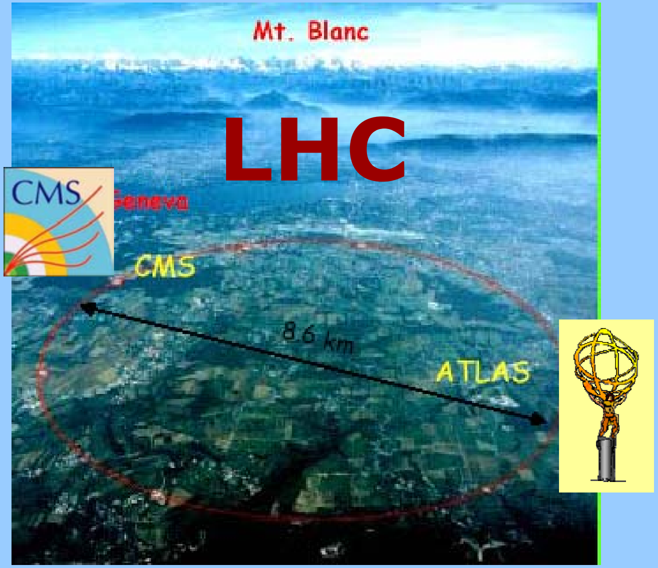
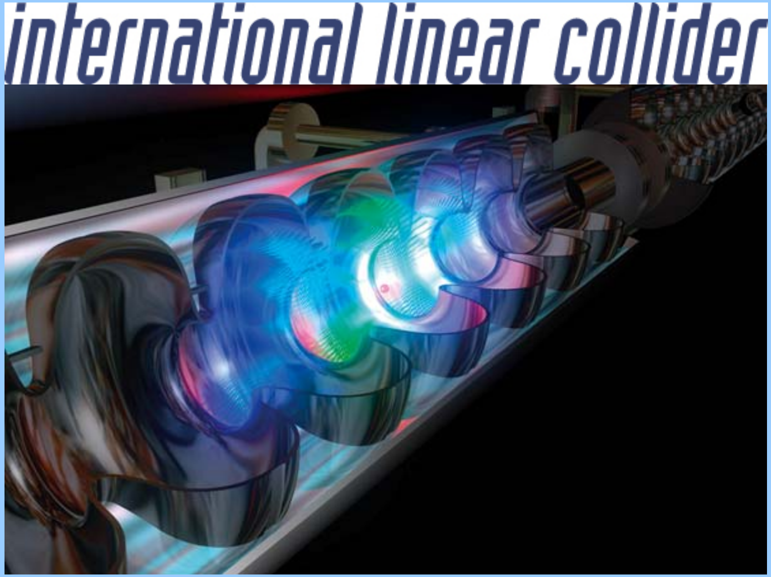
Terascale Physics:
from LHC to ILC





LINEAR COLLIDER
PHYSICS SCHOOL 2006

Klaus Desch
University of Bonn

Second Linear Collider Physics School
Ambleside, UK, 15/09/06

High Energy and High Precision

Unique role of high energy hadron and lepton colliders:

There are two distinct and complementary strategies for gaining understanding of matter, space and time at colliders

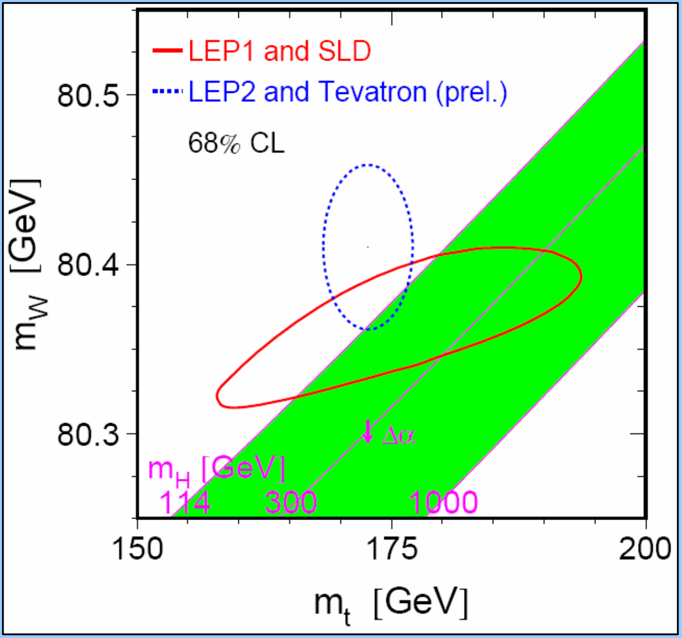
High Energy
direct discovery of new phenomena

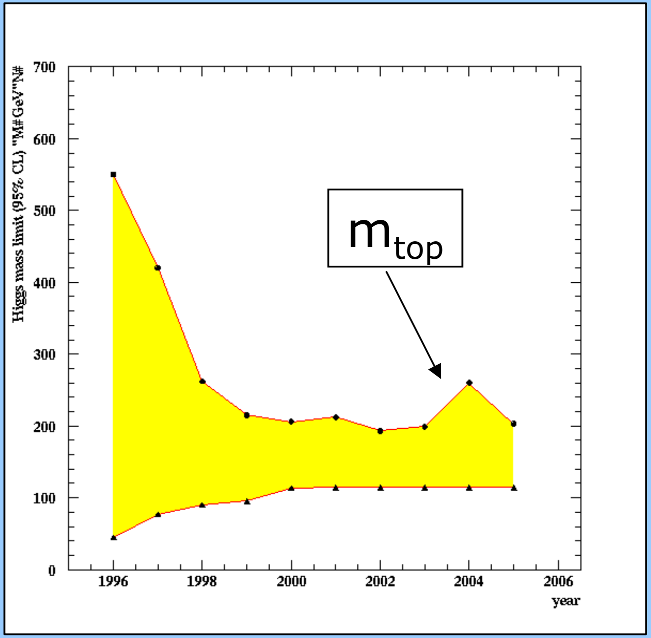
High Precision
quantum effects of new physics at high energies through precise measurements of phenomena at lower scales

Both strategies have worked well together
→ much more complete understanding than from either one alone

prime example: LEP+SLC / Tevatron

LEP+Tevatron: a success story





→ led to understanding the SM at the quantum level

→ possibility to predict phenomena at the TeV scale and beyond

The Terascale

Very good reasons to explore the TeV-scale:

- Evidence for light Higgs
- SM without Higgs violates unitarity at ~1.3 TeV
- Hierarchy between m_{weak} and m_{Planck} to be protected at TeV scale
- Dark matter consistent with sub-TeV-scale WIMP (e.g. SUSY-LSP)
- $2m_{top}$ = 350 GeV

But no clear case yet to enter the 10-TeV scale
(need TeV scale knowledge)

Driving Physics Questions

Broad and rich spectrum of fundamental questions are awaiting answers at the Terascale:

- Electroweak Symmetry Breaking
- New Symmetries and Unification of Forces
- Space-Time Structure

\+ Connecting Cosmology and Particle Physics

and surprises…

Entering the Terascale: the LHC

We expect big discoveries from the LHC!

- Where are we today?

- When can we expect results?

- Ultimate reach of the LHC?

- Upgrades?

