The Physics case for a Linear Collider after the LHC

Klaus Mönig

❶ Introduction

❷ The top Quark

❸ Higgs Physics

❹ SUSY

❺ Exotics

❻ Conclusions

➊ Introduction

The LHC will explore the energy range to to $\sim 3\,\text{TeV}$

Why do we want an e^+e^- collider in the same or even lower energy range?

- Electrons are elementary particles:
  - well known initial state
  - energy-momentum conservation can be used in event-reconstruction
  - energy scans allow precise mass measurements
- Electrons and positrons can be polarised: in a parity violating model the helicity structure can be probed
- Electrons don't have strong interactions: all processes have similar cross sections

Possible e^+e^- collider projects

Synchrotron radiation goes like $\left(\frac{E}{m}\right)^4/r$

➠ only linear colliders are possible to go significantly beyond LEP

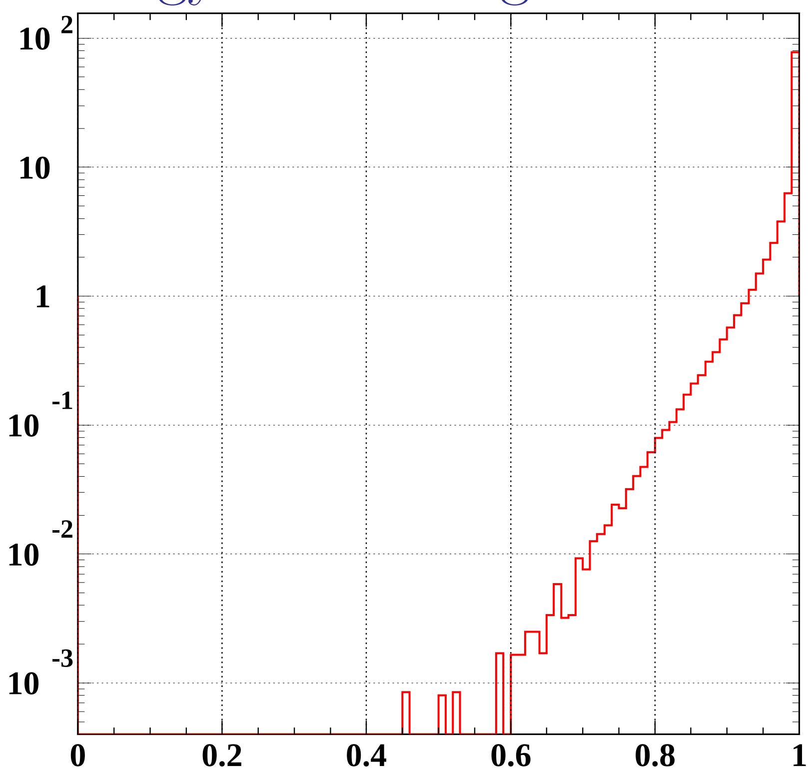
Two projects under study:

- ILC
  - Linear collider in superconducting technology
  - Energy range: $200\,\text{GeV} \leq \sqrt{s} \leq 500\,\text{GeV}$, upgradable to 1 TeV
  - Detailed design exists from a world-wide collaboration
- CLIC
  - Linear collider in two-beam technology
  - Higher gradient allows energy range $\sqrt{s} \leq 3\,\text{TeV}$
  - Studied in an international collaboration at CERN
  - Proof of principle in the next few years

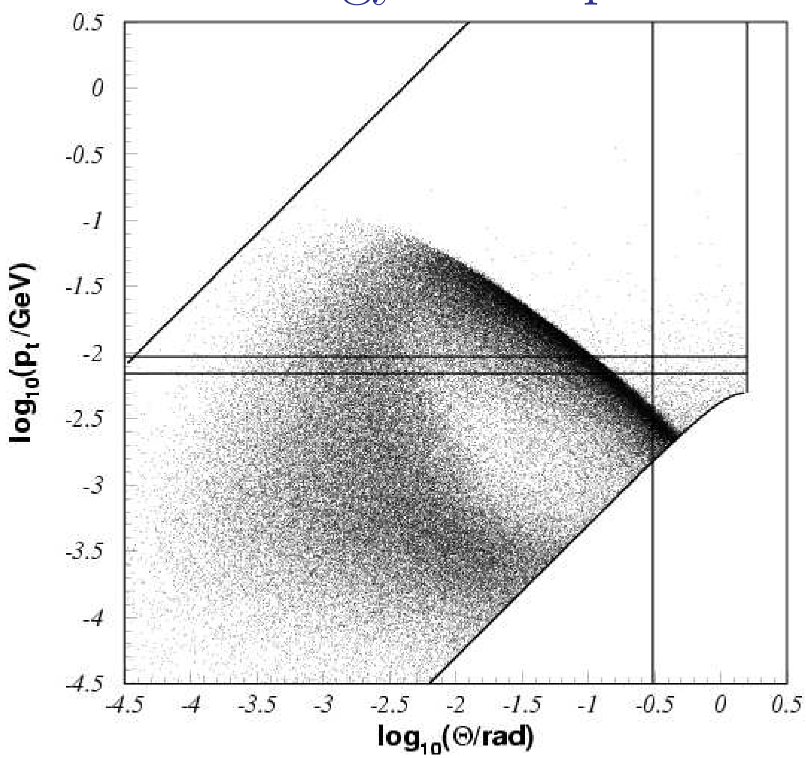
General features for linear colliders

- Beams can only be used once ➠ loss of luminosity
- To compensate for this beams must be squeezed to nm size
  ➠ Beamstrahlung
  – Beam energy not exactly defined anymore
  – Large background from low energy e^+e^- pairs close to the beampipe

Energy of colliding electrons



Low energy e^+e^--pairs



Beam Parameters

	ILC 500	CLIC 500	CLIC 3000
Luminosity $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	2	2	8
Beam size [nm^2]	5.7×640	12×202	0.7×60
Bunch length [μm]	300	35	35
Bunch spacing [ns]	370	0.67	0.67
Train frequency [Hz]	5	200	100
Train length [bunches]	2600	154	154
Electrons/bunch [10^{10}]	2	0.4	0.4
Crossing angle [mrad]	14	20	20
Energy loss from beamstrahlung [%]	2.4	4.4	21

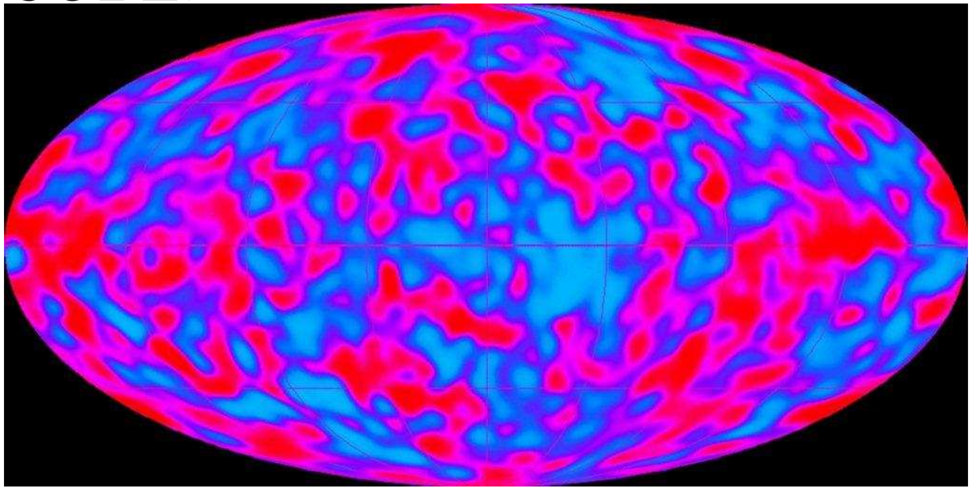
The Physics Case for a Linear Collider

- Assume that LHC is fully explored when LC starts
- The direction of physics beyond the SM should be known
- Most new particles in the LC energy range are discovered
  ➠ can design the LC according to expected physics
- However masses and couplings are known with only moderate precision
  ➠ need a new machine to really fix the model
- Many examples have been studied in detailed
  ➠ will show few examples to illustrate the case
- Up to now no example is known where no significant improvement due to the LC was seen
- In the past better precision always led to new insights

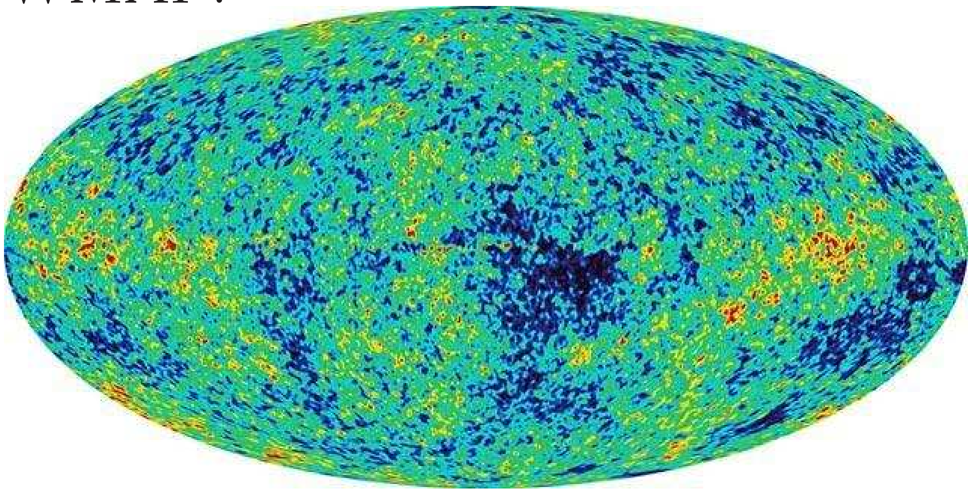
What precision buys you

Example 1: Cosmic microwave background

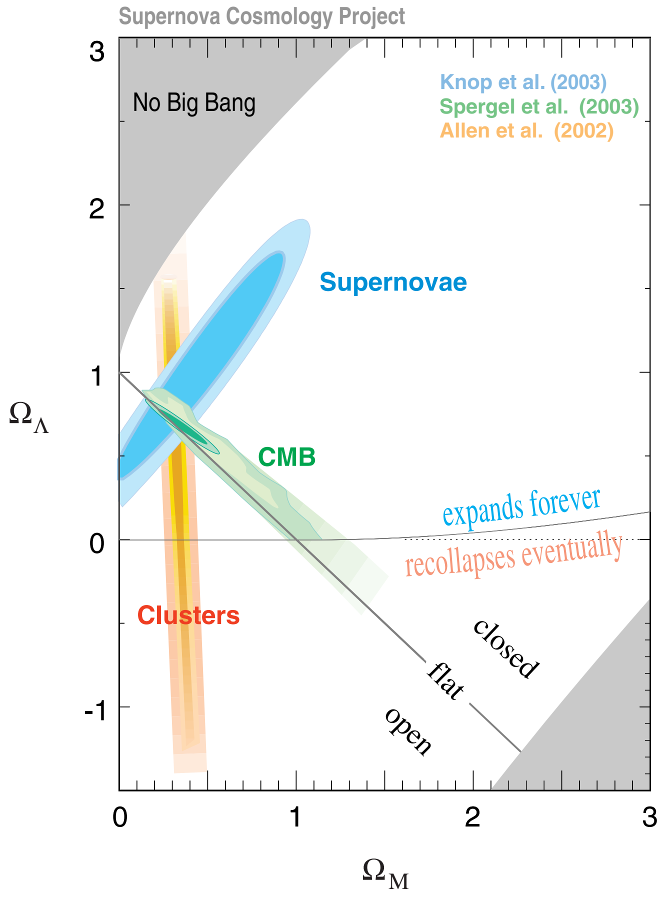
COBE:



WMAP:

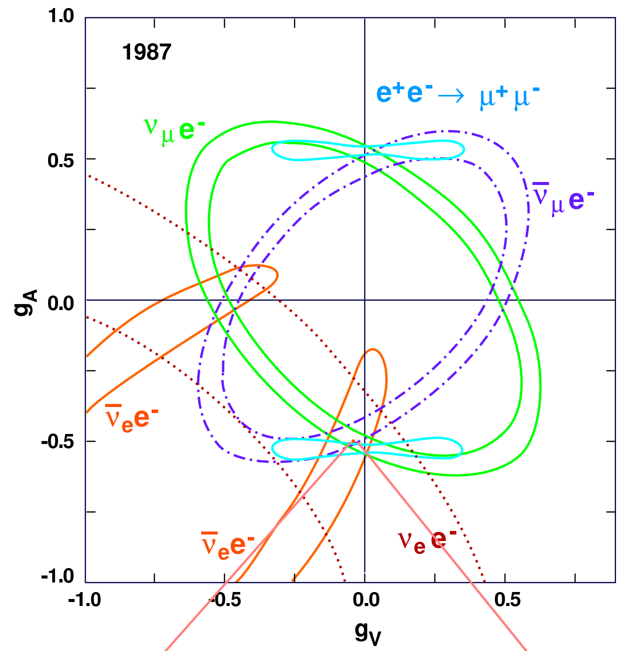


$\Longrightarrow$

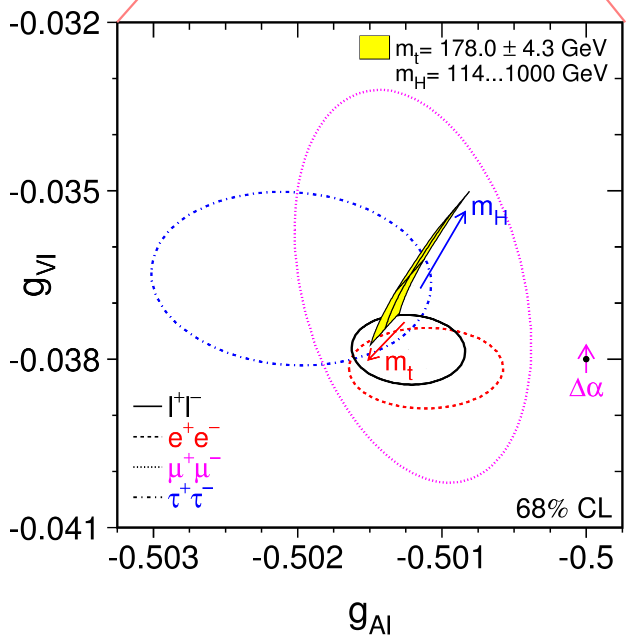


Example 2: Z couplings

Before LEP & SLD

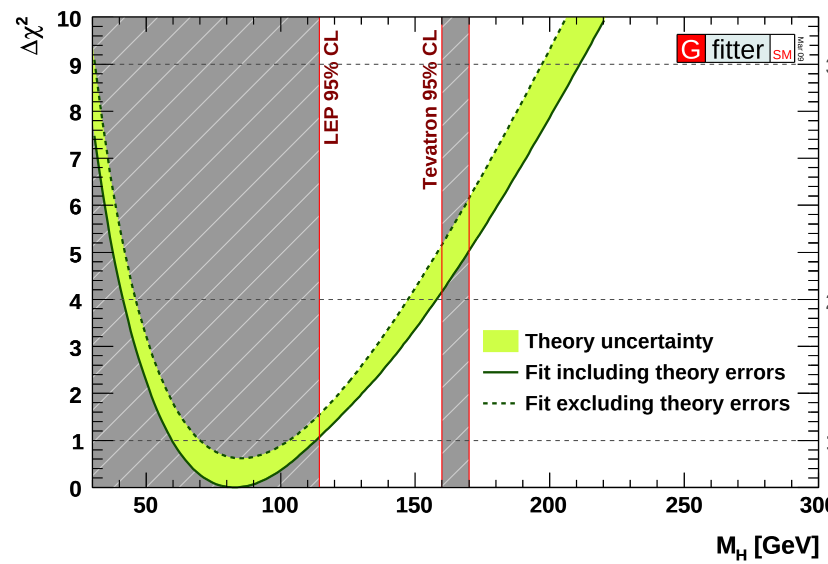


LEP & SLD



Better precision allows for a completely new quality of understanding

⟹

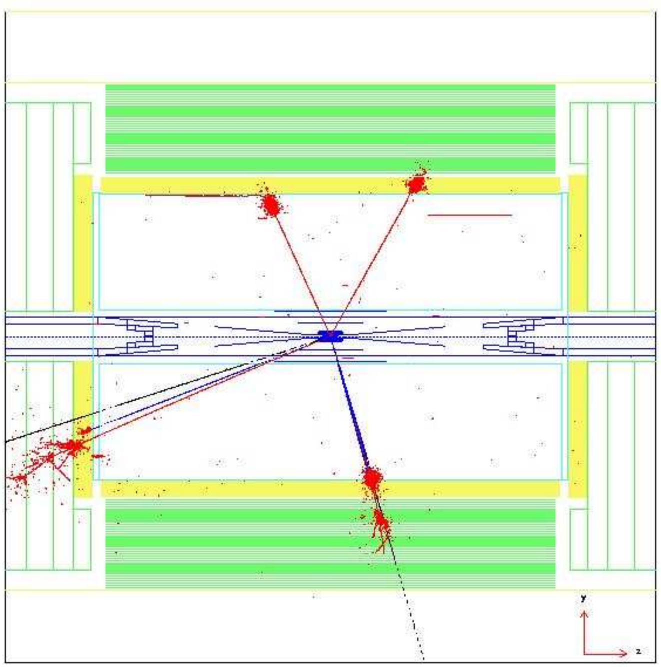


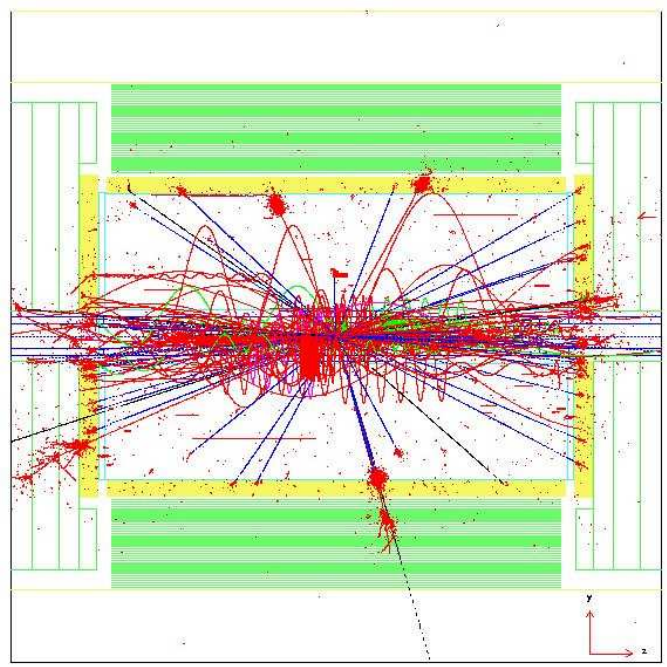
Disclaimers

Disclaimer I: Most detailed physics studies are done for the ILC assuming model parameters that give signals in the ILC range. If the new physics is at higher energies they can easily be transferred to CLIC.

Disclaimer II: CLIC can also run in the ILC energy range. We know that the precision must be worse due to the less favourable beam parameters but we are missing detailed studies to quantify this.

$HZ \to \tau^+\tau^-\mathrm{e}^+\mathrm{e}^-$ ILC 32BX (= 16ns) CLIC500 (K. Desch)





❷ The top Quark

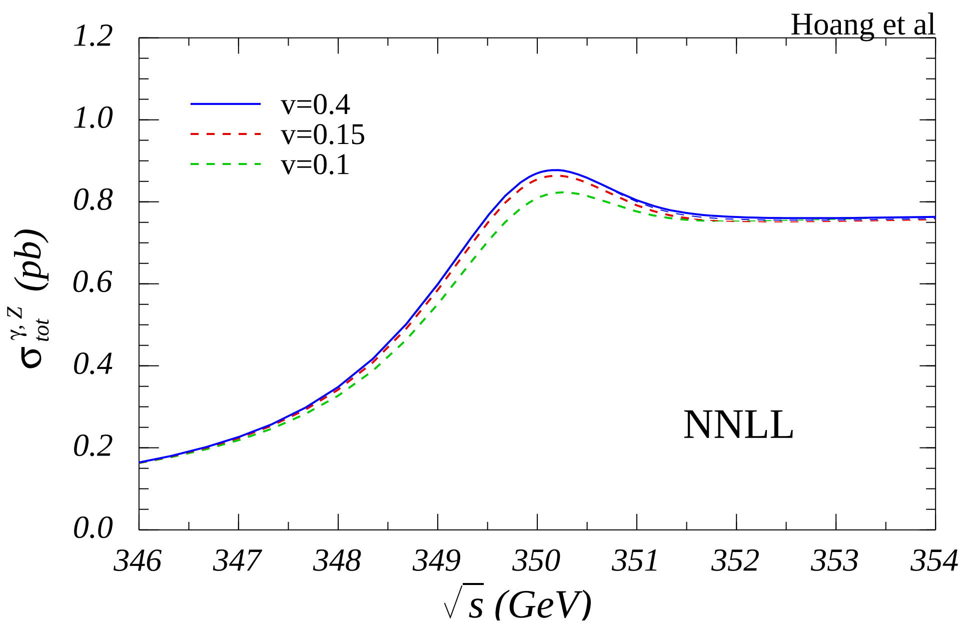
The top mass

- Hadron colliders can measure the top-mass to $\sim 1\,\mathrm{GeV}$ at most
- For electroweak precision tests this is sufficient
- However in models where the Higgs mass can be obtained from other model parameters (e..g. SUSY) there a large corrections from top-loops $(\Delta m_{\mathrm{H}}/\Delta m_{\mathrm{t}} = \mathcal{O}(1))$

  ➟ Higgs mass only useful if top-mass is known to similar precision

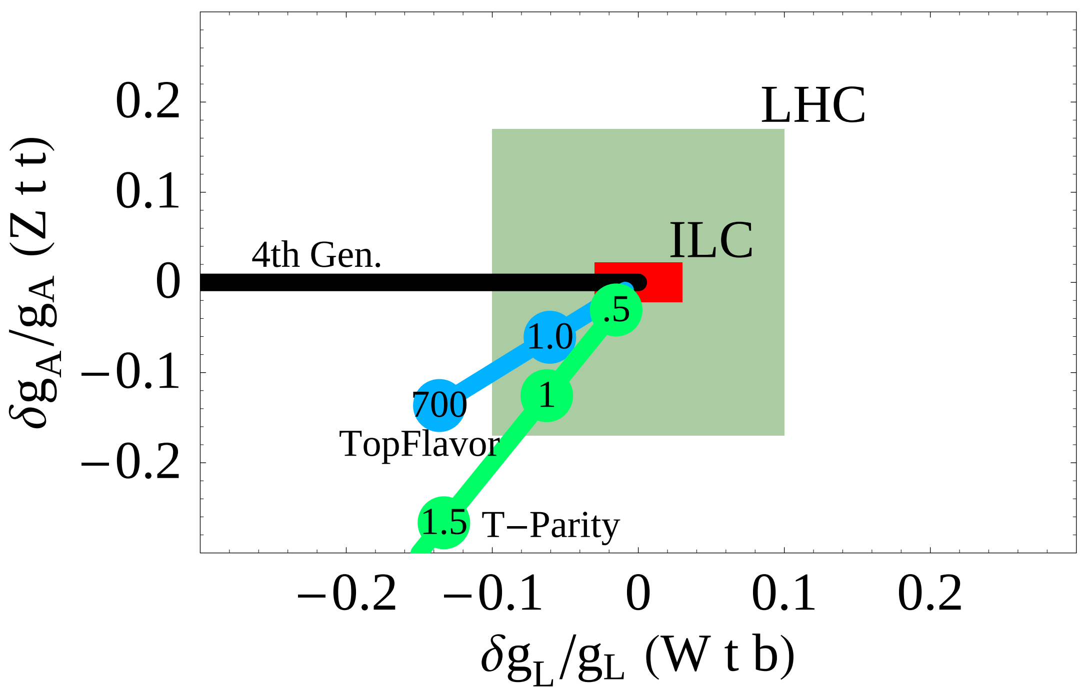
- LC can measure m_{t} and Γ_{t} with a threshold scan to $\sim 50\,\mathrm{MeV}$ precision
- Contrary to reconstruction methods (LHC) the threshold mass is theoretically well under control

  ➟ $\Delta m_{\mathrm{t}}(\overline{\mathrm{MS}}) \approx 100\,\mathrm{MeV}$ possible



Top-quark couplings

- The top-mass is close to the vacuum expectation value of the Higgs
- In many models of electroweak symmetry breaking it therefore plays a special role
- The $t\bar{t}W$ couplings can be measured from the top-decay
- A LC can measure $t\bar{t}Z$ couplings from the top-production using cross section, A_{LR}, A_{FB} and top polarisation
- A large sensitivity to BSM-physics can be achieved

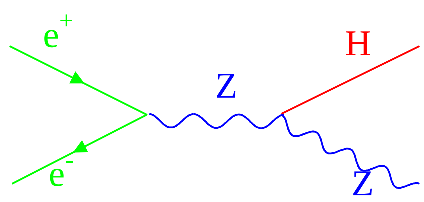


❸ Higgs physics

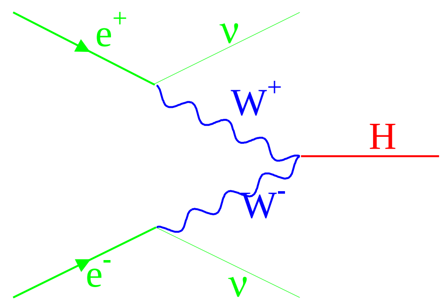
- If a roughly SM like Higgs exists LHC will find it
- However ILC has still a lot to do to figure out the exact model and to measure its parameters

