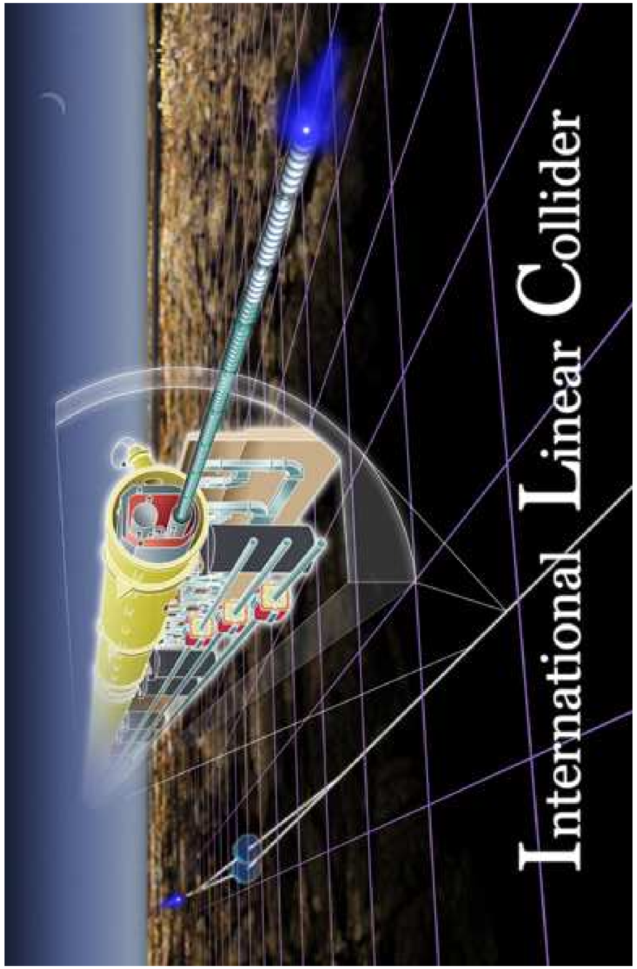


ILC : PHYSICS SCENARIOS

1. Introduction

  – Physics base and exp instruments

2. ILC Physics Targets in Micro-Universe

  – Electroweak Symmetry Breaking

  – Supersymmetry

  – Extra Space Dimensions

3. Cosmology Connection

4. Conclusions

1. INTRODUCTION

HIGH ENERGY PHYSICS: tremendously successful in creating and establishing

STANDARD MODEL OF PARTICLE PHYSICS

⇐ Lykken

Open problems and new questions at short distances ...

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

... and large distances

- Connection with cosmology ⇐ CDM, n_B, ...?

Expectation: *Machines of the next generation will reach experimental solutions of these fundamental problems of nature*

LHC breakthrough discoveries:
– Higgs mechanism
– supersymmetry
– extra space dimensions

ILC add. discoveries and analyses of precision measurements $\Rightarrow$
unraveling underlying laws of nature

- $\sqrt{s}$ up to 500 GeV : light Higgs / light SUSY / top quark / ...
  up to 1 TeV : strong SB / heavy SUSY / extra dimensions / ...
- exp tools:
  – polarization of $e^-[e^+]$ beams [$\leftarrow$ utilizing full precision potential
  – GigaZ mode [$\leftarrow$ ult picture of elw sector
  – e^-e^- | $e\gamma$ and $\gamma\gamma$ [$\leftarrow$ unique complements

2A. ELECTROWEAK SYMMETRY BREAKING

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

$\Downarrow$

strong elw symmetry breaking [LH, higgsless, extra dim, ...]

$\Rightarrow$ *fundamental law of nature for generating mass*

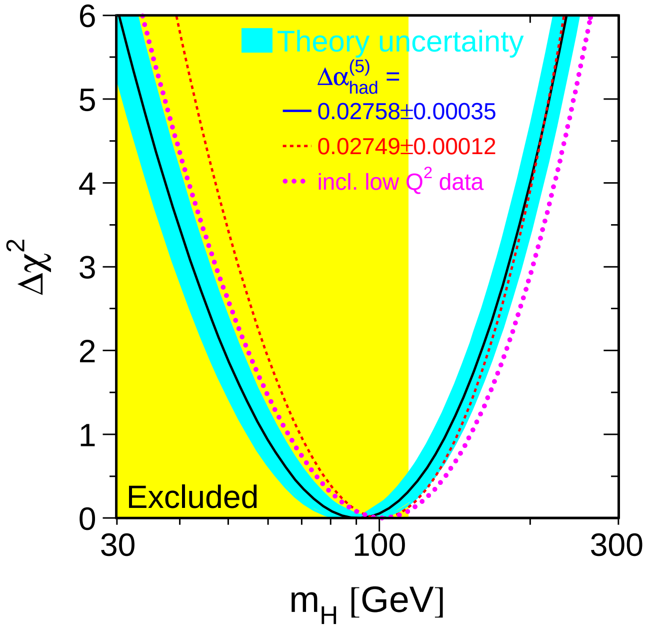
$\Leftarrow$ Dawson

a) SM HIGGS MECHANISM

– cornerstone for completing Standard Model

– light Higgs: suggested by precision data [EWWG:

$$M_H = 91^{+45}_{-32}\ \text{GeV} \mid < 186\ \text{GeV}\ (95\%\ \text{CL})$$

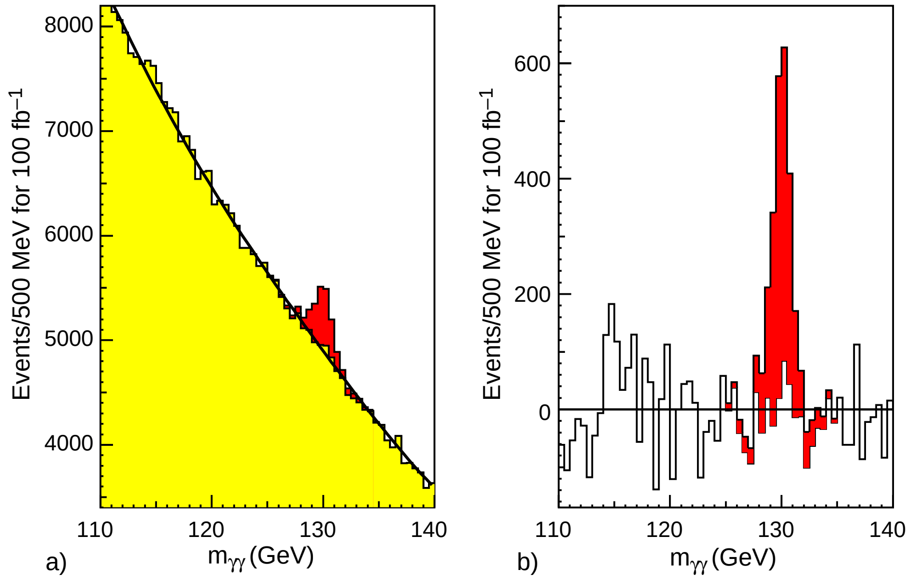


(1) LHC/Tevatron: discover SM Higgs

first analysis steps: Higgs mass

couplings: ratios

CMS $H \to \gamma\gamma$ events :



HIGGS MECHANISM : EXP DISCOVERY PATH

(1) LHC/Tevatron: discover SM Higgs

first analysis steps: Higgs mass $[10^{-3}]$
couplings: ratios

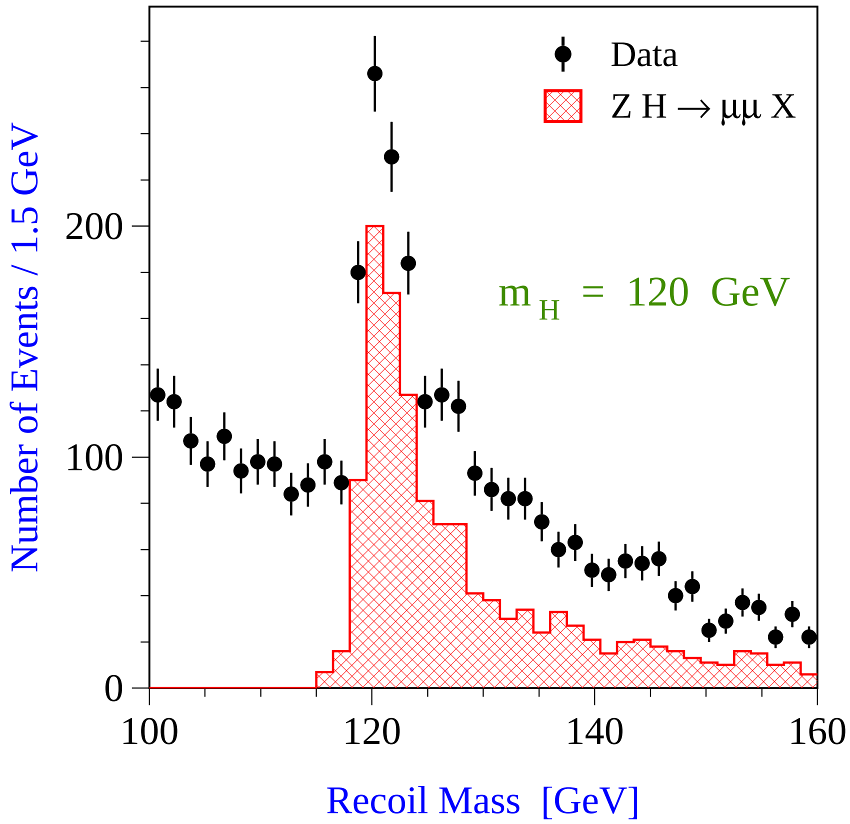
(2) ILC : clean sample of Higgs events

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

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

Higgs profile: mass, spin, ...

couplings : generation of mass
Higgs field in vacuum



Lohmann ea.

