Physics Potential of the High Energy e^+e^- Linear Collider

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ASI Praha, 12 July 2003

- Introduction to the machines
- Physics working groups
- Higgs
- Supersymmetry
- Extra dimensions
- Summary

The Machines

- JLC,NLC, TESLA, CLIC are all projects for a linear e^+e^- machine:
- JLC-X/NLC 0.5-1 TeV copper cavities operating at 11.4 GHz.
- TESLA 0.5-0.8 TeV superconducting Niobium cavities operating at 1.3 GHz
- CLIC 0.5-3 TeV copper cavities operating at 30 GHz

See ILC-TRC megatables for detailed overview:

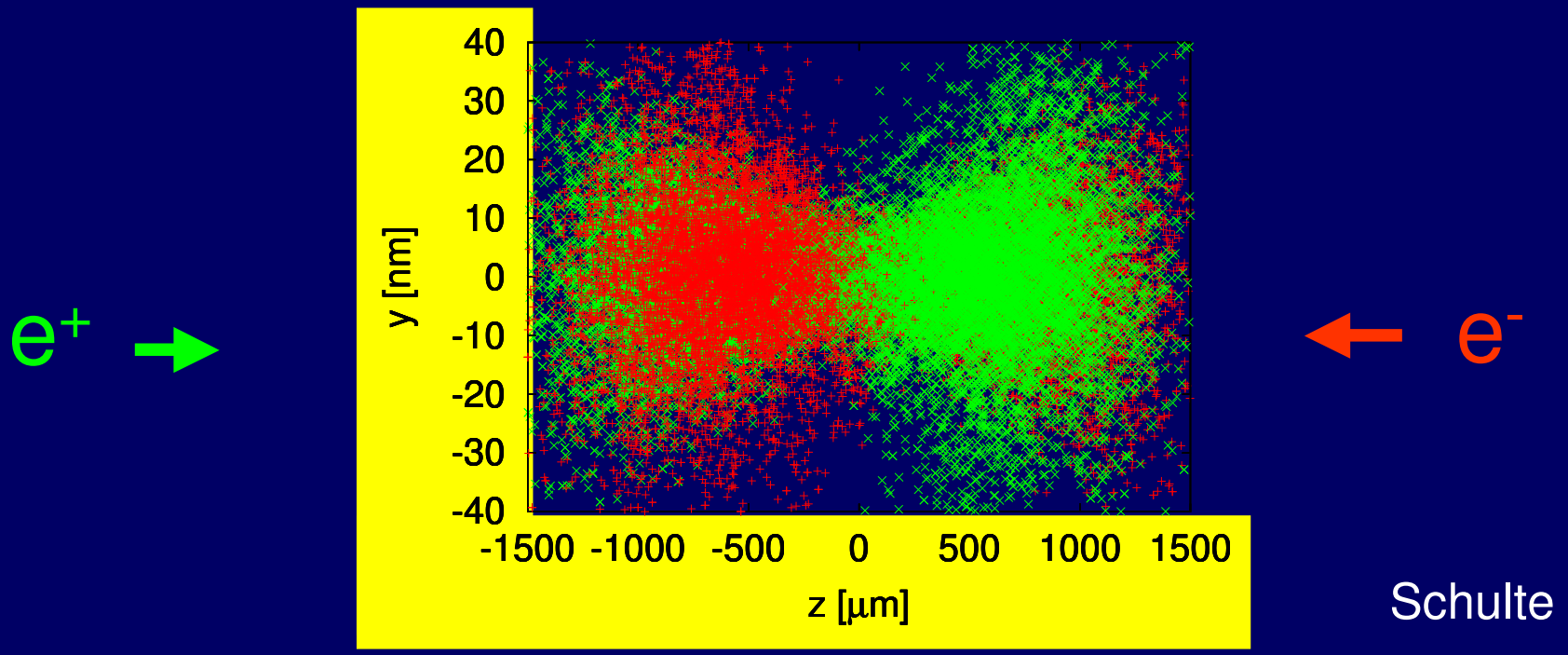
http://www.slac.stanford.edu/xorg/ilc-trc/2002/2002/report/03rep.htm

LC for this talk:

- e^+e^- collisions with $\sqrt{s}$ tuneable 0.5 – O(1) TeV
- e^-e^- mode.
- Polarisation: e^- 80% (L/R); e^+ 60% (?).
- Possiblity to run at $\sqrt{s}$ ~ 90 – 160 GeV ("GigaZ")
- Luminosity 3-6.10^{34} cm^{-2} s^{-1} $\Rightarrow$ specific analyses can assume up to about 1 ab^{-1}

Also possible/important; Compton scattering to produce $\gamma\gamma$ or $e\gamma$

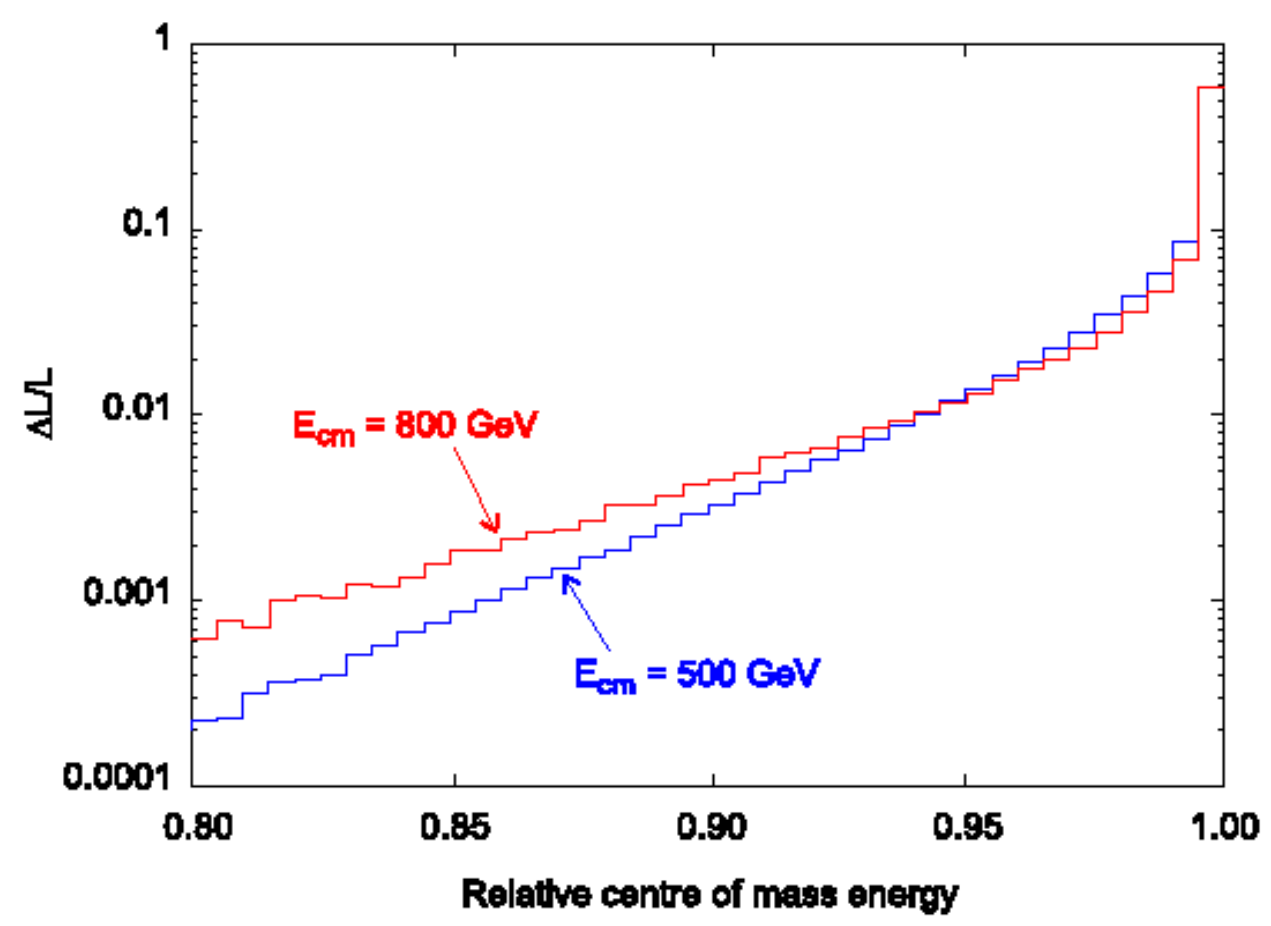
Bunch Interactions



Schulte

- Increase in luminosity (×~2)
- Beamstrahlung ⇒ Lumi. Spectrum

Luminosity Spectrum



TESLA TDR

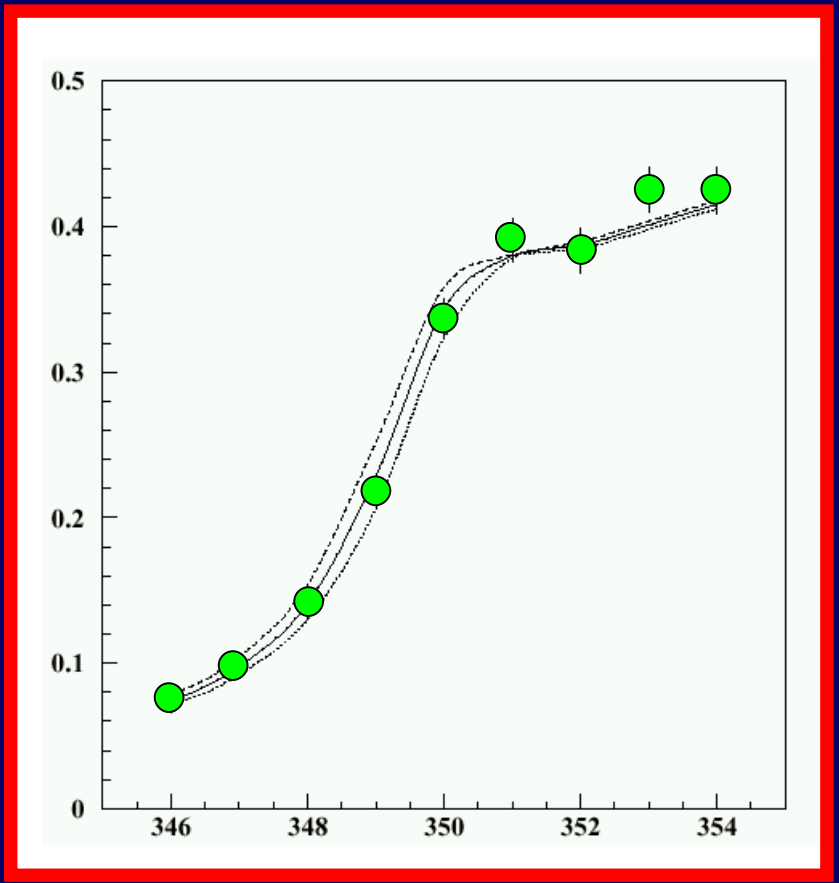
- sharp peak
- approx same as ISR (tuned) – few % in tail for 0.5-1 TeV machines

Precision Measurement of the Top Mass

Precision measurement of fundamental particle properties

The top quark is the heaviest: most sensitive to new physics

Cross section (pb)



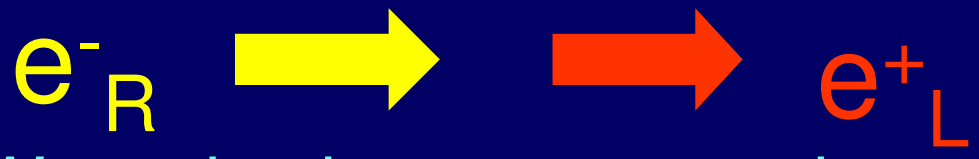
M_{top}=175 GeV
100 fb^{-1} per point

Statistical Precision ~0.05 GeV ⇒0.02%

E_{tot}(GeV)

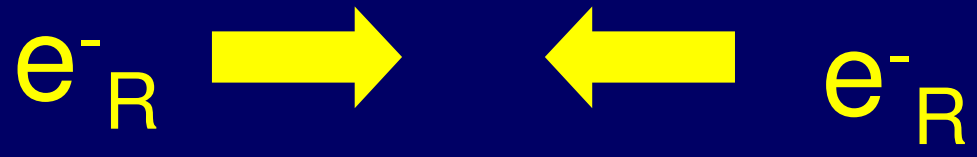
Martinez et al.

