ILC Physics Case

From the LHC to a future collider
CERN Theory Institute 2009

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Summary

It is fundamental to complement the results of the LHC with measurements at a linear collider. In the energy range of 0.5 to 1 TeV, the ILC, based on superconducting technology, will provide a unique scientific opportunity at the precision frontier; *there should be a strong well-coordinated European activity, including CERN, through the Global Design Effort, for its design and technical preparation towards the construction decision, to be ready for a new assessment by Council around 2010.*

Unanimously approved by the CERN Council at the special Session held in Lisbon on 14 July 2006

LC <u>physics case</u> is as robust as ever

Comment on different LC technologies in the end

Why e^+e^- ?

Two distinct and complementary strategies for advancing in particle physics with the help of colliders:

High Energy

direct discovery of new phenomena

High Precision

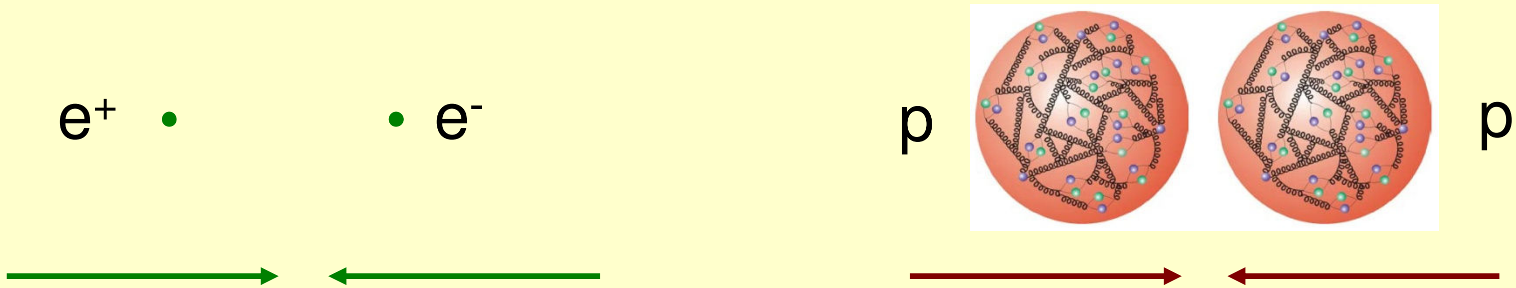
quantum effects of new physics at high energies through precise measurements of phenomena at lower scales

Both strategies have worked well together

→ much more complete understanding than from either one alone

(see LEP+SLC / Tevatron)

Why e^+e^- ?



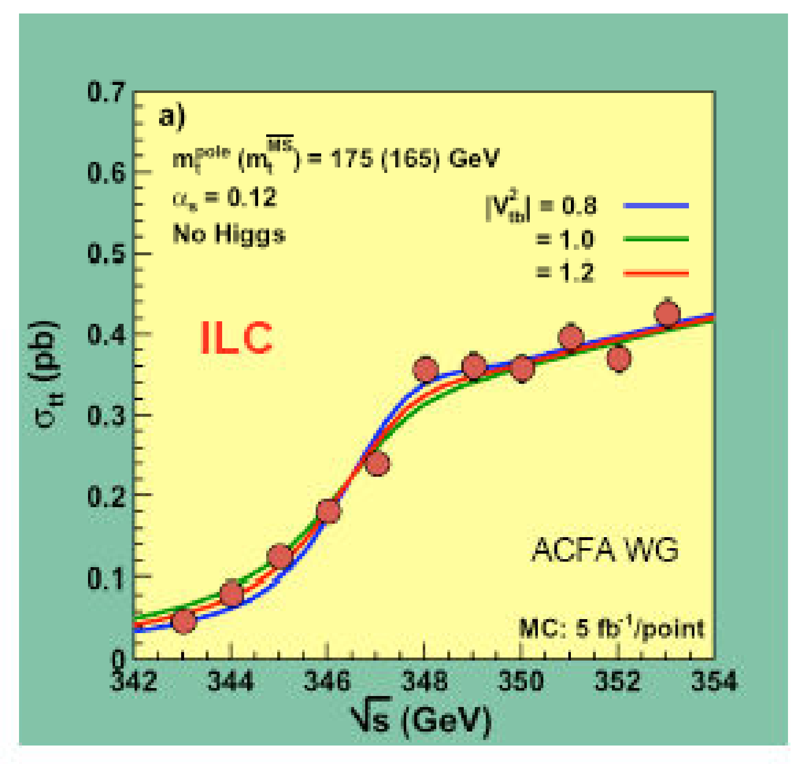
Key features of e^+e^- ("what does not work with hadron collisions")

- precisely defined and known centre-of-mass energy of hard process
  (machine requirement: low beam energy spread, low beamstrahlung)
- tunable centre-of-mass energy
  (machine requirement: flexibility, high luminosity)
- polarized beams
  (machine requirement: do it! – detectors: measure it!)
- clean, fully reconstructable events (also hadronic f.s.)
  (detector requirement: jet (flavour), lepton reconstruction, full hermeticity)
- moderate backgrounds → no trigger → unbiased physics
  (detector requirement)

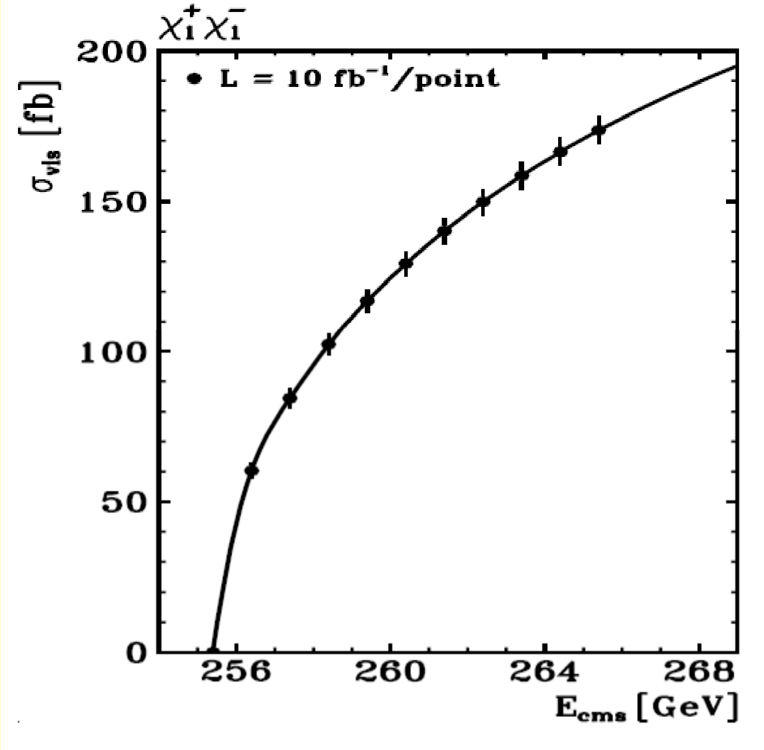
→ Examples

Things we'll never do with a hadron machine:

Ultraprecise mass determinations from threshold scans



Top quark mass with ~100 MeV precision

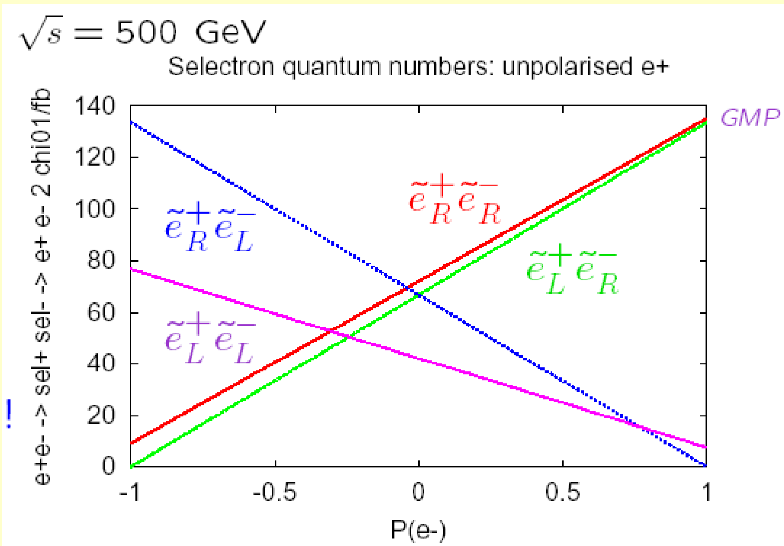


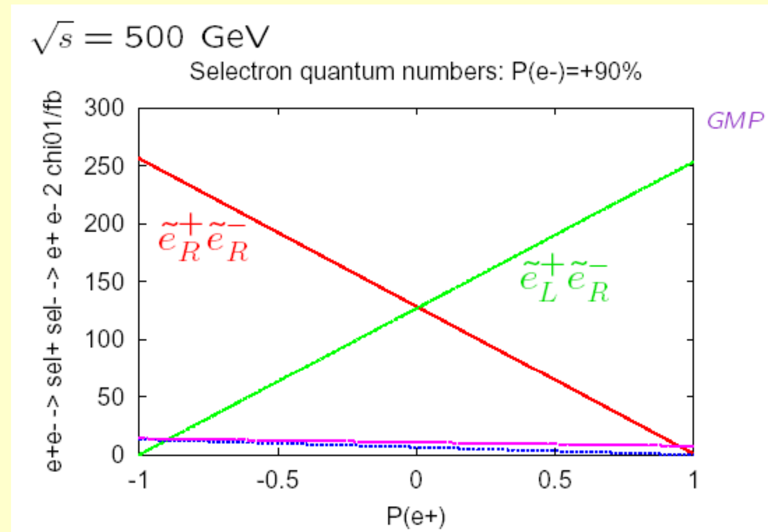
Chargino production at threshold

[Martyn]

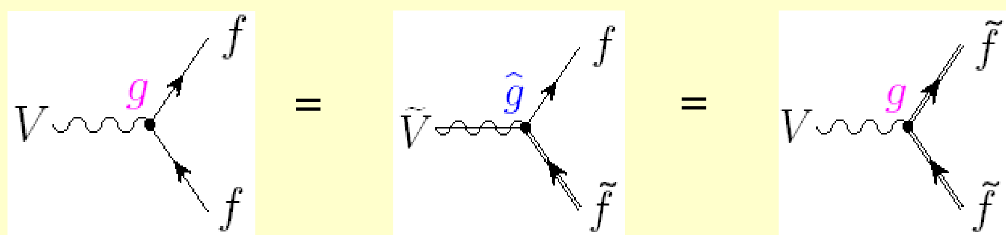
Things we'll never do with a hadron machine:

Directly disentagle chiral structure with polarized beams





Test fundamental SUSY relations



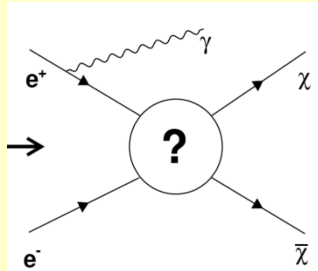
[Moortgat-Pick]

Things we'll never do with a hadron machine:

Reconstruct the invisible

Model-independent WIMP reconstruction:

$$M^2_{recoil} = s - 2\sqrt{s}E_\gamma$$



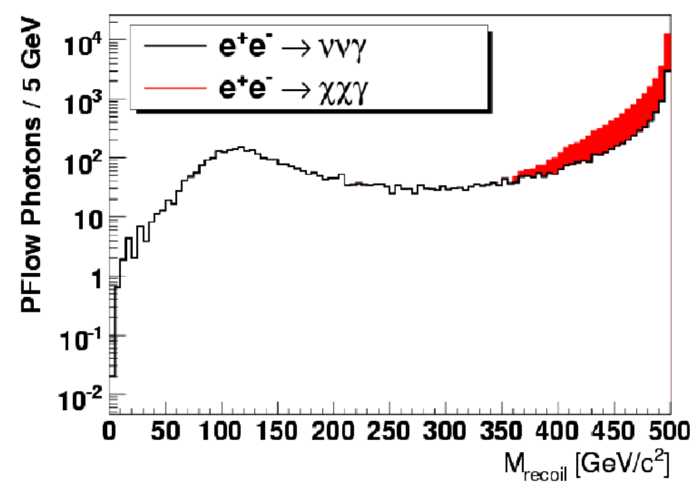
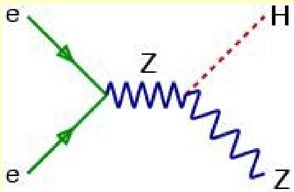


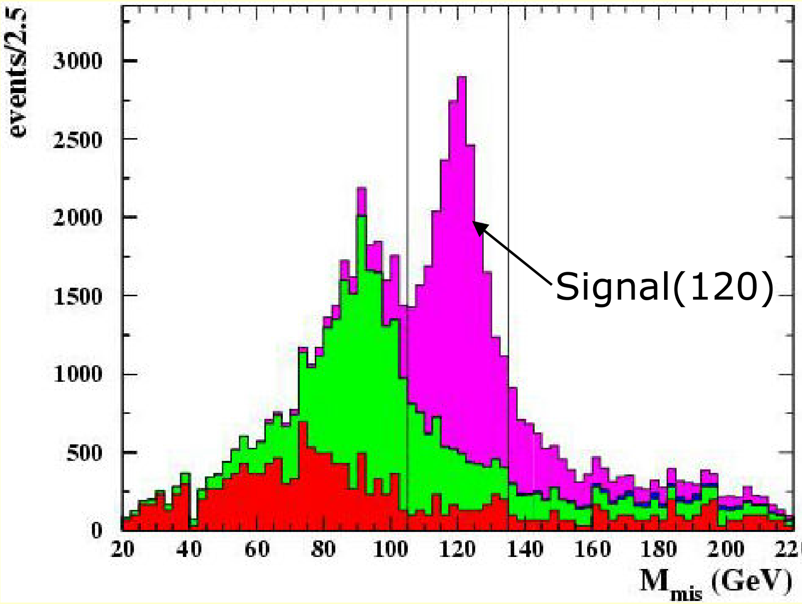
Figure 4: Recoil mass distribution for a 180 GeV Spin-1 WIMP.

