The International Linear Collider: Report to Snowmass 2021

THE ILC INTERNATIONAL DEVELOPMENT TEAM AND THE ILC COMMUNITY

arXiv:2203.07622v3

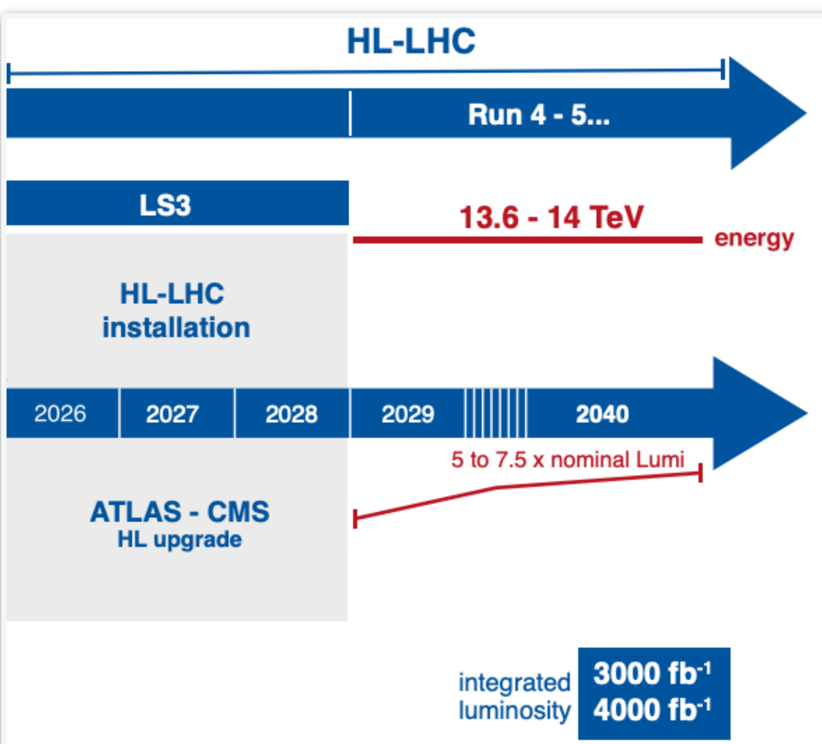
ILC250

Energy Extension

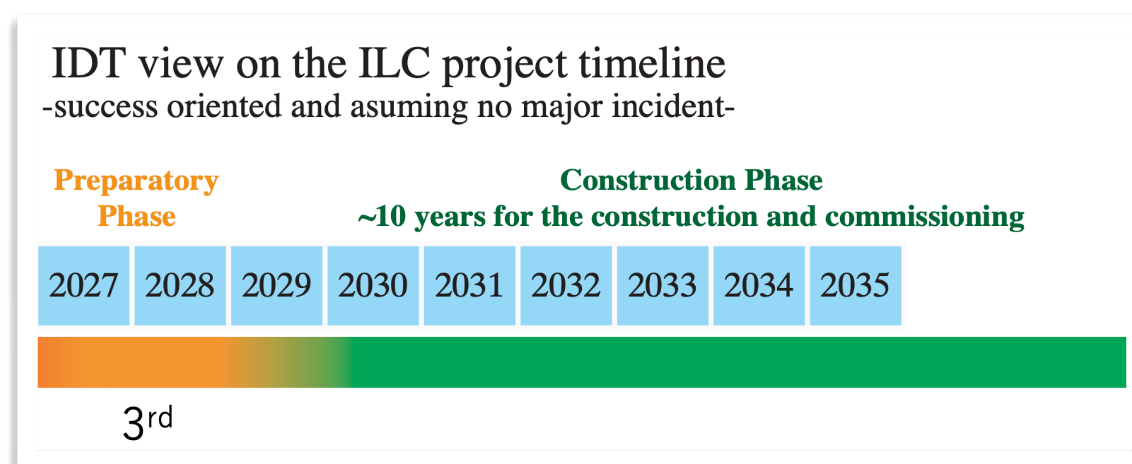
A Set of Physics Program at the ILC 250, 380, 1000

They can be a Killer Science in 2040?

(late 2030?)

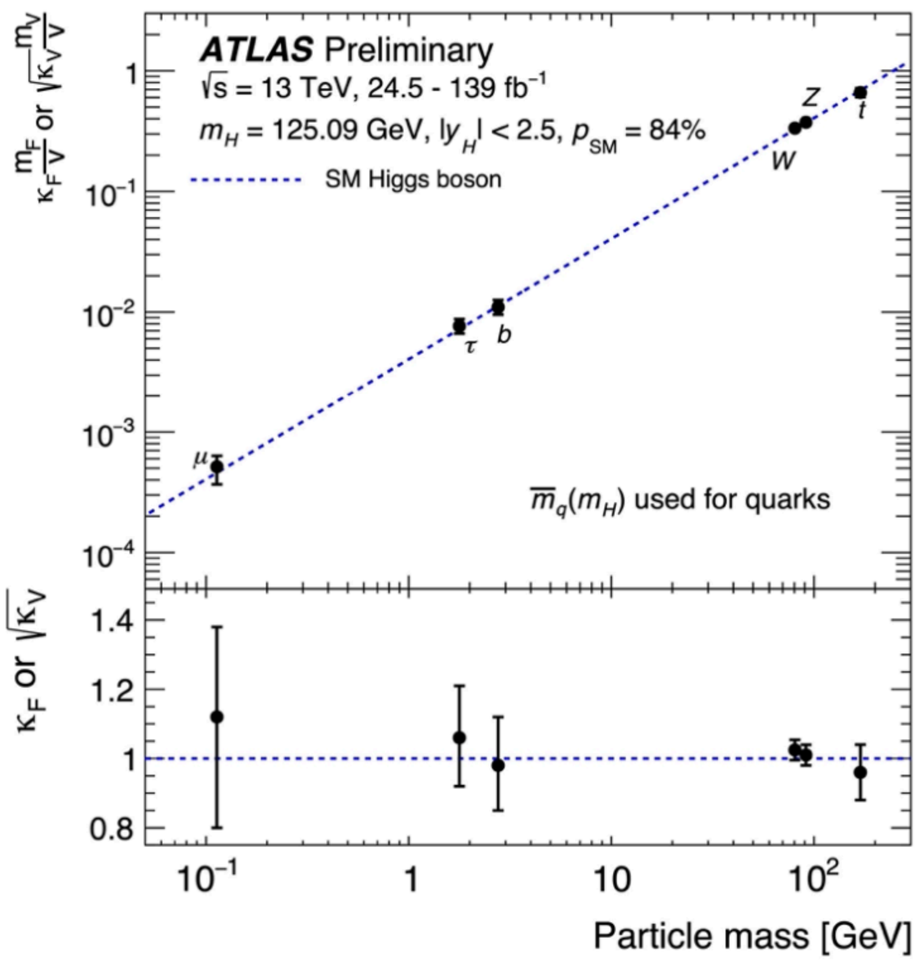


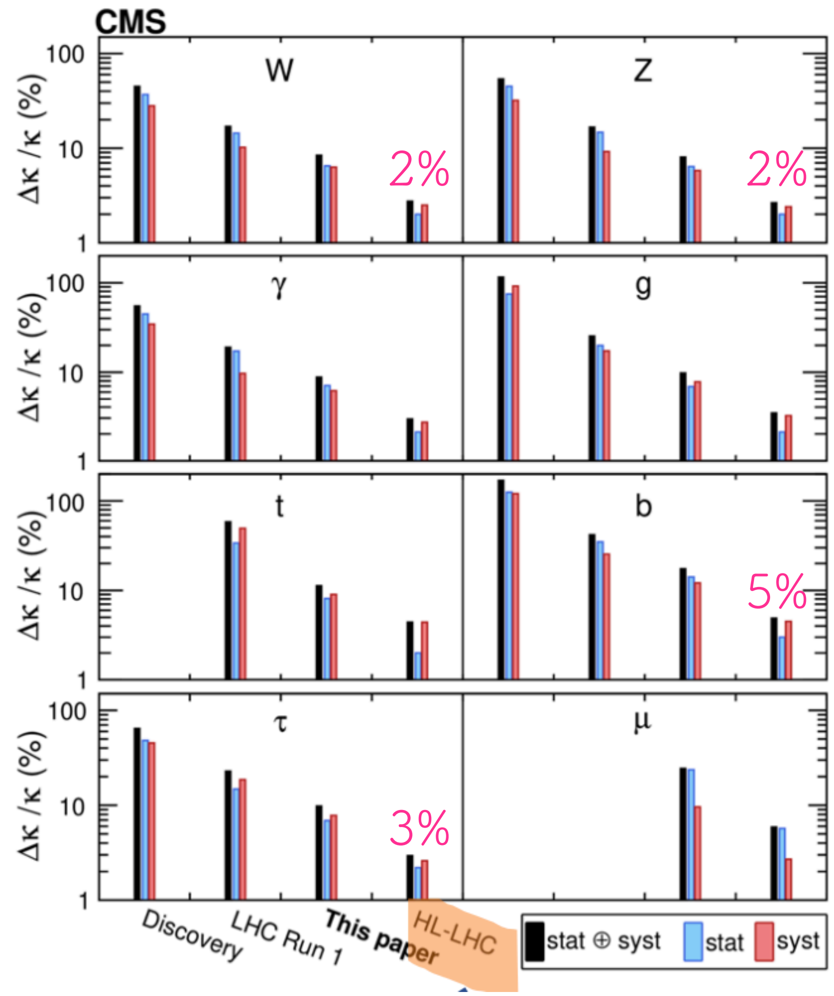
HL-LHC Run4 (Start 2029) for ~ 10+ years



Coupling Measurement of Hff/HVV @ HL-LHC

(HL-) LHC





$\kappa = g_X / g_X^{SM} = 1 + \Delta\kappa$

$\Delta\kappa \sim O(v^2/\Lambda^2)$

e.g. A New Phys. at 1TeV

Expected Deviation **~6%**

- Higher accuracy w.r.t. HL-LHC may be necessary
- Higher accuracy probes higher energy scale

Precision in Run-2

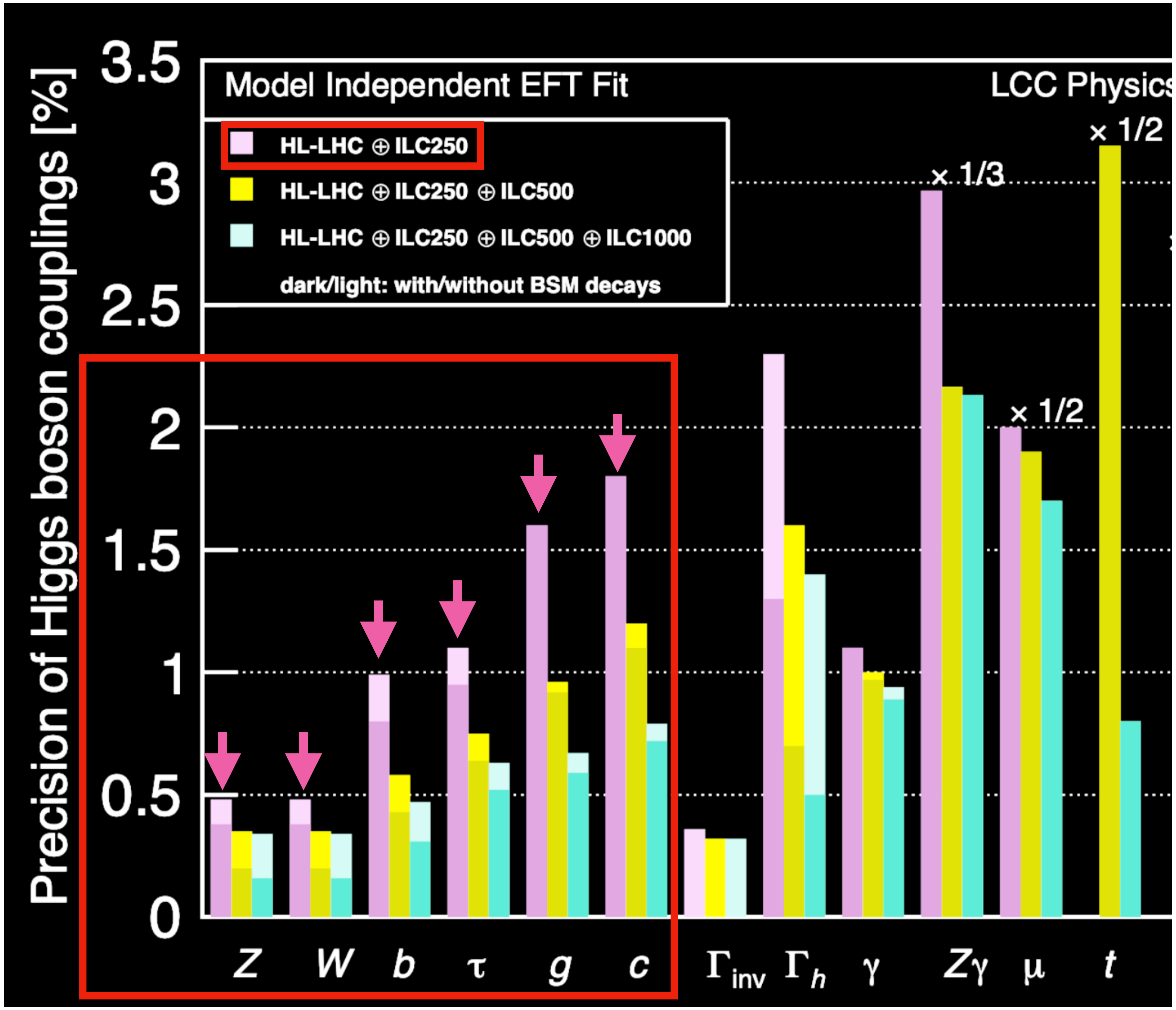
- W/Z: 5-10%
- 3rd Gen.: 10%
- 2nd Gen.: First Obs.

