The ILC and its complementarity to the LHC

Outline:

1. ILC physics motivation

2. ILC $\oplus$ LHC synergy

3. LHC $\rightarrow$ ILC implications

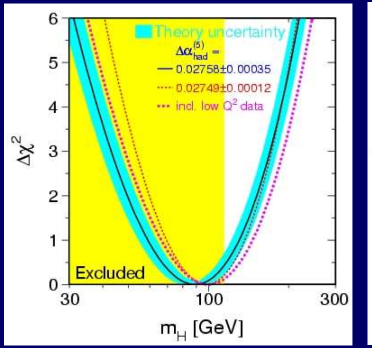
31st Johns Hopkins Workshop
Heidelberg 2007

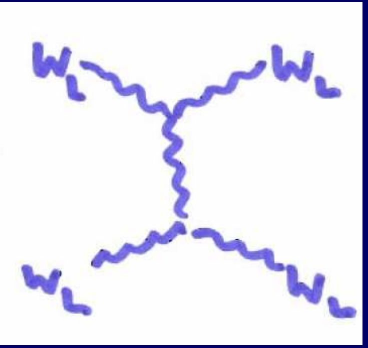
Klaus Desch
Universität Bonn

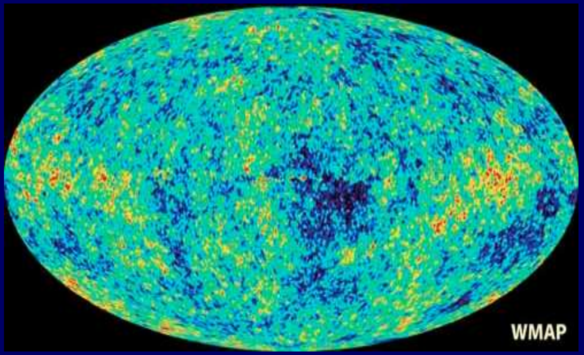
The Terascale

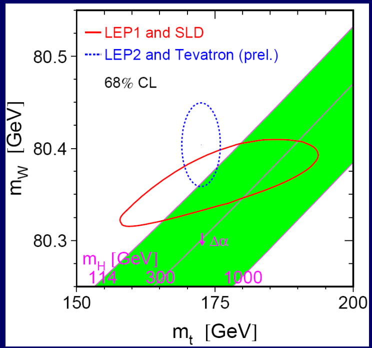
Very good reasons to explore the TeV scale:

- 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 WIMP (e.g. SUSY-LSP)
- $2m_{top} \cong 350$ GeV



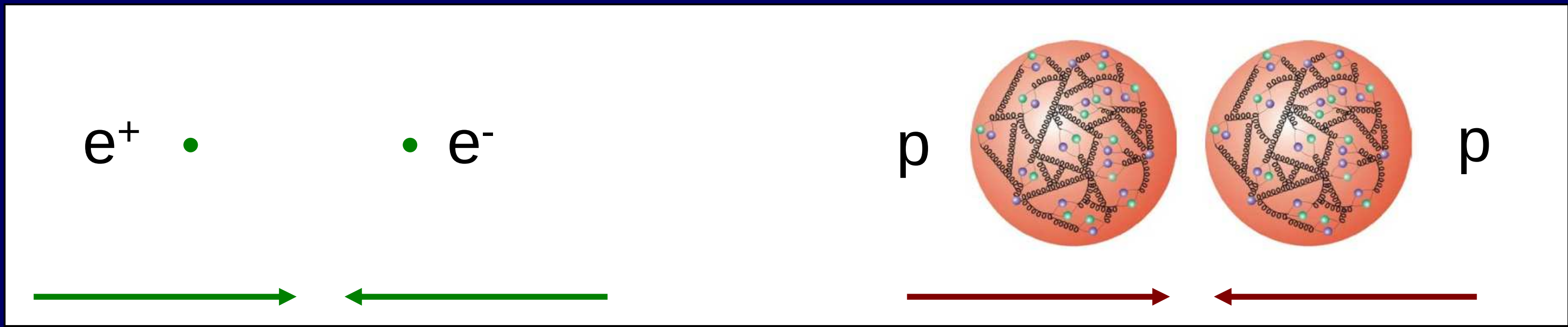






⇨ LHC will directly open the Terascale window for the first time
Will this be sufficient?

Complementarity of tools



Electron positron collisions: complementary tool to the LHC

point-like structure and absence of strong interactions →

- **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

ILC parameters

defined by ICFA parameter group – recently confirmed in RDR process

Baseline:

e^+e^- LC operating from 200 to 500 GeV, tunable energy
at least 80% e^- polarization
at least 500 fb^{-1} in the first 4 years
beam energy precision 0.1% or better

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

Options :
- **60% positron polarisation**
- **GigaZ (high luminosity running at M_Z)**
- **$\gamma\gamma$, $e\gamma$, e^-e^- collisions**

Choice of options depends on LHC+ILC results

ILC Reference Design Report (RDR) meets these parameters

ILC physics case

Significant advance w.r.t. LHC in understanding of Terascale physics through high precision at high energy

Recent summary (to appear very soon): Physics part of the RDR

July 6, 2007

The Physics Case for the International Linear Collider

Edtors: Abdelhak Djouadi[1], Joe Lykken[2], Klaus Mönig[3], Yasuhiro Okada[4], Mark Oreglia [5], Satoru Yamashita[6]

no change in conclusions from TESLA TDR, Snowmass report, ACFA study (~2001) ⇨ ILC physics is rock solid ☺

Physics case: Highlights

Higgs precision physics

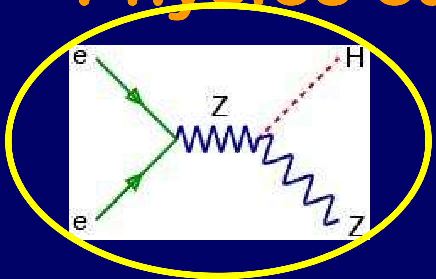
Gauge Bosons („SM probes of BSM physics“)