ILC HIGGS ANALYSIS

- Higgs couplings / mod.independent

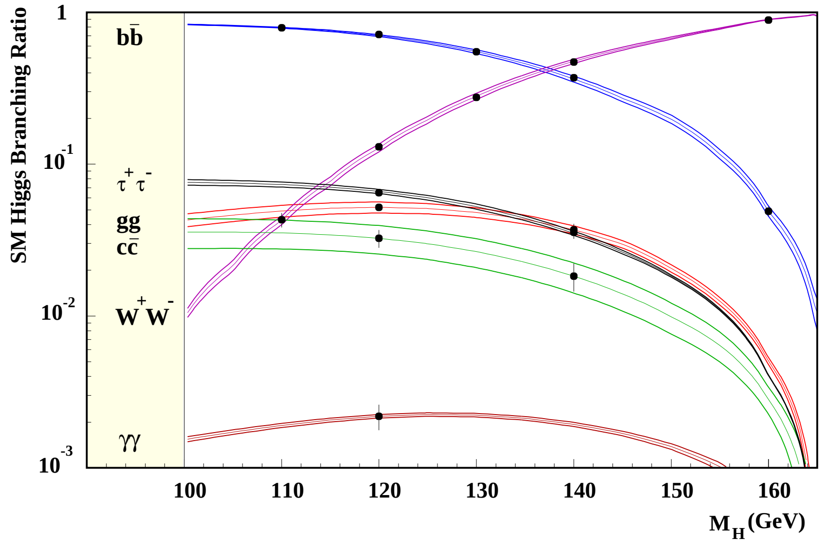
$M_H < 140$ GeV rich: Z, W, t, b, c, τ

$M_H > 140$ GeV red.: Z, W, t

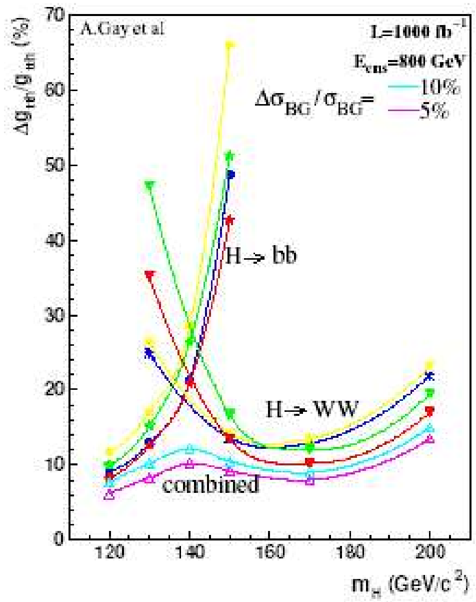
$\Rightarrow$ production cross sections

$\Rightarrow$ decay branching ratios

$\Rightarrow$ Higgs radiation off *top*



F: Battaglia



ILC HIGGS ANALYSIS

- Higgs couplings / mod.independent

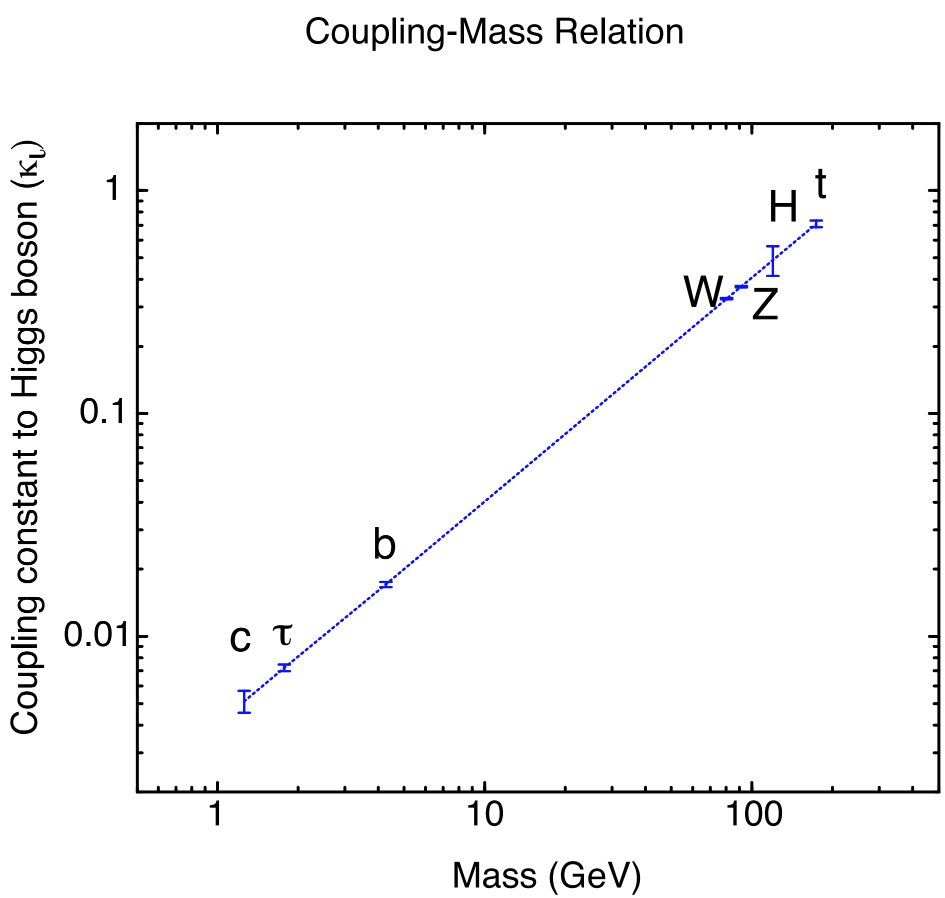
$M_H < 140$ GeV rich: Z, W, t, b, c, τ

$M_H < 140$ GeV red.: Z, W, t

Higgs coupling – mass relation:

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

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



ACFA LC Study

ILC HIGGS ANALYSIS

- Higgs couplings / mod.independent

Higgs coupling – mass relation:

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

- Higgs potential

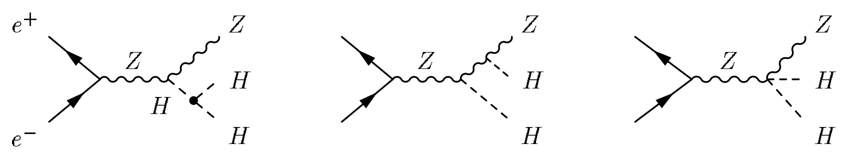
$$V = \frac{1}{2} M_H^2 + \frac{1}{2}\frac{M_H^2}{v} H^3 + \frac{1}{8}\frac{M_H^2}{v^2} H^4$$

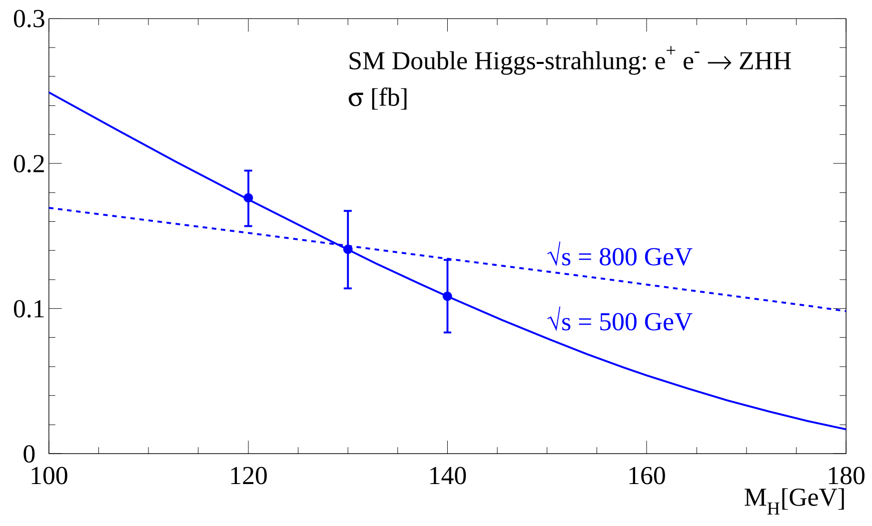
$H^3 \Rightarrow$ non-zero vacuum Higgs field:

measurable to 10% accuracy

for $M_H < 140$ GeV [> SLHC]

$\Rightarrow$ medium for mass generation





Mühlleitner ea | Yamashita (ea)

