The Linear Collider Physics Case in view of LHC

SFB Block Meeting
February 23/24, 2012

J.List (DESY)

DESY

Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

News from Japan

- December 2011: Japan expresses interest in hosting the ILC
- Prime Minister Noda gave address at ILC symposium in Japan
- talked about
  - the Higgs search at the LHC
  - importance of the accelerator science and its application
  - International framework to solve remaining issues and to realize the ILC
- "ILC goes one step further"

further details e.g. in ILC NEWSLINE SPECIAL ISSUE of 19 December 2011:
http://newsline.linearcollider.org/2011/12/19/

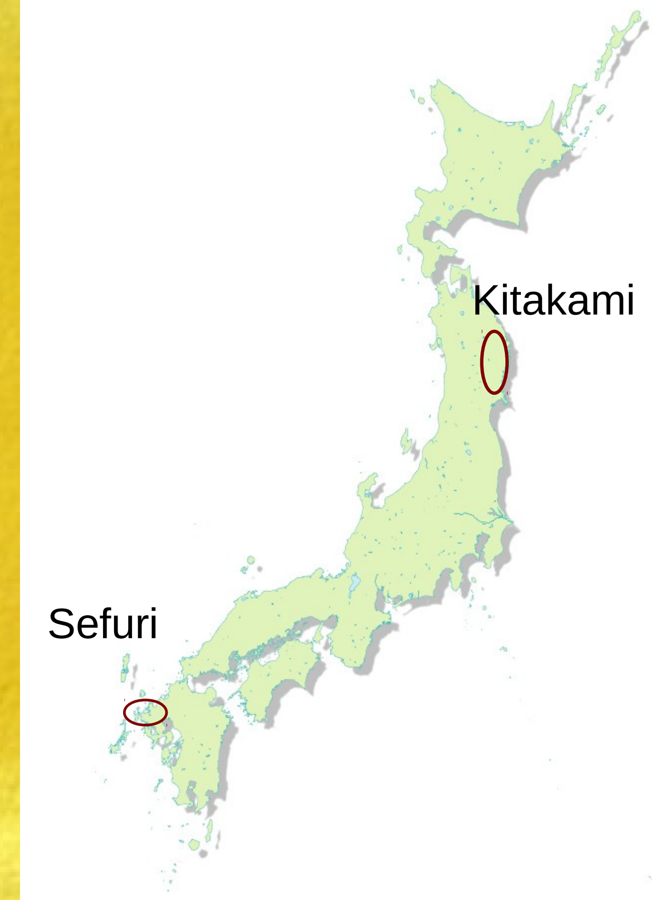
Candidate sites in Japan

Sefuri-mountain site in Kyushu island (southern-western Japan) promoted by

- Fukuoka and Saga prefectures
- Kyushu and Saga universities
- Kyushu Economic Federation

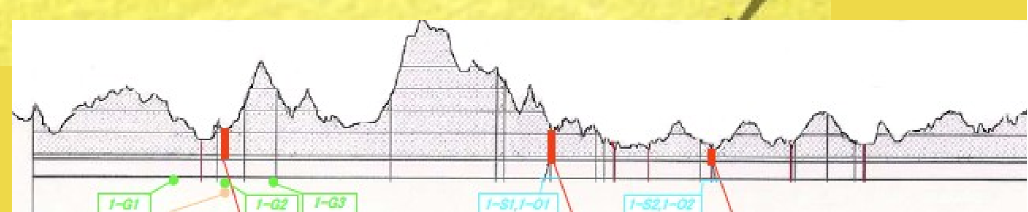
Kitakami-mountain site in Tohoku area (northern Japan) promoted by

- Iwate and Miyagi prefectures
  - Iwate prefecture proposed the ILC as a core of the earthquake disaster recovery project.
- Tohoku university
- Tohoku Economic Federation



Each mountain site consists of stable hard granite rocks, suitable for the ILC construction. Each local team has been working on

- Geological surveys including boring investigation
- City-planning with the ILC as the core.



News from Hamburg (a little more modest...;-)

- February 2012: LCForum
- 3-day conference on Linear Collider physics
- >100 participants
- from 16 countries
- >50 contributions

=> will try to give you an impression

(all presentations: https://indico.desy.de/conferenceOtherViews.py?confId=4980)

Outline

- Introduction:
  - What? - ILC & CLIC
  - Why? - the basic questions
- Physics highlights – updated
  - Bread & Butter: the Top Quark
  - The Expected: the Higgs Boson
  - The Speculative: Beyond the Standard Model
- Conclusions & Outlook

Introduction

- What? - ILC & CLIC
- Why? - the basic questions

Two e^+e^- Linear Colliders on the market

ILC

- Based on superconducting RF cavities
- Gradient 32 MV/m
- **Energy: 500 GeV, upgradeable to 1 TeV**
  (possible GigaZ factory at 90 GeV or
  ZZ factory at ~200 GeV is also
  dered)
- studies focus mostly on 500 GeV

FLASH & XFEL

technology available

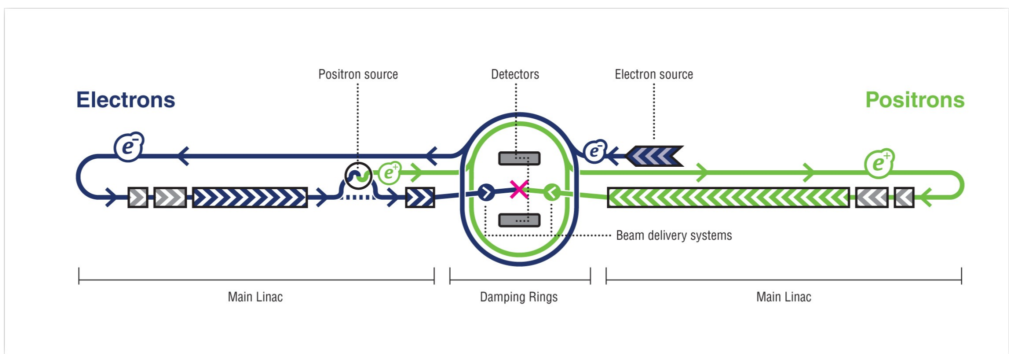
CLIC

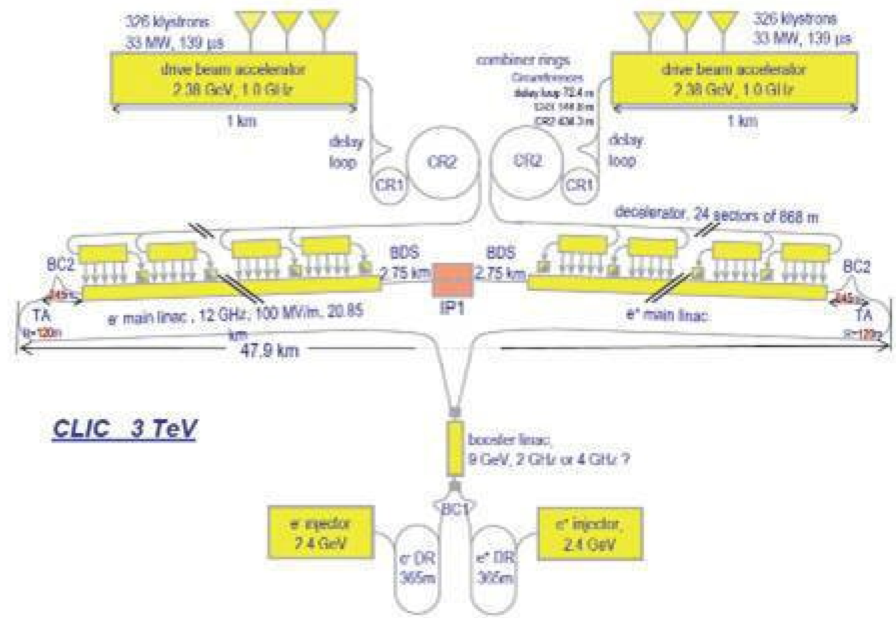
- Based on 2-beam acceleration scheme
  (warm cavities)
- Gradient 100 MV/m
- **Energy: 3 TeV**, though will probably start
  at lower energy (~0.5 TeV)
- Detector study focuses on 3 TeV

feasibility still to be demonstrated

LC Forum – CLIC Status *Michael Hauschild - CERN, 7-Feb-2012, page 2*

Two e^+e^- Linear Colliders on the market





ILC

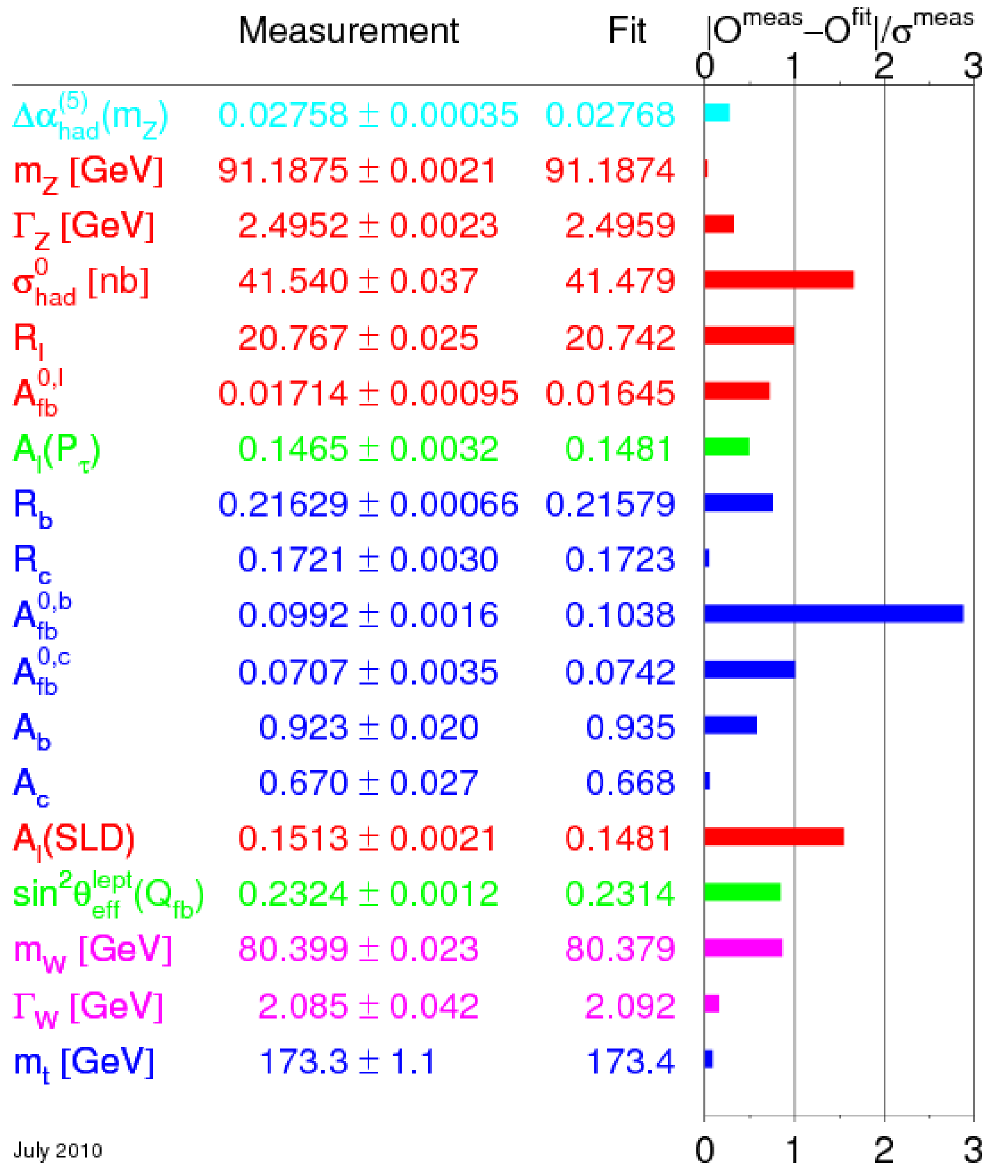
- 2007: Reference Design Report (RDR)
- 2009: Letters of Intent (LoI)
- 2012: Technical Design Report (TDR)

CLIC

- 2011: Conceptual Design Report

Why? - The Standard Model (of Particle Physics)

- Standard model of particle physics very successful down to quantum loop level
- but:
  has important omissions and open questions!