→

HL-LHC

- **2-5%** for most of the channels

Coupling Measurement @ HL-LHC + ILC250



$\kappa = g_X / g_X^{SM} = 1 + \Delta\kappa$

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e.g. A New Phys. at 1TeV

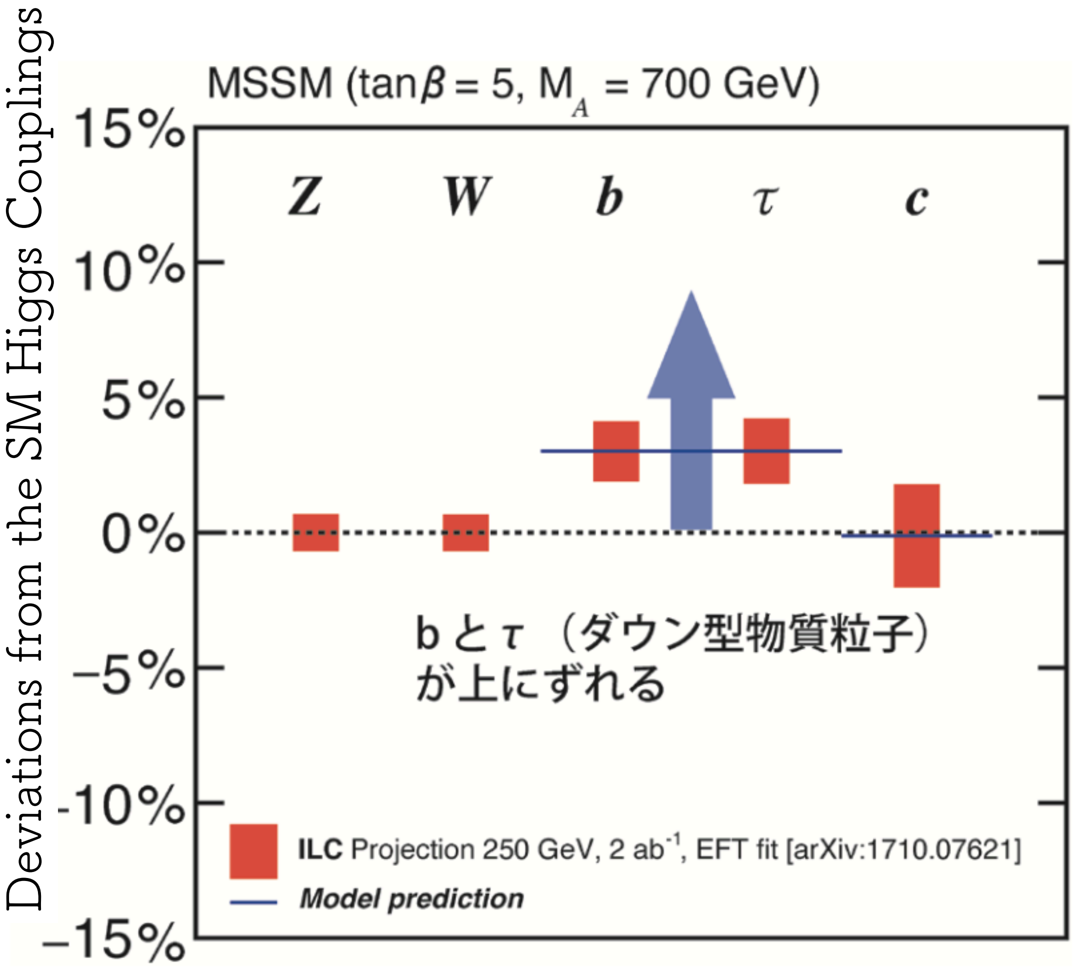
Expected Deviation **~6%**

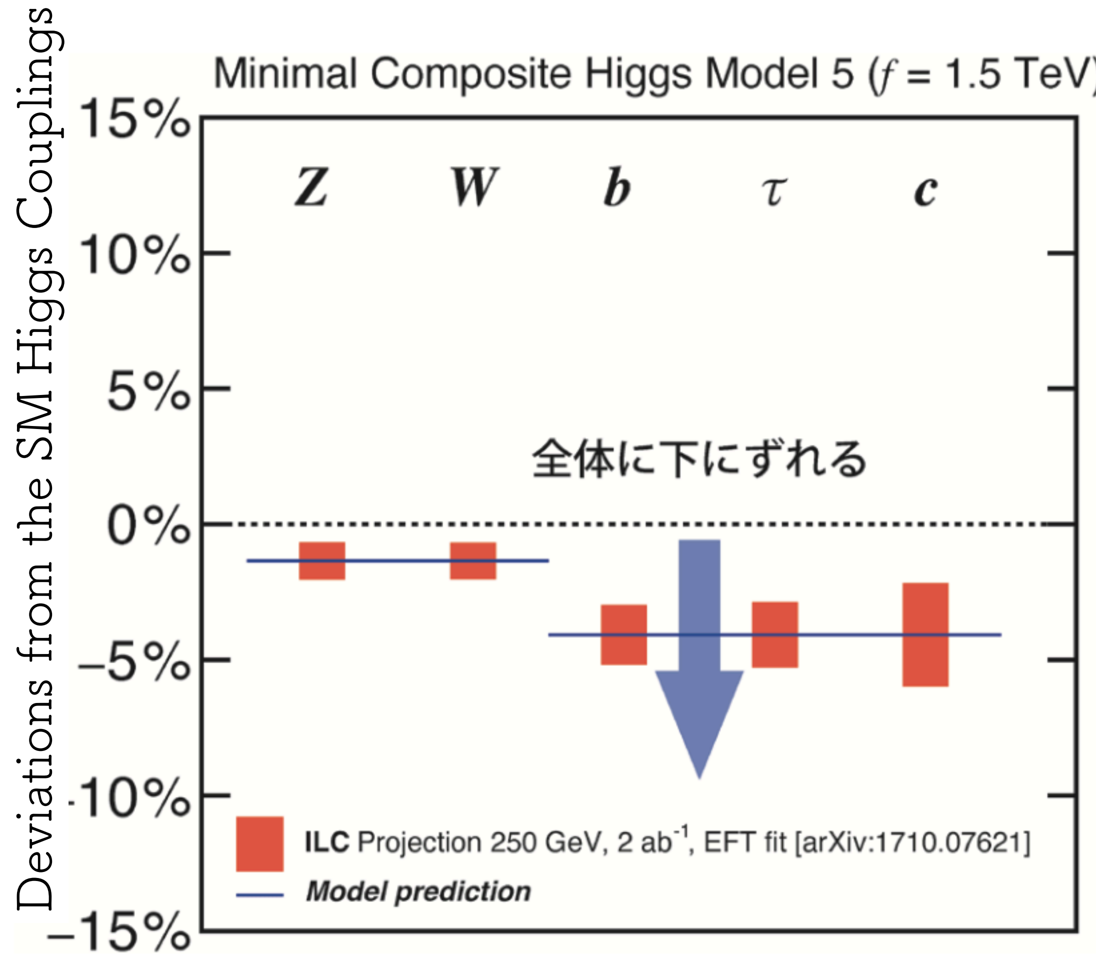
ILC250

- **0.5-2%** for Z, W, b, τ, g, c

The high precision measurement makes sense to explore a New Phys. @ TeV Scale

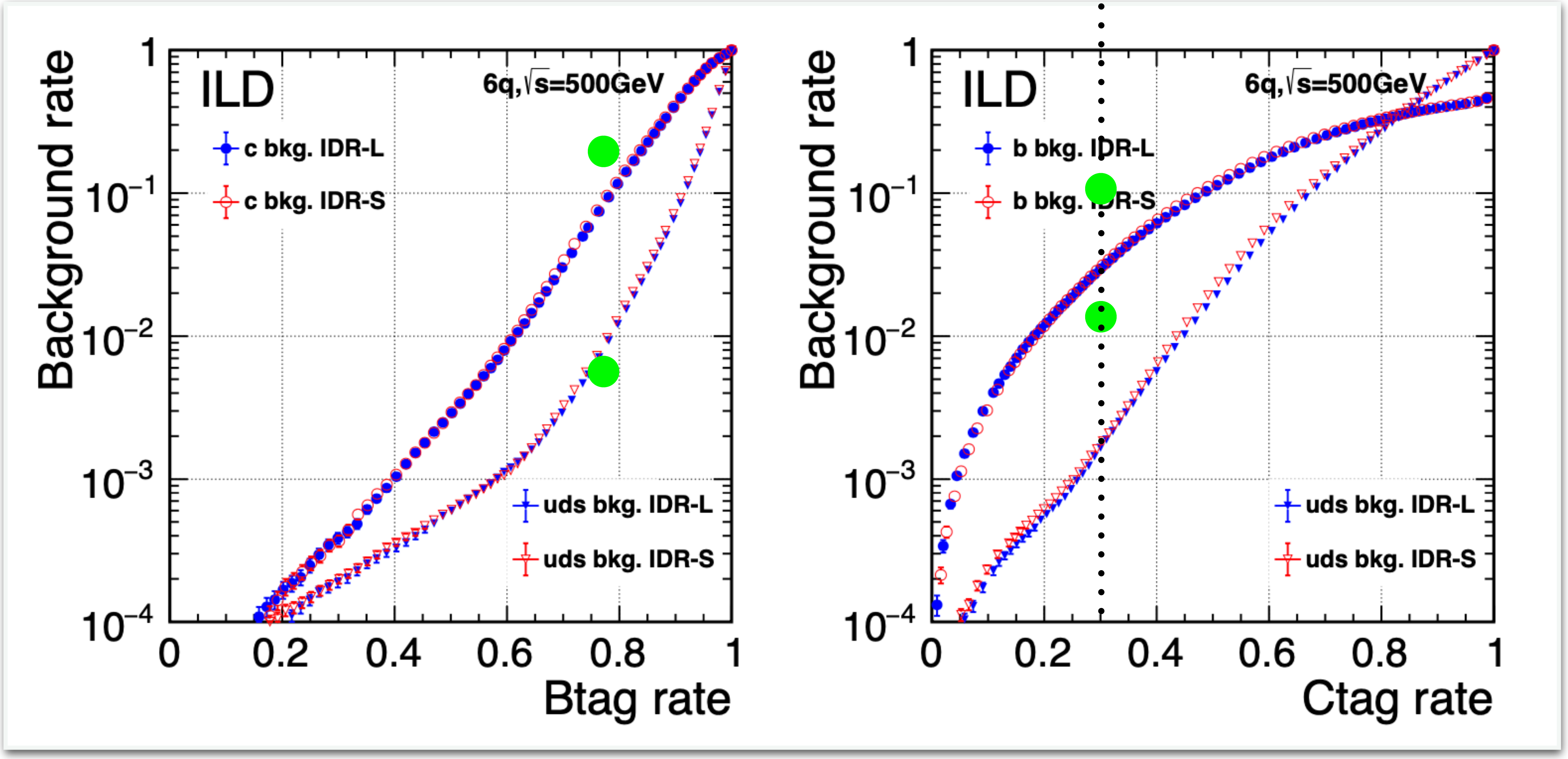
Two Example Scenarios of BSM





The precision of 5% (b) / 3% (τ) is not enough and better precision is highly demanded

by the way, Flavor Tagging Performance



b-tag 77%, light jet: 1/170(= 6E-3)

c-jet: 1/5

Large Room to improve b-tagging on ILC side?