LHC⊕ILC $\Rightarrow$ essential Higgs elements

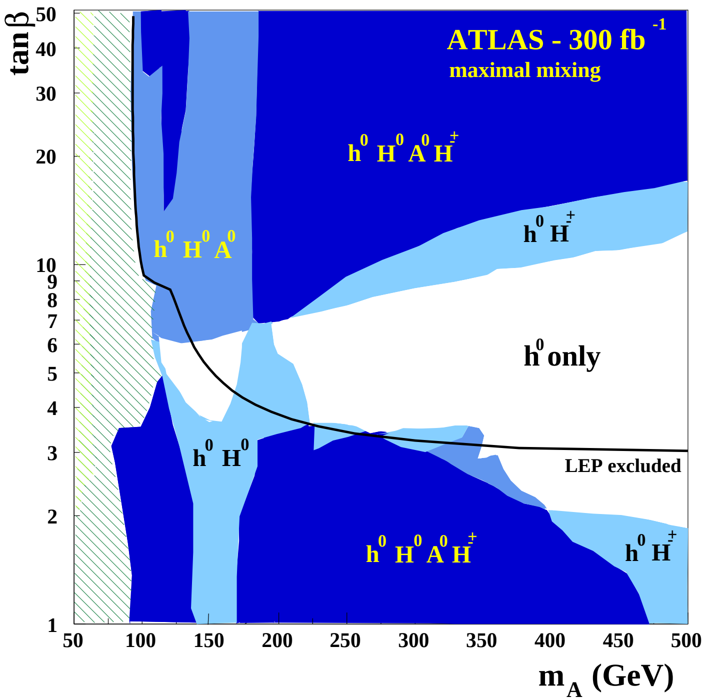
SUSY HIGGS BOSONS

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

h^0 light $\leq$ 140 GeV

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

detection at LHC: tot / wedge



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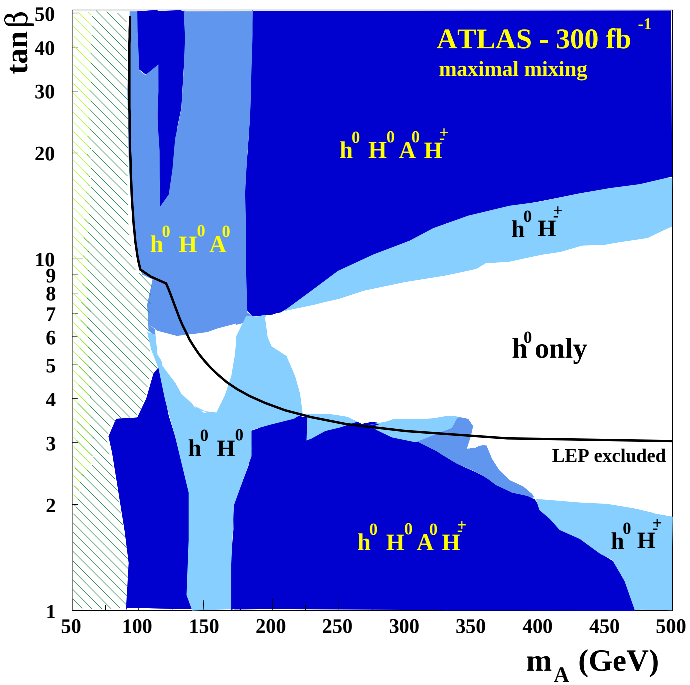
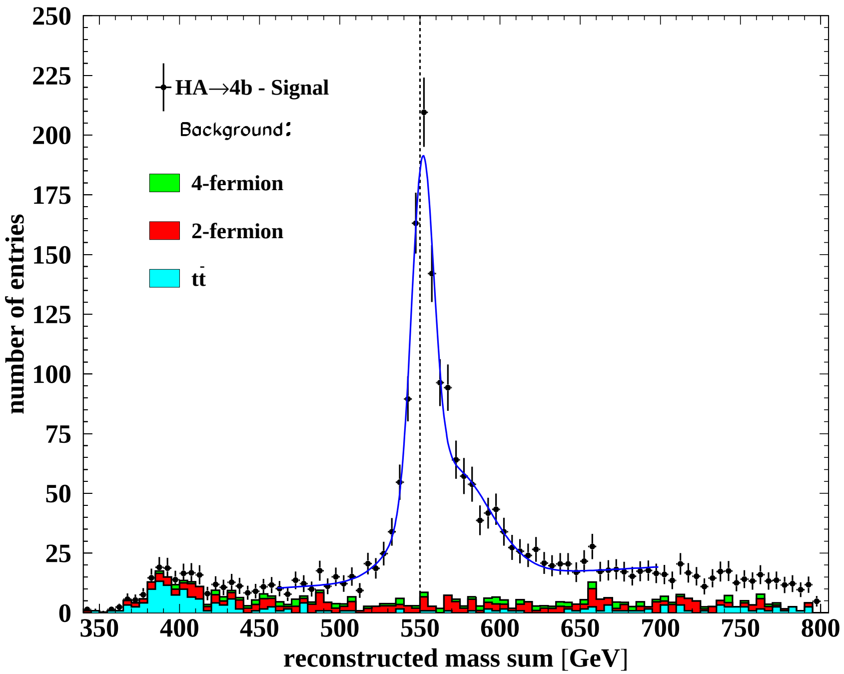


ILC: pairs /w mass up to E_B [Desch ea]



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h^0 light $\leq$ 140 GeV

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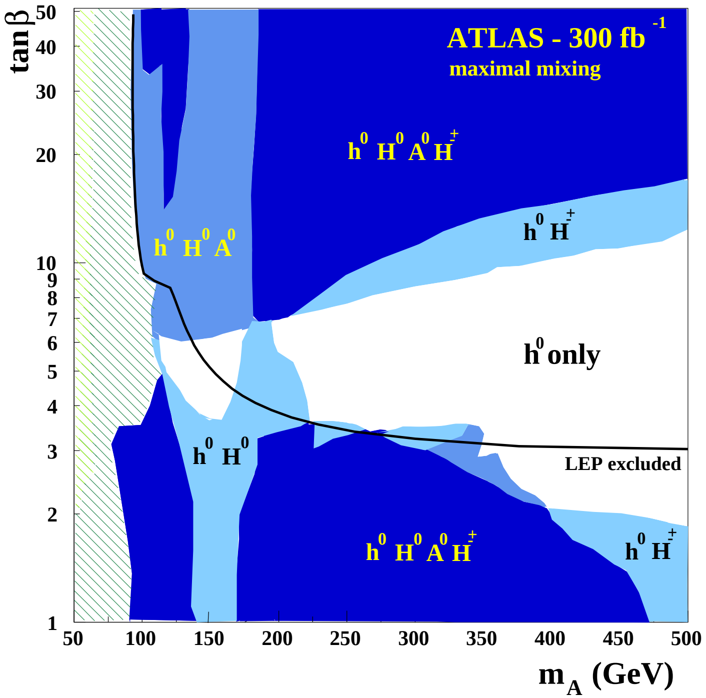
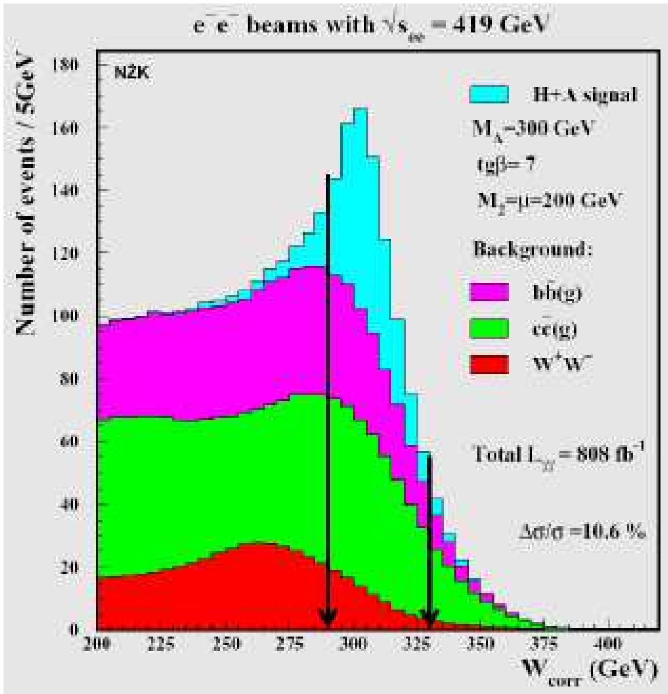
detection at LHC: blind wedge

$\gamma\gamma \to H, A$: 30% [Mühlleitner ea, Gunion ea, F: Niezurawski ea]





STRONG ELW SYMMETRY BREAKING

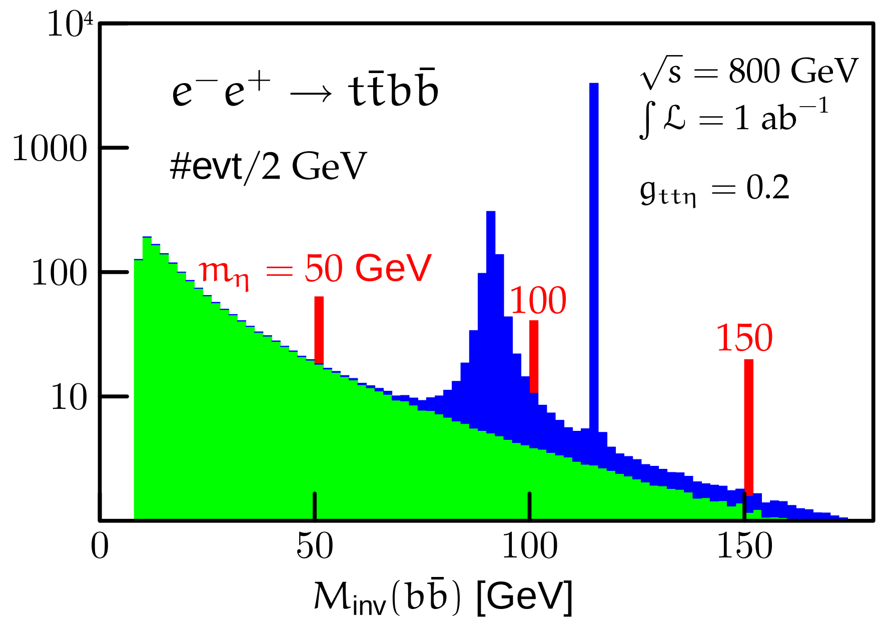
- LITTLE(st) HIGGS

  Higgs $\Leftarrow$ *Goldstone boson*
  to SB of large symmetry group

  rich spectrum of new particles $O(\mathrm{TeV})$ +

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

  F: Kilian, Rainwater, Reuter



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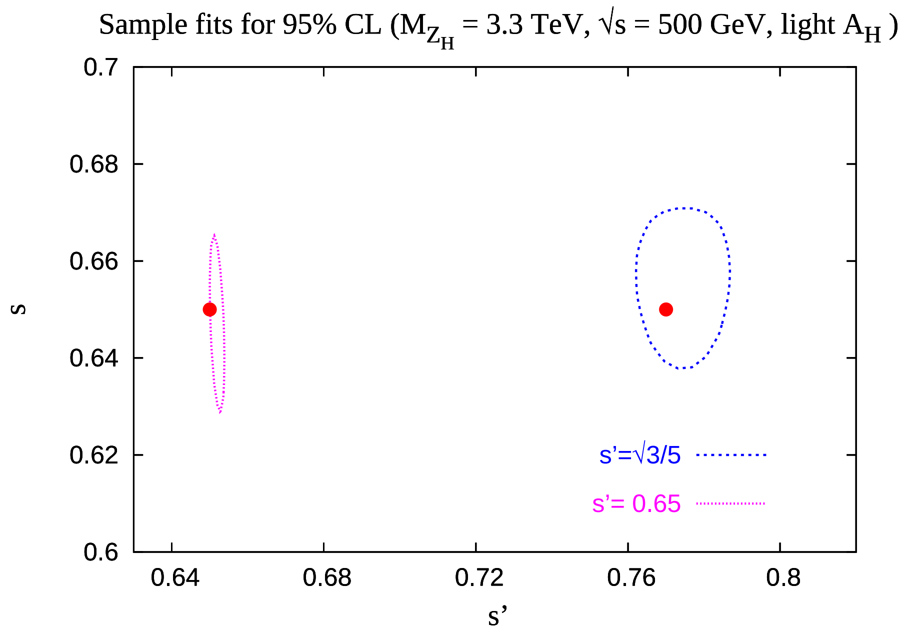
  rich spectrum of new particles $O(\text{TeV})$ +

