Precis of the Physics Case for the ILC

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on behalf of the LCC Physics Working Group

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Context

- For the currently ongoing review by MEXT, the LCC Physics Working Group* has been tasked to prepare a short document to present the physics case for the ILC in a way that is accessible to the experts on the review panel
  - NB: Not all of them are physicists, so there is a difficult balance between “general audience” and sufficient specificity to keep the document relevant and to the point

*_**LCC Physics Working Group**_: Keisuke Fujii (KEK), Christophe Grojean (IFAE Barcelona), Michael E. Peskin (SLAC) (conveners); Tim Barklow (SLAC), Roberto Contino (EPFL Lausanne and CERN), Shinya Kanemura (Toyama), Hyungdo Kim (Seoul National U), Jenny List (DESY), Mihoko Nojiri (KEK), Maxim Perelstein (Cornell), Juergen Reuter (DESY), Frank Simon (MPP Munich), Tomohiko Tanabe (Tokyo U), Jaehoon Yu (U Texas Arlington), James Wells (Michigan); Hitoshi Murayama (IPMU), Hitoshi Yamamoto (Tohoku) (ex officio)

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  - NB: Not all of them are physicists, so there is a difficult balance between “general audience” and sufficient specificity to keep the document relevant and to the point
- The document has 5 parts:
  - Introduction
  - Higgs Boson
  - Top Quark
  - New Particles
  - Conclusions

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Introduction

- The most important aspects of the ILC physics program are:
  1. measurement of the properties of the newly-discovered Higgs boson with very high precision
  2. measurement of the properties of the top quark with very high precision
  3. searches for and studies of new particles expected in models of physics at the TeV energy scale

Introduction: The Role of the ILC

- The discovery of the Higgs particle at the LHC is a milestone in particle physics: With it the complete spectrum of particles in the Standard Model is in hand, a theory which could in principle be valid to energies 13 orders of magnitude higher than those probed in present experiments. Yet it has its shortcomings - among them:
  - It does not explain *why* the Higgs field gives mass to all particles
  - It does not provide a particle or particles that could explain dark matter
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LHC gives access to very high energies, but as an e^+e^- collider, the ILC provides a high degree of complementarity to the LHC:

- “Interesting” processes constitute a large fraction of the total event rate (in contrast to ~10^{-10} at the LHC)
- Background levels are low, allowing the study of all decay modes of heavy particles and precision measurements giving indirect access to high scales

Introduction: The Role of the ILC

- The need for larger and more powerful accelerators has driven particle physics to be more globalized than any other field of science
- Today, there is one energy-frontier proton-proton collider, the LHC
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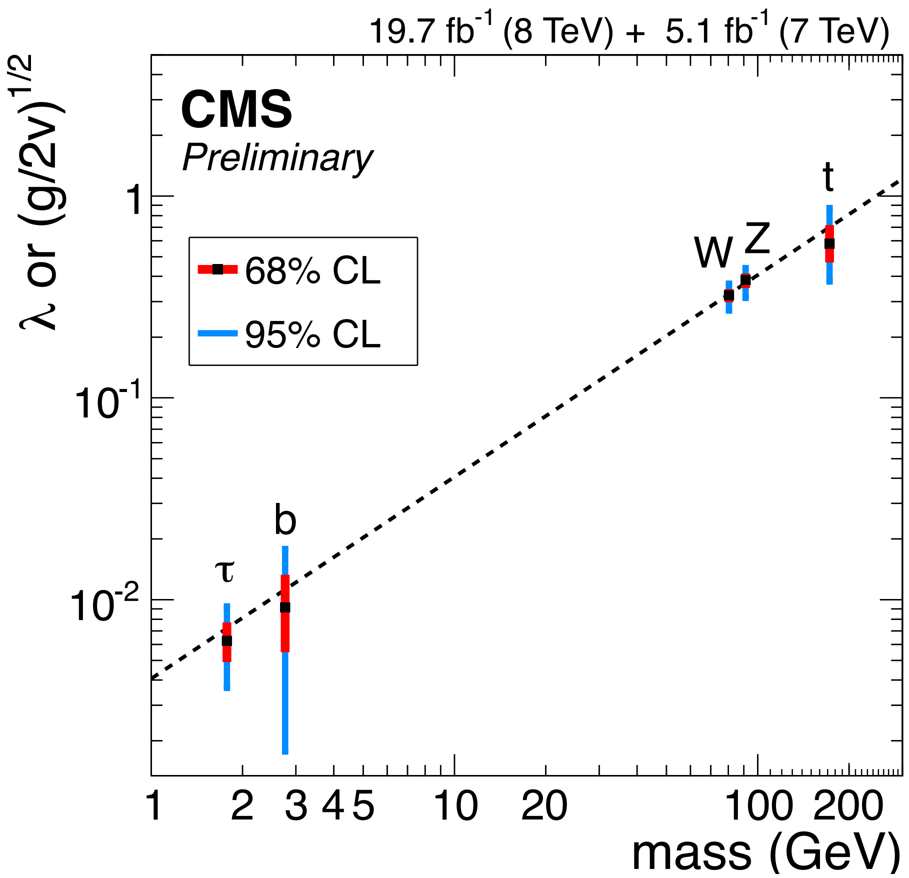
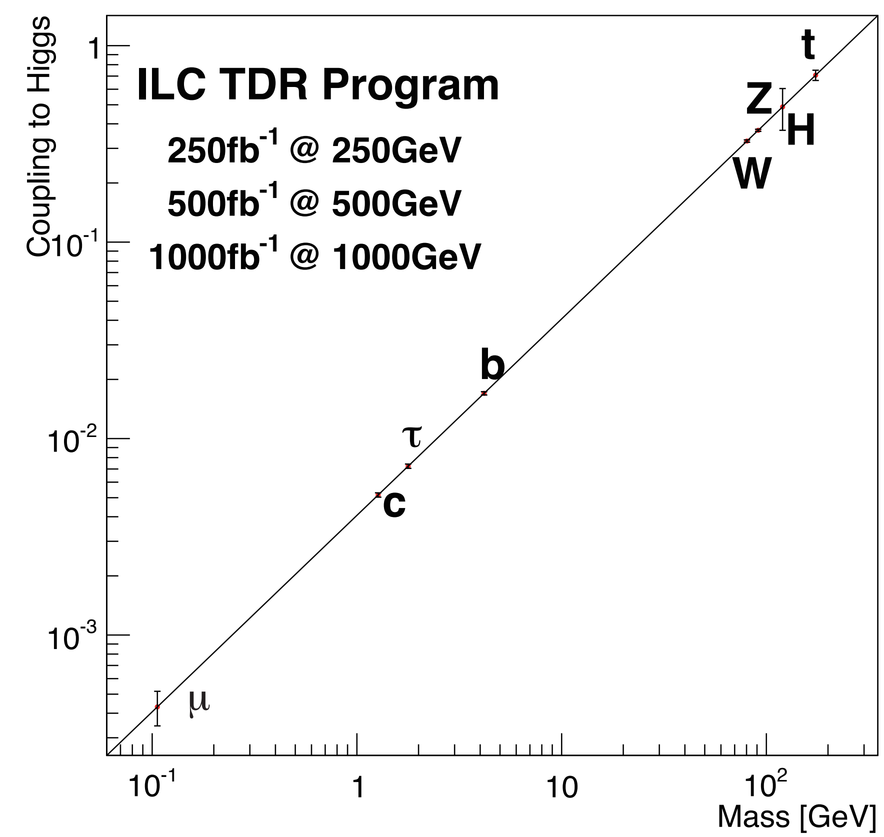
- An energy-frontier e^+e^- collider that reaches substantially beyond the energy reached by its predecessors needs to be a linear collider
- The ILC infrastructure will provide the basis for collisions at 500 GeV, and the possibility for upgrades to still higher energies

▸ It will allow Japan to host a laboratory in Asia of comparable importance to CERN on the world scene in particle physics, one that will be the global host for experiments with electron and positron beams into the longer-term future

Higgs: Introduction

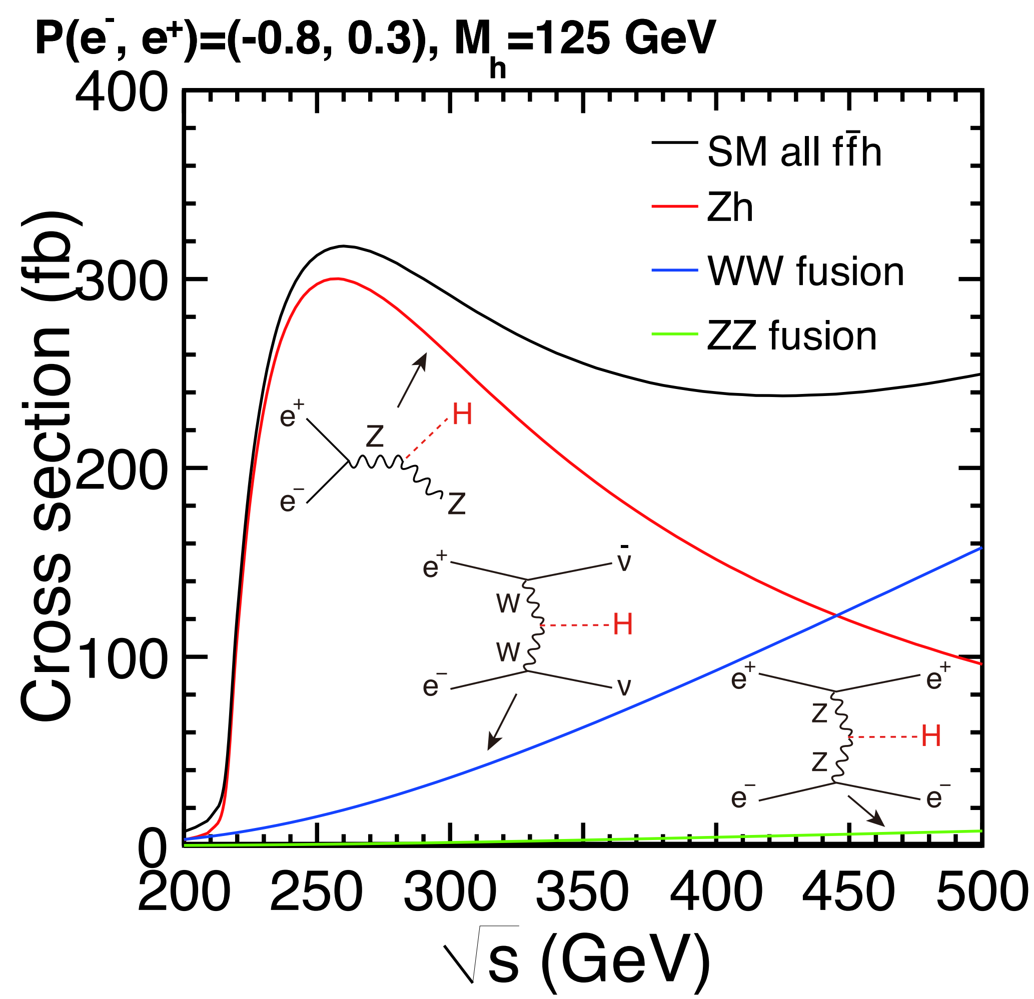


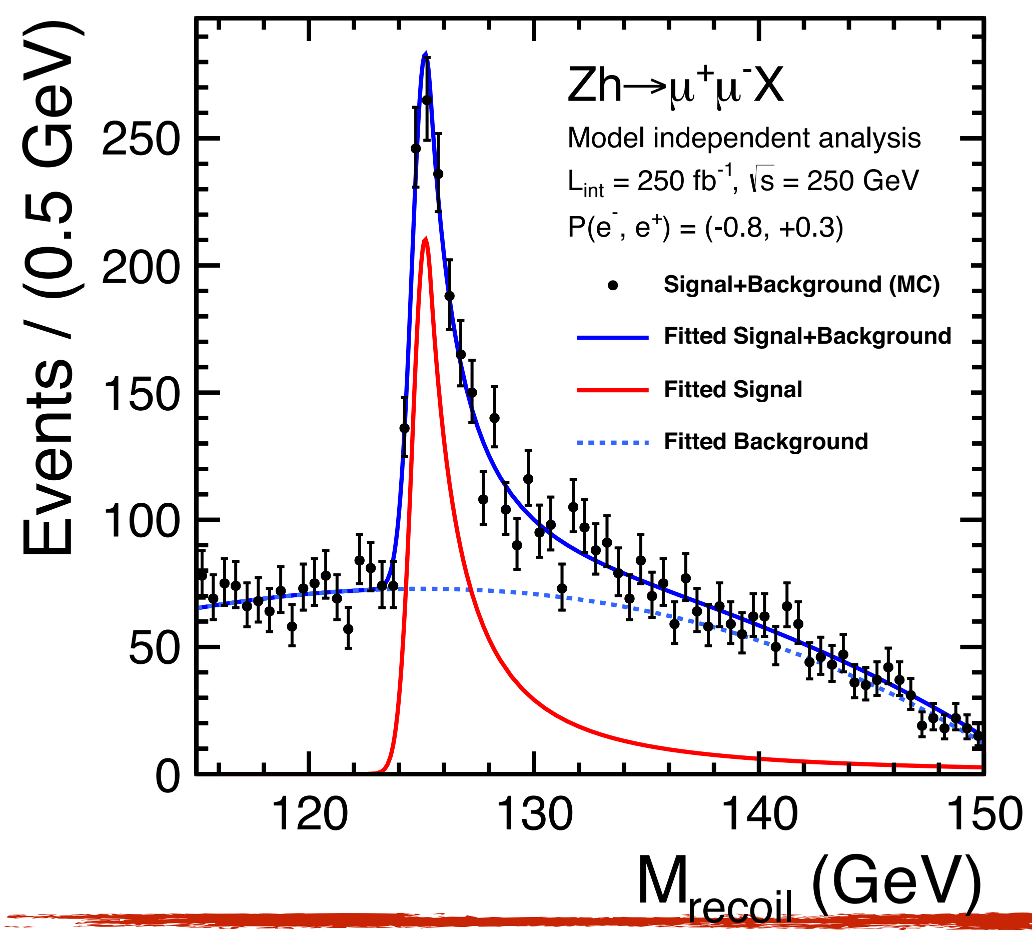


- The measurements at the LHC already now strongly support the expectation that the Higgs is responsible for the particle masses - confirming the SM explanation of the breaking of electroweak symmetry
- They do not address why the symmetry is broken, and why the Higgs field acquires its non-zero value
  - Explanations are provided by different models of BSM physics - These models can be detected by deviations of the observables from SM expectation, typically on the % level - and ILC will provide the required precision

Higgs: Production at the ILC

- Two major production modes: Higgsstrahlung and WW fusion
  - Different energy dependence
  - The combination of both processes is crucial for the measurements of Higgs couplings - the capability to run at different energies (and 350 GeV and up) is key

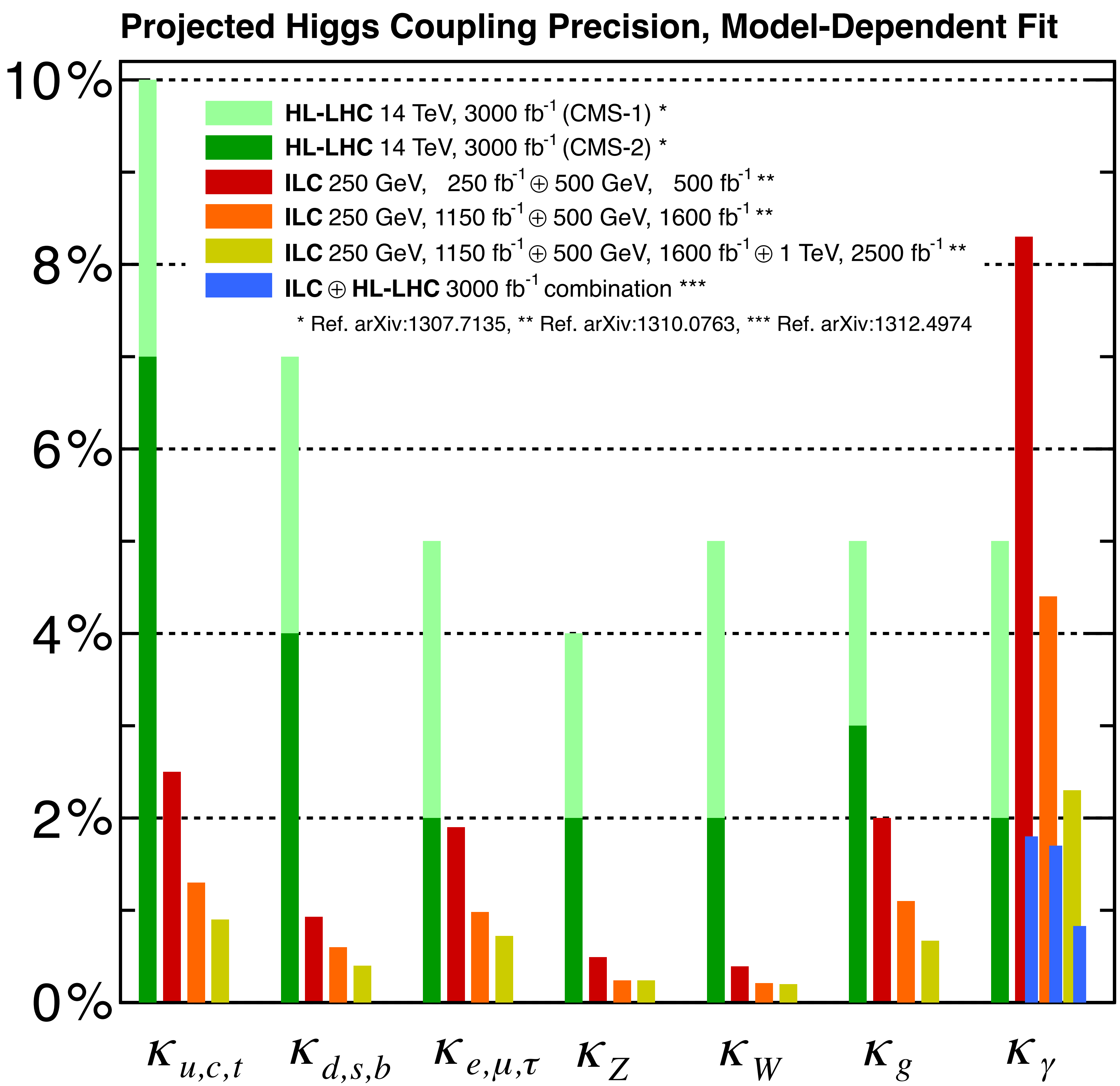




- Program highlights - hard or impossible at LHC:
  - Model-independent coupling measurements
  - Precise measurements of couplings to all particles, including b, c quarks and gluons

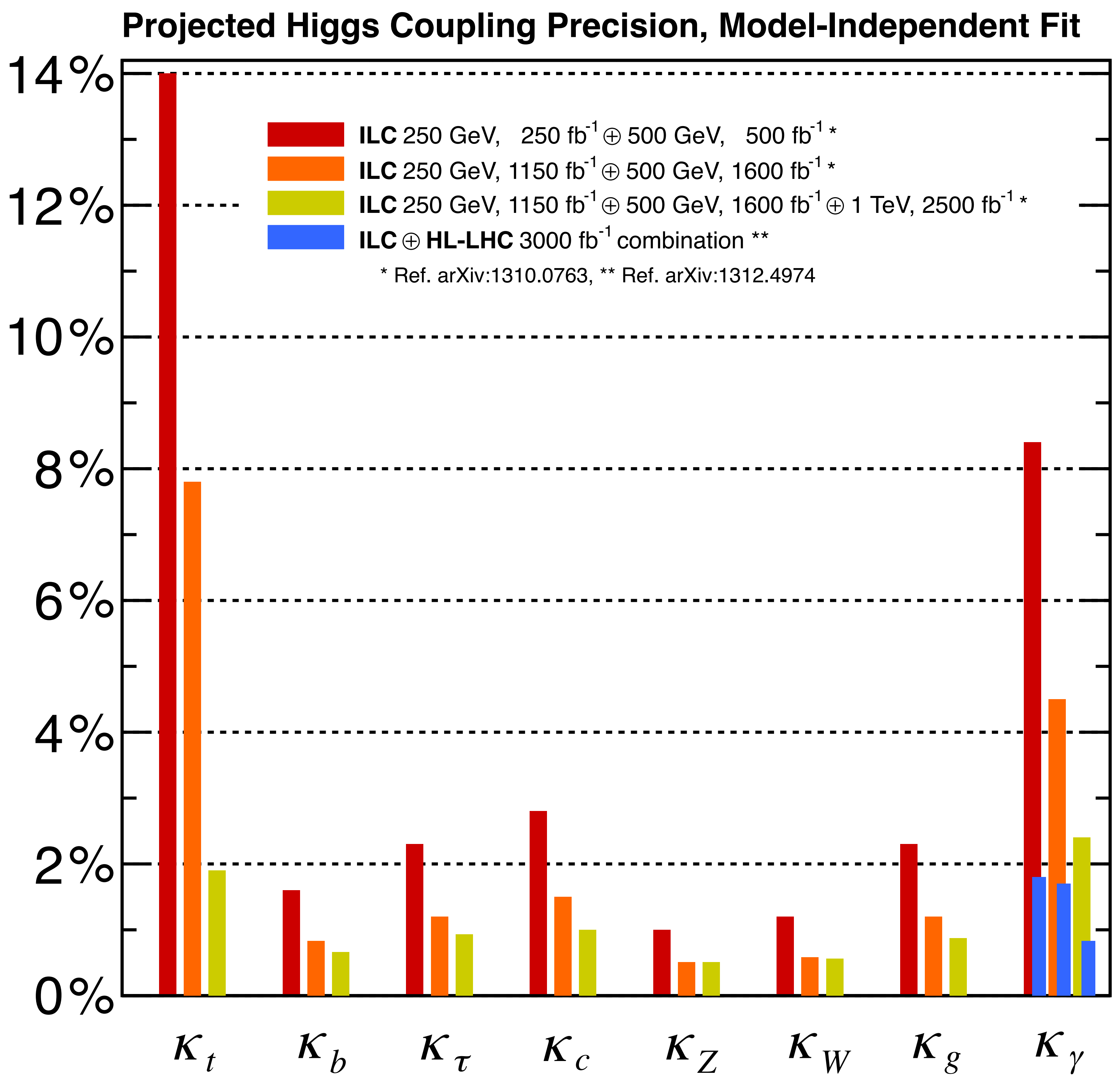
Higgs: Added value with respect to LHC

- Compared to the HL-LHC, ILC will provide factors of 2 - 10 improvement on couplings in model-dependent studies
- High degree of synergies for H->γγ, where LHC will provide the highest precision

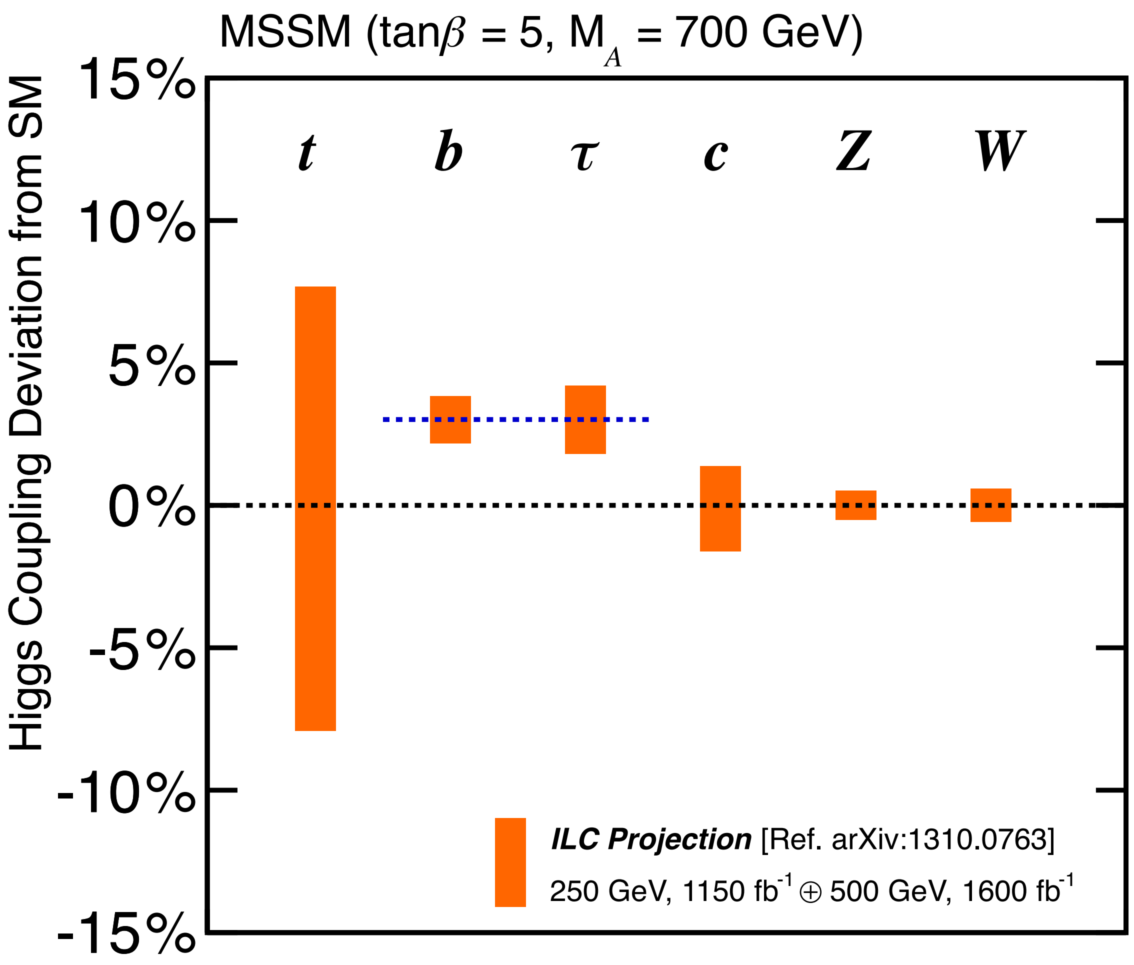


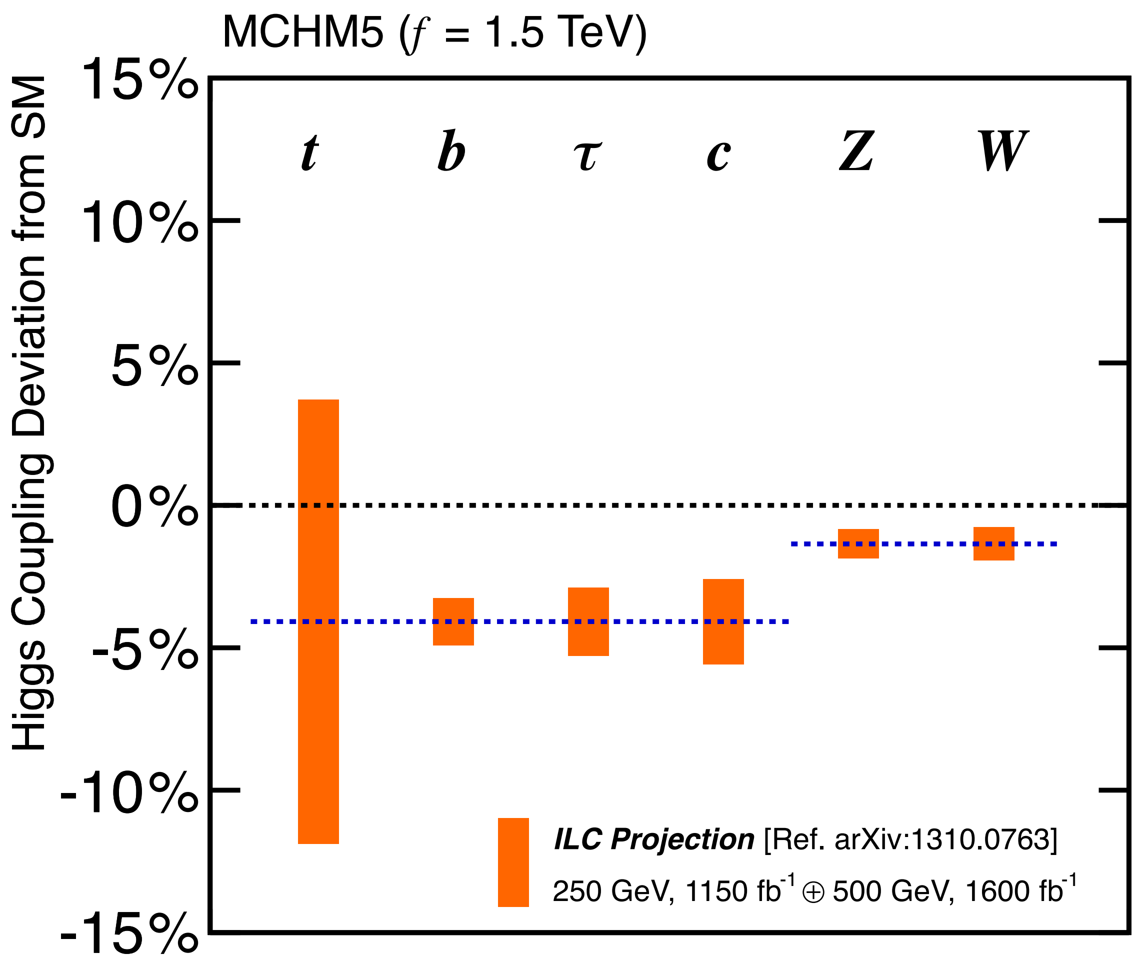
Higgs: Unique Model-Independent Measurements

- A unique feature of ILC: Model-independence: 0.5% - 1% precision for almost all couplings except top and γ
- The ttH coupling is a special case, with a threshold very close to 500 GeV. Here an increase of the energy to 550 GeV would result in an increase of the cross-section by a factor of 4, and correspondingly in a sizeable improvement of precision



Higgs: Fingerprinting the Higgs Nature





- ILC precision matters - ILC will be capable to distinguish between different models of more complex Higgs sectors
  - SUSY - multiple Higgs bosons
  - Composite Higgs boson

Higgs: The Self-Coupling

- A measurement of the self-coupling provides information on the nature of the Higgs potential, and on the details of the electroweak phase transition
  - Could provide evidence for CP violation in the Higgs sector, a possibility to explain the matter / antimatter asymmetry in the Universe
  - This could results in deviations of a factor of 2 from the Standard Model predictions

- The measurement of the self-coupling is a challenge at every collider: Two-Higgs final state, with low production cross section
  - At LHC: ~50% precision expected with HL-LHC
  - At ILC: currently 30% possible with high luminosity of 4 ab^{-1}, further improvements due to analysis technique and more decay channels expected
  - Improved prospects at 1 TeV: 18% for a single final state and 2 ab^{-1} - further improvement with increased luminosity and additional final states considered in the analysis

Top: Introduction

- The top quark has a special role in the SM: As the heaviest elementary particle, it is most closely connected to the Higgs and plays a central role in many models for New Physics
- It is the only quark that has been studied exclusively at hadron colliders (Tevatron, LHC)
    - For the lighter c and b quarks, measurements at lepton colliders have provided an impressive richness of results, including crucial evidence for the Kobayashi-Maskawa model of CP violation
- The properties of the top quark have profound consequences - the stability of the Standard Model vacuum depends on the precise value of the top (and Higgs) mass

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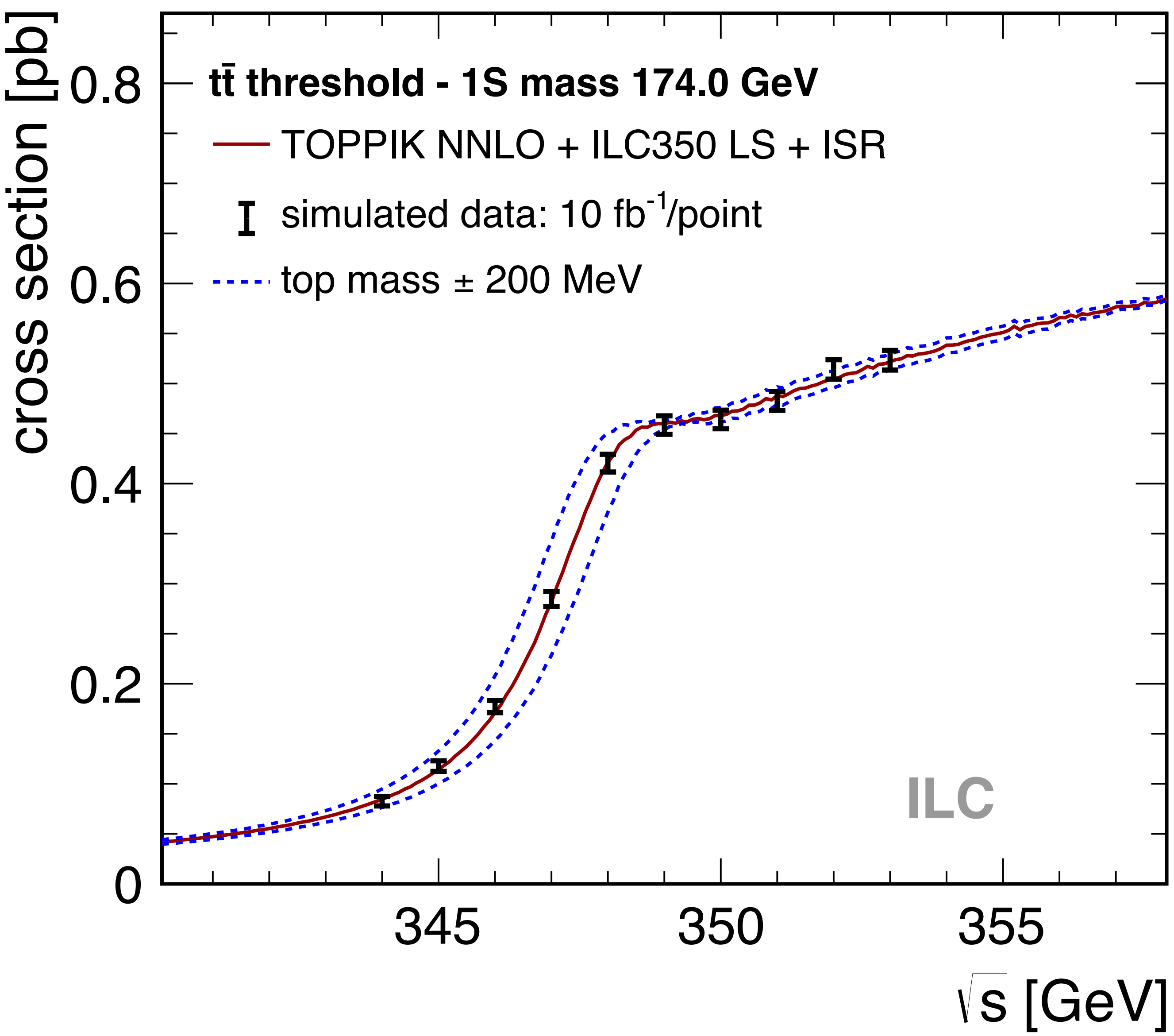
- Two somewhat distinct physics programs:
  - Top properties at the ttbar production threshold
  - Probing New Physics with top quarks above the threshold

Top: Threshold Scan

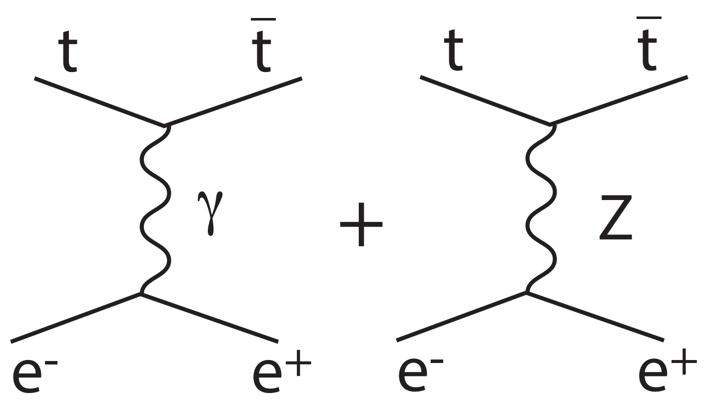
- A threshold scan probes the "hydrogen atom" of the strong interaction
  - The short lifetime of the top quark prevents the formation of a physically observable bound state
- The behavior of the cross-section near the threshold can be calculated very precisely, with small theoretical uncertainties

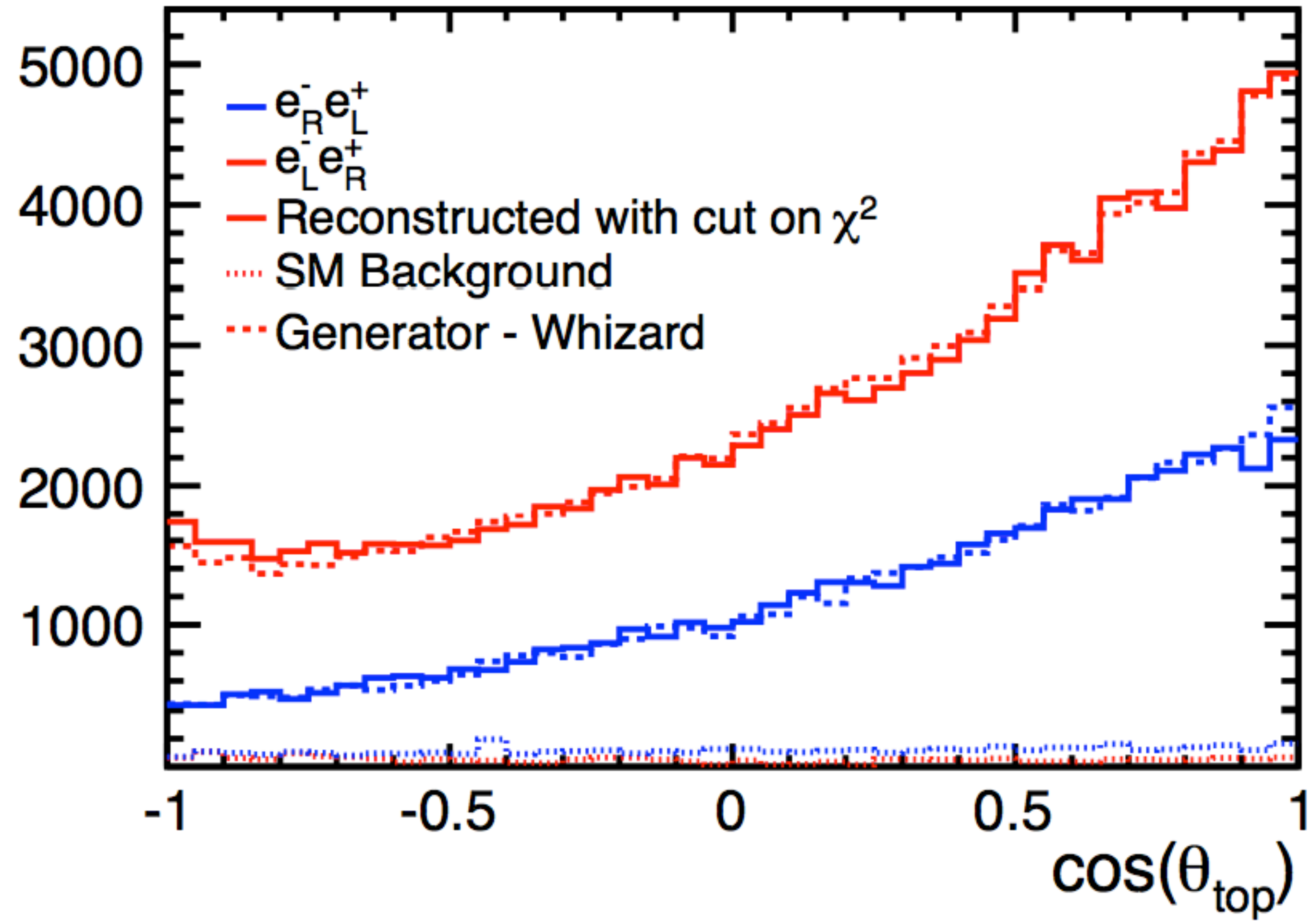


- The threshold behavior strongly depends on mass and width of the top quark, as well as on the coupling to the Higgs and on the strong coupling constant

⇨ The mass can be determined with statistical uncertainties below 20 MeV, and with a total uncertainty including all theoretical uncertainty of 100 MeV or below

Top: Weak and EM Couplings

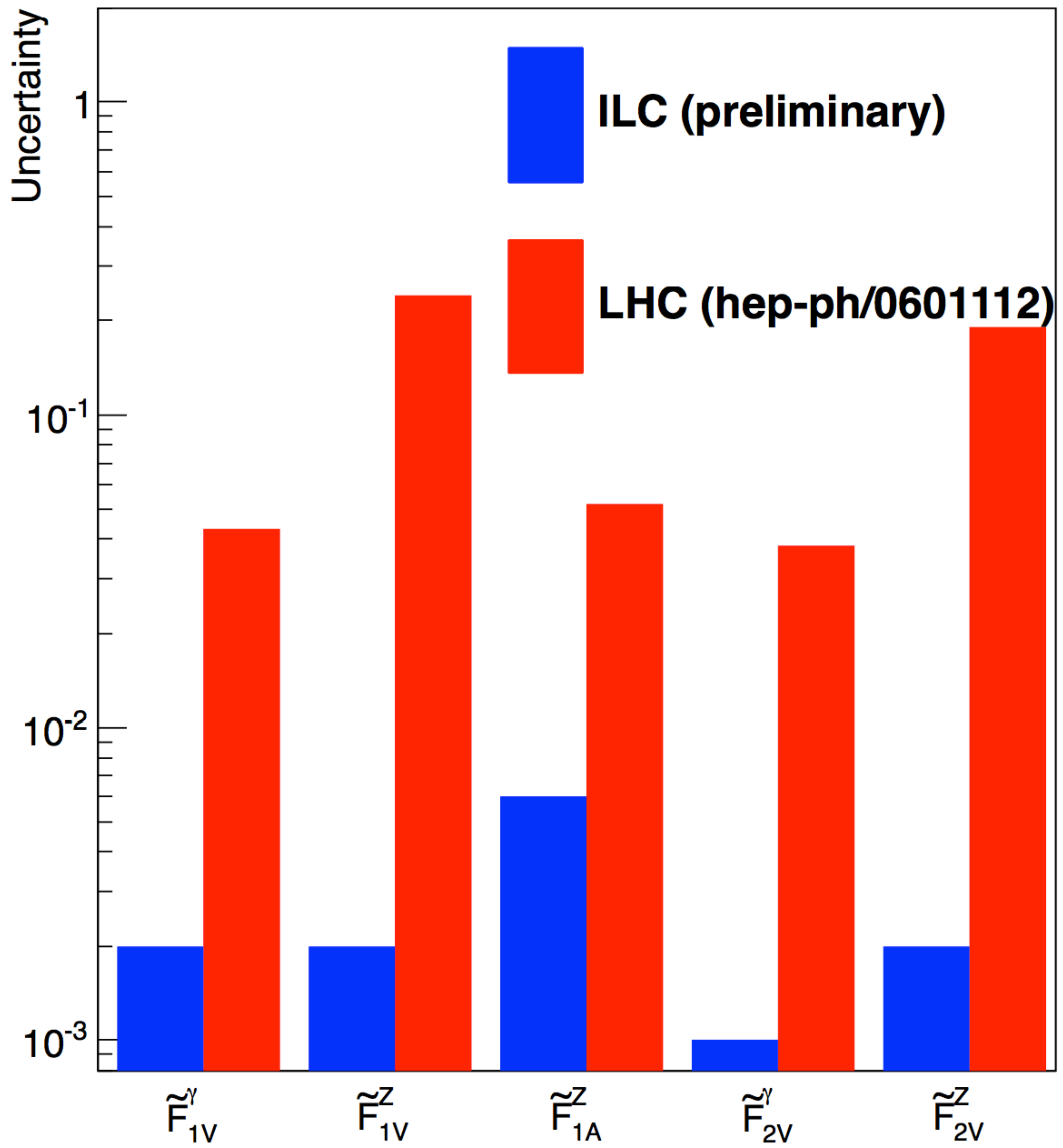




- The capability for polarized electron and positron beams at the ILC allows the precise measurements of the couplings of the top quark to the Z and to the photon by measuring polarization-dependent asymmetries and cross-sections
  - High sensitivity to deviations from the Standard Model - as expected for composite Higgs bosons

Top: Weak and EM Couplings

- ILC will provide very precise measurements of left- and right-handed top couplings
  - Excellent separation of different models of New Physics
  - Substantial increase in precision compared to LHC