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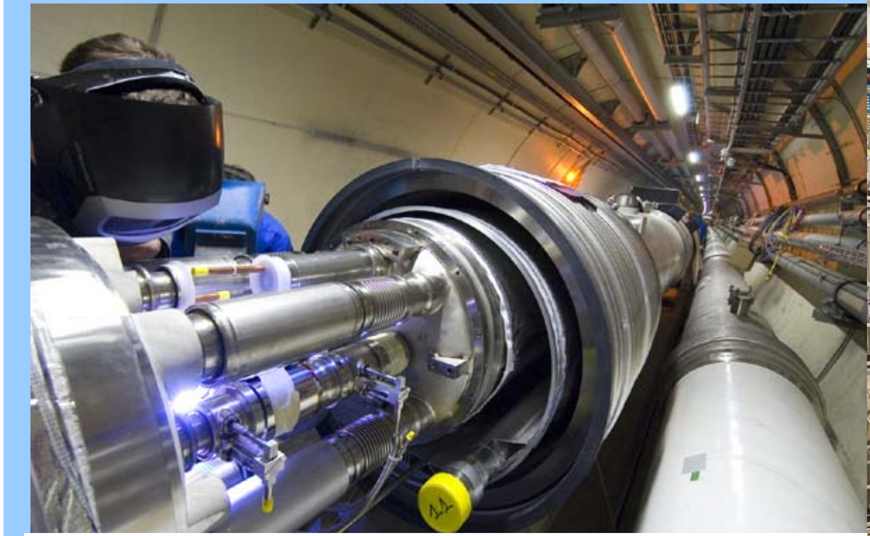
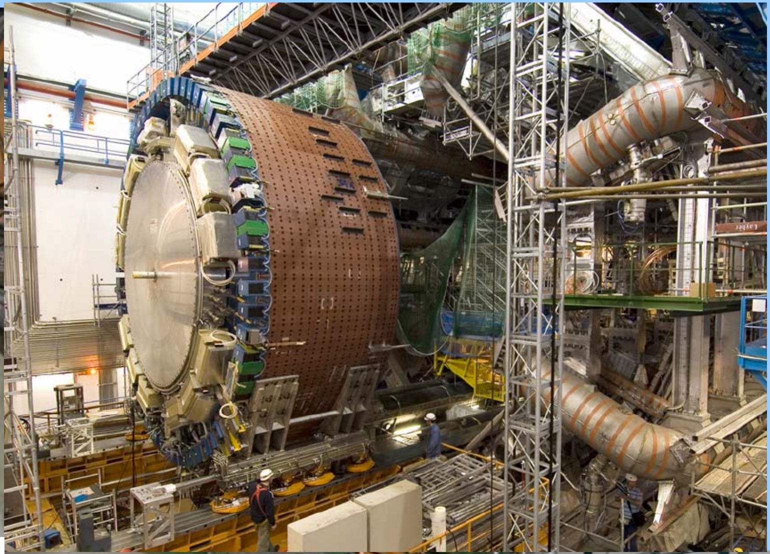
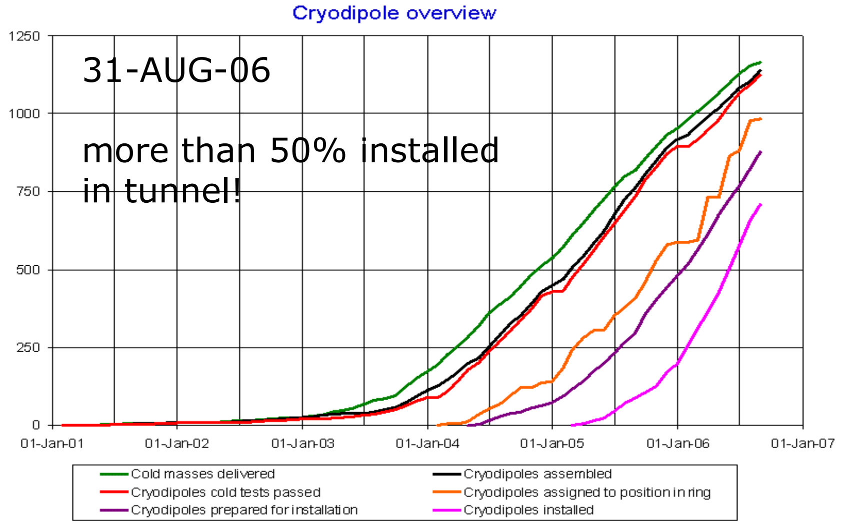
LHC: where we are today?

tremendous effort → tremendous progress







31-AUG-06

more than 50% installed in tunnel!

CMS magnet reached nominal 4T field yesterday!

expect first collisions in 2007 with ATLAS+CMS ready to take data!

LHC: when can we expect results?

May expect o(30) fb^{-1} by 2010
With these data we may:

- discover SM/MSSM Higgs boson
- discover SUSY if m_{SUSY} < 2-2.5 TeV
- discover dilepton-resonances (Z',RS,…) if m < ~3 TeV

but: data on disk ≠ paper published!

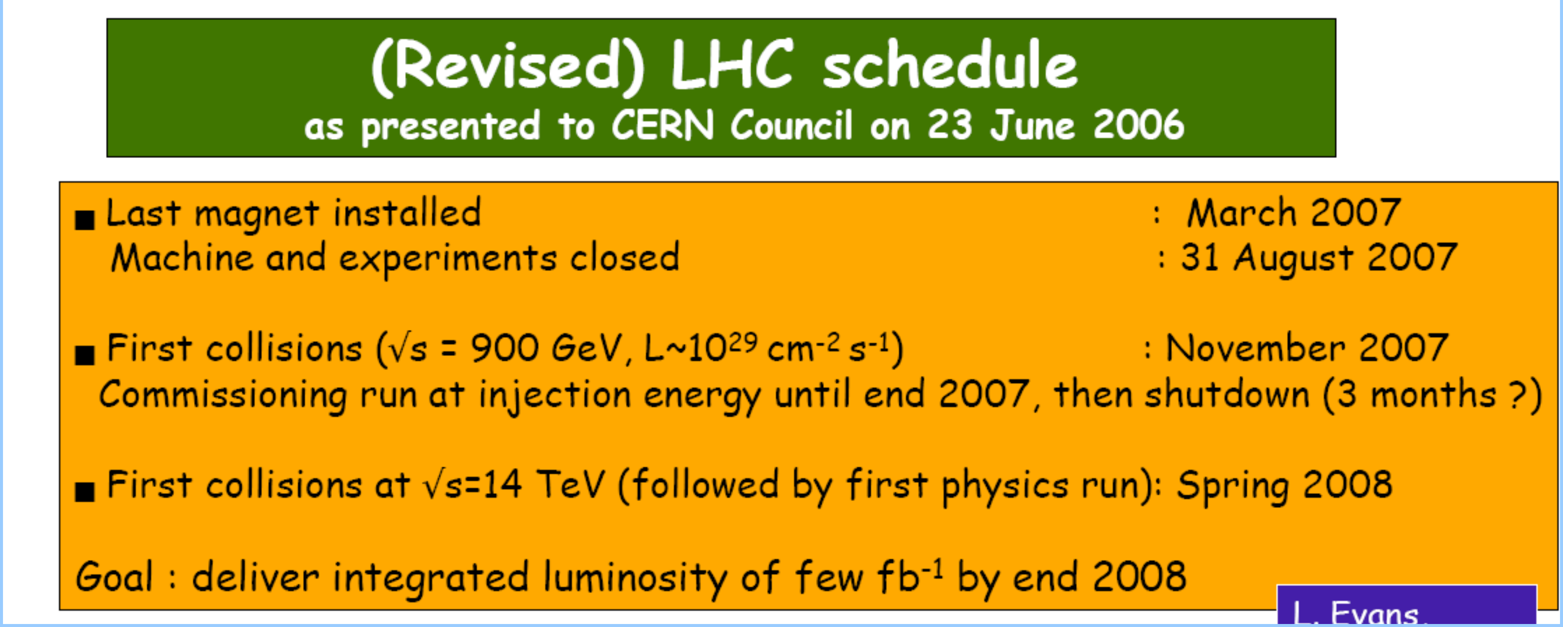
need to:

- commission/align/calibrate detectors+triggers
- calibrate physics objects (e,μ,τ,b,jets,E_T^{miss}) with SM candles (Z, W, t, jets, …)
- understand SM-backgrounds from data and tune MC

how fast a signal can be established depends on its complexity

→ examples

From F. Gianotti, ICHEP06



(Revised) LHC schedule

as presented to CERN Council on 23 June 2006

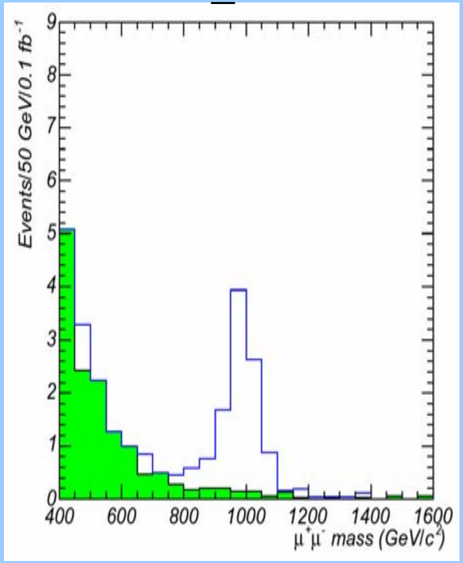
- Last magnet installed : March 2007
  Machine and experiments closed : 31 August 2007
- First collisions ($\sqrt{s}$ = 900 GeV, L~10^{29} cm^{-2} s^{-1}) : November 2007
  Commissioning run at injection energy until end 2007, then shutdown (3 months ?)
- First collisions at $\sqrt{s}$=14 TeV (followed by first physics run): Spring 2008