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

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

  masses known from LHC :
  ILC determines model specific cplgs $\Rightarrow$

  F: Conley, Hewett, Le



STRONG ELW SYMMETRY BREAKING

- LITTLE HIGGS

  Higgs $\Leftarrow$ *Goldstone boson*
  to SB of large symmetry group

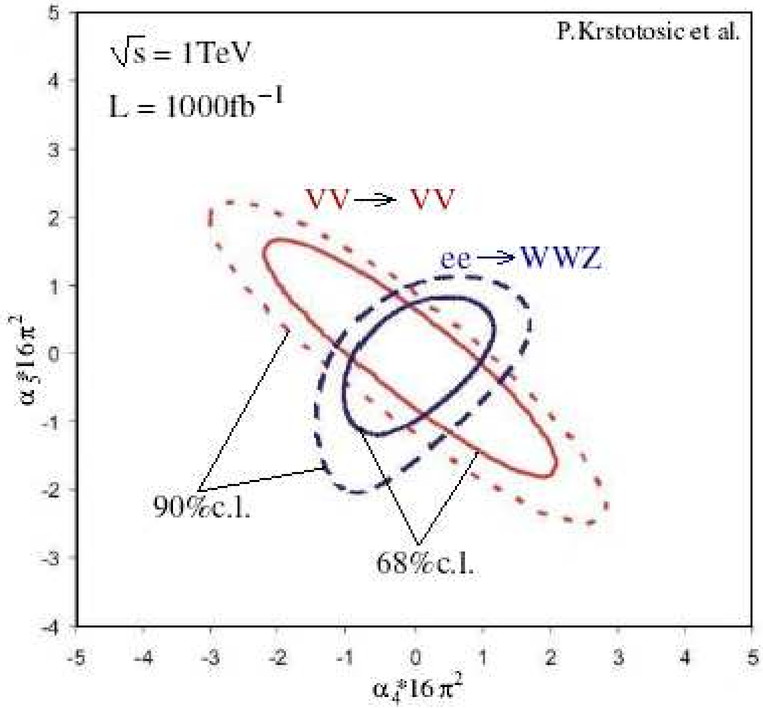
- STRONG WW INTERACTIONS

  no light Higgs boson $\Rightarrow$
  $D = 4$: strong WW interactions $\sqrt{s} = 1$ TeV

  processes : $e^+e^- \rightarrow \bar{\nu}\nu\, WW$
  $e^+e^- \rightarrow \bar{\nu}\nu\, ZZ$ F: Krstotosic ea

  sensitivity : across entire threshold region

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



STRONG ELW SYMMETRY BREAKING

- LITTLE HIGGS

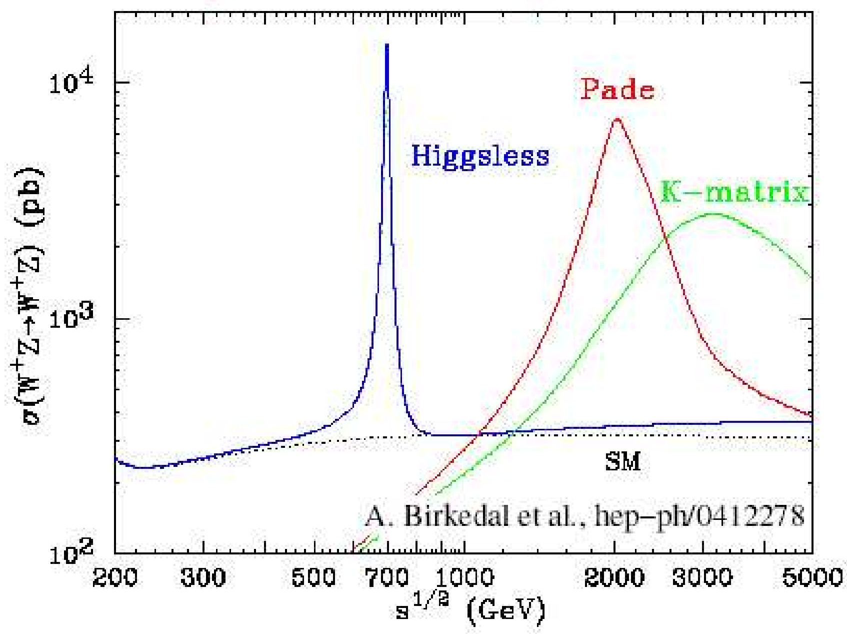
Higgs $\Leftarrow$ *Goldstone boson*
to SB of large symmetry group

- WZ RESONANCE

Higgsless models in Extra Dimensions
$\Rightarrow$ formation of WZ resonance

processes : $e^+e^- \to \nu e + WZ$
$e^+e^- \to W + WZ$

LHC $\Rightarrow$ mass | ILC $\Rightarrow$ spin and couplings



COMMENTS: Precision in Higgs Sector

coupling ZZH to 1% $\Rightarrow$ New Physics scales probed up to 3 TeV

coupling HHH to 10% $\Rightarrow$ New Physics Higgs scales probed up to 1 TeV

$\Leftarrow$ *not necessarily accessible directly at LHC*

$\mathcal{Q}$

SUSY Higgs physics:

MSSM *quantum loop relations*:

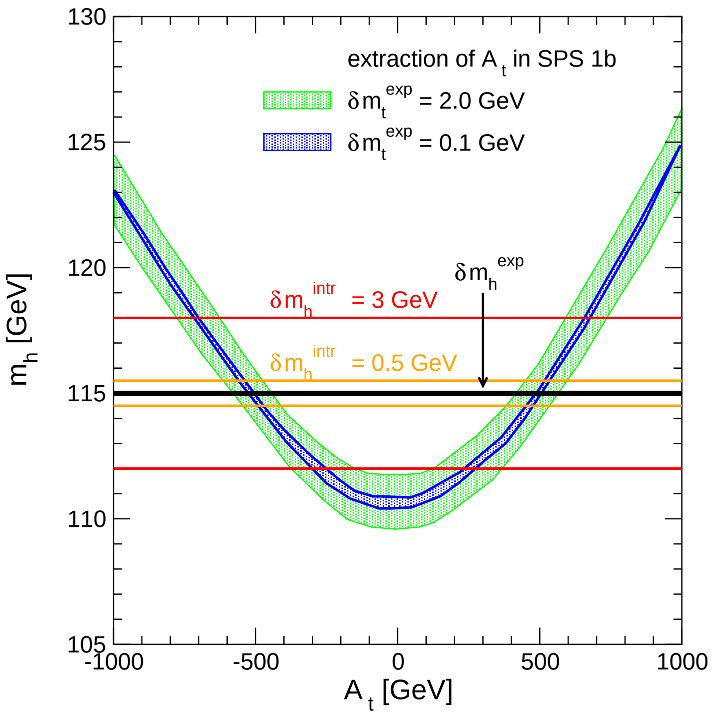
Higgs mass : $\delta m_h = 50\,/\,500$ MeV

top mass : $\delta m_t = 100$ MeV

$\Rightarrow$ new parameter determination

[Higgs-stop-stop cplg, M_A, ...]

F: Heinemeyer, Hollik, Weiglein



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coupling ZZH to 1% $\Rightarrow$ New Physics scales probed up to 3 TeV

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$\mathcal{Q}$

Complexity in Higgs Sector

Little Higgs, ...

SUSY: non-min scenarios [gut, string, ...] : $N \geq 7$ Higgs fields ...

$\Leftarrow$ e^+e^- *exp with well defined kinematics, resolve and analyze such complex phenomena*

SUMMARY / HIGGS

- *In standard scenarios of electroweak symmetry breaking [SM, MSSM] ILC provides a comprehensive and high-resolution picture of mass generation – adequate for this fundamental mechanism*
- *In non-standard scenarios of electroweak symmetry breaking [ext SUSY,...] phenomena are so complex that ILC clearly necessary to resolve the microscopic picture*

2B. SUPERSYMMETRY

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

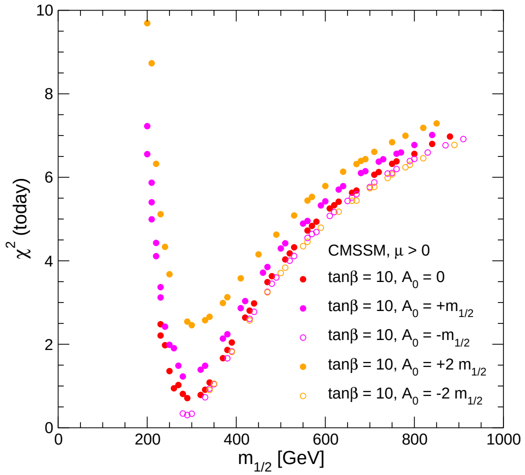
– generating and stabilizing light Higgs boson

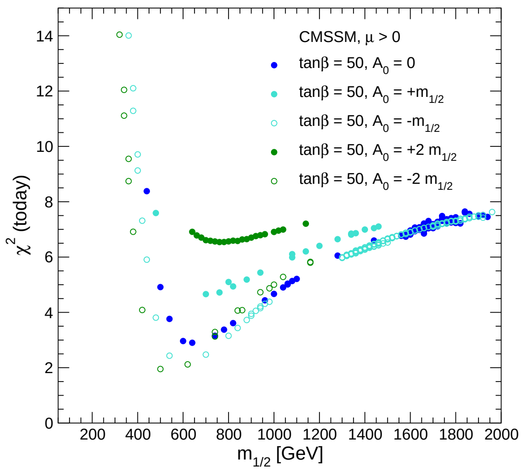
– strongly supporting unification of gauge couplings / paving path to gravity

– providing candidate particle for Cold Dark Matter component

MASS SCALE : no firm prediction

LE data + CDM : preference (slight) for low mass spectrum





Ellis, Heinemeyer, Olive, Weiglein

2B. SUPERSYMMETRY

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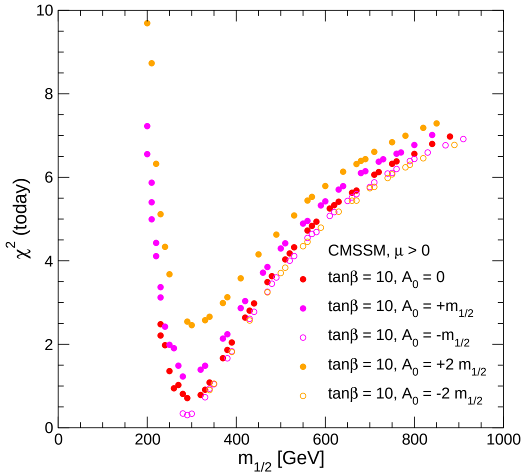
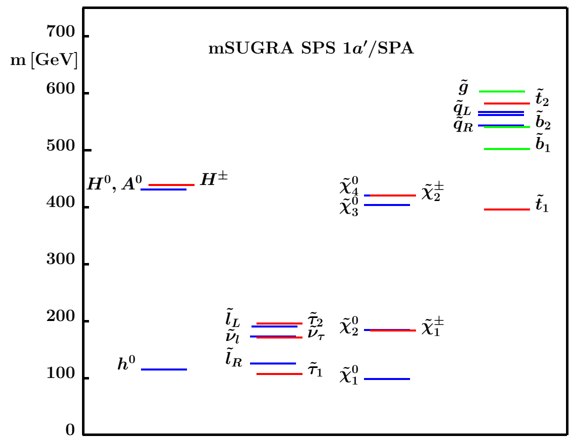
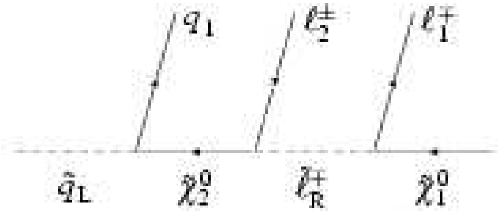




Weiglein:LHC/ILC

LHC discovery sensitivity: 2.5 to 3 TeV [early 10 fb^{-1} : 1 to 1.5 TeV

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

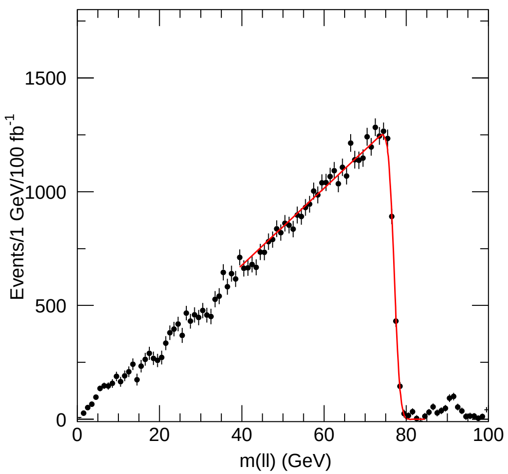


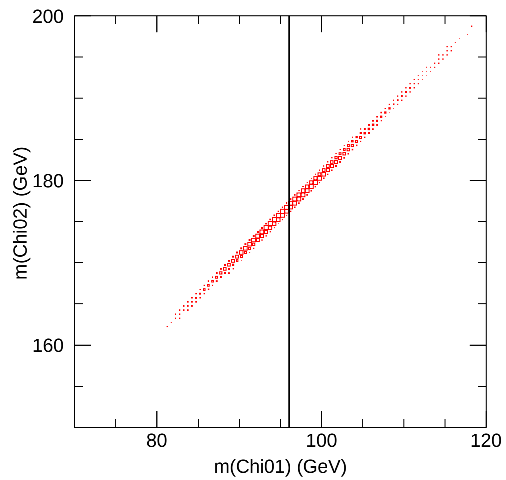
/ 30 / 12 / 100%

a) not all *non-colored light* particles *i.g.* detected

b) invariant masses $\Rightarrow$ edges $\Rightarrow$ particle mass [-differences]

masses strongly correlated [with invisible lightest neutralino]





ILC $\Rightarrow$

LHC discovery sensitivity: 2.5 to 3 TeV [early 10 fb^{-1} : 1 to 1.5 TeV

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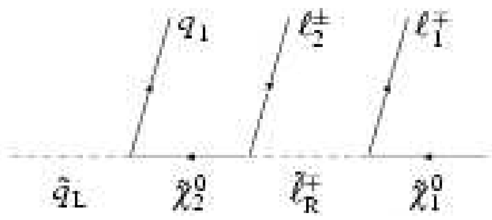

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b) invariant masses ⇒ edges ⇒ particle mass [-differences]

masses strongly correlated [with invisible lightest neutralino]

⇓

ILC determines the essential light non-colored part of spectrum:

⇒ climbing up LHC chain: entire susy world reconstructed

⇒ precision measurements of particle properties:

particle mass, spin, q-number, wave-function, couplings

MASSES at ILC

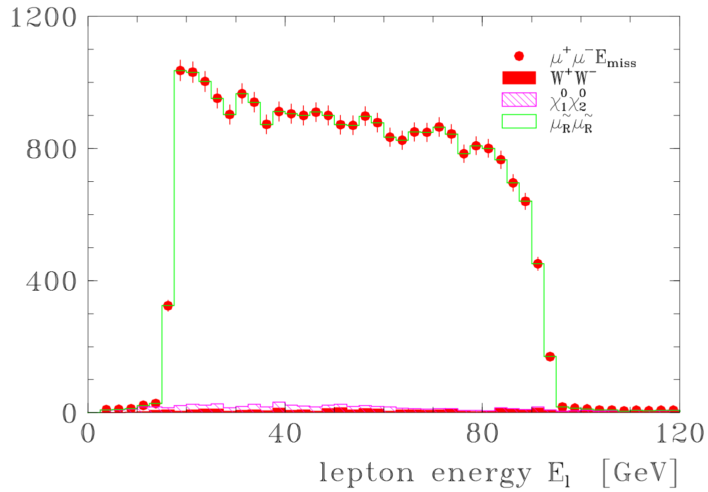
a) Edge effects: $\tilde{\mu}_R \rightarrow \mu + \tilde{\chi}_1^0$

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

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

F: Martyn

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



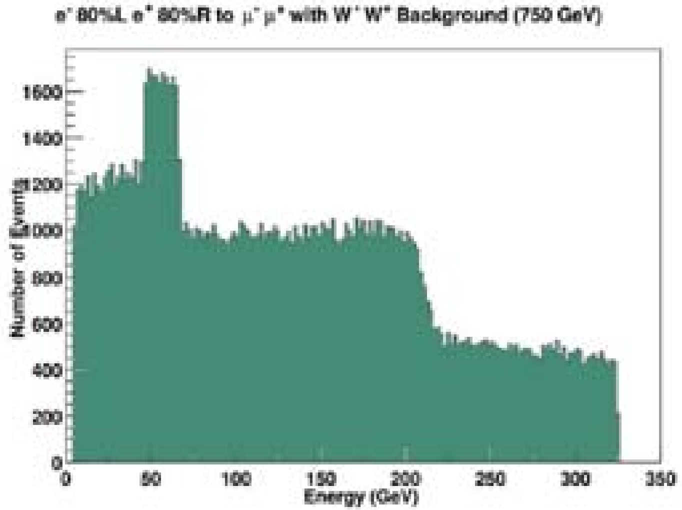
b) Support by e^+ and e^- polarization:

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

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

$WW \rightarrow \mu\mu$ bkgd hel suppr.

F: Nauenberg ea



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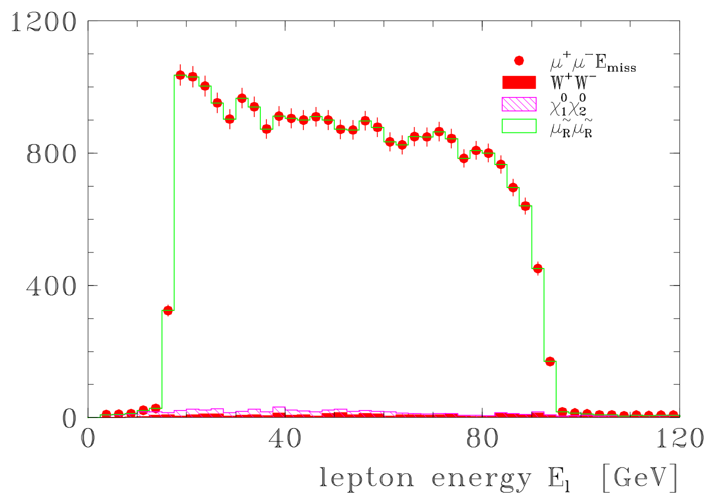

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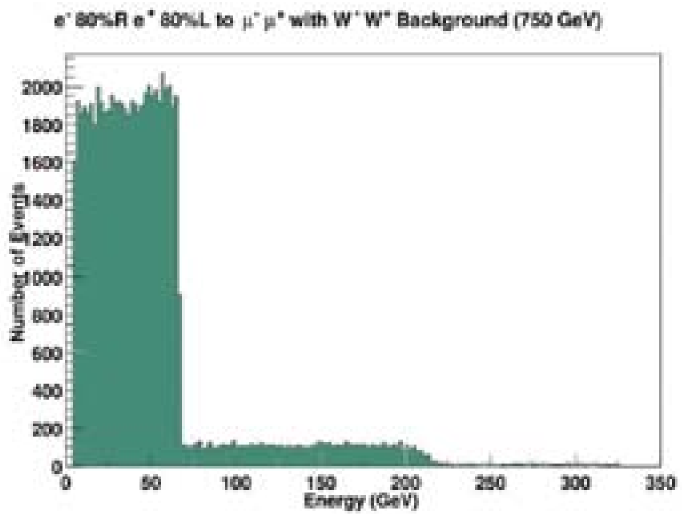
$WW \to \mu\mu$ hel suppr. $\Rightarrow$



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F: Martyn

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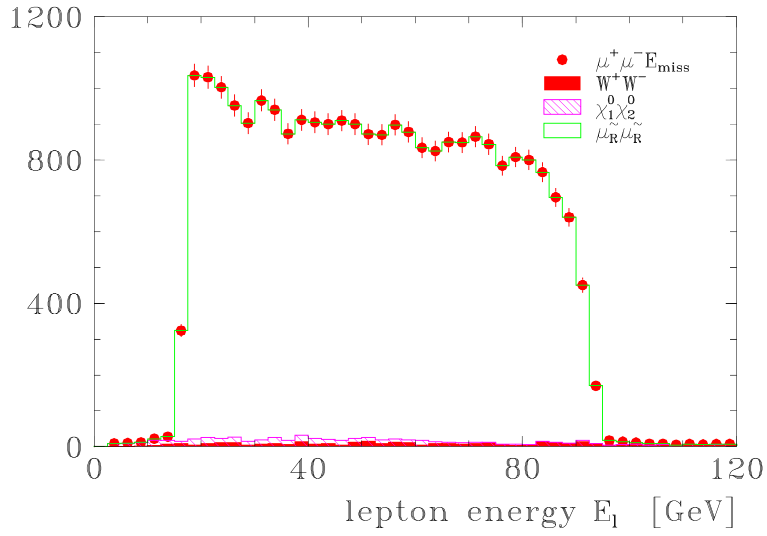


c) Threshold excitations:

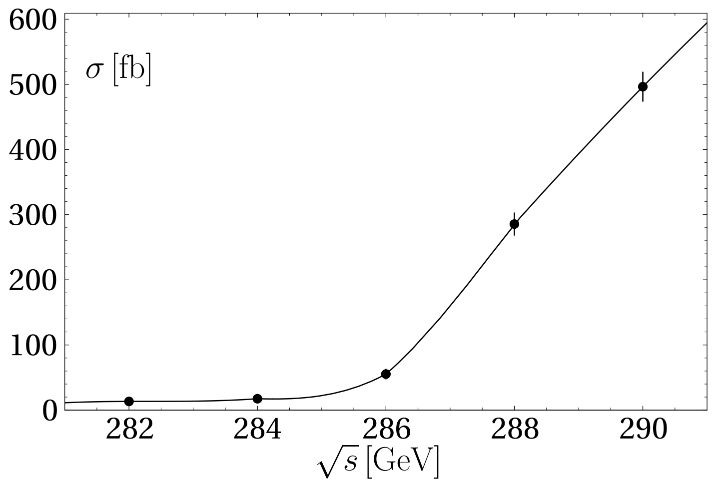
$$e^+e^- \to \tilde{\mu}_R^+ + \tilde{\mu}_R^- \to \mu^+\mu^- + E_{miss}$$

P-wave: slow β^3 rise

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

S-wave: fast β rise [imp ~ 3]

Feng, Peskin | F: Freitas ea



Summary [Allanach ea]:

LHC+ILC

Coherent LHC+ILC analyses completed / resolution increased significantly

SFITTER

Lafaye, Plehn, Zerwas.D

FITTINO

Bechtle, Desch, Wienemann

$\mathcal{SPA}$ Project

+ Benchmarks

	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

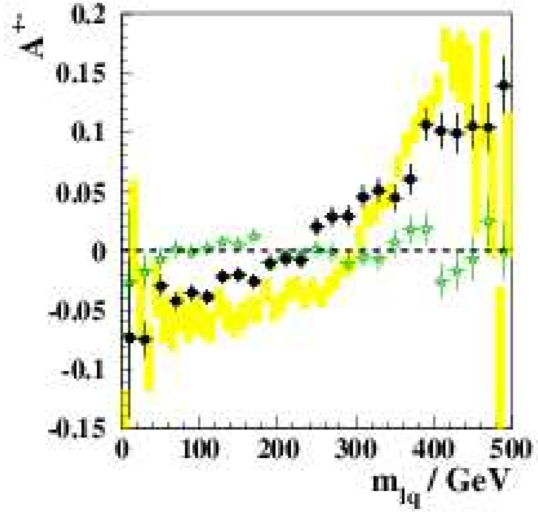
SPIN at ILC

a) LHC: spin correlations

SPA-chain / spin corr : inv masses distorted

$[\ell^+ jet]$ diff $[\ell^- jet]$ distribution: not p specific

difficult analysis   F: Barr ⇒



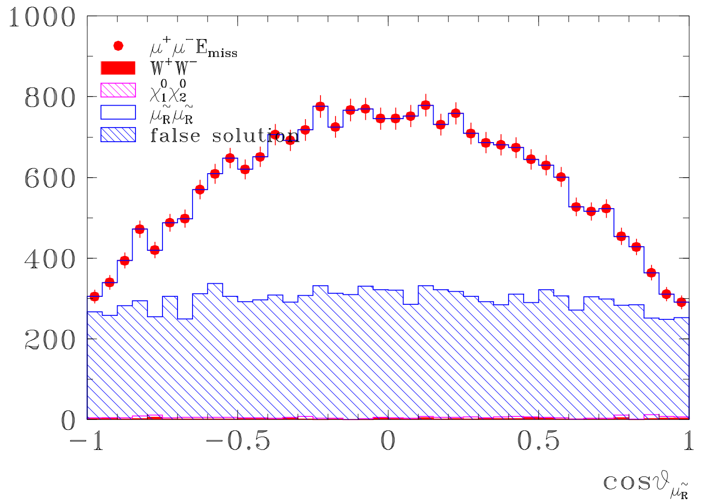
b) ILC: angular distribution

production angle : $e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$

rec. from $\mu^+\mu^- + E_{miss}$

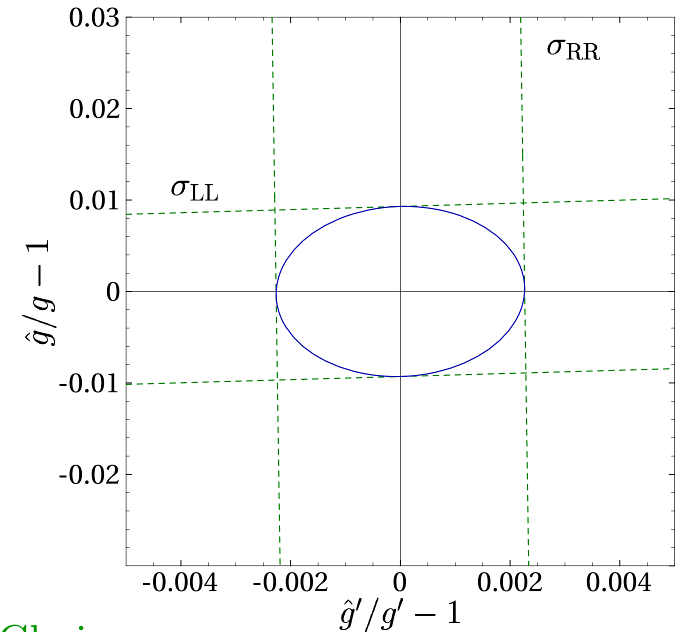
asymptotically $\to \sin^2\beta$

F: Martyn



COUPLINGS ... at ILC

SUSY id: Yukawa = gauge cplgs



Choi ea

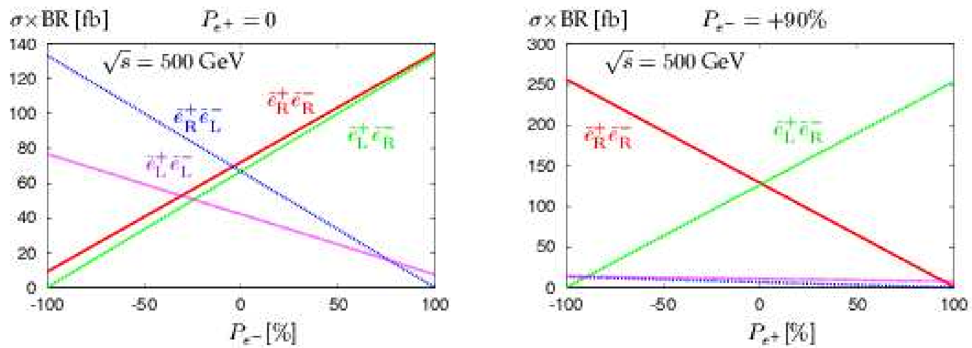
q-numbers / mixings

Moortgat-Pick Rpt

e^- polarization crucial for analysis

e^+ polarization increasing accuracy

crucial in some scenarios :



SUMMARY / SUSY

1. LHC/ILC: *complementary coverage of susy particle spectrum*
2. prim.ILC : *precise profile of particles* $\Rightarrow$ *SUSY exp proven !*

EXTRAPOLATION TO GUT SCALE

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

Extrapolation to high scale [RGE]:

- 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

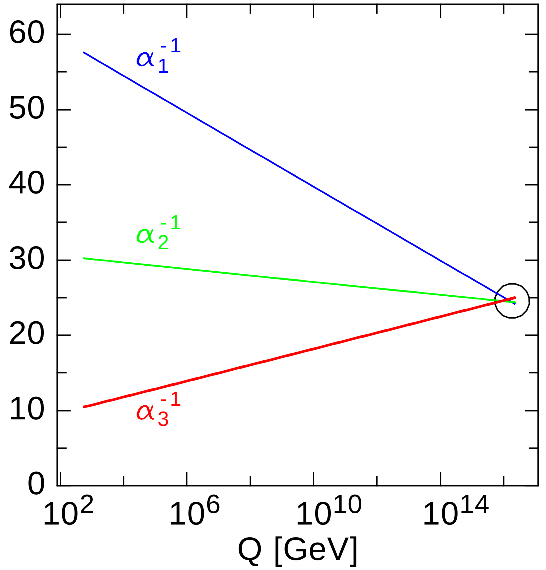
GAUGE COUPLINGS

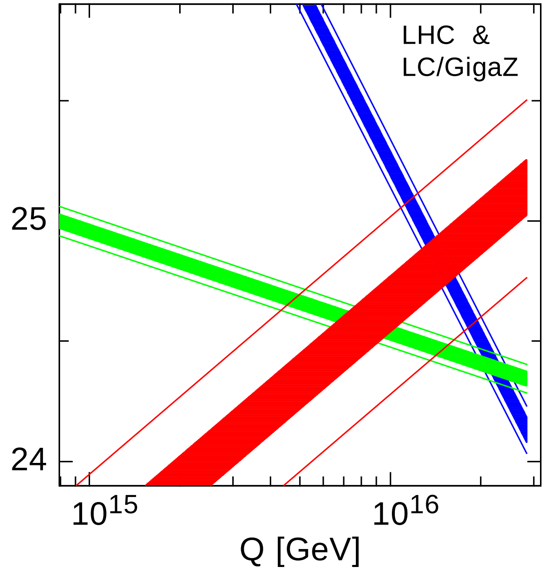
Evolution: present elw/strong gauge couplings $\oplus$ SUSY threshold corr $\sim$ LHC

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

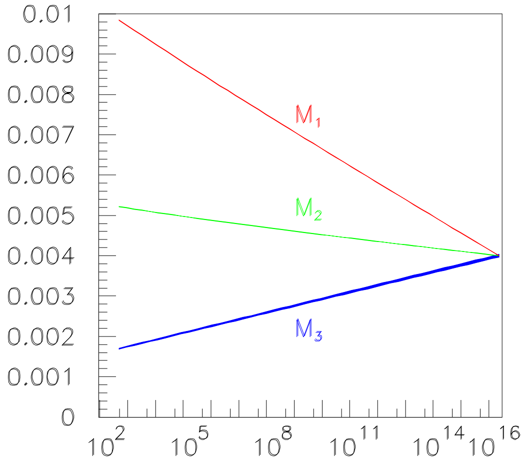
UNIVERSALITY : MASSES AND SUSY BREAKING

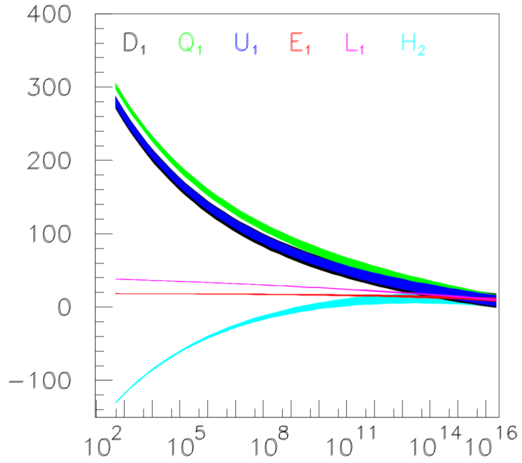
Evolution :

Gaugino / scalar masses

universal in mSUGRA

F: Allanach, Blair, Porod, ea

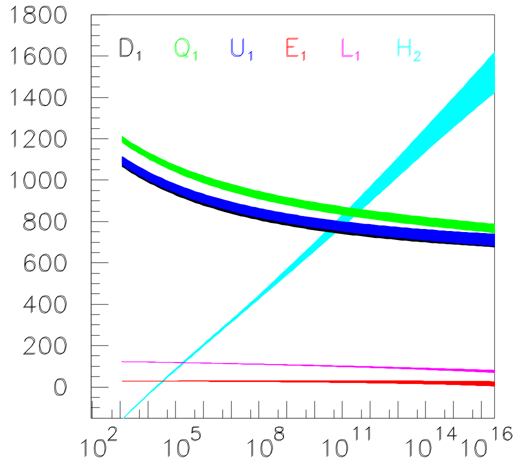




Scalars in GMSB

evolution distinctly different $\Rightarrow$

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



INTERMEDIATE SCALE : Z' BOSON

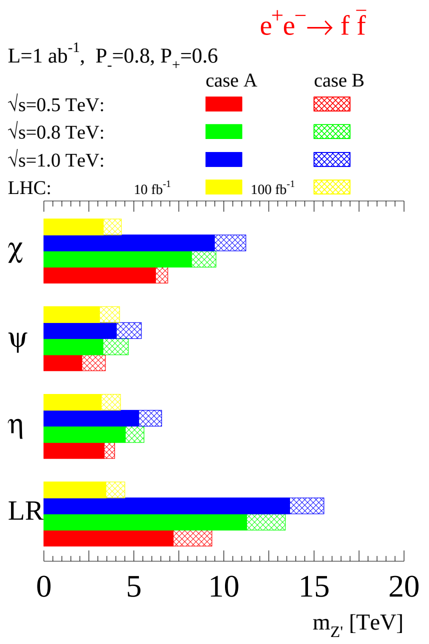
Heavy Z' vector boson motivated by TeV scale remnants of grand unified theories, string theories etc

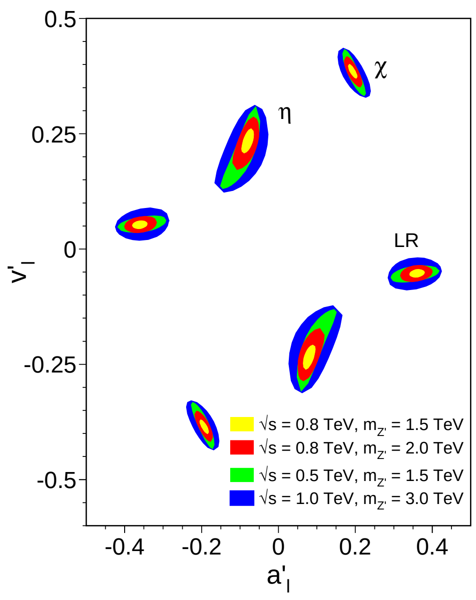
Examples : Z' in SO_{10}, E_6 : LHC : $M_{Z'}$ up to $\sim$ 5 TeV

ILC : virtual extension up to 15 TeV

Z' couplings to fermions etc

Riemann.S



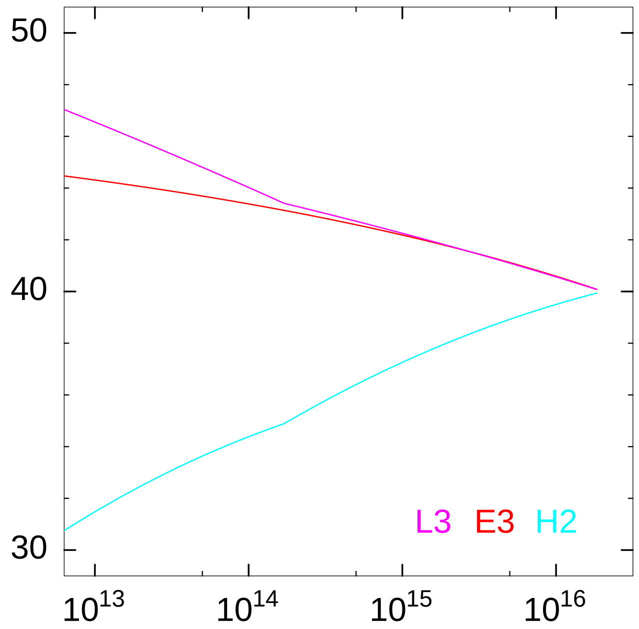


INTERMEDIATE SCALE : SEE-SAW IN ν PHYSICS

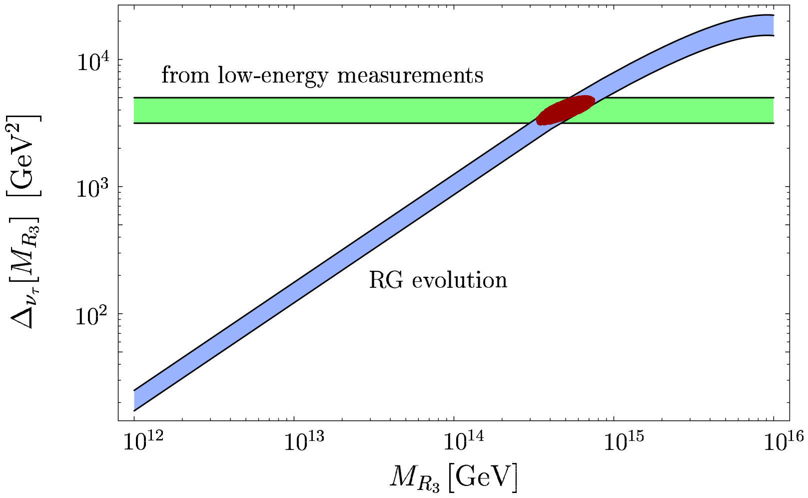
Example : neutrino mass generated by see-saw mechnism $\Rightarrow$

intermediate see-saw scale $M[\nu_R] \sim 10^{10}/10^{14}$ measurable ? "qualified yes"

Seesaw-scale affects evolution of $\tilde{\tau}/\tilde{\nu}_\tau$ masses in third generation :



F: Blair, Freitas, Porod, ea



$M_{\nu_{R3}} \sim 10^{14}$ GeV at 30% level

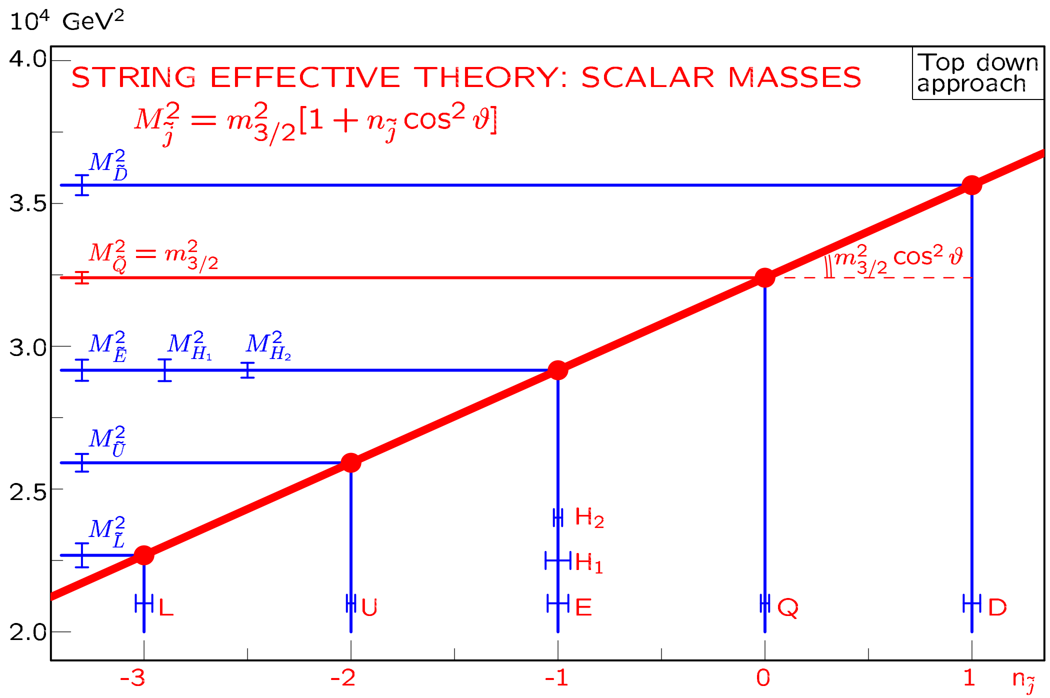
STRING EFFECTIVE THEORIES

$\mathcal{Q}$

Scenario : string effective theory :: heterotic string / orbifold compactification

scalar Masses (n-univ) : $M^2_{\tilde{j}} = m^2_{3/2}[1 + n_j \cos^2\theta] + \ldots \;\; (n_j \text{ integ})$

"SUSY Chew-Frautschi Plot"



$\Leftarrow$ stringent test of integer modular weights

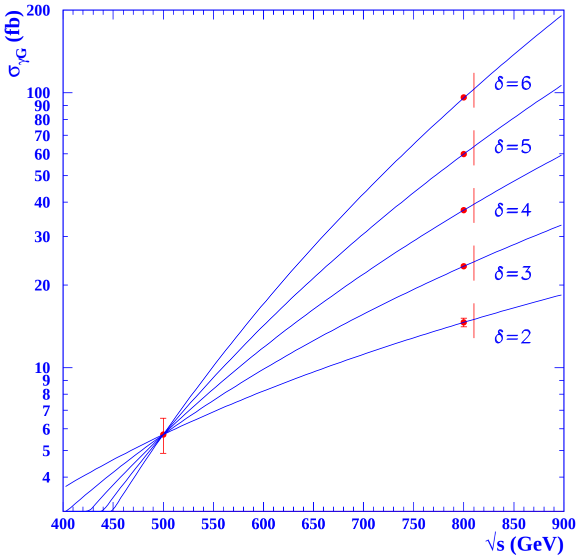
2C. EXTRA SPACE DIMENSIONS

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

ADD: flat geometry : $\Lambda_{Pl} \sim$ TeV range $\Rightarrow$ 0.5 to 8/3 TeV

$\delta = dim - 4$

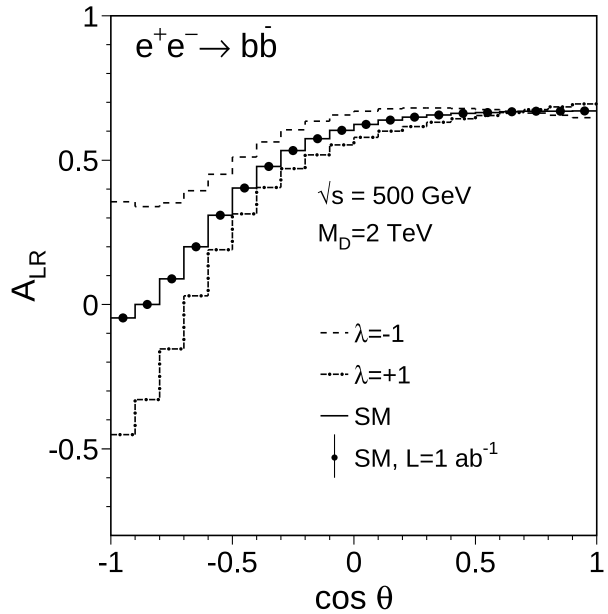
$e^+e^- \to \Sigma KK_G + \gamma$



Wilson.G

crucial: variation of energy

$e^+e^- \to f\bar{f}$: $S = 2$ CI



Riemann.S

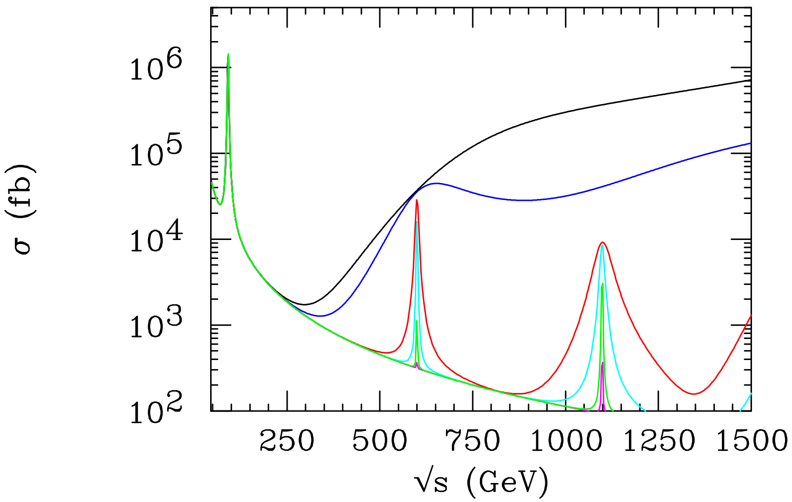
2C. EXTRA SPACE DIMENSIONS

essential element: gravity extends to higher dimensions

RS: warped geometry : *curvature* k

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

excitation of KK_G towers



Hewett ea

Many other phenomena:

- high precision analysis of mixing between KK states and standard states
  [vector bosons, fermions, ...]
- mixing of scalar radion field with Higgs field
- spin measurements of KK states

...

