Physics Case for the ILC

In view of the 8 TeV LHC results
and 14 TeV LHC/HL-LHC prospects

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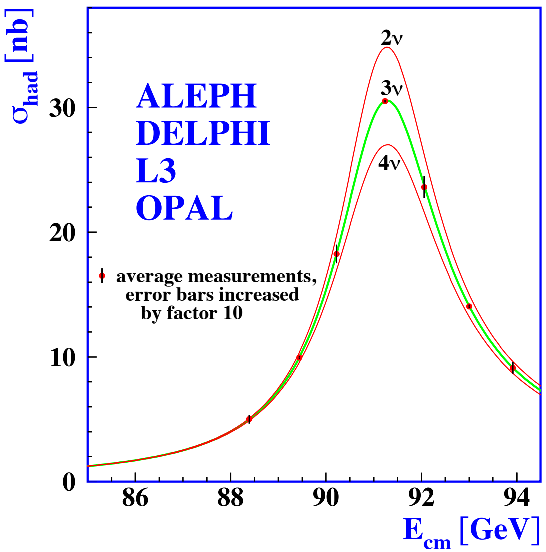
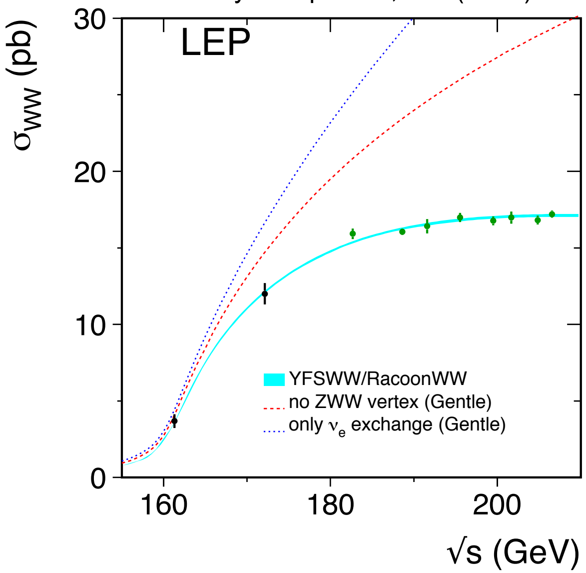
Achievements of e+e- colliders

e^+e^- Energy Frontier :
LEP ($\sqrt{s}$=90–209 GeV, 1989-2000) & SLC ($\sqrt{s}$=90–100 GeV, 1989-1998)

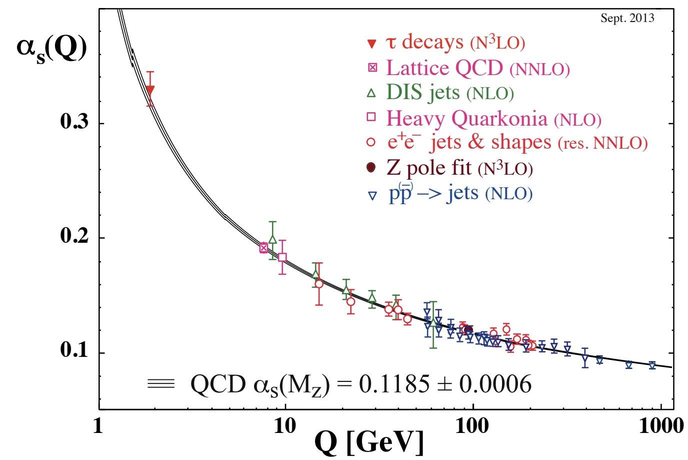
Phys. Rept. 427, 257 (2006)



Phys. Rept. 532, 119 (2013)



PDG, Phys. Rev. D86, 010001 (2012)



generations = 3

From the Z lineshape, the number of light neutrinos is determined to be three.

Electroweak interactions

Measurement of ZWW interactions: weak interactions obey *SU*(2)×*U*(1) gauge symmetry

Strong interactions

Measurement of strong coupling constant α_s: strong interaction has SU(3) gauge symmetry

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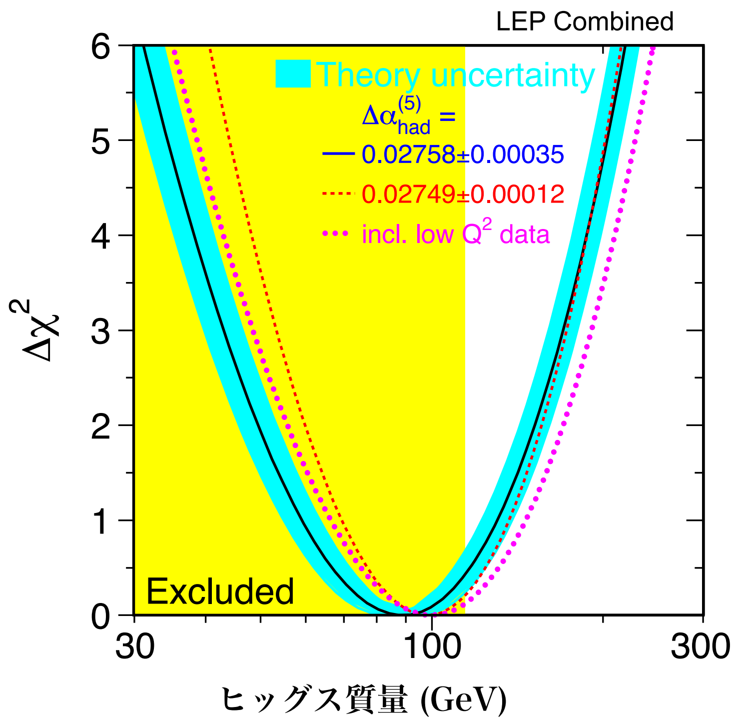
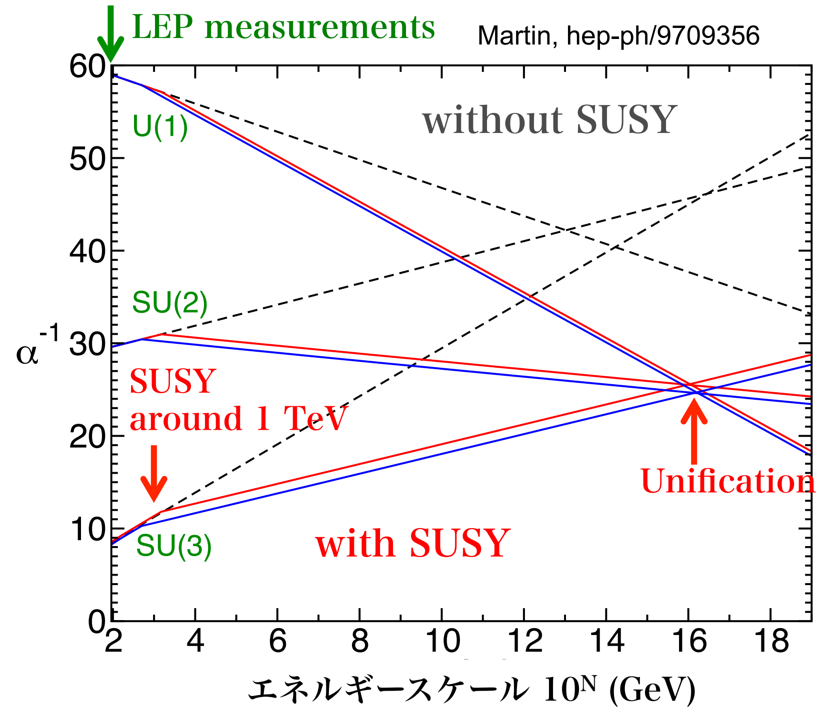


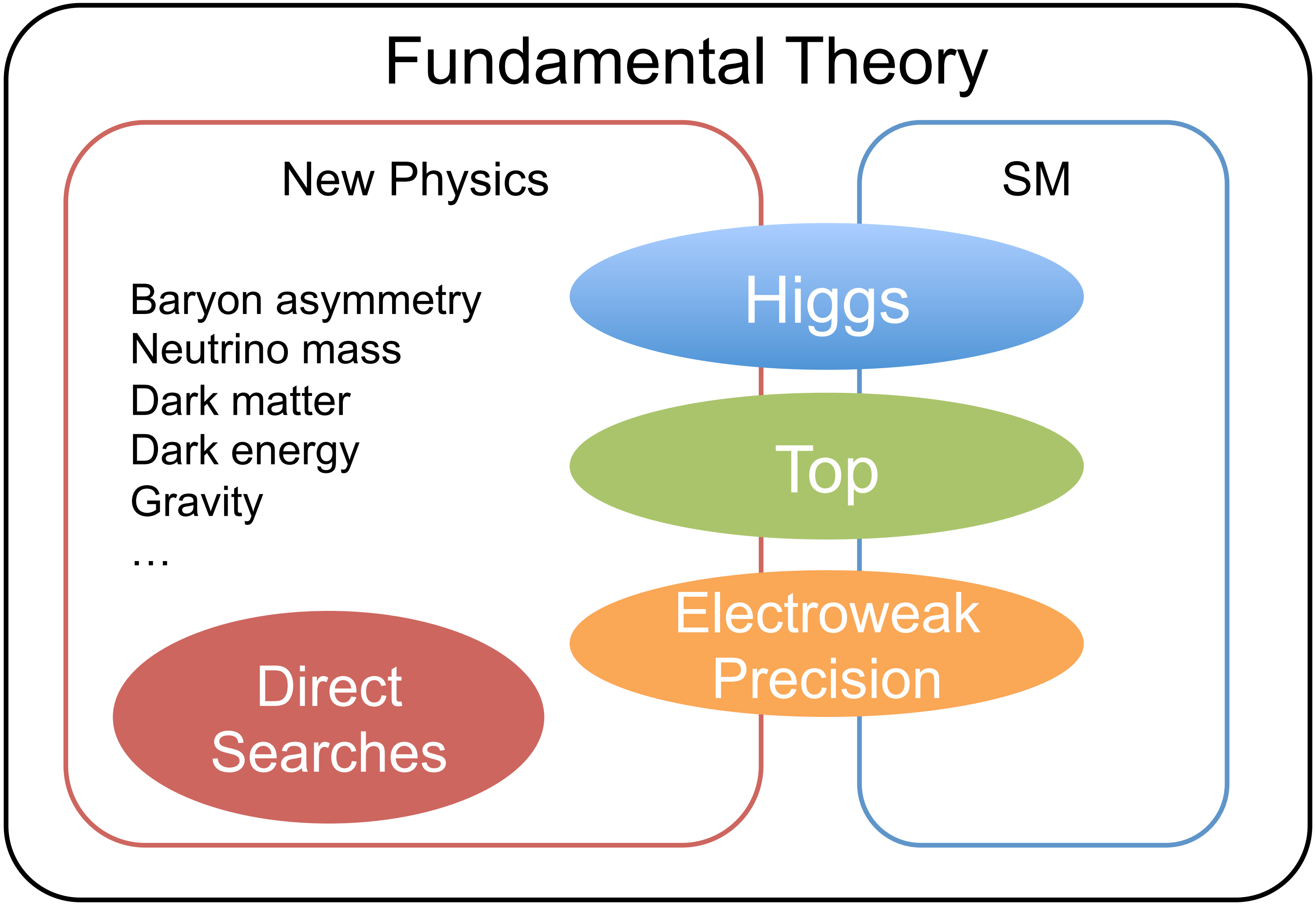


Higgs boson is light

LEP/SLC electroweak precision measurements predicted the SM Higgs boson mass to be around 100 GeV. (Actual discovery by LHC at around 126 GeV.)

Unification with supersymmetry (SUSY)

Precise measurement of the gauge couplings with RGE calculations indicate: if supersymmetry exists around 1-10 TeV, the three forces unify at around 10^{16} GeV.


Fundamental Theory
New Physics
SM
Baryon asymmetry
Neutrino mass
Dark matter
Dark energy
Gravity
…
Higgs
Top
Electroweak Precision
Direct Searches

Higgs As a Probe for New Physics

The **Higgs boson**, recently discovered at the LHC, is a completely new type of elementary particle. The ILC will enable us, for the first time, to study this particle in complete detail.

"Use the Higgs boson as a new tool for discovery"

– U.S. P5 Report, May 2014

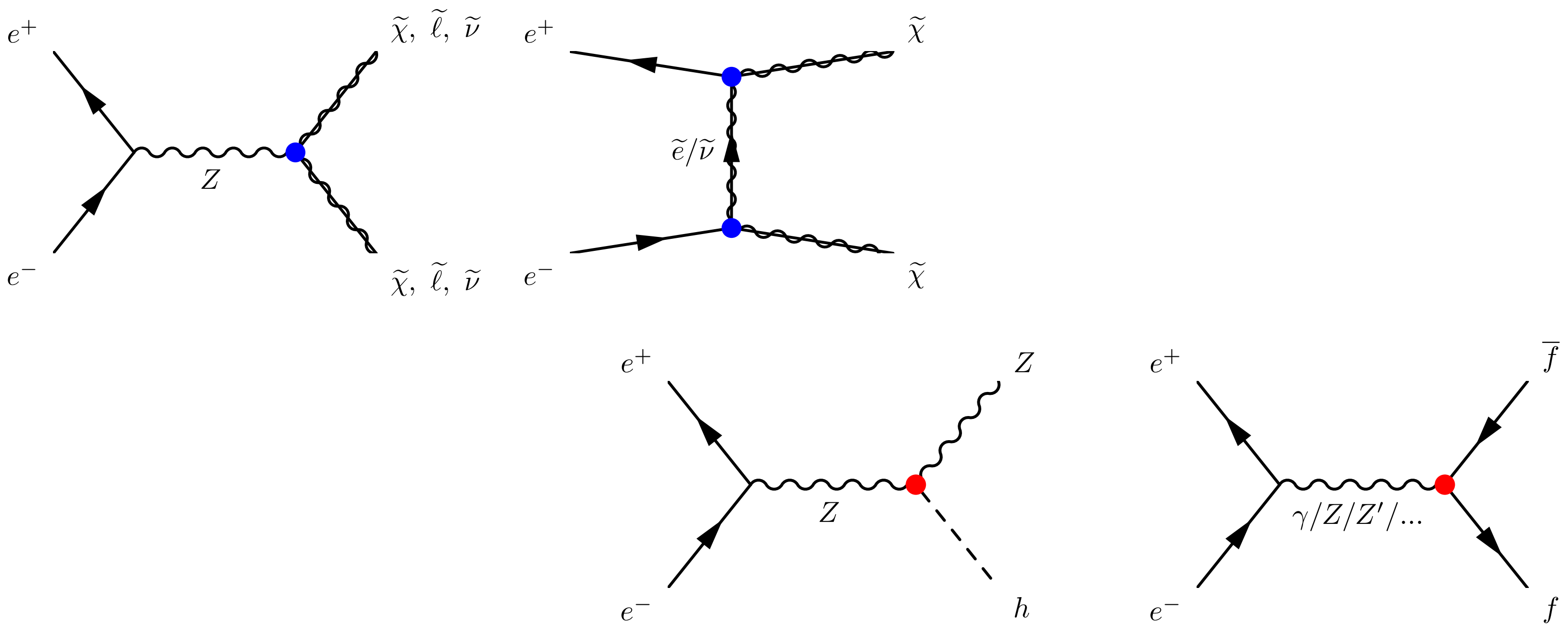
We have discovered the lightest particle in the Higgs sector. There may be many more.

- Is the Higgs boson **elementary** or **composite**?
- Can strong interactions of **top quark** with Higgs probe the Higgs sector?
- Does the Higgs interact with **dark matter**?
- ..

Big Questions for the ILC

- What is the physics behind the **electroweak symmetry breaking**?
- What is the nature of **dark matter** of the universe?
- Are there **new forces/symmetries**?
- What causes the **baryon asymmetry** of the universe?

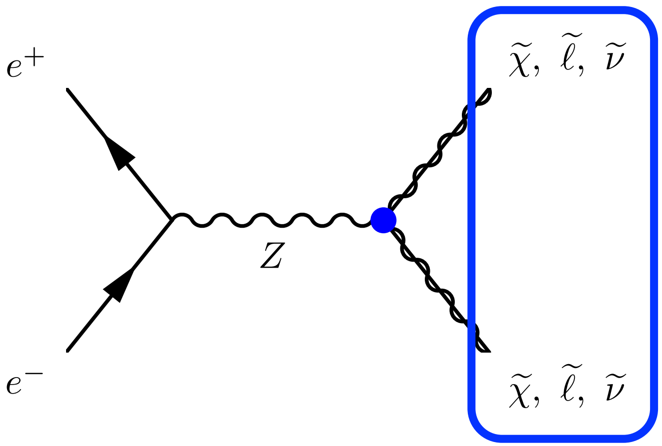
The ILC will tackle these big problems!

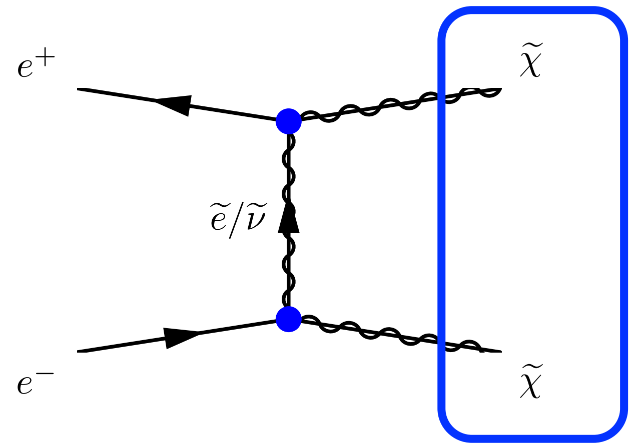


Search for New Physics

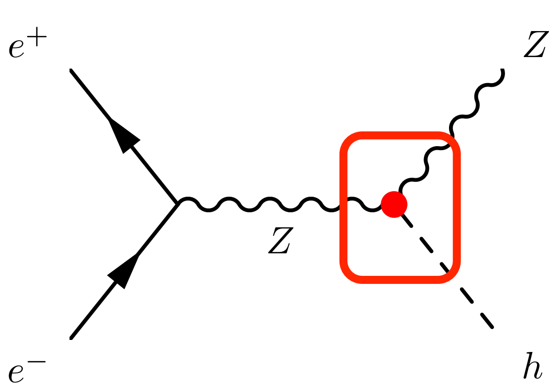
How can the ILC search for new physics?   Two major points:

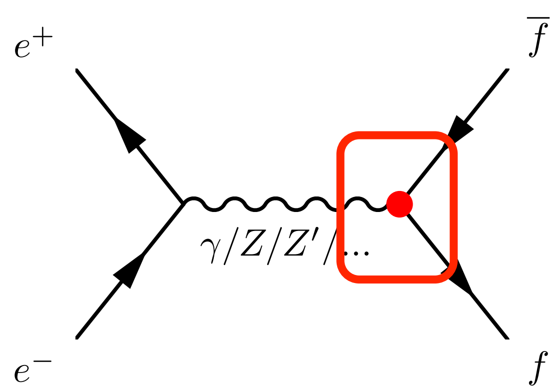
1. Discover new particles with only electroweak interactions that are difficult to observe at the LHC / HL-LHC.



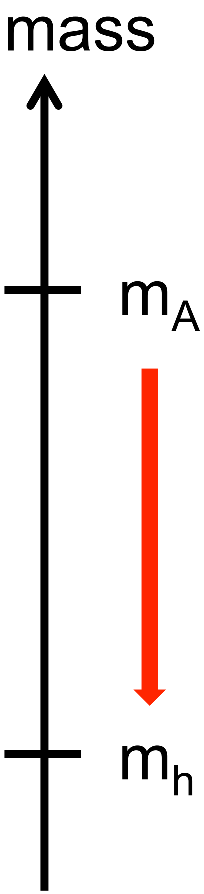


2. Search for new interactions through effective interactions or higher-dimensional operators. These searches often go beyond the reach of the LHC / HL-LHC in direct particle searches.





Standard Model as a Decoupling Limit



Many new physics models predict deviations in the properties of SM particles. In general, the amount of the deviation depends on the scale at which the new physics appears.

As the scale is pushed higher, the properties of the low-scale particles become closer to those of the SM particles. This is known as the **decoupling limit**.

Example:

Minimally Supersymmetric Standard Model (MSSM)
with tanβ=5 (assuming SUSY radiative corrections ≈ 1)

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$$

If the extra Higgs boson is around the 1 TeV scale, a deviation of O(1)% is expected in the Yukawa couplings of the bottom quark and the tau lepton.

Physics behind EWSB

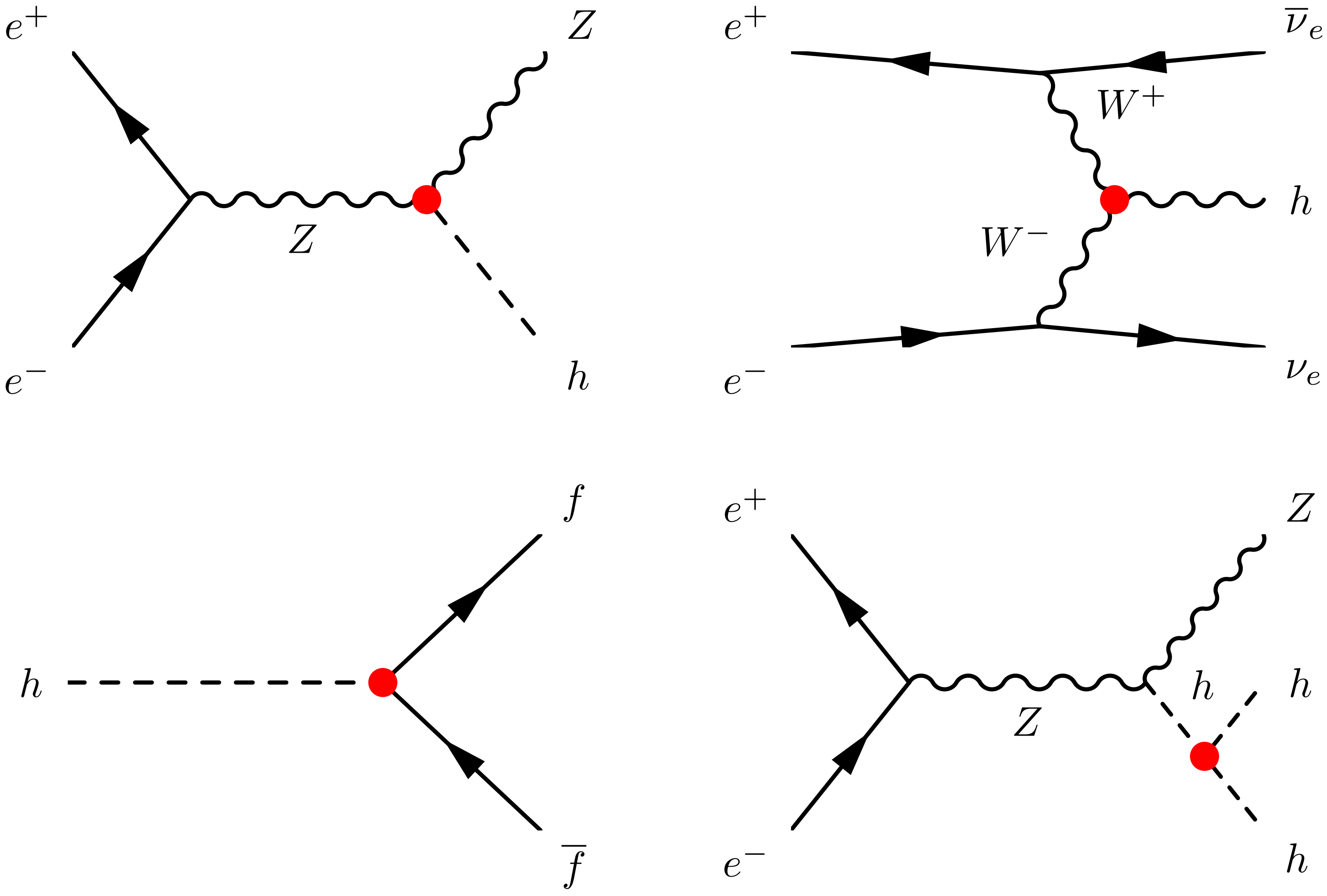
After the **discovery of the Higgs boson**, the physics behind the **electroweak symmetry breaking (EWSB)** has become one of the most urgent issues in particle physics.

There are two possible scenarios for the physics behind EWSB around the TeV scale:

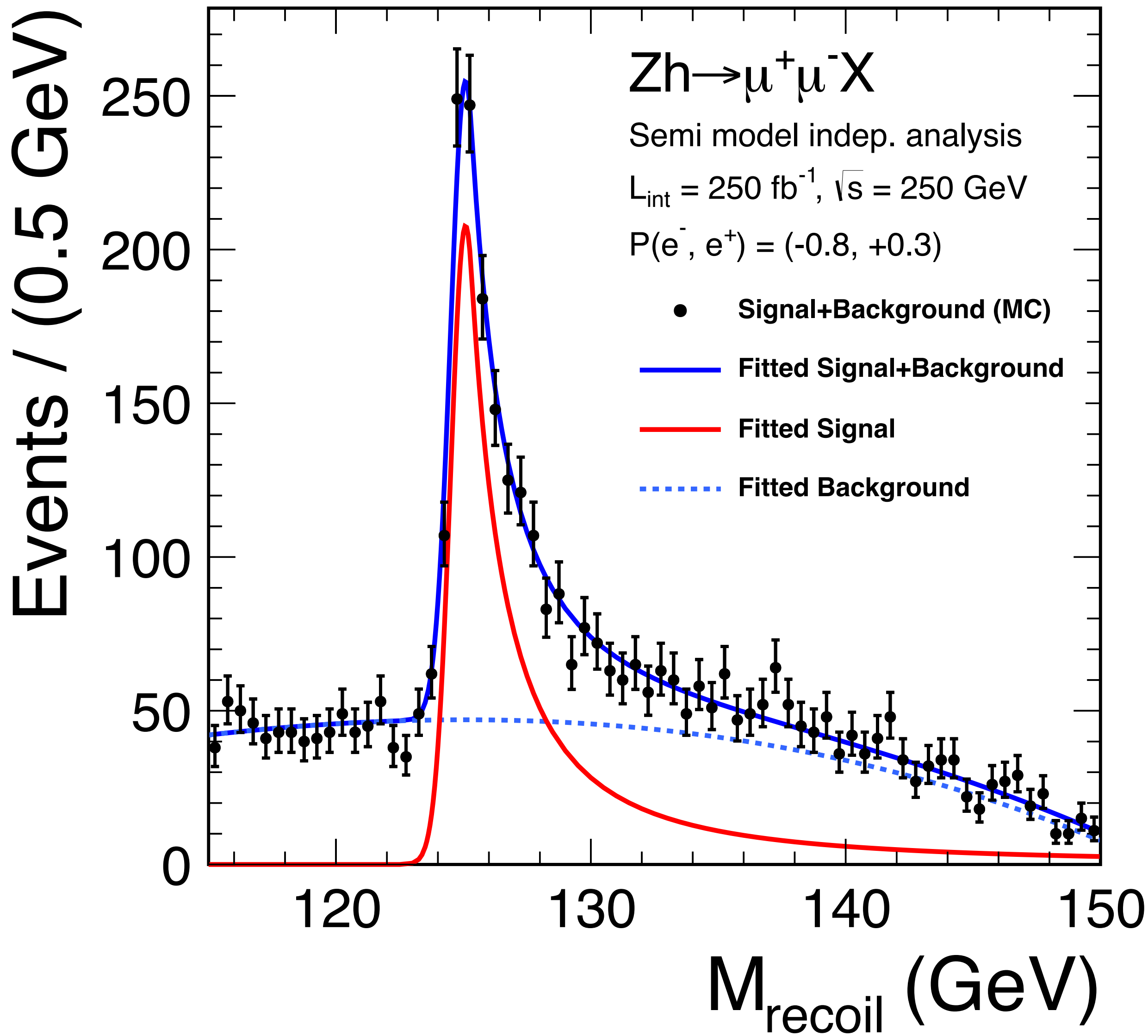
1. **Composite Higgs:** a QCD-like theory is behind the EWSB.
2. **Supersymmetry (SUSY):** SUSY breaking triggers EWSB.

Studying the **Higgs boson** and the **top quark** are crucial to probe and distinguish these possibilities.

Higgs Processes

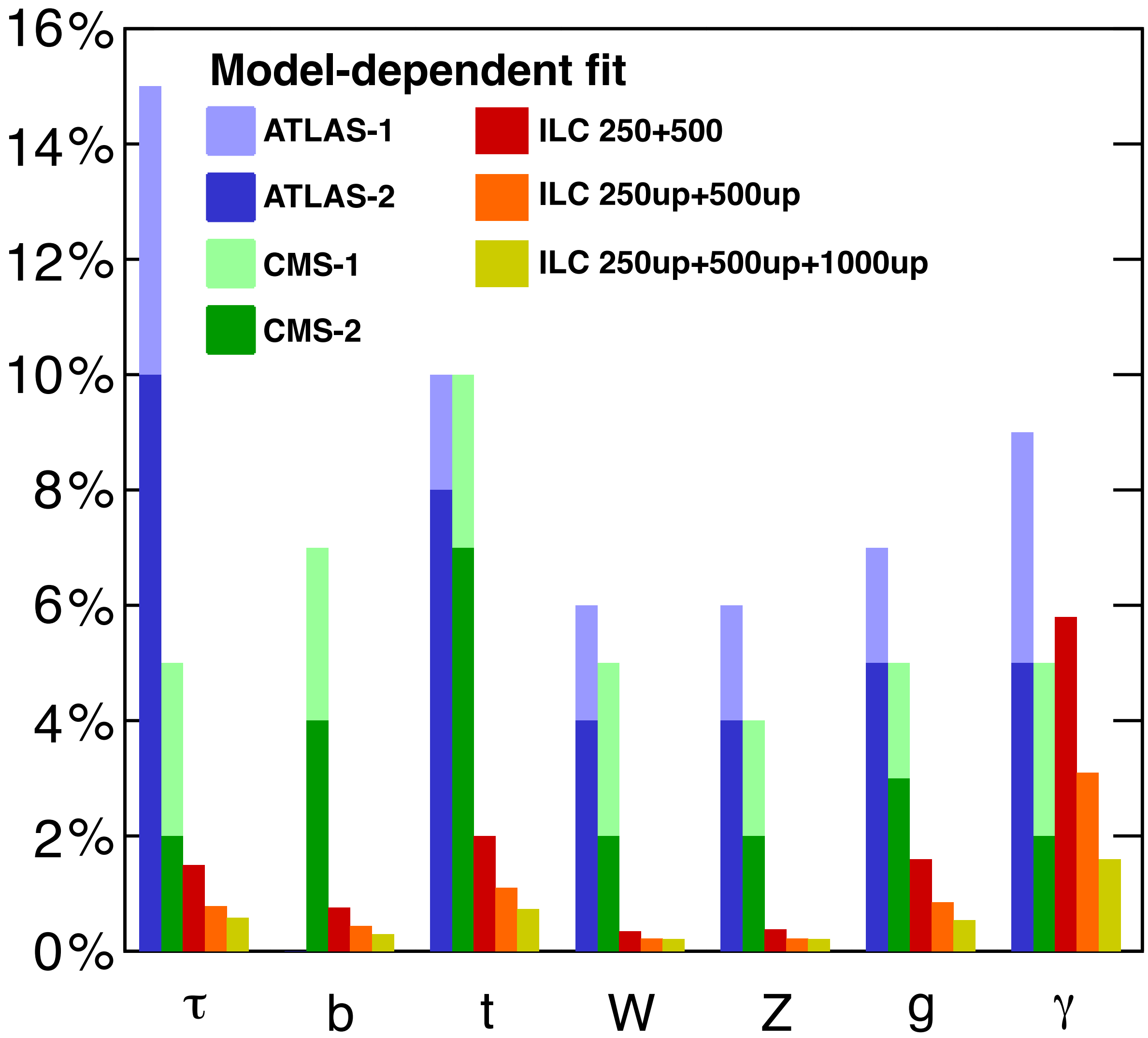


Higgs recoil mass



Watanuki et al.

Higgs Couplings (1/2)



ATLAS/CMS:
Lumi 3000 fb-1, sqrt(s) = 14 TeV

ILC 250:
Lumi 417 fb-1, sqrt(s) = 250 GeV

ILC 500:
Lumi 833 fb-1, sqrt(s) = 500 GeV

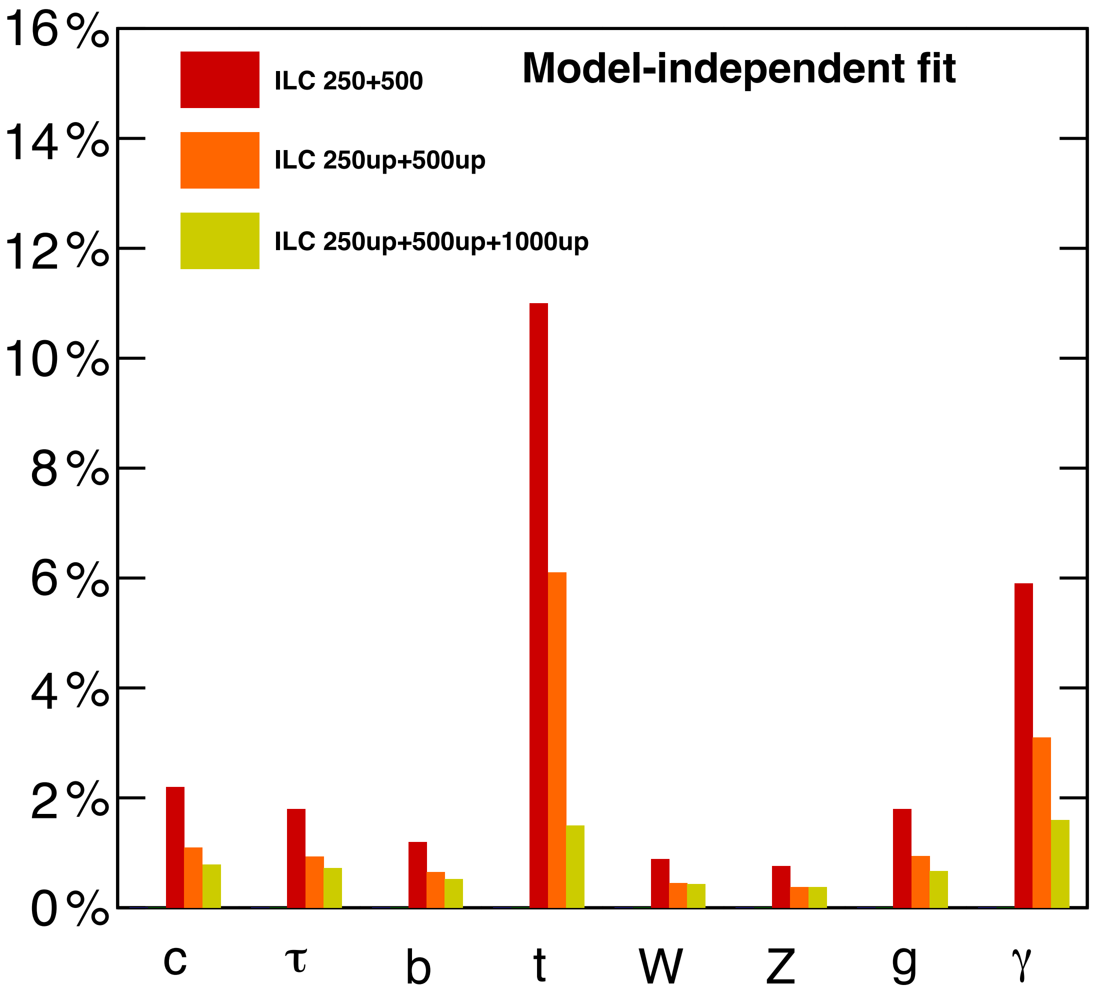
ILC 250up:
Lumi 1920 fb-1, sqrt(s) = 250 GeV

ILC 500up:
Lumi 2670 fb-1, sqrt(s) = 500 GeV

ILC 1000up:
Lumi 4170 fb-1, sqrt(s) = 1 TeV

Higgs Couplings (2/2)

Model-independent coupling determination is unique to the ILC



ILC 250:
Lumi 417 fb-1, sqrt(s) = 250 GeV

ILC 500:
Lumi 833 fb-1, sqrt(s) = 500 GeV

ILC 250up:
Lumi 1920 fb-1, sqrt(s) = 250 GeV

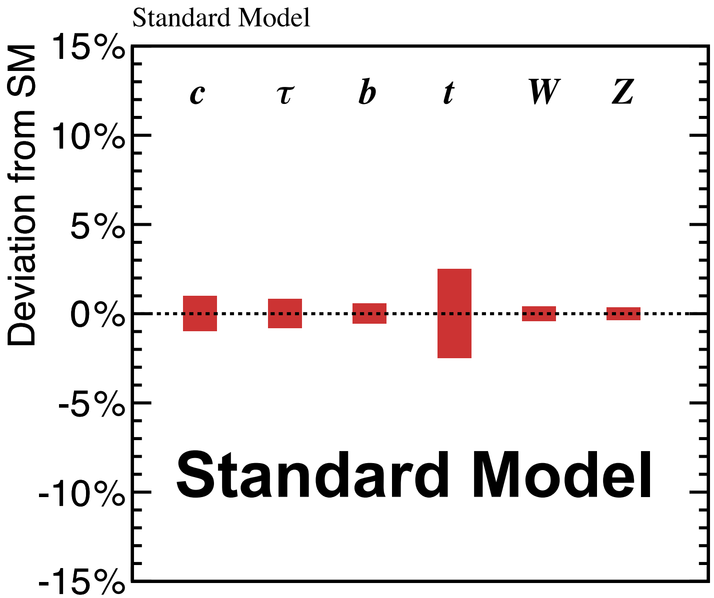
ILC 500up:
Lumi 2670 fb-1, sqrt(s) = 500 GeV

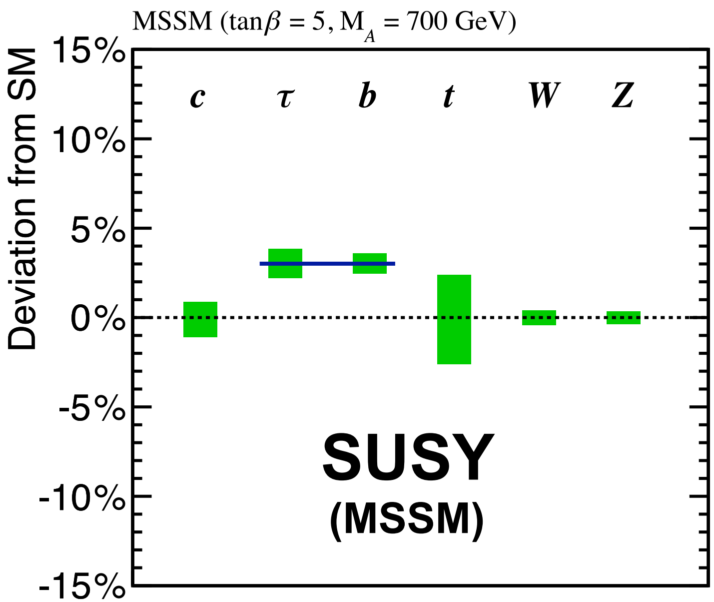
ILC 1000up:
Lumi 4170 fb-1, sqrt(s) = 1 TeV

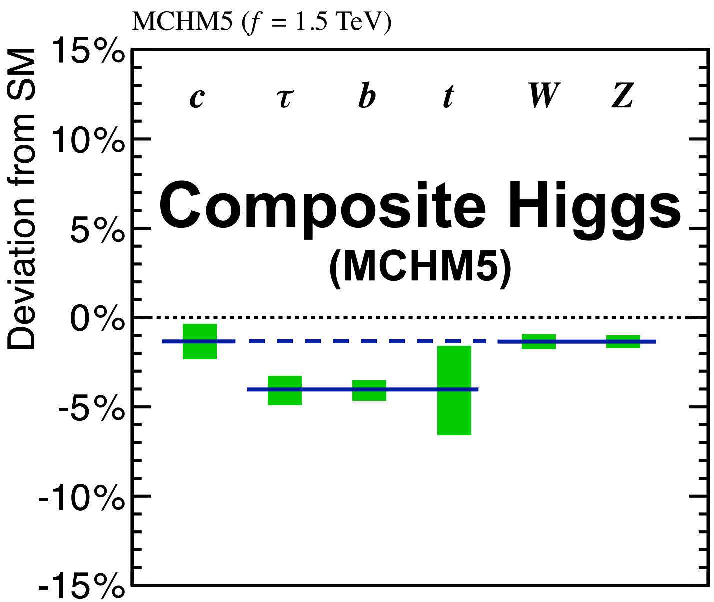
Impact of BSM on Higgs Sector

Deviations in Higgs couplings is a signature of many BSM theories. The pattern of the deviations can be specific to certain models. The precision Higgs coupling measurements at the ILC at the 1% level enable us to fingerprint the different models.

Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV







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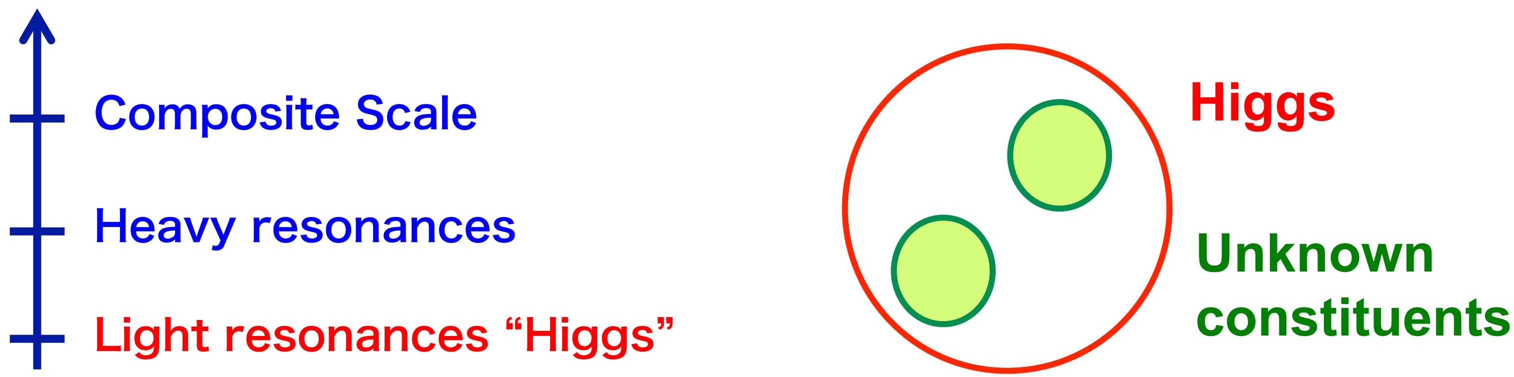
Composite Higgs

Composite Higgs models are based on the idea that the Higgs boson is a pseudo-Nambu Goldstone boson arising from the breaking of a new symmetry. The Higgs is a composite particle, similar to the pion in QCD.



In QCD, there are light scalars (pions, ~0.1 GeV) and heavy vector particles (rho mesons, ~1 GeV). Similarly in composite Higgs models, **heavy resonances are predicted which can be probed via direct searches at the LHC.**

The effect of the new physics also manifests as **deviations in the Higgs couplings, which can be probed at the ILC.**

Typically, the top quark is partially composite and has a role in the symmetry breaking mechanism. This is probed through **deviations in top couplings → ILC.**

1) Future hadron colliders allow for direct VV resonance production up to roughly sqrt(s)/7 due to parton luminosities

2) ILC (500) allows for a cleaner measurements because of separation of longitudinal and transversal mode, esp. cleaner measurement of the W+W- isospin zero channel without the top background penalty from LHC

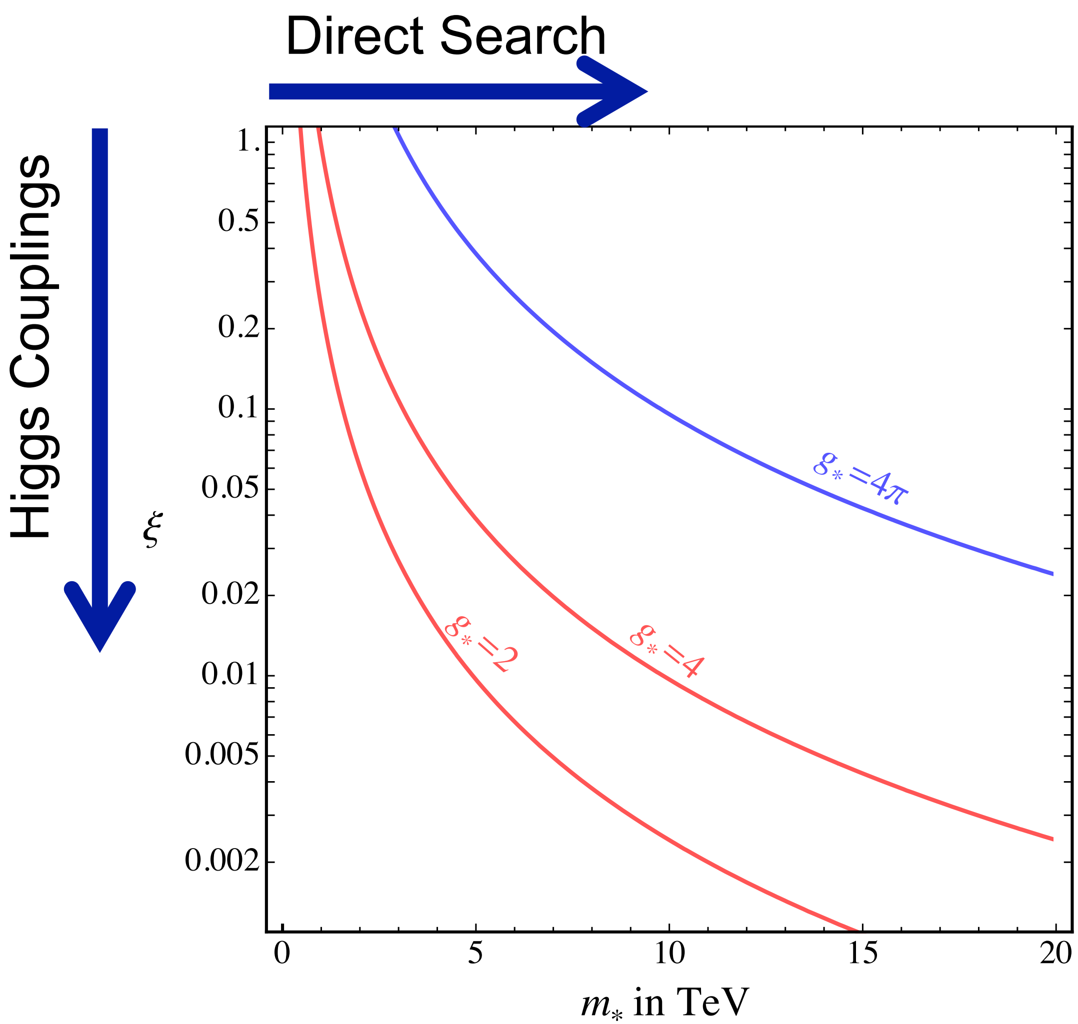
3) Quantum number measurements of new physics in the VV system are accessible at the ILC (cf. the EW Snowmass report or hep-ph/0604048) and allows to possibly give a hint on the scale of new resonances as input for a new hadron machine

Composite Higgs: Reach

Complementary approaches to probe composite Higgs models

- Direct search for heavy resonances at the LHC
- Indirect search via Higgs couplings at the ILC

Comparison depends on the coupling strength (g_*)



Rattazzi,
based on Contino, Grojean, Pappadopulo, Rattazzi, Thamm,
JHEP 1402 (2014) 006 [arXiv:1309.7038]

$$\xi = \frac{g_*^2}{m_*^2} v^2$$

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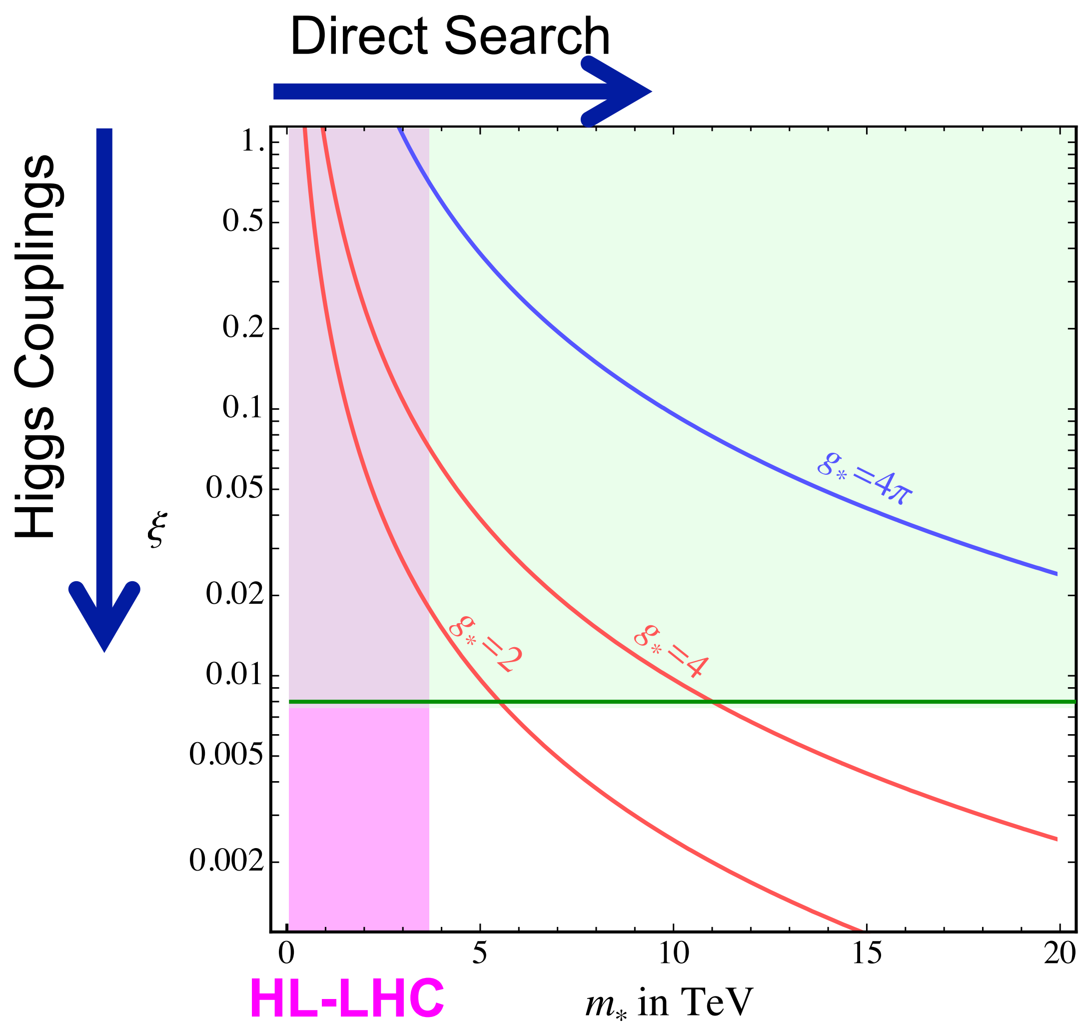


$$\xi = \frac{g_*^2}{m_*^2} v^2$$

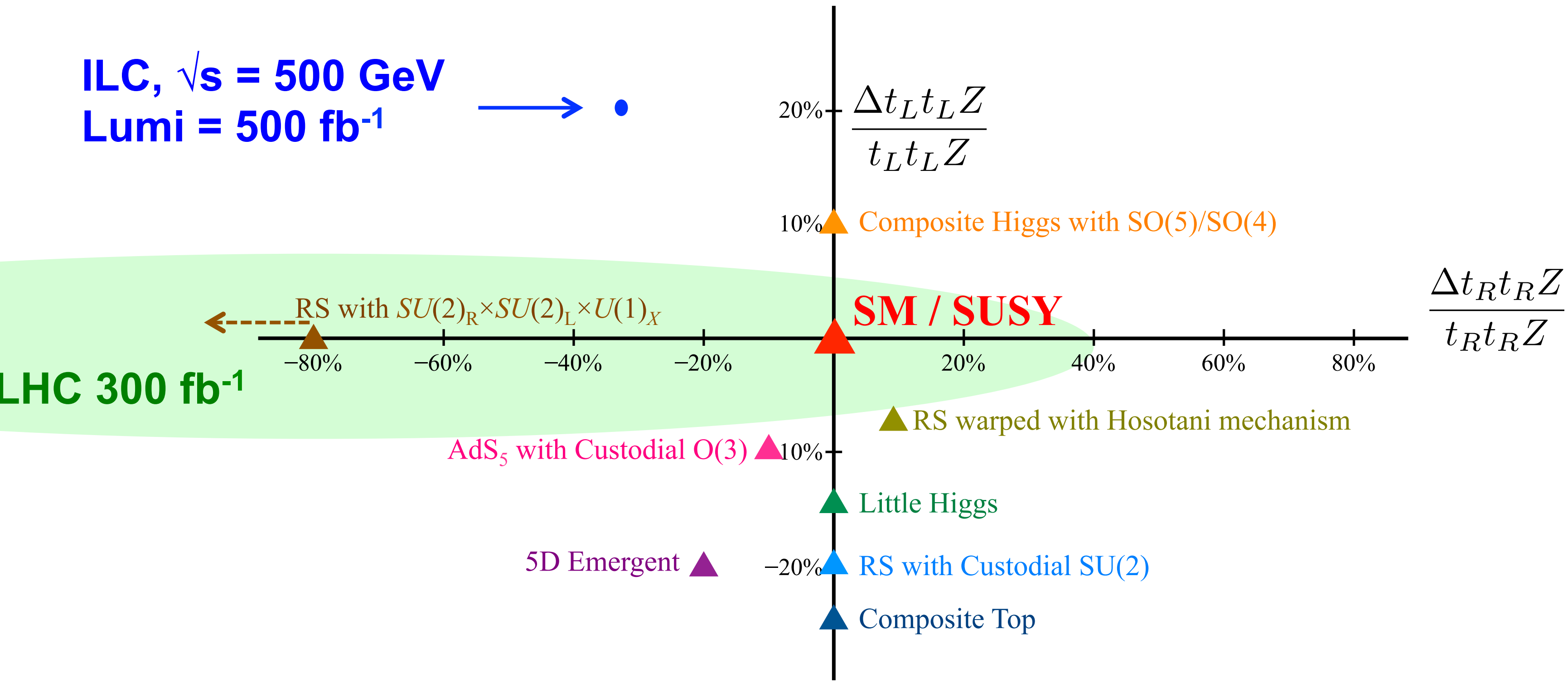
$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} = \sqrt{1-\xi}$$

ILC

$$\frac{\Delta g_{hVV}}{g_{hVV}} = 0.4\%$$

Impact on Top Sector

Composite Higgs theories have an impact on the top sector. Composite Higgs models can be tested at the ILC through precise measurements of the top couplings. Beam polarization (both e- and e+) is essential to distinguish the ttZ and ttγ couplings.



Deviations for different models for new physics scale at ~1 TeV.
Based on F. Richard, arXiv:1403.2893

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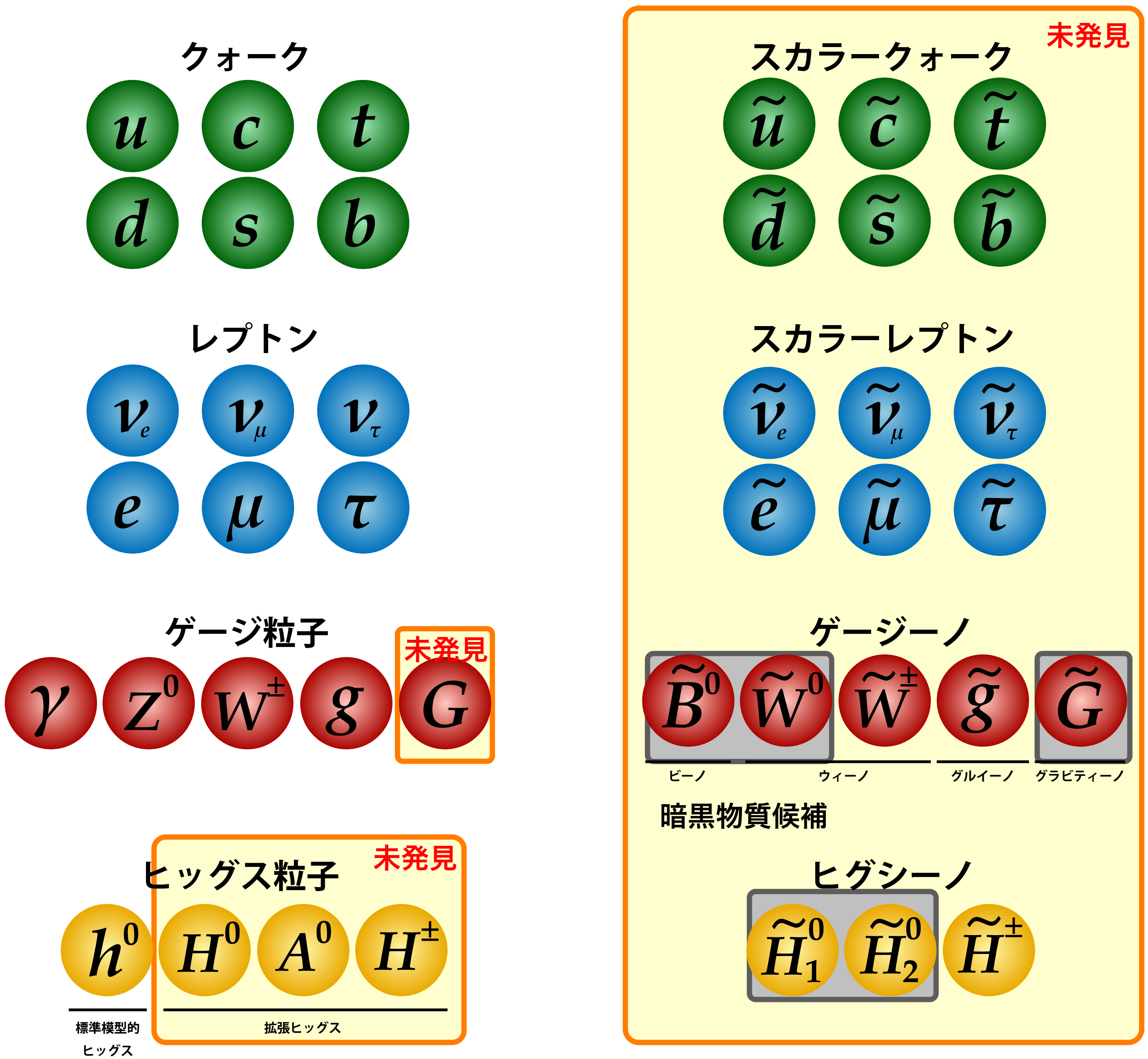
Supersymmetry (SUSY)



Supersymmetry

Symmetry between fermions and bosons. Can explain why the Higgs scale is so low compared to the Planck scale. Super-string theories require SUSY.

SUSY partners have not yet been found – SUSY must be spontaneously broken. Many mediation mechanisms are proposed that realize the symmetry breaking.

The lightest supersymmetric particle (LSP) is a dark matter candidate.

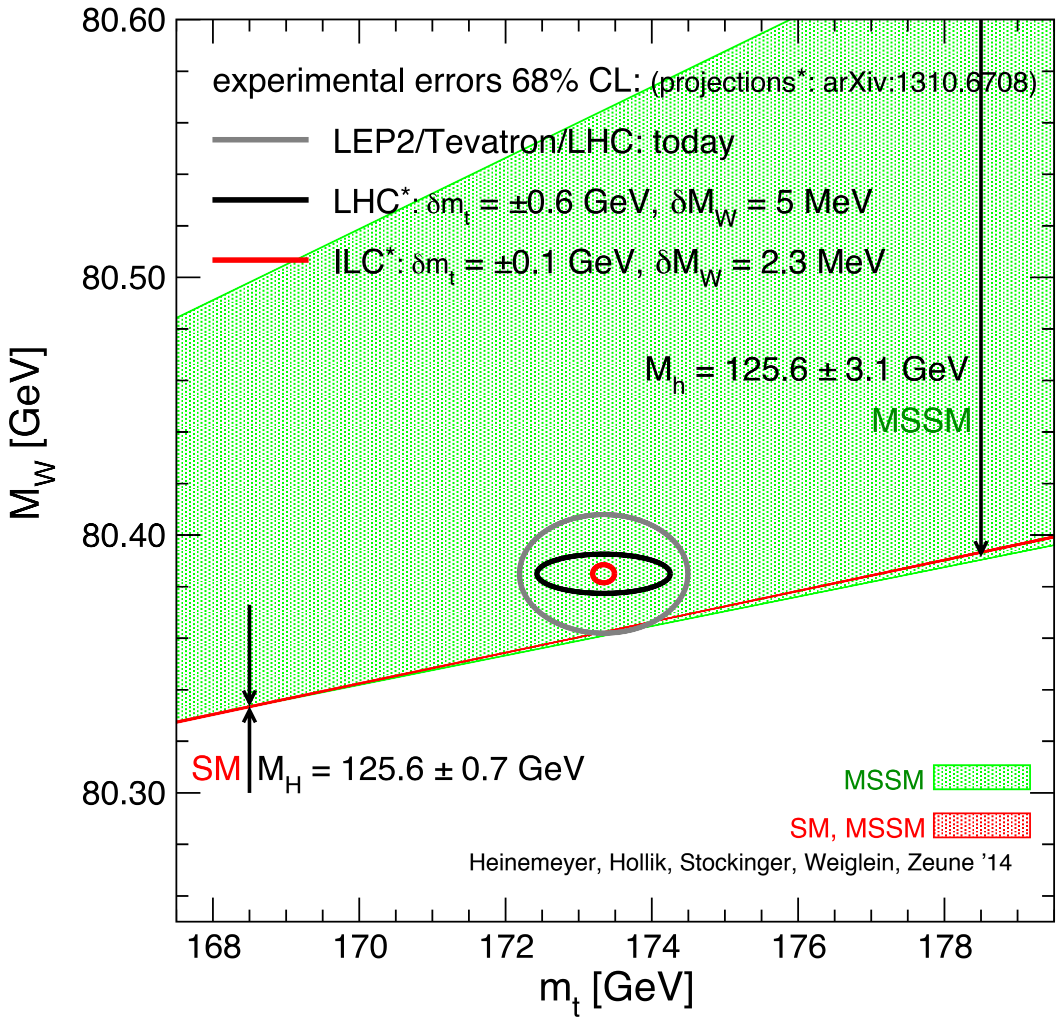
DM candidates

- Bino
- Wino
- Higgsino
- Gravitino

Electroweak Observables

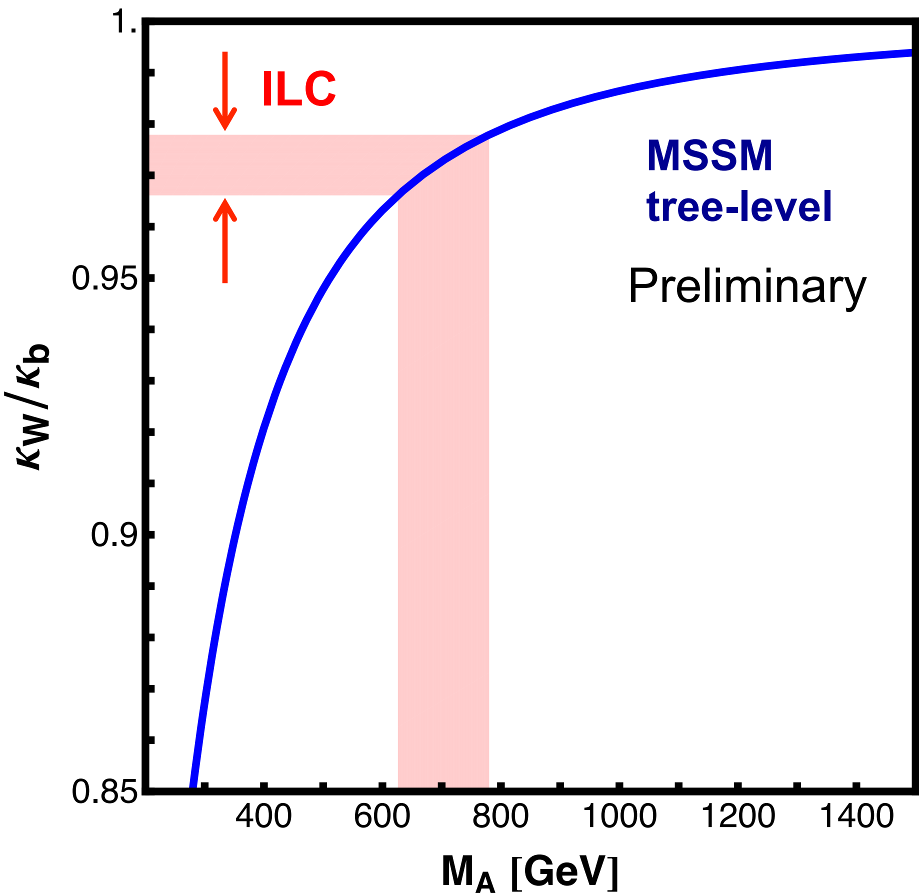
Electroweak observables can be also used to test the consistency of the MSSM.

The W boson mass and the top quark mass are important measurements. They will be both improved by the ILC.



Heavy Higgs Predictions

If deviations in Higgs couplings consistent with an extended Higgs sector are found, the heavy Higgs mass can be predicted from the size of the deviation. Here we give an example based on the MSSM.



Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV

The effect of the multiple Higgs fields manifests as deviations in Higgs couplings of the lightest (SM-like) Higgs boson.

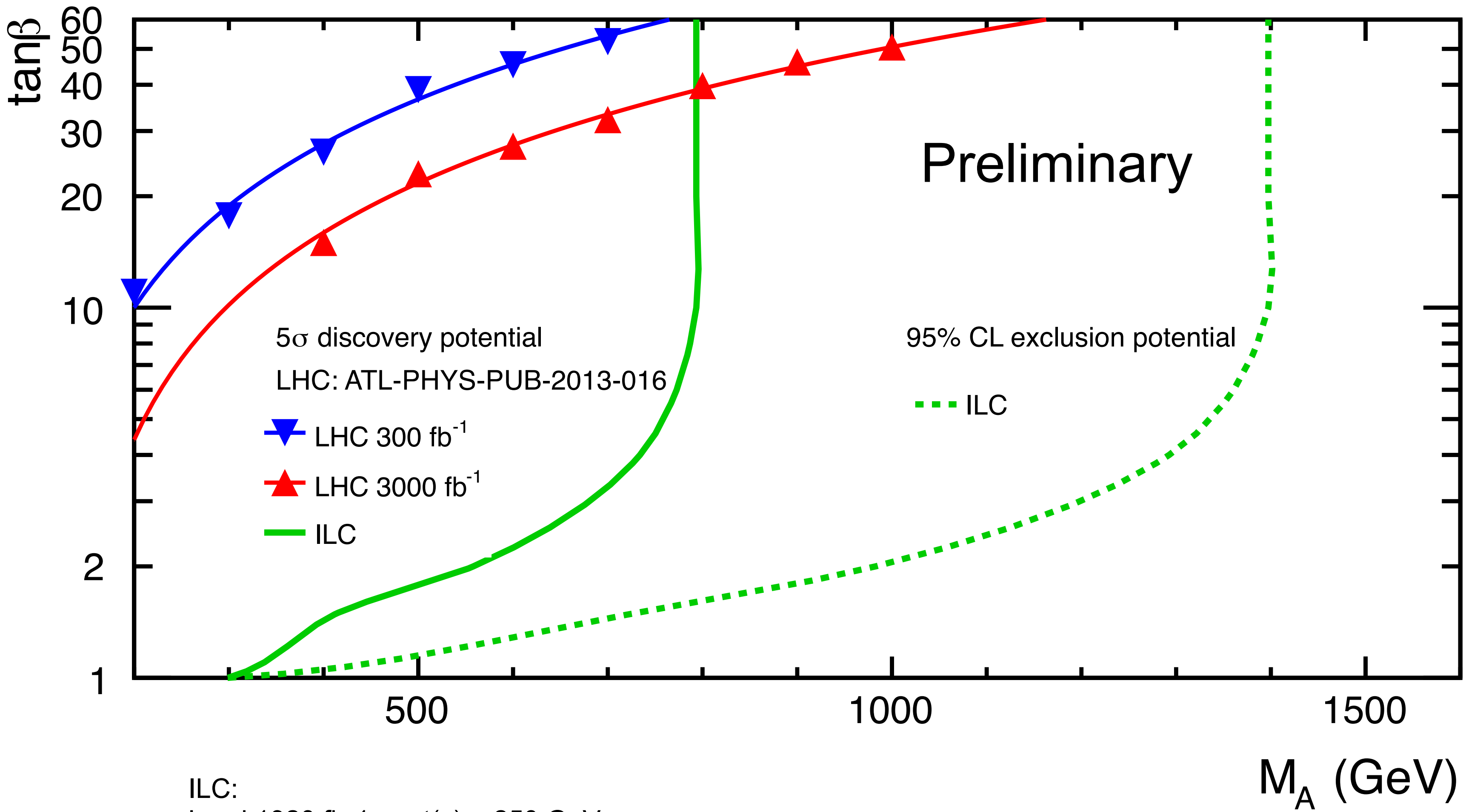
The size of the deviations depends on the mass of the heavy Higgs (MSSM)

The mass of the heavy Higgs can be predicted with precise Higgs measurements at the ILC

n.b. systematic uncertainties are suppressed by taking the ratio of the couplings.

Heavy Higgs Mass Reach

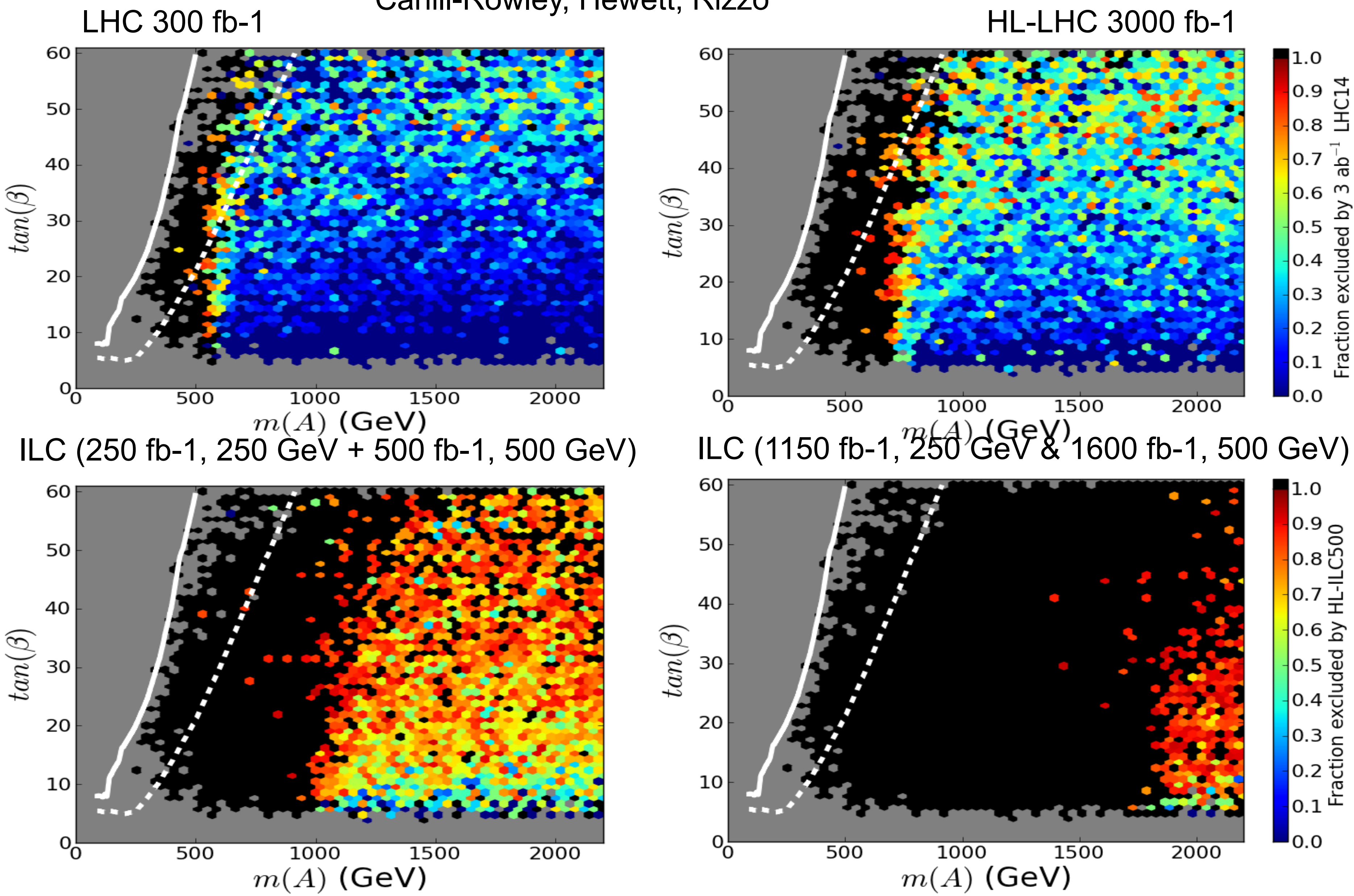
- **LHC:** Heavy Higgs direct search
- **ILC:** Indirect search via effect on Higgs couplings BR(h→WW)/BR(h→bb) and BR(h→WW)/BR(h→ττ)



ILC:
Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV

Combined Effect of γγ, ττ, bb Channels

Cahill-Rowley, Hewett, Rizzo

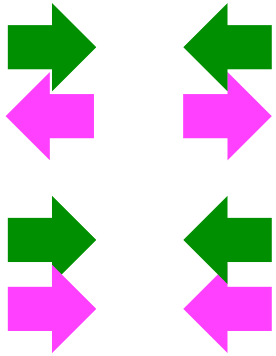


SUSY Parameter Determination

Observables

Mass and Mixing

Polarized Cross Section



SUSY Parameters

$\mathbf{M_1}$

$\mathbf{M_2}$

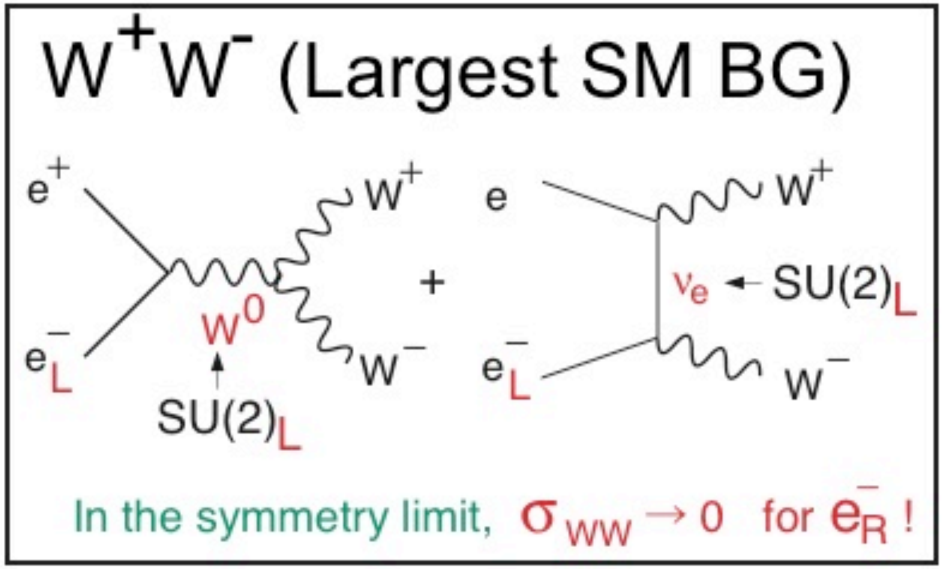
$\boldsymbol{\mu}$

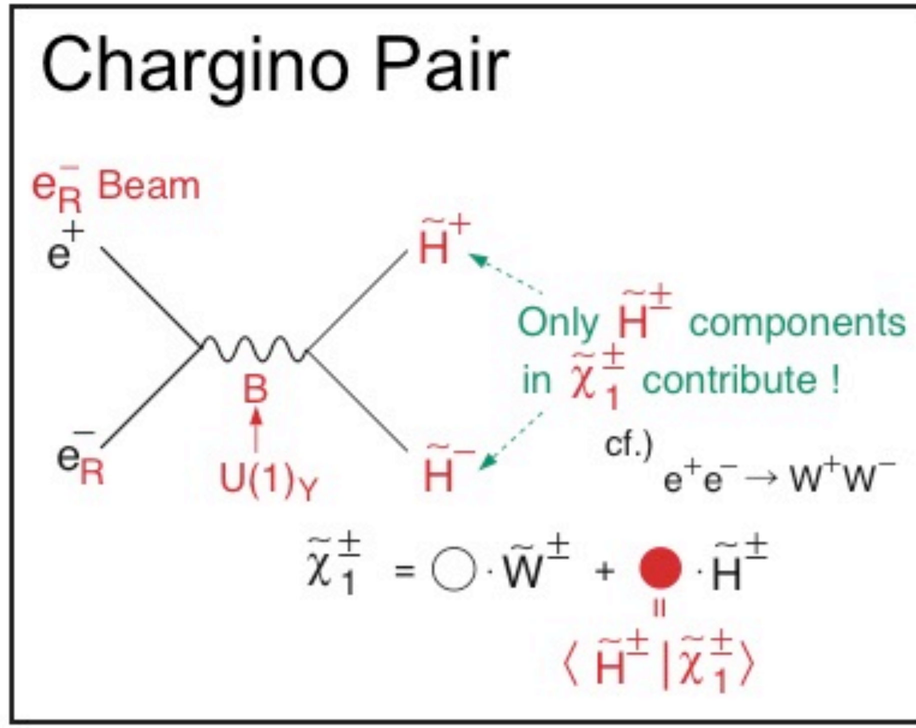
$\mathbf{\tan\beta}$

Power of Beam Polarization

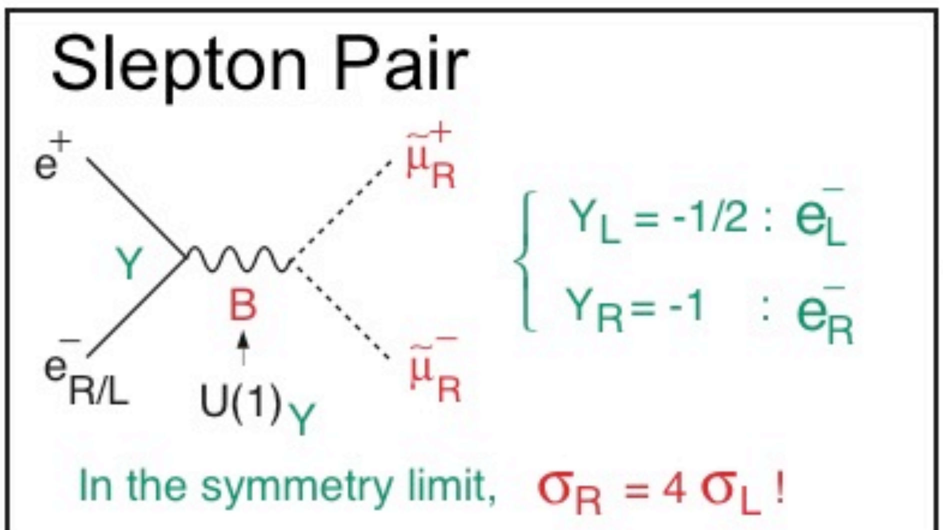
[Fujii]

BG Suppression

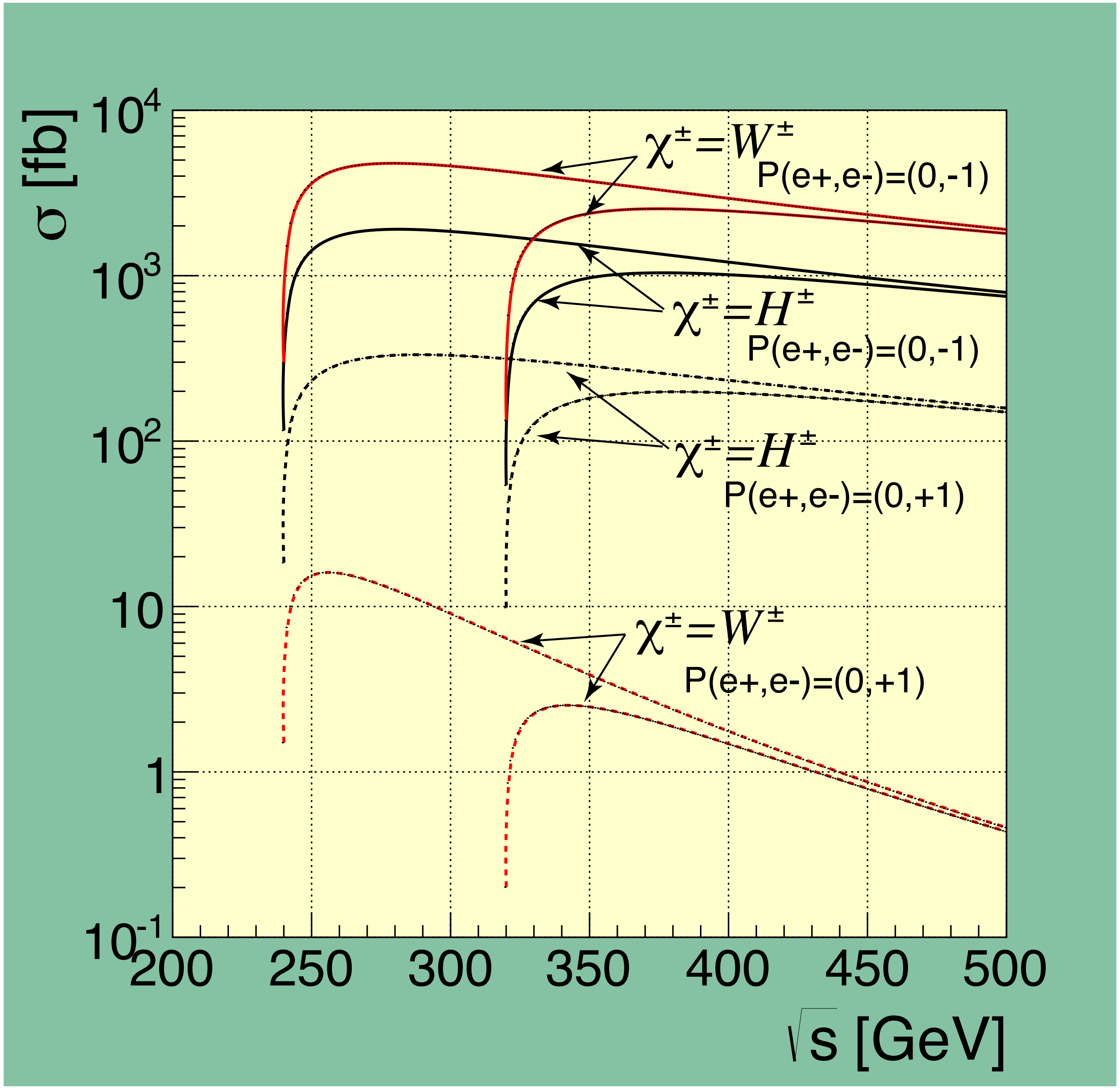




Decomposition



Signal Enhancement

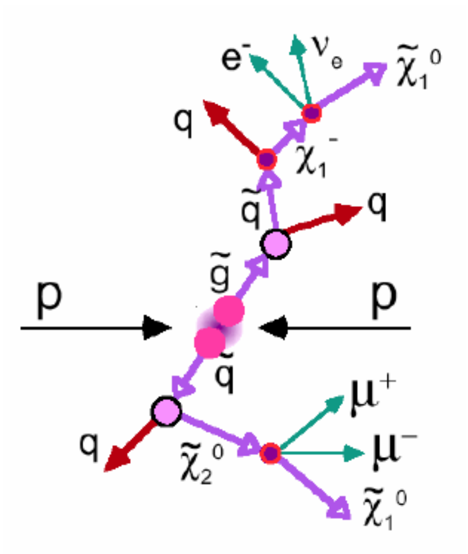


σ [fb]
10^4
10^3
10^2
10
1
10^-1
200
250
300
350
400
450
500
√s [GeV]
χ±=W±
P(e+,e-)=(0,-1)
χ±=H±
P(e+,e-)=(0,-1)
χ±=H±
P(e+,e-)=(0,+1)
χ±=W±
P(e+,e-)=(0,+1)

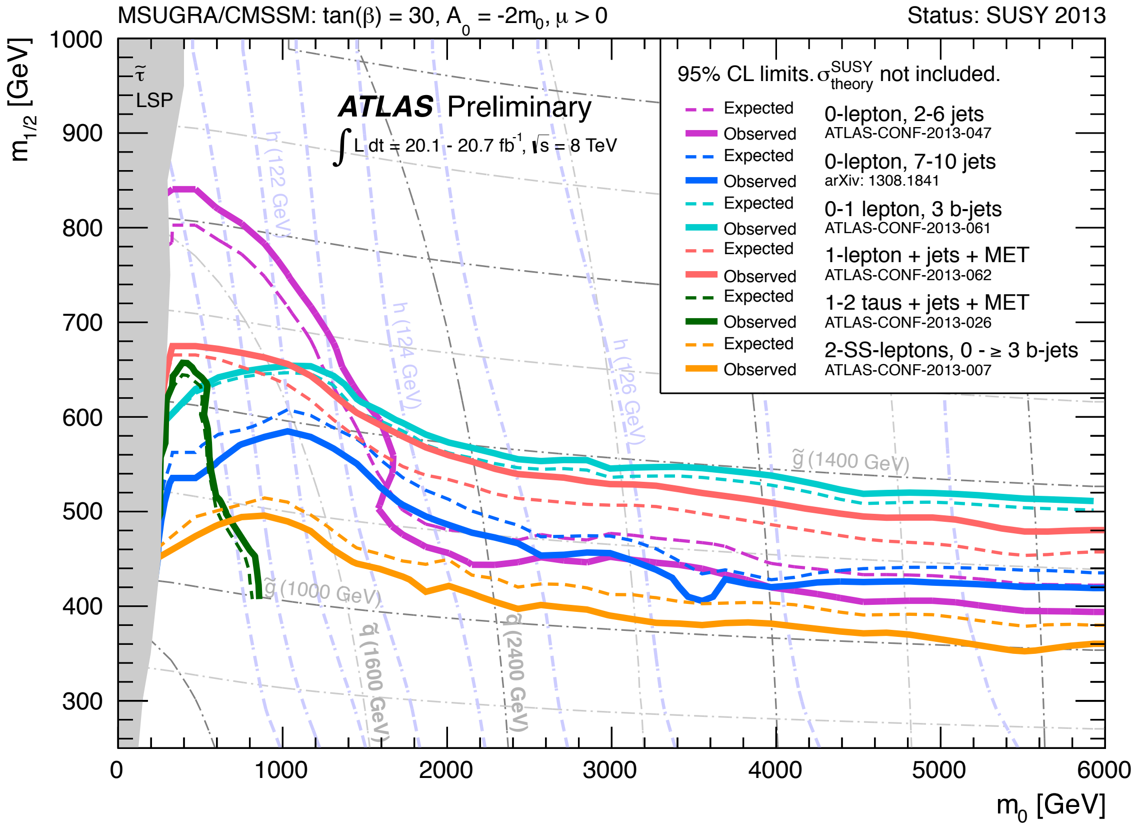
Fujii

LHC SUSY Search

LHC looks for cascade decays of the gluino



8 TeV LHC results (2013)



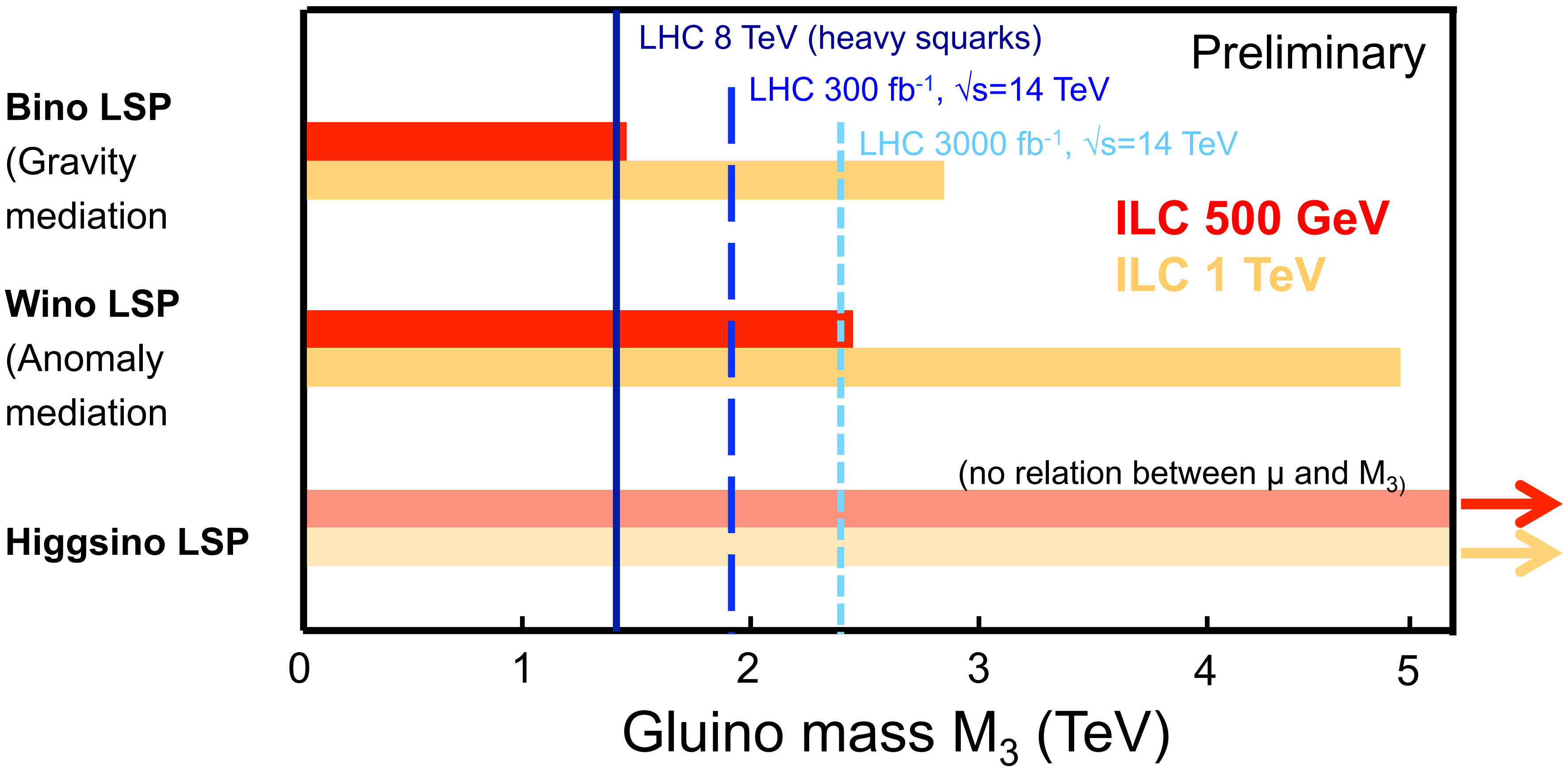
Gluino mass exclusions

Up to 1.4 TeV (heavy squarks)

Up to 1.7 TeV (squark mass ~ gluino mass)

Sensitivity to SUSY

Gluino search at LHC
Chargino/Neutralino search at ILC
→ Comparison assuming gaugino mass relations

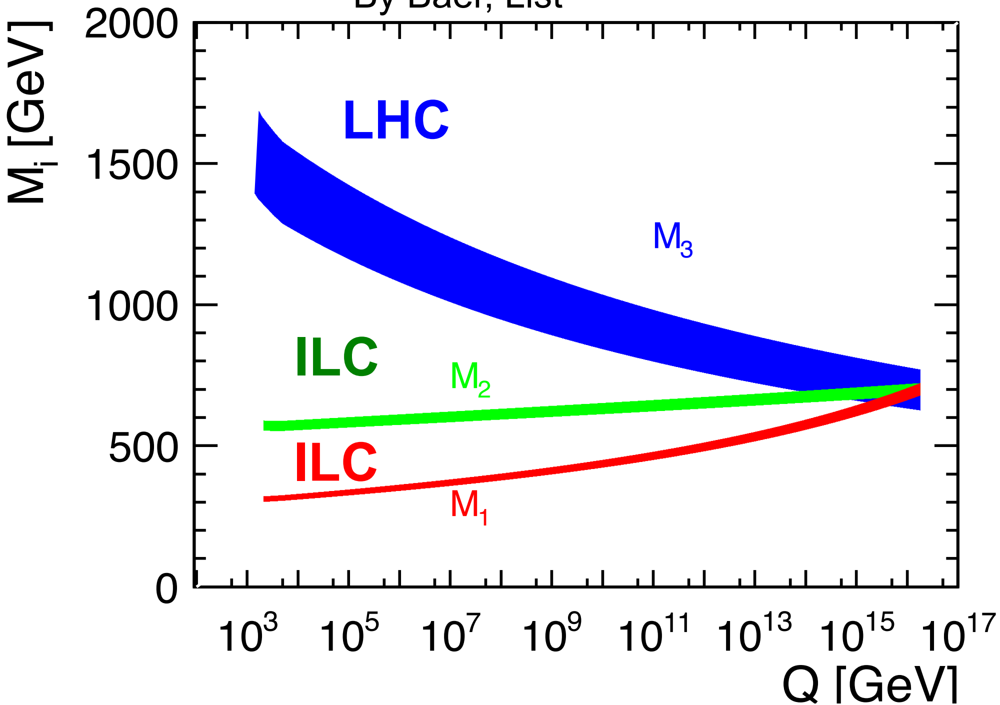


* Assumptions: MSUGRA/GMSB relation $M_1 : M_2 : M_3 = 1 : 2 : 6$; AMSB relation $M_1 : M_2 : M_3 = 3.3 : 1 : 10.5$

Gaugino mass relation

- ILC can probe M_1-M_2 GUT relation if it sees the chargino
- If the LHC sees the gluino – the gaugino mass relation can be tested by ILC-LHC complementarity
- If the LHC does not see the gluino (but ILC sees the chargino), the gluino mass can be predicted assuming the mass relation → scale of next pp collider
- Check of M_1-M_2 relation → discrimination of SUSY spontaneous symmetry breaking scenario!

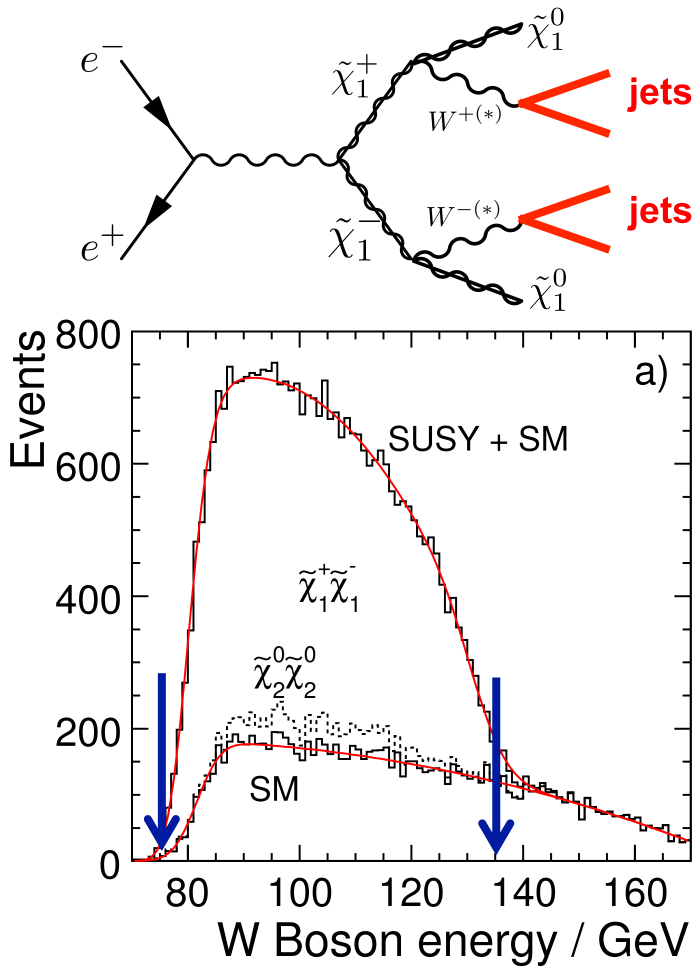
Gaugino mass unification:
Higgsino-like LSP scenario
By Baer, List

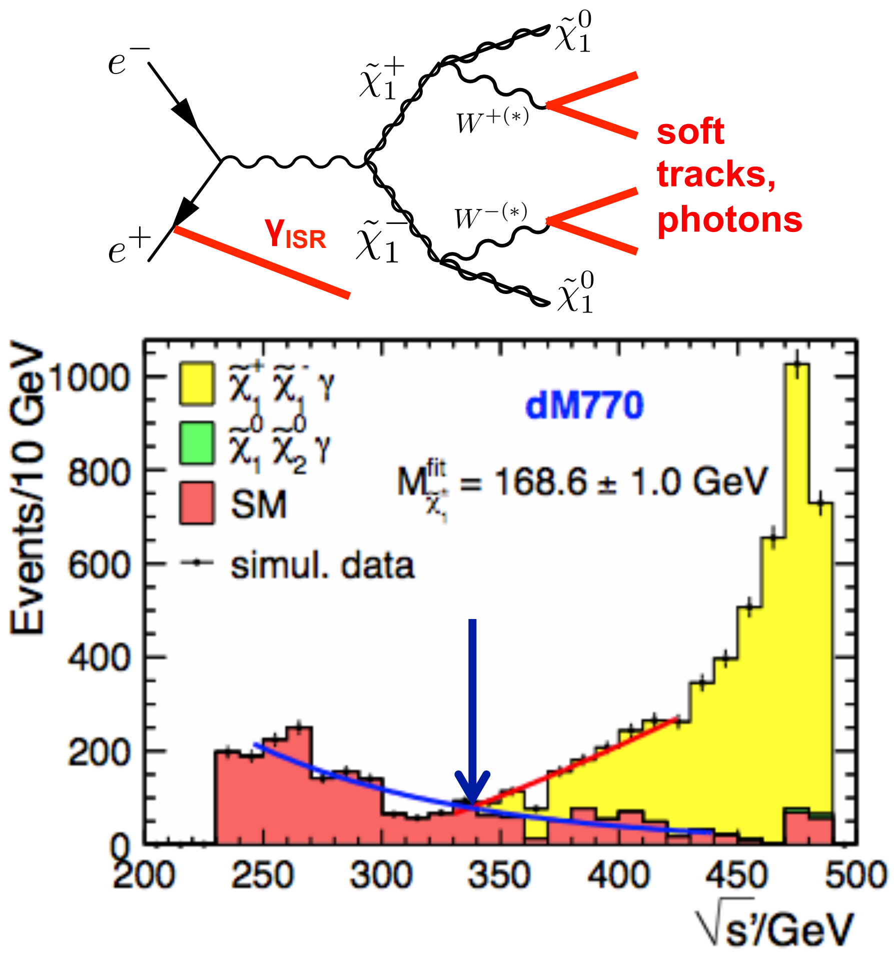


LHC: gluino discovery
→ mass determination

ILC: Higgsino discovery
→ M1, M2 via mixing between Higgsino and Bino/Wino

SUSY Precision Measurements





Mass determination via kinematic edges

Large mass differences between chargino/neutralino; decays to jets.
O(1)% mass precision

Small mass differences between chargino/neutralino; ISR photon tag.
O(1)% mass precision

Physics behind EWSB

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There are three possible scenarios for the physics behind EWSB.

1. **Composite Higgs:** a QCD-like theory is behind the EWSB.
2. **Supersymmetry (SUSY):** SUSY breaking triggers EWSB.
3. **Standard Model (SM):** Origin of EWSB is at a very high scale.

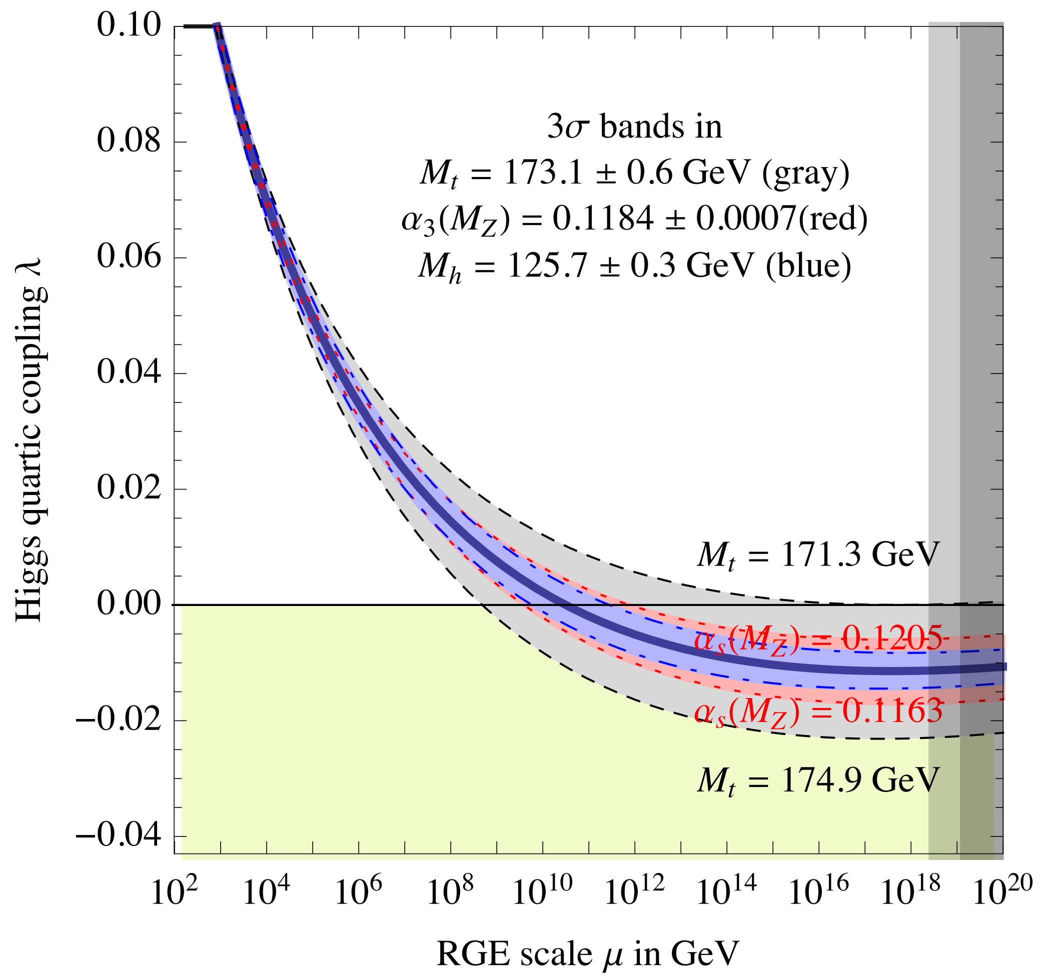
Extrapolating SM to Very High Energies

The SM can be valid up to very high energies. Under this hypothesis, the stability of our vacuum can be tested via precise measurements of electroweak observables.

Current measurements are limited by the uncertainties in the top quark mass and α_s measurements.

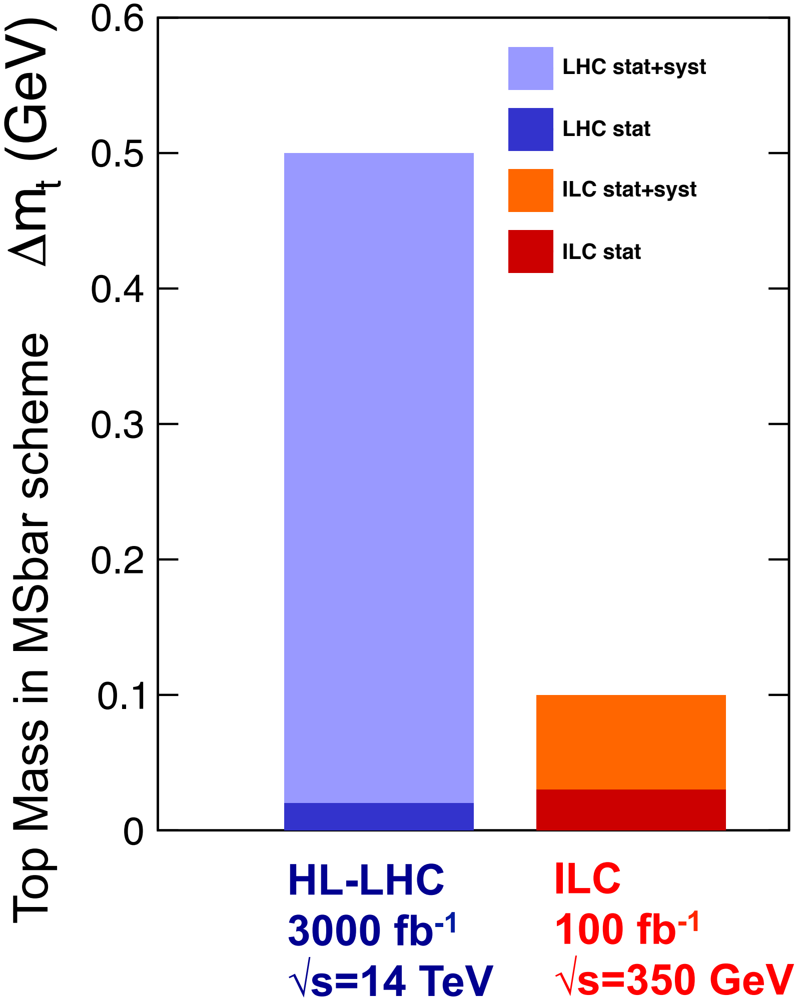
ILC will improve the top quark measurement by five fold (100 MeV) over the HL-LHC (500 MeV).

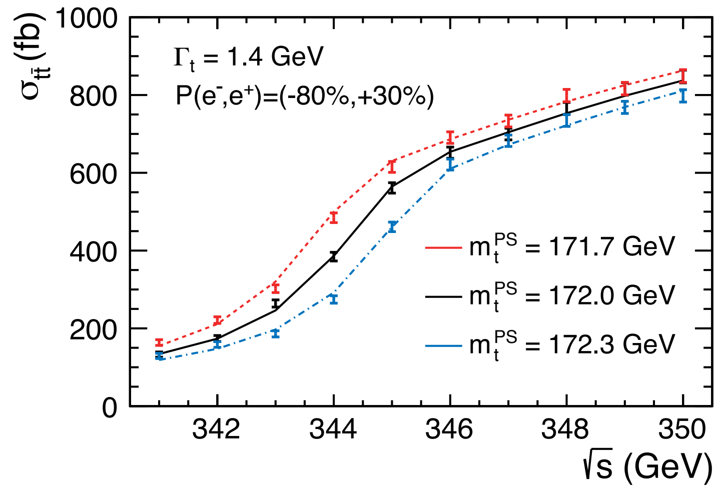
Future Lattice QCD calculations can provide precise α_s calculations at the 0.08% level (Lepage, McKenzie, Peskin, arXiv: 1404.0319).

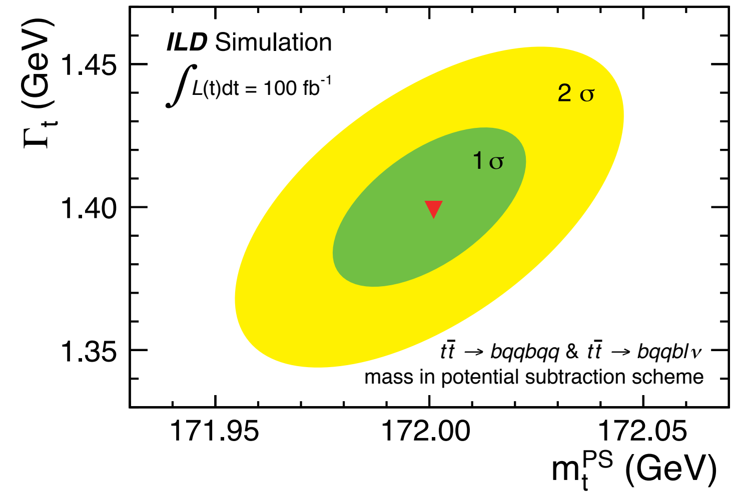


Degrassi et al.
JHEP 1208 (2012) 098
arXiv:1205.6497

Top Quark Mass



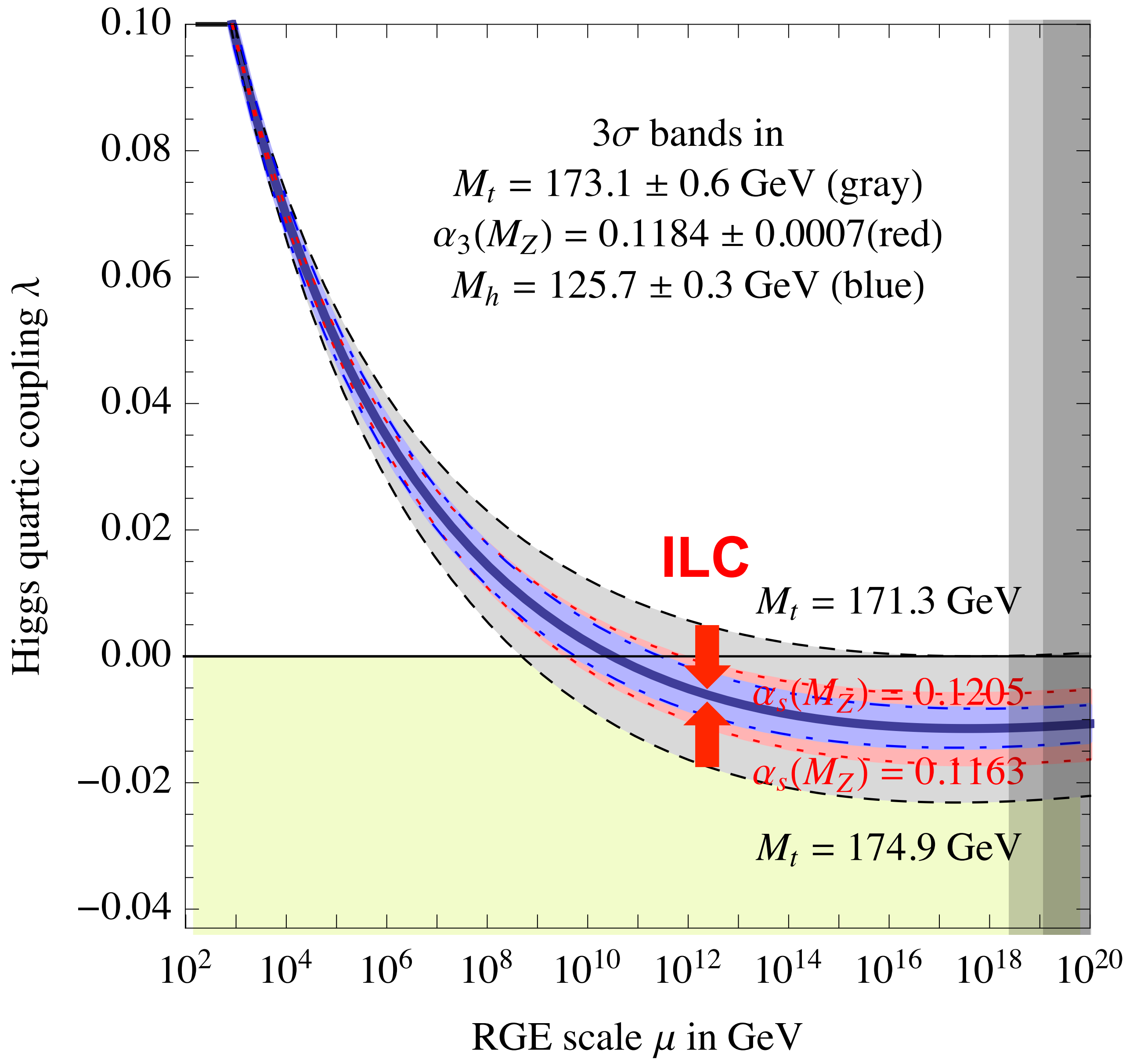




HL-LHC: arXiv:1311.2028

ILC: T. Horiguchi et al.

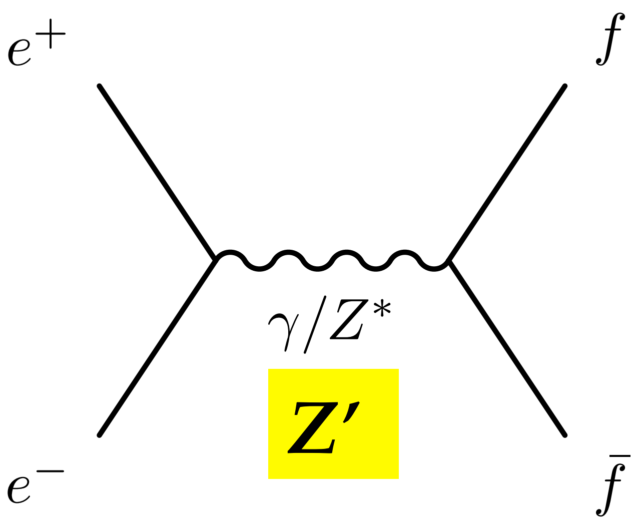
Extrapolation of SM at High Energies

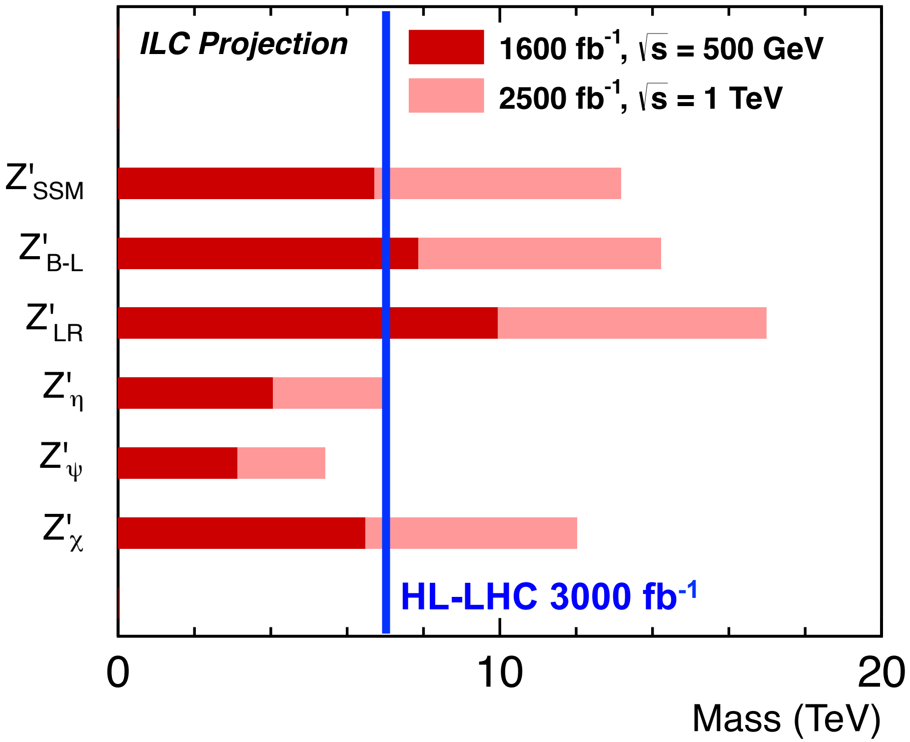


Dark Matter & Other New Particles

Z' : Heavy Neutral Gauge Bosons

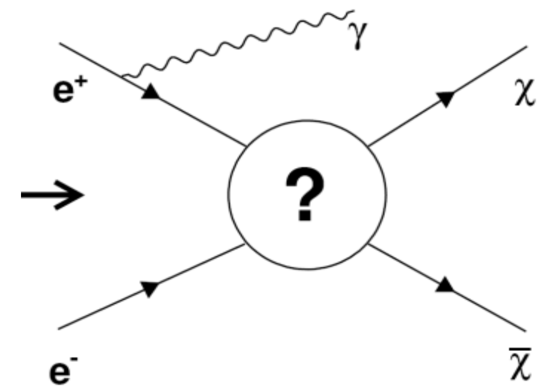
- Examples: L-R symmetric models, string-inspired model (E8), etc.
- Complementary approaches
  - Direct search for heavy resonances (Z') at the LHC (mass determination)
  - Indirect searches via interference effects at the ILC (coupling measurements and model discrimination) – beam polarizations improve reach and discrimination power

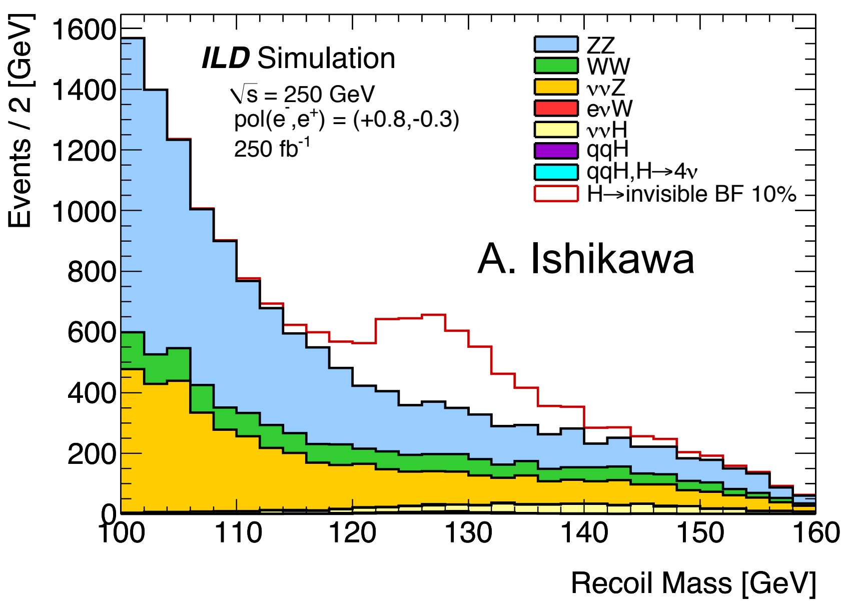




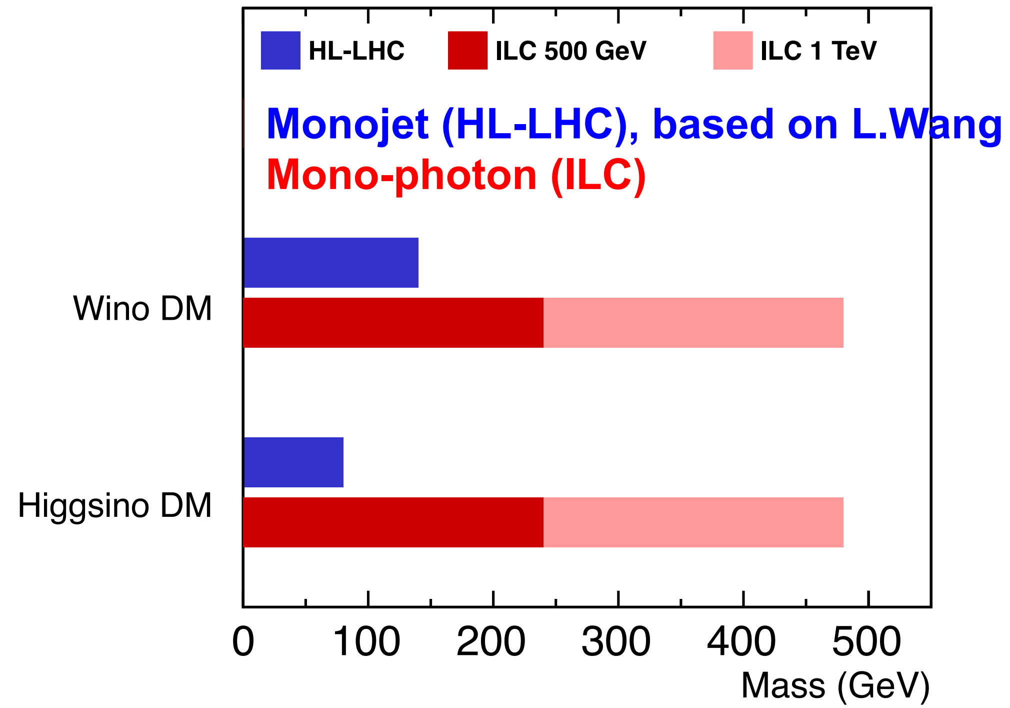
Dark Matter Frontier @ ILC

1. Invisible Higgs decays (Higgs portal scenarios)
   - LHC: 10% 14 TeV HL−LHC (snowmass paper)
   - **ILC: < 0.6%**
2. Mono-photon/Monojet searches
   - LHC: up to ~100 GeV
   - ILC: essential up to half CM energy
3. SUSY-motivated searches – NLSP decays, etc



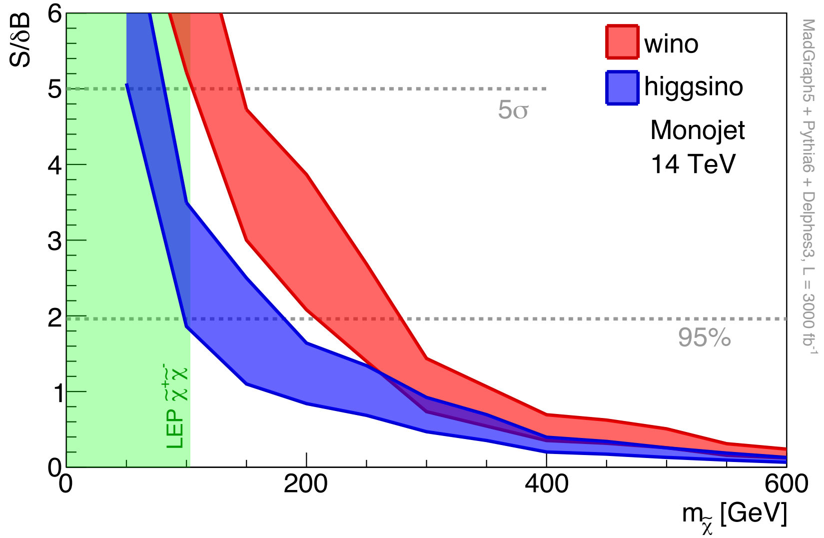


Higgs invisible decay



HL-LHC: monojet search

Mono-X

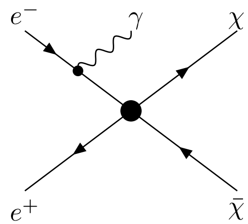


- Very challenging. Systematics dominated
  - No limit from the 8 TeV run.
  - Very weak discovery reach at 14 TeV, 3 ab^{-1} .
- Reach at lepton collider, about 1/2 E_{CM}.

Monday, May 12, 14

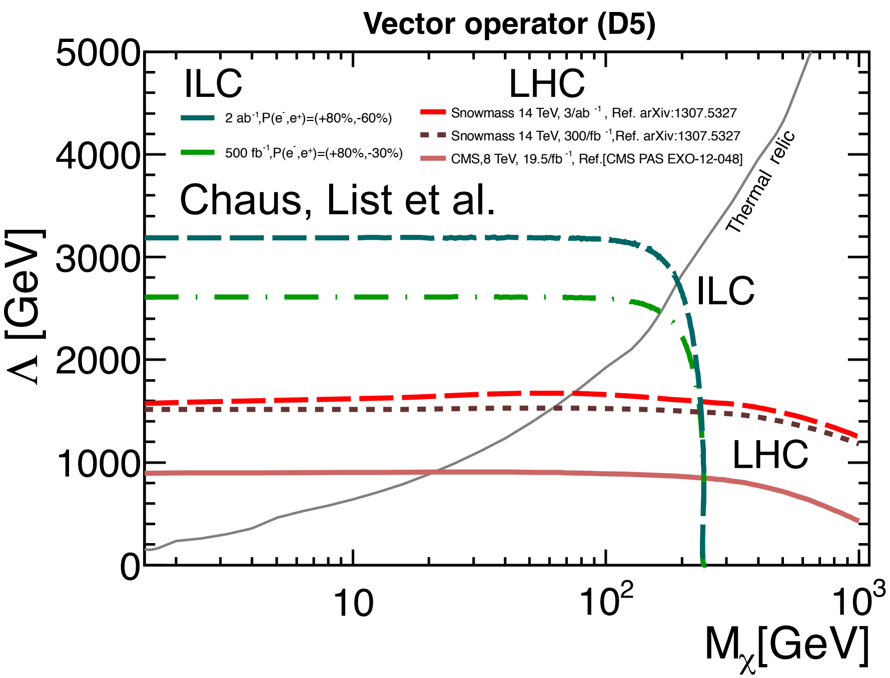
Lian-Tao Wang, AWLC14

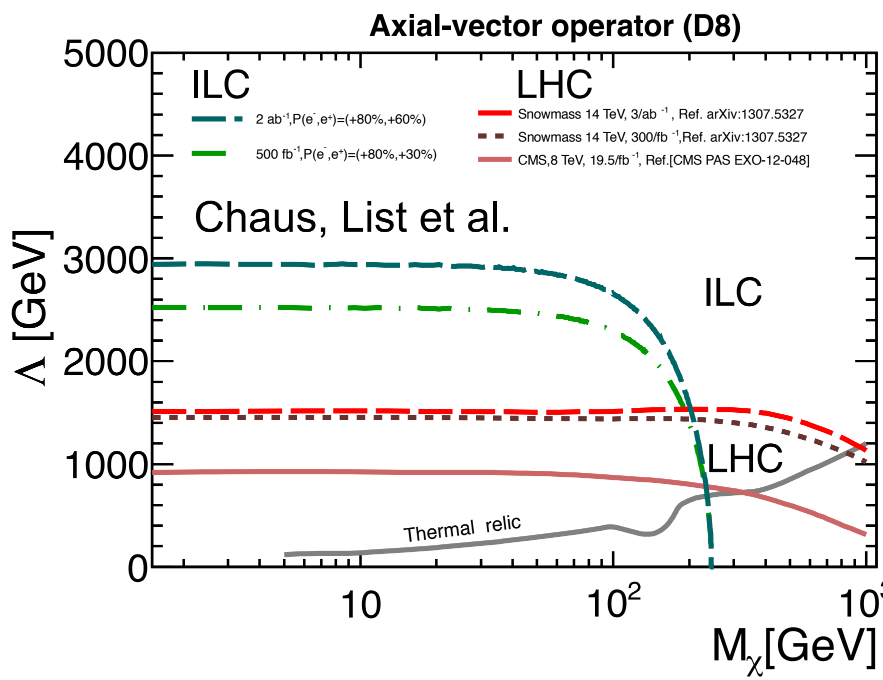
DM: effective operator approach



$$\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

$$\mathcal{O}_V = (\overline{\chi}\gamma_\mu\chi)(\overline{\ell}\gamma^\mu\ell) \qquad \mathcal{O}_A = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{\ell}\gamma^\mu\gamma^5\ell)$$





ILC sensitivity:

- DM mass up to ~√s/2
- Mediator mass up to Λ~3 TeV

SUSY and Dark Matter

The LHC results exclude many previously considered scenarios for dark matter within supersymmetry. However, several attractive scenarios are still in play, e.g.:

“well-tempered neutralino”

The lightest SUSY particle is a mixture of the Higgsino and either a bino or singlino. This enables just-so annihilations into W^+W^- and Z^0Z^0.

Higgsino, bino, singlino = superpartners of the Higgs, hypercharge gauge boson and singlet field. The singlet is often introduced to raise the Higgs boson mass predictions.

“stau coannihilation”

The lightest SUSY particle is the partner of the hypercharge gauge boson. It is close in mass to the SUSY partner of the tau lepton. Annihilation and coannihilation of the staus determine the dark matter density. Dark matter annihilates mainly to b quarks.

“non-thermal dark matter”

Light Higgsinos or winos (superpartner of W^0 gauge boson) are viable dark matter if their relic abundance is set by non-thermal sources, such as decays of gravitinos or moduli in the early universe. This is generic in some approaches to SUSY. Annihilates to W^+W^-, Z^0Z^0.

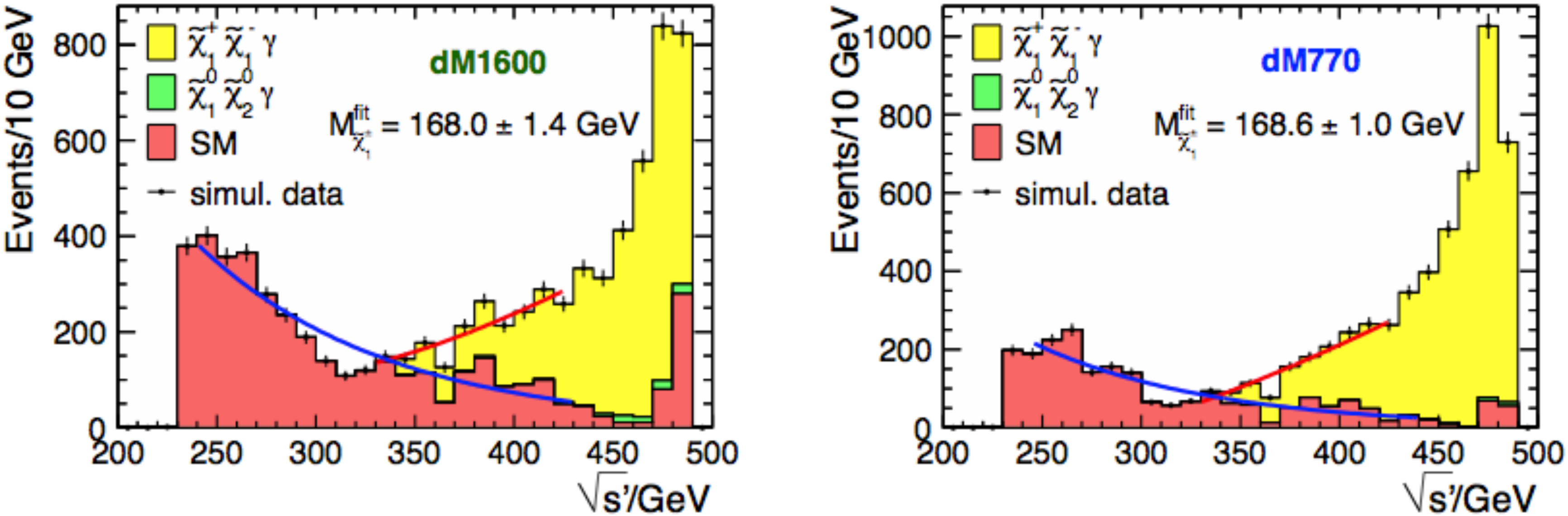
To test these scenarios, we need to observe Higgsino, Wino or stau pair production, in a situation where these decay to the dark matter particle with very small energy release.

Higgsinos with small mass differences

Study of Higgsino pair production, with ISR tag

Benchmark models with
m(NLSP) – M(LSP) = 1.6 GeV and 0.8 GeV

Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert,
EPJ C73 (2013) 2660 [arXiv:1307.3566]



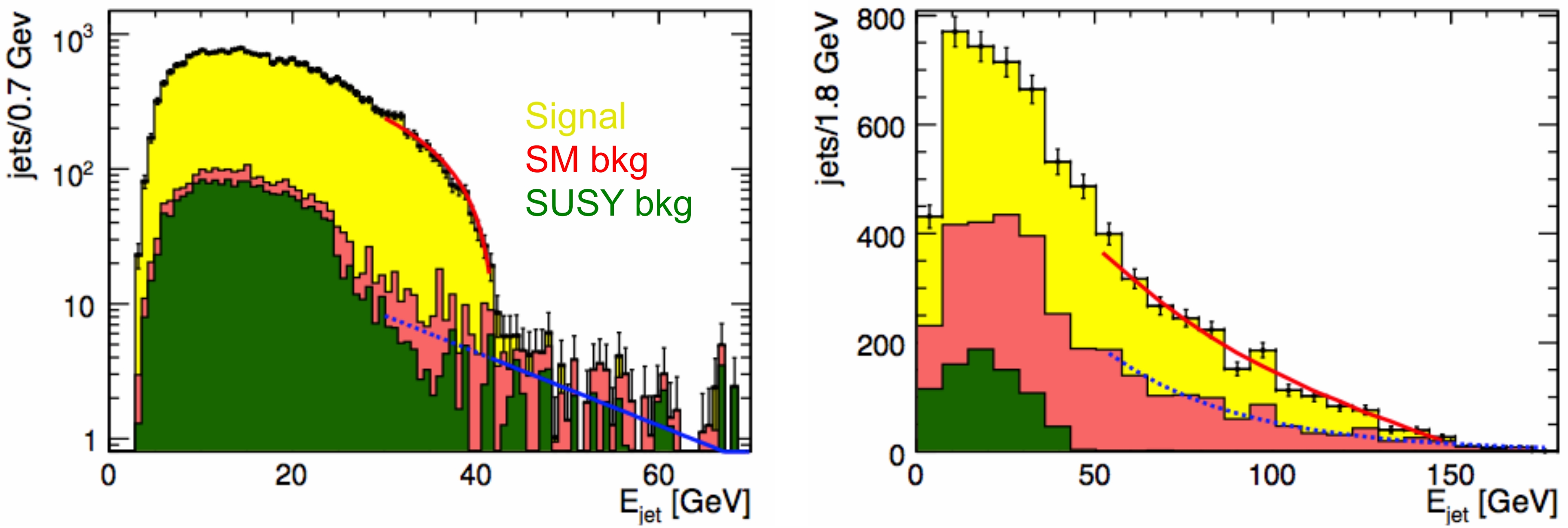
LSP mass resolution ~1%
even for very small mass differences ~1 GeV

Slepton decays to DM

Study of stau pair production at the ILC
Observation of lighter and heavier stau states with decay to DM + hadronic tau

Benchmark point: m(LSP) = 98 GeV, m(stau1) = 108 GeV, m(stau2) = 195 GeV

Bechtle, Berggren, List, Schade, Stempel, arXiv:0908.0876, PRD82, 055016 (2010)

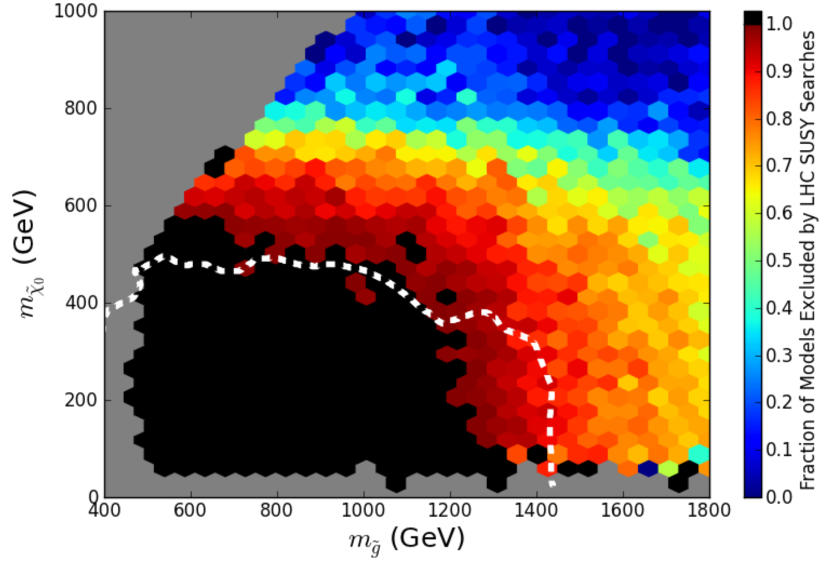


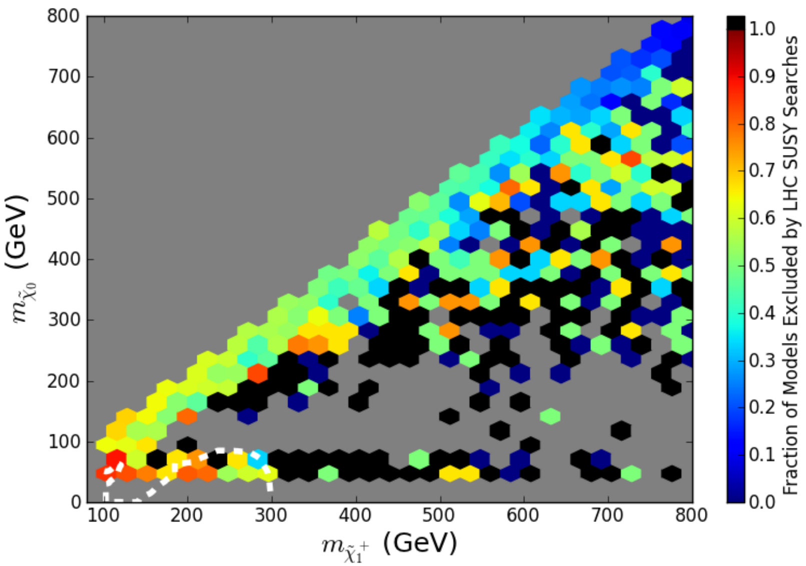
Stau1 mass resolution ~0.1%
Stau2 mass resolution ~3%
→ LSP mass resolution ~1.7%

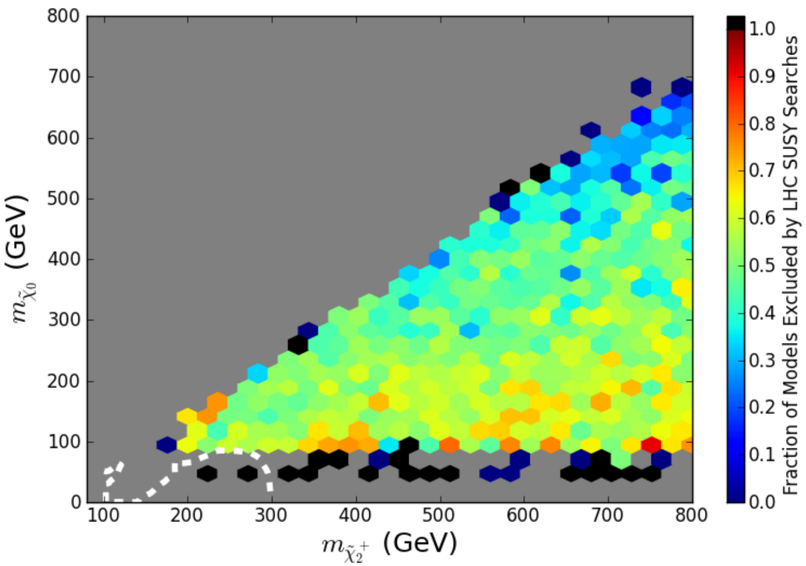
pMSSM models

Cahill-Rowley, Hewett, Rizzo [to be published]

pMSSM models with the flavor and dark matter constraints applied







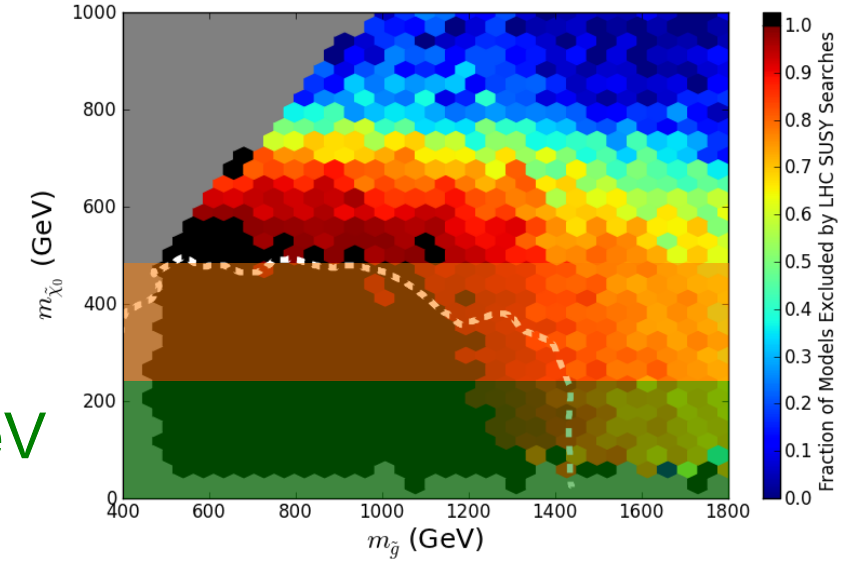
pMSSM models

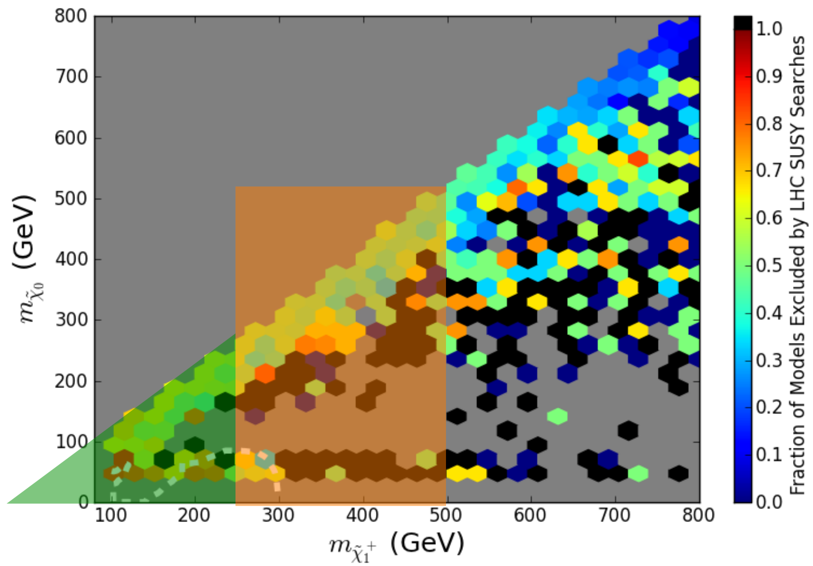
Cahill-Rowley, Hewett, Rizzo [to be published]

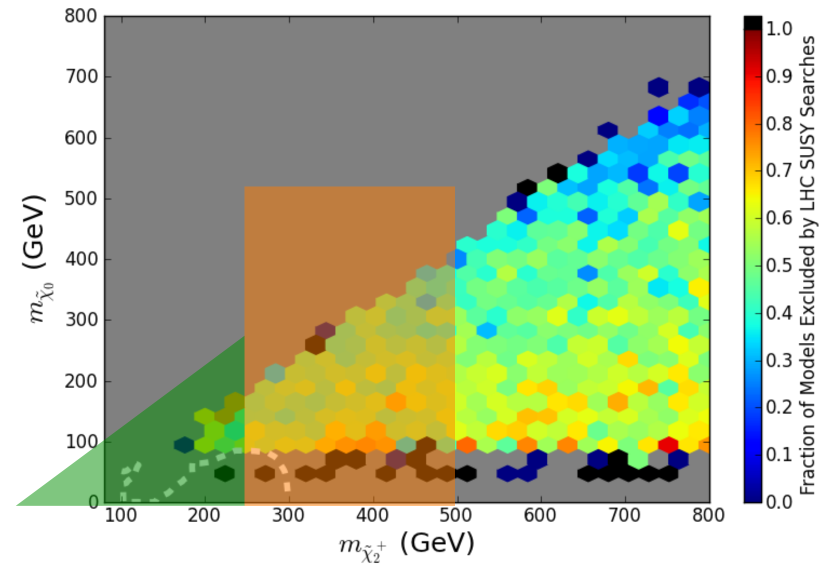
pMSSM models with the flavor and dark matter constraints applied

ILC 1 TeV

ILC 500 GeV



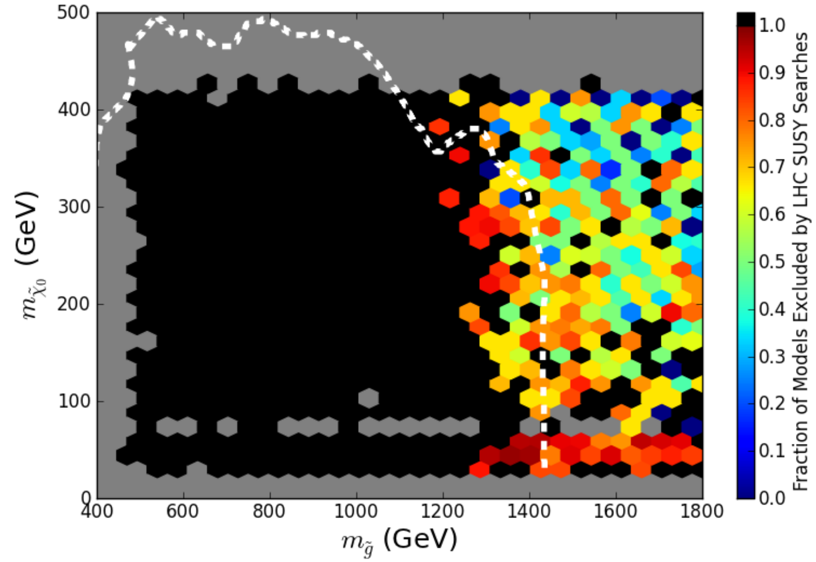


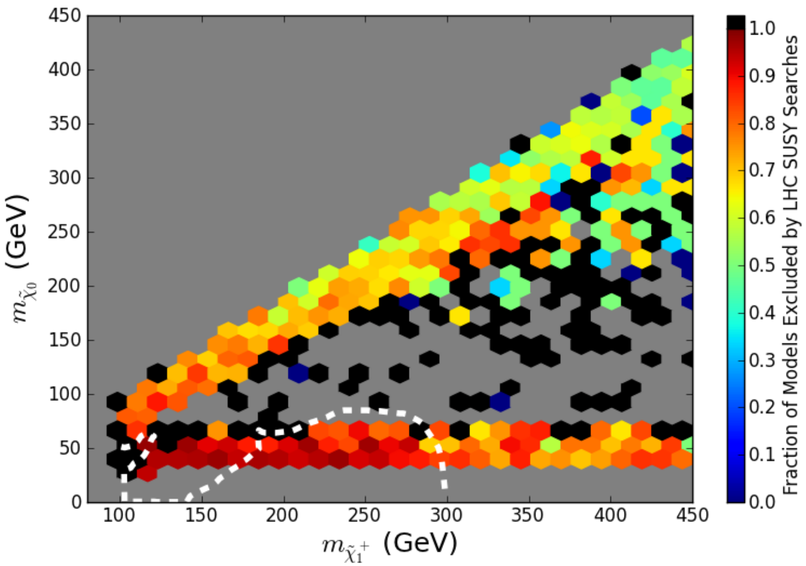


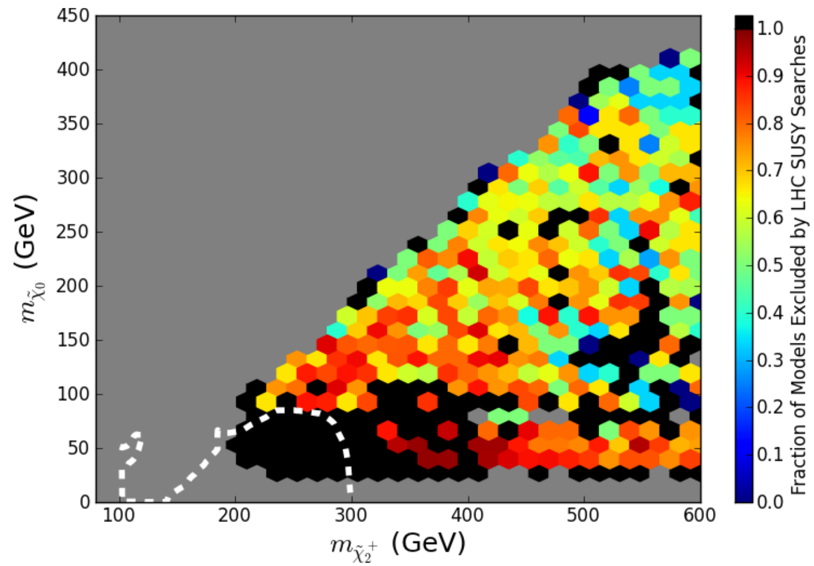
pMSSM models with low fine-tuning

Cahill-Rowley, Hewett, Rizzo [to be published]

pMSSM models with the flavor and dark matter constraints applied,
and with low fine-tuning
($\Delta_{\text{Barbieri-Giudice}}$ < 100)







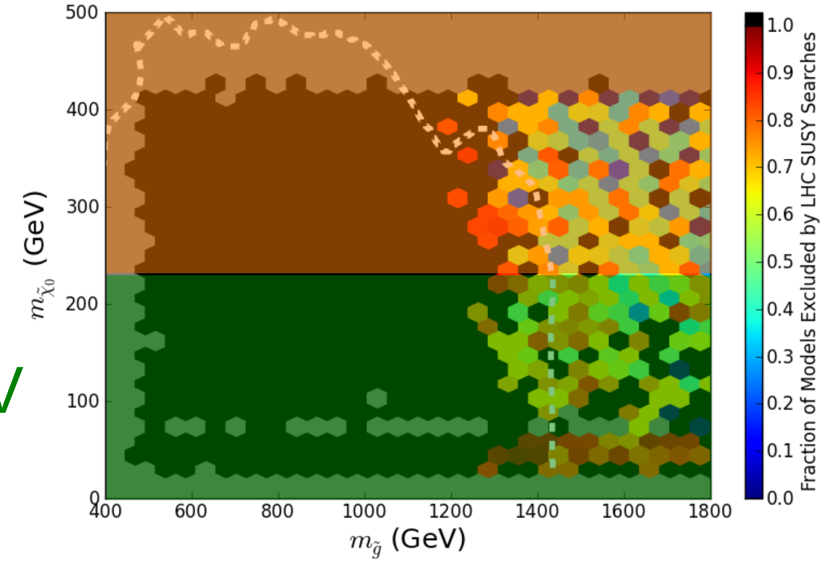
pMSSM models with low fine-tuning

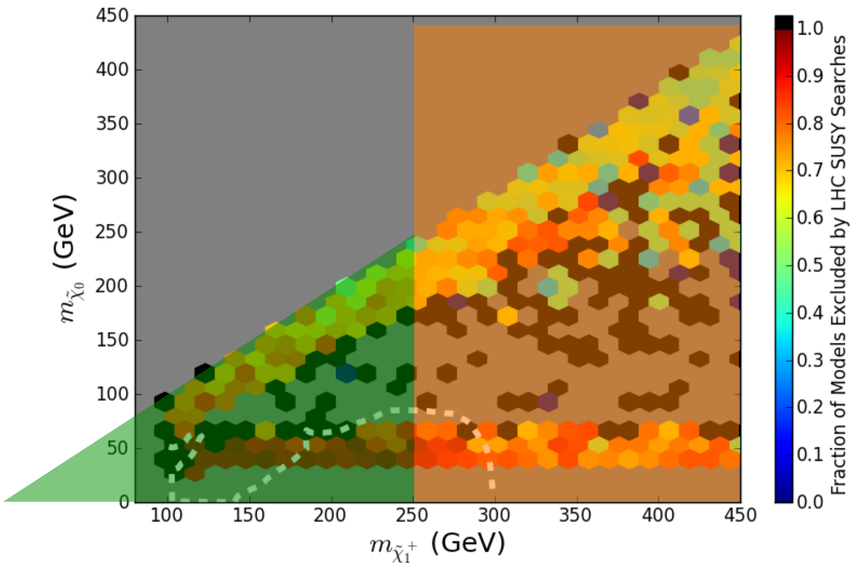
Cahill-Rowley, Hewett, Rizzo [to be published]

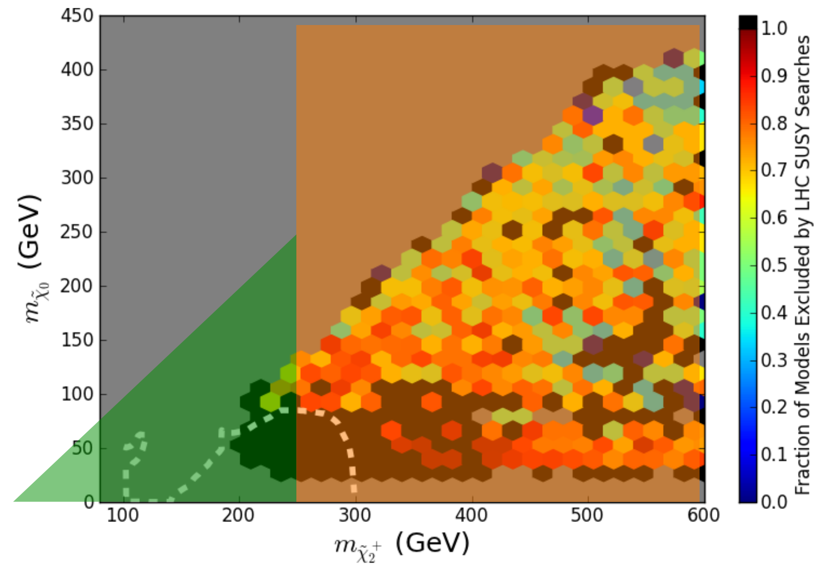
pMSSM models with the flavor and dark matter constraints applied, and with low fine-tuning ($\Delta_{\text{Barbieri-Giudice}} < 100$)

ILC 1 TeV

ILC 500 GeV



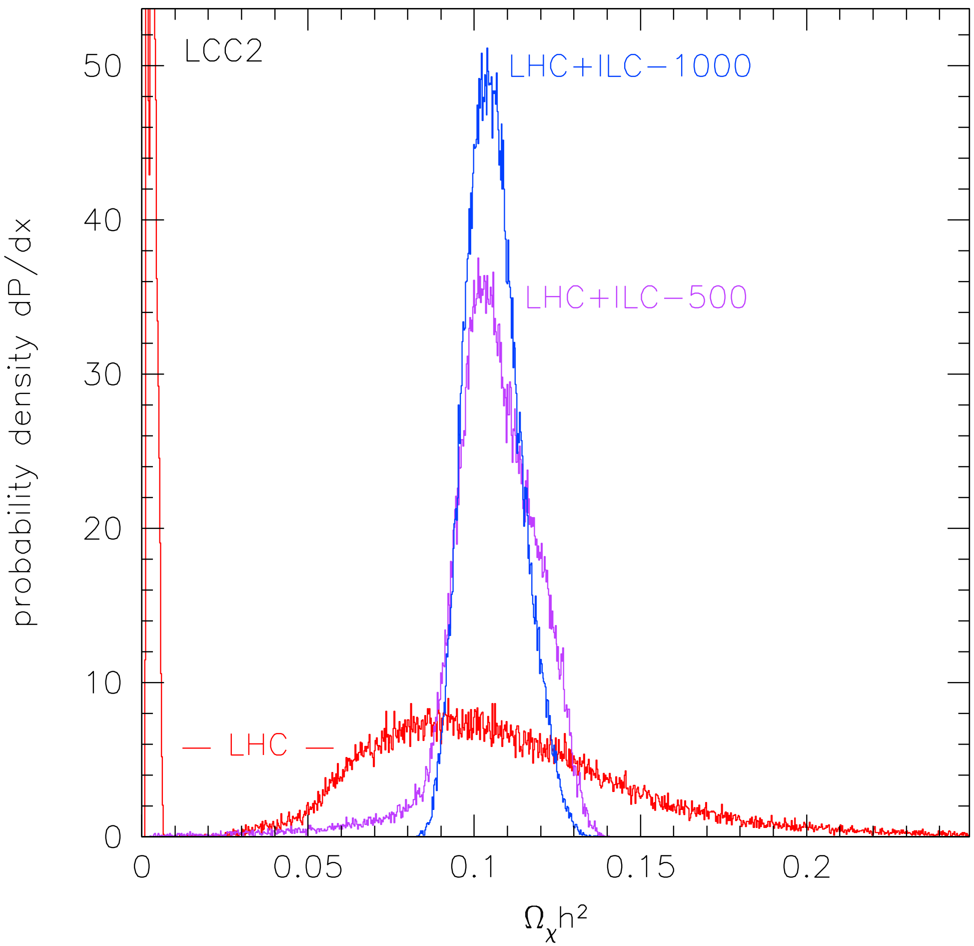




DM Relic Abundance

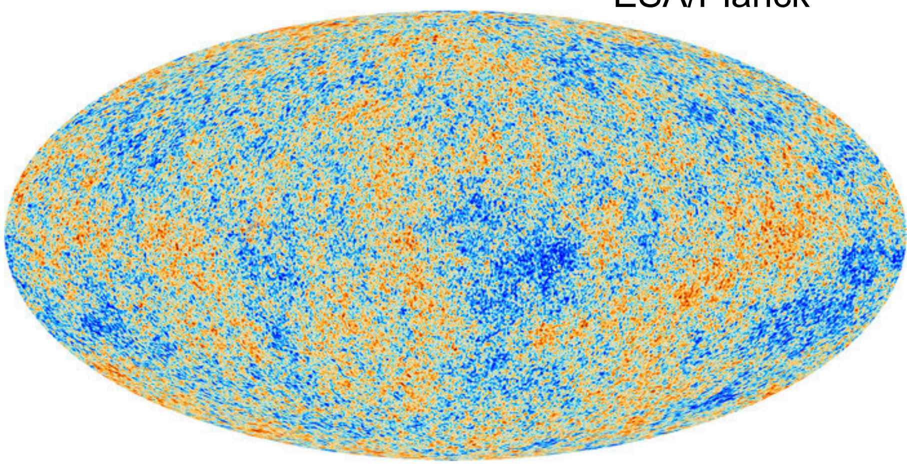
WMAP/Planck

$$\Omega_\chi h^2 = 0.1199 \pm 0.0027$$



Baltz, Battaglia, Peskin, Wizansky
PRD74 (2006) 103521, arXiv:hep-ph/0602187

ESA/Planck



Once a DM candidate is discovered, crucial to test consistency with the measured DM relic abundance.

→ ILC precise measurements of mass and cross sections

Baryon Asymmetry of the Universe

Baryon Asymmetry of Universe

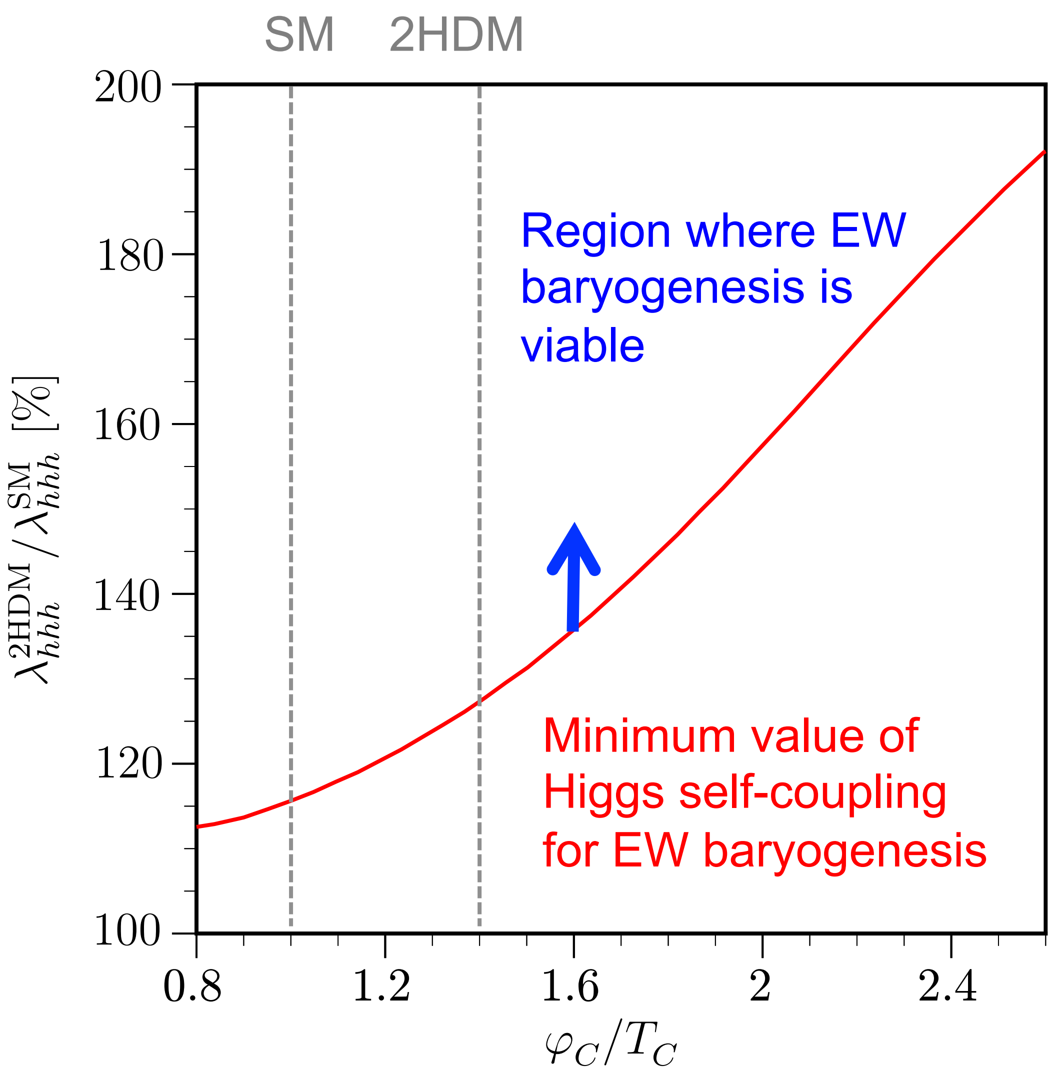
Sakharov's conditions
→ Need new physics that generates baryon number.

There exist different models of baryogenesis for different energy scales.

- EW scale: EW baryogenesis
- Middle scale: Affleck-Dine baryogenesis
- GUT scale: Leptogenesis

Electroweak baryogenesis can be tested at the ILC via Higgs self-coupling measurements

Electroweak Baryogenesis



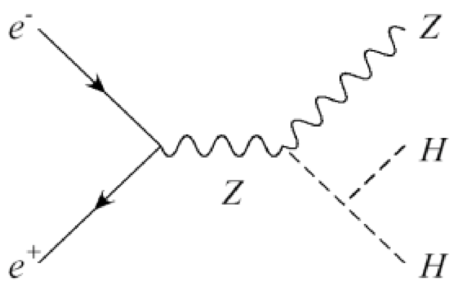
Senaha, Kanemura

<u>Example:</u>
Electroweak baryogenesis in a Two Higgs Doublet Model

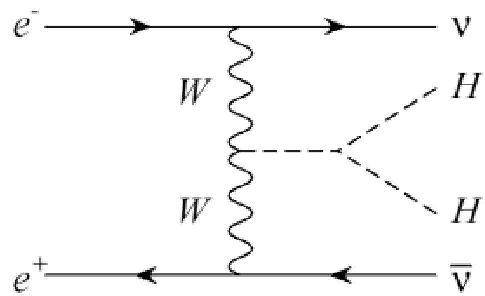
Large deviations in Higgs self-coupling are generally predicted in EW baryogenesis scenarios.

ILC can test the idea of baryogenesis occurring at the electroweak scale.

Higgs self-coupling (1/2)



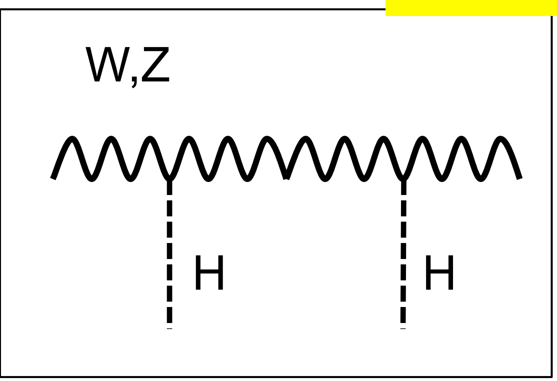
500 GeV (ZHH)



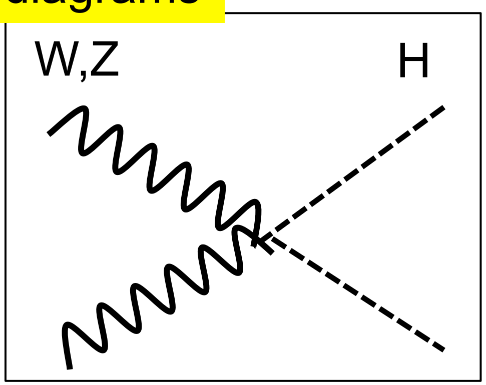
1 TeV (ννHH)

1. Small cross section O(100) events in total
2. Sensitivity reduced due to interfering diagrams

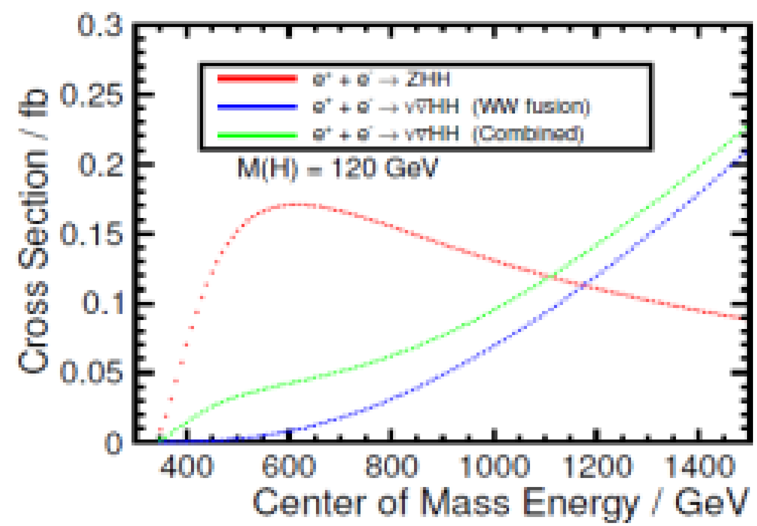
Interfering diagrams



(VVH coupling)^2



VVHH coupling



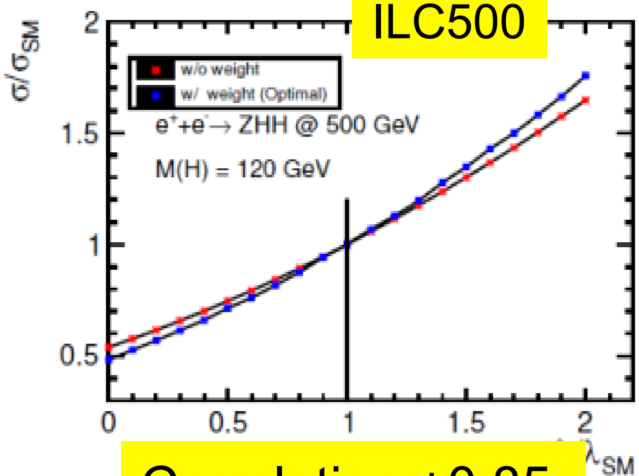
Number of events @ 2ab^{-1}

500 GeV: S ~ 40, S/N ~ 0.2-1 (from Z decay)
1000 GeV: S ~ 30, S/N ~ 1

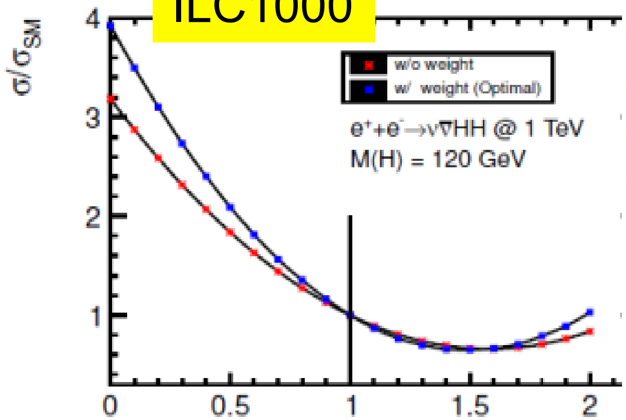
Higgs self-coupling (2/2)

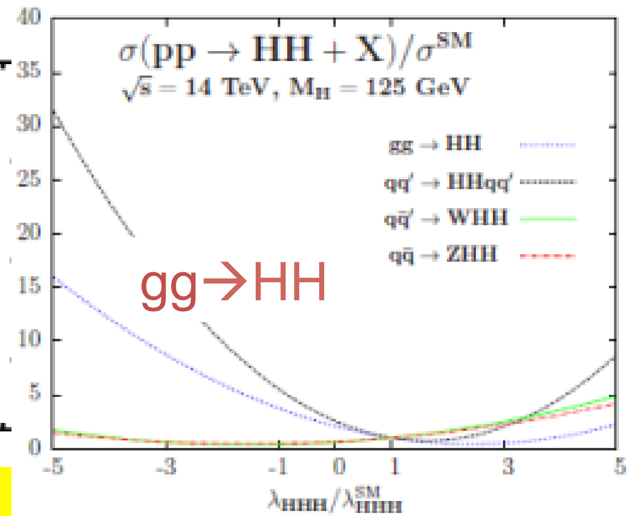
HL-LHC

ILC500



ILC1000





Correlation +0.85
36% @ ILC500up

Correlation -1.8
10% @ ILC1000up

Correlation -0.8

Lumi 2670 fb-1, sqrt(s) = 500 GeV
Lumi 4170 fb-1, sqrt(s) = 1 TeV

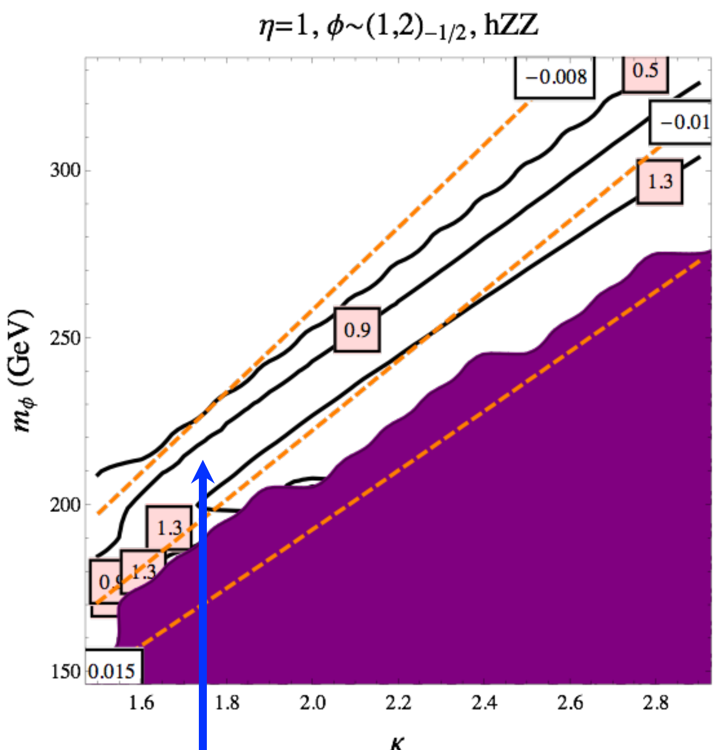
ILC-LHC synergy

- Effect of interfering diagrams:
  - Negative correlation: better sensitivity for λ<1 (HL-LHC)
  - Positive correlation: better sensitivity for λ>1 (ILC500)
- Large deviations predicted by EW baryogenesis scenarios, testable at ILC
- 10% precision achievable with ILC1000

Additional Slides

Electroweak Phase Transition & Higgs Couplings

Example: a BSM Model with a 1st Order PT



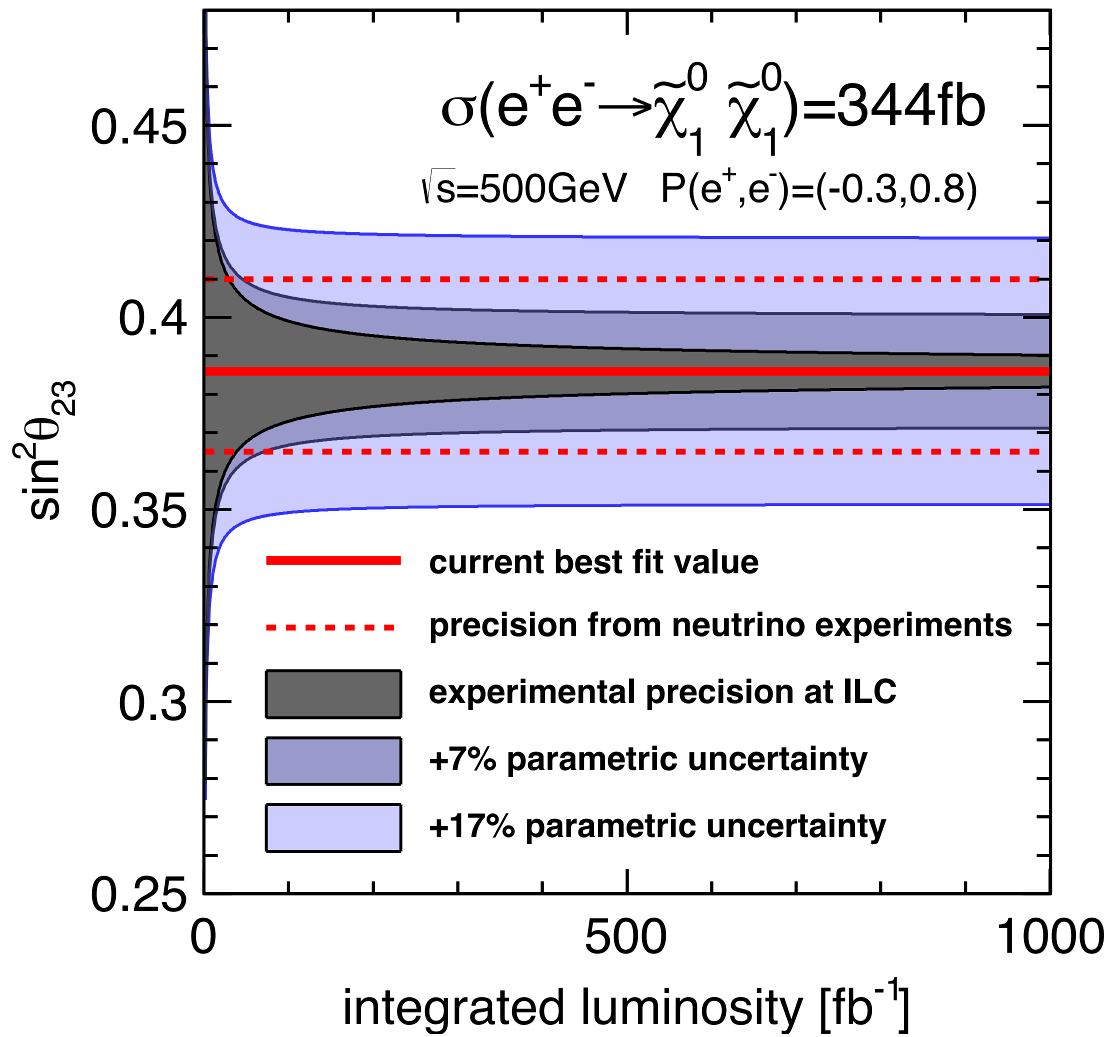
$\delta g_{hZZ} \geq 0.8\%$

throughout the parameter region with 1st Order PT

[Katz, Perelstein, 1401.1827]

- Electroweak Phase Transition occurred about 10^{-10} s after the Big Bang
- PT could be 1st or 2nd order; if 1st order, matter-antimatter asymmetry could be generated during the phase transition ("electroweak baryogenesis")
- In the SM, PT is 2nd order; in weak-scale BSM models, PT may be either 1st or 2nd order
- Even after LHC-14, both types of BSM models will most likely be allowed
- Models with 1st order transition generically predict deviations in Higgs couplings from the SM large enough to be observed at the ILC
- Neither at the LHC nor at the ILC, we don't have a direct access to the Higgs potential at finite temperature but that it can be reconstructed using standard QFT technics provided one is able to measure with a good accuracy all the couplings at zero temperature. Hence the need for precision.

Neutrino Connection



Type-III Seesaw:

connects flavor-changing neutralino decays to neutrino mixing angles

Vormwald, List
EPJ C74 (2014) 2720
arXiv:1307.4074

Neutrino mass

- Generation of small neutrino masses is a mystery, and at the same time could be a hint for new physics.
- The seesaw mechanism introduces physics at a very high energy scale. This can be well accommodated in the SUSY model or SUSY GUT, and also lead to leptogenesis.
- In such a case, sleptons are key particles, which are not yet strongly constrained at LHC searches. New interactions at the seesaw scale reflects itself to the masses and mixings of the sleptons.
- There are many examples of neutrino mass generation mechanism at the TeV scale (loop, RPV SUSY, LR model, triplet Higgs VEV, etc.) There could be various phenomenological impacts in LHC and LC, mostly non colored sectors. (need studies)

Slepton mass splitting due to interaction at the seesaw scale

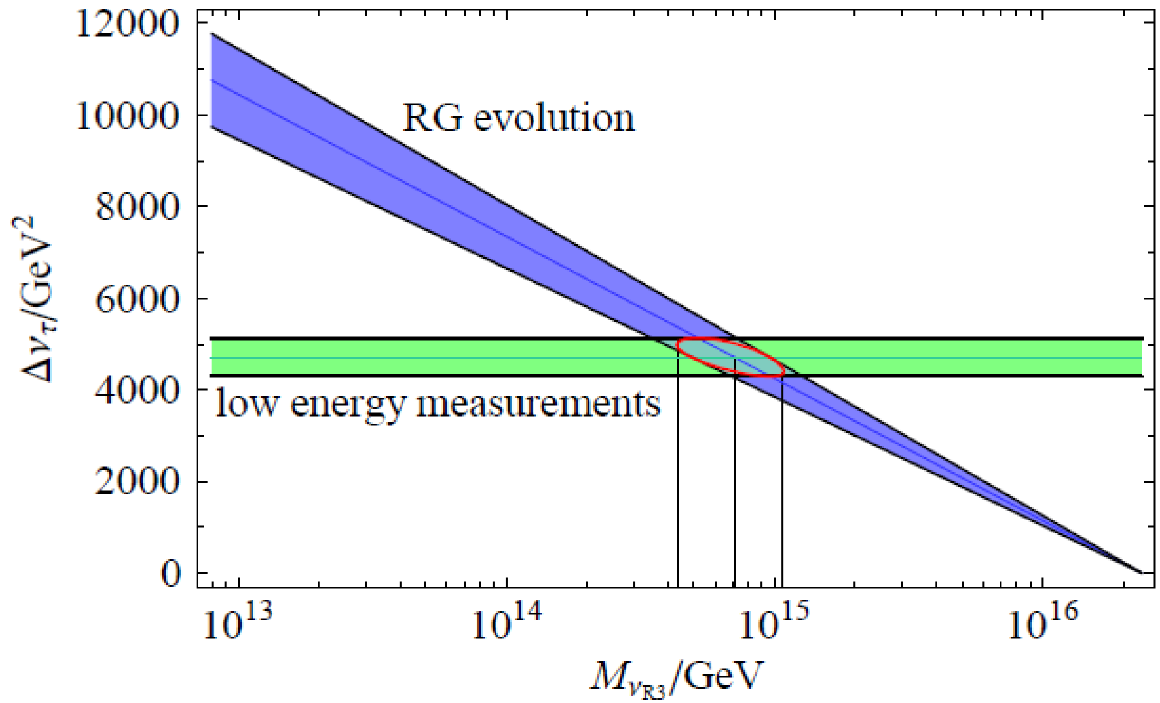


FIGURE 7.8. ILC resolution in the estimate of the mass of the heaviest right–handed neutrino from the RGE evolution of slepton mass [210].

A recent example of study on LFV sleptoton production at LC

Lepton flavour violation: physics potential of a Linear Collider

A. Abada[a], A. J. R. Figueiredo[b,c], J. C. Rom˜ao[b] and A. M. Teixeira[c]

arXiv: 1206.2306

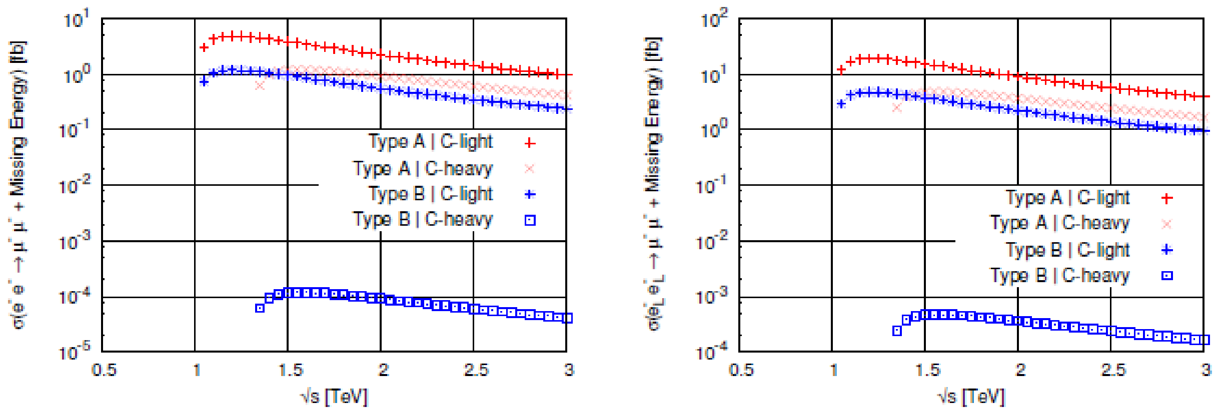


Figure 13: Cross section for $e^-e^- \to \mu^-\mu^- + E^T_{\rm miss}$ (with $E^T_{\rm miss} = 2\chi^0_1, 2\chi^0_1 + (2,4)\nu, (2,4)\nu$), for points C-light and C-heavy as a function of the centre of mass energy, $\sqrt{s}$, in the unpolarised beam case (left) and for fully polarised beams $(P_{e^-}, P_{e^-}) = (-100\%, -100\%)$ (right). C-light: the signal (SUSY background) is denoted by red crosses (blue asterisks); C-heavy: the signal (SUSY background) is represented by red times (blue squares). We have taken a degenerate right-handed neutrino spectrum ($M_R = 10^{12}$ GeV) and set $\theta_{13} = 10°$.

Note: This paper takes benchmark points with standard cMSSM points, so that RH-sleptons are heavier than 300 GeV. If we depart from CMSSM assumptions, lighter sleptons can be considered. (Need studies)

Original references: arXiv:hep-ph/9603431, arXiv:hep-ph/9704205(include CPV)

Natural SUSY

Natural SUSY はLHCが示唆していて重要なSUSYシナリオ

ILC は natural, Higgsino-rich LSP シナリオを完璧にカバーする

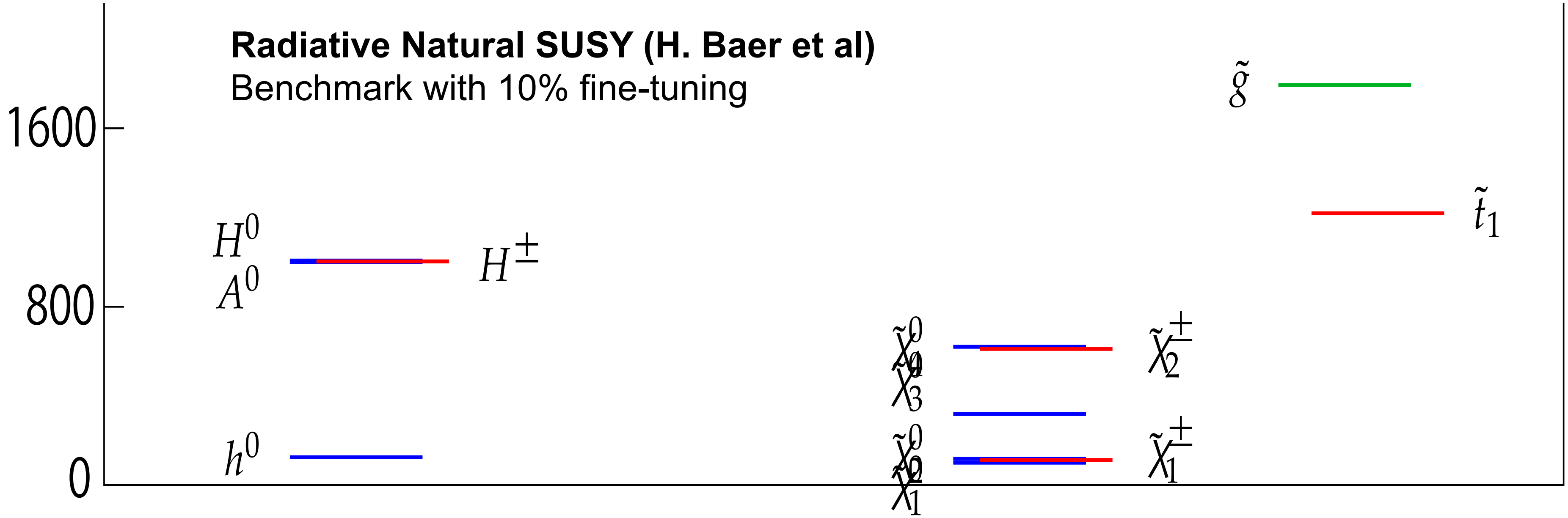
$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

~1% fine-tuning

gluino $m(\tilde{g}) \lesssim 3\ \mathrm{TeV}$

stop $m(\tilde{t}) \lesssim 1\ \mathrm{TeV}$

Higgsino $\mu \lesssim 200\ \mathrm{GeV}$



Dark Matter

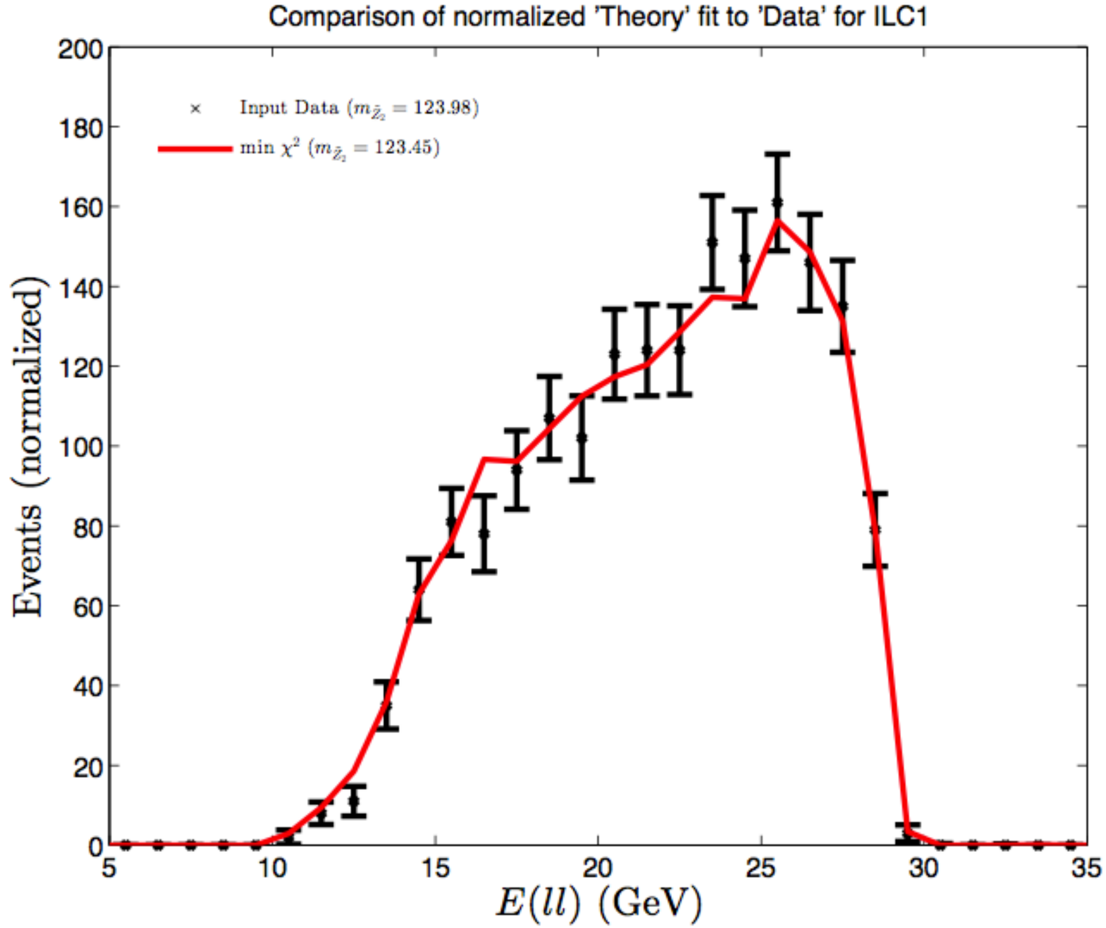
暗黒物質の候補:
- WIMPs: 宇宙論および宇宙観測の立場から有力な候補
- その他: sterile neutrinos, アクシオン, etc.

Properties of WIMP DM:
- Spin unknown
- No EM / color charge

	Mass	Spin	Color	EM	Isospin	Collider signals
Case 1	$< m_H/2$	???	Singlet	None	Singlet	Invisible H width
Case 2	$> m_H/2$	???	Singlet	None	Singlet	Mono-photon, jet
Case 3	> 0.1TeV	???	Singlet	None	Non-singlet	Direct prod., etc.

コライダー探索はWIMP dark matter探索には必須
探索方法は暗黒物質の弱アイソスピンに依存

Study of $e^+e^- \to \widetilde{H}_1^0 \widetilde{H}_2^0 \to \ell^+\ell^- + (\text{invisible})$



$$m(\widetilde{H}_1^0) = 102.7 \pm 0.3 \text{ GeV} \qquad m(\widetilde{H}_2^0) = 123.7 \pm 0.2 \text{ GeV}$$

Baer, Barger, Mickelson, Mustafayev, Tata, arXiv:1404.7510

CPV in Higgs Sector

- Is there CPV in Higgs sector?
- Constraints from EDM ?

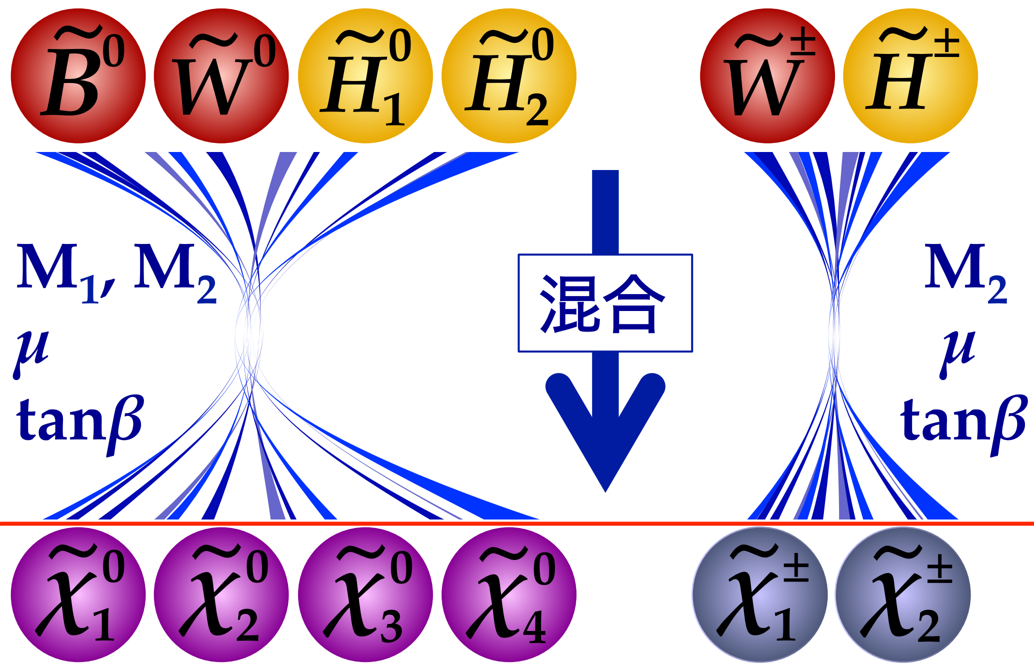
- Motivated by EW baryogenesis → need Higgs-related CPV
  - top CPV → large top Yukawa coupling → **interesting**
  - electron CPV → does not couple to Higgs, not interesting

- 1HDM → not viable for EWBG.
- 2HDM → neutral Higgs x3
  - usually 2 CP-even, 1 CP-odd.
  - generally: CP-mixing among the three
  - appearance of Landau pole around 10-100 TeV

Neutralino, chargino

Gauge eigenstates

超対称性の自発的破れに直結



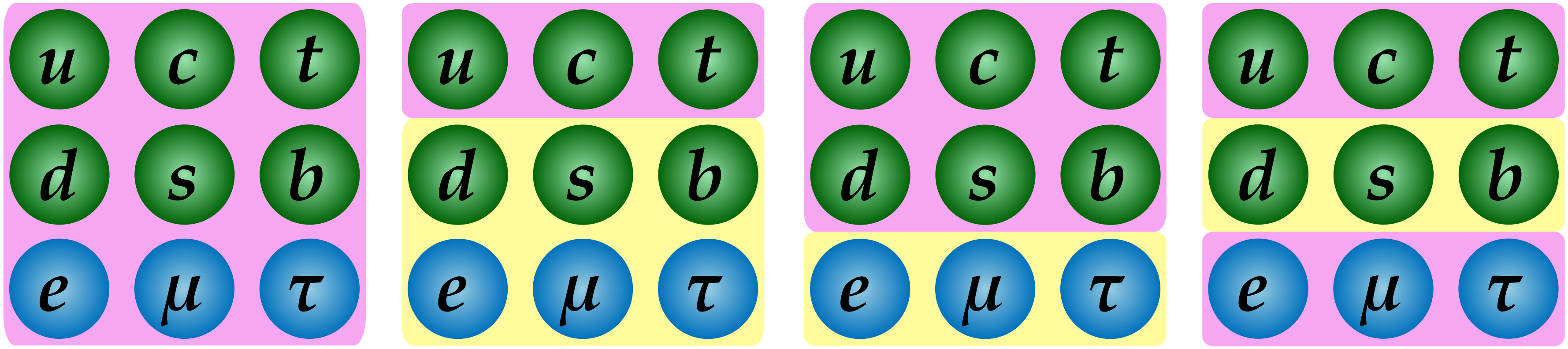
ニュートラリーノ　　チャージーノ

Mass eigenstates

コライダー実験で実際に観測される粒子

Two Higgs Doublet Model (2HDM)

Two Higgs doublets Φ_1, Φ_2 -- four patterns of Yukawa couplings



Type I

(Φ_2 no Yukawa coupling)
neutrino mass

Type II

SUSY

Type X

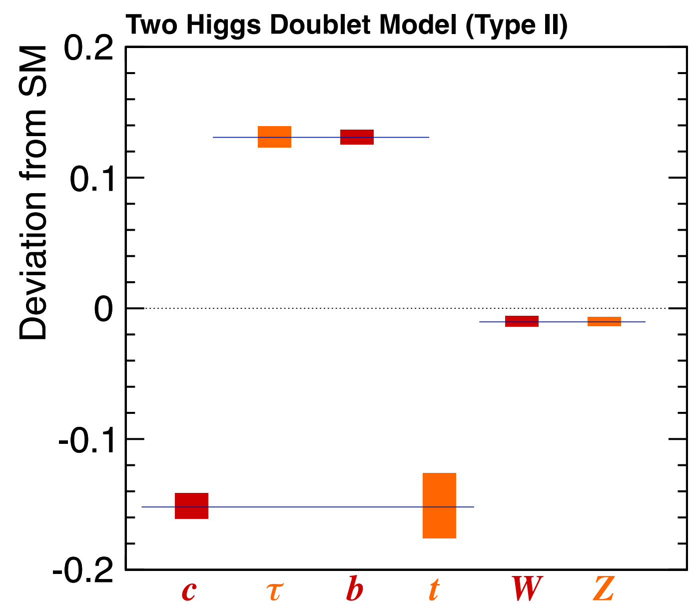
3-loop neutrino mass

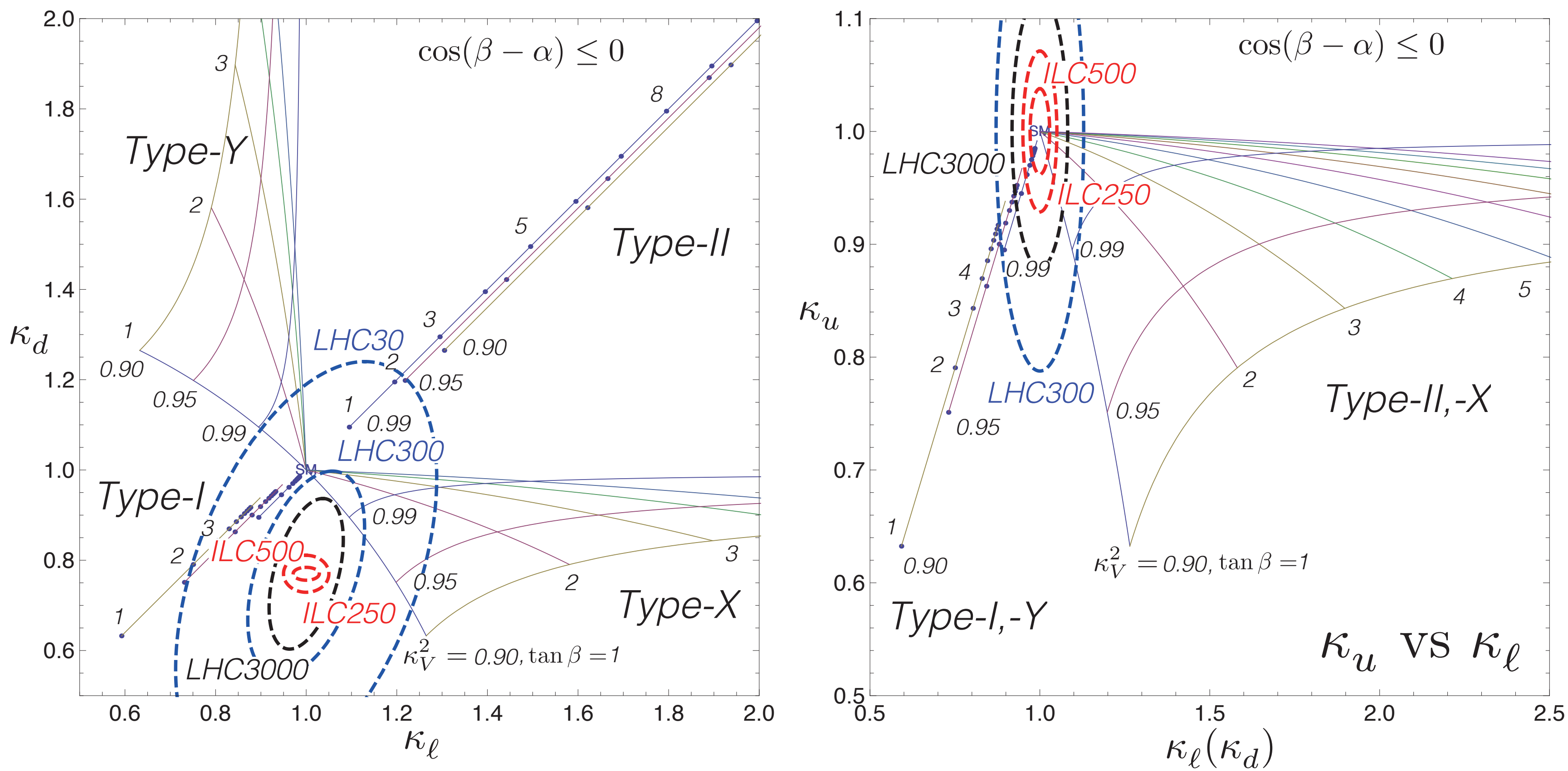
Type Y

??? (flipped)

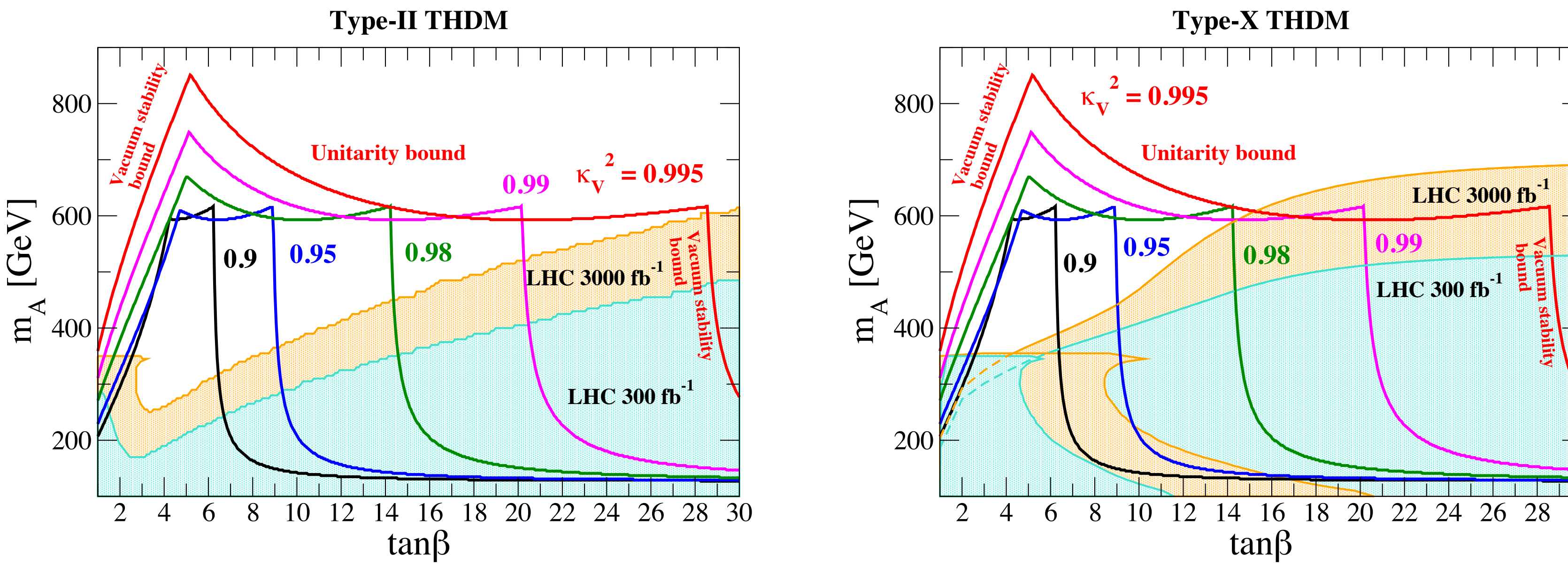
Higgs couplings deviate from the SM values. The deviations can be in groups (up to two). At tree-level, the amount of deviation is uniform across the same group and no differences across the generations.

SUSY requires Type-II 2HDM. Some BSM phenomena can be explained by 2HDMs (or similar extensions), such as the baryon asymmetry, and neutrino mass.





cos(β − α) ≤ 0
Type-Y
Type-II
Type-I
Type-X
LHC30
LHC300
LHC3000
ILC500
ILC250
κ_V^2 = 0.90, tan β = 1
κ_d
κ_ℓ
cos(β − α) ≤ 0
ILC500
LHC3000
ILC250
LHC300
Type-II,-X
Type-I,-Y
κ_u vs κ_ℓ
κ_u
κ_ℓ(κ_d)


Type-II THDM
Type-X THDM
Vacuum stability bound
Unitarity bound
$\kappa_V^2 = 0.995$
0.99
0.98
0.95
0.9
LHC 3000 fb^{-1}
LHC 300 fb^{-1}
m_A [GeV]
tanβ