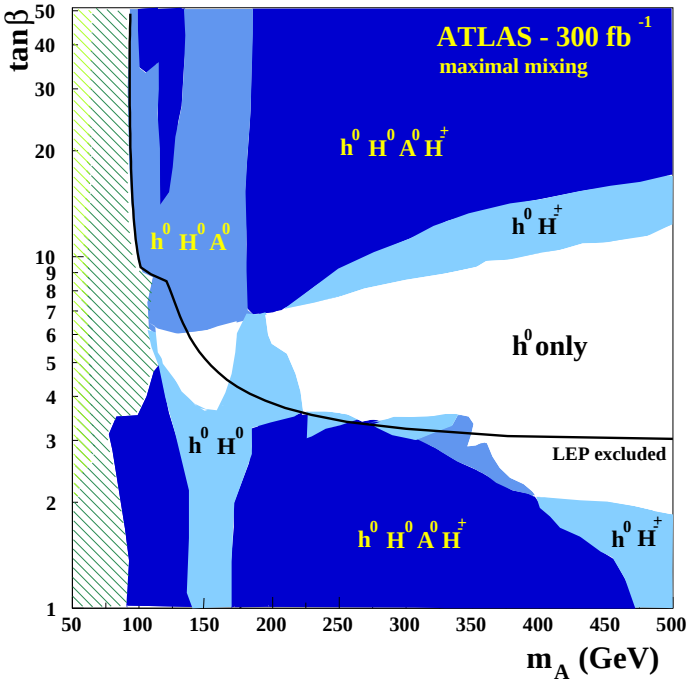
Higgs sector extended to 2 doublets $\Rightarrow$ 5 physical particles in MSSM :

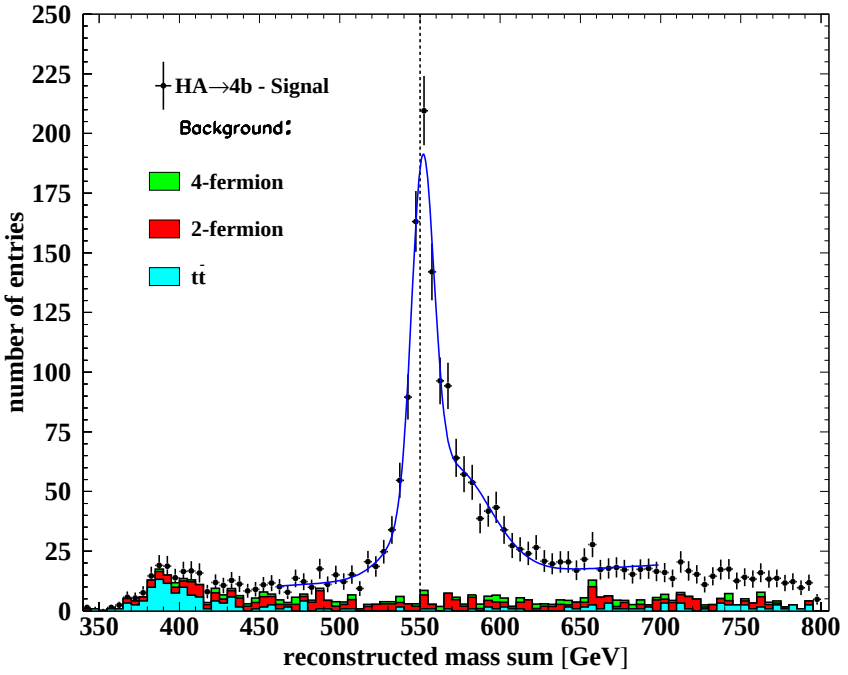
h^0 light $\leq$ 140 GeV | generically $<$ 200 GeV

$H^0, A^0, H^\pm$ typically v to 1 TeV

detection at LHC: blind wedge

ILC: pairs /w mass up to E_B [Desch ea]





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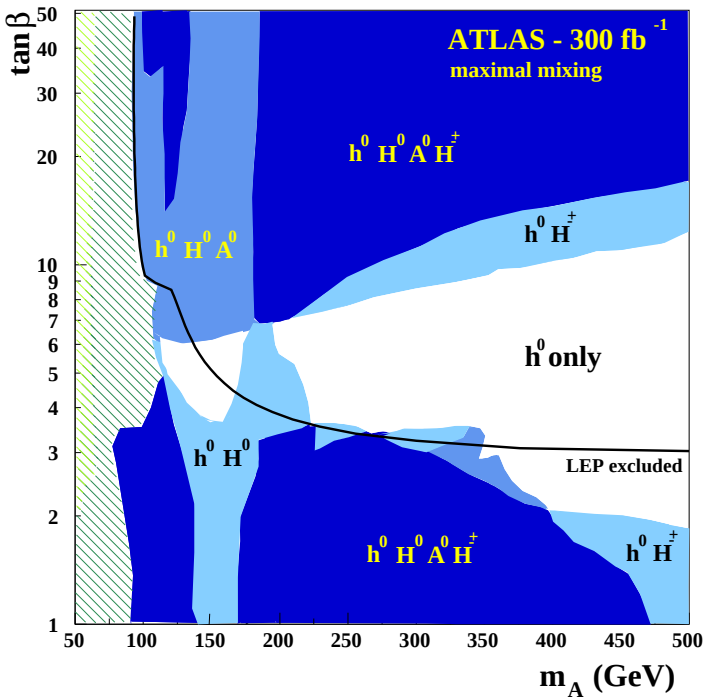
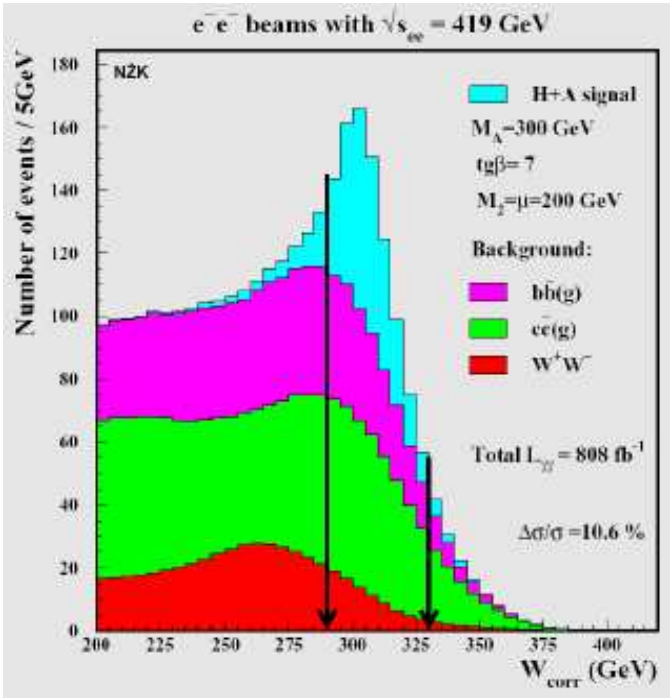
detection at LHC: blind wedge

$\gamma\gamma \to H, A$: +50%

[Mühlleitner ea, Gunion ea, F: Niezurawski ea]





SUSY EXTENSIONS :

CP Violation :