- Main production at e^+e^- colliders

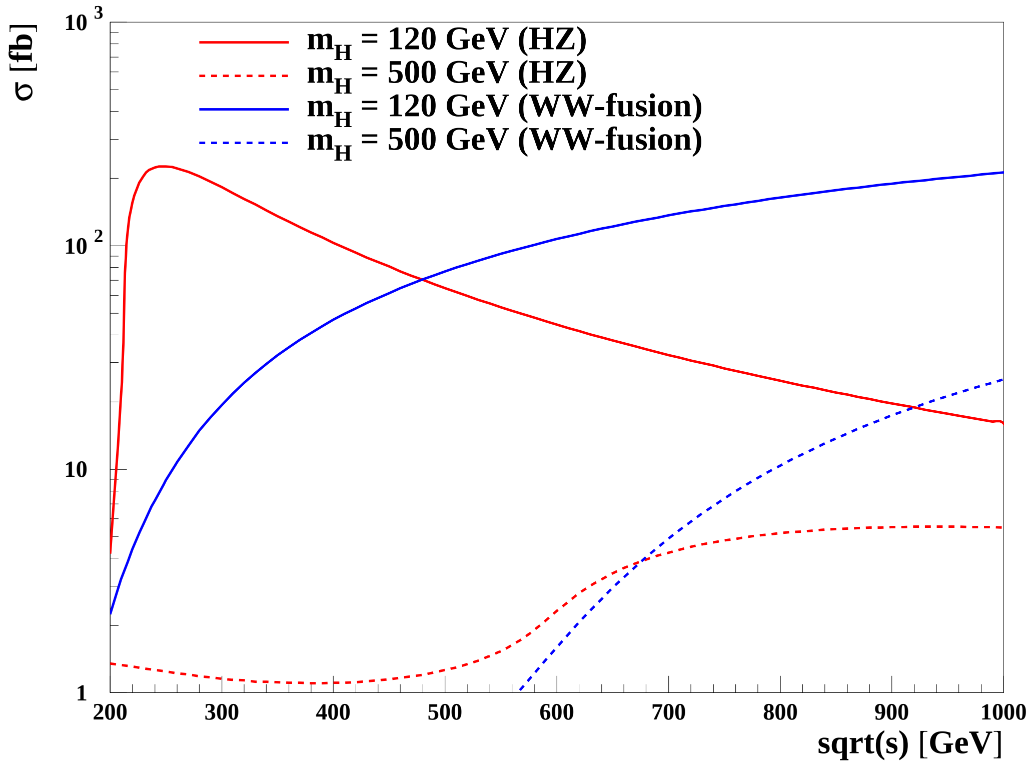
Higgsstrahlung



W-fusion



- Cross section:



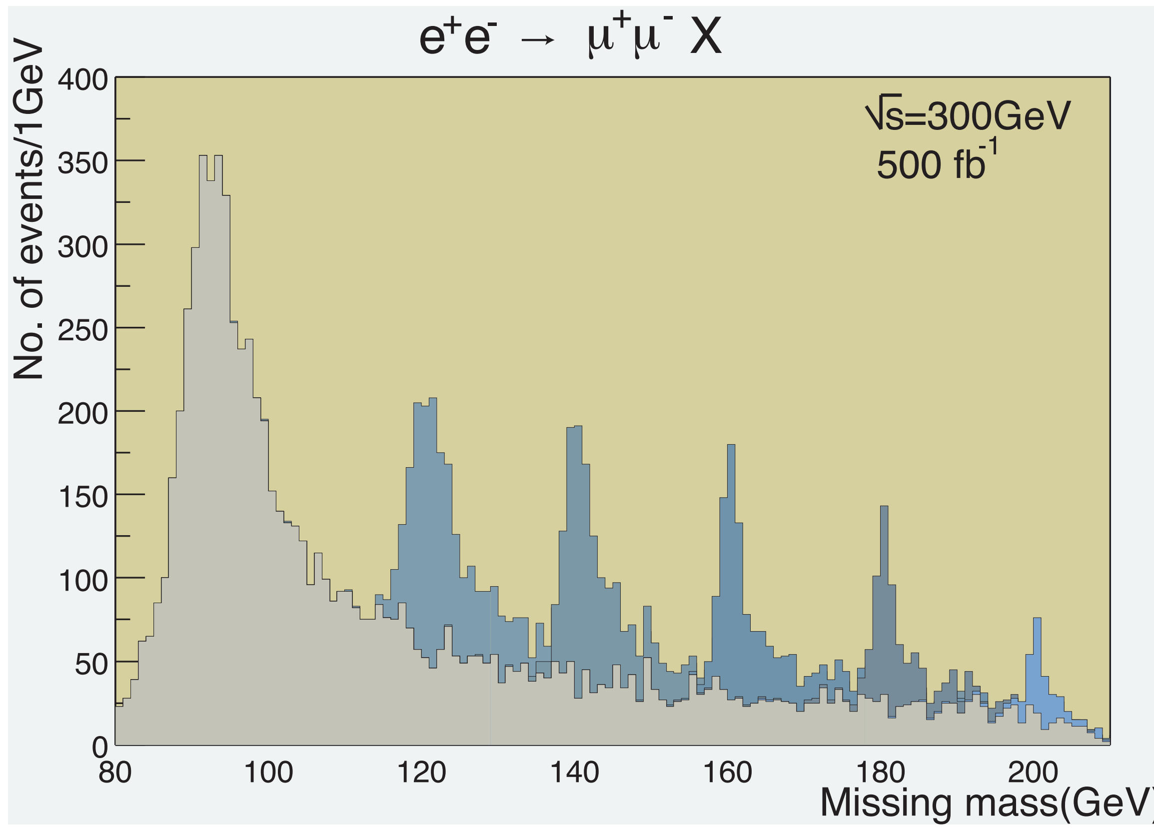
First key measurement: Unbiased $e^+e^- \to HZ$ measurement from recoil mass

- Select events $e^+e^- \to ZX$ with $Z \to \ell^+\ell^-$
- Can see Higgs peak in recoil-mass spectrum without any link to Higgs decay products

➡ Unbiased measurement of HZZ coupling

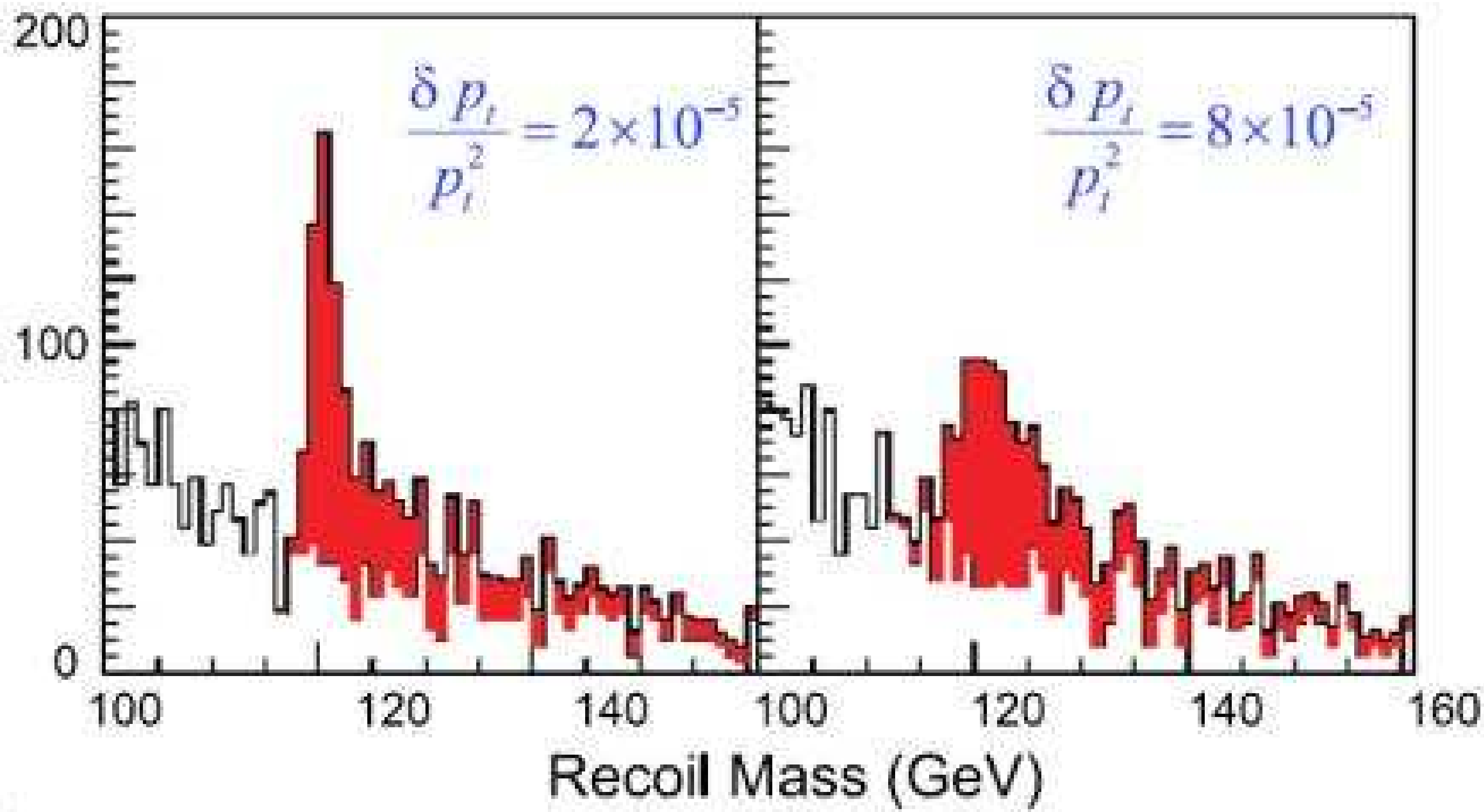
➡ Unbiased basis for Higgs branching ratios

- Measurement best at cross section maximum $\sqrt{s} \approx m_H + m_Z + 40\,\mathrm{GeV}$
- However possible in a rather wide energy range



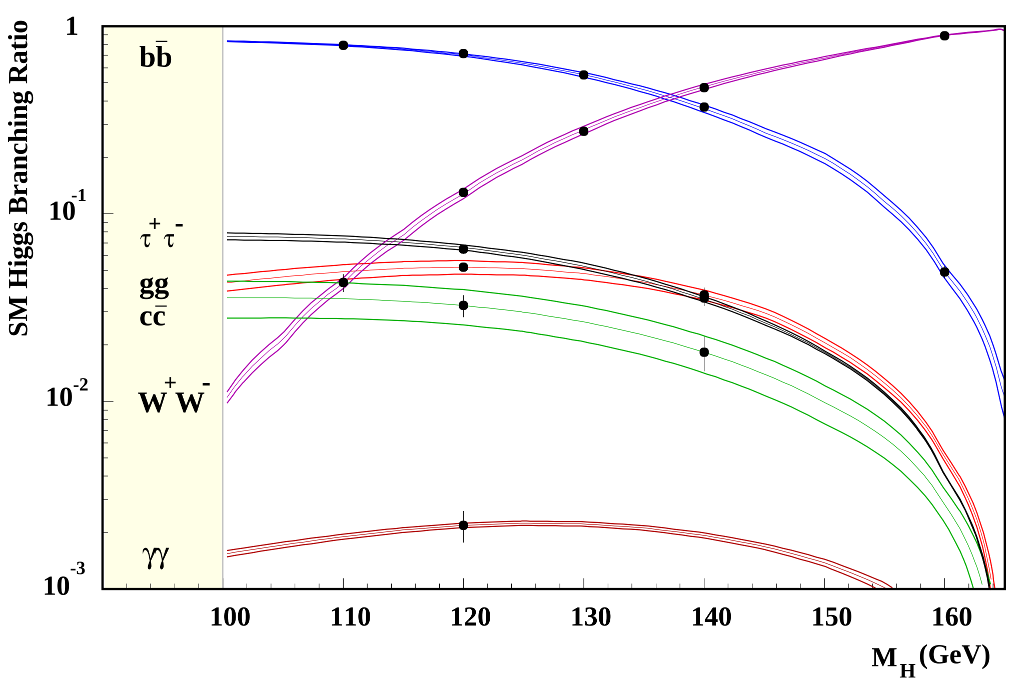
Since we are at en EUDET meeting...