Why? - The basic questions (well, some of...)

- How can elementary particles be massive?
  → the Higgs Boson, mass hierarchy and fine tuning
- How can their masses be so different?
- How does it fit with cosmology?
  → dark matter, dark energy, baryon asymmetry
- Why three generations?
- What about neutrino masses?
- Is there a unification of forces?
- Are there extra space-time dimensions?

=> good reasons for expecting answers
at the Terascale → **LHC!**

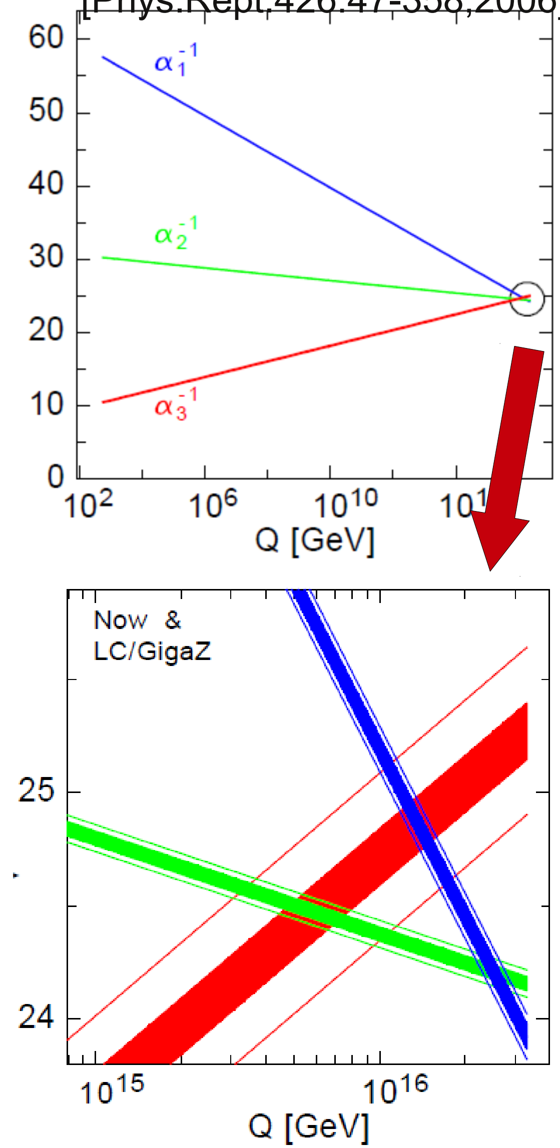
Why an electron-positron Collider?

- understanding discoveries:
  - identify nature of new particle
  - find the theory behind
  - and determine its parameters

=> high energy frontier ↔ high precision frontier

- at an e^+e^- Linear Collider, the initial state is
  - clean
  - tunable in energy
    → threshold scans
  - tunable in helicity
    → test chiral structure

[Phys.Rept.426:47-358,2006]



Physics Highlights - updated

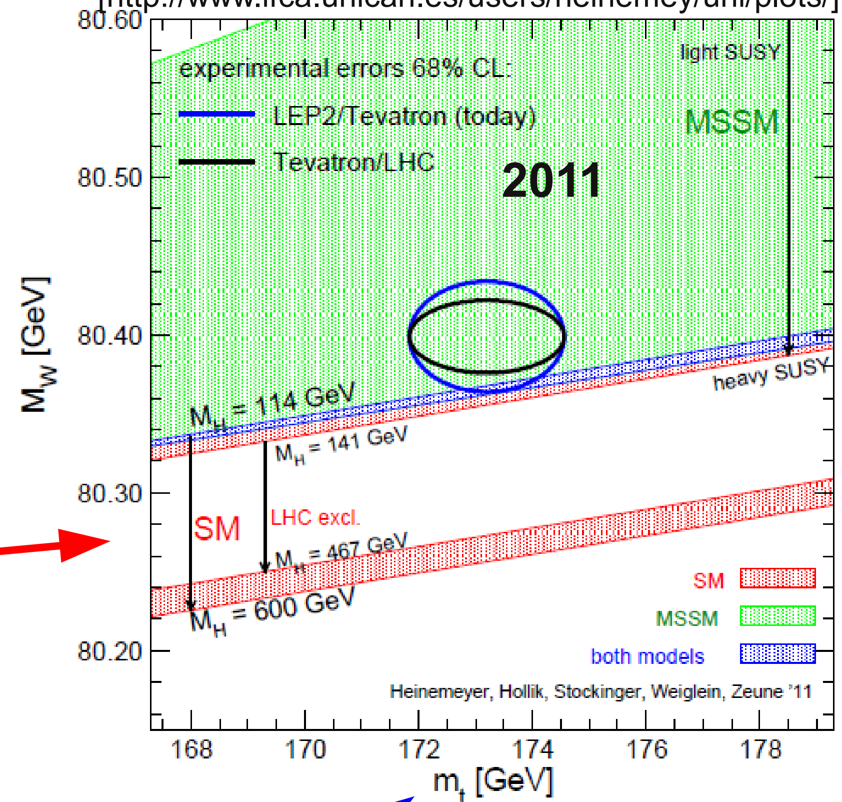
Bread & Butter: the Top Quark

What's there for sure: the Top Quark

The top quark

- is the heaviest known elementary particle (173 GeV)
- gives dominant contribution to loop corrections to Standard Model parameters
- is intimitely connected to the Higgs (or more general: mechanism generating particle masses)

[http://www.ifca.unican.es/users/heinemey/uni/plots/]

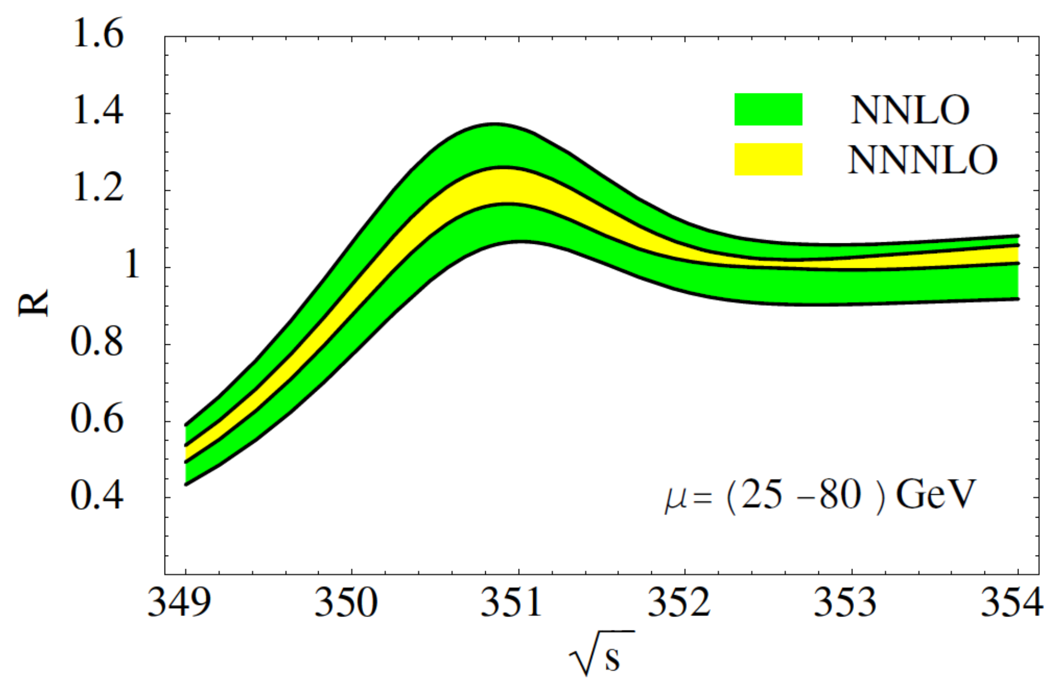


=> precision measurements of top quark properties!

Example here: mass,
see e.g. LCForum for more!

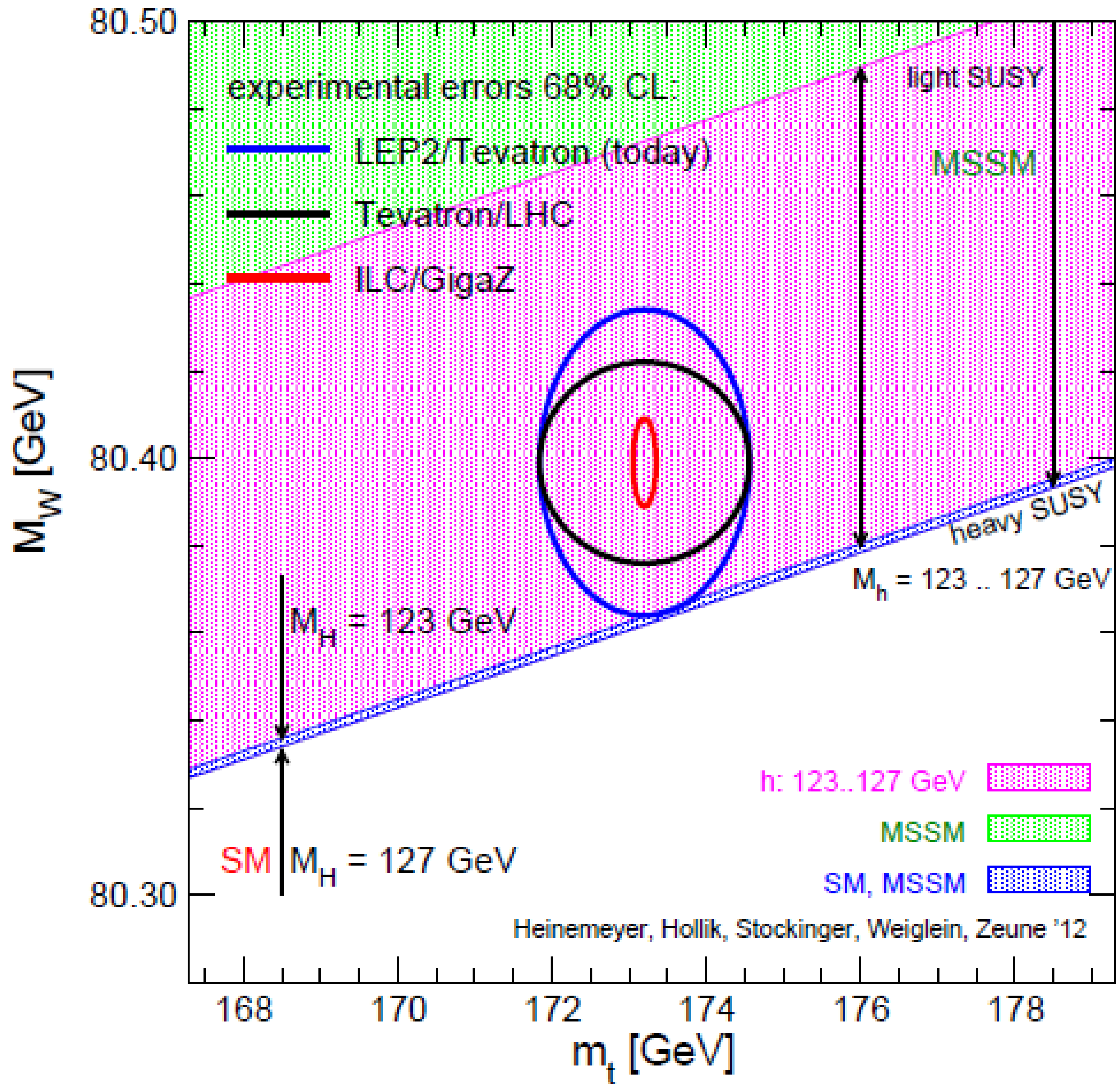
Top Mass: How to improve significantly?