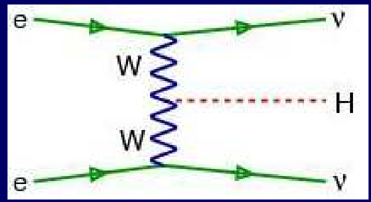
Top Quark

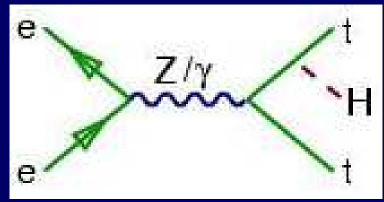
Supersymmetry

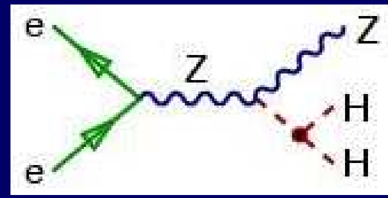
Large extra dimensions

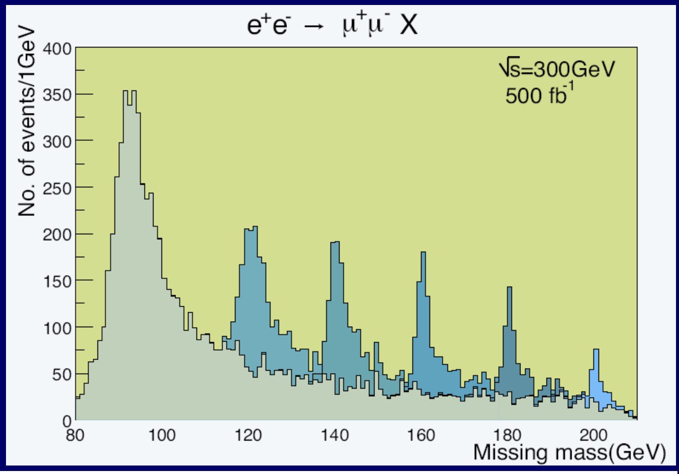
Physics case: Higgs

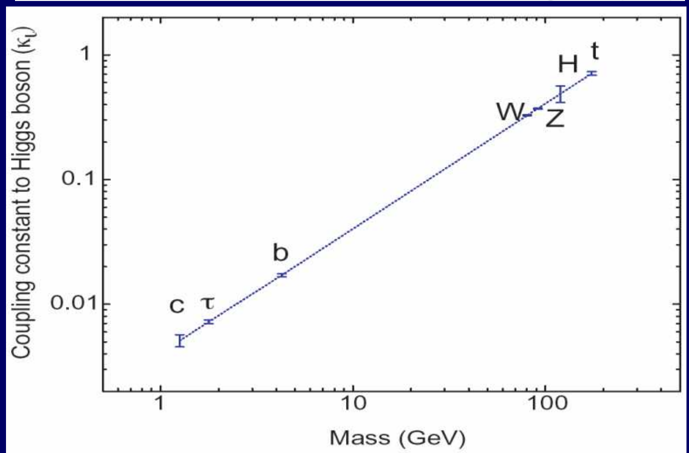








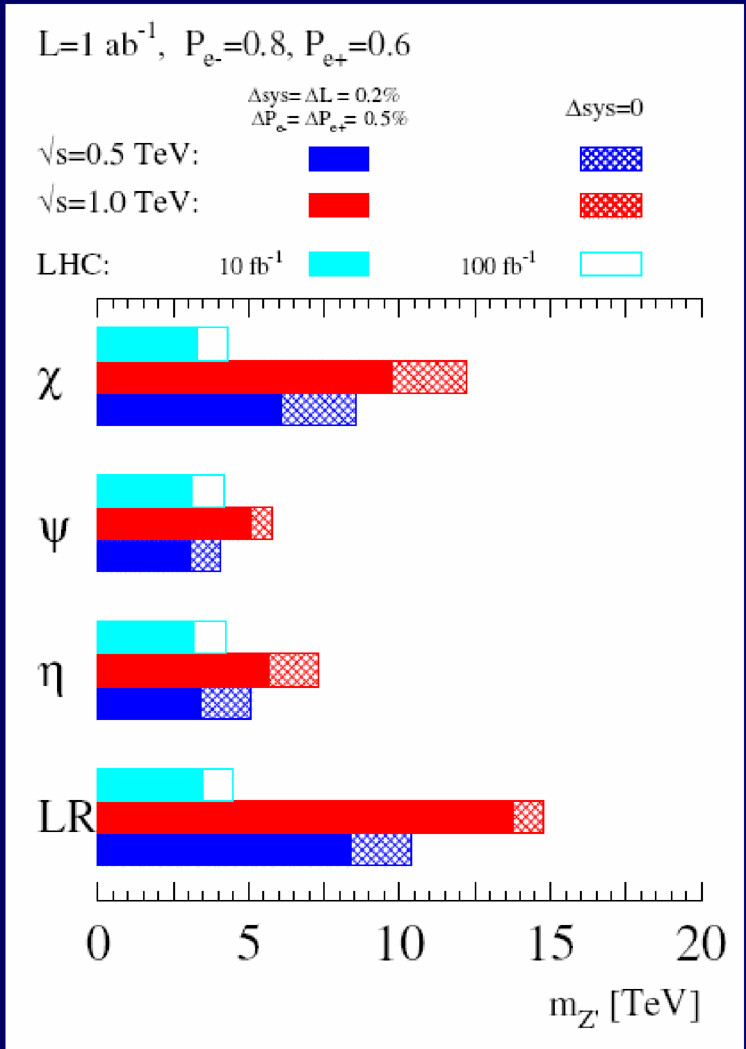


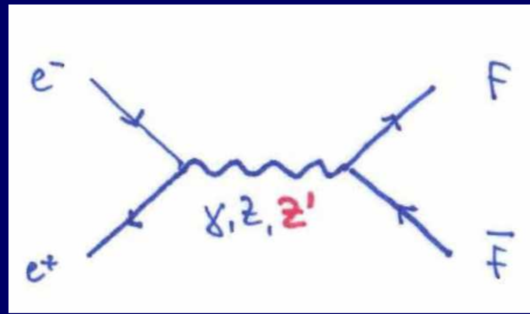


- decay-mode-independent observation
- mass (50 MeV)
- absolute couplings (Z,W,t,b,c,τ) (1-5%)
- total width (model-independent)
- spin, CP
- top Yukawa coupling (~5%)
- self coupling (~20%, 120-140 GeV)
- $\Gamma_{\gamma\gamma}$ at photon collider (2%)

fully establish Higgs mechanism!

Physics case: Gauge Bosons





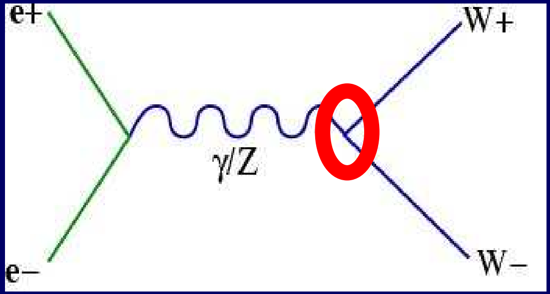
precision measurement of SM processes ($e^+e^- \rightarrow f\bar{f}$)

higher mass reach for new Z´-like particles than direct search at LHC

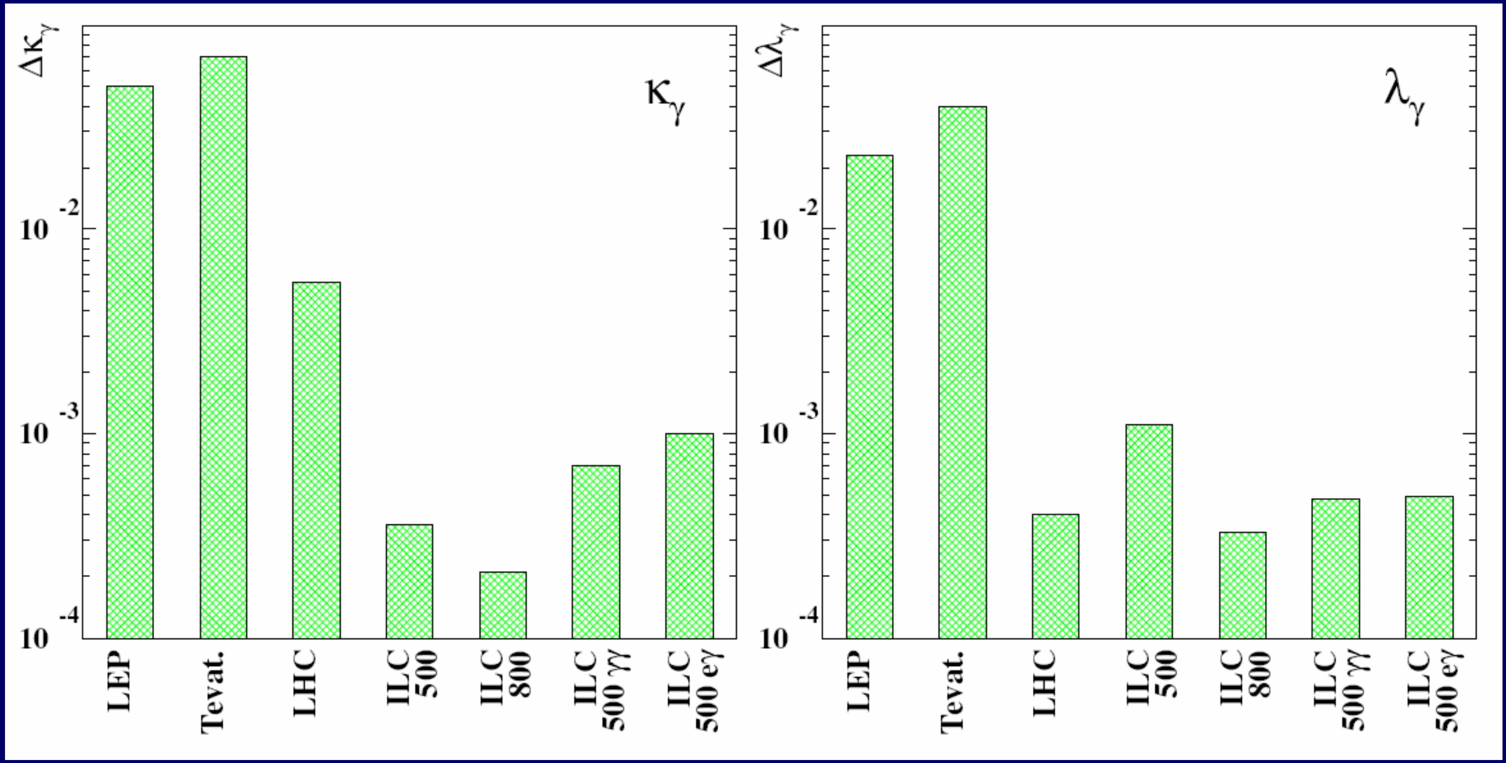
expect effects for large classes of new physics (Little Higgs, Higgsless, ...)