Goal : deliver integrated luminosity of few fb^{-1} by end 2008

L. Evans

Possible discoveries at LHC with 10 fb^{-1}

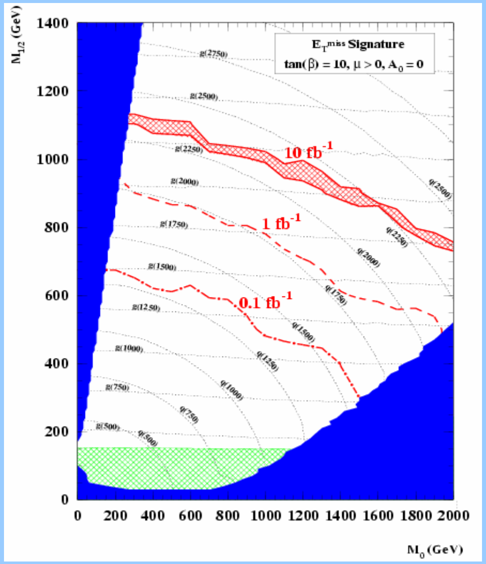
di-lepton resonance (Z',RS,Z_H,…)



with 10 fb^{-1}:

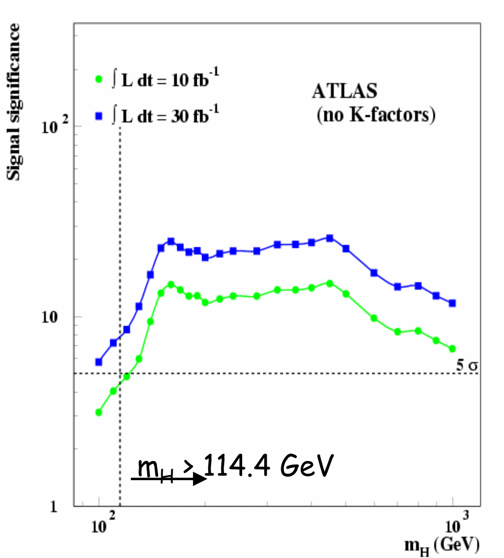
m<~3 TeV
dep. on model

inclusive SUSY



$m_{sq,gl}$<2-2.5 TeV
in mSugra

SM/MSSM Higgs



full range

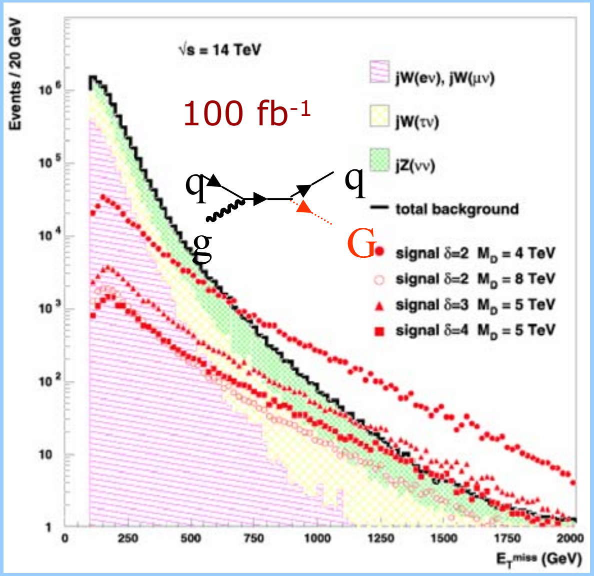
more easy…

…more challenging

“Later” discoveries at LHC

in general more difficult: non-resonant hadronic or very rare leptonic final states will need more luminosity and better detector understanding

Large Extra Dimensions (ADD)



100 fb^{-1}	$\delta = 2$	$\delta = 3$	$\delta = 4$
M_D^{max}	9 TeV	7 TeV	6 TeV

Strong EW Symmetry Breaking

deviations from SM due to new interaction in $W_L W_L \rightarrow W_L W_L$ in absence of Higgs:

very challenging
sign. 2 lept + forw. jets + Emiss
possibly non-resonant

possibly only ~3σ with 100 fb^{-1}

Beyond discovery: Properties of particles

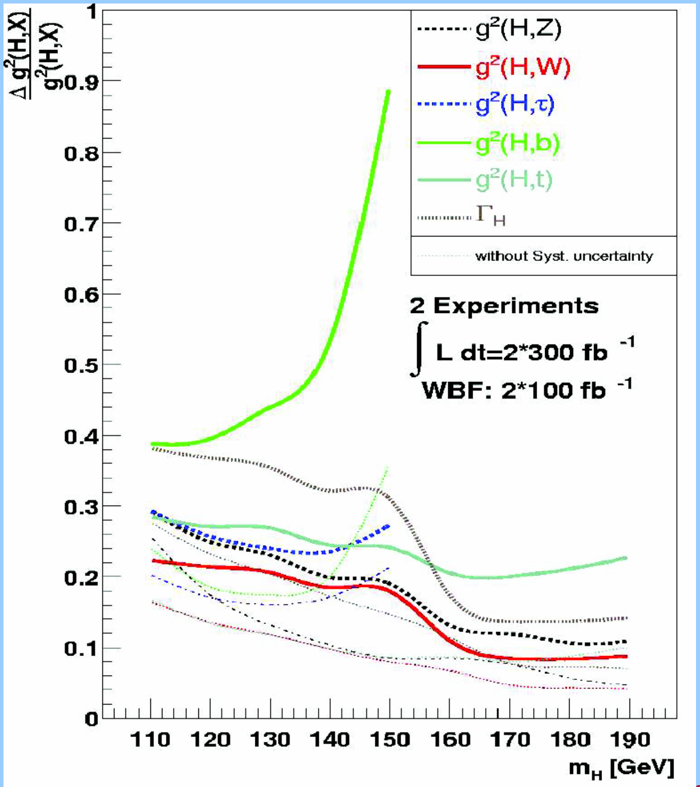
Example 1: Top: $\Delta m_t \sim 1$ GeV (limited by hadronic scale + theory)

Example 2: Higgs: $\Delta m_H(120) \sim 200$ MeV

Higgs couplings:

take advantage of different
production/decay channels
need some model assumptions

generic difficulty:
not possible to disentangle
production and decay
→ model dependence
systematic limitations
(strong production)

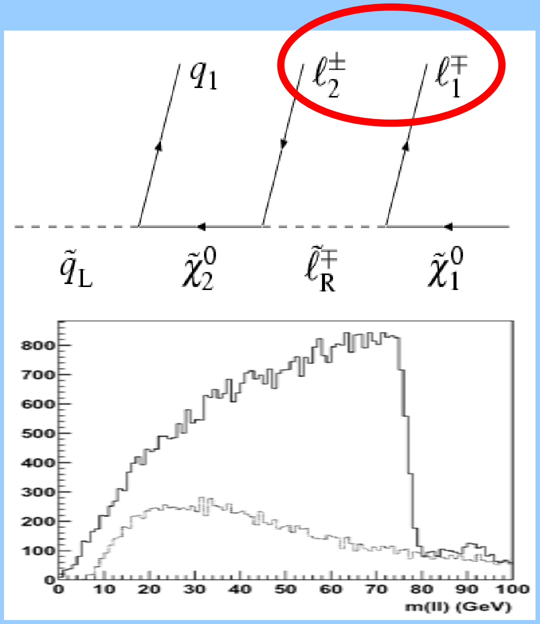


Beyond discovery: Properties of particles

Example 3: SUSY

challenge: disentangle long decay chains in presence of 2 LSPs

- possibility of mass reconstruction depends on model point
- joint fit of kinematic edges can give access to masses
- particular difficult: LSP mass



optimistic scenario (SPS1a)

Sparticle	Error on Mass (GeV)
g	8.0
q_L	8.7
q_R	7-12
b_1	7.5
b_2	7.9
χ_1^0	4.8
χ_2^0	4.7
χ_4^0	5.1
$\chi_1^{\pm}$ $\tilde{\ell}_R$	25
	5.0
τ_1	5-8

Luminosity Upgrade of LHC (=SLHC)