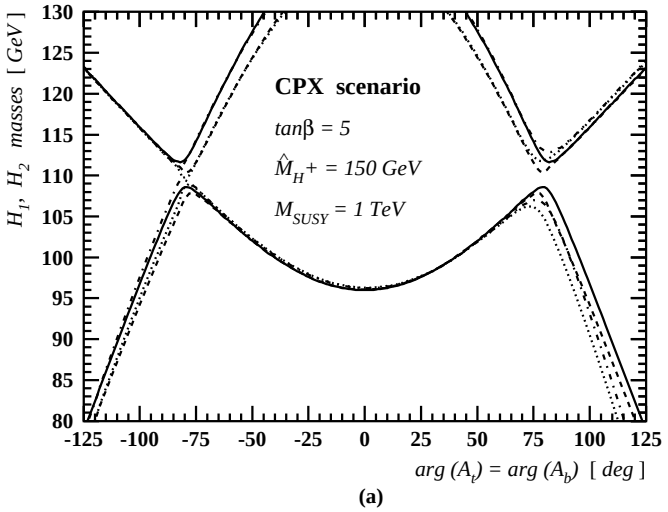
h^0, H^0 mix $A^0 \Rightarrow H_1^0, H_2^0, H_3^0$

– changing spectra and production

F: Carena ea

– CP : $\tau\tau$ polarization

asymmetry in circularly pol $\gamma\gamma$



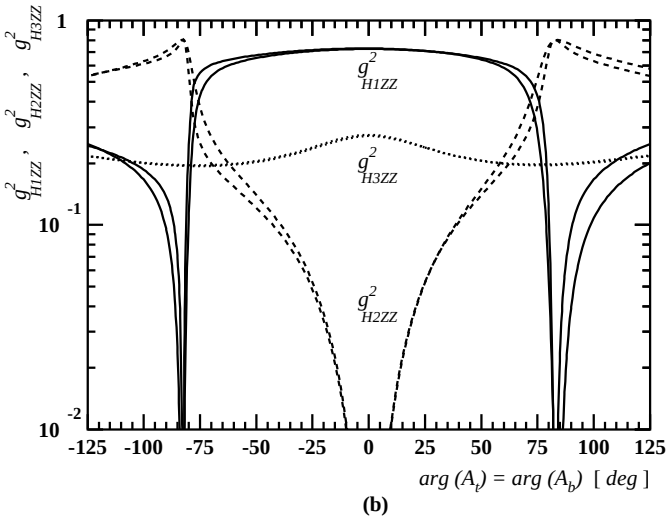
USSM, NMSSM, *etc* :

– additional (light) singlets:

$h^0, H^0 \oplus H'^0 \Rightarrow H_1^0, H_2^0, H_3^0$

$A^0 \oplus A'^0 \Rightarrow A_1^0, A_2^0$

F: Miller,D.J. ea



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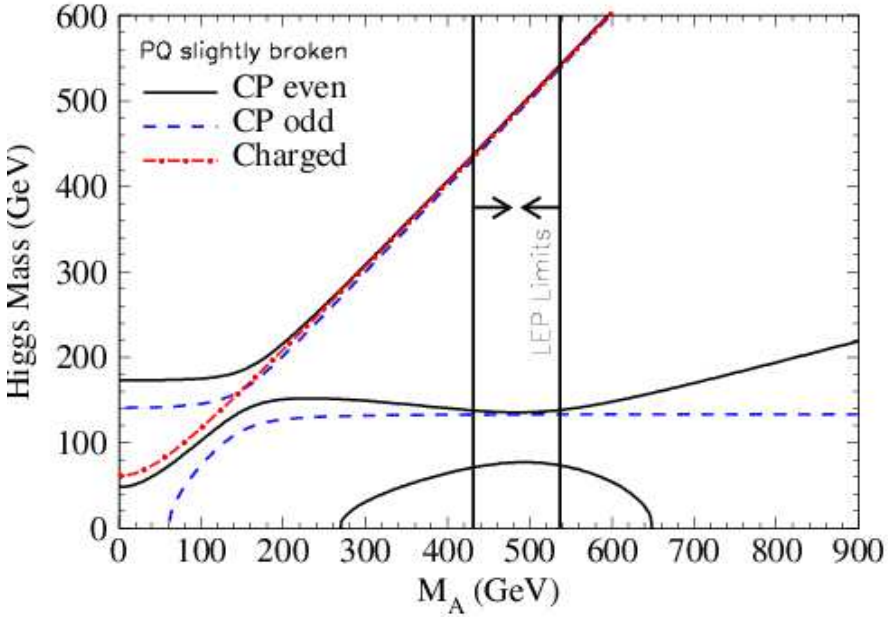
F: Miller ea



c) STRONG ELW SYMMETRY BREAKING

new strong interaction sector: global symmetry breaking $\Rightarrow$ Goldstone bosons

absorbed by gauge bosons: shift mass M_V to non-zero value [$\oplus$ Higgs particles]

- **LITTLE HIGGS THEORIES**

large global symmetry group | $\sim F_{TeV}$:

rich spectrum of TeV particles

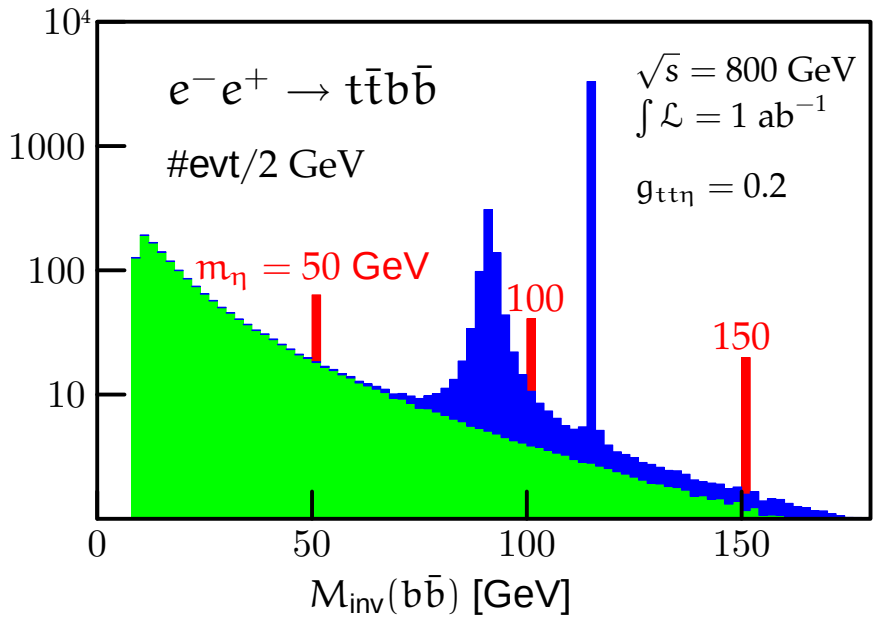
plus light Higgs sector

pseudoscalar η : $e^+e^- \to t\bar{t}\,\eta$ | $\eta \to b\bar{b}$

F: Kilian, Rainwater, Reuter

parameters: $e^+e^- \to f\bar{f}$ and $Z\,h$

almost completely covered



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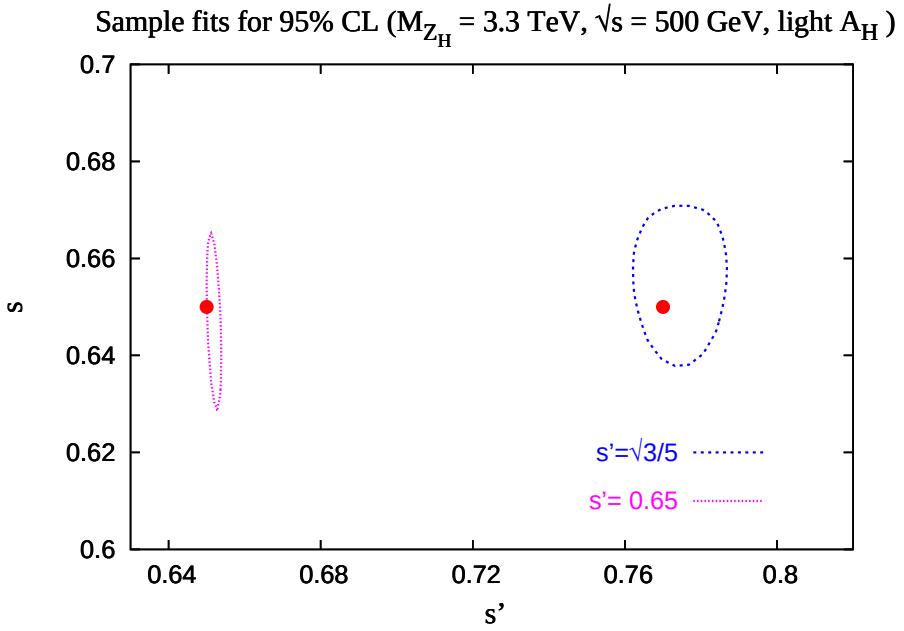
masses known from LHC :

ILC determines model specific cplgs $\Rightarrow$



F: Conley, Hewett, Le

c) STRONG ELW SYMMETRY BREAKING

new strong interaction sector: global symmetry breaking $\Rightarrow$ Goldstone bosons

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- MINIMAL STRONG THEORY

no light states : $[WW]$ in $0^+, 1^-, \ldots \sim 1$ TeV

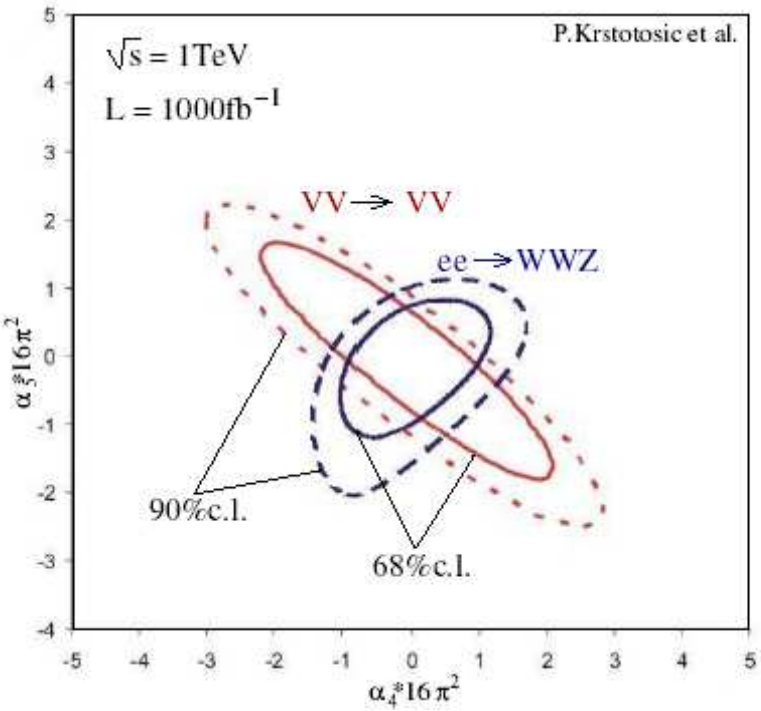
observed in WW scattering $\sqrt{s} = 1$ TeV

$$e^+e^- \to \bar{\nu}\nu\, WW$$

$$e^+e^- \to WWZ \quad \text{Krstotosic, Beyer ea}$$

sensitivity : across entire threshold region

SI scale: $\Lambda_* < 4\pi v \simeq 3$ TeV



d) EXTRA SPACE DIMENSIONS

– large variety : RS warped, ...

– Higgs as a 5th gauge field component in 5 dimensions

– no Higgs / BC mechanism: symmetry breaking by boundary conditions

⇓

generic: KK states [TeV range]

specific: radion ∼ Higgs particle

isolation/mixing ⇒ LC precision analyses

CONCLUSIONS

ILC ⇒ standard: *high-resolution picture of electroweak symmetry breaking*
unravelling mechanism of generating mass

non-standard: *necessary to resolve complex phenomena*

... plus: CLOSURE of SM

– GigaZ : *ultimate precision in SM elw/QCD sector* :

elw mix angle $\sin^2\theta_W \sim 10^{-5}$
QCD coupling $\alpha_s \sim 10^{-3}$ to 10^{-4}
W mass $M_W \sim 10^{-4}$

– SU(2) gauge symmetry : *tri- and quattro-linear couplings : WWW etc*

anomalous magnetic dipole moment $\Delta[e/2M_W] \sim 10^{-3}$
anomalous electric quadrupole moment $\Delta[e/M_W^2] \sim 10^{-3}$

Weyl gauge principle proven basis
of fundamental forces in Nature

– top quark : *t-quark mass* m_t *to* $\frac{1}{2} \cdot 10^{-3}$

key observable for flavor physics

2B. SUPERSYMMETRY

Fundamental symmetry with impact across all micro-areas plus cosmology:

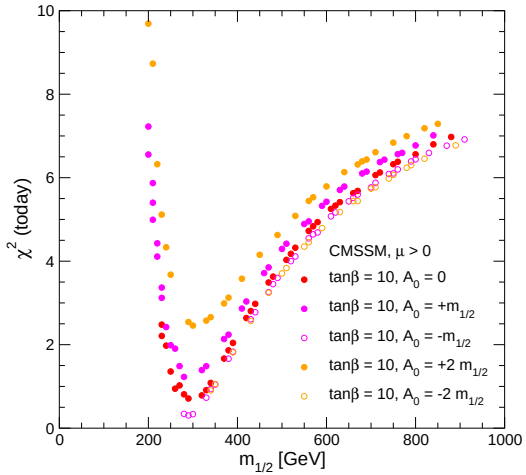
– generating and stabilizing light Higgs boson

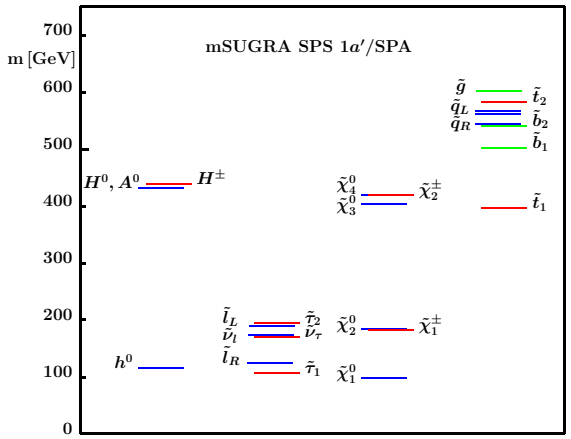
– leading to unification of gauge couplings / paving path to gravity

– providing candidate particle for Cold Dark Matter

MASS SCALE : LEdata + CDM small/mod tan β : [mild] pref low mass spectrum

[no firm pred] focus pt [EGRET] : $\tilde{\chi} < 200$ GeV, $\tilde{F} \sim 1$ TeV





F:Ellis,Heinemeyer, Olive,Weiglein

Allanach,Lester,Weber

LHC discovery sensitivity $\sim$ 2.5 to 3 TeV

first steps in exploring spectrum

ILC high-resolution profile of supersymmetric particles :

