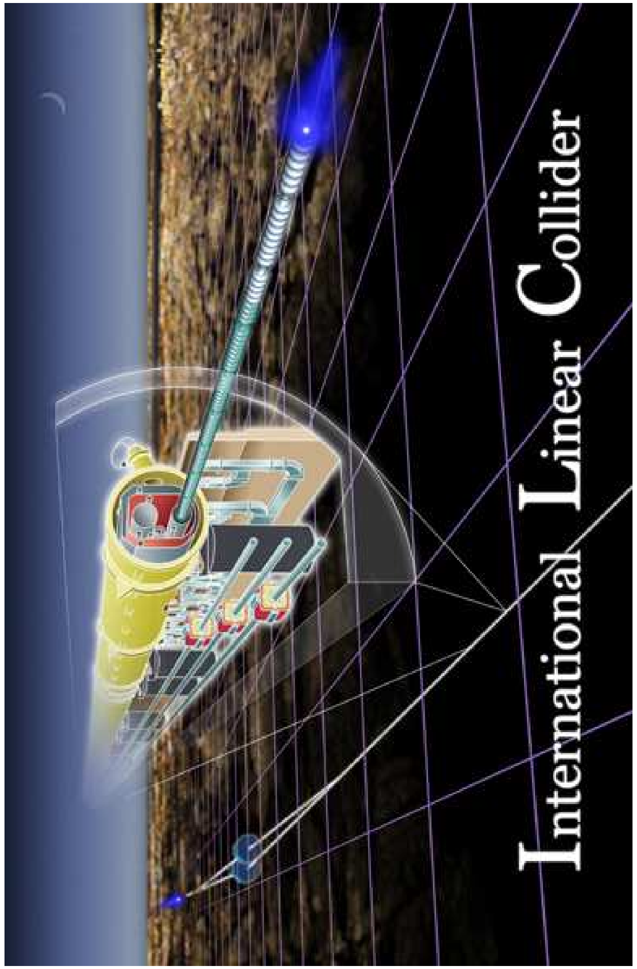

ILC : PHYSICS
FROM TERA- TO PLANCK-SCALE

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 discovery 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 $\Rightarrow$ Extra Space Dims : stdd | TeV Planck Scenario

SCENARIOS :

– generally not without tension but:

– representative for extended classes [MSSM $\sim$ SUSY]

– prove comprehensive coverage of theoretical glacis [weak ... strong elwSB]

LITERATURE :

- *"Physics Chapter of RDR"* : A.Djouadi, J.Lykken, K.Mönig, Y.Okada, M.Oreglia, S.Yamashita
- *"Scenarios for ILC in 2010"* : F.Richard, arXiv:0707.3723 [hep-ph]
- *"Snowmass ILC Report / LCWS07"* : Kilian, Z: hep-ph/0601217

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BASE OF TALK :

... central physics targets of ILC : $\sqrt{s} = 500$ GeV | upgrade $= 1$ TeV
$e^-/90$ $[e^+/60]$ polarization
e^-e^- | $e\gamma/\gamma\gamma$ | GigaZ

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2A. ELECTROWEAK SYMMETRY BREAKING

– *missing keystone of Standard Model*

– *indicator of physics landscape beyond SM*

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

$\Downarrow$

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

$\Uparrow$

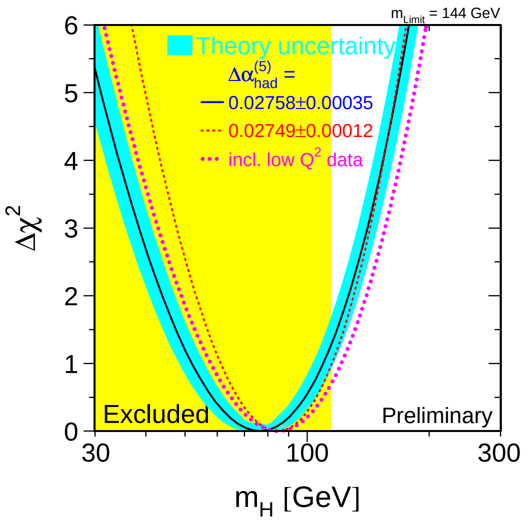
topology extra space dim [$H \sim$ 5th gauge field, BC : higgsless, ...]

a) SM HIGGS MECHANISM

– light Higgs: suggested by precision data [EWWG:

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

– probability 15%



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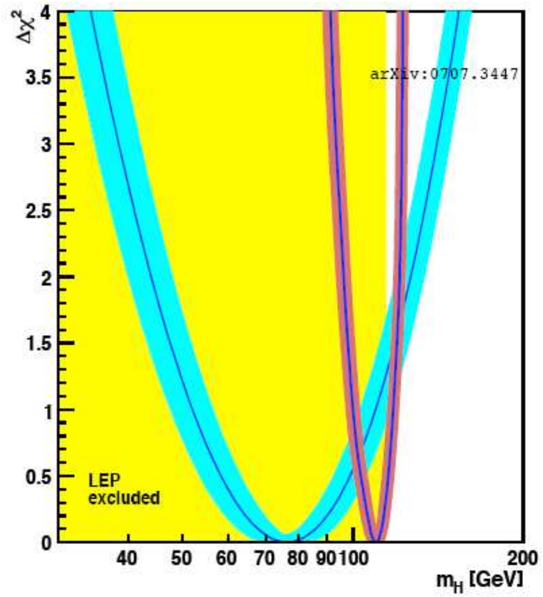
a) SM HIGGS MECHANISM

– light Higgs: suggested by precision data

digression:

$\Rightarrow\ 110^{+8}_{-10} \pm 3$ GeV in mSUGRA Buchmüller ea



Three central questions

$\Leftarrow$ after Higgs discovery at LHC

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*

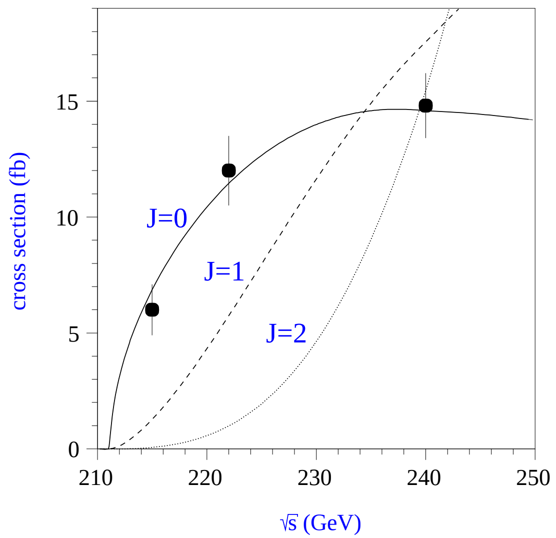
(1) Higgs = fundamental scalar :

Higgs-strahlung near threshold:

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

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

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



Lohmann ea

(2) Higgs couplings to SM particles :

Higgs coupling – mass relation:

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

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

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

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

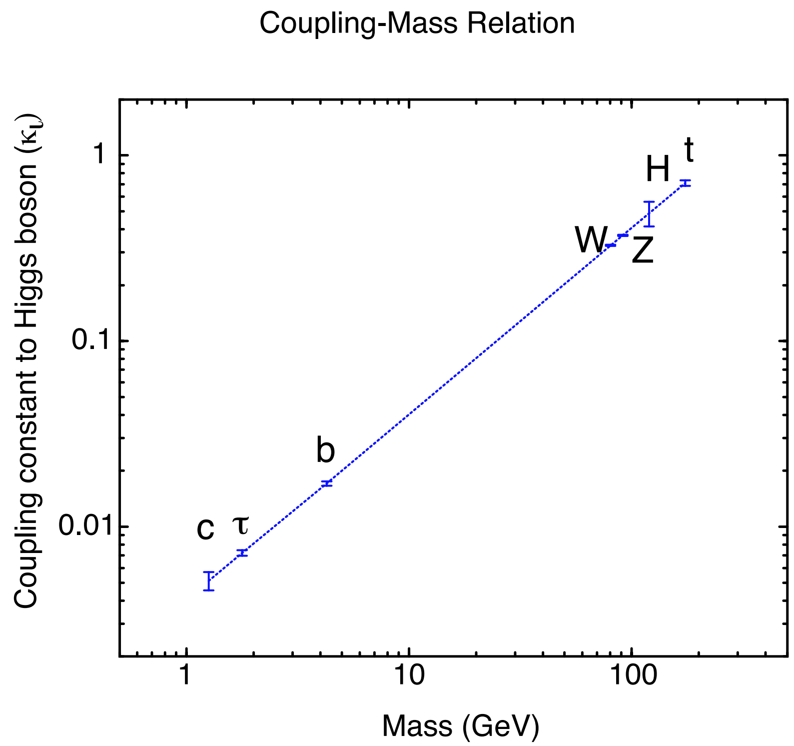
$\Rightarrow$ production cross sections

$\Rightarrow$ decay branching ratios

$\Rightarrow$ Higgs radiation off *top*

$\sim$ strg BSM scale 2 .. 3 TeV

$\sim$ univ 0^+ mix [radion]



ACFA LC Study

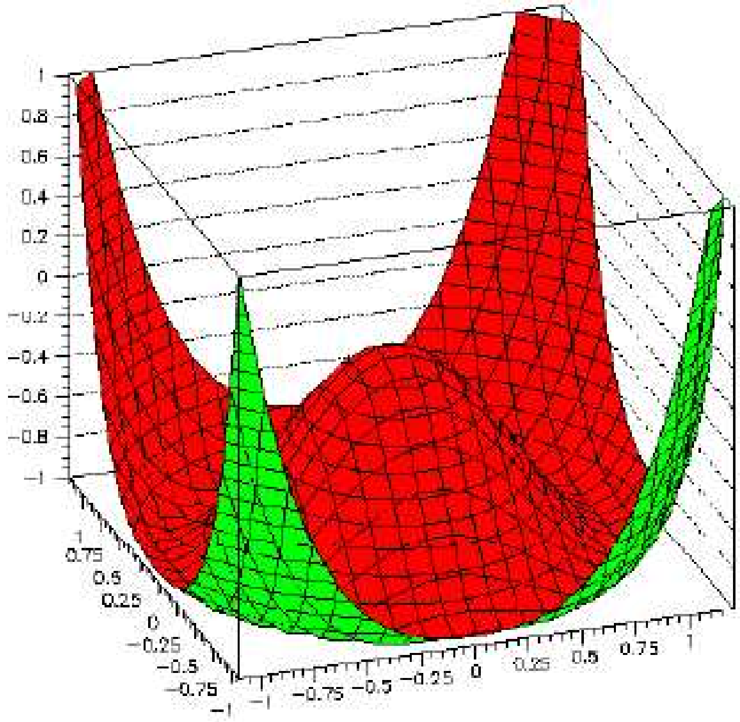
improving on LHC significantly:
precision and model-indep slope

$/Z/W/\tau/b/t/ = /1/1/3/2/2\%$

(3) Higgs potential

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

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



<u>self-interaction</u> :

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

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

<u>measurement</u>: $e^+e^- \to ZHH$
$e^+e^- \to \nu\nu HH$

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

<u>BSM H sector $\sim$ 1 TeV</u>

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

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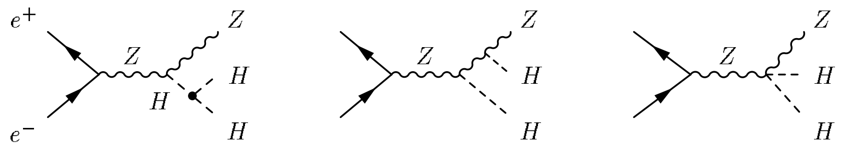
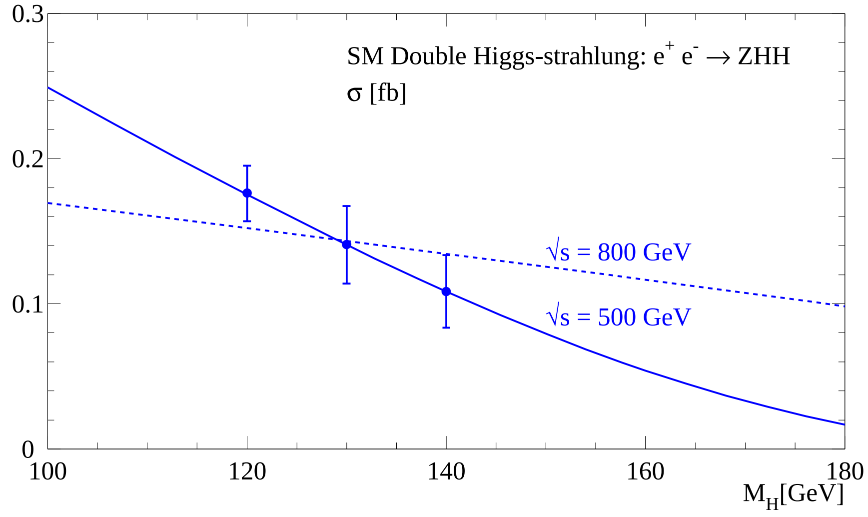




Mühlleitner ea | Gay | Yamashita (ea)

b) SUSY HIGGS BOSONS

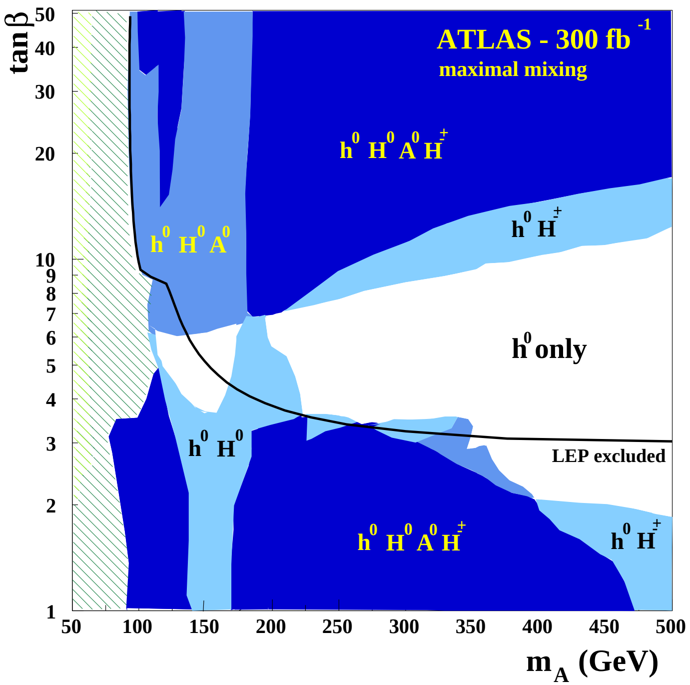
Higgs sector extended to 2 doublets $\Rightarrow$ 5 physical particles in MSSM :