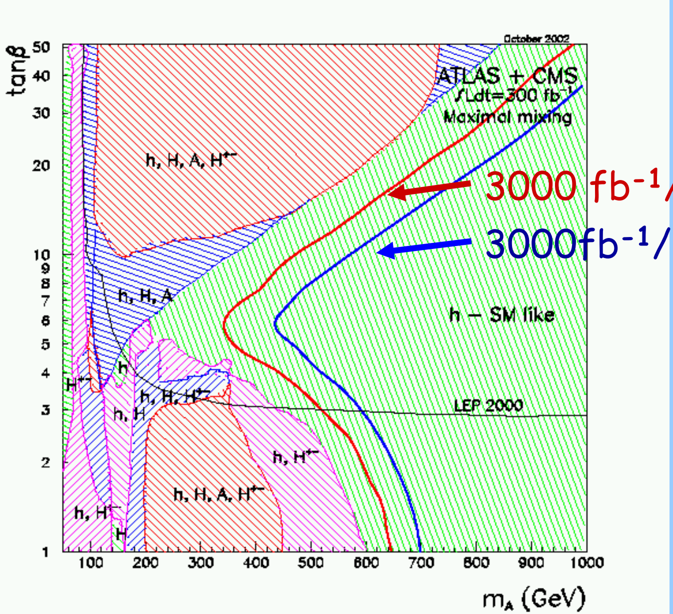
Plans to increase luminosity to 10^{35} $cm^{-2}s^{-1}$
with moderate effort (injection system, collimation,…)
natural evolution after LHC-running for several years at design-L

Consequences for detectors:
shorter bunch spacing, larger pile-up
needs improved detectors + trigger/DAQ → R&D needed now
expect some degradation of detector resolutions
(b-tagging, track finding, forward jet tagging, …)

Physics potential:
- 20-30% increase in discovery potential e.g. SUSY 2.5→3 TeV
- improve on precision of statistically limited measurements
- some sensitivity to triple Higgs coupling for m_H~160 GeV

Examples of SLHC improvements

Heavy SUSY Higgs:
observable region increased by ~100 GeV.

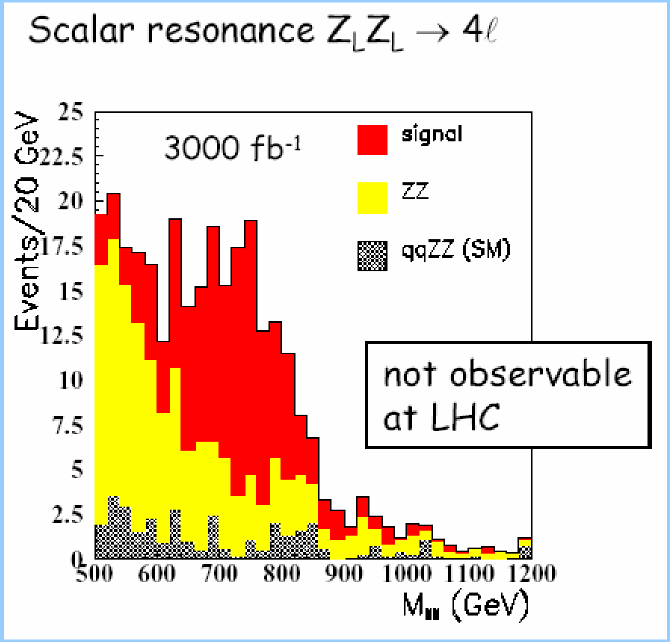


$3000\ \mathrm{fb}^{-1}/5\sigma$

$3000\mathrm{fb}^{-1}/95\%\ CL$

Broad resonances in no-Higgs scenarios:

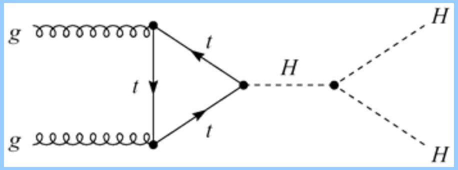
Scalar resonance $Z_LZ_L \to 4\ell$



not observable at LHC

Examples of SLHC improvements

Higgs self coupling: potential for first observation
if m_H~160 GeV with 3000 fb^{-1}



Energy Upgrade of LHC (=DLHC)

ideas to double beam energy to 14 TeV
needs new magnets = new machine = major effort →Raimondi

in general larger discovery potential than SLHC
(but also less well studied)

needs very good physics justification from future data

Summary LHC+upgrades

- LHC and ATLAS/CMS progressing well. Expect first collisions in 2007 (at 900 GeV, 14 TeV in 2008)
- First data set with excellent prospects for discoveries (10-30 fb^{-1}) may be expected for 2009/10. Analysis needs detailed understanding of detectors and backgrounds.
- SM Higgs, SUSY (-2.5 TeV), di-lepton resonances (-3 TeV) can be seen within these data.
- Full LHC luminosity allows for discovery of very broad range of high-pt phenomena and measurements of new particle properties.
- LHC luminosity upgrade (SLHC) increases discovery reach by 20-30%, better precision for statistically limited processes.
- Energy upgrade (DLHC) has larger discovery reach but represents a significantly larger effort.

Electron Positron Collisions

Electron positron collisions at high energy provide a powerful tool to explore TeV-scale physics complementary to the LHC

Due to their point-like structure and absence of strong interactions there are clear advantages of e^+e^- collisions:

- known and tunable centre-of-mass energy
- clean, fully reconstructable events
- polarized beams
- moderate backgrounds
  → no trigger

→broad consensus for a Linear Collider with up to at least ~500 GeV

The International Linear Collider

Huge world-wide effort to be ready for construction in 2009/10 (Global Design Effort GDE)

Result of an intense R&D process since 1992

Parameters (ICFA parameter document/ILC baseline)

The baseline:

e^+e^- LC operating from M_Z to 500 GeV, tunable energy
e^-/e^+ polarization
at least 500 fb^{-1} in the first 4 years

Upgrade: to ~ 1 TeV 500 fb^{-1} /year

Options :

- GigaZ (high luminosity running at M_Z)
- $\gamma\gamma$, $e\gamma$, e^-e^- collisions

Choice of options depends on LHC+ILC results

The ILC physics case

0. Top quark at threshold

1. 'Light' Higgs (consistent with precision EW)
   ➪ verify the Higgs mechanism is at work in all elements

2. 'Heavy' Higgs (inconsistent with precision EW)
   ➪ verify the Higgs mechanism is at work in all elements
   ➪ find out why prec. EW data are inconsistent

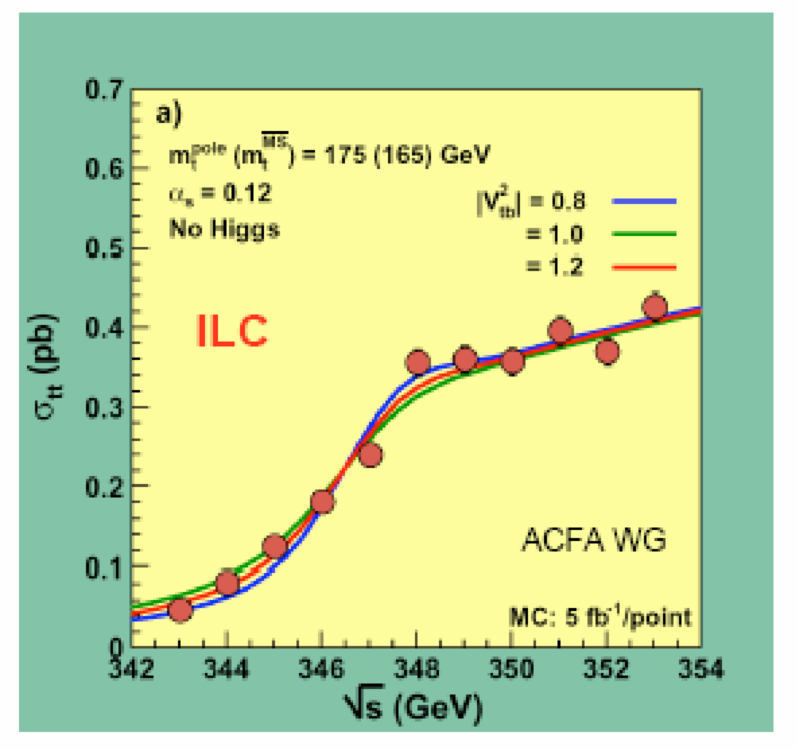
3. 1./2. + new states (SUSY, XD, little H, Z', …)
   ➪ precise spectroscopy of the new states
   ➪ precision measurements of couplings of SM&new states
   properties of new particles above kinematic limit

4. No Higgs, no new states (inconsistent with precision EW)
   ➪ find out why precision EW data are inconsistent
   ➪ look for threshold effects of strong/delayed EWSB

Early LHC data likely to guide the direction → choice of ILC options and upgrade to 1 TeV depends on LHC+ILC(500) results
LHC + ILC data analysed together → synergy!

Guaranteed and needed: top mass

- top-quark could play a key role in the understanding of flavour physics
- m_{top} fundamental parameter
- Δm_{top} will limit many predictions



requires precise determination of its properties

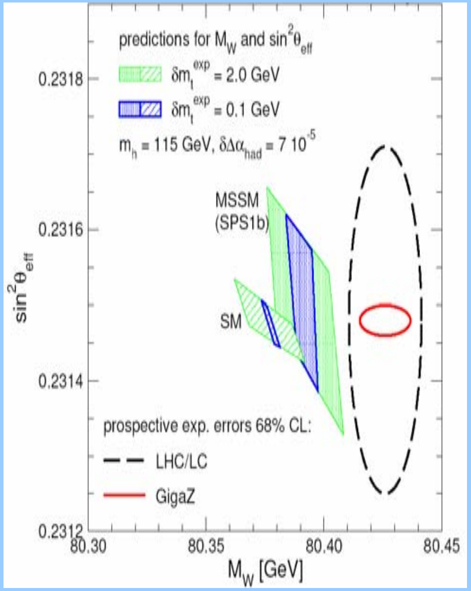
Energy scan of
top-quark threshold:

$\Delta M_{top} \approx 100$ MeV

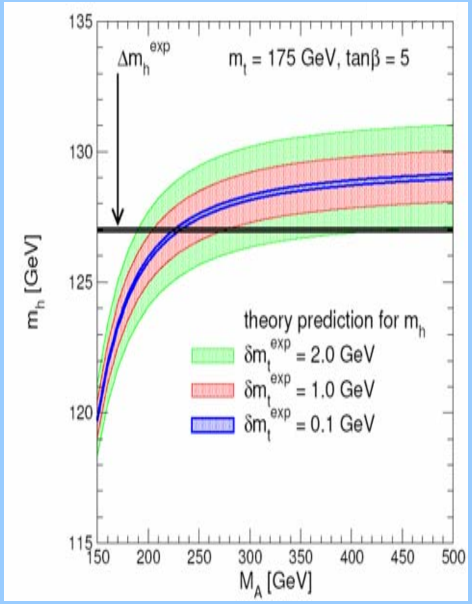
(dominated by theory)

Where the top mass comes into play

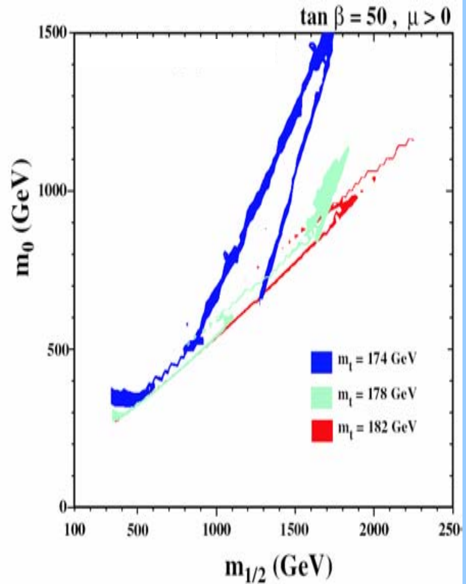
predictions of EW parameters:



Light Higgs mass prediction in SUSY:

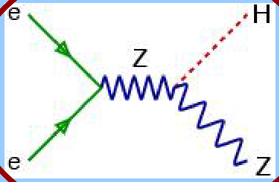


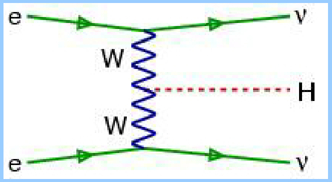
Prediction of DM density

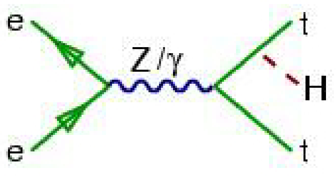


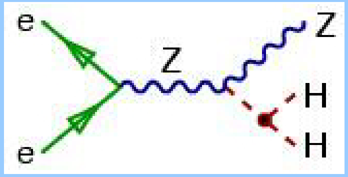
$$\Delta m_H/\Delta m_t \sim 1!$$

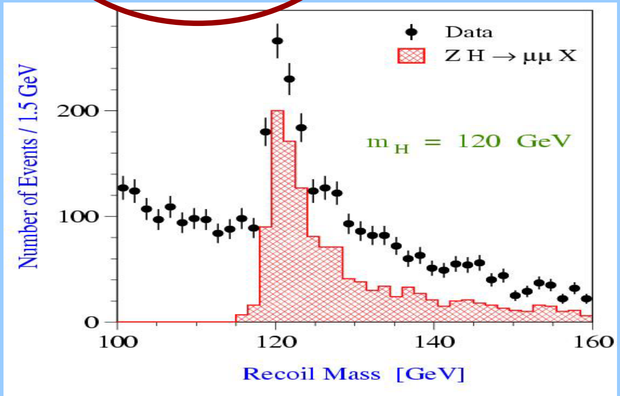
Precision Higgs Physics at ILC

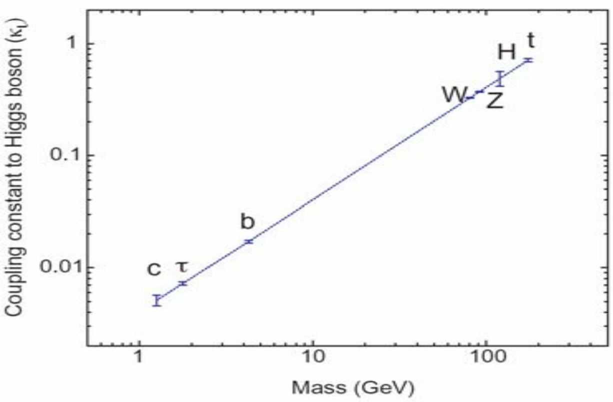










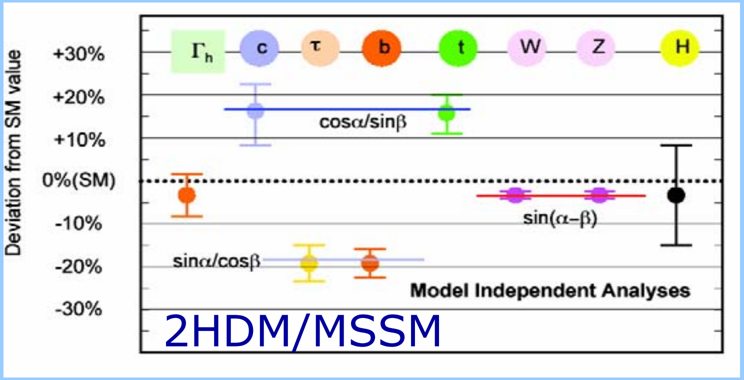


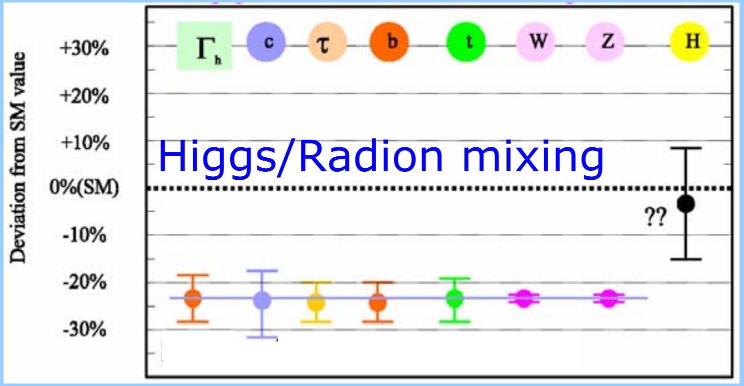
- decay-mode-independent observation
- mass (50 MeV)
- absolute couplings (Z,W,t,b,c,τ) (1-5%)
- total width (model-independent)
- spin, CP
- top Yukawa coupling (~5%)
- self coupling (~20%, 120-140 GeV)
- $\Gamma_{\gamma\gamma}$ at photon collider (2%)

fully establish Higgs mechanism!

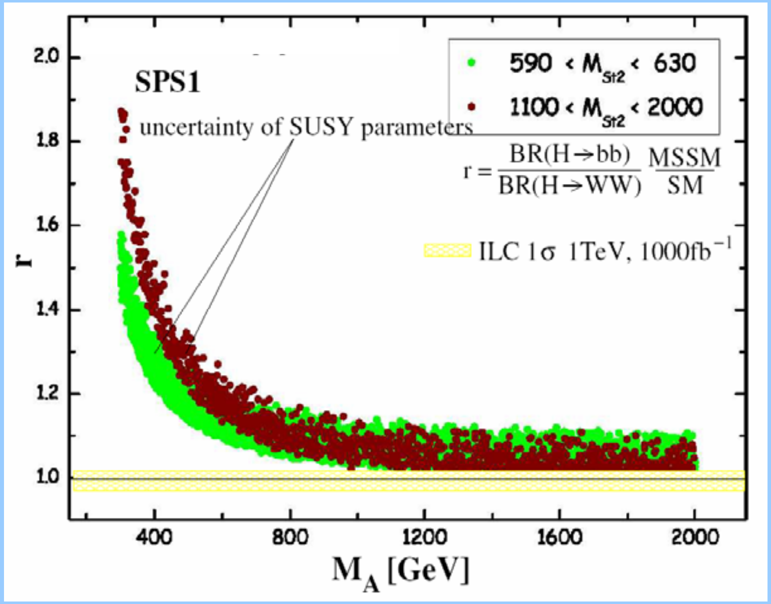
What the ILC precision is good for

Distinguish models:





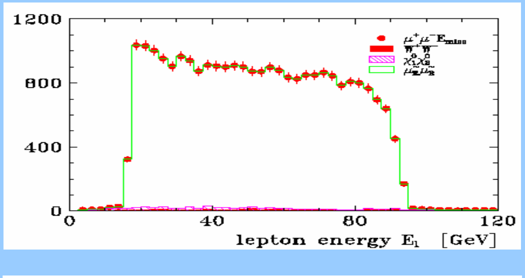
Constrain masses of heavy Higgses:



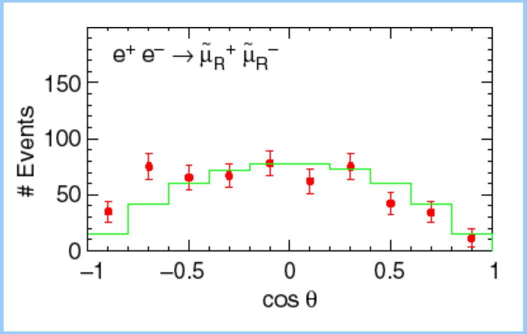
Δm_A = 30% for m_A = 800 GeV

Photon collider: direct production of H,A up to ~ 800 GeV at ILC(1000)

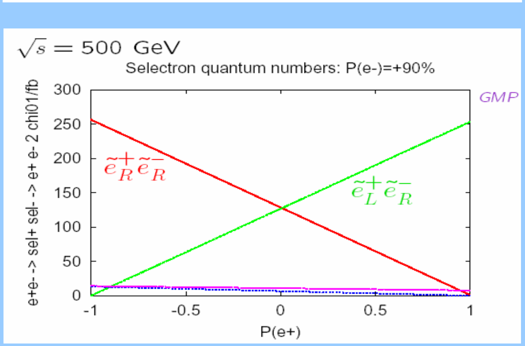
SUSY at ILC



precise masses of color-neutral states (50 MeV to 1 GeV)



spin (angular distributions)

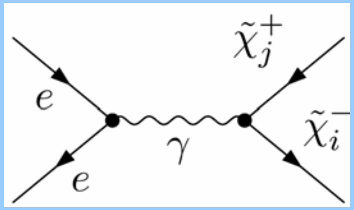


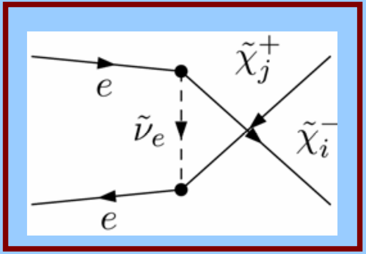
chiral quantum numbers (polarisation!)

→ prove that it is SUSY
→ no model assumptions
→ learn about SUSY breaking

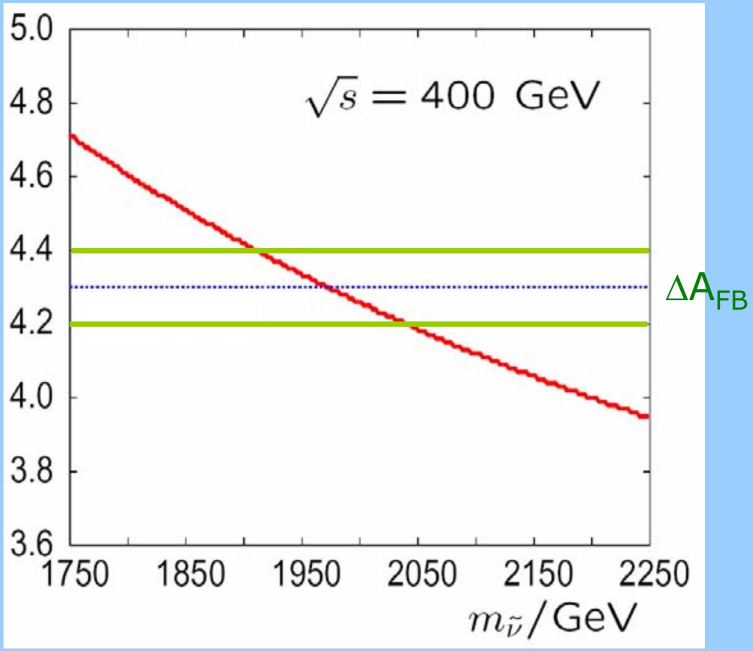
SUSY at ILC

Even a partial spectrum can tell a lot…





E.g. scenario, where ‘only’ chargino production large at ILC(500)



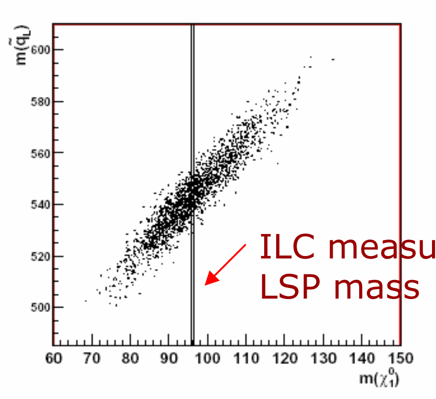
obtain sneutrino mass
distinguish models
(e.g. focus point SUSY from
split SUSY)

SUSY at ILC+LHC

1. ILC measurements improve LHC precision:

$\Delta m(\chi^0_1)$ @ LHC: 5 GeV
$\Delta m(\chi^0_1)$ @ ILC: 0.05 GeV

(SPS1a)



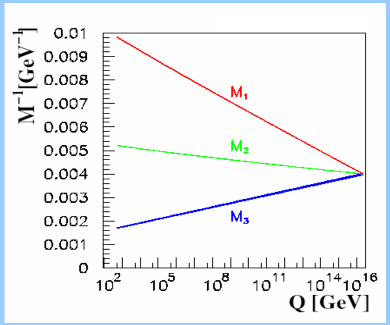
squark mass

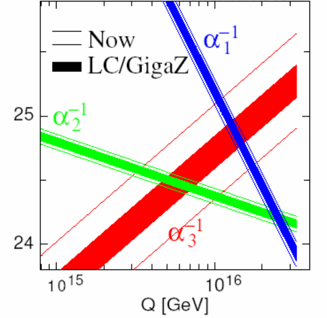
ILC measurement of LSP mass

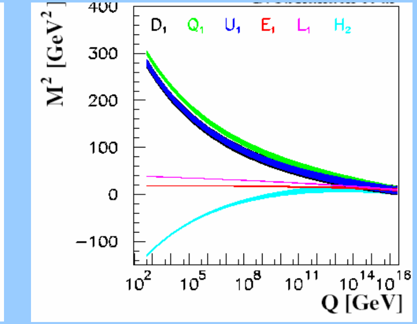
LSP mass

2. ILC precision + LHC mass reach for squarks/gluinos does allows for a general MSSM parameter determination (19 parameters)
this will not be possible with either LHC or ILC alone – need both!