– complete spectrum, particularly in light non-colored sector

particle masses

– q-numbers: spin

elw chirality charges | mix parameters | Majorana nature

– couplings: identity of Yukawa with gauge couplings

$\Rightarrow$ extracting basic Lagrangian parameters at Terascale

$\Rightarrow$ reconstructing fundamental theory at GUT/Planck scale

$\Leftarrow$ complexity SUSY $>$ SM : analysis to be successful needs high-precision data

MASSES at ILC

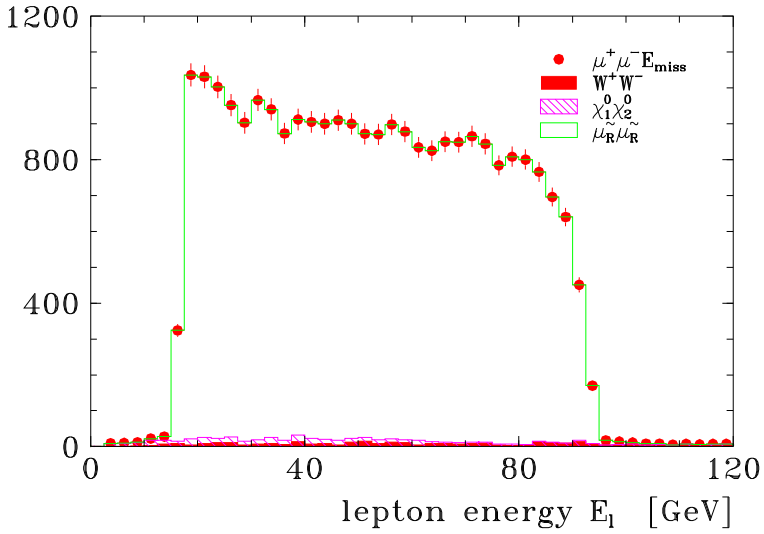
a) Edge effects: $\tilde{\mu}_R \rightarrow \mu + \tilde{\chi}_1^0$

$$m_{\tilde{\ell}} = \sqrt{s}\,[E_+E_-]^{\frac{1}{2}}/(E_+ + E_-)$$

$$m_{\tilde{\chi}_1^0} = m_{\tilde{\ell}}\,[1 - 2(E_+ + E_-)/\sqrt{s}]^{\frac{1}{2}}$$

F: Martyn

precision on χ_1^0 increased by $\sim 10^2$



b) Threshold excitations:

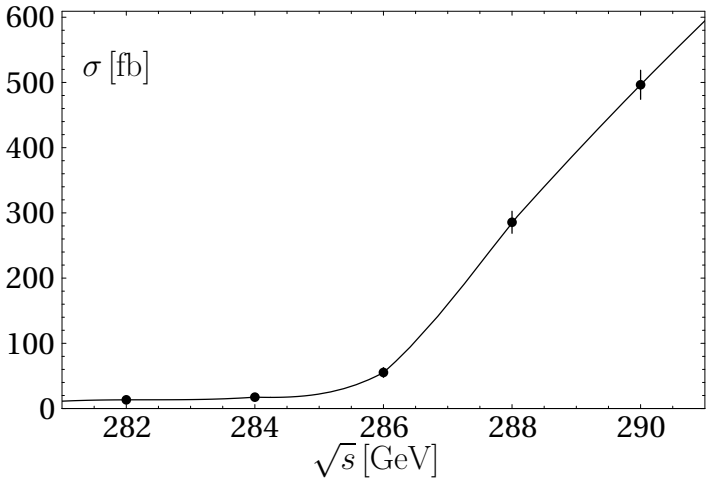
$$e^+e^- \rightarrow \tilde{\mu}_R^+ + \tilde{\mu}_R^- \rightarrow \mu^+\mu^- + E_{miss}$$

P-wave: slow β^3 rise

$$e^-e^- \rightarrow \tilde{e}_R^- + \tilde{e}_R^- \rightarrow e^-e^- + E_{miss}$$

S-wave: fast β rise

F: Freitas ea



c) Max $\tilde{e}$: $e\gamma \rightarrow \tilde{e}\tilde{\chi}^0$: $m_{\tilde{e}} \sim \sqrt{s} - m_{\tilde{\chi}}$

Summary [Weiglein ea]:

LHC :

- voids in LE spectrum
- accuracy per-cent
- mass diff per-mille

ILC :

- filling voids
- accuracy increased by one to two orders

LHC+ILC coherent :

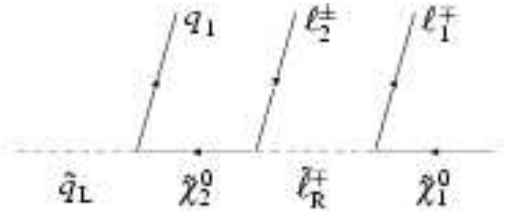
comprehensive and high-resolution susy picture

	Mass, ideal	"LHC"	"ILC"	"LHC+ILC"
$\tilde{\chi}_1^\pm$	179.7		0.55	0.55
$\tilde{\chi}_2^\pm$	382.3	–	3.0	3.0
$\tilde{\chi}_1^0$	97.2	4.8	0.05	0.05
$\tilde{\chi}_2^0$	180.7	4.7	1.2	0.08
$\tilde{e}_R$	143.9	4.8	0.05	0.05
$\tilde{e}_L$	207.1	5.0	0.2	0.2
$\tilde{\nu}_e$	191.3	–	1.2	1.2
$\tilde{\mu}_R$	143.9	4.8	0.2	0.2
$\tilde{\tau}_1$	134.8	5-8	0.3	0.3
$\tilde{\tau}_2$	210.7	–	1.1	1.1
$\tilde{q}_L$	570.6	8.7	–	4.9
$\tilde{t}_1$	399.5		2.0	2.0
$\tilde{t}_2$	586.3		–	
$\tilde{g}$	604.0	8.0	–	6.5
h^0	110.8	0.25	0.05	0.05
A^0	399.4		1.5	1.5

NATURE OF SUPERSYMMETRIC PARTICLES

SPIN OF PARTICLES

SUSY cascade decays : $\tilde{q} \to q\,\tilde{\chi}_2^0 \to q\,(\tilde{\ell}\ell) \to q\,(\ell\ell)\,\tilde{\chi}_1^0$



/ 30 / 12 / 100%

UED cascade decays : $q_1 \to q\,Z_1 \to q\,(l_1 l) \to q(ll)\,\gamma_1$ [isomorphic]

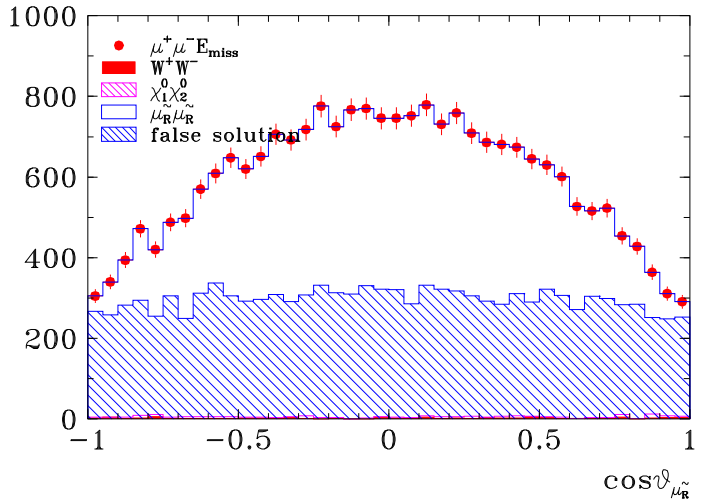
distinction by spin :