- Problem: *what* are we measuring? [P.Uwer @ LCForum]
- "there is no pole in full QCD"
  => need: measurable *and* theoretically calculable observable observable, with *small non-perturbative corrections* and in a *well defined mass scheme*
- only known method so far: remnant of 1S resonance at the production threshold in e^+e^-
- → measure cross-section for several center-of-mass energies
- obtain δM_t = 100 MeV



[Beneke, Kiyo, Schuller 08]

Top Mass: Where does this lead us?



- zoom into previous plot with LHC Higgs exclusion limits
- or assume there is a Higgs signal

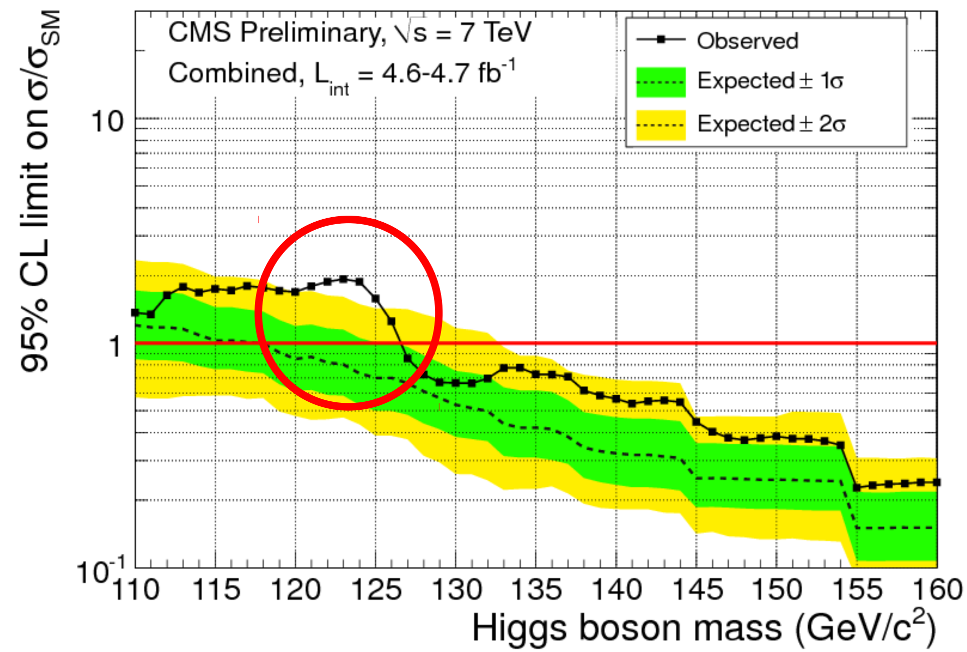
ILC precision truely challenges Standard Model even if new particles not visible at the LHC

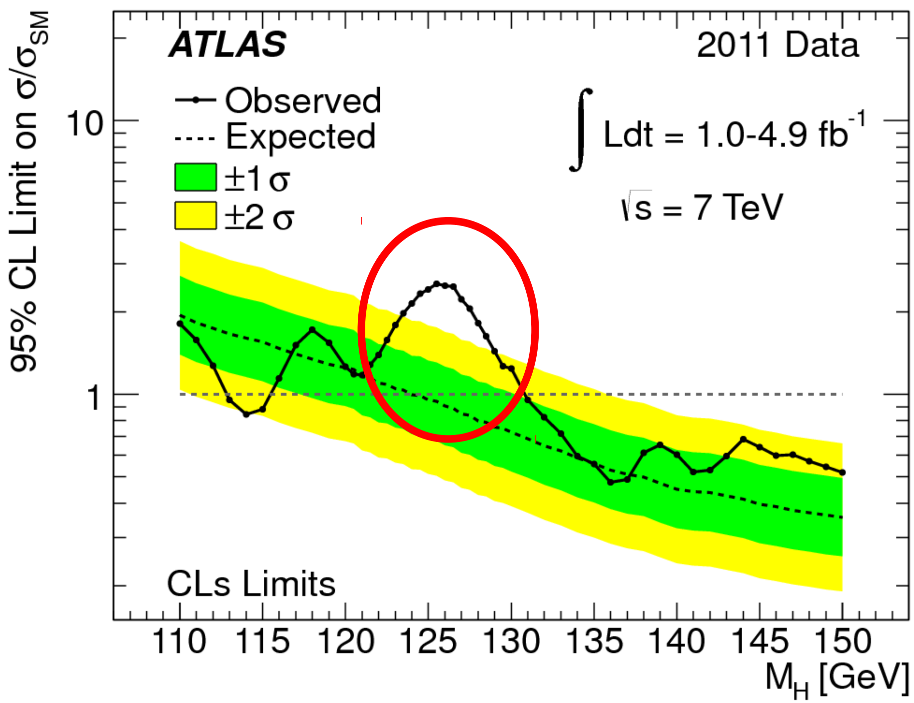
Physics Highlights - updated

The Expected: The Higgs Boson

What's probably there: The Higgs Boson

- ATLAS & CMS data contain temptating hints....





=> c.f. A. Schmidts presentation this morning

Found it – Done?

Not at all – then the fun is just about to start:

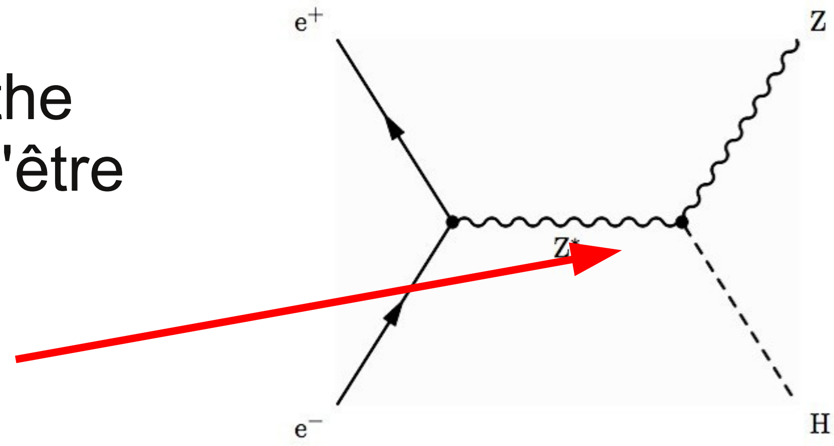
That's something fundamentally new!

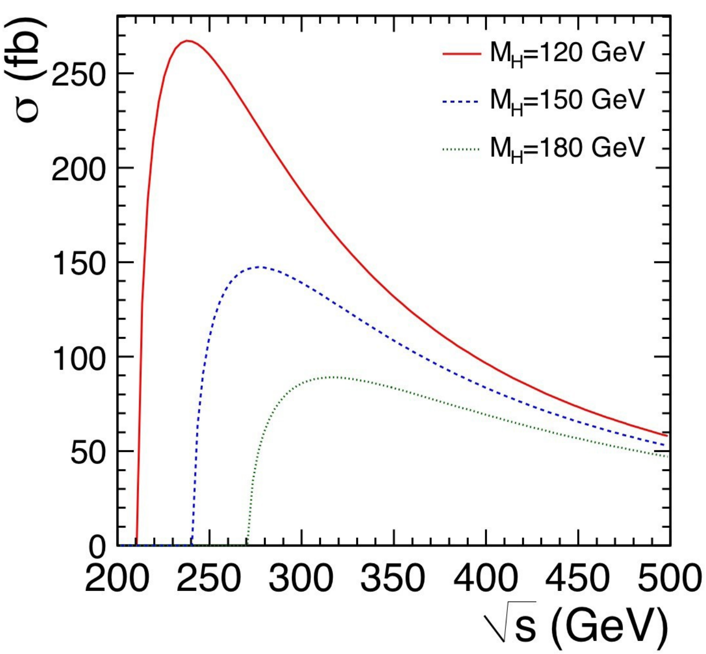
- Is “it” **a** Higgs Boson?
  - elementary?
  - spin-0?
- Is “it” **the** Standard Model Higgs Boson?
  Or part of a non-minimal Higgs sector?
  Or does it even mix with other new stuff?
  - CP = ++?
  - check relative couting rates of all decay modes (“Branching ratios”)
  - from these: couplings to SM particles proportional to mass?
  - and to finally prove the SM Higgs mechanism: the Higgs' coupling to itself!

Measure all this –
precisely, and in a *model-independent* way!

The key to model-independency

- Higgs-Strahlung
  Reminder: creating the mass of the Z (and W) bosons is the raison d'être of the Higgs mechanism!
- SM: m_H fixes ZZH coupling





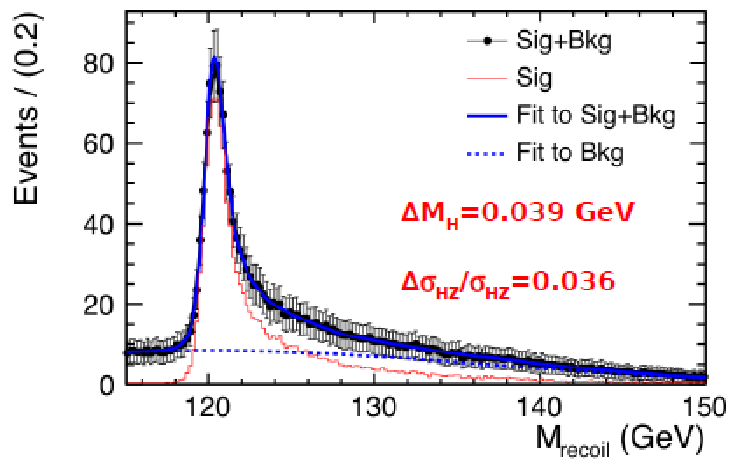
- measure cross-section
- measure mass

…. without looking at the Higgs !