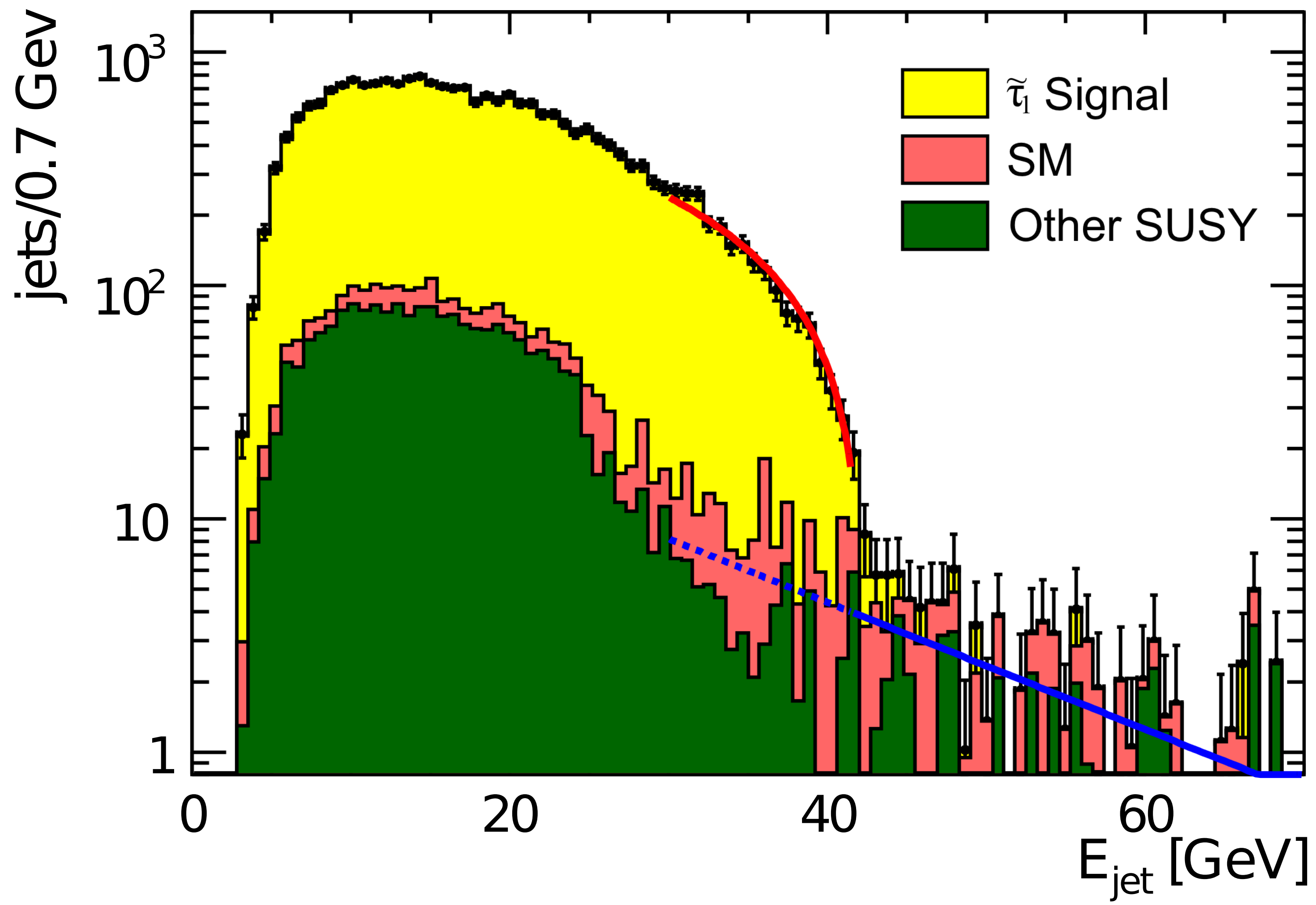


New Particles: Introduction

- LHC has already searched for new particles, and has placed limits which reach and even surpass 1 TeV in some cases
- Still, there are many well-motivated scenarios where new particles are accessible at lower energies which are not visible at the LHC but can easily be discovered at the ILC
- The capability for polarized beams substantially enhances the possibilities to explore new phenomena, by giving direct access to the electroweak quantum numbers of new states
- A linear collider offers the possibility for extendability - if there are indications from measurements for new particles beyond the immediate reach of the collider, the energy can be increased to reach this scale, while this is virtually impossible for a circular e^+e^- collider

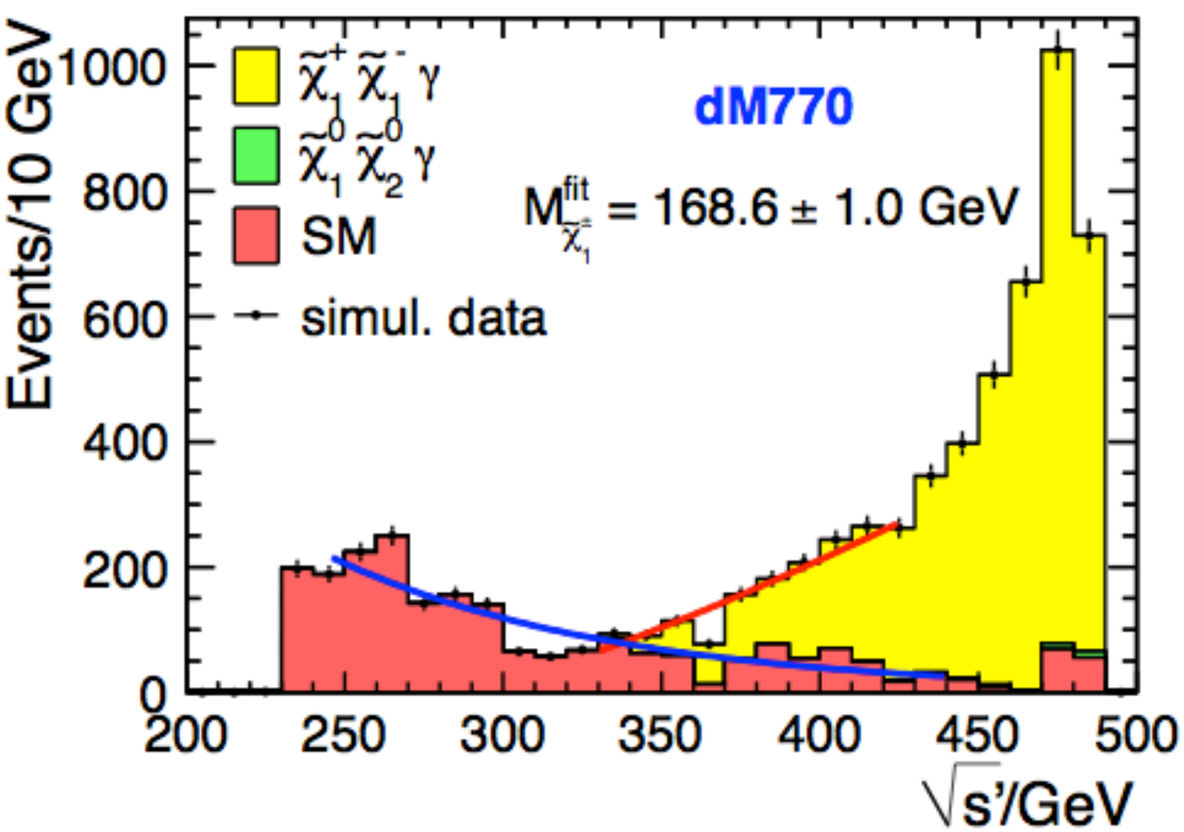
New Particles - Precision Measurements

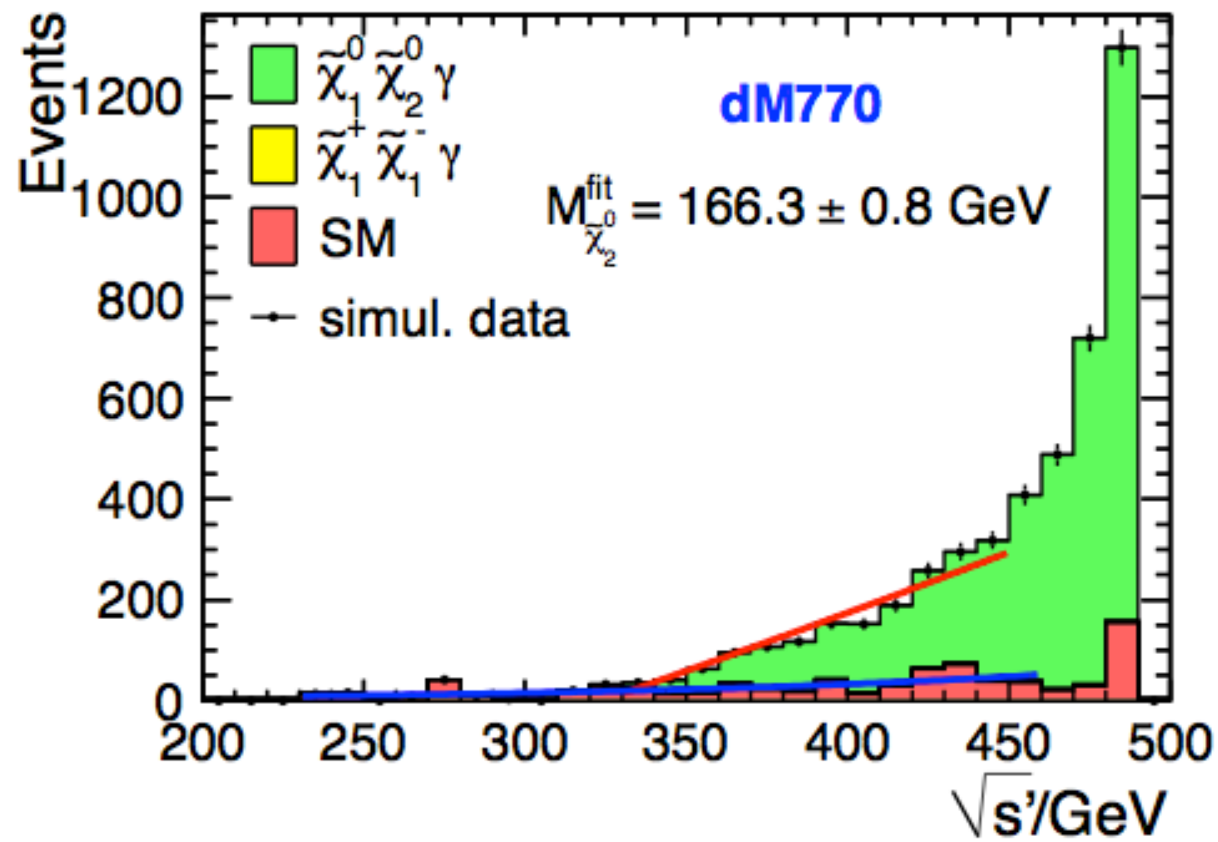
- One example for ILC capabilities are situations with small mass differences between new particles
  - These are motivated by "coannihilation" scenarios for dark matter, which have a heavier charged particle which decays into a SM particle and the slightly lighter dark matter particle



