

# Snowmass ILC paper review: drawing overall picture

— based on Chapter 13 & 14

preliminary!

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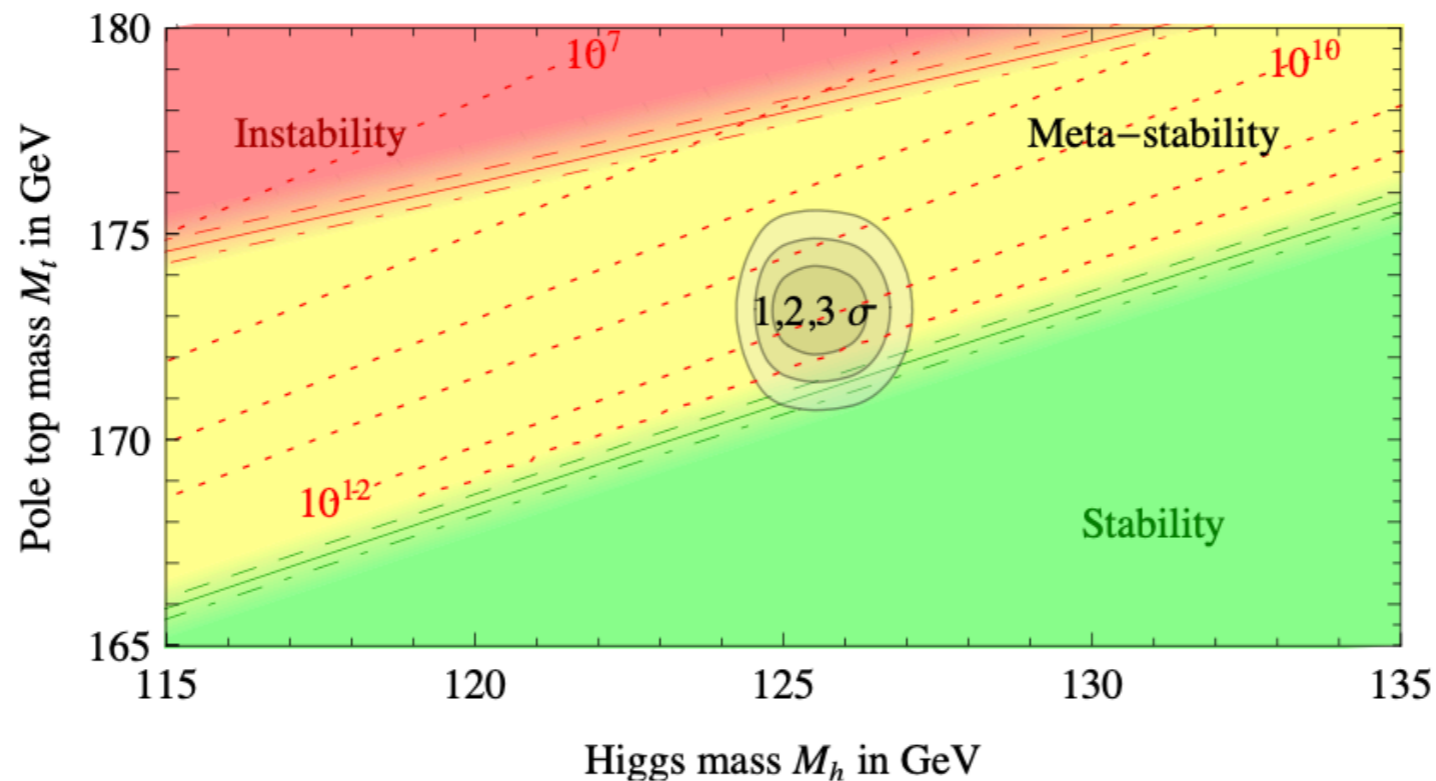
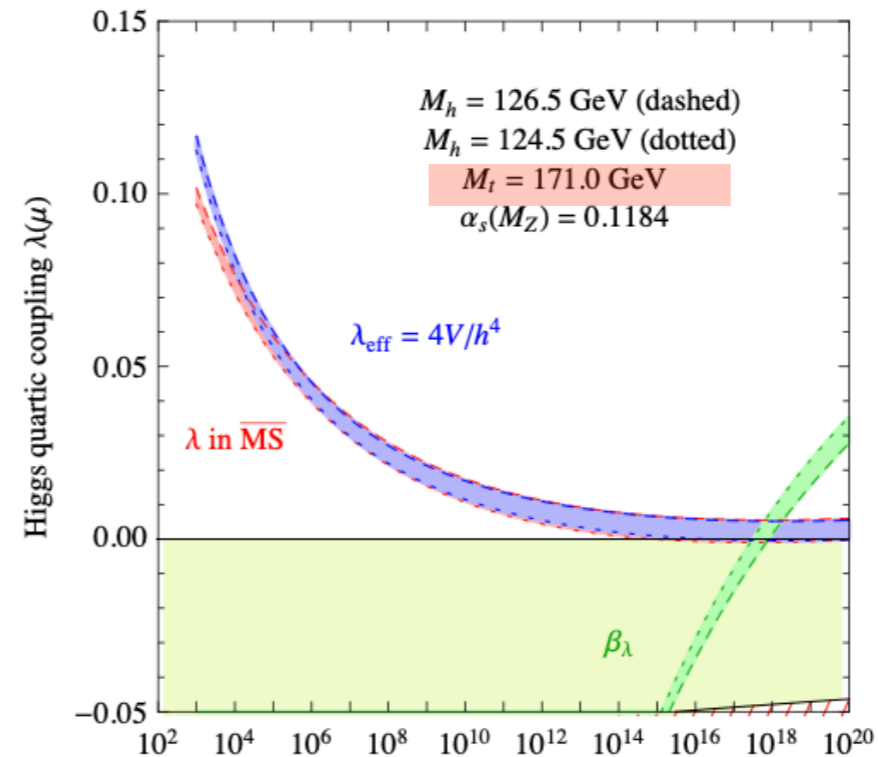
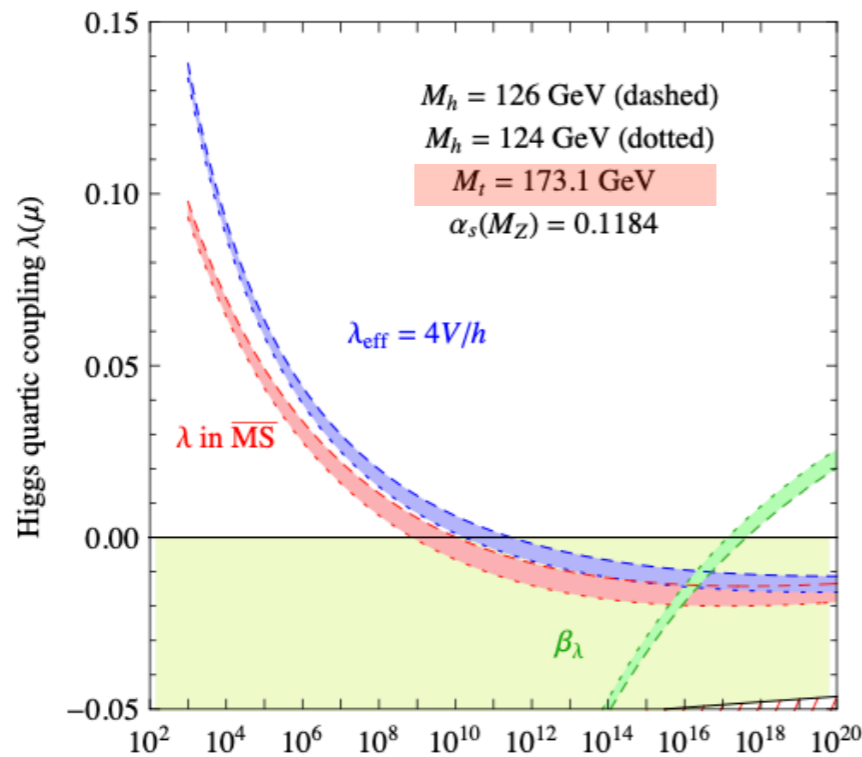
4th ILC-Japan General Physics Meeting, Sept. 4, 2023 @ U.Tokyo

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# 1. Can the SM be exact to very high energies?

- from the angle of EW vacuum stability:  $\lambda < 0$  at high scales?



ILC (350)

$\Delta m_t \sim 50 \text{ MeV}$

$\Delta m_H \sim 14 \text{ MeV}$

# Vacuum Stability

Meta-stable

Stable

Exactly aligned?

new discovery

SM is exact up to  $\sim 10^{10}$  GeV?

SM is exact up to Planck Scale?

Yes

No

No

Yes

How the early universe settled down?

Higgs is the inflaton?

