Physics of the Linear Collider

The Role of the Linear Collider

Driving Physics
- Higgs or no Higgs ?
- Supersymmetry
- Extra Dimensions
- Top

Conclusion

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Introduction

Success of the Standard Model

Describes matter and interactions of observed particles consistent up to Planck scale

<u>but:</u>

The SM is unstable:

Higgs mass not protected against very large corrections

$200^2 = (10^{19})^2 - (10^{19})^2$ strange…

The SM is incomplete:

95% of the total energy of the universe does not appear in the SM!

and

The SM Higgs boson hasn't been found yet

clear motivation to look beyond – how?

Introduction

Variety of very different experimental approaches is successful and necessary

- Astrophysics (SN, CMB, cosmic rays, WIMP searches)
- Neutrino Physics (cosmic, solar, atmospheric, reactors, accelerators)
- High precision experiments at low energy (B-Factories, g-2, $\mu \to e\gamma$, …)

- Colliders! They play a central role: high energies and high precision

Synergy of accelerator and non-accelerator experiments,

in particular a strong connection between particle physics and astrophysics

→ The Cosmic Connection (Mark Trodden)

→ Synergy of Hadron and Lepton Colliders (JoAnne Hewett)

The Role of Electron Positron Colliders

Explore new Physics through <u>high precision at high energy</u>

microscopic	telescopic
$e^+e^- \rightarrow X_{new}(+Y_{SM})$	$e^+e^- \rightarrow SM$
Study the properties of new particles (cross sections, BR's, quantum numbers)	Study known SM processes to look for tiny deviations through virtual effects (needs ultimate precision of measurements and theoretical predictions)

Reason: low experimental backgrounds,
weakly interacting initial state → high precision predictions

The Electron Positron Linear Collider

Worldwide consensus: LC should be next big machine

Which machine ? ICFA LC parameter document (Heuer et al)

The baseline:

- $e^+ e^-$ LC operating from M_Z to 500 GeV, variable energy (threshold scans)
- polarized e^- (80 %)
- at least 500 fb^{-1} in the first 4 years
- upgradeable to ~ 1 TeV 500 fb^{-1} /year

a lot of flexibility!

Options :

- e^+ polarization (60%), transverse polarization
- GigaZ (high lumi running at M_Z)
- e-e-, $\gamma\gamma$ $e\gamma$

2 viable technologies NLC/GLC (warm) and TESLA (cold) → Jim Brau

Which detector ? → Slawek Tkaczyk

Driving Physics

1. Electroweak symmetry breaking

   light Higgs

   no Higgs

   ← and many(!) new models in between

2. Hierarchy and Unification

   SUSY

   Extra Dimensions

   and much more…

3. Flavor

EWSB: Higgs

Discovery and first measurements at LHC → K. Jakobs

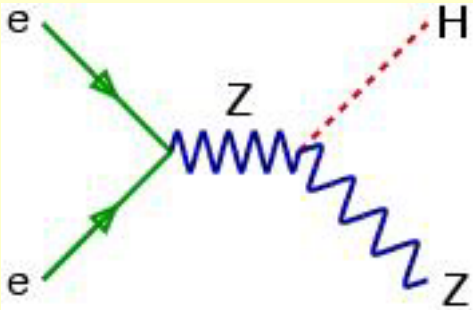
Linear Collider:

Establish Higgs mechanism as the mechanism responsible for electro-weak symmetry breaking

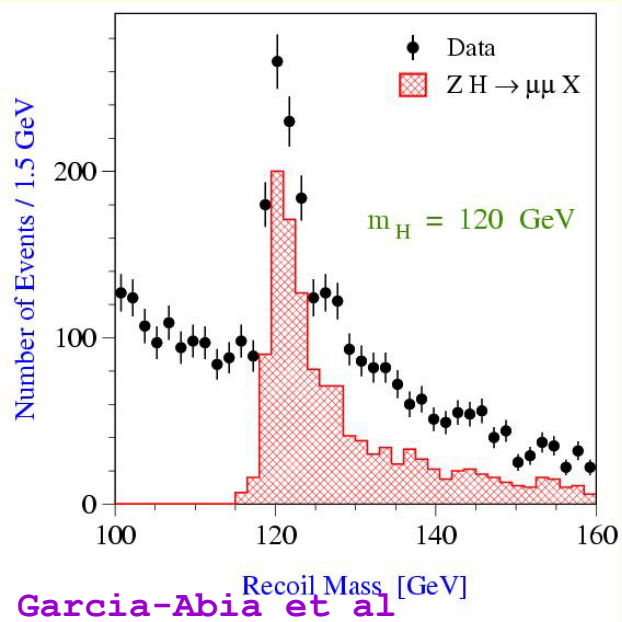
1. Is it a Higgs-Boson ?
2. Is it responsible for mass generation ?
3. Does the Higgs field have a non-zero v.e.v. ?
4. Structure of Higgs sector !

EWSB: Higgs

"seeing it without looking at it":
decay-mode independent observation



100000 Higgs bosons/1-2 years
very little background



applies also e.g. to invisible, hadronic(non-b), semi-invisible, any scalar coupling to Z

- recoil mass in $Z \to \ell^+\ell^-$ events (E-p conservation)

