Physics at the ILC

Peter Wienemann
University of Freiburg

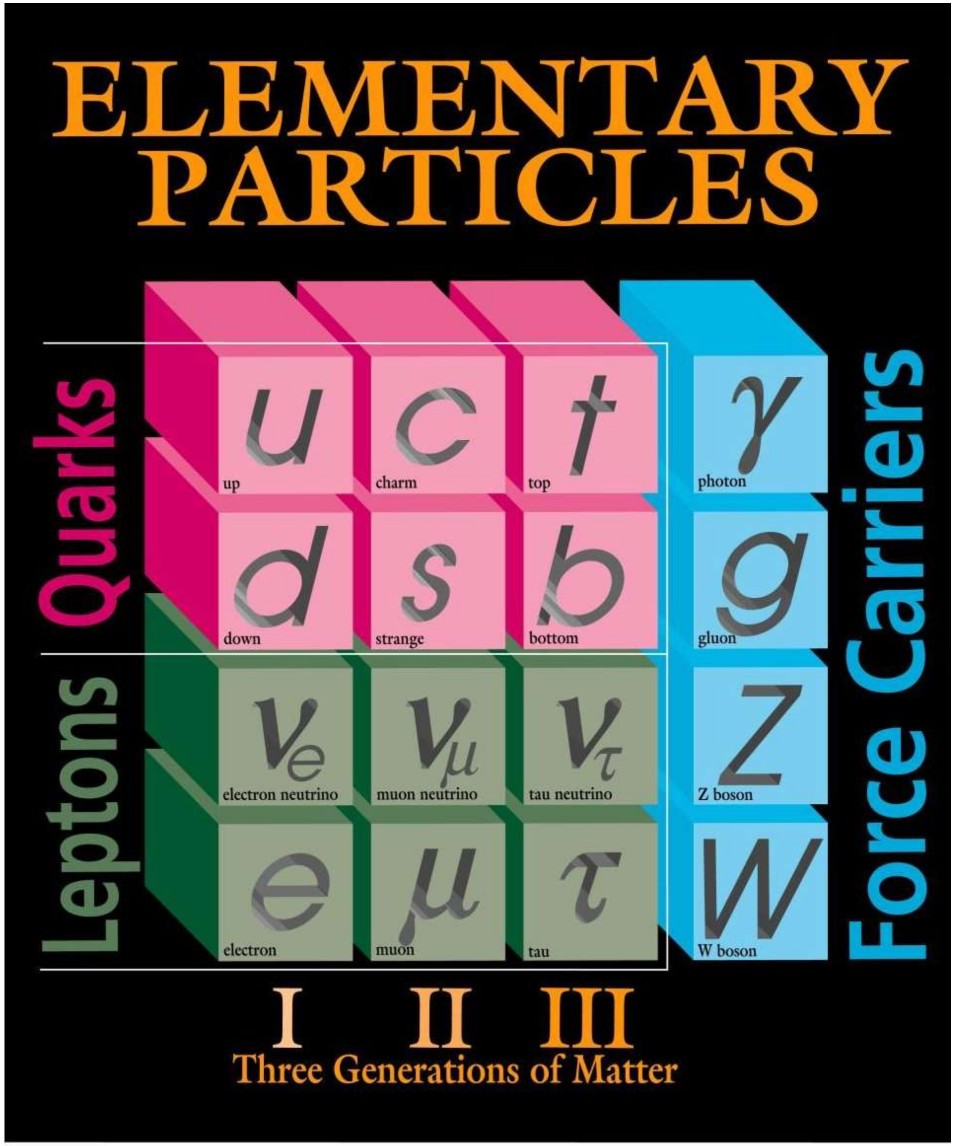
ILC Summer School 2005
Tsinghua University
Beijing, China

Lecture overview

- Introduction to SM – some SM highlights – shortcomings and what the ILC can do about them
- Higgs Physics
- Supersymmetry
- Physics beyond the SM besides SUSY
- Synergy between LHC and ILC

Standard Model of particle physics

Standard Model of particle physics



Fermilab 95-759

Two pillars: Glashow-Salam-Weinberg theory (electroweak forces) and QCD (strong forces)

Common approach to describe interactions between constituents of matter: gauge invariance

Self-consistent at the level of quantum corrections

Successes of SM

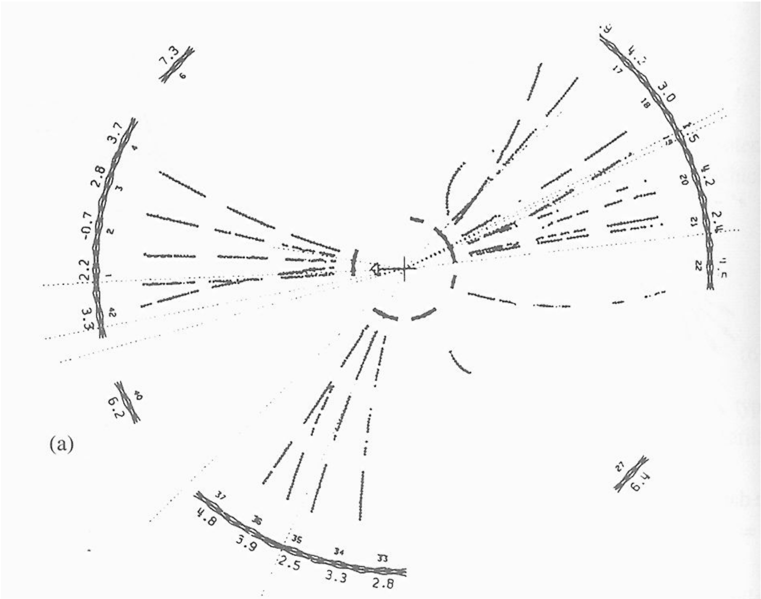
GSW model was developed in the 1960s (Glashow, Salam, Weinberg), QCD in the early 1970s (Gross, Politzer, Wilczek, Fritzsch, ...)

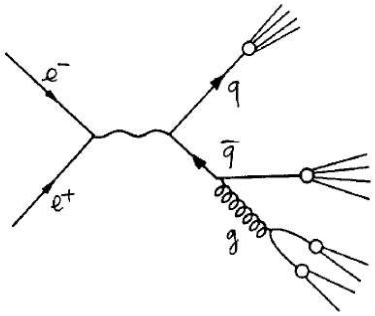
Since then the Standard Model has undergone many stringent experimental tests and it “survived” all of them

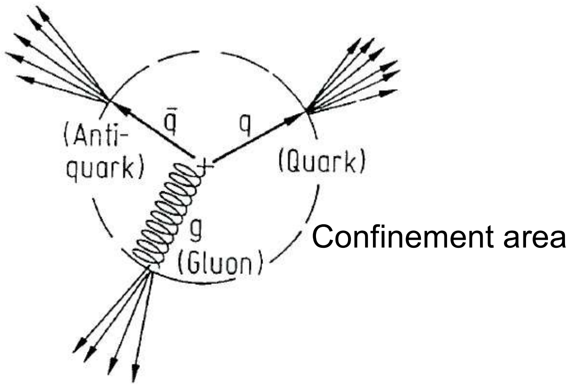
→ extremely successful theory

Here are *some* highlights (no exhaustive list) ...

Discovery of the gluon

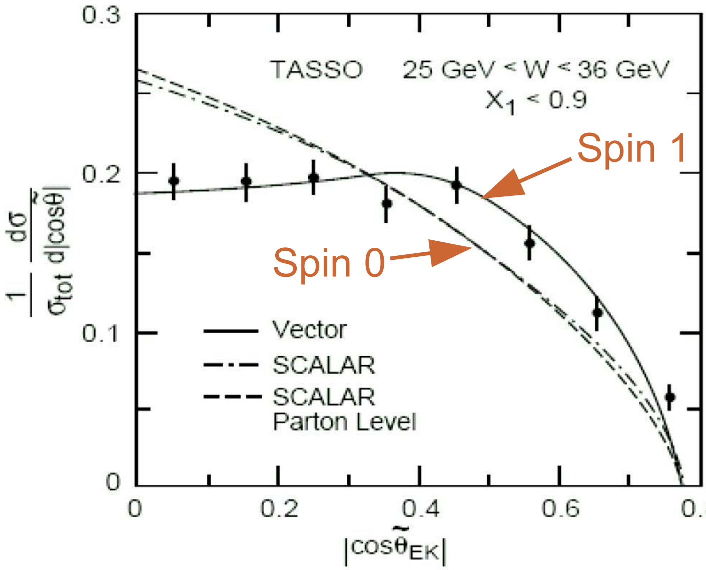




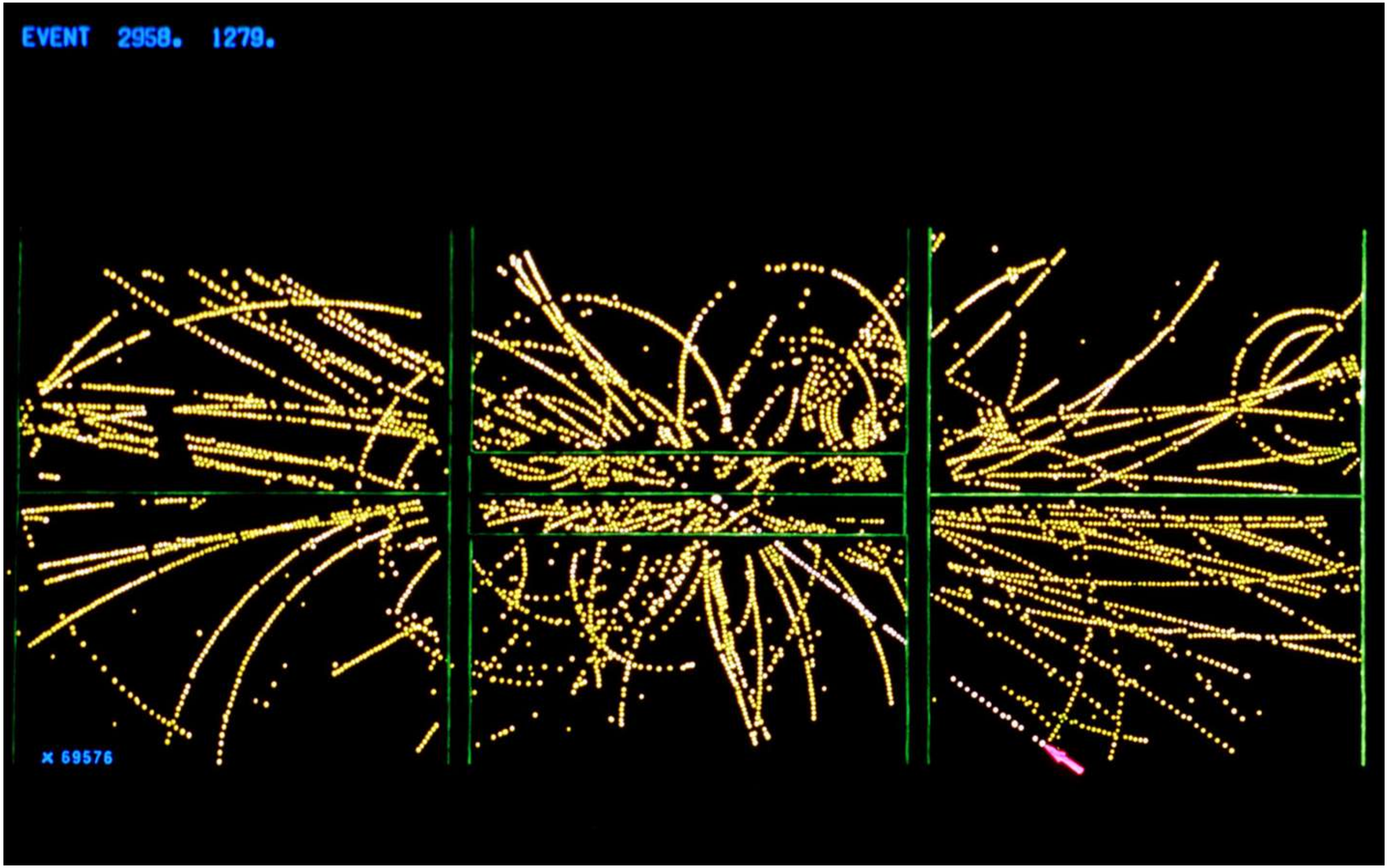


Three-jet event observed in the JADE detector at PETRA storage ring (1979)

Determination of gluon spin with the TASSO experiment at PETRA



Discovery of the W boson

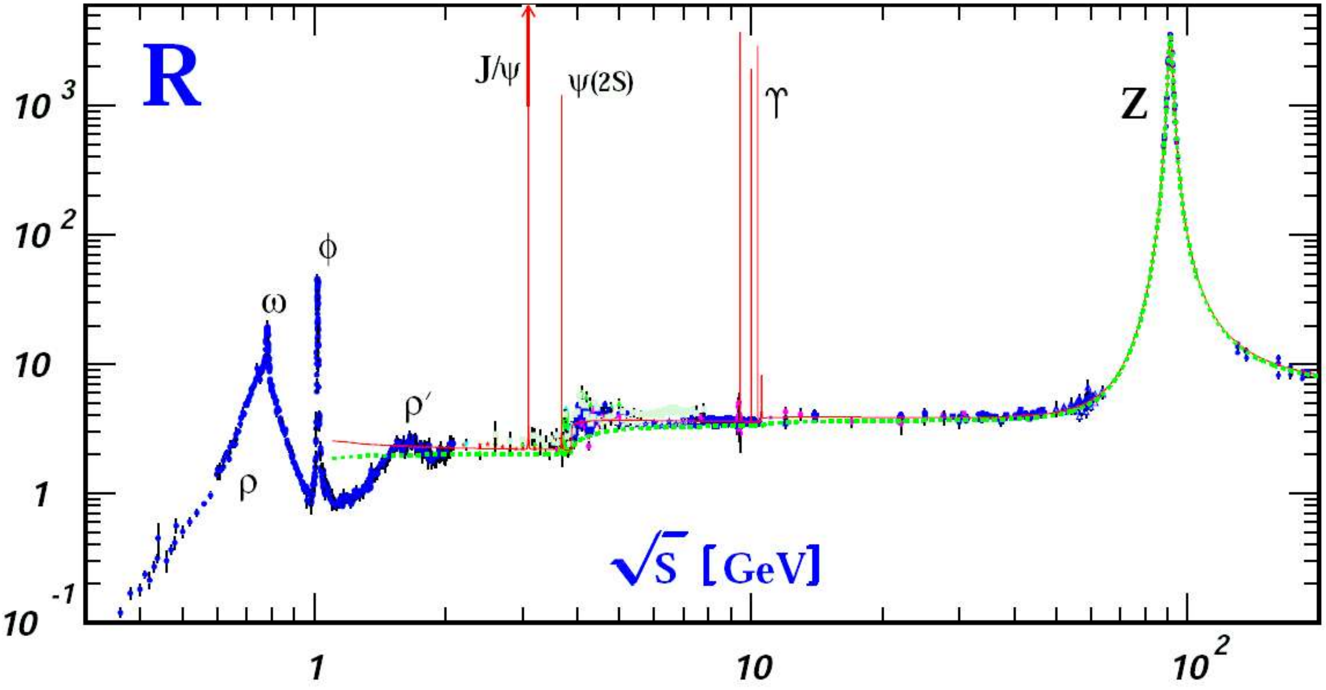


Discovery of the W boson in the UA1 detector (1982)

Experimental verification of color

$$R(E) = \frac{\sigma\left(e^+\,e^- \to \text{hadrons}\right)}{\sigma\left(e^+\,e^- \to \mu^+\,\mu^-\right)} = \boxed{3}\sum_f Q_f^2$$

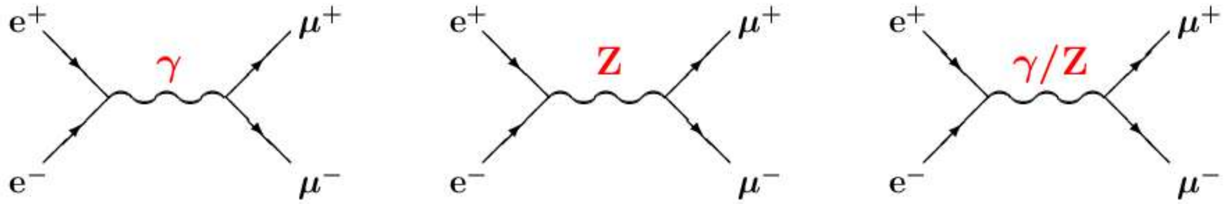
Number of colors

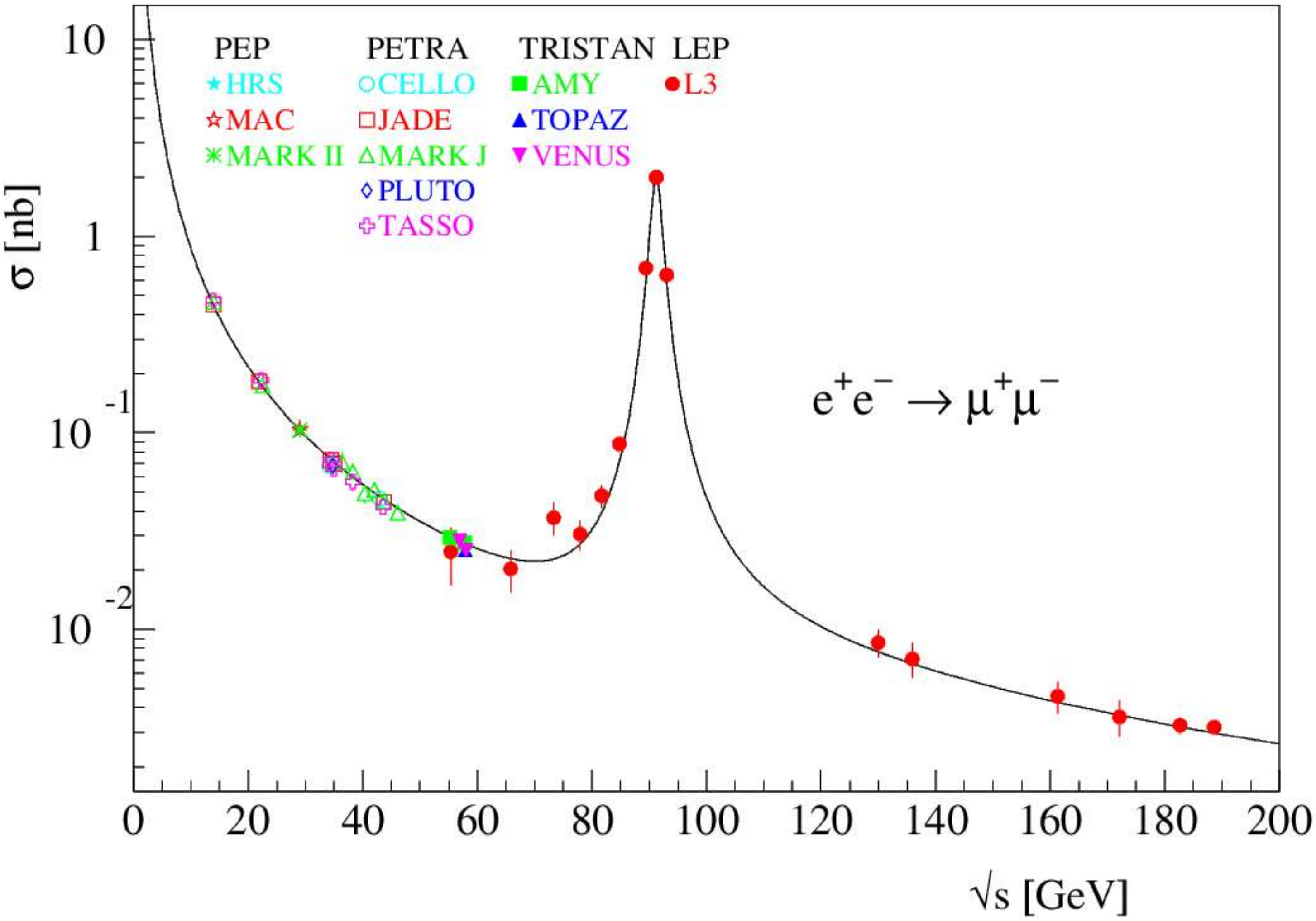


Flavor	Mass (MeV)	Q	R
u	1.5-4	$+\frac{2}{3}$	$\frac{4}{3}$
d	4-8	$-\frac{1}{3}$	$\frac{5}{3}$
s	80-130	$-\frac{1}{3}$	2
c	1150-1350	$+\frac{2}{3}$	$\frac{10}{3}$
b	4100-4400	$-\frac{1}{3}$	$\frac{11}{3}$
t	178000	$+\frac{2}{3}$	5

Expect: $2 \qquad \frac{10}{3} \qquad \frac{11}{3} \qquad 5$

e^+e^- annihilation cross-section

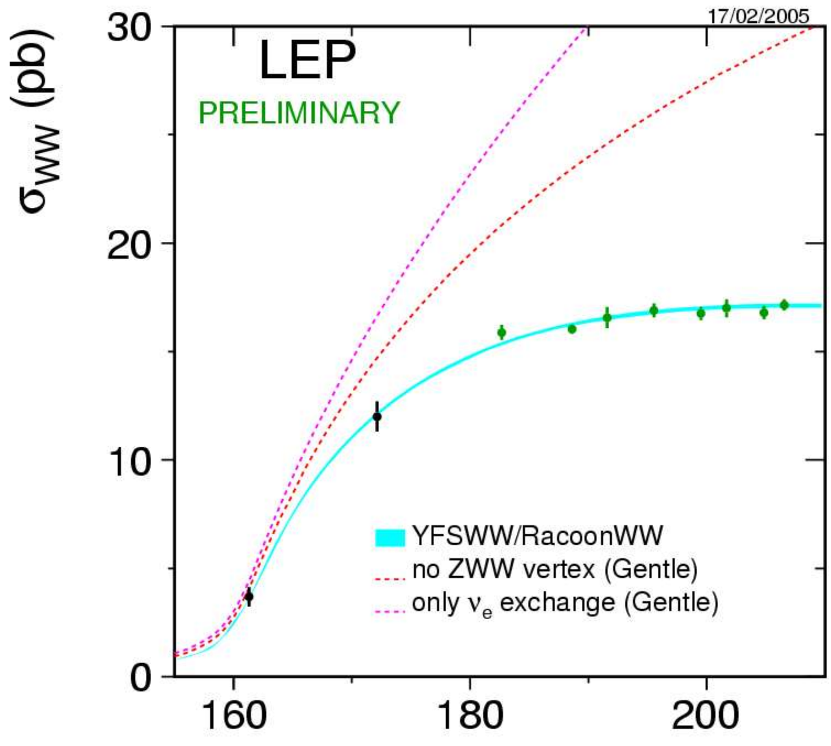


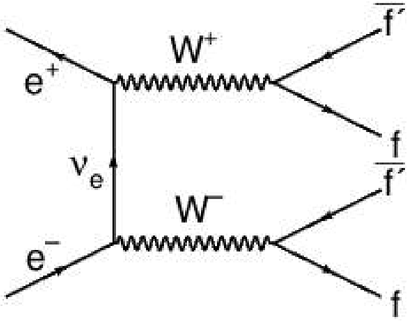


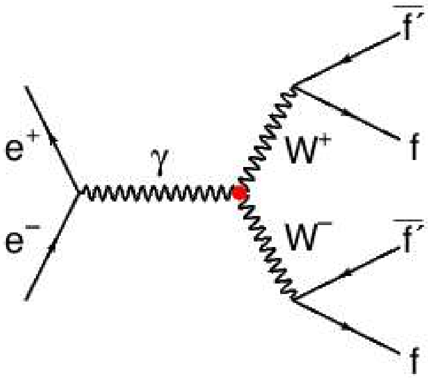
Non-abelian structure of EW theory

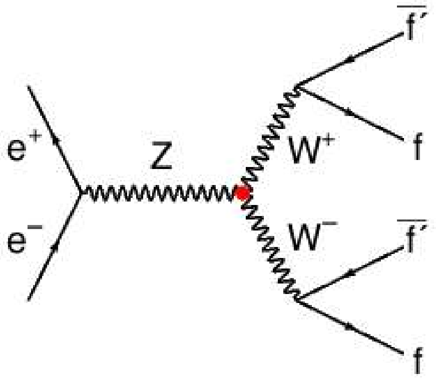
Verification of gauge vertices from $e^+e^- \to W^+W^-$ cross section at LEP (1996-2000)

Non-abelian structure of GSW theory experimentally confirmed



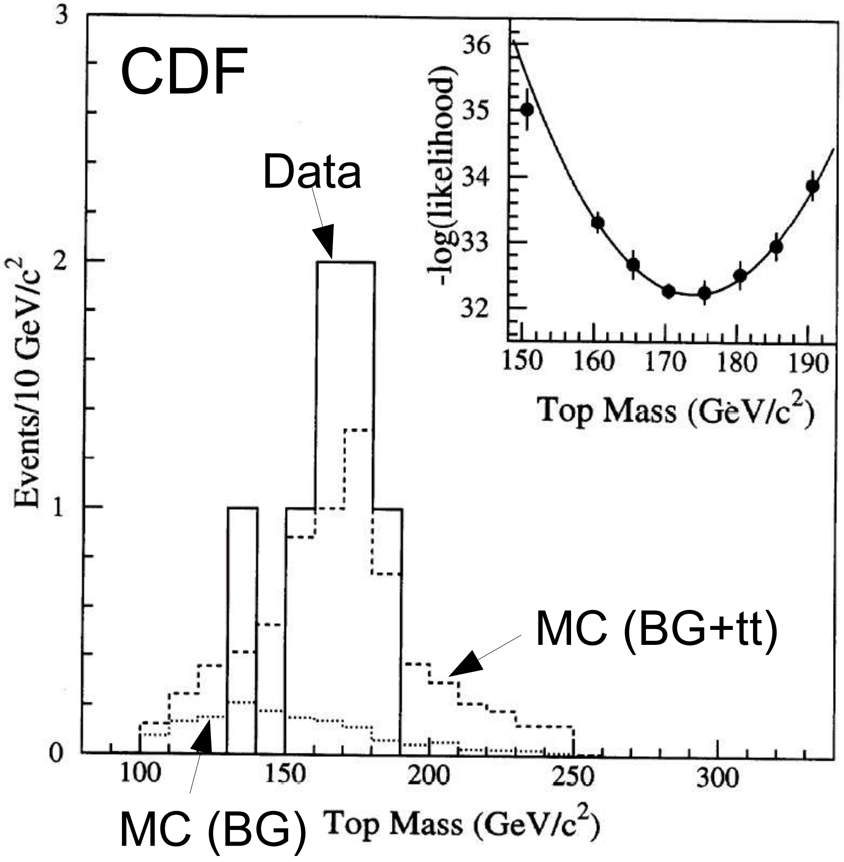


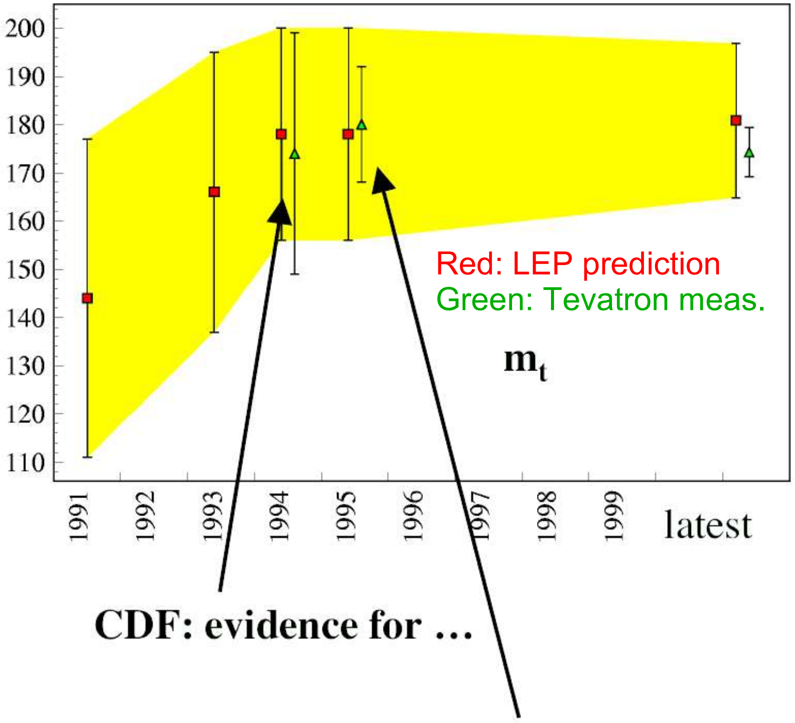




Discovery of the top quark

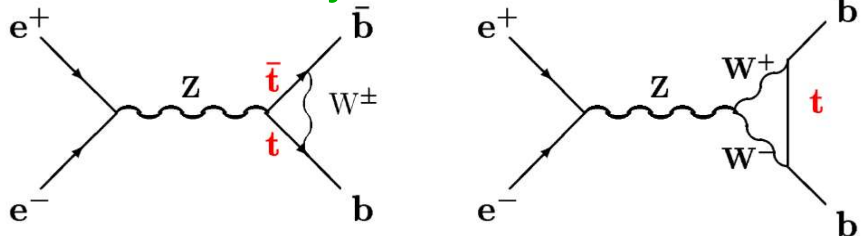
Discovery of top quark at the Tevatron collider (1994), measured top mass agrees with prediction from quantum corrections at LEP





LEP sensitivity:

observation of ...



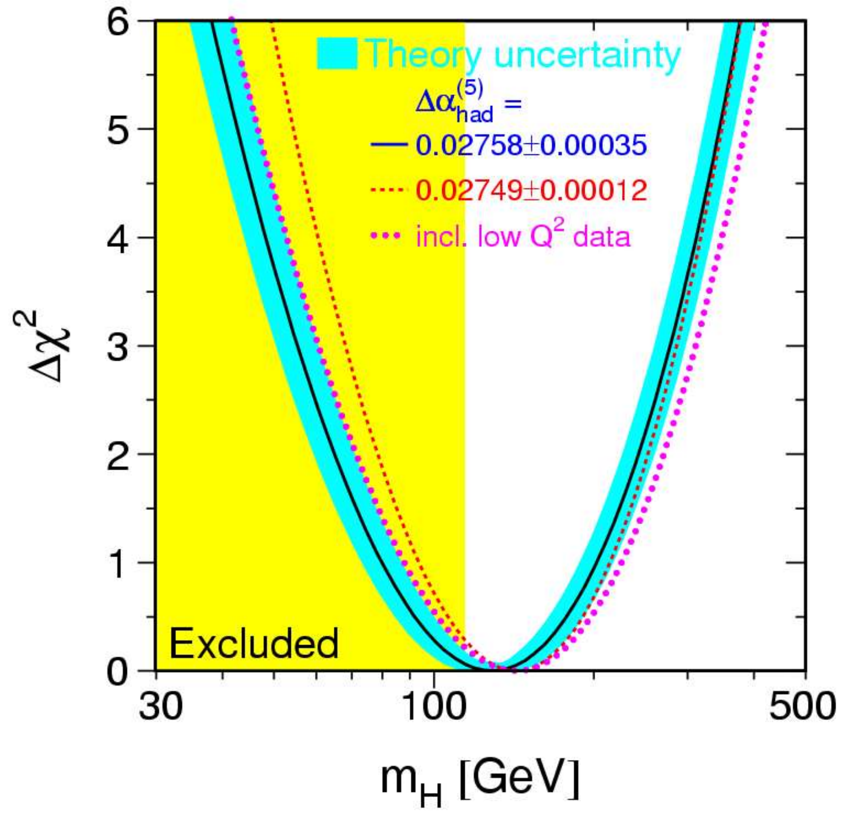
and tt vacuum polarization

Shortcomings

nice, but ...

Missing verification of EWSB

In the SM, masses are introduced by dynamical breaking of SU(2)xU(1) gauge symmetry → Higgs mechanism



Postulated Higgs boson has not yet been found

If Nature has chosen this mechanism, predictions from precision data (→ top quark) indicate a light Higgs boson

Fine-tuning problem

If a light Higgs boson is the solution:

Why is it so light?

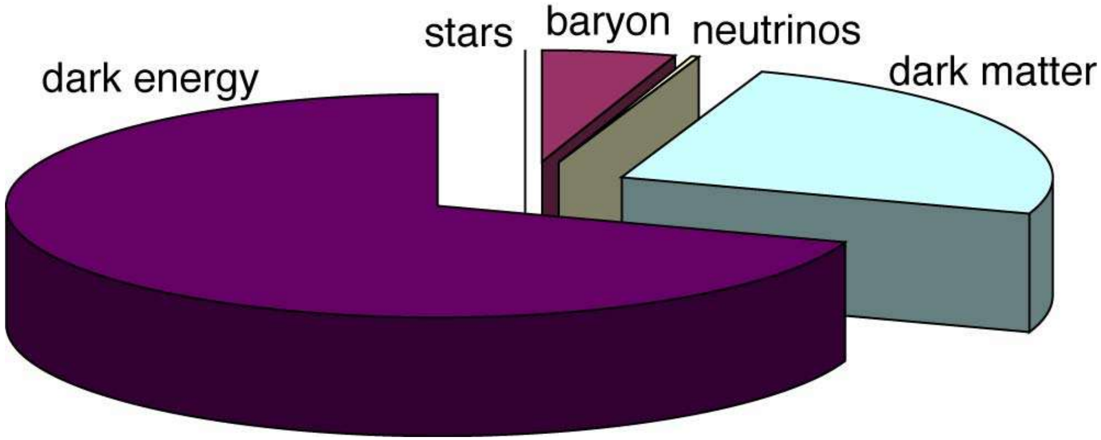
If the are no new phenomena which protect radiative corrections to the Higgs mass, it will receive un-naturally large (quadratic) corrections:

$m_H = m_{bare} - \delta m \approx 200$ GeV

m_{bare} and δm are both $\mathcal{O}(\Lambda^2)$ but almost equal

Fine-tuning

Nature of dark matter and energy



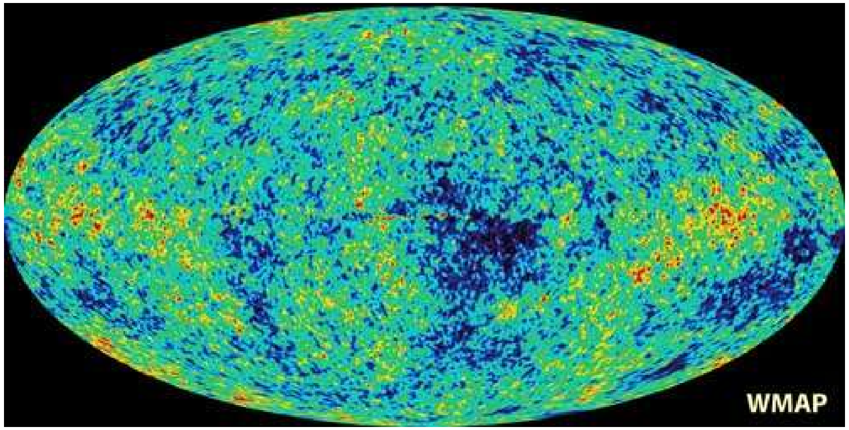
The universe:

5%   SM matter

25% dark matter

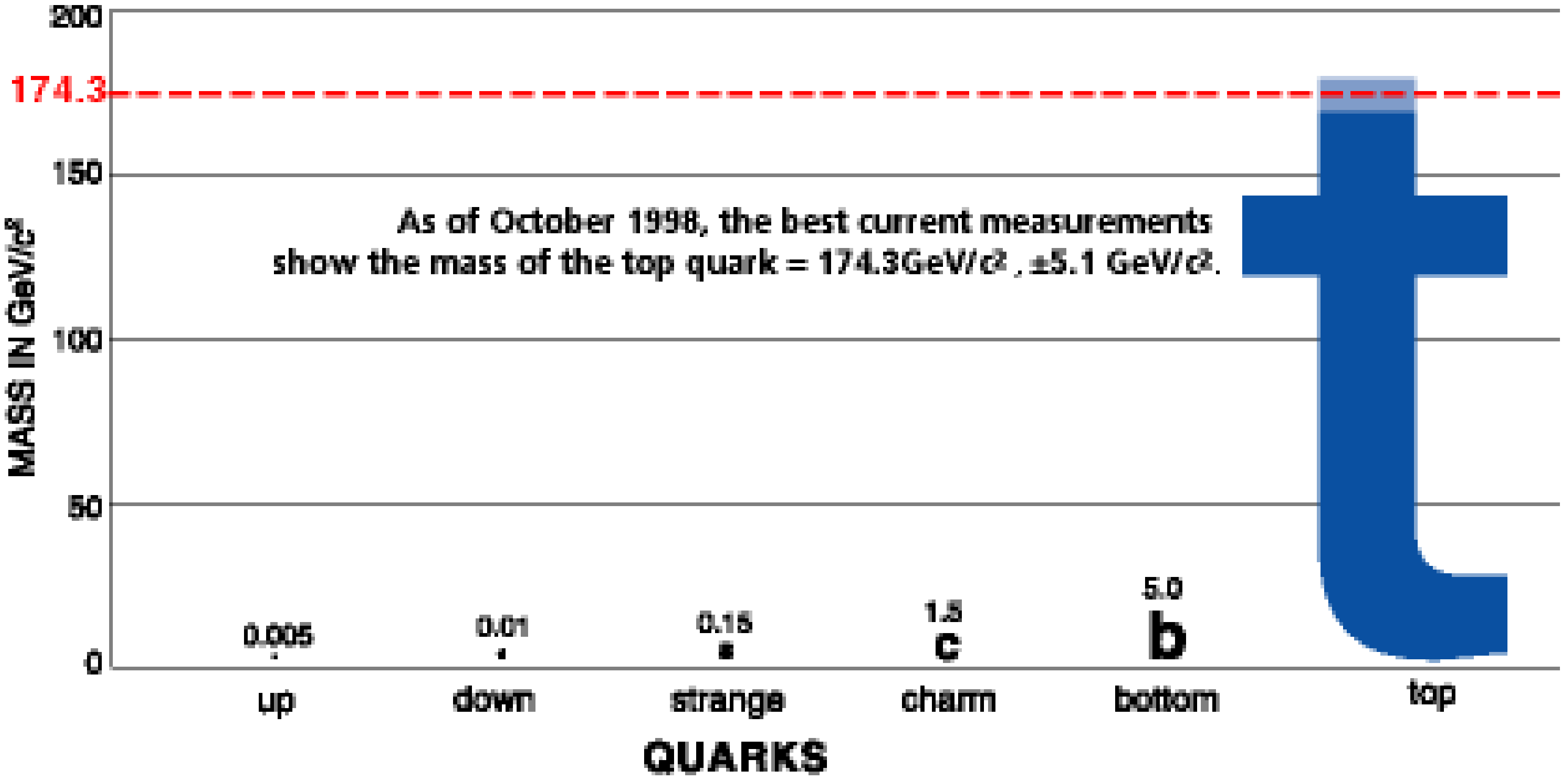
70% dark energy

We learned from precision measurements of cosmic microwave background that SM matter only contributes 5 % to the mass of our universe. Within SM there is no explanation for neither dark matter nor dark energy.