c-tag 30%, light jet: 1/70

b-jet: 1/9

https://bib-pubdb1.desy.de/record/588608/files/230807_s10052-023-11699-1.pdf

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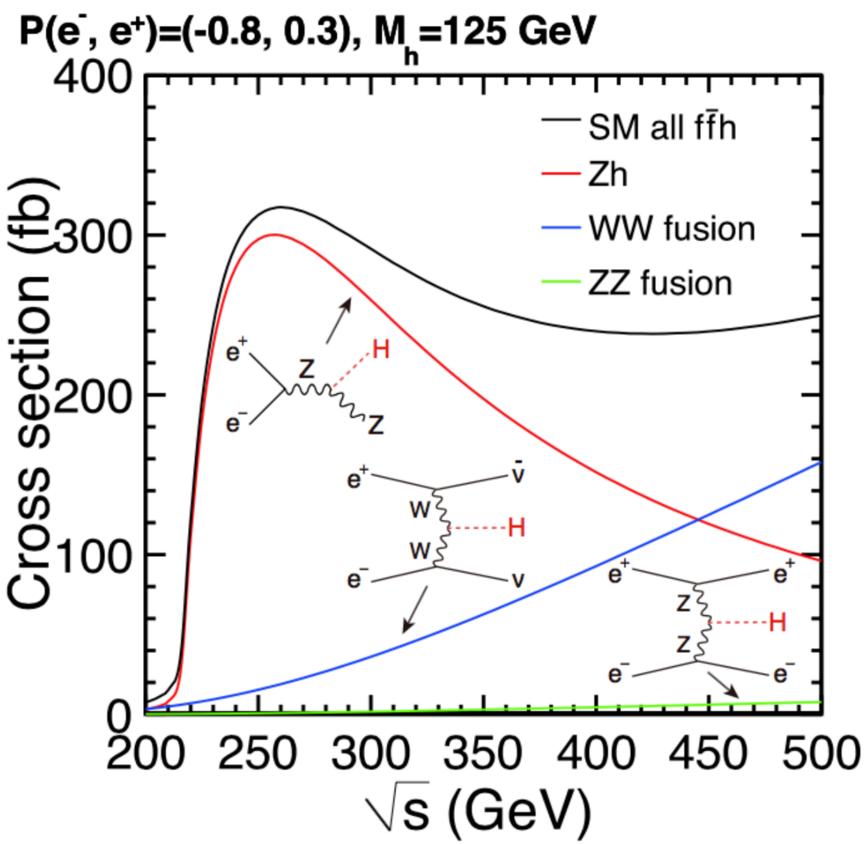
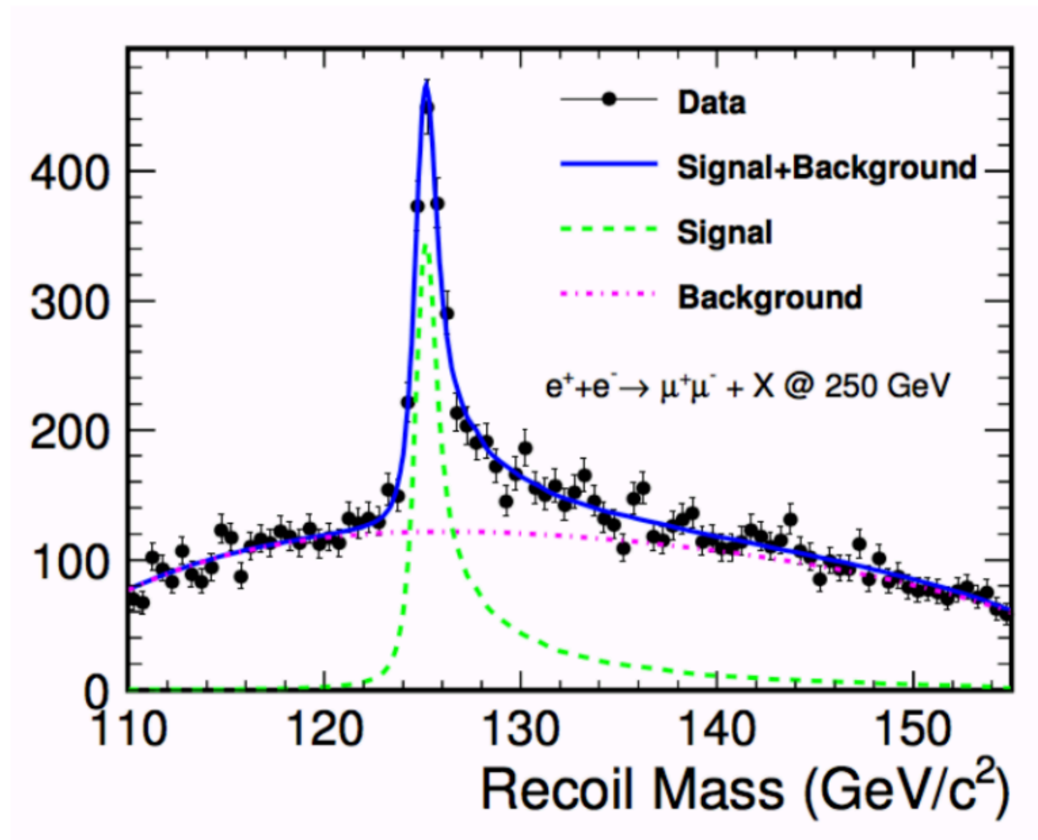
Abstract The flavour-tagging algorithms developed by the ATLAS Collaboration and used to analyse its dataset of $\sqrt{s} = 13$ TeV *pp* collisions from Run 2 of the Large Hadron Collider are presented. These new tagging algorithms are based on recurrent and deep neural networks, and their performance is evaluated in simulated collision events. These developments yield considerable improvements over previous jet-flavour identification strategies. At the 77% *b*-jet identification efficiency operating point, light-jet (charm-jet) rejection factors of 170 (5) are achieved in a sample of simulated Standard Model $t\bar{t}$ events; similarly, at a *c*-jet identification efficiency of 30%, a light-jet (*b*-jet) rejection factor of 70 (9) is obtained.

Model Independent Γ_h Measurement





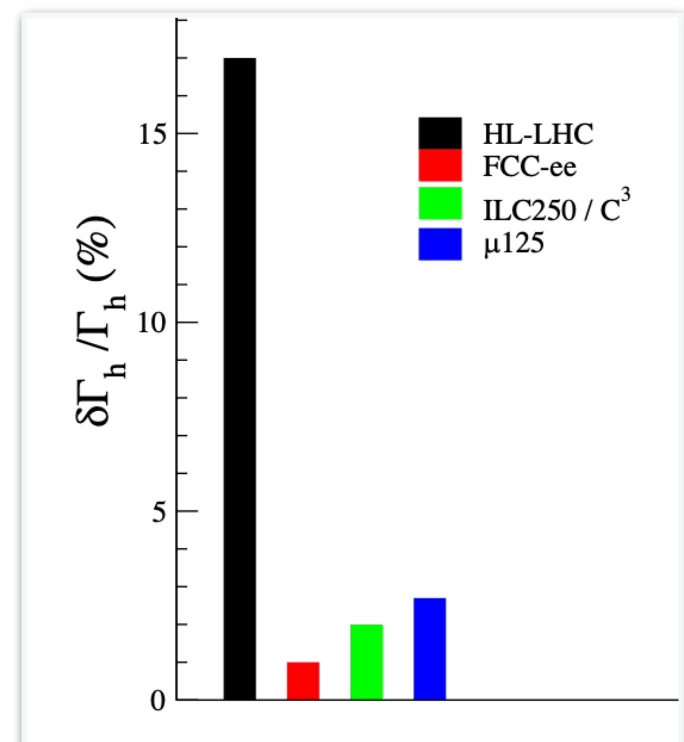
Higgs Production Zh: $\sigma_{Zh} \propto (g_{hZZ})^2$

Partial Width $\Gamma(h \to XX) \propto (g_{hXX})^2$

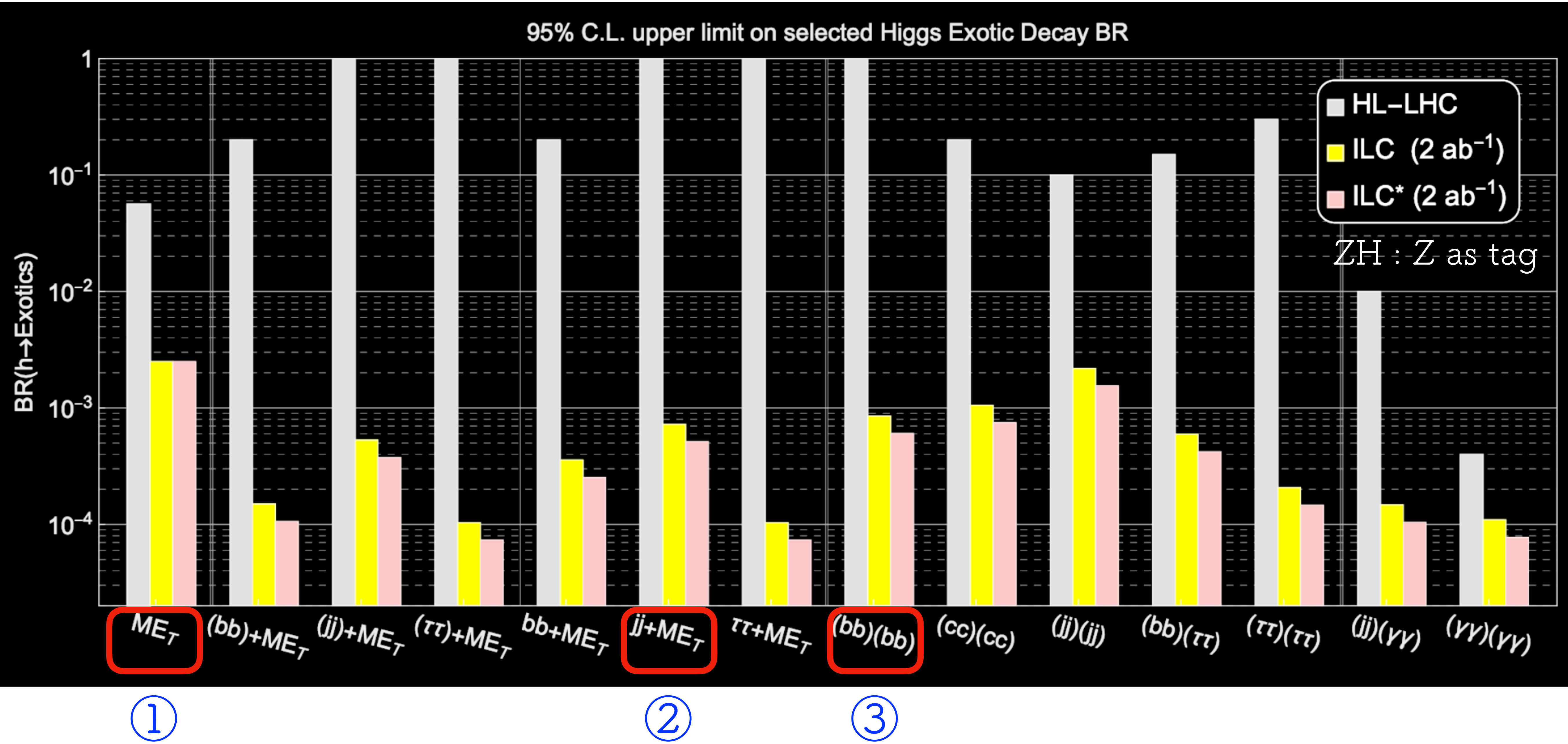
X-section measurement with Recoil Mass Method (@ Higgs Factory)

$$
\begin{aligned}
& \sigma_{ZH} \times Br(h \to XX) \\
= \; & \sigma_{ZH} \times \Gamma(h \to XX) \,/\, \Gamma_H \\
\propto \; & (g_{hZZ})^2 \, (g_{hXX})^2 \,/\, \Gamma_H
\end{aligned}
$$

X = Z, W → extract Γ_h



Exotic Higgs Decays - Portal to Dark Sector?