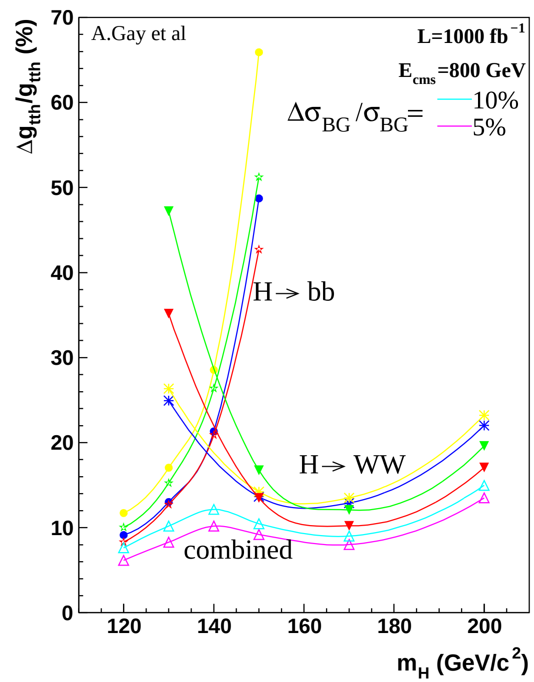
...resolution matters



Higgs couplings

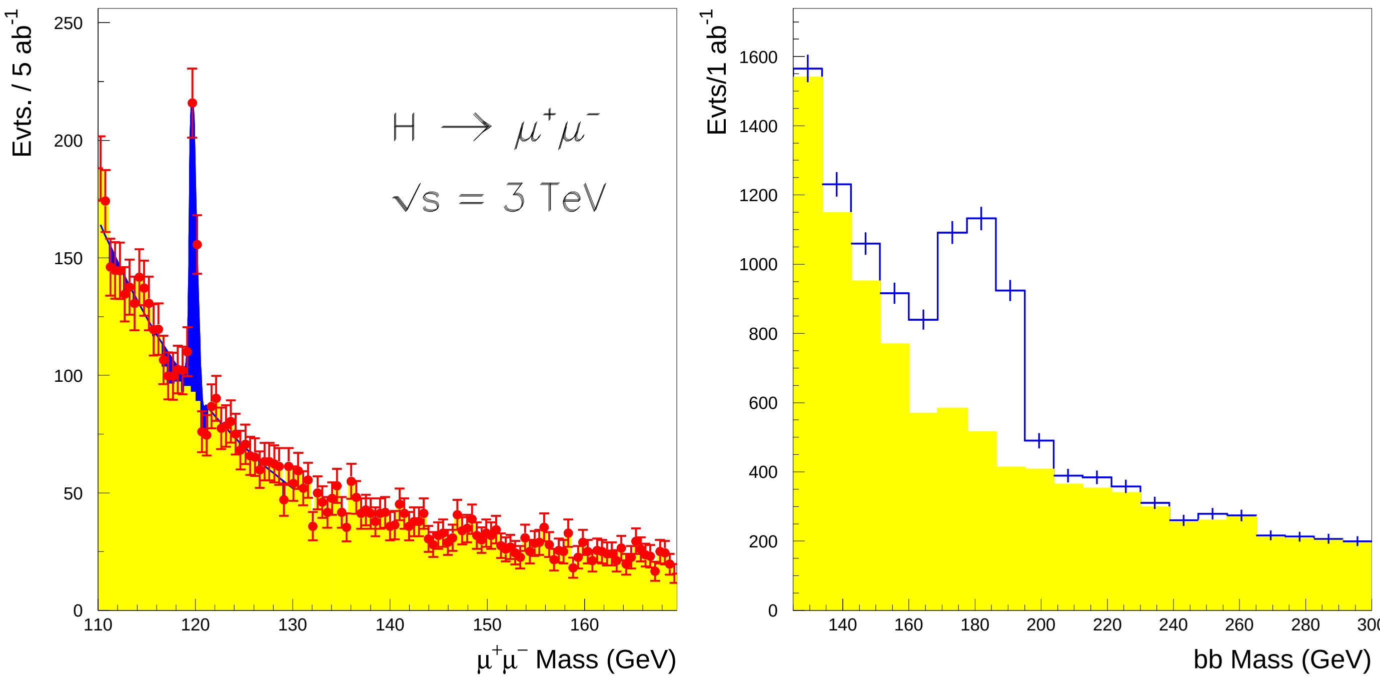
- The HZZ coupling can be directly obtained on the 3% level from the recoil measurement
- If the Higgs is reasonably light ($m_{\mathrm{H}} \lesssim 140\,\mathrm{GeV}$) the branching ratios to many fermions can be measured with good accuracy
- $H\mathrm{b\bar{b}}$ remains visible up to around $m_{\mathrm{H}} \lesssim 200\,\mathrm{GeV}$
- The $\mathrm{t\bar{t}}H$ coupling can be measured from $\mathrm{t\bar{t}}H$ final states





Advantage of high energy (CLIC): fusion cross section rises

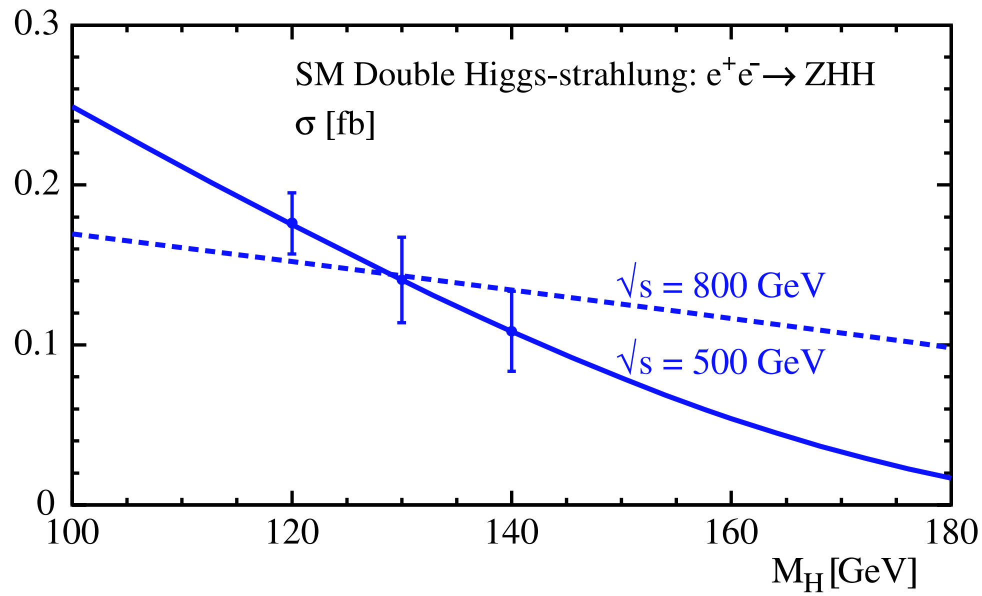
$\Rightarrow$ rare decays can be measured with better precision

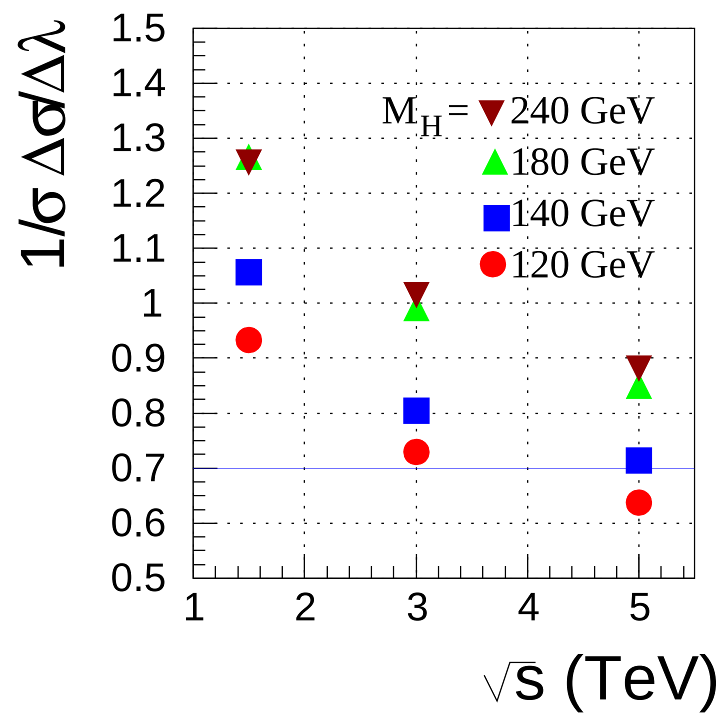


- $H \rightarrow \mu^+\mu^-$: 4.2% precision for $m_{\mathrm{H}} = 120\,\mathrm{GeV}$
- $H \rightarrow \mathrm{b\bar{b}}$: 3.4% precision for $m_{\mathrm{H}} = 220\,\mathrm{GeV}$

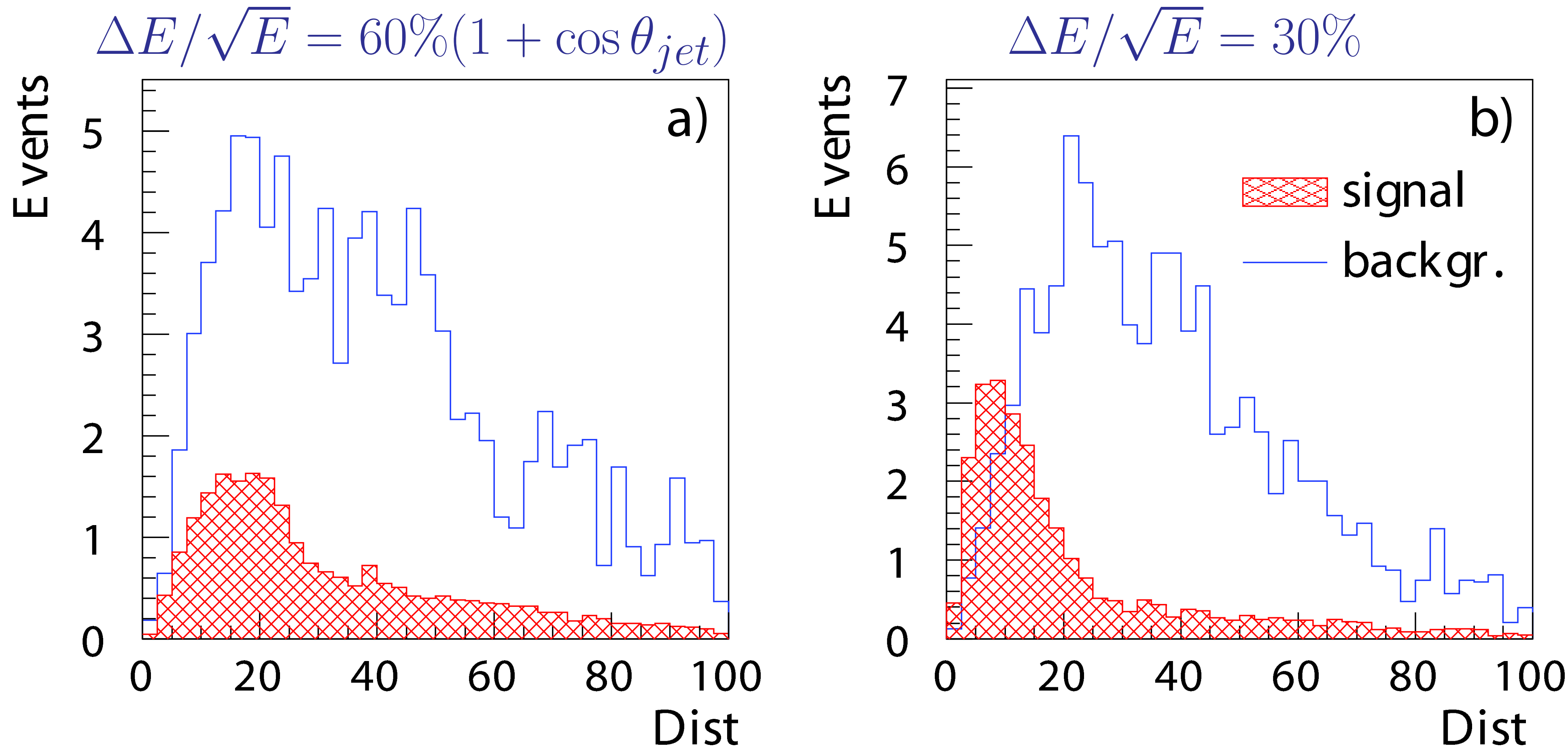
The Higgs self-coupling

- The HHH coupling can be measured from ZHH events at $\sqrt{s} = 500\,\mathrm{GeV}$ and $\nu\nu HH$ events at $\sqrt{s} \sim 1\,\mathrm{TeV}$
- Studies up to now use $H \to \mathrm{b\bar{b}}$
- Combining both energies gives $\Delta\lambda_{HHH} = 12\%$ for $m_{\mathrm{H}} = 120\,\mathrm{GeV}$ degrading with higher Higgs masses
- For higher energies the larger cross section gets partly compensated by a lower sensitivity
  ➠ significant gain only for heavier Higgses