→ just reconstruct the Z
  and calculate its recoil

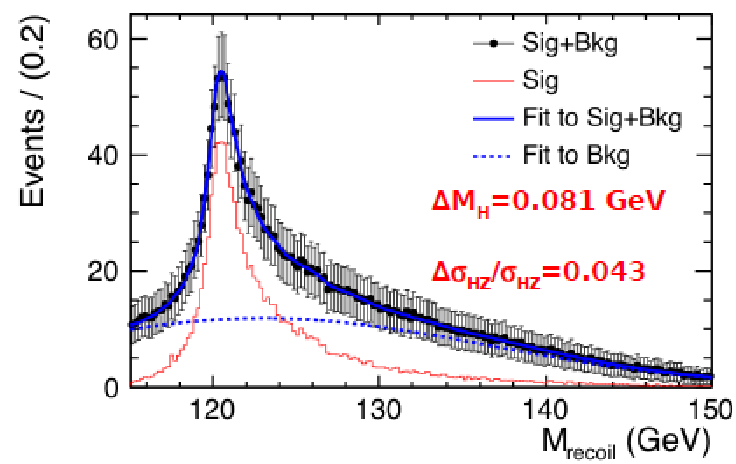
Recoil Mass Results (c.f. LC Note LC_PHSM-2009-006)

Muon Channel



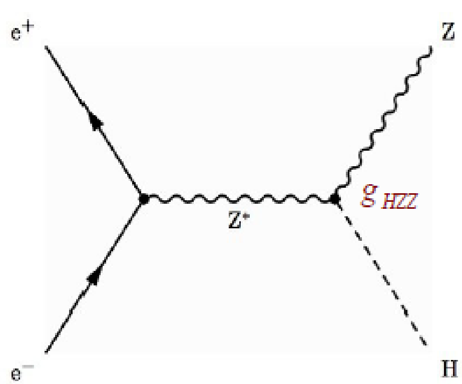
Very Precise Measurement
S/B = 8 in Peak Region

Electron Channel



Less Precise
Bremsstrahlung in detector material

Combined: ΔM_H=0.035 GeV, $\Delta\sigma_{HZ}/\sigma_{HZ}$=0.027



$$\sigma_{HZ} \sim g^2_{HZZ}$$

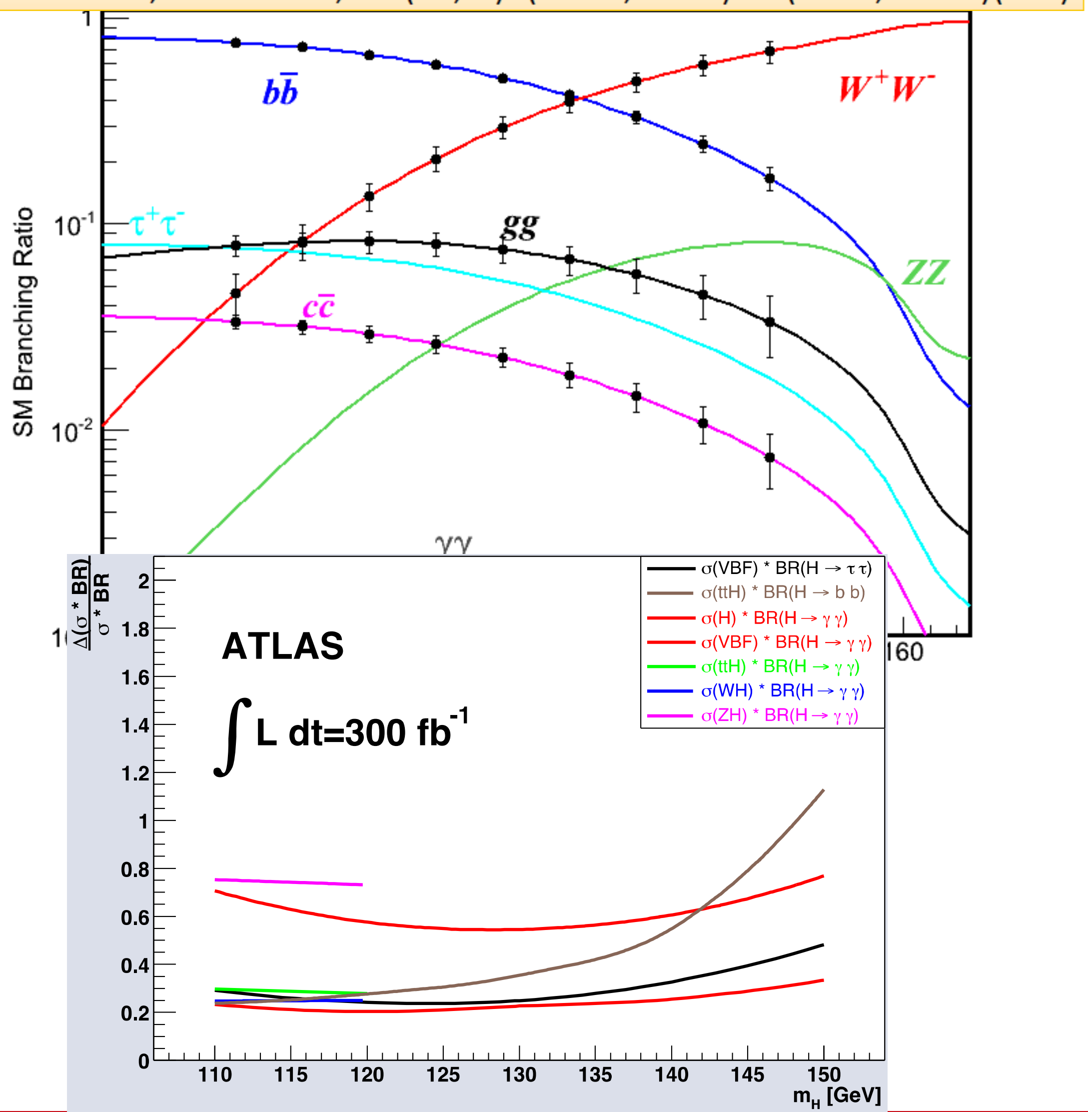
⇒ Precision in g_{HZZ} coupling 1-2%

Sensitivity to 15% deviations
SM prediction of cross section

3rd LCForum DESY Hamburg R.Poeschl 7

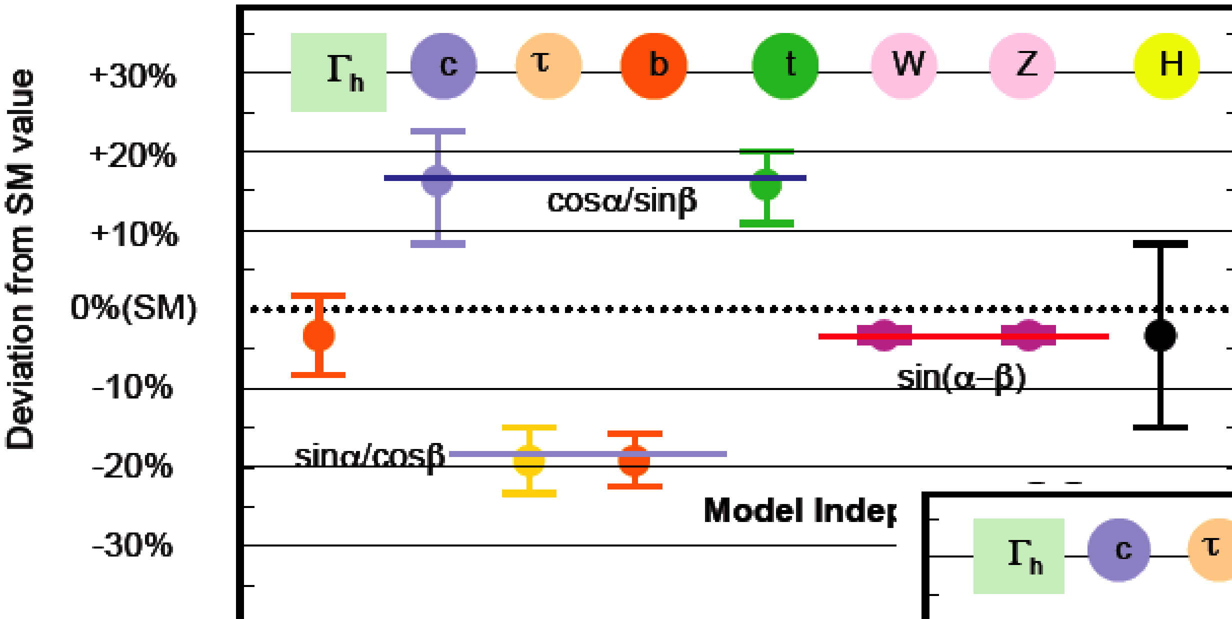
Branching Ratio Results

Ecm=250 GeV, L=250 fb-1, Pol(e+,e-)=(+30%, -80%) or (-30%, +80%)(ww)



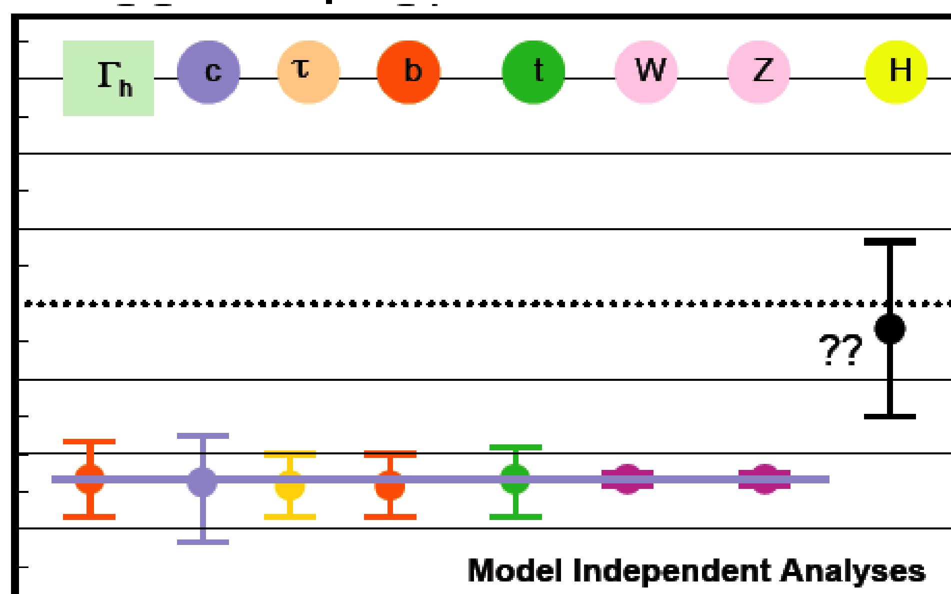
- preliminary full simulation results by H.Ono (c.f. LCWS11)
- ΔBR/BR(bb) ~ 3%
  ΔBR/BR(cc) ~ 9%
  ΔBR/BR(gg) ~ 10%
  Error includes $\Delta\sigma_{HZ}$
- LHC?
  typ. 20...30% on cross-section x BR

Isn't 20% good enough?



Expect deviations from SM at few percent level!

2 Higgs Doublet Model (like MSSM)



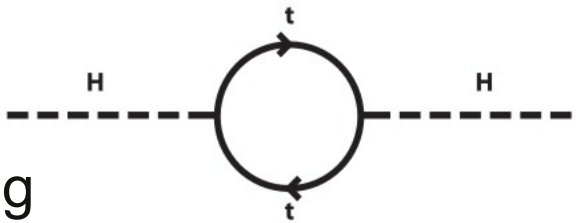
Extra dimensions: Higgs-Radion mixing

Physics Highlights - updated

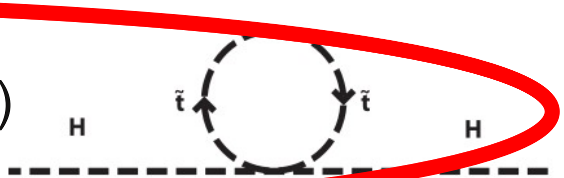
The Speculative:
Beyond the Standard Model

Is this all there is?