Initial State



- W-production suppressed
- s-wave production of charginos ~ $\beta \Rightarrow$ sharp threshold
- Specific polarisations for specific couplings (eg SUSY)

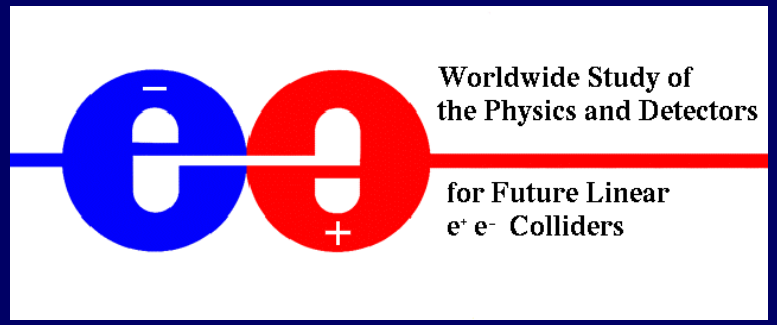
http://www.ippp.dur.ac.uk/~gudrid/power/



- s-wave production of selectrons ~ $\beta \Rightarrow$ sharp threshold

- Direct production of higgs

Worldwide LC Studies



http://blueox.uoregon.edu/~lc/wwstudy/

http://blueox.uoregon.edu/~lc/alcpg/

ACFA Joint Linear Collider
Physics and Detector Working Group

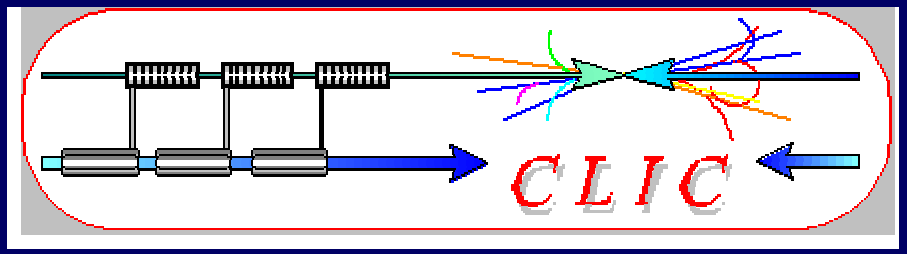
http://acfahep.kek.jp/

Worldwide studies (2)

ECFA Study

Physics and Detectors
for a Linear Collider

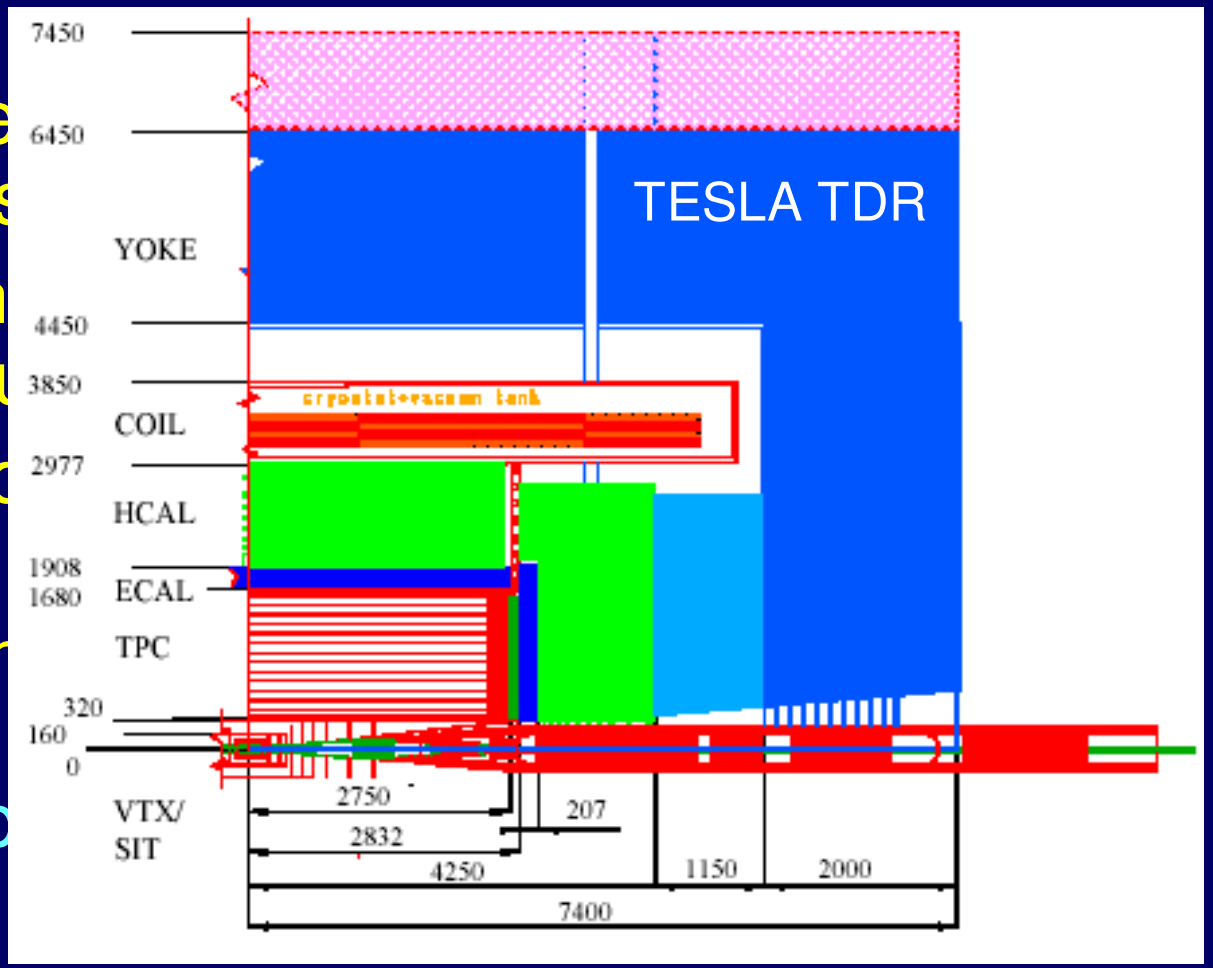
http://www.desy.de/conferences/ecfa-lc-study.html



http://clicphysics.web.cern.ch/CLICphysics/

Status of the studies

- All the re
  physics s
- Many an
  reconstru
- Worldwic
  forming/
- Increasir
  LHC/LC
  http



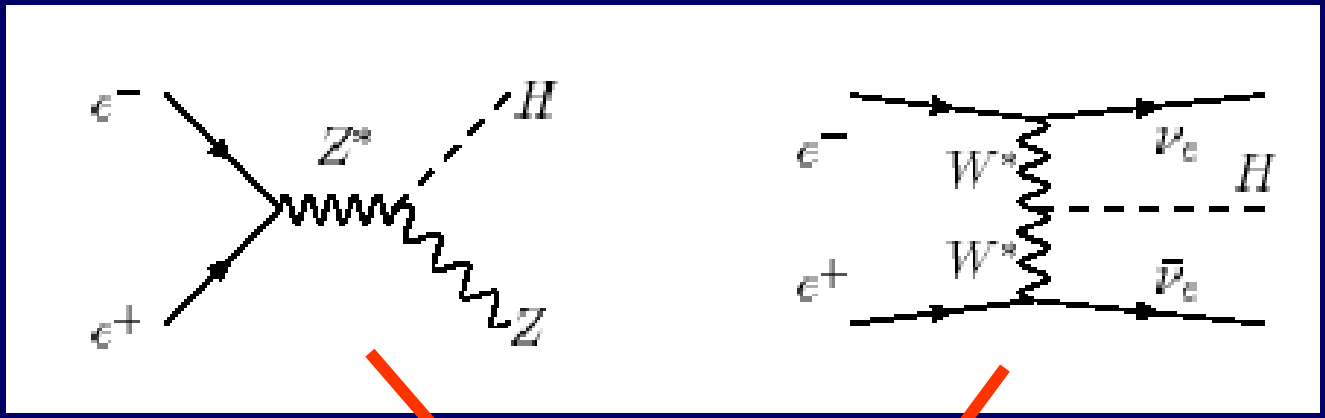
The TESLA Technical Design Report, DESY-2001-011, March 2001.
The JLC TDR http://lcdev.kek.jp/RMdraft/
The Case for a 500 GeV Linear Collider
http://xxx.lanl.gov/abs/hep-ex/0007022

Particle/Machine Physics

- The LC will be a very challenging machine
- Particle physicists are taking part in machine studies
- Beam diagnostics and control
- Background estimates
- Design studies
- The particle physics programme now goes beyond “what comes **out** of the IP”.