Physics case: Gauge Bosons

Anomalous Triple Gauge Boson couplings:

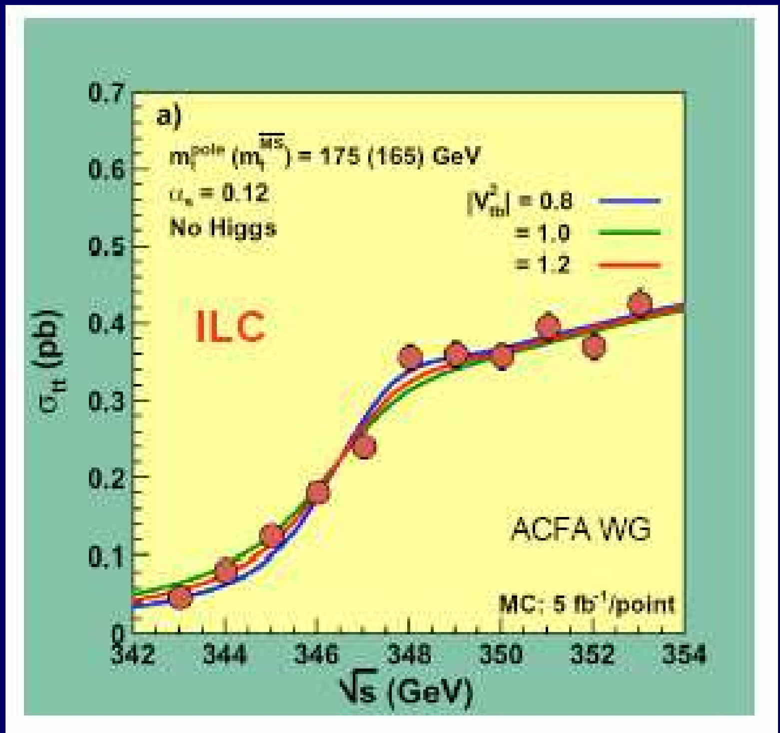


higher sensitivity than LHC for some couplings
beam polarisation (both beams)
important e.g. for Higgsless models



Physics case: Top Quark

- m_{top} fundamental parameter
- Δm_{top} will limit many predictions, e.g.
  - prediction of SM parameters ($\sin\theta_W$, m_W)
  - prediction of m_h in MSSM
  - prediction of relic DM density in MSSM

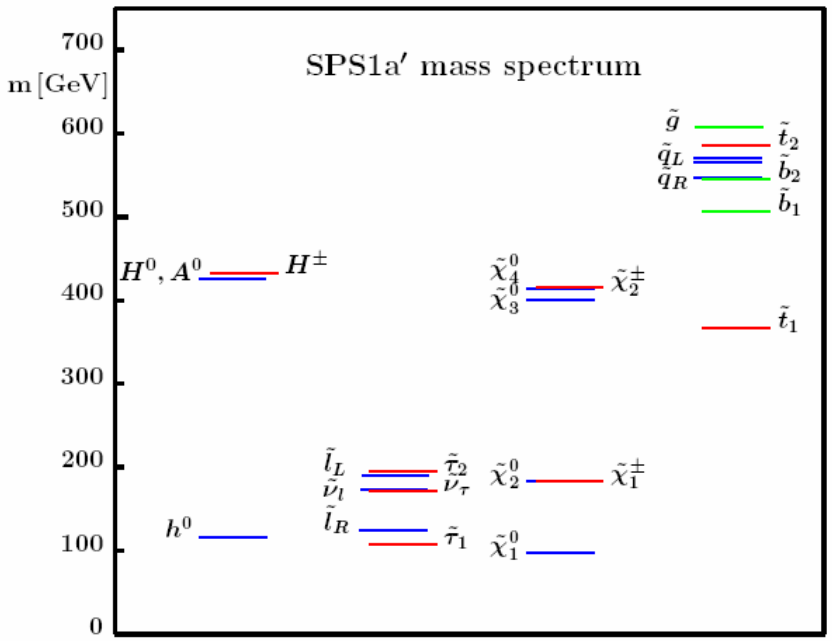


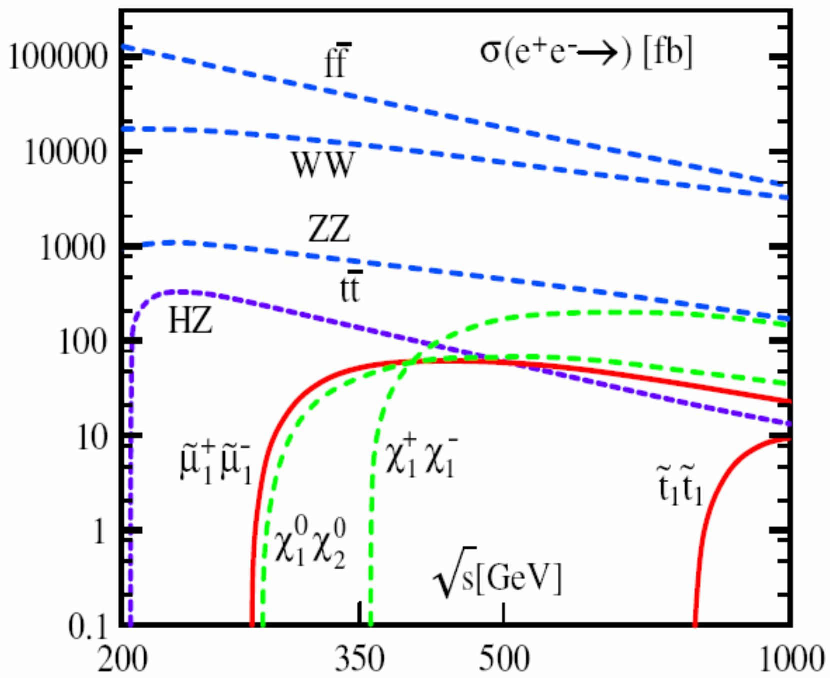
Energy scan of
top-quark threshold:

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

(dominated by theory error)

Physics case: Supersymmetry



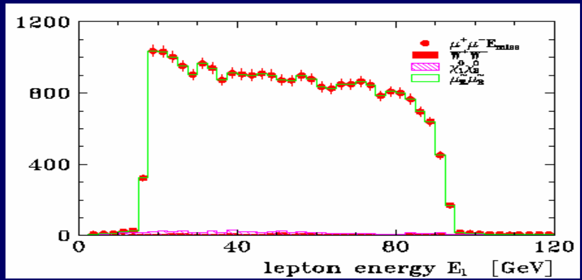


If colourless part of SUSY spectrum within ILC mass reach, ILC is the place to study the properties of these sparticles

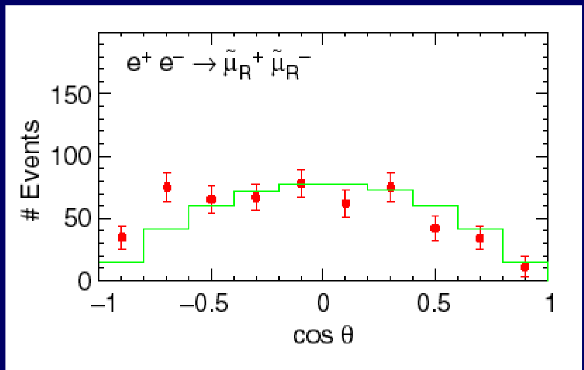
beam constraint allows for much improved kinematic reconstruction compared to LHC

⇨ expeditious test of SUSY predictions

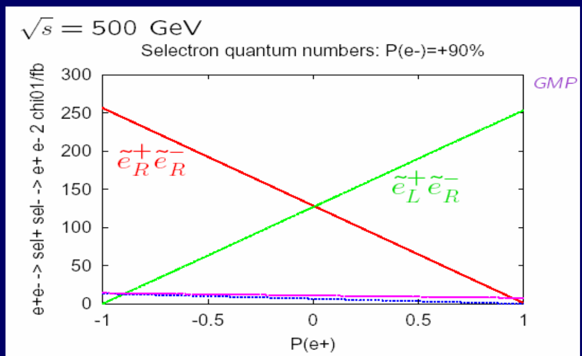
Physics case: Supersymmetry



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



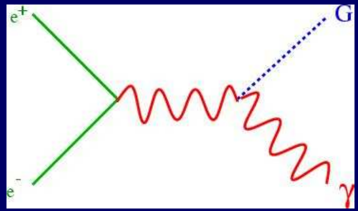
spins (angular distributions)



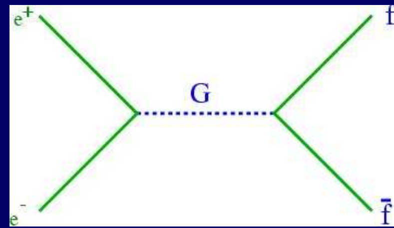
chiral quantum numbers (polarisation!)

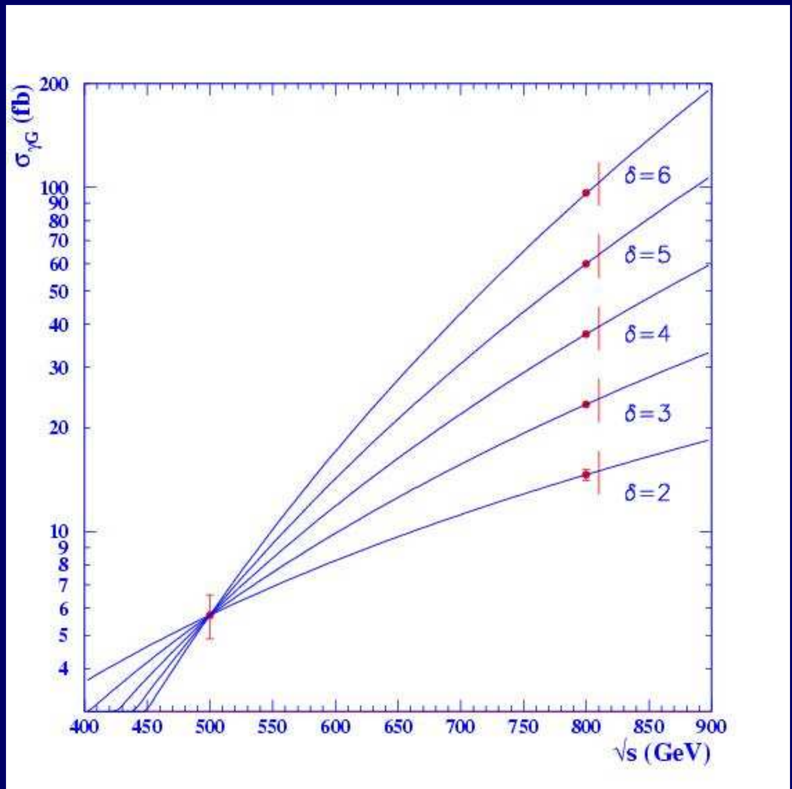
→ prove that it is SUSY
→ no model assumptions
→ learn about SUSY breaking