[List et al, Birkedal et al]

Mass reconstruction of invisible Higgs:

$$m_H^2 = (p_{visible} - p_{initial})^2$$





[Schumacher]

LC specs – what any LC needs to fulfil (at least)

[http://www.fnal.gov/directorate/icfa/para-Nov20-final.pdf, Heuer et al]

The baseline:

e^+e^- LC operating from M_Z to 500 GeV, tunable energy

beam energy stability and precision: 10^{-3} or better

e^- polarization 80%

at least 500 fb^{-1} in the first 4 years (L ~ $2 \times 10^{34} cm^{-2}s^{-1}$)

Upgrade: to ~ 1 TeV 1 ab^{-1} / 3-4 years

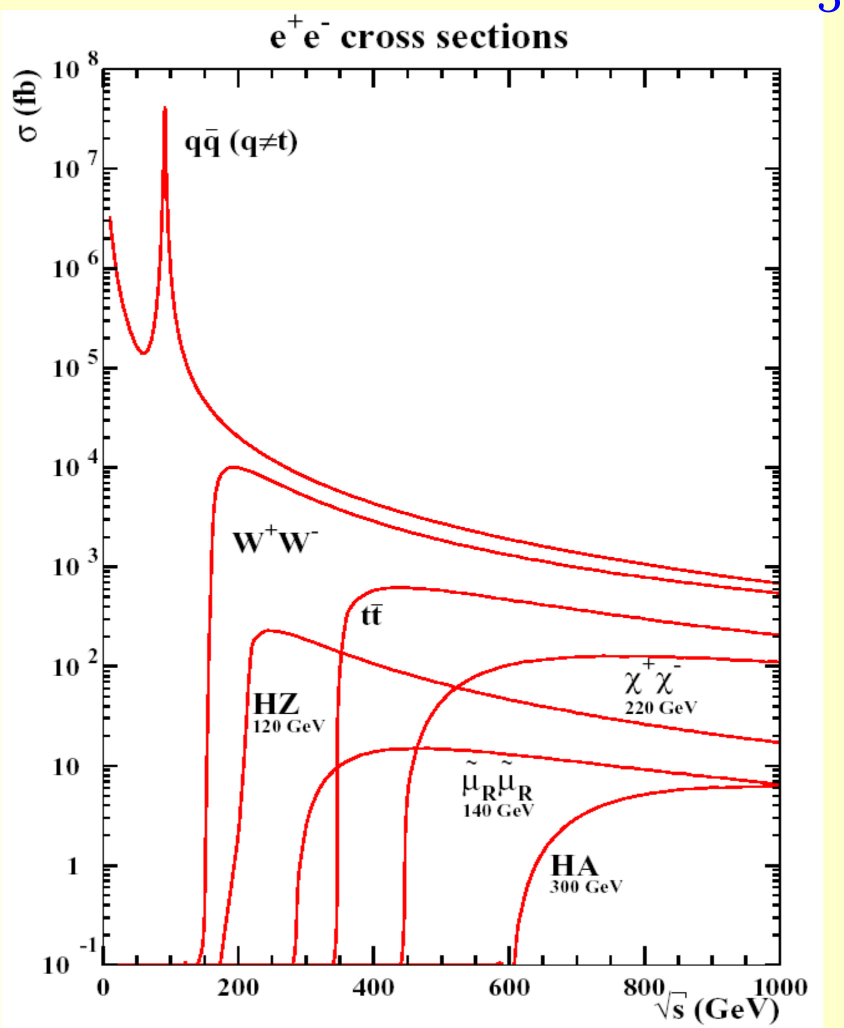
Options :

- e^+ polarization >50%
- GigaZ (high luminosity running at M_Z and $2M_W$)
- $\gamma\gamma$, $e\gamma$, e^-e^- collisions

Choice of options depends on LHC+ILC results (but they are needed!)

LC specs – What any LC needs to fulfil

$$\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-) = (\hbar c)^2 \frac{4\pi\alpha^2}{3s} = \frac{87\ \mathrm{nb}}{s\,(\mathrm{GeV}^2)} = 87\ \mathrm{fb\ at\ 1\ TeV}$$



<u>Remark:</u>

e^+e^- cross section at √s > 500 GeV are small o (10-100 fb), multi-fermion processes smaller

500 fb^{-1} at 500 GeV are „only“

- 40000 HZ events
- 2500 HZ, Z→ll events
- 5000 smoun (m=140) pairs
- 200 HHZ events

By far most measurements at LC will be statistics-limited

Possibly have many thresholds to scan

→ Luminosity requirement of 2×10^{34} is a lower limit!

Higgs physics

LHC trigger:

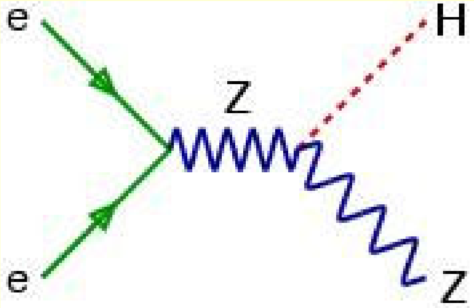
- any discovery of a Higgs-like state
- or absence of Higgs and absence of strong WW interactions (missed it?)

LC objective:

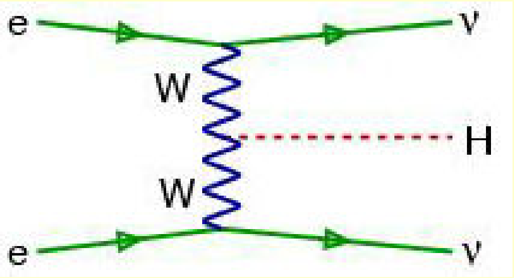
- precise and model-independent measurement of Higgs properties
- discrimination of different Higgs models
- consistency of visible Higgs sector with electro-weak precision measurements (→ Giga-Z + …)

Higgs physics

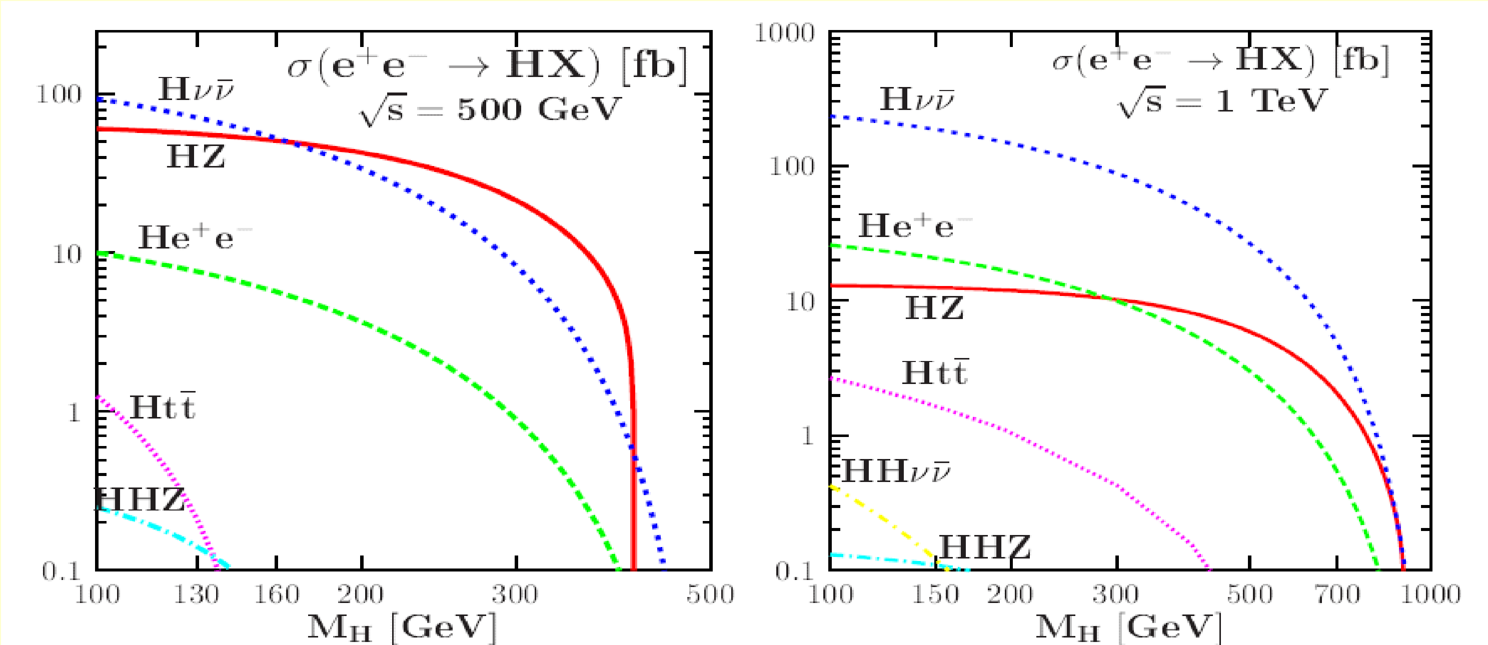
Dominant production processes at LC:



Higgs-strahlung



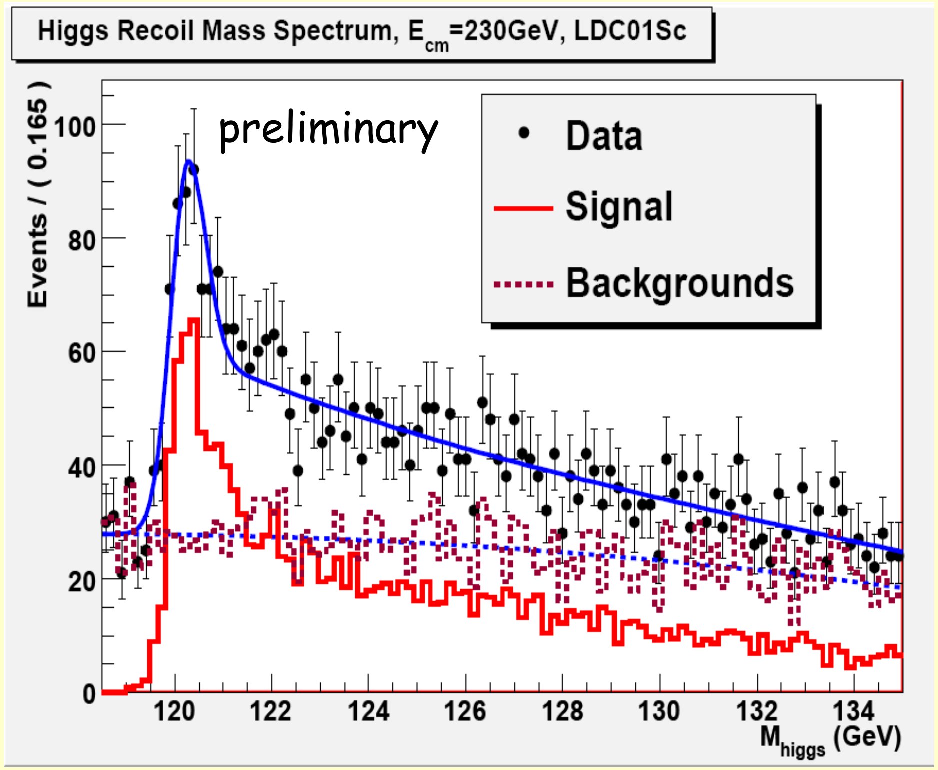
WW fusion



[Djouadi;…]

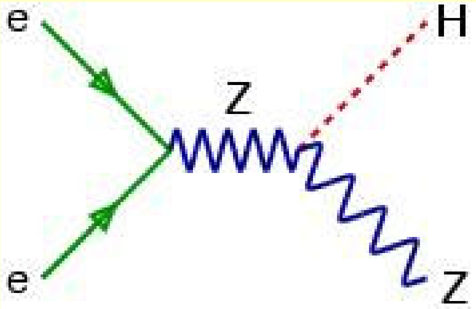
Higgs physics – model independent

Anchor of LC Higgs physics
(why LC Higgs physics is qualitatively different from LHC)



Full detector simulation & Analysis

[Li,Richard,Poeschl,Zhang 09]



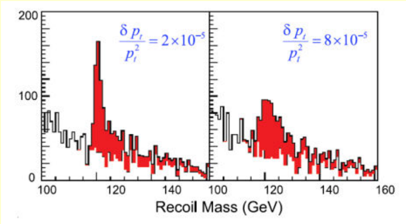
- select di-lepton events consistent with Z→ee/μμ
- calculate recoil mass:

$$m_H^2 = (p_{\ell\ell} - p_{\text{initial}})^2$$

model independent,

decay-mode independent

small note:
tracking resolution counts!