- Mass of an elementary spin-0 particle is not stable w.r.t. higher order corrections (worst guy: top quark!)
- validity of the Standard Model up to the Planck scale requires an enormous amount of fine-tuning



- 3 basic approaches to avoid this:
  - Planck scale is much smaller (Extra Dimensions)
  - Higgs is composite (composite Higgs)
  - new particles at ~TeV scale cancel loops (SUSY)

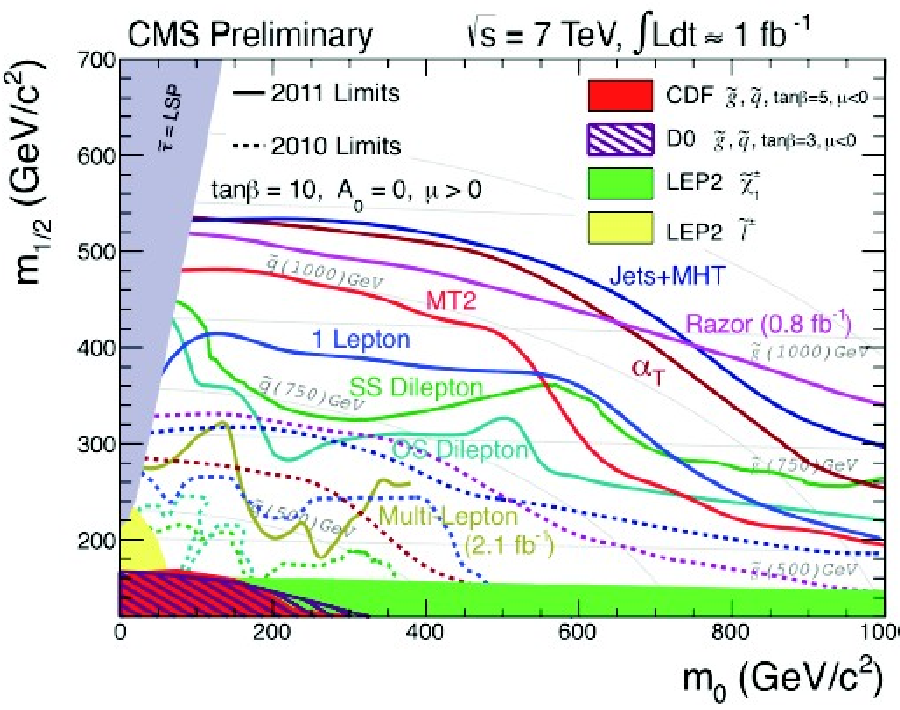


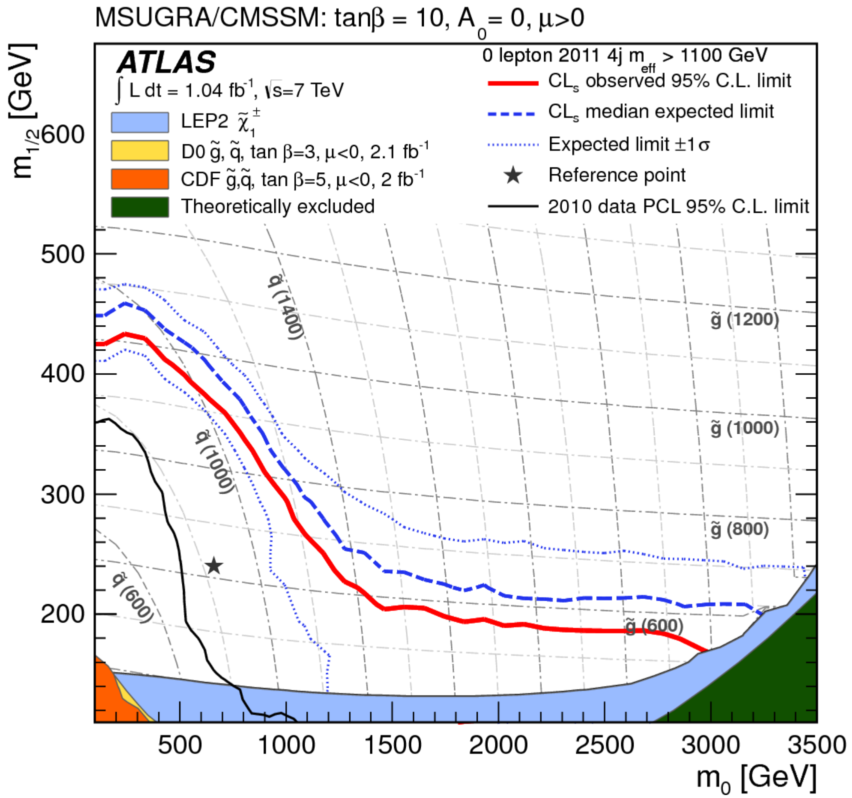
take this example for today – other options → c.f. LCForum

- Furthermore:
  - Dark Matter, Dark Energy, Baryon-Antibaryon-Asymmetry
  - Neutrinos, Grand Unification?
  - electroweak precision observables, $(g\text{-}2)_{\mu}$, ...

LHC

- LHC & experiments to an extremely good job
- but still: direct searches sofar only with negative results

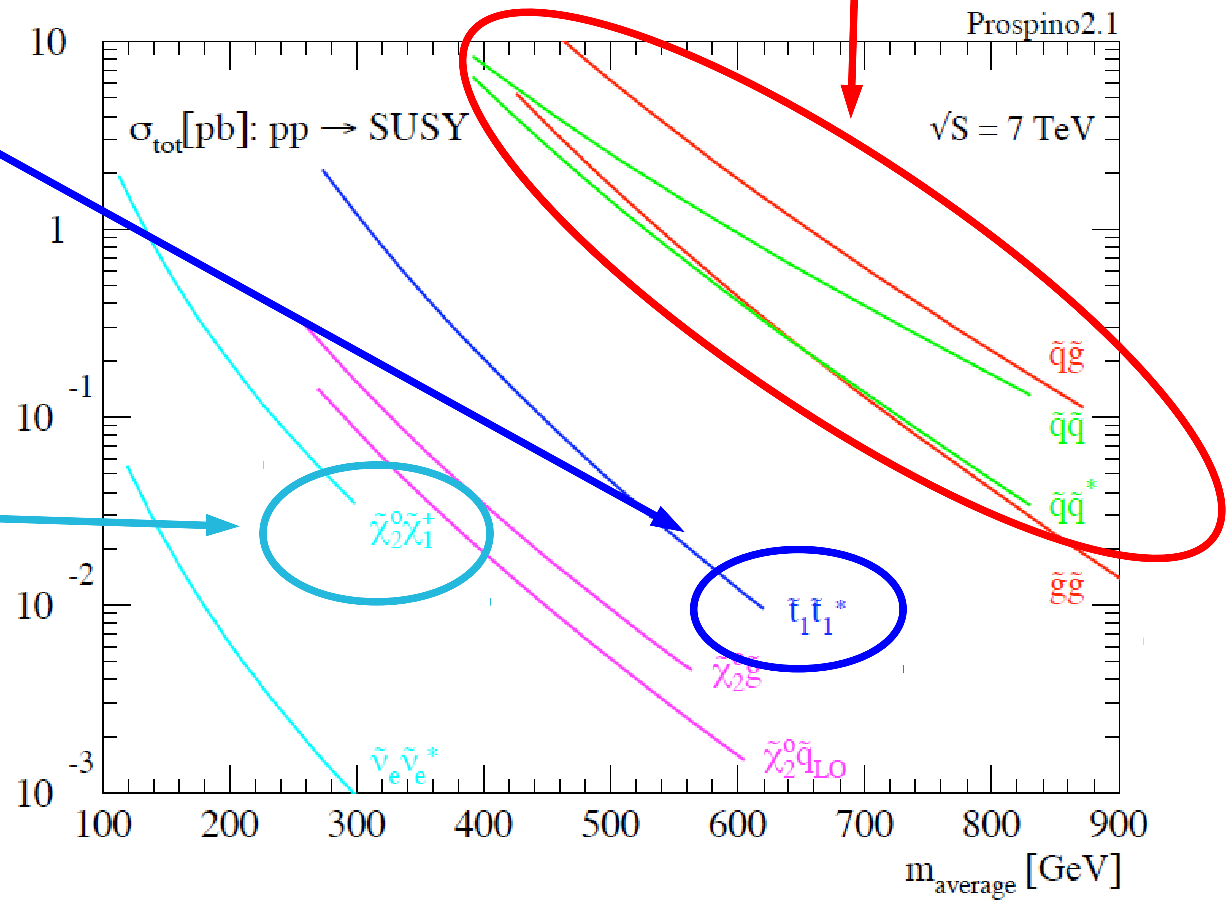




=> Does this look bad for precision measurements of new particles at a Linear Collider?

Let's take a closer look: cross-sections

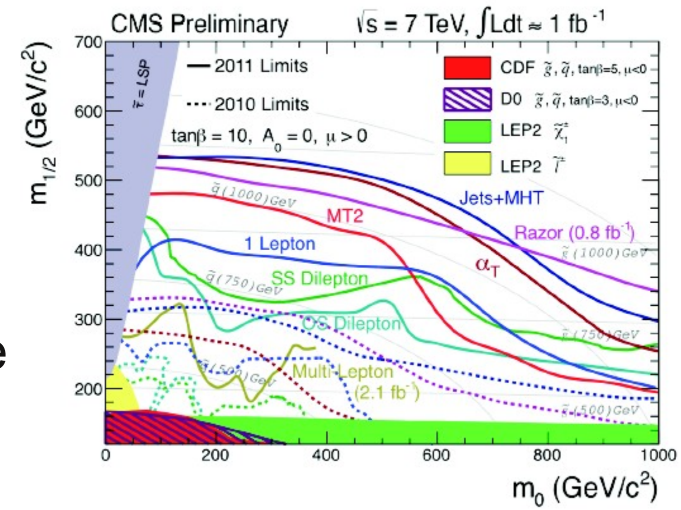
- LHC results up to now rely on production of squarks and gluinos via strong interaction → large rates!
- naturalness:
  → "light stops"
- DM, ew precision:
  → "light electro-weak sparticles"



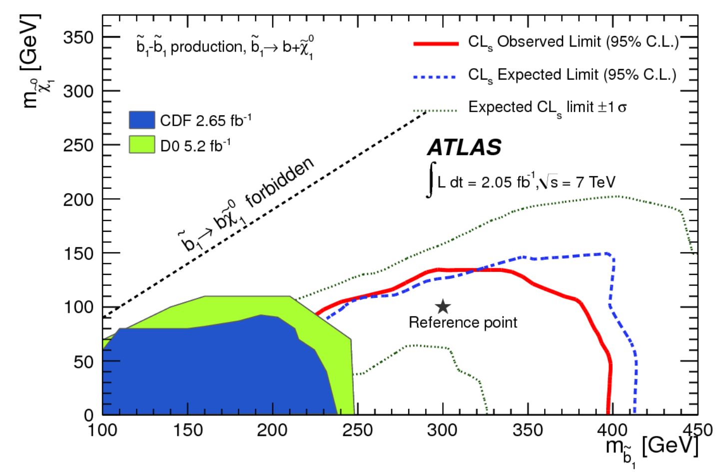
Prospino: Beenacker, Plehn, Spira et al.