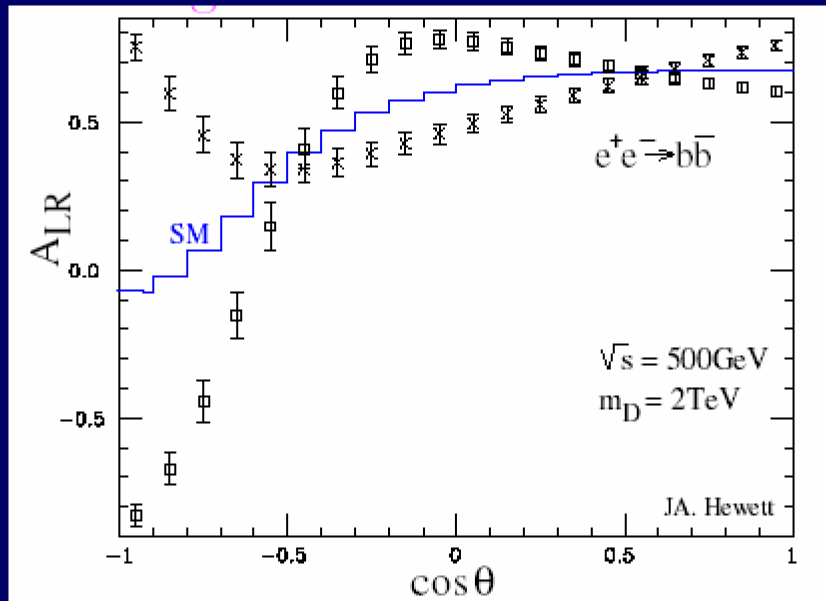
Physics case: Large Extra Dimensions



can determine Spin=2
number of XD's

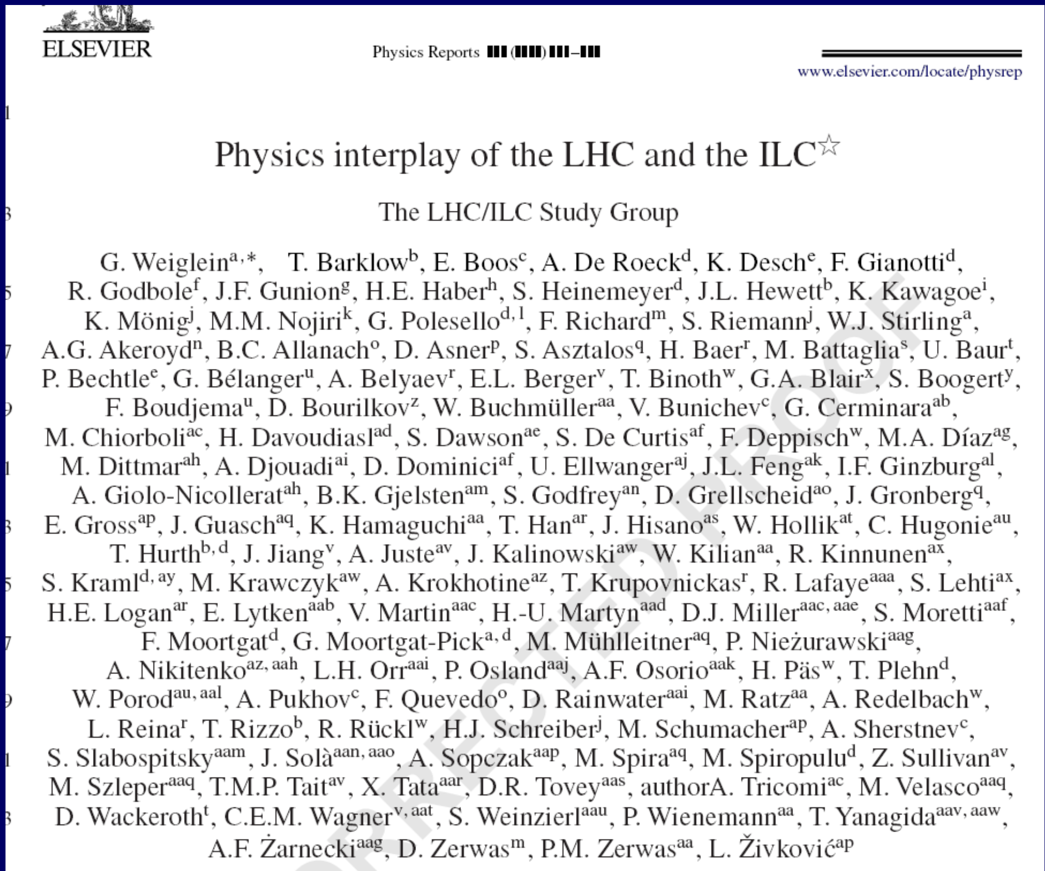






Interplay and Synergy

LHC/ILC Study group,
Weiglein et al.
Phys. Rept. 426 (2006) 47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Physics interplay of the LHC and the ILC☆

The LHC/ILC Study Group

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Main questions:
How can our view of the Terascale be improved if results from both tools, LHC ⊕ ILC are interpreted simultaneously?

(also: are there cases which justify a simlutaneous running of LHC and ILC?

became somewhat less important ☹)

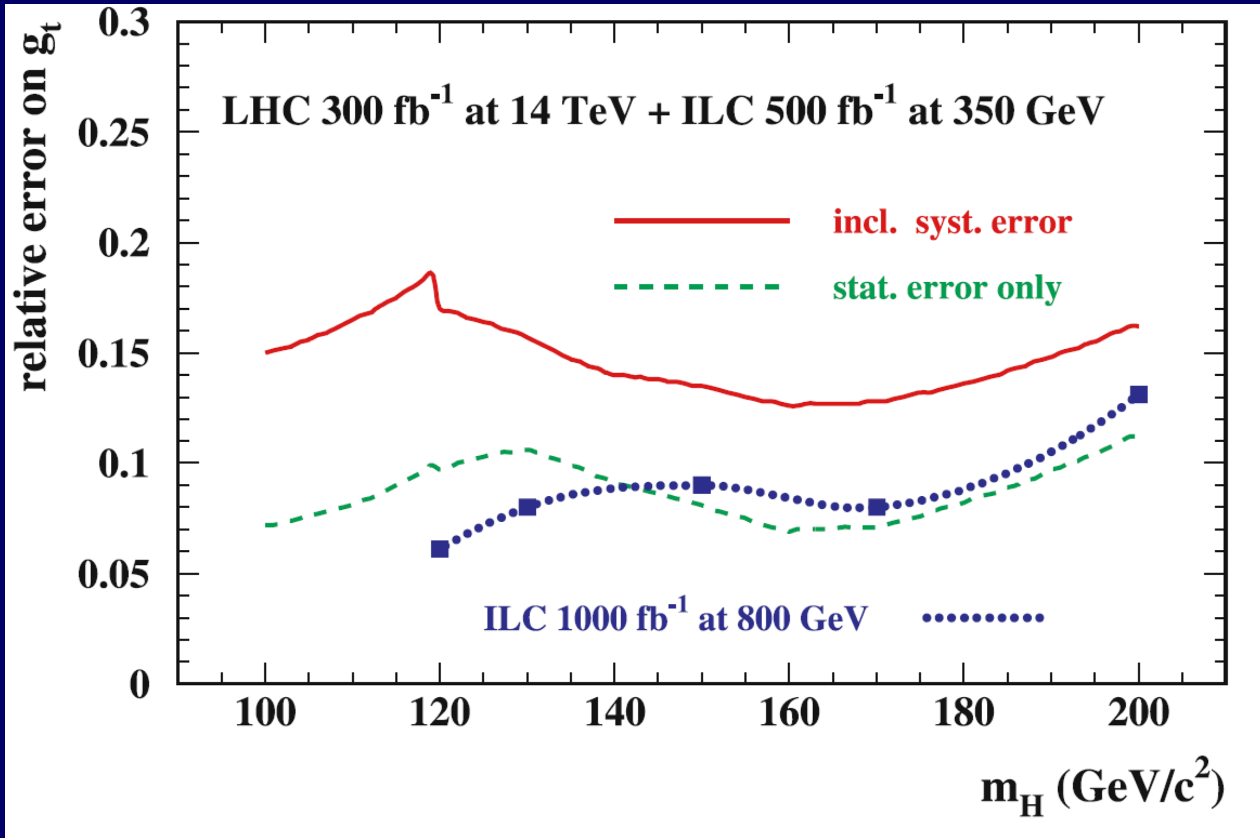
LHC⊕ILC example: Top Yukawa Coupling

LHC: measures

- σ_{tth} x BR(H→bb)
- σ_{tth} x BR(H→WW)
- → g_t^2 x BR(H→xx)