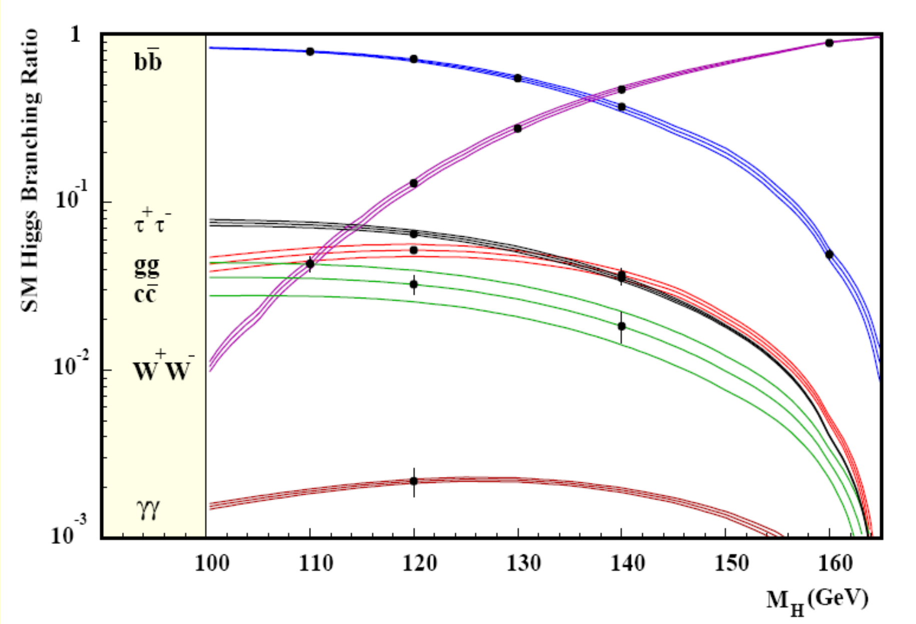


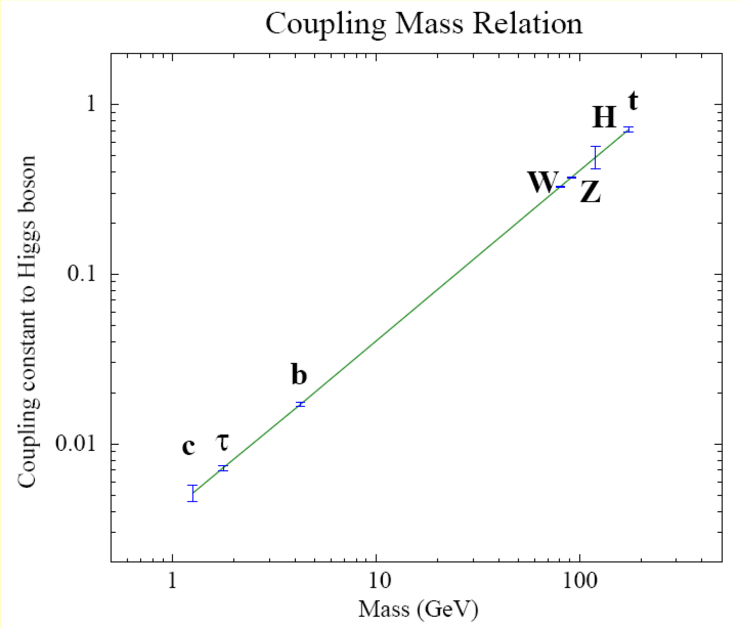
Higgs physics – the light Higgs case (m <160 GeV)

precise measurements of

- couplings to bosons, up- and down-type fermions
- mass, total width
- quantum numbers J^{PC} (incl. sensitivity to CP violation)
- (not so precise but only) measurement of λ_{HHH}

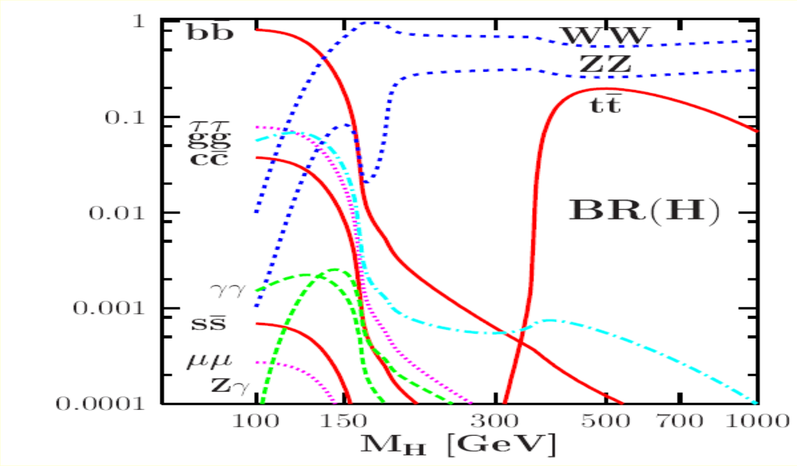
→ K.Mönig´s talk yesterday





[Battaglia]

Comments on m_H = 160 … 200+ GeV



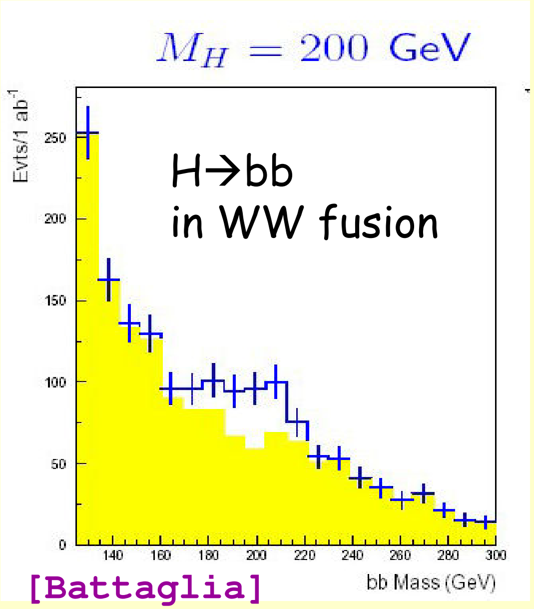
- Higgs phenomenology less rich
- Gauge boson couplings dominant
- LC vital to measure

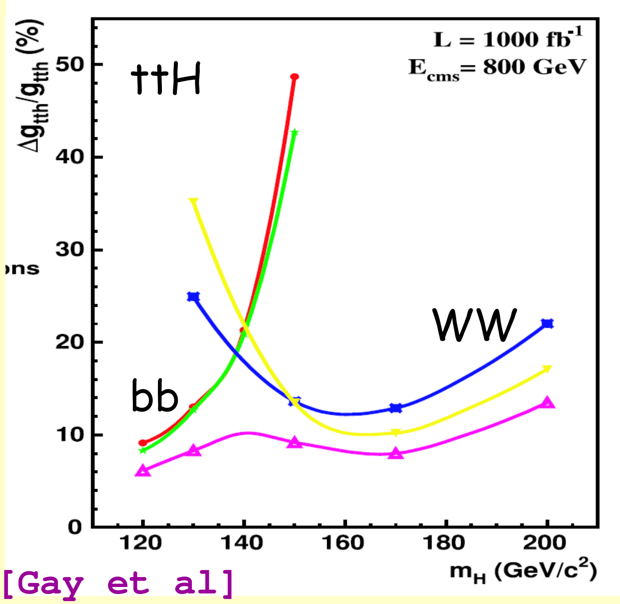
b-Yukawa coupling from H->bb

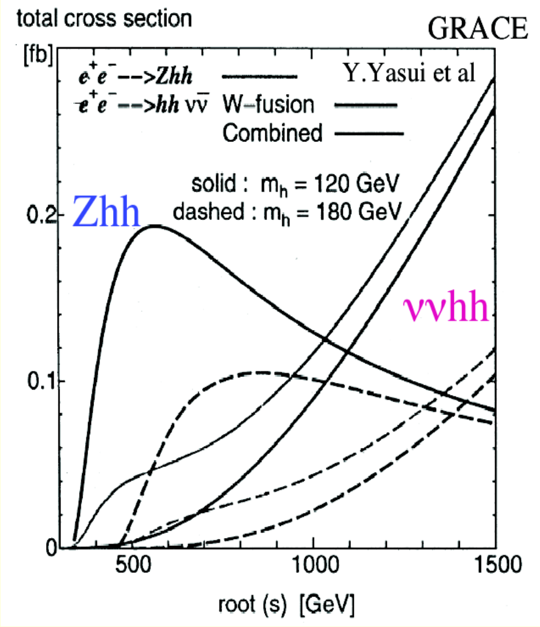
t-Yukawa coupling from ttH -> ttWW

total width from WW→H→WW + HZ→WWZ

selfcoupling? (maybe…)







Higgs physics – what precision is good for

a very recent example: catalog of deviations from SM Higgs partial widths

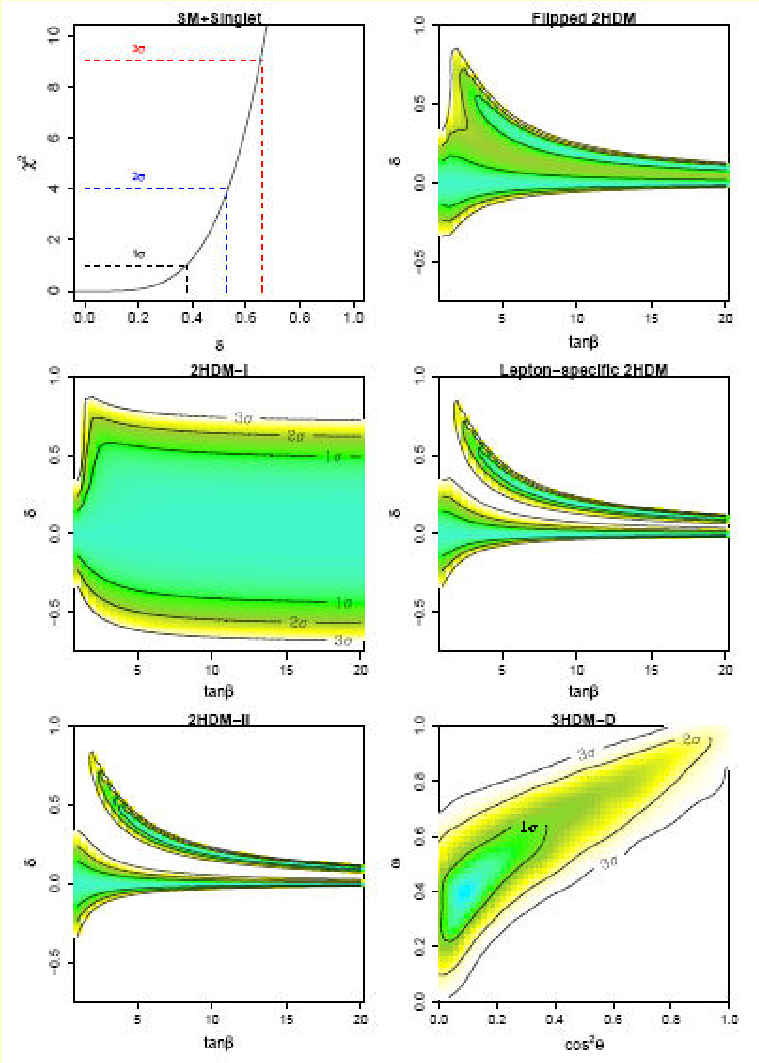
for various types of non-Standard Higgs sectors

Model	Γ^h_W/Γ^{SM}_W	Γ^h_d/Γ^{SM}_d	Γ^h_u/Γ^{SM}_u	$\Gamma^h_\ell/\Gamma^{SM}_\ell$
SM	1	1	1	1
SM+S	$1-\delta^2$	$1-\delta^2$	$1-\delta^2$	$1-\delta^2$
2HDM-I	$1-\delta^2$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$
2HDM-II	$1-\delta^2$	$1-2t_\beta\delta$	$1+2\delta/t_\beta$	$1-2t_\beta\delta$
2HDM-II+S	$1-\delta^2-\epsilon^2$	$1-2t_\beta\delta-\epsilon^2$	$1+2\delta/t_\beta-\epsilon^2$	$1-2t_\beta\delta-\epsilon^2$
2HDM-II+D	$1-\delta^2$	$1-2\delta(s_\gamma t_\beta/c_\Omega+c_\gamma t_\Omega)$	$1+2\delta(s_\gamma/c_\Omega t_\beta-c_\gamma t_\Omega)$	$1-2\delta(s_\gamma t_\beta/c_\Omega+c_\gamma t_\Omega)$
Flipped 2HDM	$1-\delta^2$	$1-2t_\beta\delta$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$
Lepton-specific 2HDM	$1-\delta^2$	$1+2\delta/t_\beta$	$1+2\delta/t_\beta$	$1-2t_\beta\delta$
MSSM	$1-\delta^2$	$1-2t'_\beta\delta$	$1+2\delta/t_\beta$	$1-2t_\beta\delta$
3HDM-D	$1-\delta^2$	$1-2\delta(s_\gamma t_\beta/c_\Omega+c_\gamma t_\Omega)$	$1+2\delta(s_\gamma/c_\Omega t_\beta-c_\gamma t_\Omega)$	$1+2\delta c_\gamma/t_\Omega$

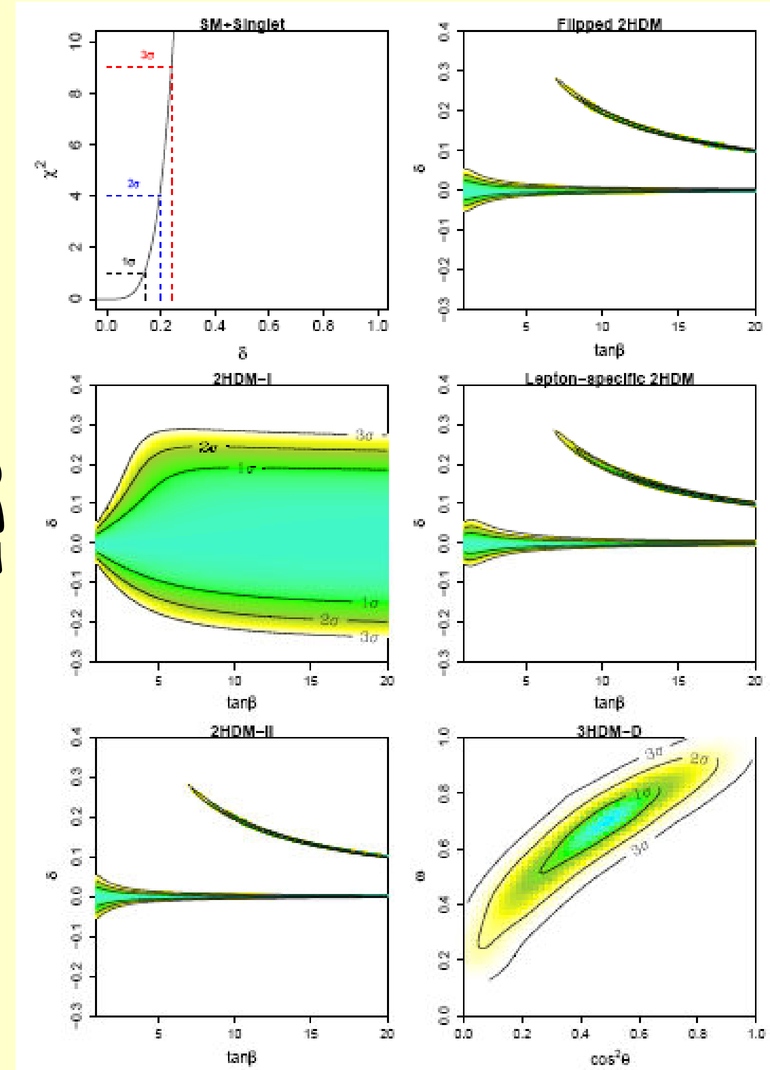
[Barger,Logan,Shaughnessy arXiv:0902.0170]