① Fully Invisible Higgs Decay:

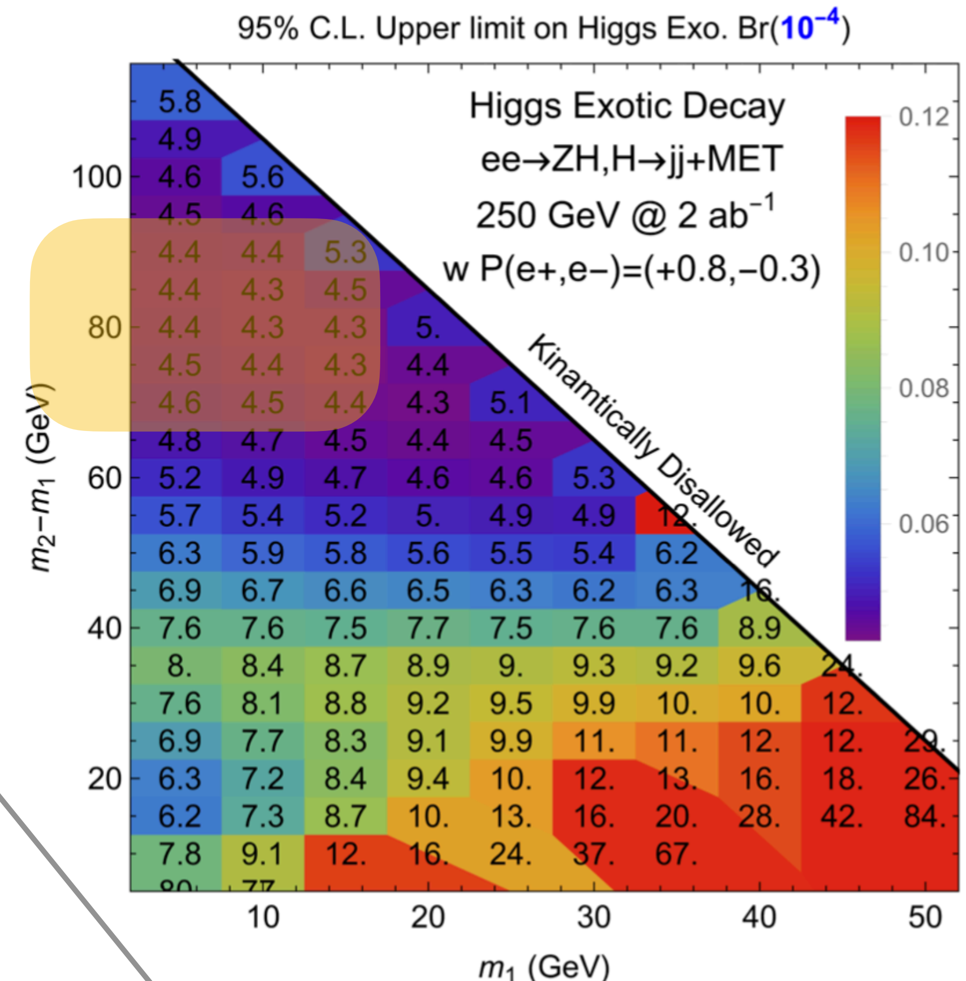
$H \rightarrow 4\,\nu$ (0.1%), 95% Confidence Upper Limit on Br = 0.16%

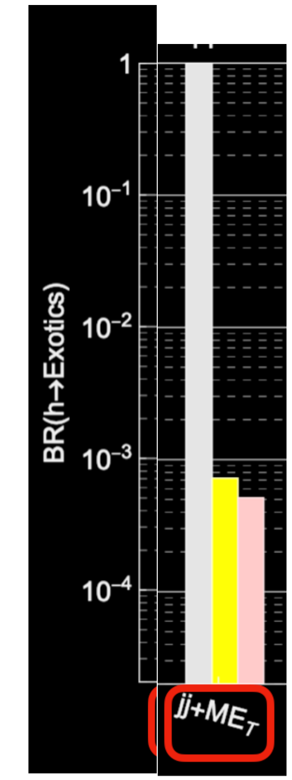
Exotic Higgs Decay - Partially Visible Case

② H → X1 + (X2) → X1 + (X1 + 2-jets)

BG.: H → ZZ* → qq ν ν

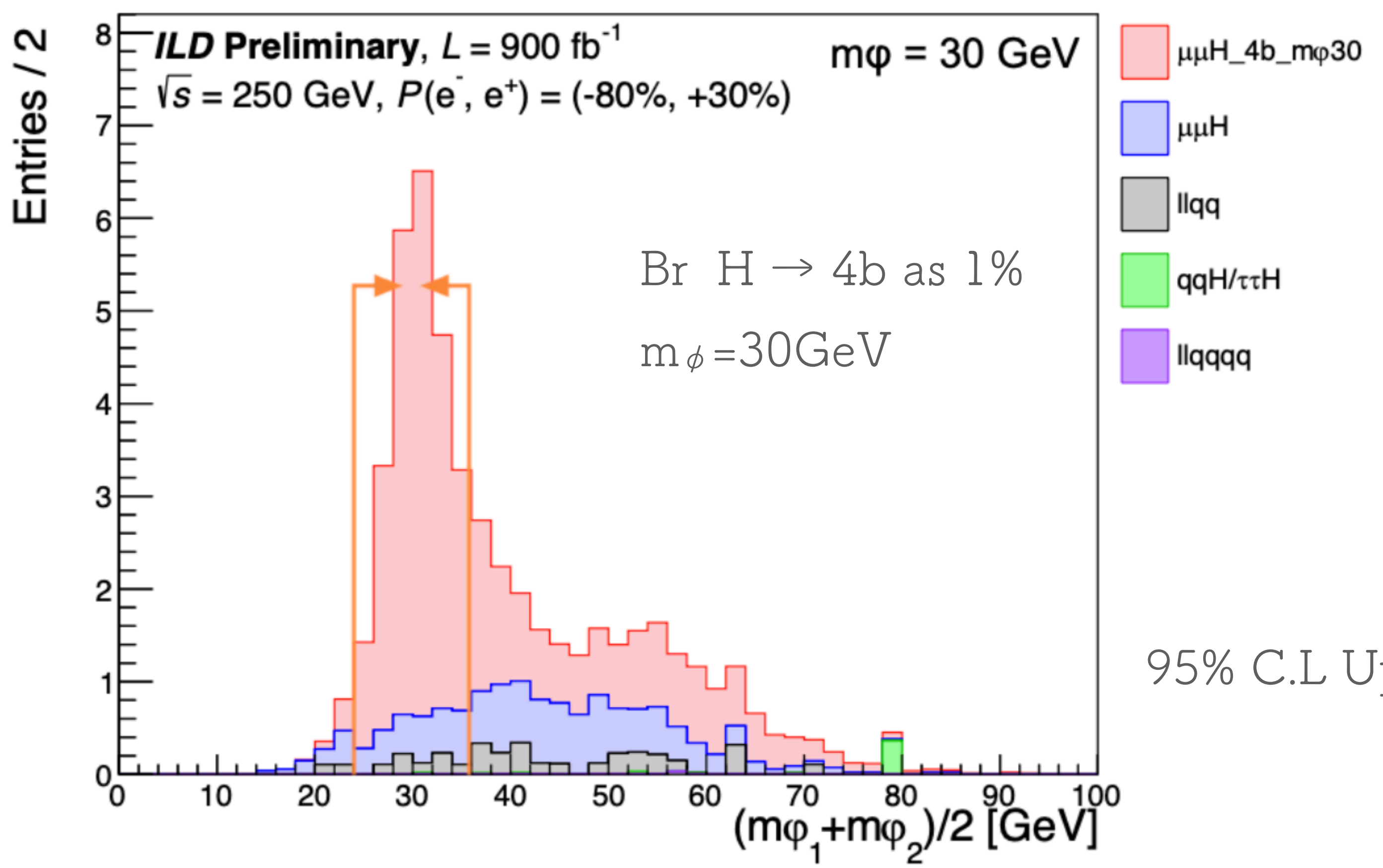
95% C.L. Upper Limit Br. = 4 E-4 ~ 8E-4





ZH

③ $H \to \phi\phi \to (b\bar{b})(b\bar{b})$

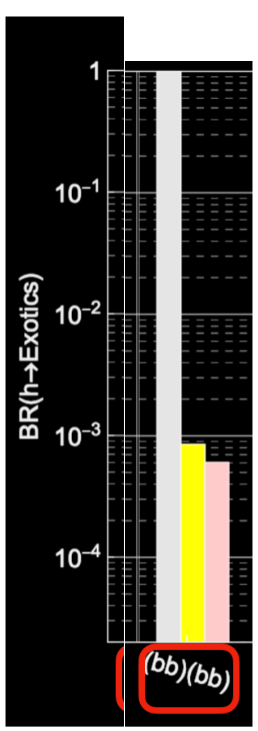


Br H → 4b as 1%

m_ϕ=30GeV

95% C.L Upper Limit is expected as 0.1%

(1E-3)



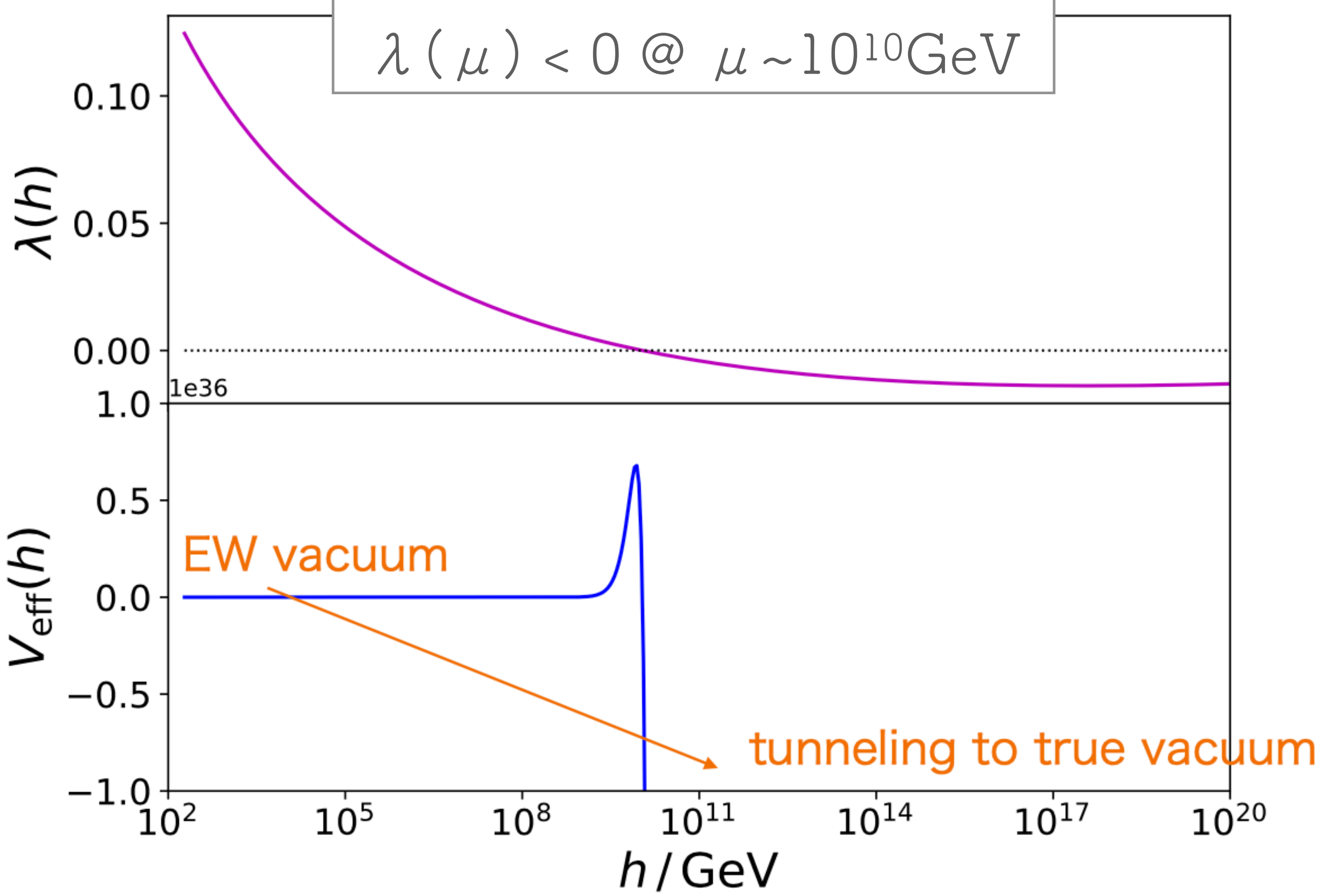
EW Vacuum Stability - m_{top}

one-loop RG equation of λ and y_t useful to understand $\lambda(\mu)$

$$16\pi^2 \frac{d\lambda}{d\ln\mu}\bigg|_{\text{one-loop}} = 12\lambda\left(2\lambda + y_t^2 - \frac{g_Y^2+g_2^2}{4} - \frac{g_2^2}{2}\right) - 6y_t^4 + 6\left(\frac{g_Y^2+g_2^2}{4}\right)^2 + 12\left(\frac{g_2^2}{4}\right)^2$$