ILC prod angle : $e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- \to \mu^+\mu^- + E_{miss}$

mod.indep $S = 0$: $\sin^2\theta$

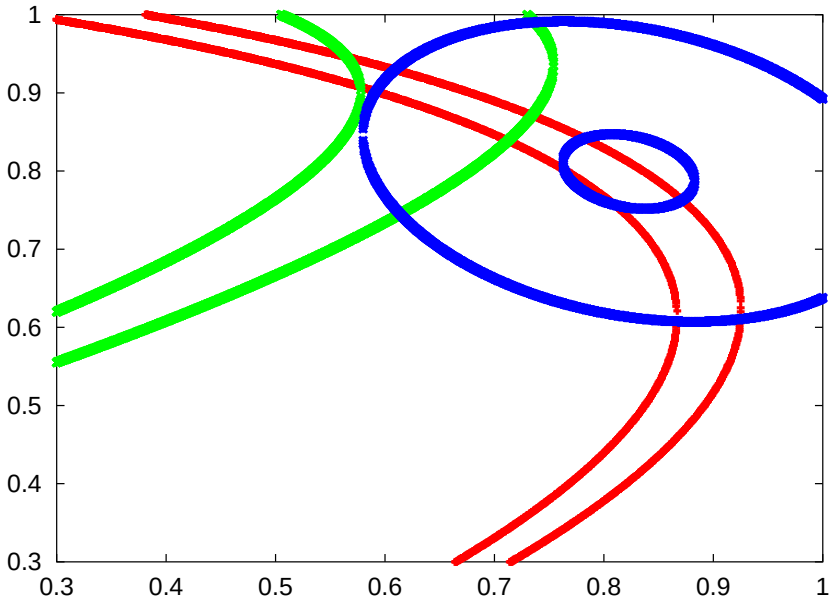
$\tilde{\chi}^{\pm}$ etc: fs analysis required

F: Martyn, Choi ea



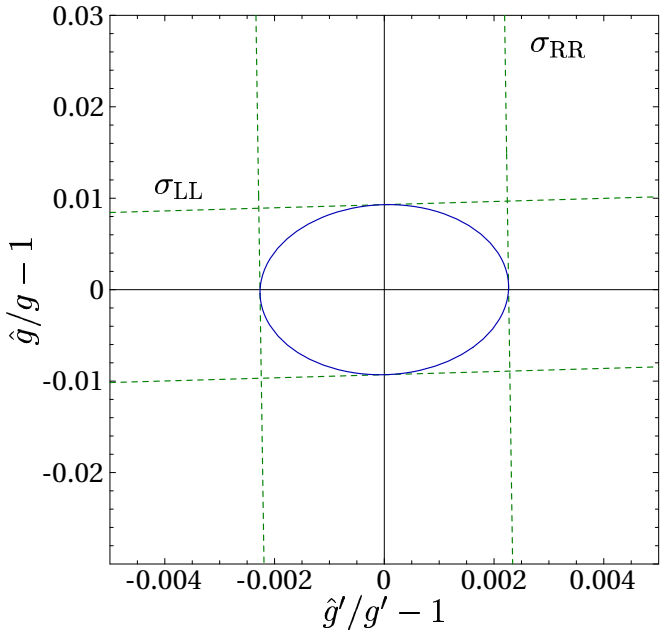
MIXING AND COUPLINGS

Mixing $\tilde{g} \oplus \tilde{h}$ of charginos :



Desch ea: $[c_{2L}, c_{2R}]$: *r,g: L[11]; b: R[11]*

SUSY id: Yukawa = gauge cplgs :



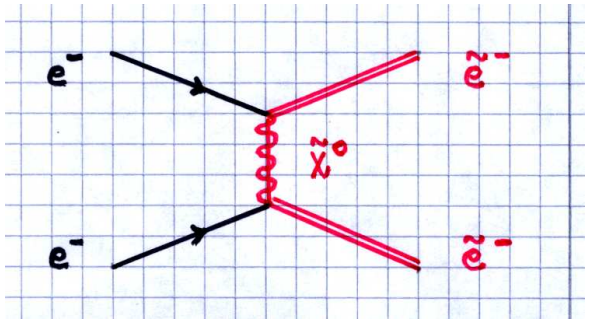
Choi ea

MAJORANA NATURE OF NEUTRALINOS

classical reaction: $e^- e^- \to \tilde{e}^- \tilde{e}^-$

two fermion charges annihilated

only by Majorana $\tilde{\chi}^0$ t-exchange



Extracting SUSY Parameters at Terascale

Gaugino, higgsino, scalar mass parameters, trilinear couplings, etc:

integral LHC/LC analysis $\oplus$ loops: $\mathcal{O} = \mathcal{O}[\mathcal{MSSM}]$: SPA Project

EXC	LHC	LC	LHC+LC	SPS1a
M_1	102.5±5.3	102.3±0.1	102.2±0.1	102.2
M_2	191.8±7.3	192.5±0.7	191.8±0.2	191.8
M_3	578.±15.	→	588.±11.	589.4
$M_{\tilde{e}_L}$	198.7±5.1	198.7±0.2	198.7±0.2	198.7
$M_{\tilde{e}_R}$	138.2±5.0	138.2±0.05	138.2±0.05	138.2
$M_{\tilde{q}_L}$	550.±13.	→	553.3±6.5	553.7
$M_{\tilde{u}_R}$	529.±20.	→	532.±15.	532.1
$M_{\tilde{d}_R}$	526.±20.	→	529.±15.	529.3
A_t	-507.±91.	-501.9±2.7	-505.2±3.3	-504.9
μ	345.2±7.3	344.3±2.3	344.4±1.0	344.3
$\tan\beta$	10.2±9.1	10.3±0.3	10.06±0.2	10

SFitter [Lafaye,Plehn,Zerwas.D]

consistent with :

Fittino [Bechtle,Desch,Wienemann]

GUT/PLANCK-SCALE SCENARIOS

High-precision measurement of SUSY Lagrangian parameters $\Rightarrow$

Extrapolation to high scale :

- reconstruction of fundamental theory $\sim \Lambda_{Pl}$
- exploration of microscopic SUSY breaking
- symmetries/universal behavior at Λ_{Pl}?
- impact of high-scale physics?