Higgs physics – what precision is good for

LHC



→ ILC



[Barger, Logan, Shaughnessy arXiv:0902.0170]

note different scale on most plots

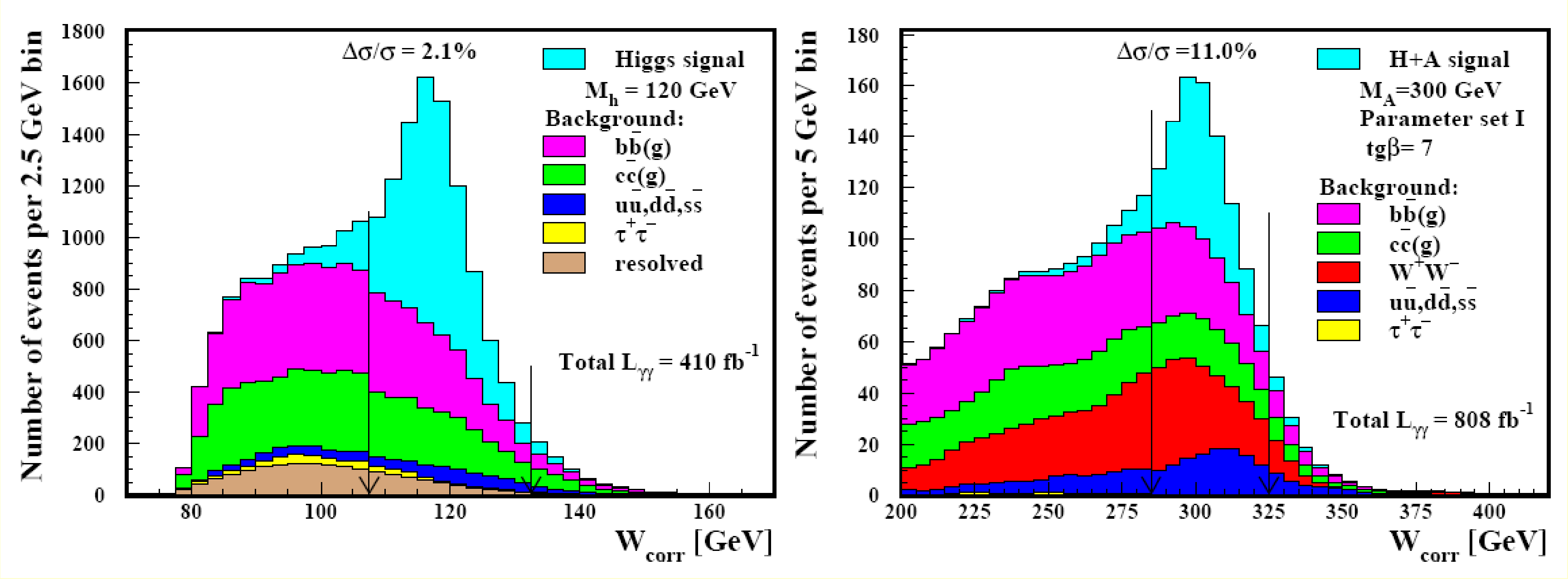
Higgs physics at a Photon Collider

unique opportunity to measure the Hγγ coupling

- sensitive to anything that´s charged and massive in the loop…

- adds to LC (e^+e^-) case, completes picture

- unique: single production of heavy H,A bosons + disentangle them



[Niezurawski,Zarnecki,Krawczyk]

Supersymmetry (+ related pheno)

LHC trigger:

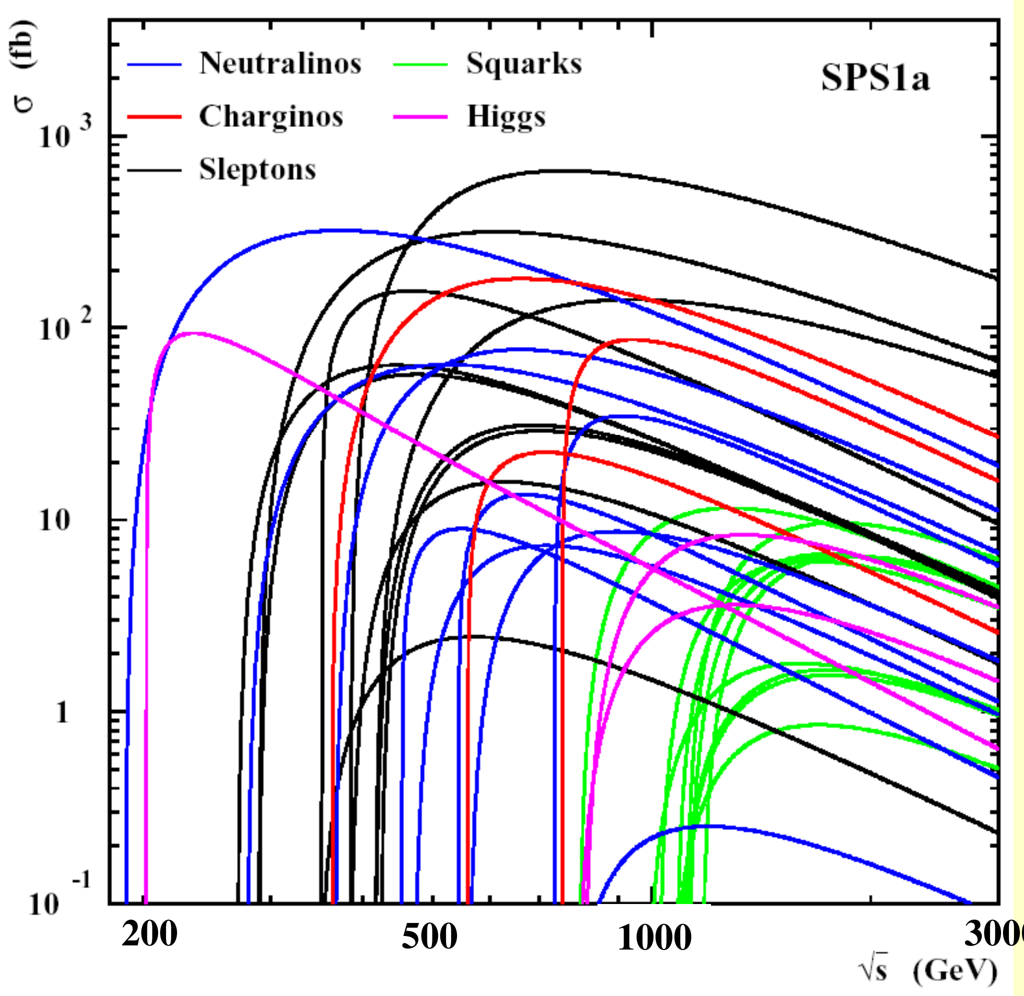
- evidence for excess of missing-E_T events consistent with existence of new m ~ $\sqrt{s_{LC}}/2$ particles
- or observation (mass reconstruction) of RPV SUSY particles at m ~ $\sqrt{s_{LC}}/2$

LC objective:

- precise and model-independent measurement of properties of kin. accessible sparticles
- test of fundamental SUSY relations
- together with LHC data pin-down model of SUSY breaking (determine pattern of high-scale unification)
- determine properties of dark matter candidate

Supersymmetry

may well be fun at LC in spite of all „Unkenrufe"



cross sections in the

10 – 1000 fb range

o(10^3 – 10^5) events

to disentangle this 'chaos'

the various LC options,

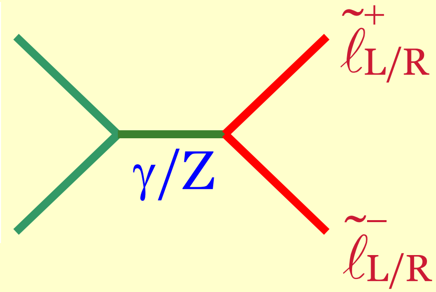
in particular are vital!

- tunable √s
- tunable beam polarisation
- high luminostiy!

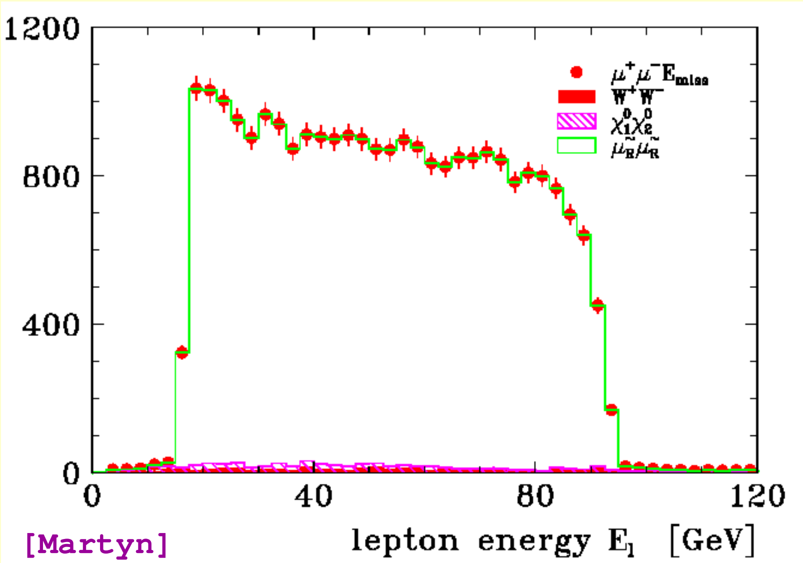
Supersymmetry - Sleptons

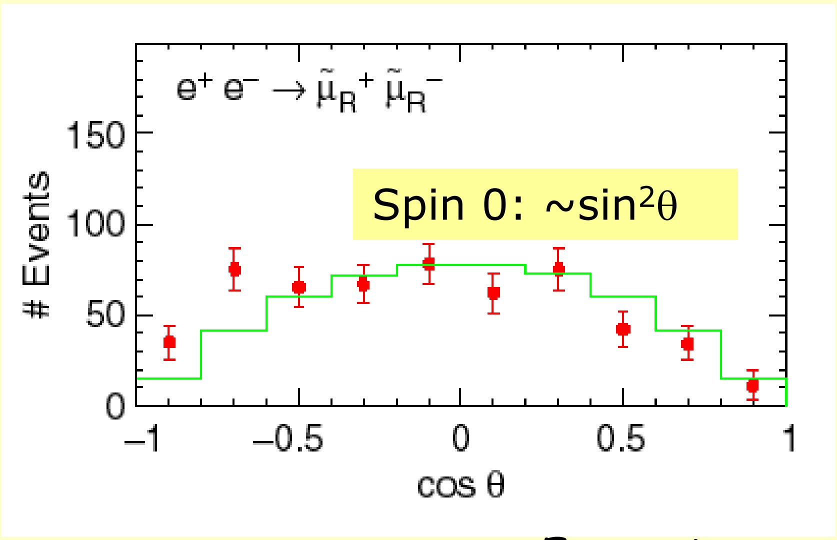
Pair-production

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



Examples:





Easy spin measurement

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

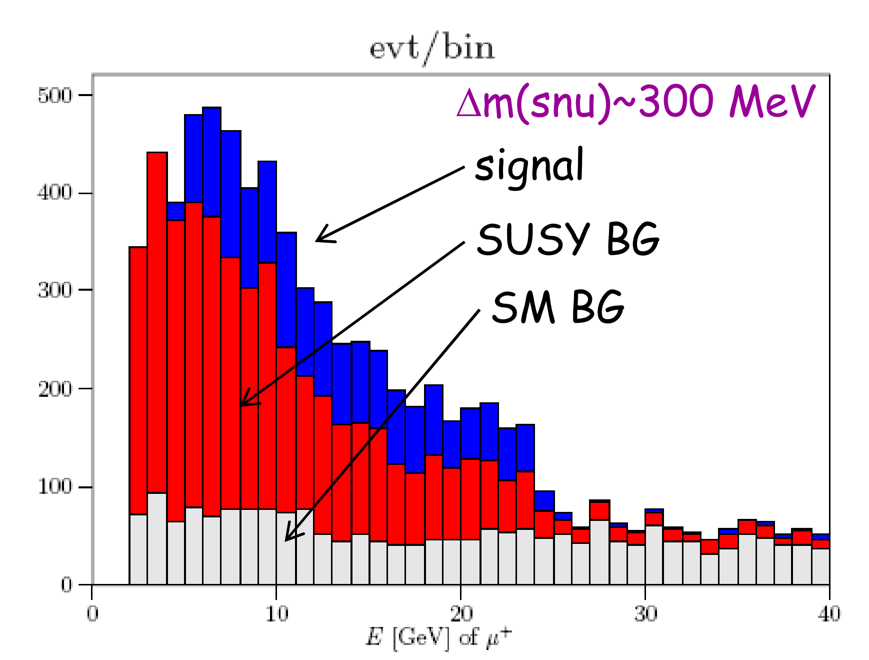
$$
\begin{aligned}
m_{\tilde{l}} &= \frac{\sqrt{s}}{E_- + E_+}\sqrt{E_- E_+} \\
m_{\tilde{\chi}} &= m_{\tilde{l}}\sqrt{1 - \frac{E_- + E_+}{\sqrt{s}/2}}
\end{aligned}
$$