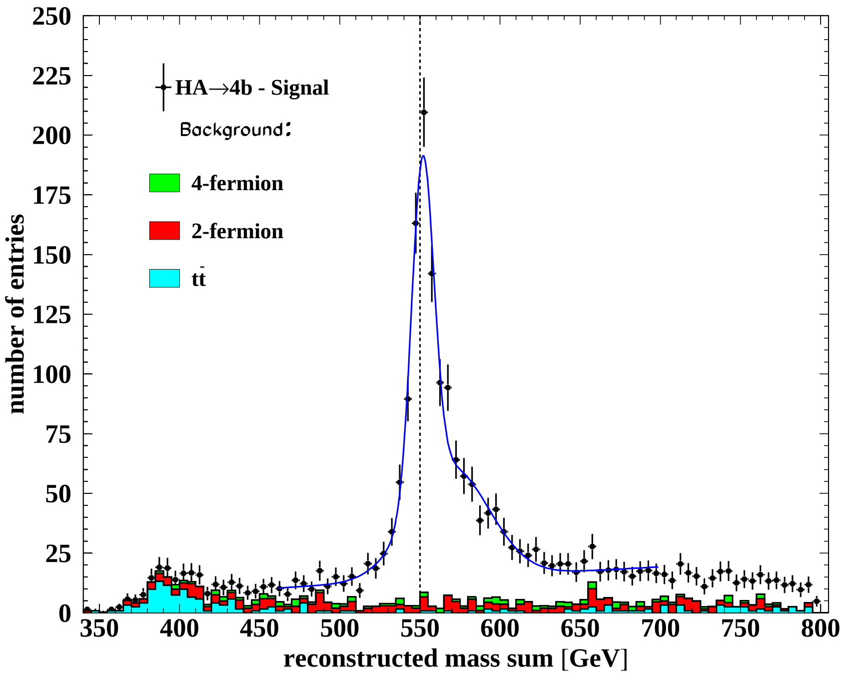
h^0 light ≤ 140 GeV | generically < 200 GeV

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

detection at LHC: blind wedge

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





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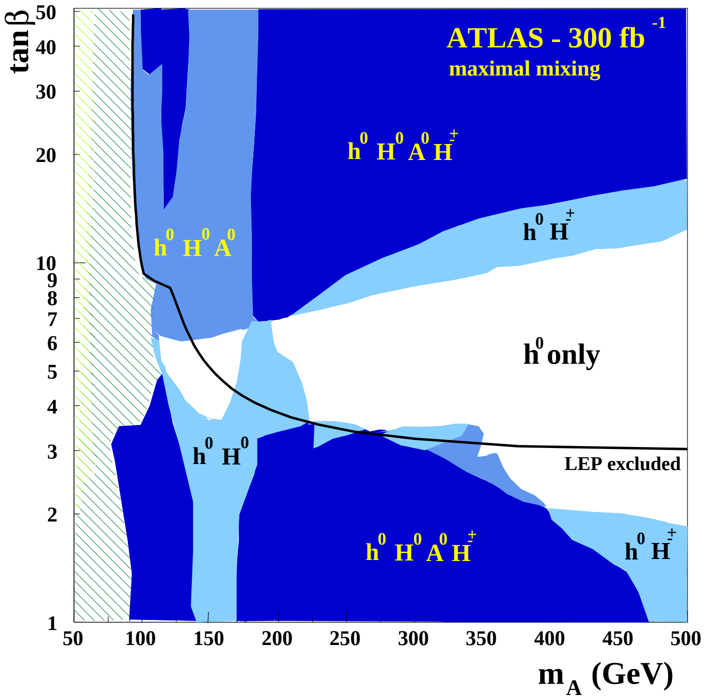
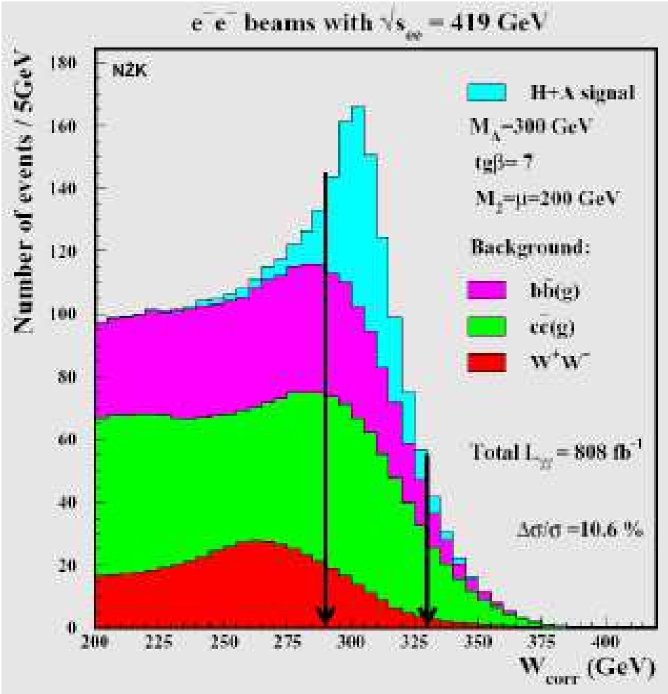
$\gamma\gamma \to H, A : +50\%$ [Mühlleitner ea, Gunion ea, F: Niezurawski ea]





SUSY EXTENSIONS :

CP Violation :

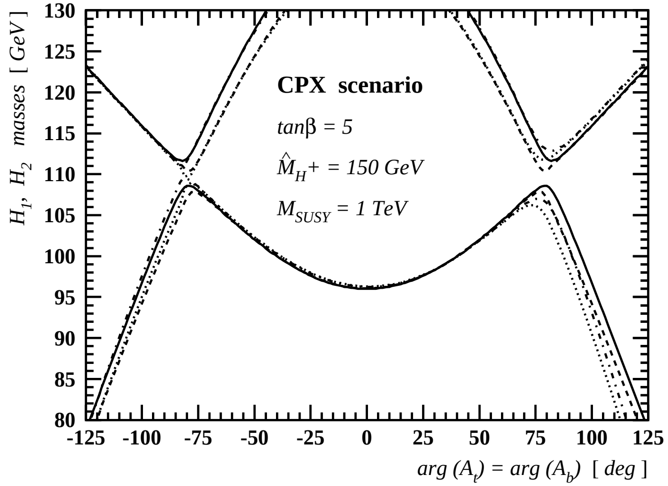
h^0, H^0 mix $A^0 \Rightarrow H_1^0, H_2^0, H_3^0$

– changing spectra and production

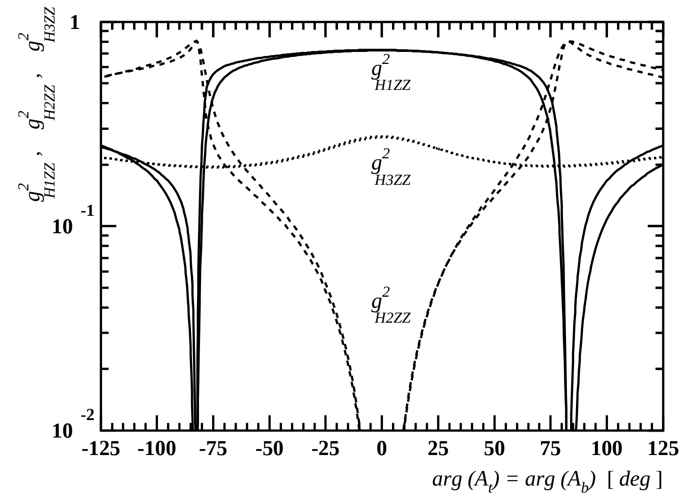
F: Carena ea

– CP : $\tau\tau$ polarization

asymmetry in circularly pol $\gamma\gamma$



(a)



(b)