$\Delta\sigma \sim 2\text{-}3\%$

model independent measurement of g_{HZZ}

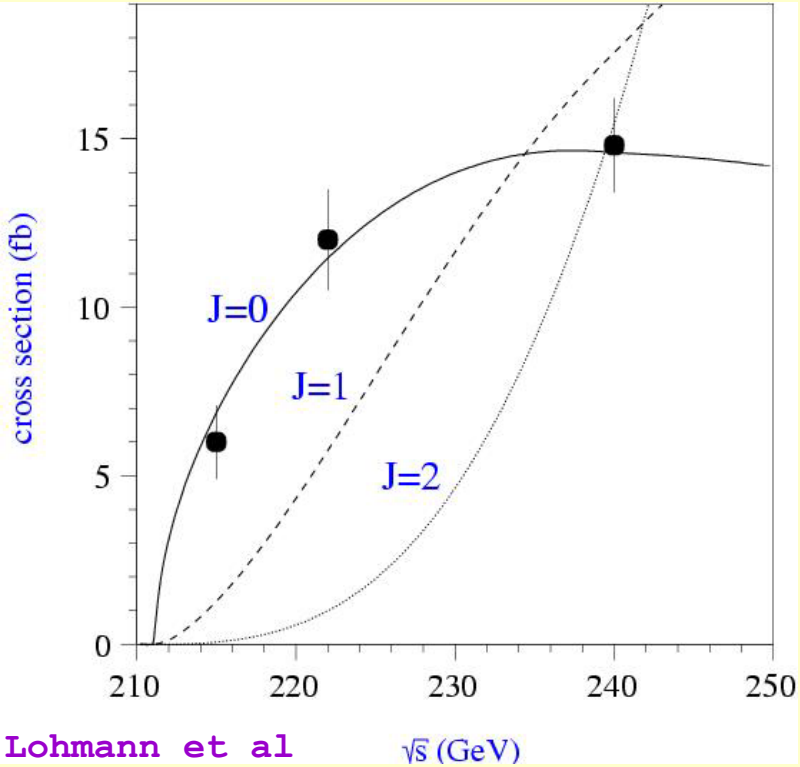
$\Delta m \sim 50$ MeV

precise mass measurement

EWSB: Higgs

Is it a Higgs?
Quantum numbers

Spin from threshold scan



CP quantum number (or CP violation!) from

- angular distributions of Z and H

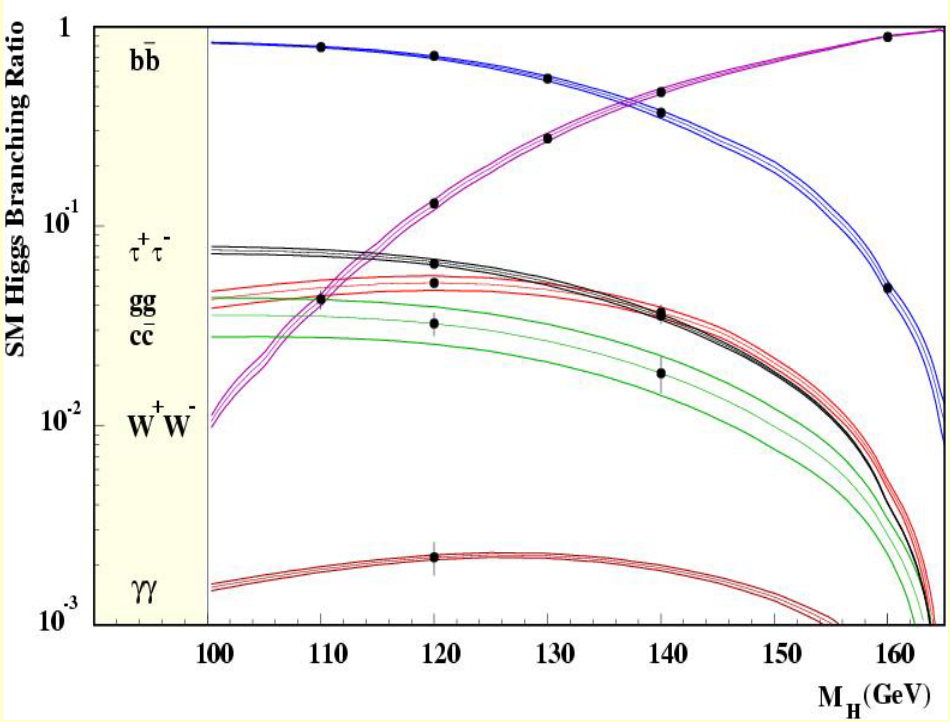
- spin correlations of Higgs decay products (accessible in $H \to \tau\tau$ decays)

EWSB: Higgs

Battaglia/Brient/Brau ea/Barklow/Kuhl ea/…

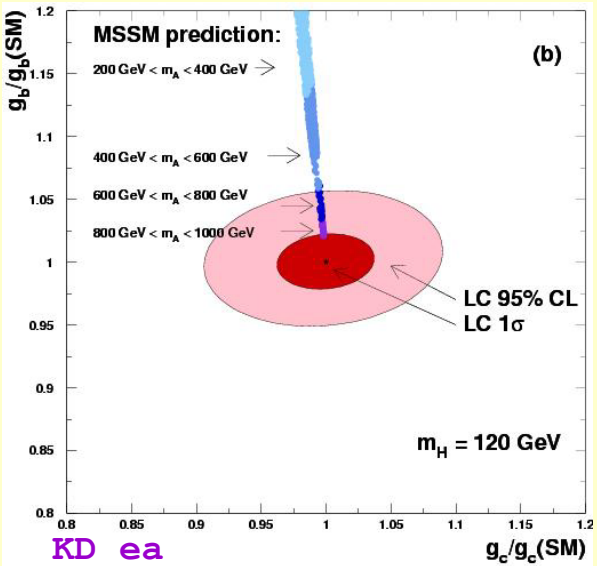
Higgs field is responsible for particle masses
couplings must be proportional to masses!

decisive test:
precision analysis of Higgs decays:



percent level measurements

Decay	ΔBR/BR for m_H=120GeV
H→bb	≈ 2%
H→cc	≈12%
H→gg	≈ 9%
H→WW	≈ 5% / 2% (1 TeV)
H→ττ	≈ 5%
H→γγ	≈ 10% / 5% (1 TeV)

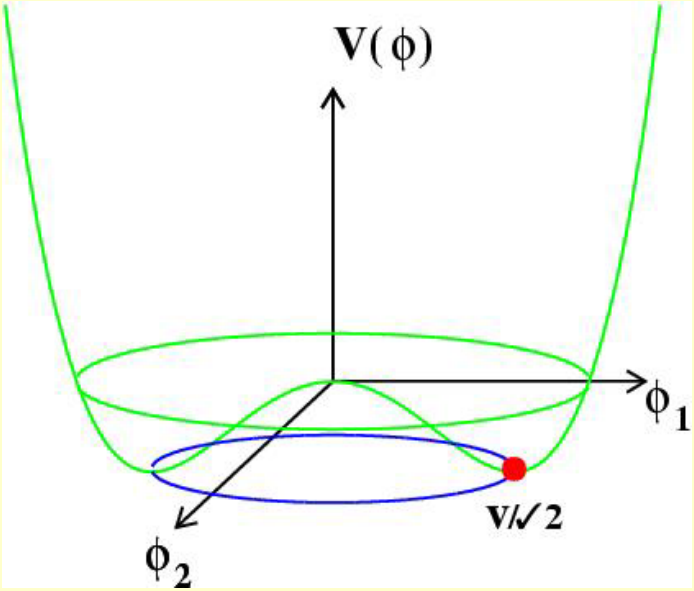


KD ea

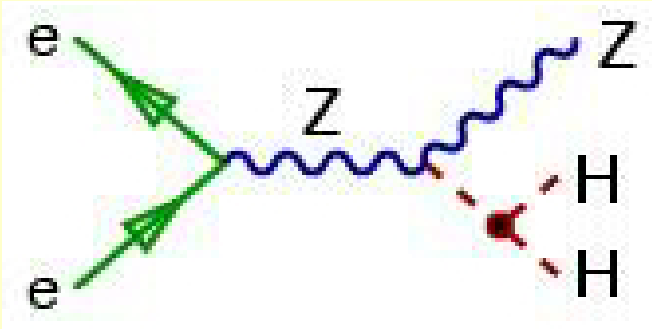
consequence: sensitivity to beyond-SM effects, e.g. heavy SUSY Higgs bosons:

EWSB: Higgs

Does the Higgs receive its mass from its own v.e.v.?