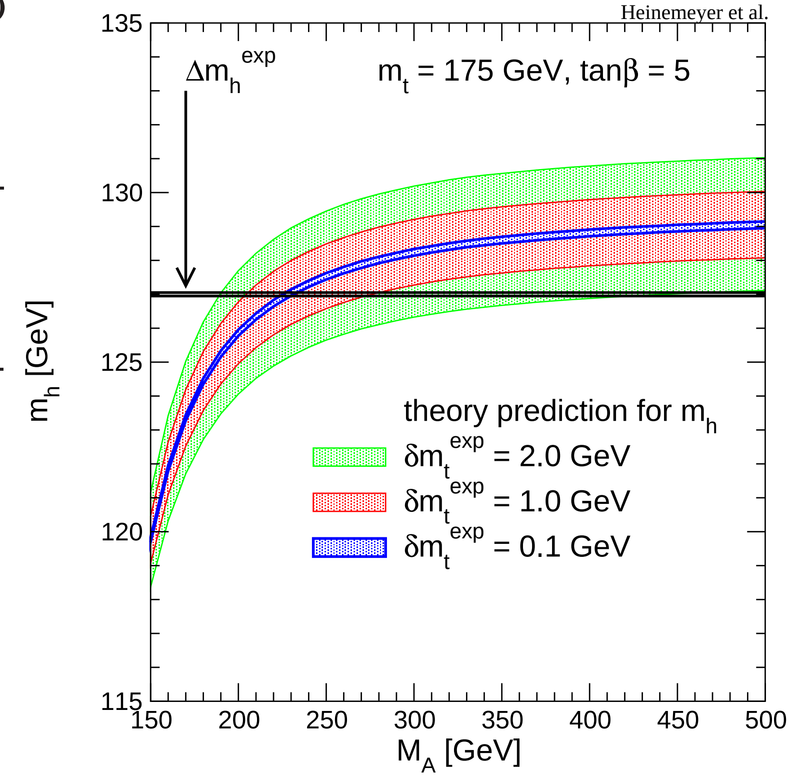


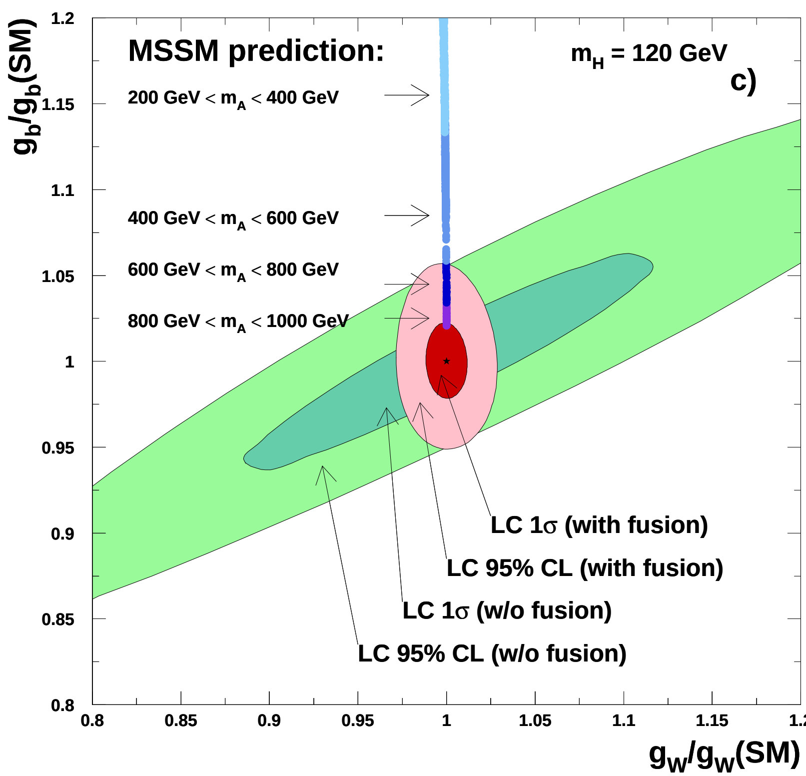
...and again:

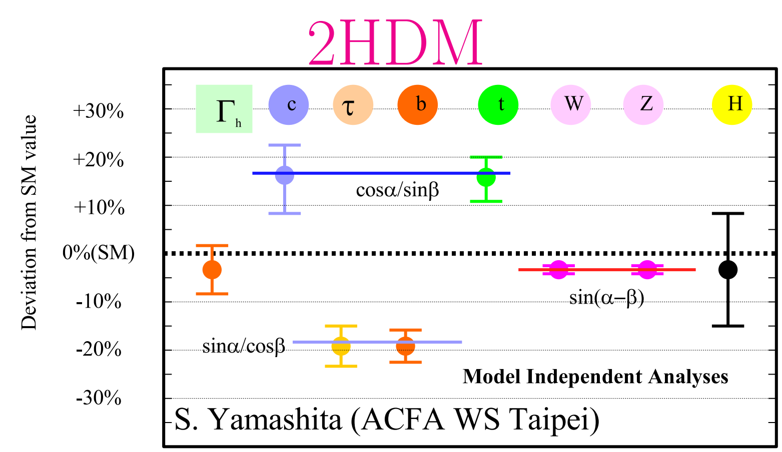

$\Delta E/\sqrt{E} = 60\%(1+\cos\theta_{jet})$
Events
a)
Dist
$\Delta E/\sqrt{E} = 30\%$
b)
signal
backgr.

Applications of precision Higgs measurements

- Many coupling measurements lead way to new physics looking at patterns
- In a model (SUSY) precision couplings allow measurements of model parameters
- Similarly mass measurements allow determination of model parameters



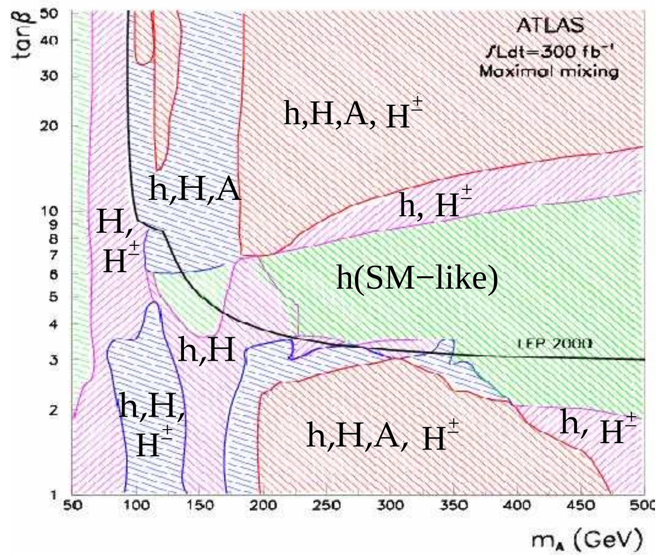


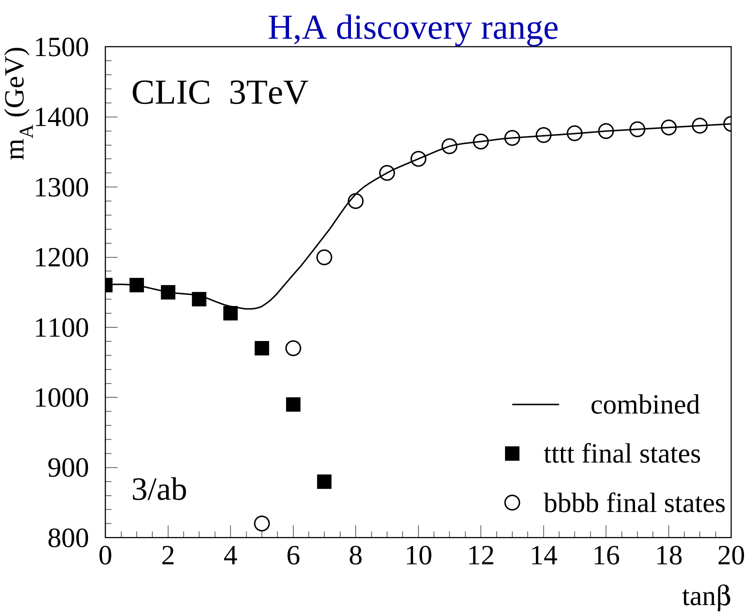


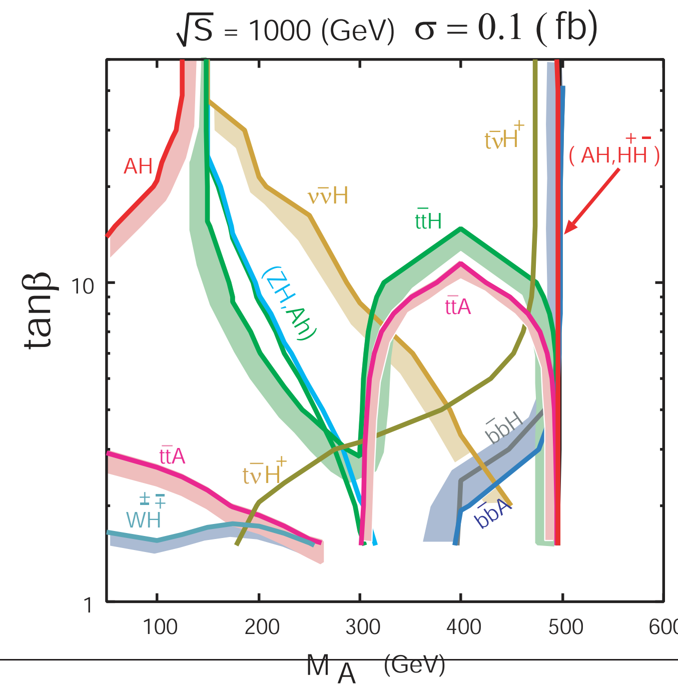
Heavy SUSY Higgses

- The LHC has problems to see heavy SUSY Higgses for medium $\tan\beta$
- An e^+e^--LC is sensitive up to almost $\sqrt{s}/2$
- In a photon-collider-mode it can see heavy (neutral) Higgses even up to $0.8\sqrt{s_{ee}}$

Visible SUSY-Higgses at the LHC



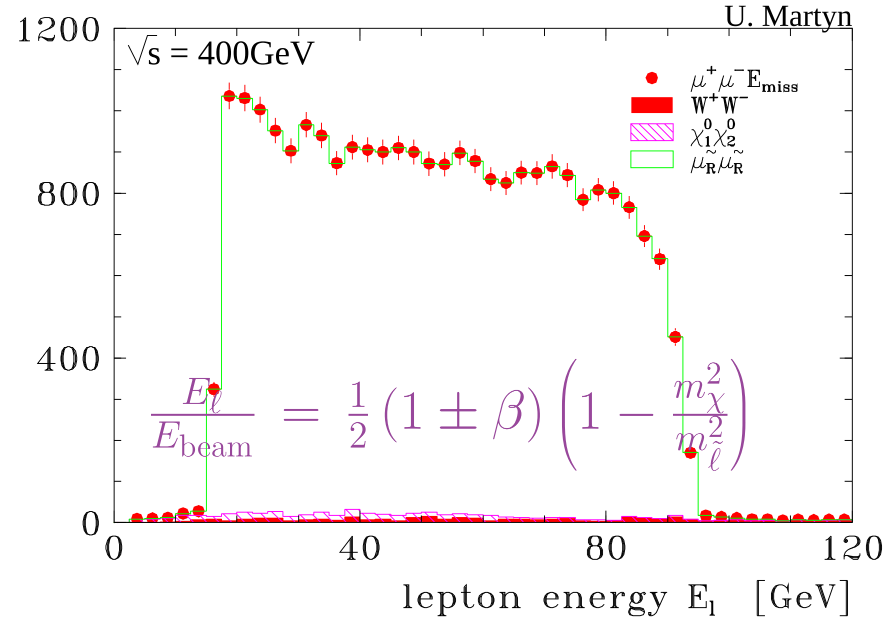


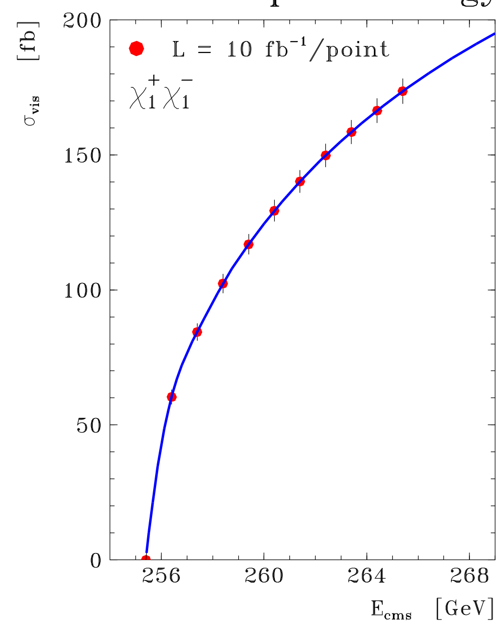


❹ Supersymmetry

- If SUSY is in an LC range LHC should have discovered it
- If R-parity is conserved (dark matter!) the LHC has problems to measure the absolute mass scale
- The LC can measure all masses, including the invisible LSP, with reconstruction methods and threshold scans
- A mass precision in the 100 MeV region is possible

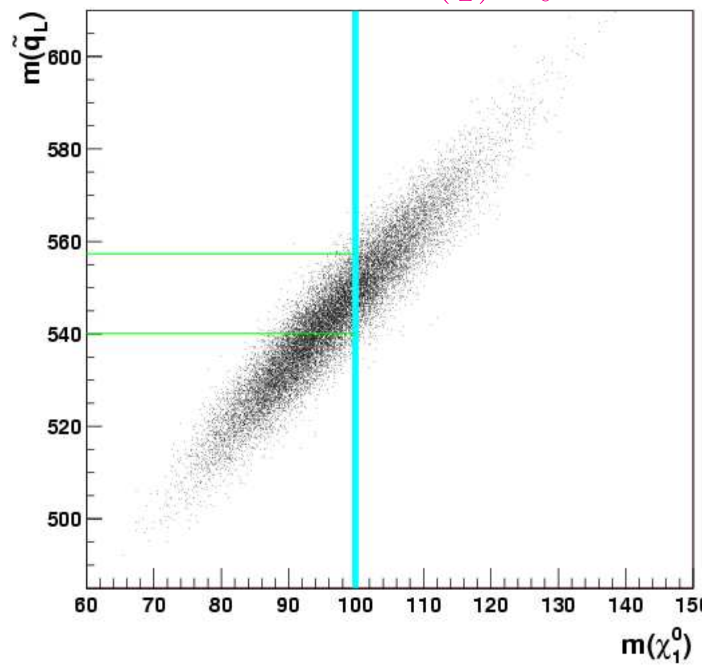
μ energy from $e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^-$