Program in parallel to : Proton decay and related phenomena

Neutrino physics – e.g. see-saw mechanism

Cosmology / early times

picture coarse $\Rightarrow$ *HEP SUSY addition highly valuable*

to reconstruct Planck scale scenario

GAUGE COUPLINGS

Evolution: present elw/strong gauge couplings

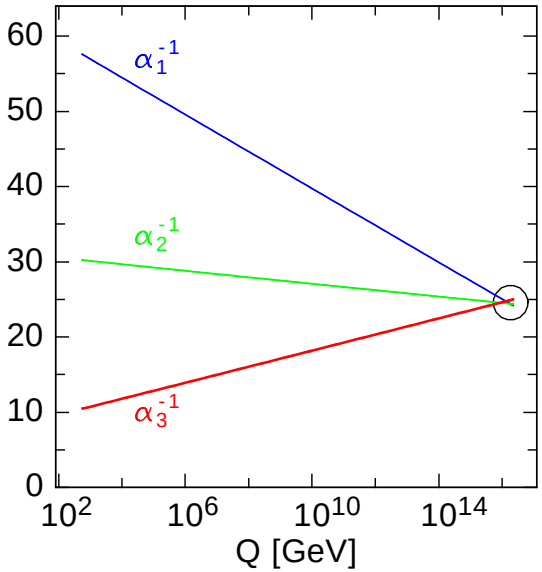
$\oplus$ SUSY threshold corr $\sim$ LHC

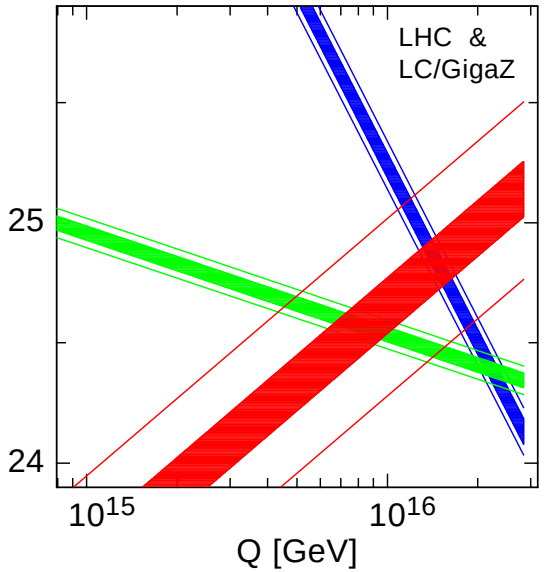
GigaZ : $\Delta s^2_W/\alpha_s \leq 10^{-5/-3}$

$\oplus$ ILC completed

Grand Unification : $\sim 2\sigma$ / g^U : 2%

Δ_3 at 8σ level : high sc phys





	Present/"LHC"	GigaZ/"LHC+LC"
M_U	$(2.36 \pm 0.06) \cdot 10^{16}$ GeV	$(2.360 \pm 0.016) \cdot 10^{16}$ GeV
α_U^{-1}	24.19 ± 0.10	24.19 ± 0.05
$\alpha_3^{-1} - \alpha_U^{-1}$	0.97 ± 0.45	0.95 ± 0.12

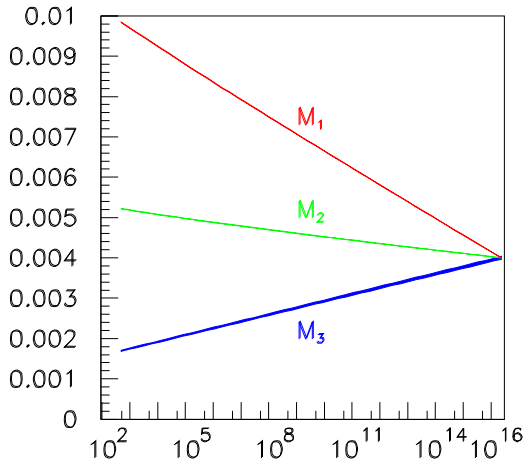
UNIVERSALITY : MASSES AND SUSY BREAKING

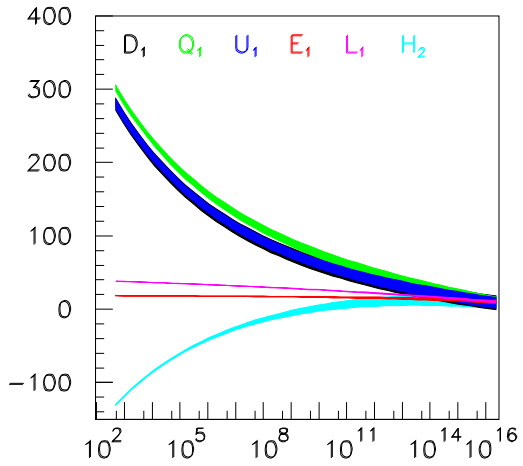
Evolution :

Gaugino / scalar masses

universal in mSUGRA

F: Blair, Porod, ea

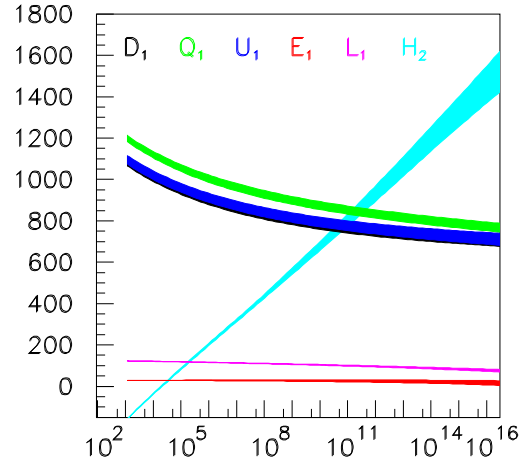




Scalars in GMSB

evolution distinctly different ⇒

- *Micro-picture of SUSY breaking*
- *GUT/Pl physics scenarios*



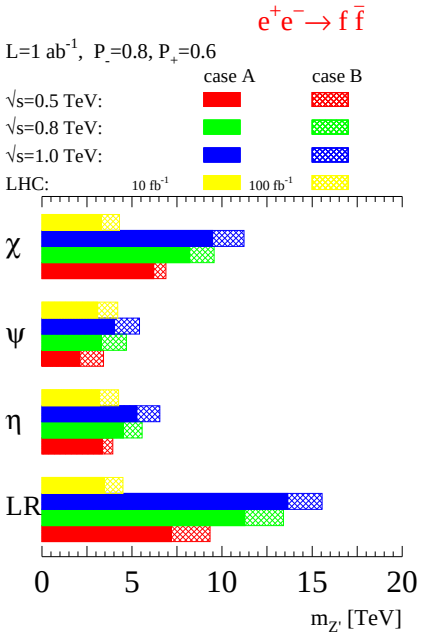
INTERMEDIATE SCALE : Z' BOSON

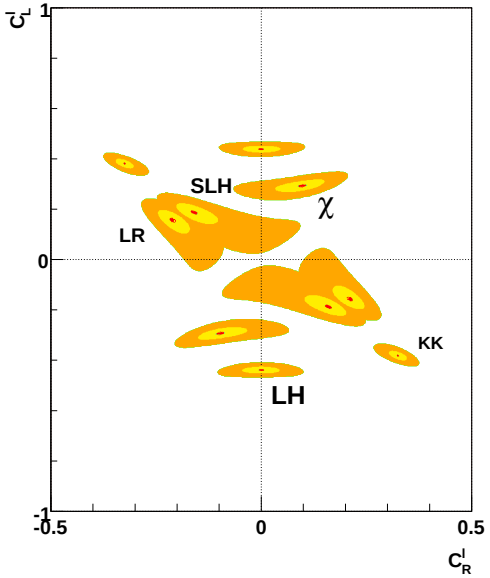
Heavy Z' vector boson motivated by TeV scale remnants of grand unified theories and string theories, ext.Higgs and extra.dim models, etc