Supersymmetry

More difficult things are possible:

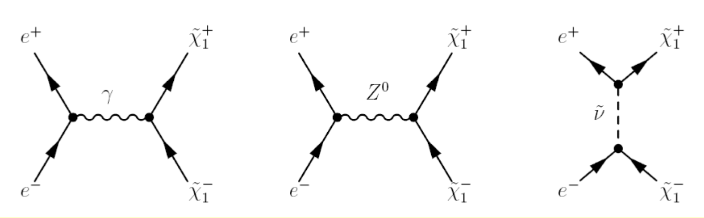
Example: Sneutrinos from Chargino decay

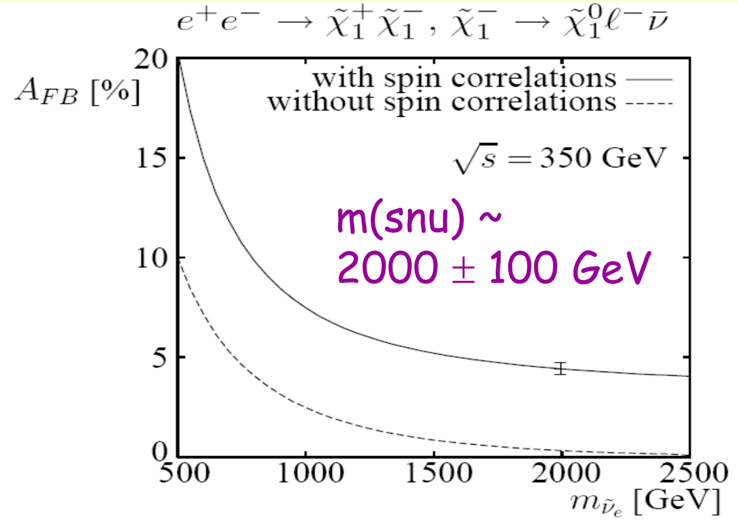
$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\nu}_e^* e^- \tilde{\nu}_\mu \mu^+ \rightarrow e^- \mu^+ \bar{\nu}_e \nu_\mu \tilde{\chi}_1^0 \tilde{\chi}_1^0$$



[Kalinowski,Kilian,Reuter,Robens,Rolbiecki 09]

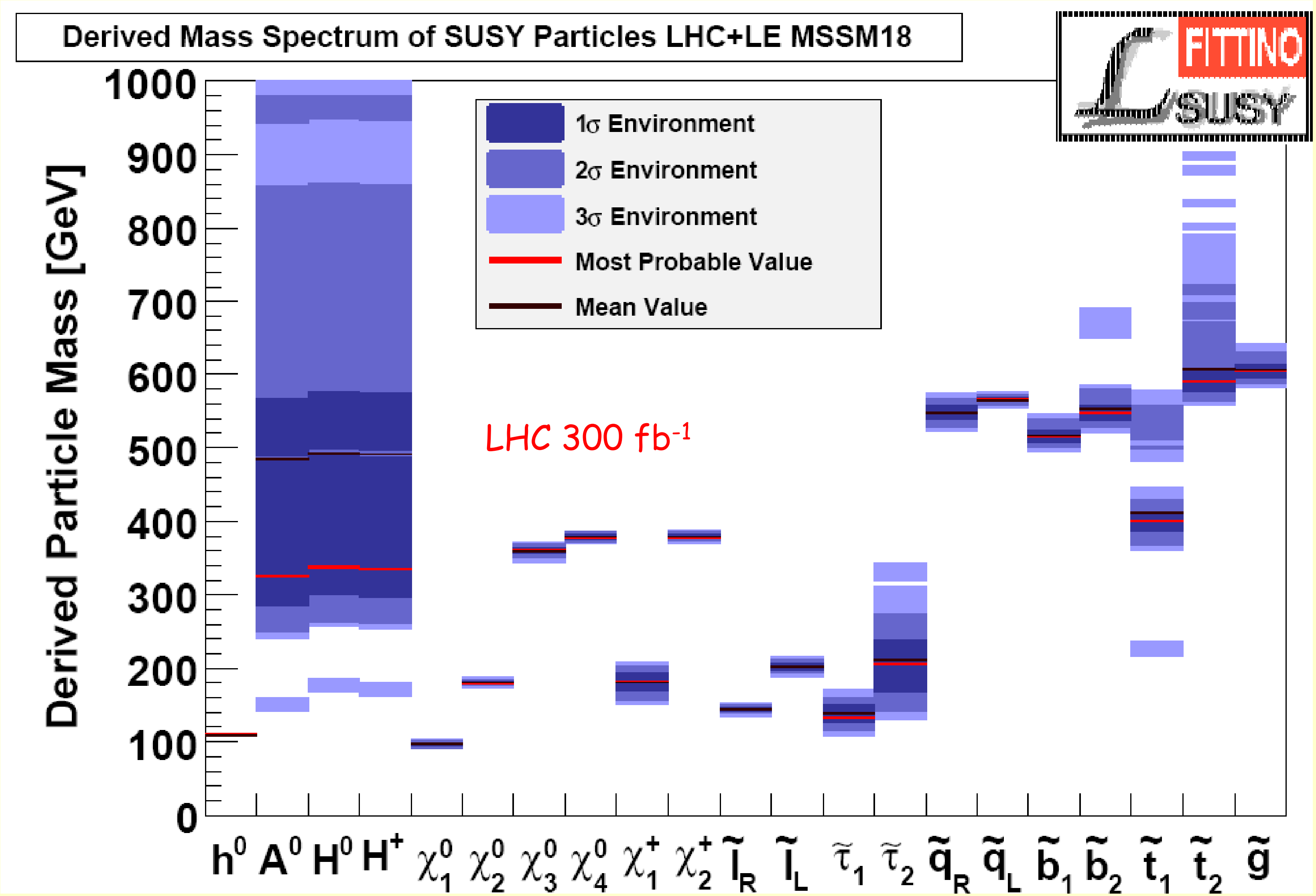
Example: sensitivity to very heavy sneutrinos in t-channel exchange of chargino production





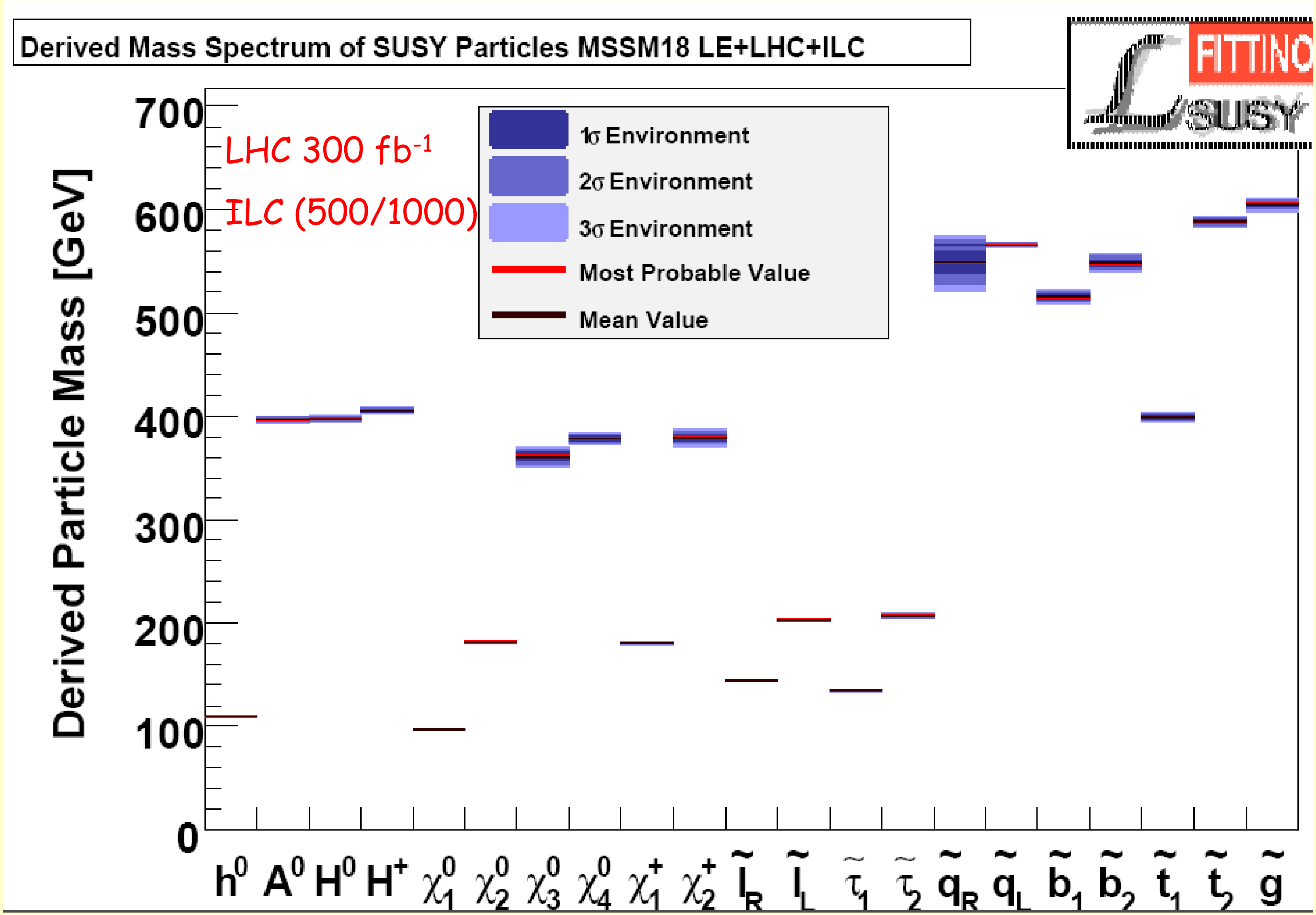
[Kalinowski,Moorgat-Pick,Rolbiecki, Stirling,KD 06]

Supersymmetry



[Bechtle,Wienemann,Uhlenbrock,KD 09]

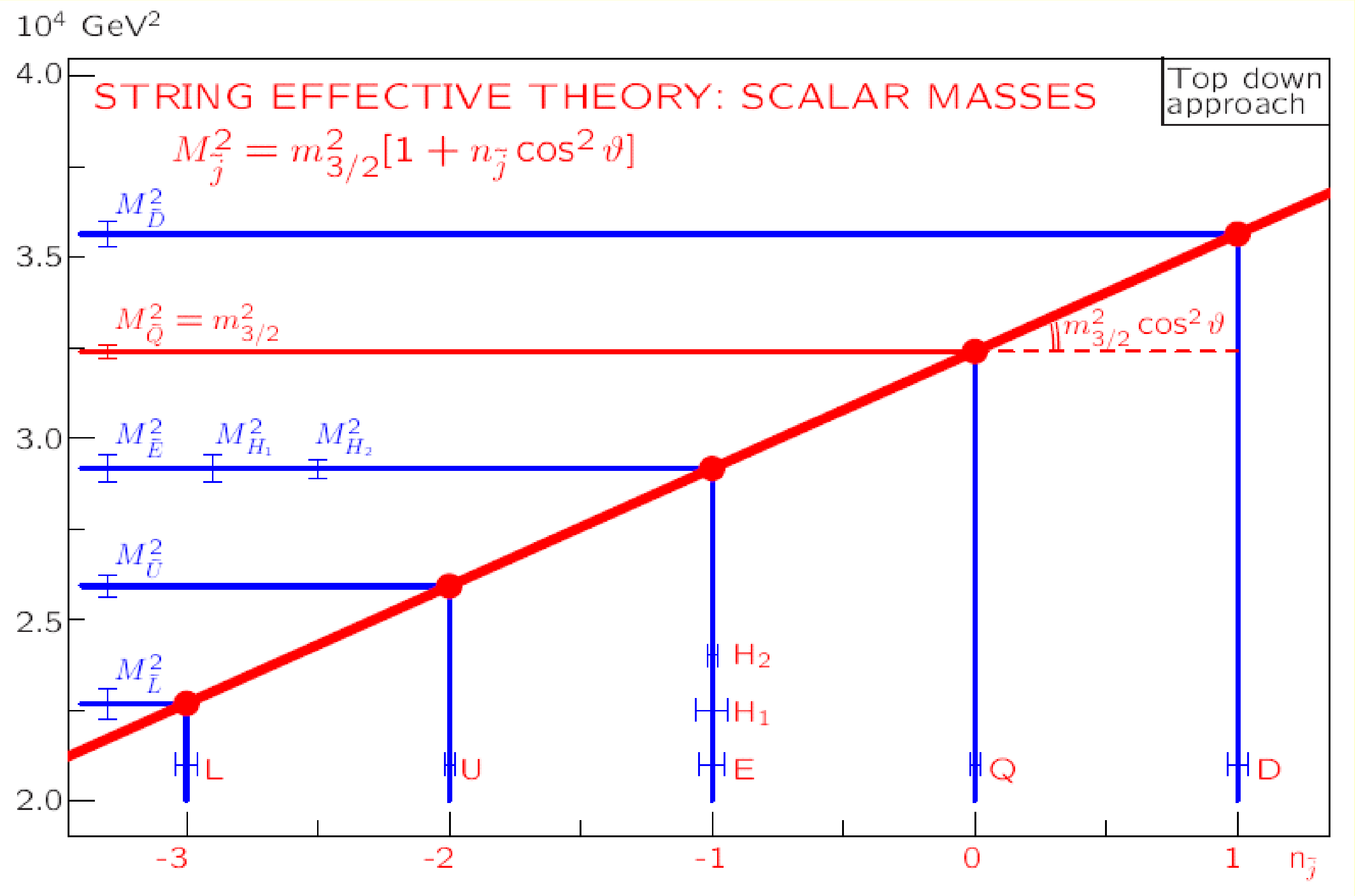
Supersymmetry



[Bechtle,Wienemann,Uhlenbrock,KD 09]