decisive test:
measure Higgs self coupling
(sensitive to shape of Higgs potential)



needs highest possible luminosity
calls for ultimate detector resolution

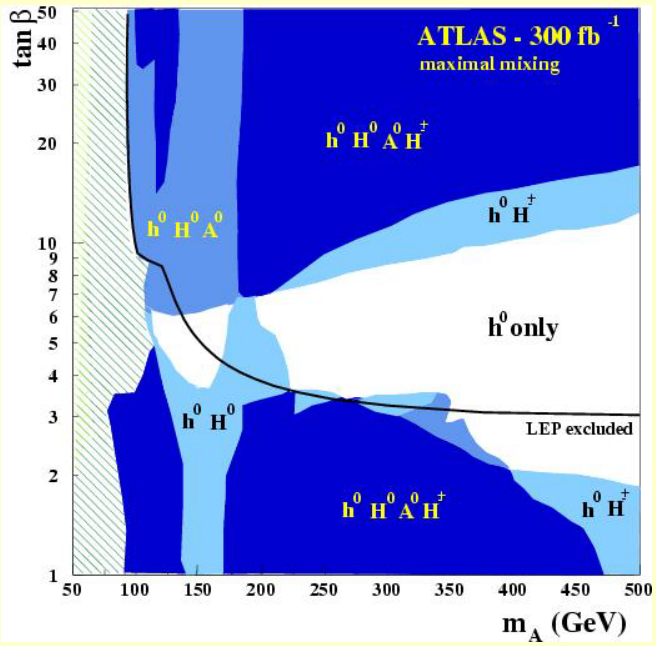
$$\Delta\lambda/\lambda \cong 20\%$$

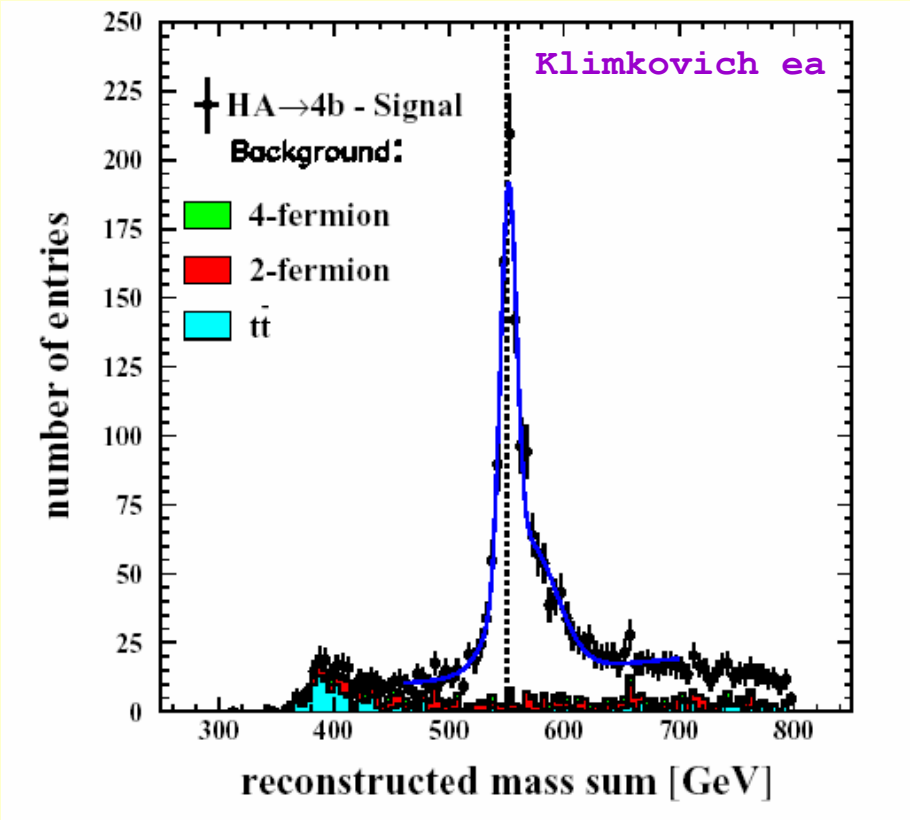
Gay ea

for 1 ab^{-1} at 500 GeV (m_H=120 GeV)

EWSB: Higgs

Heavy SUSY Higgs bosons:
observation and mass/BR/width measurements
deep into the LHC wedge region at 800-1000 GeV LC





HA→ bbbb and HA → bbττ/ττbb observable

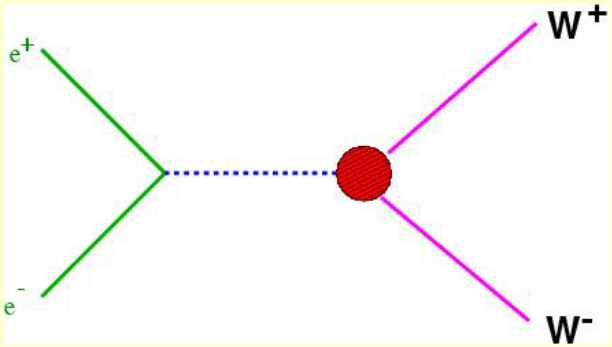
EWSB: no Higgs

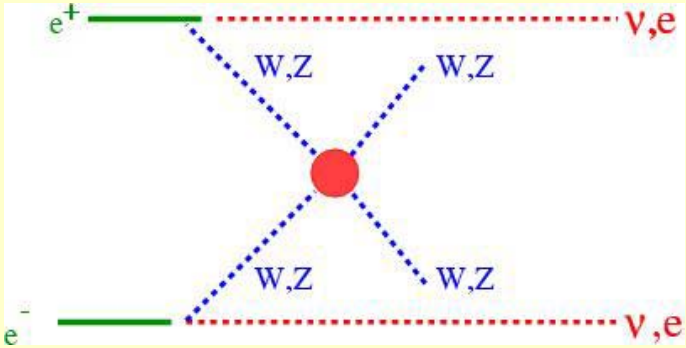
→ divergent $W_L W_L \to W_L W_L$ amplitude at $\Lambda^2 = o\left(\frac{4\pi\sqrt{2}}{G_F}\right) \approx (1.2\text{TeV})^2$

→ SM becomes inconsistent unless a new strong QCD-like interaction sets on

→ Goldstone bosons ("Pions") = W_L states ("technicolor")

Experimental consequences:
deviations in triple and quartic gauge couplings:





LC (800 GeV): sensitivity to energy scale Λ:
triple gauge couplings: ~ 8 TeV
quartic gauge couplings: ~ 3 TeV ⇨ complete threshold region covered

Summary: EWSB

The LC is an excellent tool study in detail the properties of

a) Higgs bosons

b) longitudinal gauge bosons

All models of EWSB (that I know of) require either

the study of a) or b) or both

Supersymmetry

LC task: precision measurements of kin. accessible part of the SUSY spectrum

- superpartner masses o(0.1-1) GeV
- quantum numbers
- couplings (polarized cross section, branching ratios, differential distributions) at % level

Goal: reconstruction of EW-scale MSSM parameters w/o model assumptions

→ explore SSB mechanism

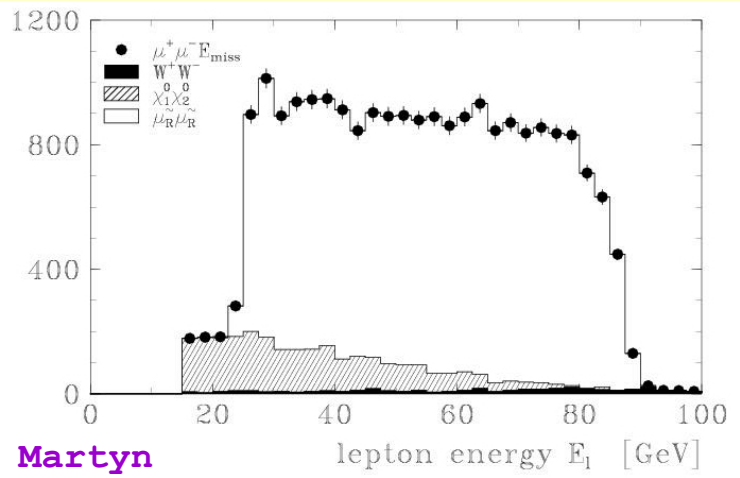
→ constrain SUSY constribution to CDM relic densitiy at 1% level