Examples : Z' in SO_{10}, LH, etc : LHC : $M_{Z'}$ up to ~ 5 TeV

ILC : virtual extension up to 15 TeV — Riemann.S

Z' cplgs : discriminatg models — Godfrey ea



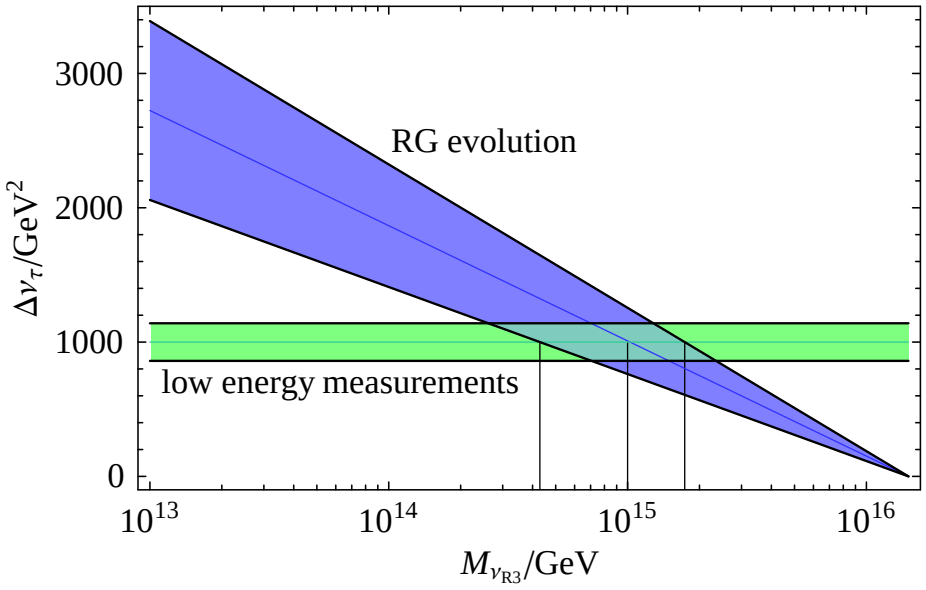


INTERMEDIATE SCALE : SEE-SAW IN ν PHYSICS

Example : neutrino mass generated by see-saw mechanism $\Rightarrow$

intermediate see-saw scale $M[\nu_R] \sim 10^{10}/10^{15}$ measurable ? "qualified yes"

Seesaw-scale affects evolution of $\tilde{\tau}/\tilde{\nu}_\tau$ masses in third generation, but not 1st/2nd generation : $\tilde{\tau}/\tilde{\nu}_\tau$ shifted wrt $\tilde{e}/\tilde{\nu}_e$



Blair,Deppisch,Freitas,Porod,ea

$M_{\nu_{R3}} \sim 10^{15}$ GeV at 60% level

indirect evidence :

L-change: $ee \to e\tau, \mu\tau$ Deppisch ea,

cf: Hisano ea,

Guchait ea, Porod ea

2C. EXTRA SPACE DIMENSIONS

essential element: gravity extends to higher dimensions *(⊕ many variations)*

ADD: flat geometry : Λ_{Pl} up to 7 TeV

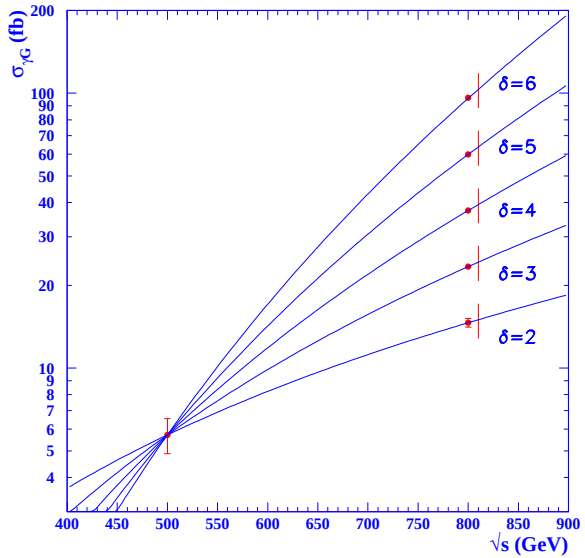
$\delta = dim - 4 > 2$

RS: warped geometry : *curvature* k

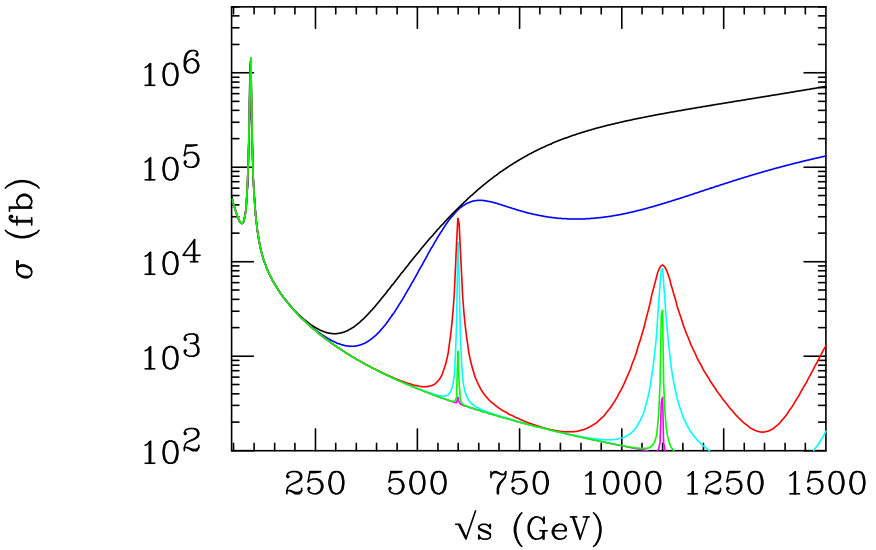
$k/\overline{M}_{pl} \sim 0.1$

$e^+e^- \to \Sigma KK_G + \gamma$ $\Uparrow$ var $\sqrt{s}$

excitation of KK_G towers



Wilson.G



Hewett ea

UED: : all SM fields extended

add: radion, [KK SM particles $M_{KK} \gg$]

3. COSMOLOGY CONNECTION

Focus: mechanism of baryon asymmetry $\rho_B = 4.0 \pm 0.4\%$

particle character of CDM $\rho_{cdm} = 24 \pm 4\%$

Baryon Asymmetry

- LEPTOGENESIS : CP violation in heavy ν_R sector

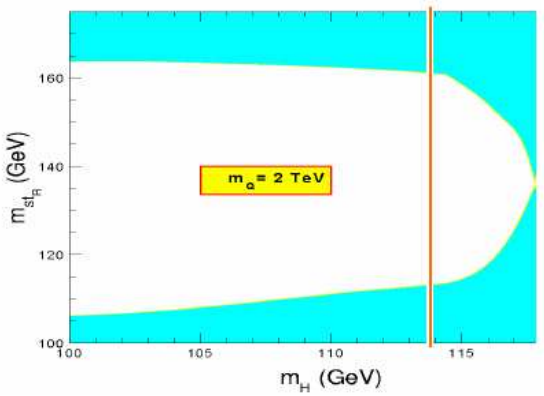
  ILC $[indirect] \Rightarrow$ mass estimate ν_R

- SUPERSYMMETRY: new CP-violation source $[\tilde{\chi}]$

  1st PT : light $\tilde{t}_R$ and Higgs

  $\Leftarrow$ window left by LEP [Higgs < 120 GeV]
  and Tevatron $[\tilde{t}_R < top]$

  $\Leftarrow$ ILC : near degeneracy $\tilde{t}_R$ and $\tilde{\chi}_1^0$ Carena ea



Many candidate particles in a variety of theoretical approaches $\Rightarrow$

CDM = mixture of different components / complex structure ?