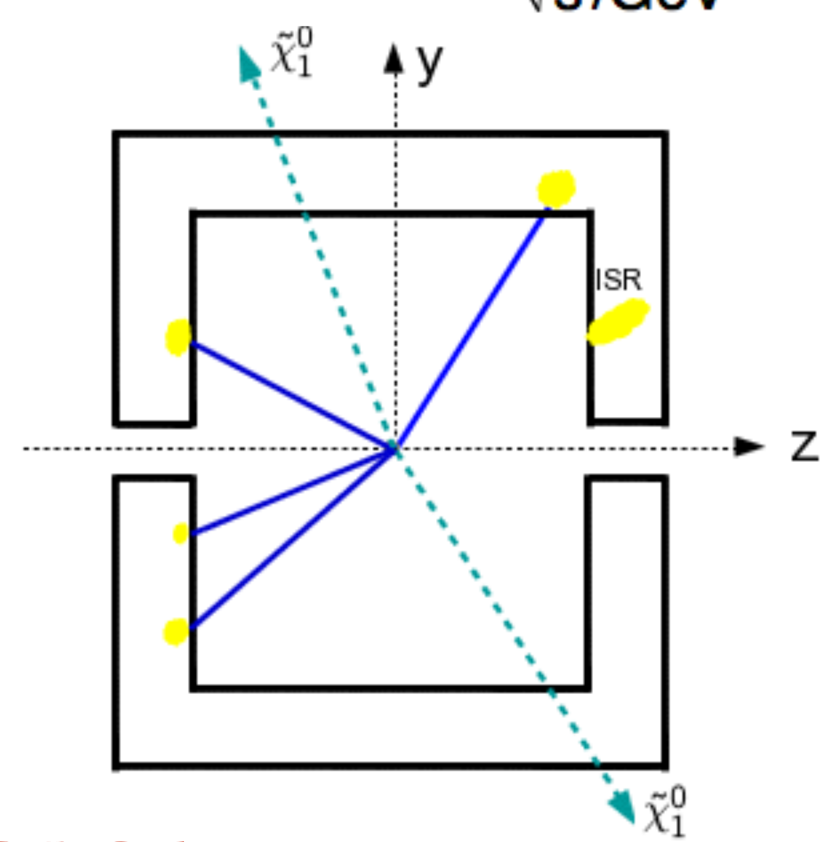
- This requires the identification of relatively low-energy particles to prove the existence and to measure the masses of the new particles - a situation that is straight-forward at the ILC but difficult or impossible at the LHC due to the requirement for trigger thresholds

New Particles: Hidden Higgsinos

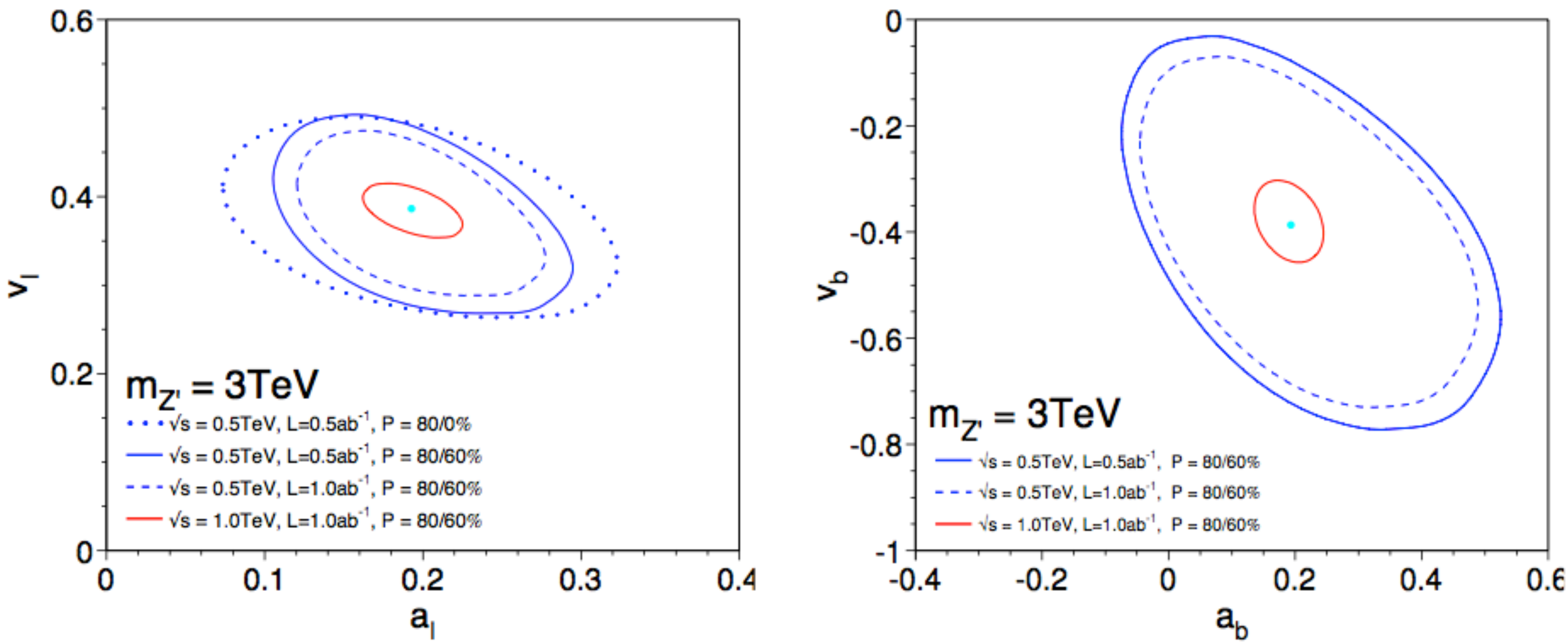




- Supersymmetry provides a possible explanation for the shape of the Higgs potential
  - It predicts the existence of partners to the Higgs, the Higgsinos, which should be relatively light
  - Very hard to discover at the LHC: Only electroweak interactions, small mass splittings
- Tagging and reconstruction of events via photons radiated of the beam particles prior to collision



New Particles: Two Fermion Measurements



- ILC can measure "two-fermion" processes like $e^+e^- \to l^+l^-$ or qq very precisely - these can be calculated in the Standard Model with high accuracy
- New heavy gauge bosons (Z') - which appear in models of grand unification - would result in deviations from the expectation, providing sensitivity far beyond the collision energy of ILC - and beyond the reach of LHC
- If such a particle is discovered at LHC, ILC can determine its precise nature

Conclusions

- The discovery of the Higgs boson has completed the Standard Model - but this models fails to answer many fundamental questions

- The ILC offers new avenues to address these open questions experimentally
  - It offers new, precise, unambiguous information on the two particles most closely connected to our questions about the Standard Model: The Higgs and the Top Quark
  - It provides new capabilities that will allow crucial searches for supersymmetric particles and particles connected with cosmic dark matter that are not possible today

⇨ The ILC will make major contributions to particle physics

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The ILC will have much to teach those of us who are trying to unearth the basic laws of nature