Let's take a closer look: models

- most limits are either given
  - in the constrained MSSM (cMSSM / mSugra): 4 parameters + 1 sign out of > 100
  - in “simplified models”: assume just one heavy new particle + lightest (stable) SUSY particle → no cascade decays etc



- a vast number of SUSY models
  - fulfill all “low energy” requirements
  - feature a 122...127 GeV Higgs
  - are accessable at a Linear Collider
  - and either
    - are still to be discovered at LHC
    - or cannot be seen even with $300 fb^{-1}$ at 14 TeV



A few examples [c.f. H.Baer @ LCForum]

- effective SUSY
- hidden SUSY (small mu)
- natural SUSY
- Yukawa-unified SUSY
- mirage mediation (compressed)
- normal mass hierarchy
- NMSSM (talk by Kraml)
- RPV SUSY (talk by Vormwald)

=> typically:

- heavy squarks 2...20 TeV
- lighter part of spectrum compressed
- light gauginos or stau / stop in LC direct reach

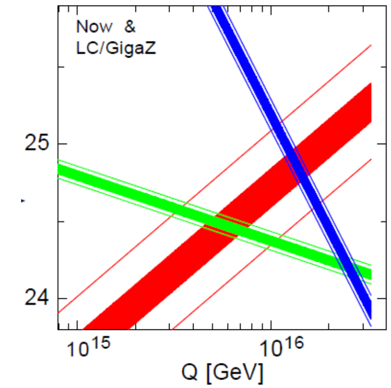
Work in progress:

Define benchmark points in such scenarios

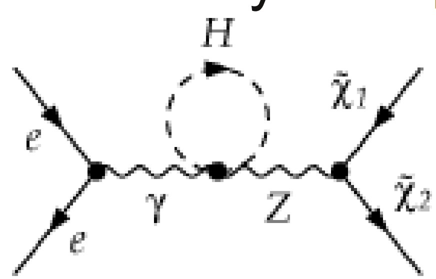
Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

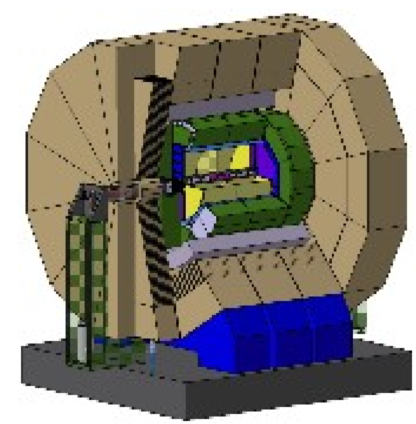
Linear Collider Tasks

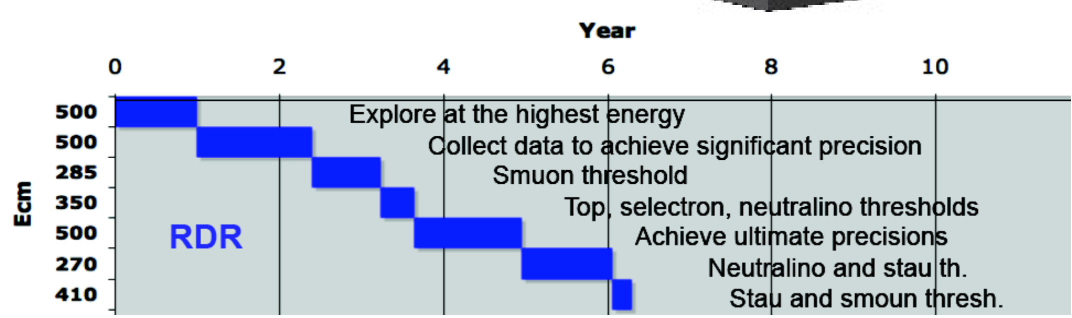
- finally:
  - do precision measurements of all accessible particles
  - figure out the fundamental theory



- needs:
  - precision calculations → higher orders
  - precision instruments → excellent detectors
  - measurement strategies → threshold scans, beam polarisation, ….







MSSM parameter determination: Charginos @ NLO

Weak LHC constraints on charginos and neutralinos

DM density

~Unification relation

Parameter	Value	Parameter	Value
$\|M_1\|$	125 GeV	M_2	250 GeV
$\|\mu\|$	180 GeV	M_{H^+}	1000 GeV
$\|M_3\|$	1 TeV	$\tan\beta$	10
$M_{\tilde{q}_{12}}$	1.5 TeV	$M_{\tilde{f}_3}$	400/800 GeV

LHC limits

Weak :

Summary

- Tree-level parameter determination possible up to $\mathcal{O}(\%)$ level at a LC via $\tilde{\chi}^0/\tilde{\chi}^\pm$ production
- Full $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$@NLO calculated
- Extract parameters $\mathbf{M_1}$, $\mathbf{M_2}$, μ, $\tan\beta$, $\mathbf{m_{\tilde{t}_i}}$ and $\cos\theta_\mathbf{t}$ from fit to **NLO** predictions for masses, polarised cross-sections and A_{fb}
- Increased sensitivity to larger number of parameters compared to LO analyses
- Show **crucial** role played by improved determination of masses from threshold scans

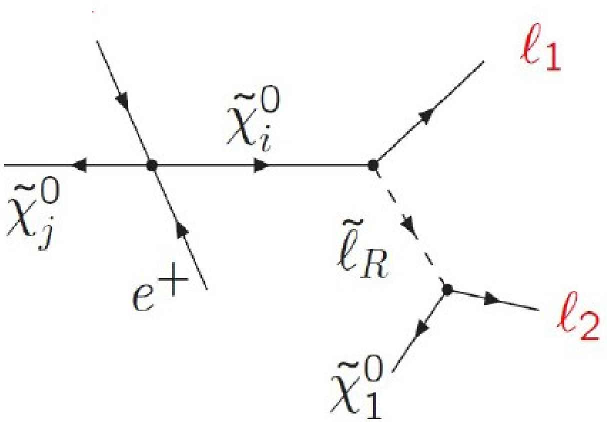
Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

Terwort@LCWS2011

Measurement of CP violation in the MSSM neutralino sector

Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

- Supersymmetry can introduce new sources of CP violation
  → MSSM has 40 new CP violating phases
- Intensive theoretical studies of SUSY CP violation at ILC and LHC
  → CP asymmetries can reach several 10%, since effects appear on tree level
- Experimental studies ongoing for LHC experiments
  → LHC studies suffer from complicated event topologies



→ CP-odd observable from triple product of momenta:

$$\mathcal{T} = [\vec{p}(e^-) \times \vec{p}(\ell_1)] \cdot \vec{p}(\ell_2)$$

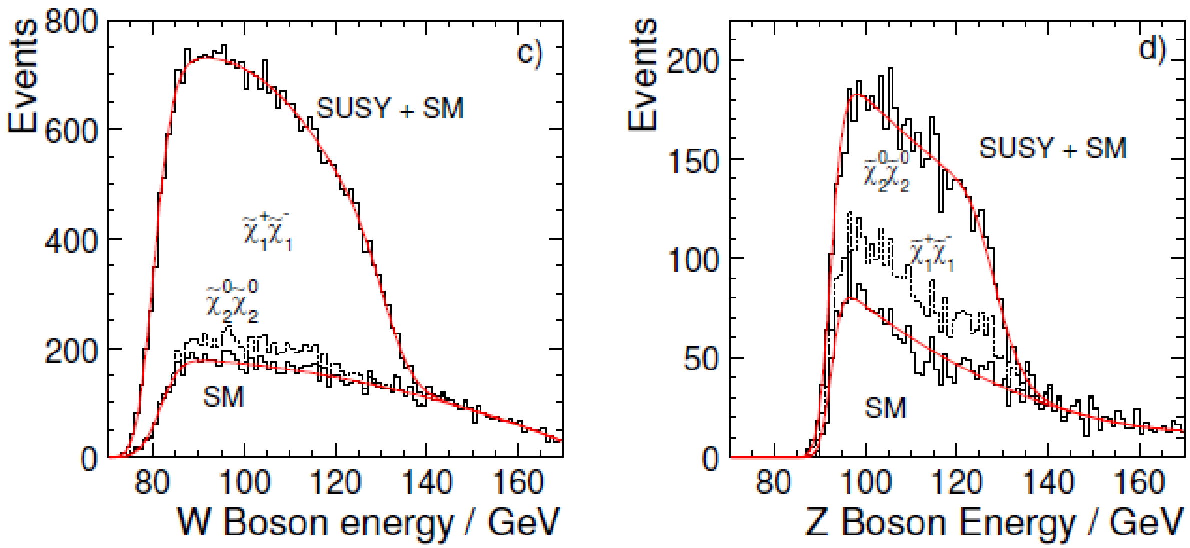
Results:

$$\begin{aligned} |M_1| &= 150.0 \pm 0.7 \text{ GeV}, \\ M_2 &= 300 \pm 5 \text{ GeV}, \\ |\mu| &= 165.0 \pm 0.3 \text{ GeV}, \\ \tan\beta &= 10.0 \pm 1.6, \\ \phi_1 &= 0.63 \pm 0.05, \\ \phi_\mu &= 0.0 \pm 0.2. \end{aligned}$$

$$\begin{aligned} \mathcal{A}^{\mathrm{CP}}(\mathbf{p}_{e^-}, \mathbf{p}_{\ell_N}, \mathbf{p}_{\ell_F})_{\tilde{\chi}_1^0\tilde{\chi}_2^0} &= -11.3\% \pm 0.7\%, \\ \mathcal{A}^{\mathrm{CP}}(\mathbf{p}_{e^-}, \mathbf{p}_{\ell_N}, \mathbf{p}_{\ell_F})_{\tilde{\chi}_1^0\tilde{\chi}_3^0} &= +10.9\% \pm 0.7\%. \end{aligned}$$

Challenging the Detector Design

- non-universal soft SUSY-breaking contributions to the Higgs masses
- M_0 = 206 GeV, $M_{½}$ = 293 GeV, tanβ = 10, A_0 = 0, μ = 375 GeV
- => $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ mass degenerate (216.5 GeV), decay into $\mathrm{W}^{\pm}\tilde{\chi}_1^0$ and $\mathrm{Z}\tilde{\chi}_1^0$, respectively (M_{LSP} = 115.7 GeV)
- detector challenge: fully hadronic decay mode 4j + missing 4-mom.



Cross-section measurement:
δσ =0.6% ($\tilde{\chi}_1^{\pm}$)/ 2% ($\tilde{\chi}_2^0$)

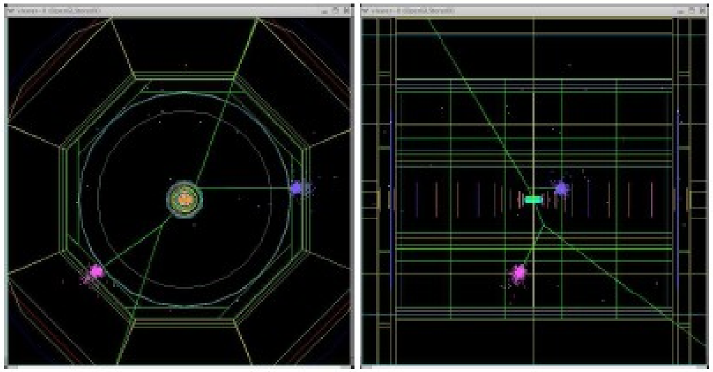
Mass measurement

δM($\tilde{\chi}_1^0$) = 0.8 GeV
δM($\tilde{\chi}_1^{\pm}$) = 0.9 GeV
δM($\tilde{\chi}_2^0$) = 2.4 GeV

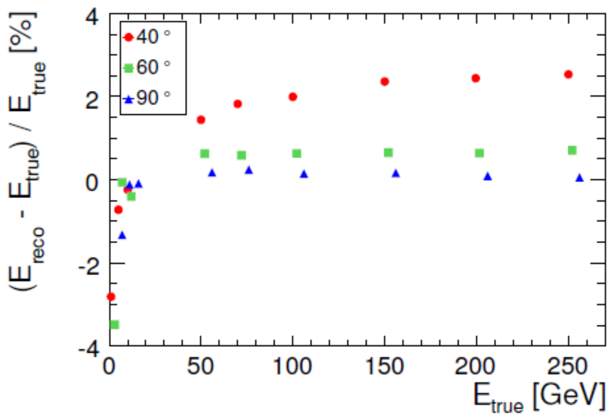
Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

GMSB: Non-pointing photons N. Wattimena, desy-thesis-10-006

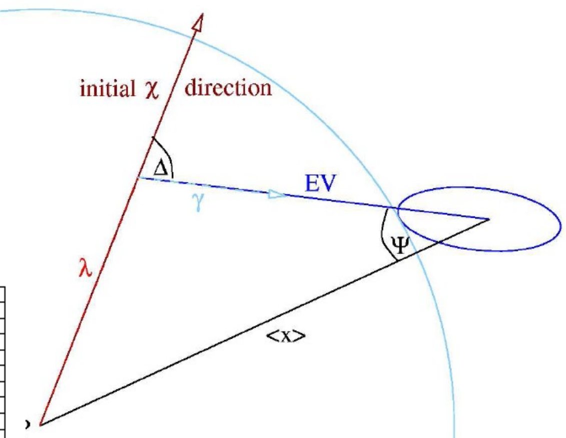
- $\chi^0 \rightarrow \gamma \tilde{G}$: reconstruct lifetime from photon direction → *cluster shape!*