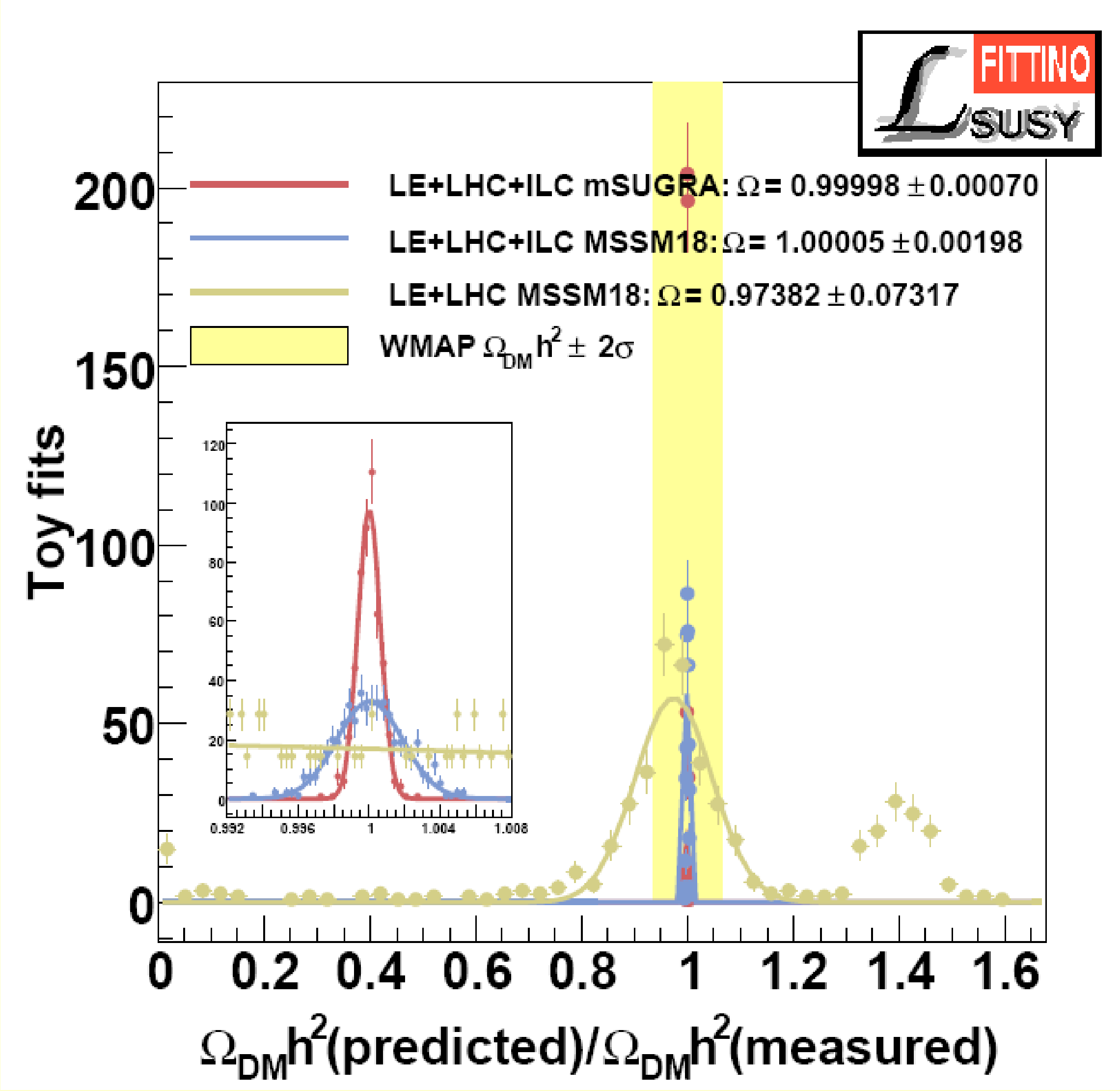
Supersymmetry – motivation for precision I

Example of distinct non-unification of mass parameters at high scale



[Blair, Porod, Zerwas]

Supersymmetry – motivation for precision



Precise prediction

for DM density

Gauge Boson Couplings

LHC trigger:

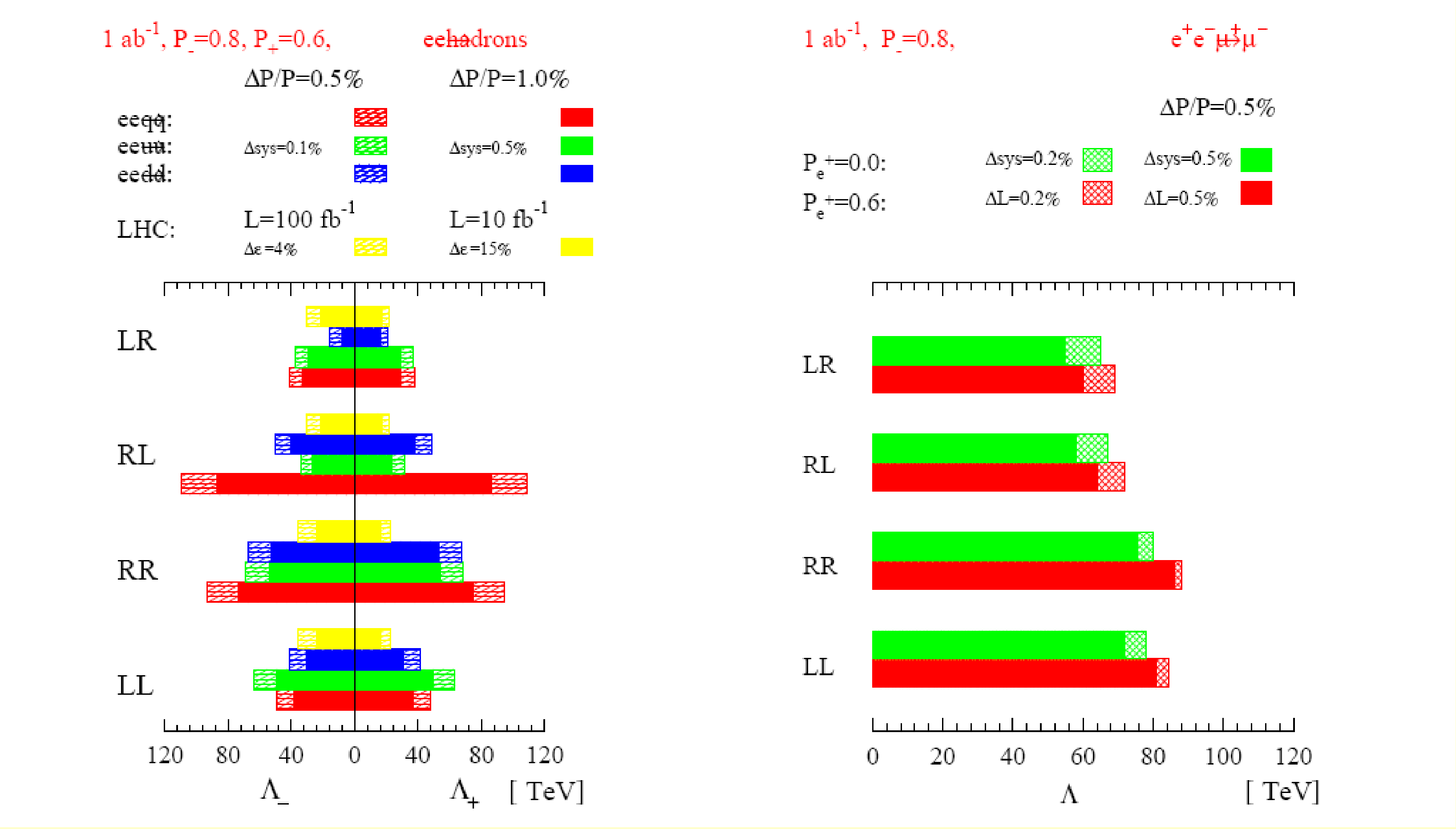
- discovery of heavy gauge boson (m <~ 5 TeV)
- or absence of Higgs boson / evidence for strong WW interactions
- or most other „surprises"

LC objective:

- (contribute to) determination of the properties of the new states / new physics through loop-level tests of SM processes at $\sqrt{s}_{max}$ and at $\sqrt{s} = M_Z$
- shine some light into the deep-multi-TeV region

Gauge Boson – Fermion - Couplings

Example: Contact Interactions:

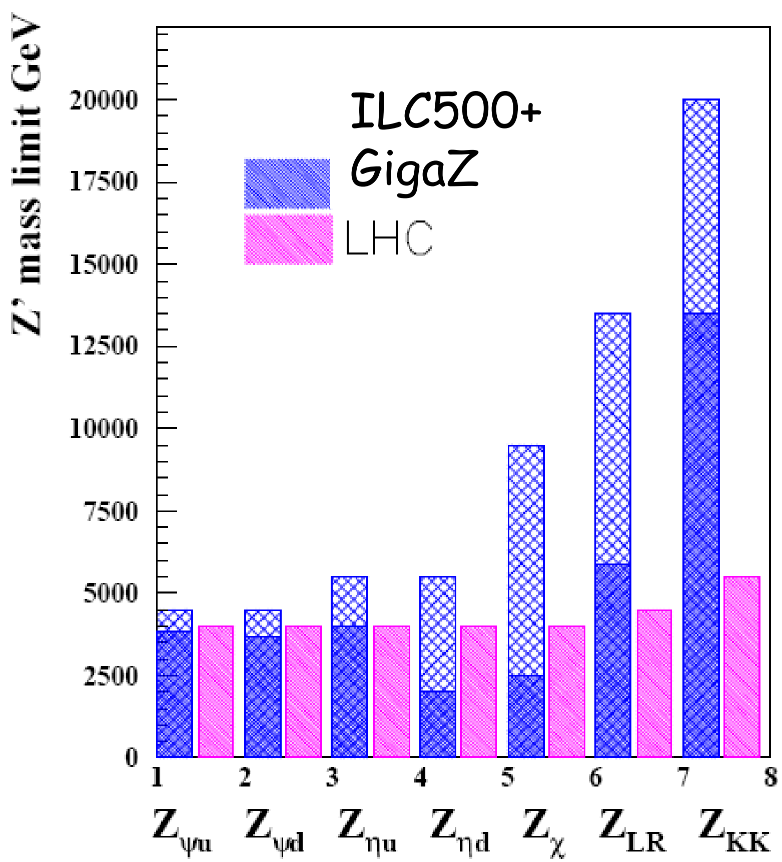


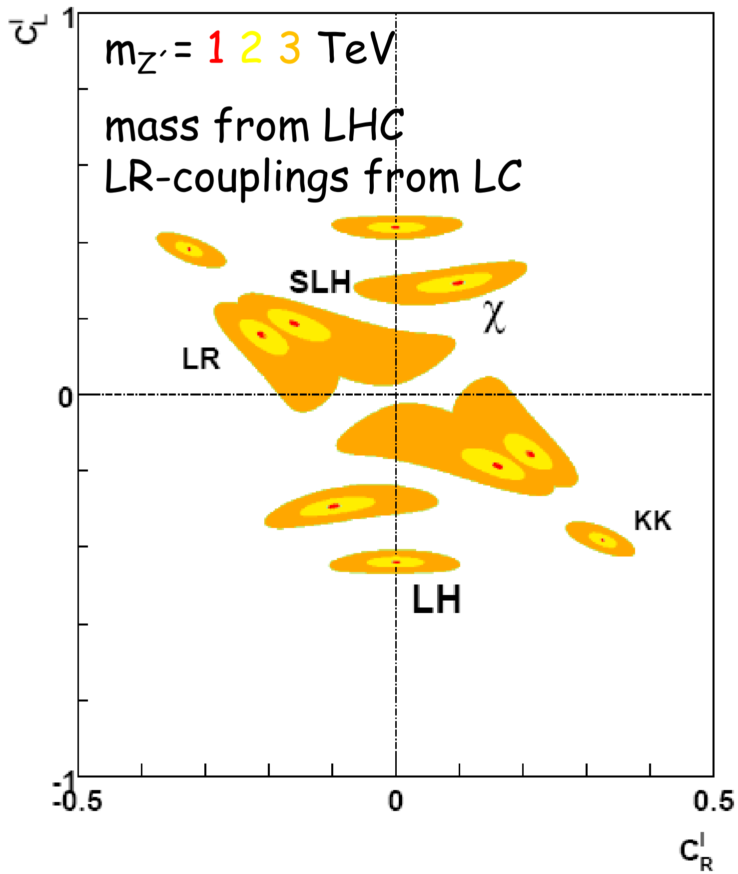
[S.Riemann]

