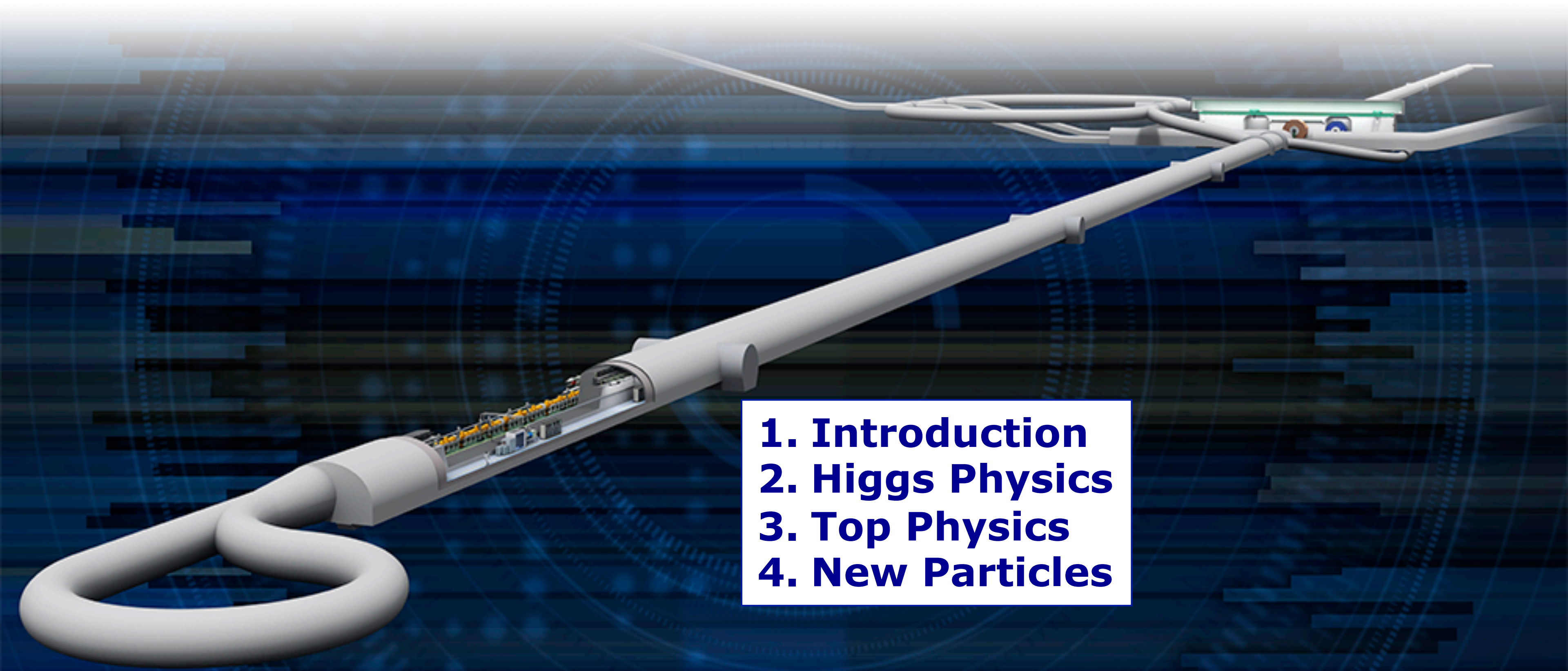
Overview of the Physics Case for the ILC

Tomohiko Tanabe (U. Tokyo)

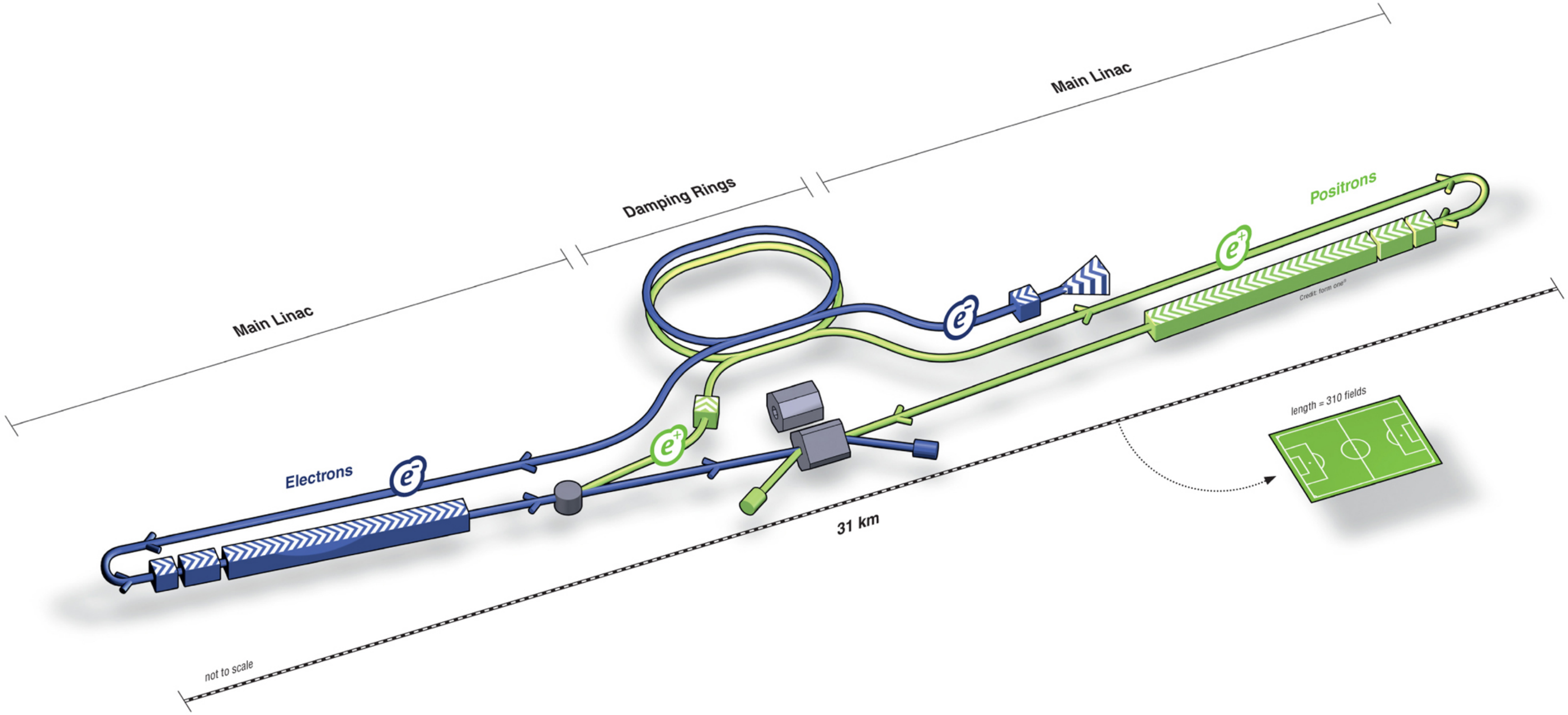
November 1, 2014

General Meeting of ILC Physics WG



1. Introduction
2. Higgs Physics
3. Top Physics
4. New Particles

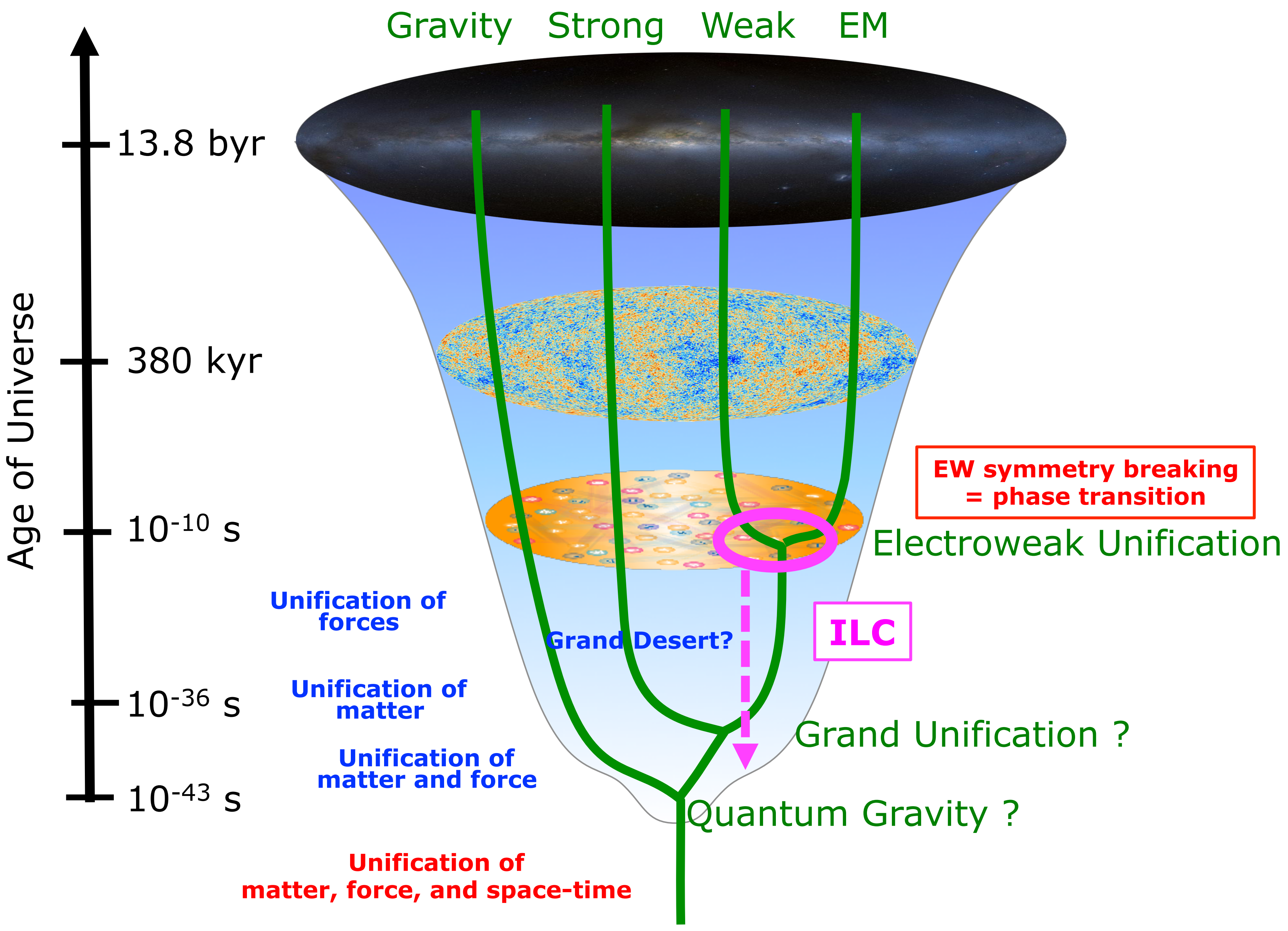
ILC in a nutshell



Stands for:	International Linear Collider
Collides:	electrons and positrons
CM energy:	250-500 GeV (baseline); ~1 TeV upgrade option
Length:	31 km @ 500 GeV → **extend for higher energy**
Beam polarization:	P(e-,e+) = (±80%, ±30%)

Most mature accelerator design for e+e- collisions.

Towards a more fundamental theory

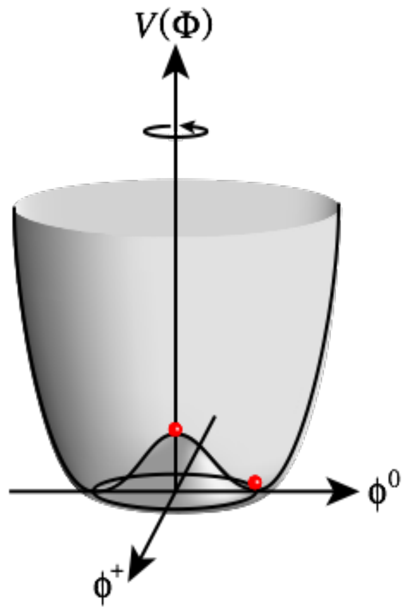


Electroweak Symmetry Breaking

- With the discovery of H(125), we now understand how EWSB occurs: via the expectation value of the Higgs field. **However, we do yet know the physics behind the EWSB.**

- In order to explain the shape of the Higgs potential (if there is an explanation), we need to go **beyond the Standard Model.**

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



- Such BSM models predict the existence of **new particles/forces**. They also affect the properties of the **Higgs, top,** and W/Z, which can be probed via **precision measurements.**

- They could be connected to the **observed BSM phenomena**:
  - baryon asymmetry of the universe
  - neutrino oscillations
  - dark matter
  - dark energy
  - …

A fork in our path

In **SUSY**, the EW symmetry is radiatively broken. It also gives a raison d'être for fundamental scalar fields like the Higgs boson.

The EWSB sector is **weakly-interacting**.

H(125) is **elementary**.

A telescope for **GUT**, with a possible **Grand Desert** along the way.

In **composite Higgs** models, a new QCD-like strong interaction causes vacuum condensation.

The EWSB sector is **strongly-interacting**.

H(125) is **composite**.

A **jungle** of new particles are expected.

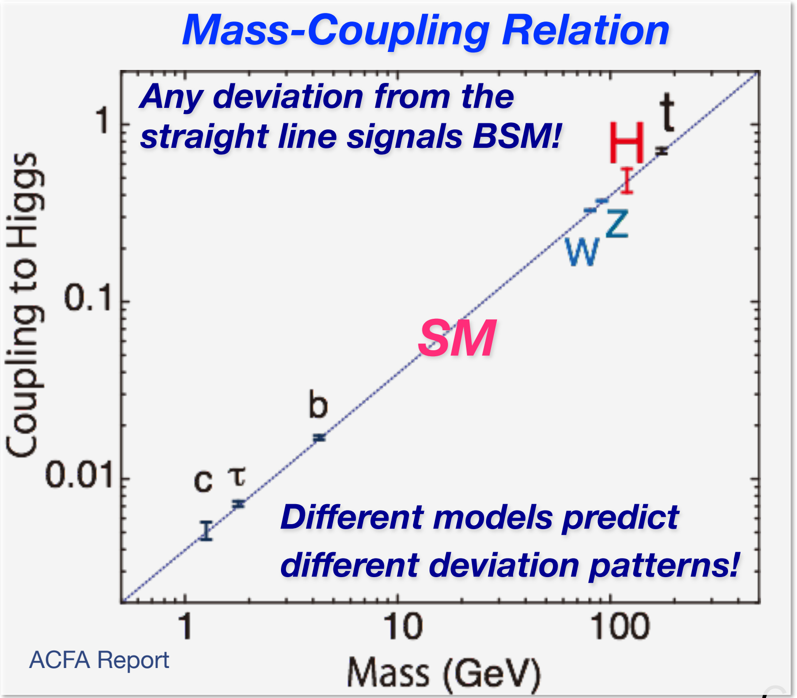
Elementary or Composite?

How can ILC address this question?

In **SUSY (elementary Higgs)**,
- Search for
  - additional Higgs bosons: **H, A, $H^{\pm}$**
  - uncolored SUSY particles: **EWK-inos, sleptons**
- Look for specific deviation patterns in
  - **Higgs couplings**
  - gauge boson properties

If **composite Higgs**,
- Look for specific deviation patterns in
  - **Higgs couplings**
  - **top (ttZ) couplings**

Both cases synergistic with LHC searches/measurements



Three key probes for BSM at ILC:

- **Higgs boson**
- **Top quark**
- **New particles**

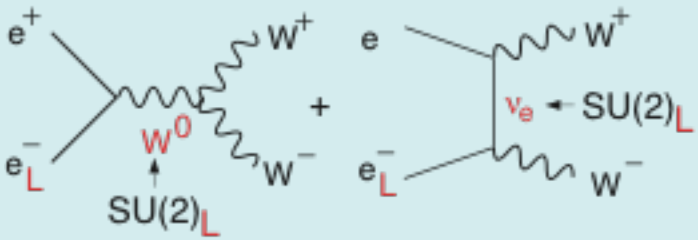
Three key tools to enable this endeavor:

- Well-defined initial states with controllable E_{CM}
- Clean environment:
  - No QCD bkg.
  - Only calculable bkg. from EW processes
- **Beam polarization (unique to linear colliders)**

Power of Beam Polarization

Bkg. Suppression

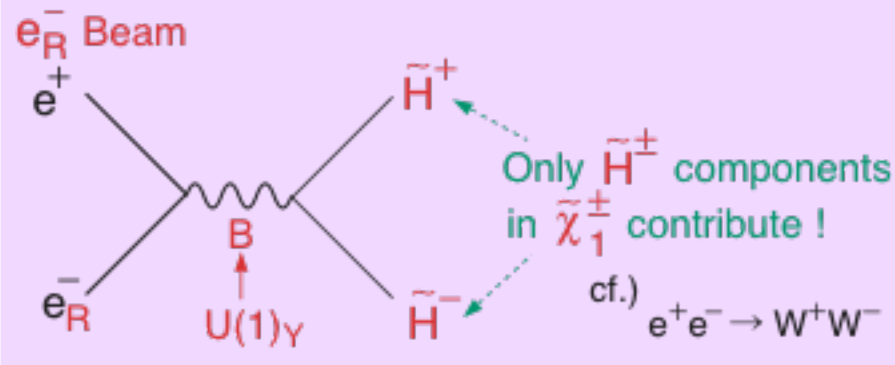
W^+W^- (Largest SM bkg in SUSY searches)



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

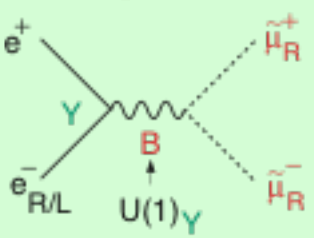
Decomposition

Chargino pair



$$\tilde{\chi}^{\pm}_1 = \bigcirc \cdot \tilde{W}^{\pm} + \bullet \cdot \tilde{H}^{\pm}, \quad \bullet = \langle \tilde{H}^{\pm} | \tilde{\chi}^{\pm}_1 \rangle$$

