Overview of ILC Physics Case

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on behalf of
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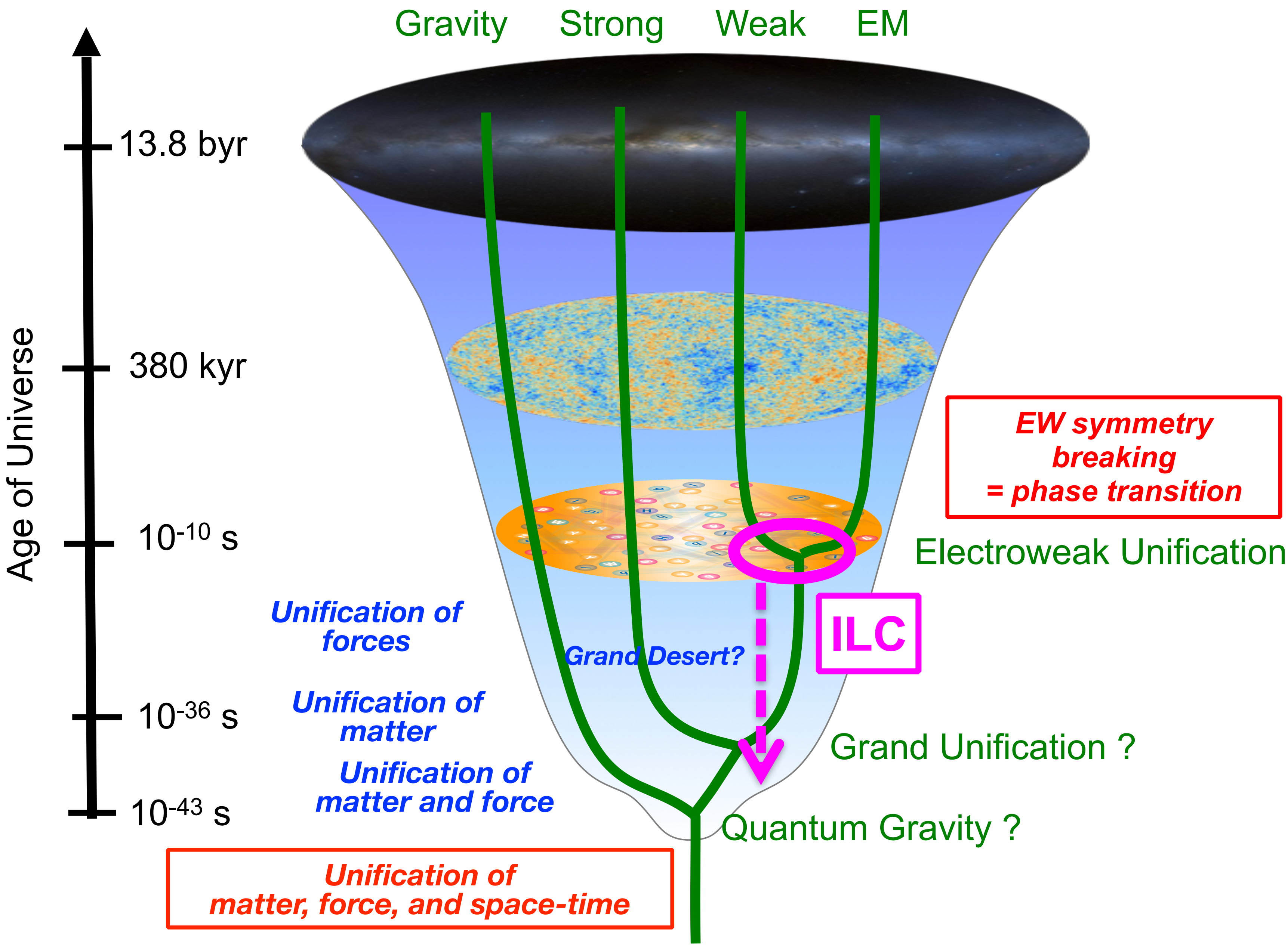
Towards ultimate unification



Why is the EW scale so important ?

Electroweak Symmetry Breaking
Mystery of something in the vacuum

- The EW symmetry forbids masses of gauge bosons and matter fermions. In order to break it without breaking that of the Lagrangian, we need ***"something" condensed in the vacuum which carries weak charge:*** $\langle 0 | I_3, Y | 0 \rangle \neq 0 \quad \langle 0 | I_3 + Y | 0 \rangle = 0$

  → ***We are living in a weakly charged vacuum!***

- The discovery of H(125) provided evidence that it is an excitation of (at least part of) this "something" in the vacuum and hence the correctness of this idea of the vacuum breaking the EW symmetry.

- In the SM, ***a single complex doublet scalar field*** is responsible for both gauge boson and matter fermion masses. The SM EWSB sector is the simplest, but other than that there is no reason for it. ***The EWSB sector might be more complex.***

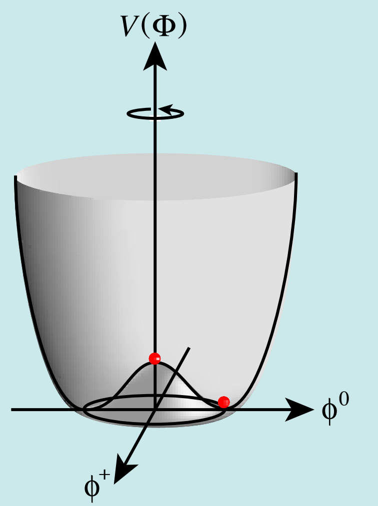
  → We need to know ***the multiplet structure*** of the EWSB sector.

- Moreover, the SM does not explain ***why the Higgs field developed a vacuum expectation value.***

  - ***In other words the SM does not answer the question:***

Why $\mu^2 < 0$?

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4$$



Why $\mu^2 < 0$?

We need to go beyond the SM to answer this question.

The Big Branch Point

- Concerning ***the dynamics behind the EWSB***.

  Is it ***weakly interacting or strongly interacting?***

  = Is the H(125) ***elementary or composite?***

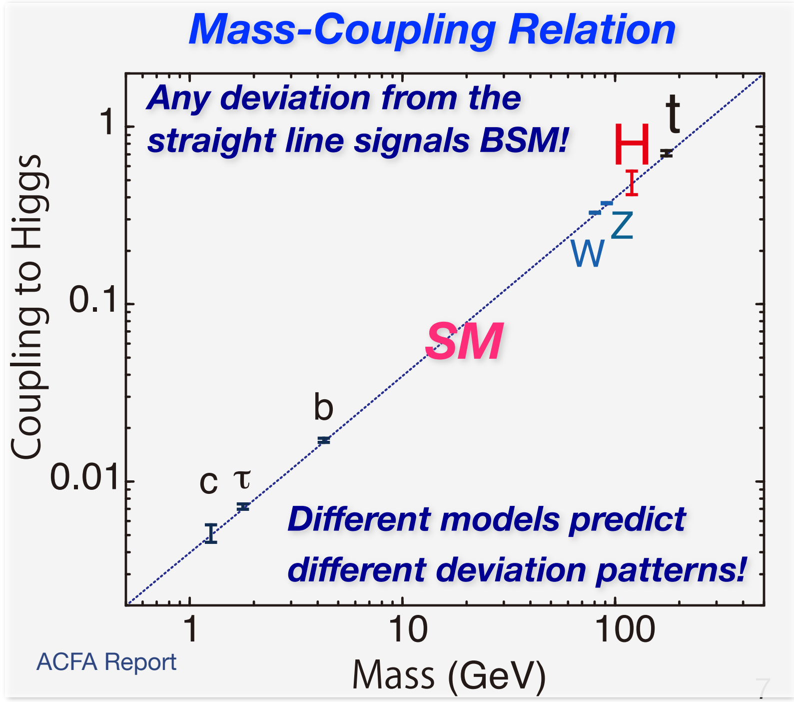
- ***SUSY***, which gives ***a raison d'être for a fundamental scalar fields***, is the most attractive scenario for the 1st branch, where EW symmetry is broken radiatively.
  → ***The EWSB sector is weakly interacting.***
  → ***H(125) is elementary*** and embedded in an ***extended multiplet structure*** (there must be ***at least 2 Higgs doublets***).

- ***Composite Higgs Models,*** the 2nd branch, where a new QCD-like strong interaction makes a vacuum condensate.
  → ***The EWSB sector is strongly interacting***.
  → ***H(125) is composite.***

Elementary or Composite?
How can ILC answer this question?

- If ***SUSY (elementary),***
  → ***(At least) 2 Higgs doublets***
  → ***Search*** for
    - extra Higgs bosons: ***H, A, H±***
    - uncolored SUSY particles: ***EWkinos, sleptons***
  → ***Look for specific deviation pattern*** in
    - ***various Higgs couplings***
    - gauge boson properties

- If ***Composite,***
  → ***Look for specific deviation pattern*** in
    - ***various Higgs couplings***
    - ***Top (ttZ) couplings***



The 3 major ways to probe BSM at ILC:

Higgs, ***Top***, and search for ***New Particles***

The 3 major tools to enable this endeavor

1. *Well defined initial state and controllable Ecm*

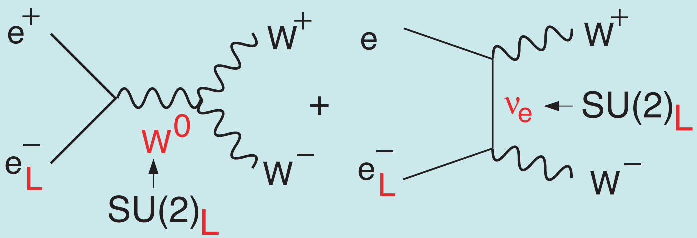
2. *Clean environment: no QCD BG, only with calculable BG from EW processes*

3. Beam polarization

Power of Beam Polarization

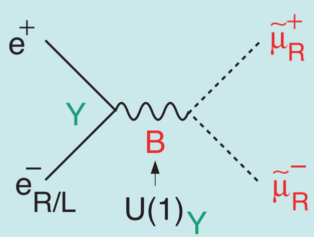
BG Suppression

W^+W^- *(Largest SM BG in SUSY searches)*



In the symmetry limit, $\sigma_{WW} \to 0$ for e^-_R !

Slepton Pair

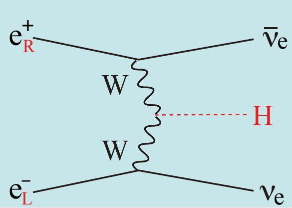


$Y_L = -1/2 : e^-_L$

$Y_R = -1 : e^-_R$

In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

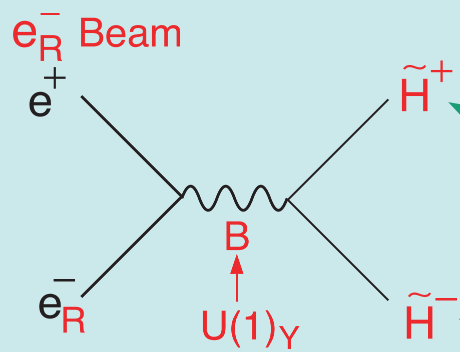
WW-fusion Higgs Prod.



	ILC
Pol (e	-0.8
Pol (e	+0.3
(σ/σ	1.8x1.3=2.34

Signal Enhancement

Chargino Pair



Only $\tilde{H}^\pm$ components in $\tilde{\chi}^\pm_1$ contribute !

cf.) $e^+e^- \to W^+W^-$

$$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$$

$\bullet = \langle \tilde{H}^\pm | \tilde{\chi}^\pm_1 \rangle$

Decomposition

Higgs Physics at ILC

Our mission is to understand

Multiplet Structure & Dynamics

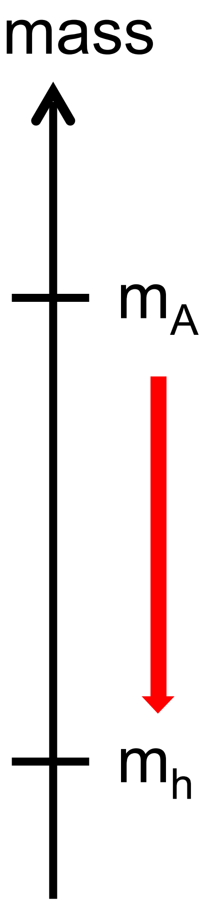
of the EWSB sector,

and their relation to

***Other Big Questions* of High Energy Physics:**

DM, baryogenesis, …

Deviation in Higgs Couplings



The size of the deviation depends on the scale of new physics.

Example 1: MSSM (tanβ=5, radiative corrections ≈ 1)

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

heavy Higgs mass

Example 2: Minimal Composite Higgs Model

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 8.3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

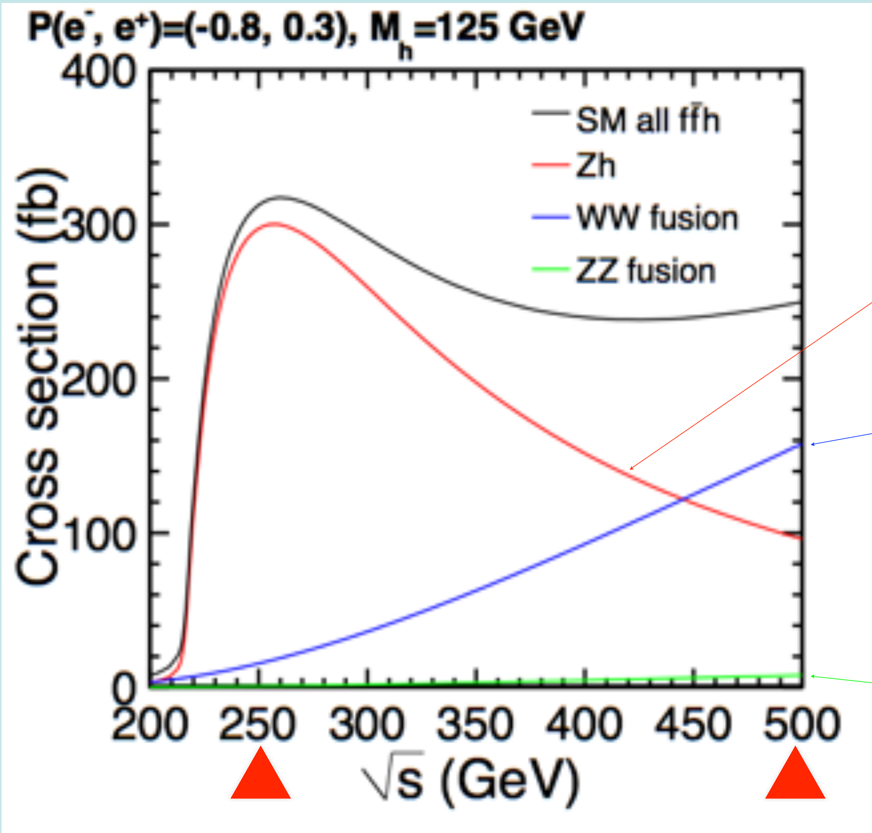
composite scale

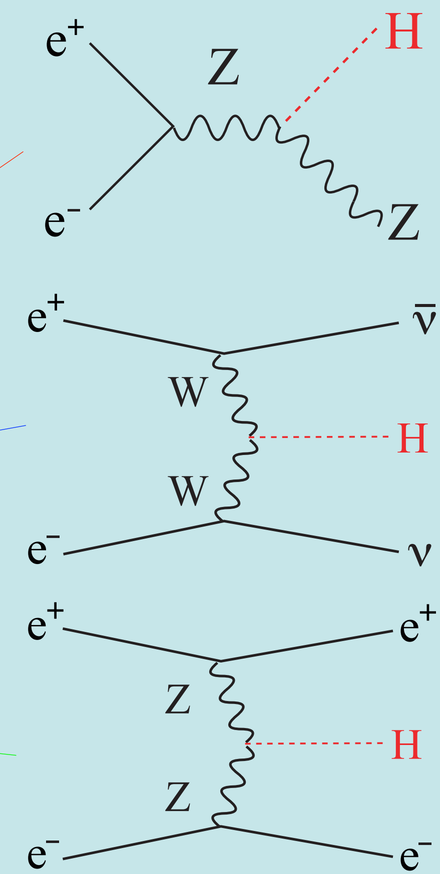
New physics at 1 TeV gives only ***a few percent*** deviation.
We ***need a %-level precision*** to see such a deviation → ***ILC***

Main Production Processes

Single Higgs Production

Production cross section





ZH dominates at 250 GeV
(~80k ev: 250 fb^{-1})

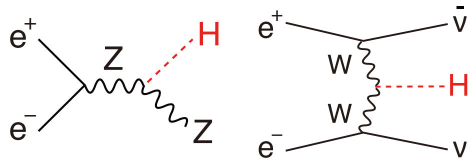
vvH takes over at 500 GeV
(~125k ev: 500 fb^{-1})

Possible to rediscover the Higgs in one day!

Key Point

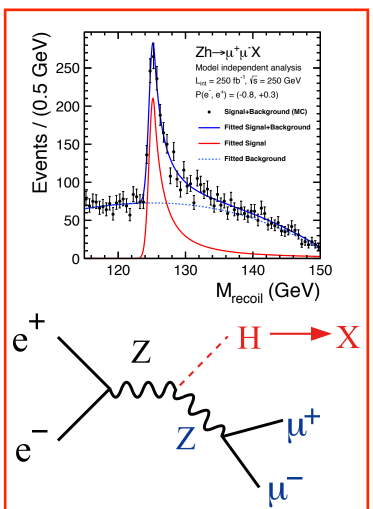
At LHC all the measurements are σ×BR measurements.

At ILC all but the σ measurement using recoil mass technique is σ×BR measurements.



$$g_{HAA}^2 \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

σ×BR → **BR** → **g coupling**

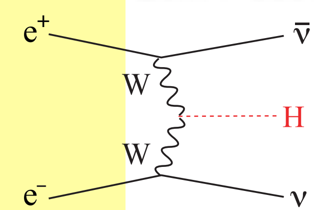


σ from recoil mass

The Key

ΓH total width

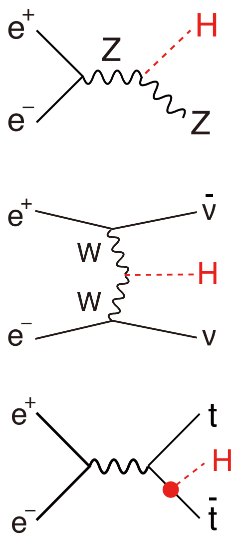
WW-fusion is crucial for precision total width measurement → Ecm > 350GeV

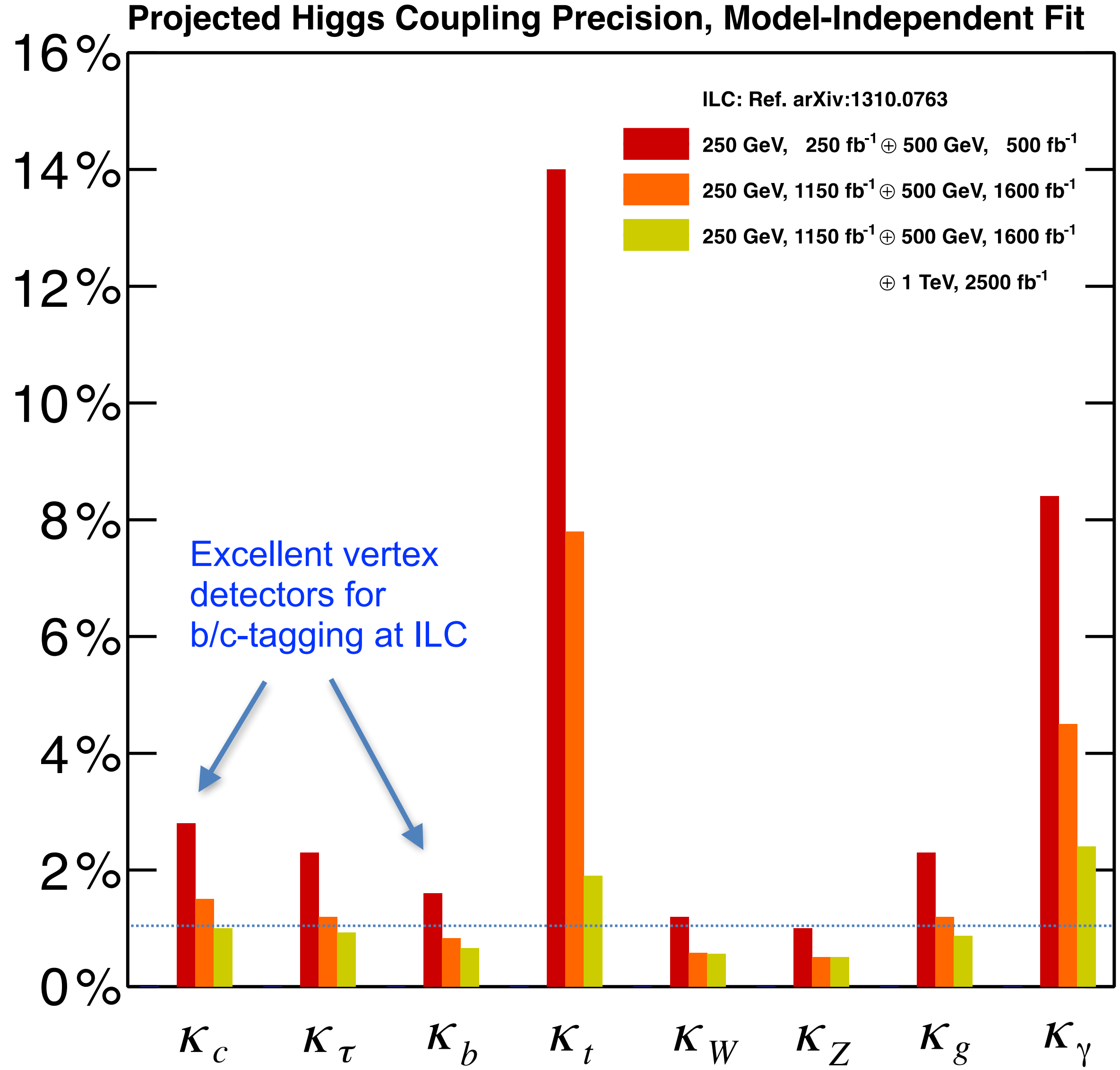


Z→qq is also usable.

Higgs Couplings

Model-independent coupling determination, impossible at LHC



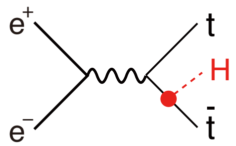


All of major Higgs decay modes accessible at ILC!

500 GeV already excellent except for K_t and K_γ

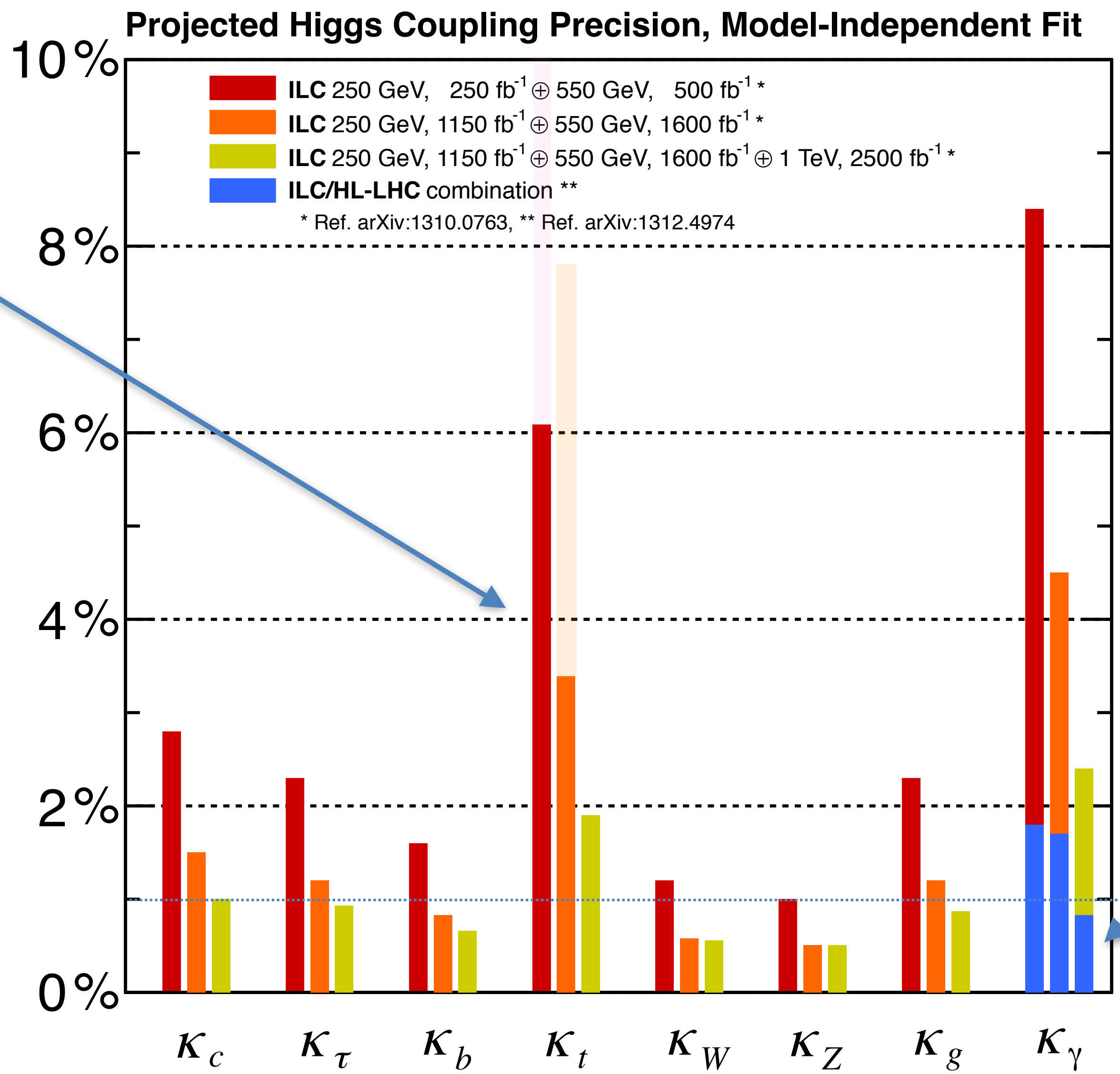
Higgs Couplings

Model-independent coupling determination, impossible at LHC



Top Yukawa improves by going to 550 GeV

Near threshold → a factor of 4 enhancement of σ_{tth} by going from 500GeV to 550 GeV



LHC can precisely measure

$BR(h\to\gamma\gamma)$ / $BR(h\to ZZ^*)$ = $(K_\gamma / K_Z)^2$

ILC can precisely measure ***K_Z***

Better hγγ with LHC/ILC synergy

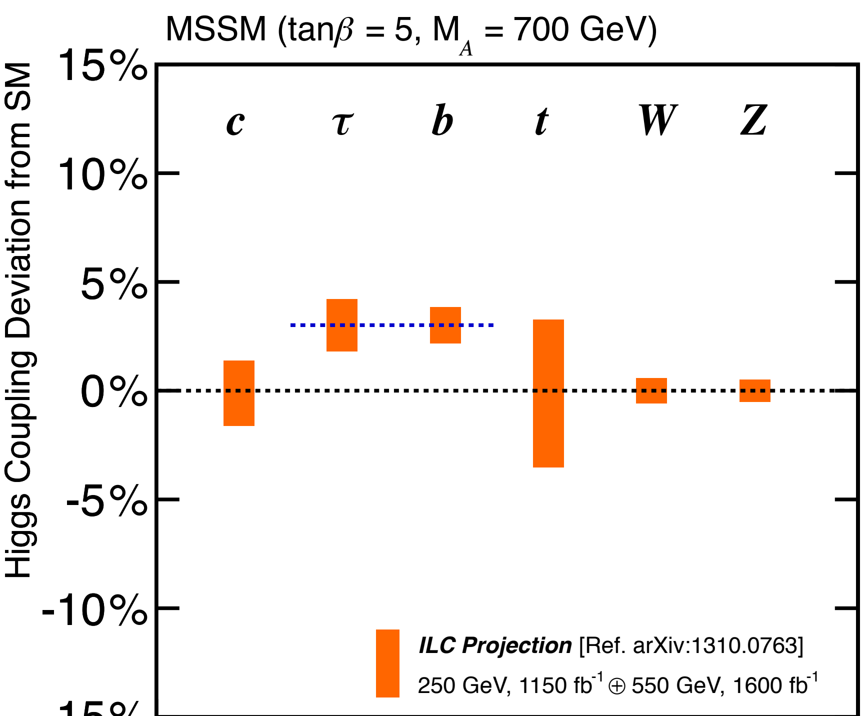
~1% or better precision for most couplings!

Fingerprinting

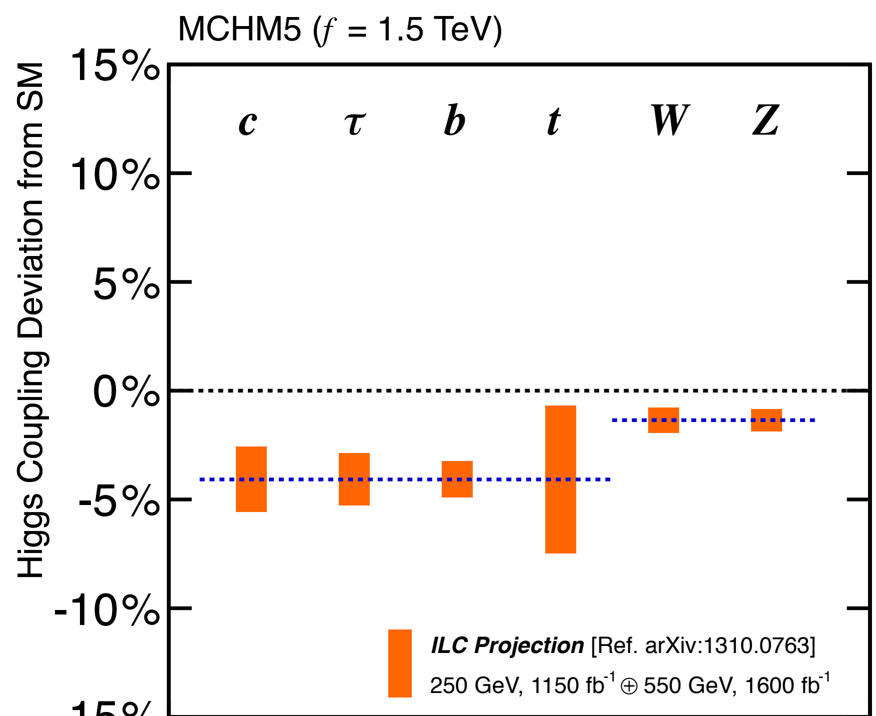
Fingerprinting

Elementary v.s. Composite

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)

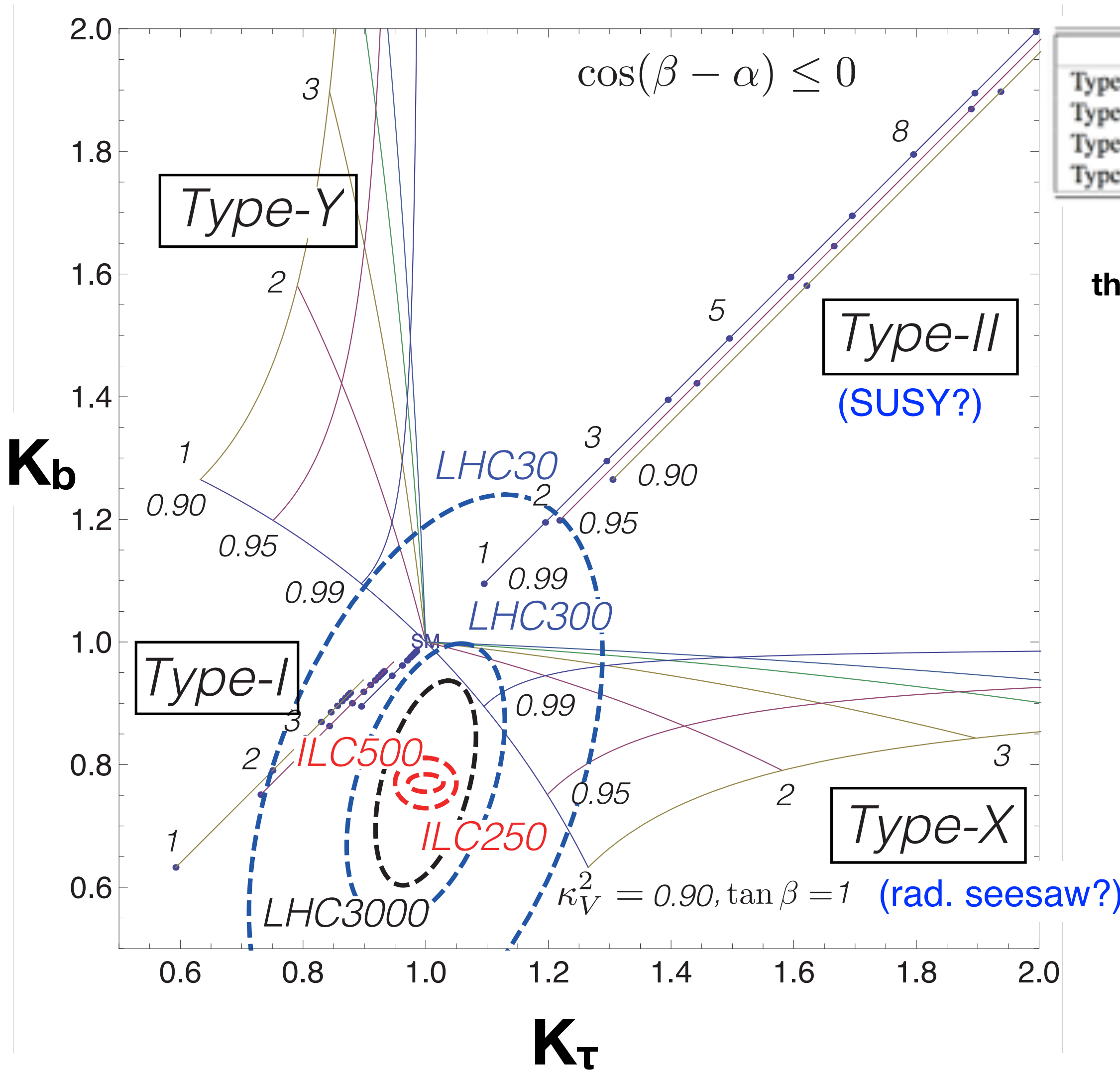


ILC 250+550 LumiUP

Fingerprinting

2HDM

Multiplet Structure



	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	+	−	−	−	−	+
Type II (SUSY)	+	−	−	+	+	+
Type X (Lepton-specific)	+	−	−	−	+	+
Type Y (Flipped)	+	−	−	+	−	+

4 Possible Z_2 Charge Assignments that forbids tree-level Higgs-induced FCNC

$K_V^2 = \sin(\beta-\alpha)^2 = 1 \Leftrightarrow$ SM

*Given a deviation of the Higgs to Z coupling: **$\Delta K_V^2 = 1 - K_V^2 = 0.01$** we will be able to **discriminate the 4 models!***

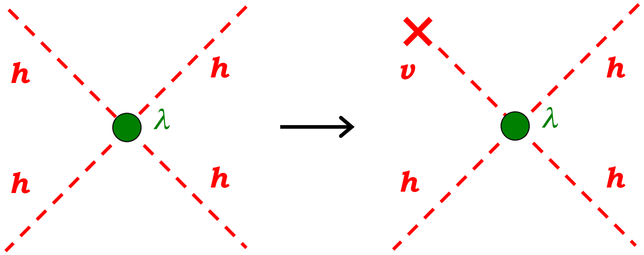
TDR ILC

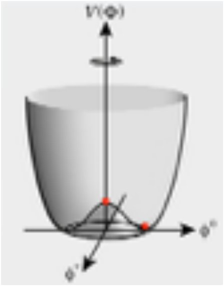
Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

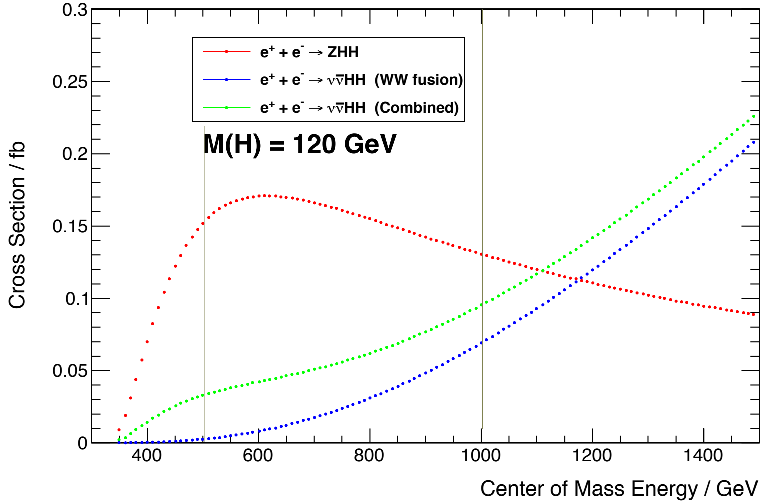
EW Phase Transition
1st order
or
2nd order ?

Higgs Self-Coupling

Existence of hhh coupling =
Direct evidence of vacuum condensation

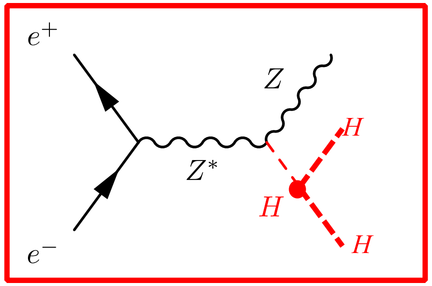


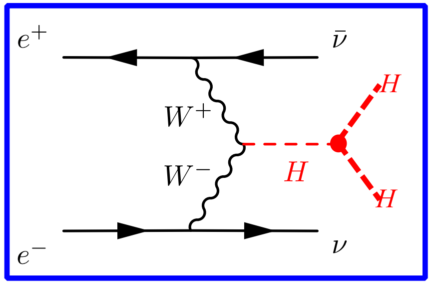




Challenging measurement because of:

- Small cross section (Zhh 0.2 fb at 500 GeV)
- Many jets in the final state
- ***Presence of interference diagrams***

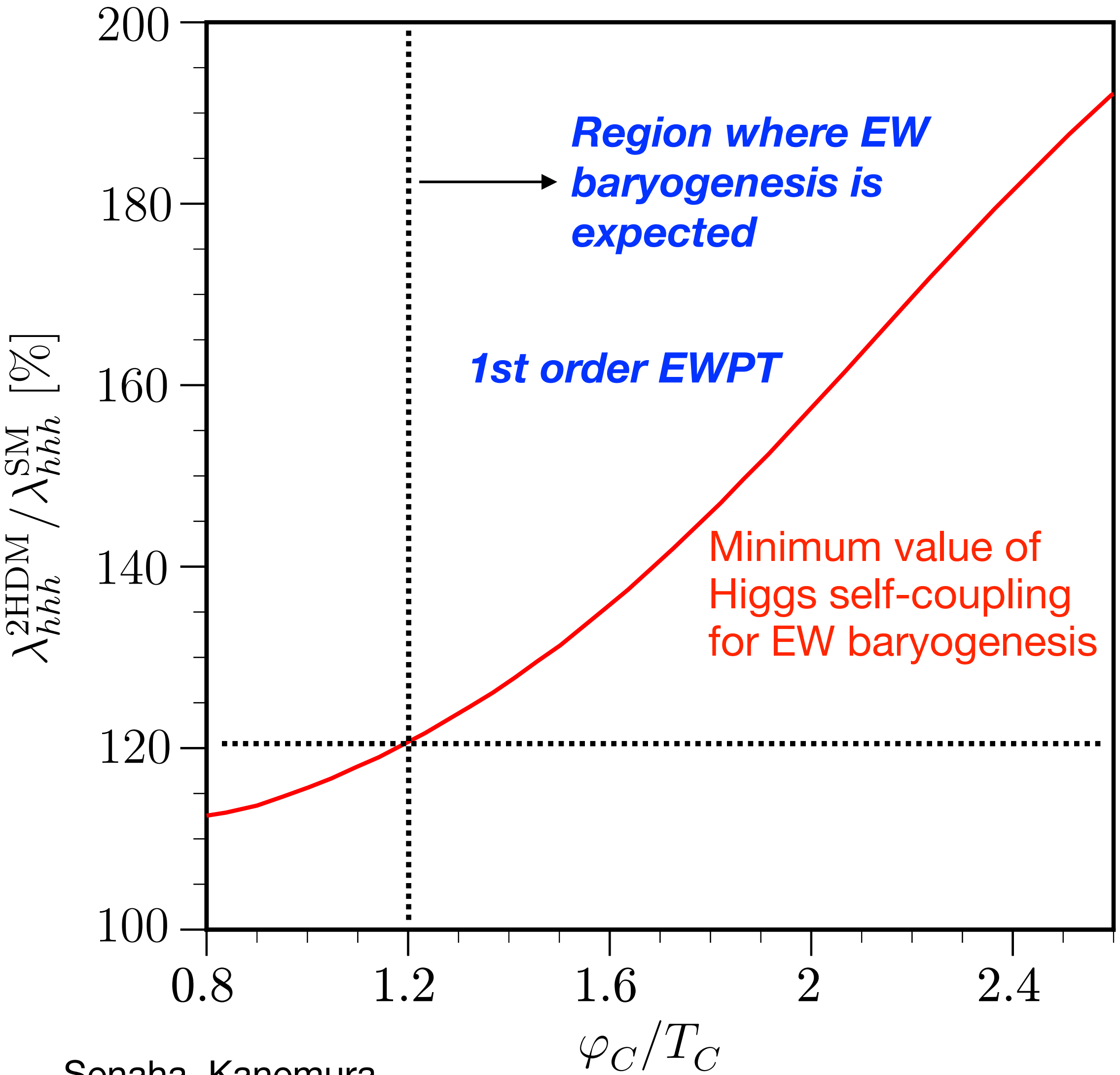




arXiv:1310.0763	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡
$P(e^-, e^+)$	(−0.8, 0.3)	(−0.8, 0.3)	(−0.8, 0.3/0.2)	(−0.8, 0.3/0.2)
$\sigma(ZHH)$	42.7%		42.7%	23.7%
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%
λ	83%	46%	21%	13%

Ongoing analysis improvements ***towards O(10)% measurement***

Electroweak Baryogenesis



Senaha, Kanemura

<u>Example:</u>

Electroweak baryogenesis in a ***Two Higgs Doublet Model***

Large deviations in Higgs self-coupling

→ ***1st order EW phase transition***

→ ***Out of equilibrium***

→ ***EW baryogenesis possible***

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

Top Physics at ILC

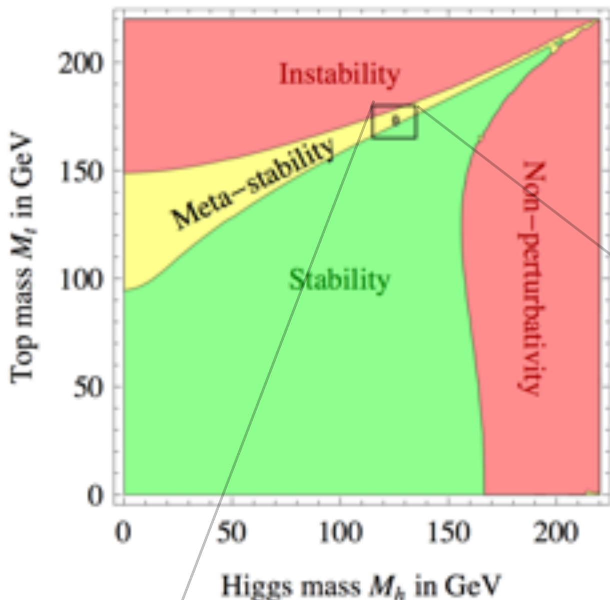
SM up to Λ_{Planck}?

What if the Higgs properties would turn out to be just like those of the SM Higgs boson, to the ILC precision, and that no BSM signal found?

We would need to question then the range of validity of the SM.

How far can the SM go?

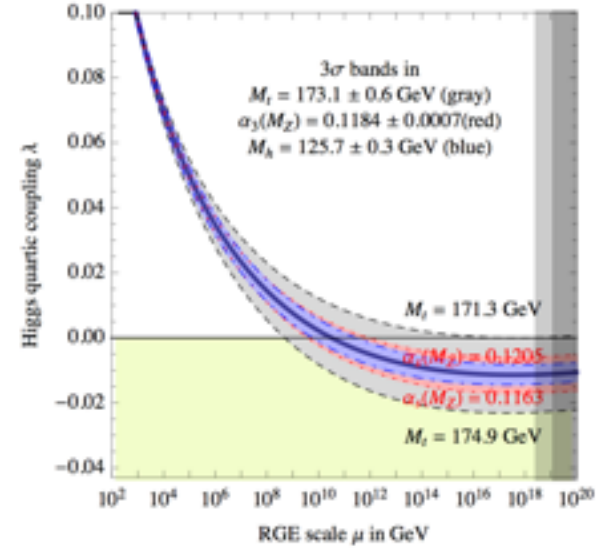
Stability of SM Vacuum



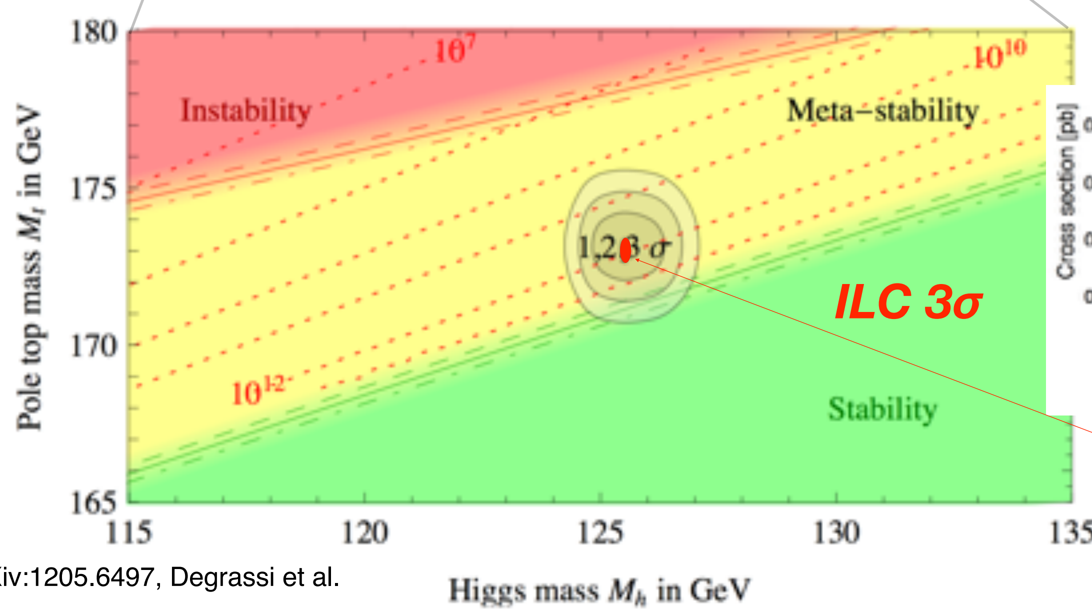
With the 125GeV Higgs boson, the SM vacuum seems to be at a subtle point of meta-stability!

Does λ really become negative below Λ_{Pl}?

or $\lambda(\Lambda_{Pl}) = 0$?

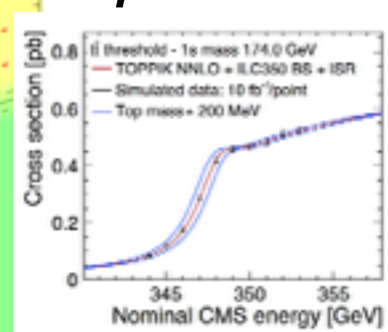


To answer this we need a precision m_t measurement!

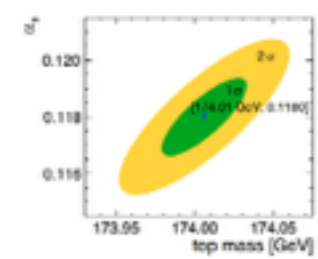


arXiv:1205.6497, Degrassi et al.

Top Pair Threshold



Theoretically very clean measurement of m_t



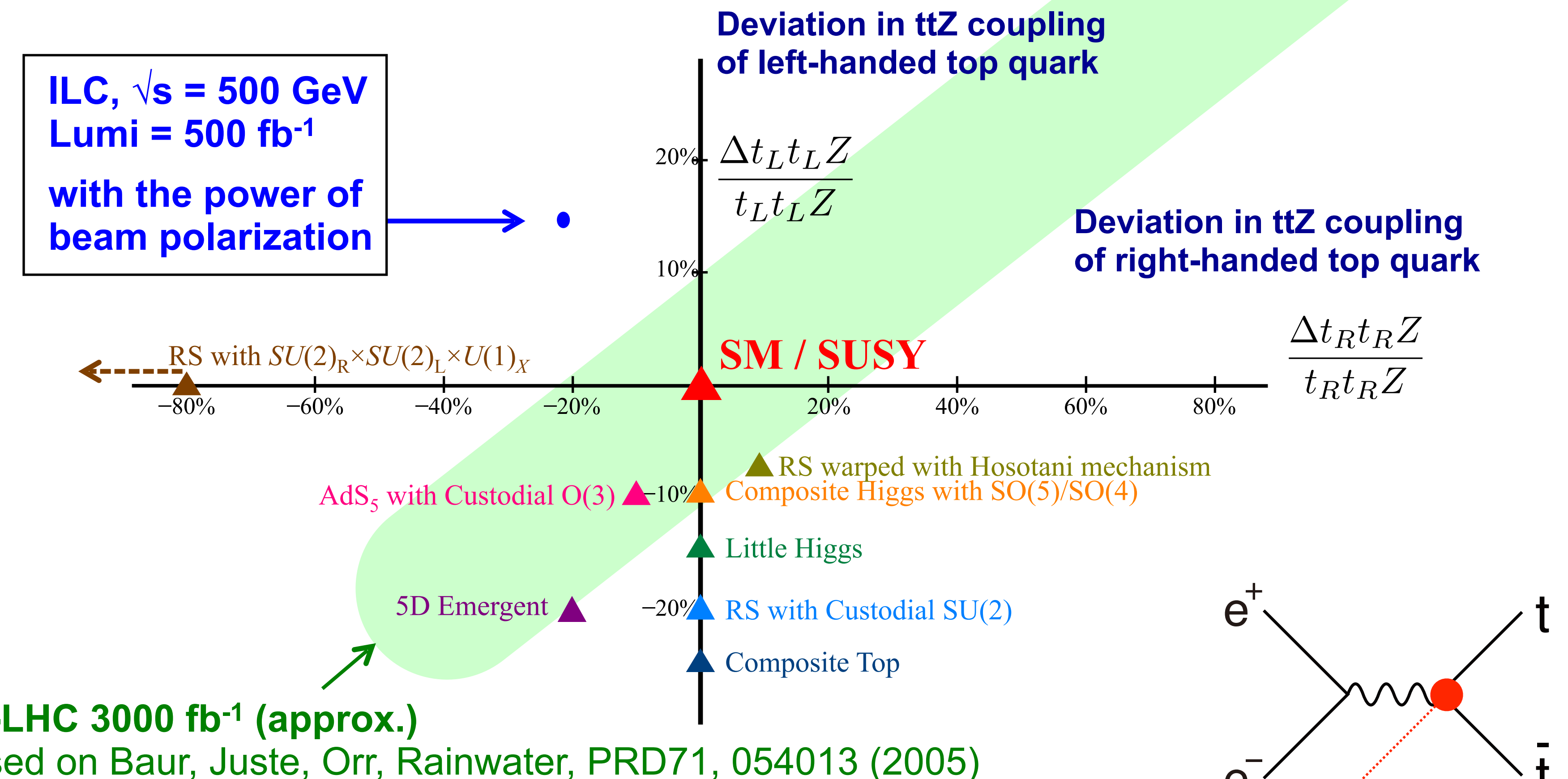
$$\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$$

$$\Delta m_H = 30\,\mathrm{MeV}$$

ILC pins down the location !

Impact of BSM on Top Sector

In composite Higgs models, it is often said that ***the top quark is partially composite***, resulting in ***form factors in ttZ couplings***, which can be measured at ILC. ***Beam polarization is essential*** to distinguish the ***left- and right-handed couplings***.



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

$$\Gamma_\mu^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\tilde{F}_{1V}^X(k^2) + \gamma_5 \tilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\tilde{F}_{2V}^X(k^2) + \gamma_5 \tilde{F}_{2A}^X(k^2)\right)\right\}$$

Searches for direct production of SUSY / DM at the ILC

What can ILC add to HL-LHC?

SUSY: LHC vs. ILC

"LHC has excluded MSSM up to high masses"	**vs.**	"LHC leaves out holes in MSSM parameter space"
"ILC can set model-indep. limits on SUSY particles"	**vs.**	"There is nothing interesting left within the reach of ILC"

These statements are all true to a certain extent…

The Big Picture:
SUSY is only complete with SUSY breaking implemented!

An example of connecting the "high mass reach of LHC" with "model-independent reach of ILC":

Gluino @ LHC vs. **Chargino/Neutralino @ ILC**

assuming various gaugino mass relations (e.g. GMSB, AMSB) and LSP types (Bino, Wino, Higgsino)

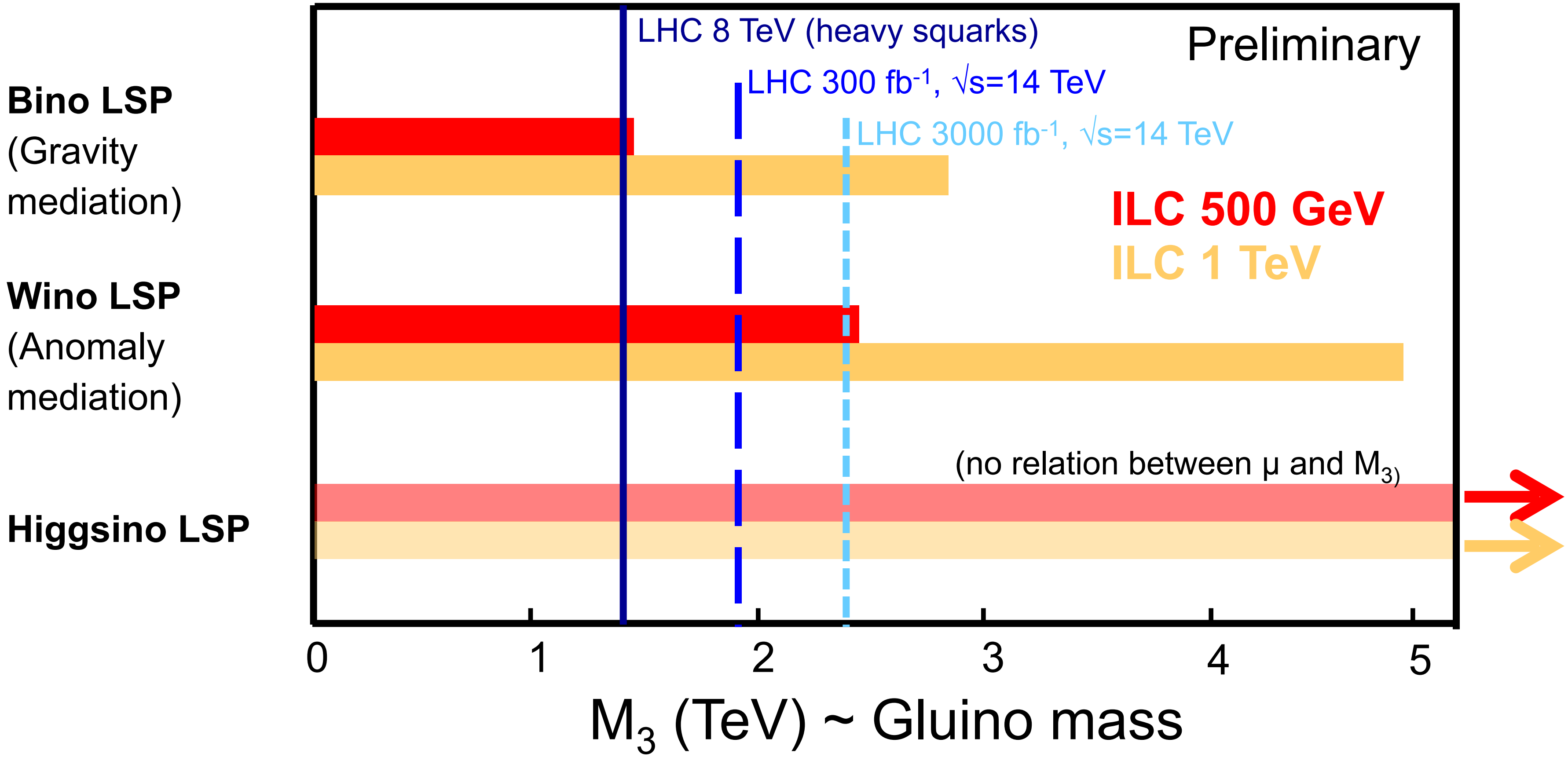
Sensitivity to SUSY

[this comparison is for illustration only; specific channels should be looked at for actual comparisons]

Examples of direct SUSY searches

- LHC: Gluino search
- ILC: EWkino (Chargino/Neutralino) search

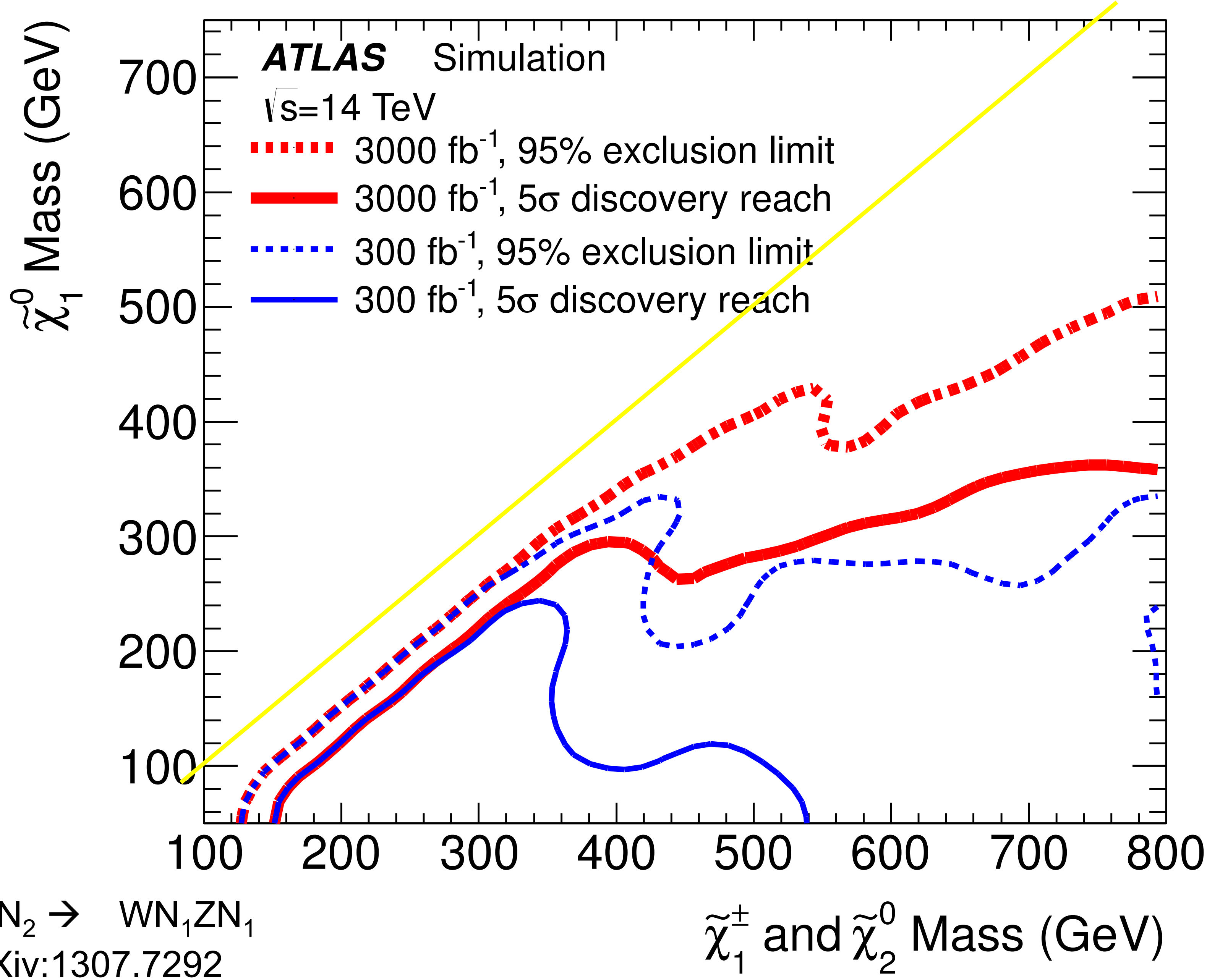
Compare using gaugino mass relations



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

But, LHC can also search for direct EWkino production

SUSY EW @ HL-LHC

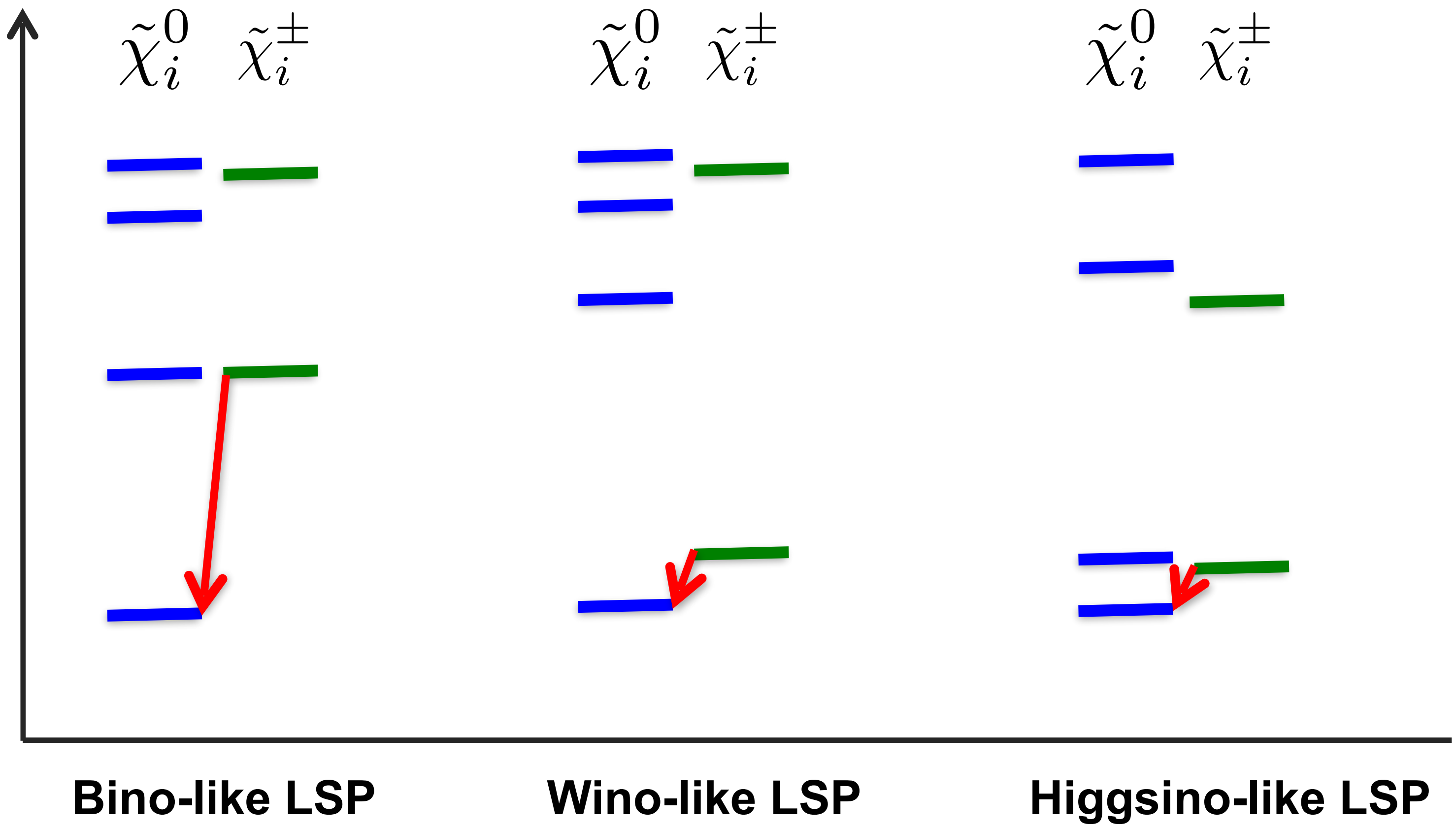


$C_1N_2 \rightarrow WN_1ZN_1$

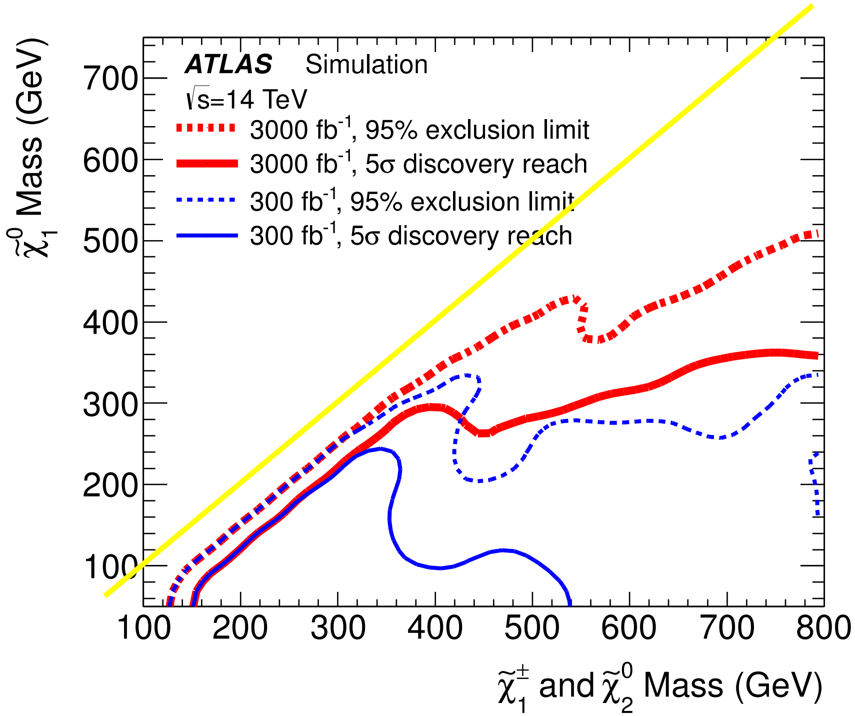
arXiv:1307.7292

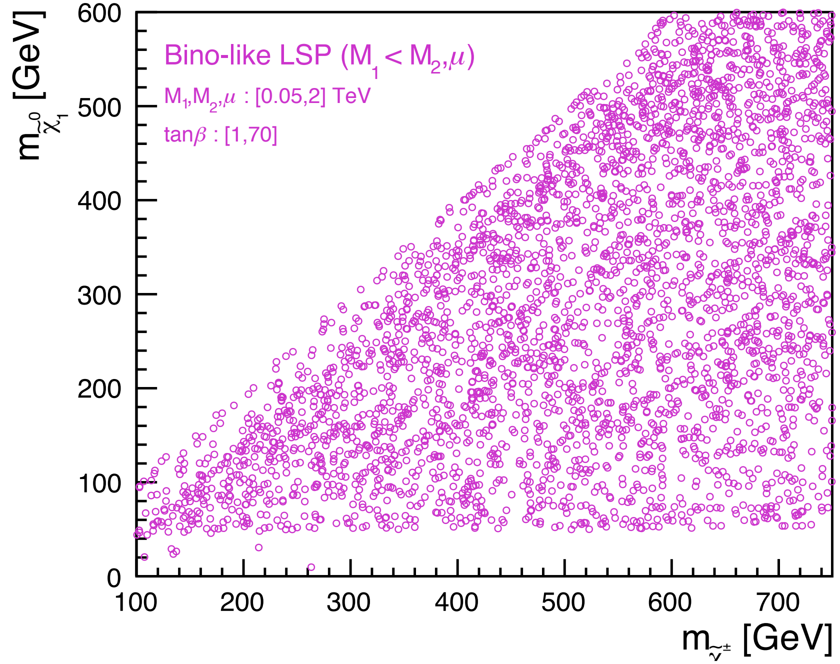
Is it only a tiny corner in the parameter space that will be left? Is ILC a gleaner?

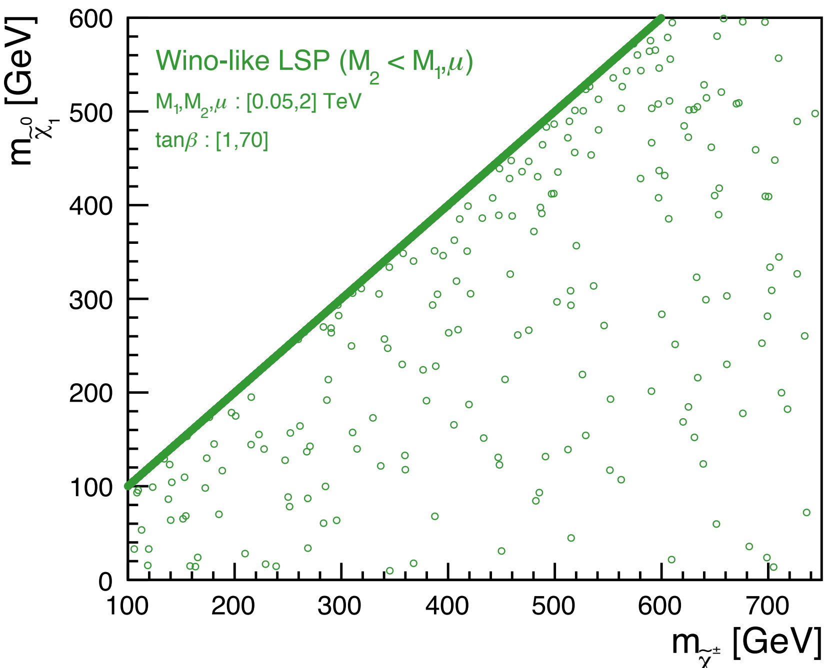
SUSY Electroweak Sector

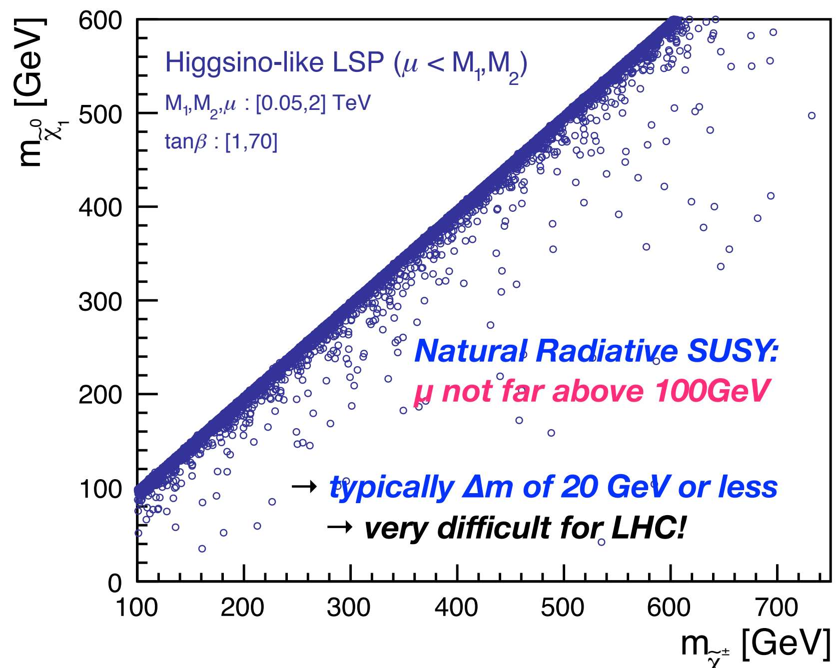


LSP/NLSP typically degenerate
(depends on mixing)


ATLAS Simulation
√s=14 TeV
3000 fb^{-1}, 95% exclusion limit
3000 fb^{-1}, 5σ discovery reach
300 fb^{-1}, 95% exclusion limit
300 fb^{-1}, 5σ discovery reach
$\tilde{\chi}_1^0$ Mass (GeV)
$\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ Mass (GeV)


Bino-like LSP ($M_1 < M_2,\mu$)
M_1,M_2,μ : [0.05,2] TeV
$\tan\beta$: [1,70]
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}^\pm}$ [GeV]


Wino-like LSP ($M_2 < M_1,\mu$)
M_1,M_2,μ : [0.05,2] TeV
$\tan\beta$: [1,70]
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]

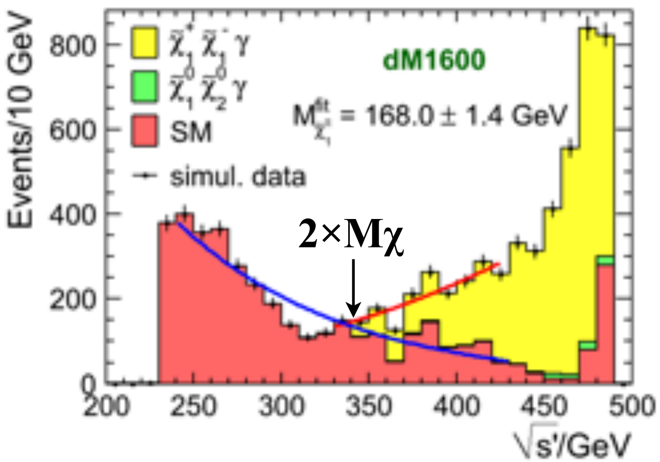

Higgsino-like LSP ($\mu < M_1,M_2$)
M_1,M_2,μ : [0.05,2] TeV
$\tan\beta$: [1,70]
Natural Radiative SUSY:
μ not far above 100GeV
→ typically Δm of 20 GeV or less
→ very difficult for LHC!
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]

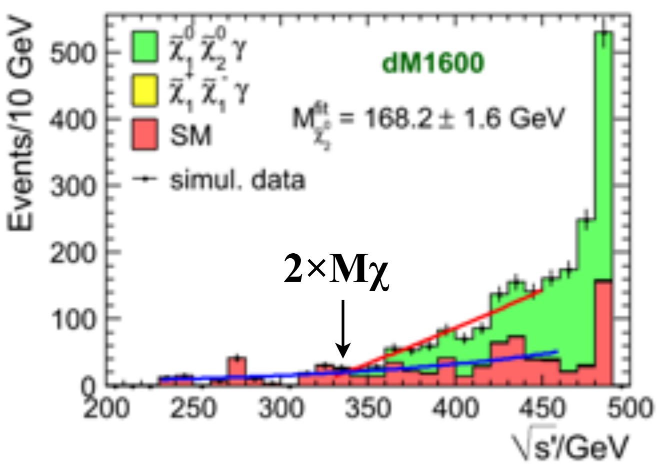
Higgsinos in Natural SUSY (ΔM<a few GeV)

ILC as a Higgsino Factory

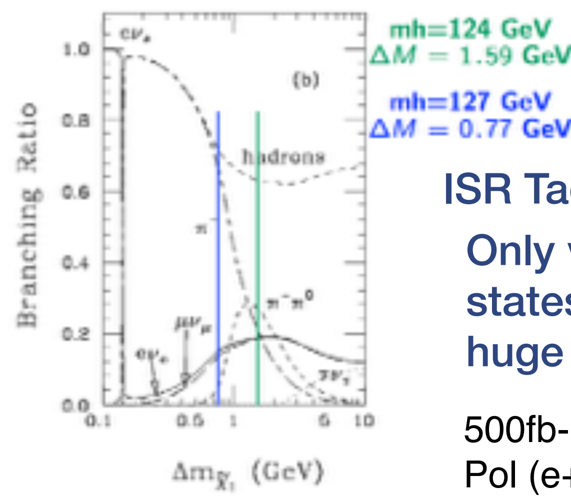
ISR Tagging

$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0\gamma$$





Ref: C.-H. Chen et al. hep-ph:9512230



Hale Sert
ECFA LCWS 2013, DESY
EPJC (2013) 73:2660

ISR Tagging

Only very soft particles in the final states → Require a hard ISR to kill huge two-photon BG!

500fb-1 @ Ecm=500GeV
Pol (e+,e-) = (+0.3,-0.8) and (-0.3,+0.8)

dm1600

Mass Spectrum

Particle	Mass (GeV)
h	124
$\tilde{\chi}_1^0$	164.17
$\tilde{\chi}_1^\pm$	165.77
$\tilde{\chi}_2^0$	166.87
H's	$\sim 10^3$
$\tilde{\chi}$'s	$\sim 2-3\times 10^3$

$\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1.59$ GeV

$$\delta(\sigma \times BR) \simeq 3\%$$
$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 2.1(3.7)\,\text{GeV}$$
$$\delta \Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \simeq 70\,\text{MeV}$$

dm770

Mass Spectrum

Particle	Mass (GeV)
h	127
$\tilde{\chi}_1^0$	166.59
$\tilde{\chi}_1^\pm$	167.36
$\tilde{\chi}_2^0$	167.63
H's	$\sim 10^3$
$\tilde{\chi}$'s	$\sim 2-3\times 10^3$

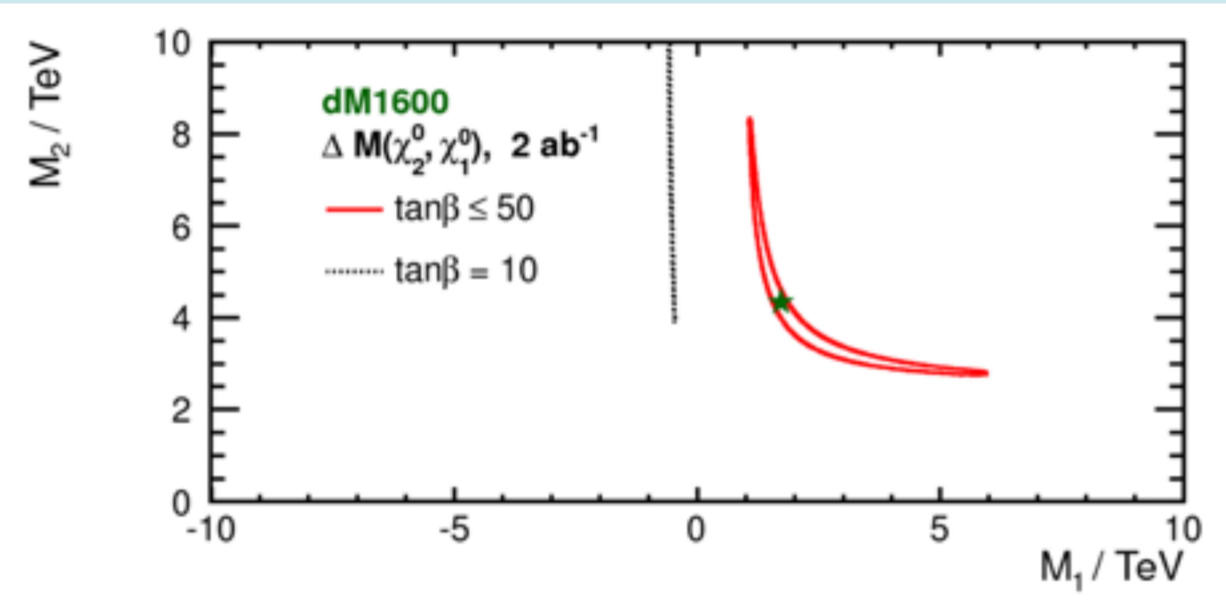
$\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.77$ GeV

$$\delta(\sigma \times BR) \simeq 1.5\%$$
$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 1.5(1.6)\,\text{GeV}$$
$$\delta \Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \simeq 20\,\text{MeV}$$

Extracting M1 and M2

$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$$
$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0\gamma$$

Hale Sert
ECFA LCWS 2013, DESY
Berggren et al. EPJC (2013) 73:2660

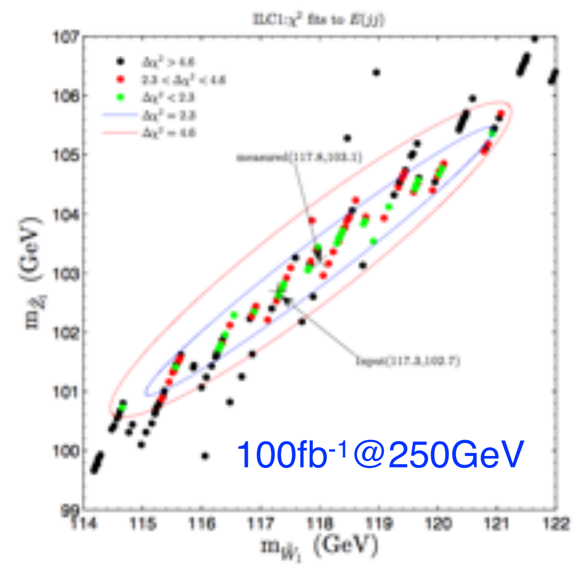


@ 2 ab^{-1}	input	lower	upper
M_1 [TeV]	1.7	∼ 1.0 (-0.4)	∼ 6.0
M_2 [TeV]	4.4	∼ 2.5 (3.5)	∼ 8.5
μ [GeV]	165.7	166.2	170.1

$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$$

RNS: Baer et al.
arXiv: 1404.7510

ΔM=15GeV



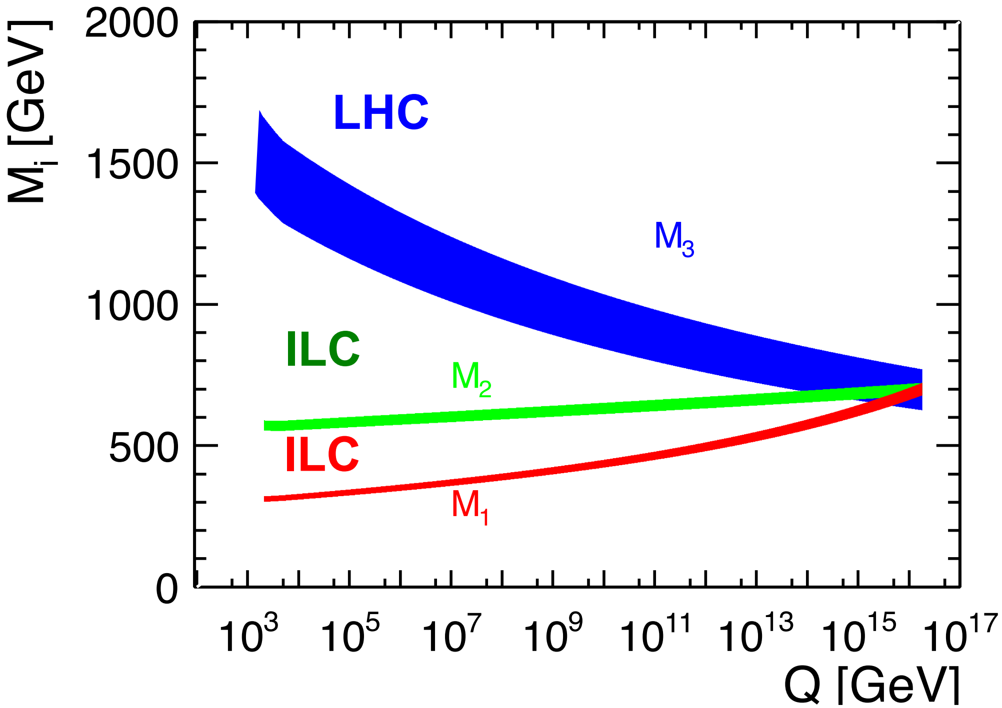
In the radiatively driven natural SUSY (RNS) scenario as in arXiv: 1404.7510, ΔM~10GeV, we can determine M1 and M2 to a few % or better, allowing us to test GUT relation!

GUT Scale Physics

Test gaugino mass unification

- Chargino/Neutralino @ ILC → probe M_1-M_2 gaugino mass relation
- Gluino @ LHC → test of gaugino mass relation by ILC-LHC complementarity
- Gives a prediction of the gluino mass scale
- Discrimination of SUSY spontaneous symmetry breaking scenarios

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



LHC: gluino discovery
→ mass determination

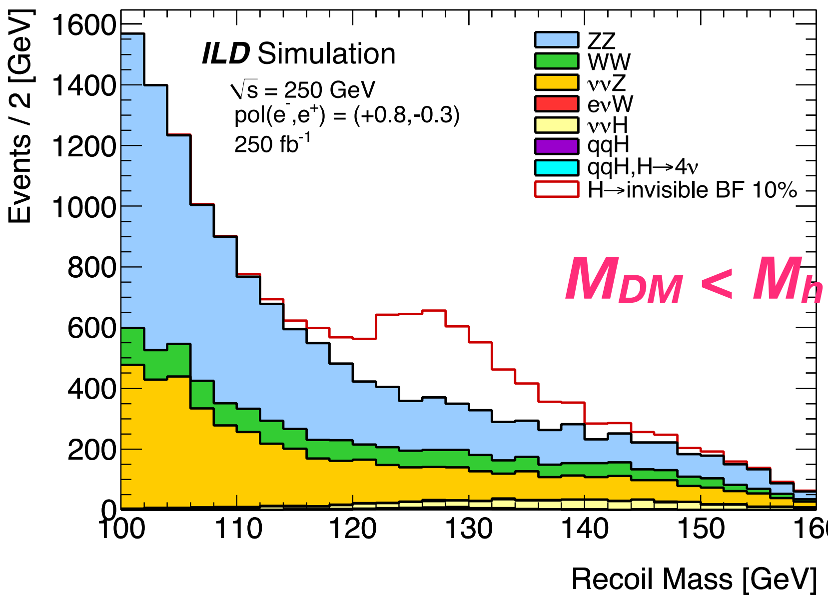
ILC: Higgsino discovery
→ M1, M2 via mixing between Higgsino and Bino/Wino

Dark Matter

WIMP Dark Matter @ ILC

WIMP searches at colliders are complementary to direct/indirect searches.
Examples at the ILC:

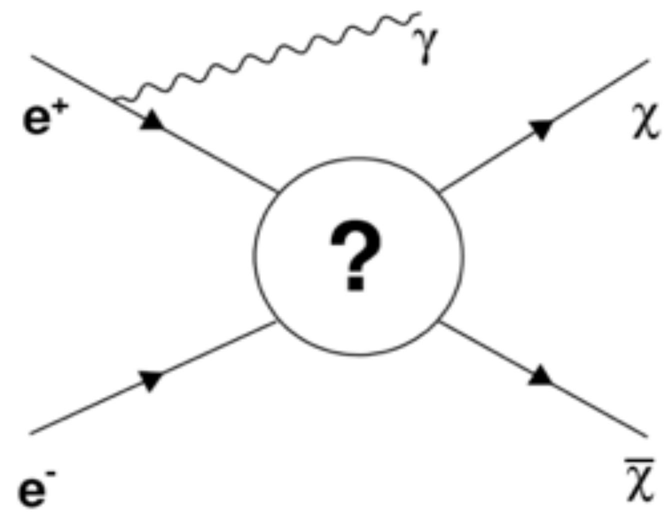
Higgs Invisible Decay



$M_{DM} < M_h/2$

BR(H→invis.) < 0.4%
at 250 GeV, 1150 fb^{-1}

Monophoton Search



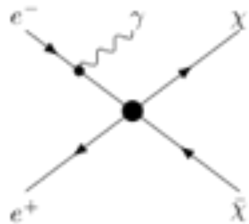
→ ***M_{DM} reach ~ Ecm/2***

In many models, DM has a charged partner as in higgsino DM case of SUSY.

SUSY-specific signatures (decays to DM)

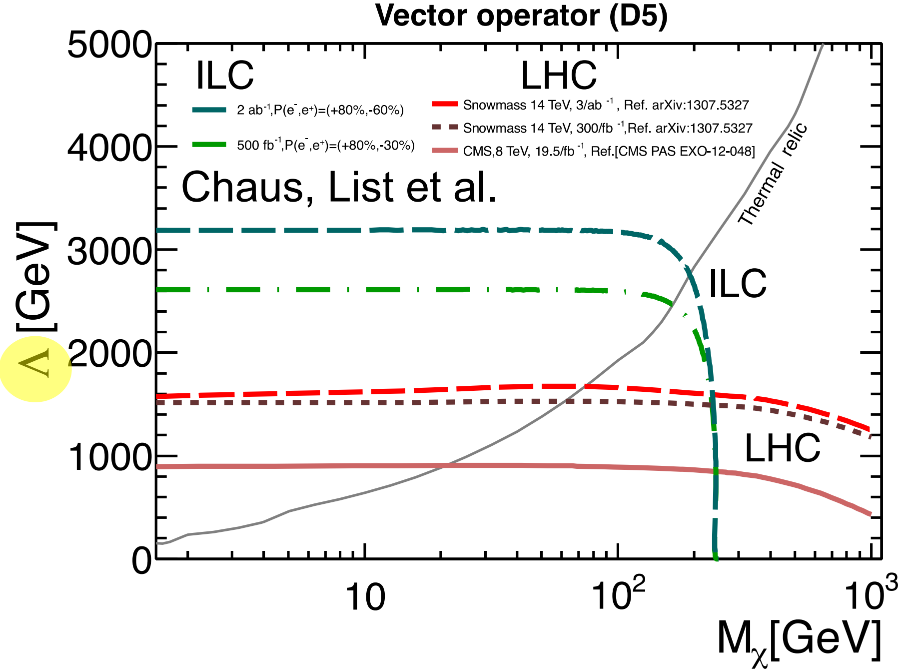
- light Higgsino, light stau, etc.

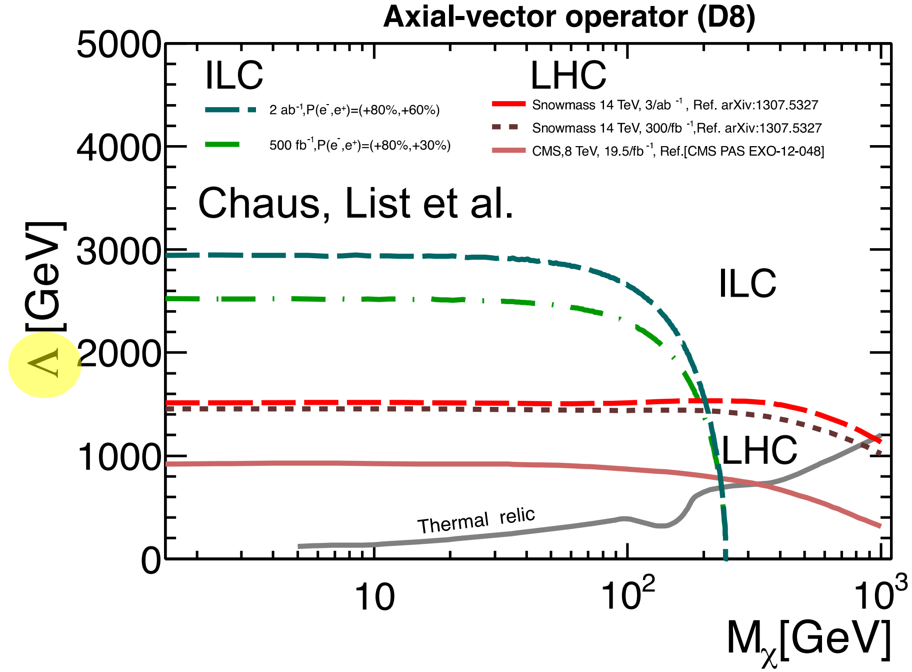
DM: Effective Operator Approach



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

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





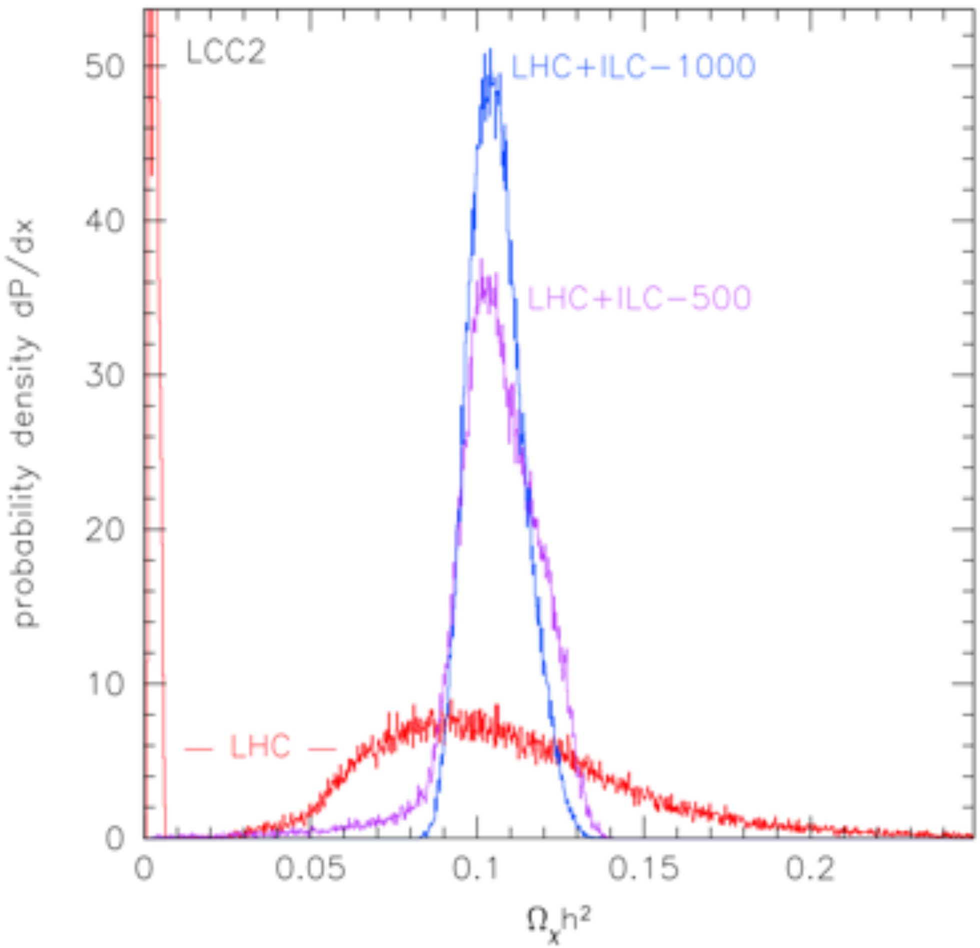
LHC sensitivity: Mediator mass up to Λ~1.5 TeV for large DM mass

ILC sensitivity: Mediator mass up to ***Λ~3 TeV*** for ***DM mass up to ~$\sqrt{s}/2$***

DM Relic Abundance

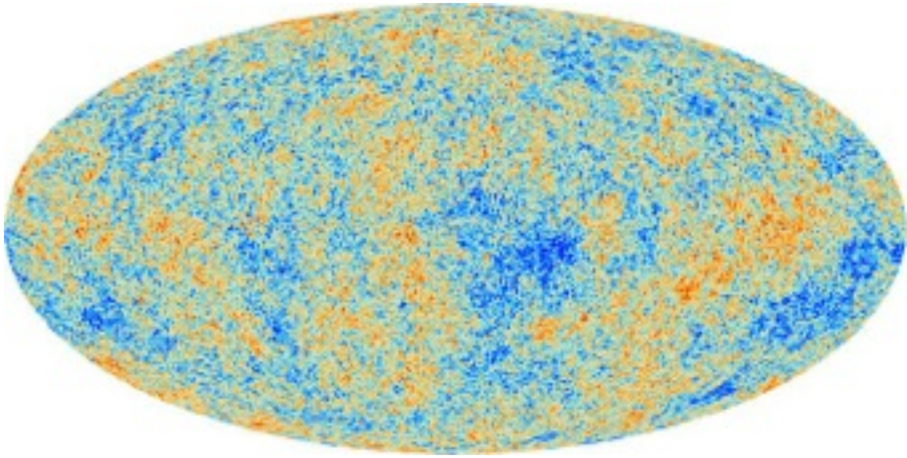
WMAP/Planck (68% CL)

$$\Omega_c h^2 = 0.1196 \pm 0.0027$$



Baltz, Battaglia, Peskin, Wizansky
PRD74 (2006) 103521, arXiv:hep-ph/0602187
**This particular benchmark point is excluded. Update is in progress.*

ESA/Planck



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

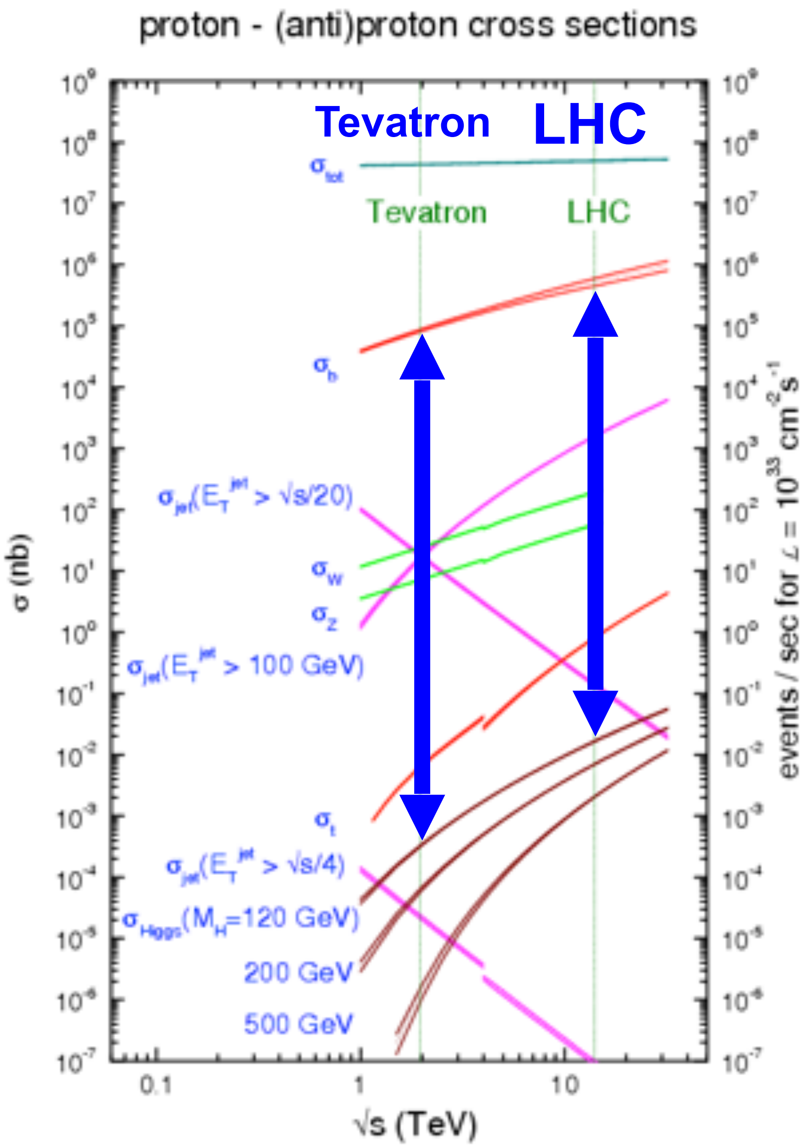
Mass and couplings measured at ILC
→ *DM relic density*

Summary

- The primary goal for the next decades is ***to uncover the secret of the EW symmetry breaking.*** The discovery of H(125) completed the SM particle spectrum and taught us how the EW symmetry was broken. However, it does not tell us why it was broken. ***Why $\mu^2 < 0$?*** To answer this question we need to go beyond the SM.
- There is a big branch point concerning the question: ***Is H(125) elementary or composite?*** There are ***two powerful probes*** in hand: ***H(125) itself and the top quark***. Different models predict different deviation patterns in Higgs and top couplings. ***ILC will measure these couplings with unprecedented precision.***
- This will open up a window to BSM and ***fingerprint BSM models***, otherwise will set the energy scale for the E-frontier machine that will follow LHC and ILC.
- ***Cubic self-coupling measurement*** will decide whether the EWSB was 1st order phase transition or not. If it was, it will provide us the possibility of understanding ***baryogenesis at the EW scale***.
- ***The ILC is an ideal machine to answer these questions*** (regardless of BSM scenarios) and we can do this ***model-independently***.
- It is also very important to stress that ***ILC, too, is an energy frontier machine.*** It will access the energy region never explored with any lepton collider. It is not a tiny corner of the parameter space that will be left after LHC. ***There is a wide and interesting region for ILC to explore.***
- Once a new particle is found at ILC, we can precisely determine its properties, making full use of ***polarized beams***. In the case of natural radiative SUSY scenario, we might even probe GUT scale physics using RGE.
- If there is a DM candidate within ILC's reach, its measured mass and couplings can be used to calculate the DM relic density and will ***reveal the nature of the cosmic DM***.
- ***In this way, ILC will pave the way to BSM physics.***

Additional Slides

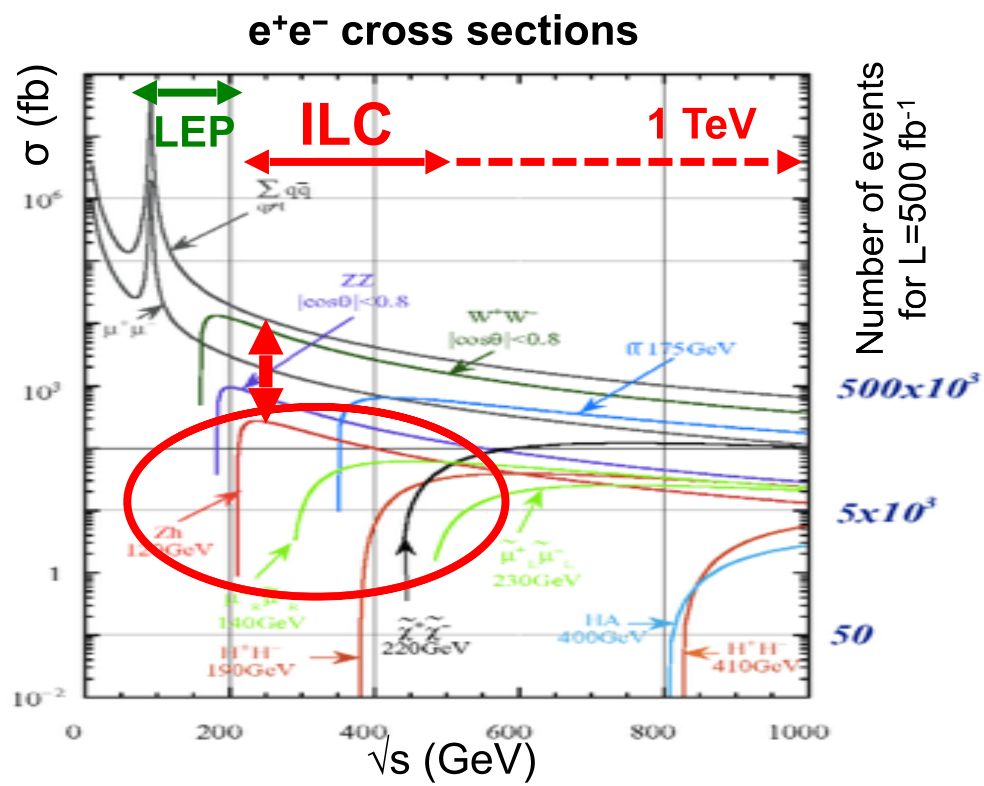
Cross Sections



Typically,

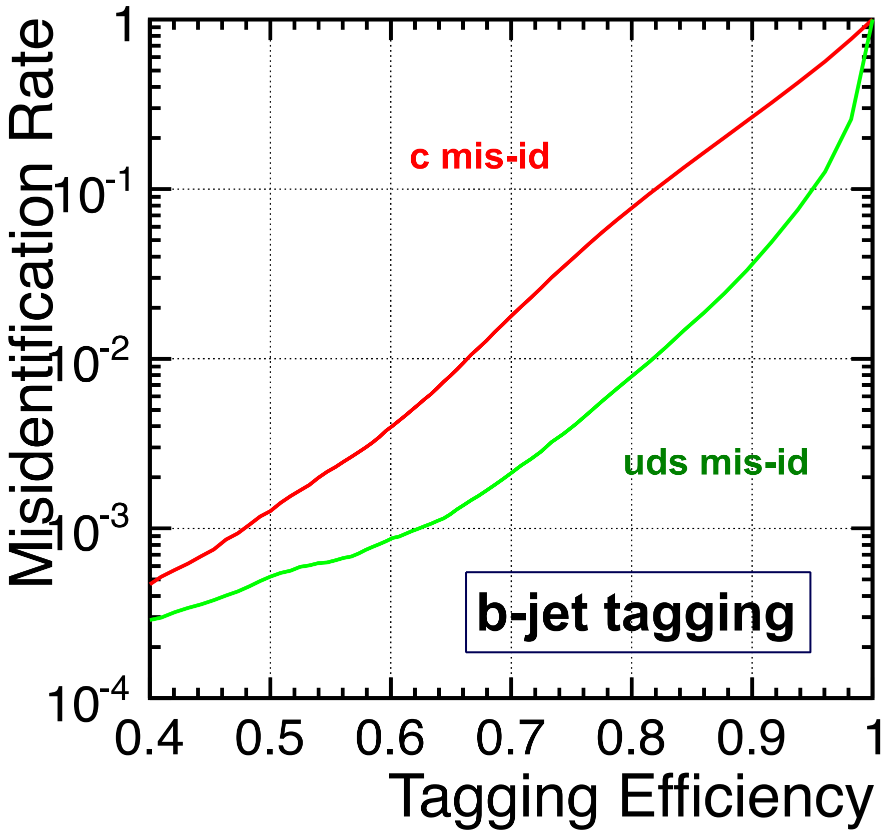
$$N_{\rm sig}^{pp} > N_{\rm sig}^{e^+e^-}$$

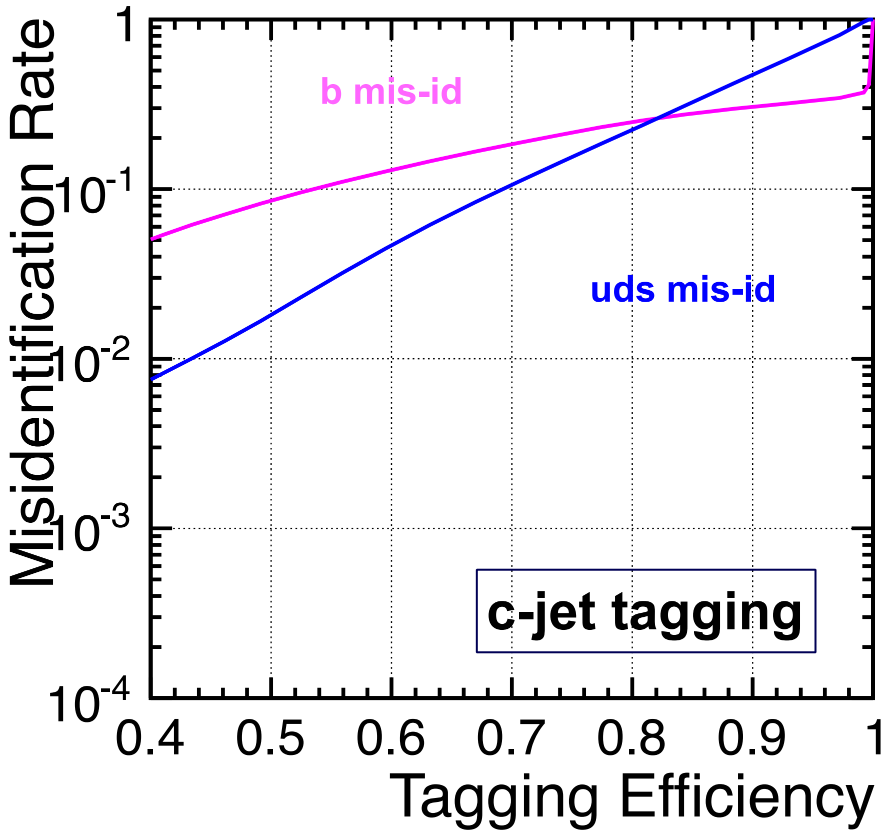
$$N_{\rm bkg}^{pp} \gg N_{\rm bkg}^{e^+e^-}$$



Higgs Hadronic Decays: Flavor Tagging

Z→qq, E_{CM}=91.2 GeV, ILD Full Simulation [Suehara, TT]



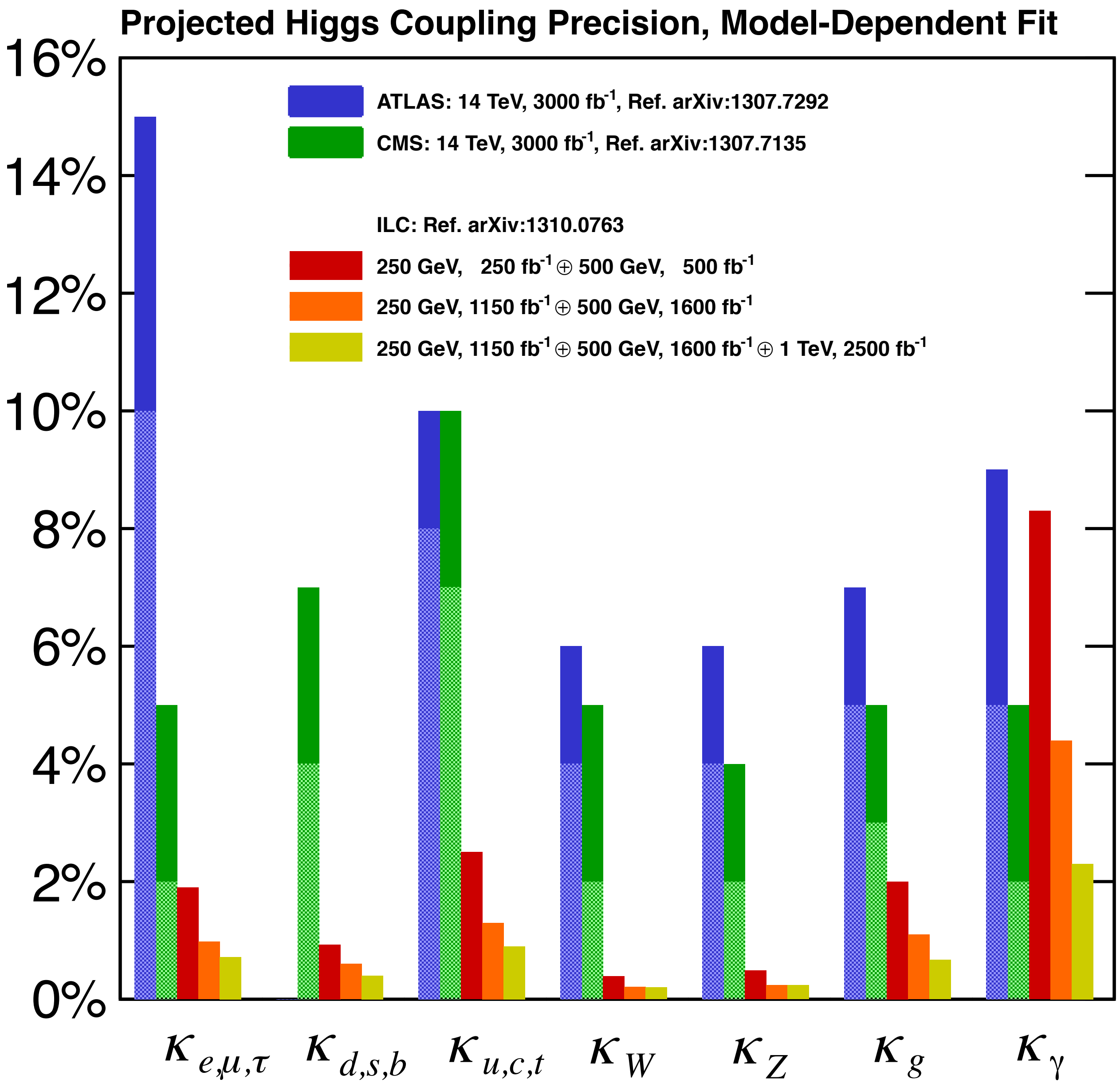


ILC detectors allow high performance b/c/g tagging
Precise measurement of BR(H→bb, cc, gg)

What if no significant deviation found?

Higgs Couplings (1/2)

[With assumptions; not model-independent.]



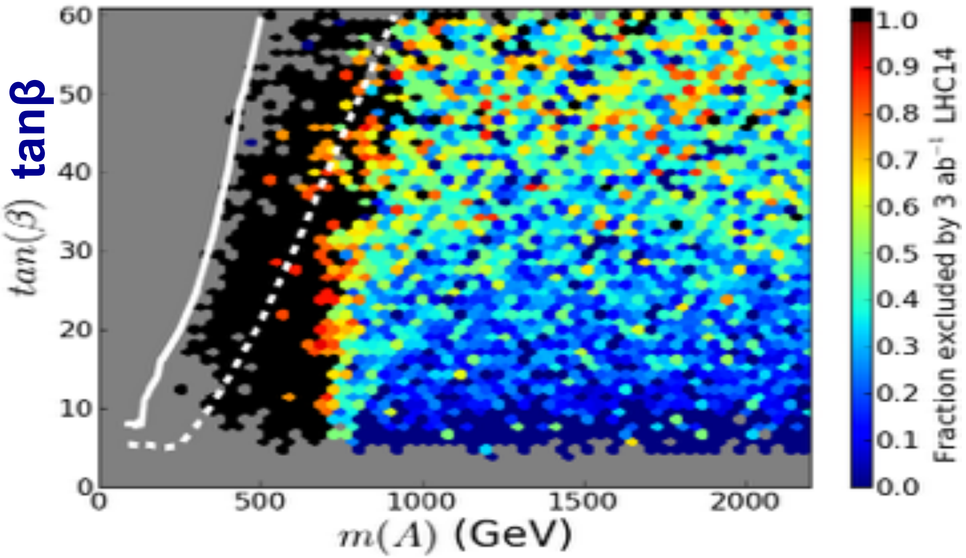
MSSM Heavy Higgs Bosons

Exclusions of pMSSM points via Higgs couplings (combining hγγ, hττ, hbb)

Cahill-Rowley, Hewett, Ismail, Rizzo, arXiv:1407.7021 [hep-ph]

HL-LHC 3000 fb-1

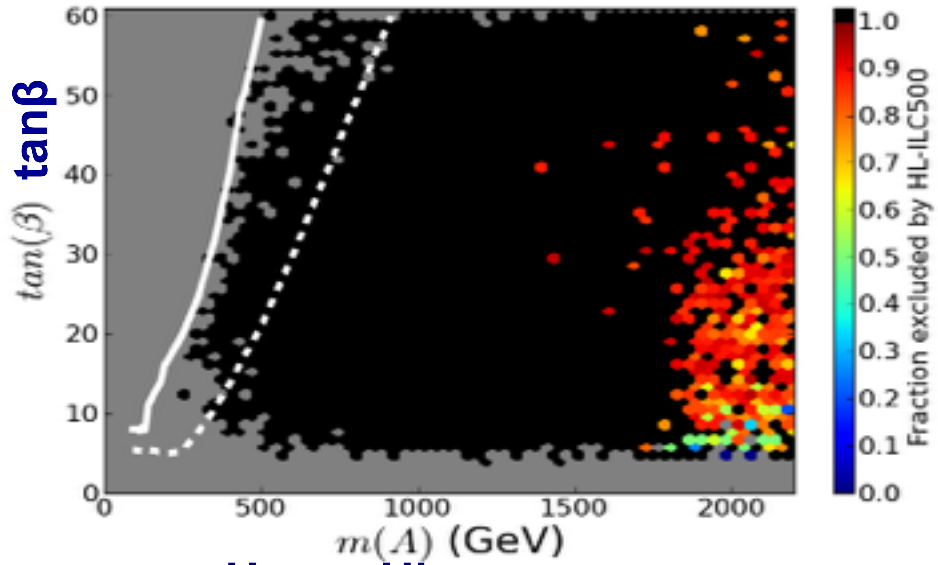
tanβ



Heavy Higgs mass

ILC (1150 fb^{-1}@250 GeV & 1600 fb^{-1}@500 GeV)

tanβ



Heavy Higgs mass

Precision Higgs coupling measurements
sensitive probe for heavy Higgs bosons
***mA ~ 2 TeV* reach for <u>any</u> tanβ at the ILC**

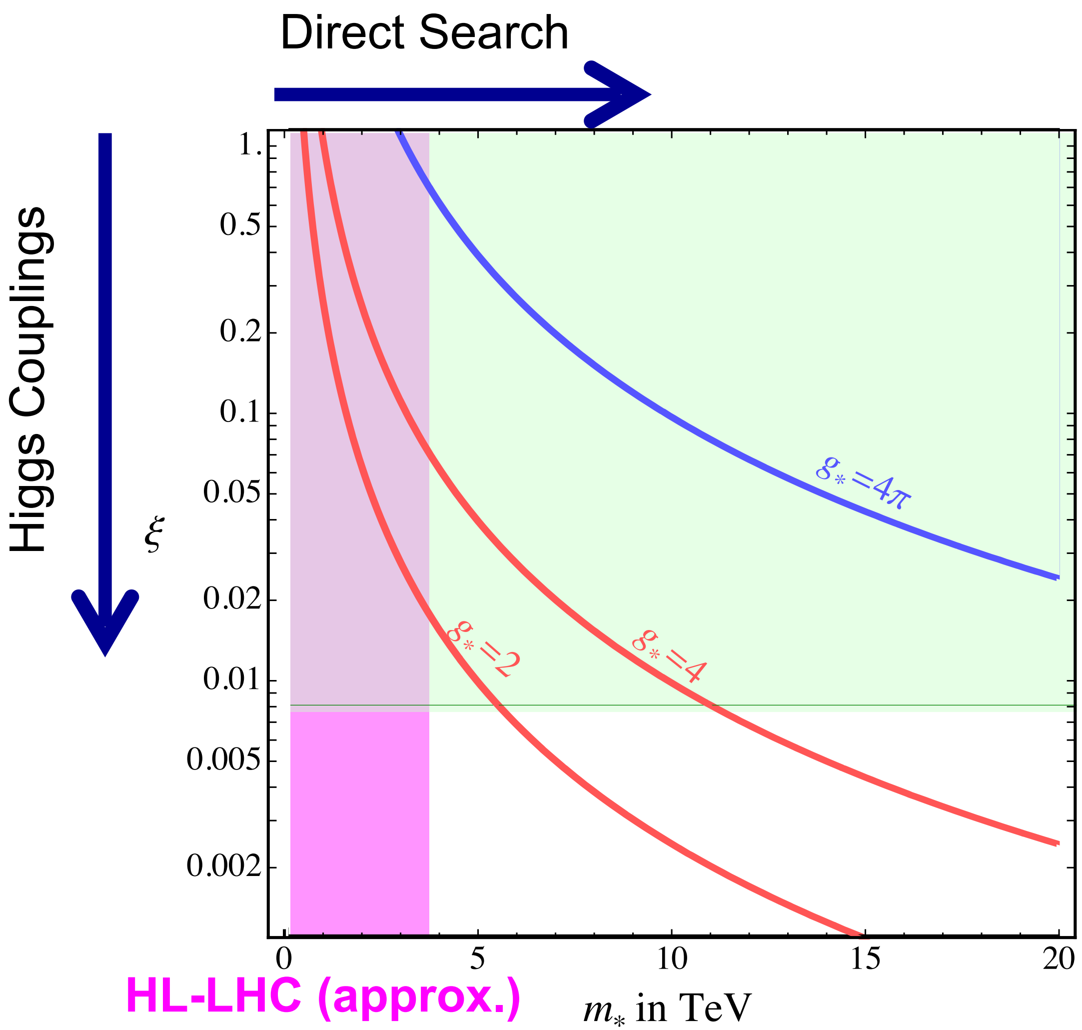
Composite Higgs: Reach

Complementary approaches to probe composite Higgs models

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

Comparison depends on the coupling strength (g_*)

Based on Contino, et al, JHEP 1402 (2014) 006



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

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

ILC (250+500 LumiUP)

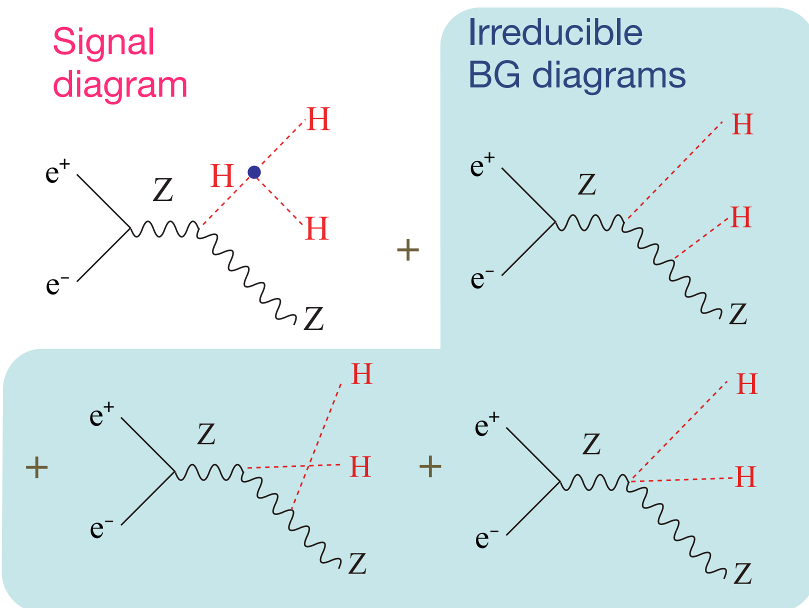
$$\Delta \frac{g_{hVV}}{g_{hVV}} = 0.4\%$$

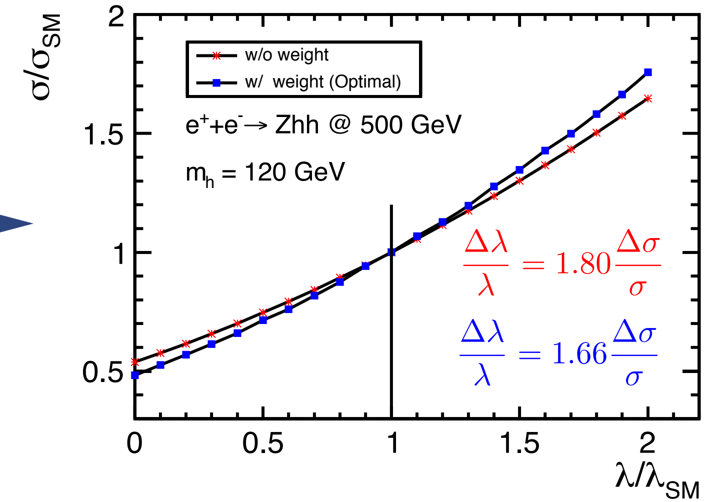
The Problem : BG diagrams dilute self-coupling contribution

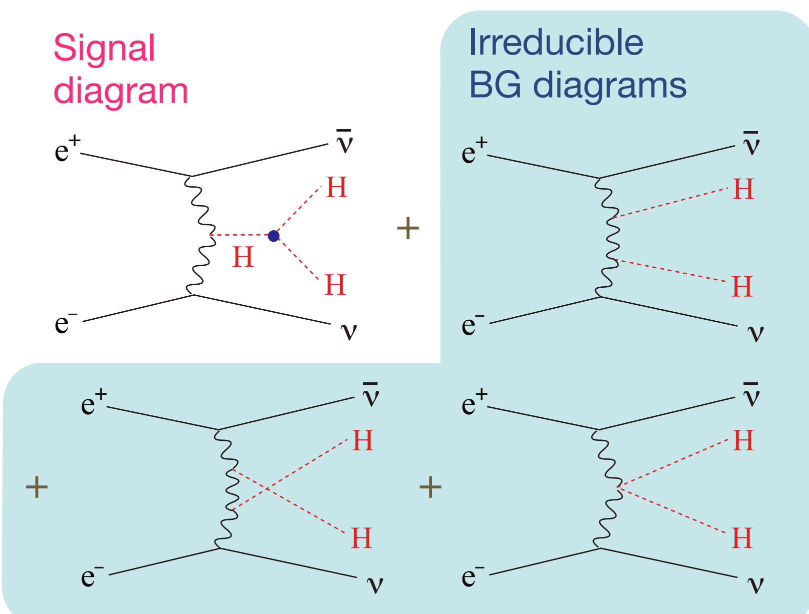
$$\sigma = \lambda^2 S + \lambda I + B$$

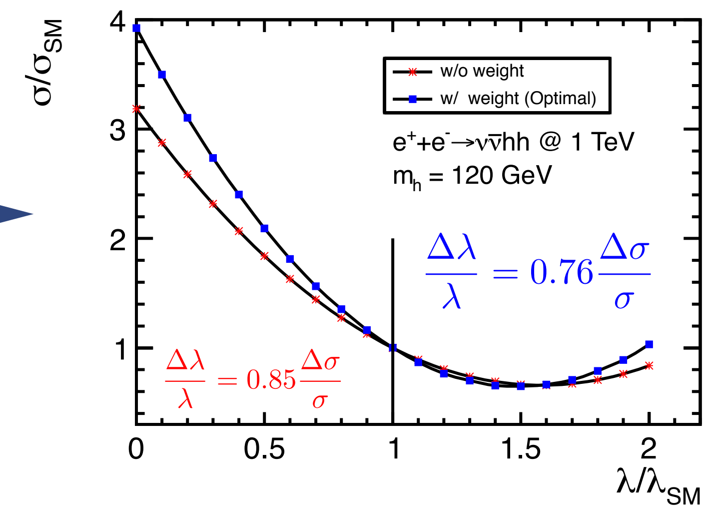
$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

F=0.5 if no BG diagrams

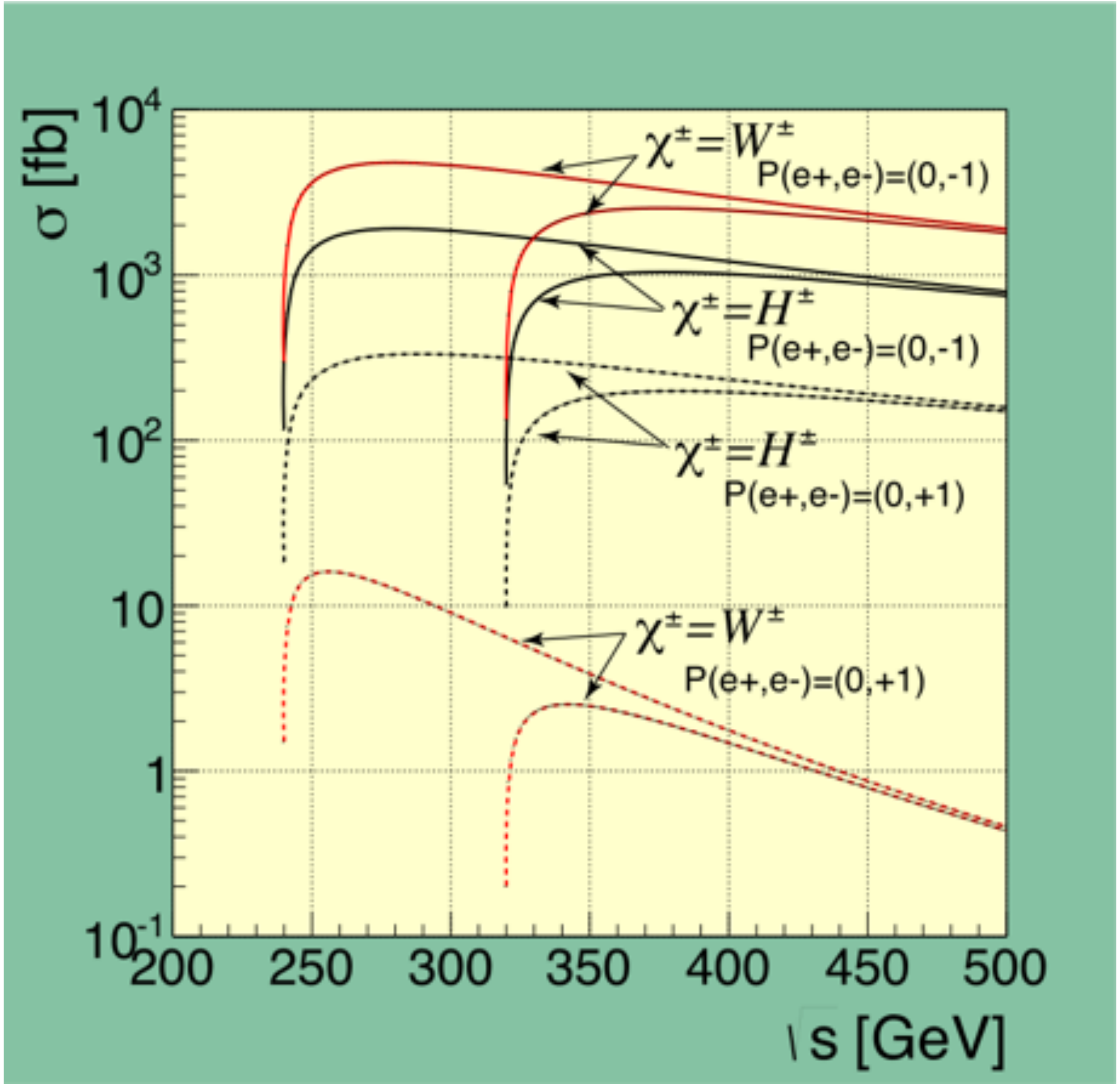








Junping Tian LC-REP-2013-003


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

Slepton decays to DM with small mass differences

Study of stau pair production at the ILC

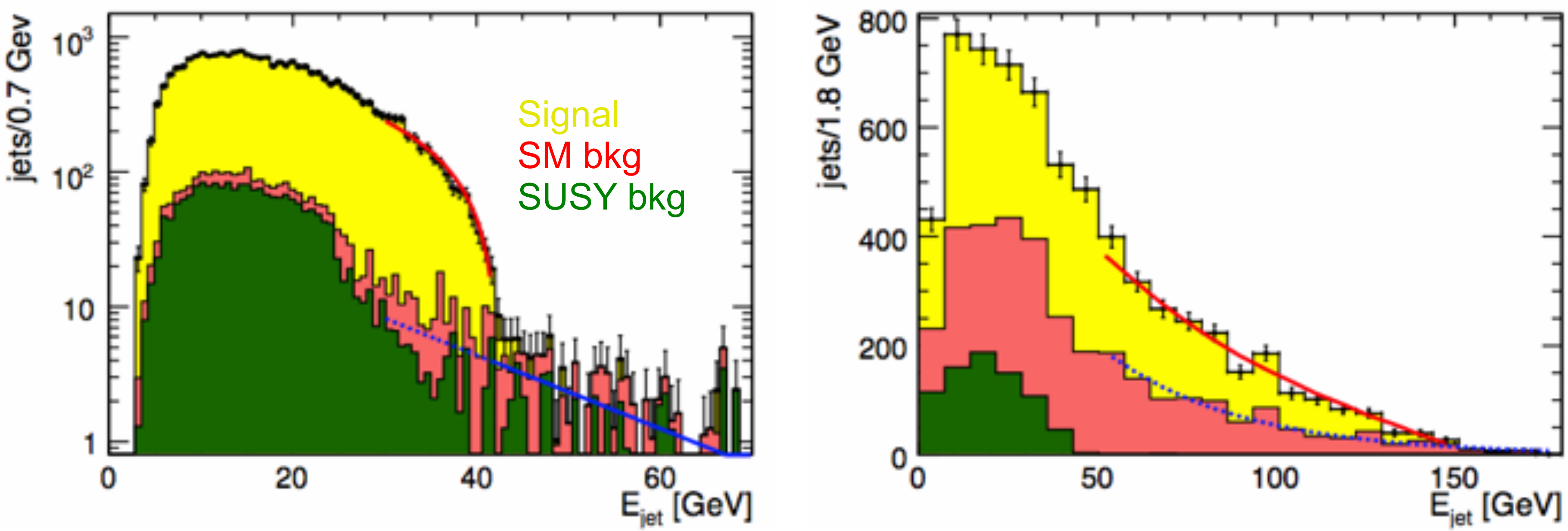
Observation of lighter and heavier stau states with decay to DM + hadronic tau

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

$$\sigma(e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-) = 158 \text{ fb}$$

$$\sigma(e^+e^- \to \tilde{\tau}_2^+\tilde{\tau}_2^-) = 18 \text{ fb}$$

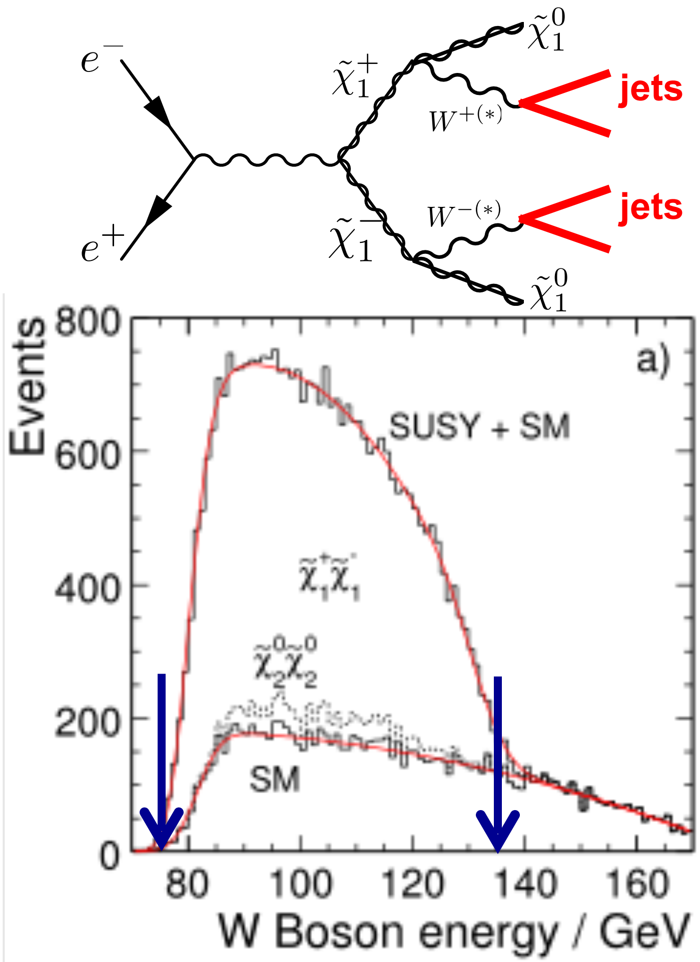
Bechtle, Berggren, List, Schade, Stempel, arXiv:0908.0876, PRD82, 055016 (2010)



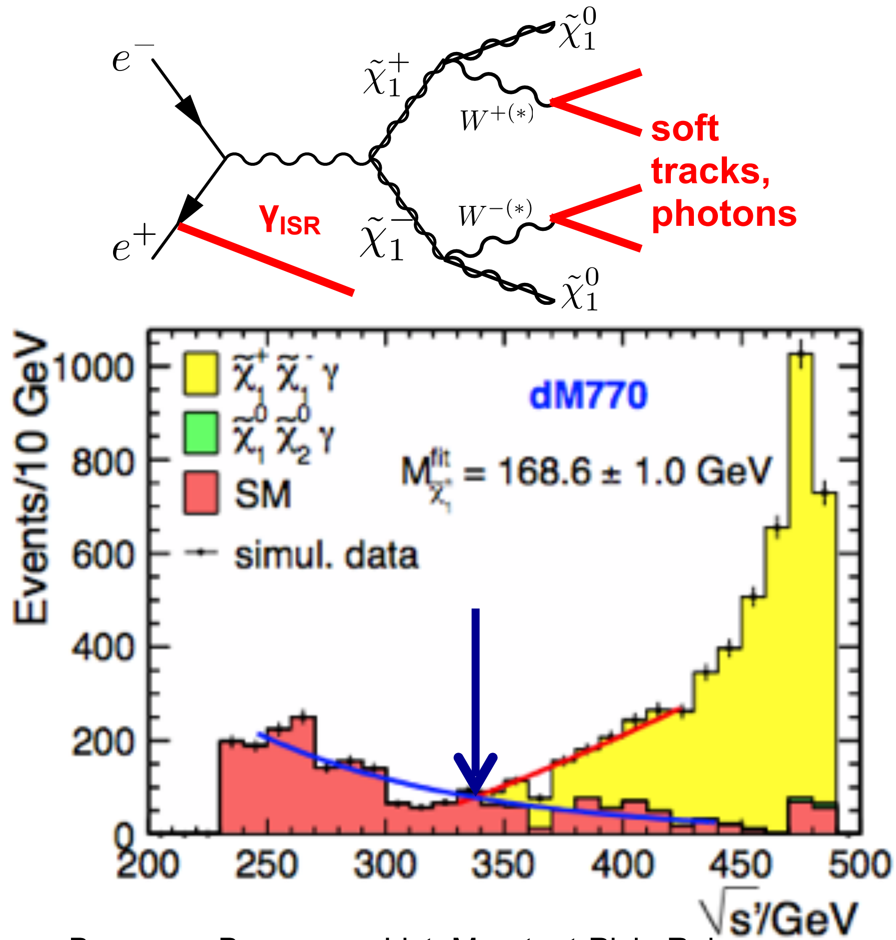
√s=500 GeV, Lumi=500 fb-1, P(e-,e+)=(+0.8,-0.3)

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

SUSY Precision Measurements



Suehara, List, arXiv:0906.5508



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

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