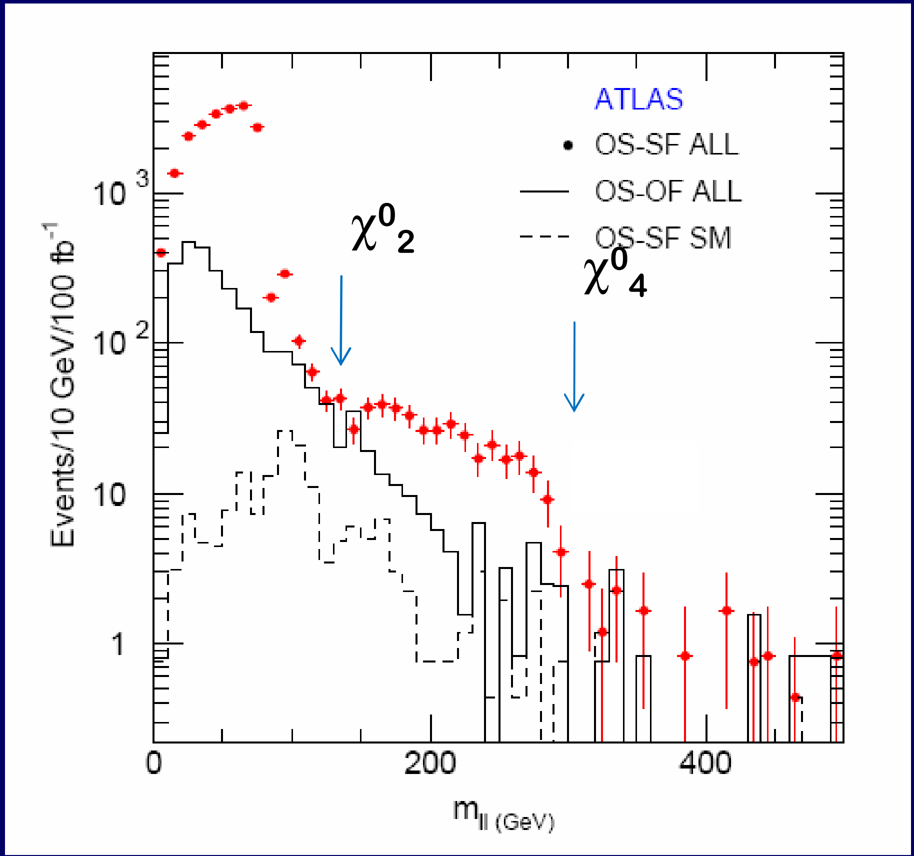
ILC(500): measures BRs

- BR(H→bb)
- BR(H→WW)



LHC⊕ILC: identification of LHC signals

SPS1a example:
from measurements of $\chi^+\chi^-$ and $\chi^0_1\ \chi^0_2$ production, neutralino+chargino sector can be fully reconstructed ⇨ prediction of all masses, couplings
e.g. $m(\chi^0_4) = 378.3 \pm 8.8$ GeV



LHC⊕ILC: global parameter determination

Ultimate goal in study of SUSY: learn about SUSY breaking and GUT unification ⇨ need to be „unbiased“ in interpretation of data

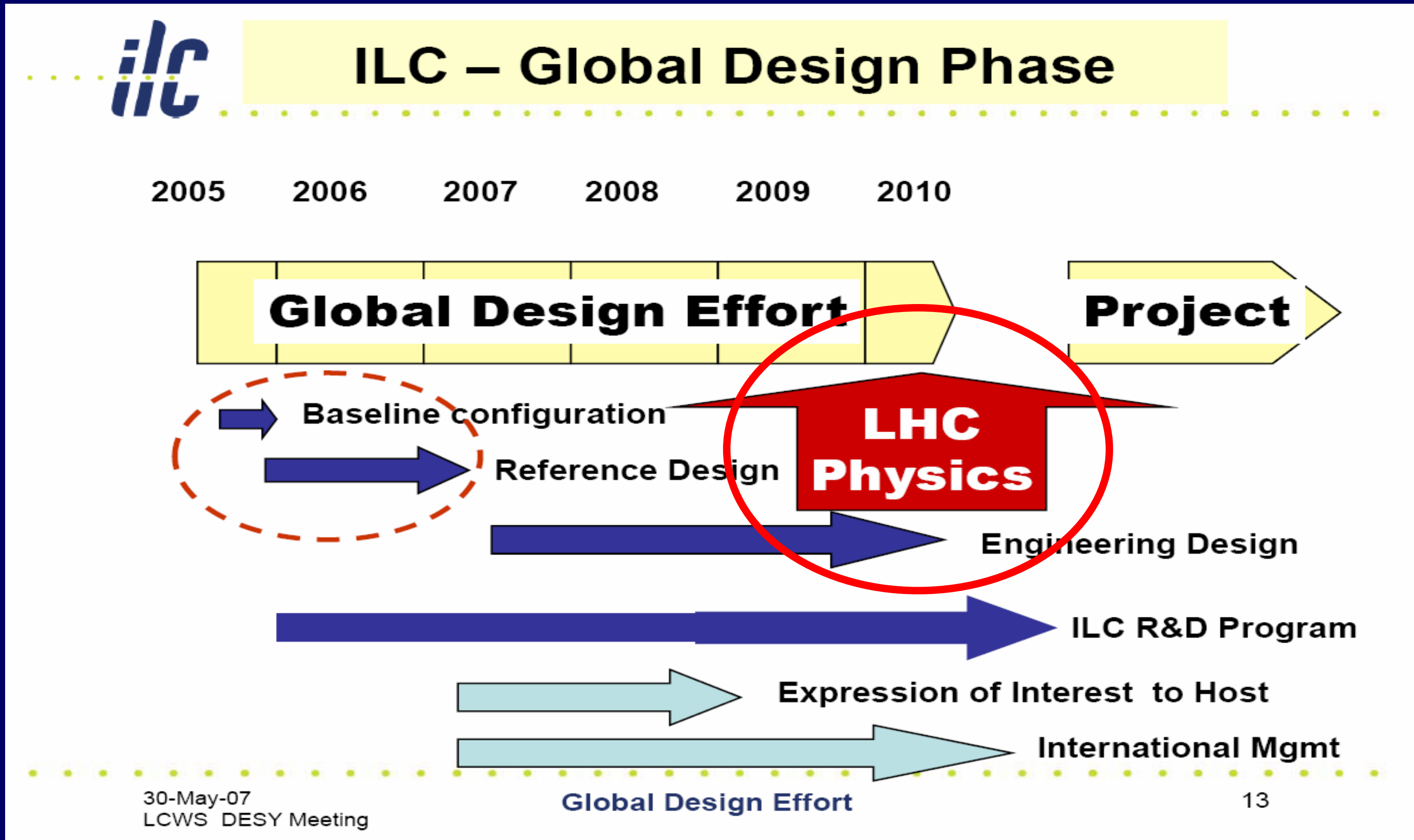
(exp observables) ⇨ (EW scale model parameters (e.g. MSSM(24)))
⇨ RGE evolution

global fit of all accessible observables from LHC and ILC needed:

TABLE 5.3-3
Results for the MSSM parameter determination in SPS1a [215] and SPS1a' [188] using the mass measurements at the ILC and the LHC [193] after a global fit. The central values are approximately reproduced.

	ΔLHC	ΔILC	ΔLHC+ILC	SPS1a	ΔLHC+ILC	SPS1a'
$\tan\beta$	±9.1	±0.3	±0.2	10	±0.3	10
μ	±7.3	±2.3	±1.0	344.3	±1.1	396
M_A	fixed 500	±0.9	±0.8	399.1	±0.8	372
A_t	±91	±2.7	±3.3	−504.9	±24.6	−565.1
M_1	±5.3	±0.1	±0.1	102.2	±0.1	103.3
M_2	±7.3	±0.7	±0.2	191.8	±0.1	193.2
M_3	±15	fixed 500	±11	589.4	±7.8	571.7
$M_{\tilde{\tau}_L}$	fixed 500	±1.2	±1.1	197.8	±1.2	179.3
$M_{\tilde{e}_L}$	±5.1	±0.2	±0.2	198.7	±0.2	181.0
$M_{\tilde{e}_R}$	±5.0	±0.05	±0.05	138.2	±0.4	115.7
$M_{\tilde{Q}3_L}$	±110	±4.4	±39	501.3	±4.9	471.4
$M_{\tilde{Q}1_L}$	±13	fixed 500	±6.5	553.7	±5.2	525.8
$M_{\tilde{d}_R}$	±20	fixed 500	±15	529.3	±17.3	505.7

Implications of first LHC data on ILC



Barish

With first collisions at 14 TeV next year, it is obvious that we have to start understanding implications of LHC discoveries for the ILC in much more detail

Implications of first LHC data on ILC

First workshop on this topic held at Fermilab, April 07

Next workshop: January 08 (?), SLAC

The LHC Early Phase for the ILC
Workshop charge

What could be the impact of early LHC results on the choice of the ultimate ILC energy range and the ILC upgrade path?

Could there be issues that would need to be implemented into the ILC machine and detectors design from the start?

Could there be cases that would change the consensus about the physics case for an ILC with an energy of about 500 GeV?