– supersymmetry: lightest neutralino $\Leftarrow$

gravitino $\Leftarrow$

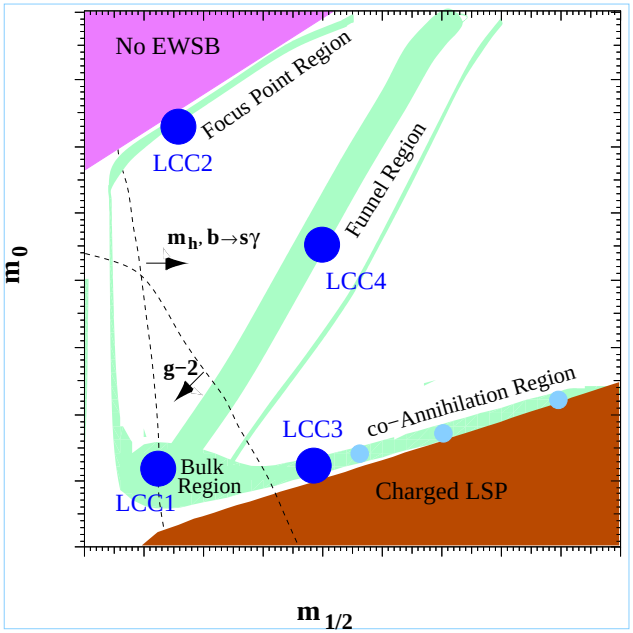
– extra dimensions: KK states, ...

- NEUTRALINO CDM:

area in mSUGRA param $\sim$ octopus

CDM predicted by $\tilde{\chi}\tilde{\chi}$ *etc* annihilation

$\Leftarrow$ precise SUSY sector required



LCC2 focus pt : Ωh^2 corr /w mass diff

$$\tilde{\chi}_1^{\pm} - \tilde{\chi}_1^0 = 51.7 \pm 0.3 \text{ GeV}$$

$$\Omega h^2 = 0.109 \pm 8\%$$

:: present accuracy [WMAP] : $\Omega h^2 = 0.104^{+0.007}_{-0.013}$: $\sim 10\%$

:: future [PLANCK] : : 1.4%

MSSM conclusion on CDM = neutralino $\tilde{\chi}^0_1$:

	character	channel	sensitivity	LHC	(500)	(1000)
SPS1a′	bulk / co-an	$\tilde{\chi}\tilde{\chi} \to \tau\tau$, bb / co-an	$\tilde{\tau}$, $\tilde{b}$	10%	2%	id
LCC2	focus point	$\tilde{\chi}\tilde{\chi} \to WW, ZZ$	$\tilde{V}\tilde{H}$ mi	80%	14%	8%
LCC3	$\tilde{\tau}\tilde{\chi}$ co-ann.	$\tilde{\tau}\tilde{\chi} \to \tau\gamma$	$M[\tilde{\tau} - \tilde{\chi}^0_1]$	176%	50%	18%
LCC4	A funnel	$\tilde{\chi}\tilde{\chi} \to A$	M_A, Γ_A	405%	85%	19%

LCC Project [Baltz ea] / SPA Project [Bélanger ea]

Note : in bottom-up approach [ILC/LHC potential not fully exploited yet]

:: significant improvement if over-all picture under better control:

msugra analyses : 8/18/19% → 3/7/5% [DCR]

- GRAVITINO CDM:

$\tilde{G}$ lightest susy particle : GMSB $\sim$ 10 GeV down to 1 eV — Ambrosanio, Blair

SUGRA $\sim$ 10 to 100 GeV — Primack ea, Buchmüller ea, Feng ea, Hamaguchi ea, Ellis ea

lifetime NLSP: $\tau[\tilde{\ell} \to \ell + \tilde{G}] = const \times M_{\tilde{G}}^2 M_{Pl}^2 / M_{\tilde{\ell}}^5$

or other modes

potentially visible NLSP decay length

even up to macroscopic lifetime of order 10^3 sec

$\Rightarrow$ *suggesting special experimental efforts to catch the long-lived sleptons and to measure their decay properties*

supergravity : collider / in conjunction with cosmological measurements

Planck mass determined from lifetime measurements — Buchmuller ea, Martyn

4. SUMMARY

ILC can contribute uniquely to solutions of key questions in physics ...

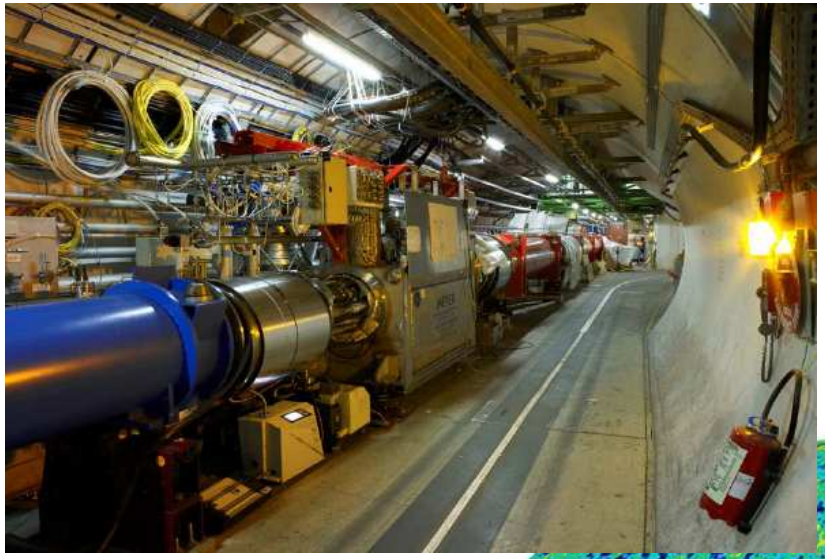
Electroweak Symmetry Breaking: establish Higgs mechanism *sui generis* for generating mass

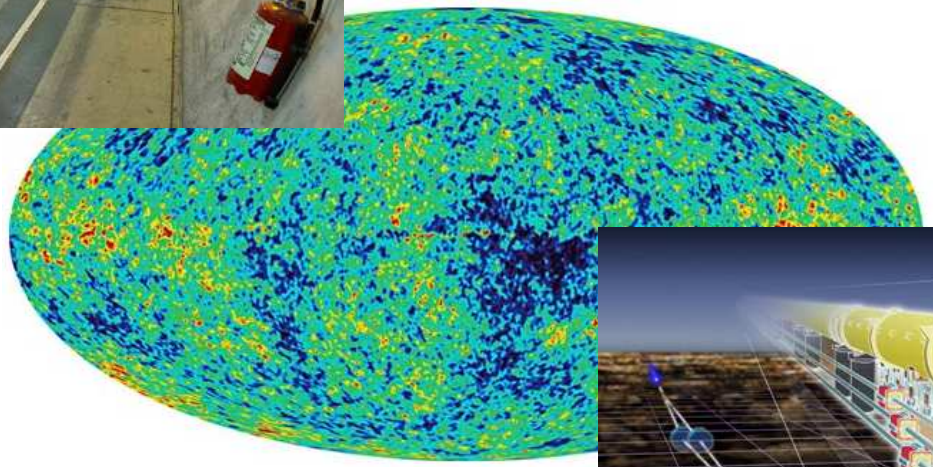
Grand/Ult Unification: comprehensive and high-resolution picture of supersymmetry
LHC⊕ILC ⇒ Telescope to *Planck*-scale physics
particle physics ∼ gravity ⇒ root of physics

Extra Space Dimensions: basic questions: Λ_{Pl} and $\#\, D$
new states, mixing of SM world with new world

Cosmology Connection: determine nature of CDM particles
establish elements of origin of matter-asymmetry in Universe

... and unravel the underlying laws of nature in the energy domain up to TeV.






International Linear Collider