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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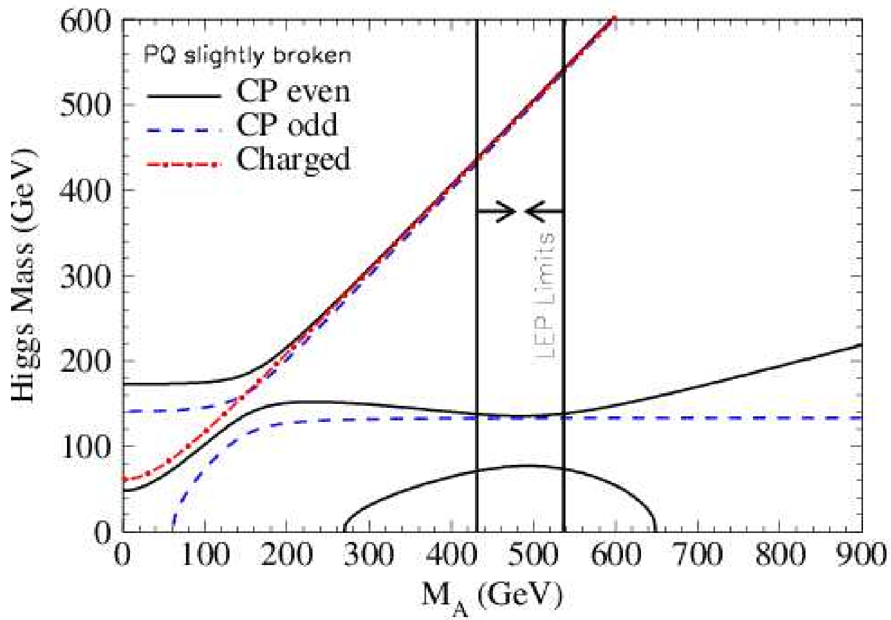

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F: Miller ea

c) STRONG ELW SYMMETRY BREAKING

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

[pseudo-] Goldstone bosons $\sim$ Higgs particles

▪ LITTLE HIGGS THEORIES

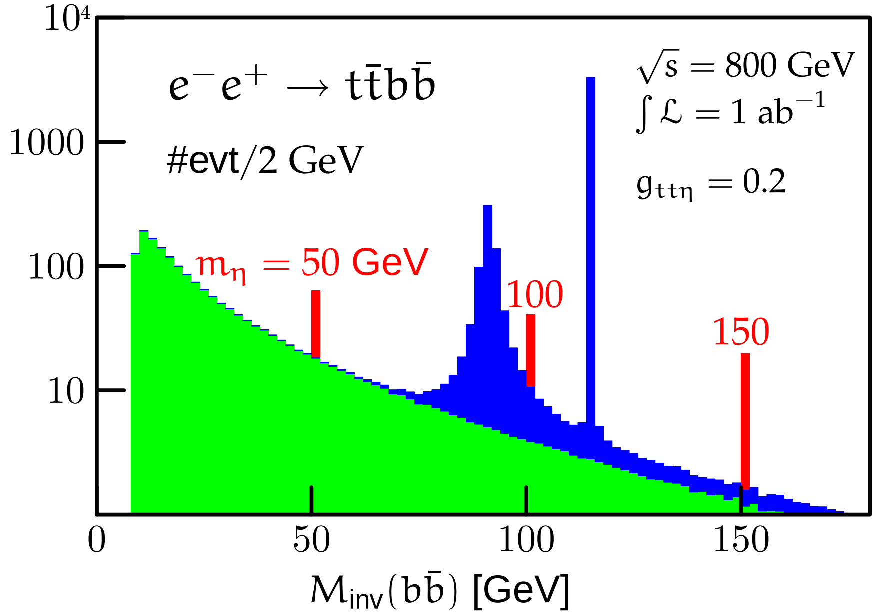
large global symmetry group | $f \sim TeV$:

rich spectrum of TeV particles

plus light Higgs sector

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

F: Kilian, Rainwater, Reuter



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

almost completely covered

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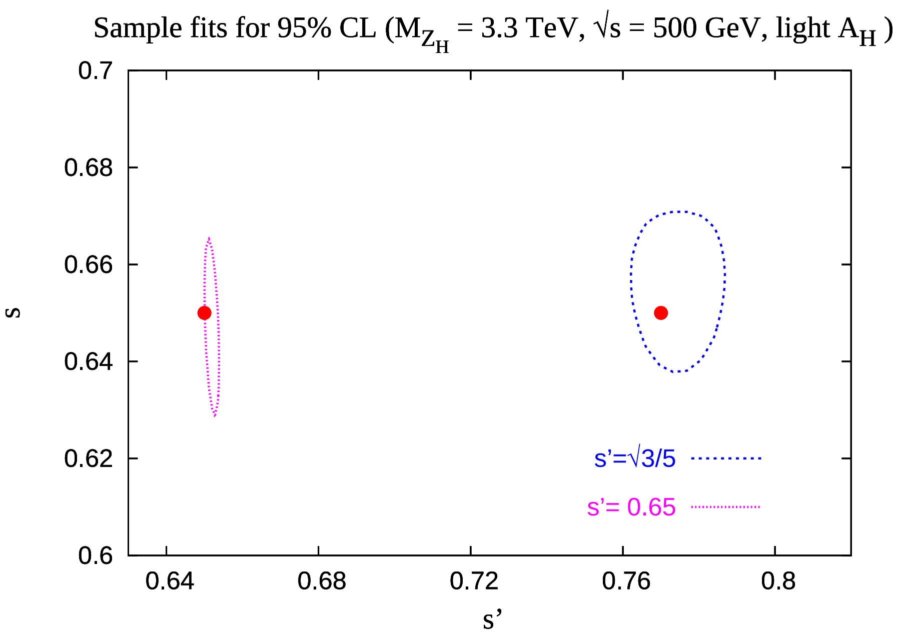
almost completely covered

masses known from LHC :

ILC determines model specific cplgs $\Rightarrow$



F: Conley, Hewett, Le

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▪ MINIMAL STRONG THEORY

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

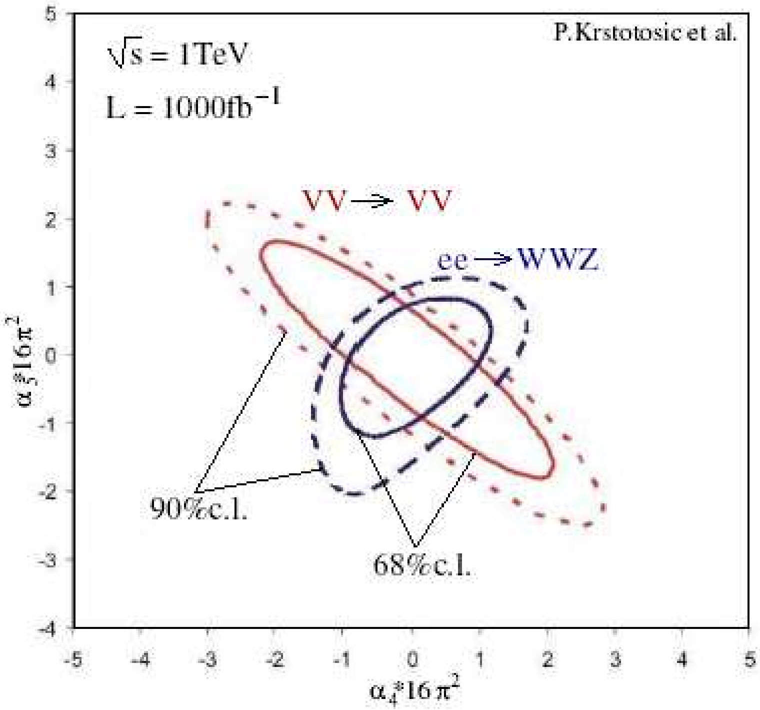
observed in WW scattering $\sqrt{s} = 1$ TeV

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

$$e^+e^- \to WWZ$$ Krstotosic, Beyer ea

sensitivity : across entire threshold region

$$\boxed{\text{SI scale: } \Lambda_* < 4\pi v \simeq 3 \text{ TeV}}$$



$\boxed{\text{CLOSURE of SM}}$ ...