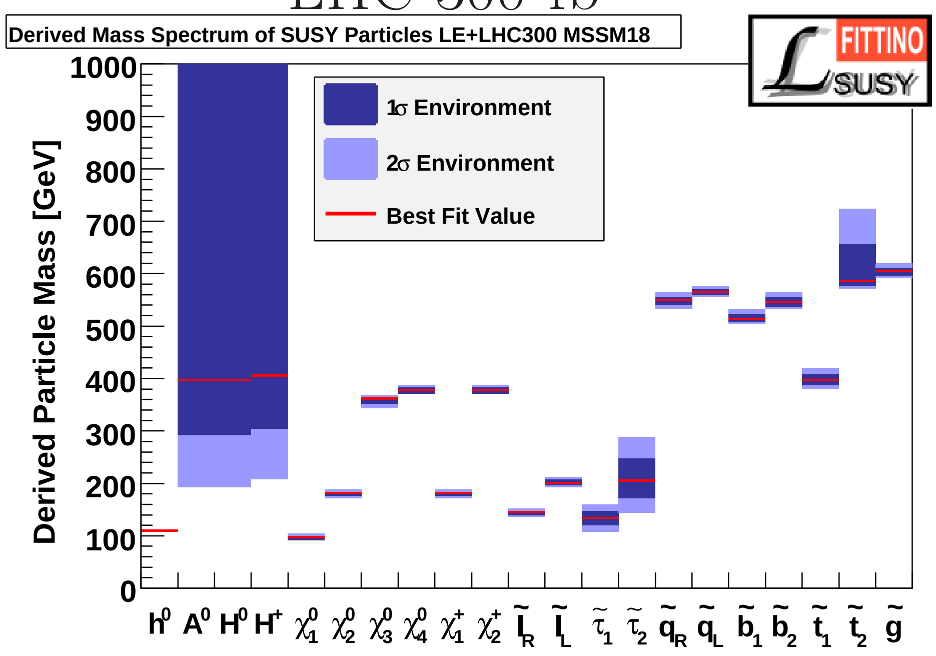
The LC measurements can also improve the LHC precision for heavy superpartners

Improvement of LHC $m(\tilde{q})$ by ILC $m(\tilde{\chi}_1^0)$

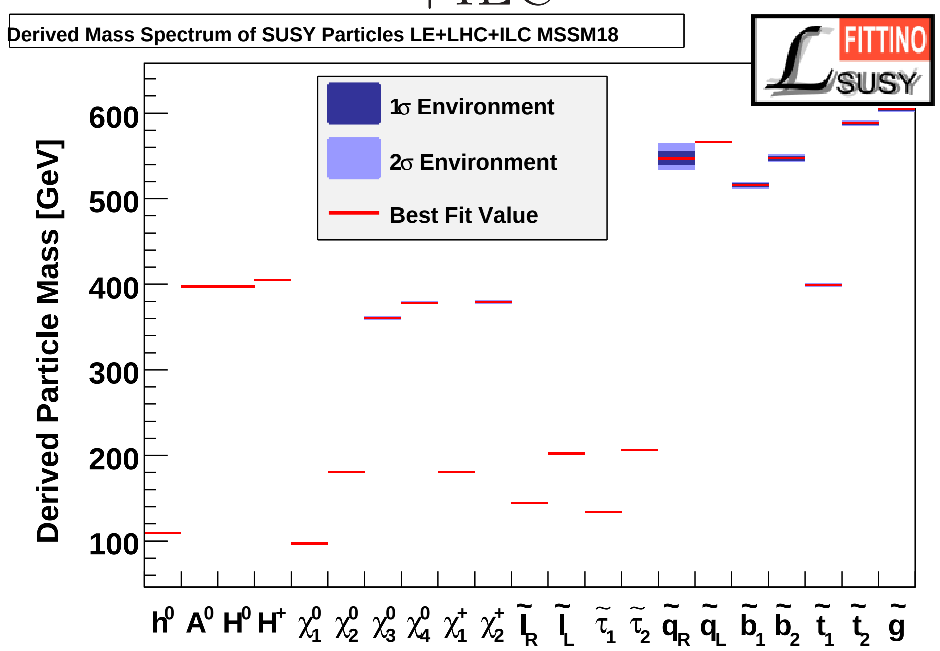


Possible precision in MSSM18:

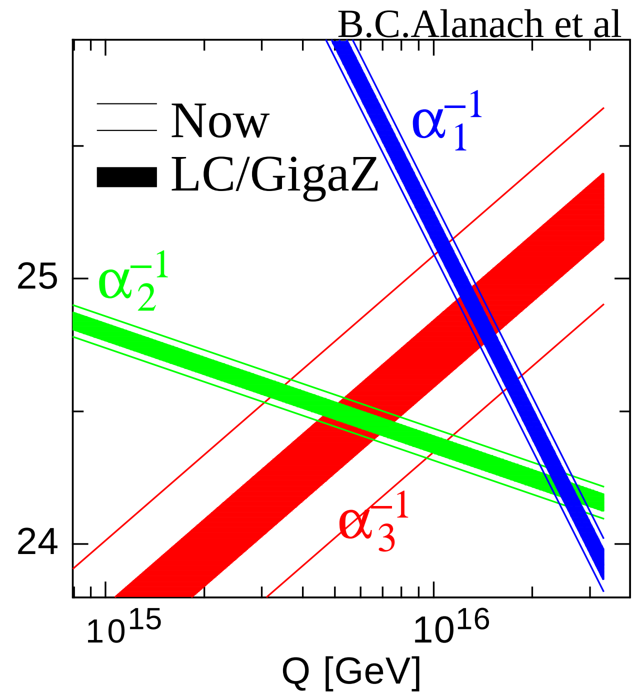
LHC 300 fb^{-1}

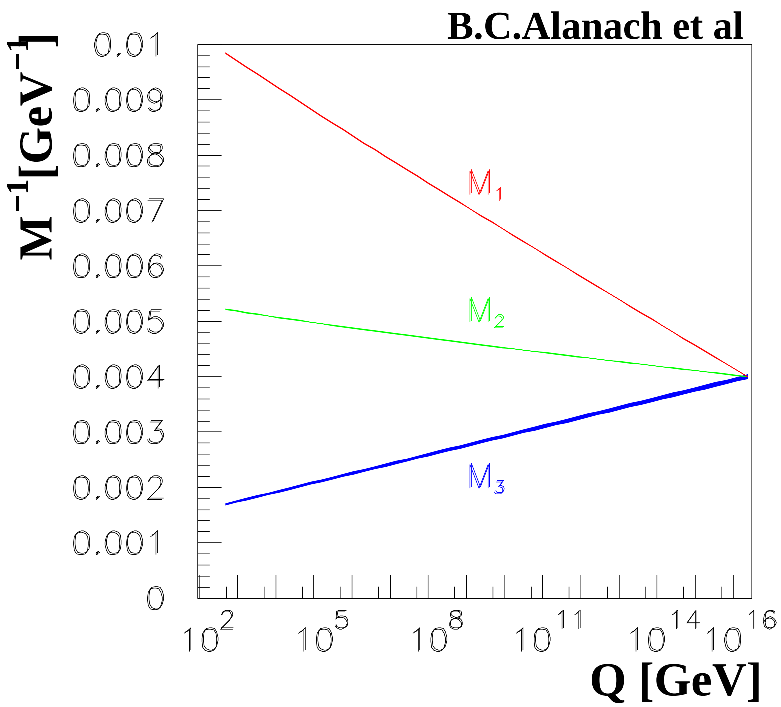


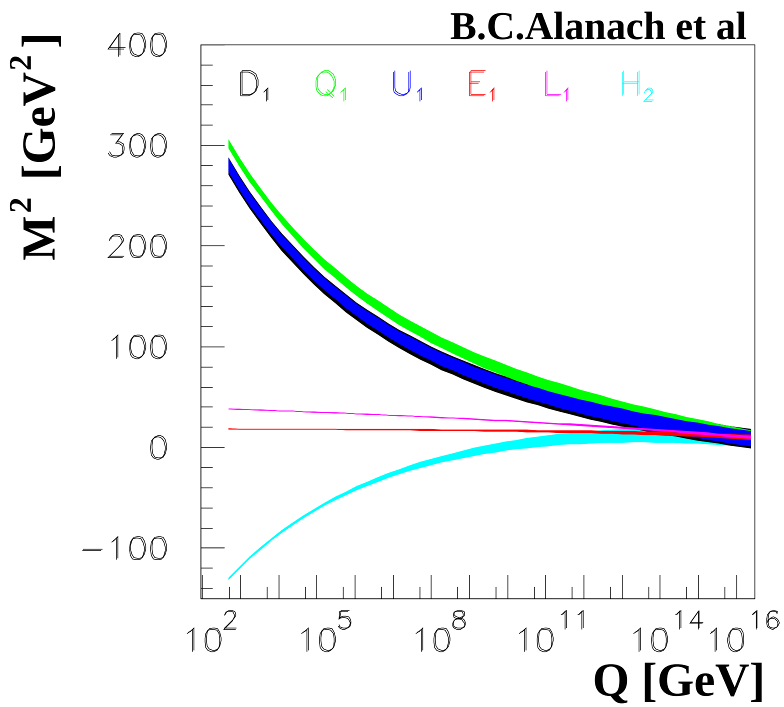
+ILC



This allows for a powerful test of unification, testing the underlying model of supersymmetry-breaking