Larger Higgs mass ➡ being stable
Larger Top mass ➡ being unstable

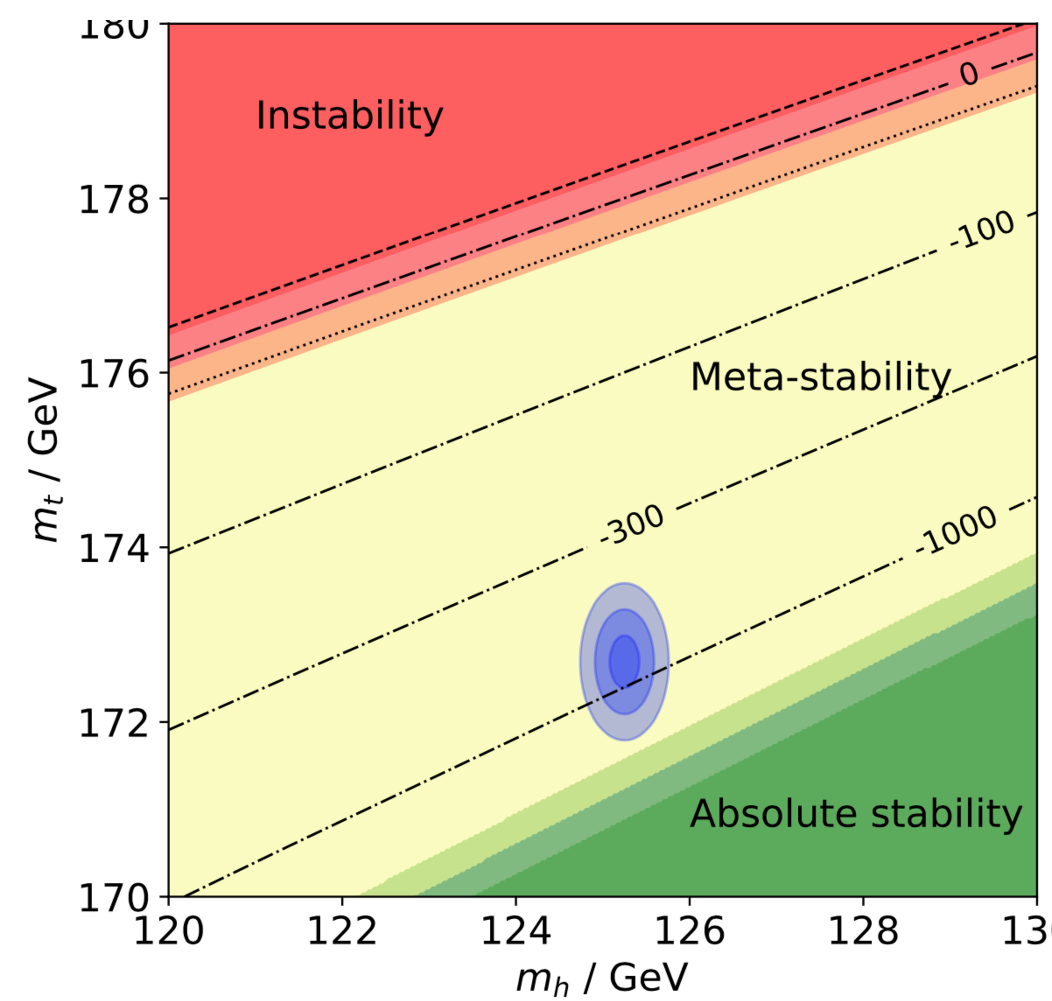
Meta-Stable EW Vac.
$\lambda(\mu) < 0$ @ $\mu \sim 10^{10}$ GeV



EW vacuum decay rate

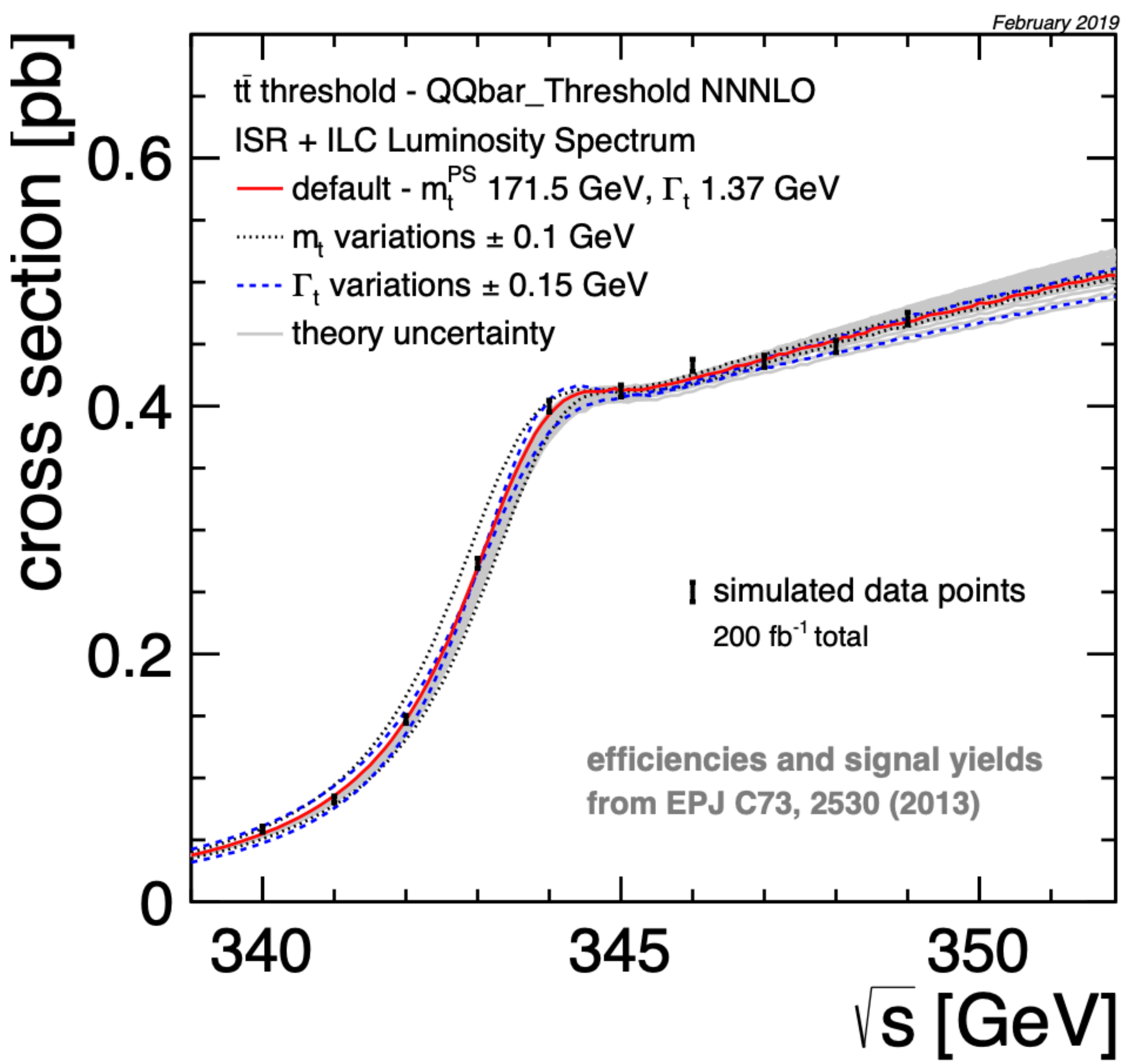
$$\log_{10}\left(\gamma \times \text{Gyr Gpc}^3\right) = -785^{+45}_{-49}{}^{+155}_{-222}{}^{+181}_{-276}$$

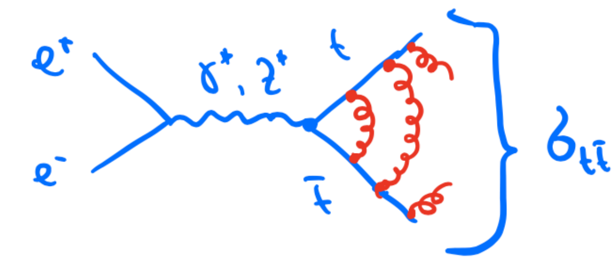
Δm_h ↗ Δm_t ↑ $\Delta\alpha_s$ ↖



c.f. So Chigusa (2023 Tera-Scale WS)

m_{top} - Threshold Scan (350)





Threshold Scan

→ short-distance mass (theoretically well defined)

$\Delta m \sim 20$ MeV (statistical)

$\Delta m \sim 50$ MeV (sys.: higher-order loop, α_s)

EPJ C73, 2530 (2013)

enough precision to resolve EW Vac. Stability

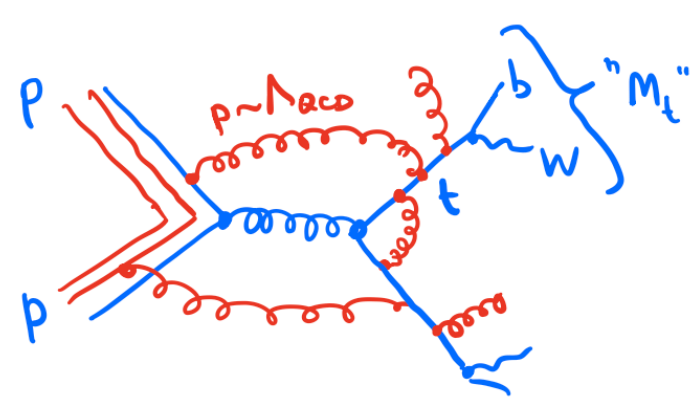
(c.f. LHC σ(tt) n-differential, NLO 173.2 ± 1.6 GeV)

a few other methods (tt γ, boosted top, angular scale, ...) are proposed at ILC

Reconstructed Top invariant mass

Need to model soft-gluon radiation/exchanges

(theoretically not well defined)



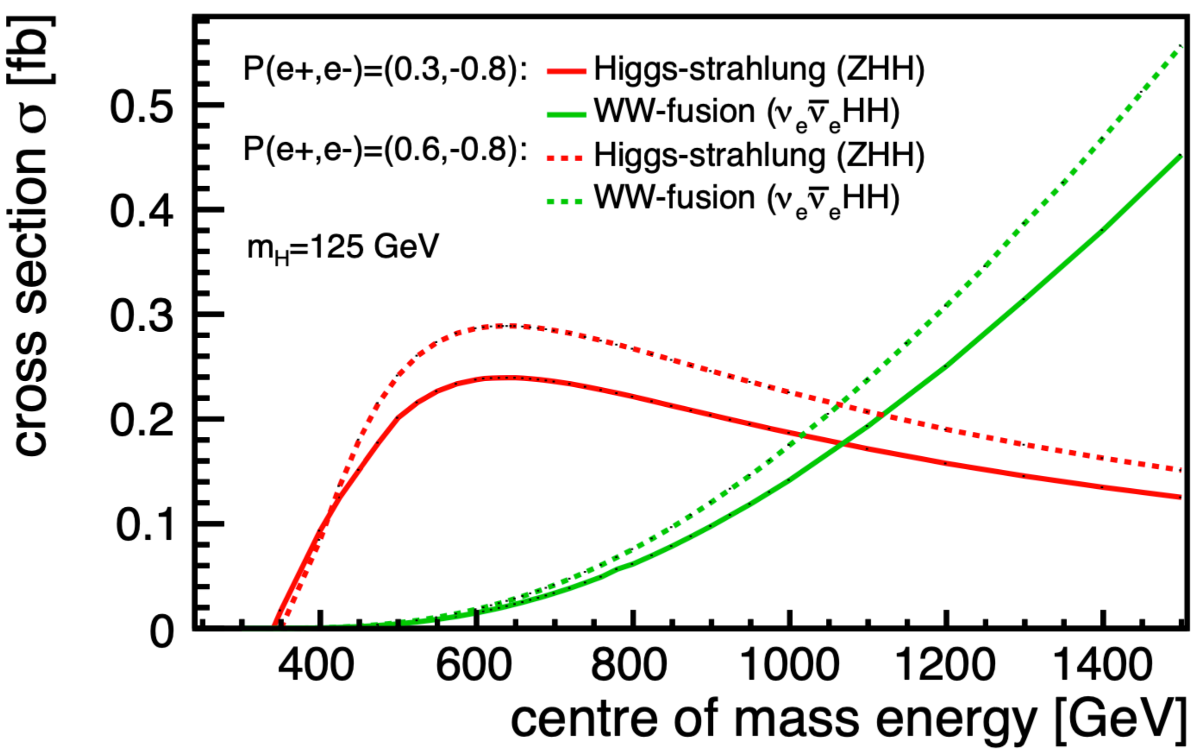
LHC MC template method: $\Delta m \sim 600$ MeV

(HL-LHC: $\Delta m \sim$ a few hundred MeV??)

MC mass ⇔ Theoretical mass mapping studies on-going

Higgs Self-Coupling (500, 1000)

<u>X-section: HH production</u>



bbbb, bbww, bb τ τ , others?

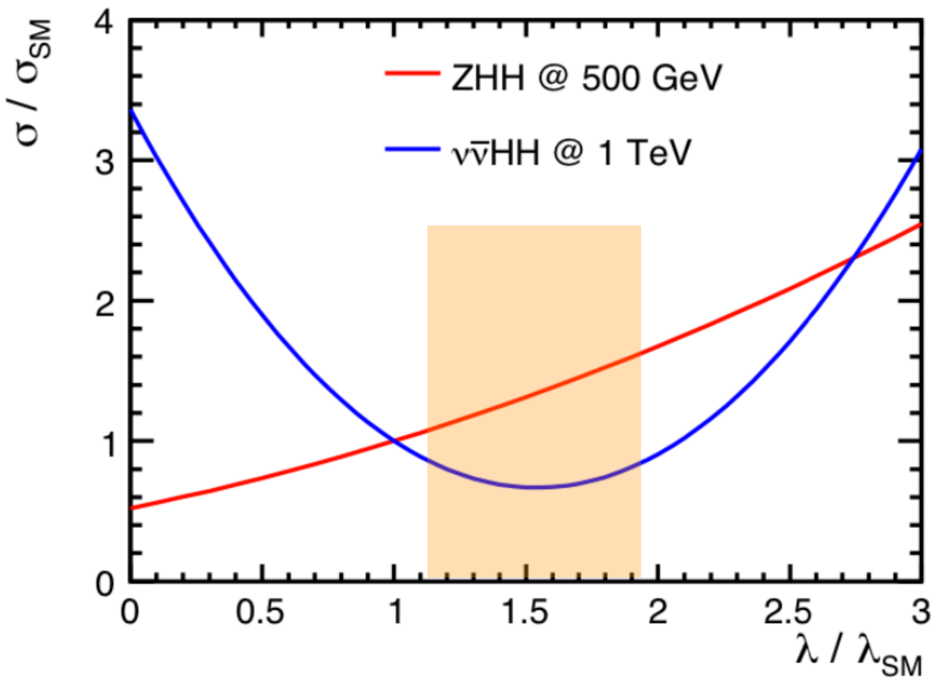
Direct measurement of Higgs cubic self-coupling
[500 GeV] ZHH (Δ λ ~ 25%)
[1 TeV] WW-fusion (Δ λ ~ 10%)

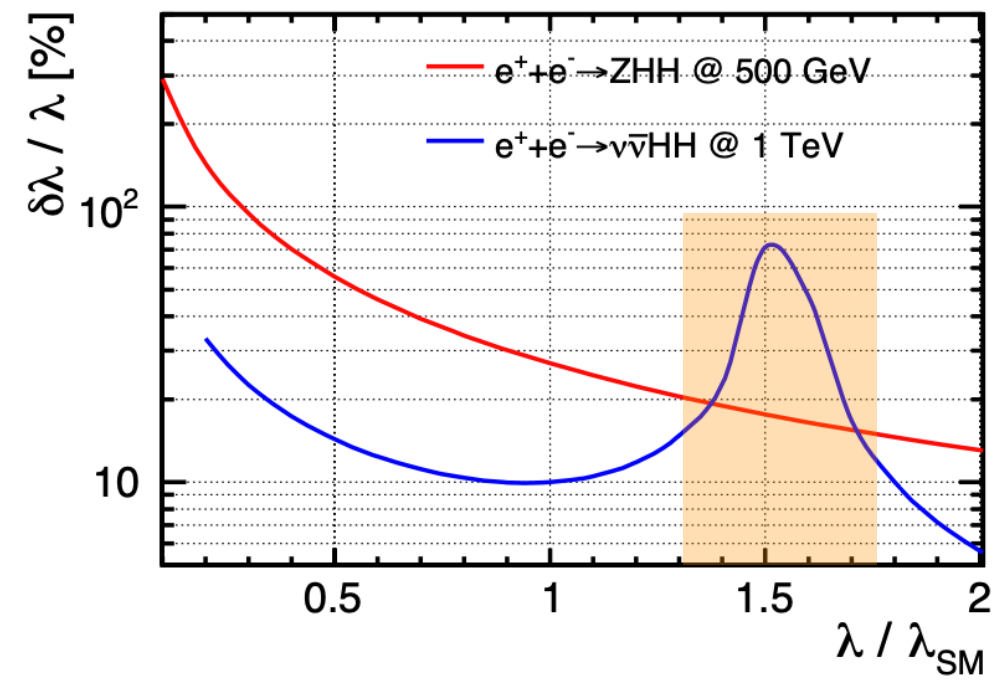
SM predicts λ_3 (w/ m_H, vev)
→ Good Test of **New Phys. in Higgs Sector**

[Example: Deviation of λ]
- 2HDM (Yukawa Type-I) λ : -0.5 ~ 1.5)
- EW Baryogenesis Model λ : 1.5 ~ 2.5)

By the way, there are two di-Higgs processes ZH & WW-fusion and they interfere ⇒

The Effect of Interference on λ_3



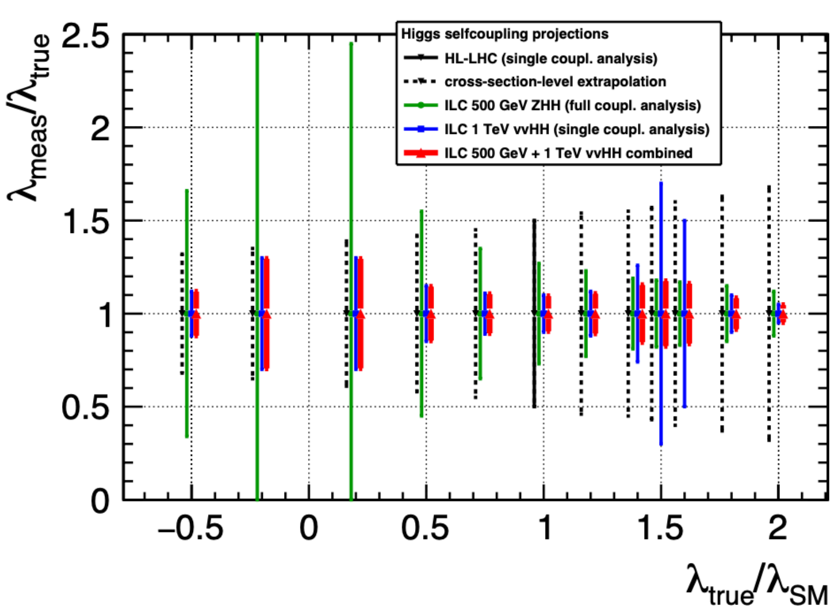


The 2 X-sections behave oppositely
- ZHH Constructive interference
- WW-fusion Destructive interference

Combination of two measurements

⇒ **a 20% precision in λ_3**, even if it deviates from the SM by 50-100%

important to run at the both 500 and 1000 GeV



LHC ⇒ gluon fusion dominant

⇒ Destructive Interference

⇒ suffered for enhanced λ_3

First-Order Phase Transition & λ_3

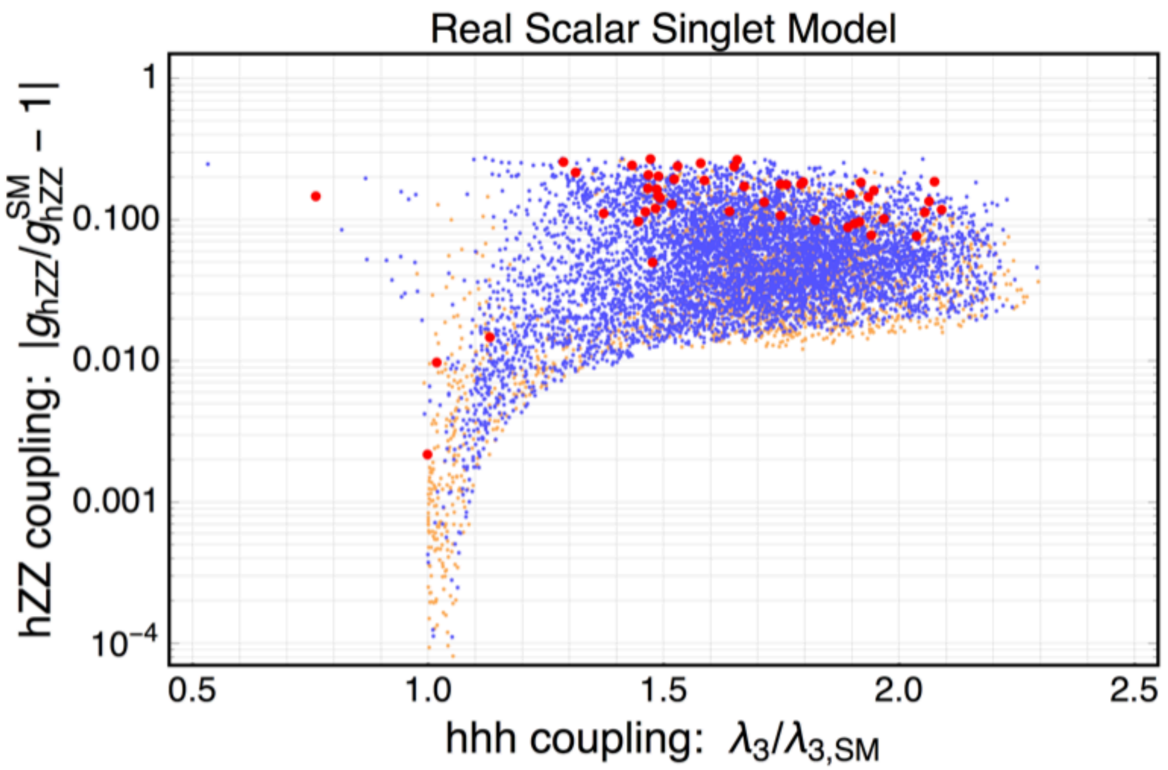
skip

Maxim's Slide in LCWS 2022

- First-order EWPT requires BSM fields, with significant coupling to Higgs and mass ~ weak scale
- A singlet scalar is the simplest benchmark:

$$V = m_S^2 S^2 + \frac{\kappa}{2} S^2 |H|^2$$

- Invisible to the LHC as long as $m_S > m_h/2$
- Models with first-order EWPT typically predict ~20-120% enhancement in h^3



[Huang, Long, L-T. Wang]