HIGGS

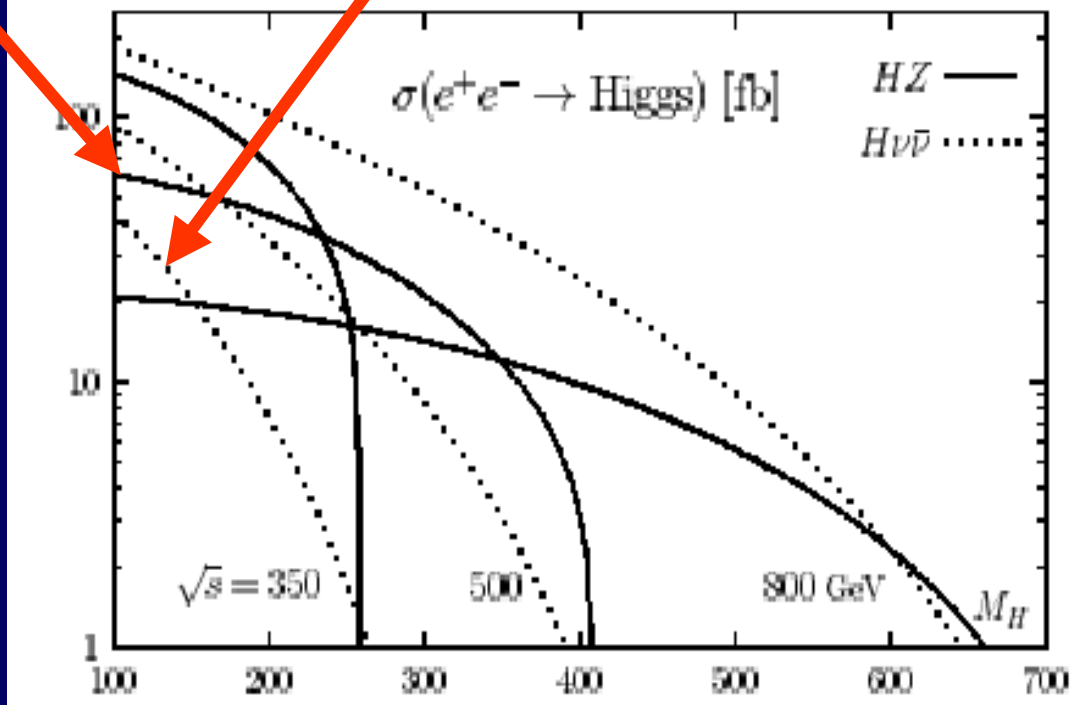
Higgs Production



For M_h~120 GeV,
500 fb^{-1}, $\sqrt{s}$=350 GeV

$\Rightarrow$80,000 Higgs

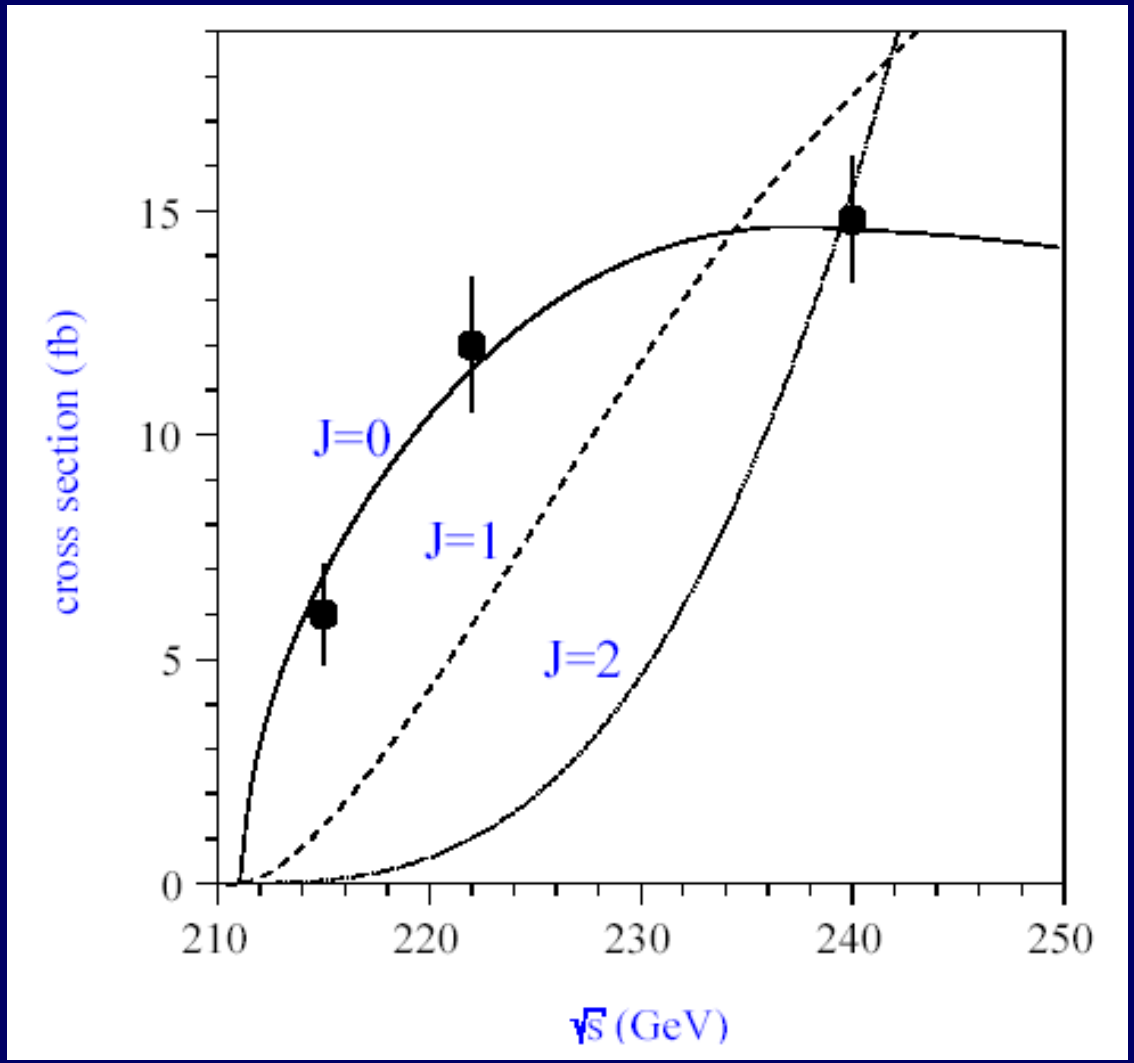
TESLA TDR



Higgs Spin

Threshold excitation curve

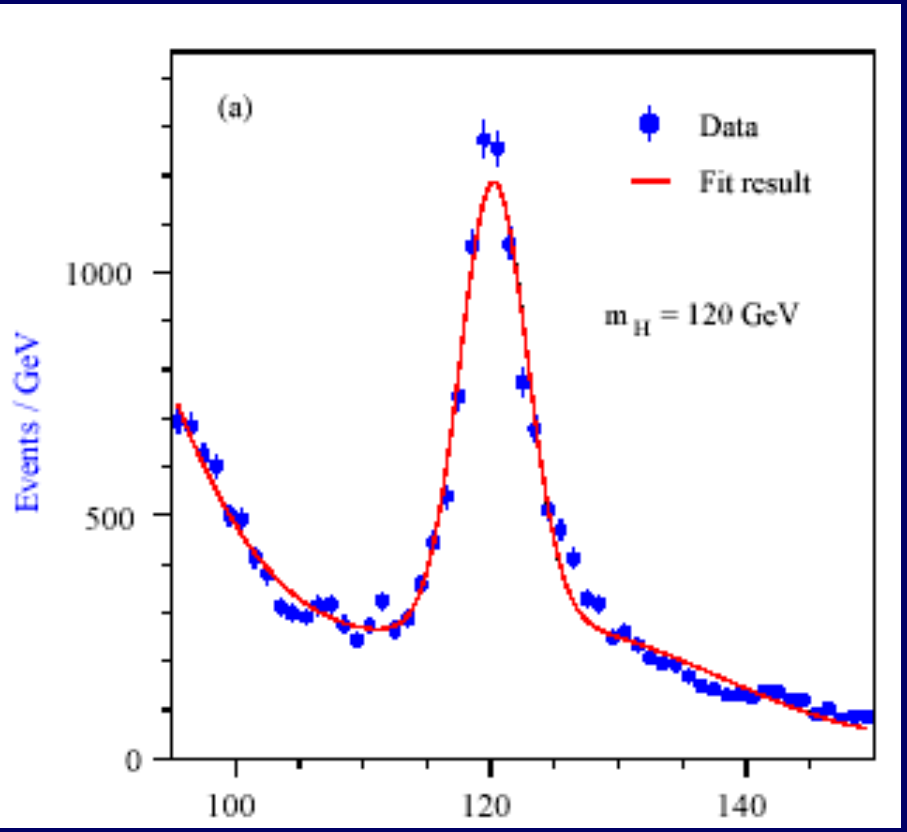
⇒ determine spin

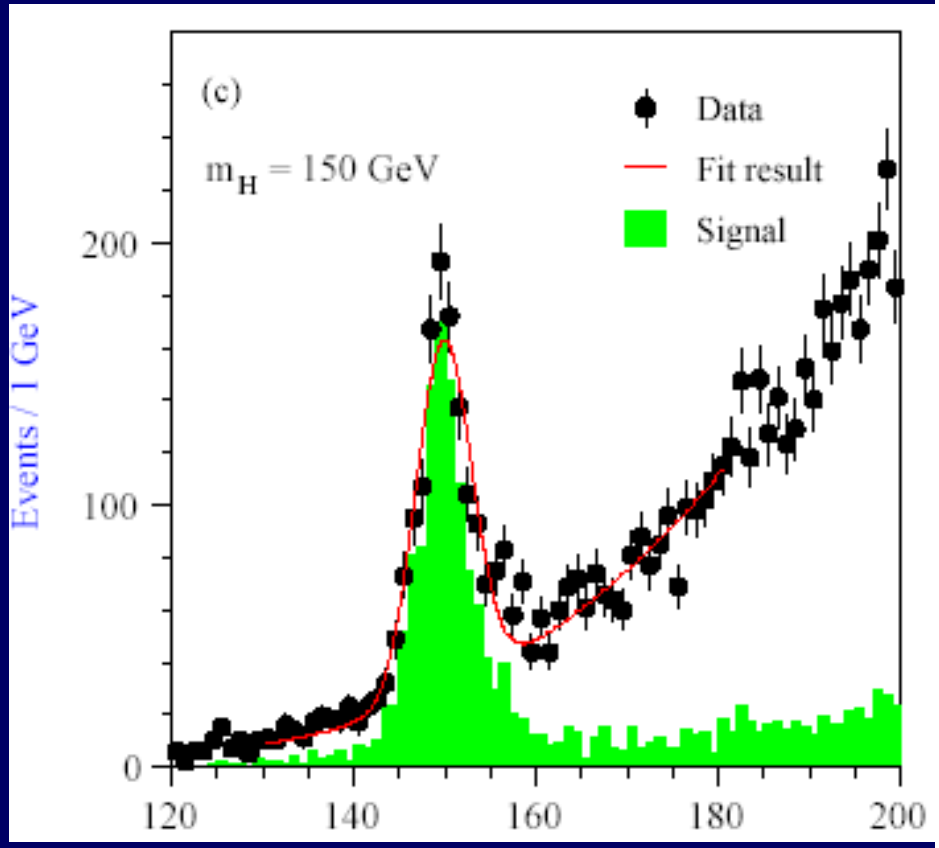


TESLA TDR

20 fb^{-1} per point

Higgs Mass





m_h=120 GeV

TESLA TDR

m_h=150 GeV

$hZ^0 \to b\bar{b}\,q\bar{q}$

$hZ^0 \to W^+W^-q\bar{q}$

500 fb^{-1} at $\sqrt{s}$=350 GeV

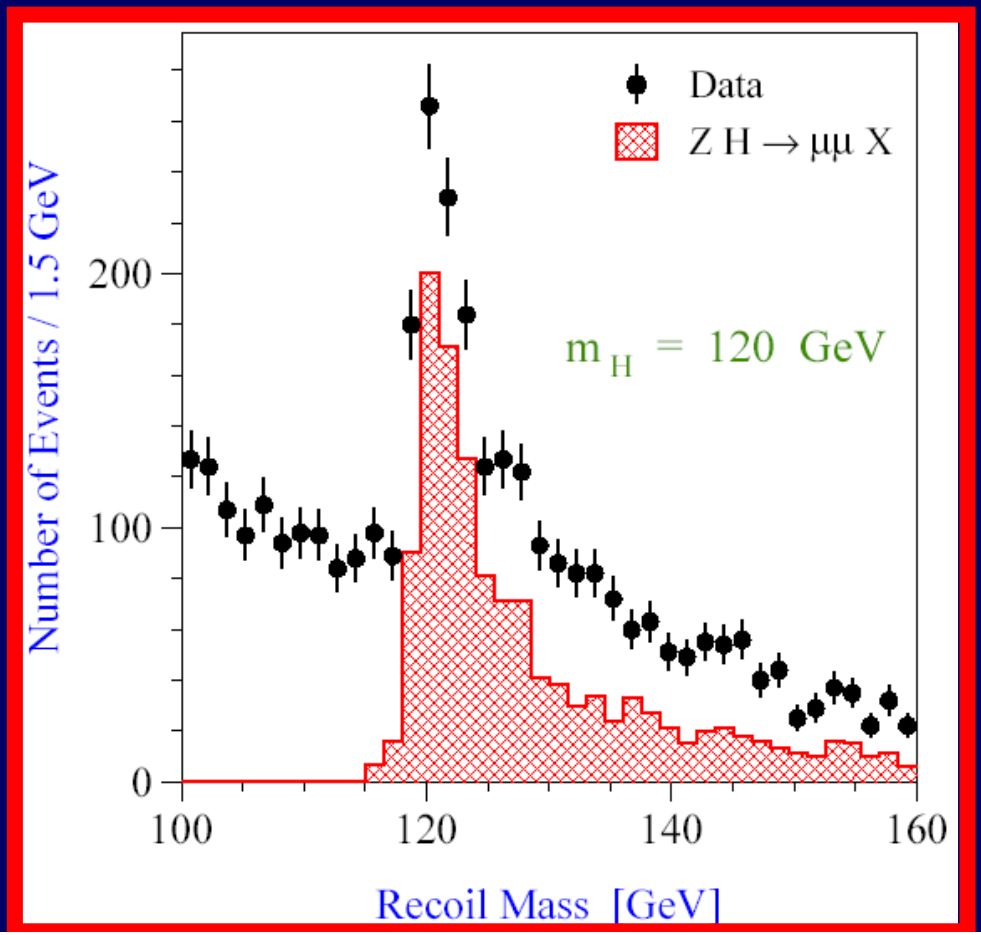
Higgs Recoil Mass

$E_{tot} = 2\ E_{beam}$

$P_{tot} = 0$

500 fb^{-1}, $\sqrt{s}$=350 GeV

TESLA TDR



Higgs Mass Precision

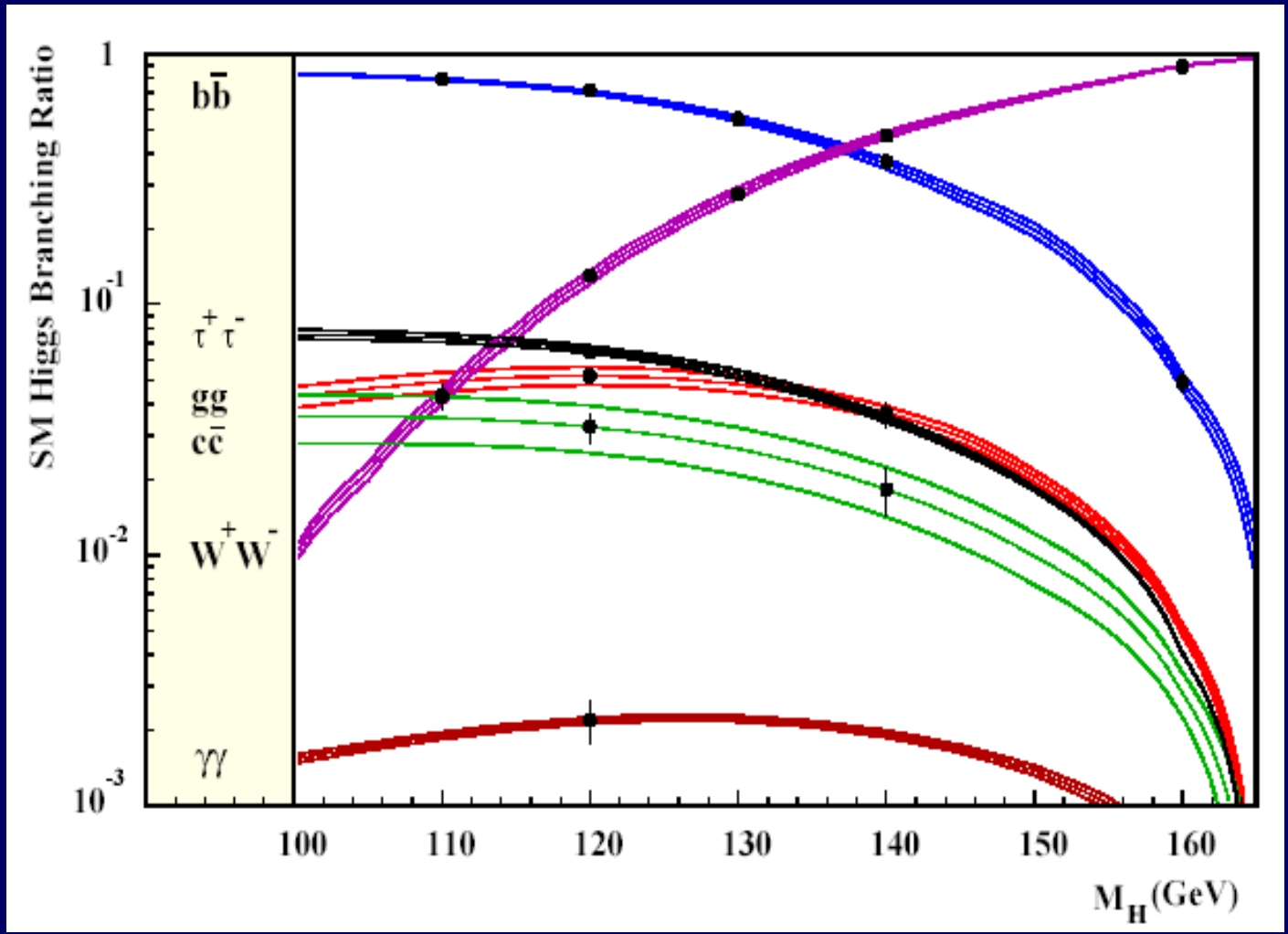
M_h(GeV)	Channel	ΔM_h (MeV)
120	llqq	70
120	qqbb	50
120	combined	40
150	ll recoil	90
150	qq WW	130
150	combined	70
180	ll recoil	100
180	qq WW	150
180	combined	80