Sensitivity to Heavy Gauge Bosons

500 GeV, 1ab^{-1}

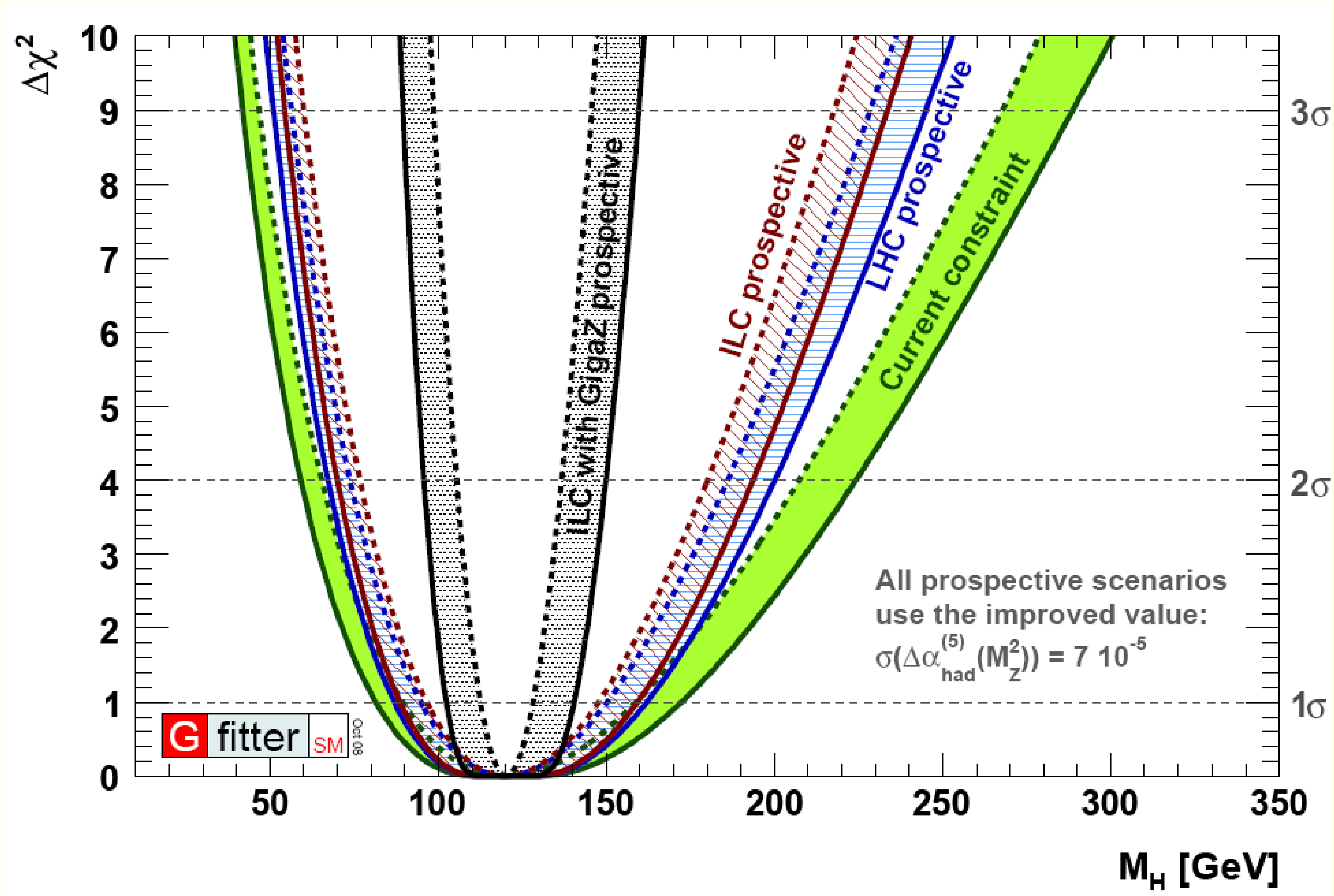
Virtual effects from Z′ in $e^+e^- \to f\bar{f}$
from interference (at high $\sqrt{s}$) and mixing (at m_Z)





[S.Riemann; Richard; Godfrey et al]

Electro-weak fit with Giga-Z



[Flächer, Goebel, Haller, Höcker, Mönig, Stelzer 08]

Top Quark Physics

LHC trigger:

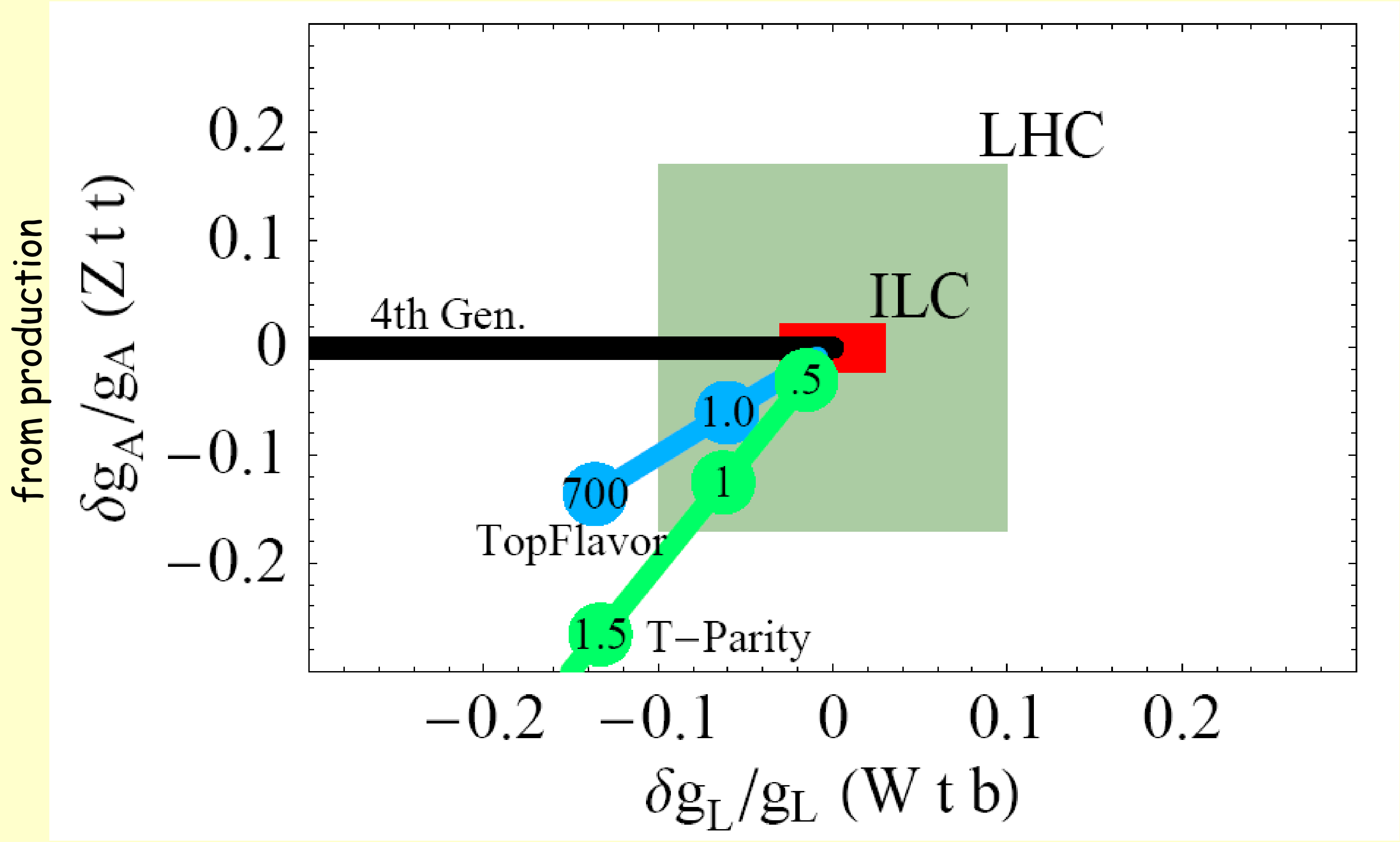
- none

LC objective:

- top mass determination factor 10 better than LHC/Tevatron (→ strong m_t dependence of many BSM predictions)
- electro-weak couplings of t (complementary to LHC)
- precise study of the ttg system (precise high-E QCD tests)

Top Quark Physics

Example: couplings to EW gauge bosons:



from decay

[Batra,Tait 06]

Alternatives

LHC trigger:

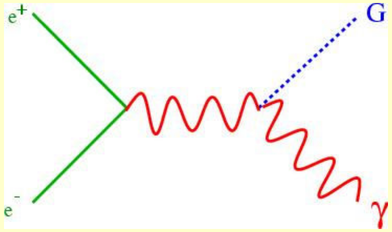
- signal of extra dimensions
- or signal of alternative EWSB (Little H, Higgsless, strong EWSB)
- or anything else (put your favourite discovery here…)

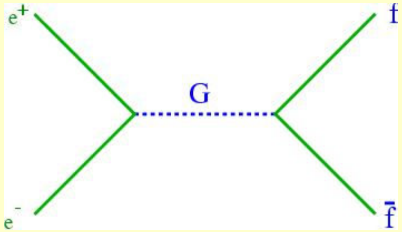
LC objective:

- study properties of new states if kinematically in reach
- study loop-effects on SM processes
  (indirect reach into deep-multi-TeV region)

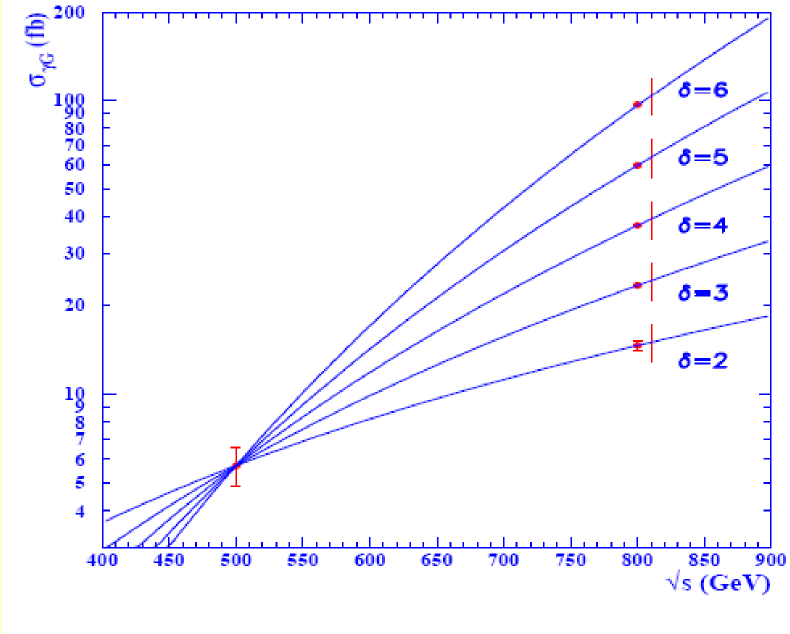
Alternatives

Example: Large Extra Dimensions (ADD)