What are the prospects for LHC/ILC interplay based on early LHC data?

Strategy

Largely signal-driven (not so much model driven) scenarios

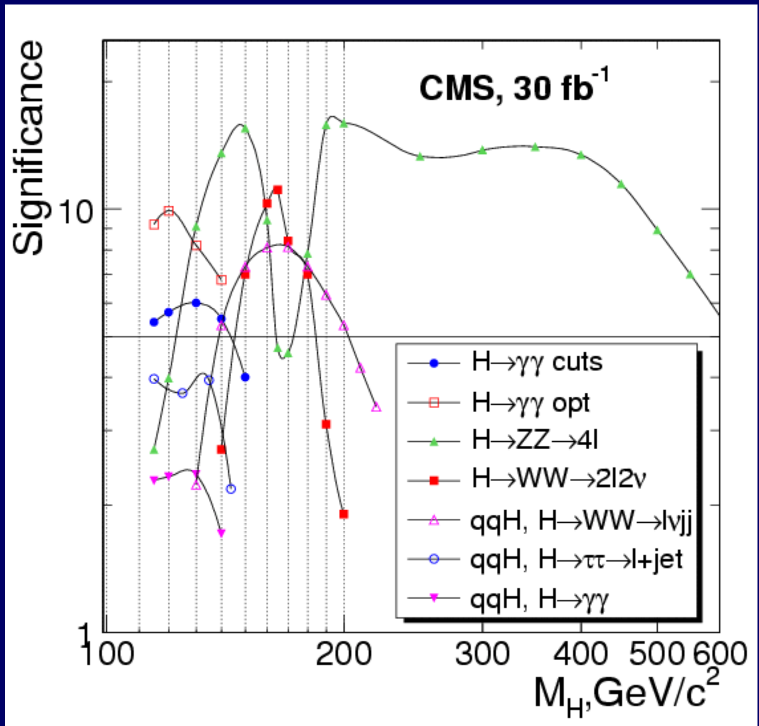
1. The detection of only one state with properties that are compatible with those of a Higgs boson

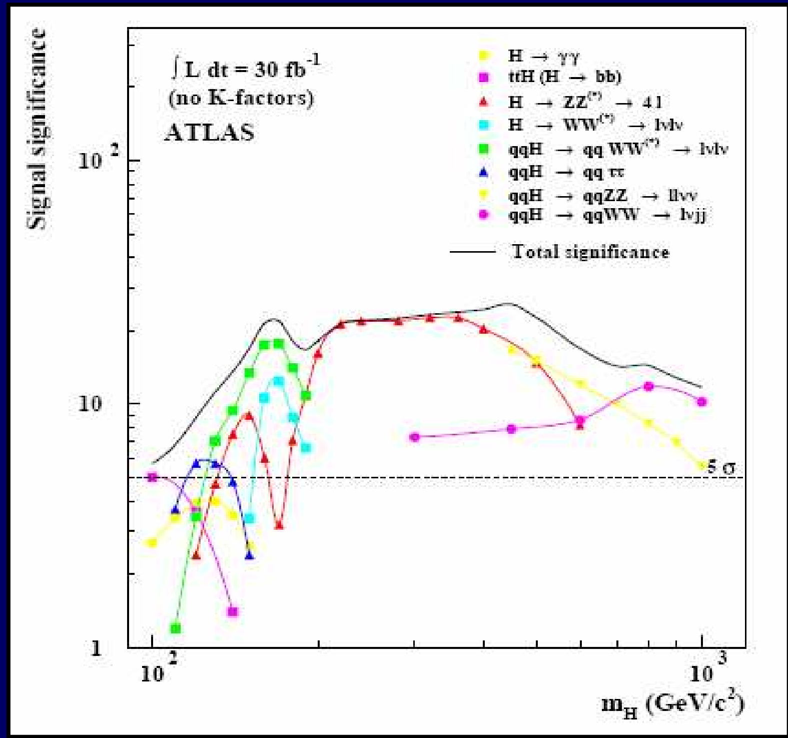
2. No experimental evidence for a Higgs boson at the early stage of LHC

3. The detection of new states of physics beyond the Standard Model.

    a. Missing Energy (+nothing, leptons, jets) signals
    b. Leptonic resonances
    c. Multi-Gauge-Boson signals
    d. Everything else.

Scenario 1: early Higgs at LHC





SM Higgs discovery with ~10 fb^{-1} over full mass range if nothing goes wrong

- rather easy (and fast) for m_H > 140 GeV
- more involved for light Higgs m_H < 140 GeV

Scenario 1: ILC implications

Depends (somewhat) on m_H

- Optimal $\sqrt{s}$ for HZ $\cong m_Z + m_H$ + 50 GeV ⇨ baseline ILC ok if m_H < ~ 350 GeV
- Yukawa couplings directly accessible at ILC up to 220 (bb), ~150 (cc,$\tau\tau$)
- HHH coupling studied up to 140 GeV so far

But not all possibilities for m_H> 160 GeV studied yet
More work necessary for the ILC!

for m_H > 160 GeV:

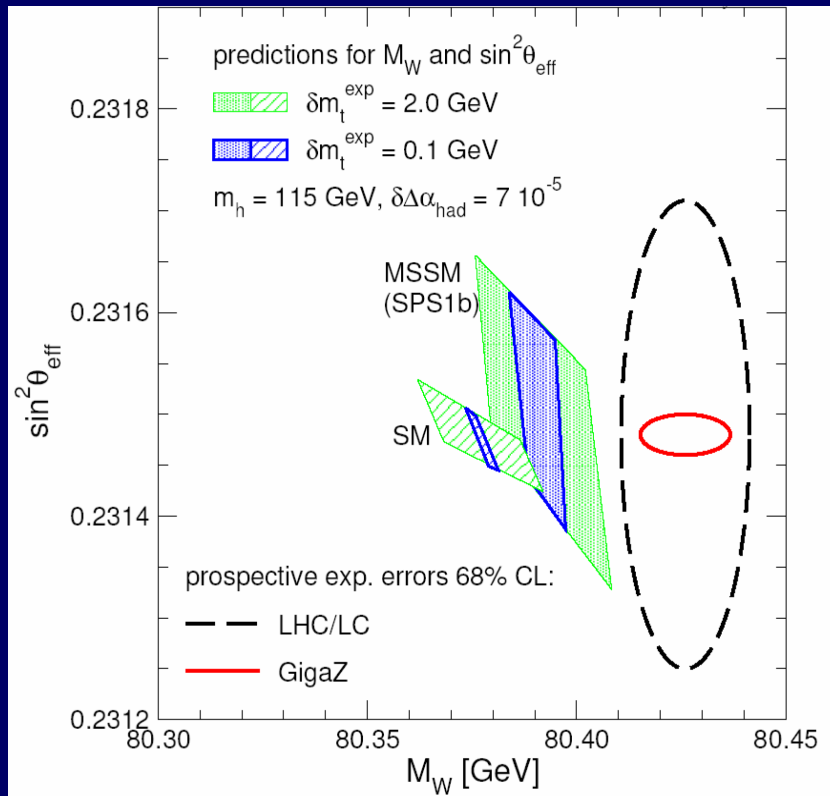
- couplings to WW, ZZ still measurable (but how much better than LHC?)
  $\rightarrow$ improve precision (include hadronic Z?, more luminosity?)
- fully explore WW-Fusion
- improvements for Yukawa couplings (H$\rightarrow$bb above 220 GeV, ttH, H $\rightarrow$tt*)
- explore total width measurement from WW$\rightarrow$H$\rightarrow$WW!
- total width from threshold scan?
- self coupling from $\nu\nu$HH$\rightarrow\nu\nu$WWWW (energy, luminosity)?

Scenario 1: m_H>>160 GeV ILC implications

If there is a heavy (>200 GeV?) SM-like Higgs we need precision measurements to test quantum structure
$\rightarrow$ indication for new physics close-by.

We will need:

- precise m_{top} (100 MeV) from tt-threshold
- precise m_W (6 MeV) from WW threshold
- precise $\sin^2\Theta_w$ from Giga-Z
- $e^+e^- \rightarrow$ ff, WW, …



Heinemeyer,Kraml,Porod,Weiglein

Scenario 2: No Higgs at early LHC

assume SM Higgs and MSSM Higgs excluded at LHC
(can probably be achieved with < 30 fb^{-1})

$\rightarrow$ 2 choices:
A: there are Higgs-like states to which the LHC is insensitive
B: there is no Higgs mechanism at work

Can the LHC tell if A or B is true?

Since A is not testable by definition, B has to be tested!

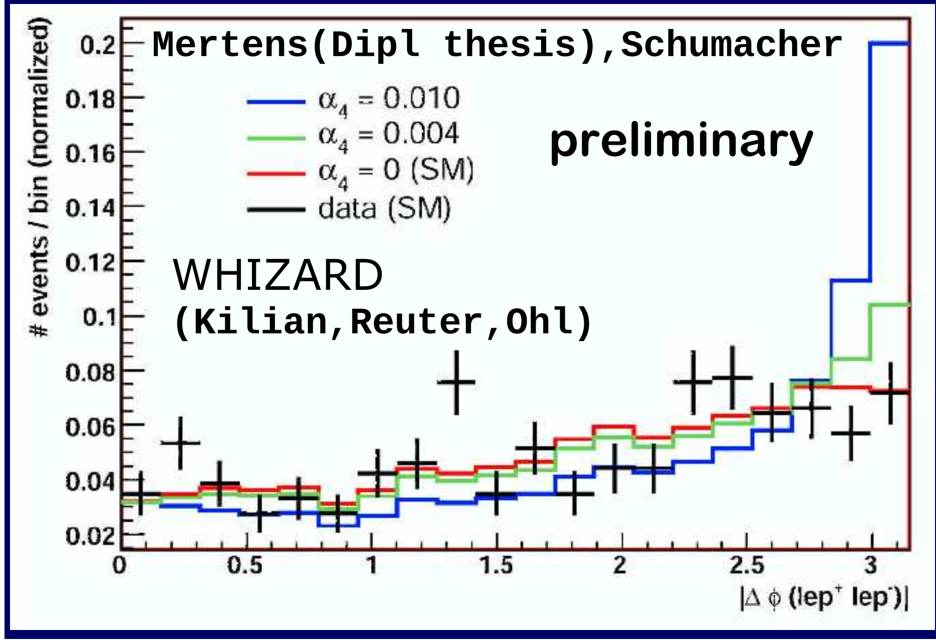
Scenario 2: if no Higgs → look at strong EWSB

Rich field

- **Measure TGCs in WW,WZ,ZZ**
- **Measure QGCs in WWZ, WWγ**

Crucial test of EWSB: Weak boson fusion at high mass:
e.g. qq →jjWW→jjlνlν

Needs more attention at LHC (did I miss something?)
Important for ILC planning!



$$L_4 = \frac{\alpha_4}{16\pi^2} tr(V_\mu V_\nu) tr(V^\mu V^\nu)$$

$$L_5 = \frac{\alpha_5}{16\pi^2} tr(V_\mu V^\mu) tr(V_\nu V^\nu)$$

effective Lagrangian approach valid at m(WW)>1.2 TeV??

exclusion potential?

Scenario 2: Implications for ILC

if WW → WW remains weak

→ Higgs has been missed!

→ ILC to look for invisible, purely hadronic, exotic (e.g. singlet continuum) Higgses

if deviations in WW → WW found

→ is ILC the right machine?

- low energy precision program still interesting (GigaZ, ee→ff, TGC, QGC)
- but clearly the multi-TeV region comes into focus which tools? (CLIC, MUC, ???)

Scenario 3: MET signal at LHC

After observation of an excess: need estimate of thresholds at ILC

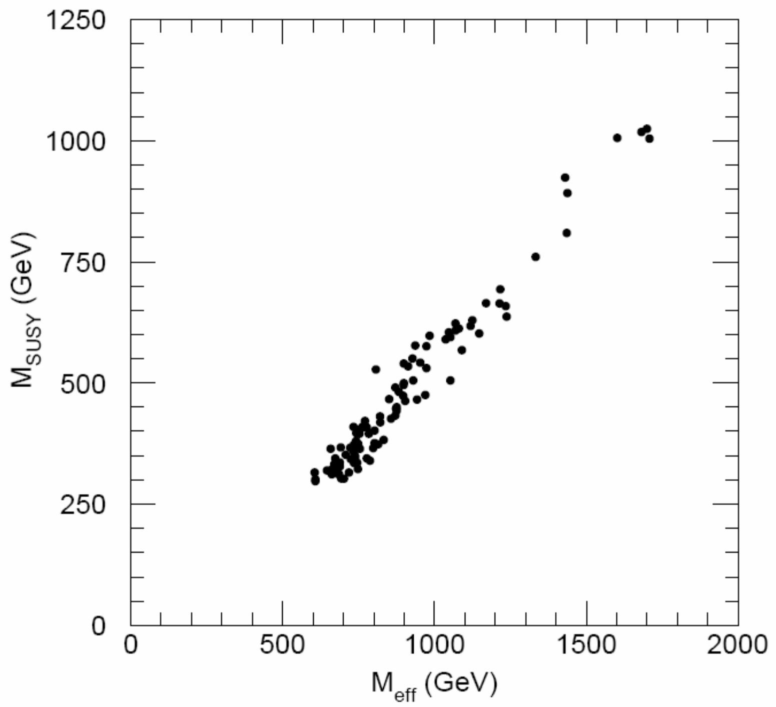
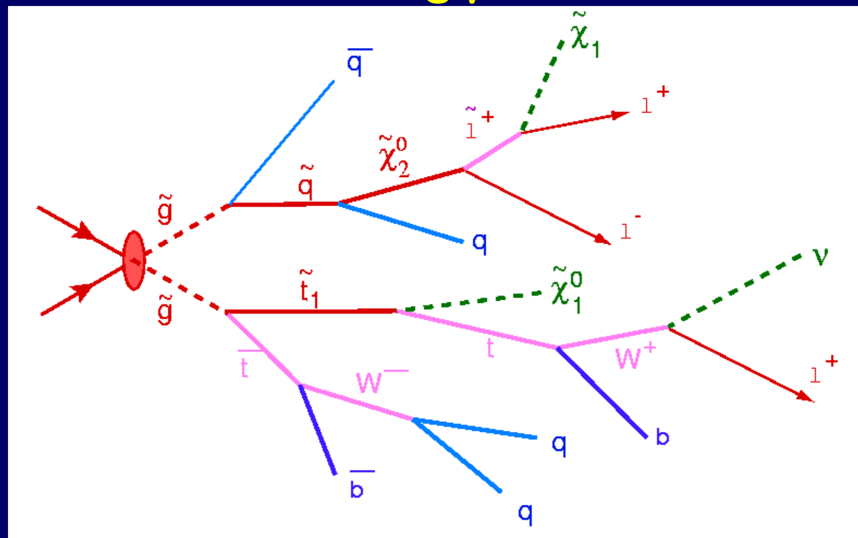


Figure 20-5 Peak of $M_{\rm eff}$ distribution as a function of. $M_{\rm SUSY} = \min(M_{\tilde{g}}, M_{\tilde{u}_R})$ for various models.

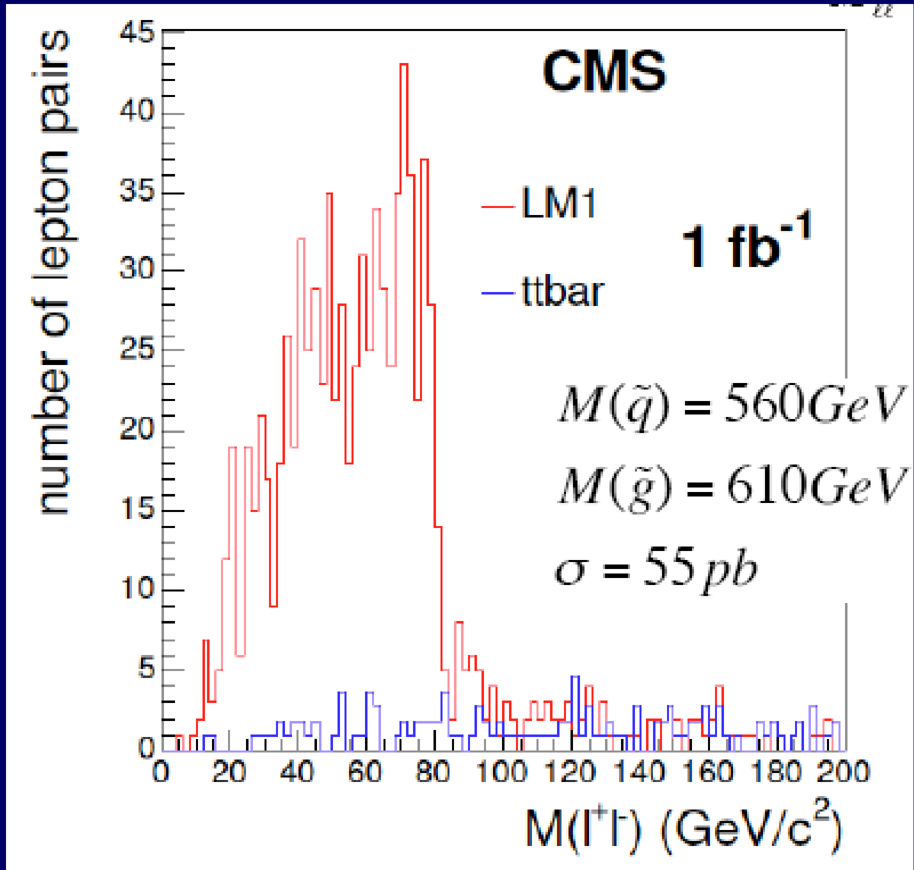
Fast estimate of m(gluino), m(squark) is not enough for ILC decision/optimization

need to get estimates of masses of the cascading particles!



Scenario 3: SUSY at LHC

Dileptons:



A sharp edge in the dilepton mass spectrum is a fast "go" for the ILC

$$M_{\ell\ell}^{\max} = m(\tilde{\chi}_2^0)\sqrt{1-\left(\frac{m(\tilde{\ell}_R^{\pm})}{m(\tilde{\chi}_2^0)}\right)^2}\sqrt{1-\left(\frac{m(\tilde{\chi}_1^0)}{m(\tilde{\ell}_R^{\pm})}\right)^2}$$

caveat:

could be (outside mSugra):

M^{edge} = 80 GeV
= 400 GeV – 320 GeV

excludable through LHC rates?