500 fb^{-1}, $\sqrt{s}$=350 GeV

Higgs Branching Ratios

For m_h=120 GeV

h⟶	ΔBR/BR
bb	0.024
cc	0.083
gg	0.055
ττ	0.050



Higgs Width

$$\Gamma_{total} = \frac{\Gamma_{H \to X}}{BR(H \to X)}$$

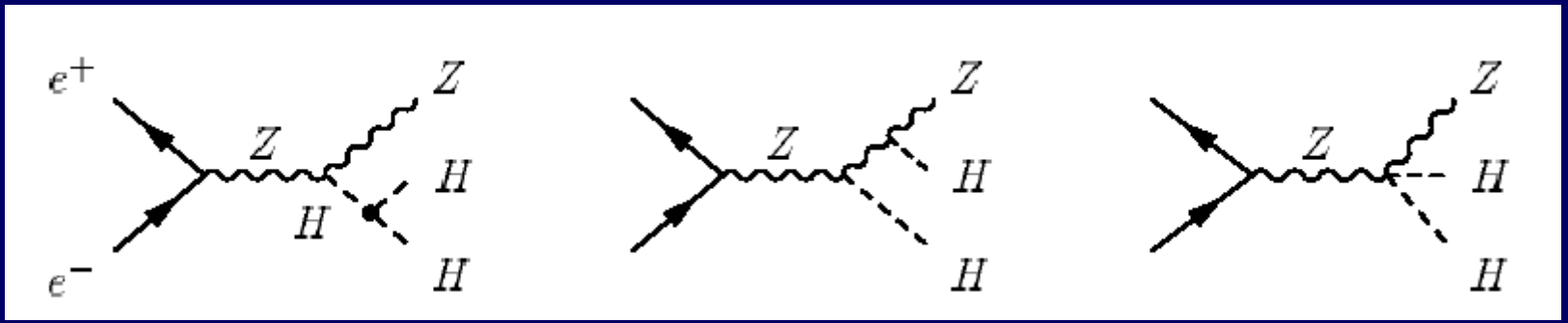
Production cross section

$\Gamma_{H \to X}$	$\mathrm{BR}(H \to X)$	$M_H = 120\,\mathrm{GeV}$	$140\,\mathrm{GeV}$	$160\,\mathrm{GeV}$
$WW = WW\nu\nu$	$H^0 \to WW$	± 0.061	± 0.045	± 0.134
$WW = HZ$	$H^0 \to WW$	± 0.056	± 0.037	± 0.036
$\gamma\gamma \to H^0$	$H^0 \to \gamma\gamma$	± 0.23	-	-

TESLA TDR

Higgs Potential

$$V = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$

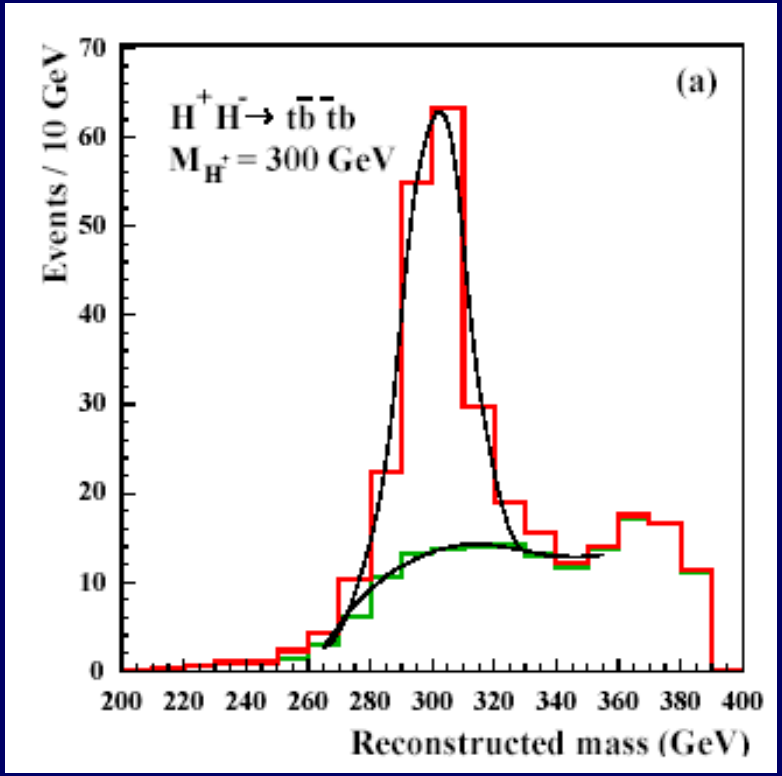


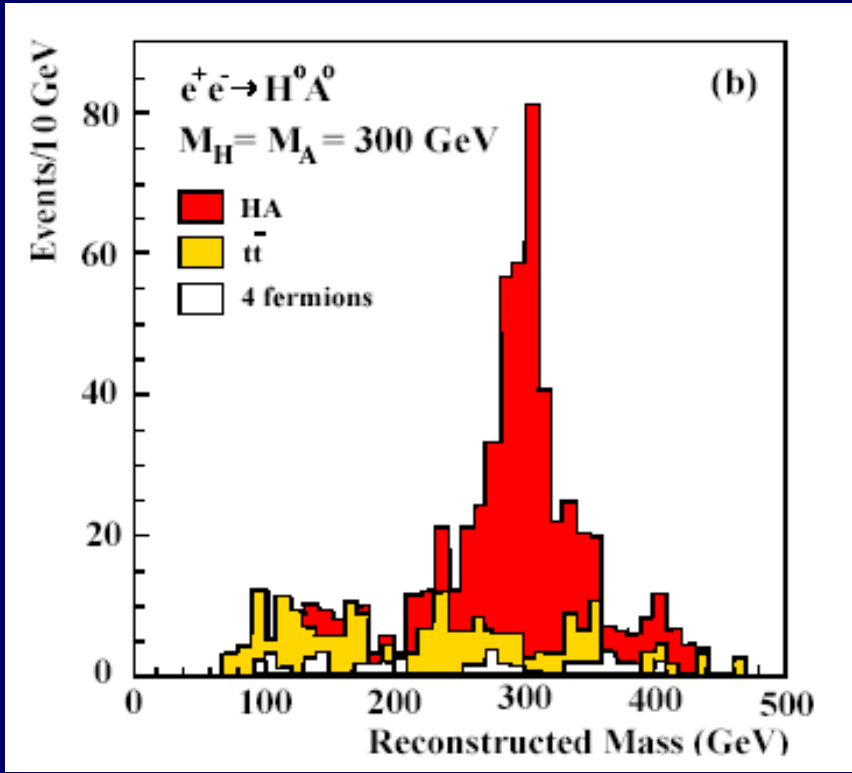
$\Delta\lambda/\lambda$=0.22 (statistical) for m_h=120 GeV
Requires 1000 fb^{-1}

Muehleittner et al.

SUSY Higgs

$\sqrt{s}$=800 GeV





$L=500\ fb^{-1}$

TESLA TDR

$L=50\ fb^{-1}$

$\Delta M \sim 1$ GeV

Supersymmetry

Supersymmetry

To prove existence of SUSY:

- Need to discover the SUSY partners
- Every SM has a superpartner
- Spins of SM/SUSY partner differ by ½
- Identical gauge quantum numbers
- Identical couplings

Needs accurate measurements of

Mass spectra, cross-sections, BRs,

Angular distributions, polarisation asymmetries

SUSY Reference Points

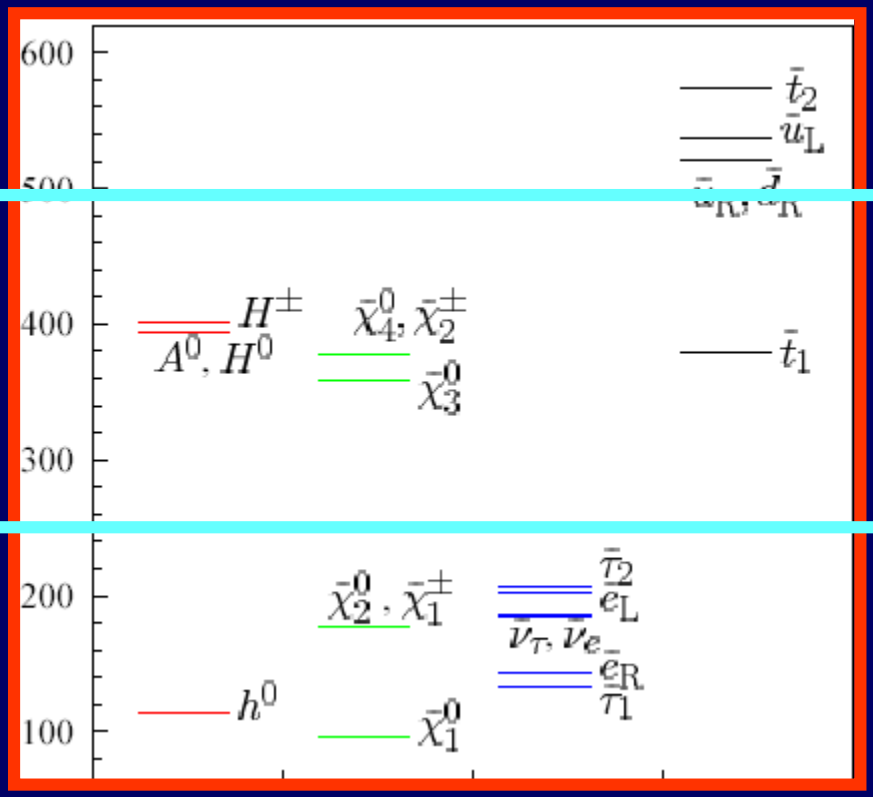
Work with Sugra SPS1a:

$M_{1/2}$=250 GeV M_0=100 GeV

A0=-100 GeV sign(μ)=+ tanβ=10

√s=1TeV

√s=500 GeV



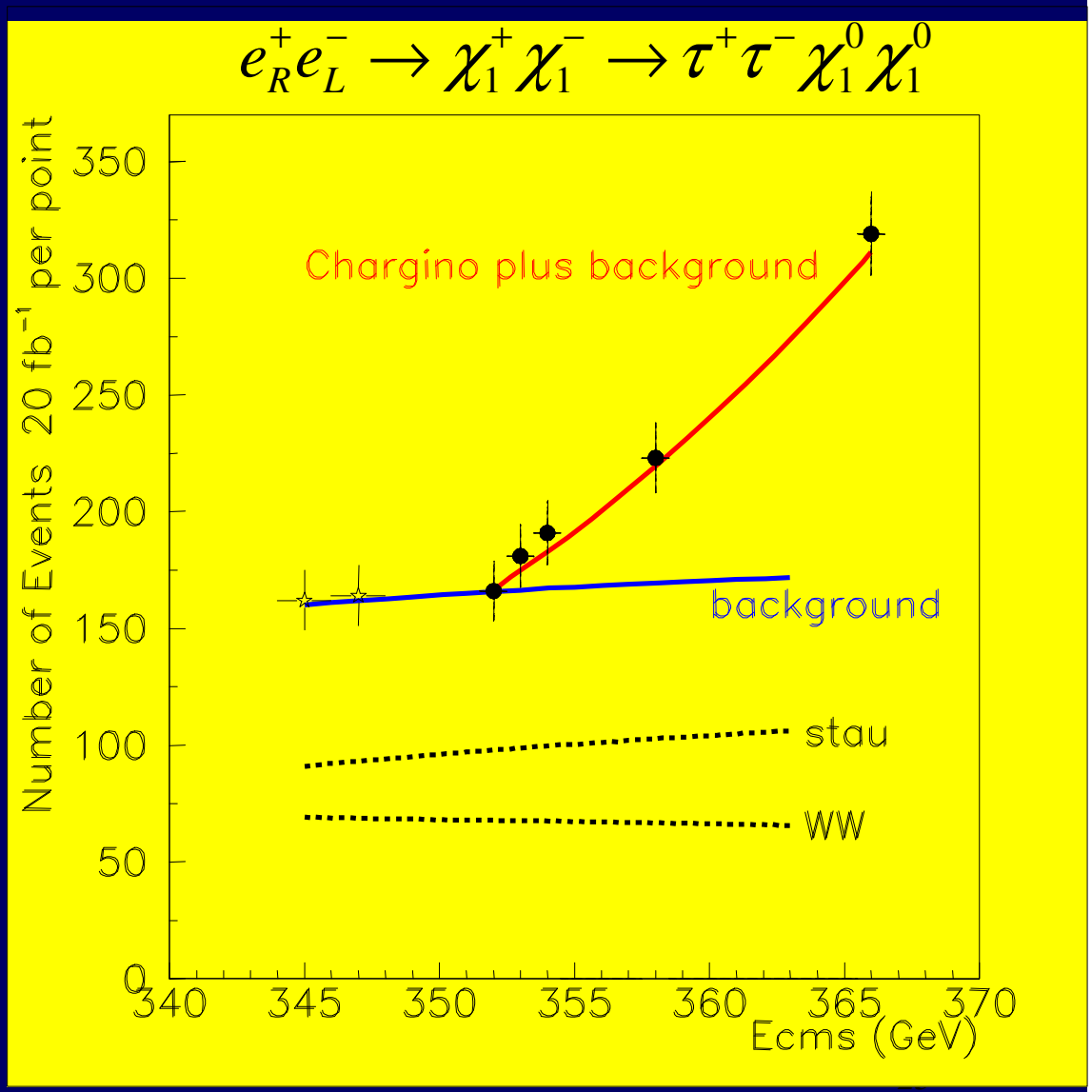
Higgs gauginos sleptons squarks

Mass Measurements

Threshold scans
chargino ~ β
slepton ~ β^3

100 fb^{-1}

$$m_{\chi^{\pm}} = 181.5 \pm 0.55$$

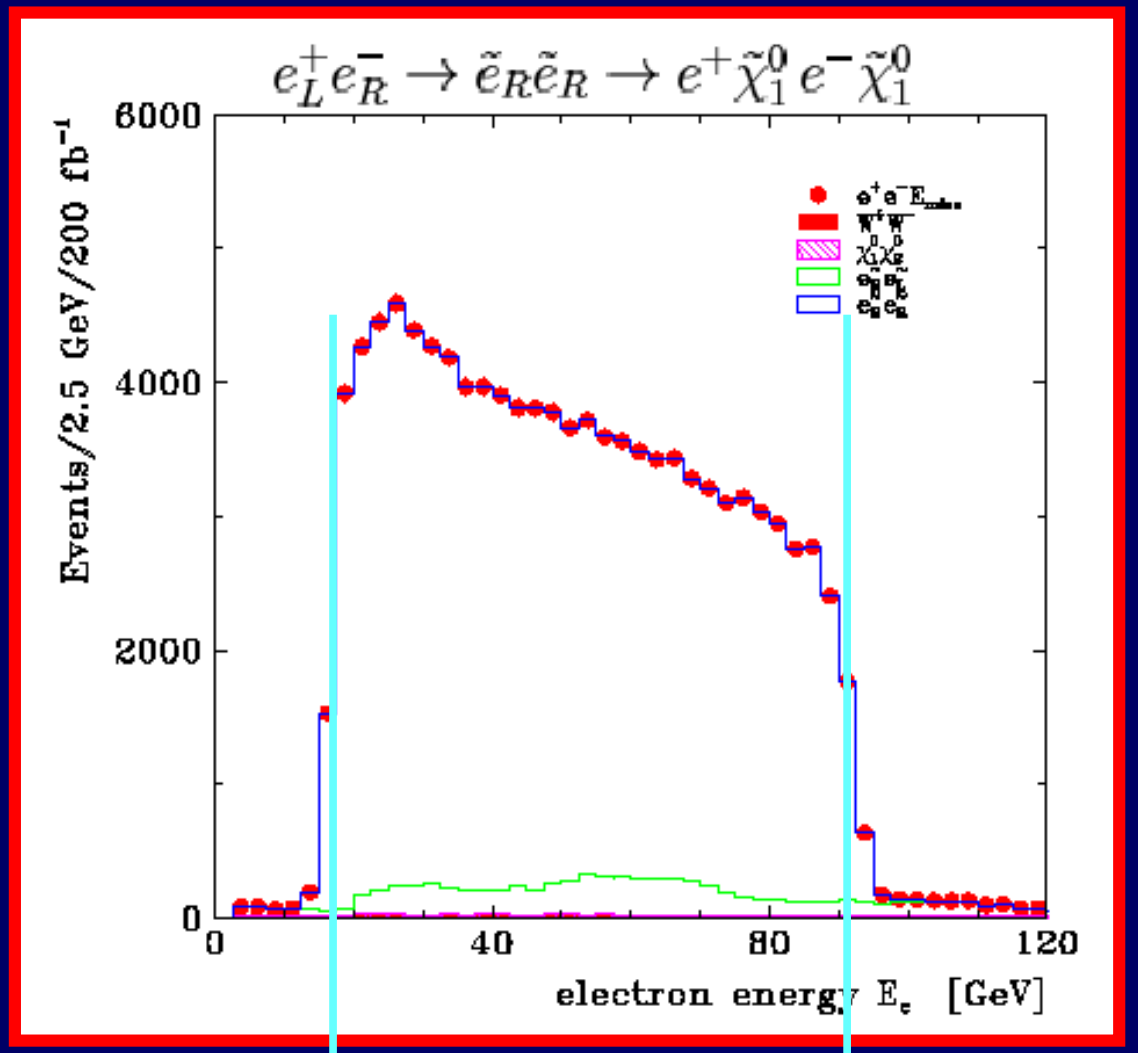


Martyn et al.

Endpoint Measurements

$\sqrt{s}$=400 GeV
L=200 fb^{-1}

$\Rightarrow$ **Both** sparticle masses



SPS1a:

LC Threshold

LC Endpoint

e^-e^- Threshold

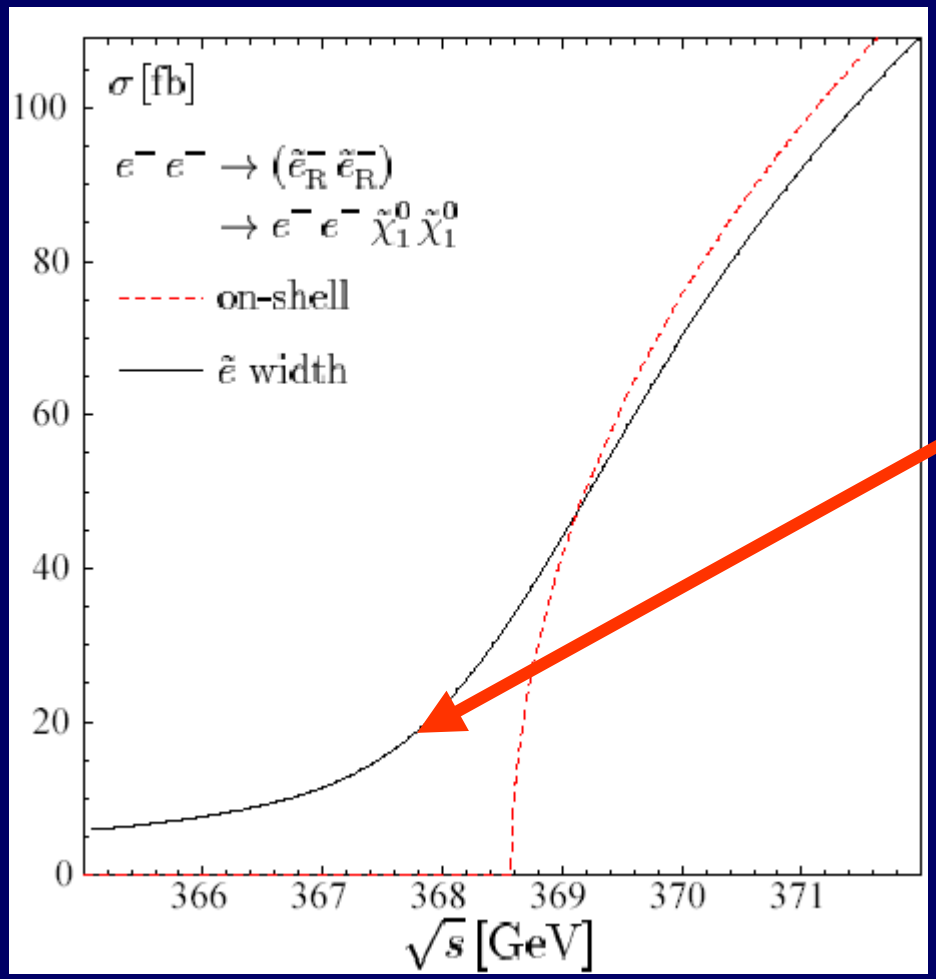
LHC+LC

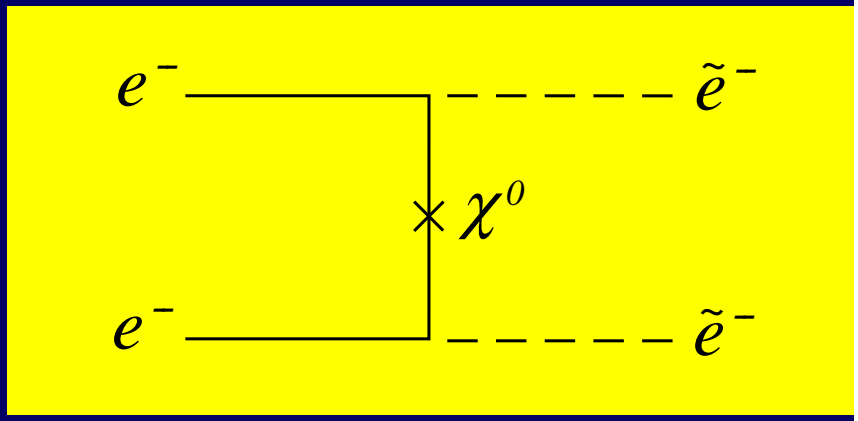
(Preliminary)

Martyn, Polesello
Porod, Zerwas, GB

	Mass, ideal	"LHC"	"LC"	"LHC+LC"
$\tilde{\chi}_1^\pm$	181.5	–	0.55	0.55
$\tilde{\chi}_2^\pm$	381.2	–	3.0	3.0
$\tilde{\chi}_1^0$	97.7	8.4	0.05	0.05
$\tilde{\chi}_2^0$	183.0	8.2	1.2	0.08
$\tilde{\chi}_3^0$	363.3	–		
$\tilde{\chi}_4^0$	381.0	8.9		2.0
$\tilde{e}_R$	143.9	8.4	0.05	0.05
$\tilde{e}_L$	206.6	8.8	0.2	0.2
$\tilde{\nu}_e$	190.5	–	0.7	0.7
$\tilde{\mu}_R$	143.8	8.4	0.2	0.2
$\tilde{\mu}_L$	206.6	8.8	0.5	0.5
$\tilde{\nu}_\mu$	190.4	–		
$\tilde{\tau}_1$	134.5	8.6	0.3	0.3
$\tilde{\tau}_2$	210.4	–	1.1	1.1
$\tilde{\nu}_\tau$	189.6	–	–	–
$\tilde{u}_R$	547.8	13.6	–	7.4
$\tilde{u}_L$	564.9	13.8	–	3.3