Vacuum Stabilized by BSM  $\sim 1$  TeV

Extended Higgs sector

New symmetry e.g. SUSY

New space-time e.g. extra-dimensions

ILC: Precision Higgs; Direct New Particle Searches

## 2. Why is there more matter than anti-matter?

- Sakharov conditions: B, C, CP violations; out of thermal equilibrium
- SM: 2<sup>nd</sup>-order phase transition; CP-violating CKM angles not enough
- ILC role focused on Electroweak Baryogenesis models

New source of  
CP violation

ILC: Higgs CP

1<sup>st</sup>-order phase  
transition

in the EW transition

in the dark sector

ILC: Heavy neutrinos etc

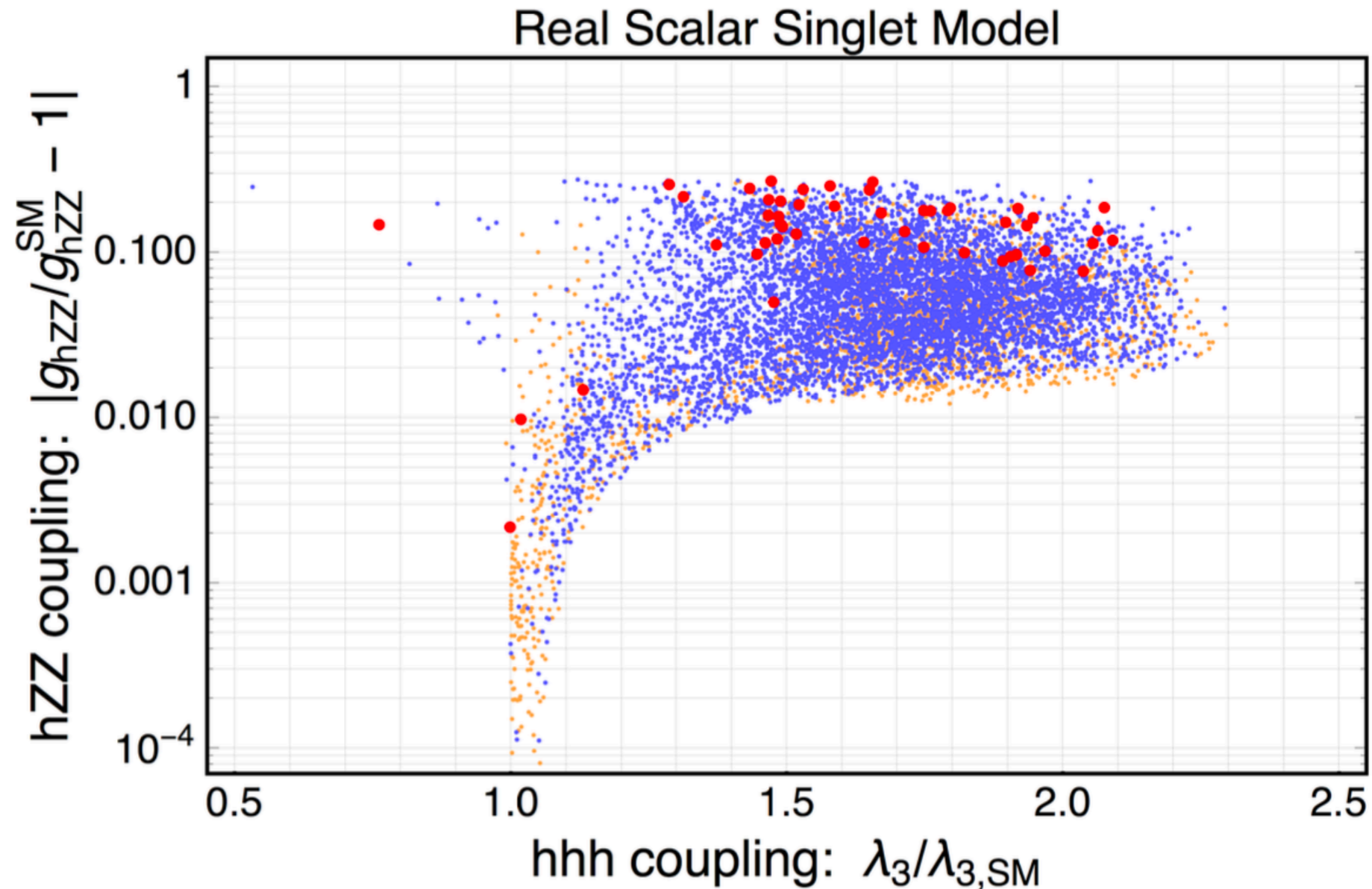
new particles < 1 TeV

deviation in Higgs couplings

ILC: extra gauge-singlet scalars

ILC:  $\lambda_{hhh}$ ,  $hZZ$  etc

## 2. Why is there more matter than anti-matter?



orange: first-order phase transition

blue: strongly first-order phase transition ( $v/T > 1.3$ )

red: very strongly first-order phase transition (GW @ eLISA)

## 2. Why is there more matter than anti-matter?

- Leptogenesis models are also possible; ILC plays a role as well

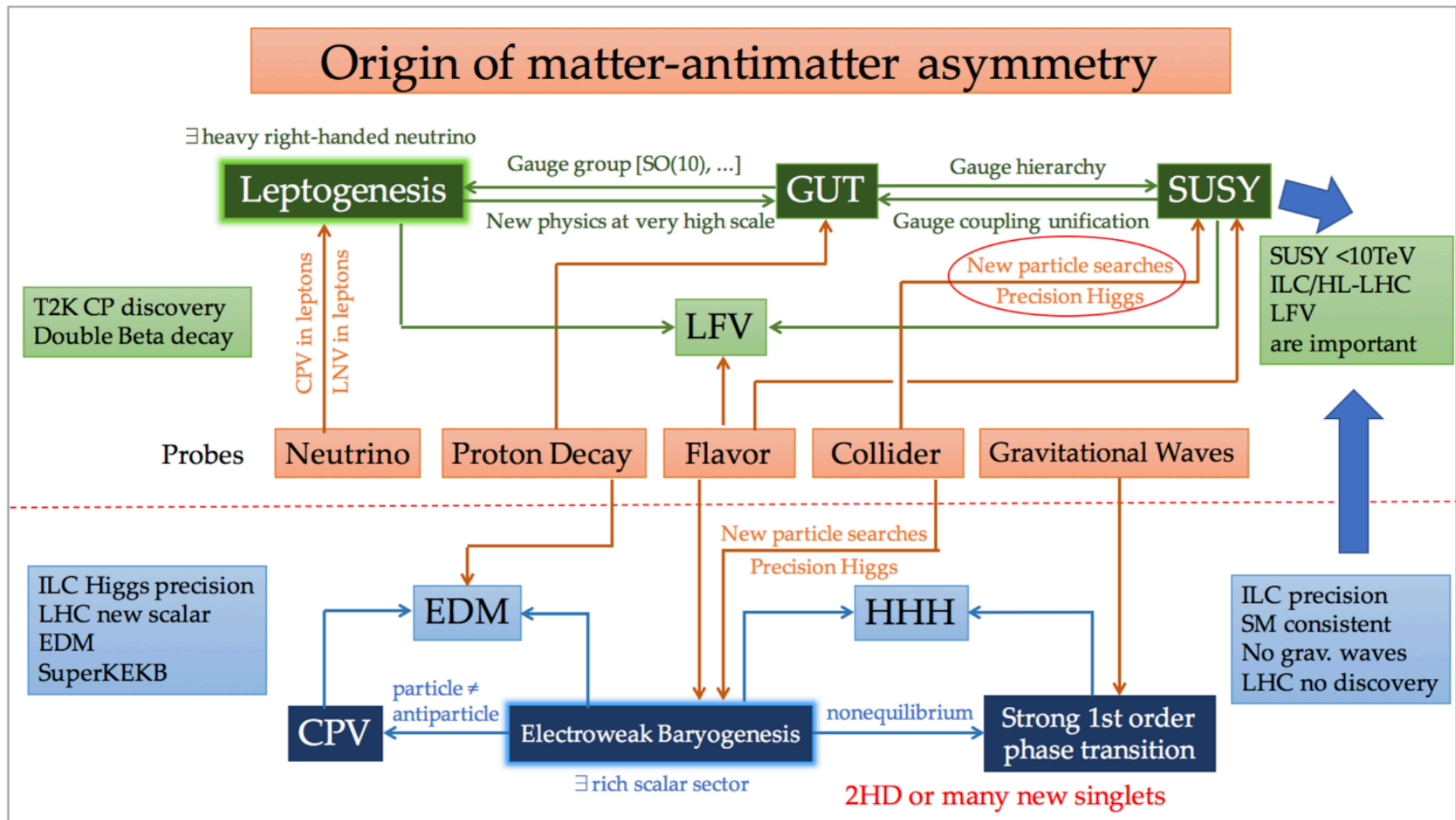
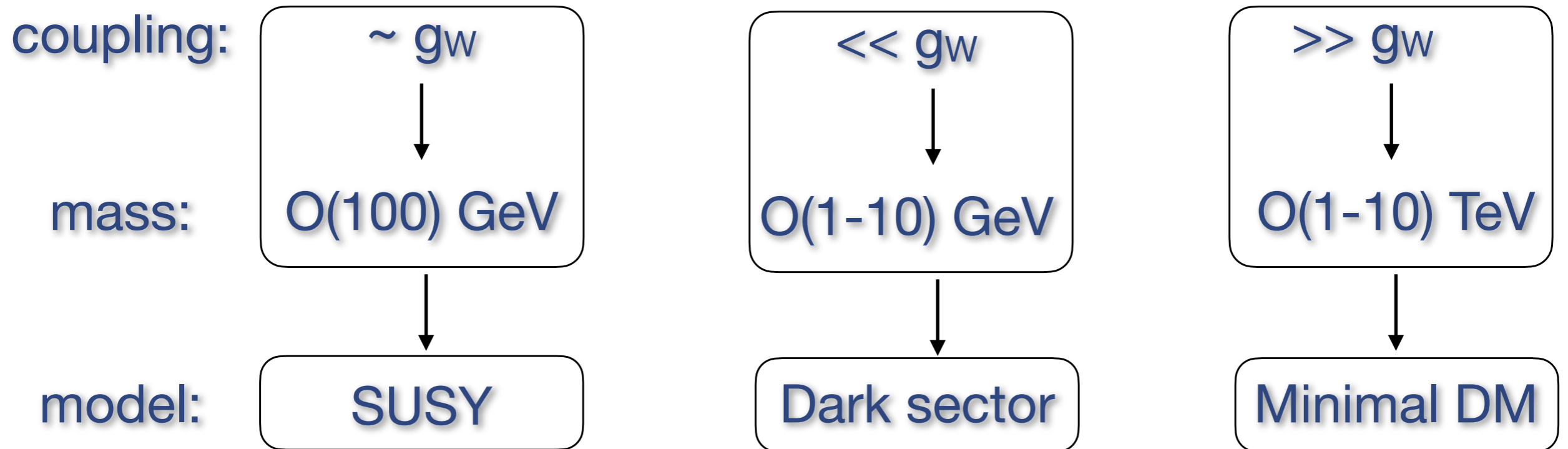


Figure 3: Origin of matter-antimatter asymmetry.

[S. Asai et al, ILC250 scientific case by JAHEP; arXiv: 1710.08639]

### 3. What is the dark matter of the universe?

- Viable enormous range of masses by 10s of orders
- ILC role focused thermal WIMP, GeV-TeV
- Guided by observed relic density, annihilation  $\sigma \sim 1 \text{ pb}$ : WIMP masses and couplings fall into three categories



ILC: Higgsino, stau,  
loop hole-free search

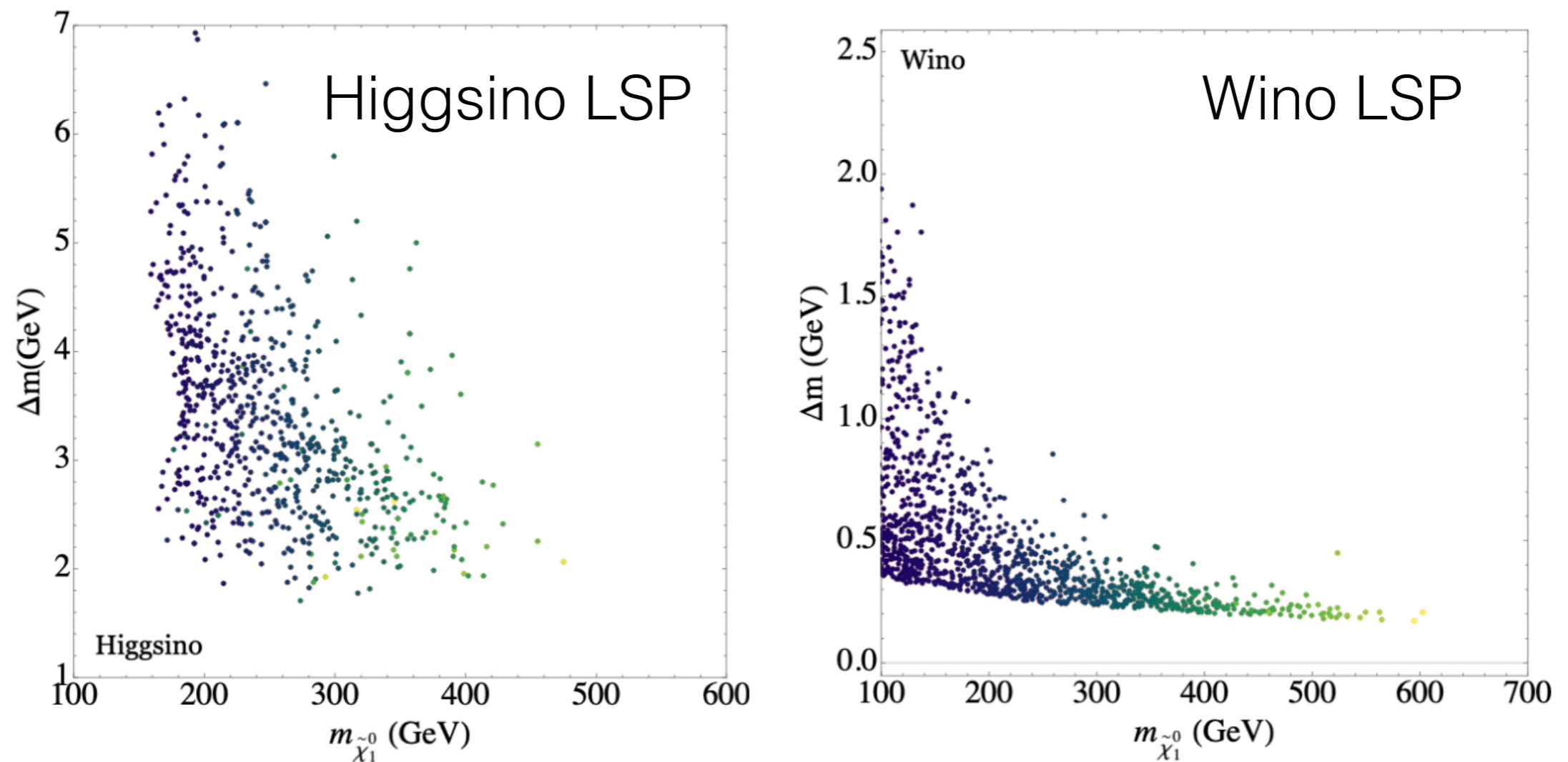
ILC: "Portal" by photon,  
Higgs, neutrinos,  
Fixed Target exp.

ILC: long-term  
future



### 3. What is the dark matter of the universe?

Scan of MSSM parameters: consistent with constraints from  $(g-2)_\mu$

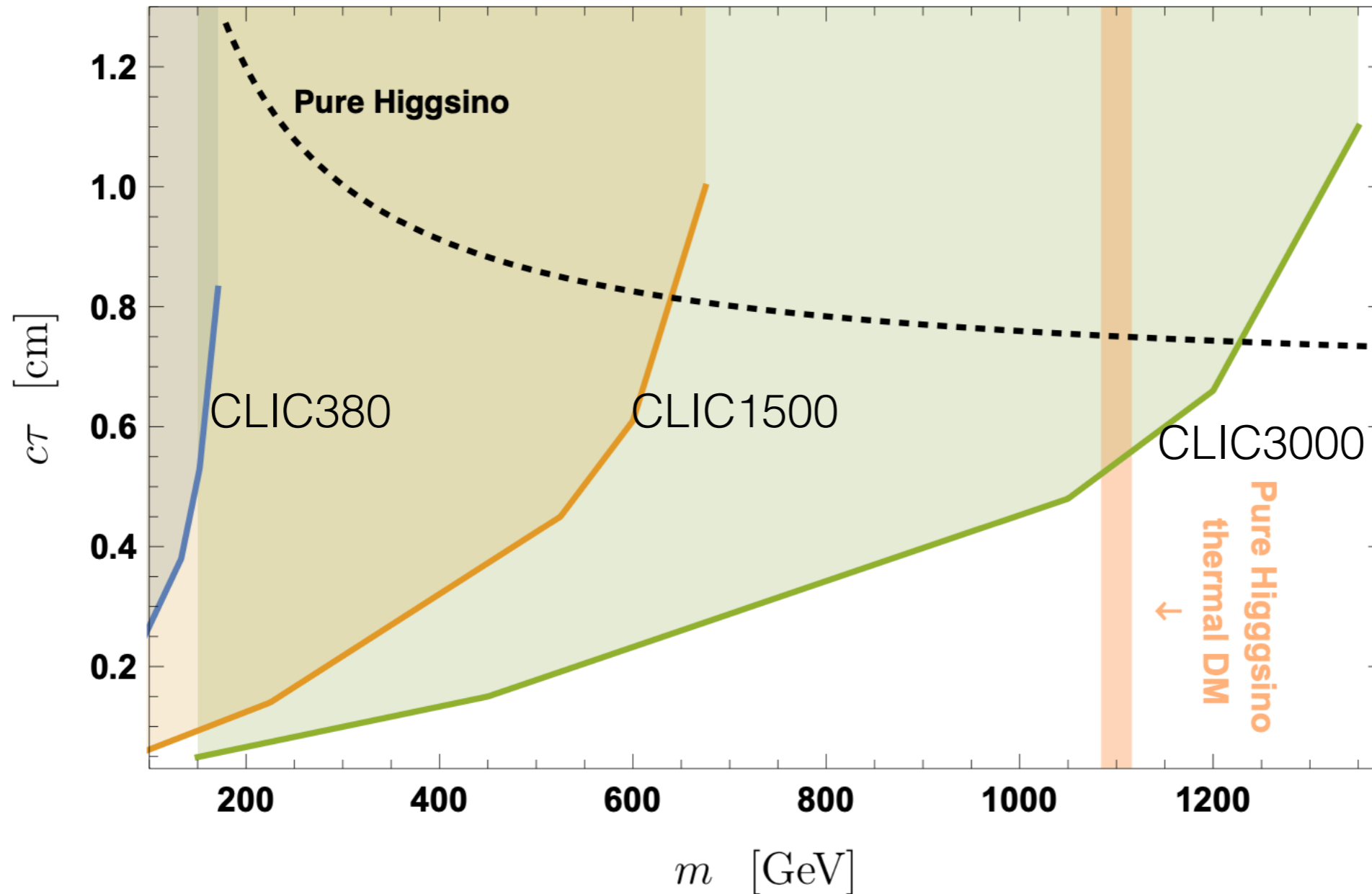


color: value of the LSP dark matter density

full coverage by  $\sim$  ILC (1000)

### 3. What is the dark matter of the universe?

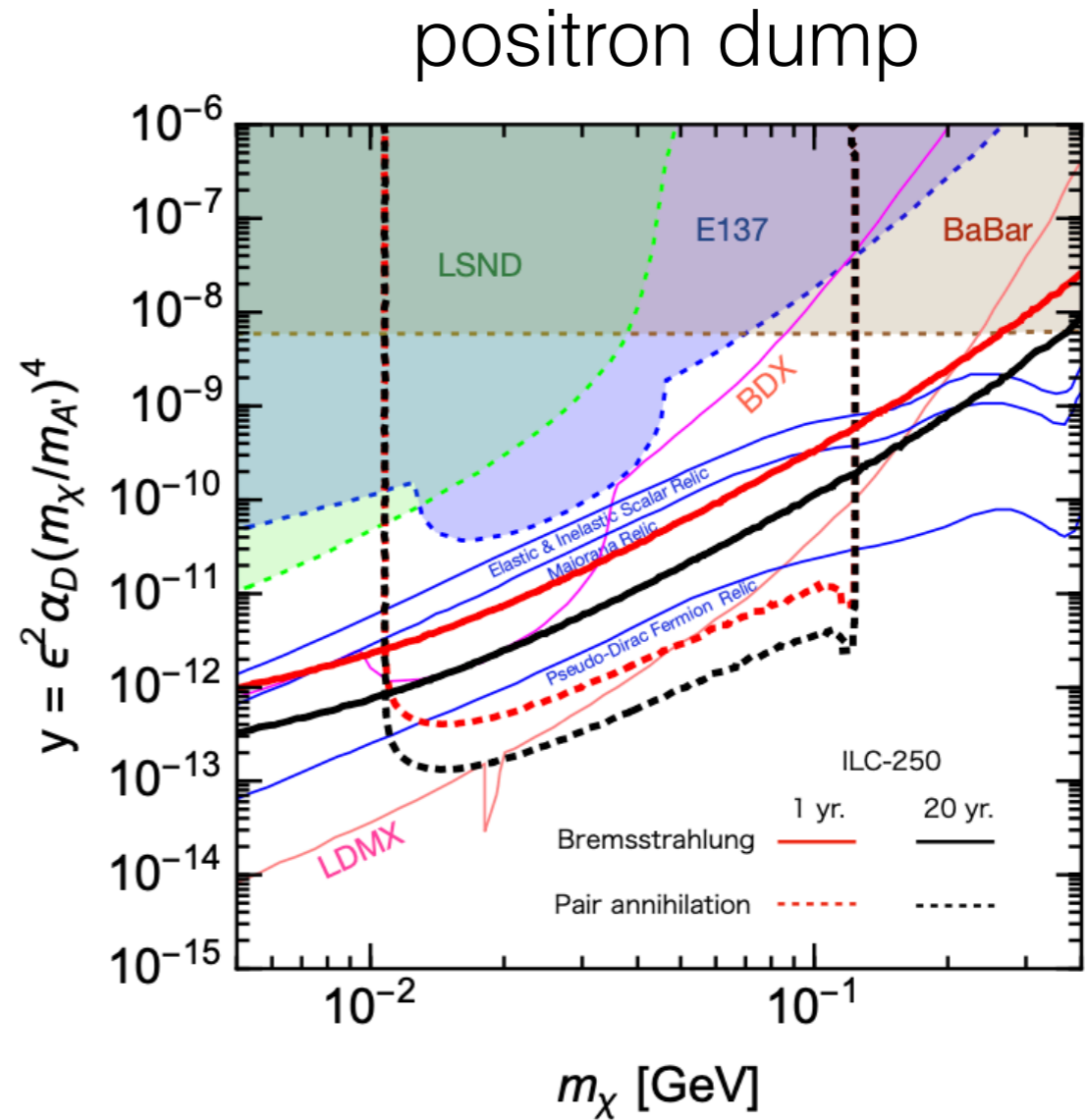
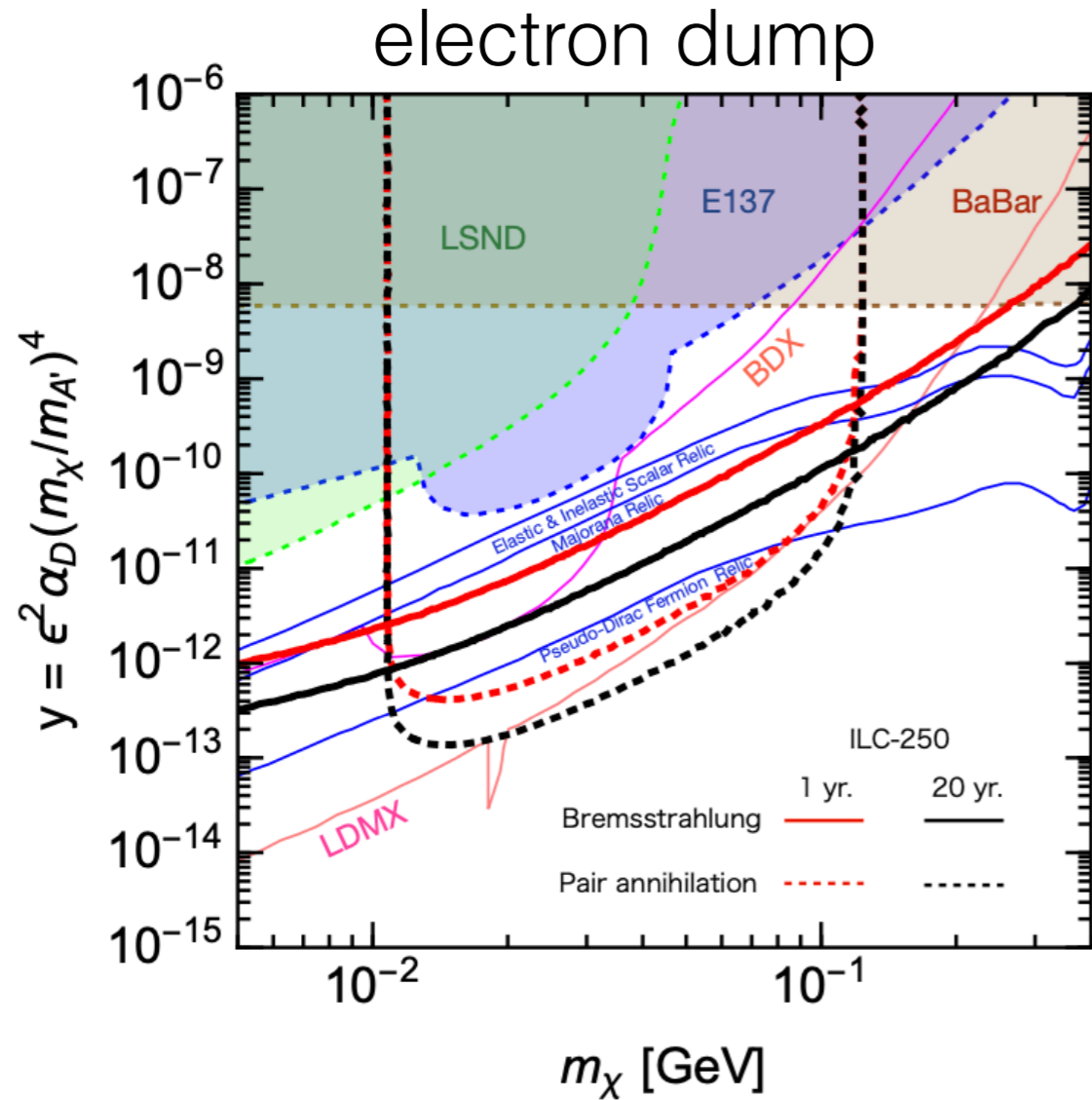
Pure Higgsino



covered by  $\sim$  ILC multi-TeV

# 3. What is the dark matter of the universe?

Dark photon portal



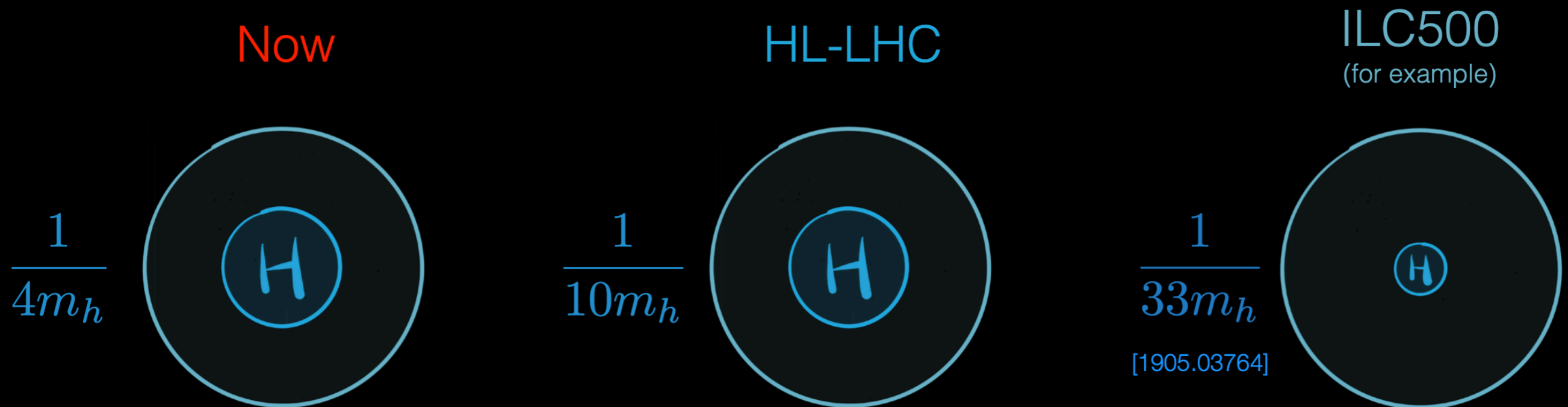
covered by ~ ILC fixed target experiment

## 4. What is the energy scale of new physics?

- Deviation from SM will tell us the new physics scale
- EFT approach by Wilson coefficient: for  $c \sim O(1)$ , 1% level deviation will indicate  $O(1\text{TeV})$  new mass scale

Figure of merit: Higgs “size” vs Compton wavelength. Beginning to probe the size of the Higgs at the LHC, but not yet to  $\pi$ -like compositeness

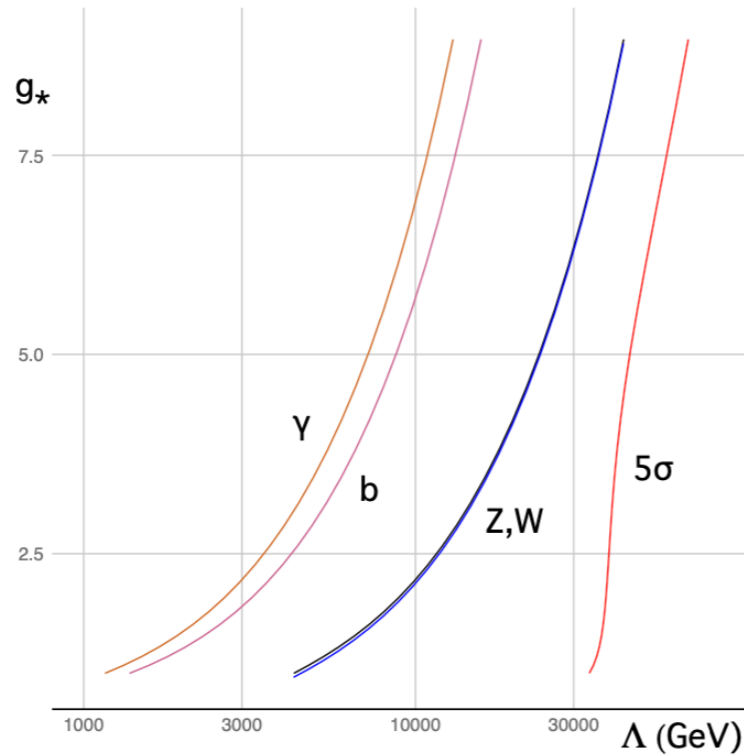
More precisely: bound “size” corrections, e.g.  $\mathcal{O}_H = \frac{1}{2\Lambda^2} (\partial_\mu |H|^2)^2$



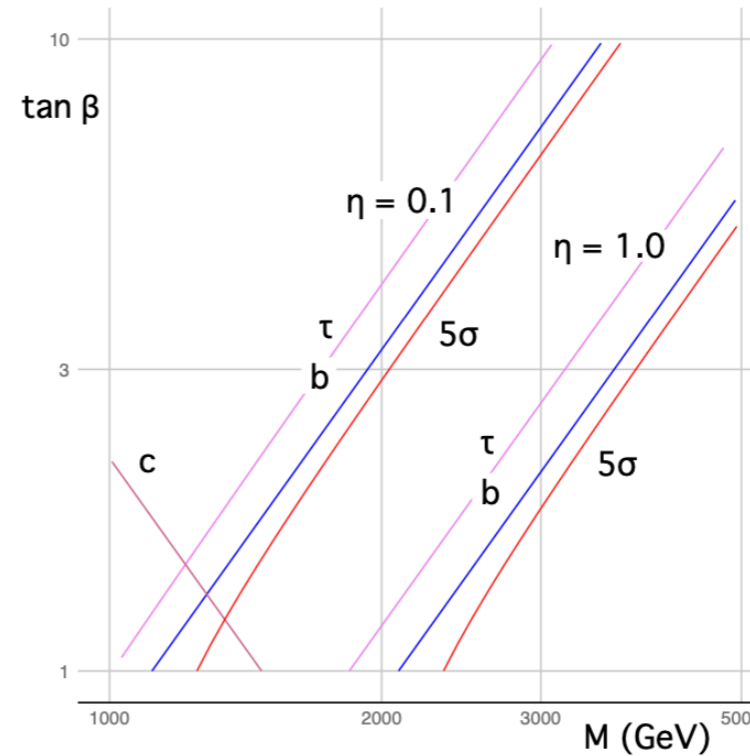
# 4. What is the energy scale of new physics?

- Concrete model approach

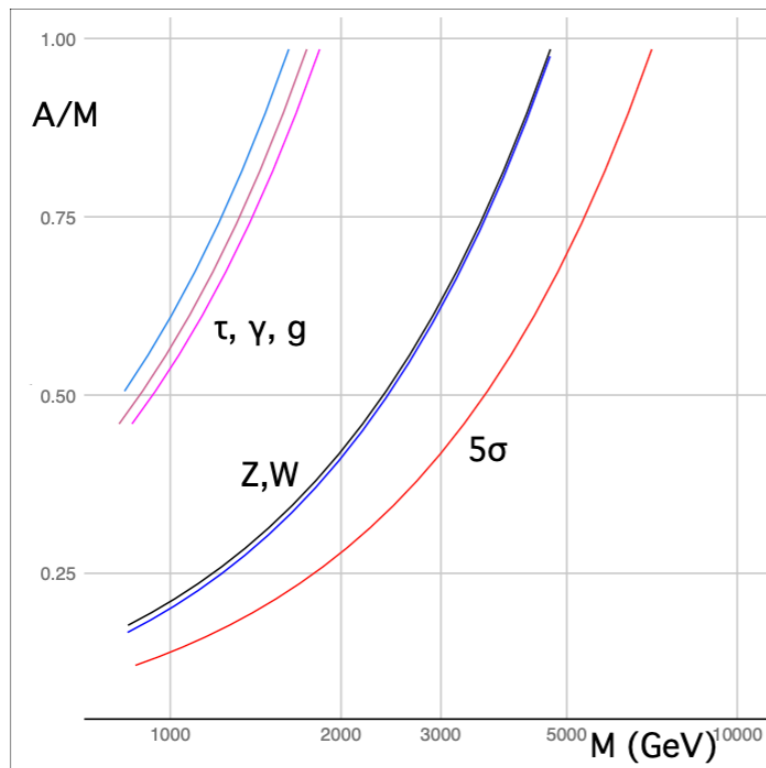
SILH



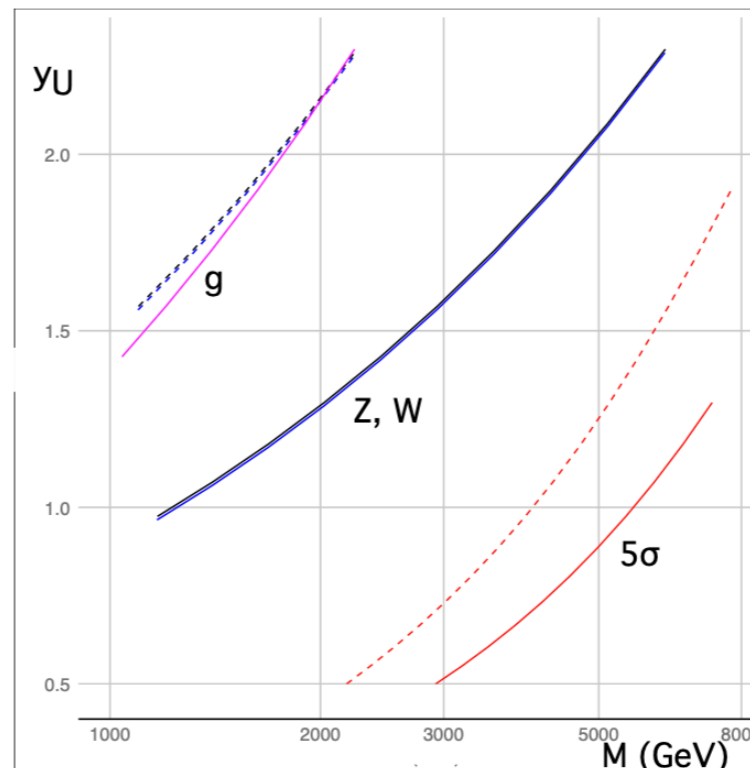
2HDM



scalar singlet



vector-like quark

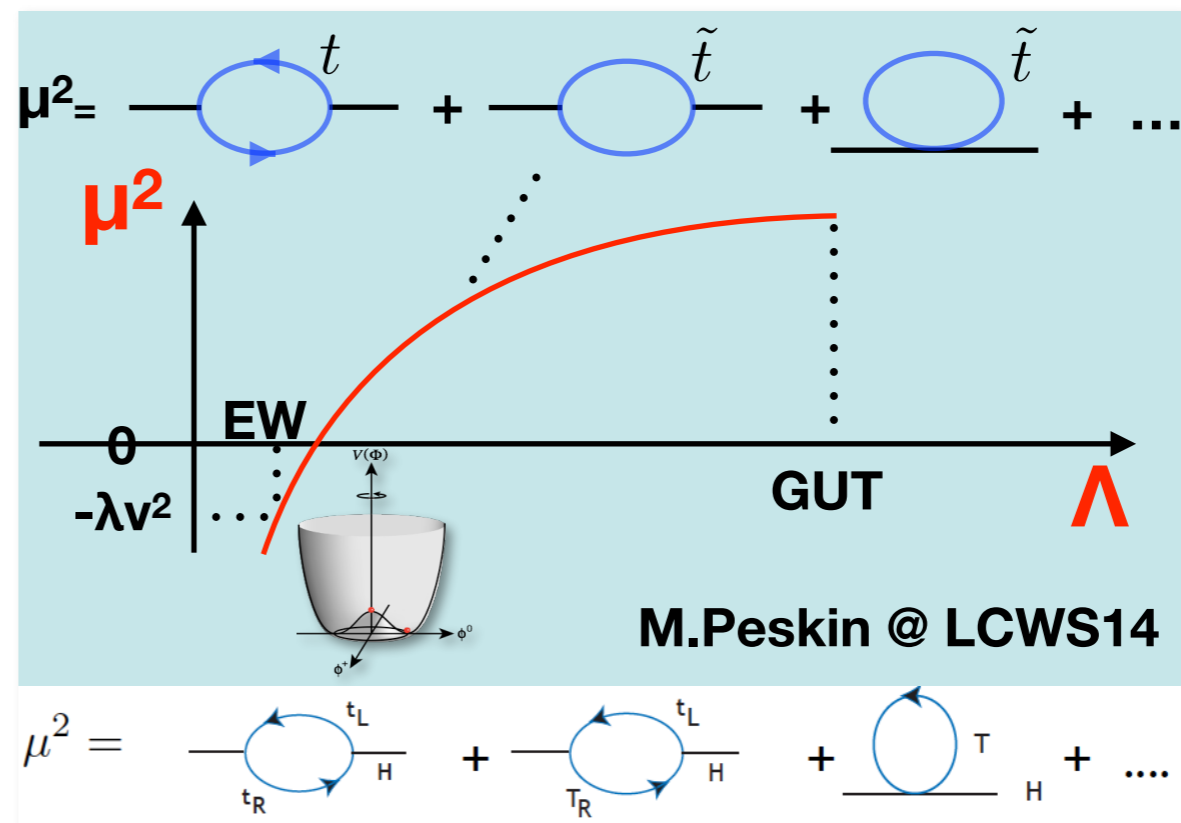
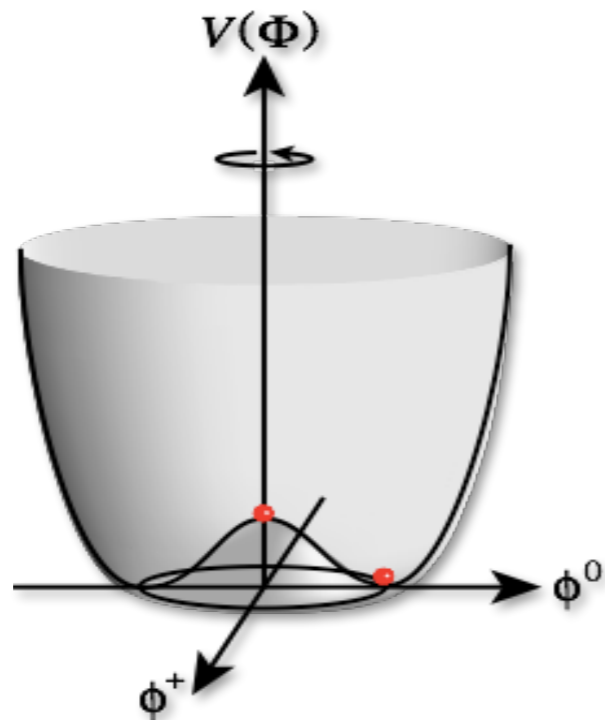


ILC can discover new physics scale well above multi-TeV

# 5. Why is electroweak symmetry breaking?

- Why  $\mu^2 < 0$ ?
- Underling physics responsible for generating it  $\sim \text{TeV}$
- ILC: deviations by MSSM, Composite, Extra Dimensions

$$V(|\Phi|) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

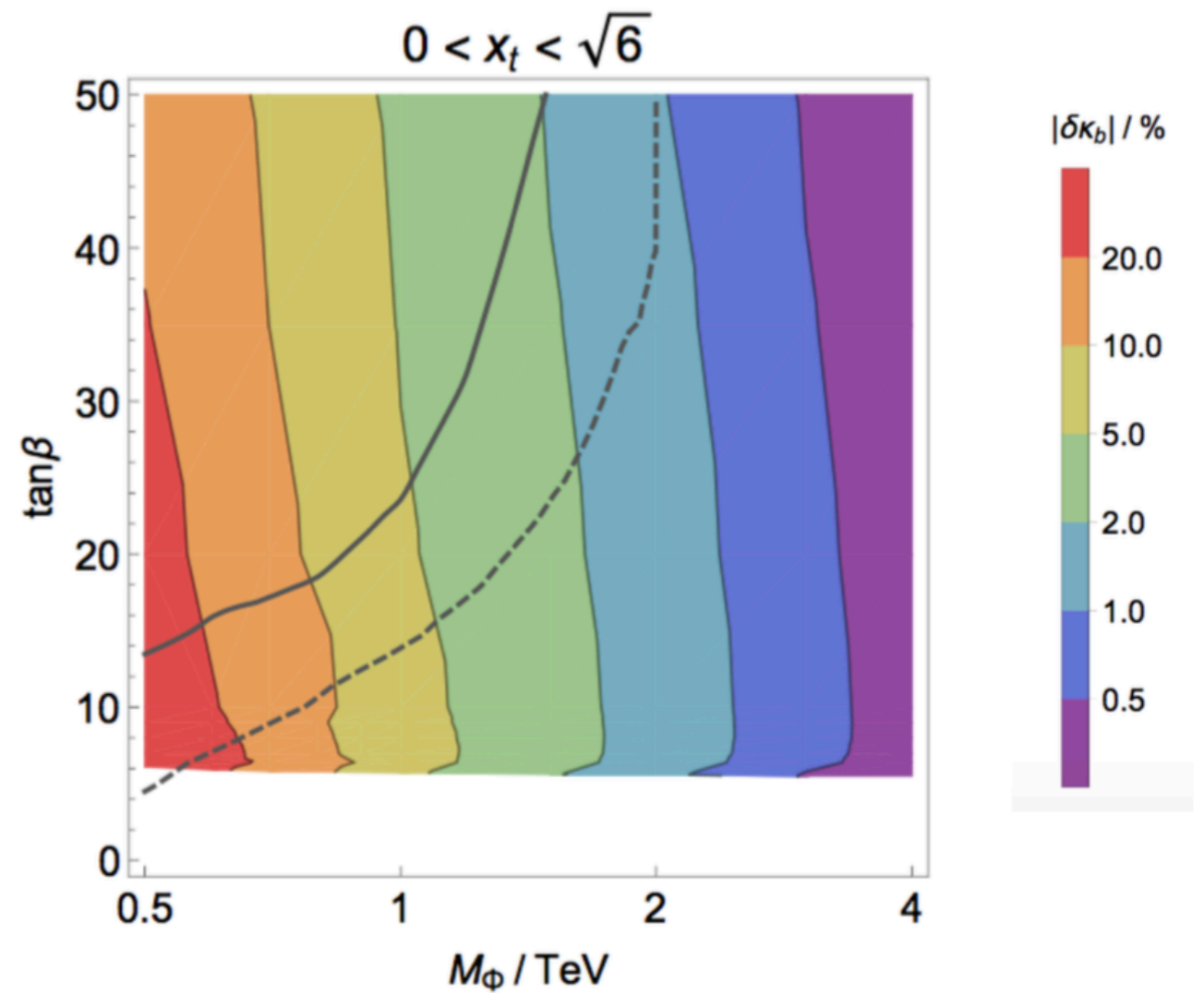
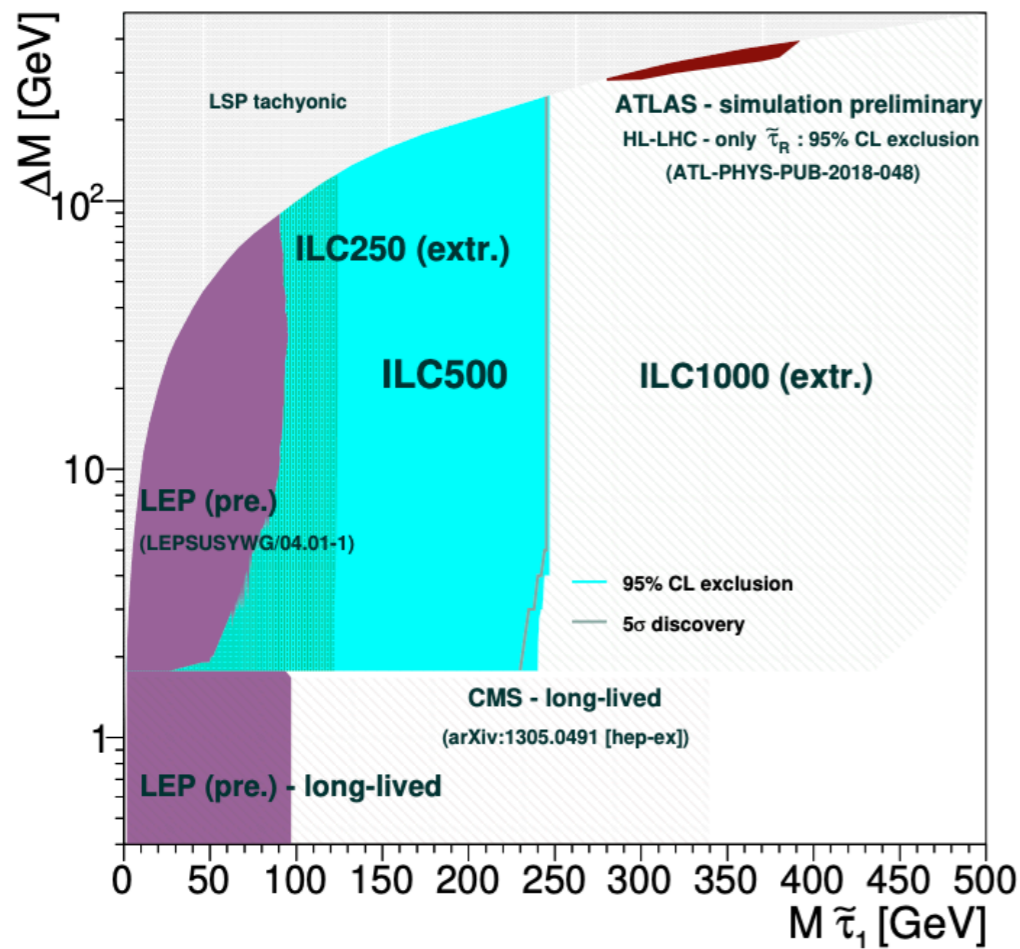


$$M_H^2 = M_{\text{tree}}^2 + \left( \text{Higgs loop} \right) + \left( \text{top quark loop} \right) + \left( \text{WZ loop} \right) + \left( \text{BSM} \right)$$

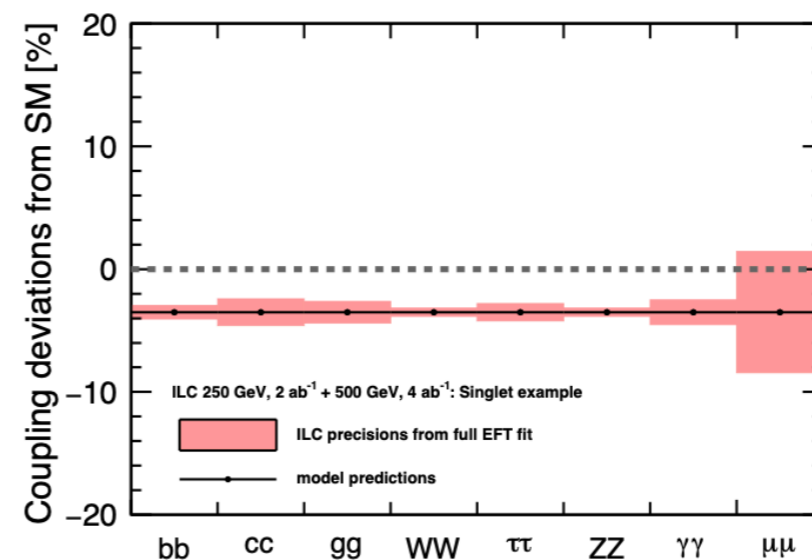
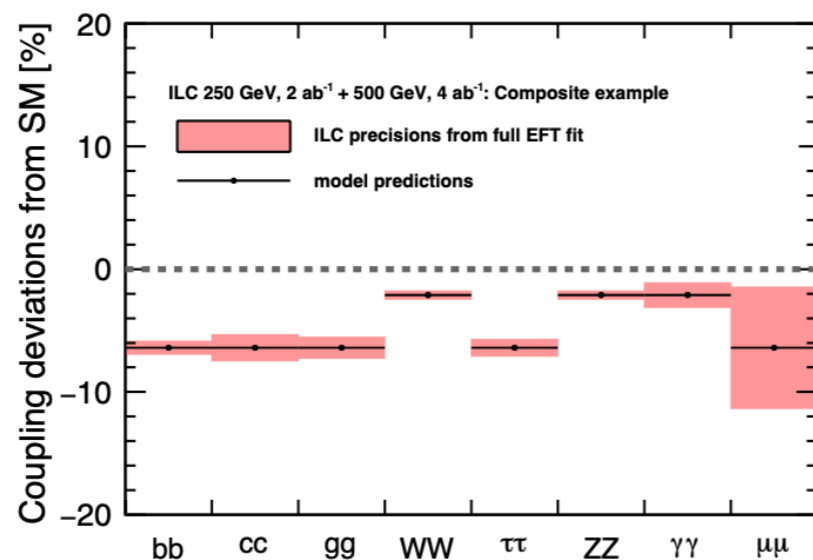
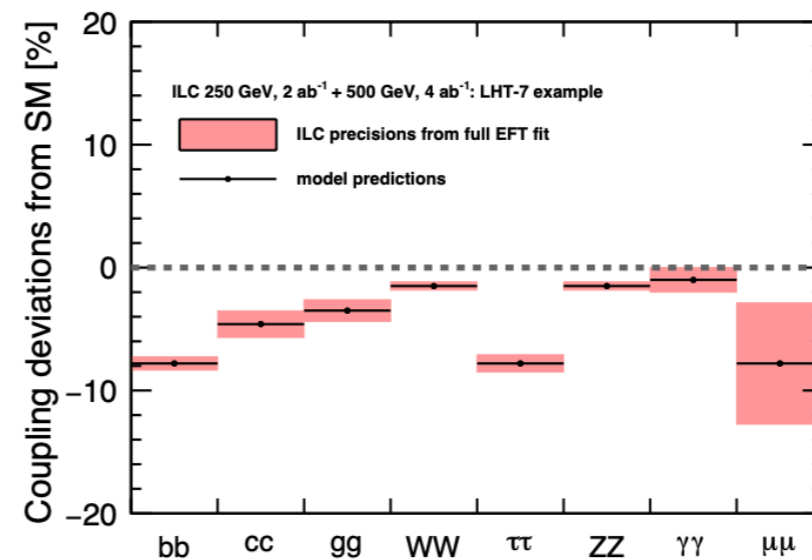
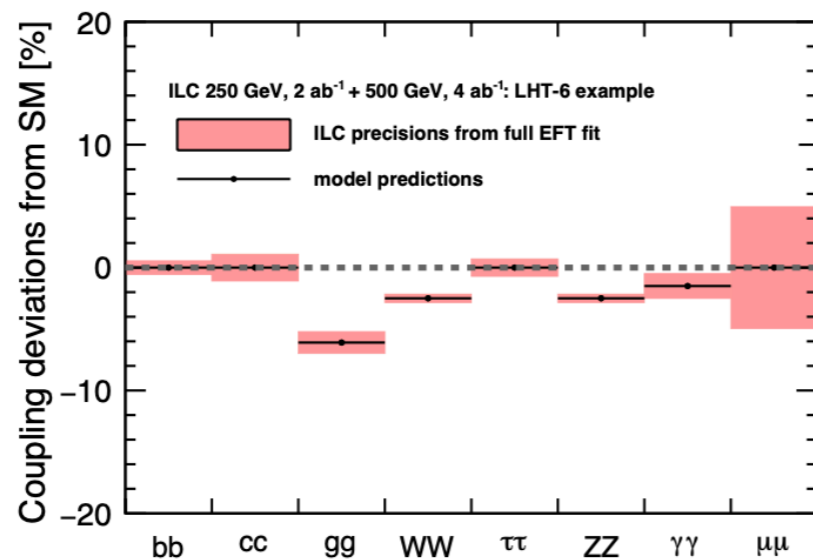
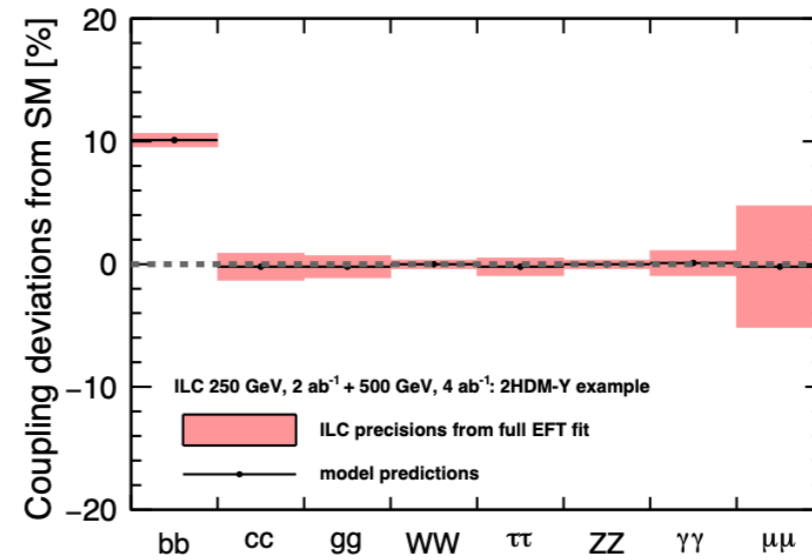
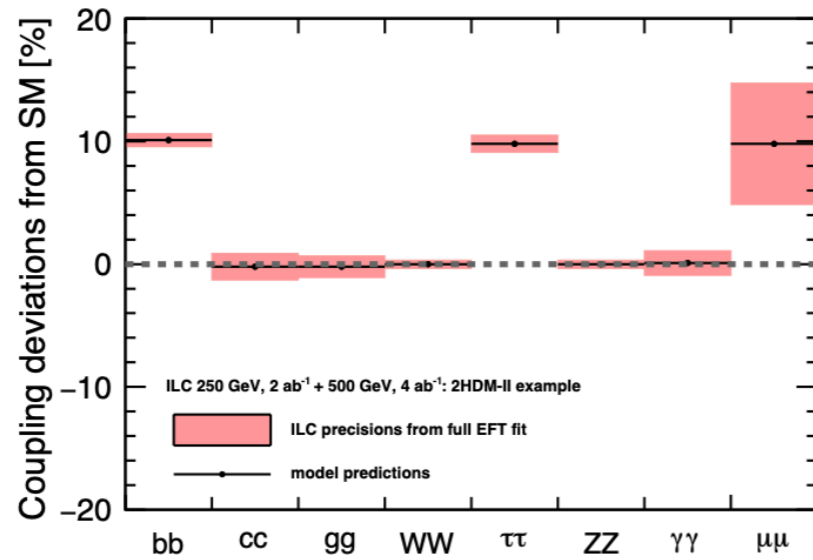
# 6. Concrete Models: ILC & SUSY

Direct Search

Indirect by precision Higgs coup.



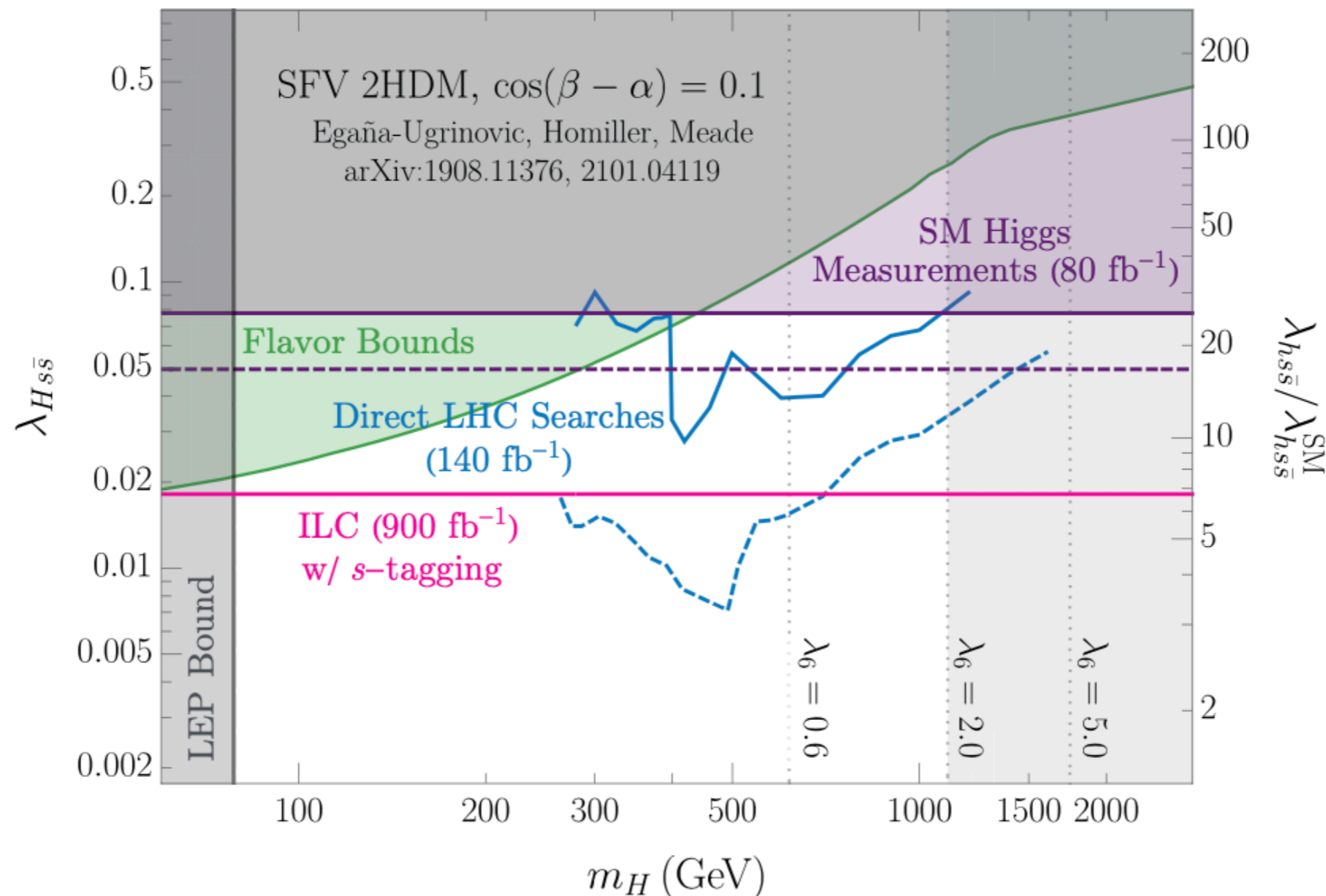
# 7. Higgs Inverse Problem





## 8. ILC and flavor

- Origin of fermion masses: ILC can measure Yukawa couplings to top, b,  $\tau$ , c,  $\mu$ , (s)
- Test of CKM unitarity: ILC  $W$  hadronic branching gives a tight constraint on first two rows of CKM elements



# Summary