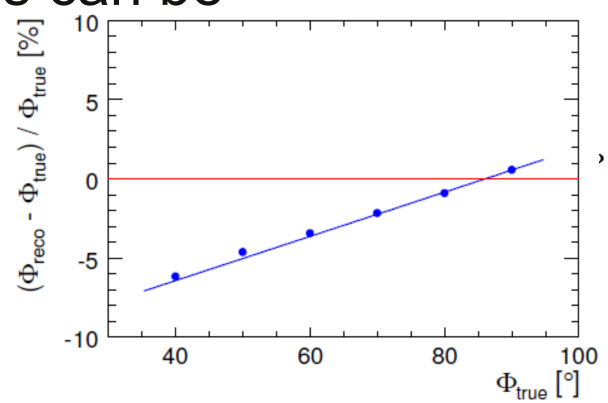
- χ^0 mass from edge of photon energy to 2 GeV (stat), although bias due to:



→ needs better photon reconstruction



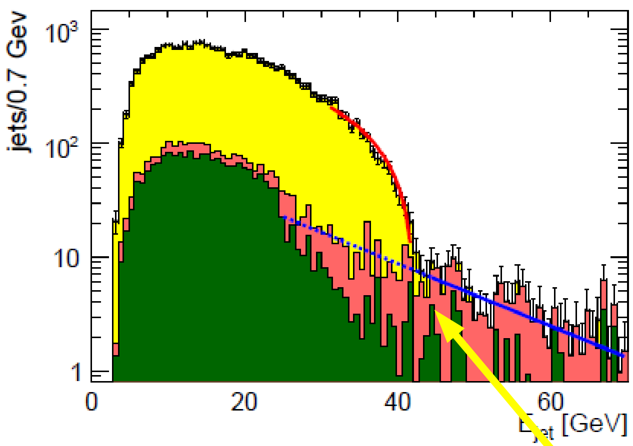
- lifetimes between 2 and 11ns can be reconstructed to a few %

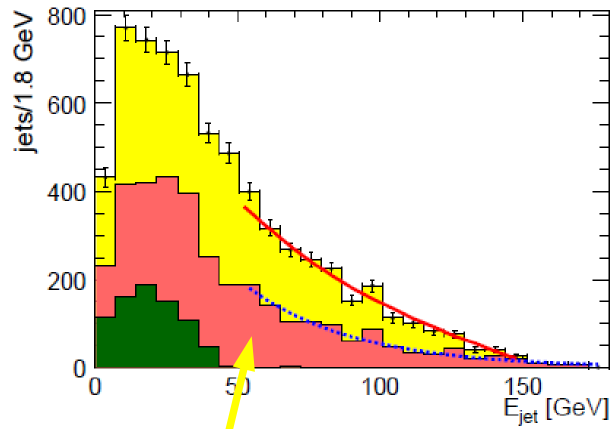


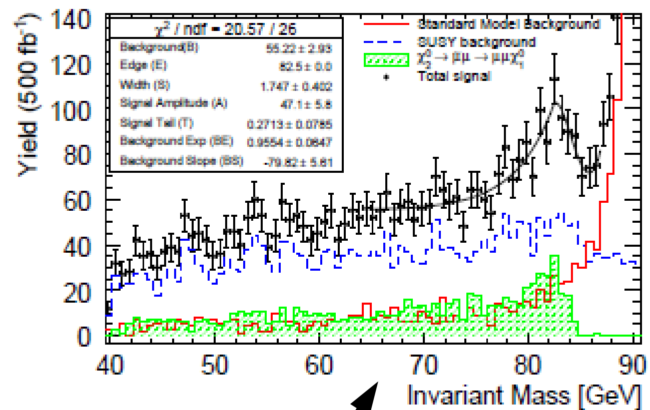
- lifetimes of O(0.1ns) again suffer reconstruction "feature"
  => repeat with better γ reco

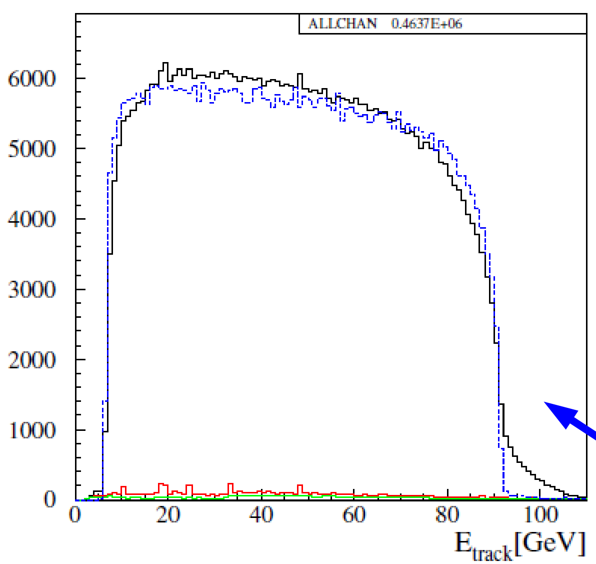
Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

Sleptons with small mass differences









- After 4 ILC years:
  - $\Delta(M_{\tilde{\tau}_1}) = 80\ \mathrm{MeV}/c^2 \oplus 1.3\Delta(M_{\tilde{\chi}^0_1})$.
    $\Delta(M_{\tilde{\tau}_2}) = 8\ \mathrm{GeV}/c^2 \oplus 18\Delta(M_{\tilde{\chi}^0_1})$.
  - $\Delta(\mathcal{P}_\tau) \approx 6\ \%$ (see backup).
  - For $\mathrm{e}^+\mathrm{e}^- \to \tilde{\mu}_\mathrm{L}\tilde{\mu}_\mathrm{L}$, we find: $\Delta(M_{\tilde{\chi}^0_1}) = 920\mathrm{MeV}/c^2$
    $\Delta(M_{\tilde{\mu}_\mathrm{L}}) = 100\mathrm{MeV}/c^2$,
  - For $\tilde{\chi}^0_1\tilde{\chi}^0_2 \to \mu\tilde{\mu}_\mathrm{R}\tilde{\chi}^0_1 \to \mu\mu\tilde{\chi}^0_1\tilde{\chi}^0_1$, we find $\Delta(M_{\tilde{\chi}^0_2}) = 1.38\mathrm{GeV}/c^2$
  - $\Delta(M_{\tilde{\chi}^0_1}) = 400\ \mathrm{MeV}/c^2$ (prospect: $170\ \mathrm{MeV}/c^2$)
    $\Delta(M_{\tilde{e}_\mathrm{R}}) = 500\ \mathrm{MeV}/c^2$ (prospect: $210\ \mathrm{MeV}/c^2$)

Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

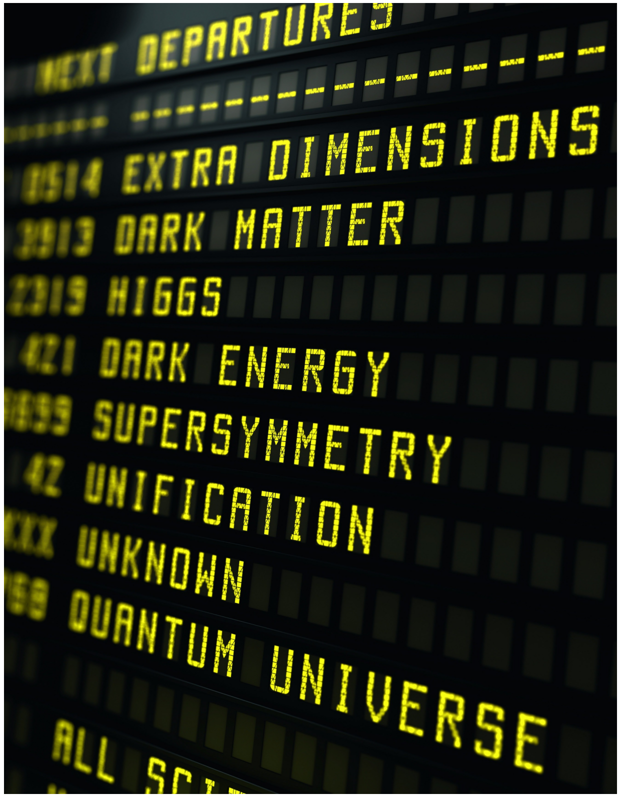
Zooming out....

- Illustrated by SUSY example:
  - in addition to the indirect constraints from Standard Model precision observables, new particles can be characterised by direct direct measurements if kinematically accessible
  - achievable precision is sufficient to determine model parameters and to discriminate models
  - even if only small fraction of the spectrum is directly accessible
- There are many more examples
  → c.f. LCForum (and you can ask me for one more ;-)

Beyond SM Physics is the desert
on top of the rich main LC physics menue!

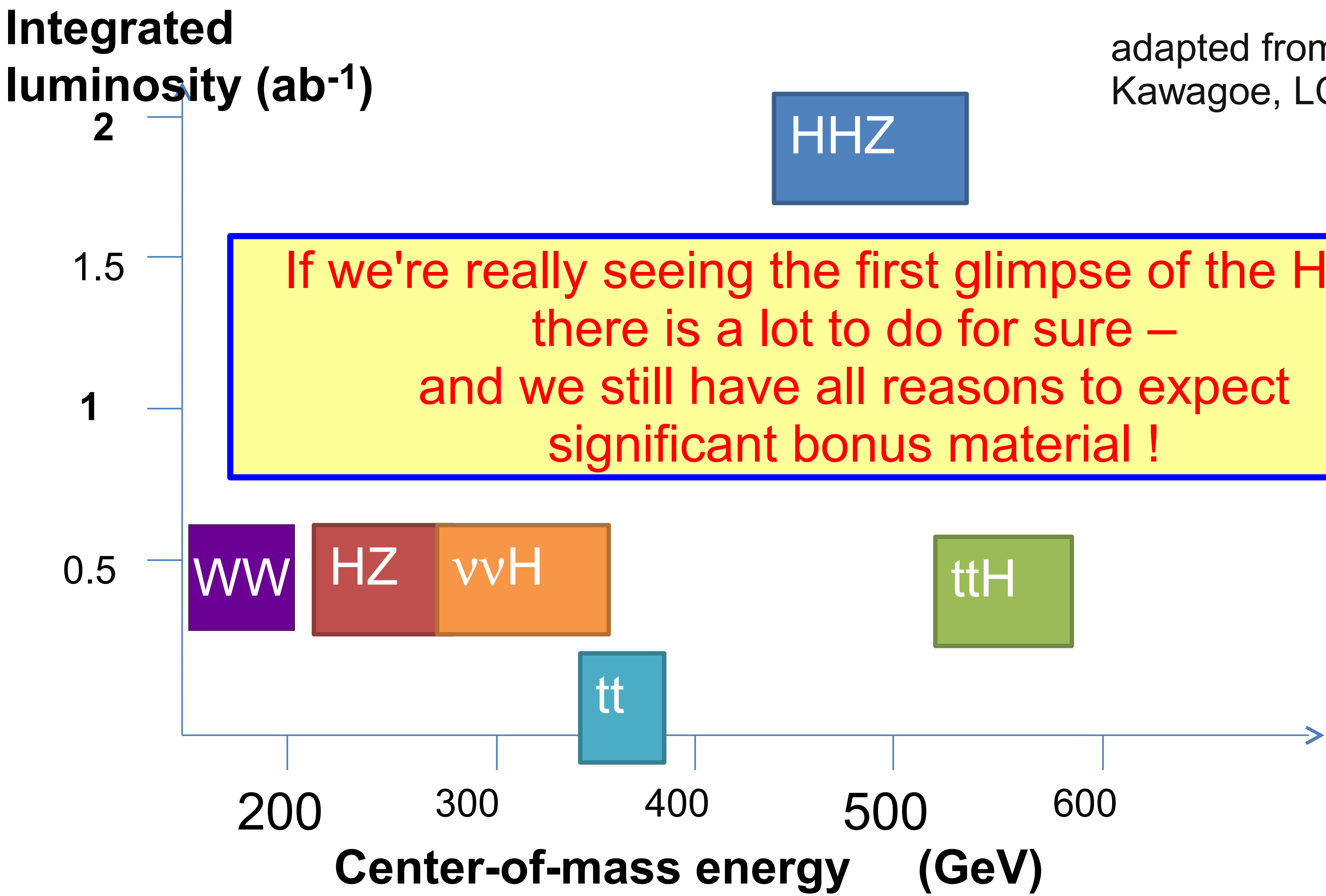
Conclusions

- Linear Collider Physics is very alive
  → many more contributions to LCForum
- encouraging news from Japan
- encouraging hints from the LHC?
- 2012 will be a very important year:
  - CLIC CDR just published
  - more LHC data / results
  - ILC TDR incl. updated physics case to come
  - September: open meeting of European Strategy Group



Outlook

adapted from
Kawagoe, LCForum



If we're really seeing the first glimpse of the Higgs,
there is a lot to do for sure –
and we still have all reasons to expect
significant bonus material !