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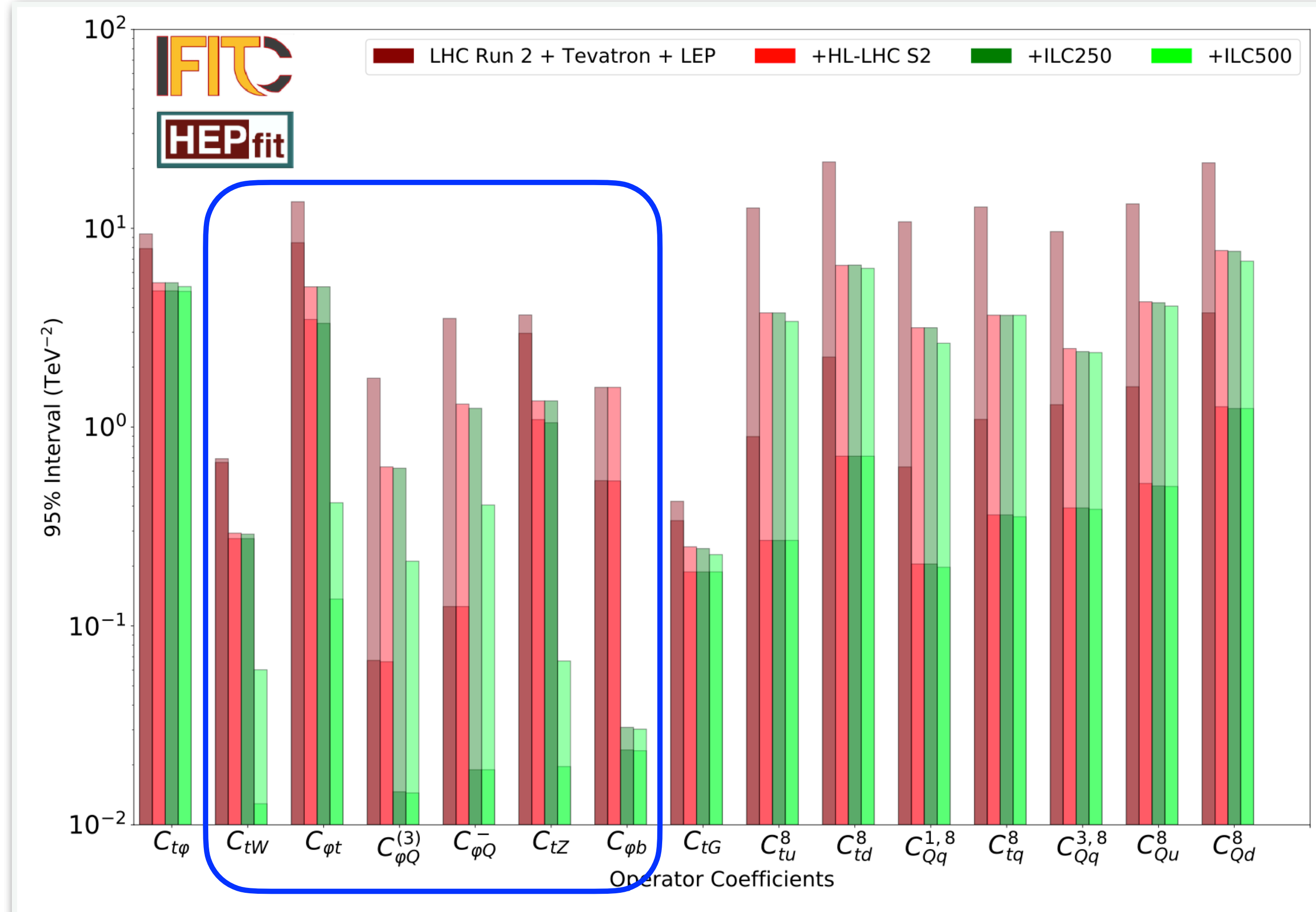
EW Precision Test (1) Top EFT Operator / FCNC

Top EFT Operator

- 500 GeV (or above) Top EW Couplings
- Deviations: Parametrized by EFT
- **1/10 - 1/100 better than HL-LHC**

pp → ttZ/tt γ   or   pp → tZq/t γ q

Precision **@ HL-LHC: 5-10%**



Top FCNC Operator

Forbidden at SM tree level

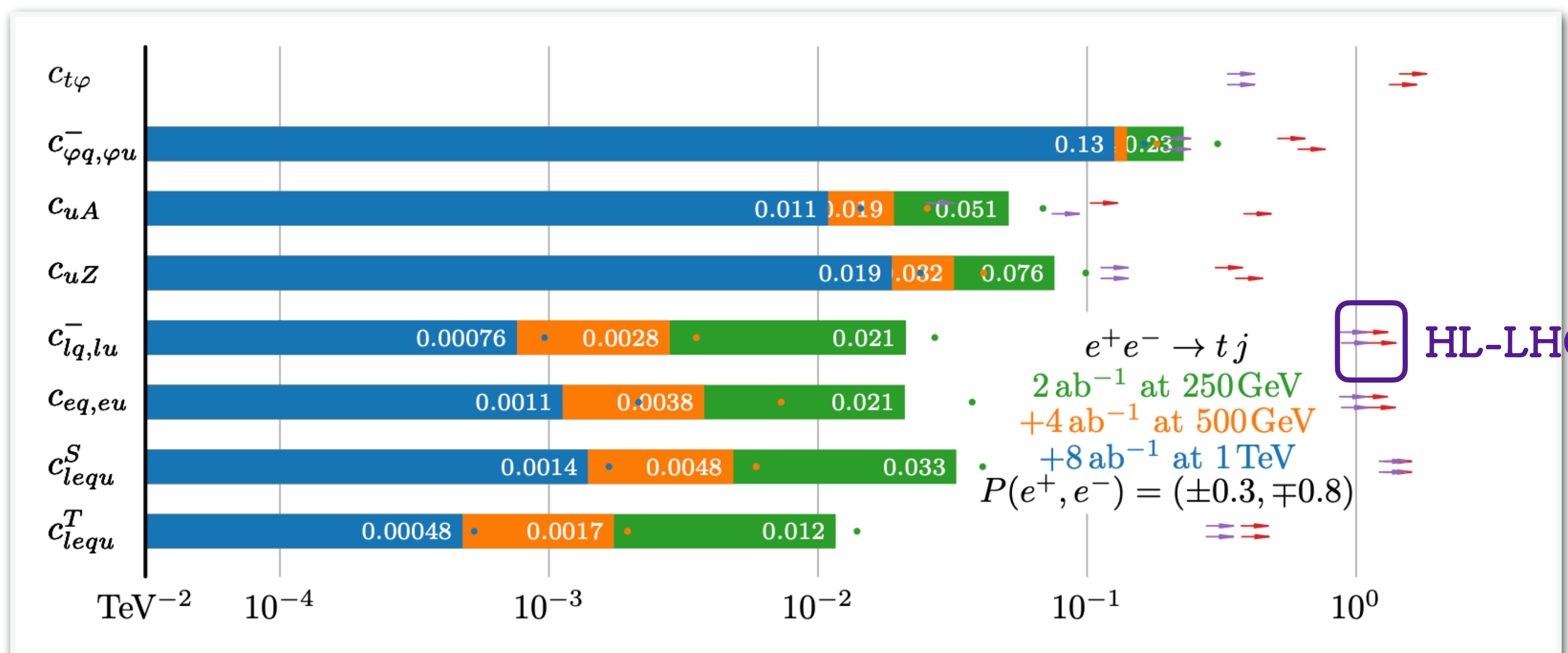
Suppressed by GIM mechanism

HL-LHC: 1E-3 ~ 1E-5

Higher Energy e⁺e⁻ is powerful

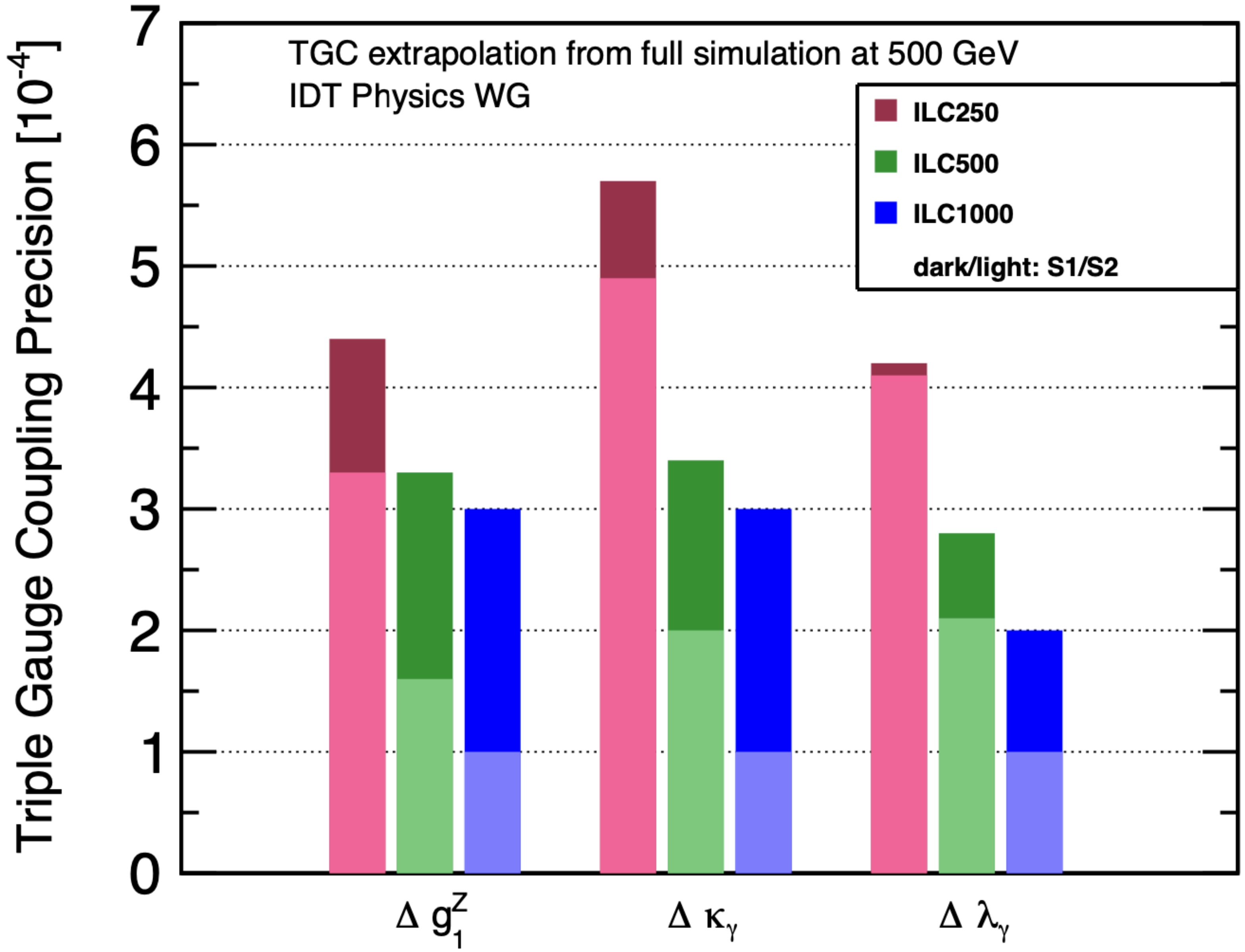
e.g. 4-f Operator ee → tq

improvement of 3 orders



[de Blas et.al.]

EW Precision Test (2) TGC (Triple Gauge boson Coupling)



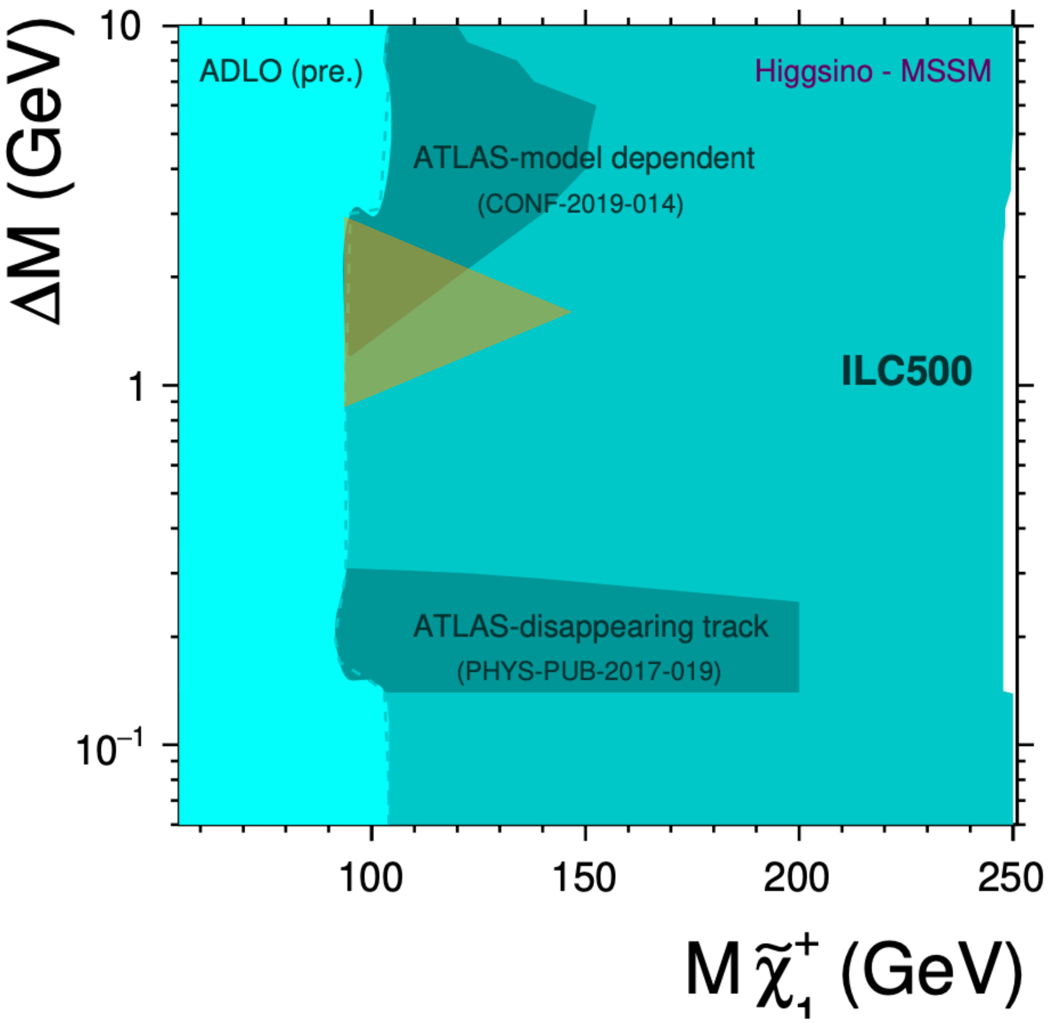
$g^Z = -c_W/s_W$, $K_\gamma = \lambda_\gamma = 1$