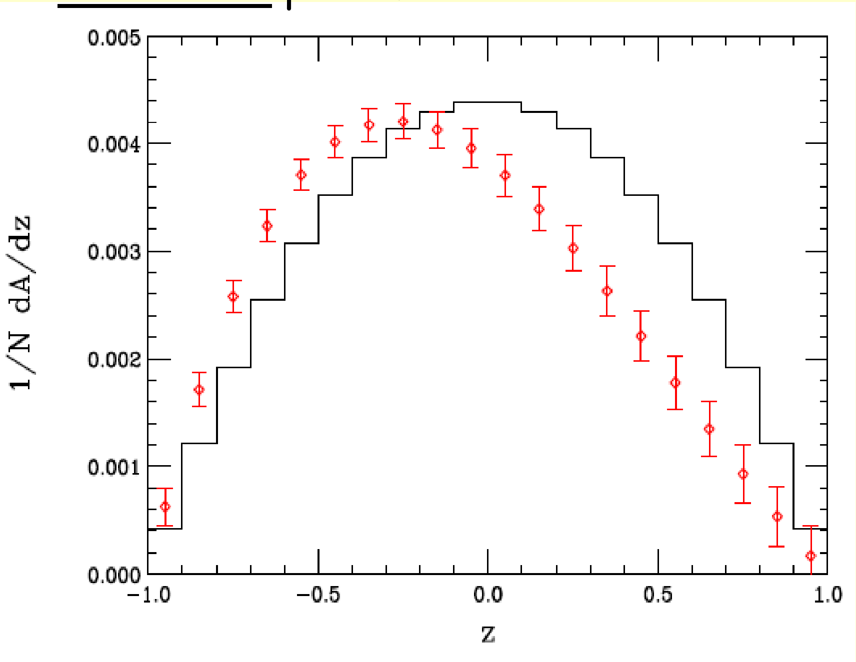




Real graviton emission



Azimuthal asymmetry with <u>transverse</u> polarization

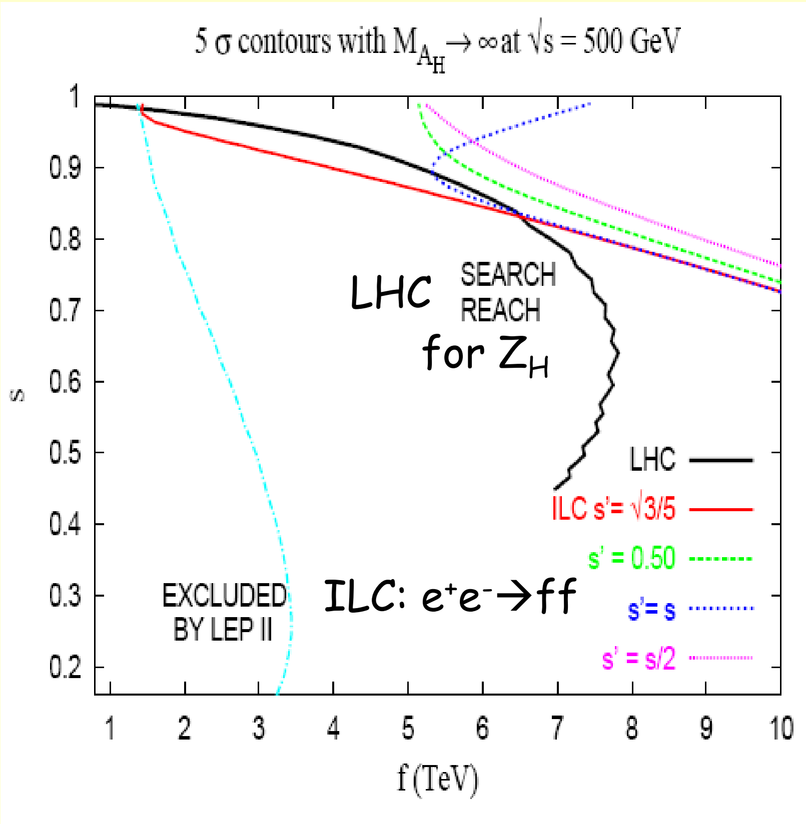


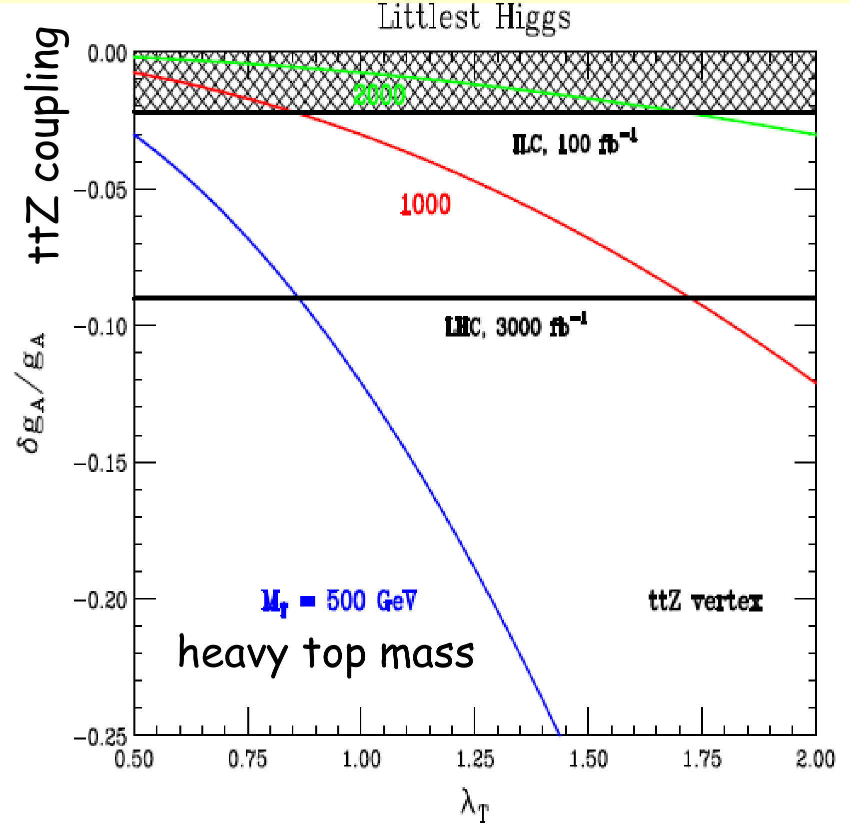
[Wilson; Rizzo]

[Rizzo]

Alternatives

Example: Little Higgs





$$m_T/f = (\lambda_t^2 + \lambda_T^2)/\lambda_T$$

f: scale of global symmetry breaking
s,s´: mixing angles of gauge symmetry breaking

[Conley,Hewett,Le] [Berger,Perelstein,Petriello]

Does LC Technology matter?

The 9th ICFA Seminar

X-band high-gradient and CLIC R&D for future colliders

R. Corsini, 30-10-08

500 GeV comparison Table

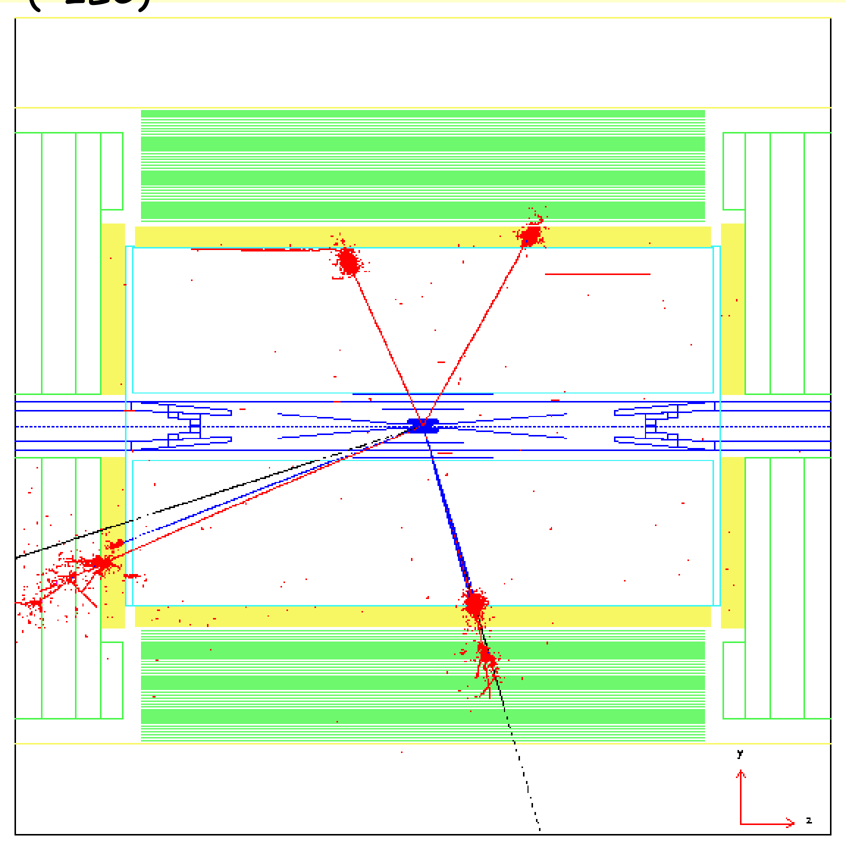
http://clic-meeting.web.cern.ch/clic-meeting/ComparisonTable.html

Center-of-mass energy	NLC 500 GeV	ILC 500 GeV	CLIC 500 GeV Conservative	CLIC 500 GeV Nominal
Total (Peak 1%) luminosity	$2.0(1.3)\cdot10^{34}$	$2.0(1.5)\cdot10^{34}$	$0.9(0.6)\cdot10^{34}$	$2.3(1.4)\cdot10^{34}$
Repetition rate (Hz)	120	5	50	
Loaded accel. gradient MV/m	50	33.5	80	
Main linac RF frequency GHz	11.4	1.3 (SC)	12	
Bunch charge10^9	7.5	20	6.8	
Bunch separation ns	1.4	176	0.5	
Beam pulse duration (ns)	400	1000	177	
Beam power/linac (MWatts)	6.9	10.2	4.9	
Hor./vert. norm. emitt $(10^{-6}/10^{-9})$	3.6/40	10/40	3 / 40	2.4 / 25
Hor/Vert FF focusing (mm)	8/0.11	20/0.4	10/0.4	8/0.1
Hor./vert. IP beam size (nm)	243/3	640/5.7	248 / 5.7	202/ 2.3
Soft Hadronic event at IP	0.10	0.12	0.07	0.19
Coherent pairs/crossing at IP	10?	10?	10	100
BDS length (km)	3.5 (1 TeV)	2.23 (1 TeV)	1.87	
Total site length (km)	18	31	13.0	
Wall plug to beam transfer eff.	7.1%	9.4%	7.5%	
Total power consumption MW	195	216	129.4	

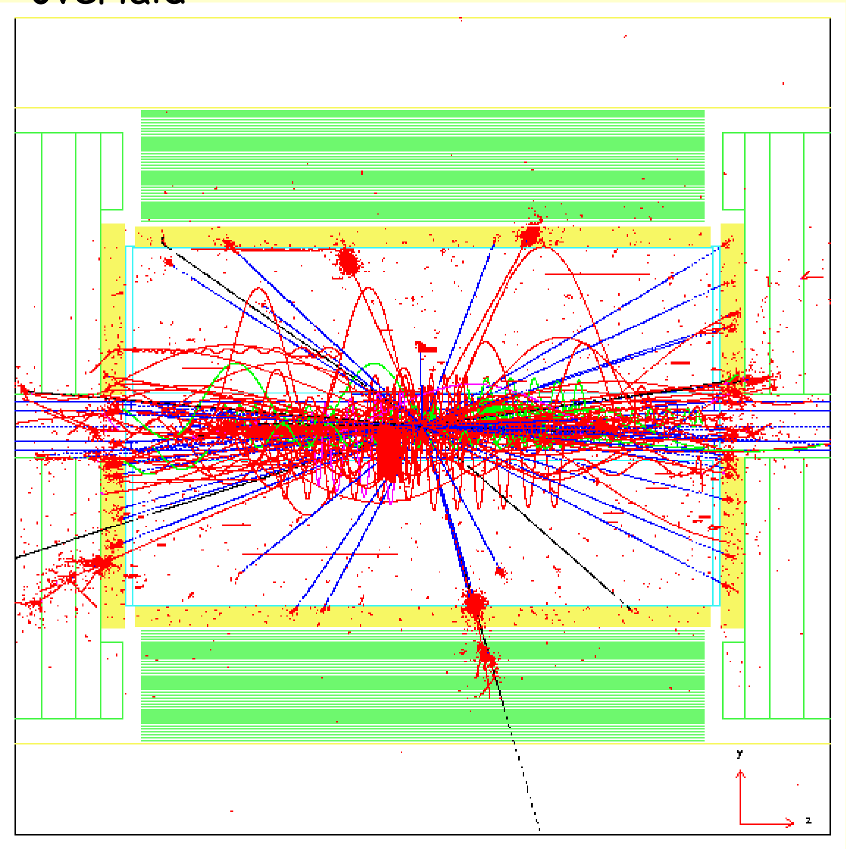
Does LC Technology matter?

HZ → ττee event

Without soft hadronic events overlaid (=ILC)



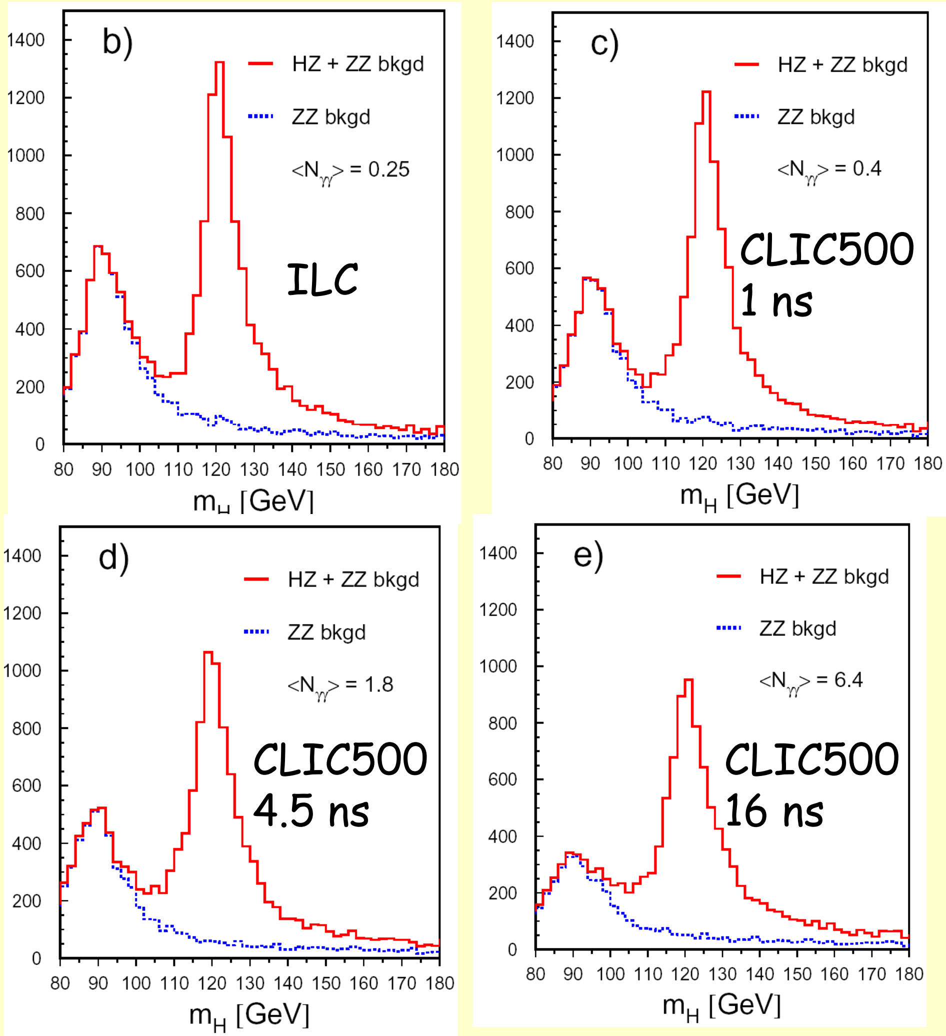
With 32 BX (=16 ns) „CLIC nominal 500" overlaid



note: CLIC 3000 nominal has 14 times CLIC500 overlaid

Does LC Technology matter?

Higgs recoil mass



many LC precision measurements

depend on machine presicions

more than on detector precision

- threshold scans
- polarized cross sections

Needs careful consideration!

Average energy loss (beamstrahlung)

2.4% / 7% / 29%
ILC500/CLIC500/CLIC300

On staging

Various „natural" stages (ordered in $\sqrt{s}$) for an e^+e^- collider:

91.2 GeV -- Giga-Z

~ 250 GeV -- maximum of HZ cross section

344 GeV -- ttbar threshold

2 m(LSP,LKP,…) + X -- model independent WIMP measurements

2 m(NLSP) + X -- SUSY spectroscopy (part I)

~ 800 GeV -- maximum of ttH cross section, HH coupling

m (Z´)

2 m (squarks) + X

3 TeV

Different stages (and when to reach them) will (hopefully) be known from LHC data

Conclusions

Hard to imagine any LHC discovery which would not trigger the start of an e^+e^- programme

Higgs <u>is</u> a discovery!

Staged approach to LC seems politically more realistic <u>and</u> physically sensible

watch out carefully for „tiny" differences between different collider technologies