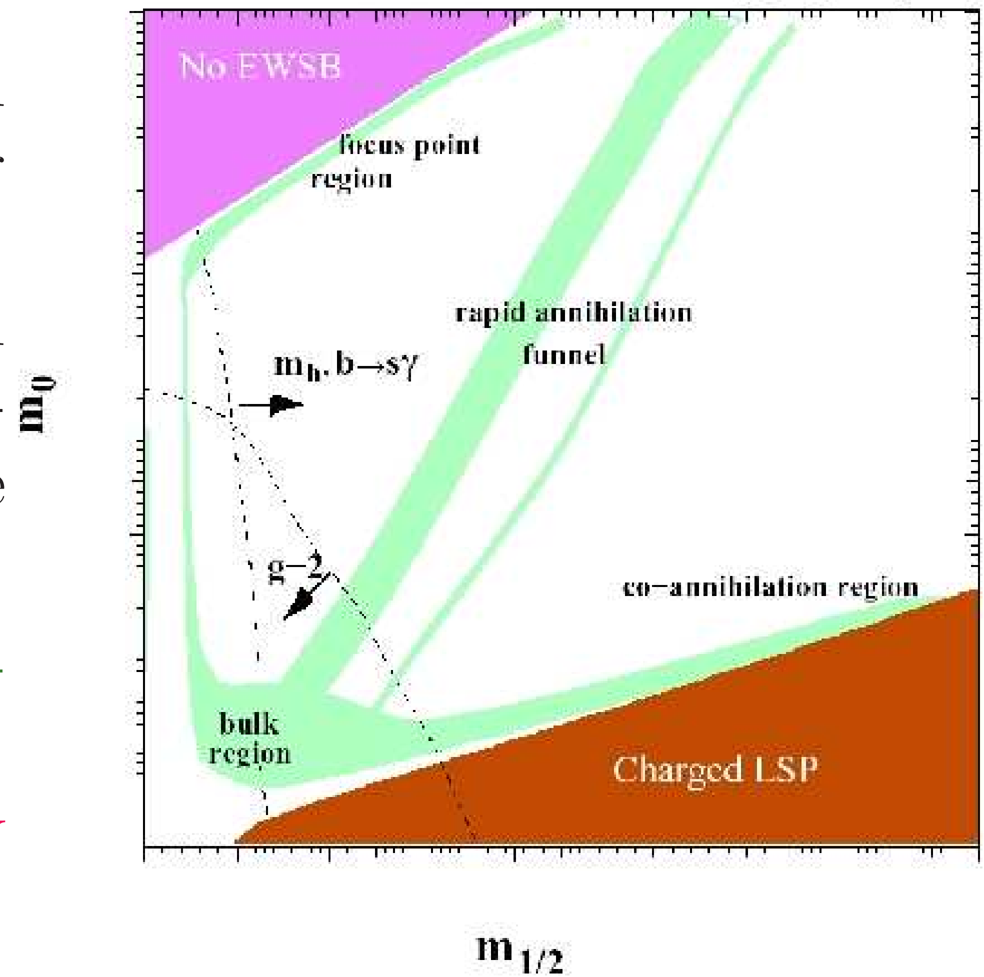




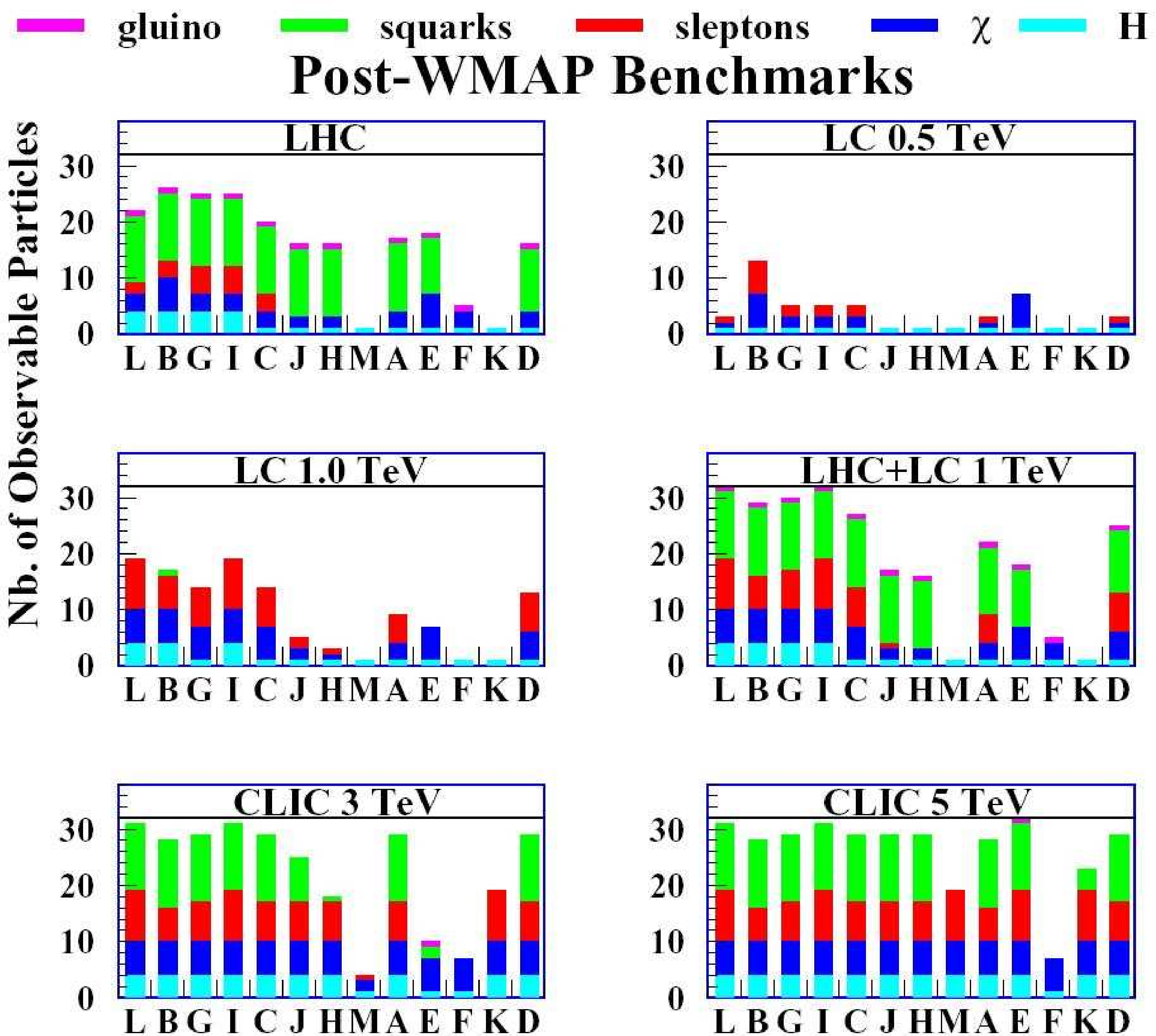
Where do we expect SUSY

- Slight indications from $(g-2)_\mu$ that SUSY is light but be careful because of $e^+e^- - \tau$ problem and recent Barbar data!
- However missing EDMs and B-physics point to heavy scalars unless phases are zero
- Dark Matter studies within mSUGRA indicate that either SUSY is light (bulk region) or in special regions like small $\tilde{\tau} - \tilde{\chi}_1^0$ or $\tilde{\chi}_1^\pm - \tilde{\chi}_1^0$ mass difference or resonance conditions like $m(\tilde{\chi}_1^0) \approx m_H/2$
- Bulk region gives lots of SUSY already for ILC
- However in special regions SUSY can be heavy

ALCPG cosmology group



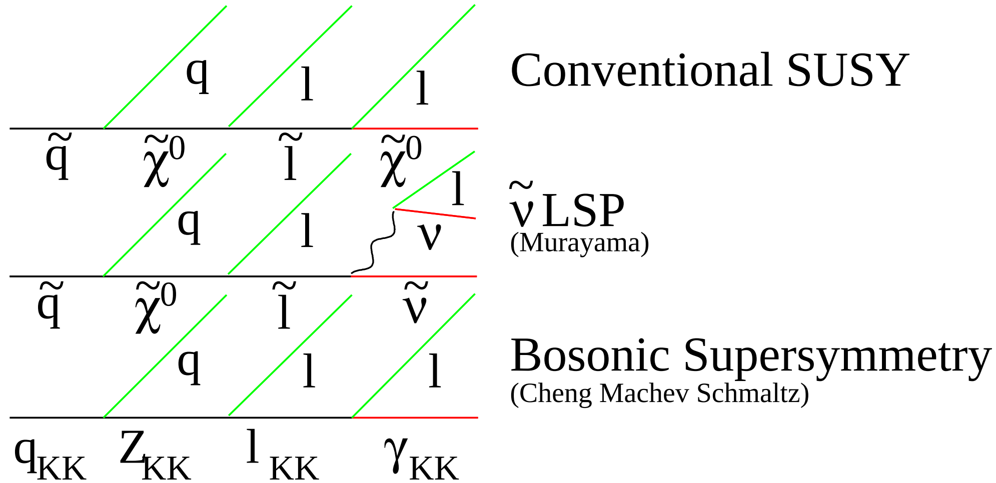
CLIC should see most of the SUSY spectrum in most cases



But is it really SUSY what we see?

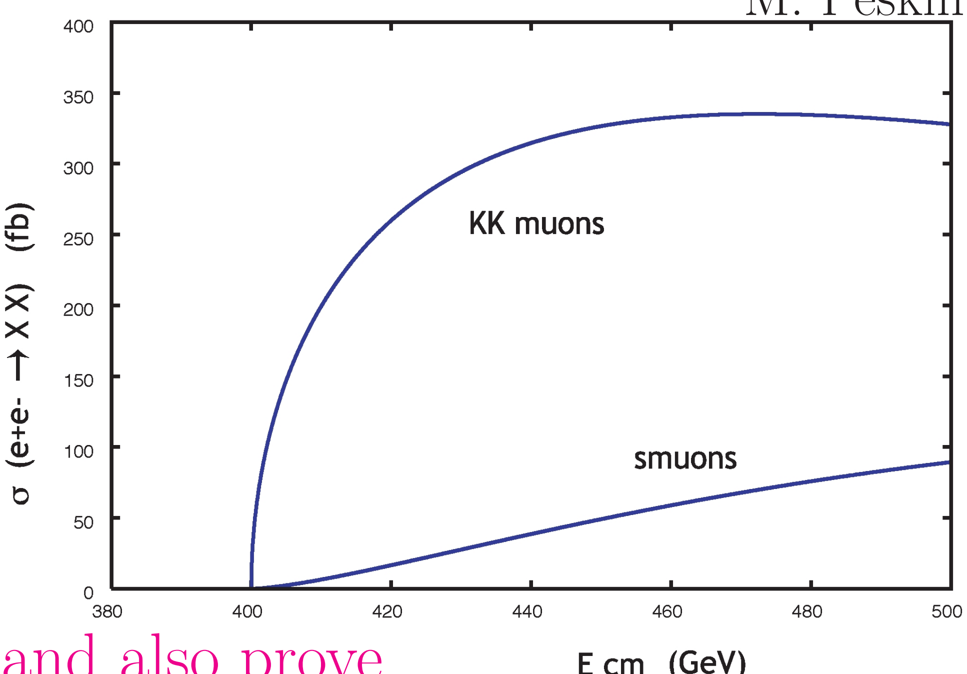
LHC sees a $\ell^+\ell^-$ mass edge, but what is it?

M. Peskin, Victoria



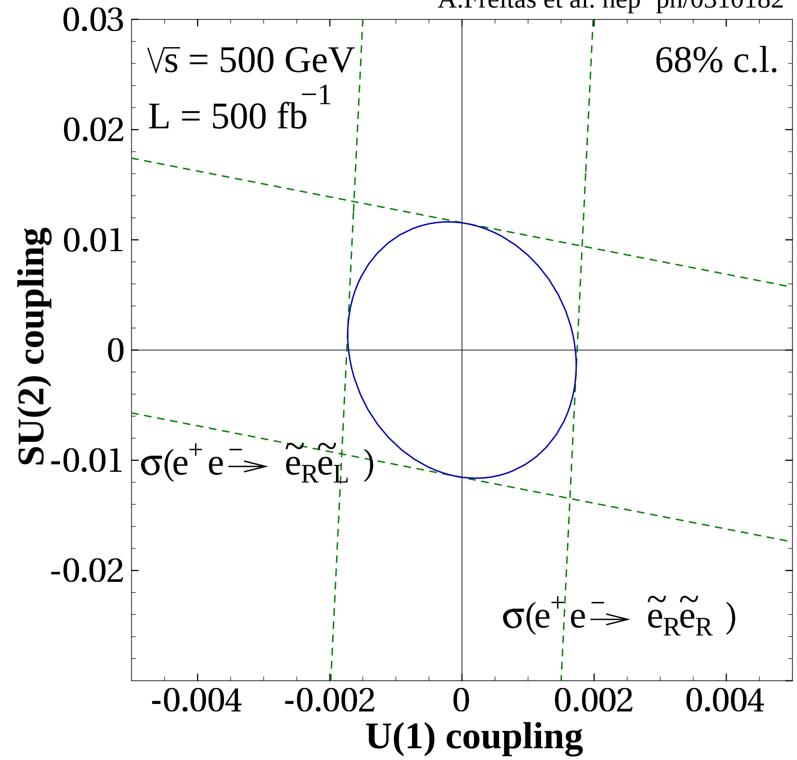
The ILC can distinguish the different models

M. Peskin



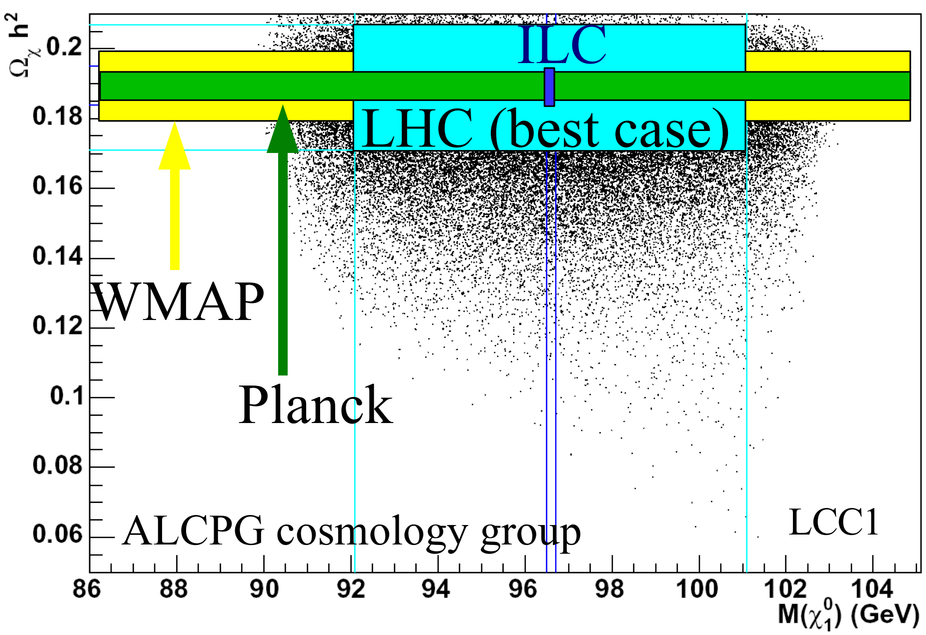
and also prove that the couplings are correct

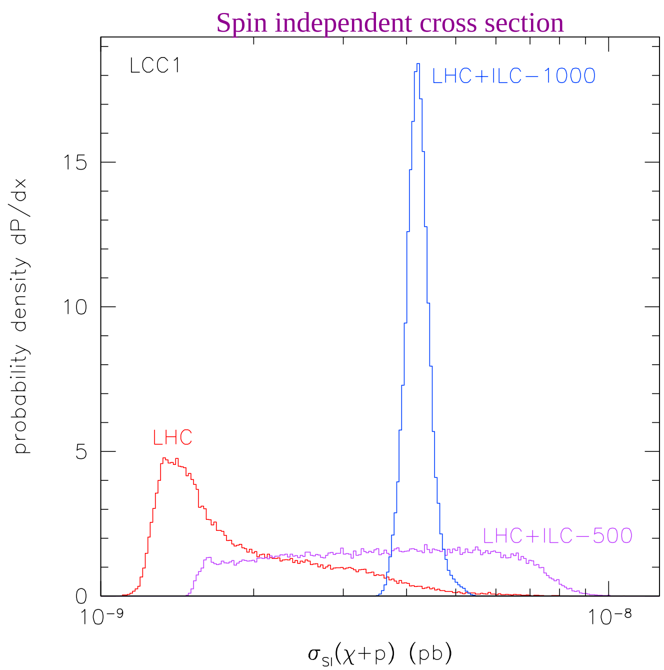
A.Freitas et al. hep-ph/0310182



Dark Matter Reconstruction

- Understanding dark matter is one of our most urgent problems
- In a model like SUSY all dark matter properties can be calculated when the model parameters are known
- In practice only the properties of a few particles are needed
- For light SUSY LHC does pretty well with the density, LC matches the precision of Planck, however for the cross section already here LC1000 is needed