– 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 $\frac{1}{2} \cdot 10^{-3}$ and static properties*

key observable for flavor physics | reflectg new interactions

2B. SUPERSYMMETRY

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

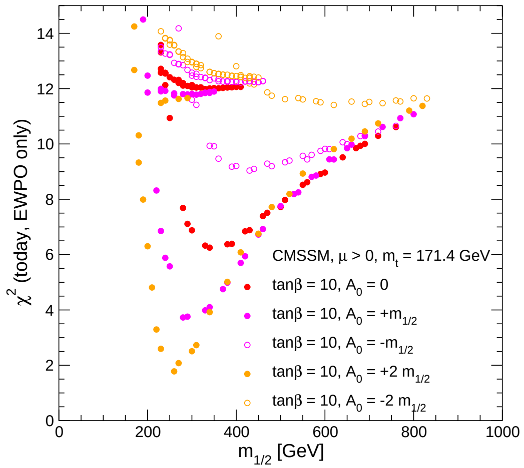
– generating and stabilizing light Higgs boson

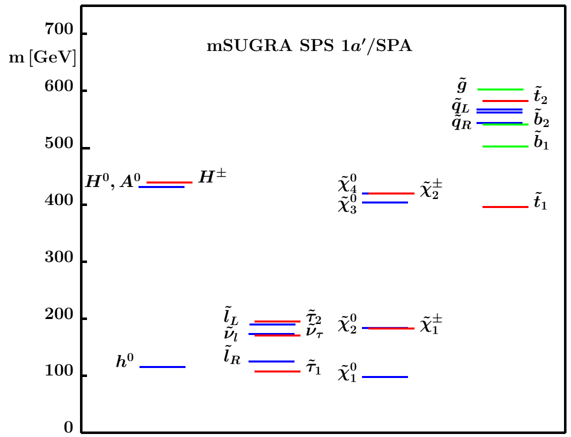
– leading to unification of gauge couplings / paving path to gravity

– providing candidate particle for Cold Dark Matter

MASS SCALE : LEdata + CDM small/mod $\tan\beta$: [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

$\boxed{\text{LHC}}$ discovery sensitivity $\sim$ 2.5 to 3 TeV

first steps in exploring spectrum

$\boxed{\text{ILC}}$ 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 Tera-scale

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

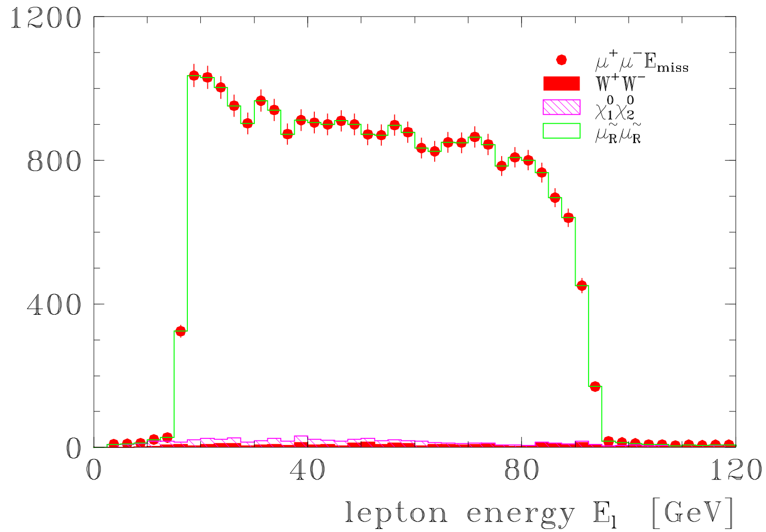
$\Leftarrow$ complexity SUSY $>$ SM : analysis to be successful needs high-precision data

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 $\sim 10^2$

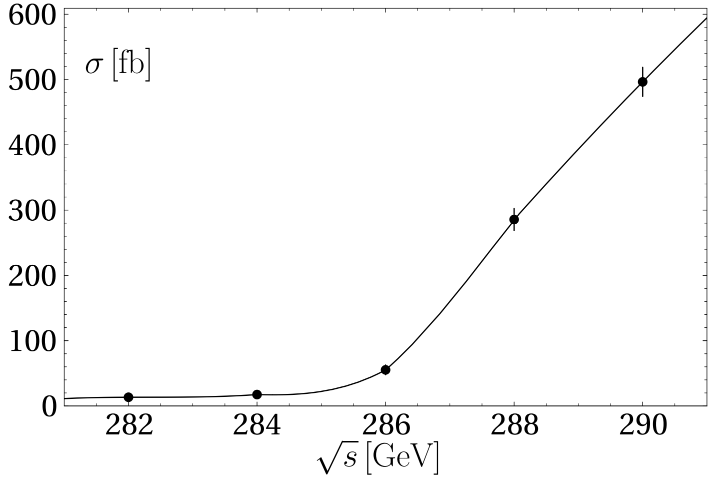
b) Threshold excitations:

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

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

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 :

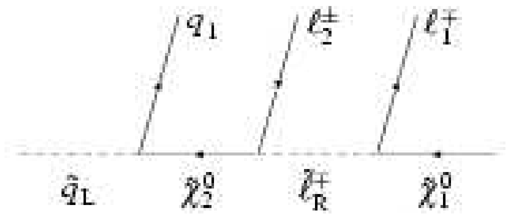
comprehensive and high-resolution susy picture

	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 : $\tilde{q} \rightarrow q\, \tilde{\chi}_2^0 \rightarrow q\, (\tilde{\ell}\ell) \rightarrow q\, (\ell\ell)\, \tilde{\chi}_1^0$



/ 30 / 12 / 100%

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

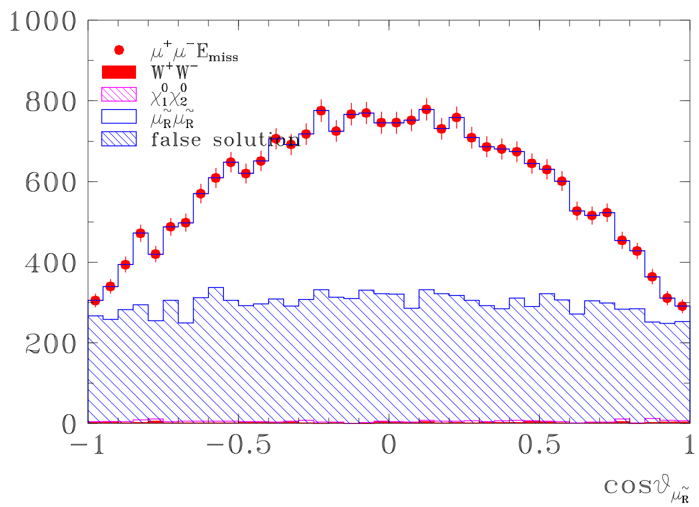
distinction by spin :