3. COSMOLOGY CONNECTION

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

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

$\Leftarrow$ Feng

Baryon Asymmetry

- LEPTOGENESIS : CP violation in heavy ν_R sector

  $\Leftarrow$ mass determination $M[\nu_R]$

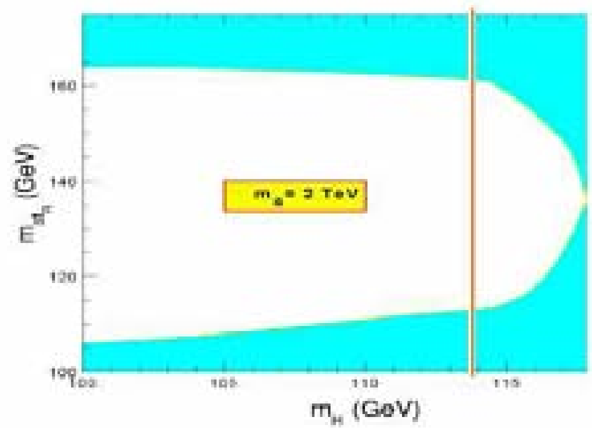
- SUPERSYMMETRY: 1st phase transition:

  light $\tilde{t}_R$ and Higgs mass

  $\Leftarrow$ 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 various theoretical approaches ⇒

CDM = mixture of different components / complex structure ?

– supersymmetry: lightest neutralino ⇐
gravitino ⇐

– extra dimensions: KK states, ...

■ NEUTRALINO CDM:

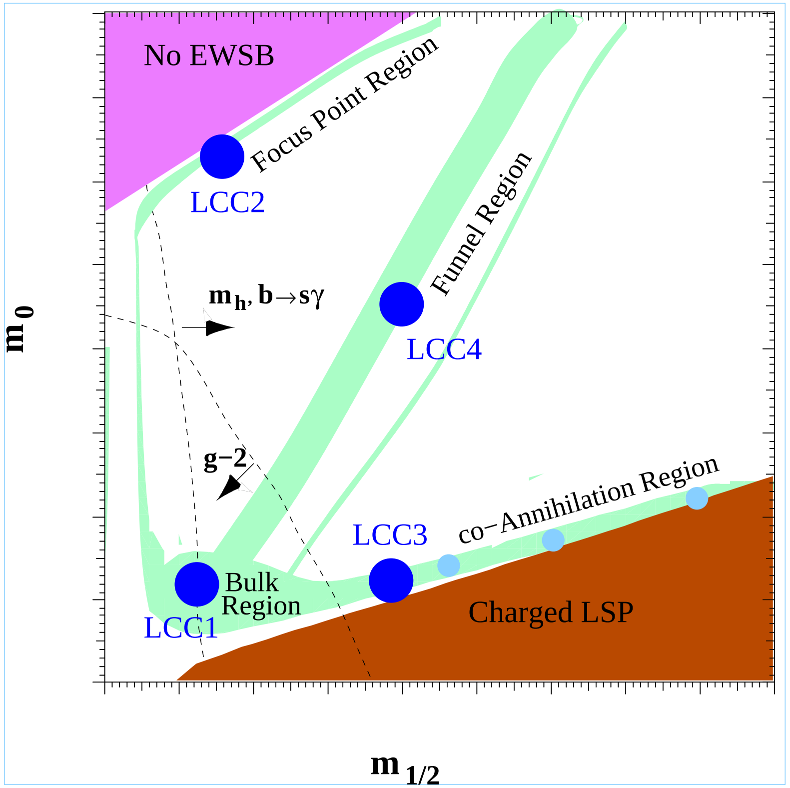
area in mSUGRA param ∼ octopus

[most areas very difficult to control at LHC]

ILC: systematics : LCC collaboration $\mathcal{Q}$

[Bambade ea; Martyn; Baer ea]

LCC2 focus point ⇒



Many candidate particles in various theoretical approaches $\Rightarrow$

CDM = mixture of different components / complex structure ?

– supersymmetry: lightest neutralino
  gravitino

- NEUTRALINO DM:

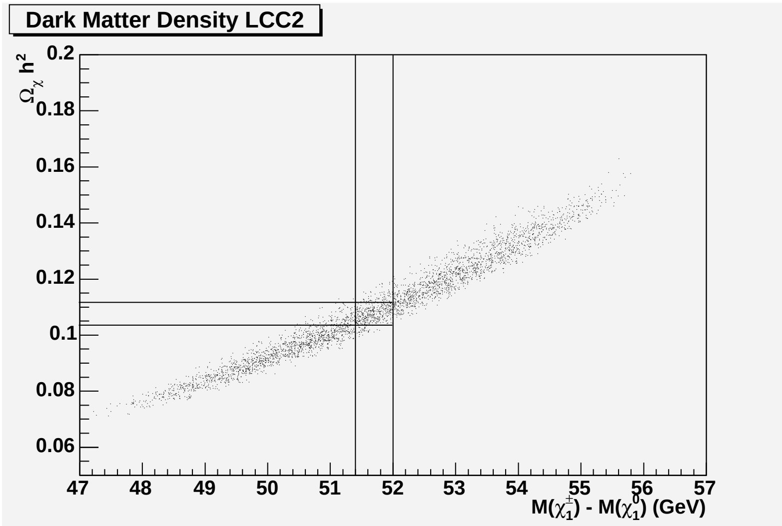
LCC2 focus point: $\tilde{\chi}\tilde{\chi} \to WW, ZZ$

Ω_χ depdg on mass differences:

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

$$\Omega_{cdm} h^2 = 0.109 \pm 3.5\%$$

WMAP $\to$ *Planck* exp : 10% $\to$ 2%



Comment: galactic γ spectra EGRET: excess over conventionally expected yield   de Boer ea

candidate : $\tilde{\chi}\tilde{\chi} \to bb \to \pi^0 \to \gamma \Rightarrow M_\chi \sim 50$ to 100 GeV | $M_{scal} \sim 1$ TeV

conclusion dep crucially on conventional bkgd: under sufficient control?

GLAST: $\chi\chi \to \gamma\gamma$ model-independent endpoint-peak : exp decisive

- GRAVITINO CDM: Feng ea, Buchmüller ea, Hamaguchi ea, Ellis ea

$\tilde{G}$ lightest supersymmetric particle : GMSB $\sim$ MeV or less
SUGRA $\sim$ 100 GeV

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

GMSB : microscopic but possibly visible decay length

SUGRA: macroscopic lifetime [up to months!]

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

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GMSB : microscopic but possibly visible decay length

SUGRA: macroscopic lifetime [up to months!]

SUGRA program :

– mass $\tilde{\ell}$ from track in detector: $e^+e^- \to \tilde{\ell}\tilde{\ell}$

– mass $\tilde{G}$ from decay of stopped $\tilde{\ell} \to \ell\tilde{G}$

– lifetime from stopped $\tilde{\ell}$ decay

– spin $S[\tilde{G}] = 3/2$ from rad decay distributions

Super-gravity : *Planck* mass can be determined from $\tilde{\ell}$ lifetime

Particle Physics – Cosmology strategy

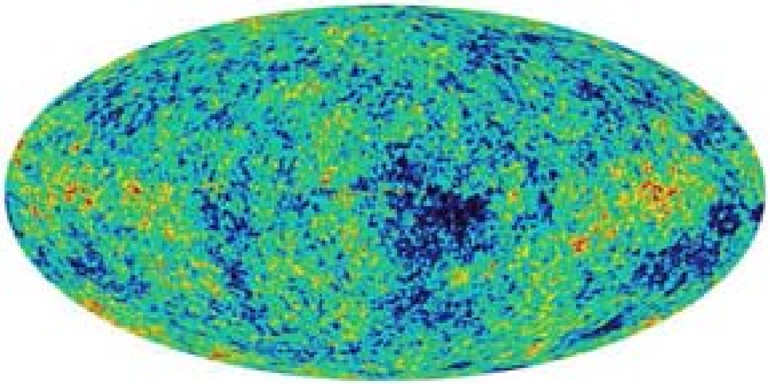
1. Establish cold dark matter particle at LHC

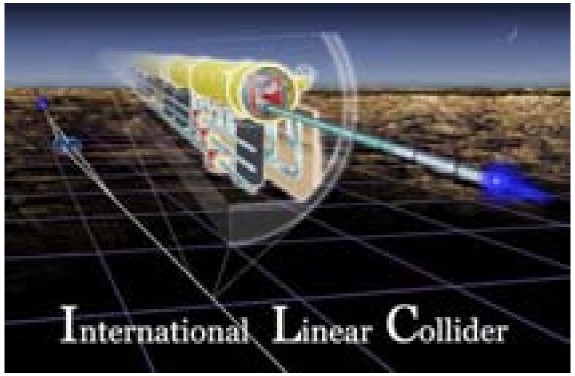
2. Determine its profile and nature in precision ILC experiments

3. Predict Cold Dark Matter Density [and search experiments]

4. Use as tool for mapping CDM distribution in Universe

$\Rightarrow$ matching of high energy physics and astrophysics/cosmology





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 properties and interactions of CDM particle:
establishing CDM nature
and tool for mapping CDM structure of Universe

... and lead us to unravel the underlying laws of nature