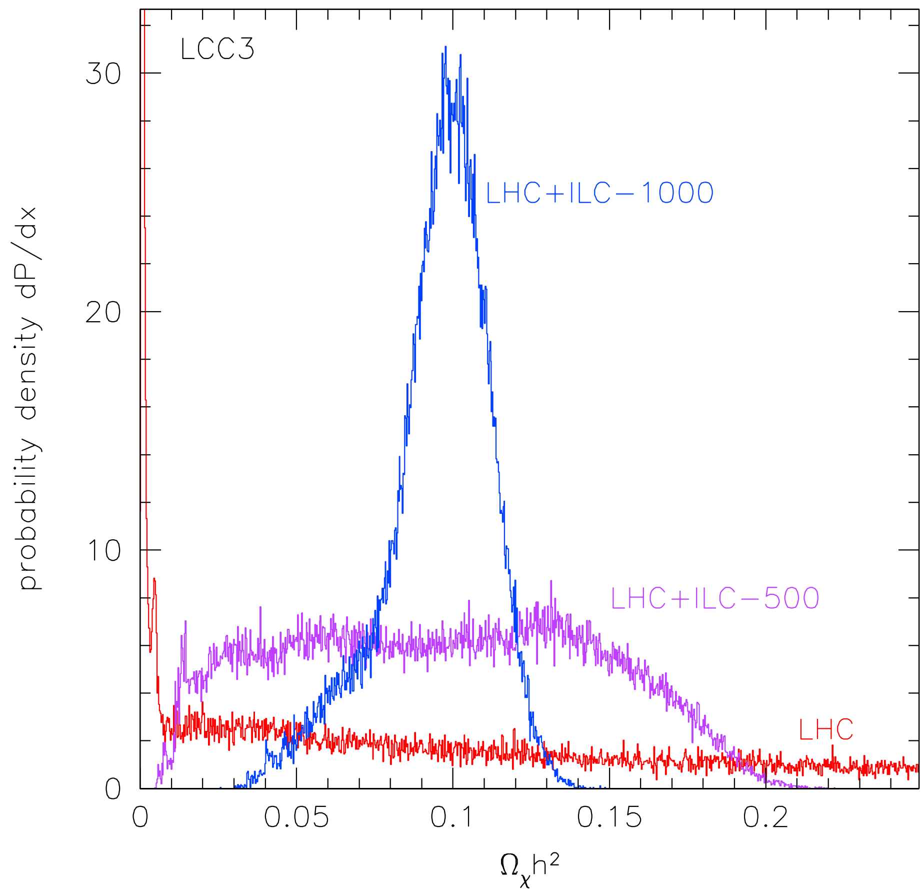




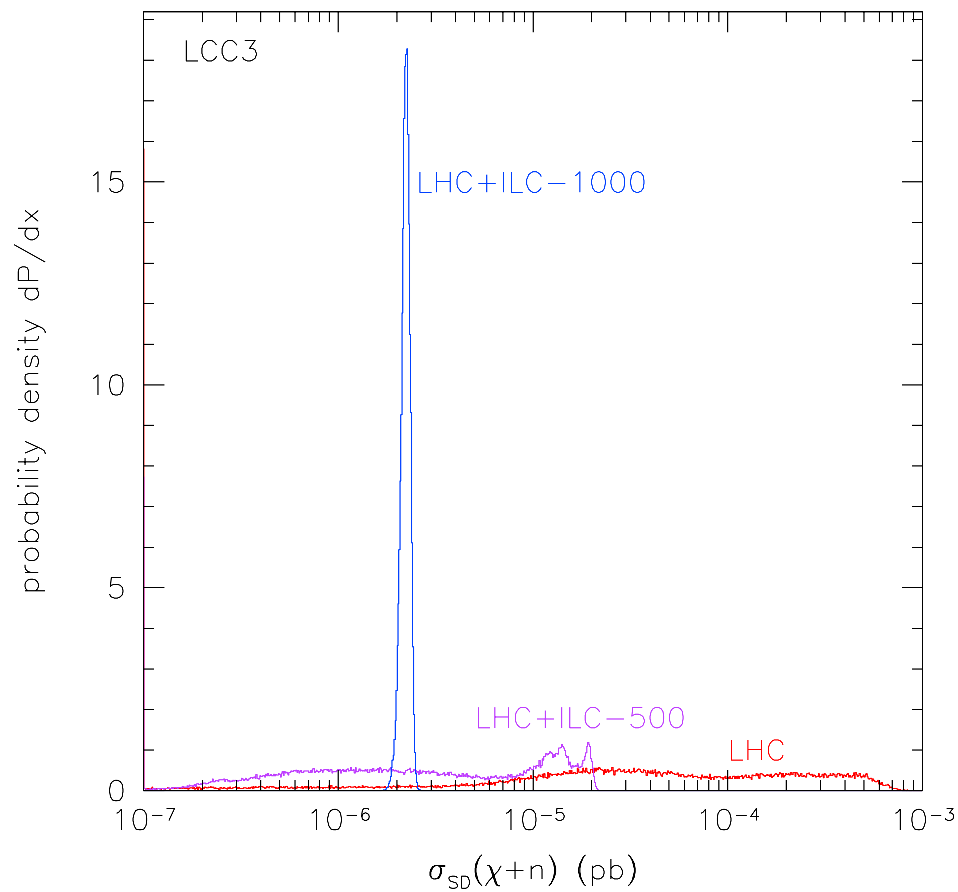
However in more difficulty scenarios nothing can be said without a LC at high energy

e.g. focus point region

Dark matter density Ωh^2



Spin dependent Xn cross section

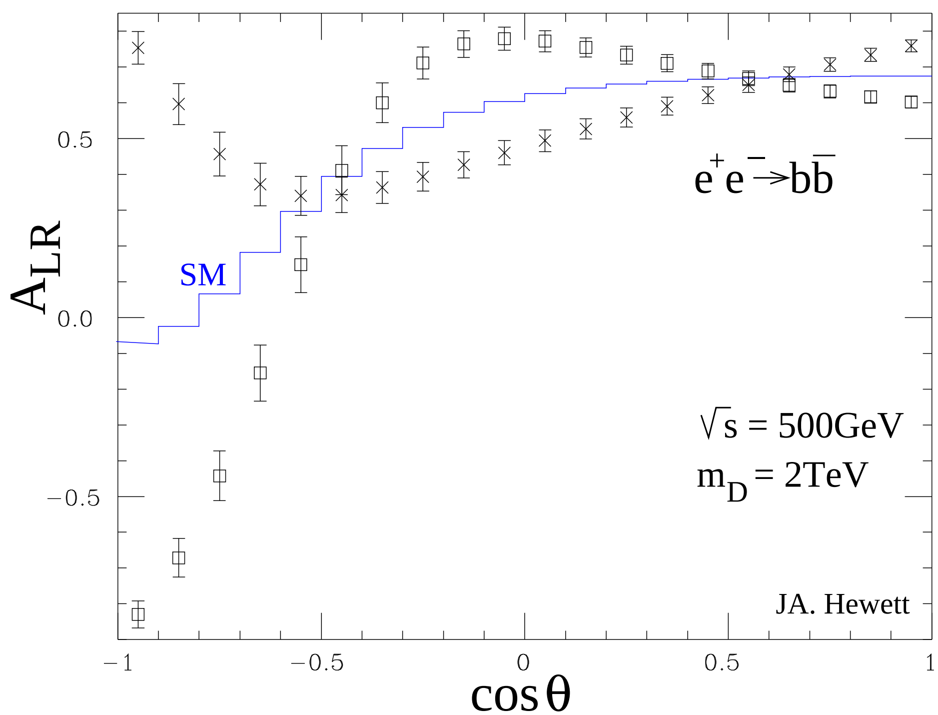


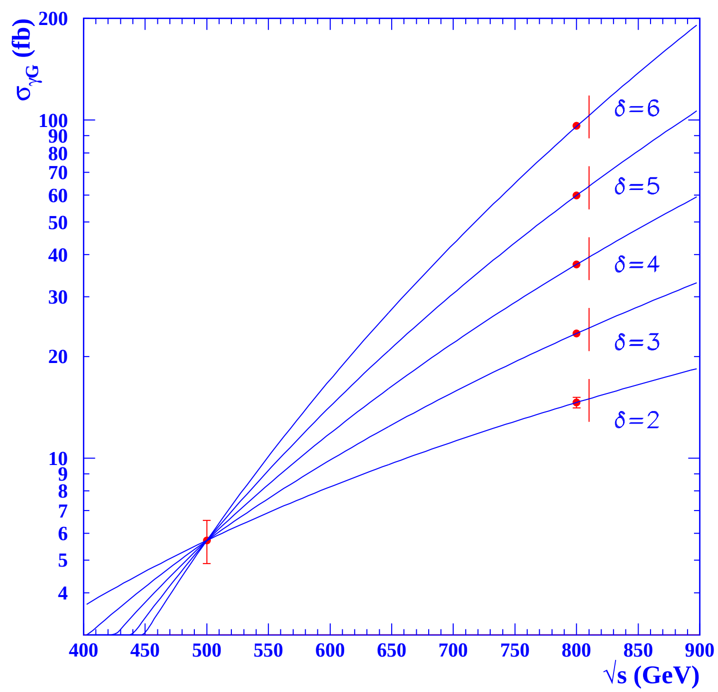
❺ Exotics

- Many alternative scenarios have been studied
- In all cases a significant gain of knowledge from a LC has been found
- Especially in the no-Higgs cases high energies $\geq 1\,\mathrm{TeV}$ are essential
- Here restrict to two cases
  - ADD extra dimensions
  - Models with an extended gauge sector

Extra dimensions (ADD)

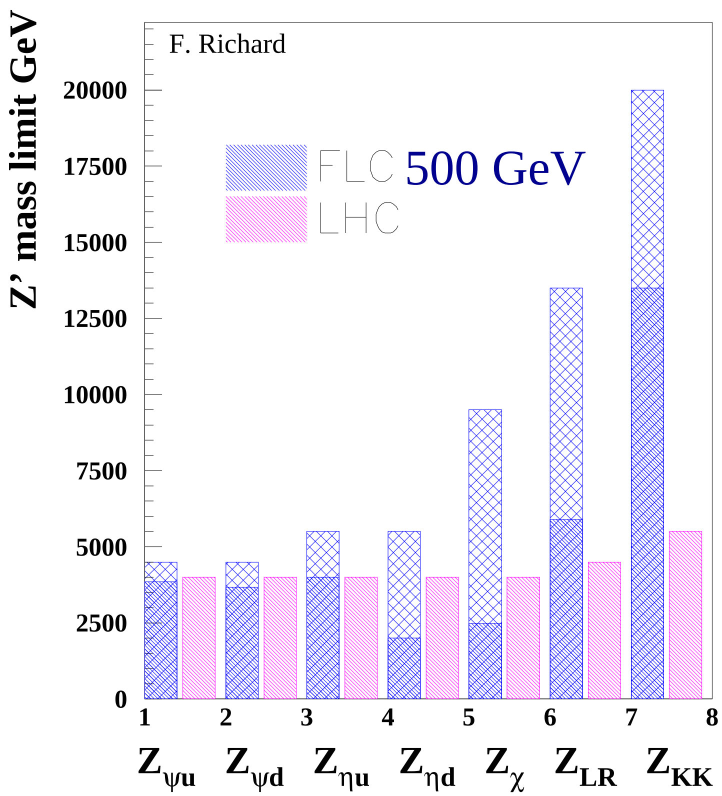
- Visible from KK-graviton radiation (missing energy) and KK-Graviton exchange (Z‘-like signal)
- Challenge: identify Graviton nature (J=2) of exchange particle
  ➡ can be done with asymmetries in 2-fermion production
- Number of extra dimensions can be measured from energy dependence

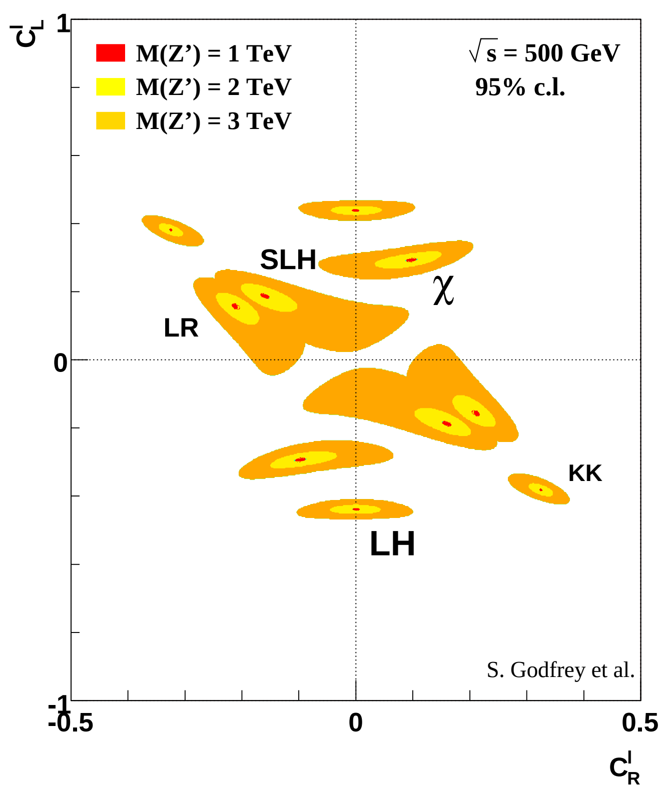




Extended Gauge Sector

- Many models predict heavy neutral gauge bosons (Z')
- Signals of the Z' can be seen in 2-f production far below the Z' mass
- Cross sections and asymmetries give access to individual couplings
- Formally a 0.5-1 TeV LC can set better limits than LHC
- More interesting, if the LHC sees a Z', the LC can identify the model





❻ Conclusions

We need a LC in addition to the LHC in any case: