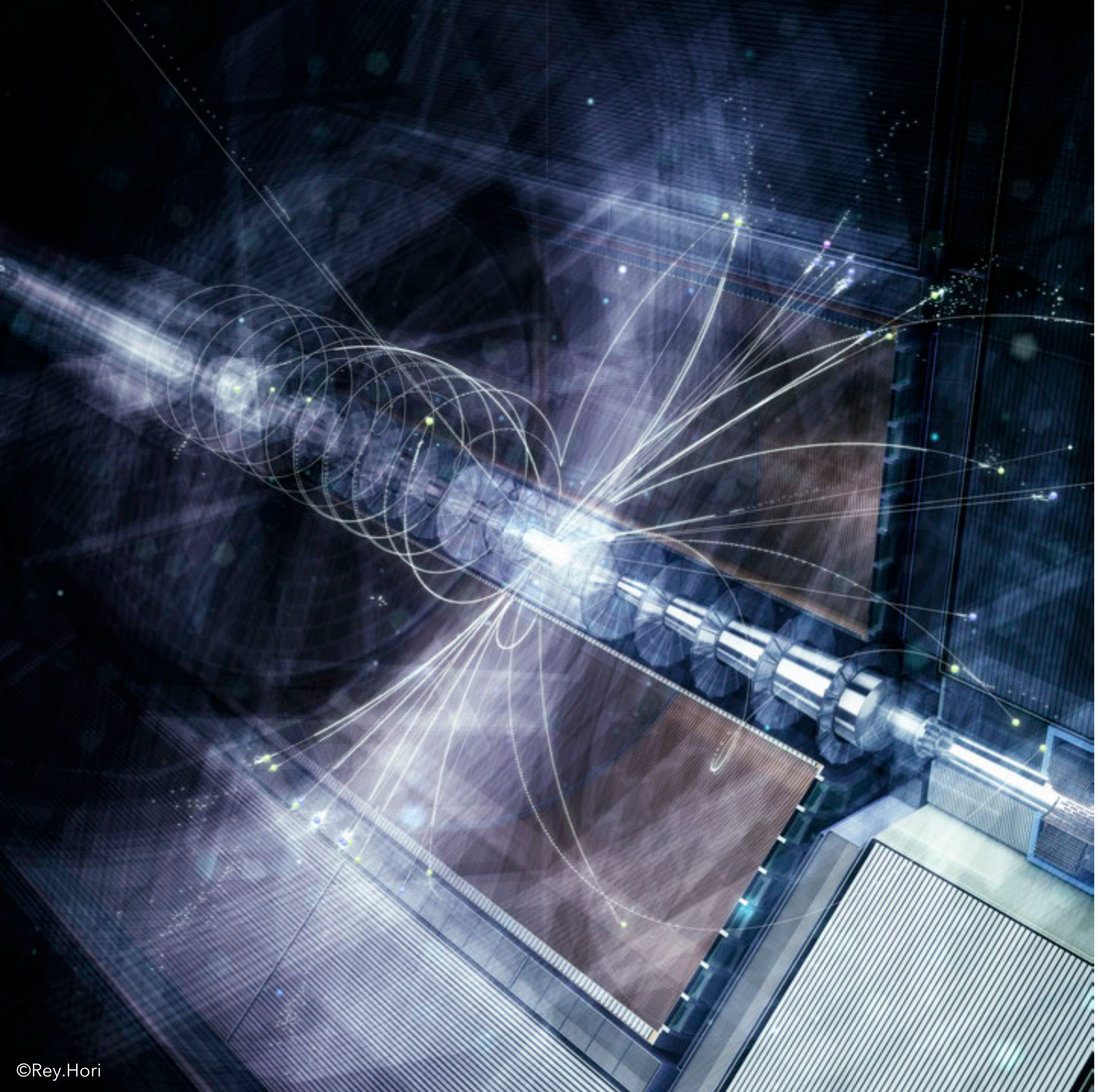
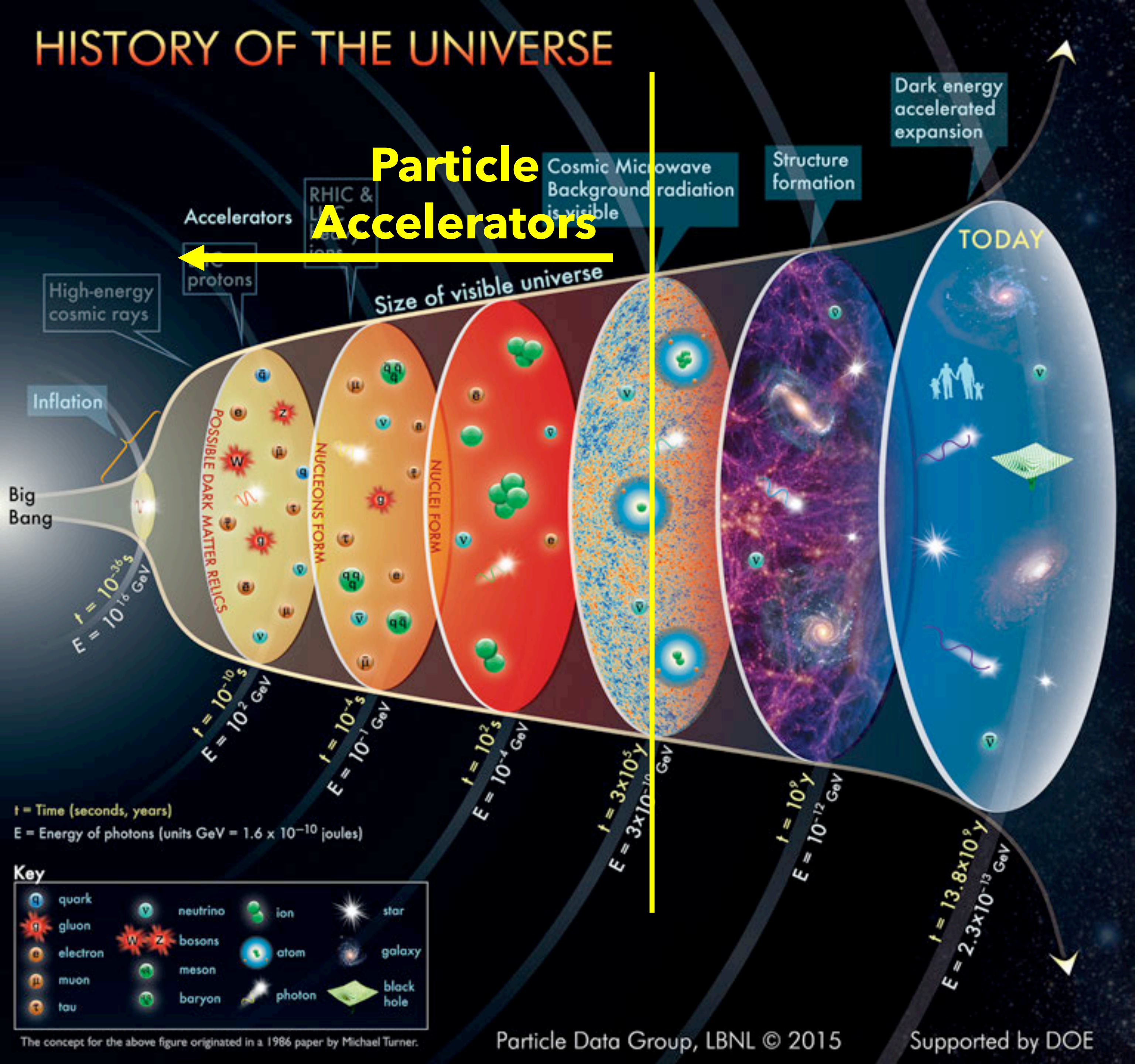


Higgs and BSM at a Linear Collider

Tomohiko Tanabe (Kavli IPMU/KEK)

LCWS2021 / March 17



Open Issues:

- Unification of forces/matter
- Supersymmetry
- Extra Dimensions
- Compositeness
- Dark Matter
- Baryon Asymmetry
- Electroweak Phase Transition
- Vacuum Stability

→ **To be addressed by LC**

Probes:

- New Particles
- Higgs Boson

} This talk

- Gauge Bosons
- Fermions

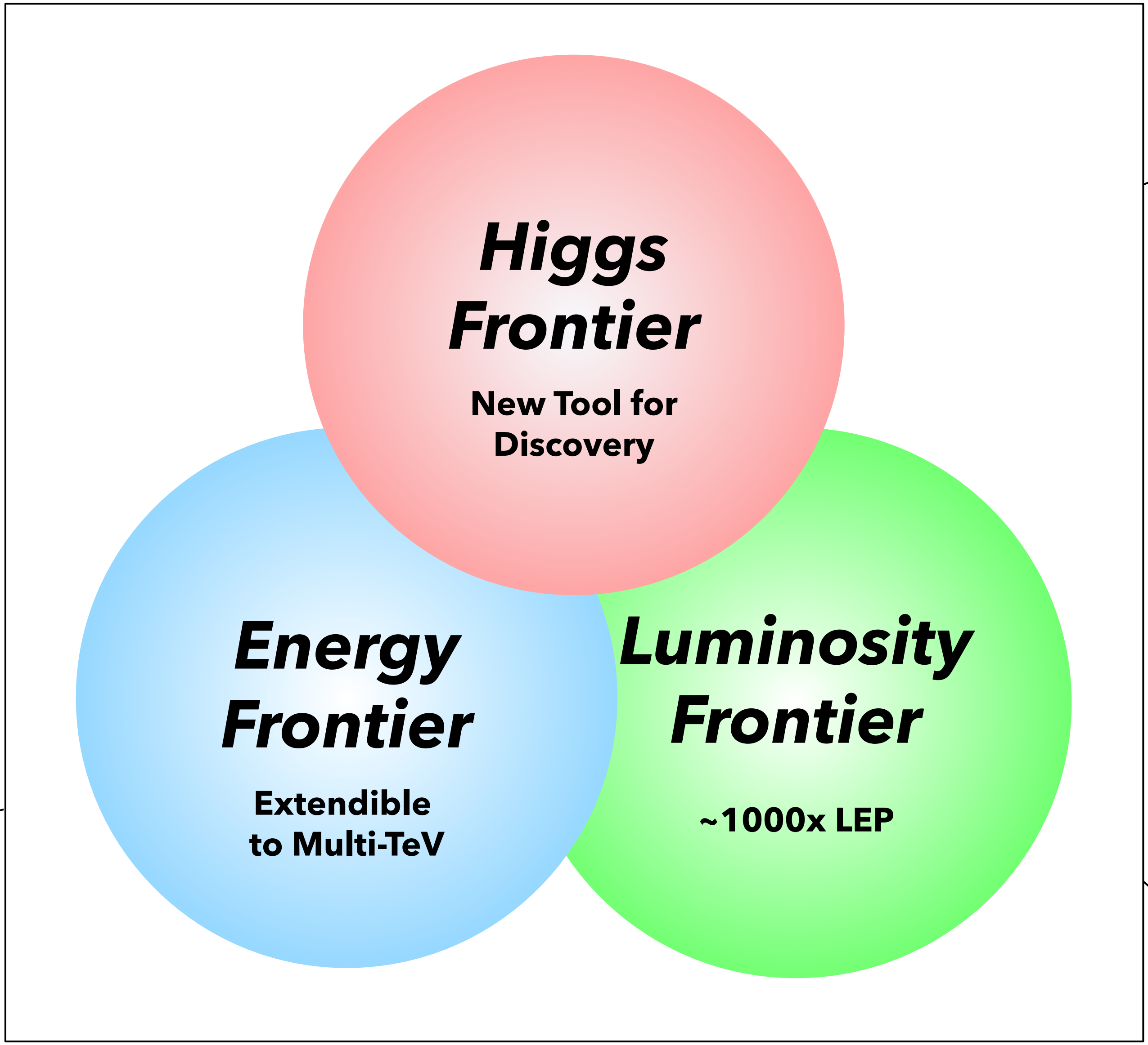
} Next talk by A. Irles

Linear Collider: Machine of 3 Frontiers

LEP II	
Year	**√s [GeV]**
1996	161-172
1997	180-184
1998	189
1999	196-202
2000	204-208

Expect uncharted territories every time the LC turns on.

Safety margin for Higgs factory energies?



The Higgs boson is a unique probe for investigating the fundamental questions in HEP today.

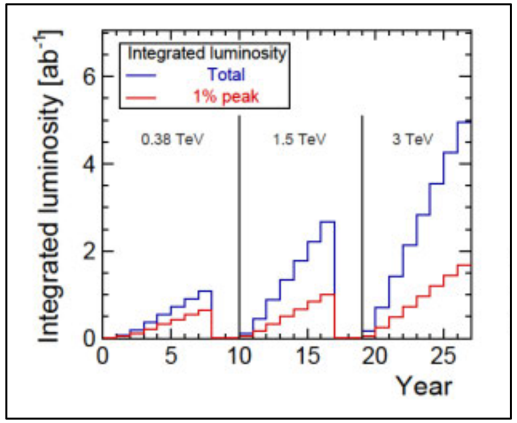
LEP & LEP II:
Total integrated luminosity = 1 fb^{-1}

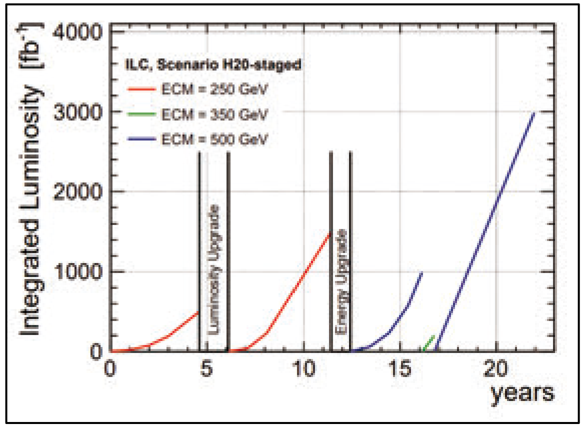
ILC 250 GeV (11 yrs.): 2000 fb^{-1}
CLIC 380GeV (8 yrs.): 1000 fb^{-1}

Possible discoveries in areas that were statistically limited.

Energy Extendibility and Beam Polarization

CLIC





ILC

Energy Frontier in e^+e^- collisions for many decades to come

"Higgs factory"

Future upgrades: TeV and beyond

Another advantage of LC is Beam Polarization:

$P(e^-) = 0.8$, $P(e^+) = 0.3$ (ILC nominal)

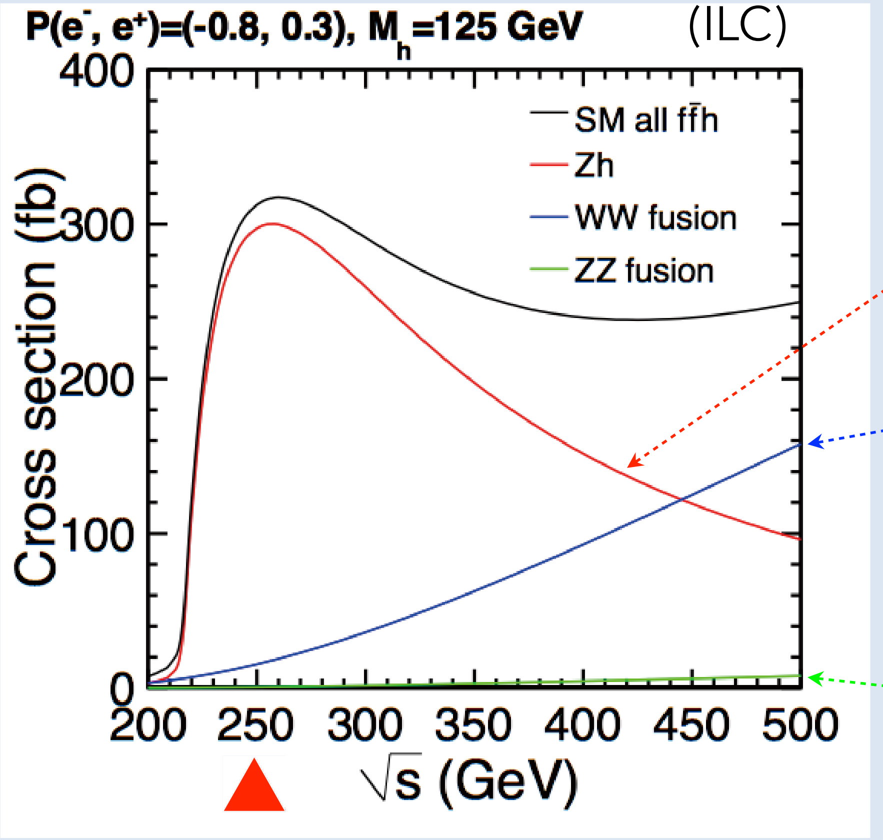
$(e^-_L e^+_R)$, $(e^-_R e^+_L)$, $(e^-_L e^+_L)$, $(e^-_R e^+_R)$

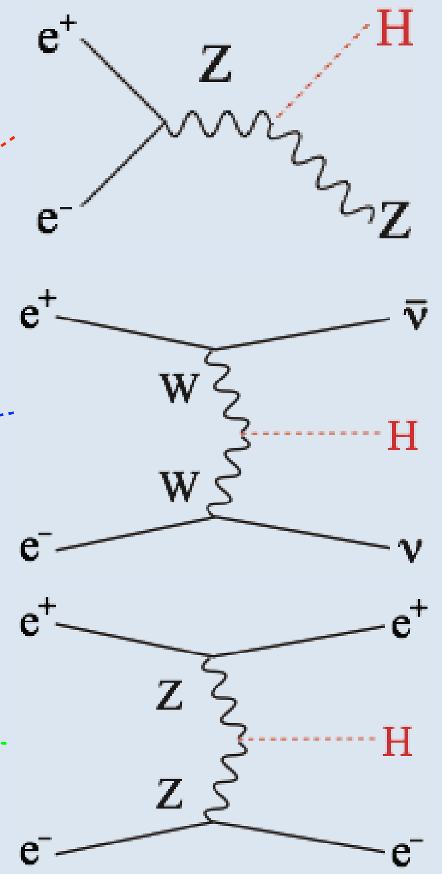
Background suppression, determination of chiral structure, control of systematics

Higgs Frontier

Higgs Production

Higgs Production Cross Section





Approx. 0.5 million Higgs bosons with 2 ab^{-1} of data

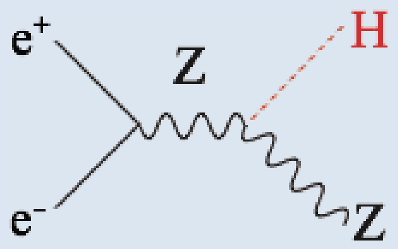
K. Fujii

Use the many Higgs bosons as a probe for New Physics

Measuring the Higgs Cross Section

The Higgs Recoil Method

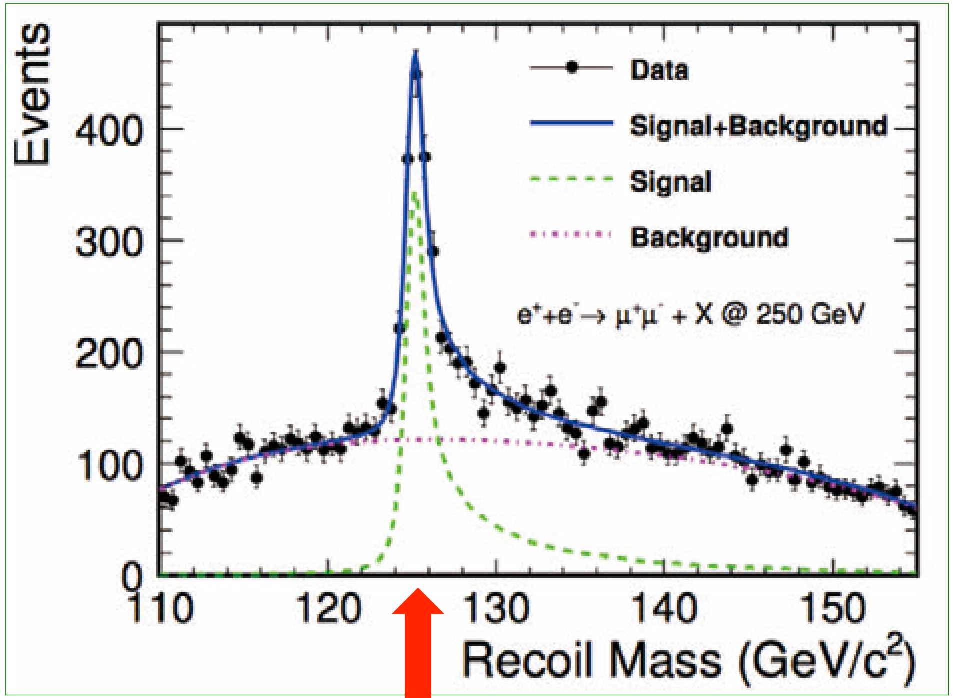
1. Initial State (e+e-) is known
2. Reconstruct Z decay
3. Compute Higgs mass



$P_H = P_Z - P_{ee}$

$M_H = \sqrt{(P_{ee} - P_Z)^2}$

PRD94 (2016) no.11, 113002



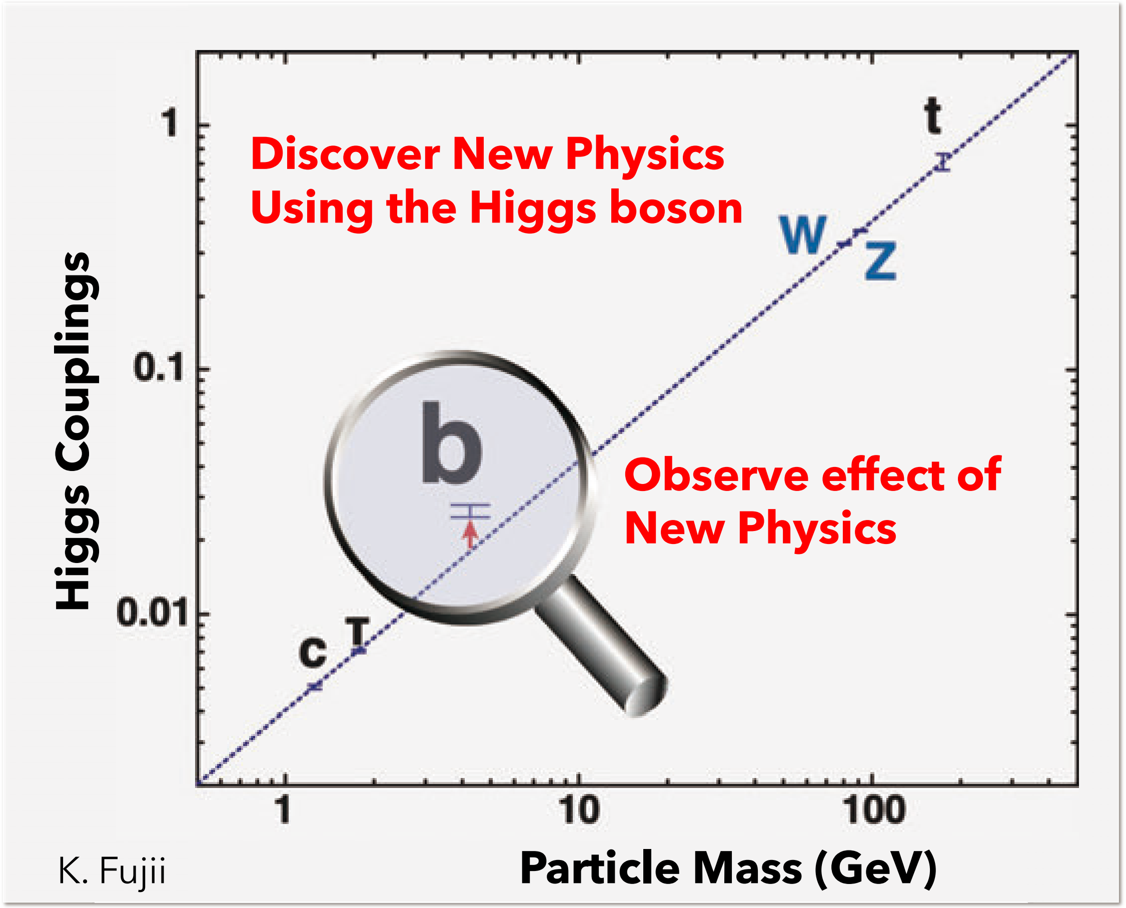
Background Events

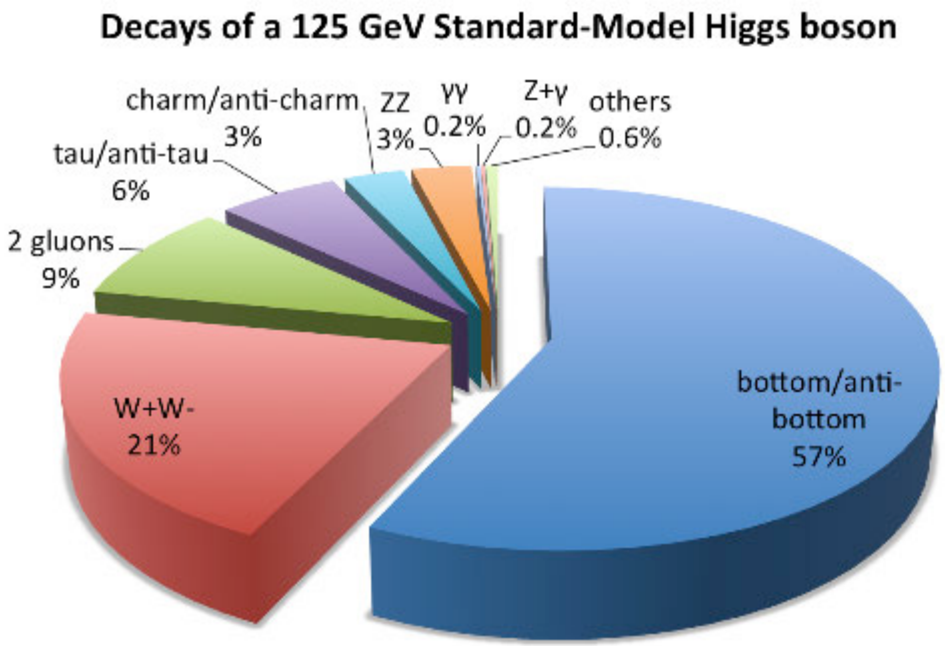
Higgs Signal Events

The most important measurement in Higgs physics:
Model-independent determination of ZH cross section

Higgs Couplings

Effects of new physics manifest as deviations in the Higgs couplings
(interaction between the Higgs boson and SM particles)



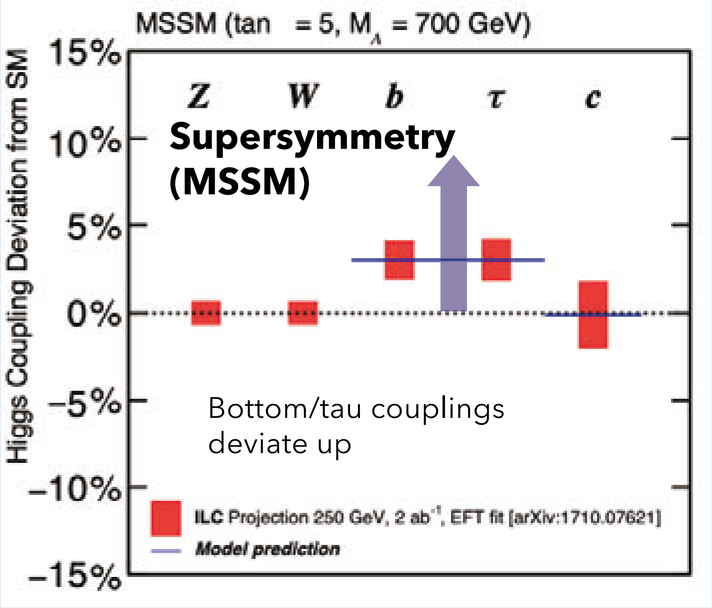


International Masterclasses for ATLAS

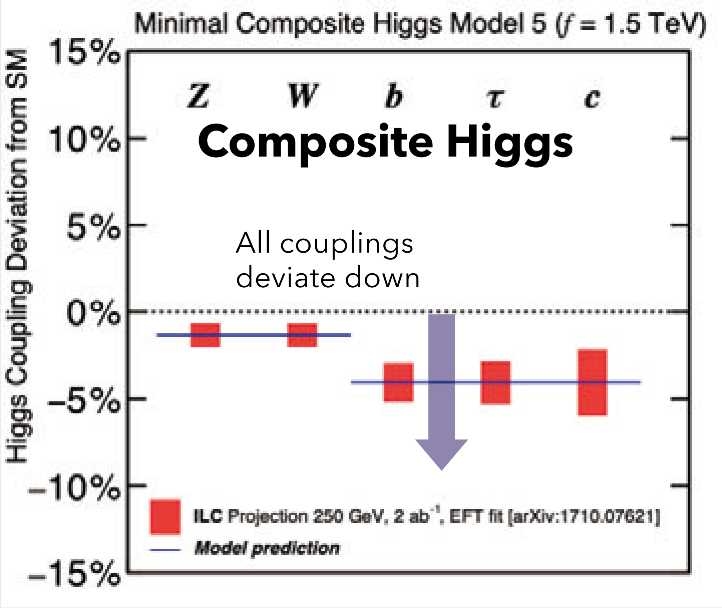
→ **Existence of New Physics will affect these ratios.**

Higgs Boson as a Discovery Probe

The pattern of Higgs boson couplings provides crucial information about the underlying new physics model:



LC sensitivity up to 2 TeV
(mass of the heavy Higgs boson m_A)



LC sensitivity beyond 10 TeV
(compositeness scale)

LC could discover signs of Supersymmetry, Extra Dimensions, or Compositeness.
If so, (1) the next direction in particle physics is determined;
(2) the next energy scale is determined;
(3) it sheds light on the type of Dark Matter favored by the model.

Global Fit with SM Effective Field Theory

Barklow et al. 1708.09079

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}$$

SU(2)xU(1) invariant
Dim-6 operators

LHC Run II results suggest 250 GeV is within the validity of EFT

Number of EFT coefficients: **17 @LC**

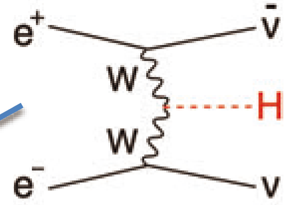
Fully exploiting the LC capabilities:

- e+e- initial state
- beam polarization
- all relevant decay channels
- access to essentially all phase space

Pre-SMEFT:

$$\Gamma_h = \frac{\Gamma(h \to WW^*)}{BR(h \to WW^*)}$$

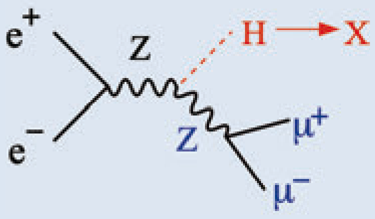
$$\Gamma(h \to WW^*) \propto \sigma(\nu\bar{\nu}h)$$

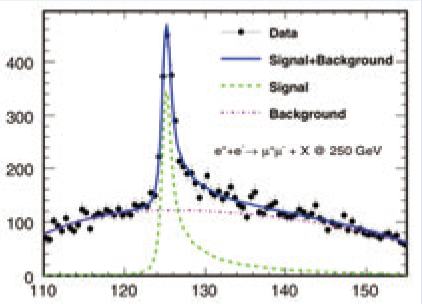


Cross section: small@250GeV

SMEFT relates hZZ and hWW couplings
→ Precise determination of Higgs total width

The importance of ***the σ_{Zh} measurement by recoil mass*** remains the same.





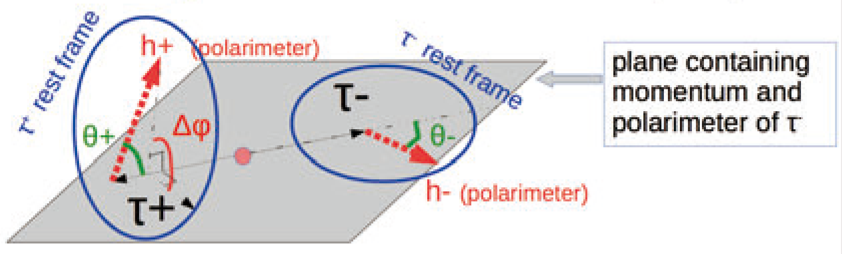
Absolute and model-independent determination of Higgs couplings possible with Higgs factory data.

Probing CP violation in Higgs sector

Measuring CP in $H \to \tau^+\tau^-$ at ILC

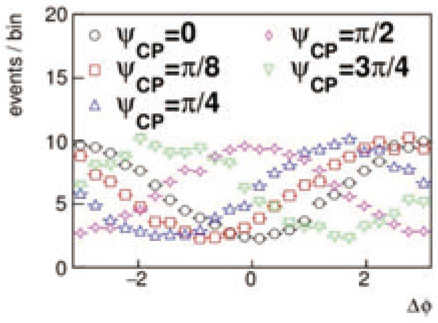
$$\mathcal{L}_{h\tau\tau} = g\bar{\tau}\left(\cos\Psi_{CP} + i\gamma_5 \sin\Psi_{CP}\right)\tau\, h$$

CP from polarimeters : taus from spin 0 parent



θ±, φ±	direction of h± with respect to τ- boost in τ± rest frame
Δφ	angle between polarimeter planes
ψ_{CP}	CP mixing angle we want to measure

Δφ at different ψ_{CP}



Δφ distribution shifts by $2\psi_{CP}$

2ab^{-1} @ 250 GeV

$$\delta\Psi_{CP} \simeq 4^\circ$$

Jeans, Wilson
PRD 98 013007 (2018)

In the SM, the Higgs boson is a CP even scalar.

BSM models with an extended Higgs sector contains multiple Higgs bosons.

If a neutral CP-odd Higgs boson

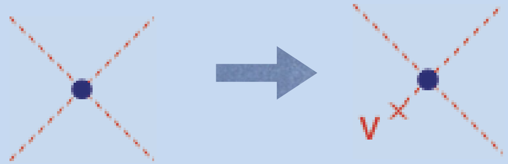
CP mixing angle precision: 4 degrees

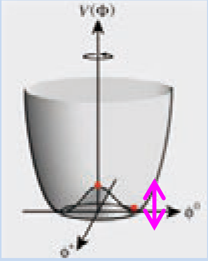
→ **Discover a new source of CP violation**
→ **Leads to Electroweak Baryogenesis**

ILC 500 GeV, 1 TeV
CLIC 1.4-3 TeV

Higgs Self-Coupling

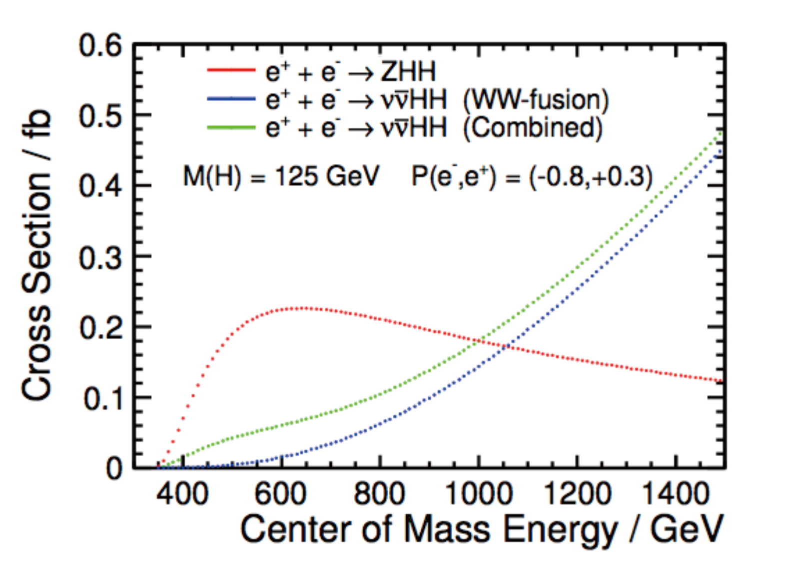
Higgs Self-coupling is direct evidence of vacuum condensation





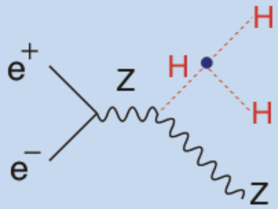
Higgs self-coupling
~depth of potential

Three-point coupling is originally absent due to gauge symmetry in the SM,
Manifests after electroweak symmetry breaking



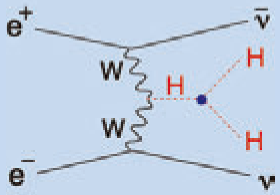
ILC [1908.11299]

~ 500 GeV



$\Delta\lambda/\lambda$ = 27%

~ 1 TeV



$\Delta\lambda/\lambda$ = 10%

CLIC

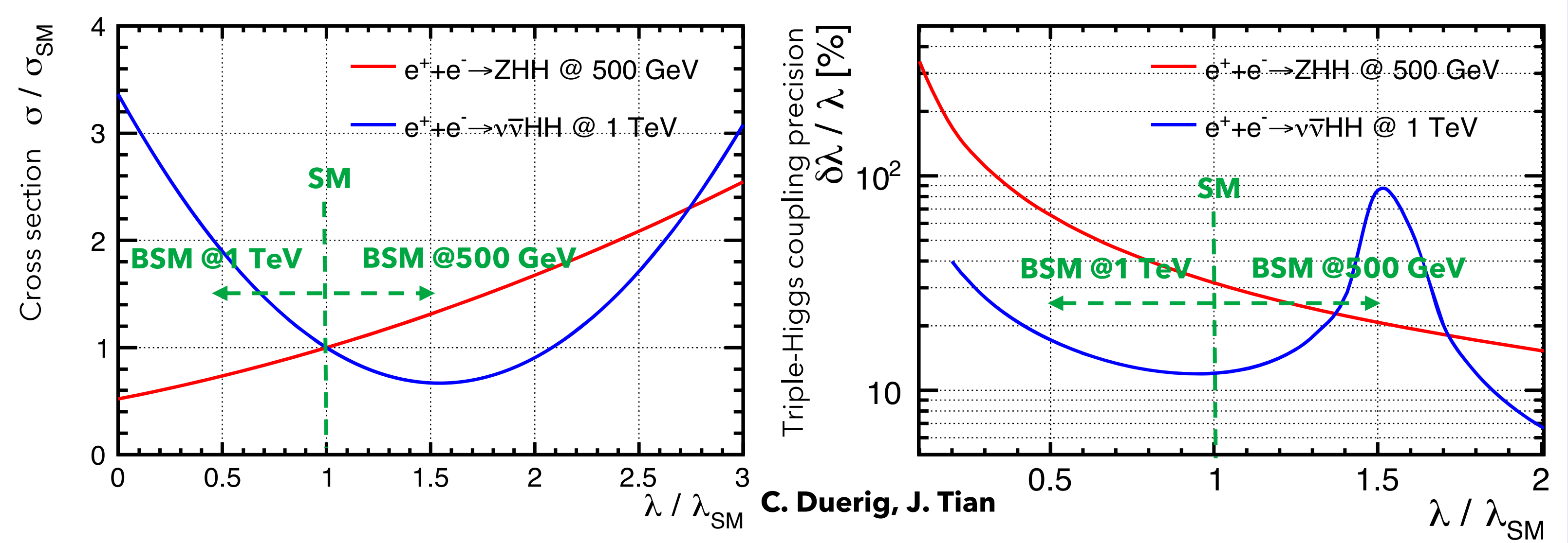
Roloff et al, EPJC 80, no. 1010 (2020)
$e+e- \to HH\nu\nu$ (bbbb, bbWW) 1.4-3 TeV
$\Delta\lambda/\lambda$ = -8%, +11%

Weber, 2008.05198
All-hadronic HHZ production at 3 TeV

ILC 500 GeV, 1 TeV
CLIC 1.4-3 TeV

Triple-Higgs coupling with BSM

- BSM can modify the triple-Higgs coupling. What effect does it have on the total cross section?
- At 500 GeV, the cross section **increases** with increasing λ. **[Unique sensitivity]**
- At 1 TeV, the cross section **decreases** with increasing λ. **[Same as LHC]**

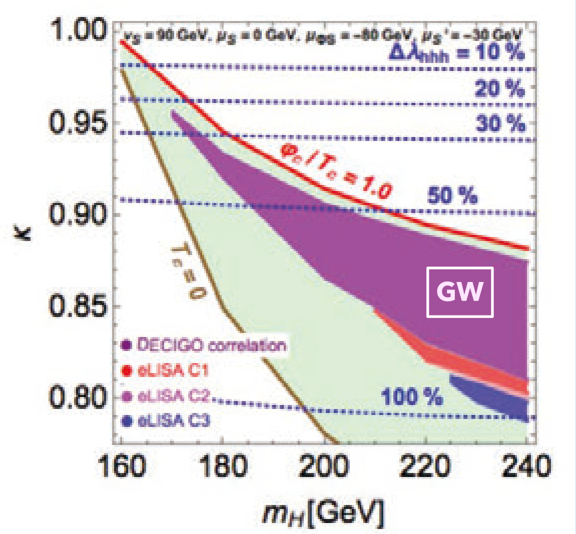


C. Duerig, J. Tian

Electroweak Baryogenesis predicts

- **Large deviation of λ from SM**
- **Relic GW due to 1st Order Phase Transition**

Synergy of ILC measurement and Satellite GW observation

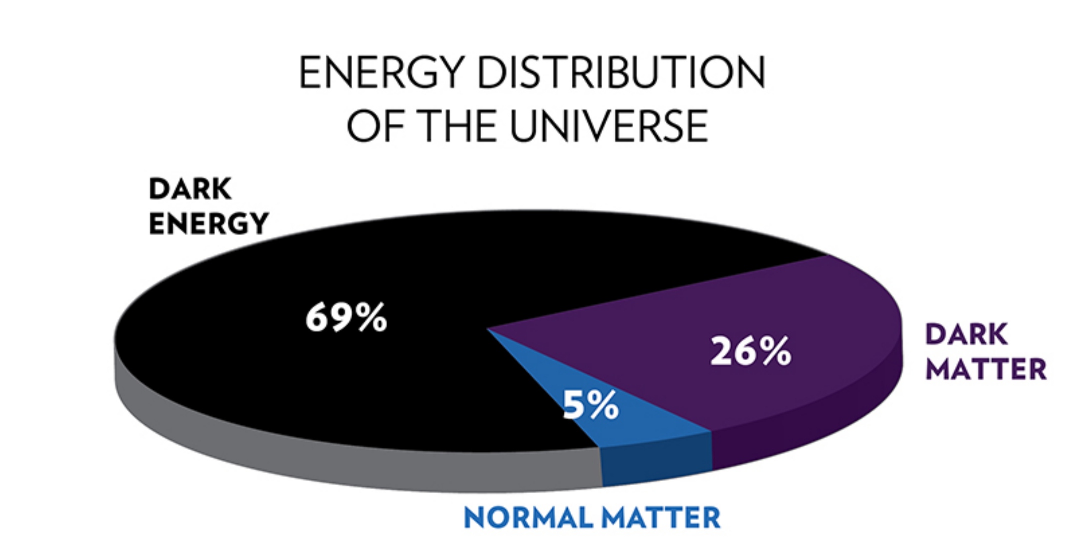


Fuyuto, Senaha, arXiv:1406.0433
Hashino, Kakizaki, Kanemura, Ko, Matsui, arXiv:1609.00297

Combination of ZHH and ννHH needed for full coverage of BSM effects

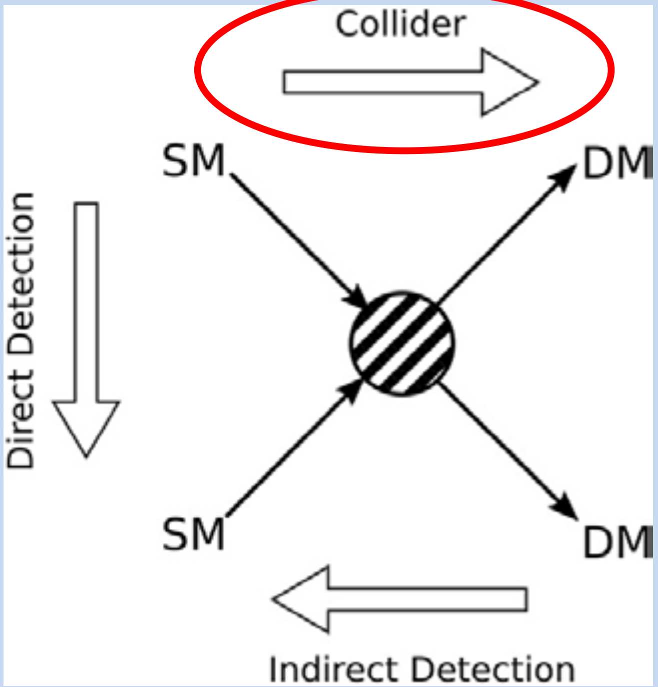
Dark Matter

Dark Matter (DM) accounts for five times the normal matter in the universe:



(Credit: NASA/CXC/K.Divona)

Various DM searches:



If DM particles can be produced & detected at LC, we will determine:
- Mass
- Cross section
- Quantum numbers (spin, chirality, etc.)

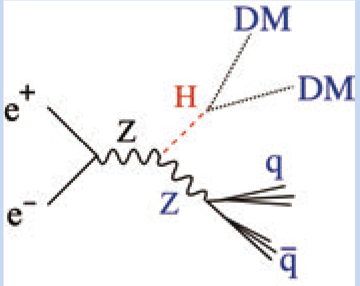
➡ Compare with cosmological observations

Beam polarization essential for determining the chiral structure of the interaction

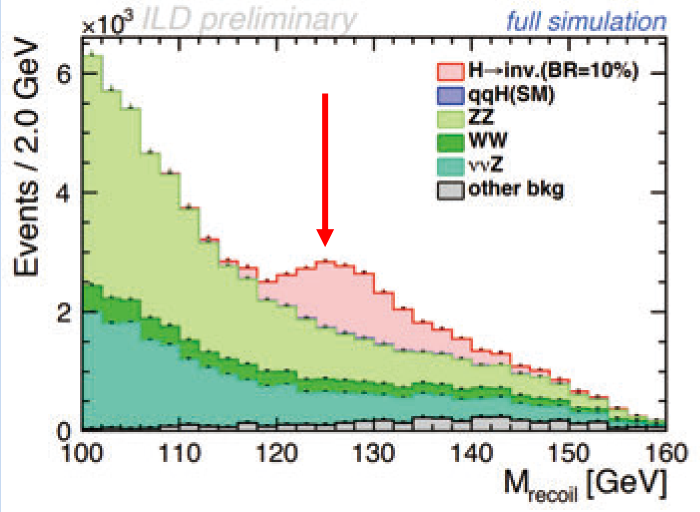
Higgs as a Portal to Dark Matter

Higgs Frontier

Higgs Invisible Decays



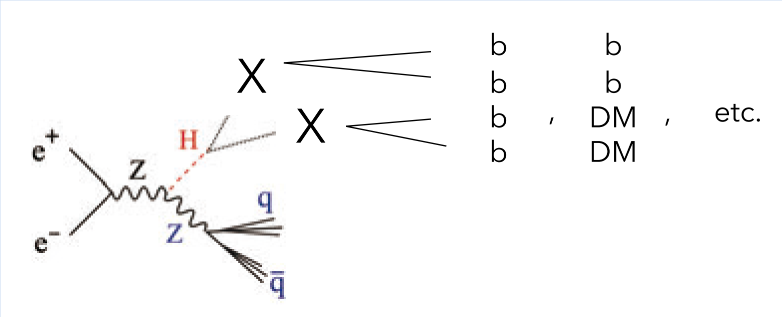
Hadronic Z decay (ILD), Kato, 2002.12048



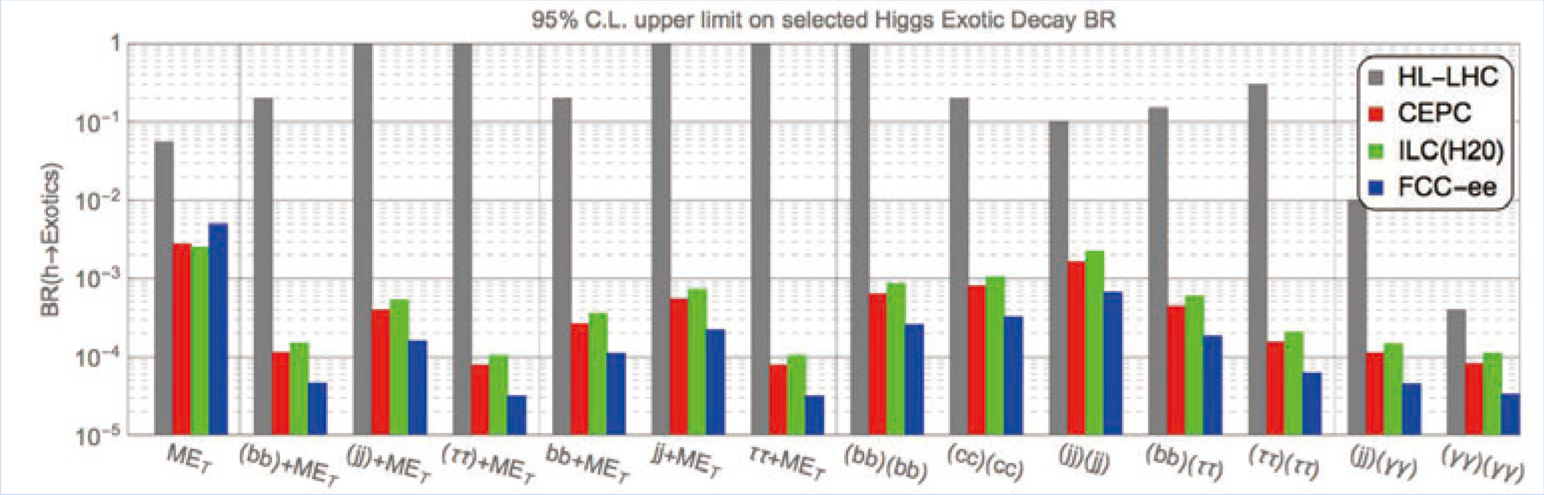
Invisible decay branching ratio: 0.3% (95% CL upper limit)

[SiD study in progress: Steinhebel, LCWS2021]

Exotic Higgs Decays



Liu, Wang, Zhang [1612.09284]

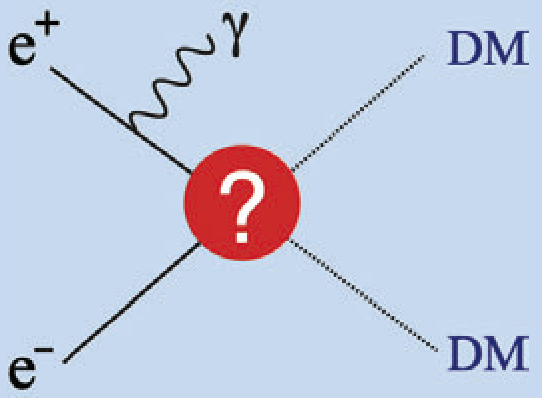


LC sensitive to various exotic Higgs decays

Mono-Photon Dark Matter Search

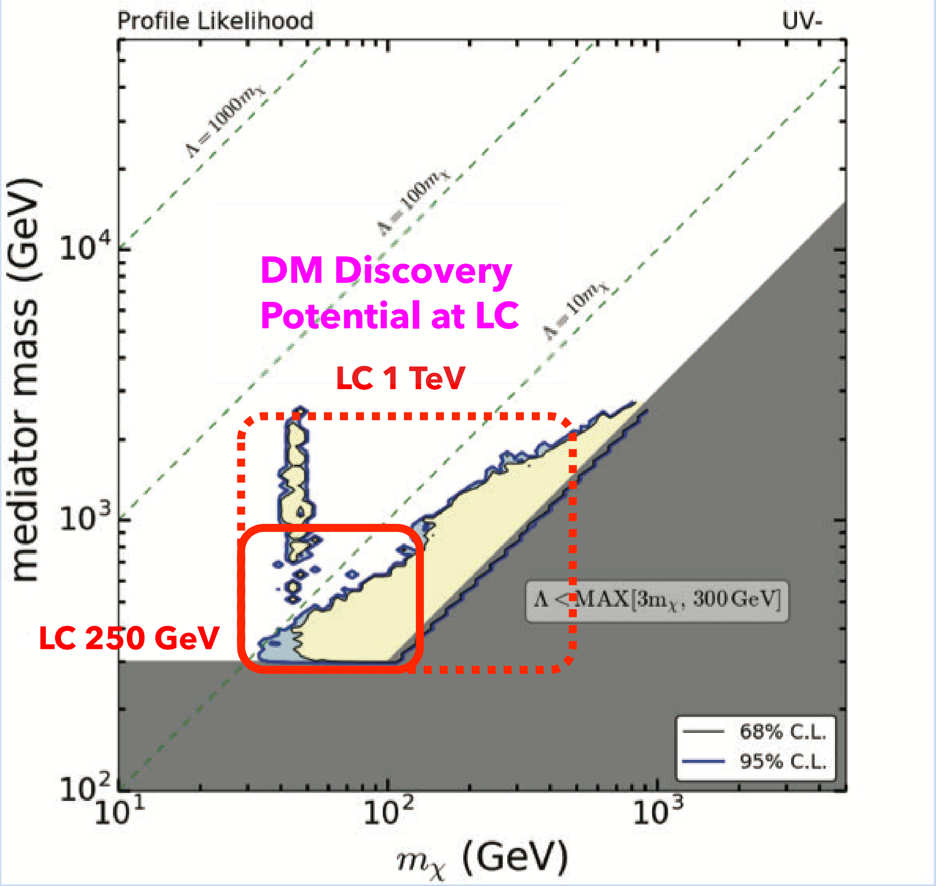
Mono-photon dark matter search is sensitive to many types of dark matter. It is especially effective for:

- Dark matter that couples to leptons
- Dark matter that couples to Z bosons



Fermionic WIMP DM with Scalar Mediator

Matsumoto, Tsai, Tseng [JHEP 07 (2019) 050]



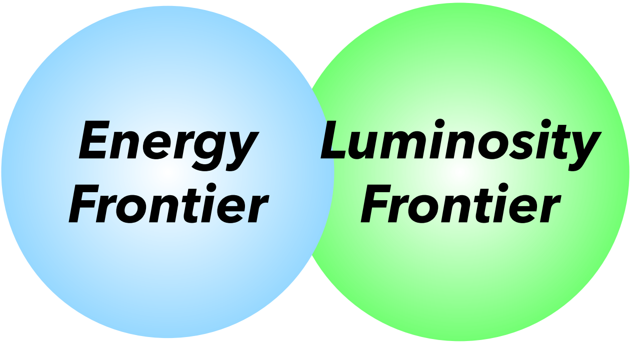
Yellow: Remaining parameter space for ILC after taking into account projections for other experiments (HL-LHC, direct/indirect detection)

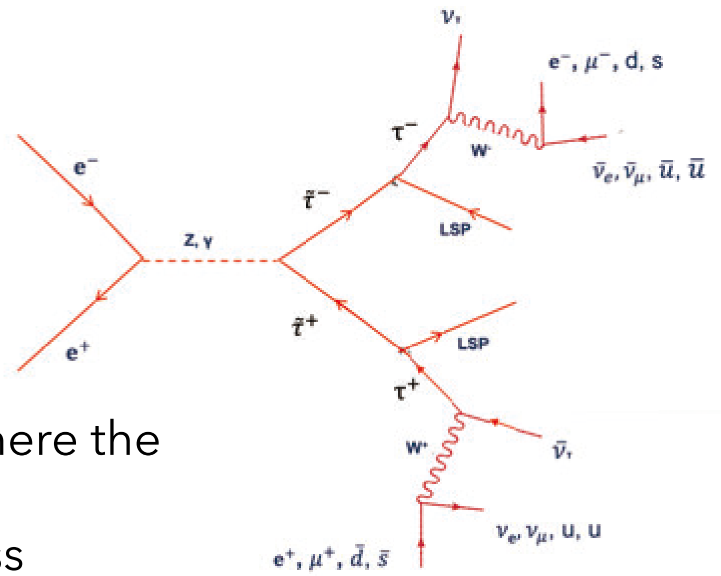
Simulation Studies:

- **ILC:** Habermehl, Berggren, List: [Phys.Rev.D 101 (2020) 7, 075053]
- **CLIC:** Blaising, Roloff, Sailer, Schnoor: [2103.06006]

LC can probe unique parameter space in Dark Matter searches

Stau Search at LC



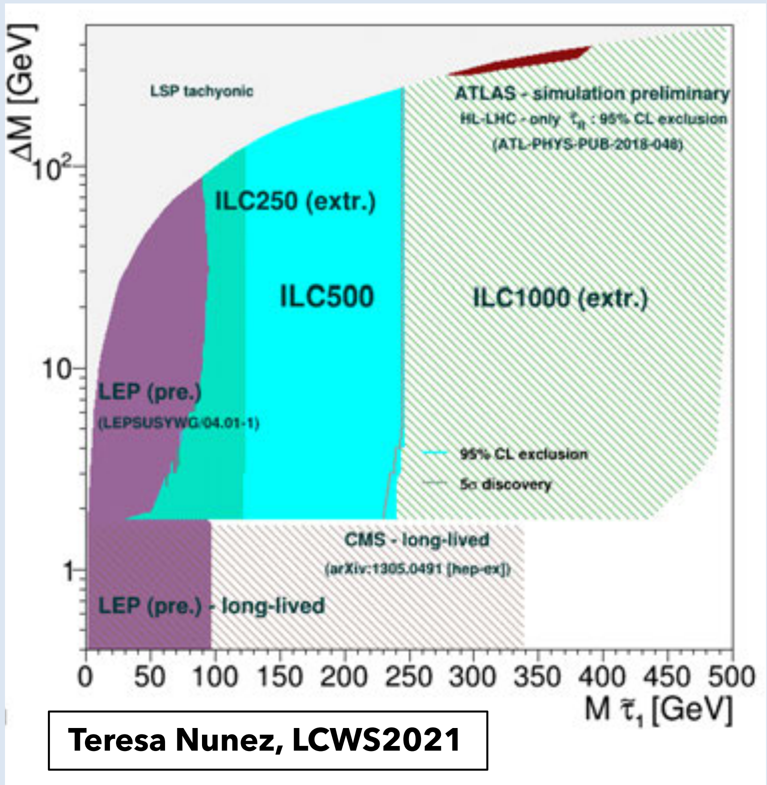


Stau search is an example where the increased luminosity of a LC, combined with the triggerless operation of the detectors, helps to significantly expand the reach.

Especially relevant for stau decays with small mass difference ΔM with respect to the LSP.

LC reach of staus: close to the kinematic limit

ILC stau reach



Higgsinos

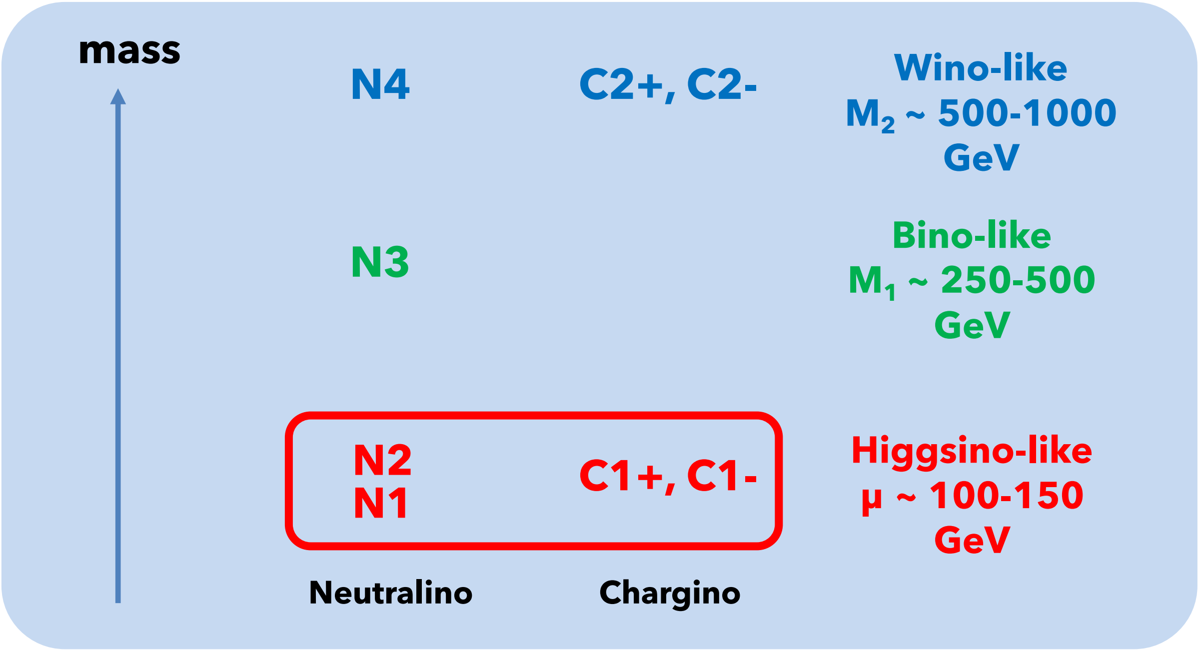
In the MSSM, the higgsino mass parameter μ enters directly into the mass relation:

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

If SUSY is realized in a natural way, the higgsino should be light around O(100) GeV.

The lower end of the range of higgsinos is already accessible at a Higgs factory.

Including the full energy upgrades, the LC can fully test natural SUSY.

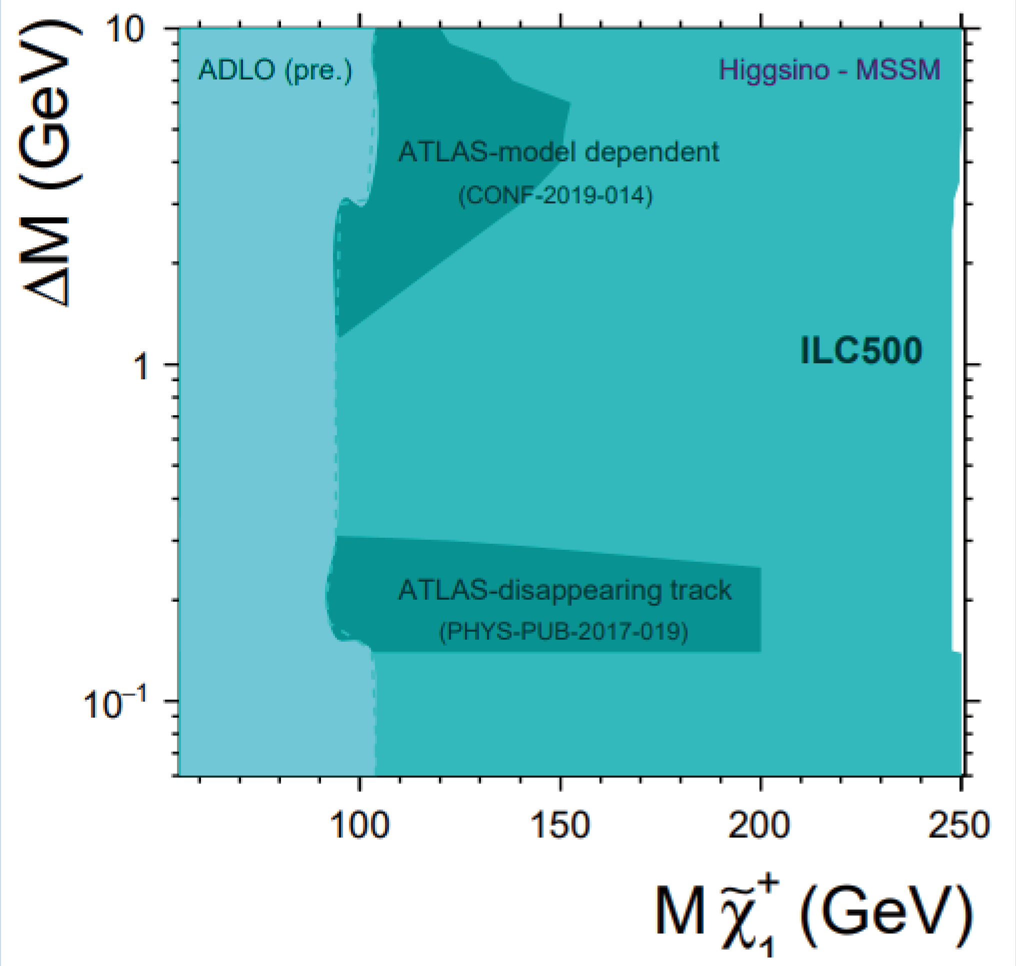


Characteristics of light higgsino + heavy gauginos:

higgsino-like neutralinos/chargino are very close in mass

Higgsino Search at LC

Higgsino Reach at ILC



Direct reconstruction

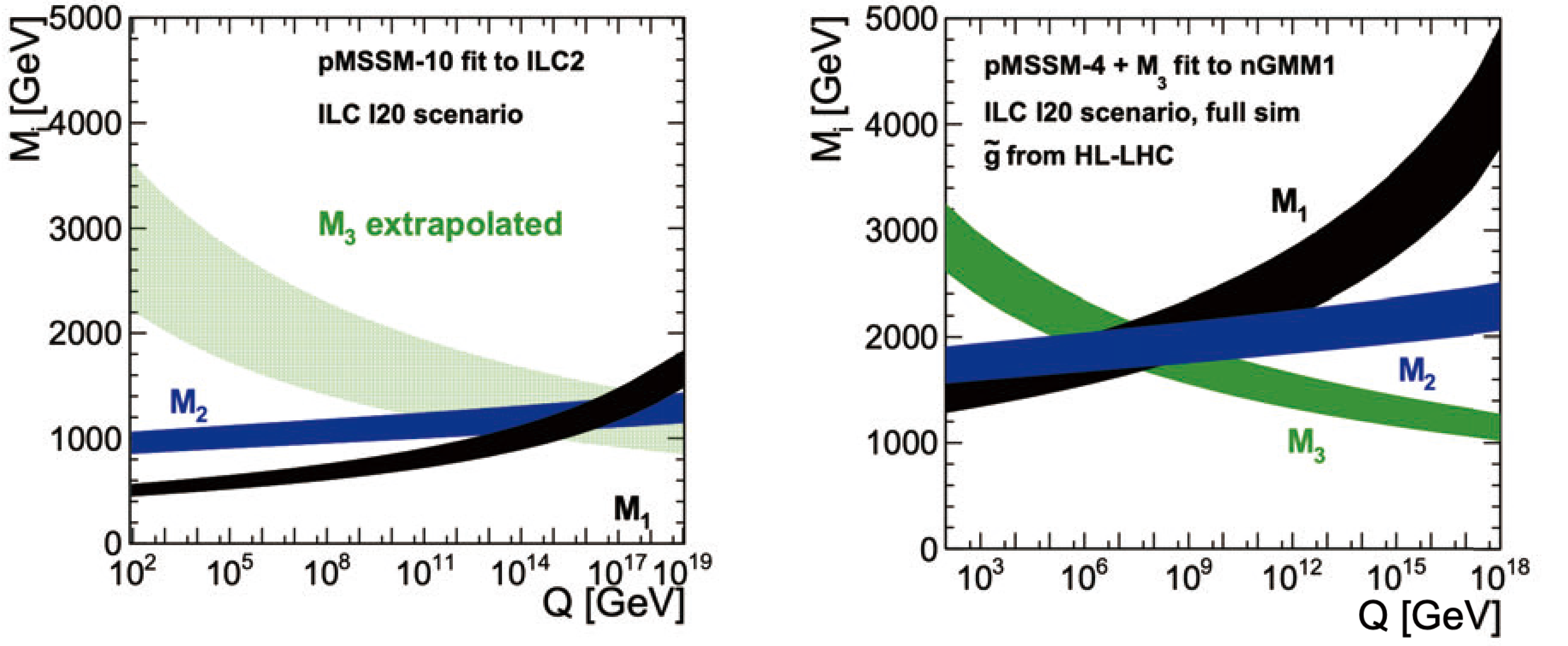
ISR tagging

Long-lived particles

Teresa Nunez, ICHEP2020 [2012.10155]

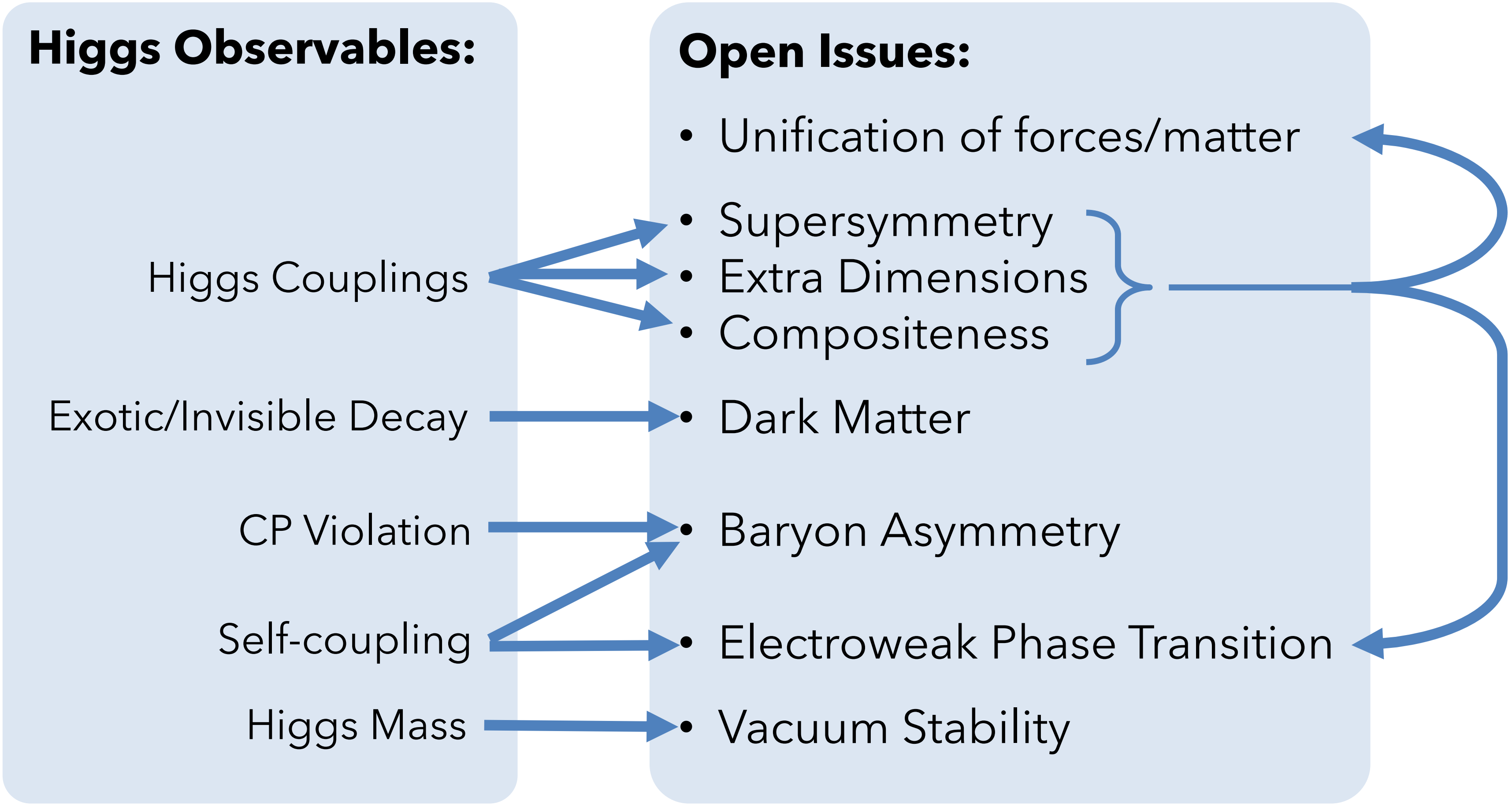
LC reach of higgsinos: close to the kinematic limit

Test of Gaugino Mass Unification

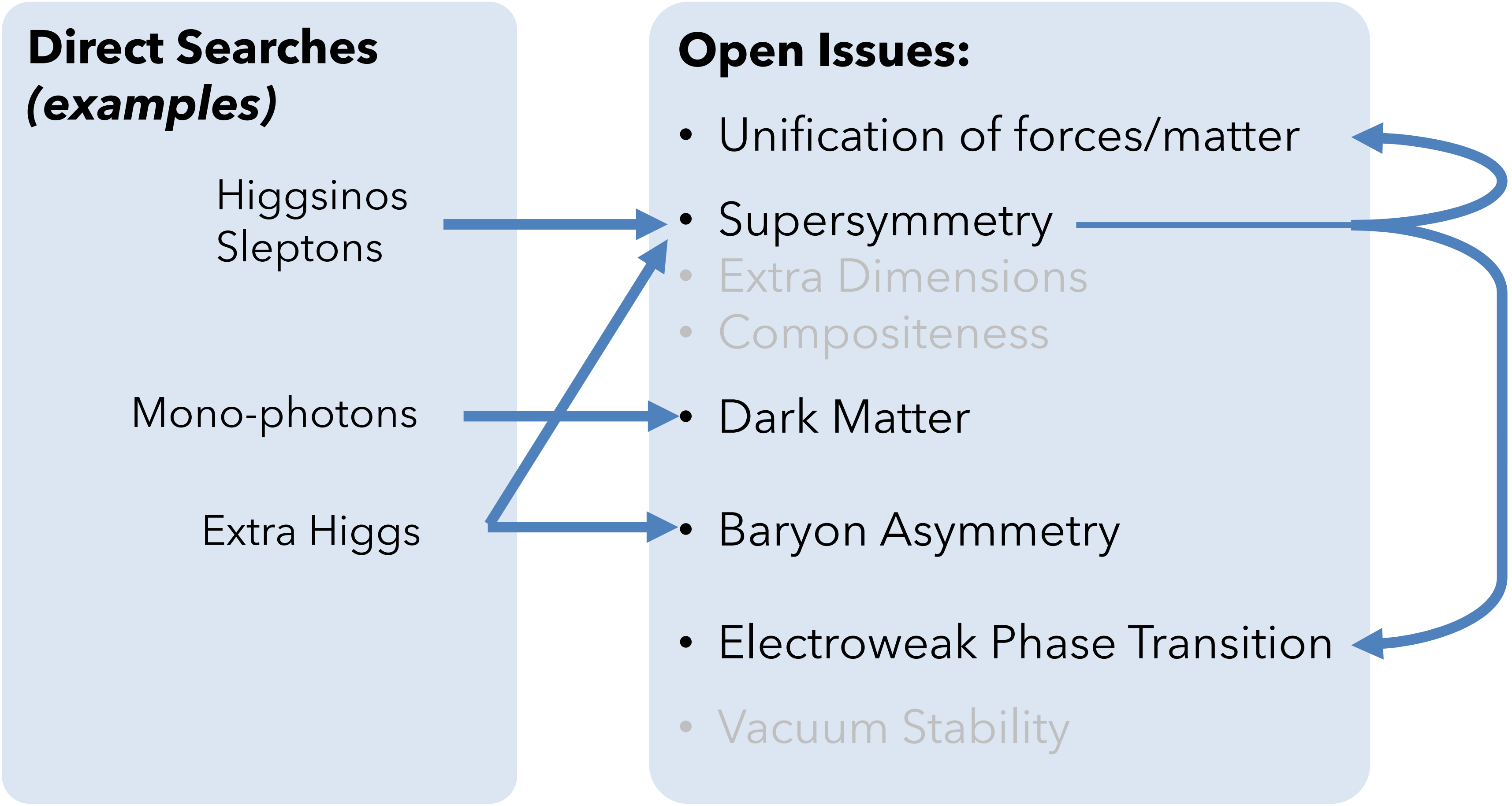


Discovery of higgsinos → Access to bino, wino masses through mixing.
→ Test of GUT-scale physics

Summary (1)


Higgs Observables:
Higgs Couplings
Exotic/Invisible Decay
CP Violation
Self-coupling
Higgs Mass
Open Issues:
• Unification of forces/matter
• Supersymmetry
• Extra Dimensions
• Compositeness
• Dark Matter
• Baryon Asymmetry
• Electroweak Phase Transition
• Vacuum Stability

Summary (2)


Direct Searches (examples)
Higgsinos
Sleptons
Mono-photons
Extra Higgs
Open Issues:
Unification of forces/matter
Supersymmetry
Extra Dimensions
Compositeness
Dark Matter
Baryon Asymmetry
Electroweak Phase Transition
Vacuum Stability