e^-e^- running



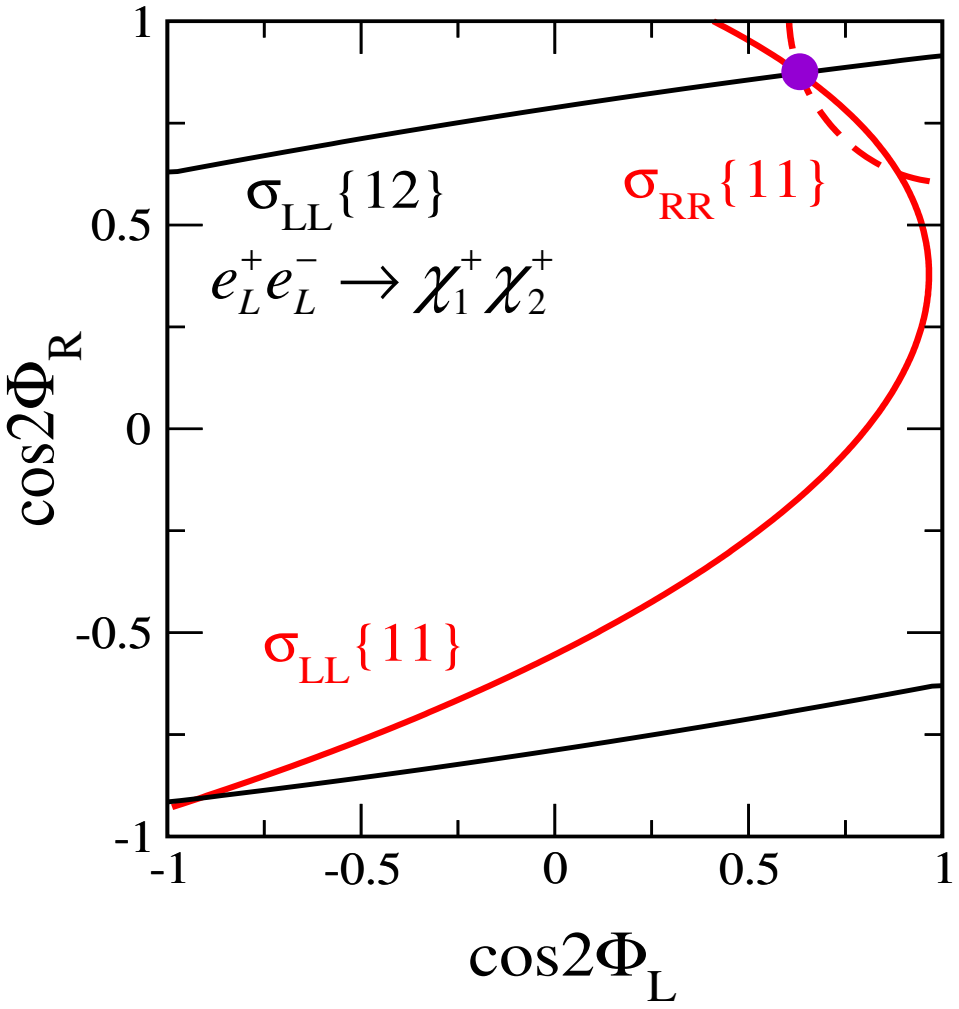


Including width effects

$\Delta m \sim 50$ MeV for 4 fb^{-1}

Freitas, Miller, Zerwas

Feng, Peskin



$$\begin{pmatrix} M_2 & \sqrt{2}m_W \cos\beta \\ \sqrt{2}m_W \sin\beta & \mu \end{pmatrix}$$

$$\cos 2\phi_L = 0.645 \pm 0.020$$
$$\cos 2\phi_R = 0.844 \pm 0.005$$

For mSugra:
M_0=100 GeV $M_{1/2}$=200 GeV
tanβ=3 sign(μ)=+

Using 2× 500 fb-1
at √s=800 GeV

Luminosity Budget

Beams	Energy	Pol.	$\int \mathcal{L}dt$	$\left[\int \mathcal{L}dt\right]_{\rm equiv}$	Comments
e^+e^-	500	L/R	335	335	Sit at top energy for sparticle masses
e^+e^-	M_Z	L/R	10	45	Calibrate with Z's
e^+e^-	270	L/R	100	185	Scan $\tilde{\chi}_1^0\,\tilde{\chi}_2^0$ threshold (L pol.) Scan $\tilde{\tau}_1\,\tilde{\tau}_1$ threshold (R pol.)
e^+e^-	285	R	50	85	Scan $\tilde{\mu}_R^+\,\tilde{\mu}_R^-$ threshold
e^+e^-	350	L/R	40	60	Scan $t\bar{t}$ threshold Scan $\tilde{e}_R\,\tilde{e}_L$ threshold (L & R pol.) Scan $\tilde{\chi}_1^+\,\tilde{\chi}_1^-$ threshold (L pol.)
e^+e^-	410	L	60	75	Scan $\tilde{\tau}_2\,\tilde{\tau}_2$ threshold Scan $\tilde{\mu}_L^+\,\tilde{\mu}_L^-$ threshold
e^+e^-	580	L/R	90	120	Sit above $\tilde{\chi}_1^\pm\,\tilde{\chi}_2^\mp$ threshold for $\tilde{\chi}_2^\pm$ mass
e^-e^-	285	RR	10	95	Scan with e^-e^- collisions for $\tilde{e}_R$ mass

Grannis et al.

- Several running modes requried.
- Input will already exist from LHC

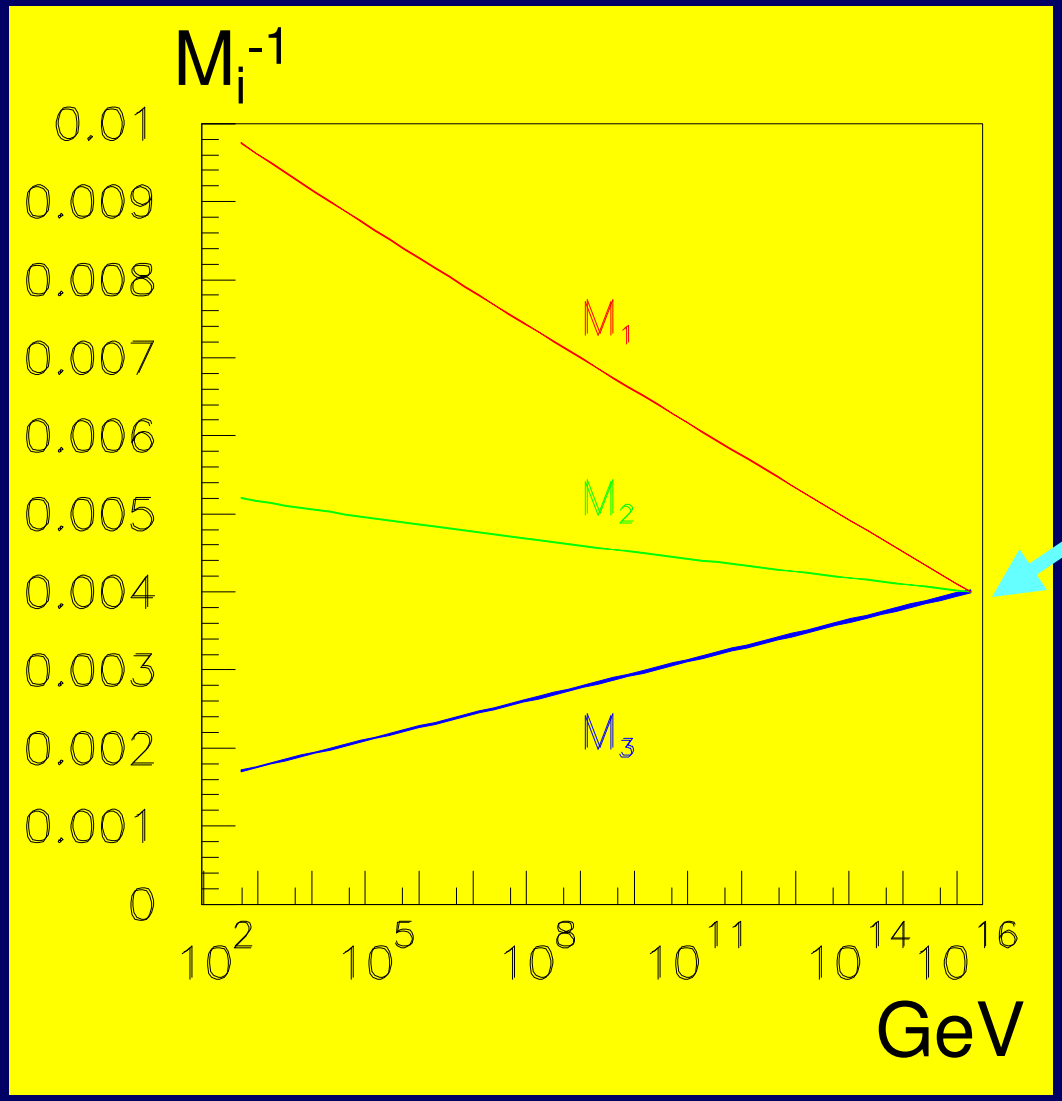
Model-Independent Extrapolation

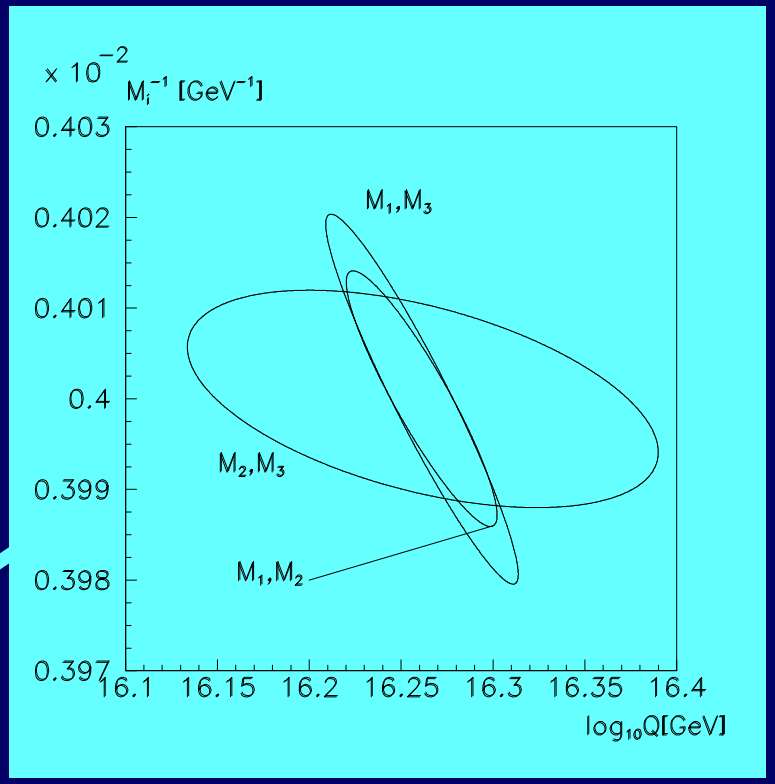
Renormalisation Group Eqns

$$\frac{\partial P_i}{\partial Q} = f(P_i, m_j, g_k, \ldots)$$

- Measure complete spectrum
- Extract soft SUSY parameters at EW scale
- Input measured masses, couplings into RGEs
- Extrapolate model independently to high scales