Mass hierarchy

SM does not offer an explanation for the observed huge spread of particles masses



Number of generations

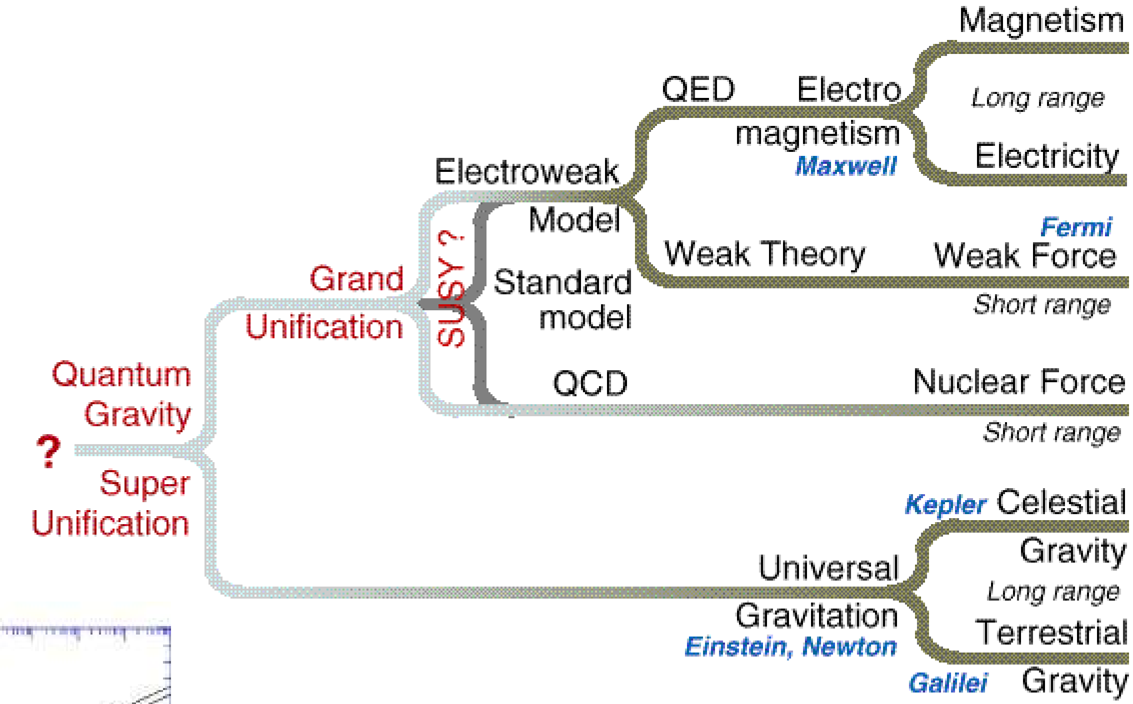
Isidor Rabi

The first generation of particles suffices to build up all normal matter. Why do we have three (or maybe more?) generations in Nature?

Unification of forces

Physics is driven by the desire for unification of interactions.

Reductionism has been very successful in the past.



Magnetism

QED Electro magnetism *Maxwell*

Long range

Electricity

Electroweak

Model

SUSY ?

Standard model

Weak Theory

Fermi Weak Force

Short range

Grand Unification

QCD

Nuclear Force

Short range

Quantum Gravity

?

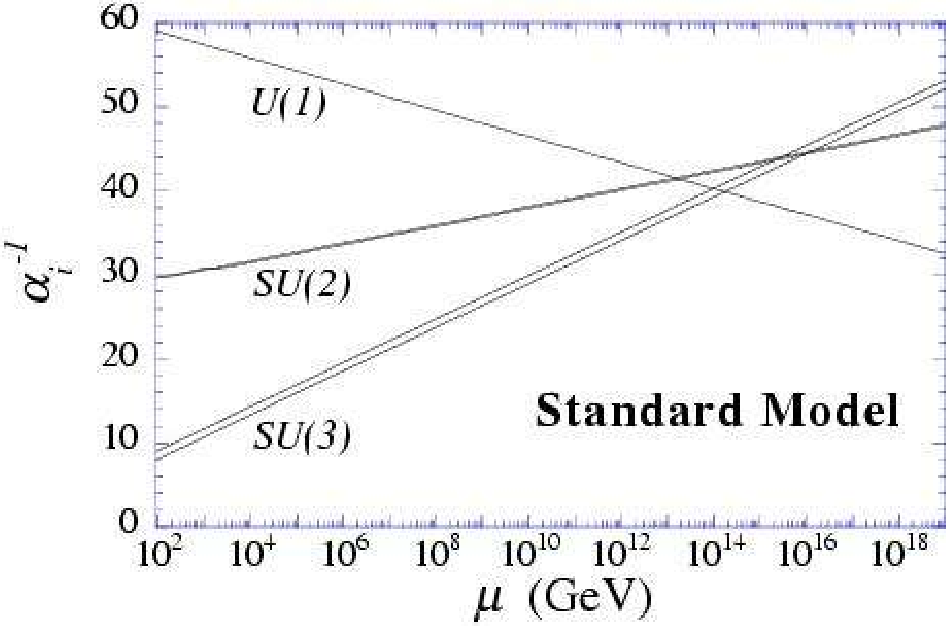
Super Unification

Kepler Celestial Gravity

Universal Gravitation *Einstein, Newton*

Long range

Terrestrial Gravity *Galilei*



SM has the flaw that its gauge coupling constants do not unify

The only way out …

Experimental input is badly
needed to clarify these
(and even more) puzzles

A common faith

Why do so many particle physicists believe that we will find an answer to some of these puzzles at the next generation colliders? Why is the TeV scale interesting?

- SM without Higgs violates unitarity (in $W_L W_L \to W_L W_L$) at 1.3 TeV (something must happen)!
- Evidence for light Higgs
- Higgs field vacuum expectation value v = 246 GeV
- Dark matter consistent with (sub-)TeV-scale WIMP (e. g. SUSY LSP)
- $2\ m_{top} = 350$ GeV

Why ILC?

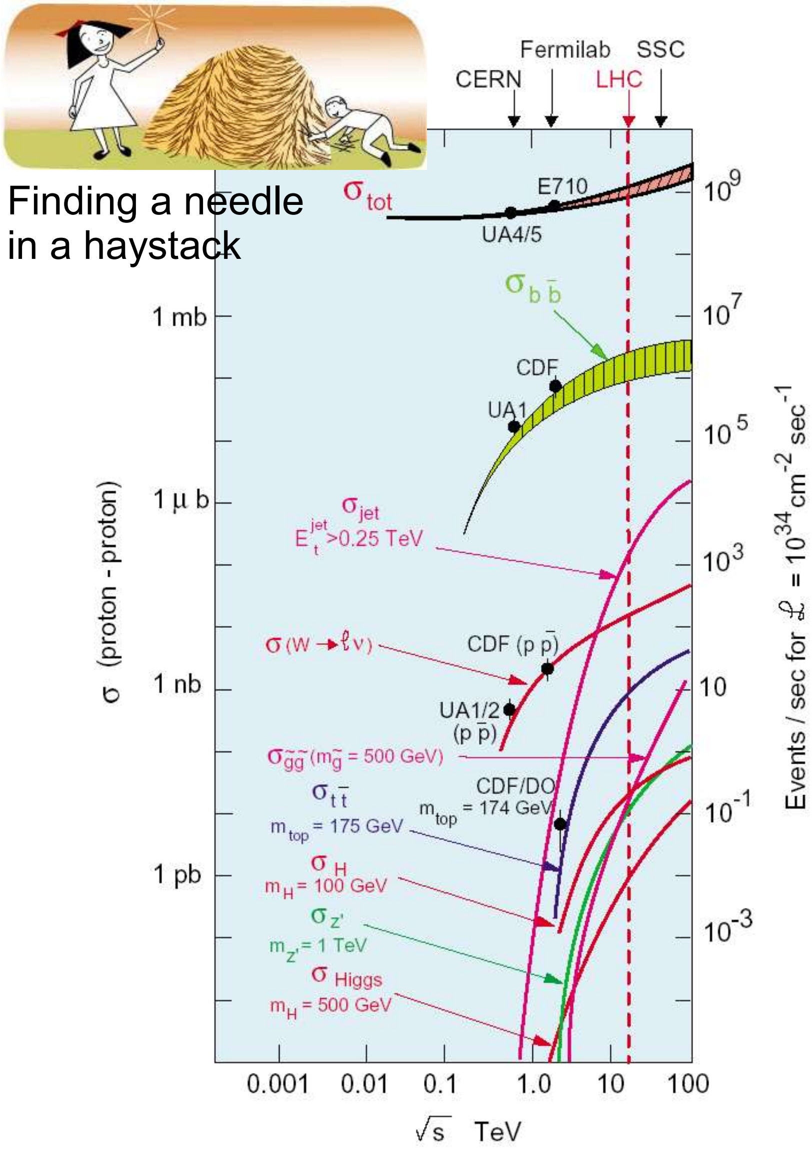
Note: ILC will probably be put into operation after major LHC discoveries. Why is the ILC still needed?

- p = composite particle:
  unknown √s of IS particles,
  no polarization of IS particles,
  parasitic collisions
- p = strongly interacting:
  huge SM backgrounds,
  highly selective trigger needed,
  radiation hard detectors needed

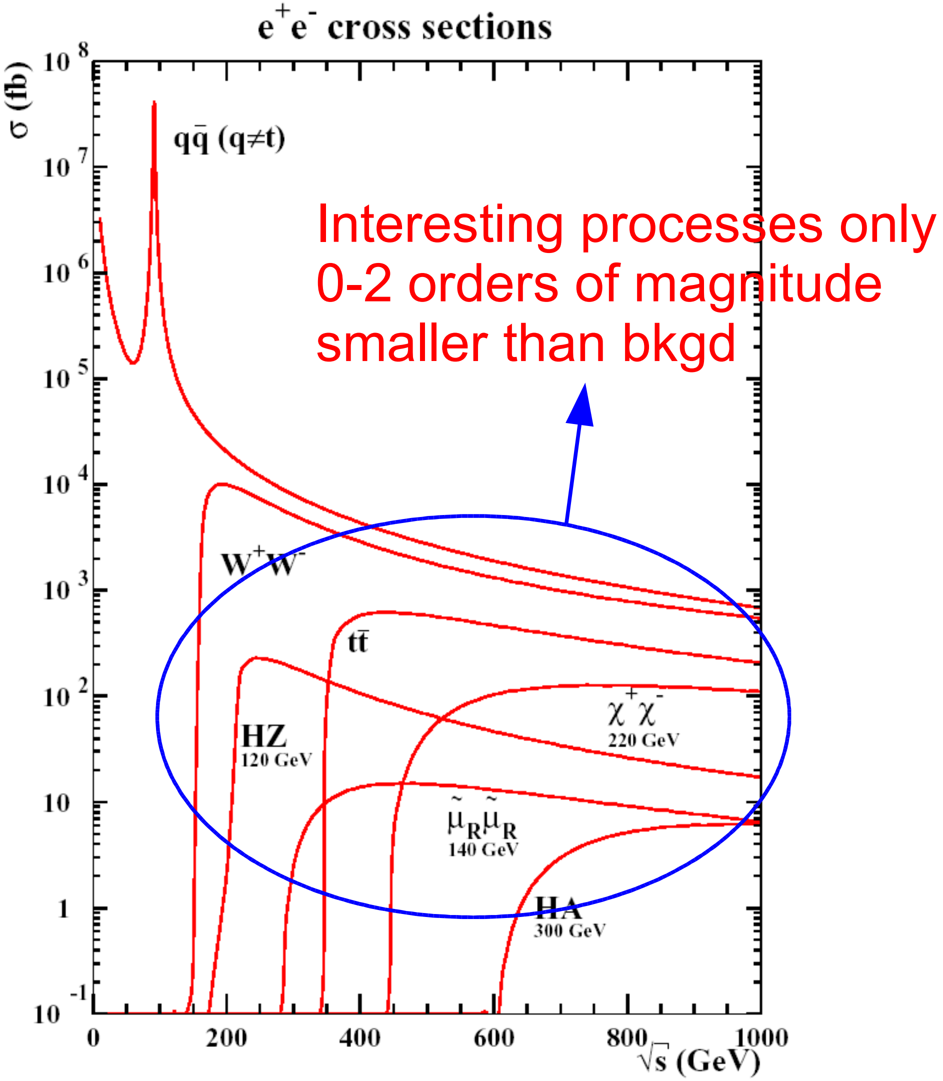
- e = pointlike particle:
  known and tunable √s of IS particles,
  polarization of IS particles possible,
  kinematic contraints can be used
- e = electroweakly interacting
  low SM backgrounds,
  no trigger needed,
  detector design driven by precision

A comparison

Hadron colliders:

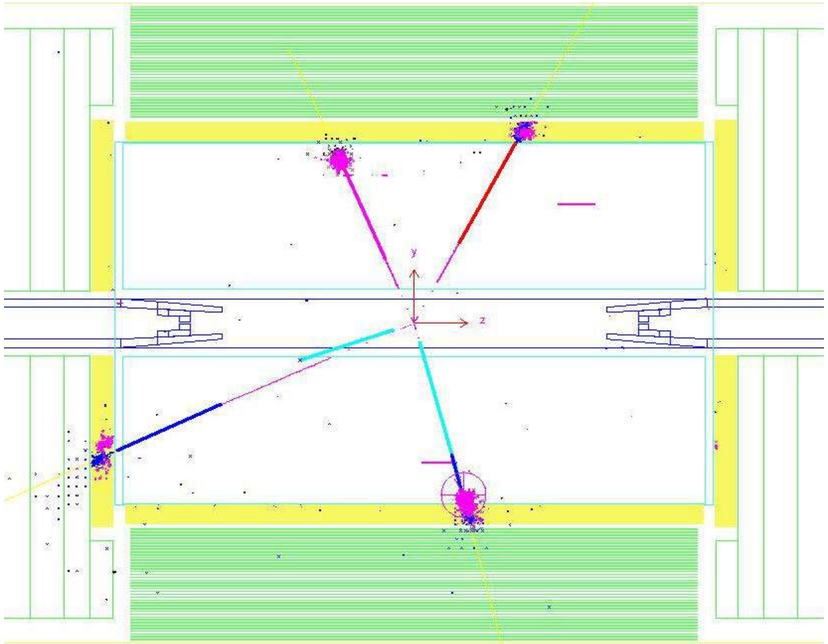

Finding a needle in a haystack

$e^+ e^-$ colliders:

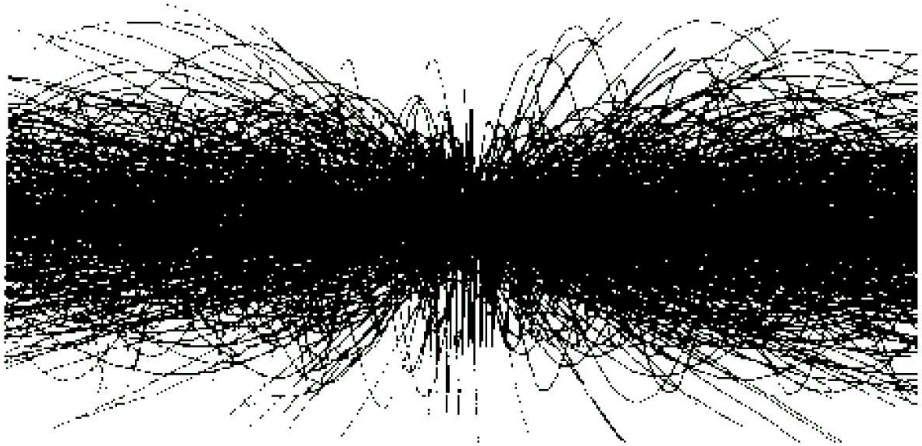

Interesting processes only 0-2 orders of magnitude smaller than bkgd

To get an impression ...

HZ → $\tau\tau ee$ event in the TESLA detector



30 minimum bias events + $H \rightarrow ZZ \rightarrow 4\mu$ in CMS inner detector



ILC parameters

International Linear Collider (ILC)

= $e^+ e^-$ linear collider based on superconducting acceleration structures

Baseline: $\sqrt{s}$ = 200-500 GeV,
integrated lumi 500 fb^{-1} within first 4 years,
80 % electron polarization,
337 ns between bunch crossing

Update: $\sqrt{s} \rightarrow$ 1 TeV, lumi 1 ab^{-1} within 4 years

Options: e^-e^-, $e\gamma$, $\gamma\gamma$,
50 % positron polarization,
“GigaZ”: high lumi at m_Z and WW threshold
double lumi at 500 GeV

ILC event rates

Typical event rates in a 500 fb^{-1} sample:

event type	$\mathcal{O}$(# events)	√s (GeV)
HZ (m_h=120 GeV)	10^5	300
tt	$3.5\ 10^5$	350
W^+W^-	10^6	500
Z	10^9	91
$\tilde{\mu}\tilde{\mu}$ (m=140 GeV)	10^4	400
$\chi^+\chi^-$ (m=220 GeV)	$5\ 10^4$	600
ttH (m_h=120 GeV)	10^3	800
HHZ (m_h=120 GeV)	10^2	500

Many processes with $\mathcal{O}$(%) or better statistical precision

Match this precision with high-resolution detector

Contribution by ILC

Whatever LHC will find, ILC will have a lot to say!

'What' depends on LHC findings:

- If there is a light Higgs (consistent with precision EW data):
  → verify that Higgs mechanism is at work in all elements
- If there is a heavy Higgs (inconsistent with prec. EW data):
  → verify that Higgs mechanism is at work in all elements
  → find out why prec. EW data are inconsistent
- Higgs + new states (SUSY, XD, Z', ...):
  → precise spectroscopy of the new states
- No Higgs, no new states (inconsistent with prec. EW data):
  → find out why prec. EW data are inconsistent
  → look for threshold effects of strong EWSB

Summary part I

- SM extremely successful theory. Nevertheless it has a number of shortcomings.
- New physics can be studied at the LHC and the ILC ("something must happen").
- The cleanliness, flexibility and precision of the ILC is crucial to establish a "new SM" (whatever it will look like).

Higgs physics

The Higgs mechanism

Introducing mass terms in the SM Lagrangian “by hand” violates SU(2)xU(1) gauge symmetry:

Boson mass term: $\frac{1}{2}m^2 B_\mu B^\mu$

Fermion mass term: $m\bar{\psi}\psi = m\left(\bar{\psi}_\mathrm{R}\psi_\mathrm{L} + \bar{\psi}_\mathrm{L}\psi_\mathrm{R}\right)$

SM solution: Higgs mechanism

= Dynamical generation of mass terms

= Rescue plan for the gauge principle

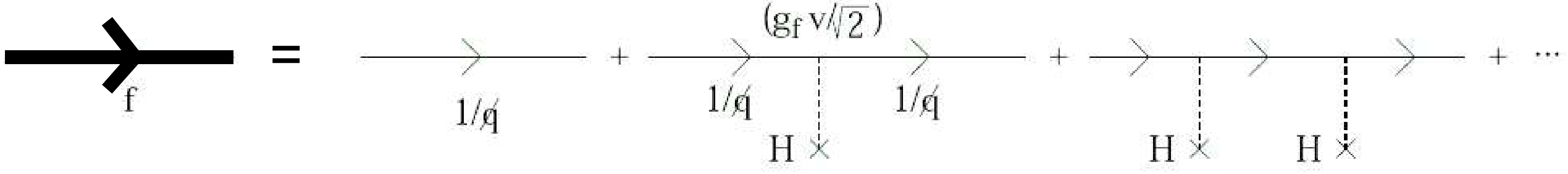
The Higgs mechanism

Paradigm: All (elementary) particles are massless

⇒ gauge principle works

⇒ renormalizable theory (finite cross sections)

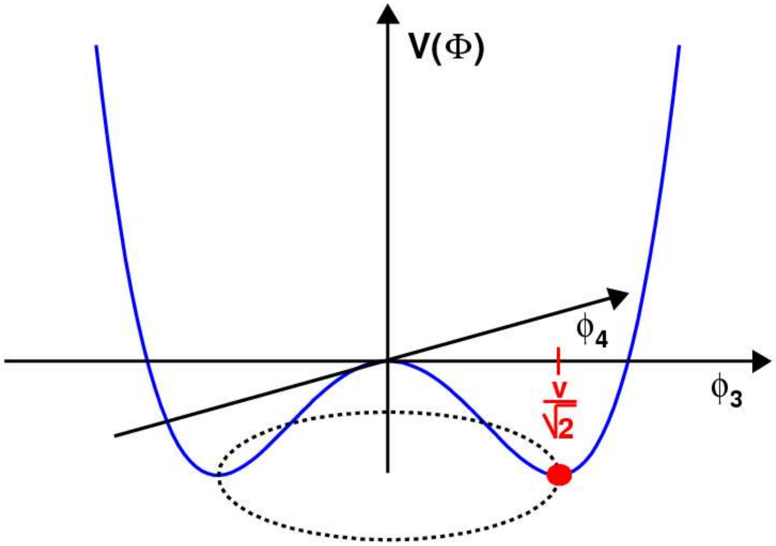
Permanent interaction of particles with a scalar Higgs field acts as if the particles had a mass (effective mass):



$$\frac{1}{\not q} + \frac{1}{\not q}\left(\frac{g_f v}{\sqrt{2}}\right)\frac{1}{\not q} + \cdots = \frac{1}{\not q}\sum_{n=0}^{\infty}\left[\left(\frac{g_f v}{\sqrt{2}}\right)\frac{1}{\not q}\right]^n = \frac{1}{\not q - \left(\frac{g_f v}{\sqrt{2}}\right)}$$

The Higgs mechanism

How to add such a field in a gauge invariant way?



Introduction of SU(2)xU(1) invariant
Mexican hat potential

$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

Simplest case (SM):

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

complex doublet of weak iso-spin

This is only the most economic way. Many more possibilities exist, e. g. two doublets (minimal SUSY), triplets, ...

Higgs mechanism requires the existence of at least one scalar, massive Higgs boson.

Tasks at the ILC

Establishing the Higgs mechanism as being responsible for EW symmetry breaking requires more than discovering one or more Higgs bosons and measuring its/their mass(es).

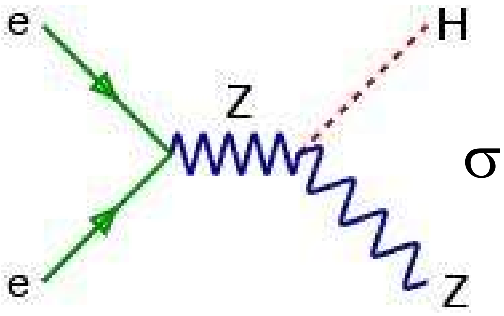
Precision measurements must comprise:

- Mass
- Total width
- Quantum numbers J^{CP} (Spin, CP even?)
- Higgs-fermion couplings ($\propto$ mass?)
- Higgs-gauge-boson couplings (W/Z masses)
- Higgs self-coupling (spontaneous symmetry breaking)

Precision should be sufficient to distinguish between different models (e. g. SM/MSSM, effects from XD, ...)

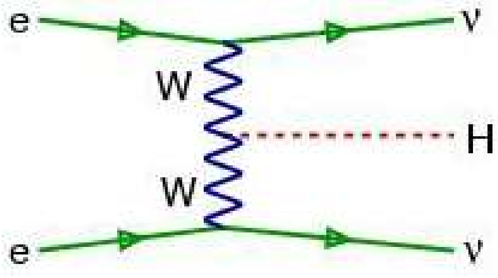
Higgs production at the ILC

Dominant production processes:



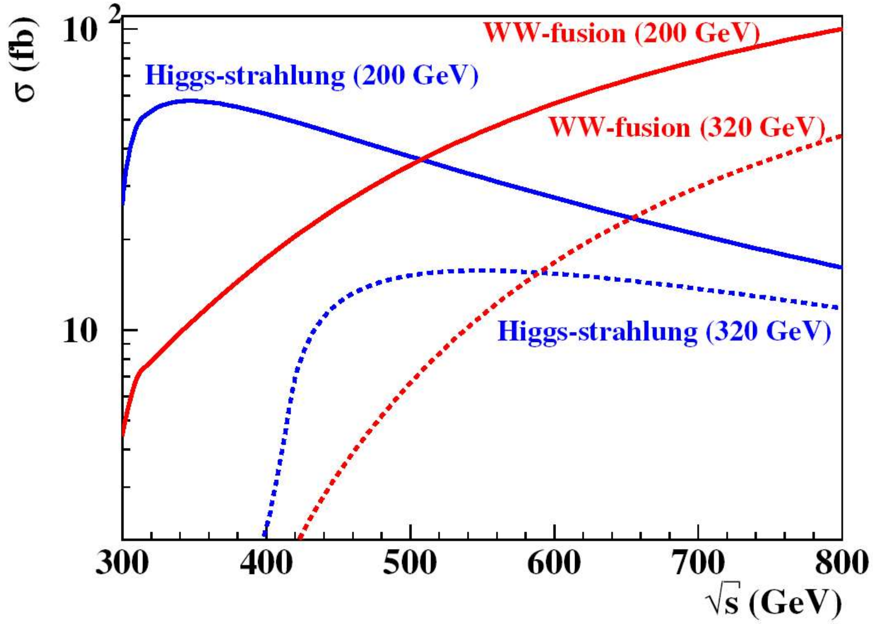
$\sigma \propto 1/s$

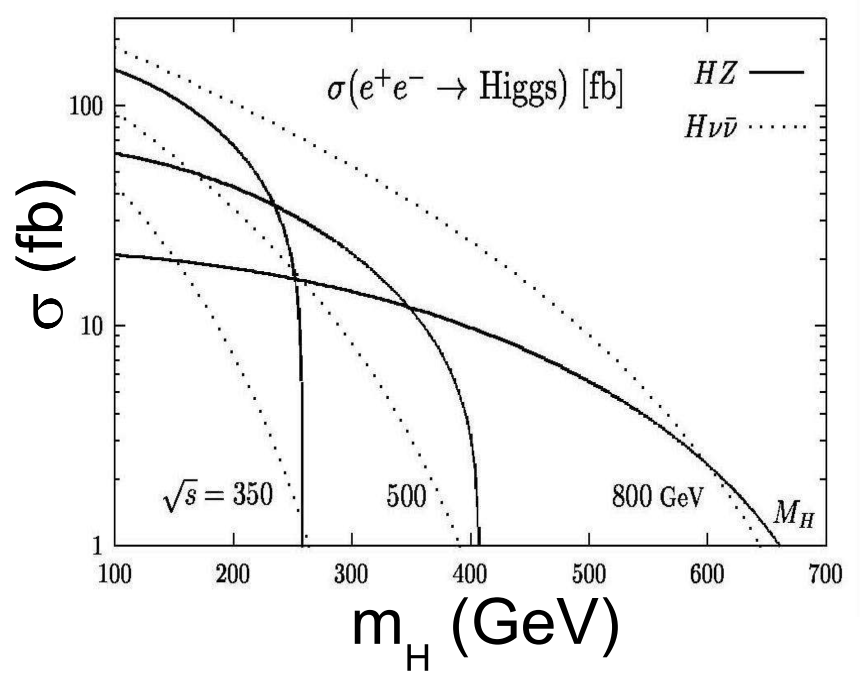
Higgs-strahlung



$\sigma \propto \ln(s)$

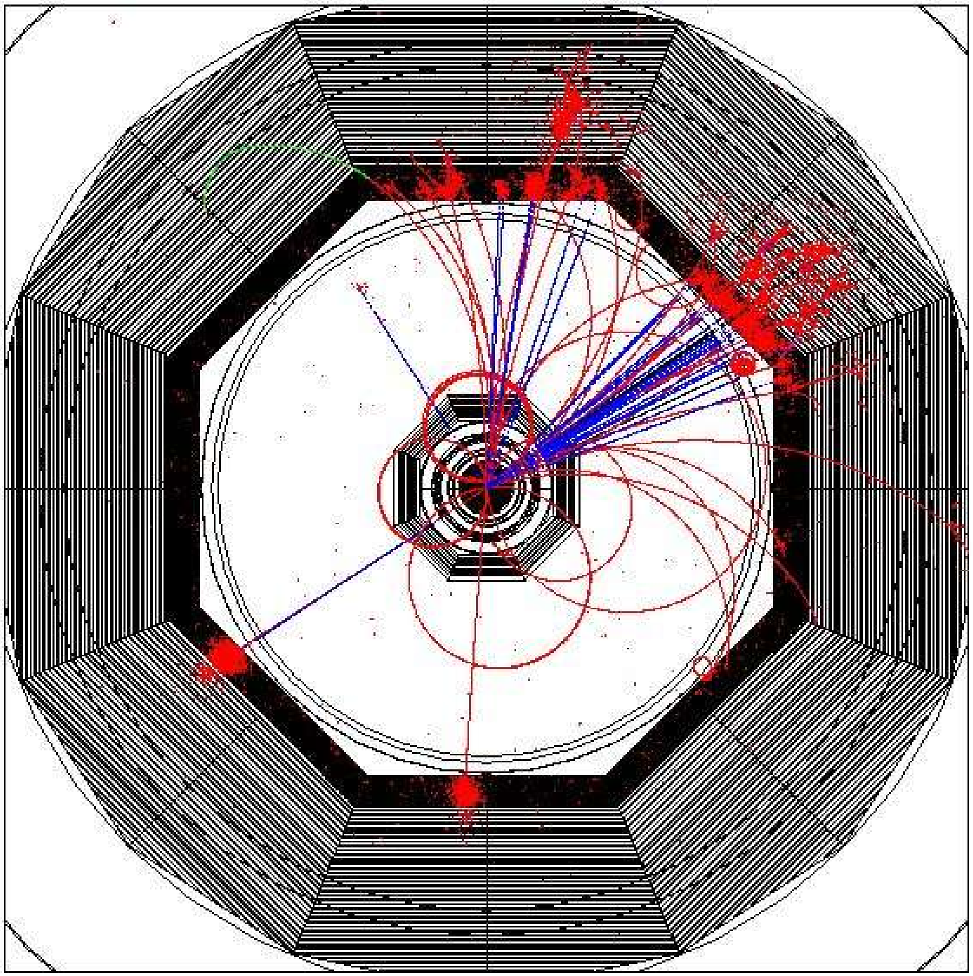
WW fusion



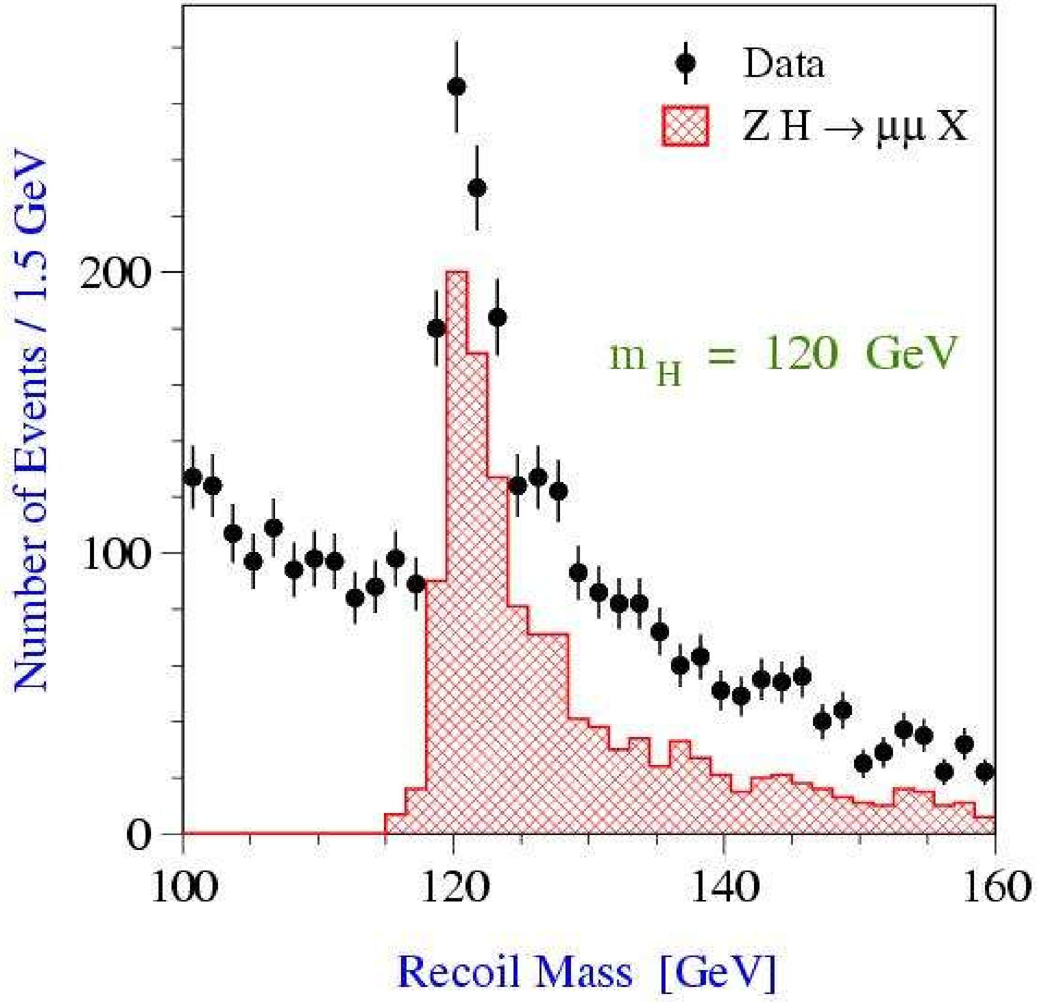


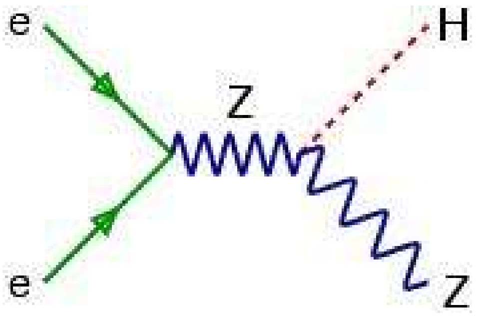
Higgs event

Higgs-strahlung event in the TESLA detector (Z→ee, H→bb):



Model-independent observation

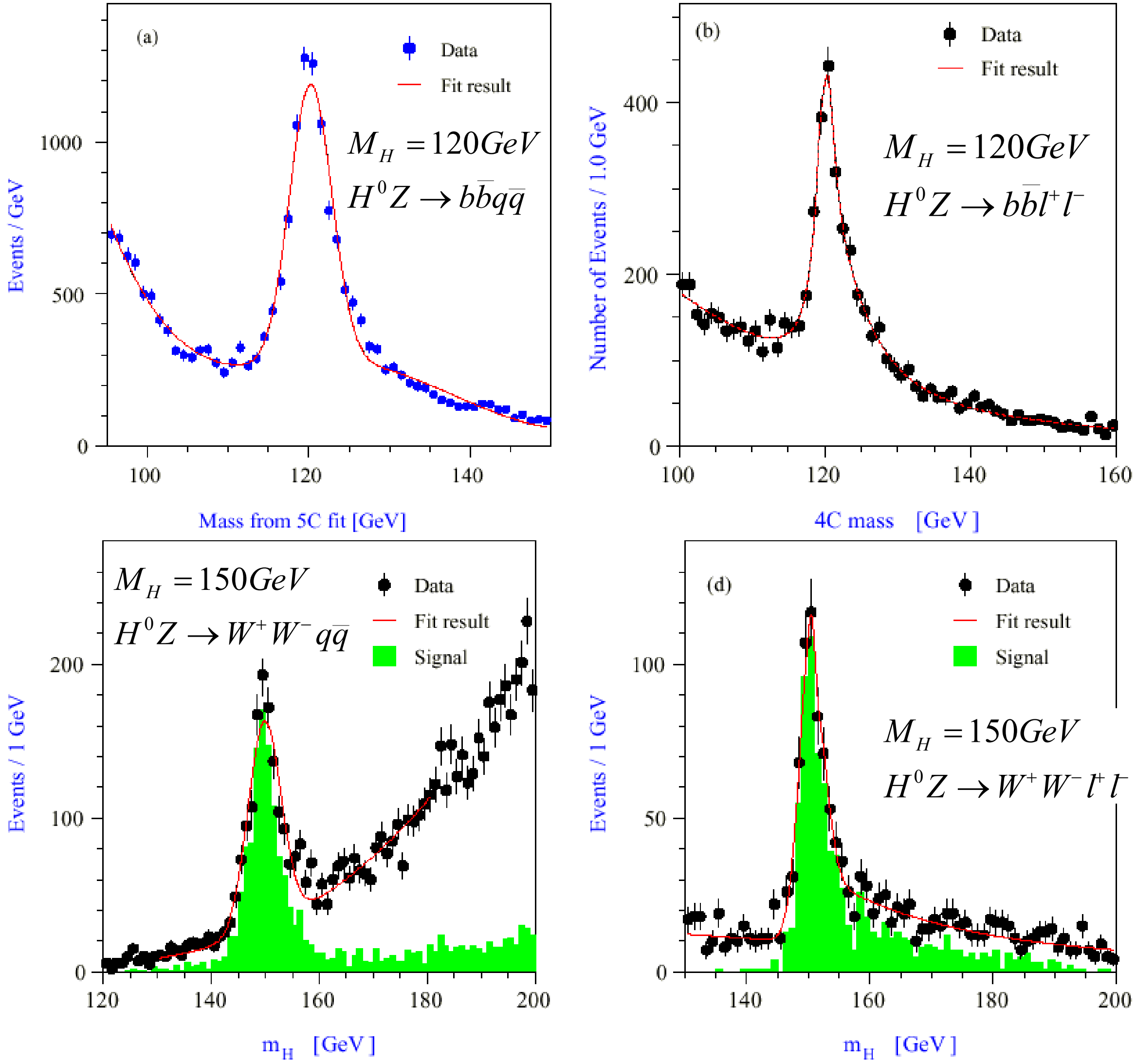




1. Select di-lepton events consistent with Z→ee/μμ
2. Calculate recoil mass $m_H^2 = (p_{initial} - p_{ll})^2$

model independent, decay-mode independent measurement!