The precision of O(1E-3) for HL-LHC (p.175)

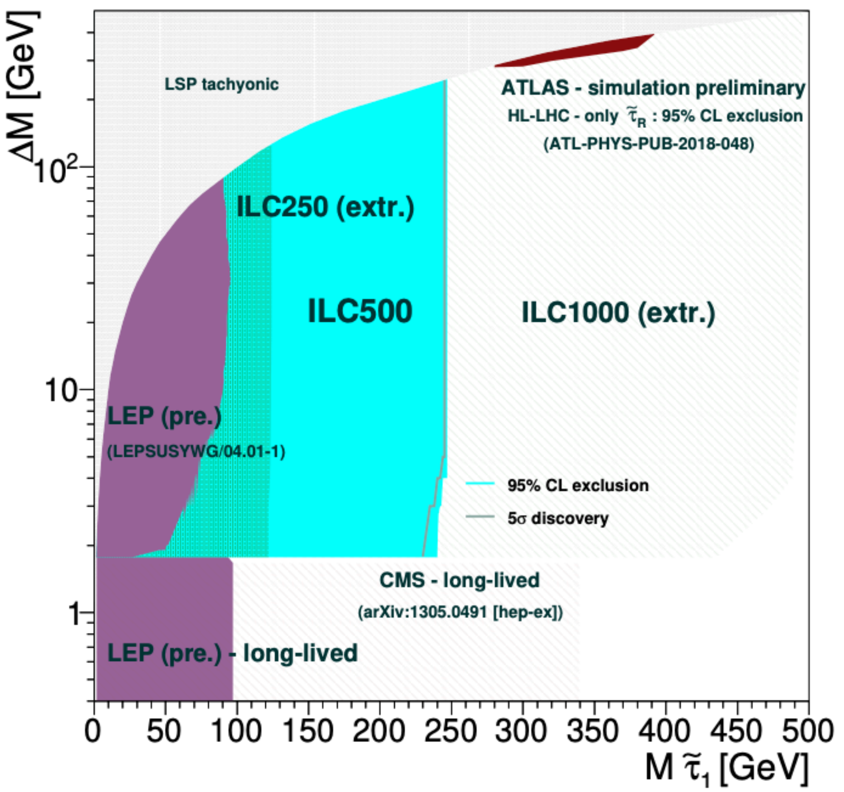
The improvement of "one order" is expected at higher $\sqrt{s}$

Search: EW SUSY

Δ m (Chargino - LSP) : small mass gap



Δ m (stau, LSP) v.s. m_stau



Low p_T lepton tracking: difficult at LHC

Very big efforts, but relatively small gain...

Great Potential to cover whole the interesting region by Higher Energy e^+e^- Machine

Dark Photon/Z

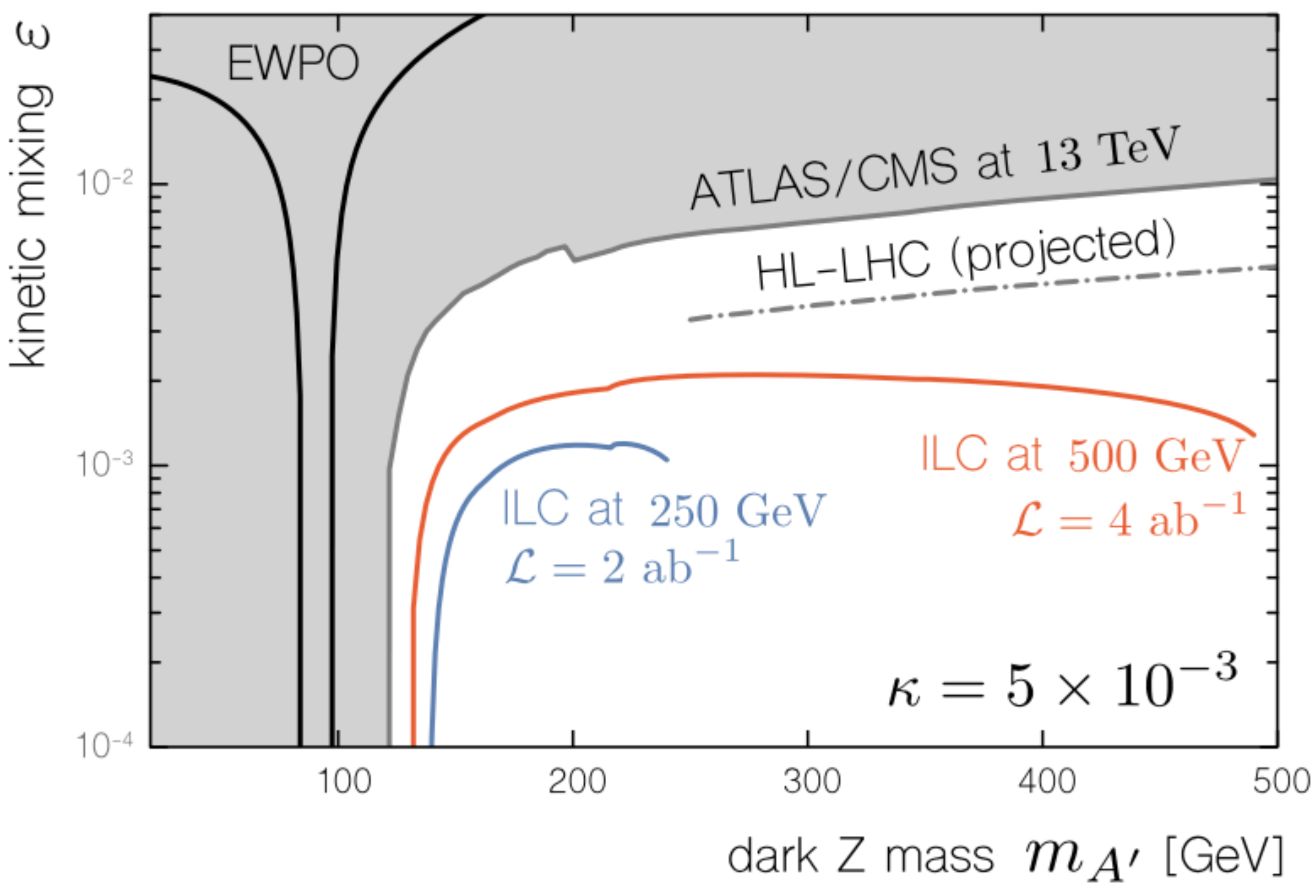
Some BSM predicts an alternative U(1) symmetry

If no SM field is charged, it could be "Dark Sector"

Maxim's Slide in LCWS 2022

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{\varepsilon}{2c_W}B_{\mu\nu}A'^{\mu\nu} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu}$$

Dominant coupling to SM is a loop effect



As long as Dark Z is within the kinematic reach of an e+e- collider, the region inaccessible by HL-LHC can be probed

[San, Tanedo, MP]

Summary

A Set of Physics Program at the ILC 250, 380, 1000

They can be a Killer Science in 2040?

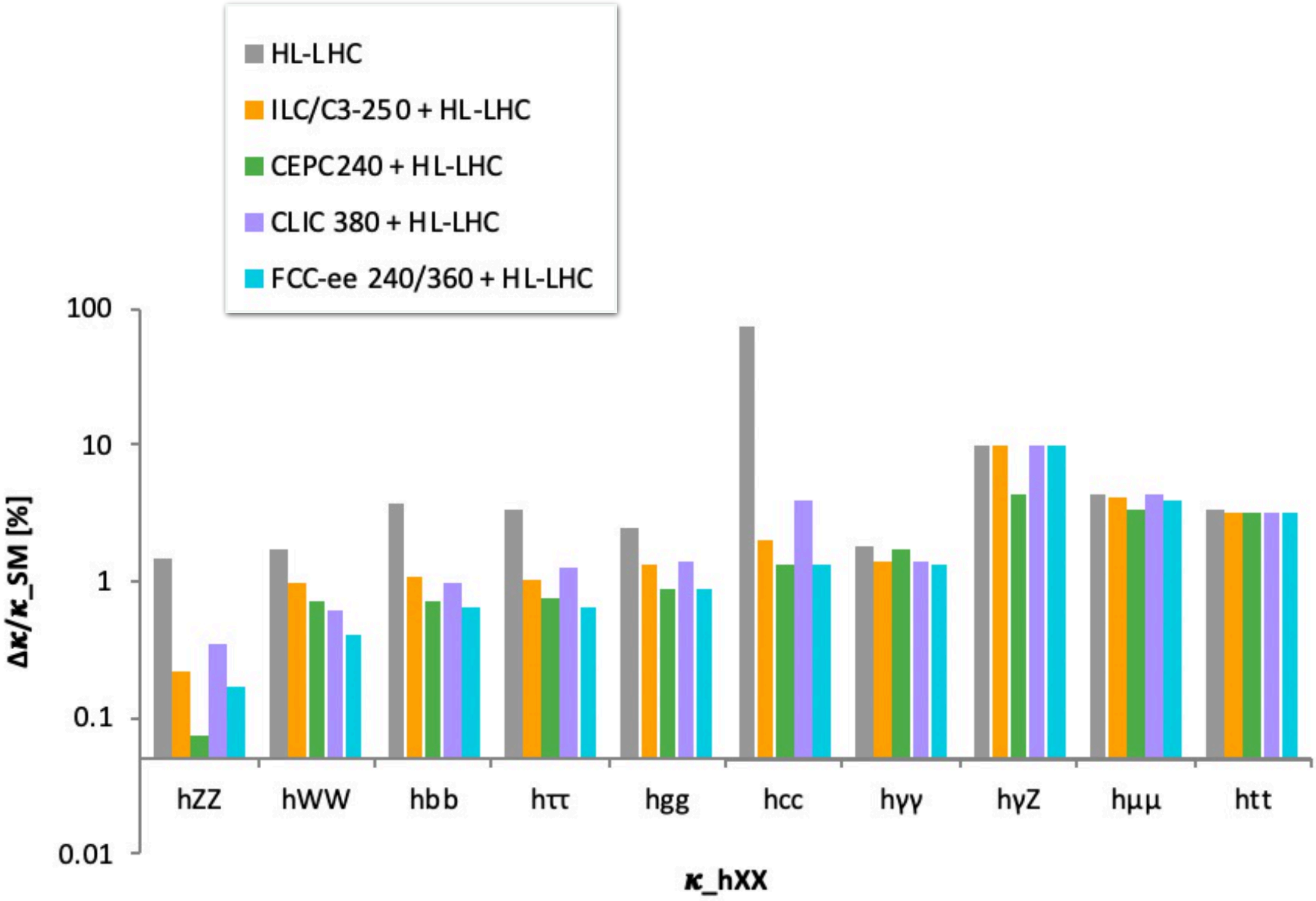
- Higgs
  - To explore a New Physics at 1 TeV, the measurement of **Higgs Couplings (0.5-2%)** is a strong approach and having advantage w.r.t. HL-LHC in 2040
  - Exotic Higgs Decays: LC has great advantage (3 orders)
  - Higgs-Self Coupling: λ_3 ($\Delta\lambda \sim 10\%$) LC has great advantage

- m_Top → y_{top}: **Energy Scan** at LC is a unique approach to determine the **pole-mass (20 MeV stat., 50 MeV sys.)** ⇒ conclude EW Vac. Stability

- EW Precision Test (1) Top (2) TGC : **1 - 3 orders** of advantage

- New Particle Search, e.g. EW SUSY @ mass degenerated region: Great advantage w.r.t. HL-LHC

YES


HL-LHC
ILC/C3-250 + HL-LHC
CEPC240 + HL-LHC
CLIC 380 + HL-LHC
FCC-ee 240/360 + HL-LHC
100
10
1
0.1
0.01
Δκ/κ_SM [%]
hZZ
hWW
hbb
hττ
hgg
hcc
hγγ
hγZ
hμμ
htt
κ_hXX