→ distinguish larger classes of SUSY models (MSSM/NMSSM, CPV, LFV, …)

Supersymmetry: examples

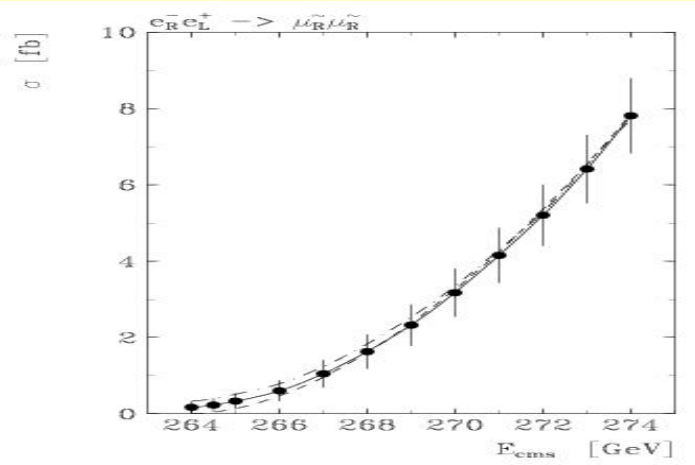
Clean signals from sleptons and charginos/neutralinos

in continuum:

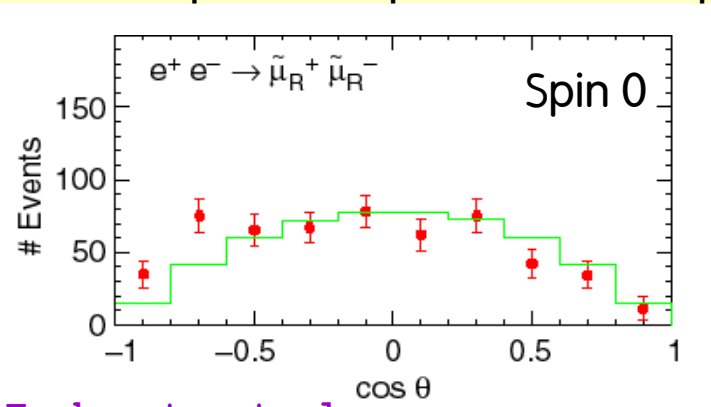


Martyn

and from threshold scan:

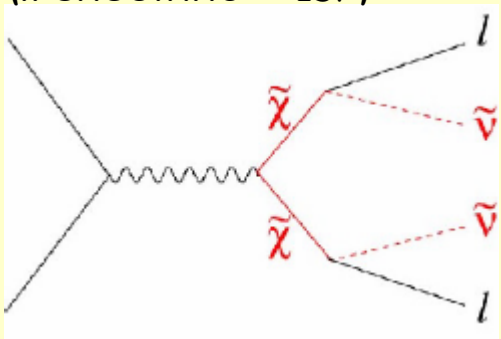


SUSY: sleptons + leptons differ in spin by ½:



Tsukamoto et al

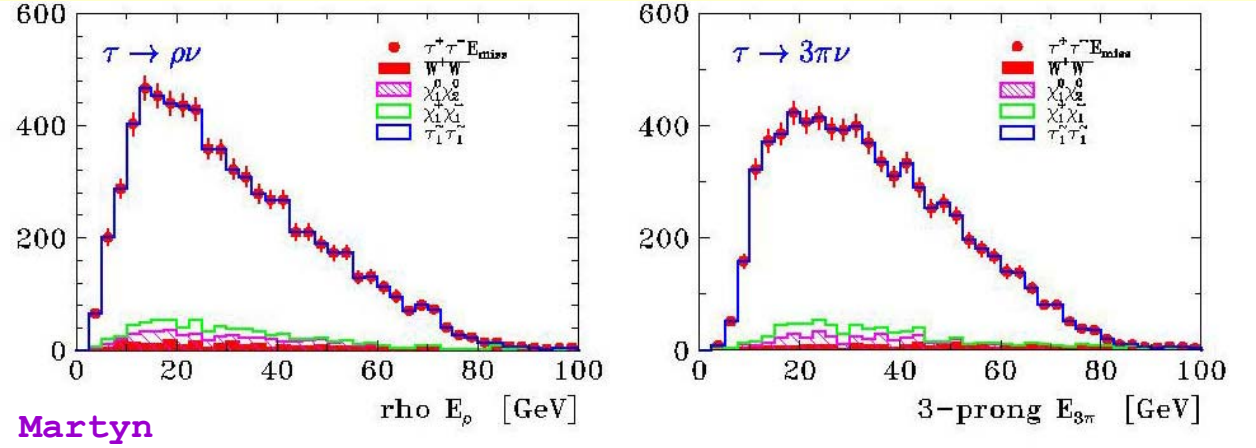
or are they charginos after all?
(if sneutrino = LSP)



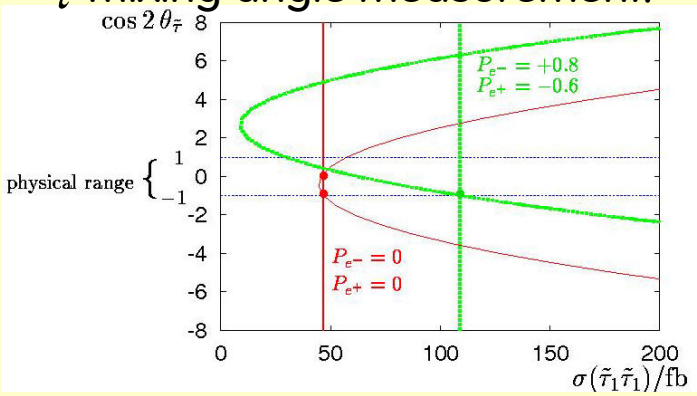
De Gouvêa et al

Supersymmetry: examples

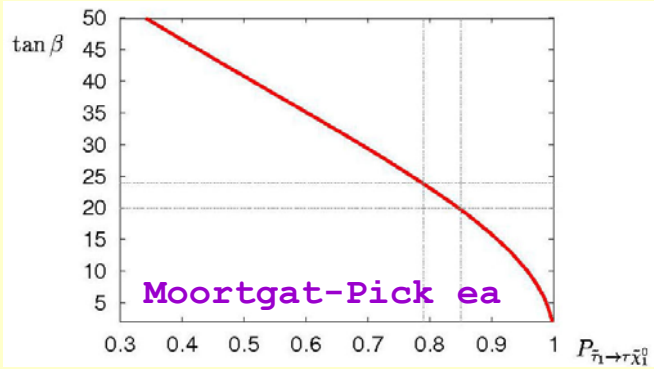
often $\tilde{\tau}_1$ = NLSP: final states with τ's are important!
new studies for SPS1: $e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1 \to \tau\tau\chi_1^0\chi_1^0$ and $e^+e^- \to \chi_2^0\chi_1^0 \to \tau\tau\chi_1^0\chi_1^0$
end-point method still works for precise mass determinations



exploit beam polarisation for $\tilde{\tau}$ mixing angle measurement:

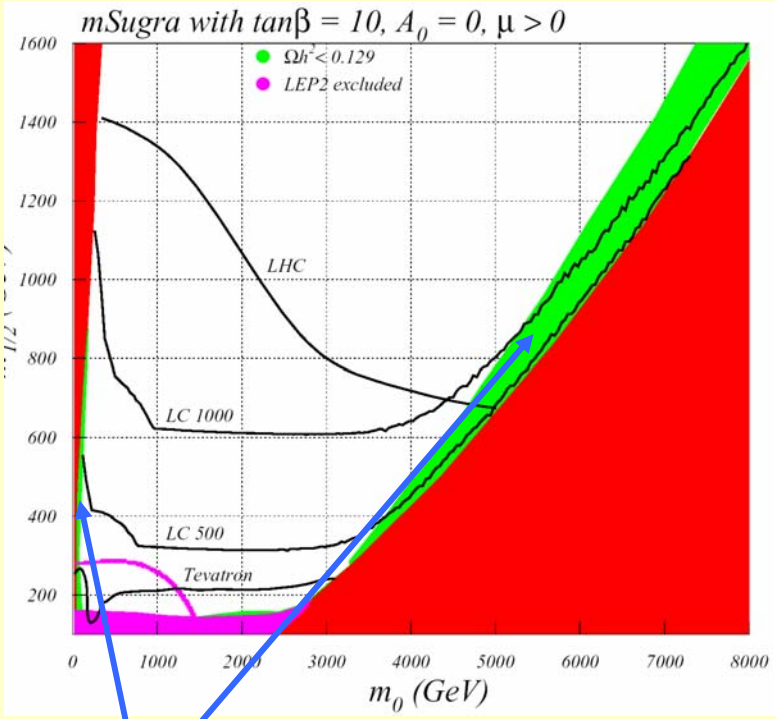


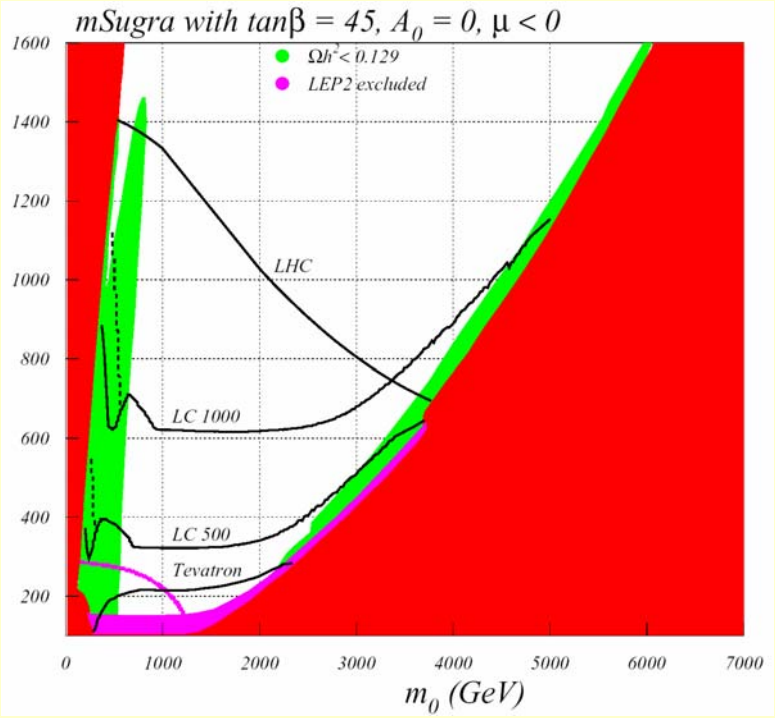
additional observable: τ polarisation sensitive to tanβ:



Supersymmetry: examples

Cold dark matter constraints reduce the dimensionality of the mSugra par.-space





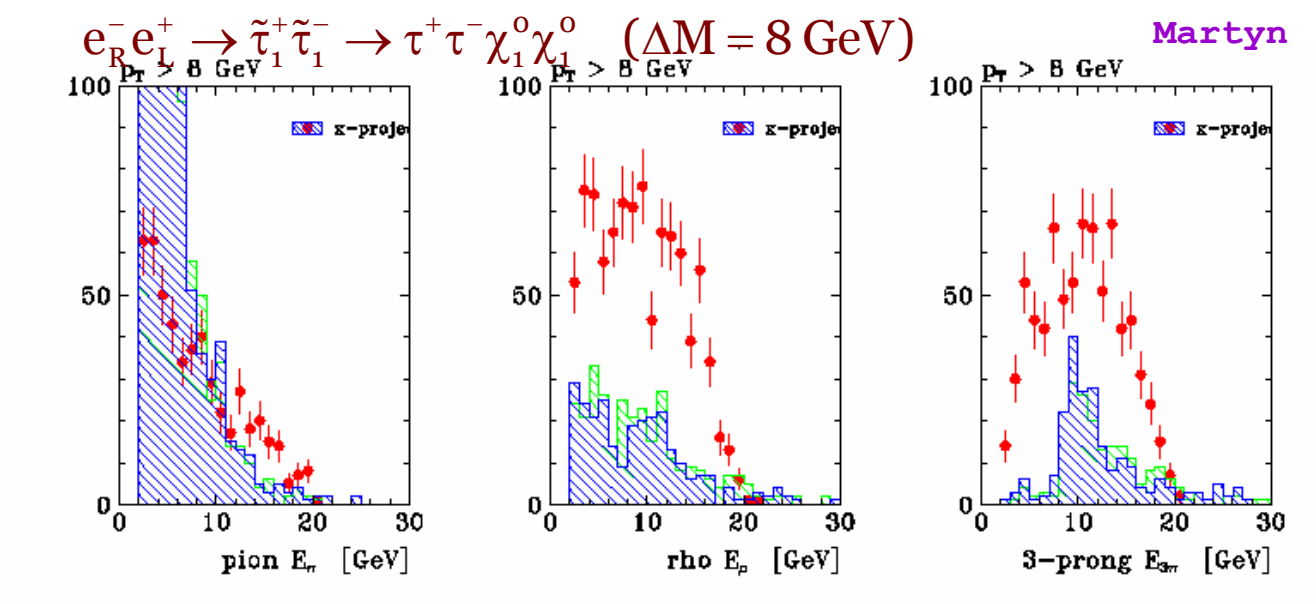
H. Baer et al

"focus point region" here LC might lead to a (late) SUSY discovery

"co-annihilation region" has small $\Delta M = M_{NLSP} - M_{LSP}$

Supersymmetry: examples

Does LC still work for small ΔM? most difficult: $\tilde{\tau}$ production



Ok for ΔM down to few GeV with standard technique
(need forward detector coverage!)

Even lower ΔM need dedicated techniques

- ISR tagging
- displaced vertices
- longlived particles

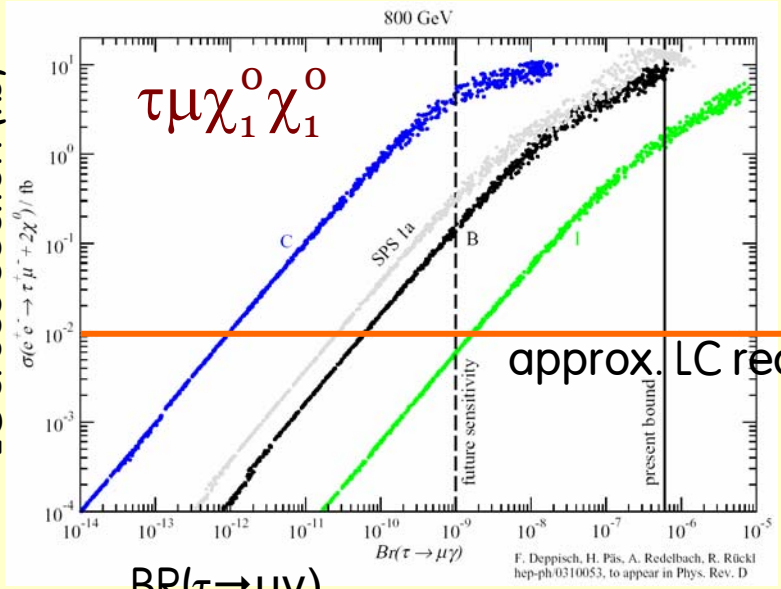
Supersymmetry: examples

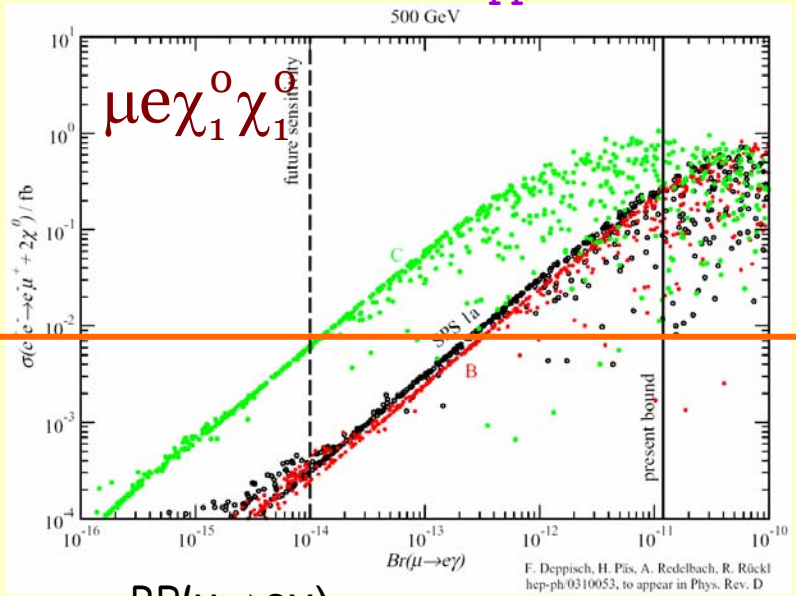
Connection to Neutrino Physics and Leptogenesis:

Lepton Flavor Violation from SUSY see-saw, example sleptons:

Deppisch et al

LC cross section (fb)





approx. LC reach

BR(τ→μγ)

BR(μ→eγ)

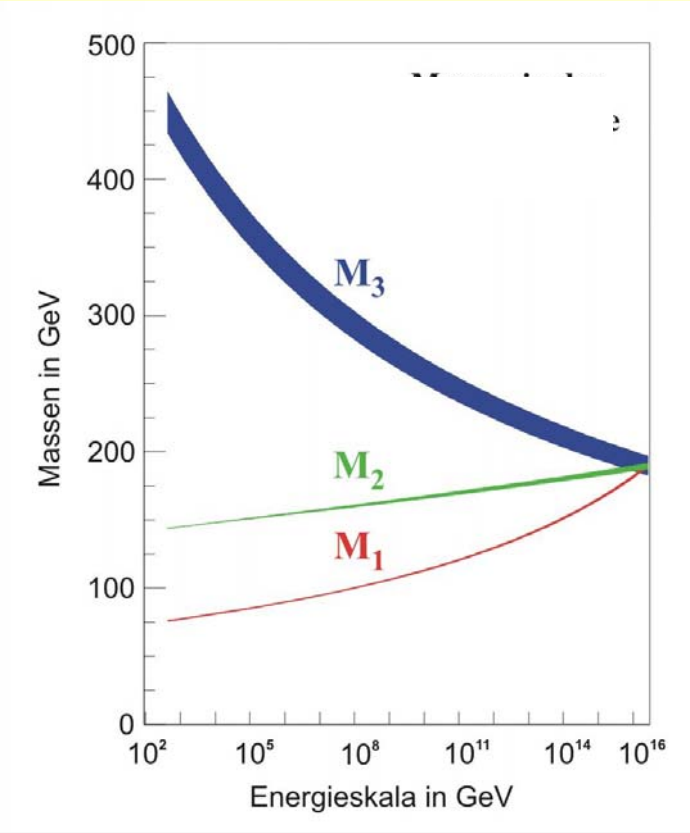
variation of heavy Majorana mass scale

needs experimental study

higher reach than τ→μγ, but it would be very nice if PSI (μ→eγ) would see sth…

Supersymmetry: Deep Field

If there is a line of sight from EW to GUT/Planck scale physics in Nature, the LC has precise enough focus and sufficient apperture to observe the signals!



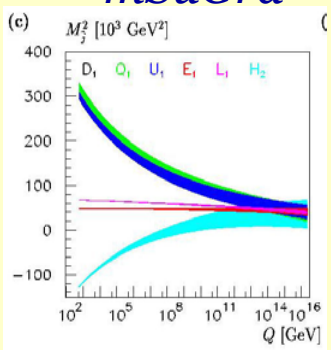
Zerwas et al

Extrapolation of the measured mass parameters (LC+LHC) over many orders of magnitude in energy through RGE's

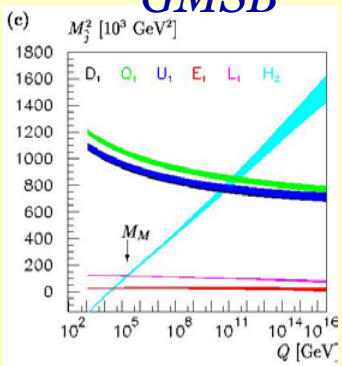
test unification hypotheses at the GUT scale
and learn about SSB mechanism:

evolution of squark+slepton mass parameters

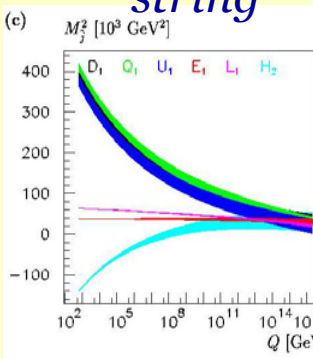
mSuGra



GMSB

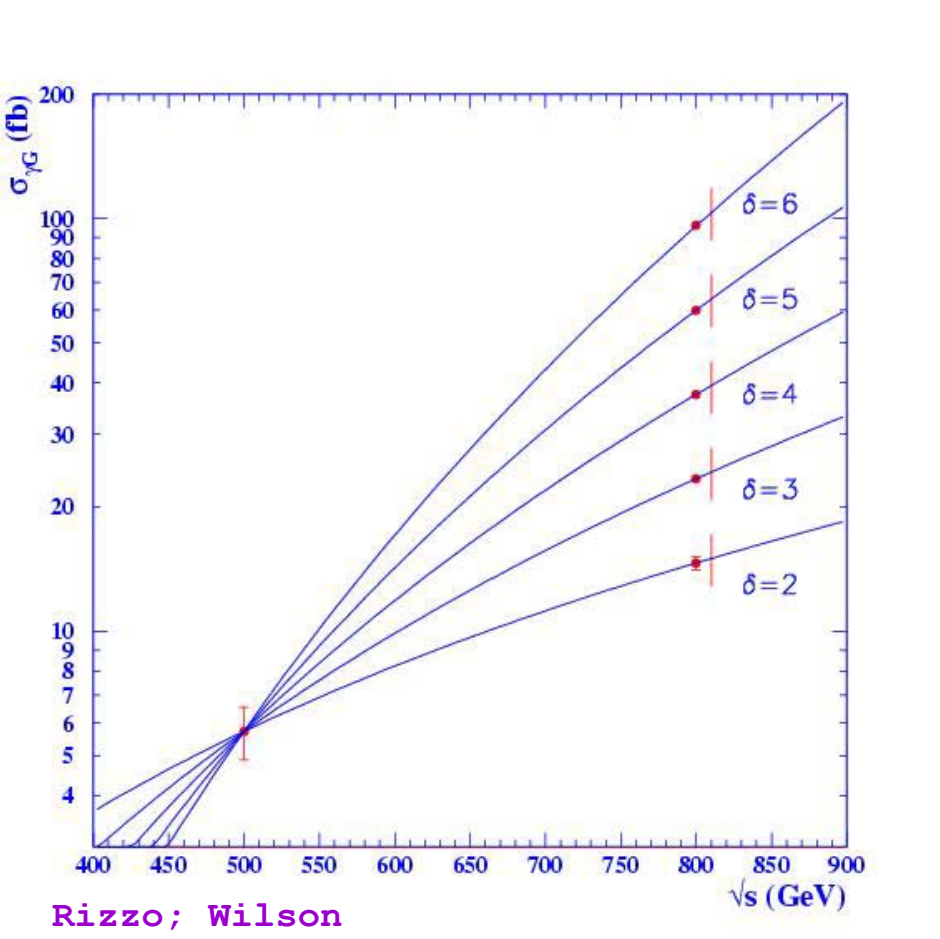


"string"

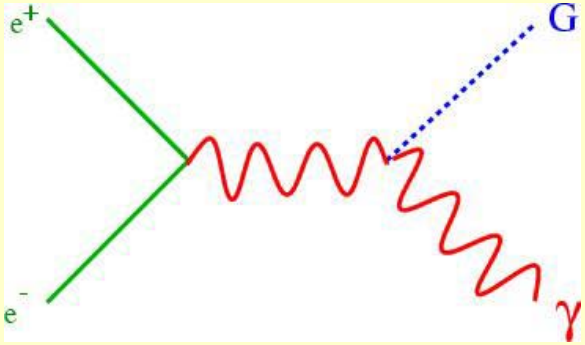


Extra Dimensions

Effects from real graviton emission:



Rizzo; Wilson



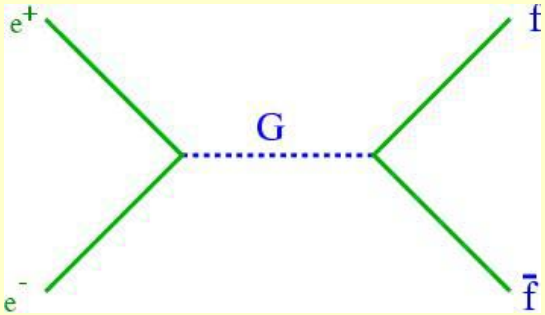
measures the number of extra dimensions!

polarisation important to reduce background!

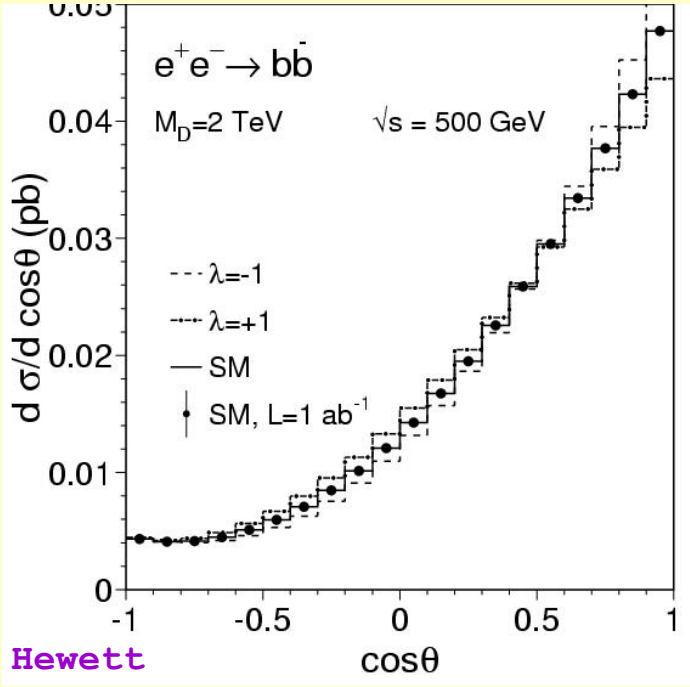
Extra Dimensions

Effects from virtual graviton exchange:

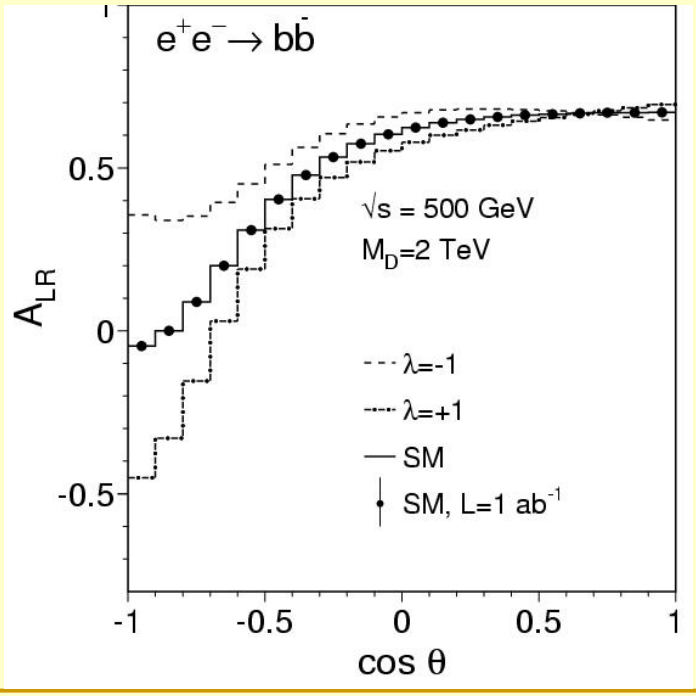
can prove Spin-2 exchange!