Back up

MSSM parameter determination: Charginos @ NLO

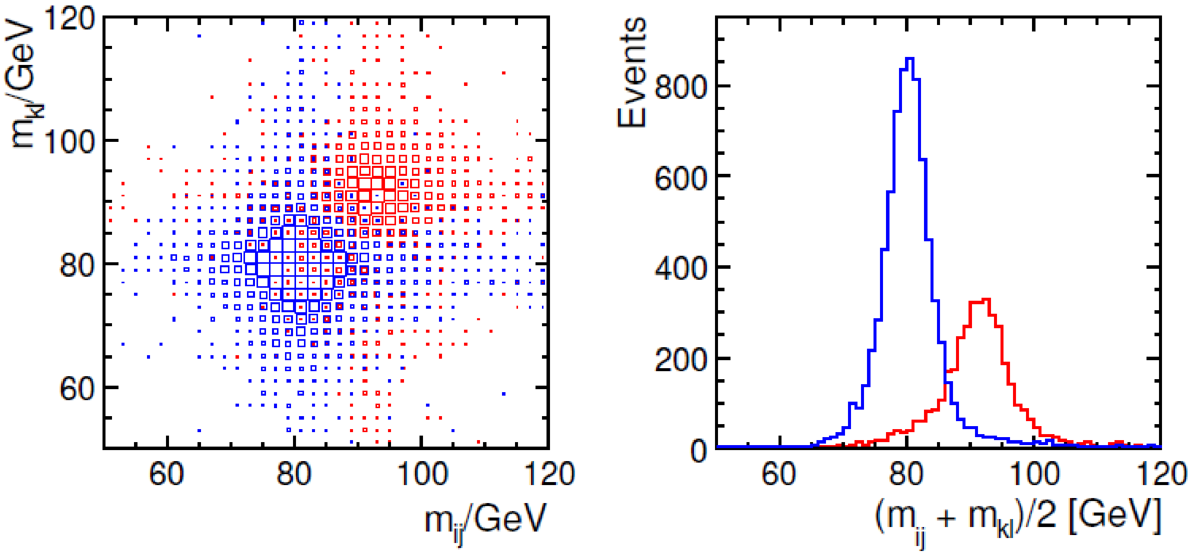
Observable	Tree value	Loop correction	Error
$m_{\tilde{\chi}_1^\pm}$	149.6	–	0.2
$m_{\tilde{\chi}_2^\pm}$	292.3	–	2.0
$m_{\tilde{\chi}_1^0}$	106.9	–	0.2
$m_{\tilde{\chi}_2^0}$	164.0	2.0	1.0
$m_{\tilde{\chi}_3^0}$	188.6	-1.5	1.0
$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)^{350}_{(-0.8,0.6)}$	2347.5	-291.3	$1.3/\varepsilon$
$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)^{350}_{(0.8,-0.6)}$	224.4	7.6	$0.4/\varepsilon$
A_{FB}^{350}	-2.2%	6.8%	0.8%
$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)^{500}_{(-0.8,0.6)}$	1450.6	-24.4	$1.0/\varepsilon$
$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)^{500}_{(0.8,-0.6)}$	154.8	12.7	$0.3/\varepsilon$
A_{FB}^{500}	-2.6%	5.3%	1%

} **Masses from the continuum**

Strong EWSB

ILD LoI

- test W⁺W⁻ → W⁺W⁻ and W⁺W⁻ → ZZ vertices by $e^+e^- \to \nu_e\overline{\nu}_e q\overline{q}q\overline{q}$ at 1 TeV (1ab^{-1}, P=(0.3,-0.8))
- di-jet mass reconstruction:

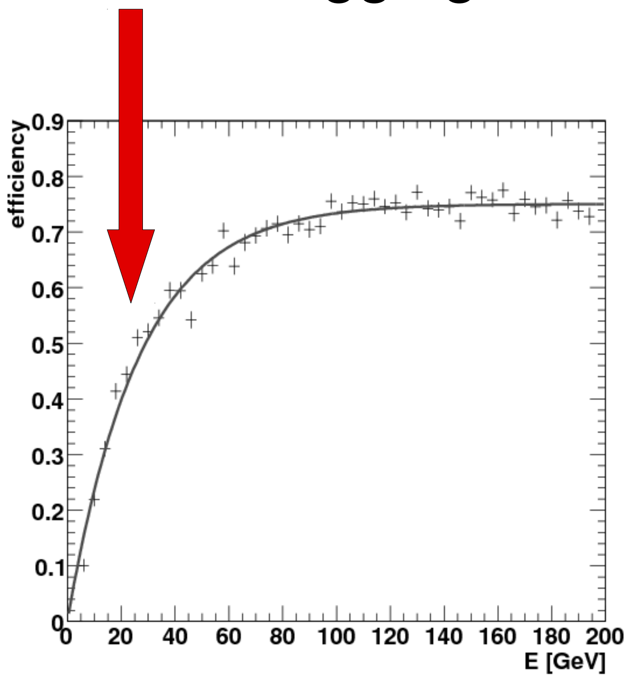


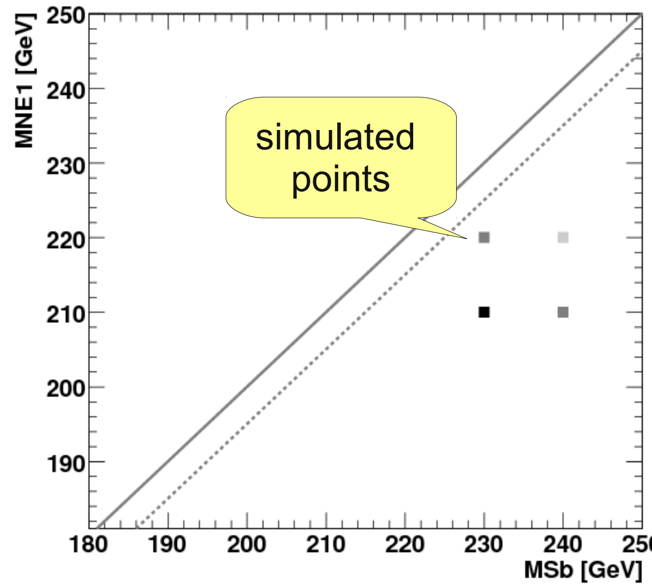
- Quartic gauge couplings (SM=0) can be limited to:

$$-1.38 < \alpha_4 < +1.10 \qquad -0.92 < \alpha_5 < +0.77$$

$\tilde{b} \to b\, \chi^0_1$

- $\tilde{b}$ is NLSP with small mass difference
- $\tilde{b}$ mass determines cross-section
- mass splitting determines jet energy
  $\to$ test b-tagging with low jet energies!





- further needs excellent coverage of forward region to veto γγ-events
- with $500 fb^{-1}$ at 500 GeV:
  between10 and 2σ (at kinematic edge)

Little Higgs with T-Parity

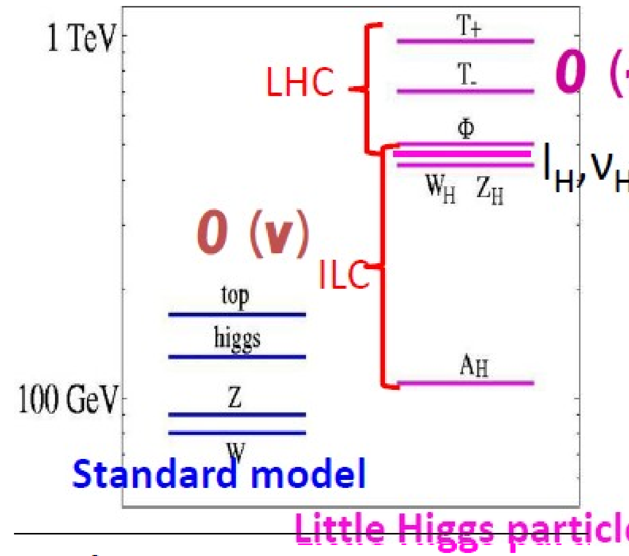
M.Asano, K.Fujii, E.Kato et al, LCWS11

E_{cm}=1TeV,
Luminocity = 500fb^{-1}

Coupling extracted from xsec

Mode	Coupling meas. Accuracy
$A_H Z_H$	3.90%
$Z_H Z_H$	0.219%
$e_H e_H$	1.49%
$\nu_H \nu_H$	0.648%
$W_H W_H$	0.174%

particle	mass	sensitivity
A_H	81.9(GeV)	1.3%
W_H	369(GeV)	0.20%
Z_H	368(GeV)	0.56%
e_H	410(GeV)	0.46%
ν_H	400(GeV)	0.10%

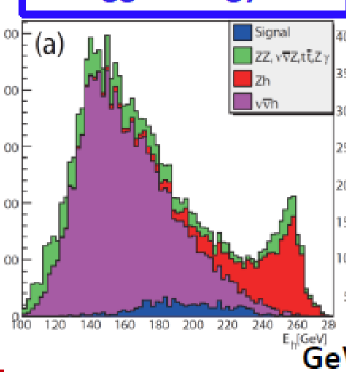


VEV of global SB

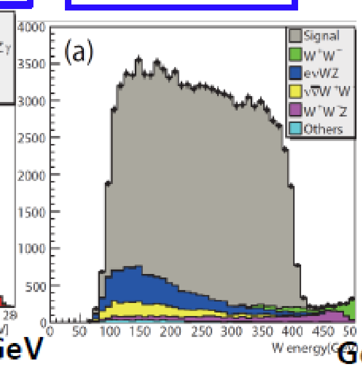
Lepton Yukawa coupling

parameter	True value	Measurement accuracy
f	580(GeV)	0.16%
K	0.5	0.01%

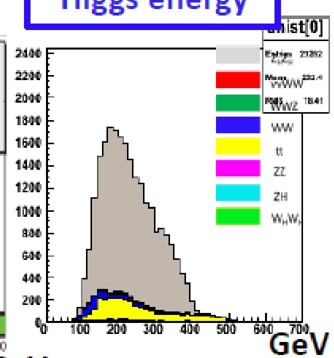
Higgs energy



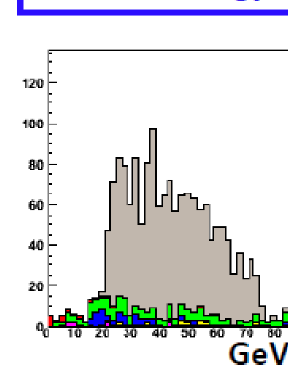
W± energy



Higgs energy



Electron energy



Electron energy