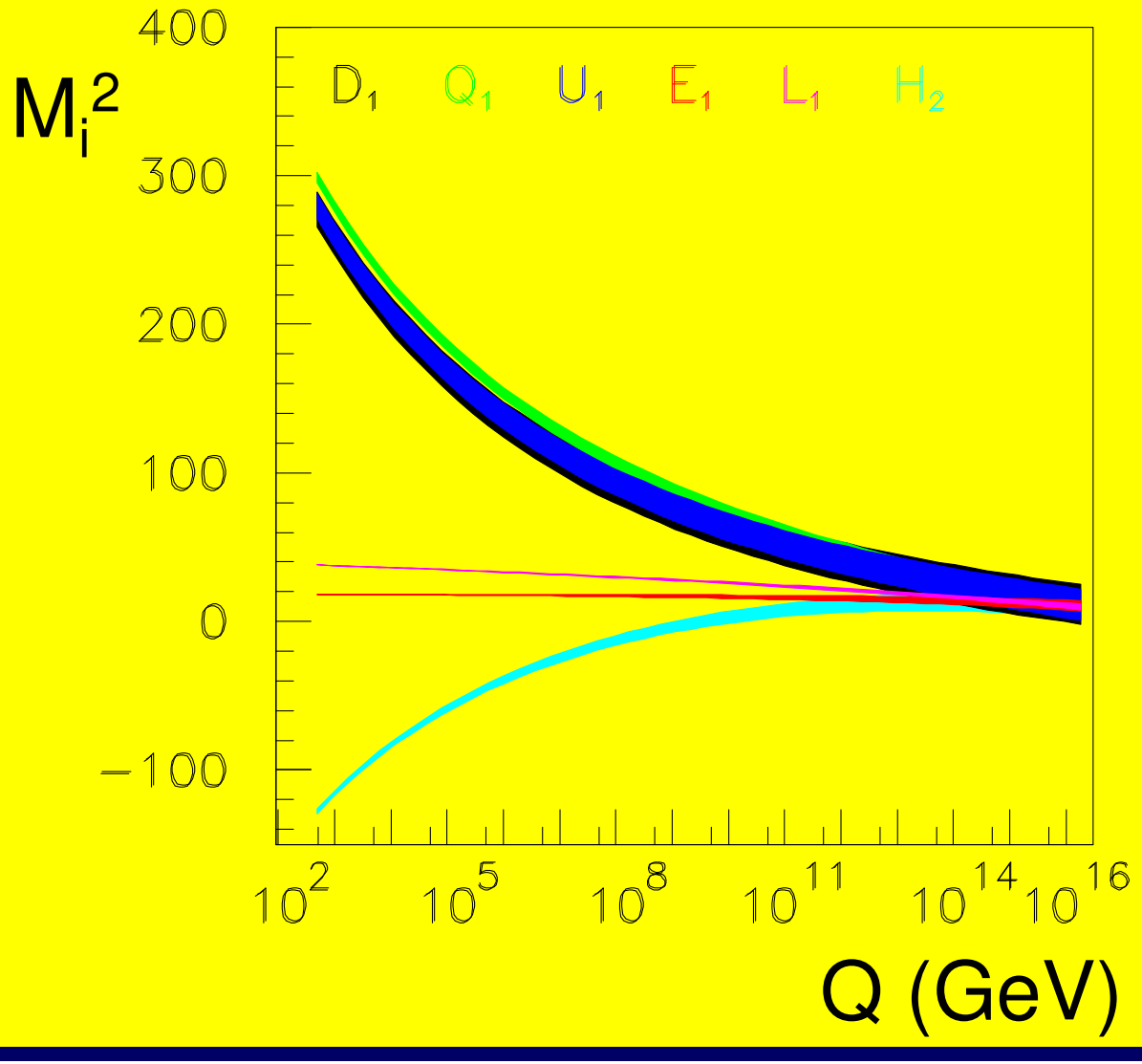
Extrapolation: gaugino





Porod, Zerwas, GB

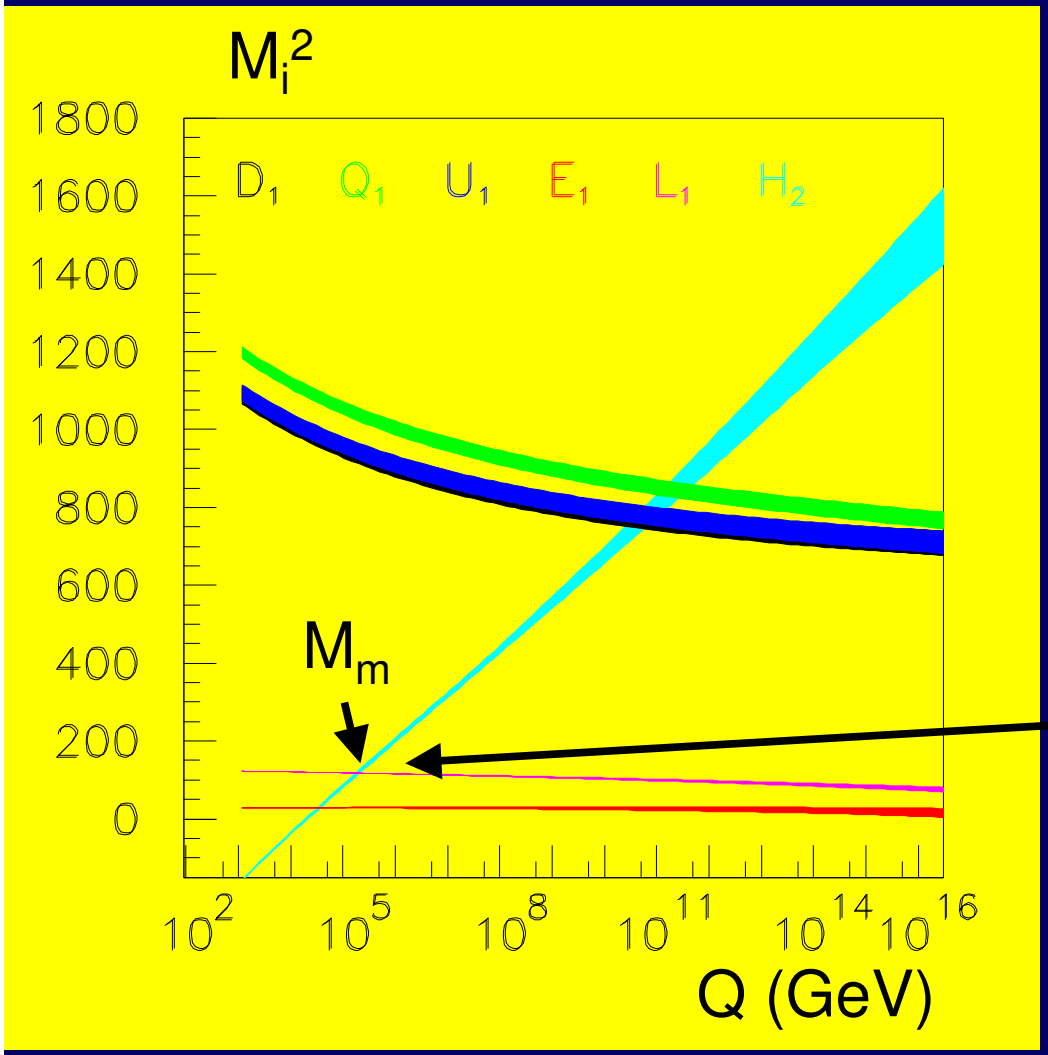
Extrapolations sfermion mass terms

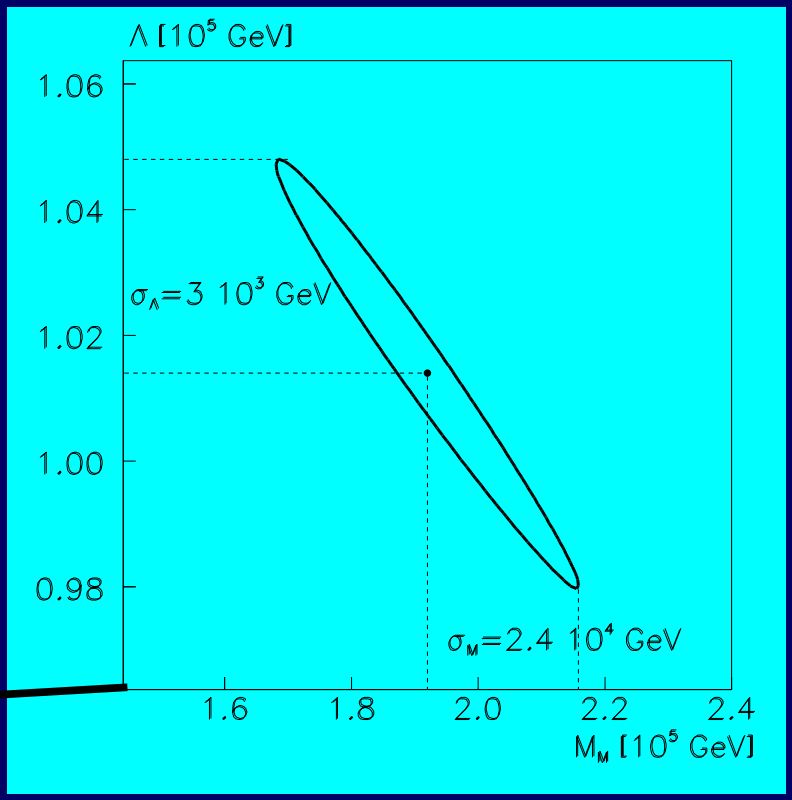


mSUGRA structure **reconstructed**

Fine structure?

GMSB





GMSB reconstructed
Messenger Scale measured

M_m=200 TeV, Λ=100 TeV, N_5=1, tanβ=15 sign(μ)=+

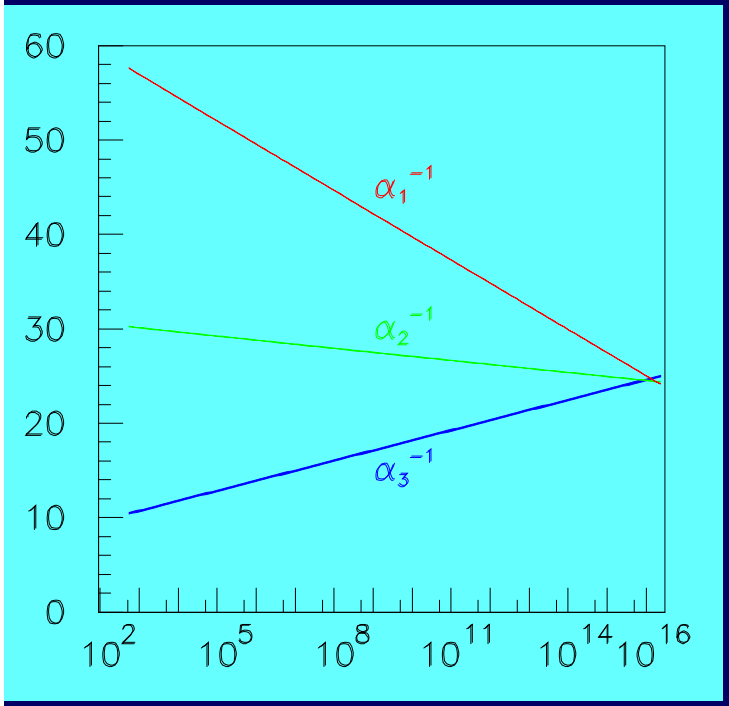
GigaZ

GigaZ

- The LC can also provide high luminosity running at the Z-pole and at W-threshold
- Approximately 100 fb^{-1} per year
- Needs specific linac bypass design

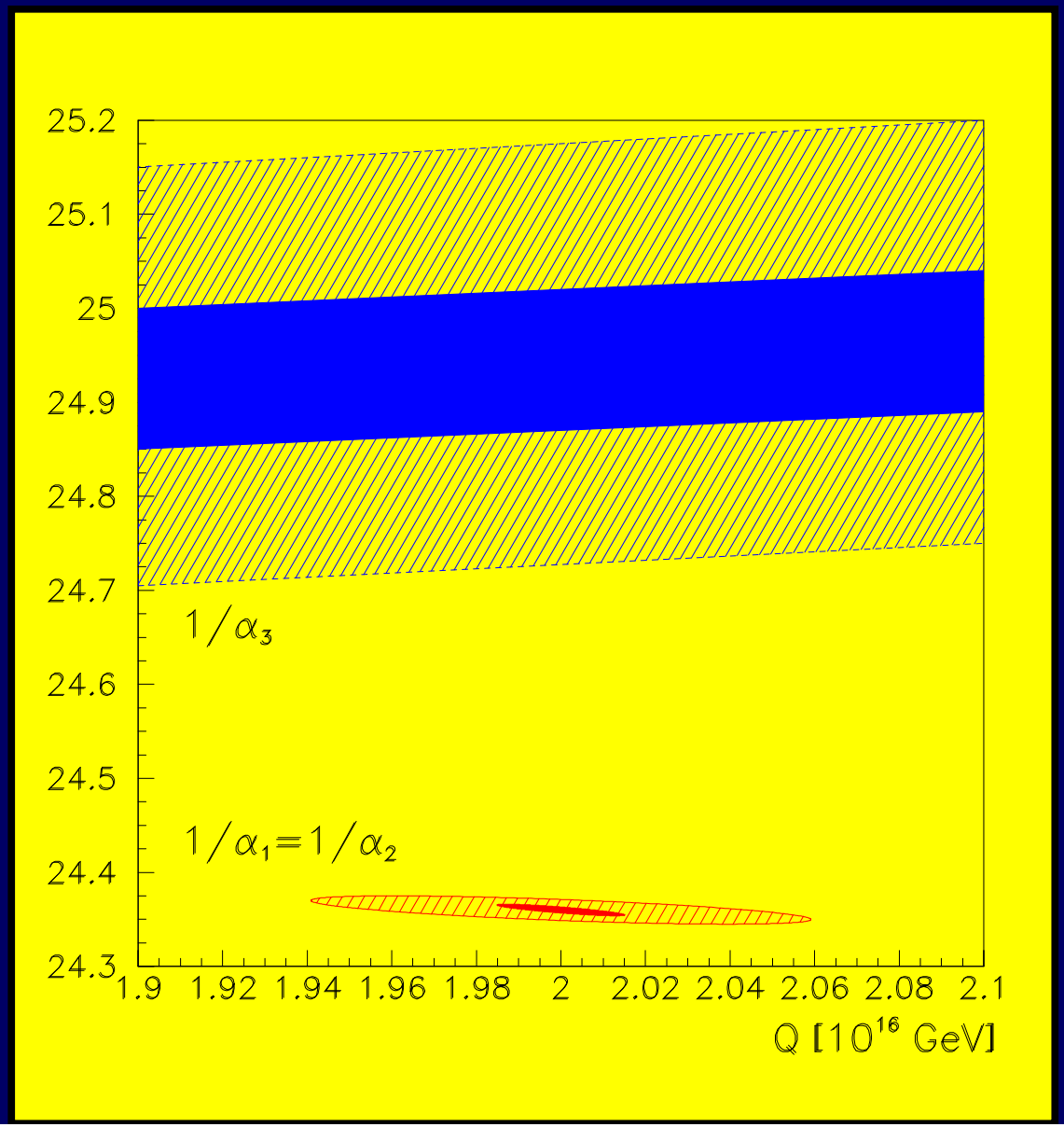
	LEP/SLC/Tev [19]	TESLA
$\sin^2\theta^\ell_{\rm eff}$	0.23146 ± 0.00017	± 0.000013
lineshape observables:		
M_Z	$91.1875 \pm 0.0021\,\mathrm{GeV}$	$\pm 0.0021\,\mathrm{GeV}$
$\alpha_s(M_Z^2)$	0.1183 ± 0.0027	± 0.0009
$\Delta\rho_\ell$	$(0.55 \pm 0.10) \cdot 10^{-2}$	$\pm 0.05 \cdot 10^{-2}$
N_ν	2.984 ± 0.008	± 0.004
heavy flavours:		
$\mathcal{A}_{\rm b}$	0.898 ± 0.015	± 0.001
$R^0_{\rm b}$	0.21653 ± 0.00069	± 0.00014
M_W	$80.436 \pm 0.036\,\mathrm{GeV}$	$\pm 0.006\,\mathrm{GeV}$