angular distribution

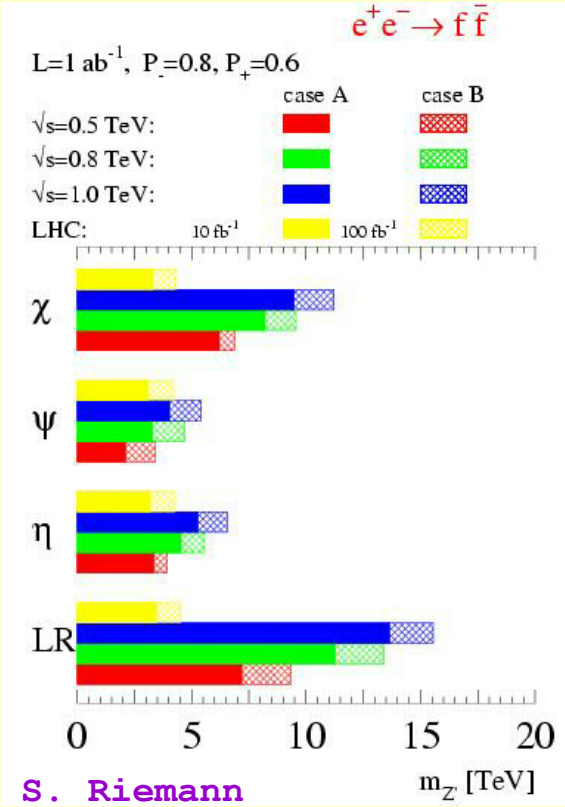


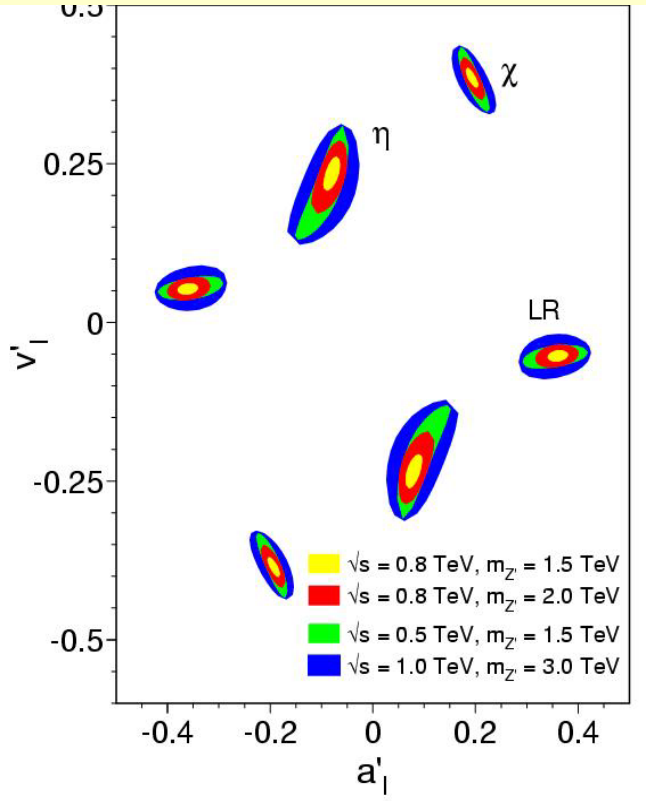
left-right asymmetry (beam polarisation!)



New Resonances Beyond √s

Telescopic sensitivity to new vector bosons through precise measurements of SM processes. Studied in great detail for Z' :

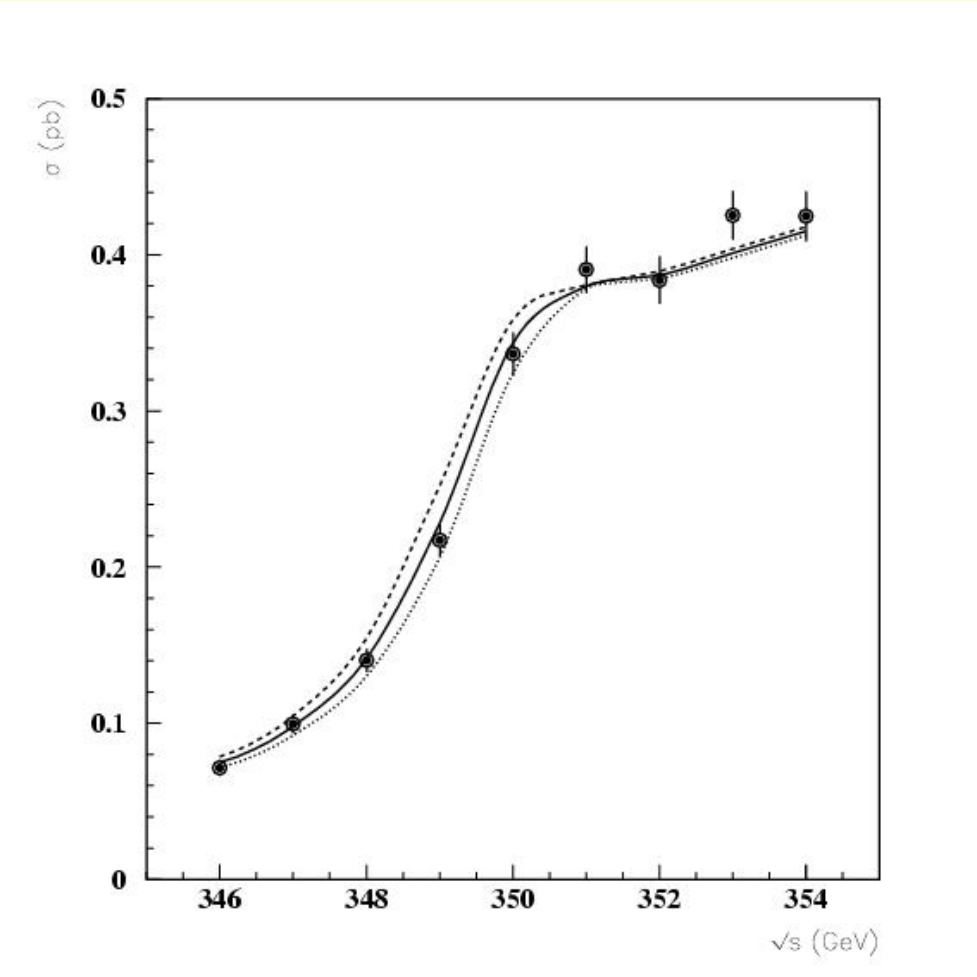




but also applies for other new models: KK, Little Higgs, …
multitude of observables will help to find out what's going on at the multi-TeV scale

Top Quark – the Key to Flavor Physics?

scan of the threshold for $e^+e^- \rightarrow t\,t$



precise mass measurement
(100 MeV)

very important ingredient to
for precise theoretical predictions

(need to know SM parameters
if we want to see beyond-SM
physics!)

Conclusion

- Linear Electron Positron Collider in 500-1000 GeV range has excellent scientific potential
- Worldwide consensus: next big HEP project – soon!
- HEP community wants to build the LC as truly global project – choice of technology in 2004