Mass



Combination of decay channels to increase statistics

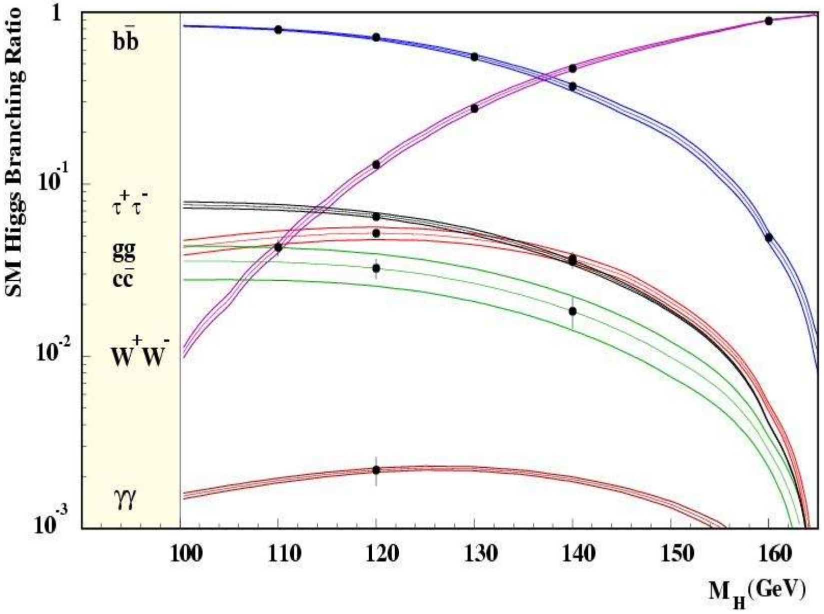
M_H (GeV)	Channel	δM_H (MeV)
120	$\ell\ell qq$	±70
120	$qqbb$	±50
120	Combined	±40
150	$\ell\ell$ Recoil	±90
150	$qqWW$	±130
150	Combined	±70
180	$\ell\ell$ Recoil	±100
180	$qqWW$	±150
180	Combined	±80

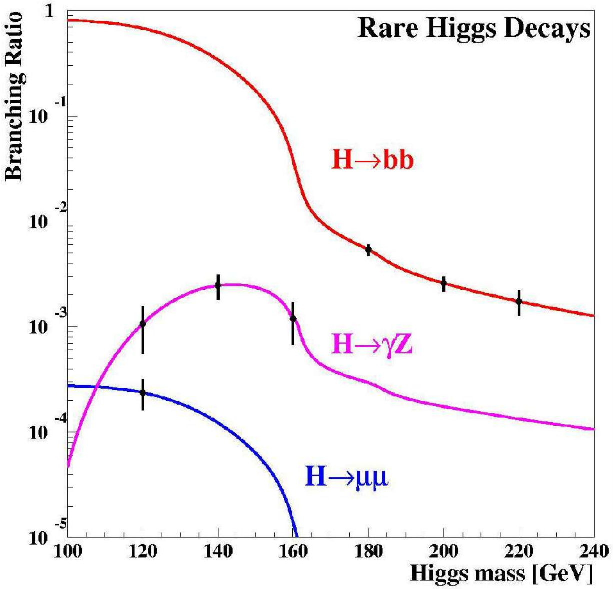
Branching fractions

ILC allows *absolute* measurement of BR because of decay mode independent g_{HZZ} measurement:

$$BR(H\rightarrow X) = \frac{\left[\sigma(HZ)\,BR(H\rightarrow X)\right]^{meas}}{\sigma(HZ)^{meas}}$$

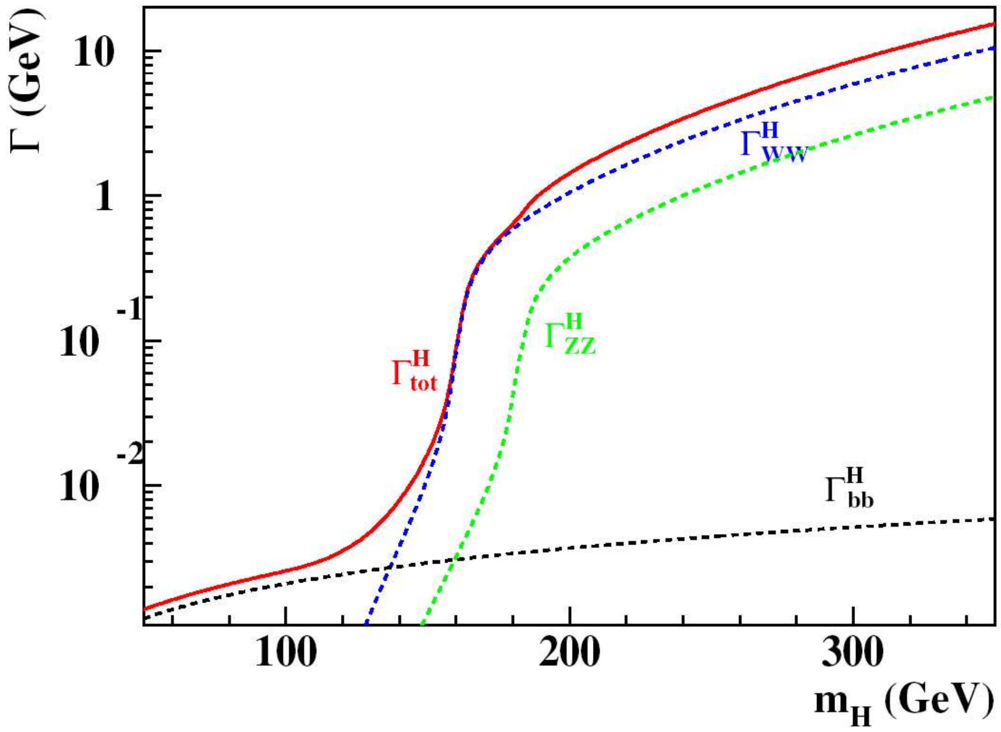
Best way to study Higgs Yukawa couplings for a light Higgs (except for top if $m_H < 2\,m_{top}$): $\Gamma(H\rightarrow ff) \propto m_f$?





Demanding for detector: Excellent flavor tagging required

Total width



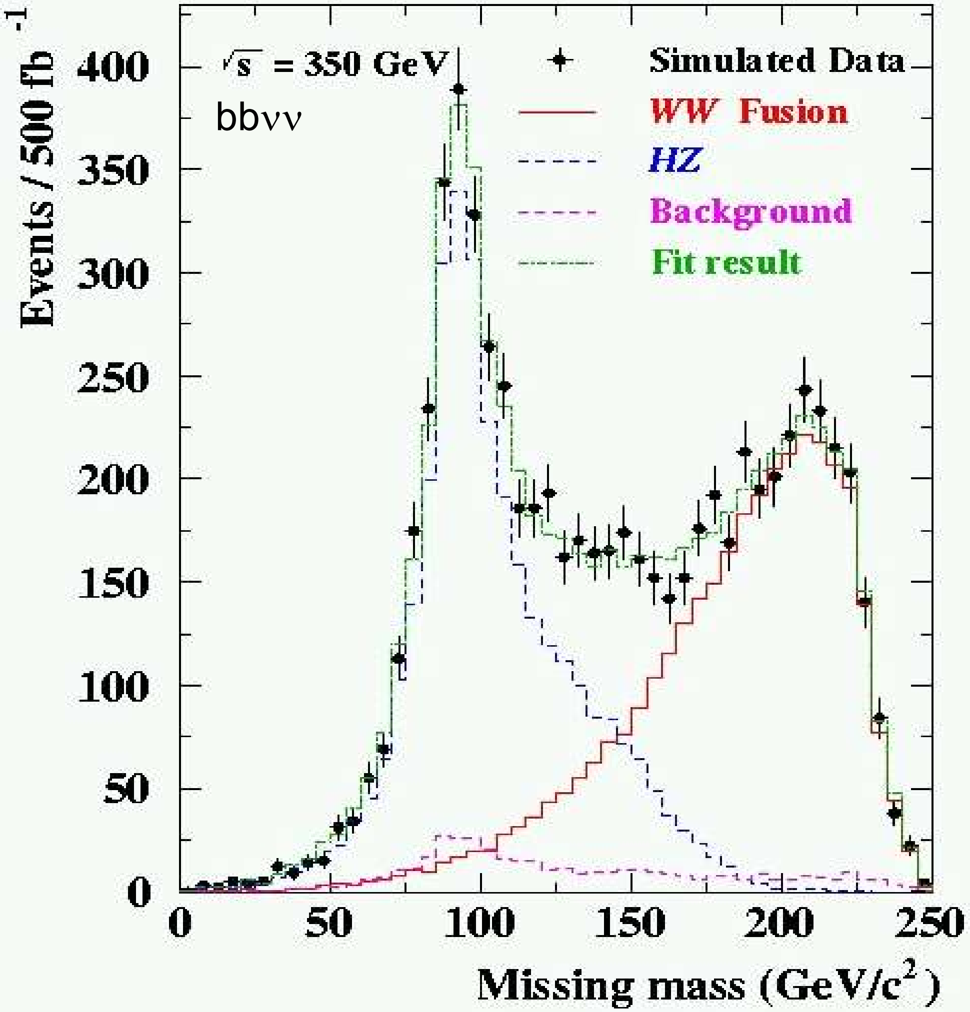
Measurement of total Higgs decay width:

m_H < 160 GeV: Γ too small to resolve in Higgs lineshape
→ indirect method

m_H > 160 GeV: Γ from Higgs lineshape

Total width

Indirect measurement (for $m_H < 2\,m_W$):



Large WW fusion cross-section at large $\sqrt{s} \Rightarrow g_{HWW} \Rightarrow \Gamma_{WW}$

Combine with BR(H→WW) measurement from Higgs-strahlung

$$\Gamma_{tot} = \frac{\Gamma_{WW}}{BR(H \to WW)}$$

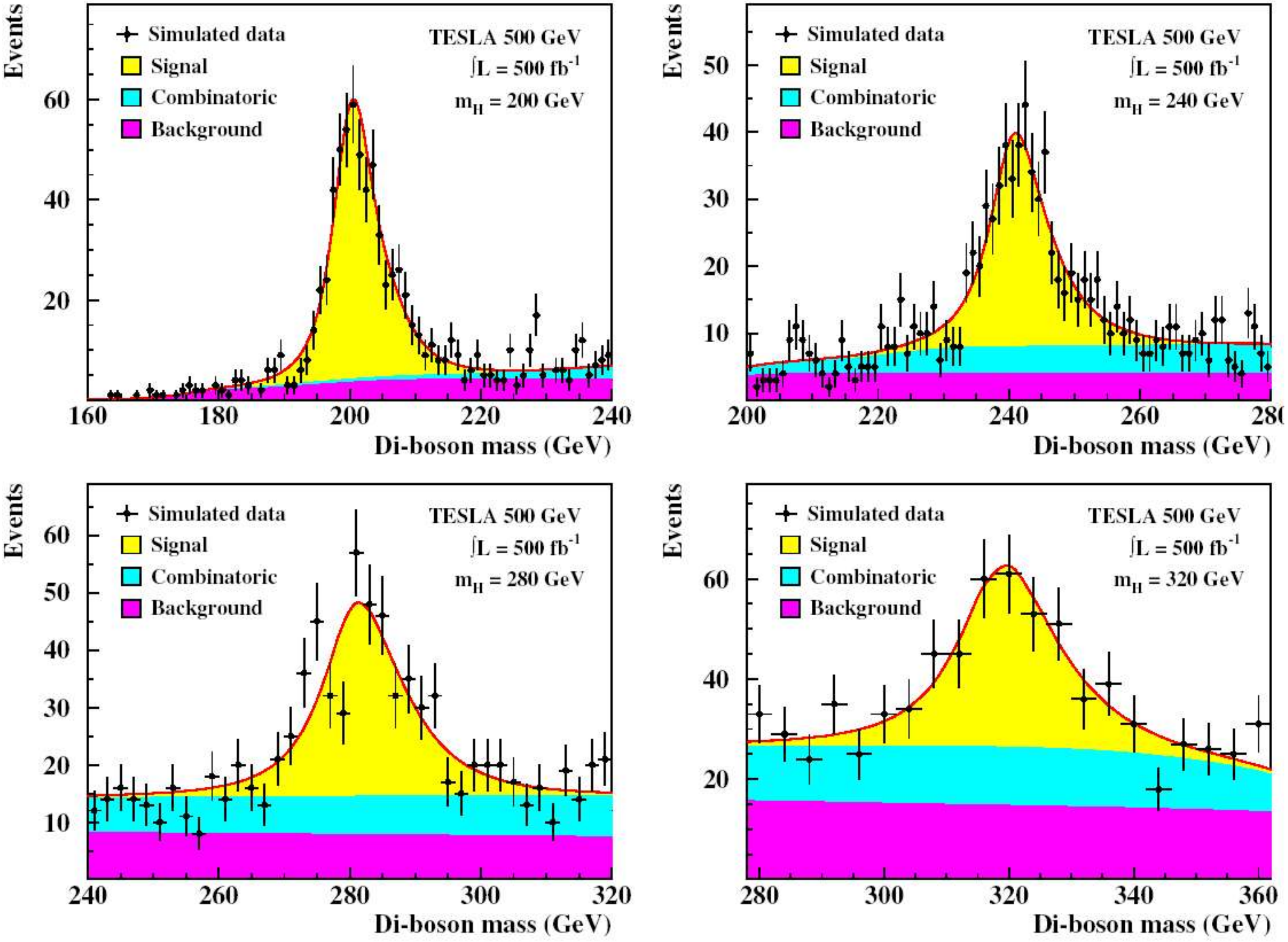
Model-independent meas.

Alternative:

$$\Gamma_{tot} = \frac{\Gamma_{\gamma\gamma}}{BR(H \to \gamma\gamma)}$$

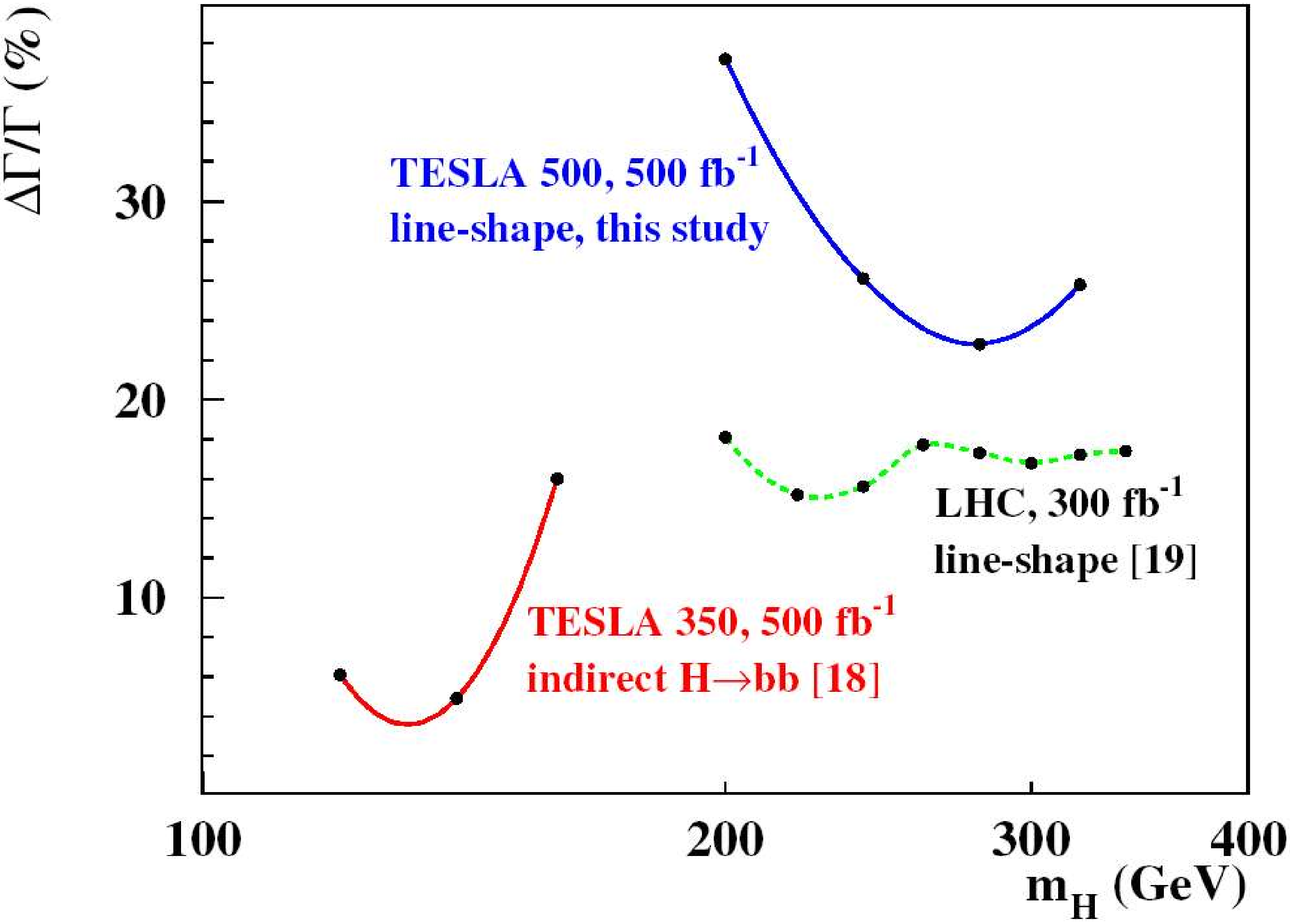
Total width

Direct measurement from lineshape (for $m_H > 2\, m_W$):



Total width

Precision overview:

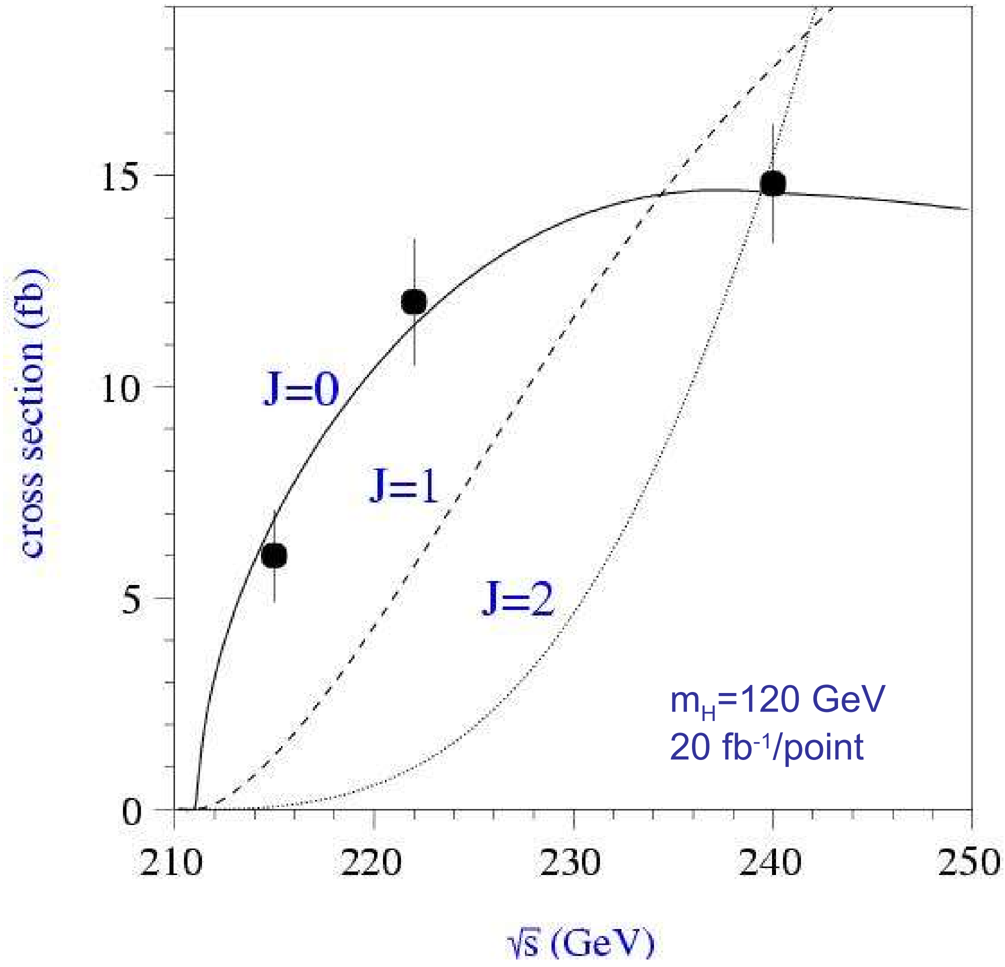


Spin

√s dependence of Higgs-strahlung cross-section near threshold has discriminative power.

Higgs spin can be measured from threshold scan.

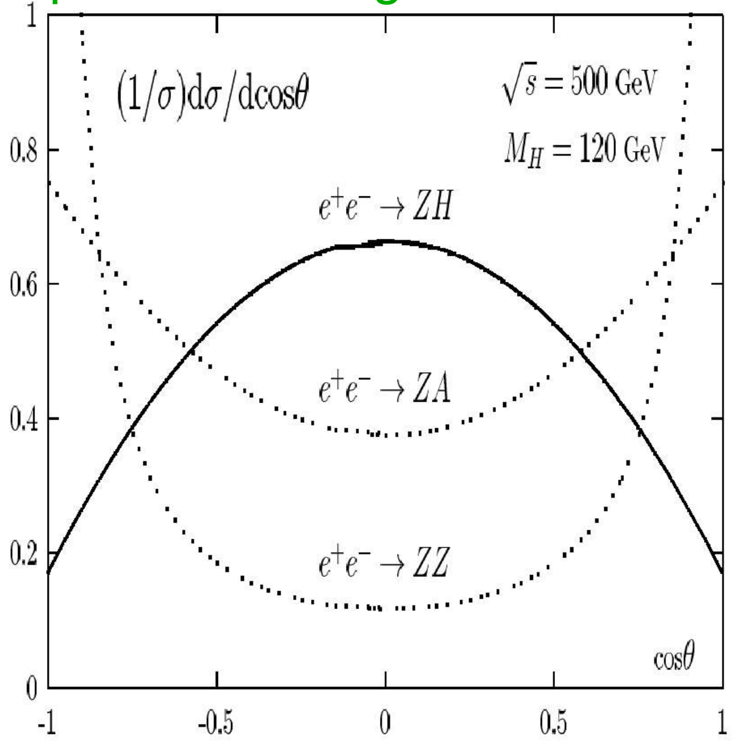
for J=0: rise $\propto \beta$
for J>0: rise $\propto \beta^k$, k>1



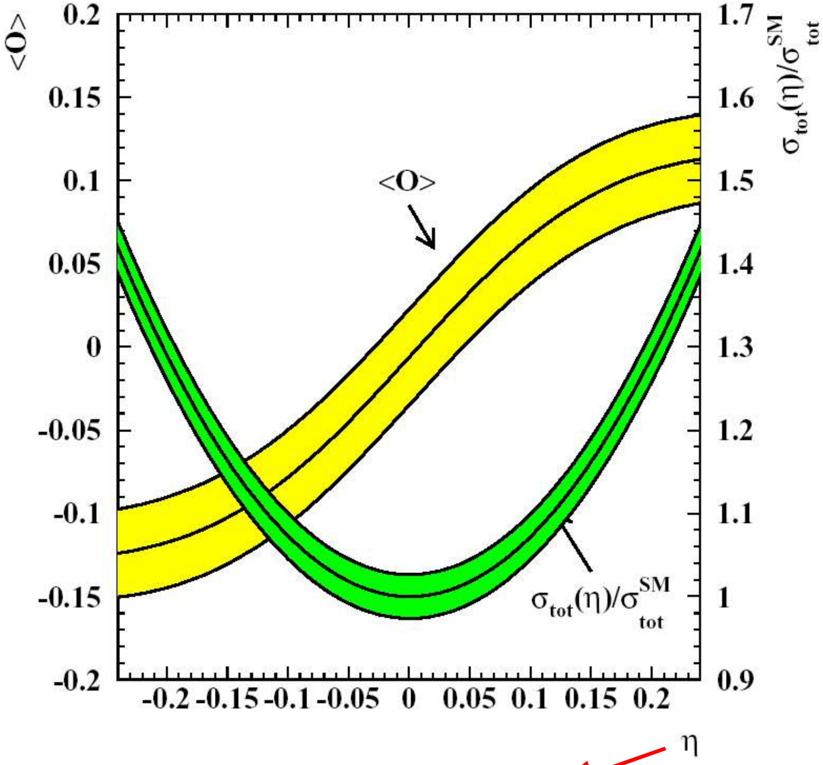
CP properties

Method 1: Study of production and decay angles of Z in Higgs-strahlung events

production angle:



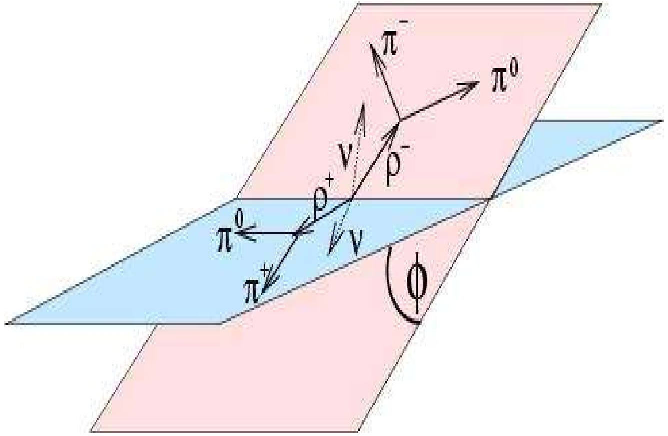
production + decay angles (optimal observable ⟨O⟩):

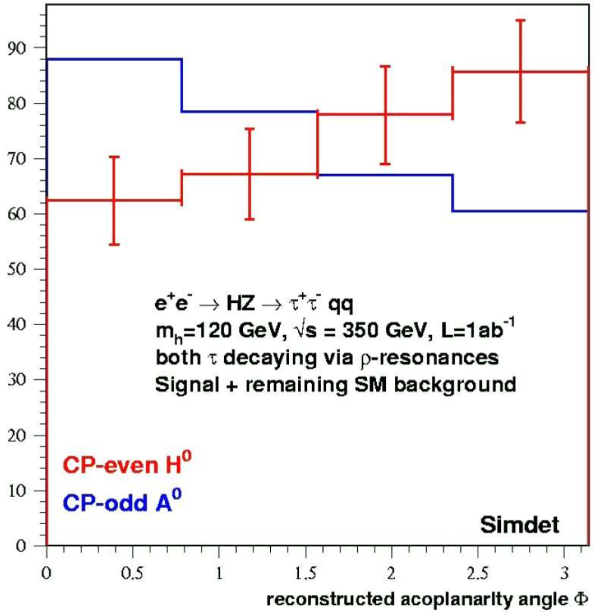


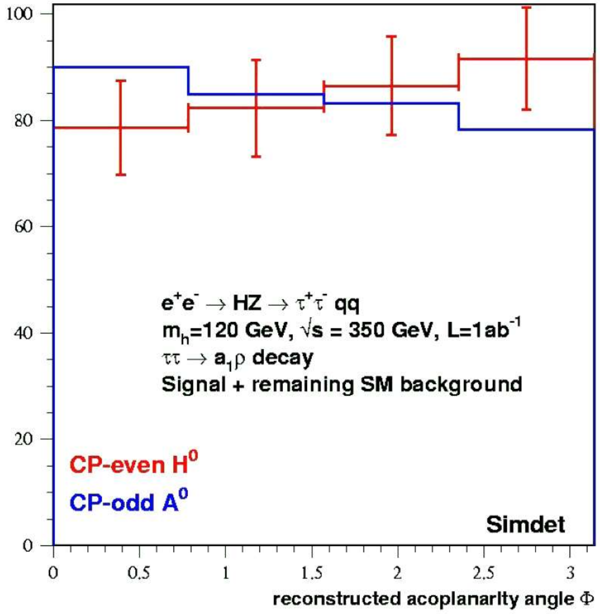
$$\mathcal{M} = \mathcal{M}_{HZ} + i\,\boxed{\eta}\,\mathcal{M}_{AZ}$$

CP properties

Method 2: CP from transverse polarization correlations in $H\rightarrow\tau\tau$







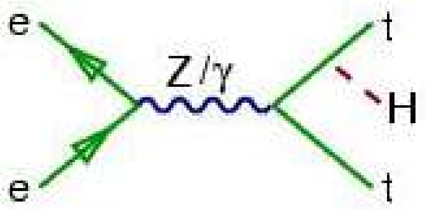
Requires exclusive reconstruction of $\tau\rightarrow\rho\nu$ and $\tau\rightarrow a_1\nu$

CP-even CP-odd separation power with 1 ab^{-1} at $\sqrt{s}$ = 350 GeV for m_H = 120 GeV: 4.7 σ

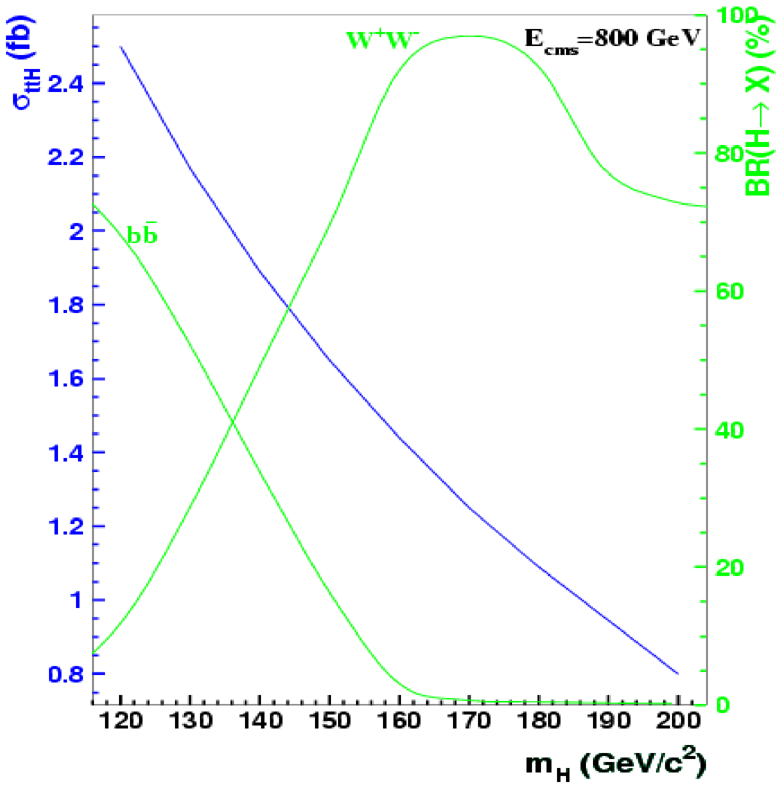
Top Yukawa coupling

Not measurable through BR(H → tt) if $m_H < 2\ m_{top}$.

Accessible through



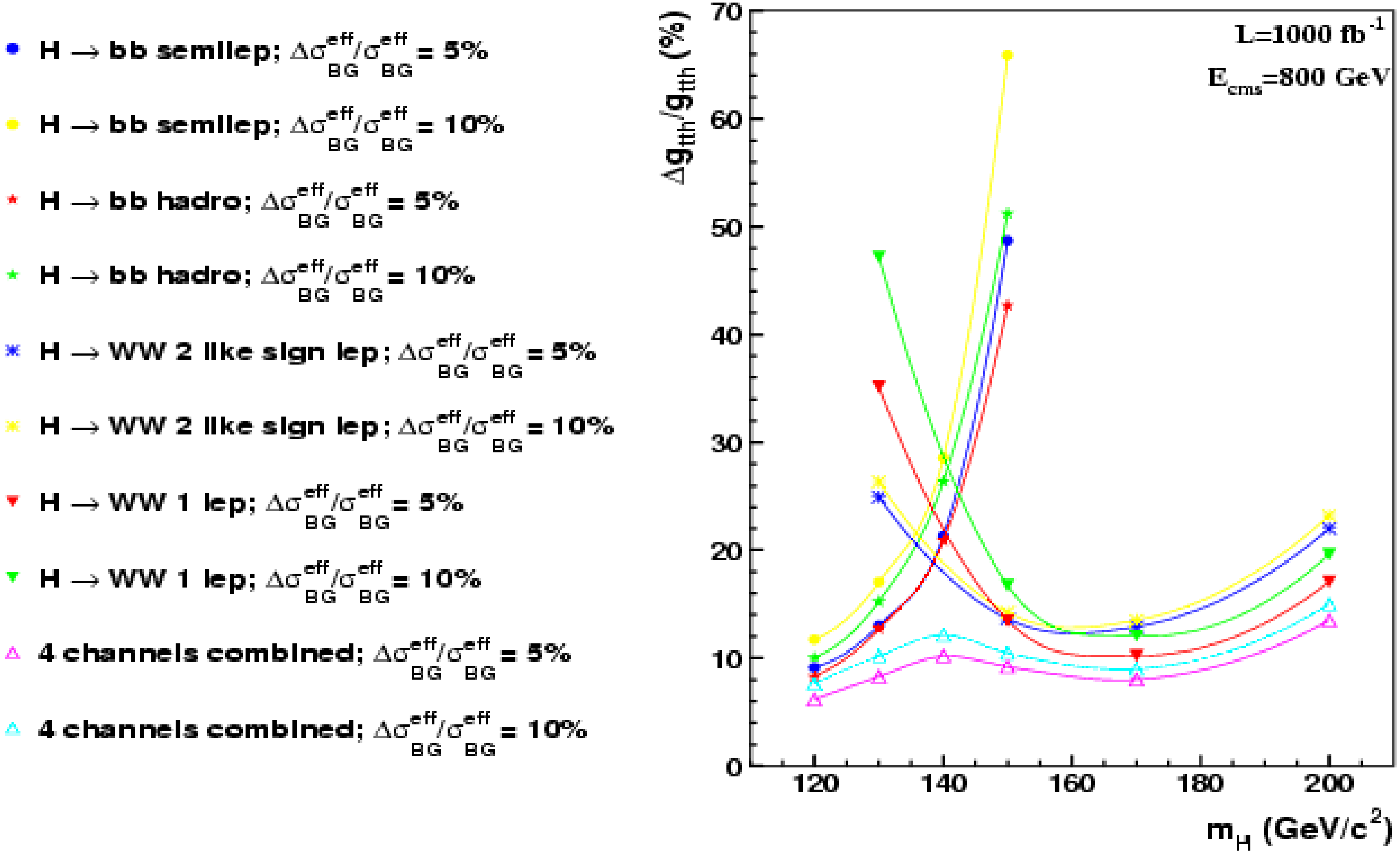
$\sigma \propto g_{Htt}^2$



- small cross-section
- high √s and lumi needed
- complicated final state (ttWW is 10-fermion final state)
- huge background
- b-tagging crucial to suppress bkgd. and reduced combinatorial bkgd.