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

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

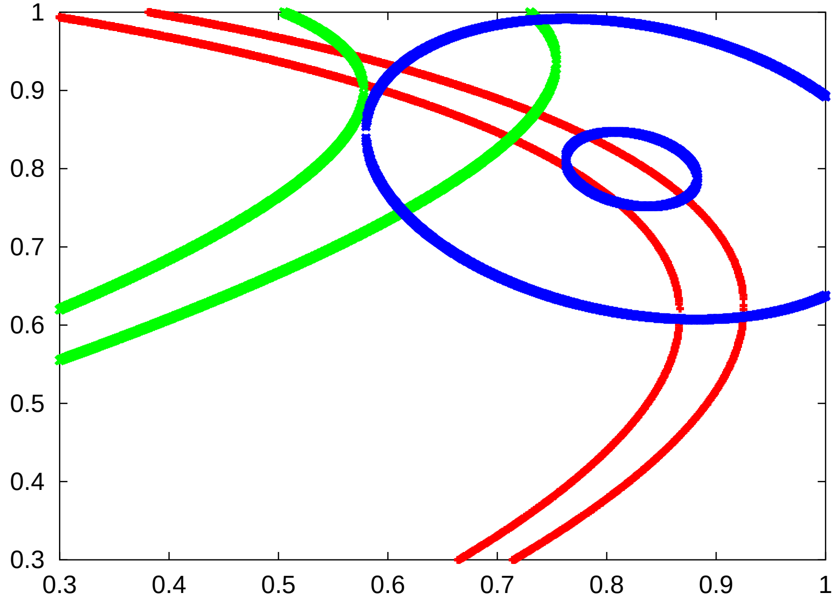
$\tilde{\chi}^\pm$ etc: fs analysis required

F: Martyn, Choi ea



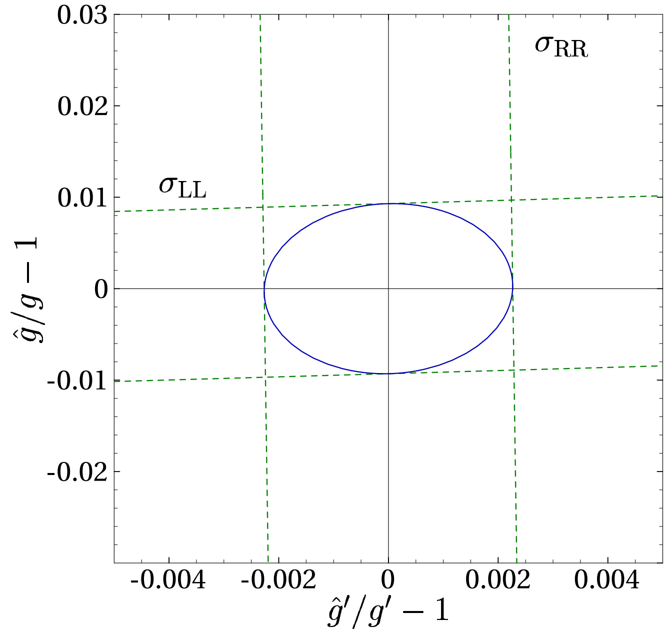
MIXING AND COUPLINGS

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 :



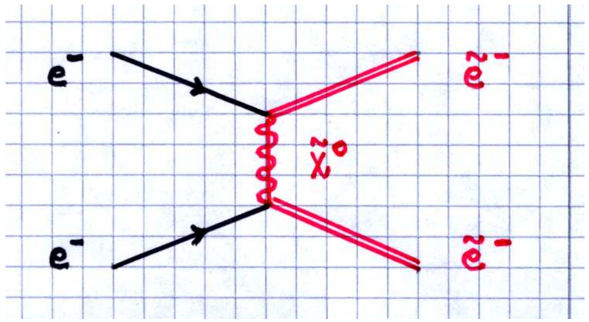
Choi ea

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.	$\rightarrow$	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.	$\rightarrow$	553.3±6.5	553.7
$M_{\tilde{u}_R}$	529.±20.	$\rightarrow$	532.±15.	532.1
$M_{\tilde{d}_R}$	526.±20.	$\rightarrow$	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*

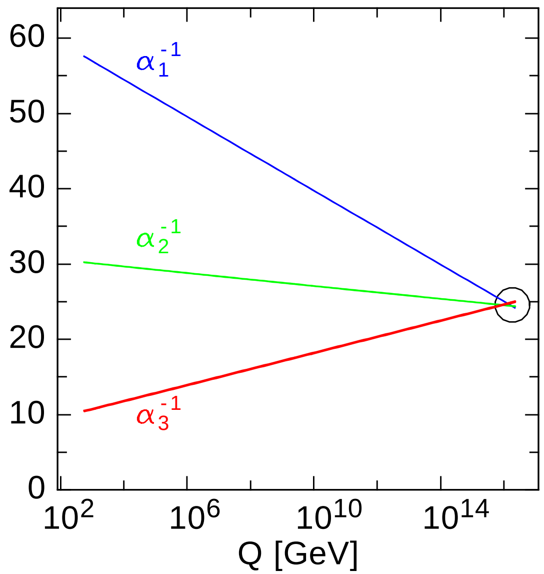
GAUGE COUPLINGS

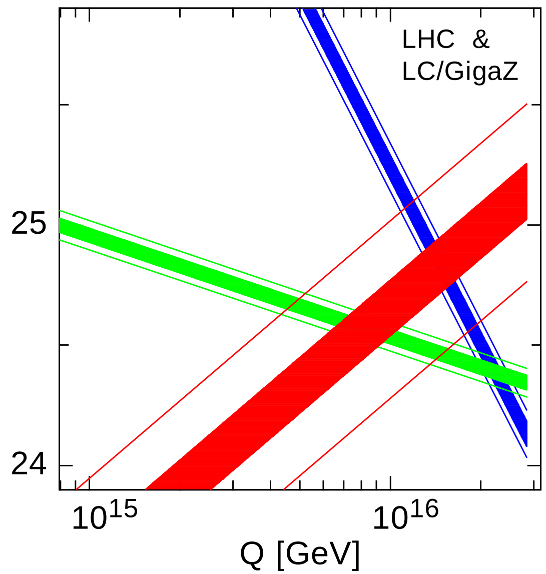
Evolution: present elw/strong gauge couplings $\oplus$ SUSY threshold corr $\sim$ LHC

GigaZ : $\Delta s_W^2 / \alpha_s \leq 10^{-5/-3}$ $\oplus$ ILC completed

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

Δ_3 at 8σ level : high sc phys





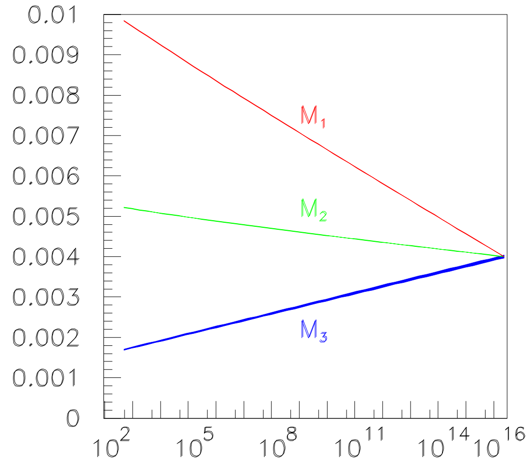
	Present/"LHC"	GigaZ/"LHC+LC"
M_U	$(2.36 \pm 0.06) \cdot 10^{16}$ GeV	$(2.360 \pm 0.016) \cdot 10^{16}$ GeV
α_U^{-1}	24.19 ± 0.10	24.19 ± 0.05
$\alpha_3^{-1} - \alpha_U^{-1}$	0.97 ± 0.45	0.95 ± 0.12