allows for model-independent study of GUT/Planck scale features:

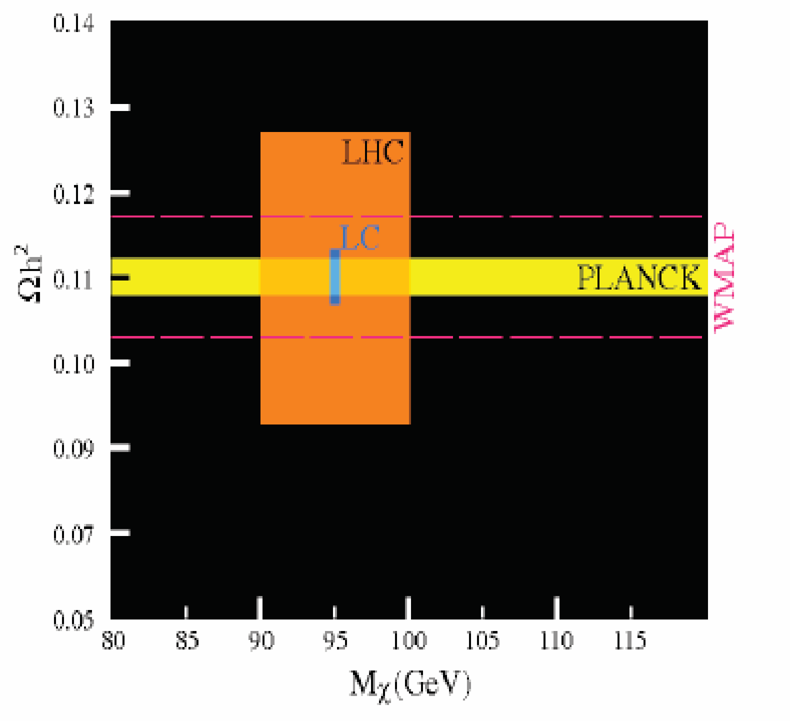






Dark Matter and SUSY

If SUSY LSP responsible for Cold Dark Matter, need accelerators to show that its properties are consistent with CMB data



DM density mainly determined by properties of lightest SUSY states

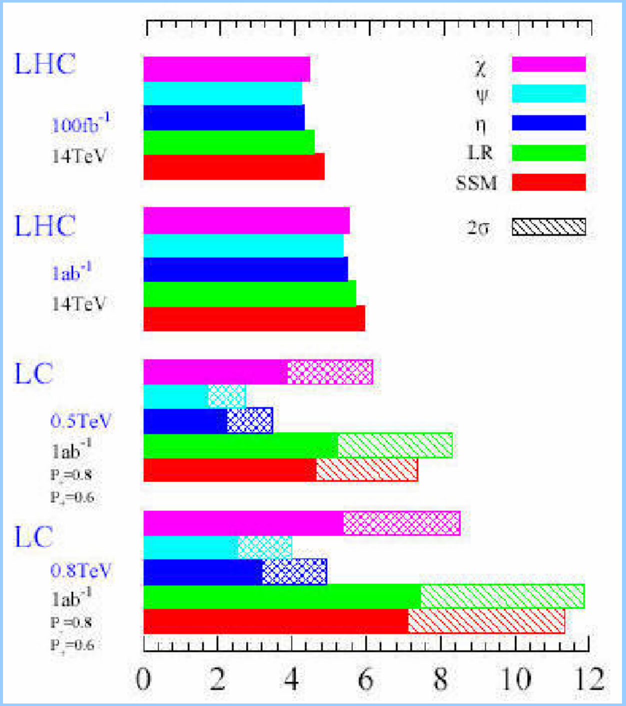
'WMAP'	7 %
LHC	~15 %
'Planck'	~2 %
ILC	~3 %

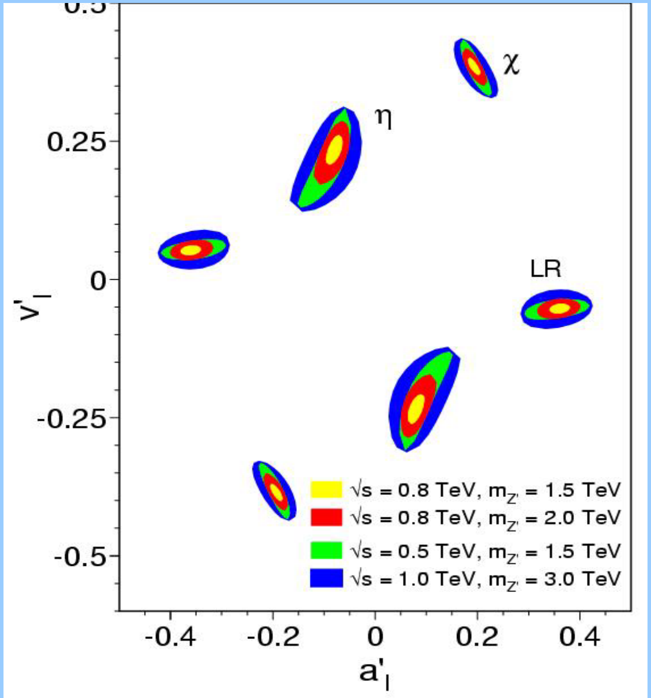
would provide overwhelming evidence that the observed particle is indeed dark matter

New Resonances

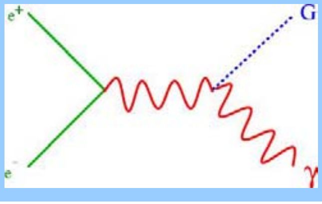
Effects from heavy dilepton resonances can be observed by the ILC up to many times the centre-of-mass energy

If LHC observes a new resonance, ILC can measure the couplings and thus distinguish its origin (Z’, XD, little-H,…)