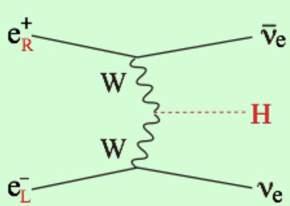
Slepton pair



$$\begin{cases} Y_L = -1/2 : e^-_L \\ Y_R = -1 \quad : e^-_R \end{cases}$$

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

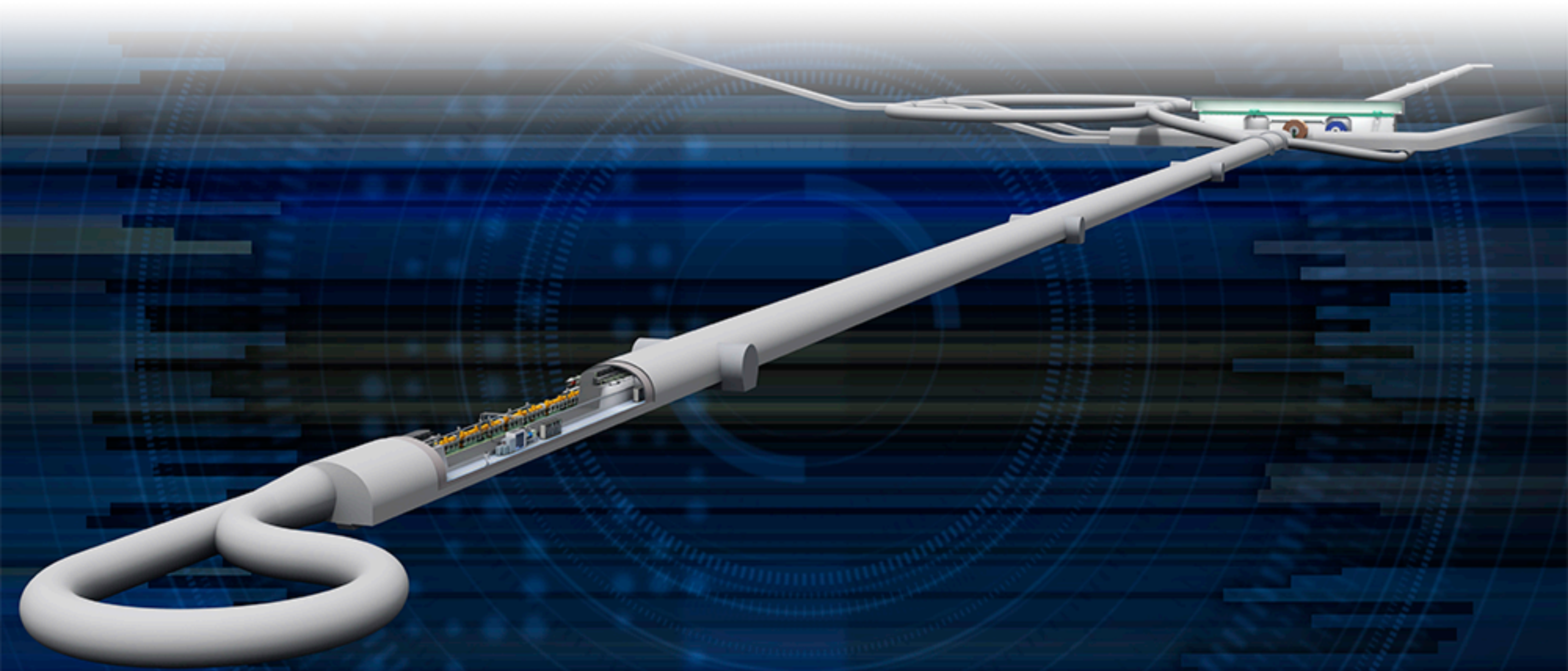
WW-fusion Higgs prod.



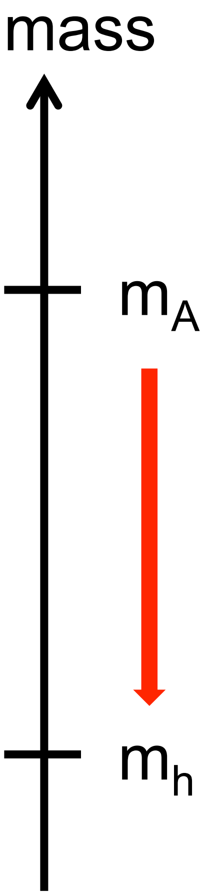
Pol(e^-)	-0.8
Pol (e^+)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=**2.34**

Signal Enhancement

Higgs Physics at ILC



Deviation in Higgs Couplings



Size of the deviation depends on the scale of new physics.

<u>Example 1:</u> MSSM (tanβ=5, radiative corrections ≈ 1)

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

heavy Higgs mass

<u>Example 2:</u> Minimal Composite Higgs Model

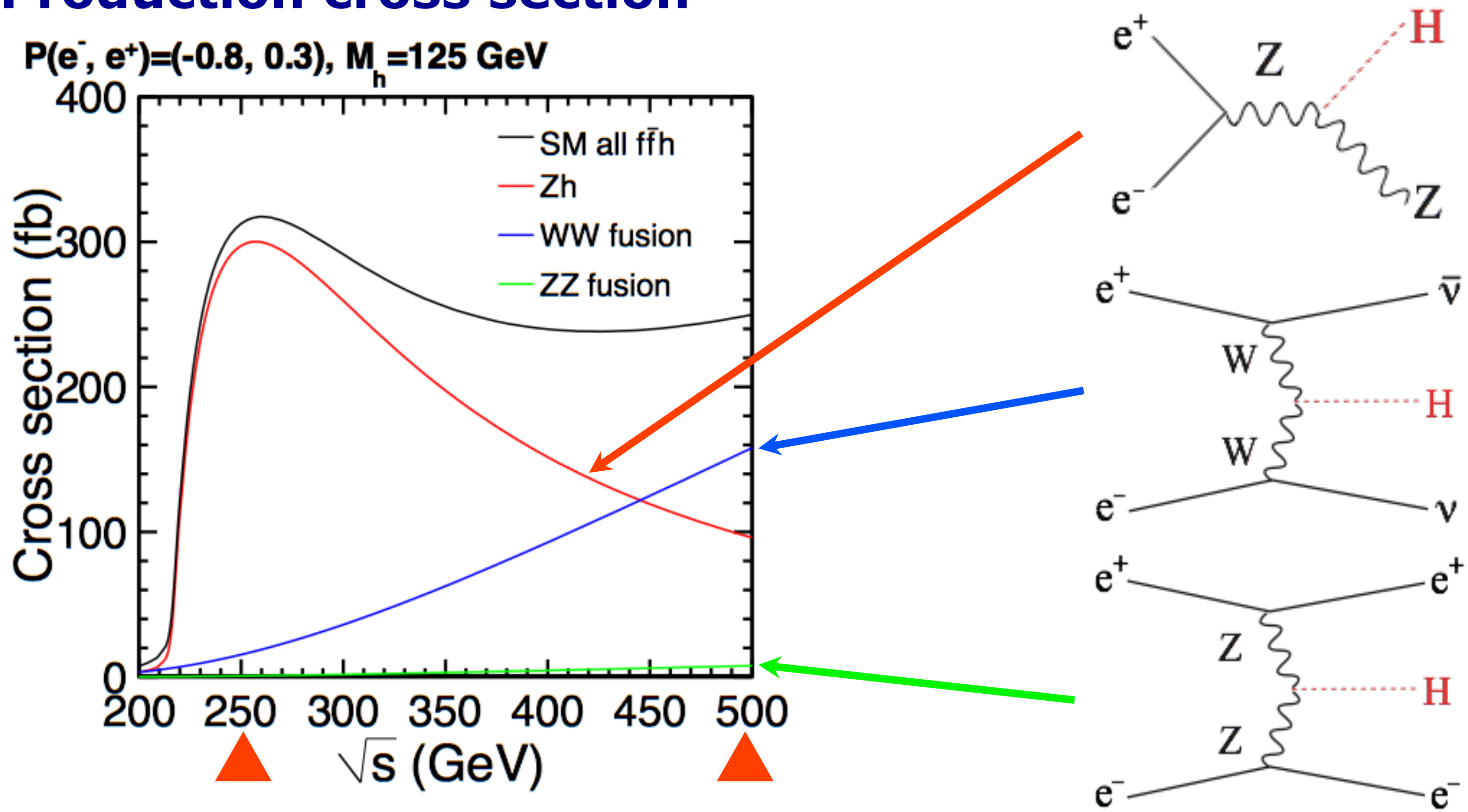
$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 8.3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

composite scale

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

Higgs Production at ILC

Production cross section



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

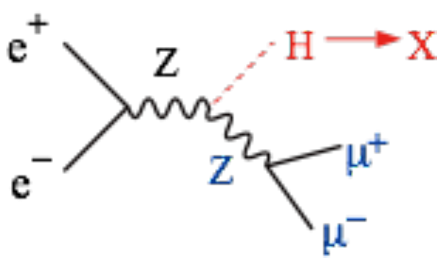
vvH takes over at 500 GeV (~125k ev: 500 fb^{-1})

Rediscovery of Higgs in one day of running

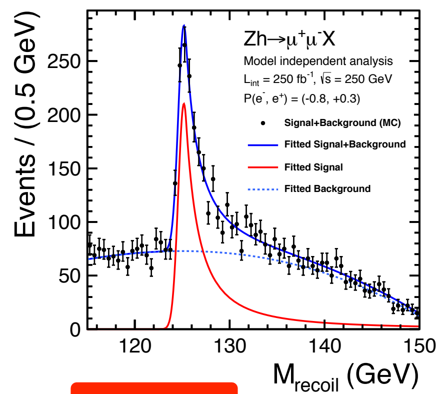
Coupling Extraction

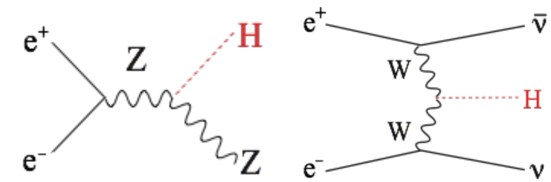
At LHC all the measurements are σ×BR measurements.
At ILC all but one measurements are σ×BR measurements.

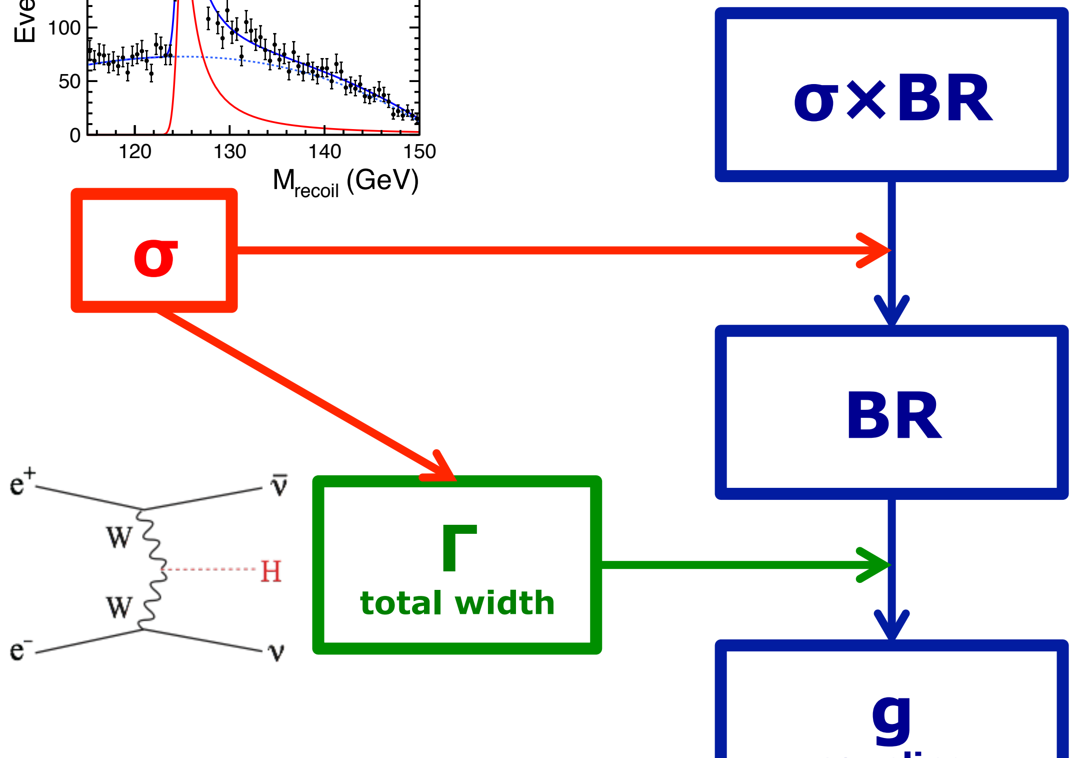
Recoil mass technique:



Z→qq also usable





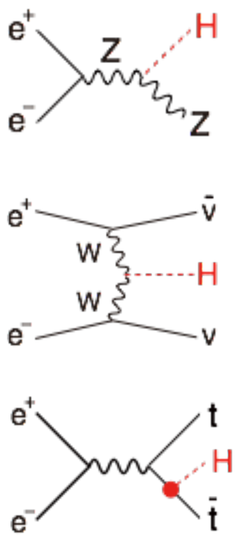


WW-fusion crucial for precise total width measurement
E_{CM} >= 350 GeV

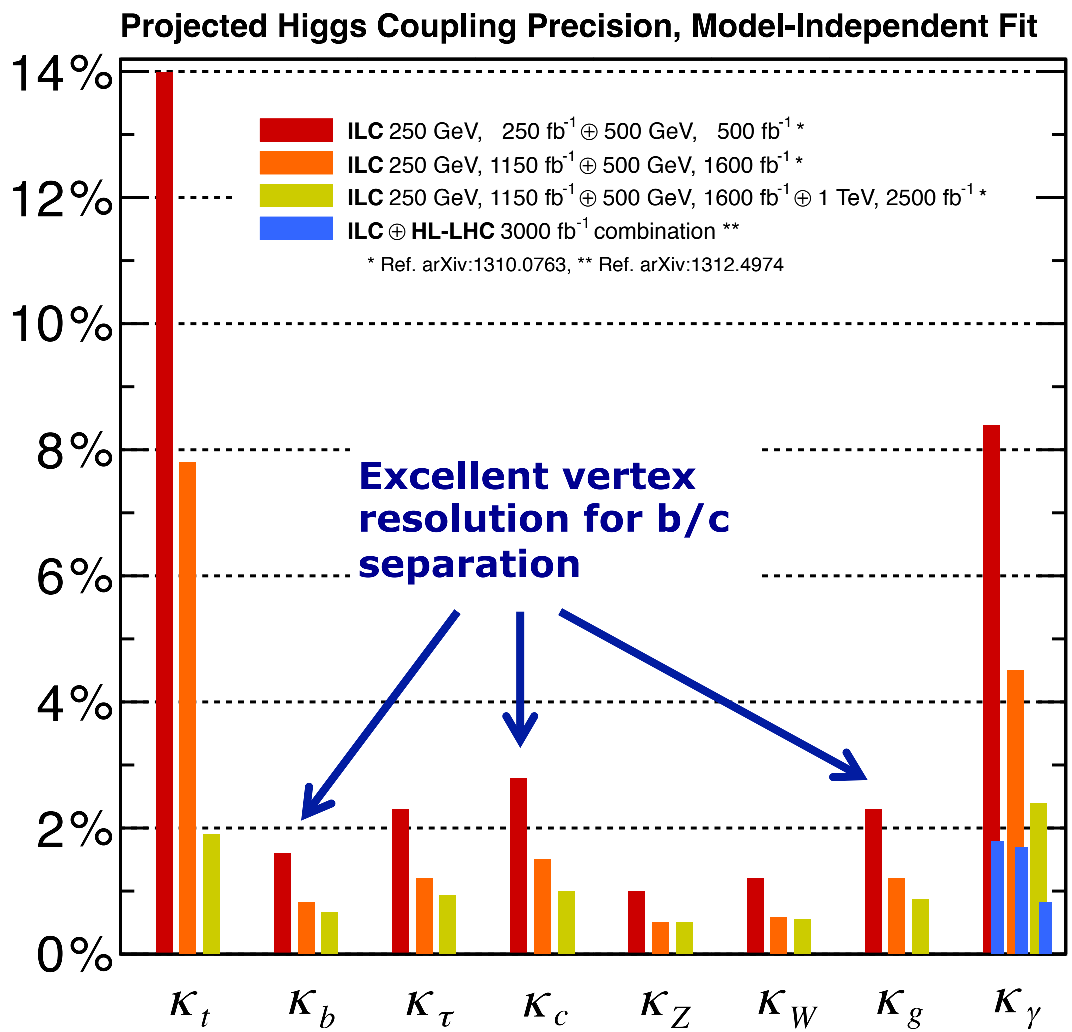
$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

Higgs Coupling

Model-independent determination: unique at ILC



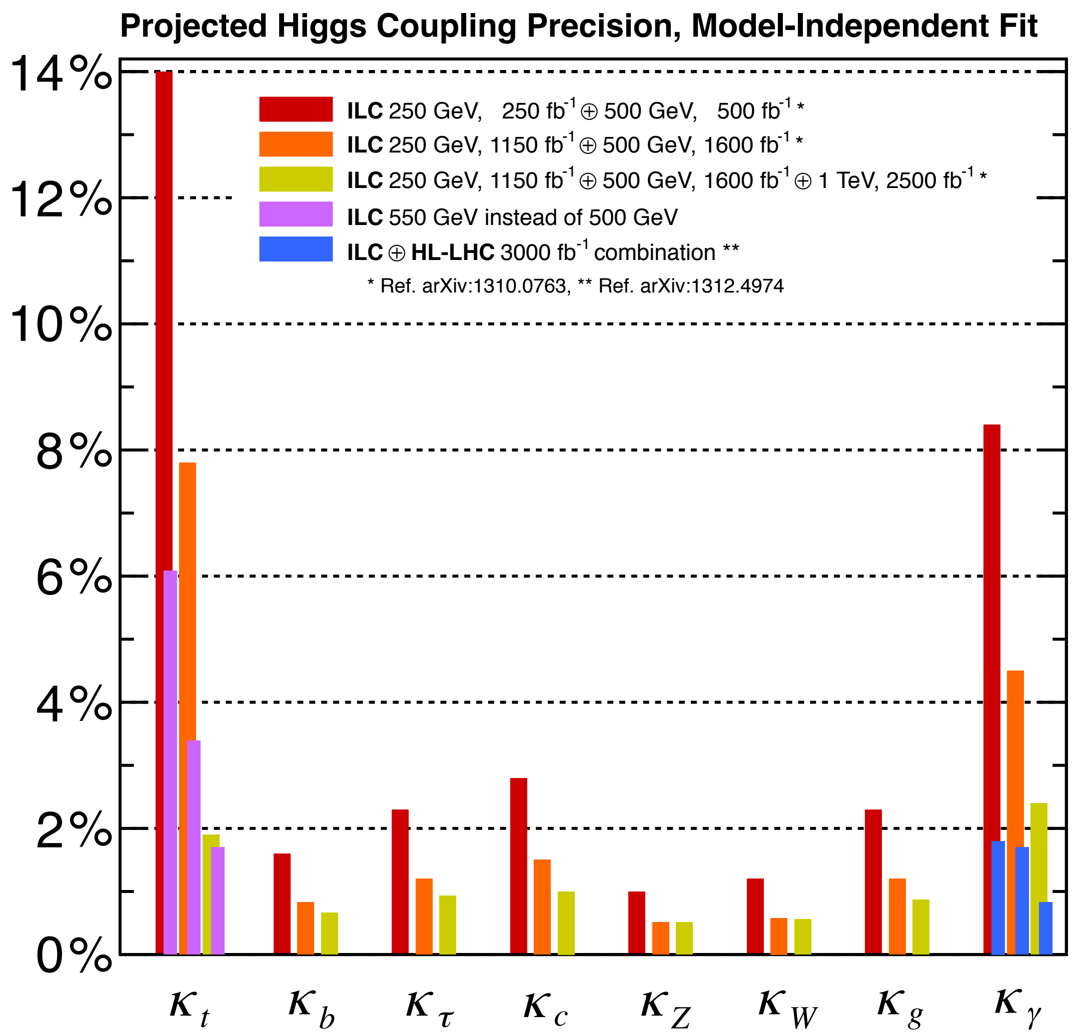
All major decay modes accessible



500 GeV already excellent except for κ_t and κ_γ

Higgs Coupling

Model-independent determination: unique at ILC



Top Yukawa improves by going to 550 GeV

Near threshold → factor ~4 enhancement of σ_{tth} by 500 GeV → 550 GeV

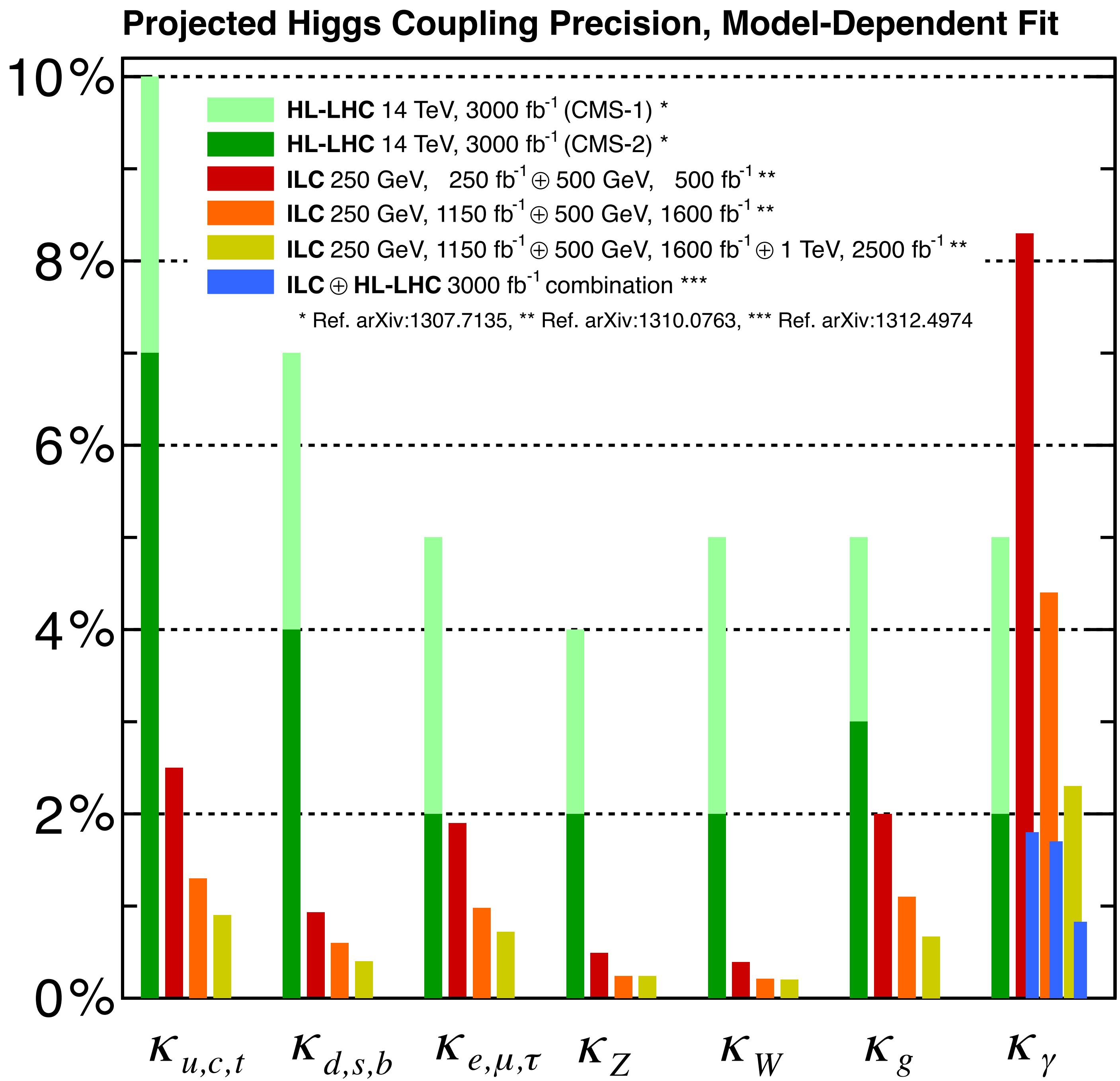
LHC can precisely measure

$BR(h\to\gamma\gamma)/BR(h\to ZZ^*) = (\kappa_\gamma / \kappa_Z)^2$

ILC can precisely measure κ_Z

Better hγγ with LHC/ILC synergy!

~1% precision for most couplings

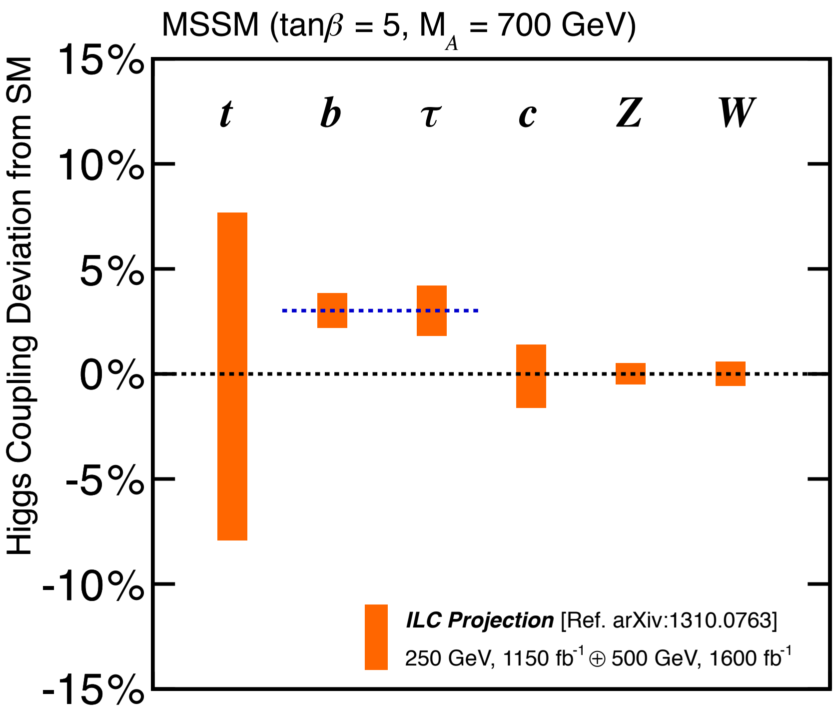

Projected Higgs Coupling Precision, Model-Dependent Fit
10%
8%
6%
4%
2%
0%
HL-LHC 14 TeV, 3000 fb-1 (CMS-1) *
HL-LHC 14 TeV, 3000 fb-1 (CMS-2) *
ILC 250 GeV, 250 fb-1 ⊕ 500 GeV, 500 fb-1 **
ILC 250 GeV, 1150 fb-1 ⊕ 500 GeV, 1600 fb-1 **
ILC 250 GeV, 1150 fb-1 ⊕ 500 GeV, 1600 fb-1 ⊕ 1 TeV, 2500 fb-1 **
ILC ⊕ HL-LHC 3000 fb-1 combination ***
* Ref. arXiv:1307.7135, ** Ref. arXiv:1310.0763, *** Ref. arXiv:1312.4974
κu,c,t
κd,s,b
κe,μ,τ
κZ
κW
κg
κγ

Fingerprinting

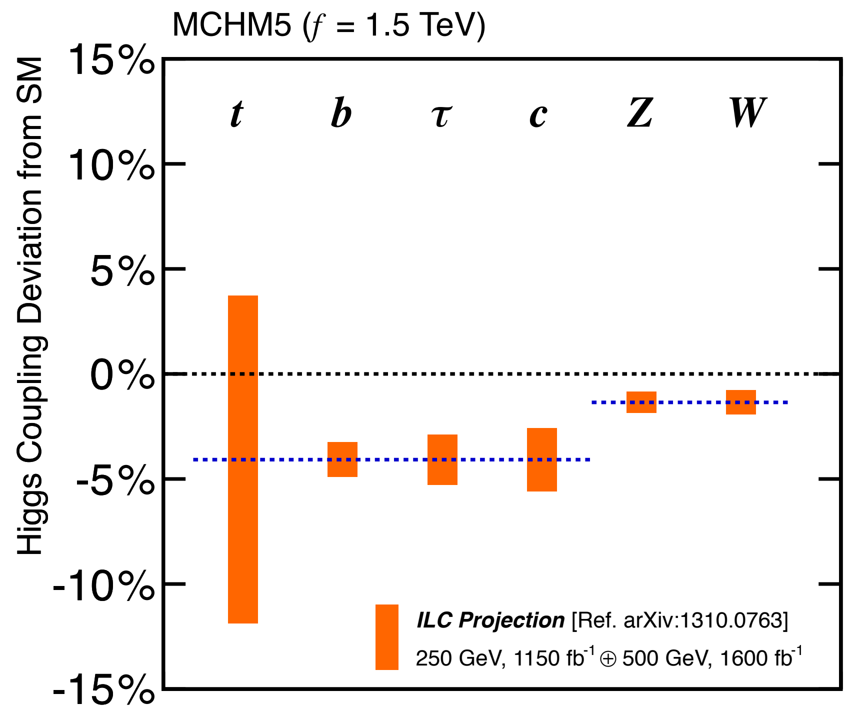
Fingerprinting

Higgs boson: elementary or composite?

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



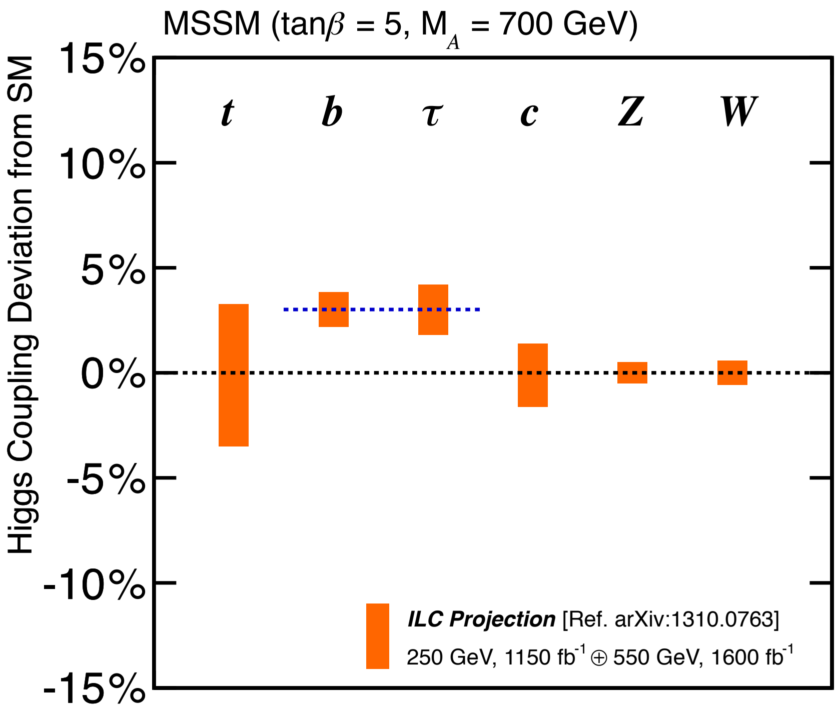
ILC 250+500 LumiUp

Able to distinguish models with specific patterns

Fingerprinting

Higgs boson: elementary or composite?

Supersymmetry
(MSSM)



Composite Higgs
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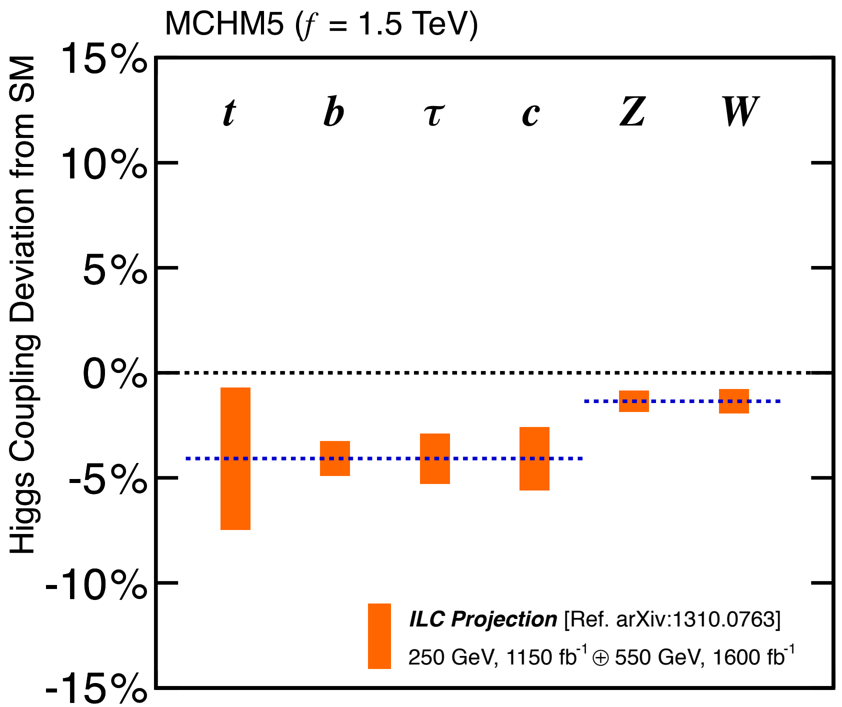
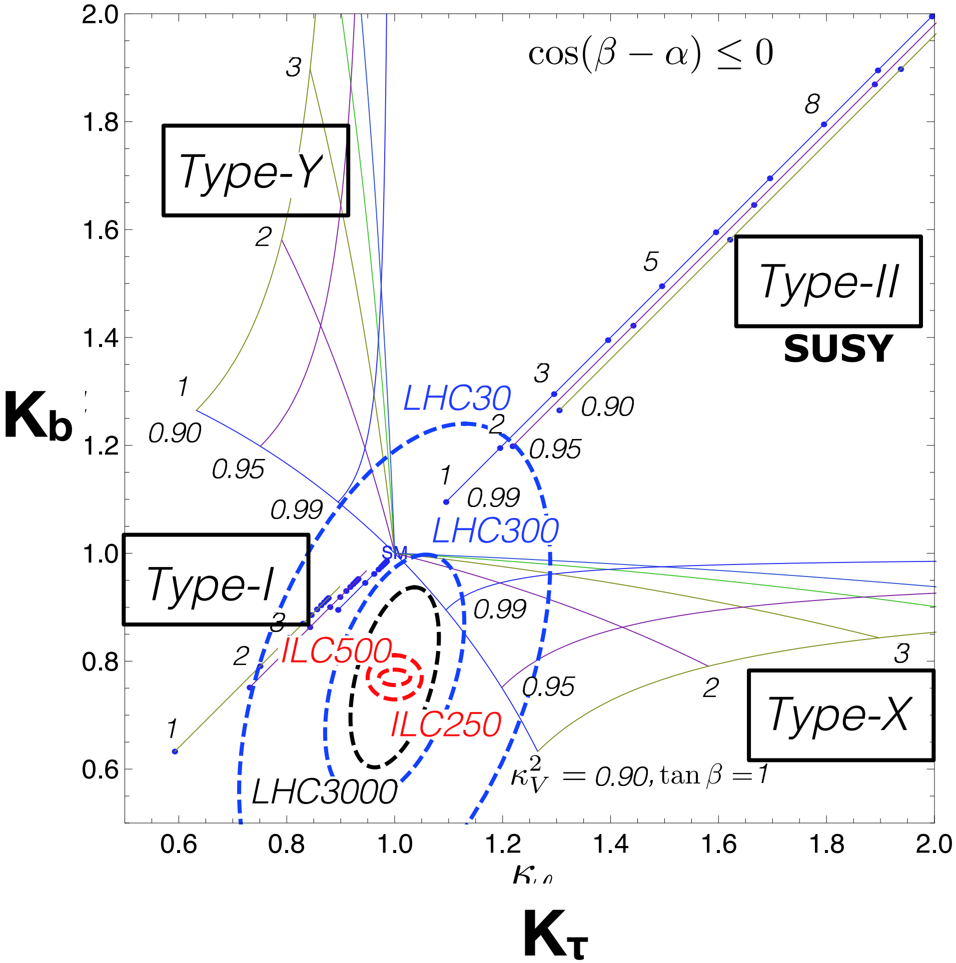


ILC 250+550 LumiUp

Able to distinguish models with specific patterns

Fingerprinting

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

If HZZ coupling deviation is $1-K_V = 0.5\%$ ($\rightarrow K_V^2 = 0.99$), able to **discriminate all four models**

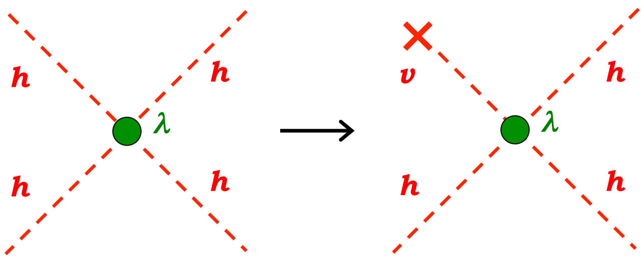
Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

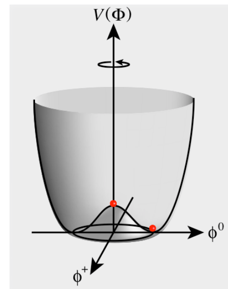
Electroweak Phase Transition

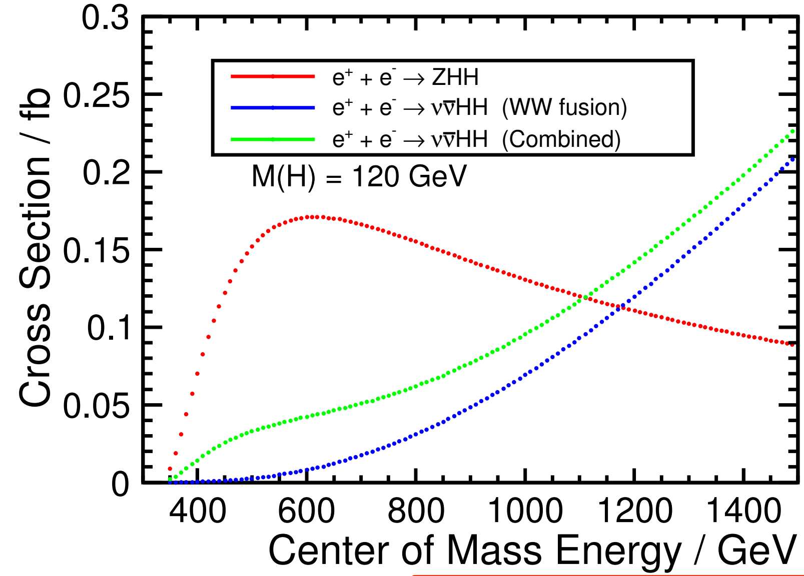
1st order or 2nd order ?

Higgs Self-Coupling

Existence of hhh coupling =
Direct evidence of vacuum condensation

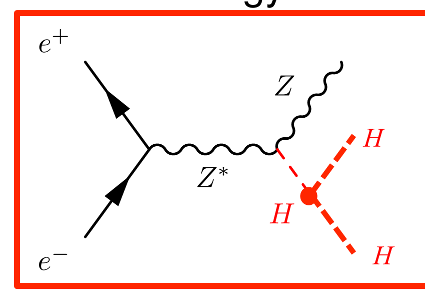


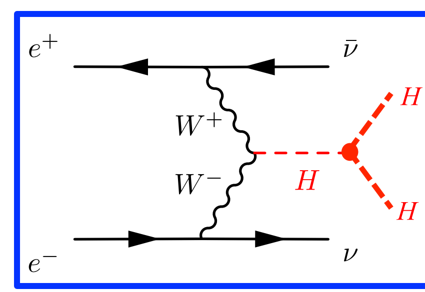




Challenging measurement because of:

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

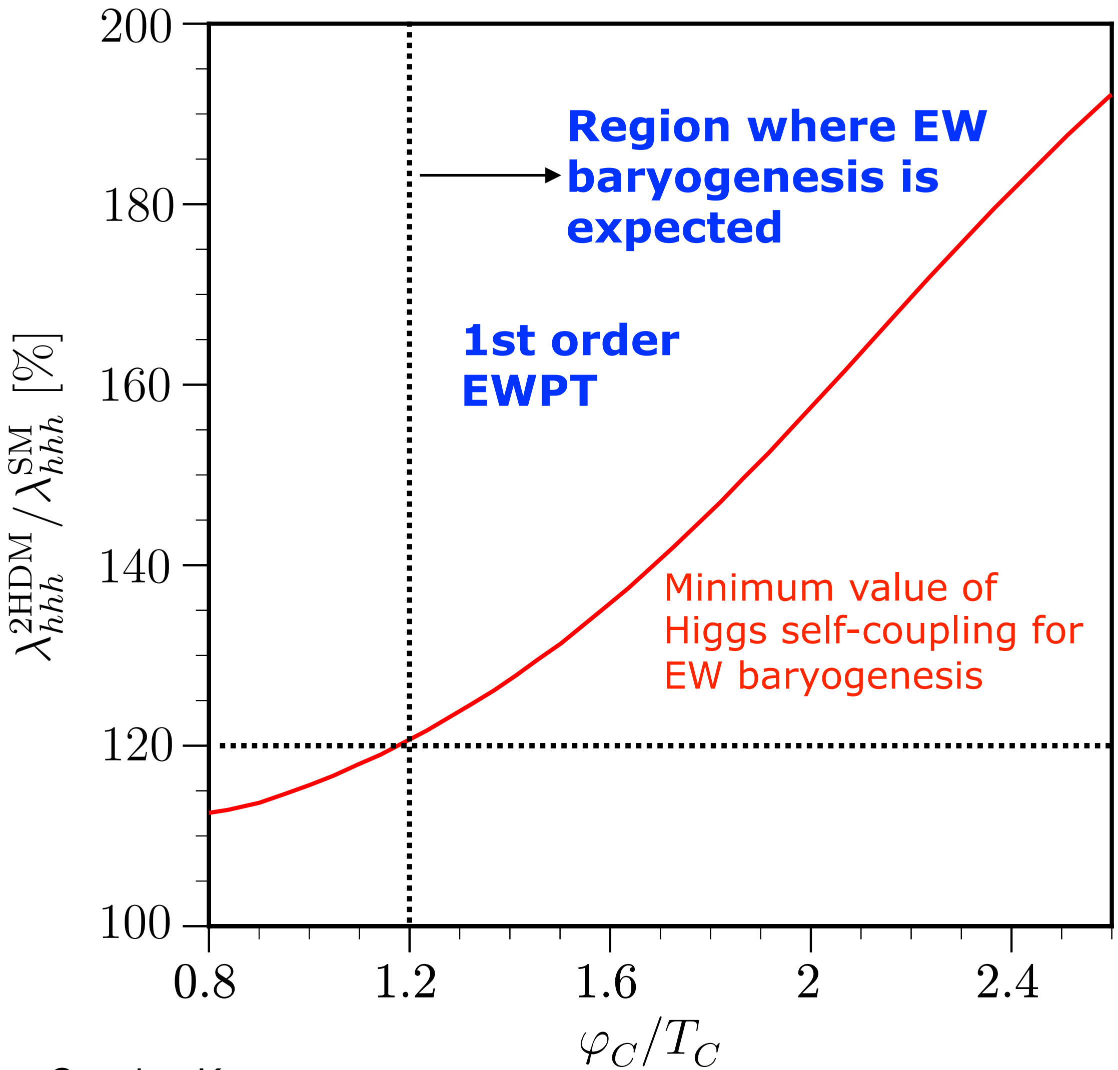




arXiv:1310.0763	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$
$\sigma\,(ZHH)$	42.7%		42.7%	23.7%
$\sigma\,(\nu\bar{\nu}HH)$	–	–	26.3%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

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

Electroweak Baryogenesis



Senaha, Kanemura

Example:

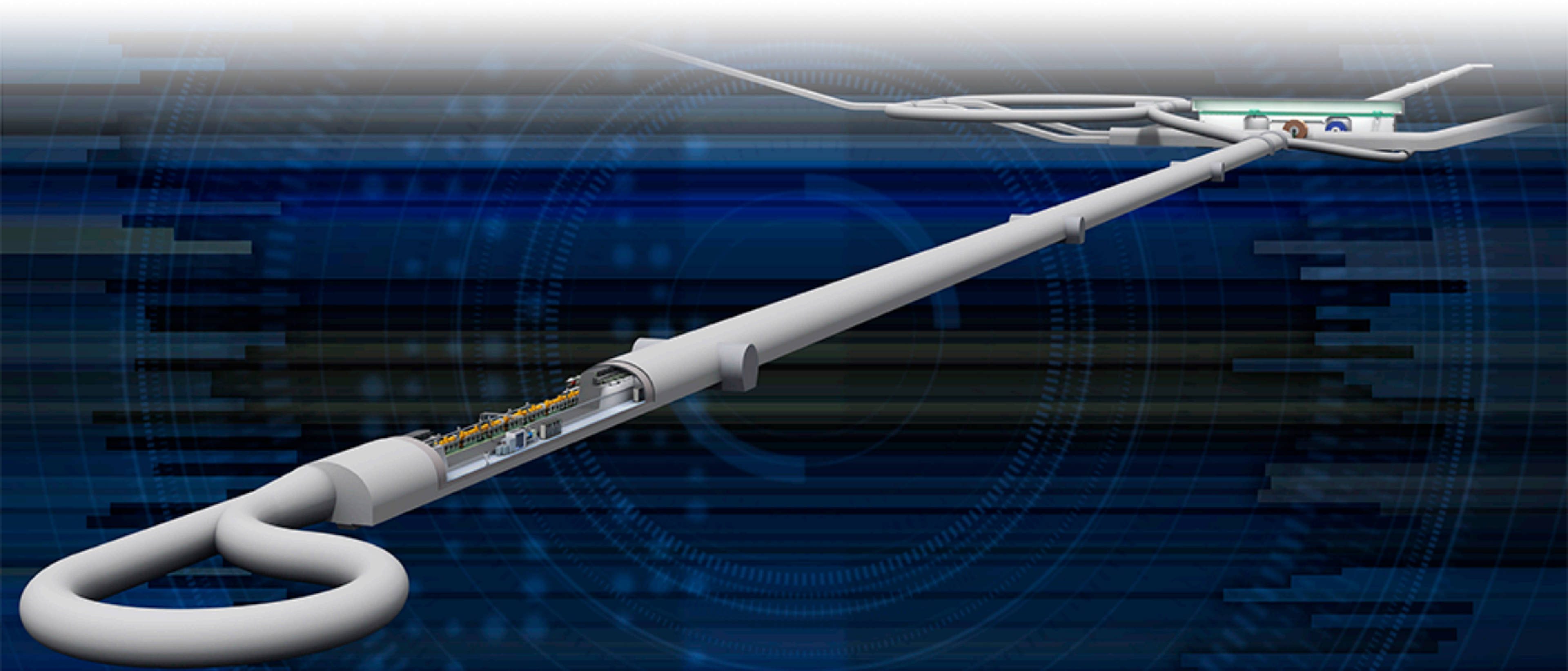
Electroweak baryogenesis in a ***Two Higgs Doublet Model***

Large deviations in Higgs self-coupling
→ **1st order EW phase transition**
→ **Out of equilibrium**

+ CPV in Higgs sector
→ **EW baryogenesis possible**

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

Top Physics at ILC



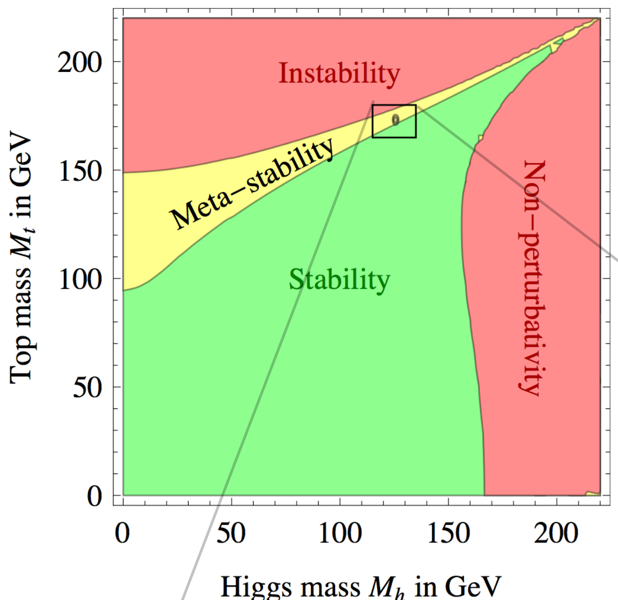
SM up to Λ_{Planck}?

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 is found?

We would need to question the validity of the SM.

How high can the SM go?

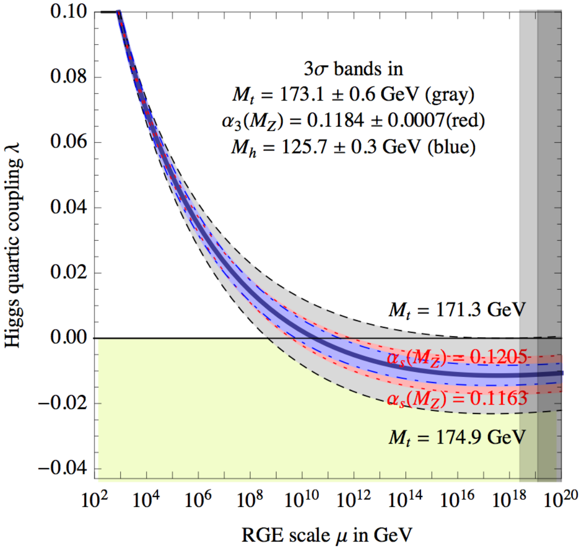
Vacuum Stability in the SM



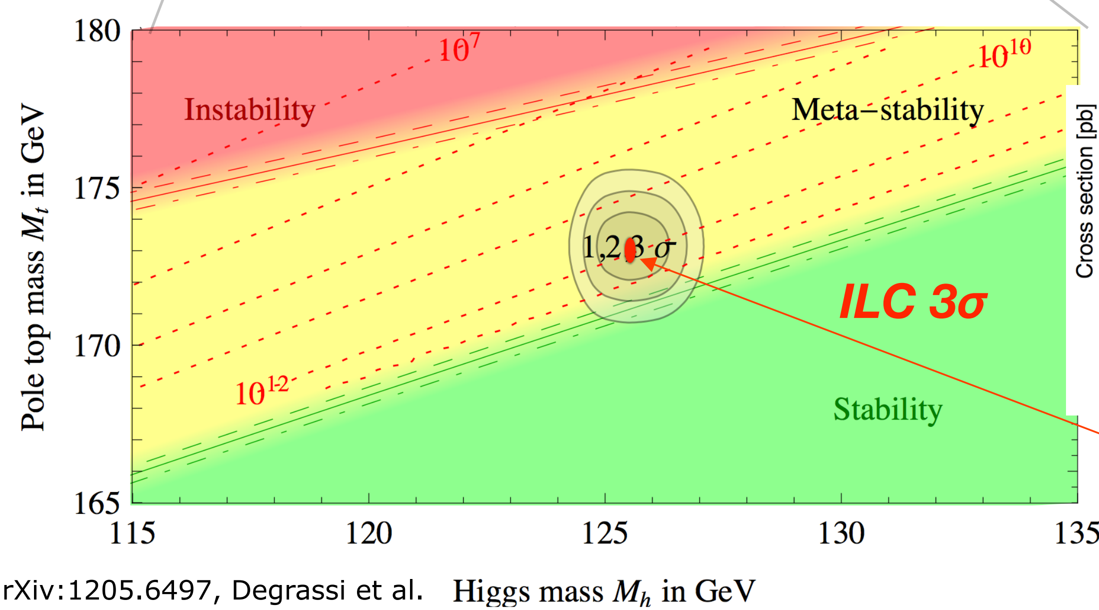
mH=125GeV → SM vacuum appears to be at a subtle point of meta-stability

Does λ really become negative below Λ_{Pl}?

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

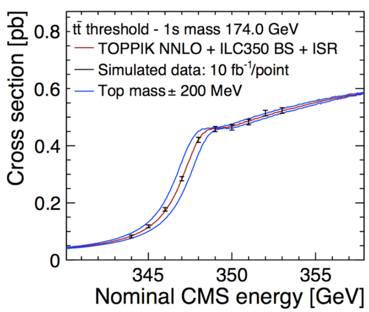


To answer this we need a precise top mass

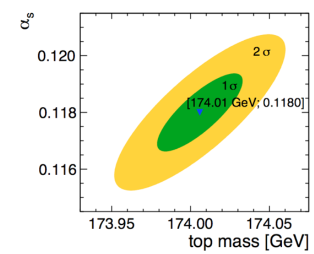


arXiv:1205.6497, Degrassi et al.

Top Pair Threshold ~350 GeV



Theoretically clean measurement of m_t



$$\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$$
$$\Delta m_H = 30\,\mathrm{MeV}$$

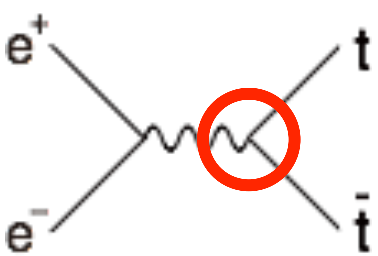
Impact of BSM on Top Sector

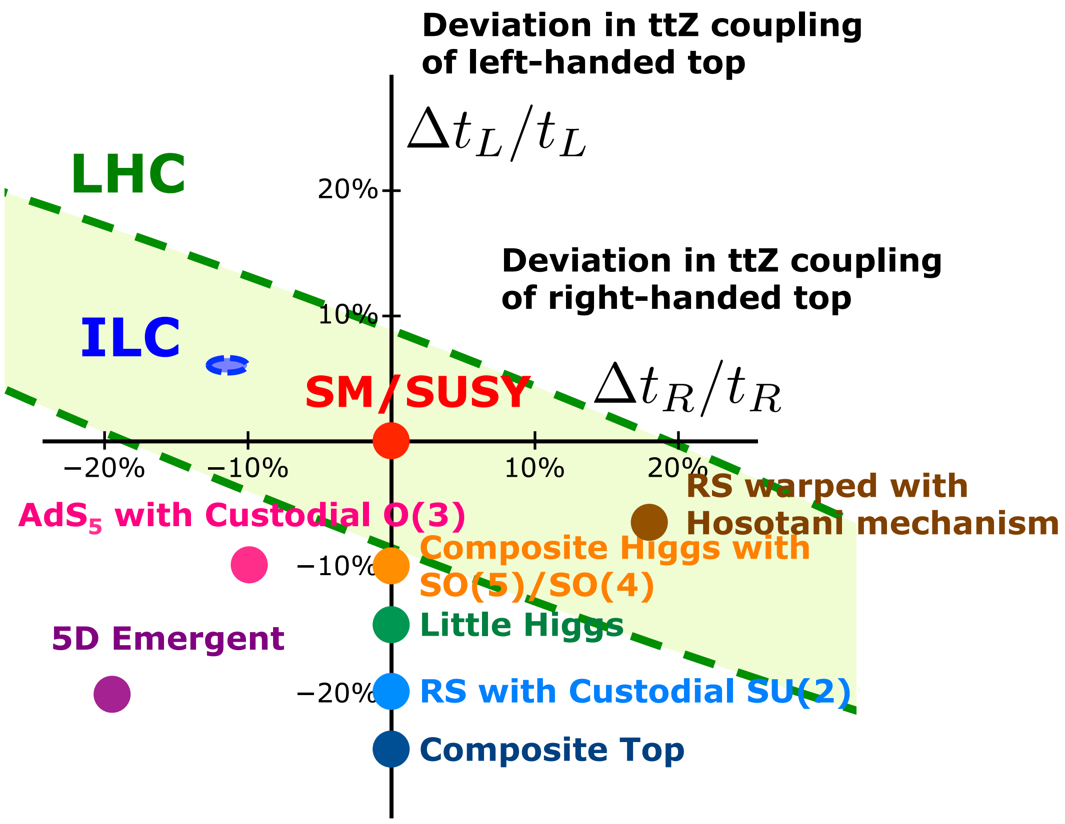
In composite Higgs models, the **top quark** is often **partially composite**.
This results in **form factors in ttZ couplings**, which can be measured at ILC.
Beam polarization is essential to distinguish **left/right-handed couplings**.

LHC, Ref. arXiv:1311.2028 →

ILC, Ref. arXiv:1307.8102 →

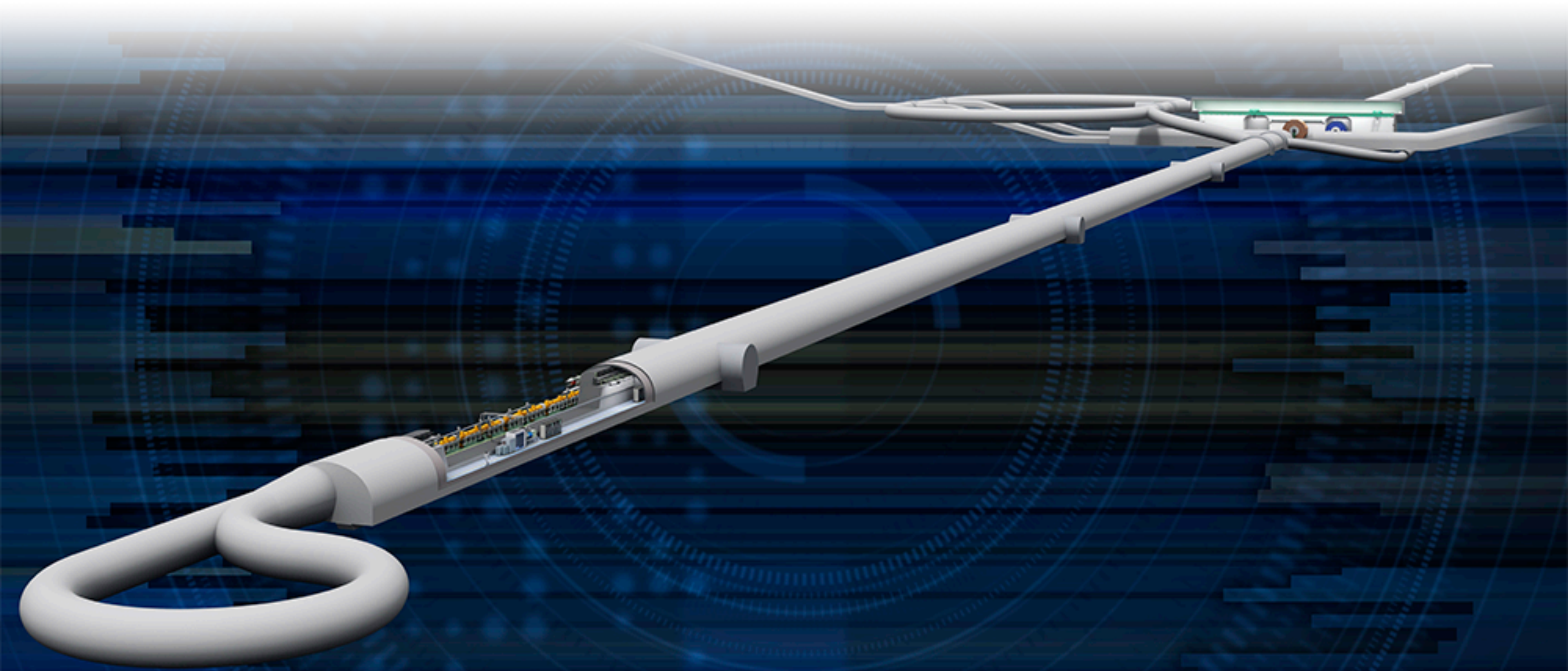
Deviations for different models for new physics scale at ~1 TeV.
Based on F. Richard, arXiv:1403.2893





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

Searches for direct production of SUSY / DM at the ILC



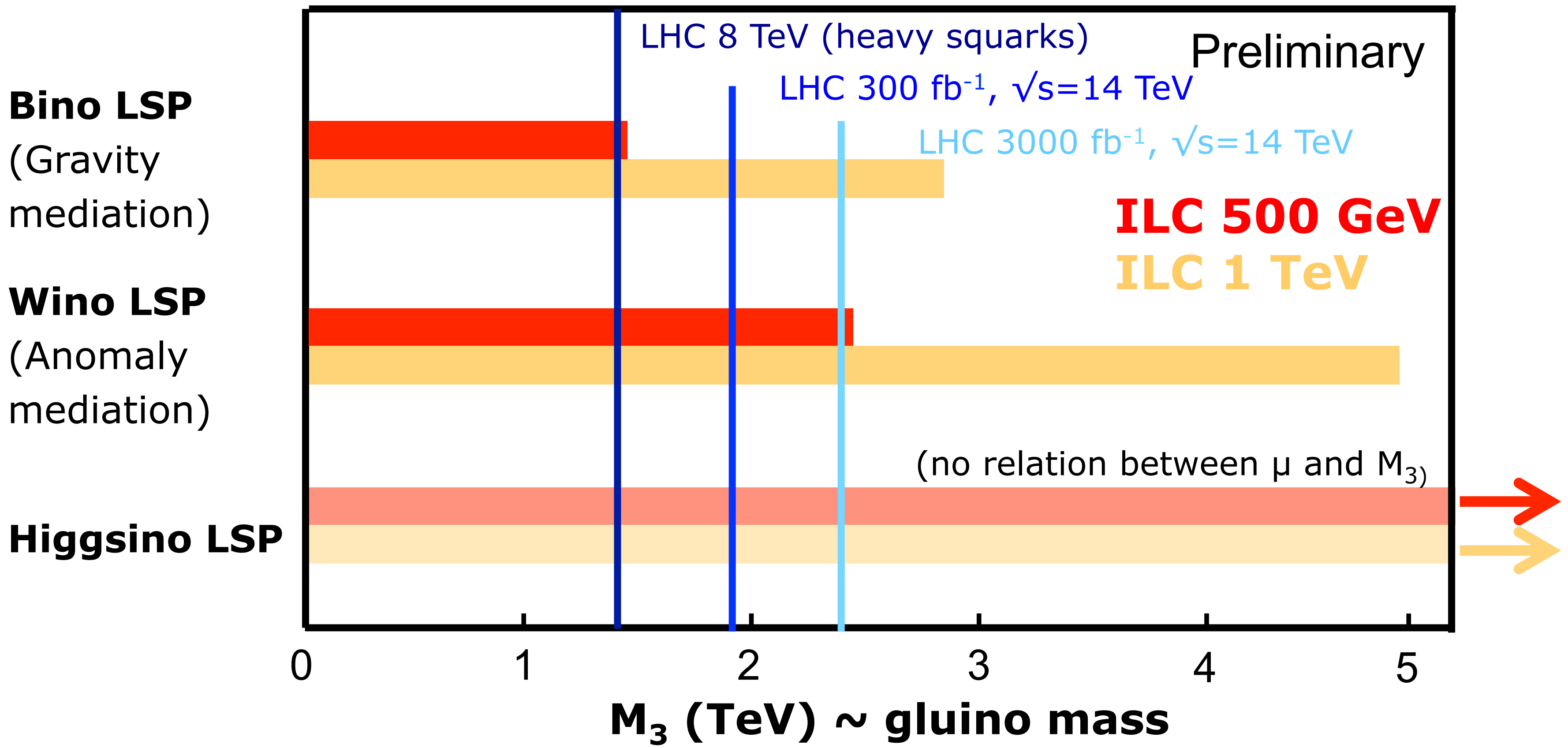
Sensitivity to SUSY

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

Examples of model-independent SUSY searches

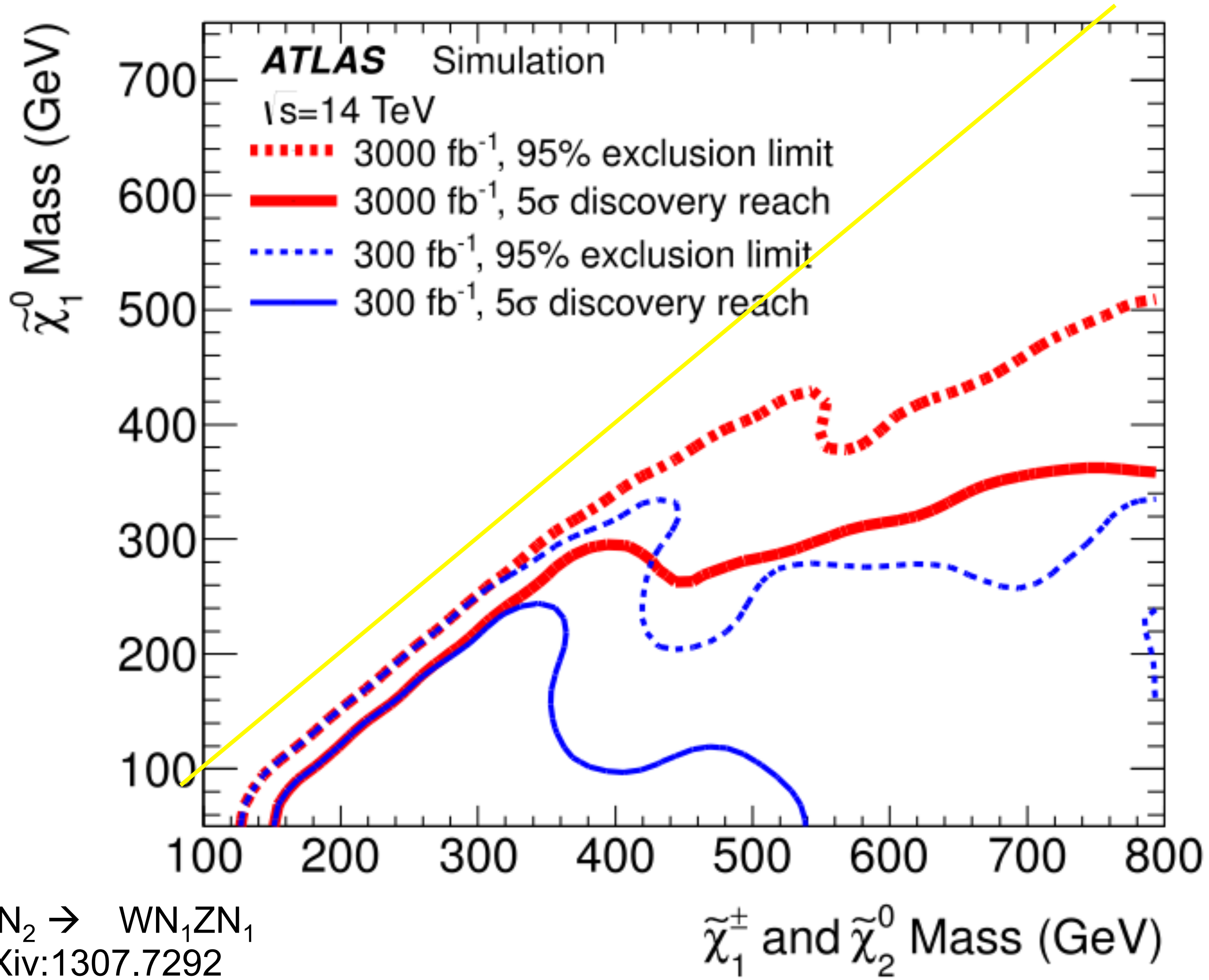
- LHC: gluino search
- ILC: EWK-ino (chargino/neutralino) search

Compare using gaugino mass relations



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

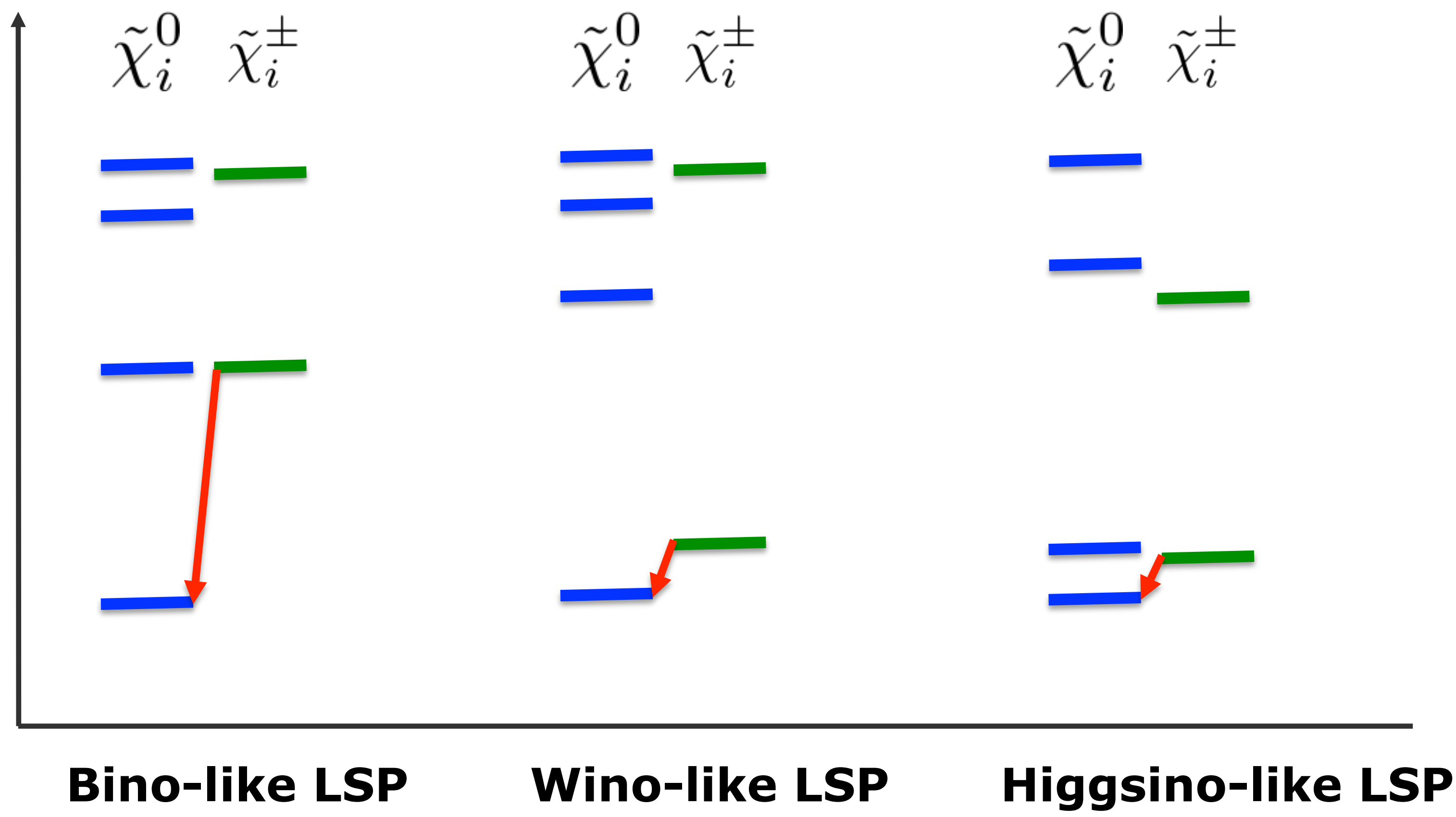
SUSY EW Prod. @ HL-LHC



$C_1N_2 \rightarrow WN_1ZN_1$

arXiv:1307.7292

SUSY Electroweak Sector



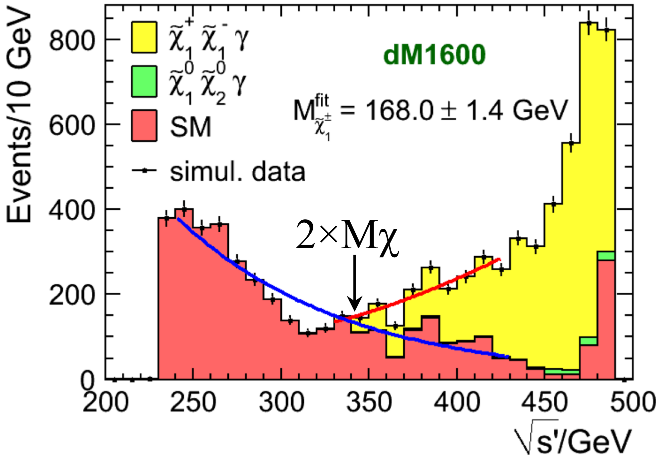
LSP/NLSP typically degenerate
(depends on mixing)

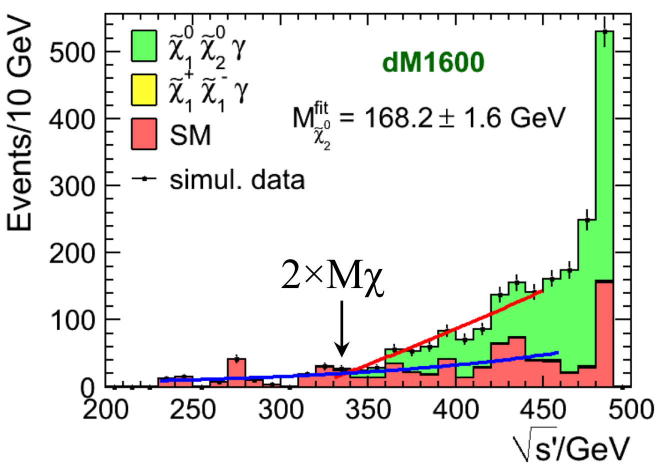
Higgsinos in Natural SUSY (ΔM ~ 1 GeV)

ILC as a Higgsino Factory

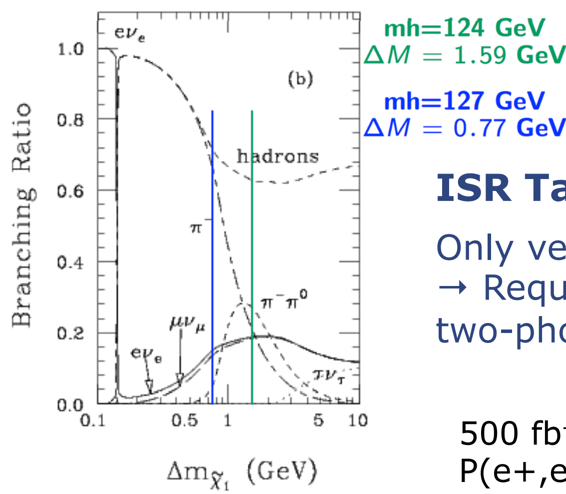
ISR Tagging

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





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 reduce large two-photon bkg

500 fb-1 @ E_{CM} = 500GeV
P(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

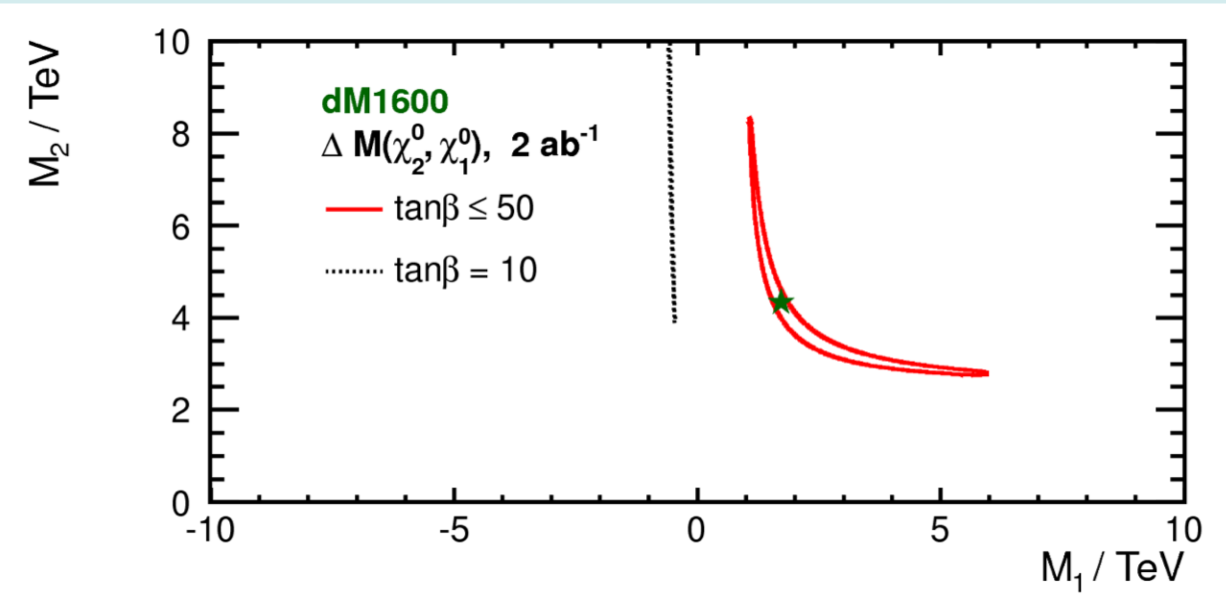
$$\delta(\sigma \times BR) \simeq 1.5\%$$
$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 1.5(1.6)\,\text{GeV}$$
$$\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \simeq 20\,\text{MeV}$$

Extracting M_1 and M_2

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

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

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

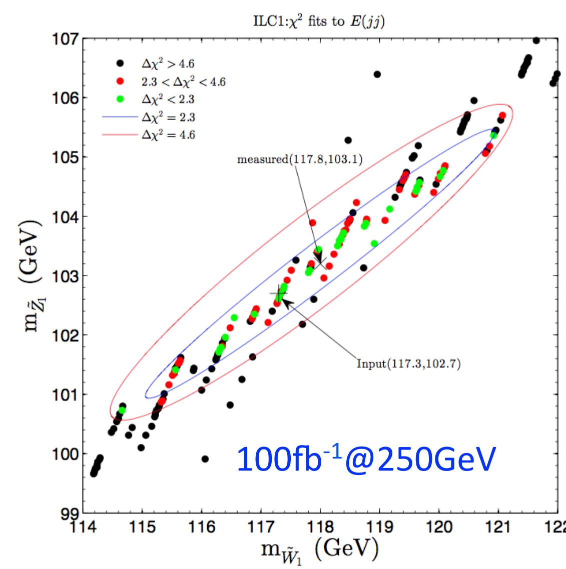


@ 2 ab^{-1}	input	lower	upper
M_1 [TeV]	1.7	∼ 1.0 (-0.4)	∼ 6.0
M_2 [TeV]	4.4	∼ 2.5 (3.5)	∼ 8.5
μ [GeV]	165.7	166.2	170.1

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

RNS: Baer et al.
arXiv: 1404.7510

ΔM=15GeV



In the radiatively driven natural SUSY (RNS) scenario as in arXiv:1404.7510, ΔM~10GeV, can determine M_1 and M_2 to a few % or better, allowing us to test the gaugino mass relation

Test of

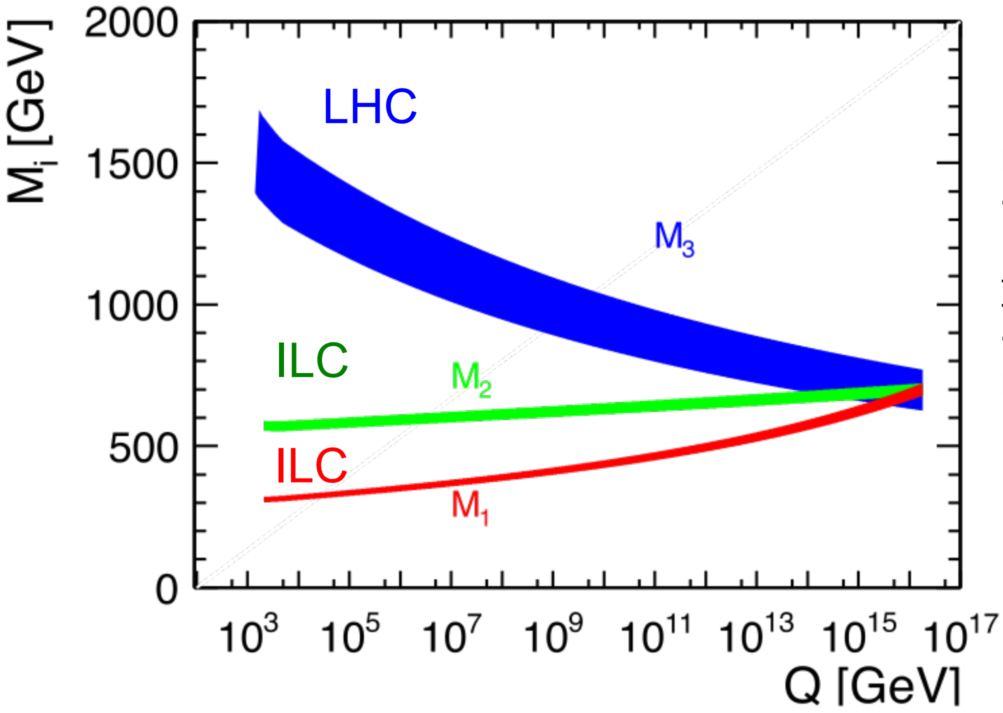
GUT-Scale

Physics

Test of Gaugino Mass Unification

- **EWK-ino @ ILC** → probe M_1-M_2 gaugino mass relation
  - Prediction of gluino mass scale under this assumption
- **Gluino @ LHC** → test of gaugino mass relation by LHC/ILC synergy
- Discrimination of SUSY spontaneous symmetry breaking scenarios

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



LHC: gluino discovery
→ mass determination

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

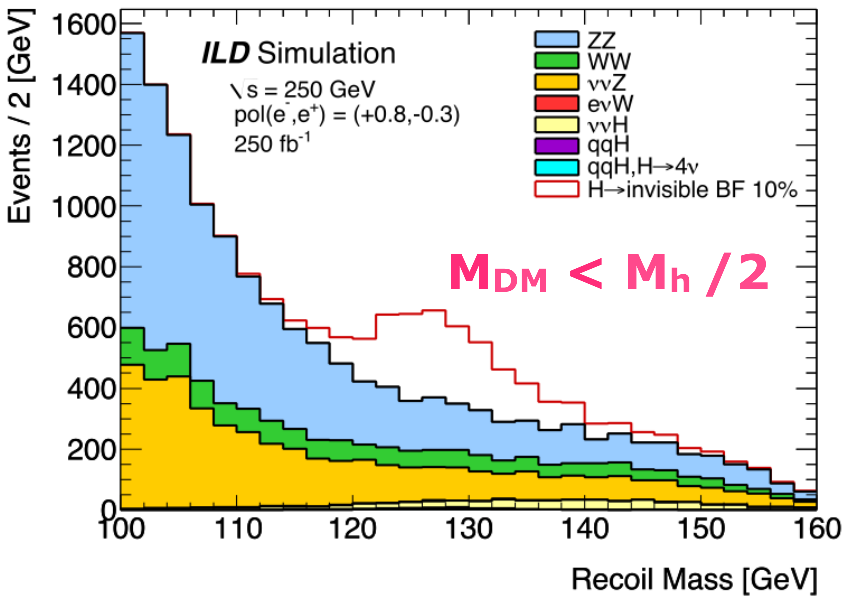
$$\chi$$

Dark Matter

WIMP Dark Matter @ ILC

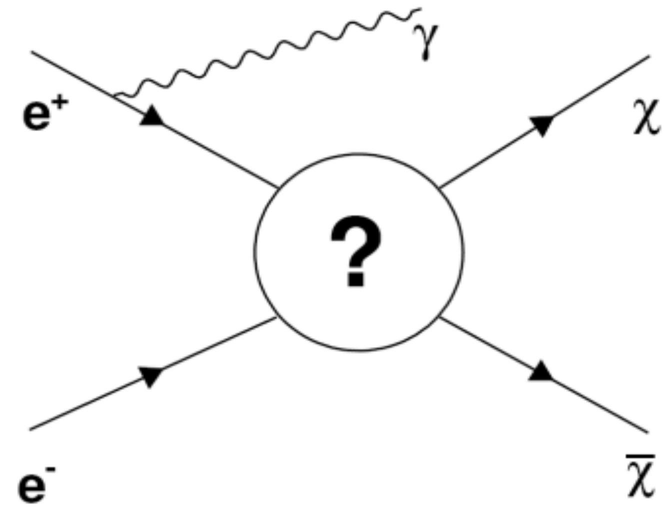
WIMP searches at colliders are complementary to direct/indirect searches.
Examples at the ILC:

Higgs Invisible Decay



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

Monophoton Search



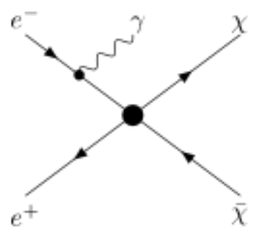
→ **M_{DM} reach ~ Ecm/2**

In many models, DM has a charged partner e.g. Wino, Higgsino

SUSY-specific signatures (decays to DM)

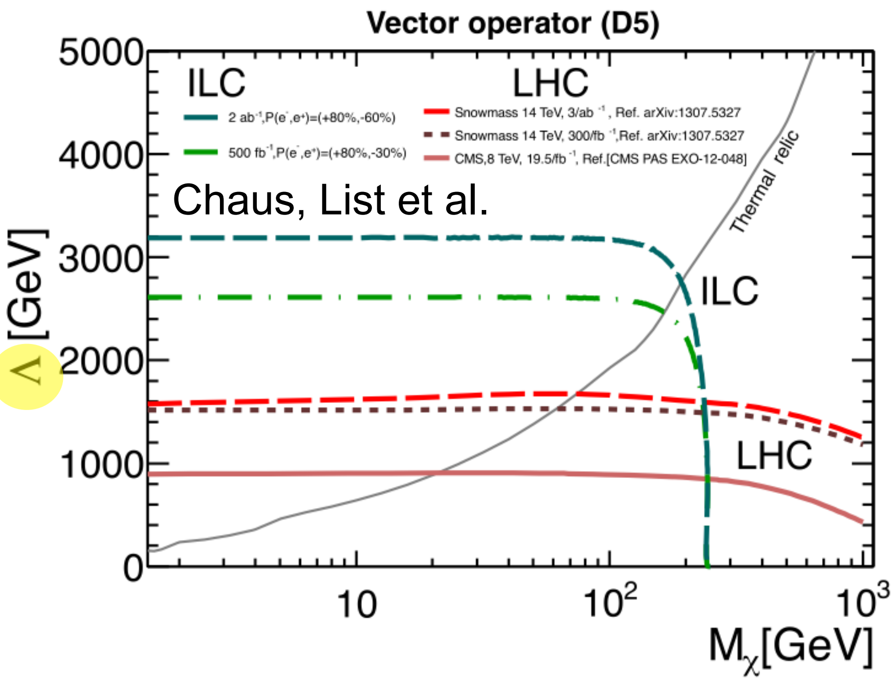
- light Higgsino, light stau, etc.

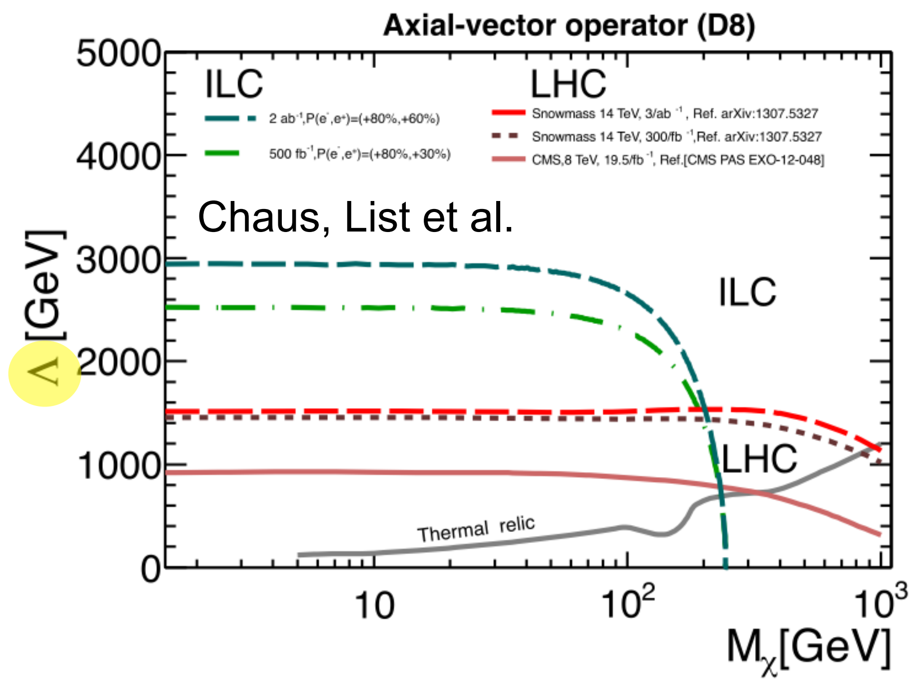
DM: Effective Operator Approach



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

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





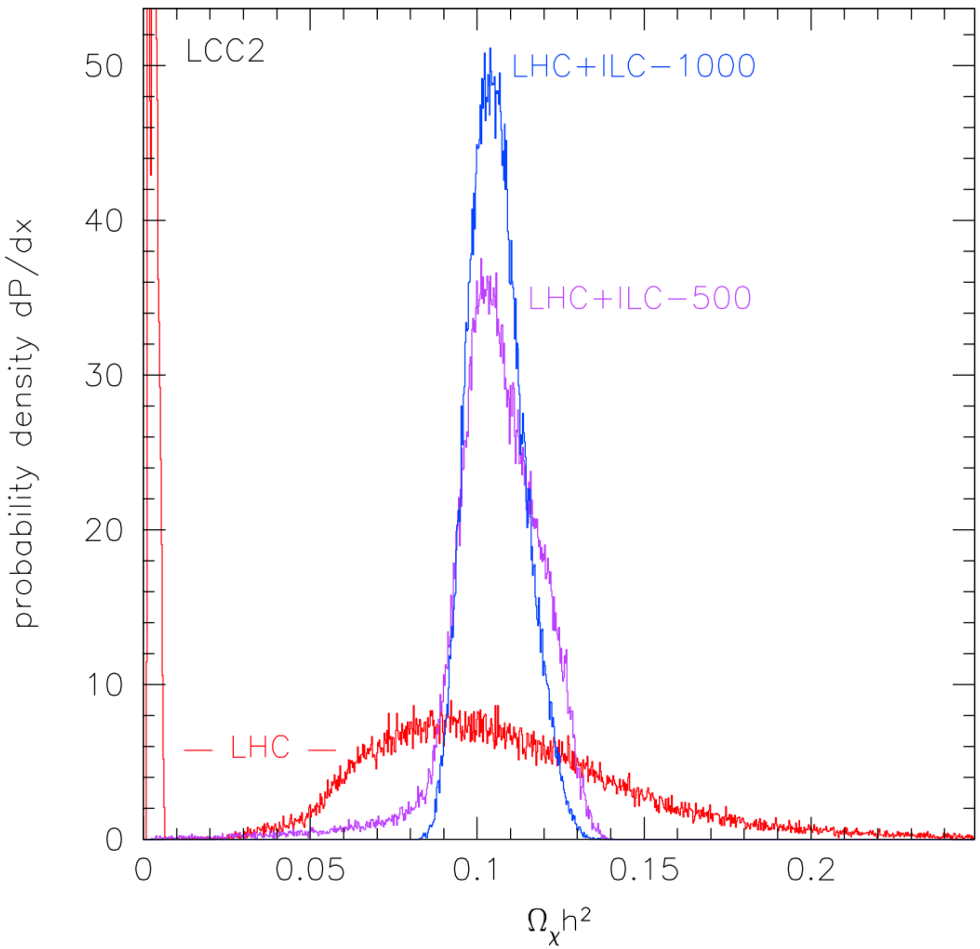
LHC: Mediator mass up to Λ~1.5 TeV for large DM mass

ILC: Mediator mass up to **Λ~3 TeV** for **DM mass up to ~√s/2**

DM Relic Abundance

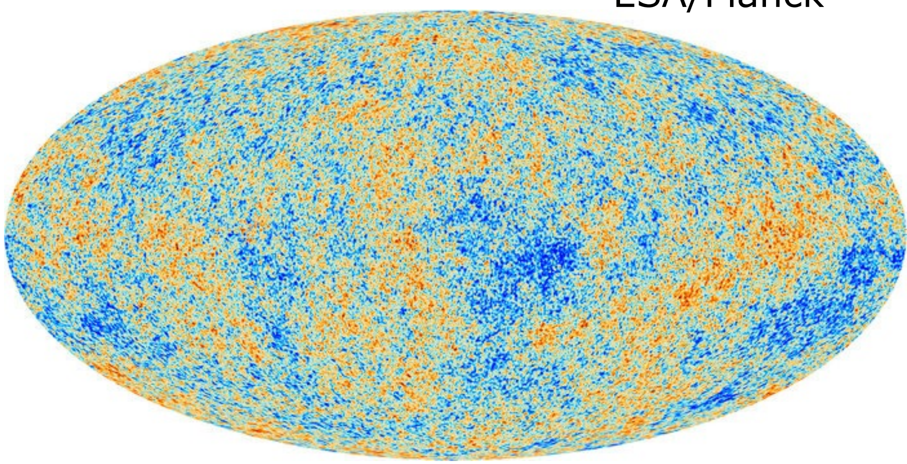
WMAP/Planck (68% CL)

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



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

Z'

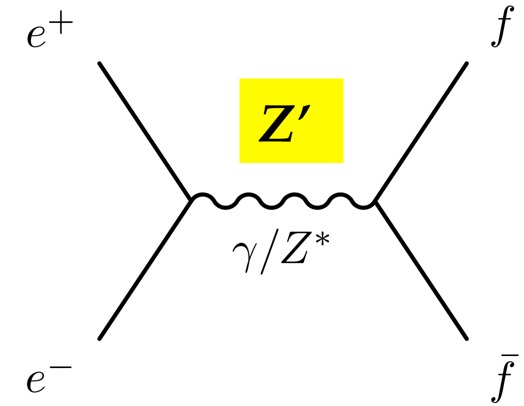
Heavy Neutral Gauge Bosons

Z′ : Heavy Neutral Gauge Bosons

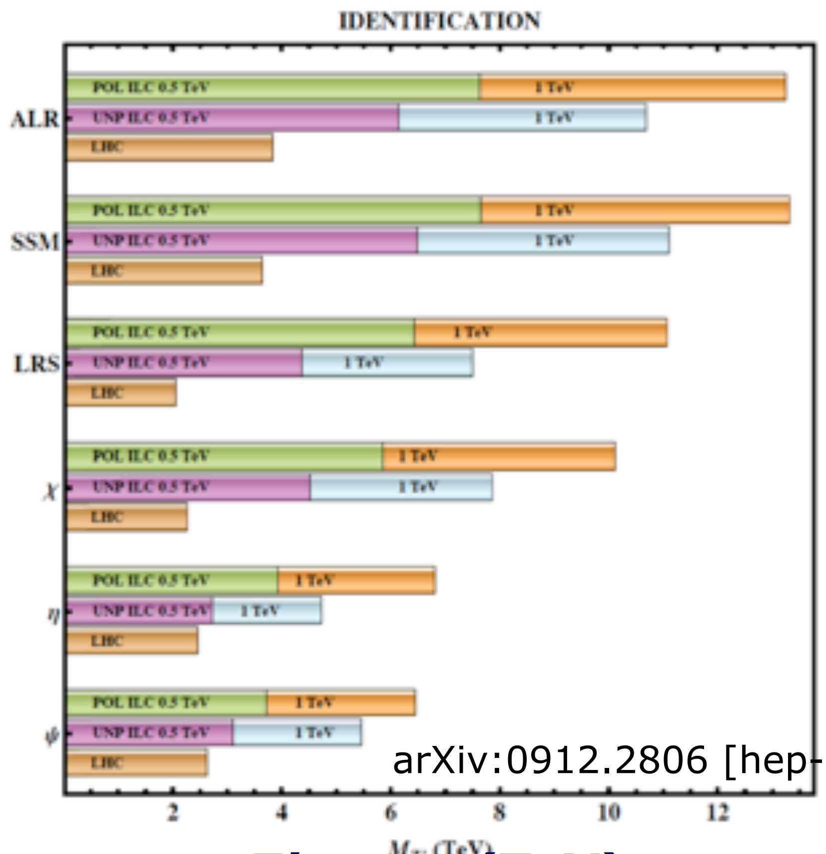
New gauge forces imply existence of heavy gauge bosons (Z′)
LHC/ILC synergy:

- **LHC discovery** → determine mass of Z′
- **ILC measurements** → indirect access to couplings

Allows model discrimination
ILC: Beam polarizations improve reach and discrimination power

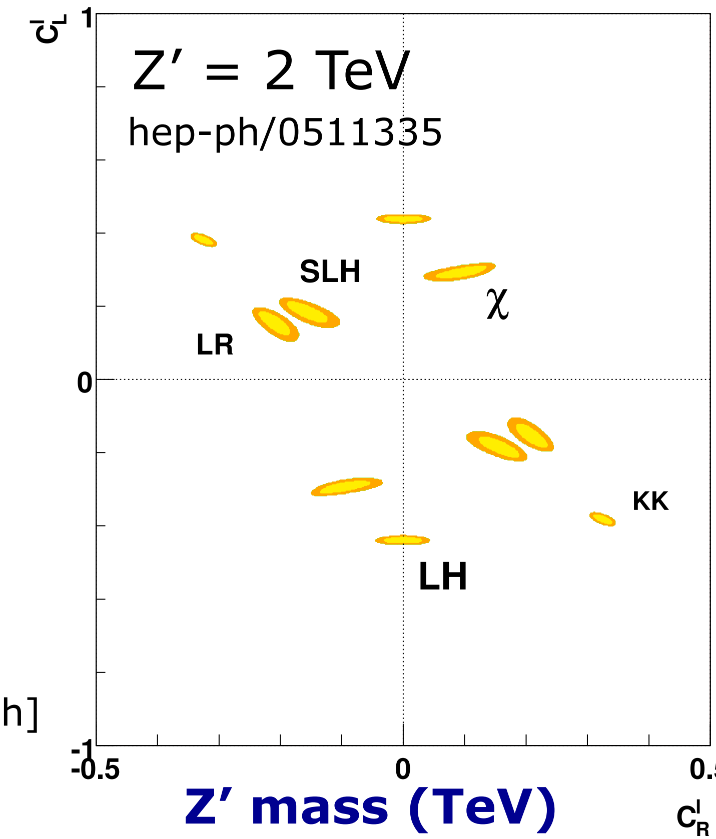


Models with Z′ boson



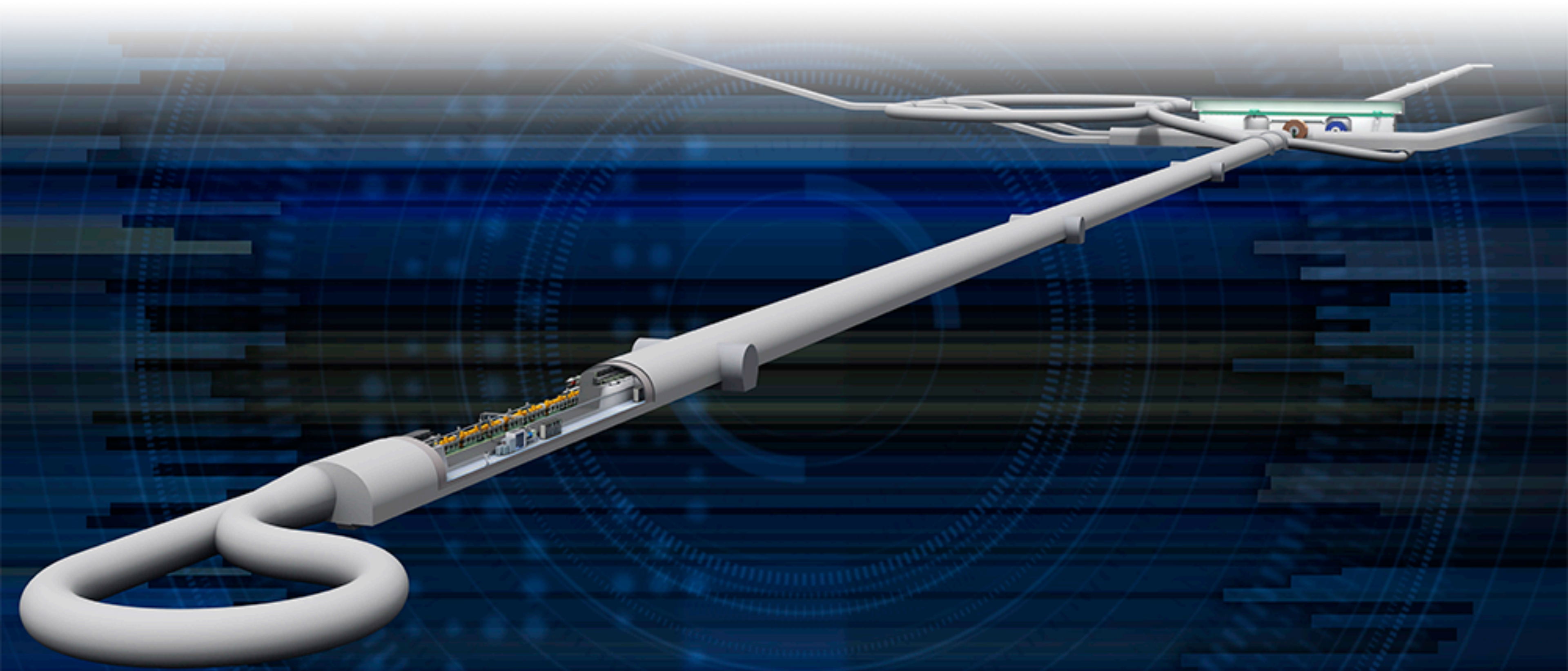
arXiv:0912.2806 [hep-ph]

Z′ mass (TeV)



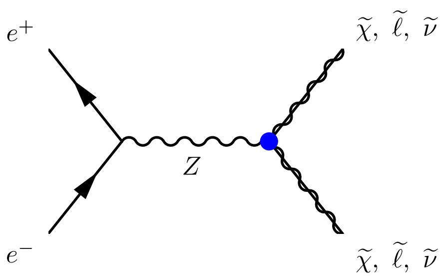
Z′ mass (TeV)

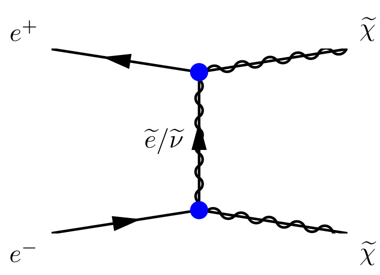
Summary

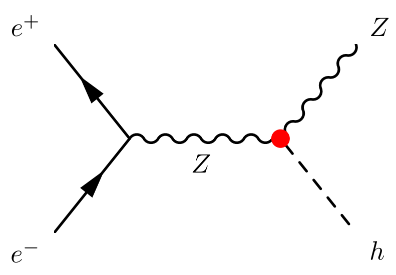


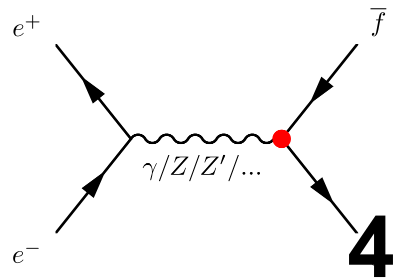
Summary

- The discovery of H(125) has taught us how the EW symmetry is broken. We now wish to know **why**. Any explanation **requires BSM.**
- Powerful probes at ILC: **H(125), top quark, and direct searches**
- Fingerprinting of BSM models / setting the next energy scale
- Self-coupling measurement probes whether EWPT is 1st order → connection to **EW baryogenesis**
- Direct searches: important parameter space to be explored **for the first time** at the ILC. Once discovered, precise measurements probe **underlying mechanism** behind it. Access to **GUT-scale** physics in some cases.
- If **DM** candidate within ILC reach, measure mass/couplings to check **consistency with the measured DM relic density**
- **ILC will pave the way for physics beyond the SM.**

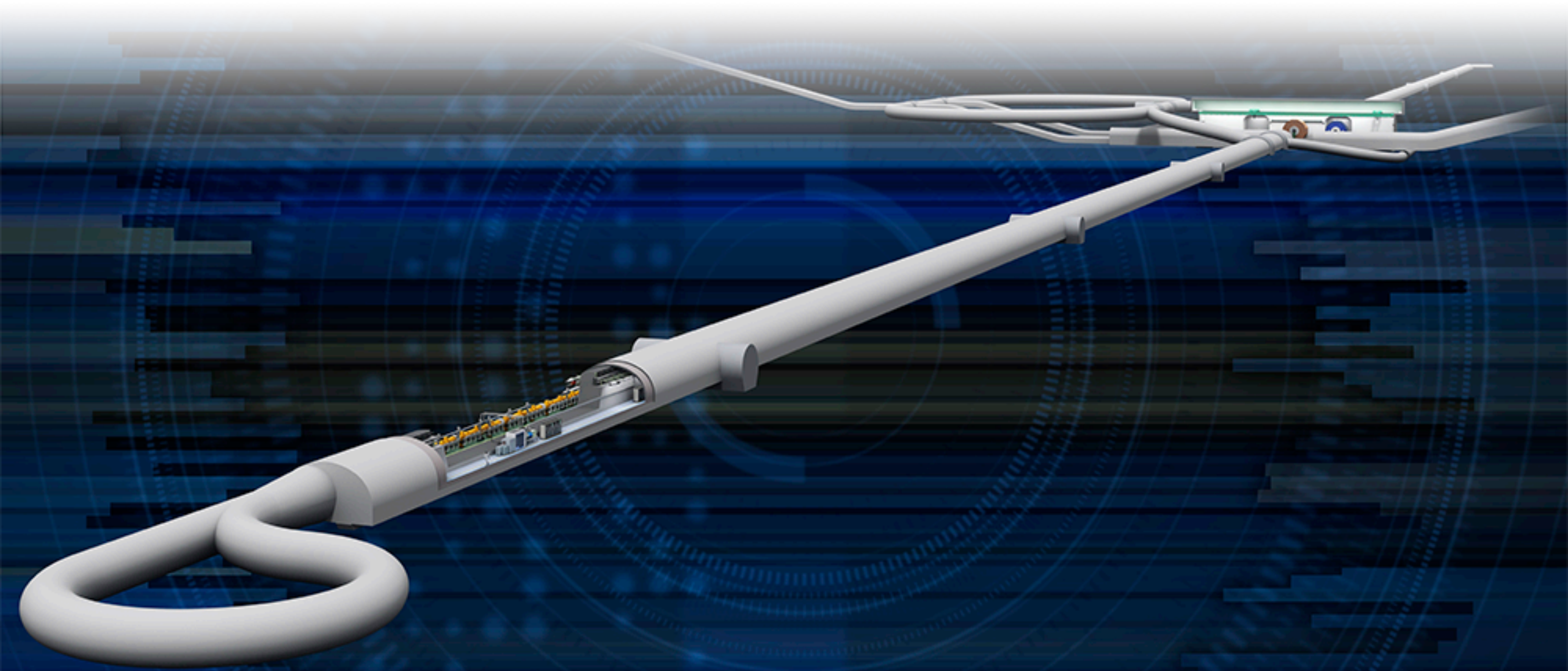








Additional Slides



Flavor-violating Higgs decays

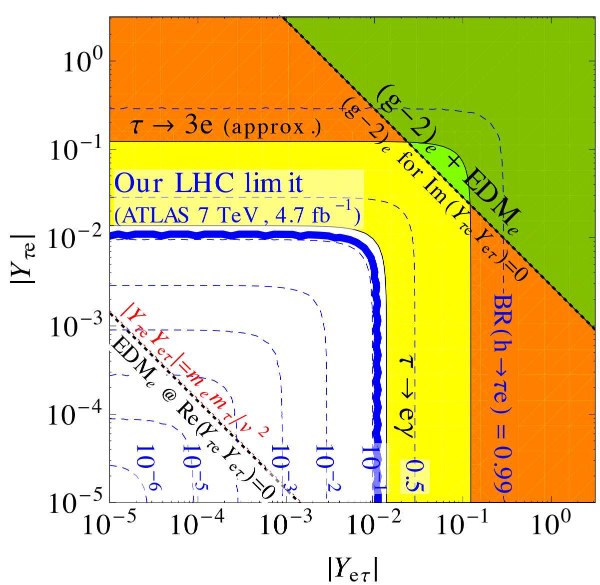
- Leptonic FV Higgs decays:
  - **H→τμ, μe, τe** → **Flavor LHC ILC ?**
- Hadronic FV Higgs decays:
  - **H→bd, bs, sd, cu**
  - **H→t*c→Wbc / H→t*u→Wbu** → **Flavor ILC ?**
  - **t→Hc (top FCNC)** → **LHC & ILC**
- **Hadronic flavor-conserving Higgs decays?** → **ILC ?**
  - **Limits on H→uu, dd, ss**

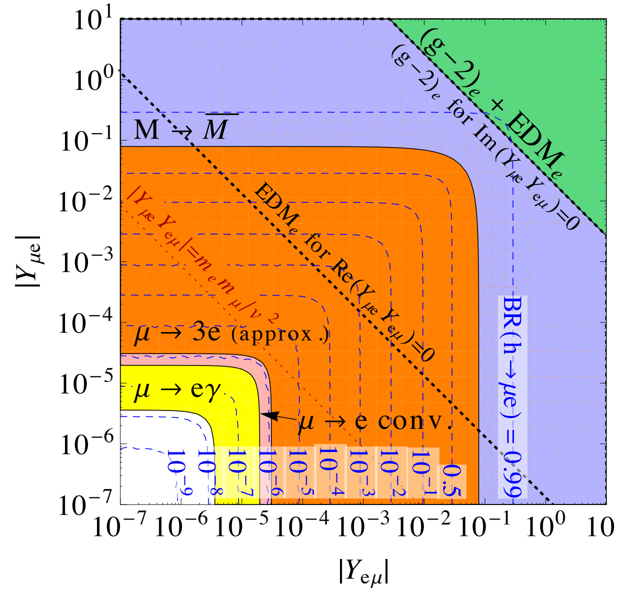
Need survey of new physics models

Leptonic FV Higgs decays

Harnik, Kopp, Zupan, arXiv:1209.1397

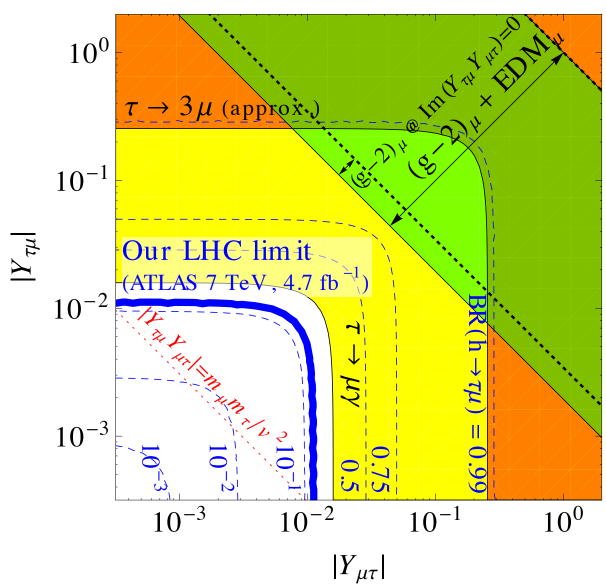
$$\Gamma(h \to \ell^\alpha \ell^\beta) = \frac{m_h}{8\pi}\left(|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2\right)$$





LHC

cLFV
g-2
EDM
B/τ factories
...



ILC ?

Hadronic FL Higgs decays

Harnik, Kopp, Zupan, arXiv:1209.1397

Technique	Coupling	Constraint
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2,\ \lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$
	$\lvert Y_{uc}Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2,\ \lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$
	$\lvert Y_{db}Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2,\ \lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$
	$\lvert Y_{sb}Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2),\ \mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$
	$\mathrm{Im}(Y_{ds}^2),\ \mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$
single-top production [49]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 3.7
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 1.6
$t \to hj$ [50]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 0.34
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 0.34
D^0 oscillations [48]	$\lvert Y_{ut}Y_{ct}\rvert,\ \lvert Y_{tu}Y_{tc}\rvert$	$< 7.6 \times 10^{-3}$
	$\lvert Y_{tu}Y_{ct}\rvert,\ \lvert Y_{ut}Y_{tc}\rvert$	$< 2.2 \times 10^{-3}$
	$\lvert Y_{ut}Y_{tu}Y_{ct}Y_{tc}\rvert^{1/2}$	$< 0.9 \times 10^{-3}$
neutron EDM [37]	$\mathrm{Im}(Y_{ut}Y_{tu})$	$< 4.4 \times 10^{-8}$

Hcu

Hbd

Hbs

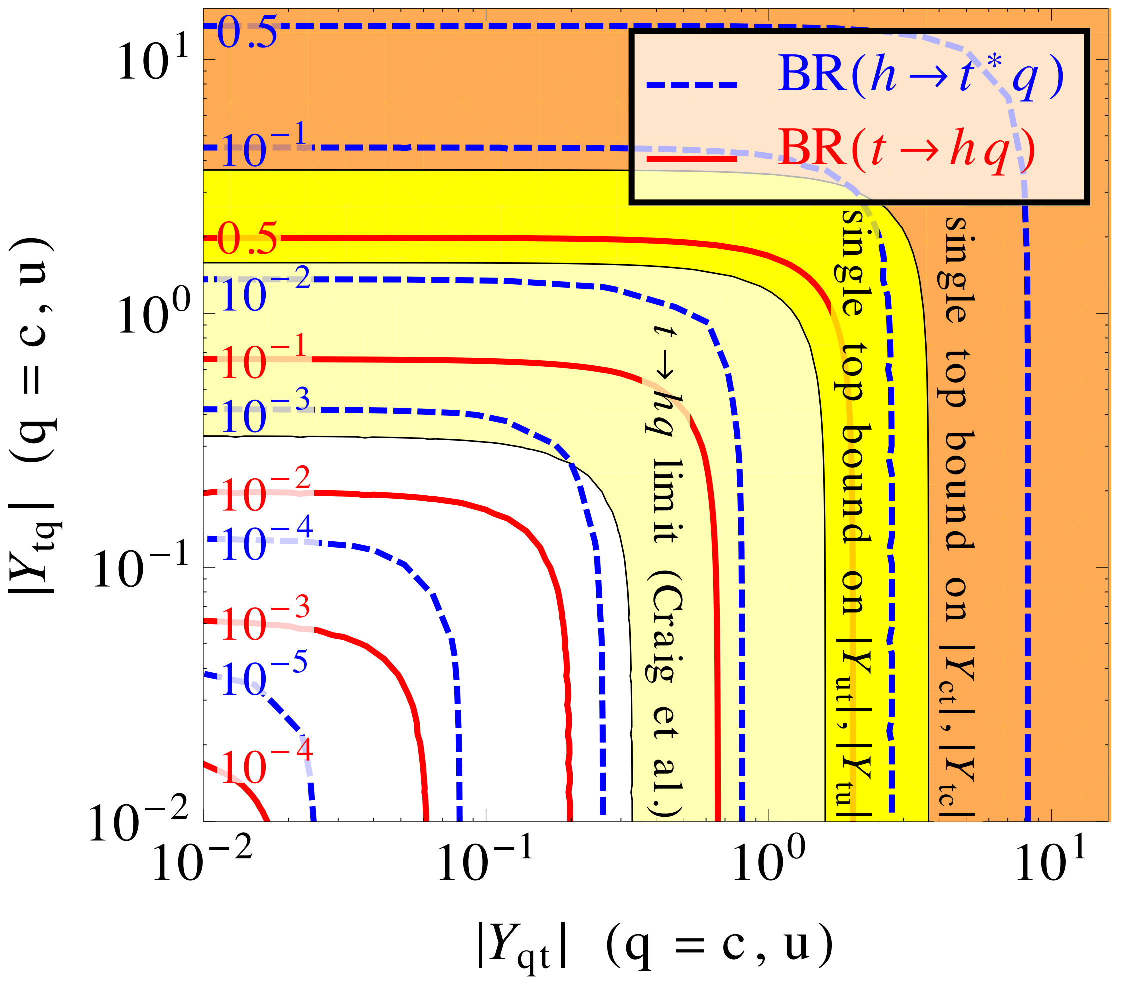
Hsd

Constrained by flavor data

Htc
Htu

Flavor data
LHC

Hadronic FL Higgs decays



Top FCNC

The top decays predominantly as t→bW. Rare decays, such as flavor-changing neutral currents (FCNC), which are suppressed in the SM but proceeds as a loop of new particles, are sensitive probes of new physics.

Observables, e.g.

$$\mathcal{B}(t \to Zq)(\gamma_\mu)$$

$$\mathcal{B}(t \to Zq)(\sigma_{\mu\nu})$$

$$\mathcal{B}(t \to \gamma q)$$

$$\mathcal{B}(t \to hq)$$

$$\mathcal{B}(t \to gq)$$

with $g = u, \underline{c}$

At ILC, accessible via:

(1) single top production (250 GeV~)

(2) top pair production (350 GeV~)

LHC/ILC projection, Snowmass Top WG arXiv:1311.2028

Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV	[140]
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV	[140]
$t \to Zq$	$5\,(2) \times 10^{-4}$	ILC single top, γ_μ ($\sigma_{\mu\nu}$)	500 fb^{-1}, 250 GeV	Extrap.
$t \to Zq$	$1.5\,(1.1) \times 10^{-4\,(-5)}$	ILC single top, γ_μ ($\sigma_{\mu\nu}$)	500 fb^{-1}, 500 GeV	[141]
$t \to Zq$	$1.6\,(1.7) \times 10^{-3}$	ILC $t\bar{t}$, γ_μ ($\sigma_{\mu\nu}$)	500 fb^{-1}, 500 GeV	[141]
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	300 fb^{-1}, 14 TeV	[140]
$t \to \gamma q$	2.5×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	3000 fb^{-1}, 14 TeV	[140]
$t \to \gamma q$	6×10^{-5}	ILC single top	500 fb^{-1}, 250 GeV	Extrap.
$t \to \gamma q$	6.4×10^{-6}	ILC single top	500 fb^{-1}, 500 GeV	[141]
$t \to \gamma q$	1.0×10^{-4}	ILC $t\bar{t}$	500 fb^{-1}, 500 GeV	[141]
$t \to gu$	4×10^{-6}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV	Extrap.
$t \to gu$	1×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to gc$	1×10^{-5}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV	Extrap.
$t \to gc$	4×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-3}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	3000 fb^{-1}, 14 TeV	Extrap.

Single top @ ILC 250
Single top @ ILC 500
Top pair @ ILC 500

Single top @ ILC 250
Single top @ ILC 500
Top pair @ ILC 500

Are there ILC studies?

ILC Ref. Aguilar-Saavedra, Riemann [arXiv:hep-ph/0102197]
TESLA fast simulation study

	LHC		TESLA	
	95%	$3\,\sigma$	95%	$3\,\sigma$
$\text{Br}(t \to Zu)$ (γ_μ)	6.2×10^{-5}	8.0×10^{-5}	1.9×10^{-4}	2.2×10^{-4}
$\text{Br}(t \to Zc)$ (γ_μ)	7.1×10^{-5}	1.0×10^{-4}	1.9×10^{-4}	2.2×10^{-4}
$\text{Br}(t \to Zu)$ ($\sigma_{\mu\nu}$)	1.8×10^{-5}	2.3×10^{-5}	6.2×10^{-6}	7.0×10^{-6}
$\text{Br}(t \to Zc)$ ($\sigma_{\mu\nu}$)	7.1×10^{-5}	1.0×10^{-4}	6.2×10^{-6}	7.0×10^{-6}
$\text{Br}(t \to \gamma u)$	2.3×10^{-6}	3.0×10^{-6}	3.7×10^{-6}	3.6×10^{-6}
$\text{Br}(t \to \gamma c)$	7.7×10^{-6}	1.2×10^{-5}	3.7×10^{-6}	3.6×10^{-6}

too old

300 fb-1 @ 500 GeV
500 fb-1 @ 800 GeV

→ would be interesting to do full simulation study with the latest flavor tagging tools

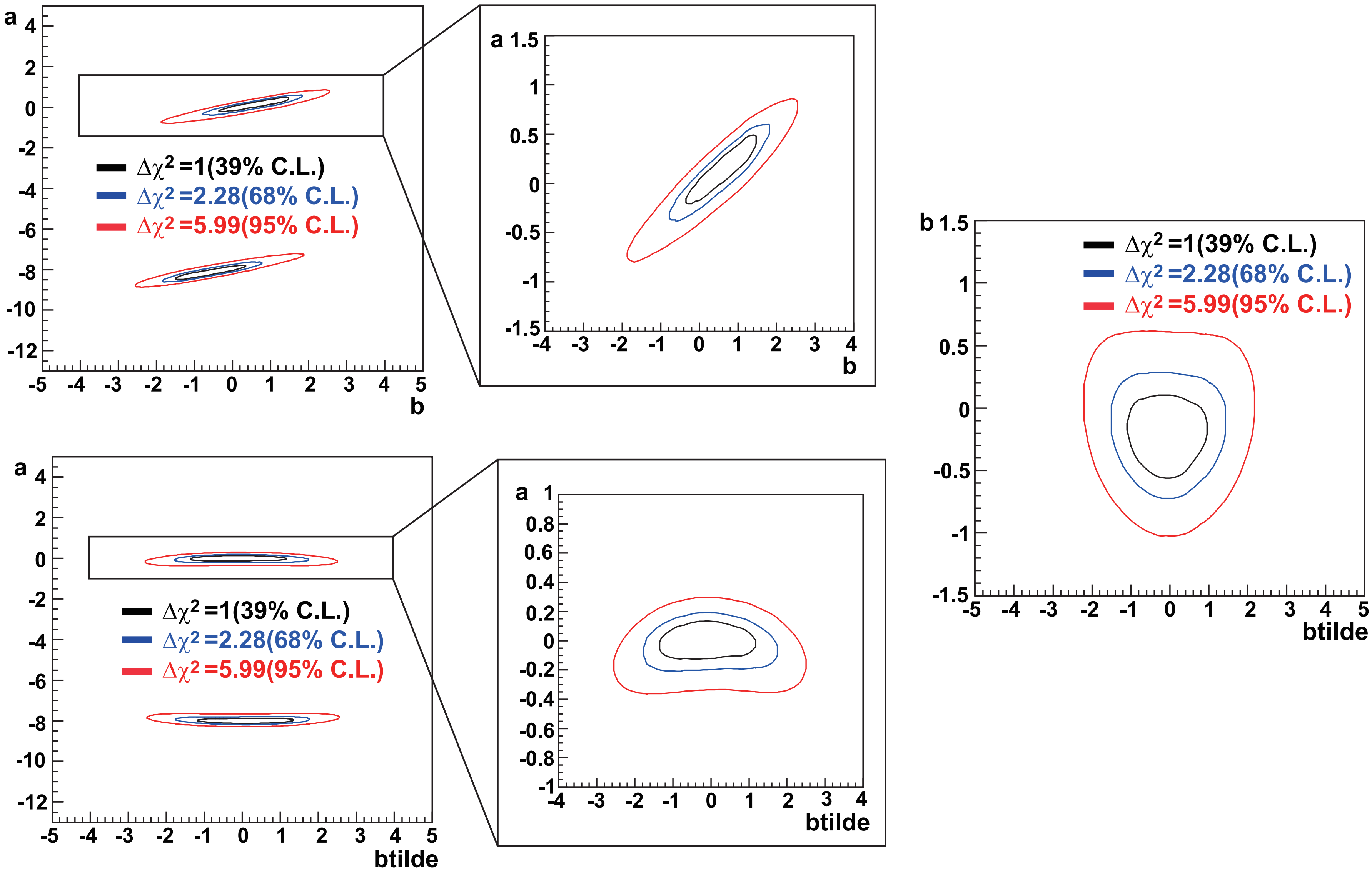
Composite gauge bosons?

- If we consider the possibility that the Higgs boson is composite, we should also consider the possibility that gauge bosons are composite.
- Predictions: Anomalous couplings ZWW, γWW, HWW, HZZ, HZγ, …
  - Chang, Lee, PRD 37 101 (1998)
  - Martinez, Queijeiro, Tun, Phys. Scr. 45 425 (1992)
- Simulation study for HWW
  - Takubo et al. PRD 88 013010 (2013)

$$\mathcal{L}_{\mathrm{HWW}} = 2M_W^2\left(\frac{1}{v}+\frac{a}{\Lambda}\right)H\ W_\mu^+W^{-\mu} + \frac{b}{\Lambda}H\ W_{\mu\nu}^+W^{-\mu\nu} + \frac{\tilde{b}}{\Lambda}H\ \epsilon^{\mu\nu\sigma\tau}W_{\mu\nu}^+W_{\sigma\tau}^-$$

- **Need to connect the compositeness scale to the size of the anomalous couplings**

Anomalous HWW coupling



Takubo et al. PRD 88 013010 (2013)

aTGC

$$\begin{aligned}\mathcal{L}_{WWV} \;=\; & g_{WWV}\Big[ig_1^V V_\mu \left(W_\nu^- W_{\mu\nu}^+ - W_{\mu\nu}^- W_\nu^+\right) + i\kappa_V W_\mu^- W_\nu^+ V_{\mu\nu} + i\frac{\lambda_V}{M_W^2} W_{\lambda\mu}^- W_{\mu\nu}^+ V_{\nu\lambda} \\ & + g_4^V W_\mu^- W_\nu^+ \left(\partial_\mu V_\nu + \partial_\nu V_\mu\right) + g_5^V \epsilon_{\mu\nu\lambda\rho}\left(W_\mu^- \partial_\lambda W_\nu^+ - \partial_\lambda W_\mu^- W_\nu^+\right) V_\rho \\ & + i\tilde{\kappa}_V W_\mu^- W_\nu^+ \tilde{V}_{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2} W_{\lambda\mu}^- W_{\mu\nu}^+ \tilde{V}_{\nu\lambda}\Big], \qquad \text{(iii)}\end{aligned}$$

ILC RDR

coupling	error $\times 10^{-4}$	
	$\sqrt{s} = 500\,\text{GeV}$	$\sqrt{s} = 800\,\text{GeV}$
Δg_1^Z	15.5	12.6
$\Delta\kappa_\gamma$	3.3	1.9
λ_γ	5.9	3.3
$\Delta\kappa_Z$	3.2	1.9
λ_Z	6.7	3.0
g_5^Z	16.5	14.4
g_4^Z	45.9	18.3
$\tilde{\kappa}_Z$	39.0	14.3
$\tilde{\lambda}_Z$	7.5	3.0

aTGC

ILC RDR

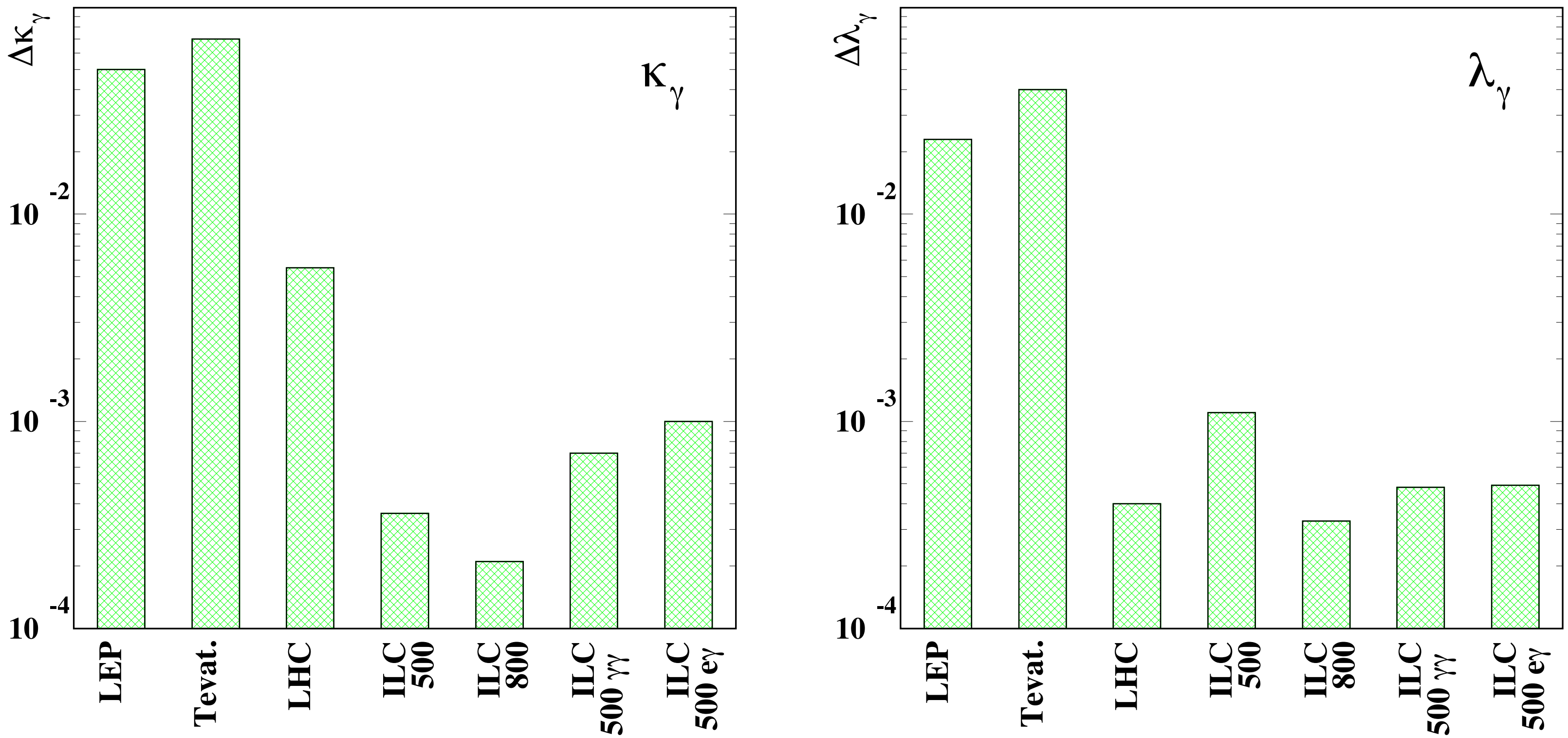


FIGURE 3.3. Comparison of $\Delta\kappa_\gamma$ and $\Delta\lambda_\gamma$ at different machines. For LHC and ILC three years of running are assumed (LHC: $300\ \mathrm{fb}^{-1}$, ILC $\sqrt{s} = 500\,\mathrm{GeV}$: $500\ \mathrm{fb}^{-1}$, ILC $\sqrt{s} = 800\,\mathrm{GeV}$: $1000\ \mathrm{fb}^{-1}$). If available the results from multi-parameter fits have been used.