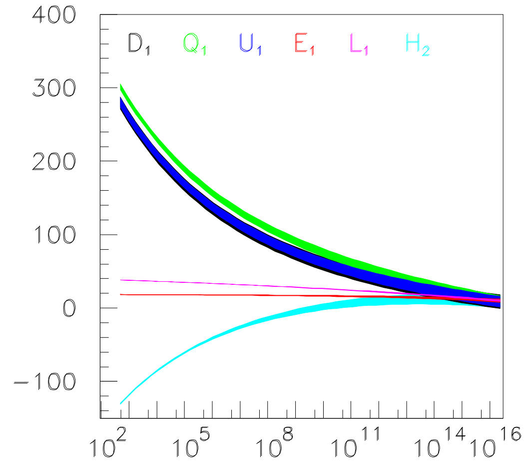
Evolution :

Gaugino / scalar masses

universal in mSUGRA

F: Blair, Porod, ea

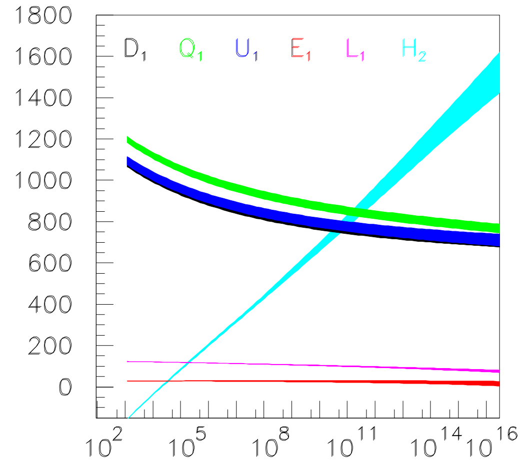




Scalars in GMSB

evolution distinctly different $\Rightarrow$

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



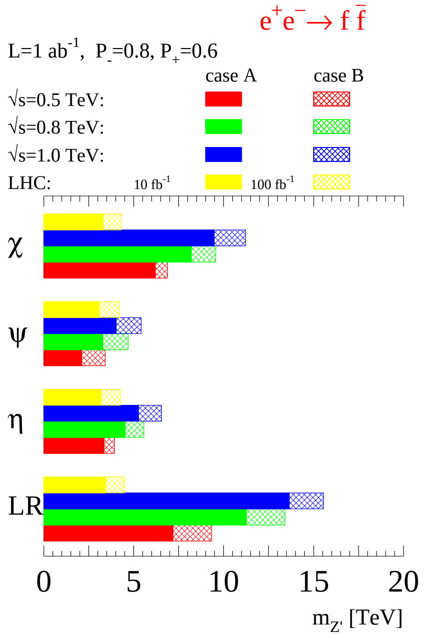
INTERMEDIATE SCALE : Z' BOSON

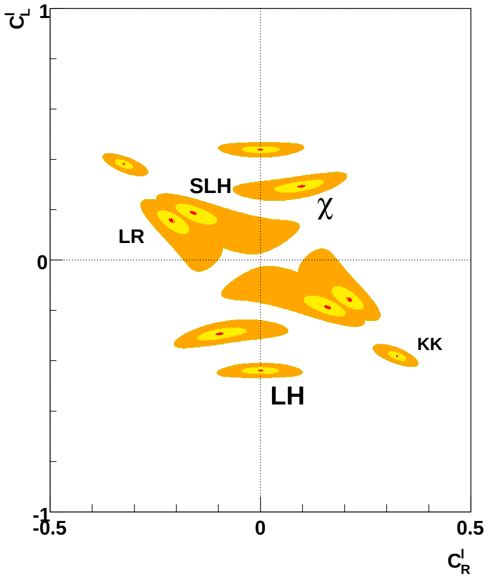
Heavy Z' vector boson motivated by TeV scale remnants of grand unified theories and string theories, ext.Higgs and extra.dim models, etc

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



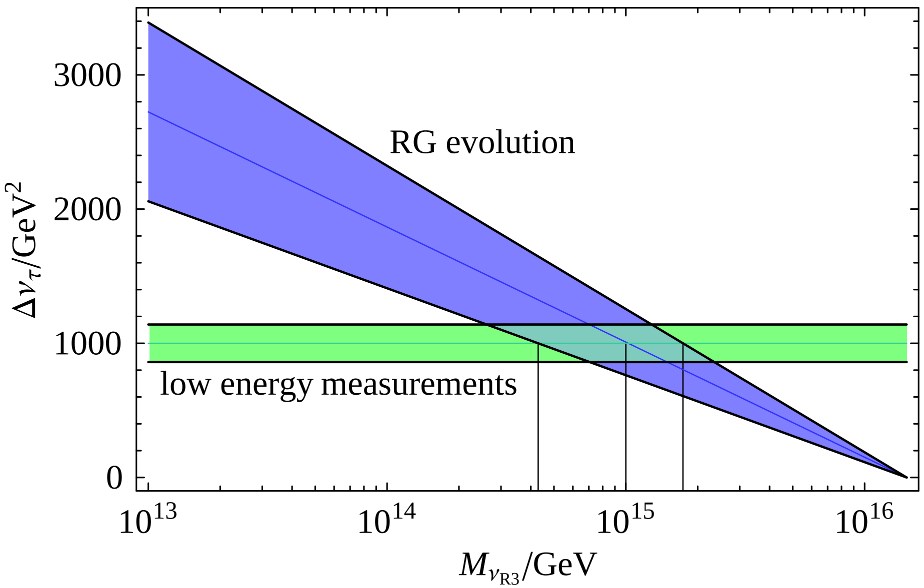


INTERMEDIATE SCALE : SEE-SAW IN ν PHYSICS

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 $\tilde{e}/\tilde{\nu}_e$



$$\boxed{M_{\nu_{R3}} \sim 1.0 \times 10^{15}\ \mathrm{GeV}\ |\ 50\%\ \mathrm{level}}$$

Deppisch, ea

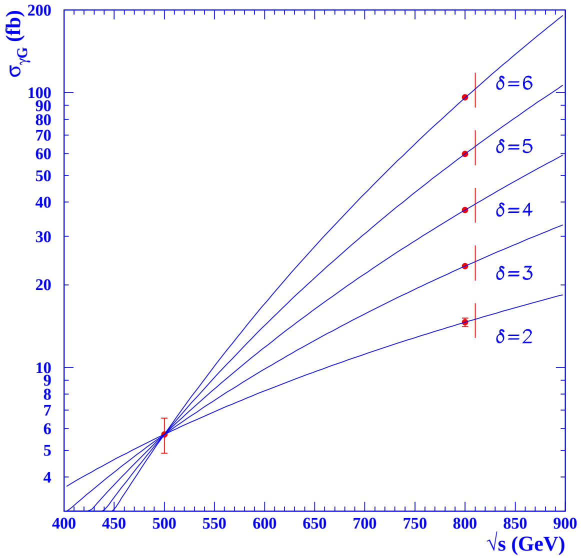
2C. EXTRA SPACE DIMENSIONS

basic element: gravity extends to higher dimensions [$\oplus$ *SM fields*]

ADD: flat geometry : Λ_{Pl} up to 7 TeV
$\delta = dim - 4 > 2$

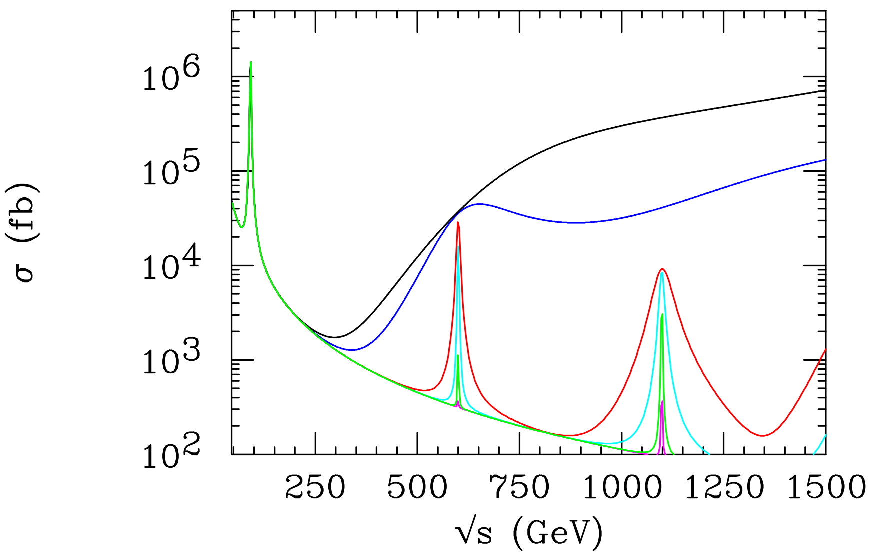
RS: warped geometry : *curvature* k
$k/\overline{M}_{pl} \sim 0.1$

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



Wilson.G

excitation of KK_G towers



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 $\rho_{cdm} = 24 \pm 4\%$

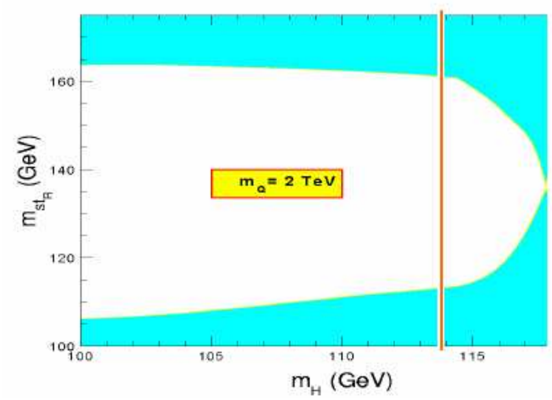
Baryon Asymmetry

- 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

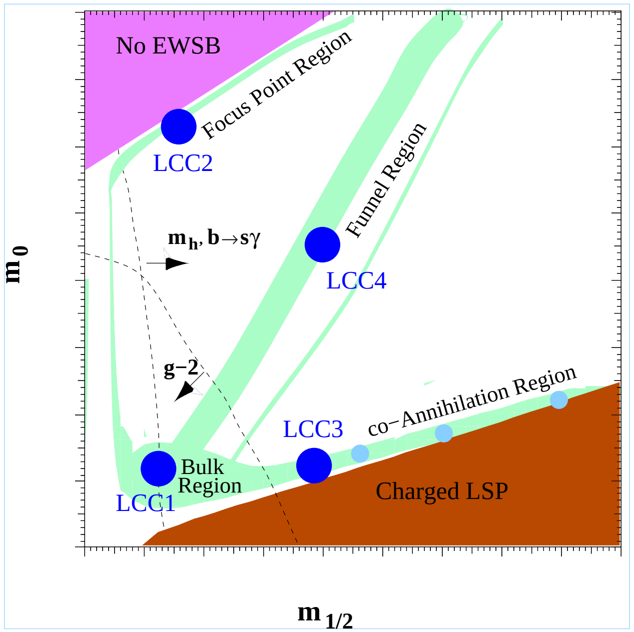
CDM predicted by $\tilde{\chi}\tilde{\chi}$ *etc* annihilation

$\Leftarrow$ 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 $\tilde{\chi}_1^0$:

	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%	3%	2%
LCC2	focus point	$\tilde{\chi}\tilde{\chi} \to WW, ZZ$	$\tilde{V}\tilde{H}$ mix	80%	14%	8%
LCC3	$\tilde{\tau}\tilde{\chi}$ co-ann.	$\tilde{\tau}\tilde{\chi} \to \tau\gamma$	$M[\tilde{\tau} - \tilde{\chi}_1^0]$	176%	50%	18%
LCC4	A funnel	$\tilde{\chi}\tilde{\chi} \to A$	$M_A,\, \Gamma_A$	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% $\to$ 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

sugra coupling determined from lifetime measurements — Buchmüller ea, Martyn

4. SUMMARY

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

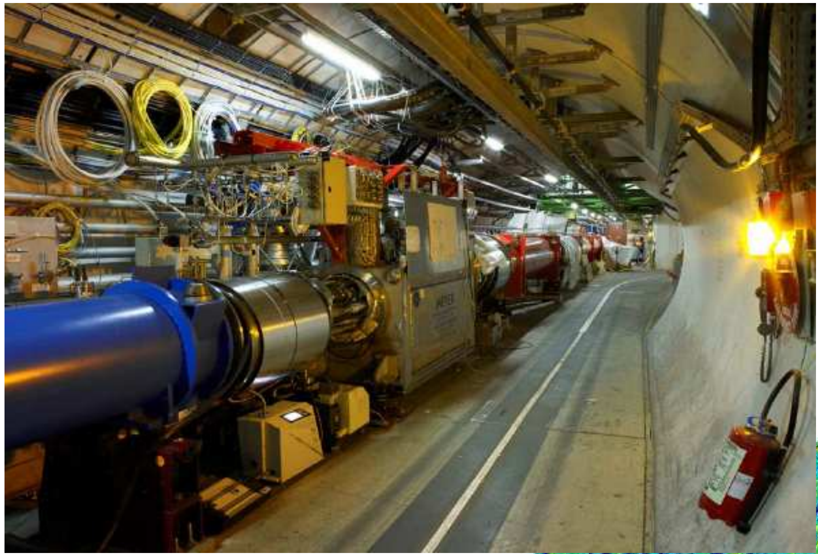
Electroweak Symmetry Breaking: establish Higgs mechanism *sui generis* for generating mass

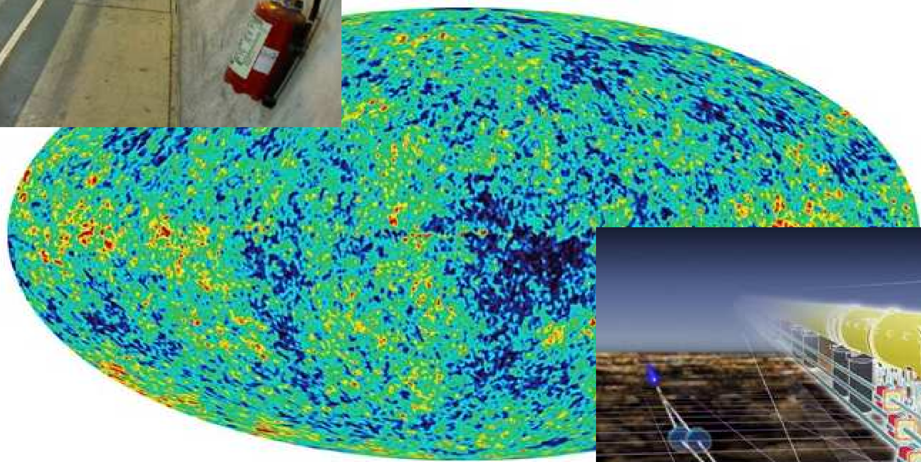
Grand/Ult Unification: comprehensive and high-resolution picture of supersymmetry
LHC$\oplus$ILC $\Rightarrow$ Telescope to *Planck*-scale physics
particle physics $\sim$ gravity $\Rightarrow$ root of physics

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