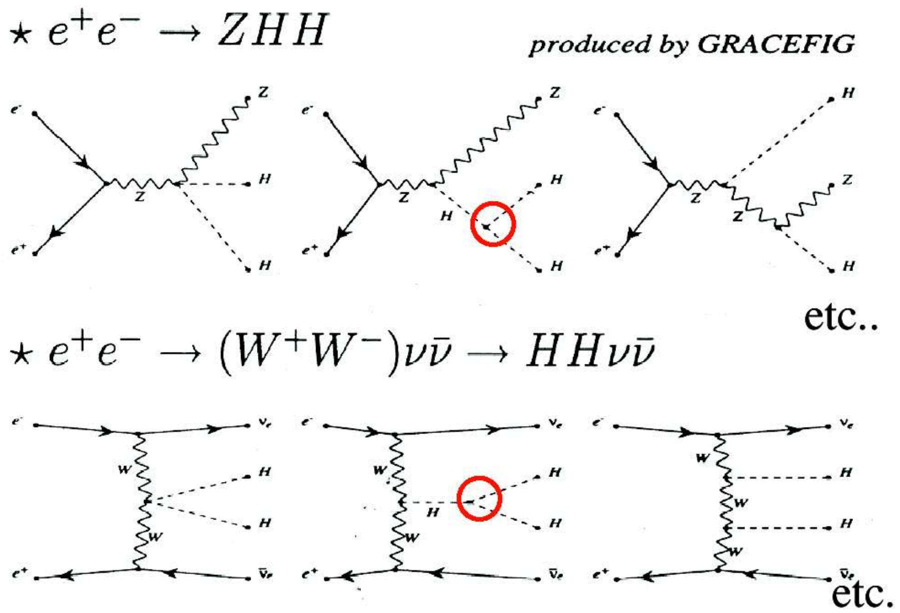
Top Yukawa coupling

Precision overview:



Self-coupling

“The holy grail”



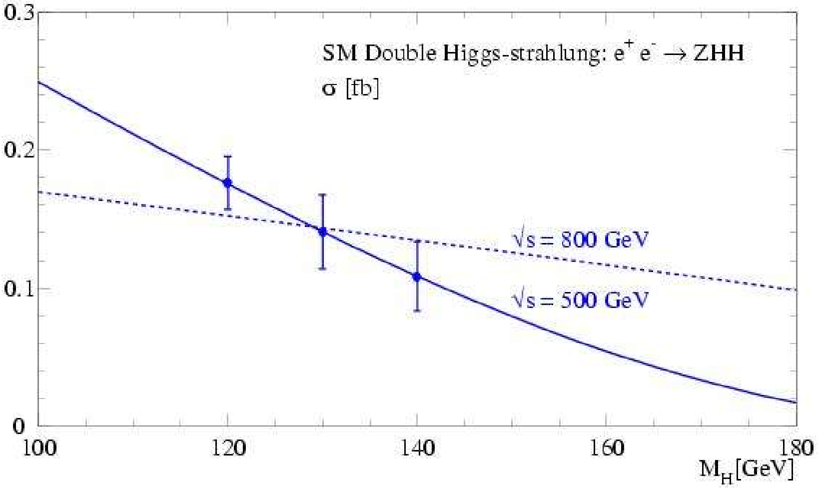
⋆ $e^+e^- \to ZHH$

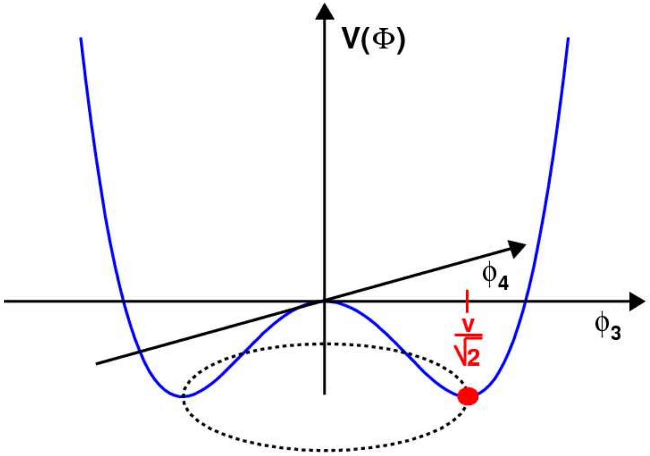
produced by GRACEFIG

etc..

⋆ $e^+e^- \to (W^+W^-)\nu\bar{\nu} \to HH\nu\bar{\nu}$

etc.





$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

Self-coupling parameter λ determines shape of potential.

Essential test of EW symmetry breaking mechanism.

$\Delta\lambda/\lambda \approx 20$ % for 1 ab^{-1}

SUSY Higgs Bosons

The SM only uses the simplest implementation of the Higgs mechanism. One extended model is the Minimal Supersymmetric Standard Model (MSSM) which needs two complex Higgs doublet fields (more on SUSY later).

2 complex doublets = 8 degrees of freedom

3 of them are absorbed by the longitudinal polarization states of W^+, W^- and Z after EWSB $\Rightarrow$ 5 physical Higgs bosons

h, H	neutral, CP even
A	neutral, CP odd
H^+, H^-	charged

Masses at tree-level are function of two parameters (e. g. $\tan\beta$ and m_A). But large radiative corrections.

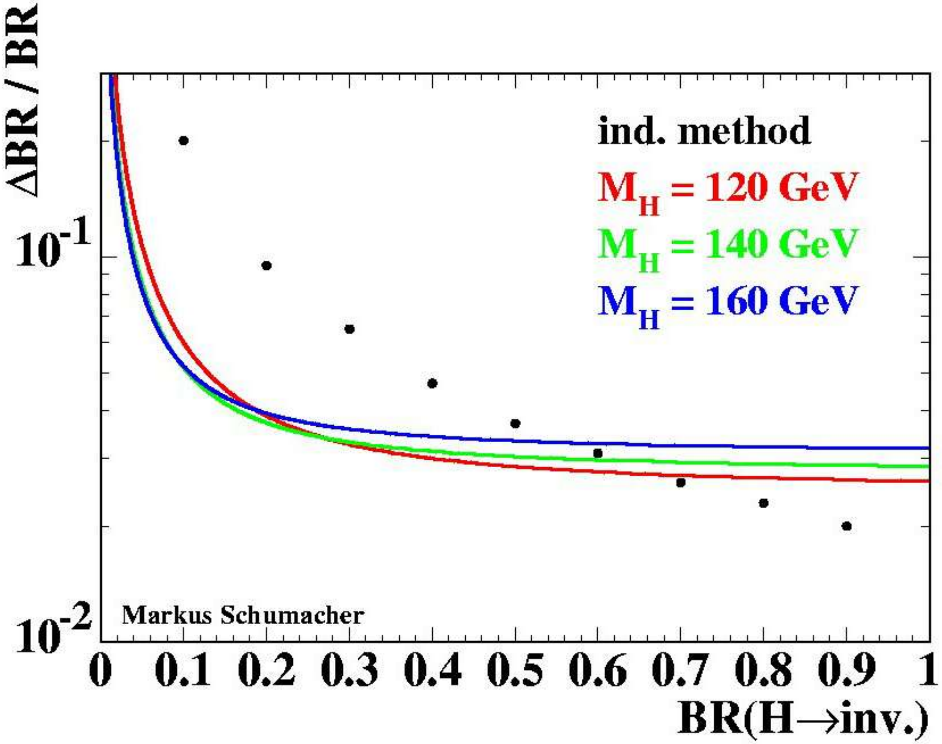
$m_h < 135$ GeV

Invisible Higgs decays

MSSM predicts invisible Higgs decays ($H \rightarrow \chi_1^0\chi_1^0$, if accessable).

$\rightarrow$ Decay independent reconstruction at ILC essential

BR(invis) = 1 - BR(vis)

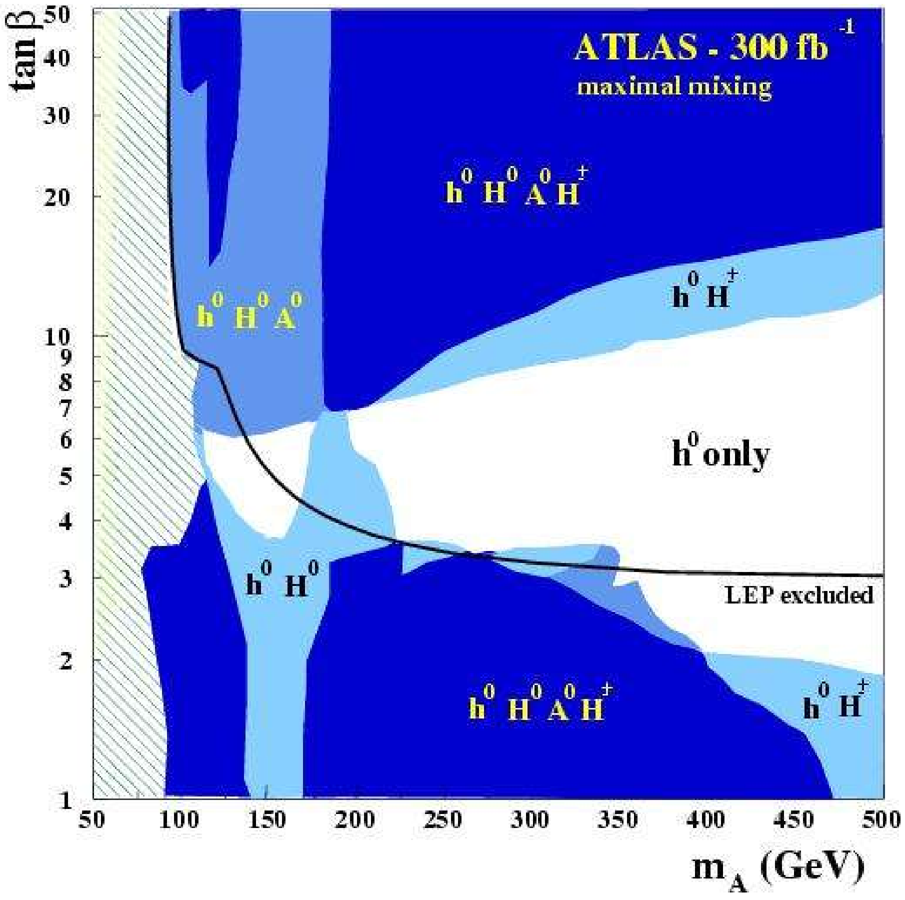


ΔBR/BR(invis) = 10 % for BR(invis) = 5 %
with 500 fb^{-1} at $\sqrt{s}$ = 350 GeV
and m_H = 120 GeV

5σ discovery down to BR = 2 %

SUSY Higgs at LHC

To uncover the nature of the Higgs sector, the heavier Higgs bosons have to be discovered either directly or through loop effects. Direct observation difficult in part of parameter space at LHC:



Decoupling limit:

h becomes SM-like,
H/A/$H^{\pm}$ heavy and mass degenerate

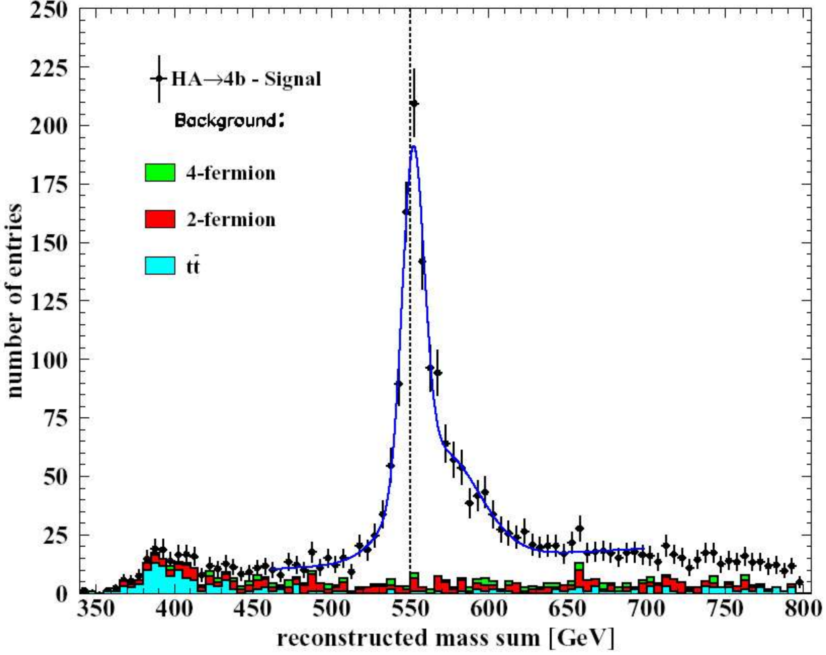
What can the ILC contribute?

SUSY Higgs at ILC

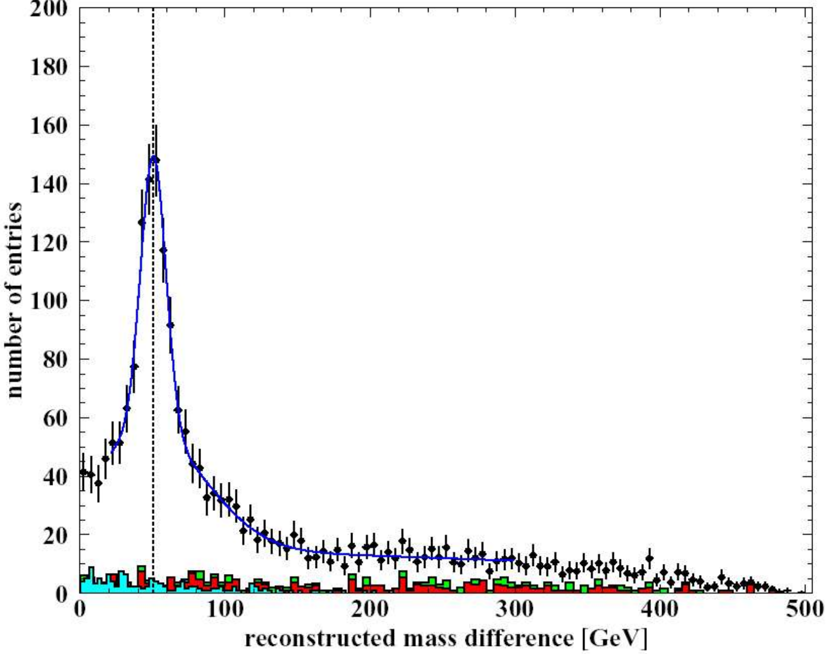
Very clear signal in HA→bbbb
100-1000 MeV mass precision due to kinematic fit
drawback: pair production → mass reach ~ √s/2

Example for m_H=250 GeV and m_A=300 GeV at √s=800 GeV:

Reconstructed mass sum:



Reconstructed mass difference:



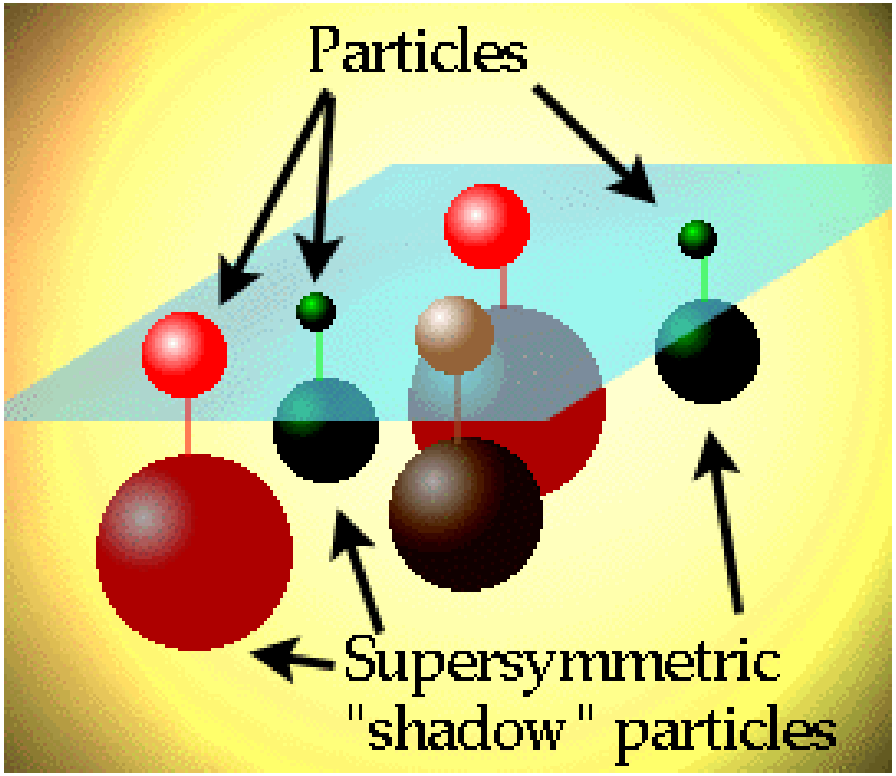
Summary part II

- Higgs mechanism dynamically generates masses for bosons and fermions.
- At least one scalar Higgs boson is predicted by the Higgs mechanism.
- ILC allows thorough experimental check of all aspects of the Higgs mechanism.

Supersymmetry

Supersymmetry

Introduction of an additional symmetry to the SM:



boson ↔ fermion symmetry

Each SM particle gets a SUSY partner whose spin differs by 1/2. All other quantum numbers are equal.

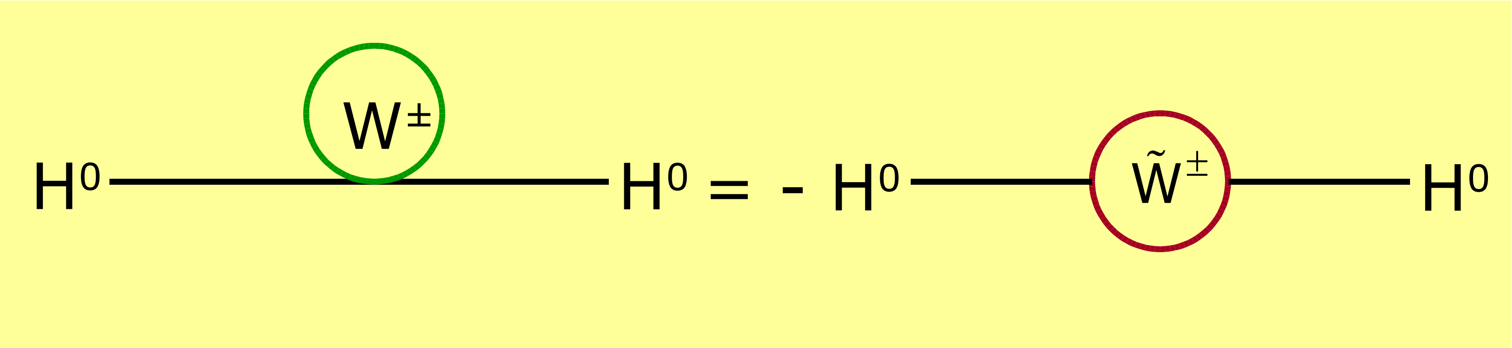
But so far no SUSY particle seen

⇒ SUSY must be a broken symmetry

And why this SUSY-mania?

Solution to hierarchy problem

Reason 1: It solves the hierarchy problem

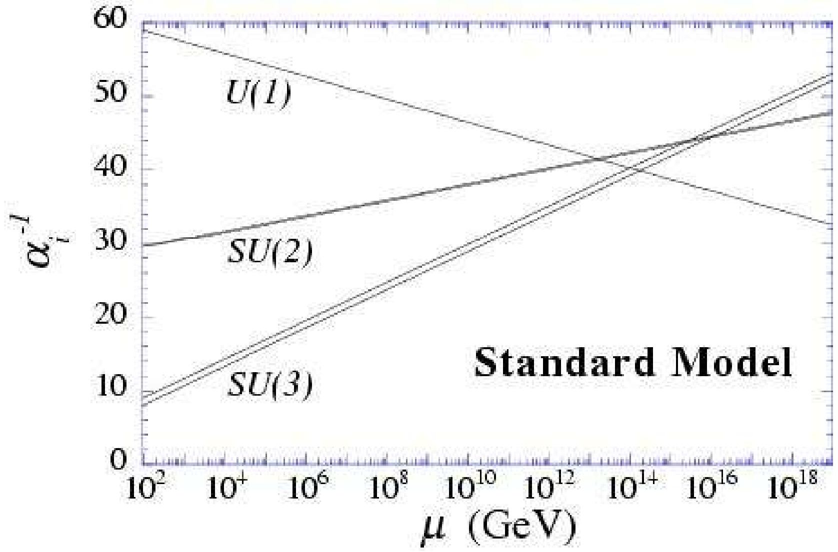


The divergence in the Higgs mass corrections is cancelled exactly for unbroken SUSY.

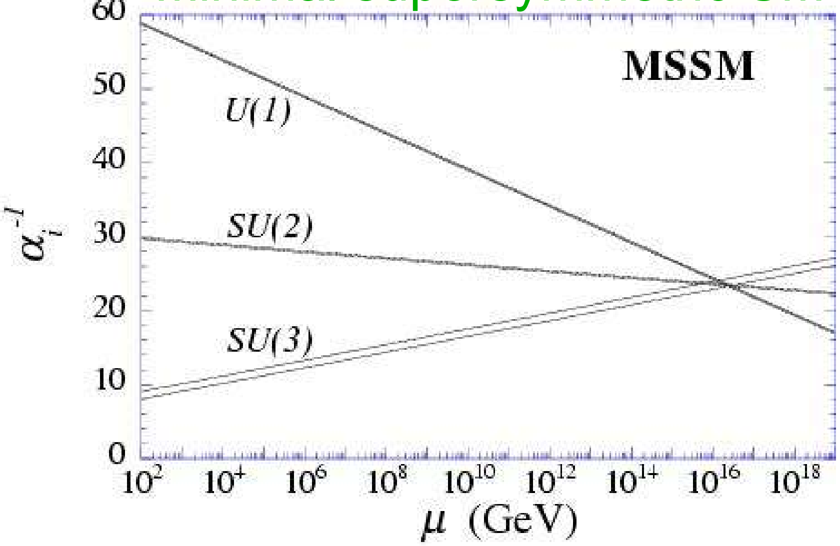
If it is not broken too strongly (i. e. if the SUSY partners are at < ~1 TeV), there is no fine tuning necessary.

Unification of gauge couplings

Reason 2: Gauge coupling constants unify



Minimal supersymmetric SM



(Requires light (< TeV) partners of EW gauge bosons)

This is achieved for $\sin^2\theta_W^{SUSY} = 0.2335(17)$

Experiment: $\sin^2\theta_W^{exp} = 0.2315(2)$

More good reasons …

Reason 3: Provides cold dark matter candidate

If lightest SUSY particle is stable, it is an excellent dark matter candidate

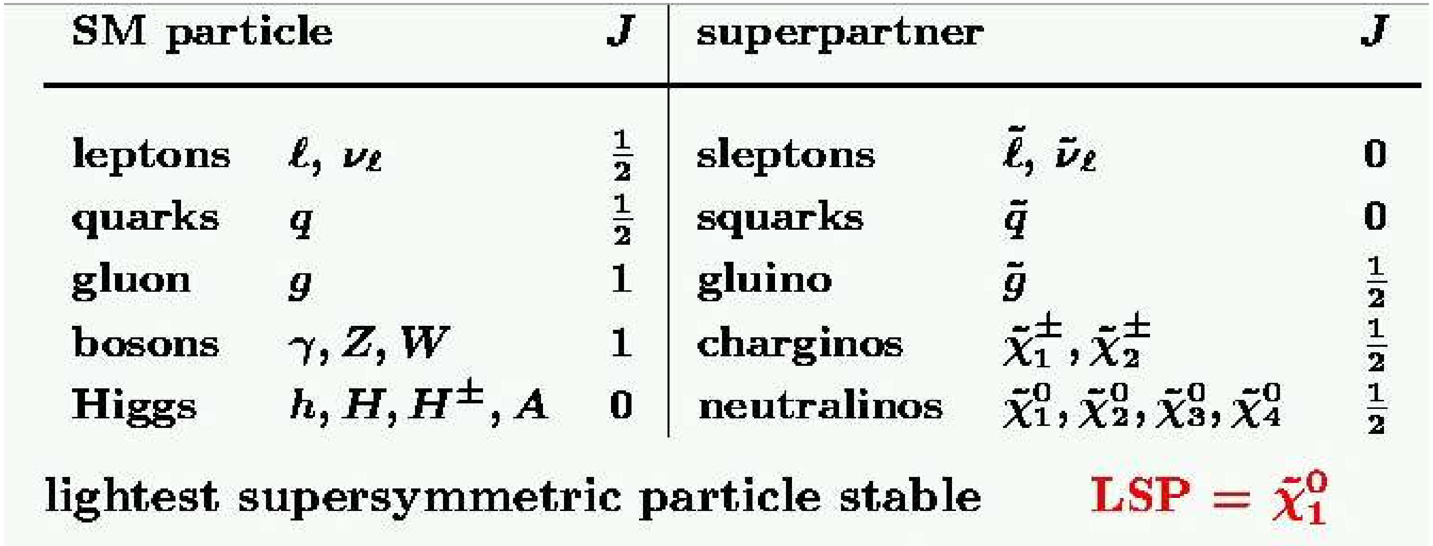
Reason 4: Link to gravity

SUSY offers the theoretical link to incorporate gravity. Most string models are supersymmetric.

Reason 5: Predicts light Higgs boson

SUSY predicts a light (< 135 GeV) Higgs boson as favored by EW precision data.

(S)particle contents



SM particle		J	superpartner		J
leptons	ℓ, ν_ℓ	$\frac{1}{2}$	sleptons	$\tilde{\ell}$, $\tilde{\nu}_\ell$	0
quarks	q	$\frac{1}{2}$	squarks	$\tilde{q}$	0
gluon	g	1	gluino	$\tilde{g}$	$\frac{1}{2}$
bosons	γ, Z, W	1	charginos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$\frac{1}{2}$
Higgs	$h, H, H^\pm, A$	0	neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	$\frac{1}{2}$

lightest supersymmetric particle stable LSP $= \tilde{\chi}_1^0$

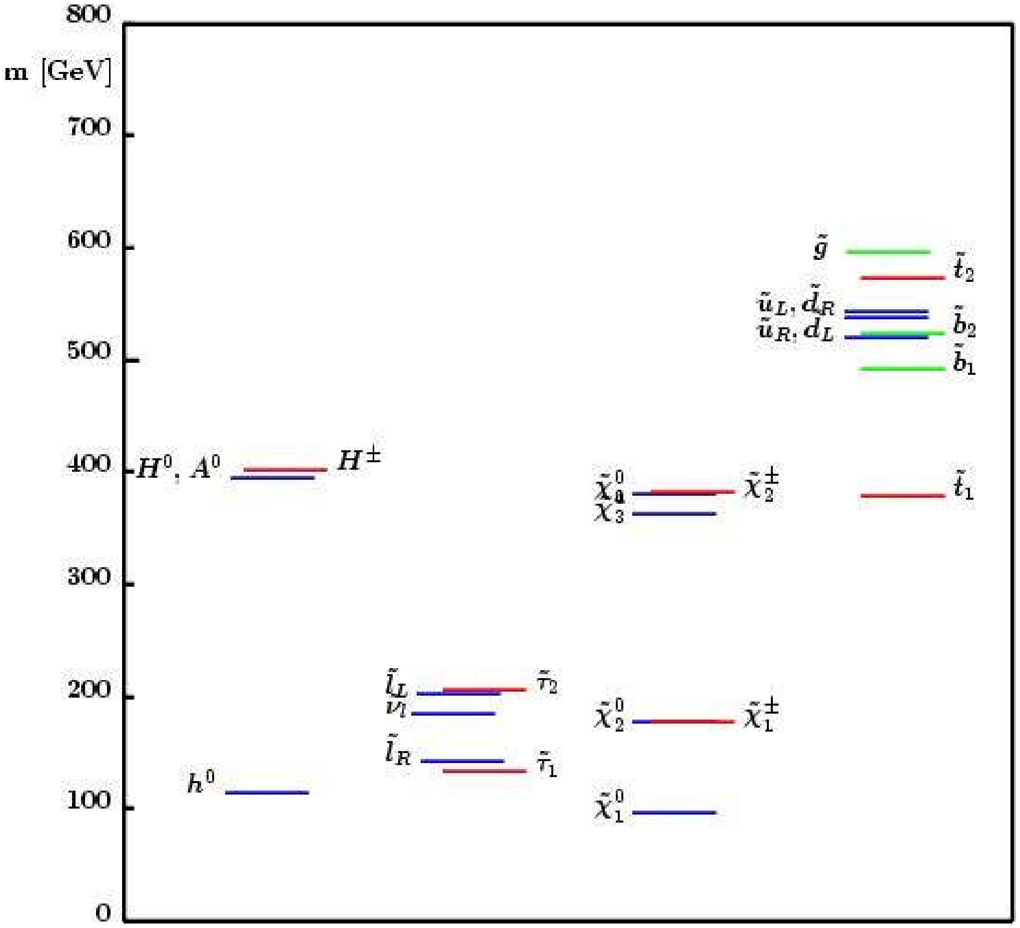
The minimal supersymmetric SM (MSSM) has 105 new parameters.

Most of them arise from our ignorance about SUSY breaking mechanism.

Specific SUSY breaking models typically have only a few parameters, e. g. mSUGRA: tan β, $m_{1/2}$, m_0, A_0, sign(μ)

An example SUSY spectrum

mSUGRA sparticle spectrum (SPS1a):

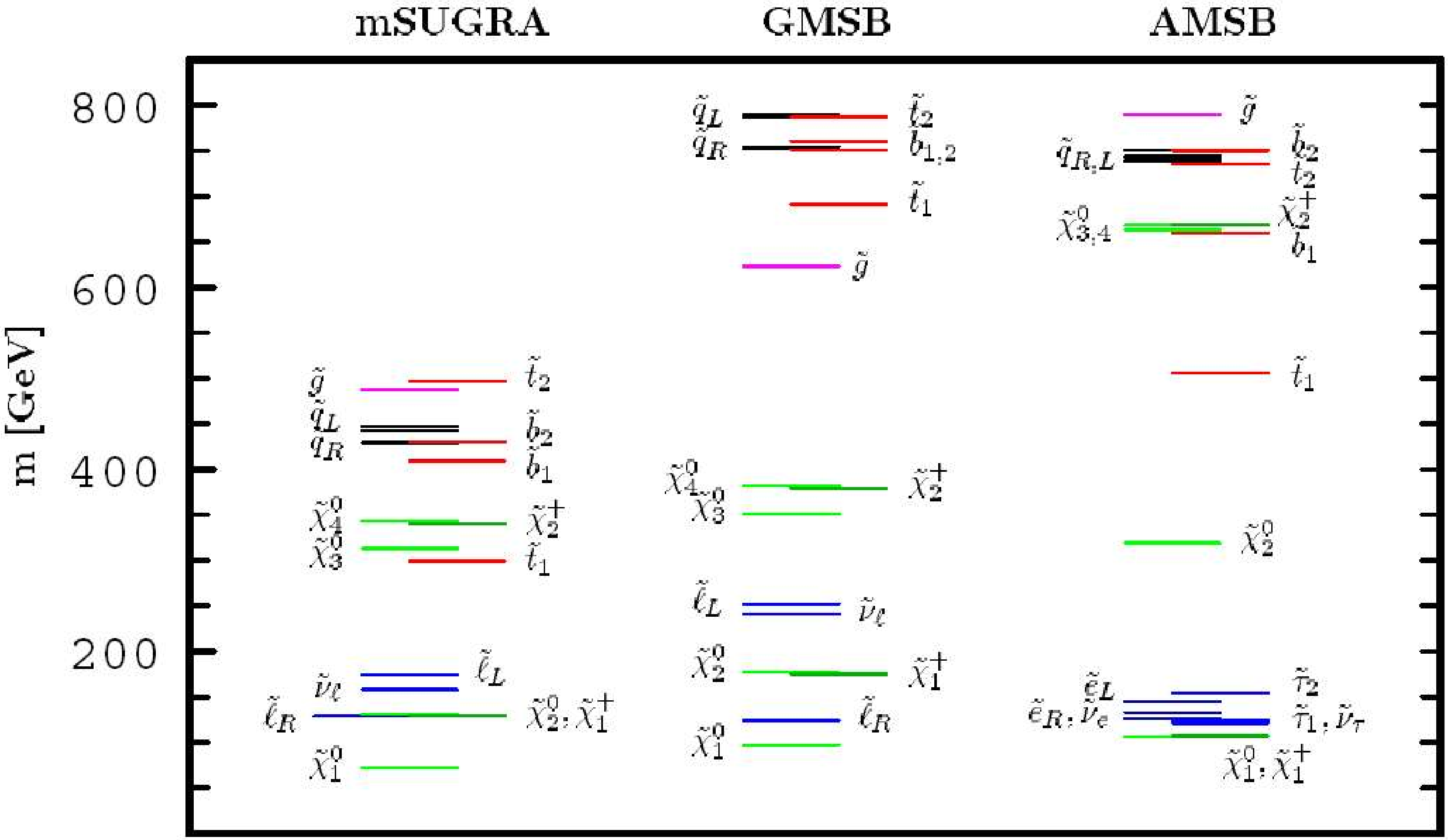


← well measurable at LHC

← precise spectroscopy at ILC

Different SUSY breaking scenarios

Different SUSY breaking scenarios yield different spectra:



Tasks of the ILC

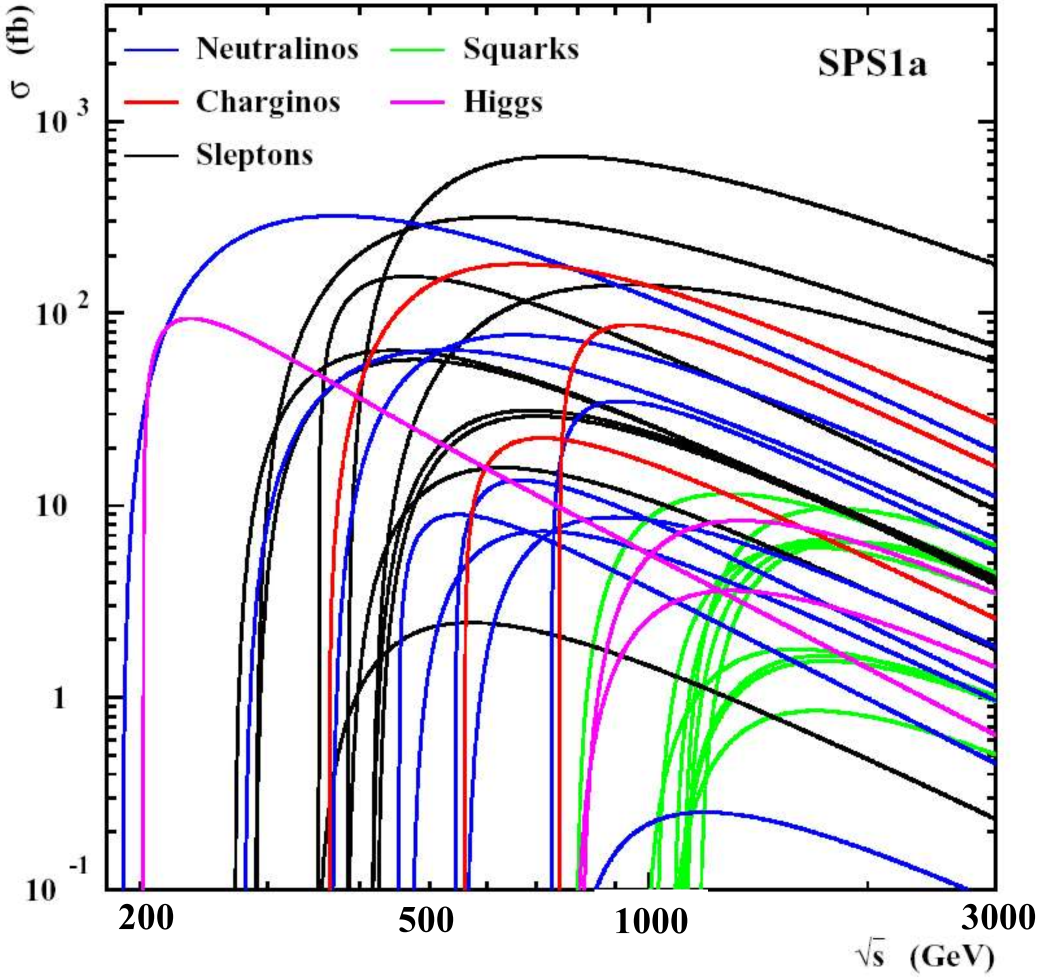
After discovery, the task will be to establish the underlying theory of SUSY breaking. The ILC can do this by precision measurements of the masses and the properties of the accessible part of the spectrum.

- Is it really SUSY?
  spin, couplings, ... as required
- How is it realized?
  particle contents: MSSM, NMSSM, ...
- How is it broken?
  Measure as many of the > 100 low energy parameters as possible, measure them as precisely as possible
  → extrapolation to the high scale (“bottom-up approach”)

Note: Successfully fitting the parameters of a constrained model to the observations is a necessary but not a sufficient test of the model.

Sparticle cross-sections at ILC

This will be fun ...



Cross-sections in the 10 – 1000 fb range

Can use full potential of ILC to disentangle this “chaos”:

- tunable √s
- tunable beam polarization

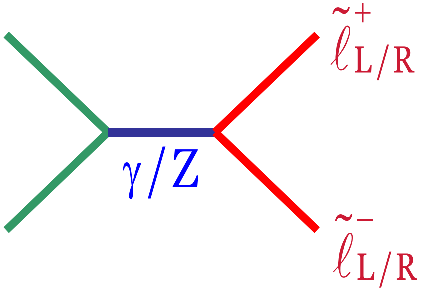
Overview: SUSY at ILC

1. Sleptons
2. Charginos + neutralinos
3. Stops
4. Dark matter
5. More exotic SUSY scenarios

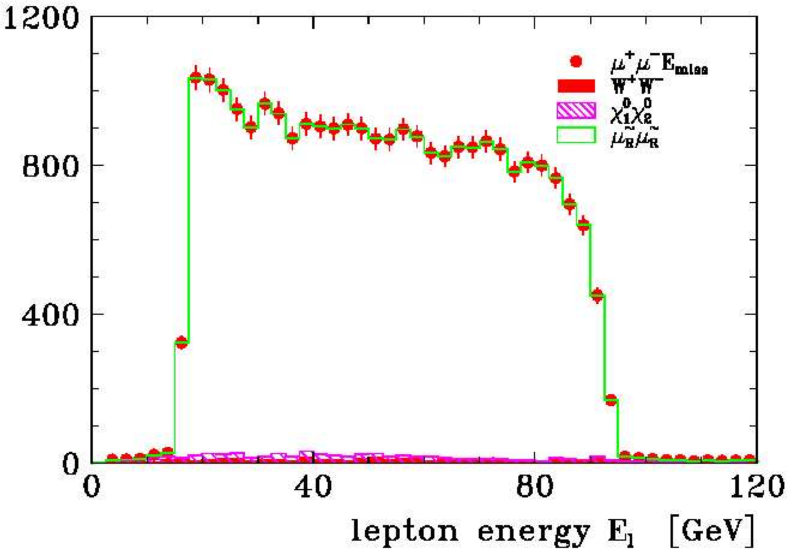
Sleptons

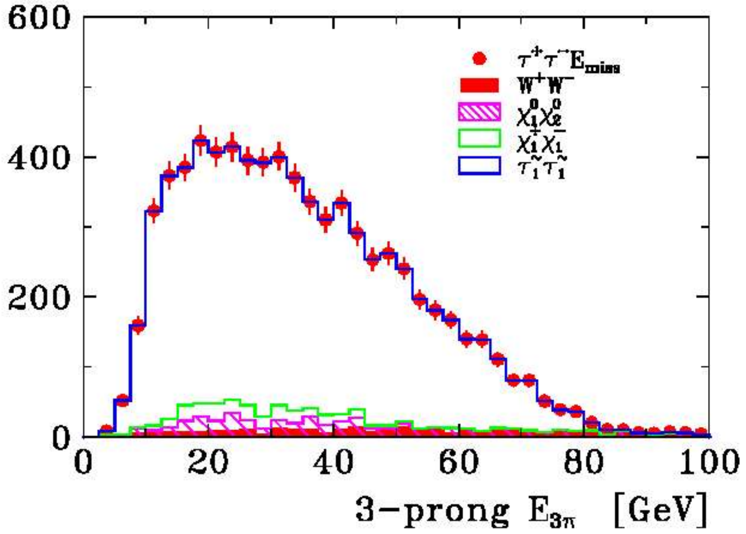
Pair production:

$$
\begin{aligned}
e^+e^- &\rightarrow \tilde{e}_R\tilde{e}_R,\ \tilde{e}_L\tilde{e}_L,\ \tilde{e}_R\tilde{e}_L,\ \tilde{\nu}_e\bar{\tilde{\nu}}_e \\
e^+e^- &\rightarrow \tilde{\mu}_R\tilde{\mu}_R,\ \tilde{\mu}_L\tilde{\mu}_L,\ \tilde{\nu}_\mu\bar{\tilde{\nu}}_\mu \\
e^+e^- &\rightarrow \tilde{\tau}_1\tilde{\tau}_1,\ \tilde{\tau}_2\tilde{\tau}_2,\ \tilde{\tau}_1\tilde{\tau}_2,\ \tilde{\nu}_\tau\bar{\tilde{\nu}}_\tau
\end{aligned}
$$



Examples:





Simple two-body decay kinematics and beam energy constraint allow for mass measurement of both slepton and lightest neutralino

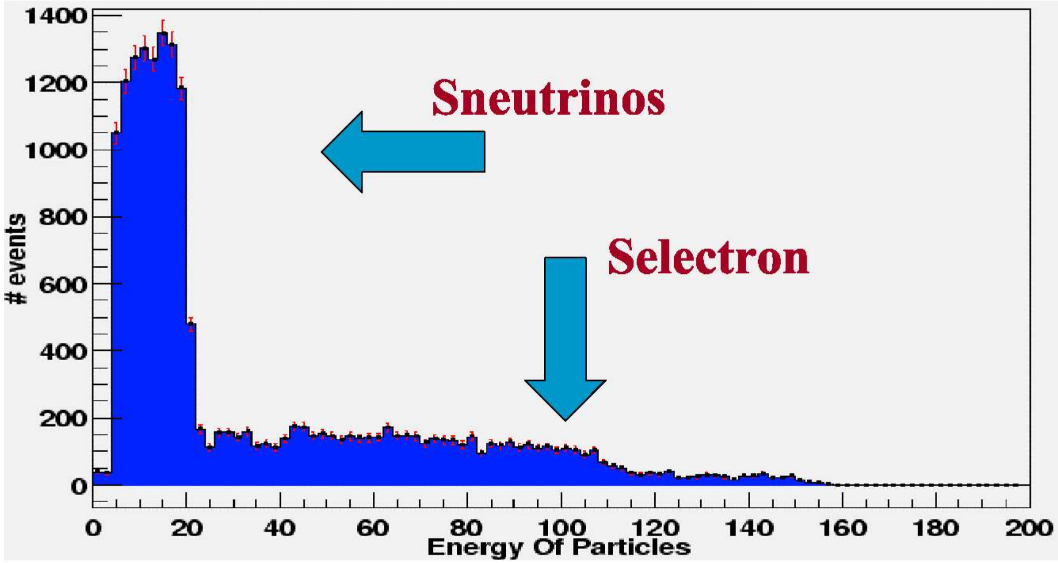
$$
\boxed{
\begin{aligned}
m_{\tilde{l}} &= \frac{\sqrt{s}}{E_- + E_+}\sqrt{E_- E_+} \\
m_{\tilde{\chi}} &= m_{\tilde{l}}\sqrt{1 - \frac{E_- + E_+}{\sqrt{s}/2}}
\end{aligned}
}
$$

Sneutrinos

Sneutrinos have huge cross-section but are difficult to detect.

If $m_{\tilde{\nu}} > m_{\chi^\pm}$, the decay $\tilde{\nu} \to e^+ \chi^- \to e^+ \mu^- \nu_\mu \chi_1^0$ is possible.

Electron spectrum in $e\,\mu$ + missing energy final states:

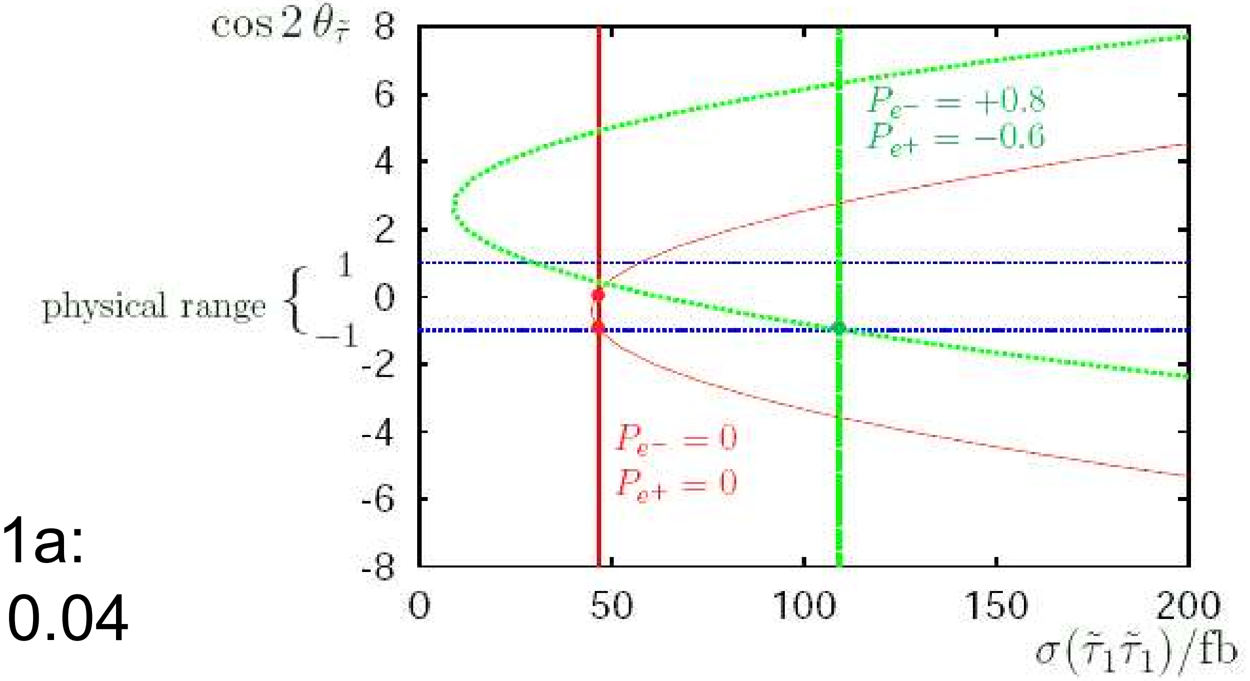


Indirect handle on $\tilde{\nu}_e$ in chargino pair production for gaugino-like charginos (→ later).

Staus

3^{rd} generation: large mixing between left and right chiral states expected

Determine mixing angle θ_τ from measurement of polarized cross-section $\sigma(\tilde\tau_1\,\tilde\tau_1)$



Precision for SPS1a:
$\cos 2\theta_\tau = -0.84 \pm 0.04$

Ultimate goal is to determine tri-linear coupling A_t:

$$A_\tau = \frac{m^2_{\tilde\tau_2} - m^2_{\tilde\tau_1}}{m_\tau}\sin 2\theta_{\tilde\tau} + \mu\tan\beta$$

from chargino/neutralino sector

from chargino/neutralino
or from Higgs sector
or from τ polarisation measurement

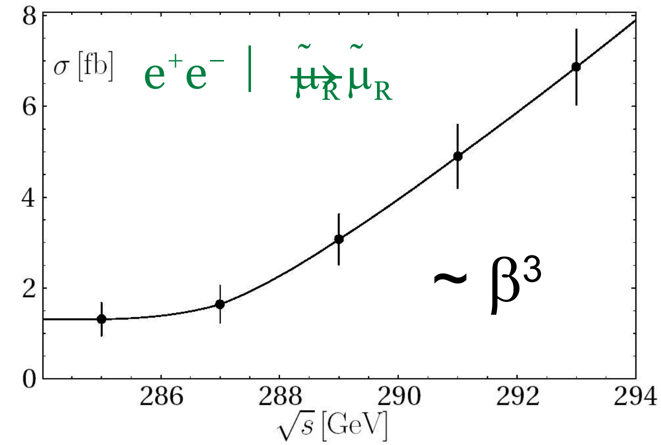
Best from global fit to all observables (→ later)!

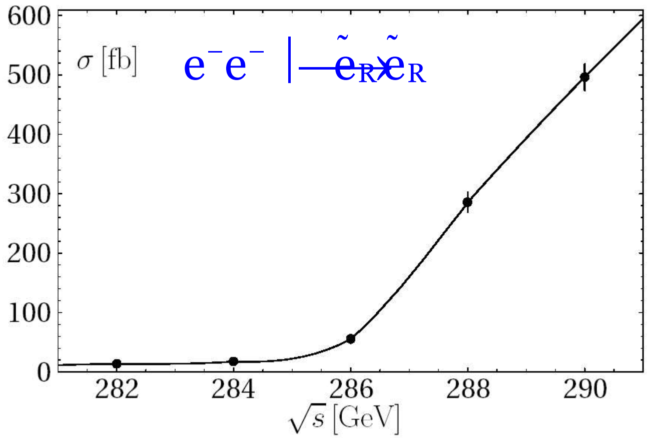
Sleptons: Threshold scans

$e^+ e^-$ offers possibility to vary √s.

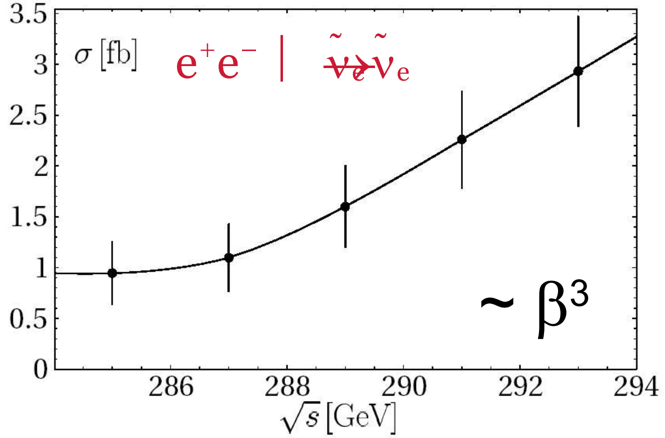
Production threshold of SUSY processes:

- most precise mass determination (50 – 500 MeV)
- sensitivity to sparticle width (50 – 200 MeV)





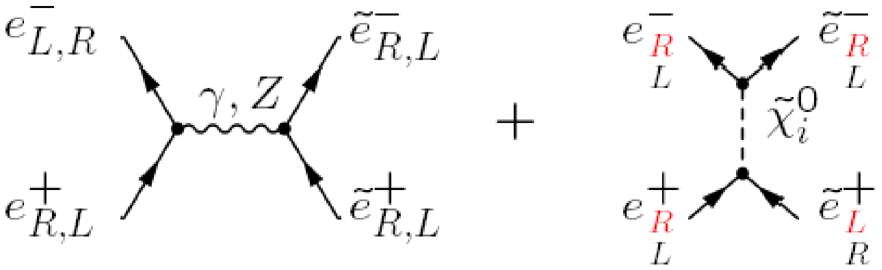
$e^- e^-$ has highest sensitivity due to steep rise ∝ β



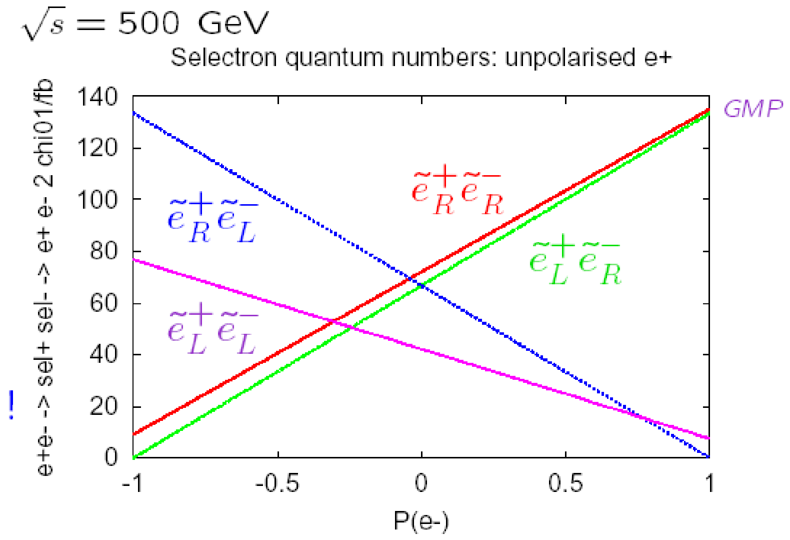
need to take into account

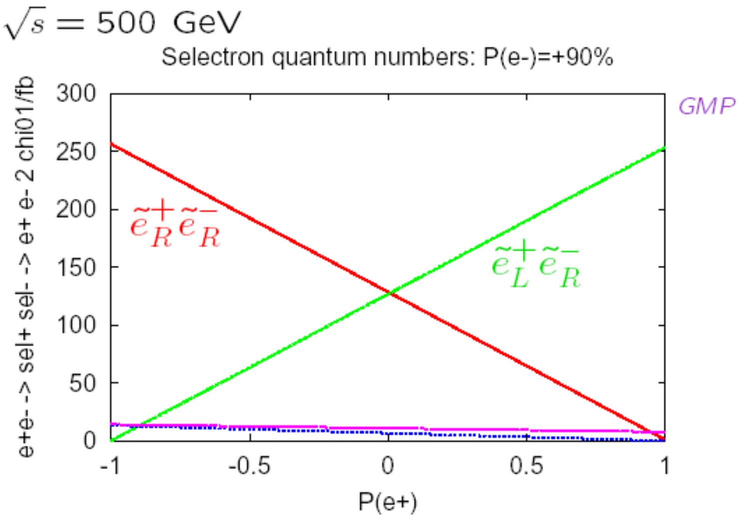
- higher-order corrections
- threshold corrections
- finite width effects
- beam spread

Selectron couplings

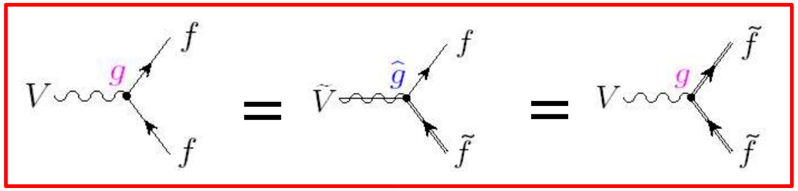


Find out which are the chiral partners of R and L electrons. Exploit t-channel diagram. Need both beams polarized.





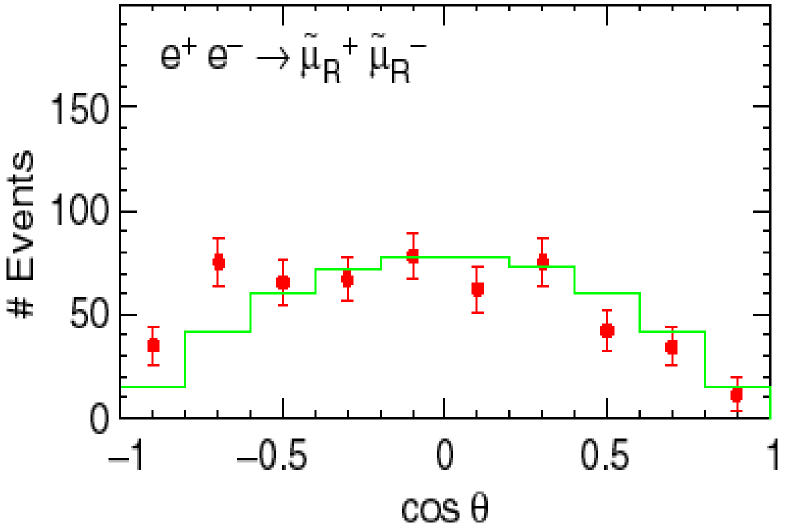
Cross section measurements check fundamental SUSY relations:



Slepton spin

SUSY: slepton and lepton spin differ by ½

Spin can be cleanly determined from production angle distribution:



Spin 0: $\propto \sin^2\theta$

Charginos

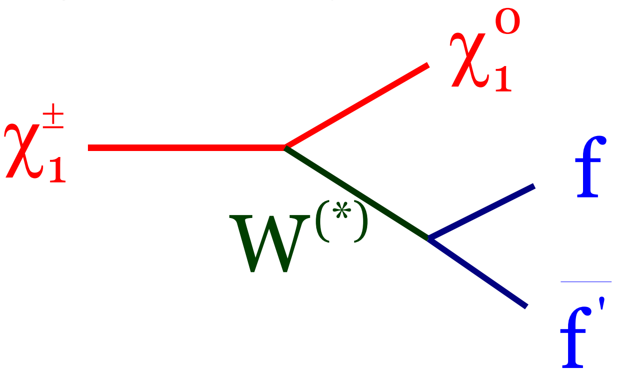
Chargino mass matrix $X = \begin{pmatrix} M_2 & \sqrt{2}\, m_W\, s_\beta \\ \sqrt{2}\, m_W\, c_\beta & \mu \end{pmatrix}$

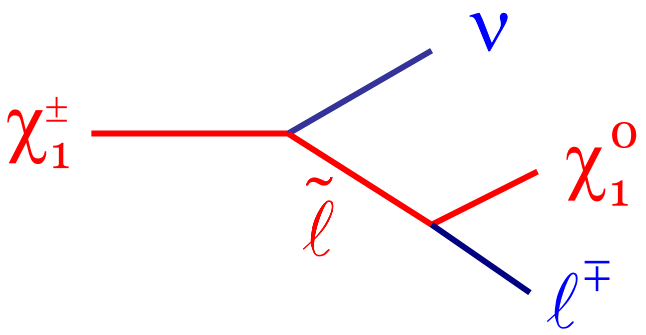
Depends on tree level on 3 parameters: M_2, μ, tan β.

Gets diagonalized by two unitary matrices (angles ϕ_R, ϕ_L).

Measurement of mass and polarized cross-section required to extract the tree-level parameters of the chargino sector.

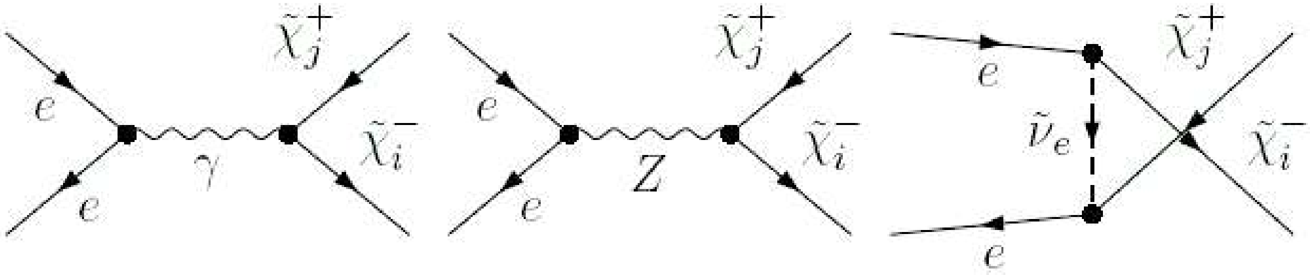
Chargino decays:

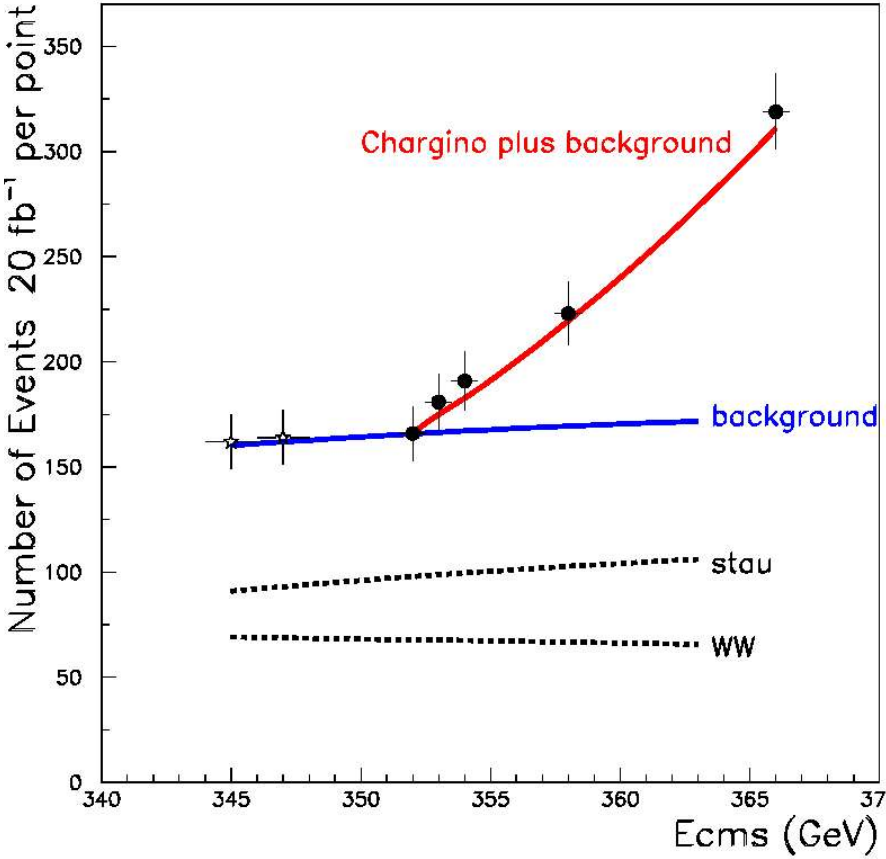




Chargino mass measurements

Production:



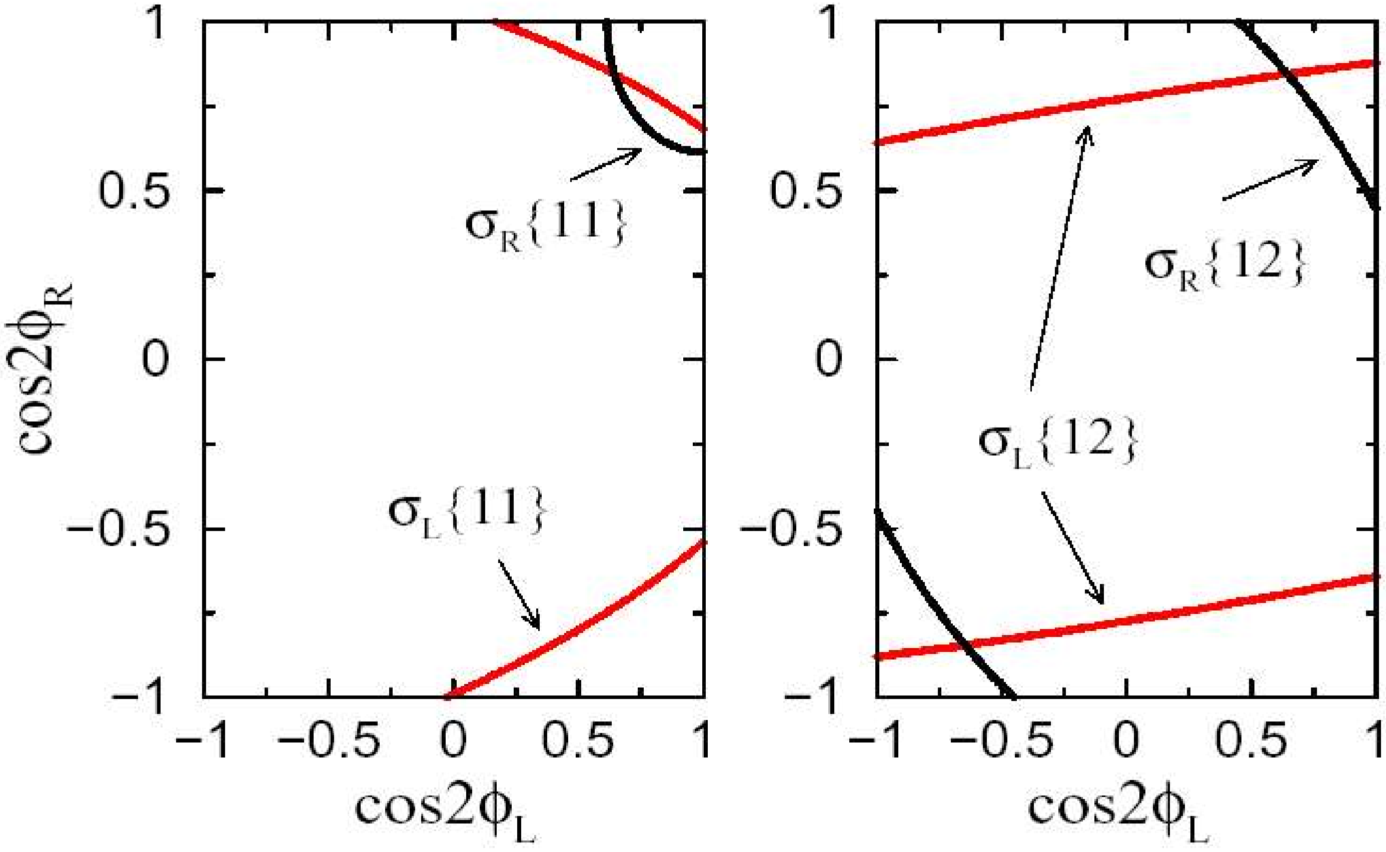


Precision:
550 MeV for 100 fb^{-1}
for SPS1a

Figure 5.32: Threshold scan of $e_R^+ e_L^- \to \tilde\chi_1^+ \tilde\chi_1^1 \to \tau^+ \nu_\tau \tilde\chi_1^0\ \tau^- \nu_\tau \tilde\chi_1^0$ for SPS 1a assuming $\mathcal{L} = 100\,\mathrm{fb}^{-1}$

Chargino cross-section meas.

Measurement of cross-section with left and right handed electrons solves for angles ϕ_R, ϕ_L which diagonalize mass matrix → parameter determination

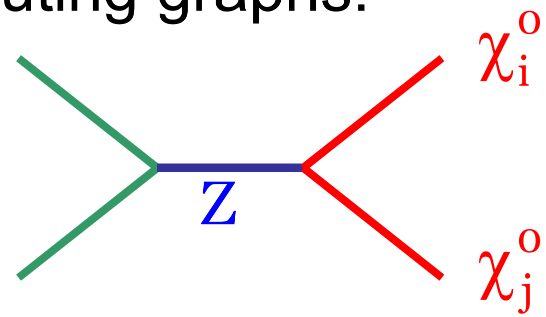


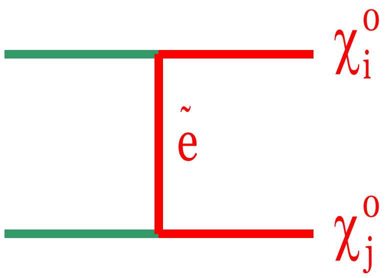
Neutralinos

Neutralinos are pair-produced via the processes:

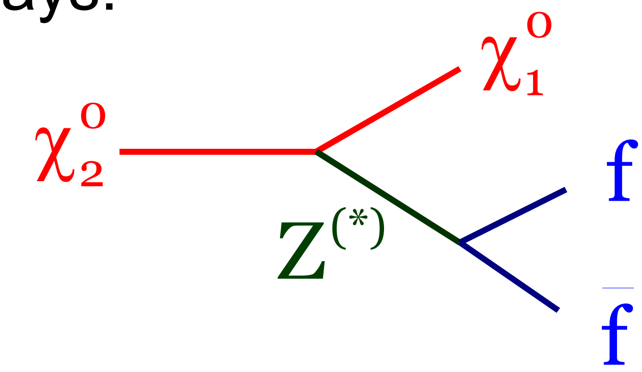
$$e^+ e^- \rightarrow \chi_i^0 \chi_j^0 \qquad i, j = 1,\ldots,4$$

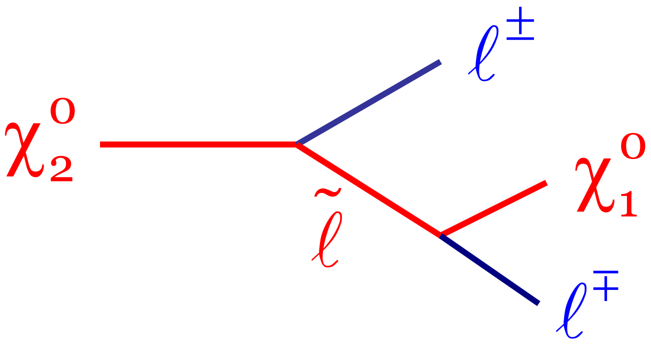
Contributing graphs:





Decays:

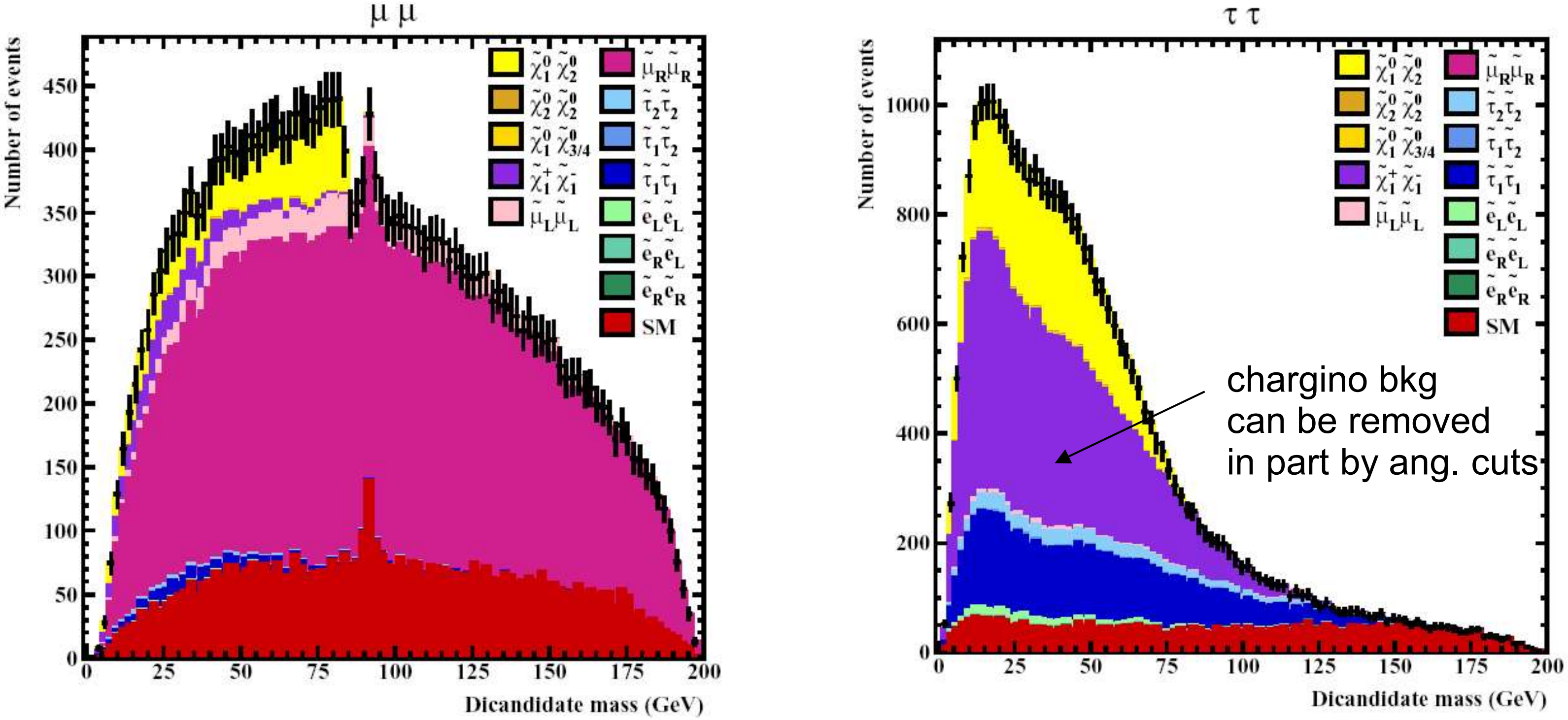




Neutralino detection

Detection of $\chi^o_1\chi^o_2$ is not straight-forward (SUSY background)

Inclusive SUSY di-lepton selection for unpolarized beams at 500 GeV:



chargino bkg
can be removed
in part by ang. cuts

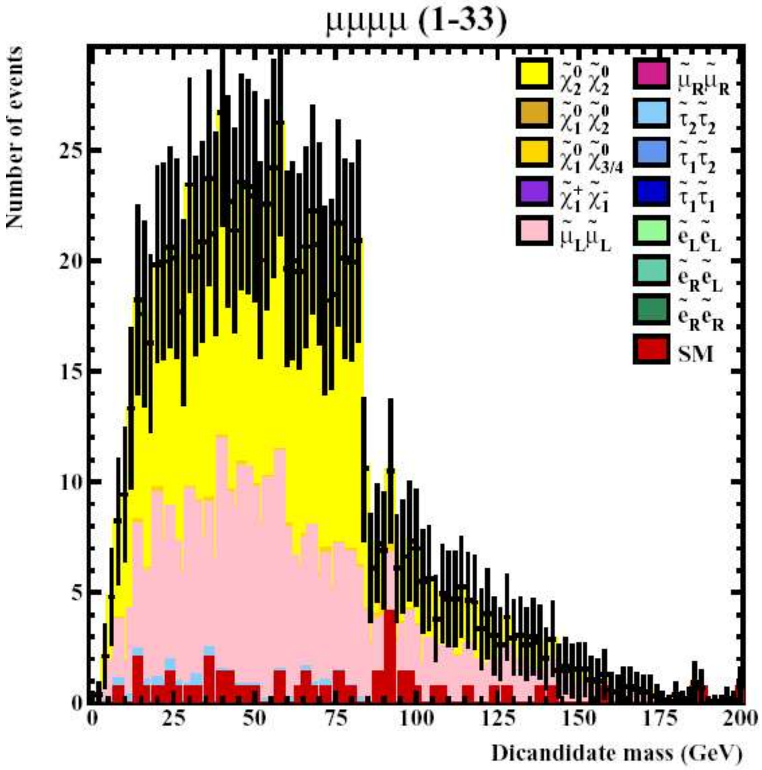
Polarization and angular distr. will help to further reduce bkgd.

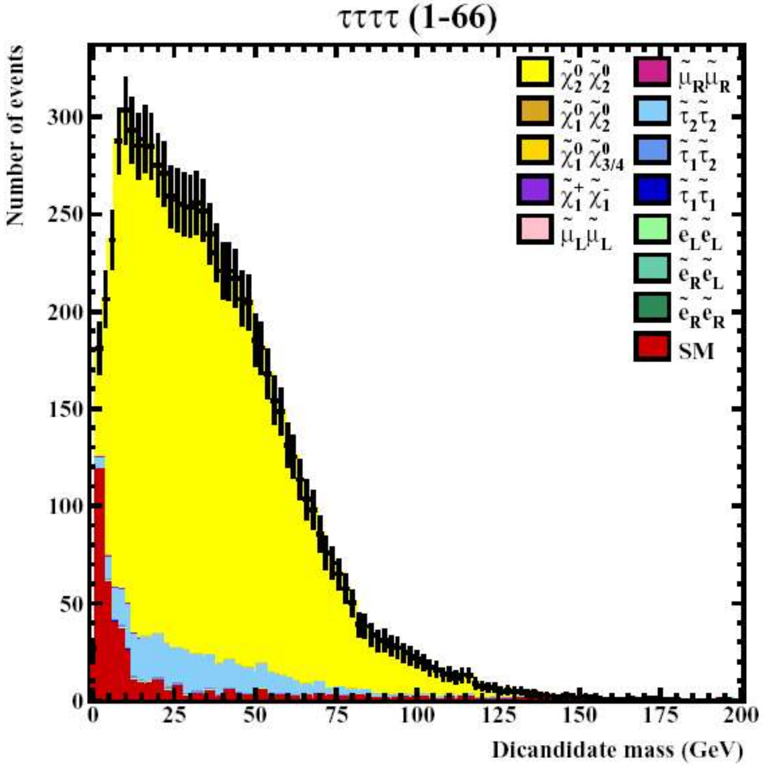
Mass measurement best if e/μ final states have high BR.

Neutralino detection

Detection of $\chi^o_2\chi^o_2$ in four-lepton final state is easier.

Two subsets of the inclusive SUSY four-lepton selection at 500 GeV:



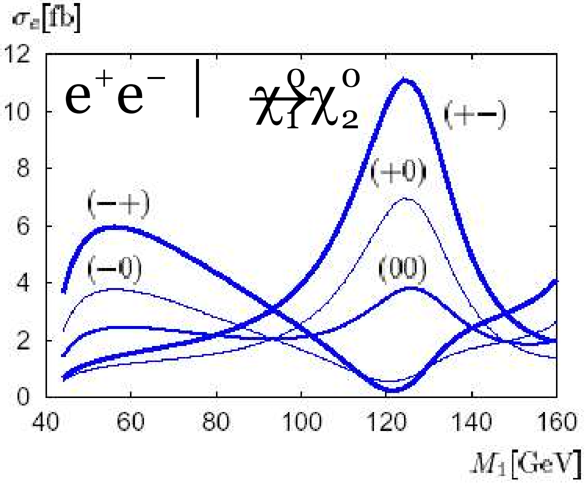


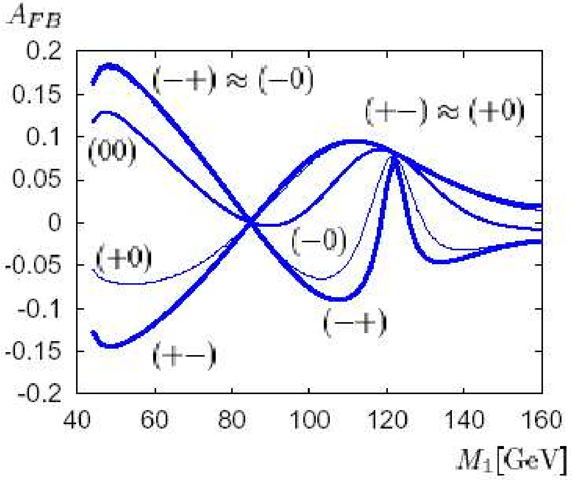
Neutralino mass matrix

Neutralino mass matrix $$Y = \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z c_W c_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

Contains M_1 in addition to chargino parameters.

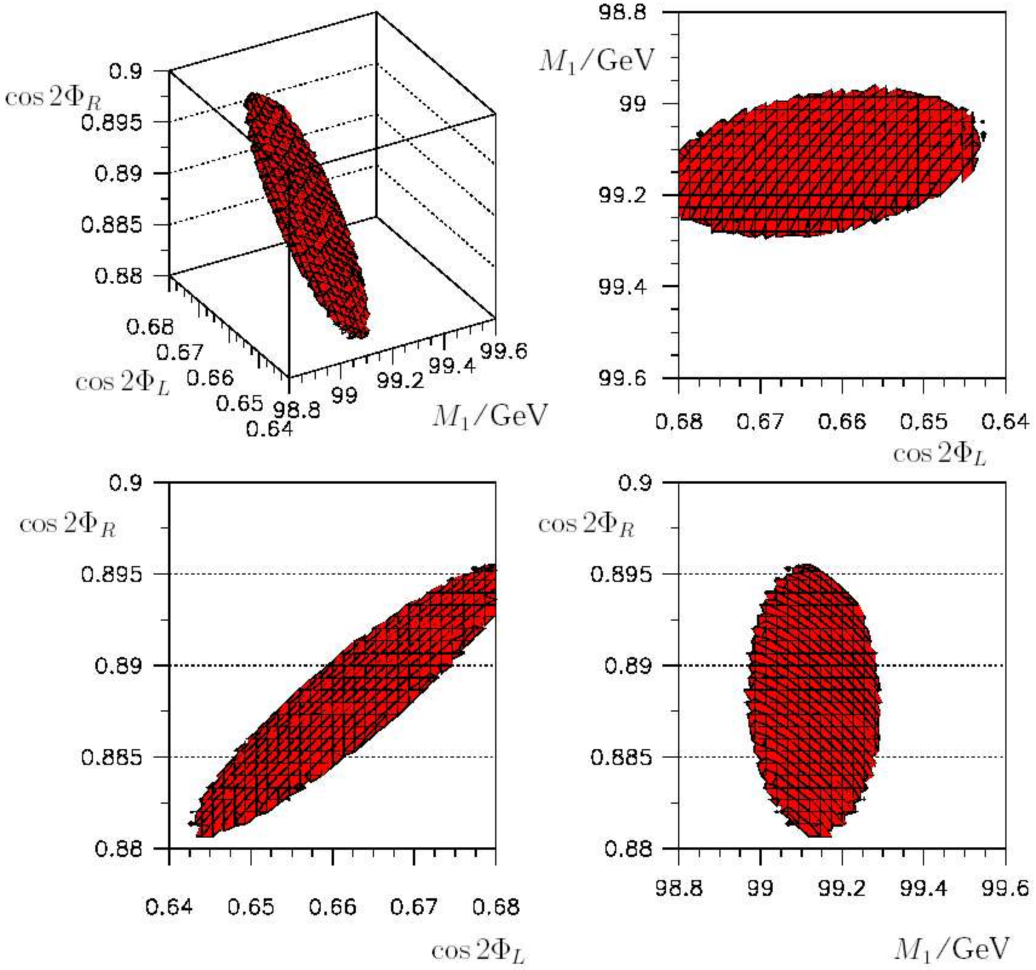
M_1 can be determined (at tree-level) from neutralino masses - but cross-section and angular distributions (FB asymmetry) gives further constraints (discriminate against larger neutralino sectors, e. g. NMSSM with 5 neutralinos).





Polarization needed

Neutralinos + charginos



An example:
mass measurements of $\chi^o_1, \chi^o_2, \chi^\pm_1$ and polarized cross-sections for $\chi^o_1\chi^o_2$, $\chi^+_1\chi^-_1$ in SPS1a fed into tree-level fit for neutralino + chargino sector

(Loop-level fits → later)

SUSY Parameters				Mass Predictions		
M_1	M_2	μ	$\tan\beta$	$m_{\tilde{\chi}^\pm_2}$	$m_{\tilde{\chi}^0_3}$	$m_{\tilde{\chi}^0_4}$
99.1 ± 0.2	192.7 ± 0.6	352.8 ± 8.9	10.3 ± 1.5	378.8 ± 7.8	359.2 ± 8.6	378.2 ± 8.1

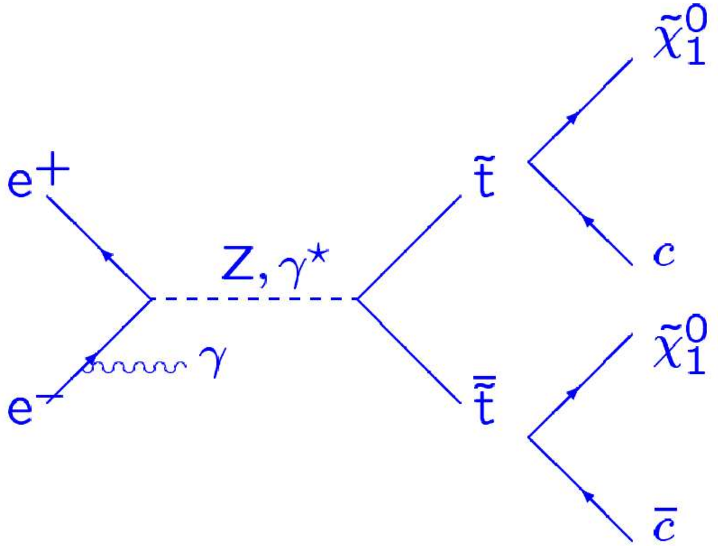
Light stop

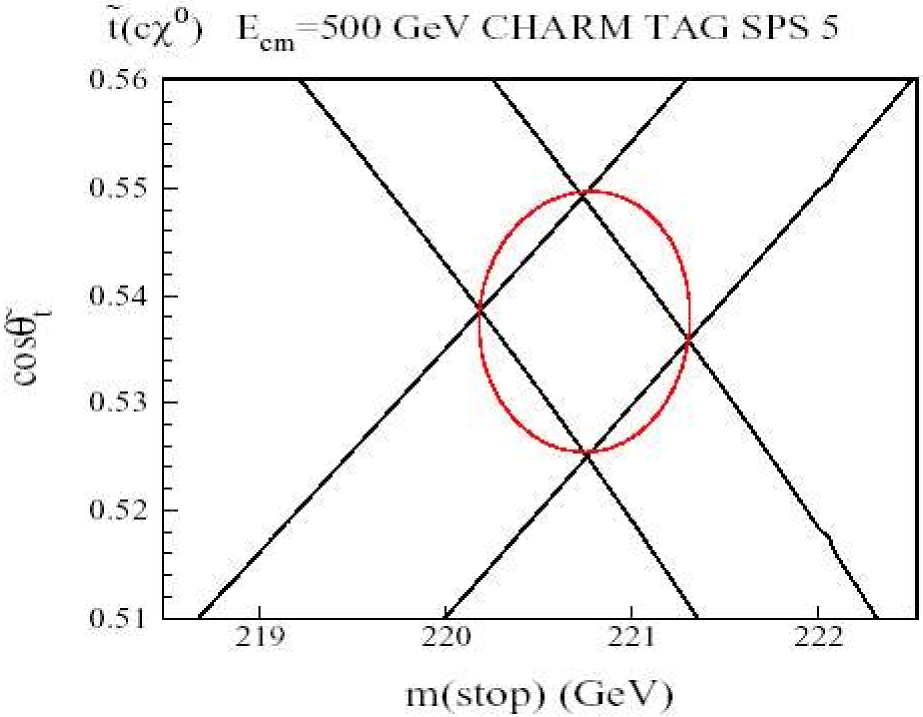
Stop squark is often lighter than other squarks due to large mixing.
Example (SPS5 benchmark):

$$m_{\tilde{t}_1} = 220\,\mathrm{GeV}$$

$$m_{\chi_1^o} = 120\,\mathrm{GeV}$$

$$\cos\theta_{\tilde{t}} = 0.54$$



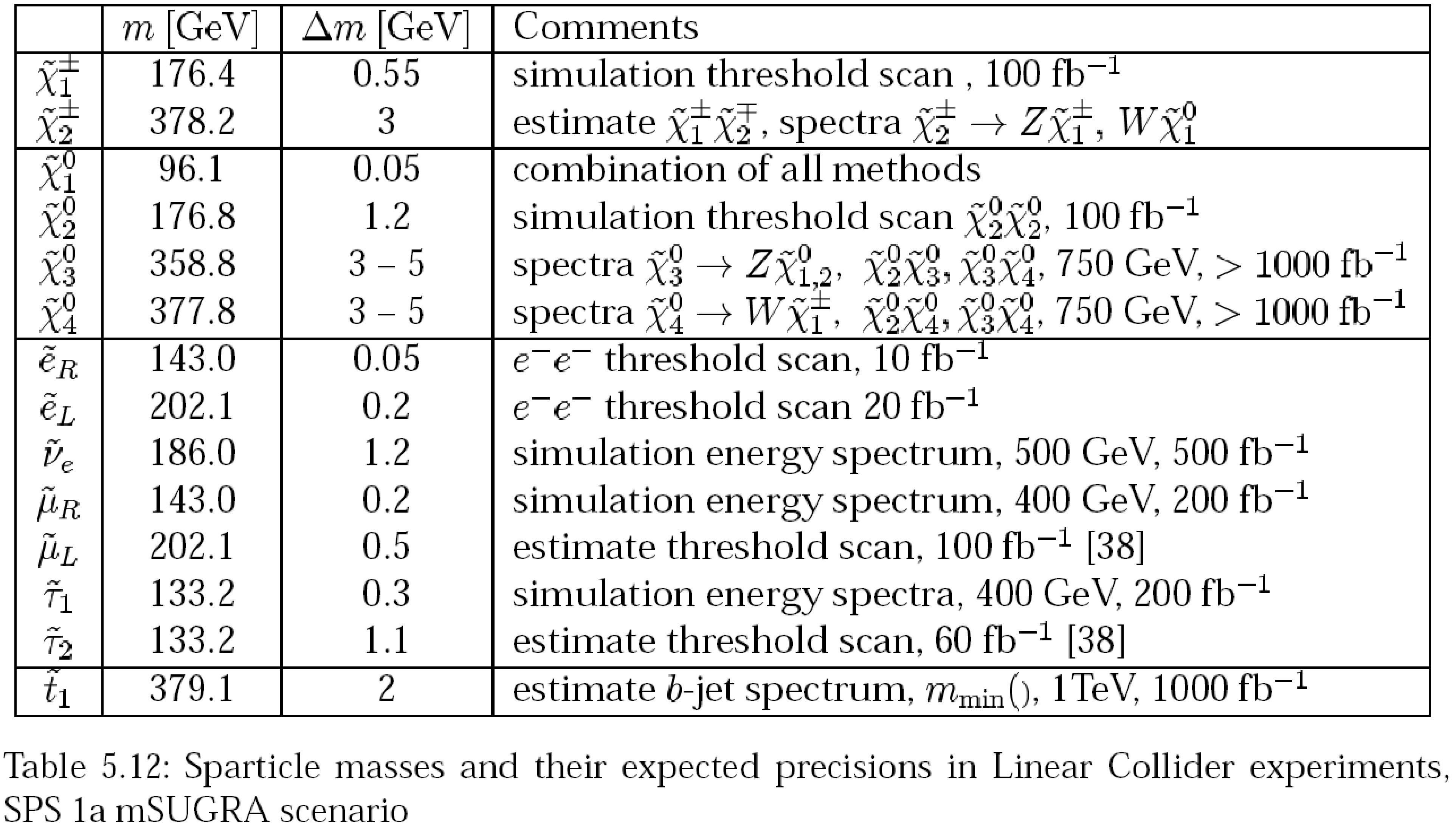


Measurement of LR and RL cross-sections to extract

$$m_{\tilde{t}_1} = 220 \pm 0.6\,\mathrm{GeV}$$

$$\cos\theta_{\tilde{t}} = 0.54 \pm 0.01$$

Summary of mass measurements



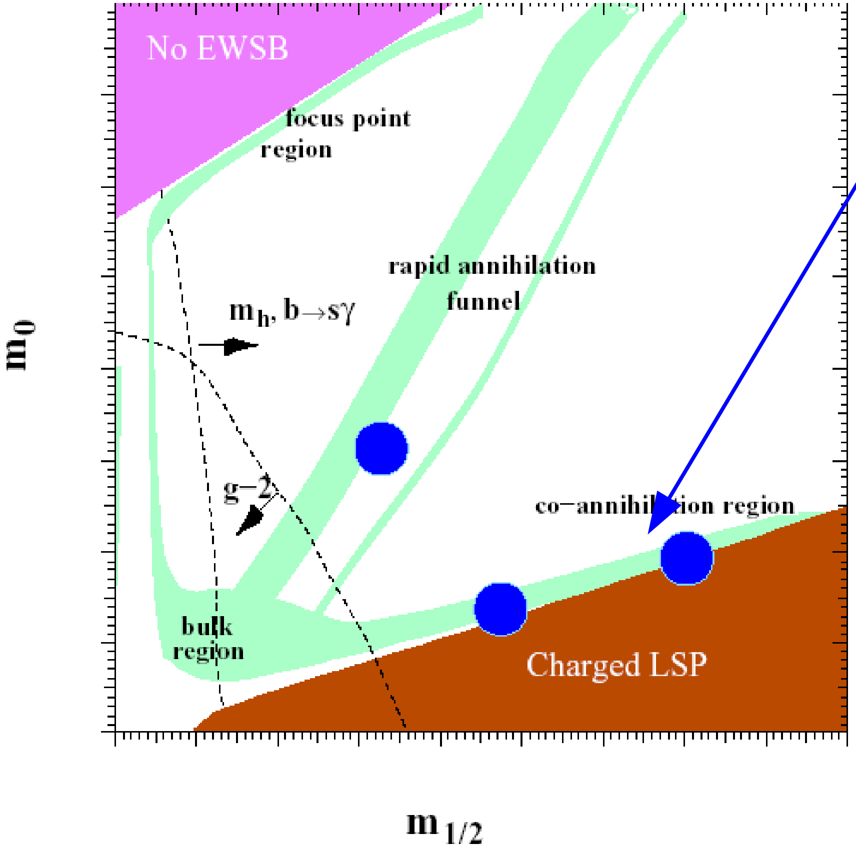
	m [GeV]	Δm [GeV]	Comments
$\tilde{\chi}_1^\pm$	176.4	0.55	simulation threshold scan , 100 fb^{-1}
$\tilde{\chi}_2^\pm$	378.2	3	estimate $\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$, spectra $\tilde{\chi}_2^\pm \to Z\tilde{\chi}_1^\pm, W\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$	96.1	0.05	combination of all methods
$\tilde{\chi}_2^0$	176.8	1.2	simulation threshold scan $\tilde{\chi}_2^0\tilde{\chi}_2^0$, 100 fb^{-1}
$\tilde{\chi}_3^0$	358.8	3 – 5	spectra $\tilde{\chi}_3^0 \to Z\tilde{\chi}_{1,2}$, $\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_3^0\tilde{\chi}_4^0$, 750 GeV, $>$ 1000 fb^{-1}
$\tilde{\chi}_4^0$	377.8	3 – 5	spectra $\tilde{\chi}_4^0 \to W\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0\tilde{\chi}_4^0, \tilde{\chi}_3^0\tilde{\chi}_4^0$, 750 GeV, $>$ 1000 fb^{-1}
$\tilde{e}_R$	143.0	0.05	e^-e^- threshold scan, 10 fb^{-1}
$\tilde{e}_L$	202.1	0.2	e^-e^- threshold scan 20 fb^{-1}
$\tilde{\nu}_e$	186.0	1.2	simulation energy spectrum, 500 GeV, 500 fb^{-1}
$\tilde{\mu}_R$	143.0	0.2	simulation energy spectrum, 400 GeV, 200 fb^{-1}
$\tilde{\mu}_L$	202.1	0.5	estimate threshold scan, 100 fb^{-1} [38]
$\tilde{\tau}_1$	133.2	0.3	simulation energy spectra, 400 GeV, 200 fb^{-1}
$\tilde{\tau}_2$	133.2	1.1	estimate threshold scan, 60 fb^{-1} [38]
$\tilde{t}_1$	379.1	2	estimate b-jet spectrum, $m_{\min}()$, 1TeV, 1000 fb^{-1}

Table 5.12: Sparticle masses and their expected precisions in Linear Collider experiments, SPS 1a mSUGRA scenario

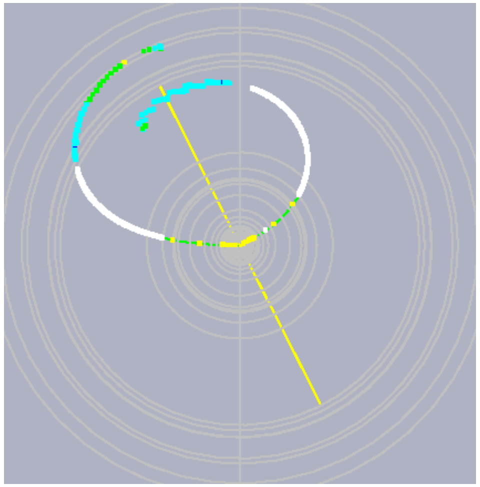
Dark matter

If SUSY LSP responsible for cold dark matter, we need accelerators to prove that its properties are consistent with CMB data.

WMAP points to certain difficult regions in parameter space:



small $\Delta M = M_{\tilde{\ell}} - M_{\chi_1^o}$



Smuon pair production at 1 TeV:
only two very soft muons,
huge background from two-photon processes: $e^+e^- \to ee\mu\mu$, etc

Split supersymmetry

In these model all scalars except h are ultra-heavy.
Fermionic sparticles remain light.

Implications for LHC:

Meta-stable gluinos (interesting → R-hadrons),
charginos + neutralinos only through Dell-Yan (challenging)

... and at the ILC:

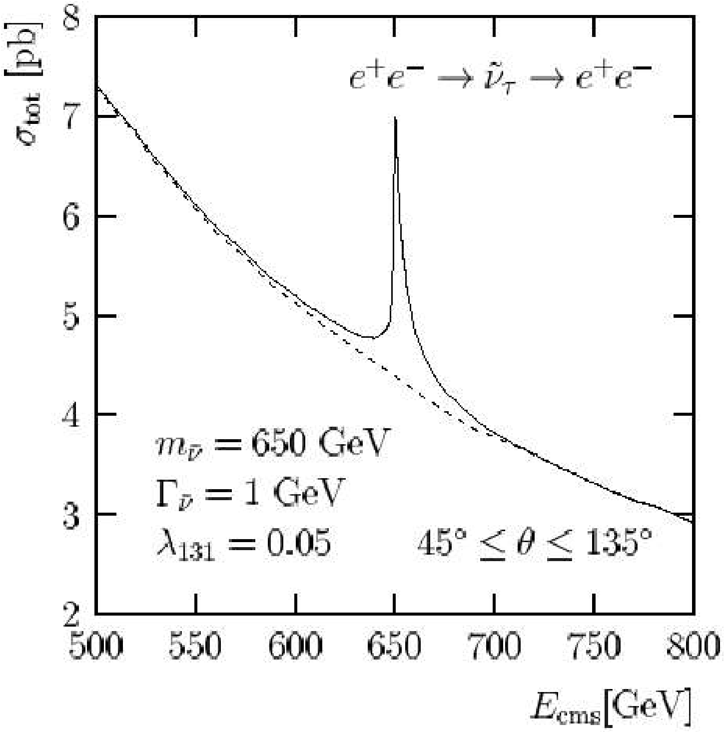
Precision measurements of masses and cross-sections in the chargino+neutralino and Higgs sector can test the model and determine the scalar mass scale.

R-parity violating SUSY

R parity quantum number = 1 for particles, = -1 for sparticles

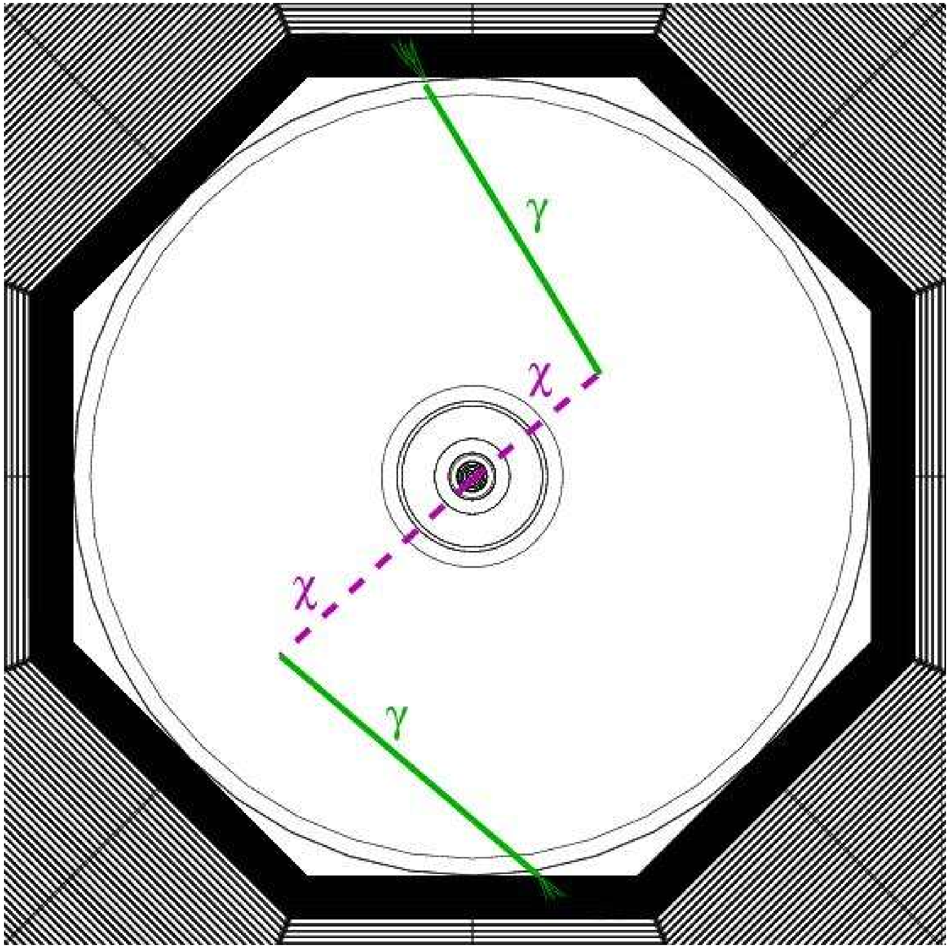
Conservation of R-parity implies:

- LSP is stable
- Sparticles can only be pair-produced



R-parity violation may provide striking signatures

Gauge-mediated SUSY breaking



In some SUSY scenarios (with GMSB) the χ_1^0 is not the LSP:

$$\chi_1^0 \rightarrow g\ \tilde{G}$$

Non-pointing photon signature

→ extremely challenging for ECAL

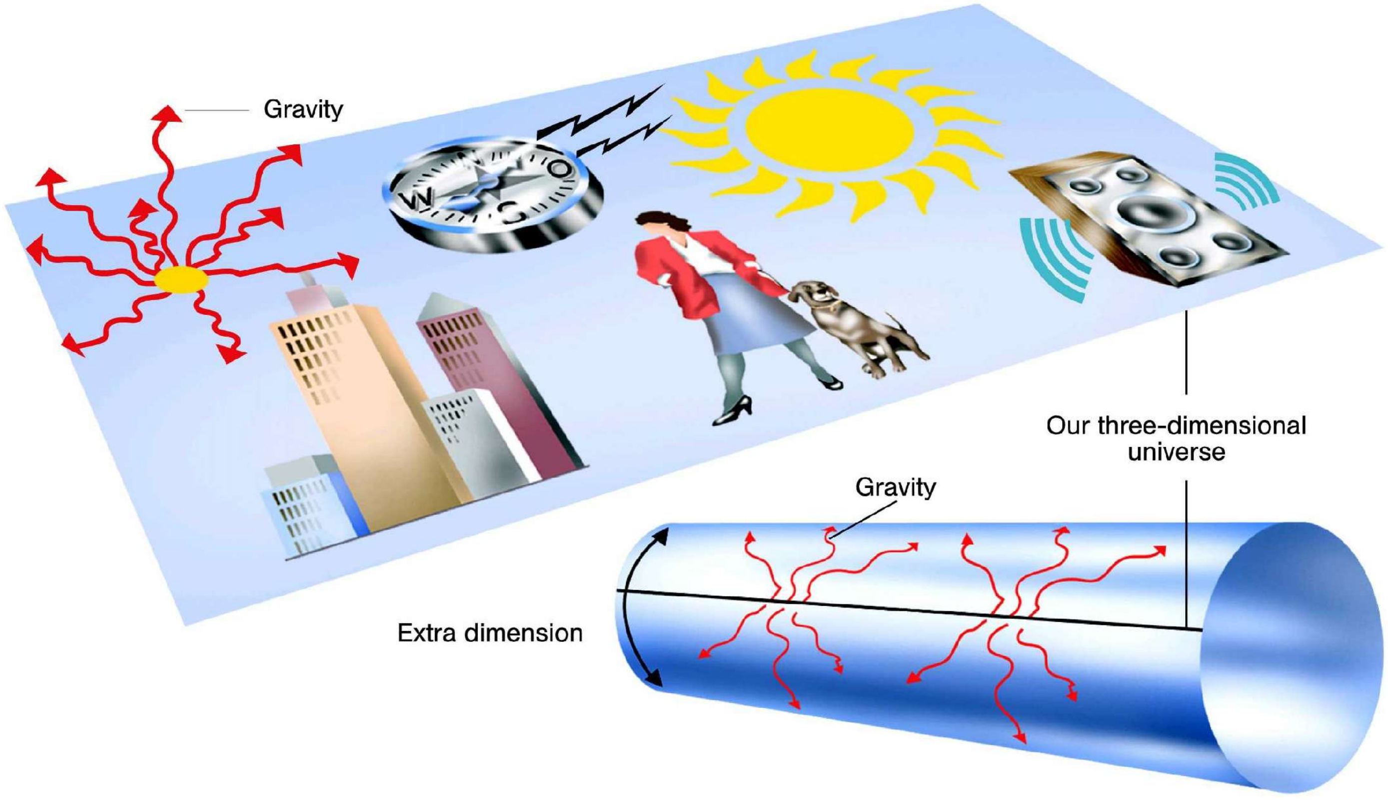
Summary part III

- SUSY is an attractive extension of the SM curing some some of its problems.
- Thanks to direct (pair-)production sparticles and their properties (masses, cross-sections, ...) can be precisely studied at the ILC.
- The availability of polarized electrons and positrons is particularly useful for SUSY studies (test of fundamental SUSY relations, ...).

Extra dimension theories

Extra dimensions

- Completely alternative approach to solve hierarchy problem: “There is no hierarchy problem”
- Suppose the SM fields live in “normal” 3+1 dim. space
- Gravity lives in 4 + δ dimensions
- δ extra dimensions are curled to a small volume (radius R)



Extra dimensions

For r < R, gravity follows Newton's law in 4 + δ dimensions:

$$V(r) = \frac{G_S}{r^{\delta+1}}$$

For r > R, gravity follows effectively Newton's law in 4 dimensions, since the “distance” in the extra dimensions does not rise anymore:

$$V(r) = \frac{G_S}{R^\delta r} = \frac{G_N}{r} \text{ with } G_N = \frac{G_S}{R^\delta}$$

The Planck mass $M^2_{Planck} = \hbar c / G_N$ only effectively appears so high at large distances. The true scale of gravity is

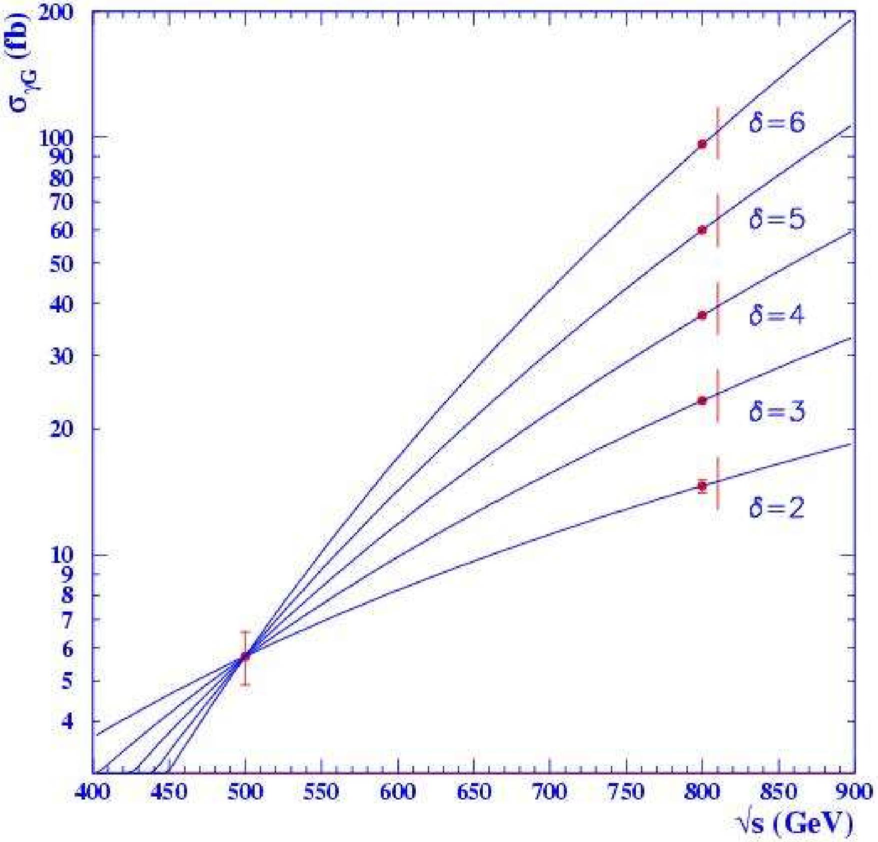
$$M^2_S = \hbar c / G_S = \hbar c R^\delta / G_N$$

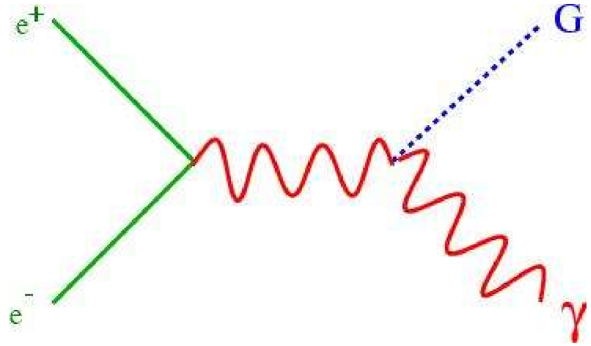
If e. g. R ~ $\mathcal{O}$(100 μm) and δ = 2, one obtains $M_S = o(1\,\mathrm{TeV})$

⇒ Gravity might become visible at TeV-scale colliders!

Real graviton emission

Effects from real graviton emission:

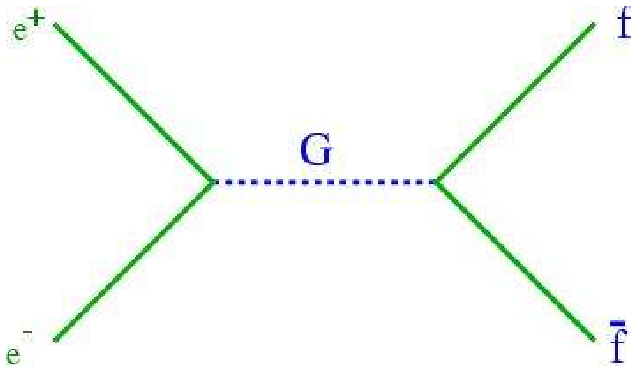




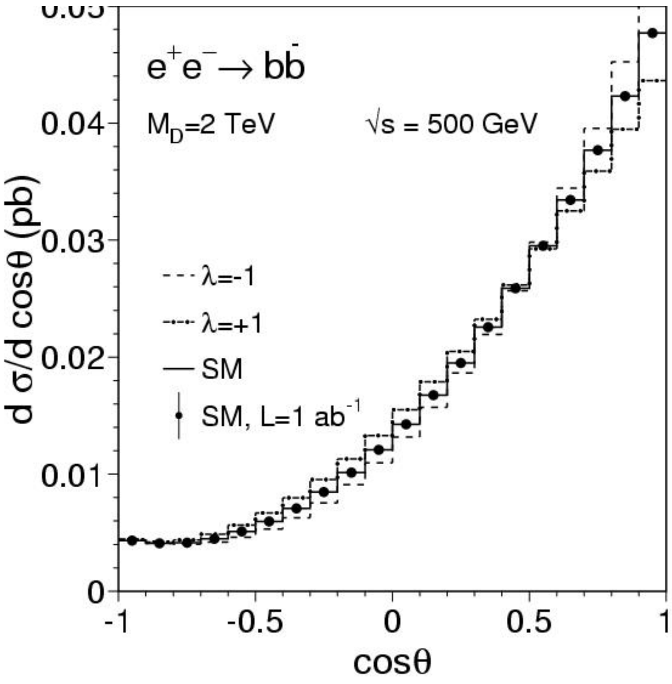
measures number of extra dimensions!

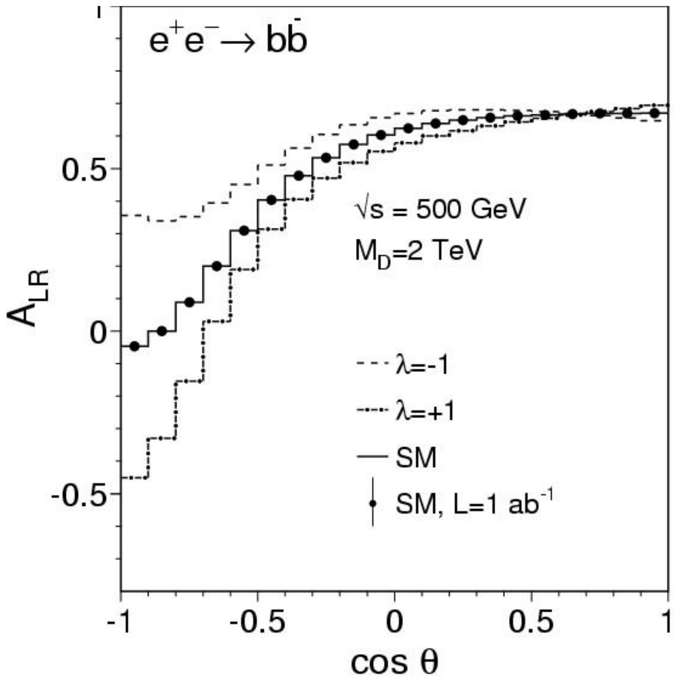
Virtual graviton exchange

Effects from virtual graviton exchange:

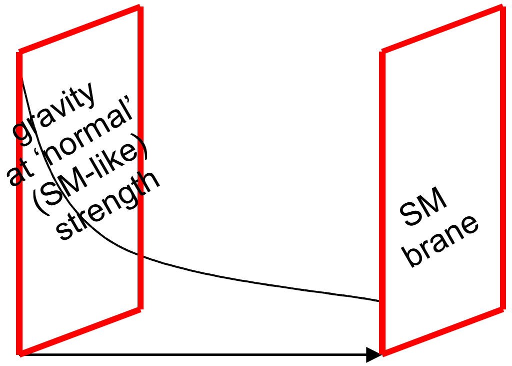


can prove spin-2 of exchange!





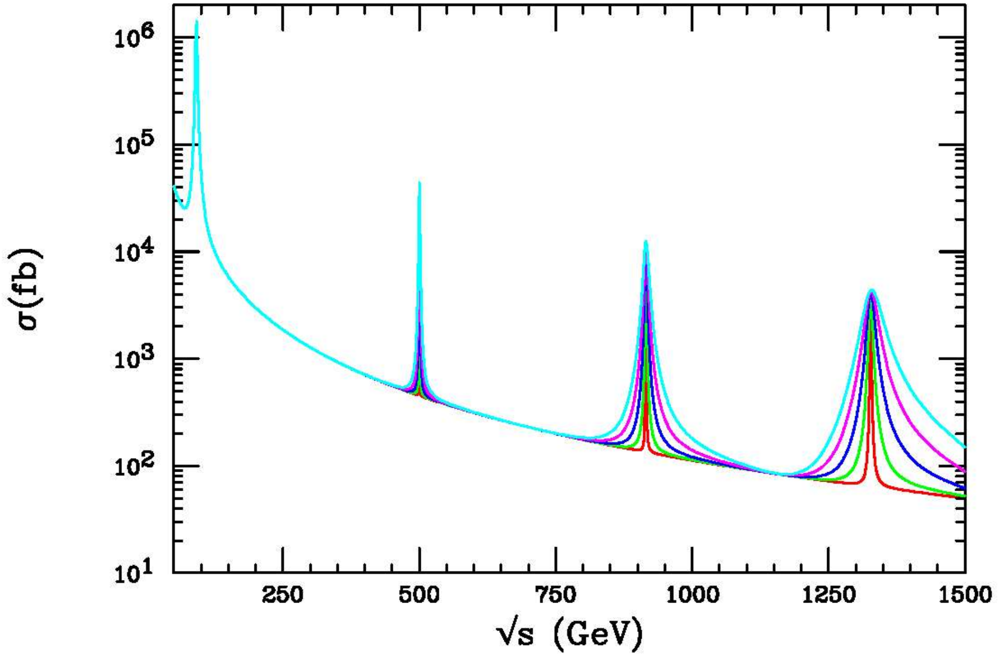
“Warped” extra dimensions



5th dimension ϕ

Gravity appears weak at the SM brane (in our world) due to exponentially “warped” metric in 5th dimension

$$ds^2 = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2$$



might observe spectacular Kaluza-Klein excitations of the graviton

+ graviscalar excitations (“Radions”) which mix with the Higgs and modify its couplings and mass.

Precision measurements of SM processes

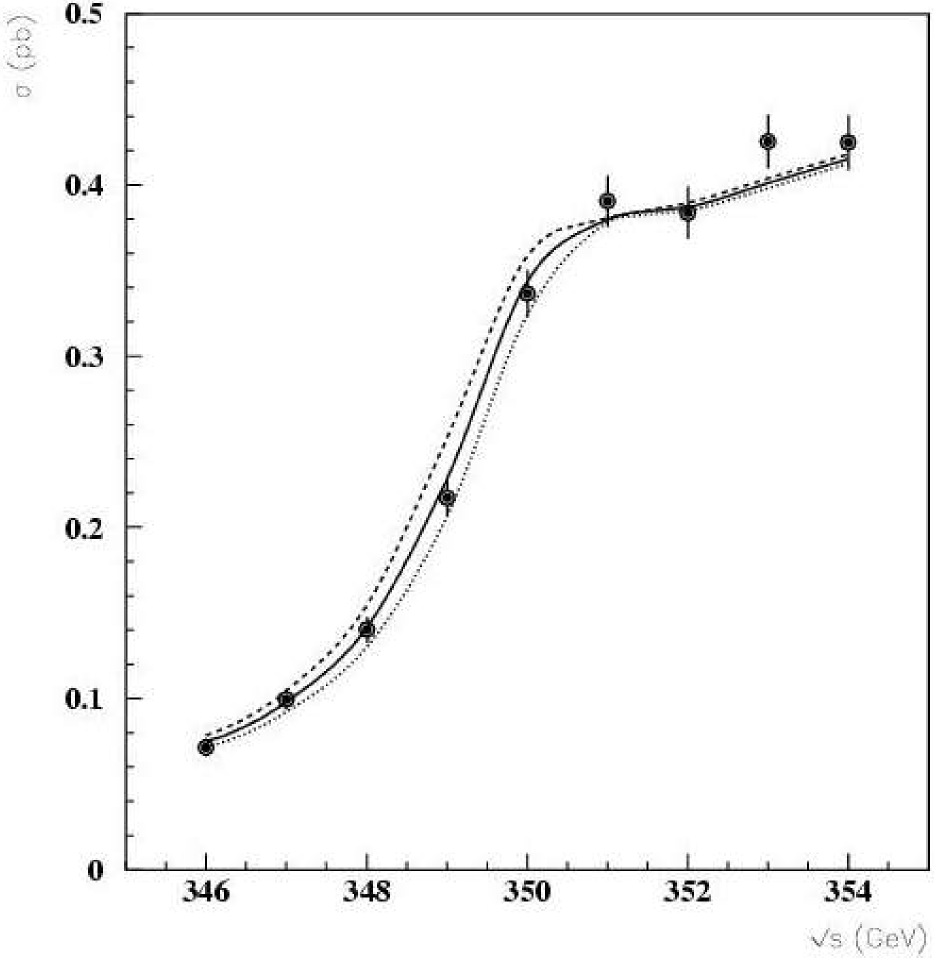
Top quark

Top is the heaviest fermion. Why do we want to know its mass as precisely as possible?

- Crucial input parameter to any future theory of flavor
- Already today the largest uncertainty in the calculation of many SM observables. With improved precision on m_W (→ later) even more important.
- In any model where m_h can be calculated (e. g. SUSY) it receives large contributions from m_t. In MSSM typically a shift of 1 GeV in m_t means a shift of 1 GeV in m_h. If $\Delta m_h = 50$ MeV, Δm_t will be limiting again.

Top quark mass

Best method to measure m_t: Threshold scan of $e^+e^- \to t\bar{t}$



Experimental precision:
~ 40 MeV

Precision reduced by theoretical uncertainty from huge QCD corrections at threshold:

Δm(top) ~ 50-100 MeV

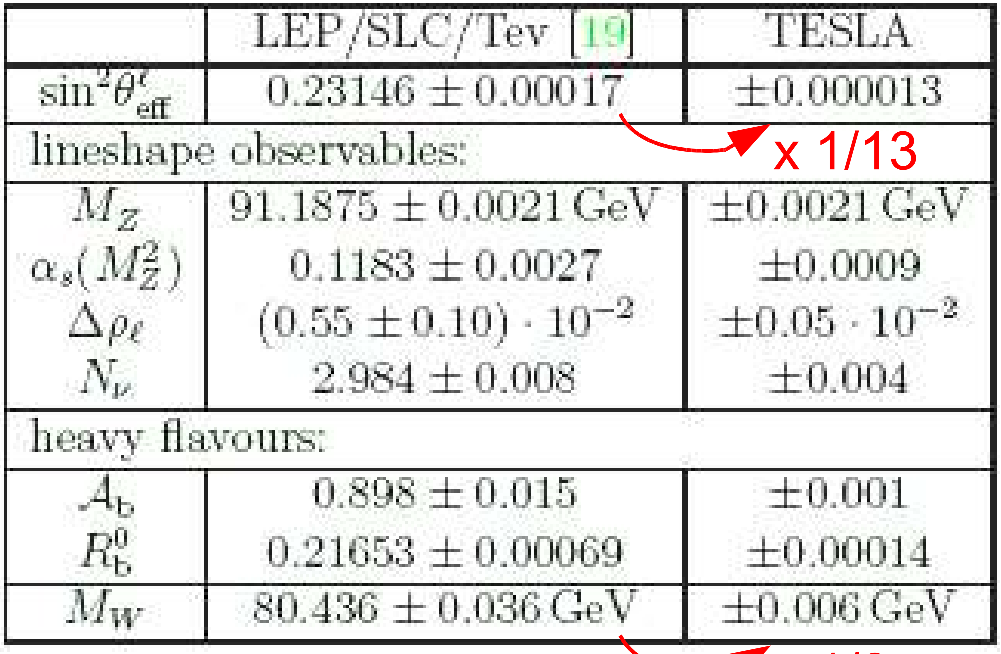
$\Delta\Gamma$(top)/Γ(top) ~ 3-5%

“GigaZ”

Production of 10^9 Z bosons in 50-100 days of running (i. e. LEP statistics in ~ 1 day!).

Similar luminosity at the WW threshold.

Repetition of LEP and SLC measurements with higher statistics:



	LEP/SLC/Tev [19]	TESLA
$\sin^2\theta^\ell_{\rm eff}$	0.23146 ± 0.00017	± 0.000013
lineshape observables:		
M_Z	91.1875 ± 0.0021 GeV	± 0.0021 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:		
A_b	0.898 ± 0.015	± 0.001
R_b^0	0.21653 ± 0.00069	± 0.00014
M_W	80.436 ± 0.036 GeV	± 0.006 GeV

56 ppm

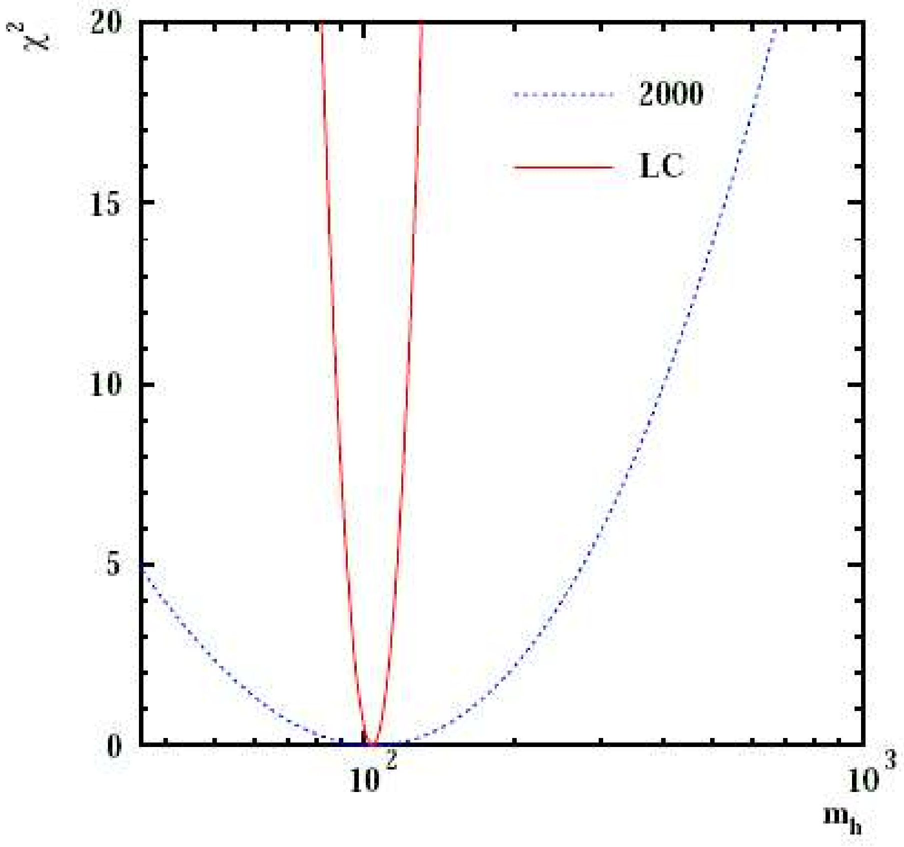
x 1/13

75 ppm

x 1/6

“GigaZ”

Improvement on EW fit from GigaZ:



m_h indirectly constrained at the 5 % level

Precision allows stringent consistency check of SM or helps to constrain free parameters in by then established extensions of SM.

Other precision measurements

Precision measurements of SM processes are a telescope to higher scale physics. Energy reach goes deep into multi-TeV range. Further precisely measurable processes which are sensitive to new physics are for example:

- 2f production: Interpretations in terms of
  - contact interactions
  - new gauge bosons (Z', ...)
  - extra dimensions
- 4f production: anomalous triple gauge couplings

Synergy between LHC and ILC

Learning from experience

In the past it was often beneficial for particle physics to have several experimental facilities available simultaneously to access closely related questions.

Latest example:

LEP+SLC+Tevatron led to many success stories

- EW standard model at quantum level
- top quark
- QCD
- prediction of (SM) Higgs mass

In order to to formulate a scientific roadmap for particle physics, we must look at the physics potential of future facilities in a coherent way.

LHC/ILC study group

An LHC/ILC study group has formed in Spring 2002, coordinated by Georg Weiglein, which addresses tasks like:

- Comparison of the physics reach of LHC and ILC
- What will we learn if information from the machines is interpreted simultaneously?
- Will we learn more if the LHC and ILC operation overlap in time?

Collaborative effort of LHC and ILC experimental communities and theorists.

First report published (`hep-ph/0410364`) – 122 authors from 75 institutions, 472 pages

Overview over LHC/ILC synergy

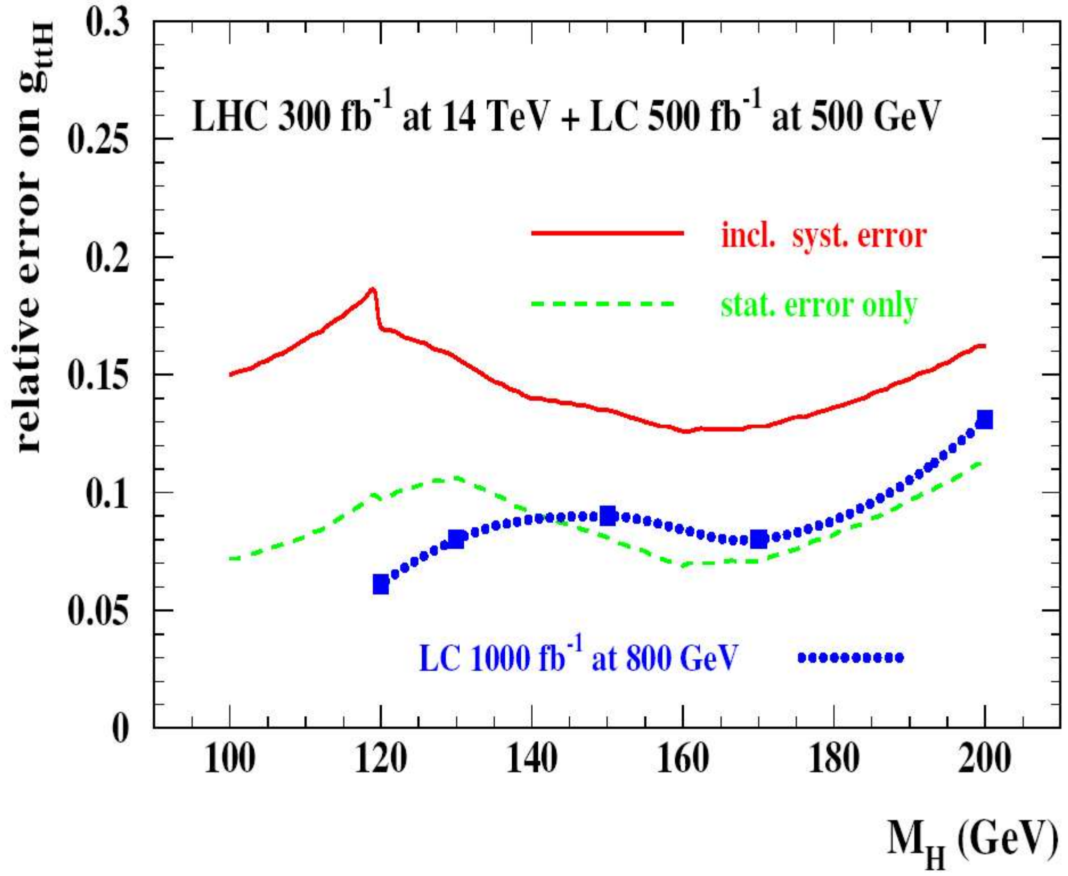
The report covers examples of synergy for the whole list of physics topics:

- Higgs physics
- SUSY
- Extra dimensions
- EW precision tests
- New gauge bosons
- Strong EWSB

Here I will only present a (personal) selection of highlights.

Top Yukawa coupling

LHC is sensitive to top Yukawa coupling of light Higgs through tth production. ILC BR measurement (h→bb and h→WW) turns the rate measurement into an absolute coupling measurement (ILC can only do it at high energy (> 800 GeV)).



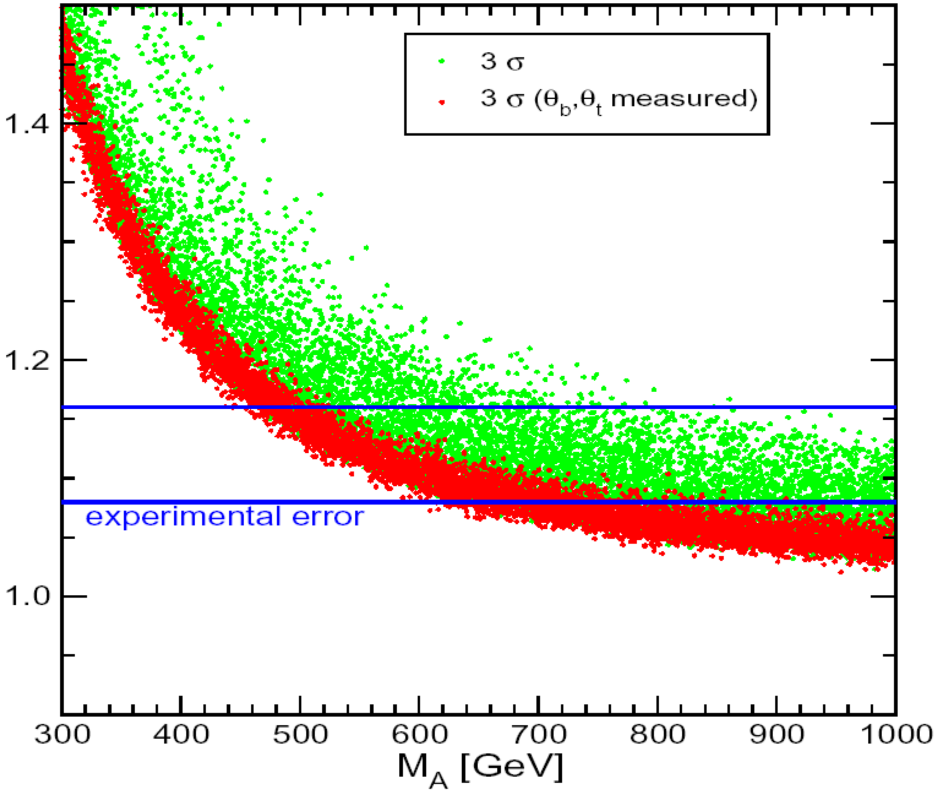
m_A prediction

Light Higgs BRs are sensitive to the mass of the heavy Higgs bosons in the MSSM. However, they are also strongly influenced by 3rd generation fermions (m_{top}!) and 3rd generation sfermions (sbottom, stop) → LHC

Sensitive observable:

$$r \equiv \frac{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{MSSM}}}{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{SM}}}$$

Need to know precise m_h, m_{top} from ILC
and sbottom/stop masses
and mixing angles from LHC

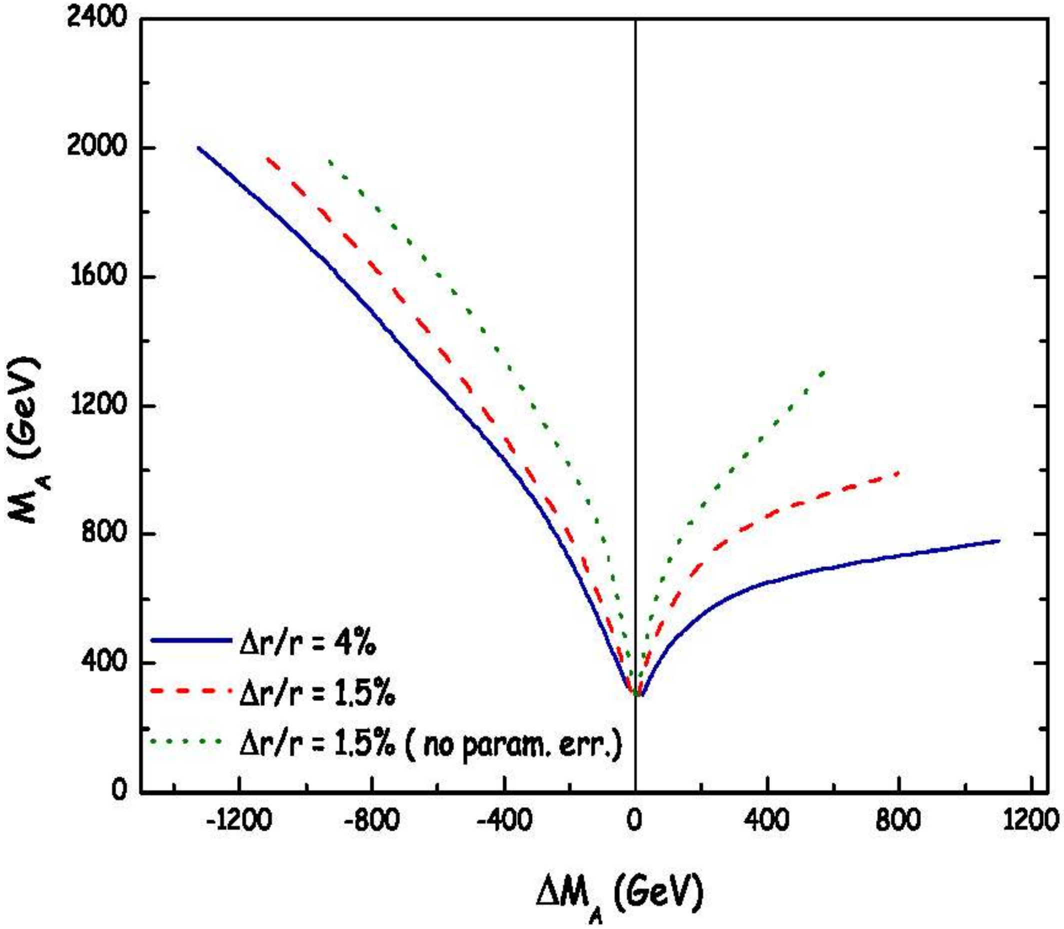


green: all SUSY points with ILC constraints

red: θ_b, θ_t known to 20 %/10 % from LHC

m_A prediction

Indirect prediction of heavy Higgs mass m_A from r measurement:



$\Delta m_A/m_A$ = 20 % (30 %)
for m_A = 600 (800) GeV

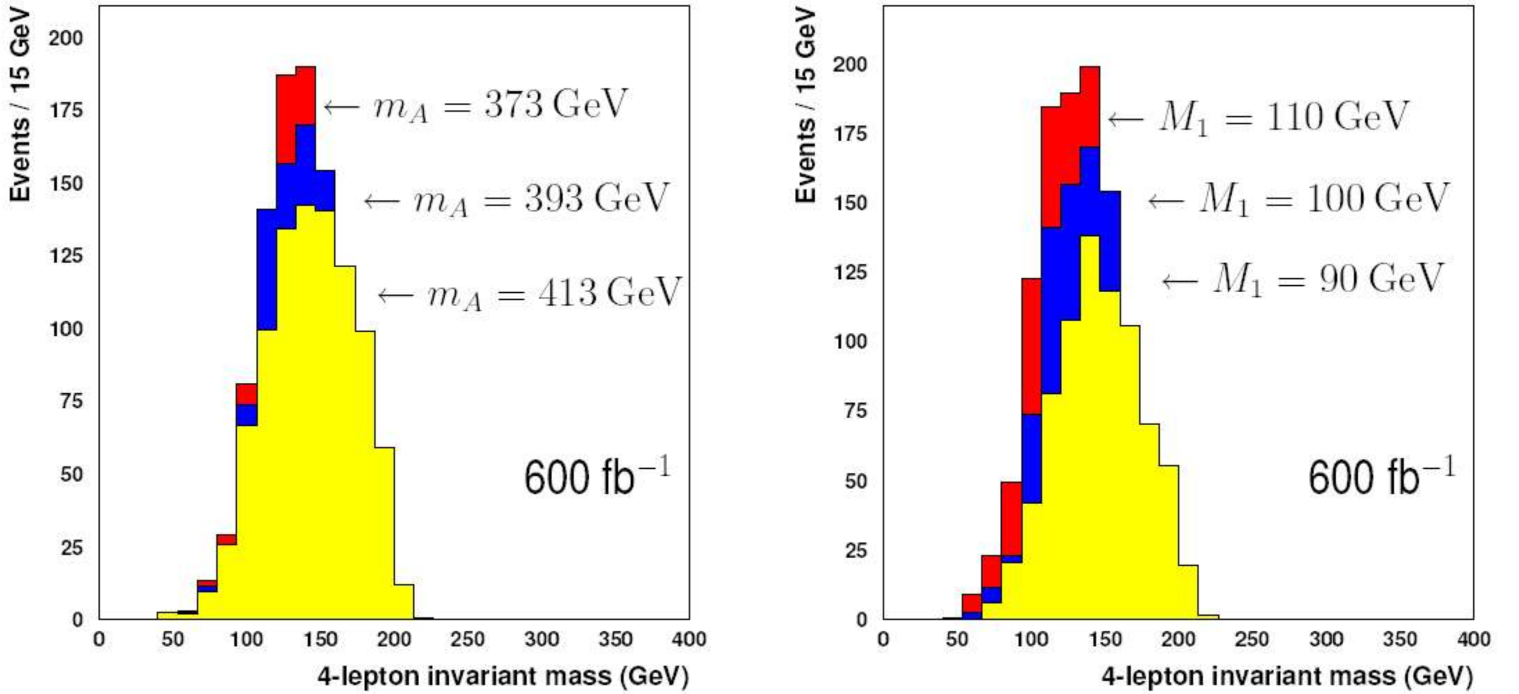
Could still be improved by using more BRs

ILC helping in LHC reconstruction

Mass measurement of heavy SUSY Higgs at LHC depends on LSP mass. Hard to get precisely from LHC (→ later). Use input from ILC:

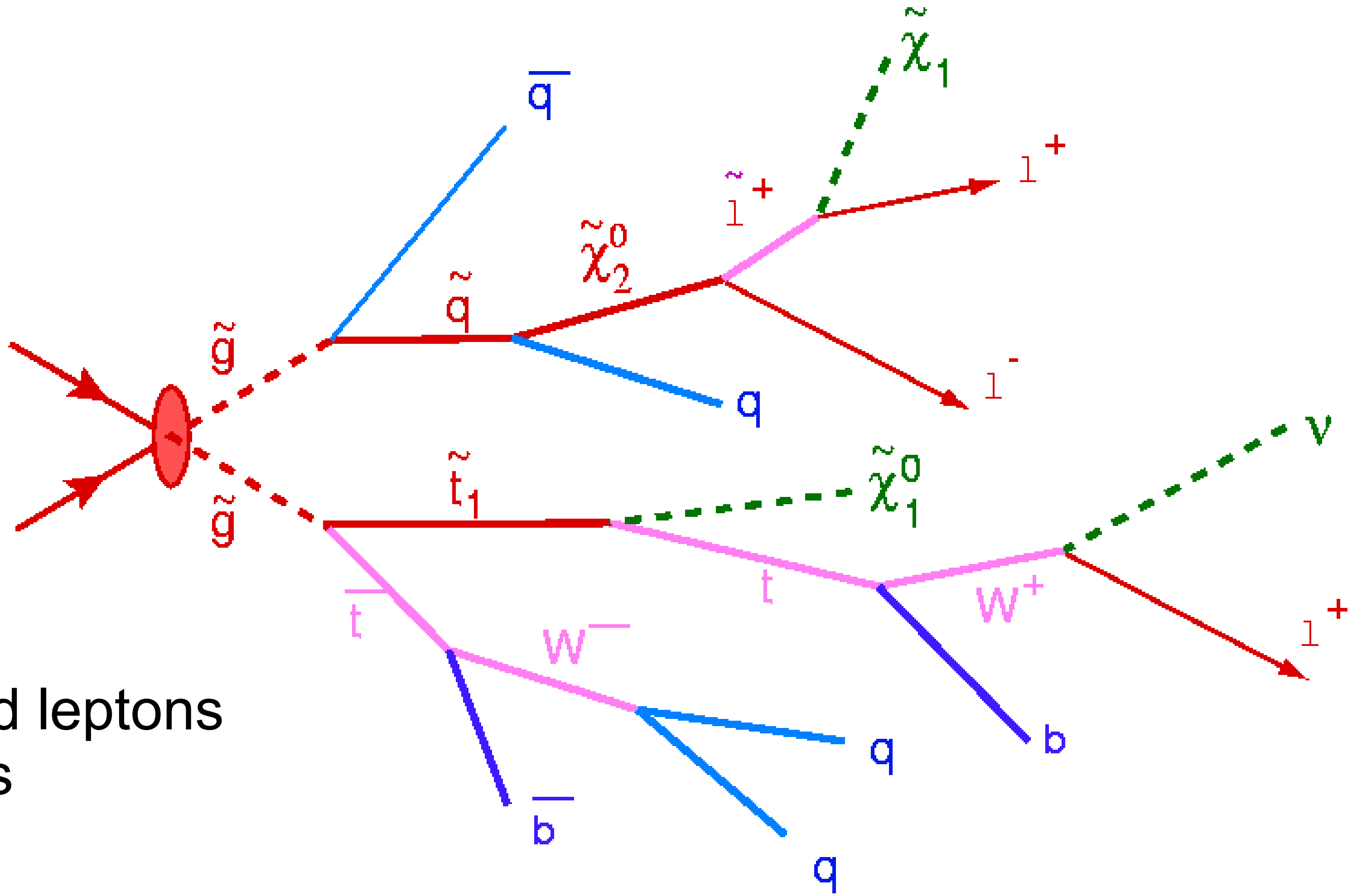
$$H/A \rightarrow \chi_2^0\chi_2^0 \rightarrow 4\ell + 2\chi_1^0$$

Possible LHC discovery channel for H/A if SUSY decays are open



Dependence of 4-lepton mass on m_A as large as on m_χ

Typical LHC SUSY event



3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_T^{miss}

SUSY mass reconstruction at LHC

Due to escaping LSP and unknown initial state momentum, full mass reconstruction cannot be performed event-by-event at LHC.

Standard trick: kinematic endpoints

Example: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\ell$

calculate di-lepton mass

endpoint at $M_{\ell\ell}^{max} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$

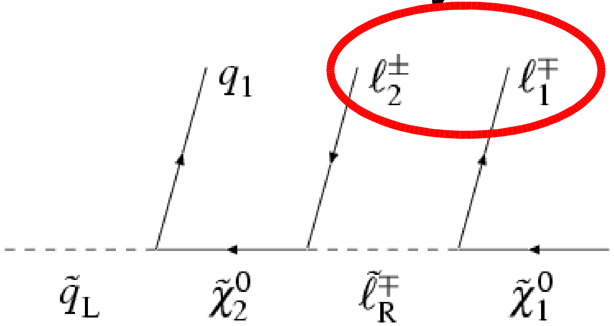
But for cascade decay

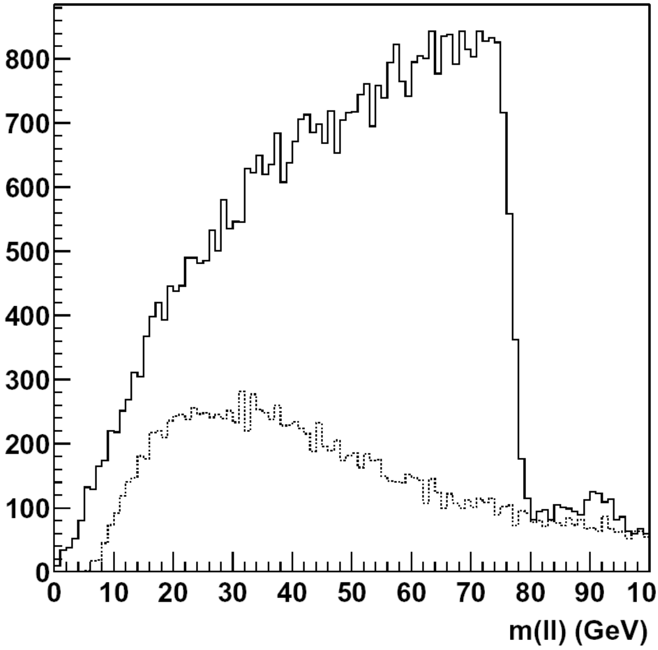
$$\tilde{\chi}_2^0 \to \tilde{\ell}\ell \to \tilde{\chi}_1^0 \ell\ell$$

endpoint at

$$M_{\ell\ell}^{max} = \frac{1}{M_{\tilde{\ell}}} \sqrt{(M^2_{\tilde{\chi}_2^0} - M^2_{\tilde{\ell}})(M^2_{\tilde{\ell}} - M^2_{\tilde{\chi}_1^0})}$$

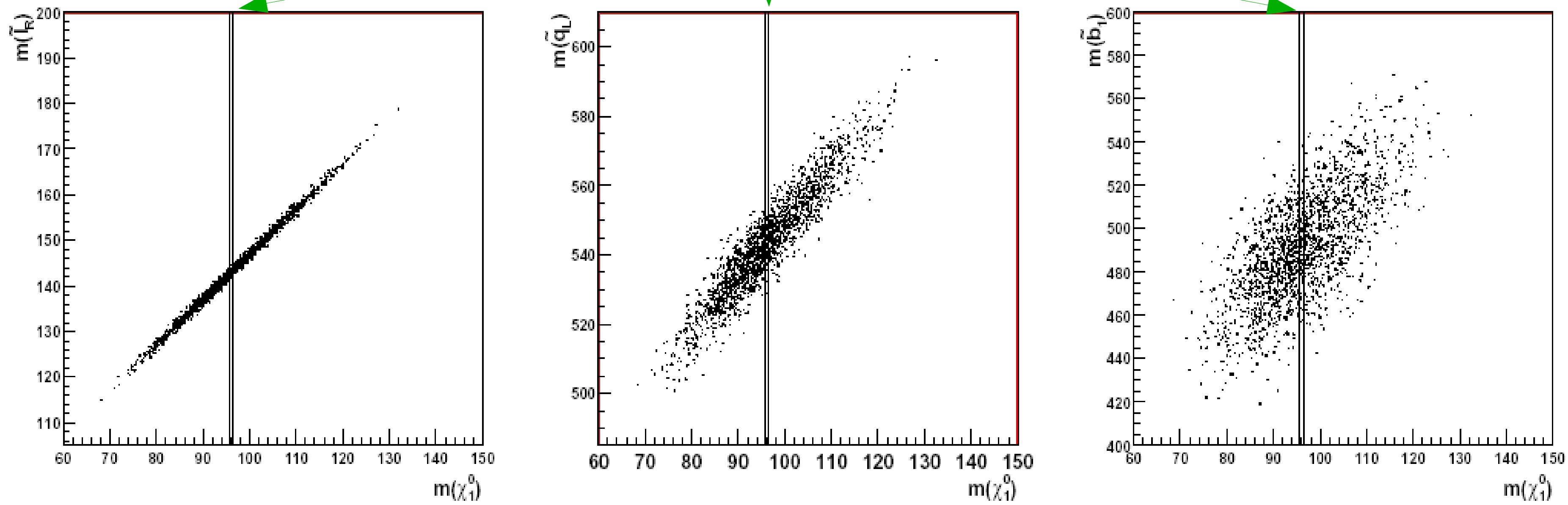
Need to know $M_{\tilde{\chi}_1^0}, M_{\tilde{l}}$





Mass correlations

Results in huge correlations between sparticle masses and mass of LSP:



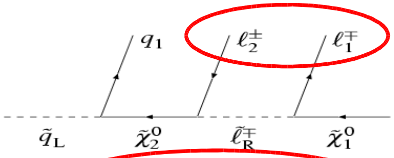
ILC $m(\chi_1^0)$ uncertainty band

But LHC can do better ...

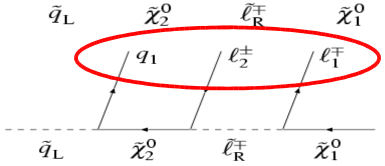
Joint fit of edges

Joint fit of various kinematic edges yields an over-constrained system:

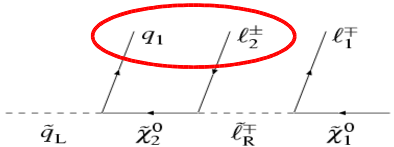
$$(m_{ll}^2)^{\rm edge} = \frac{(m^2_{\tilde\chi_2^0} - m^2_{\tilde l_R})(m^2_{\tilde l_R} - m^2_{\tilde\chi_1^0})}{m^2_{\tilde l_R}}$$



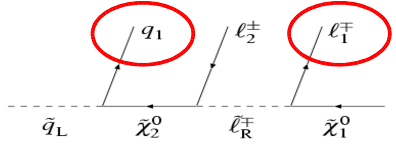
$$(m_{qll}^2)^{\rm edge} = \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi_2^0})(m^2_{\tilde\chi_2^0} - m^2_{\tilde\chi_1^0})}{m^2_{\tilde\chi_2^0}}$$



$$(m_{ql}^2)^{\rm edge}_{\rm min} = \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi_2^0})(m^2_{\tilde\chi_2^0} - m^2_{\tilde l_R})}{m^2_{\tilde\chi_2^0}}$$

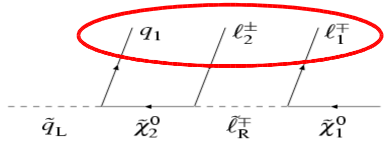


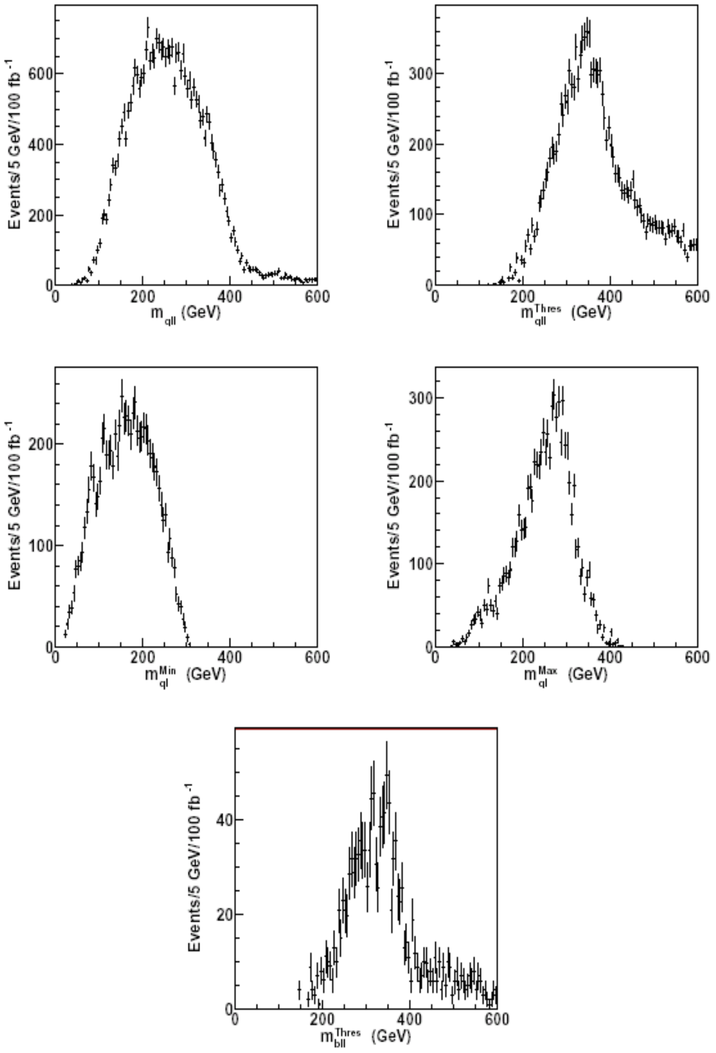
$$(m_{ql}^2)^{\rm edge}_{\rm max} = \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi_2^0})(m^2_{\tilde l_R} - m^2_{\tilde\chi_1^0})}{m^2_{\tilde l_R}}$$



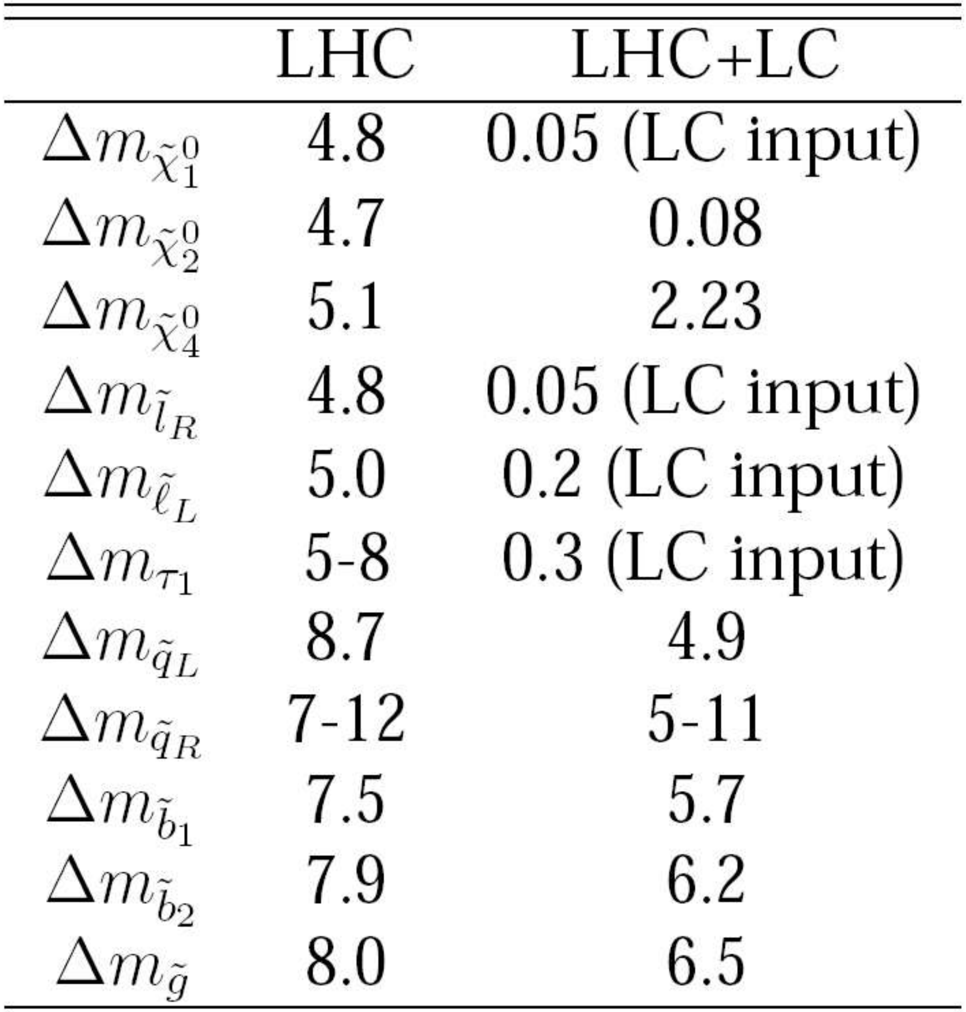
$$(m_{qll}^2)^{\rm thres} = [(m^2_{\tilde q_L} + m^2_{\tilde\chi_2^0})(m^2_{\tilde\chi_2^0} - m^2_{\tilde l_R})(m^2_{\tilde l_R} - m^2_{\tilde\chi_1^0}) - (m^2_{\tilde q_L} - m^2_{\tilde\chi_2^0})\sqrt{(m^2_{\tilde\chi_2^0} + m^2_{\tilde l_R})^2(m^2_{\tilde l_R} + m^2_{\tilde\chi_1^0})^2 - 16 m^2_{\tilde\chi_2^0} m^4_{\tilde l_R} m^2_{\tilde\chi_1^0}} + 2m^2_{\tilde l_R}(m^2_{\tilde q_L} - m^2_{\tilde\chi_2^0})(m^2_{\tilde\chi_2^0} - m^2_{\tilde\chi_1^0})]/(4m^2_{\tilde l_R} m^2_{\tilde\chi_2^0})$$

for events with large m_{ll}





Combined mass determination



	LHC	LHC+LC
$\Delta m_{\tilde{\chi}^0_1}$	4.8	0.05 (LC input)
$\Delta m_{\tilde{\chi}^0_2}$	4.7	0.08
$\Delta m_{\tilde{\chi}^0_4}$	5.1	2.23
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (LC input)
$\Delta m_{\tilde{\ell}_L}$	5.0	0.2 (LC input)
Δm_{τ_1}	5-8	0.3 (LC input)
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	7-12	5-11
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9	6.2
$\Delta m_{\tilde{g}}$	8.0	6.5

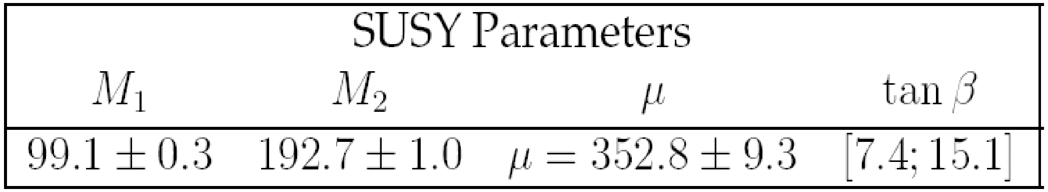
Huge improvement on sparticle masses which can only be seen at LHC, better reconstructed with ILC input.

Note: mass errors on squarks, gluino are dominated by had. scale systematics at LHC.

Any improvement on this will turn into improvement of squark/gluino mass.

Predictions of masses

At the ILC, the complete tree-level parameters of the chargino/neutralino system of the MSSM (M_1, M_2, μ, tan β) can be extracted from mass + (polarized) cross-section measurements of the lightest (χ_1^0, χ_2^0, $\chi_1^\pm$) states.



SUSY Parameters			
M_1	M_2	μ	$\tan\beta$
99.1 ± 0.3	192.7 ± 1.0	$\mu = 352.8 \pm 9.3$	$[7.4; 15.1]$

for 100/100 fb^{-1} LR/RL at 400 and 500 GeV, polarization 80/60 (e^-/e^+)

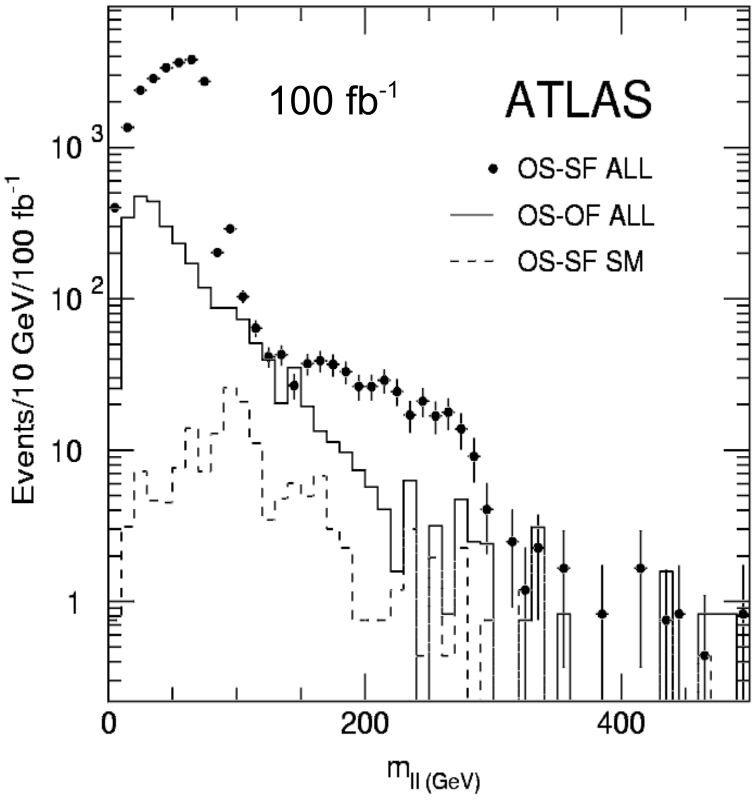
With these parameters measured all chargino and neutralino parameters can be predicted, e. g.

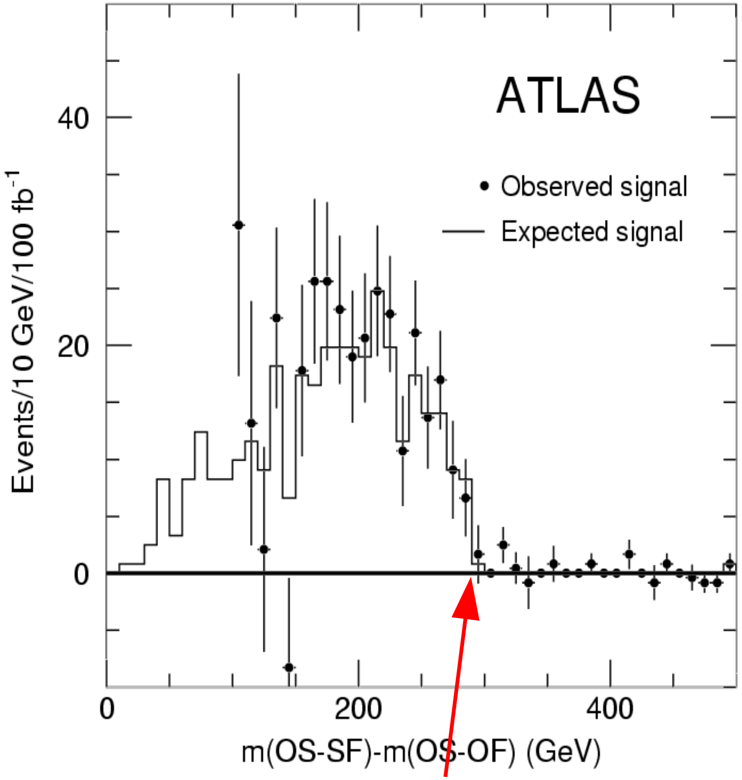
$$m(\chi_4^0) = 378.3 \pm 8.8 \text{ GeV}$$

χ_4^0 occurs occasionally also in squark decays leading to another dilepton edge at the LHC:

Predictions of masses

LC prediction turns edge search into a single hypothesis test → increased statistical sensitivity

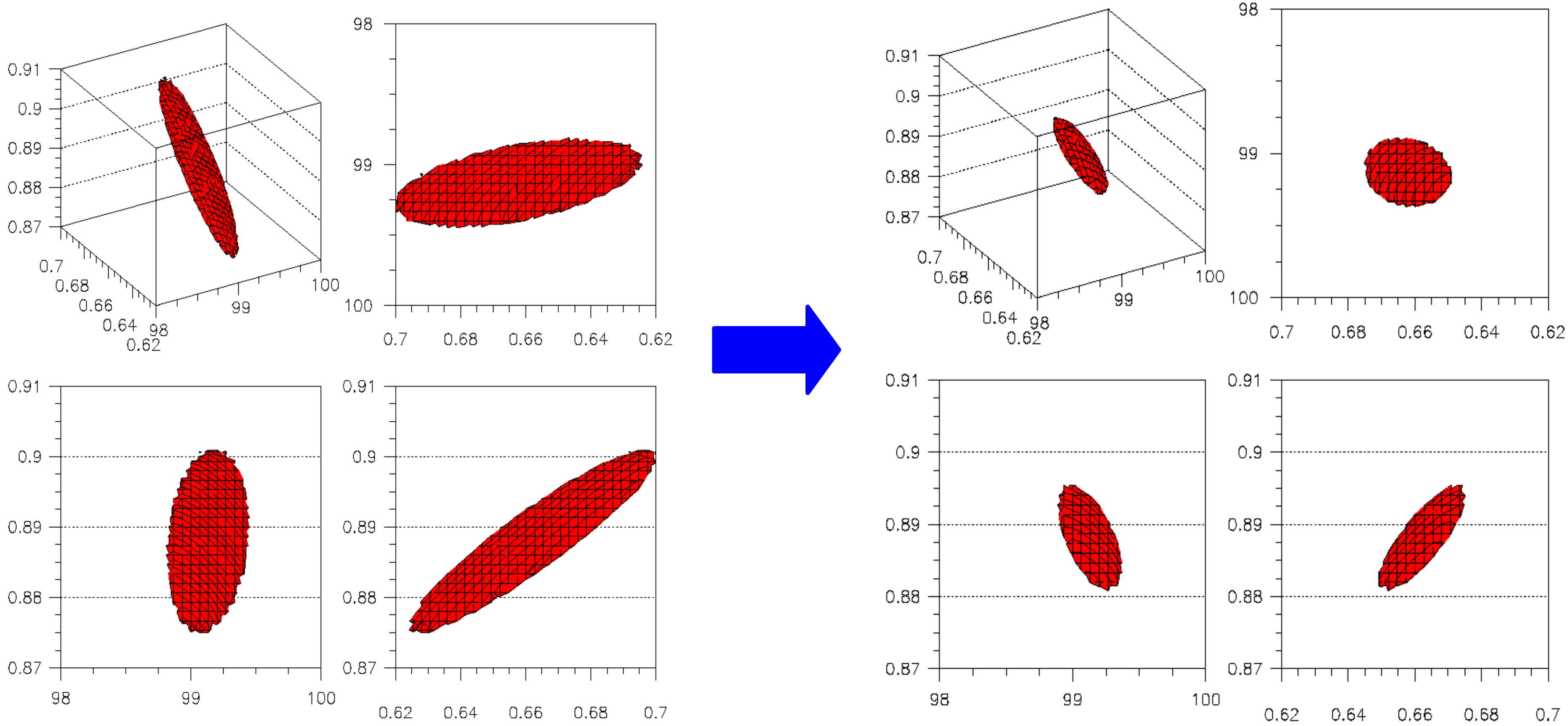




ILC can predict position of this edge

Predictions of masses

Feeding this back into parameter determination helps a lot:



Reconstruction of SUSY parameters

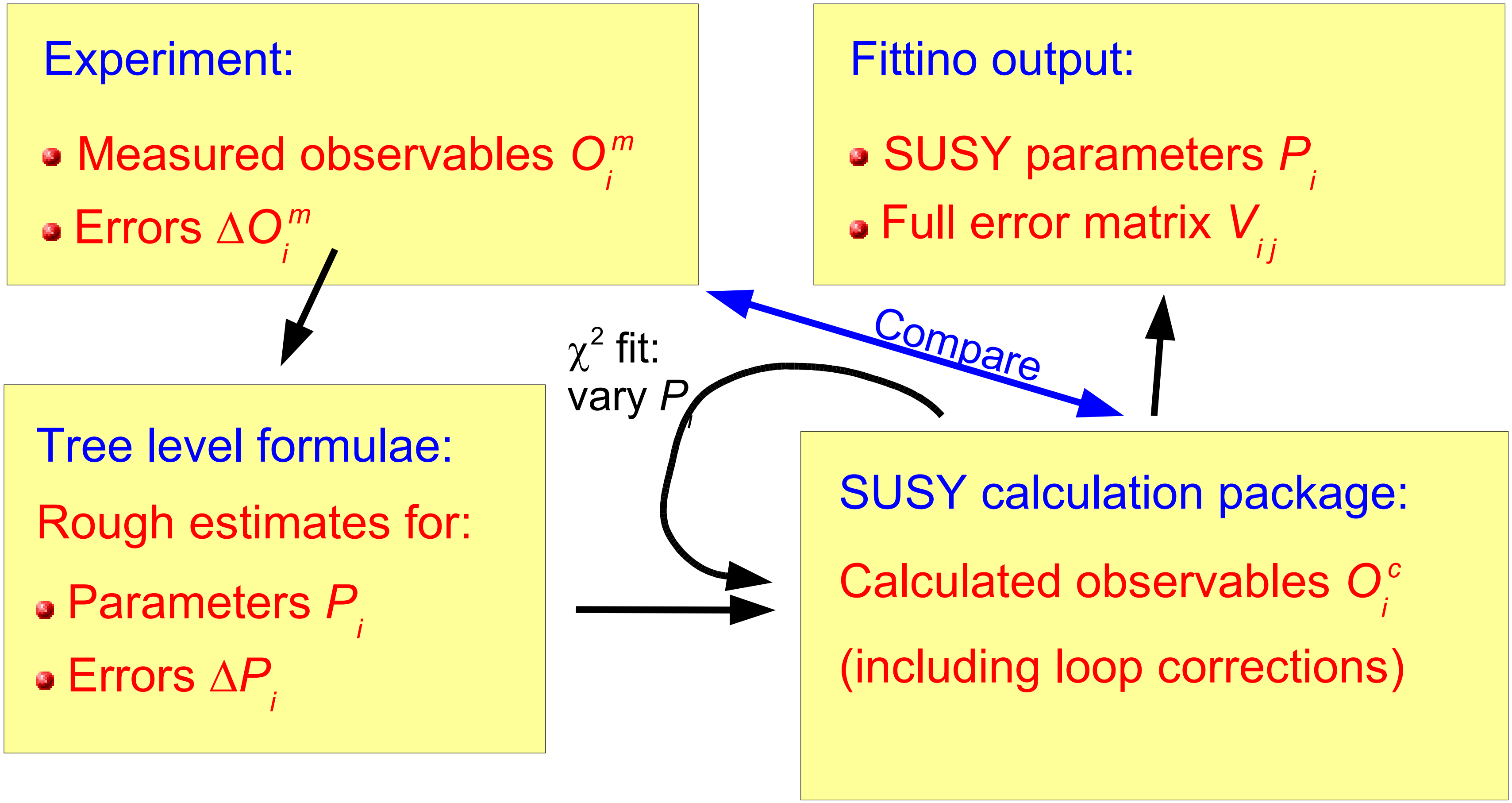
After the existence of SUSY has been established, the ultimate goal will be to extract the Lagrangian parameters ($\tan\beta$, ...) from the data.

Models assuming a certain SUSY breaking mechanism (mSUGRA, GMSB, AMSB) only have a few parameters to be fitted to observables. But we do not know which model is realized in Nature!

Even better is to fit low-energy parameters of the general MSSM to the data and extrapolate from these to the high scale to learn about SUSY breaking ("bottom-up approach")

Fit procedure

Radiative corrections important → interdependence of SUSY sectors



Experiment:

- Measured observables O_i^m
- Errors ΔO_i^m

Fittino output:

- SUSY parameters P_i
- Full error matrix $V_{i\,j}$

Compare

χ^2 fit: vary P_i

Tree level formulae:

Rough estimates for:

- Parameters P_i
- Errors ΔP_i

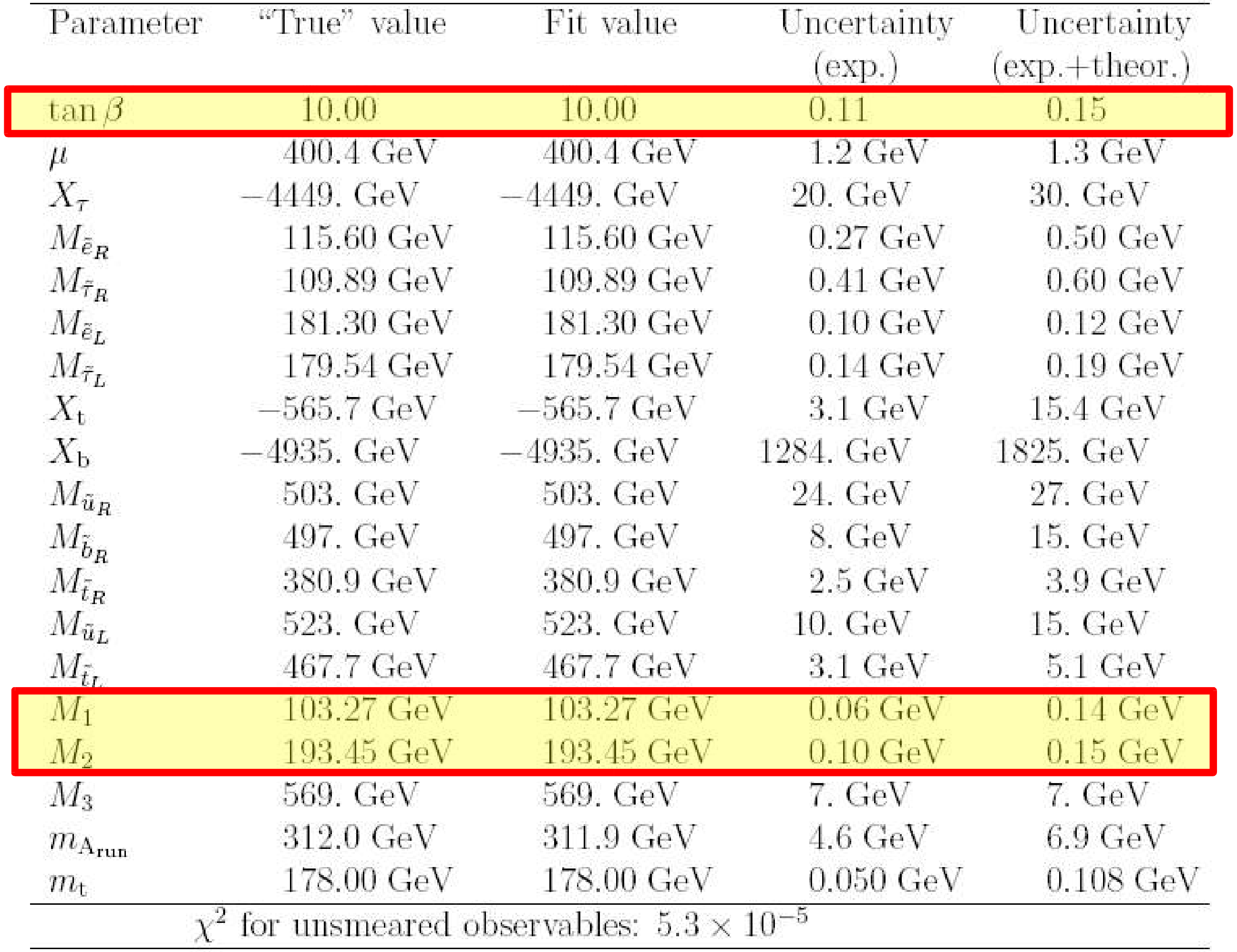
SUSY calculation package:

Calculated observables O_i^c

(including loop corrections)

LE SUSY parameter fit

"Simplified MSSM" example fit with Fittino:



Parameter	"True" value	Fit value	Uncertainty (exp.)	Uncertainty (exp.+theor.)
$\tan\beta$	10.00	10.00	0.11	0.15
μ	400.4 GeV	400.4 GeV	1.2 GeV	1.3 GeV
X_τ	−4449. GeV	−4449. GeV	20. GeV	30. GeV
$M_{\tilde{e}_R}$	115.60 GeV	115.60 GeV	0.27 GeV	0.50 GeV
$M_{\tilde{\tau}_R}$	109.89 GeV	109.89 GeV	0.41 GeV	0.60 GeV
$M_{\tilde{e}_L}$	181.30 GeV	181.30 GeV	0.10 GeV	0.12 GeV
$M_{\tilde{\tau}_L}$	179.54 GeV	179.54 GeV	0.14 GeV	0.19 GeV
X_t	−565.7 GeV	−565.7 GeV	3.1 GeV	15.4 GeV
X_b	−4935. GeV	−4935. GeV	1284. GeV	1825. GeV
$M_{\tilde{u}_R}$	503. GeV	503. GeV	24. GeV	27. GeV
$M_{\tilde{b}_R}$	497. GeV	497. GeV	8. GeV	15. GeV
$M_{\tilde{t}_R}$	380.9 GeV	380.9 GeV	2.5 GeV	3.9 GeV
$M_{\tilde{u}_L}$	523. GeV	523. GeV	10. GeV	15. GeV
$M_{\tilde{t}_L}$	467.7 GeV	467.7 GeV	3.1 GeV	5.1 GeV
M_1	103.27 GeV	103.27 GeV	0.06 GeV	0.14 GeV
M_2	193.45 GeV	193.45 GeV	0.10 GeV	0.15 GeV
M_3	569. GeV	569. GeV	7. GeV	7. GeV
$m_{A_{\rm run}}$	312.0 GeV	311.9 GeV	4.6 GeV	6.9 GeV
m_t	178.00 GeV	178.00 GeV	0.050 GeV	0.108 GeV

χ^2 for unsmeared observables: 5.3×10^{-5}

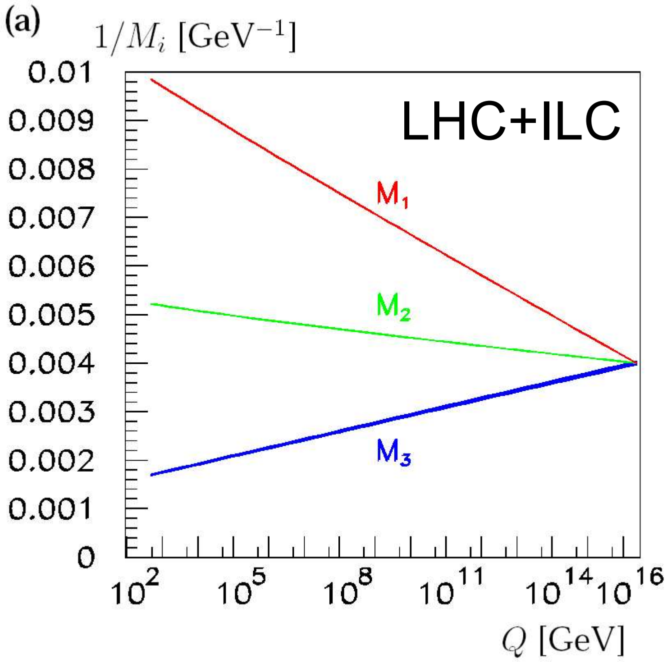
< 2 %

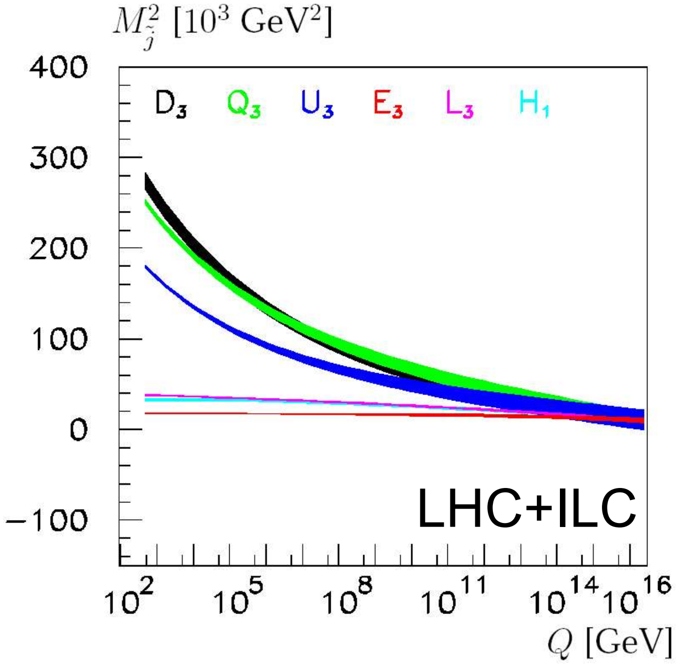
< 0.2 %

Fit does neither work with LHC only nor with ILC only inputs. Data from both machines are required!

Extrapolation to high scale

Feed output of low-energy parameter fit as input into RGE evolution:





Look for unification patterns in SUSY parameters without a-priori assumption of a SUSY breaking mechanism

Summary part IV

- ILC can reduce uncertainty on important SM parameters by more than an order of magnitude (m_{top}, $\sin^2\theta_W$, ...). These parameters are important ingredients for theoretical predictions of SM and BSM observables.

- ILC allows to learn about the physics far beyond the center-of-mass energy reach of the machine.

- LHC and ILC are looking at the same physics from different points of view. Joint analyses mean a mutual benefit: (LHC/ILC) > LHC + ILC

A new era of particle physics is about to start

Stay tuned!

Many thanks to Y. Gao for the excellent organization of this school and to K. Desch for providing material for these lectures