Scenario 3: MET signal at LHC

what we really need is a model-independent estimate of the particle masses in cascade decays, which end in an invisible massive particle (DM candidate)

Full kinematic reconstruction is tough
see e.g. Kawagoe,Nojiri,Polesello hep-ph/0410160

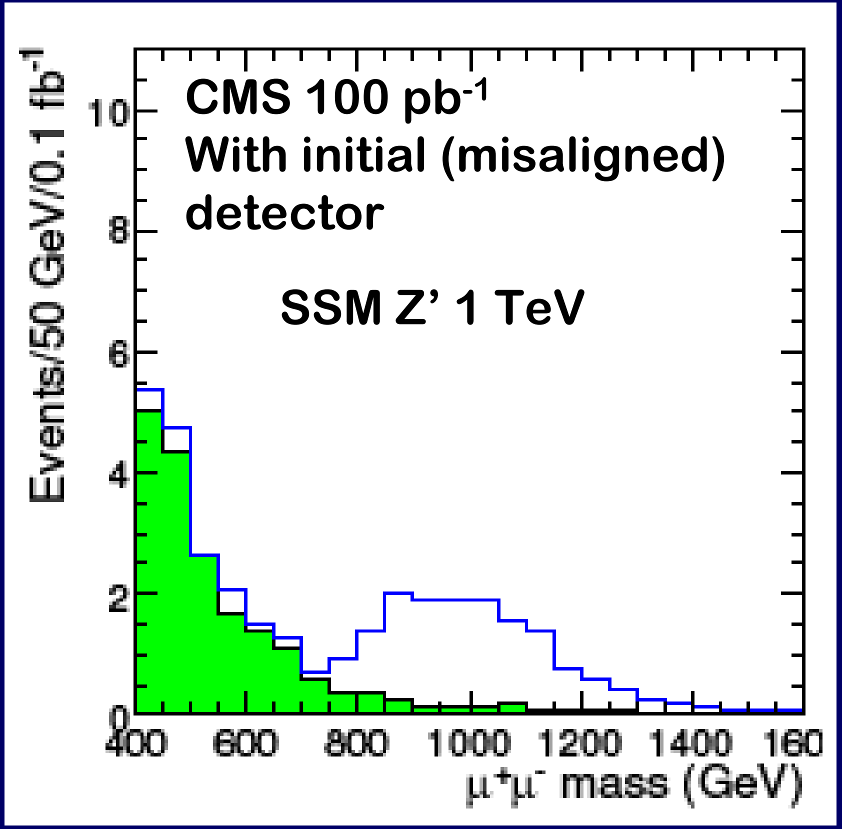
I don't think, all tricks have been played yet..

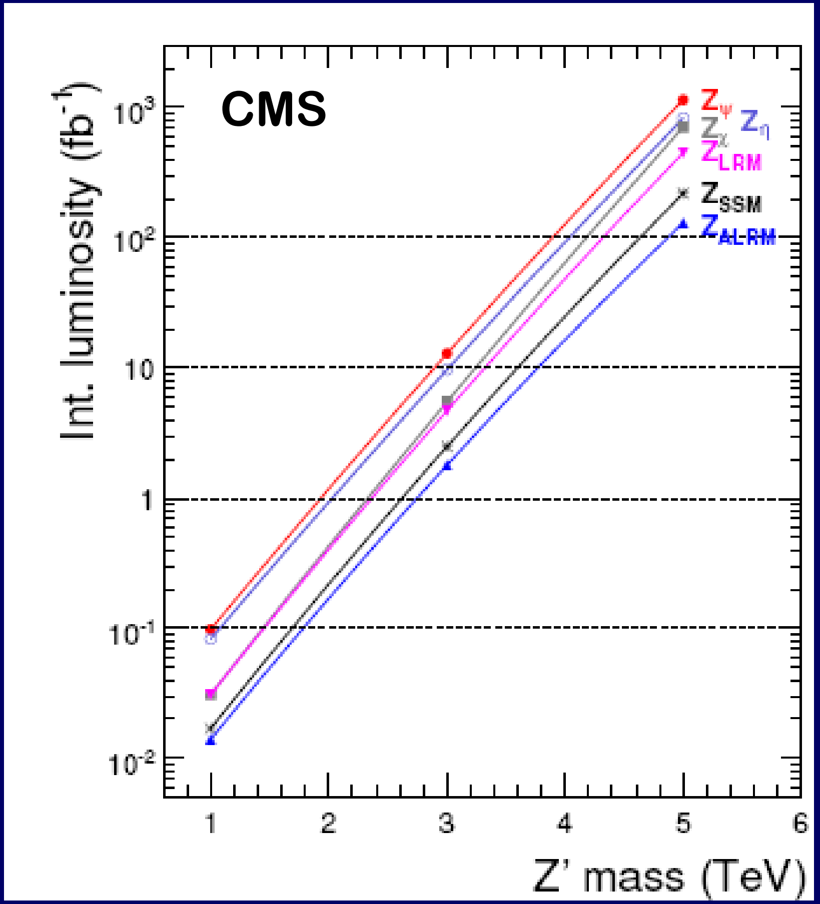
Fully exploit

- correlated p_T spectra of visible objects and MET
- invariant masses
- rates!

Scenario 3: Leptonic Resonances at LHC

can possibly be seen very early…



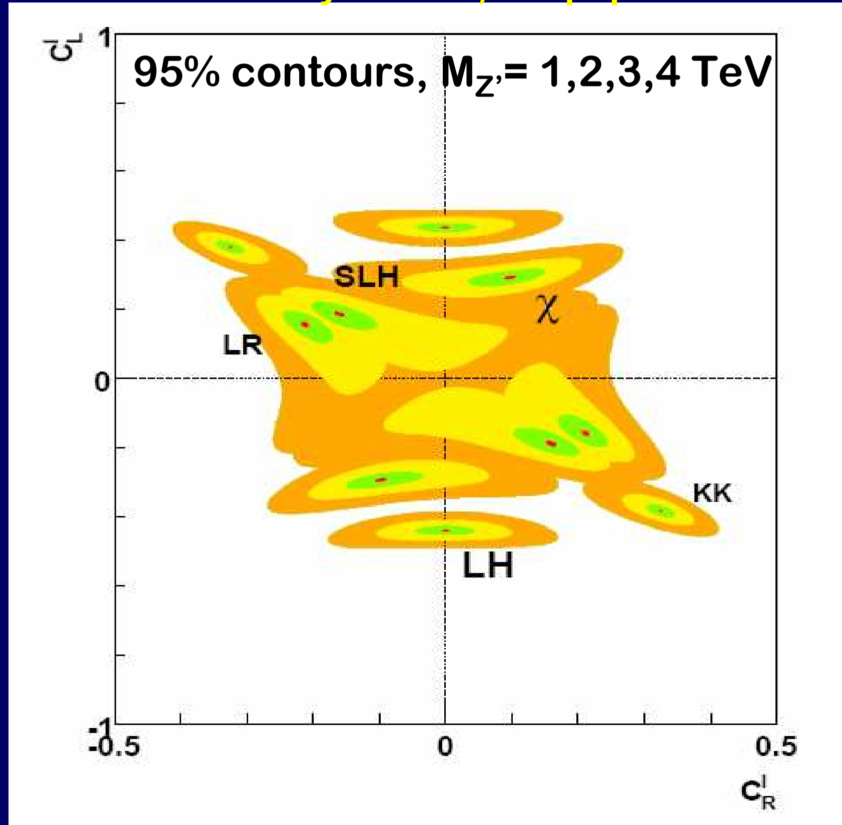


Discovery reach 3-4 TeV with 10 fb^{-1}

Scenario 3: Resonances: ILC consequences

- Not very likely, that a <500 GeV ll-Resonance appears (but ILC would of course study it in s-channel ☺☺)
- A resonance within the direct reach of an upgraded ILC would probably call for a fast upgrade path (still would like to do the precision Higgs (if there) and SM program)
- A resonance beyond the direct ILC reach: ILC+LHC can determine coupling structure from interference with γ/Z exchange to determine its nature

Godfrey et al, hep-ph/0511335



E6 χ model
LR symmetric
Littelest Higgs (LH)
Simplest Little Higgs (SLH)
KK excitations in ED

Conclusions

• ILC (as planned in the RDR) has a solid case for exploring the Terascale

• Joint interpretation of LHC and ILC data can yield additional information

• The LHC Early Phase will be exciting!
(first of all on its own – but also for the ILC…)

• We have to demonstrate that there is indeed a strong case for the ILC in the light of these data: that's no free lunch! (but I'm not nervous…)

• Some possible signals at LHC (light Higgs, SUSY-like signals, leptonic resonances,…) are clear "go ahead" signs for ILC

• Others (e.g. heavier Higgs) need more studies to assess the ILC physics potential within the various physics scenarios

• Optimal ILC run plan/upgrade path have to be inferred from LHC data