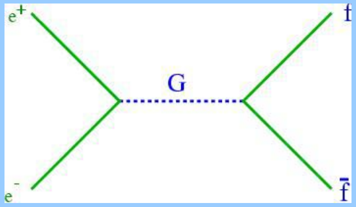


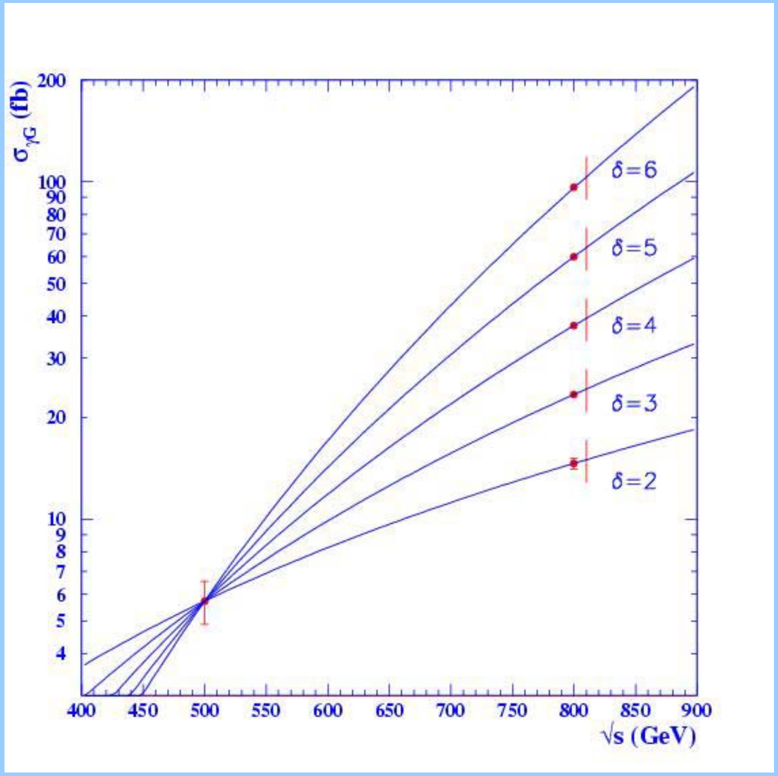


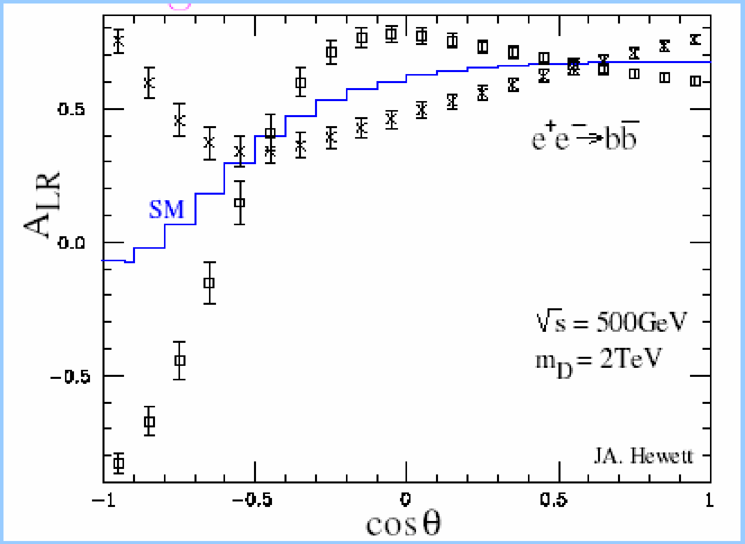
Large Extra Dimensions at ILC



can determine Spin=2
number of XD's
+ interplay LHC/ILC



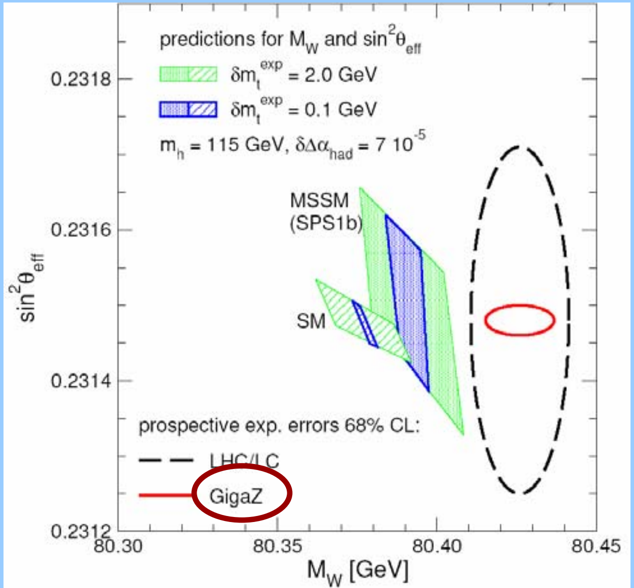




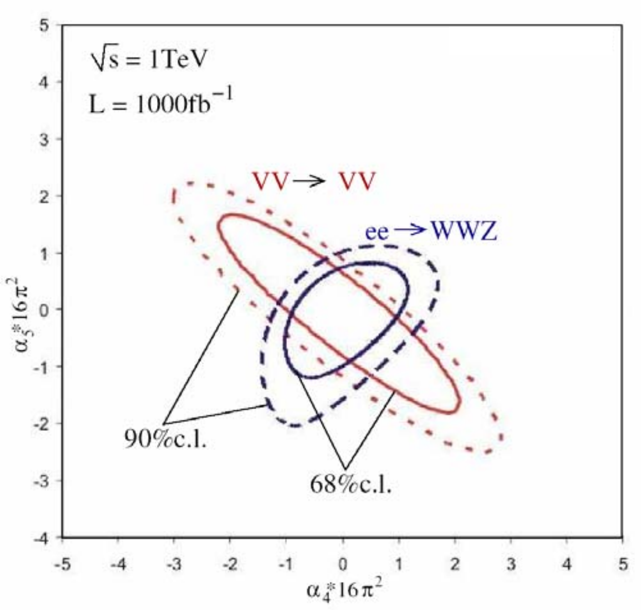
No Higgs seen at LHC: tasks for ILC

1. Make sure LHC hasn’t missed it
   e.g. invisible or purely hadronic

2. Find out why rad. corrections
   are inconsistent

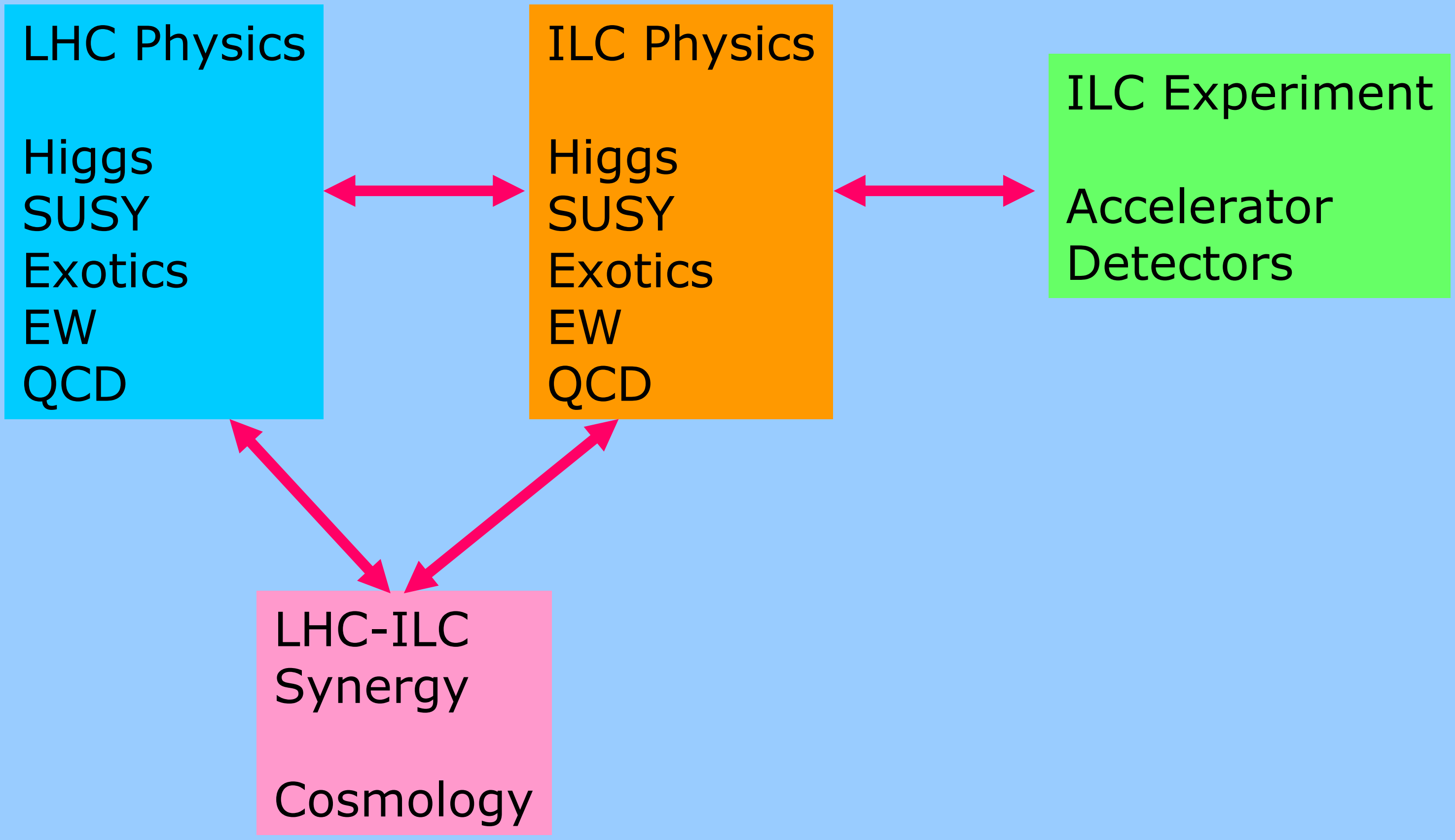


3. Look for effects of strong EWSB:
   deviations in $V_LV_L \rightarrow V_LV_L$, WWZ,
   and Triple Gauge Couplings



Sensitivity up to $\Lambda \sim 3$ TeV
similar but
complementary to LHC

Instead of a summary: Overview over the program



LHC Physics

Higgs
SUSY
Exotics
EW
QCD

ILC Physics

Higgs
SUSY
Exotics
EW
QCD

ILC Experiment

Accelerator
Detectors

LHC-ILC
Synergy

Cosmology