Unification of Gauge Couplings

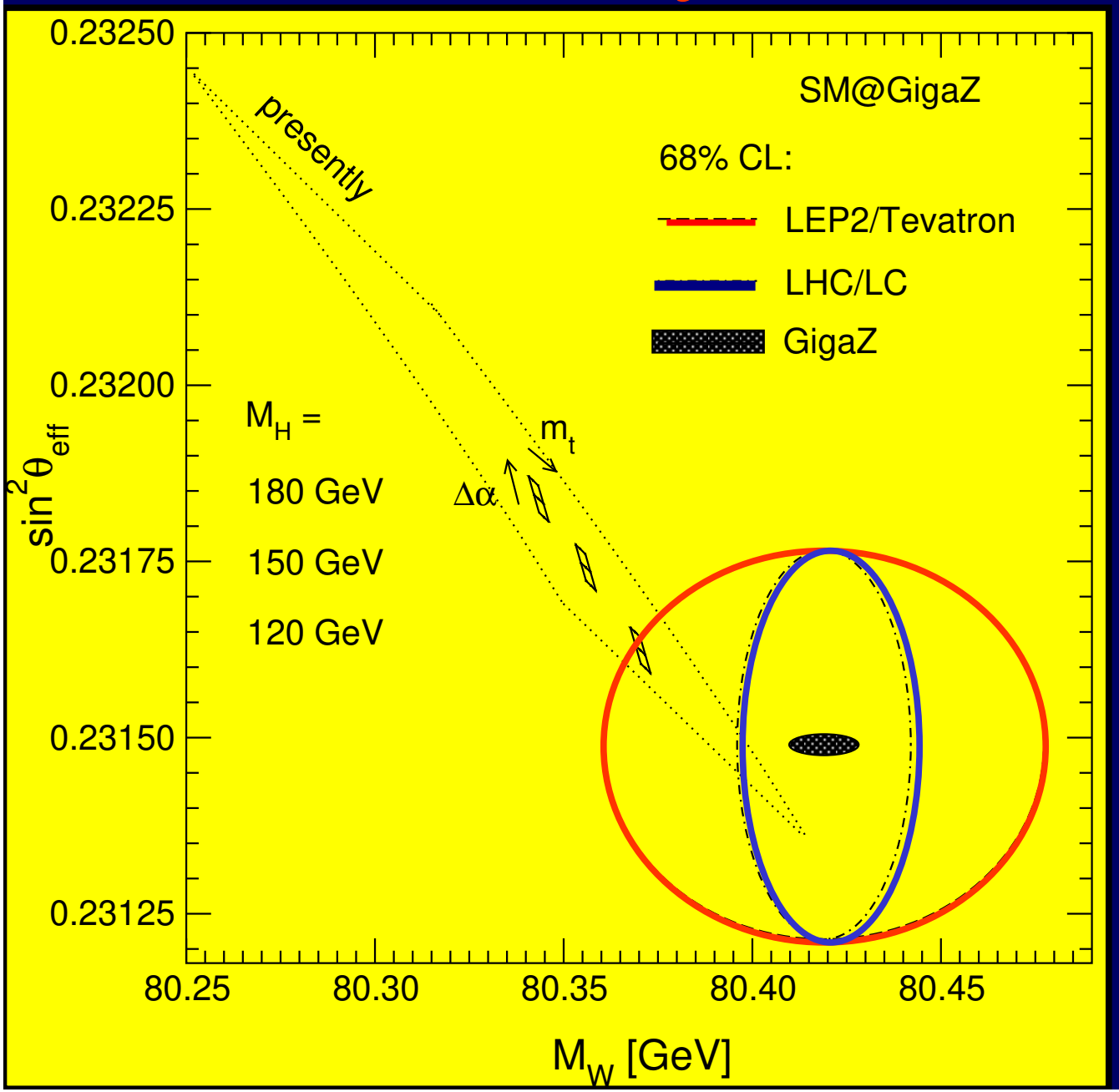


Improved measurement of GUT scale

Heavy Threshold effects eg colour triplet higgs …



Consistency of SM variables



Erler, Heinemeyer
Hollick, Weiglein,
Zerwas

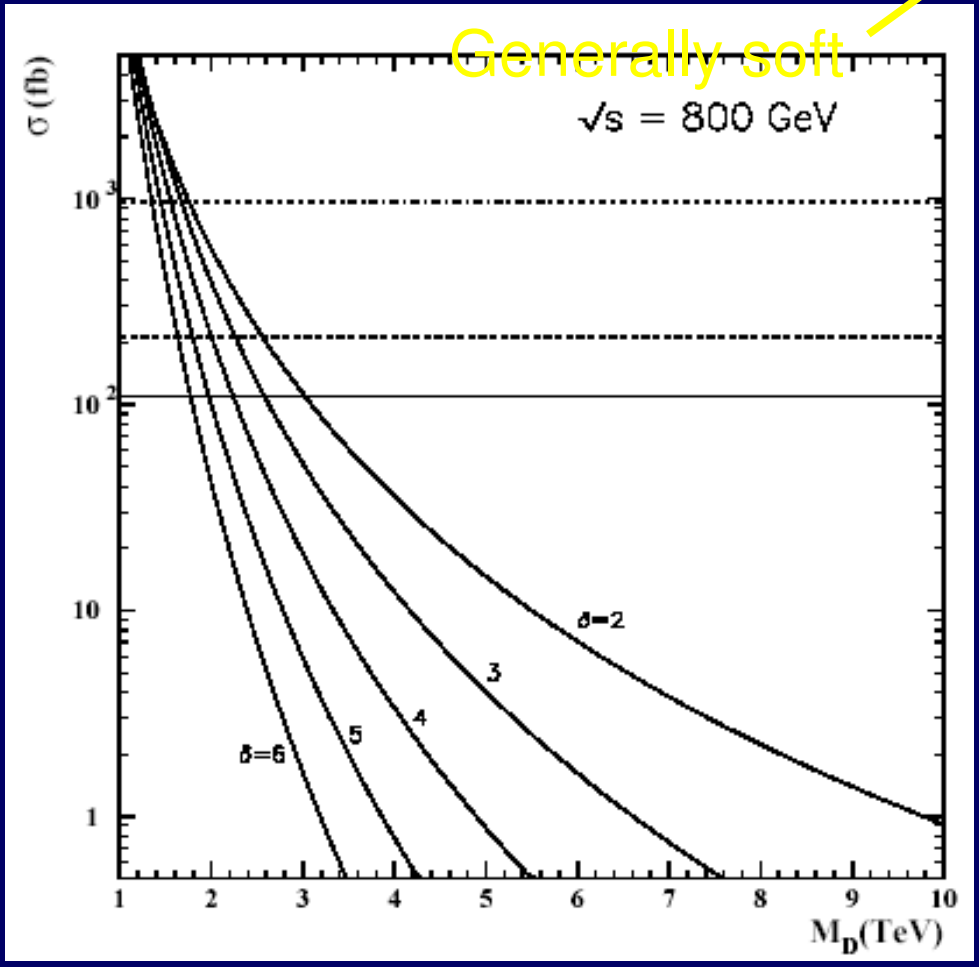
Extra Dimensions

Extra Dimensions

$$e^+e^- \rightarrow \gamma G$$

Generally soft

Escapes into bulk
⇒ missing energy

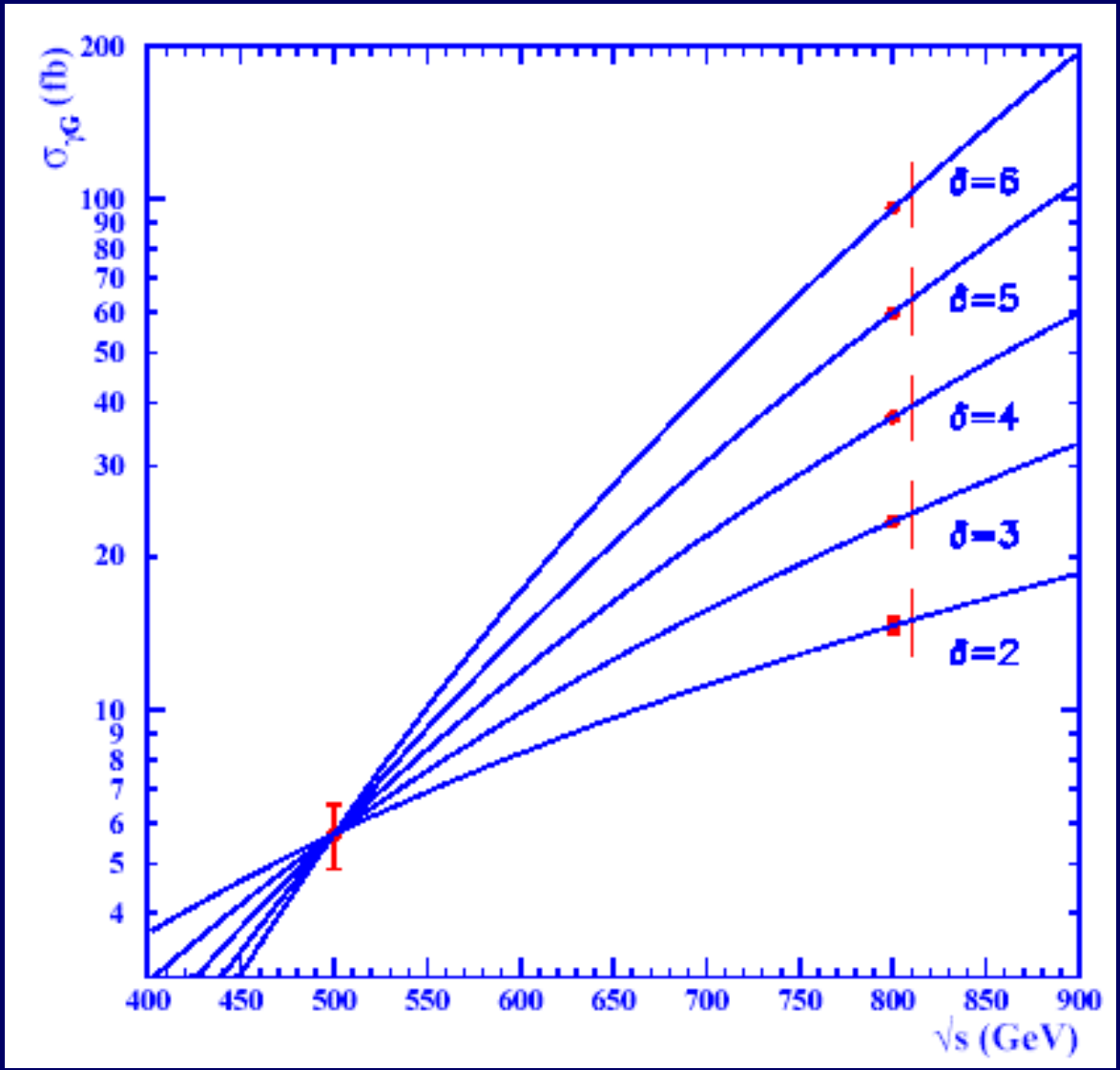


$$M_{pl}^2 = V_\delta M_D^{2+\delta}$$

$$\sigma \propto (\sqrt{s})^\delta$$

Assumes:
P(e-) =80%; P(e+) 60%

Measuring number of Dims.



Runs at two energies:
Measures δ
Tests √s dependence

Wilson

Summary

- The linear collider will provide high precision measurements at high energy: Masses, chiral couplings, branching ratios…
- Together with LHC data, LC allows model-independent extrapolations to very high energy scales.
- Structure of the theory at GUT scale may be complex and require high precision to discover.
- Exciting overlap with LHC analyses complementary searches, constraints in cascades…
- Long term programme from O(1) TeV, GigaZ, $\gamma\gamma$, multi TeV …

… and an exciting one!