Higgs properties projections @ future e+e-

arXiv:1903.01629
1708.09079
1708.08912

ESG “Higgs @ FC”
arXiv:1905.03974

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Snowmass Community Planning Meeting
“Higgs factories” session, October 6, 2020

proposals of future e+e- colliders

	$\sqrt{s}$	beam polarisation	∫Ldt (baseline)	R&D phase
ILC	0.1 - 1 TeV	e-: 80% e+: 30% (20%)	2 ab^{-1} @ 250 GeV 0.2 ab^{-1} @ 350 GeV 4 ab-1 @ 500 GeV 8 ab-1 @ 1 TeV	TDR 2013
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	1 ab^{-1} @ 380 GeV 2.5 ab^{-1} @ 1.5 TeV 5 ab^{-1} @ 3 TeV	CDR 2012
CEPC	90 - 240 GeV	e-: 0% e+: 0%	5.6 ab^{-1} @ 250 GeV 16 ab^{-1} @ M_Z 2.6 ab^{-1} @ $2M_W$	CDR 2018
FCC-ee	90 - 350 GeV	e-: 0% e+: 0%	150 ab^{-1} @ M_Z 10 ab^{-1} @ $2M_W$ 5 ab^{-1} @ 250 GeV 1.7 ab^{-1} @ 365 GeV	CDR 2018

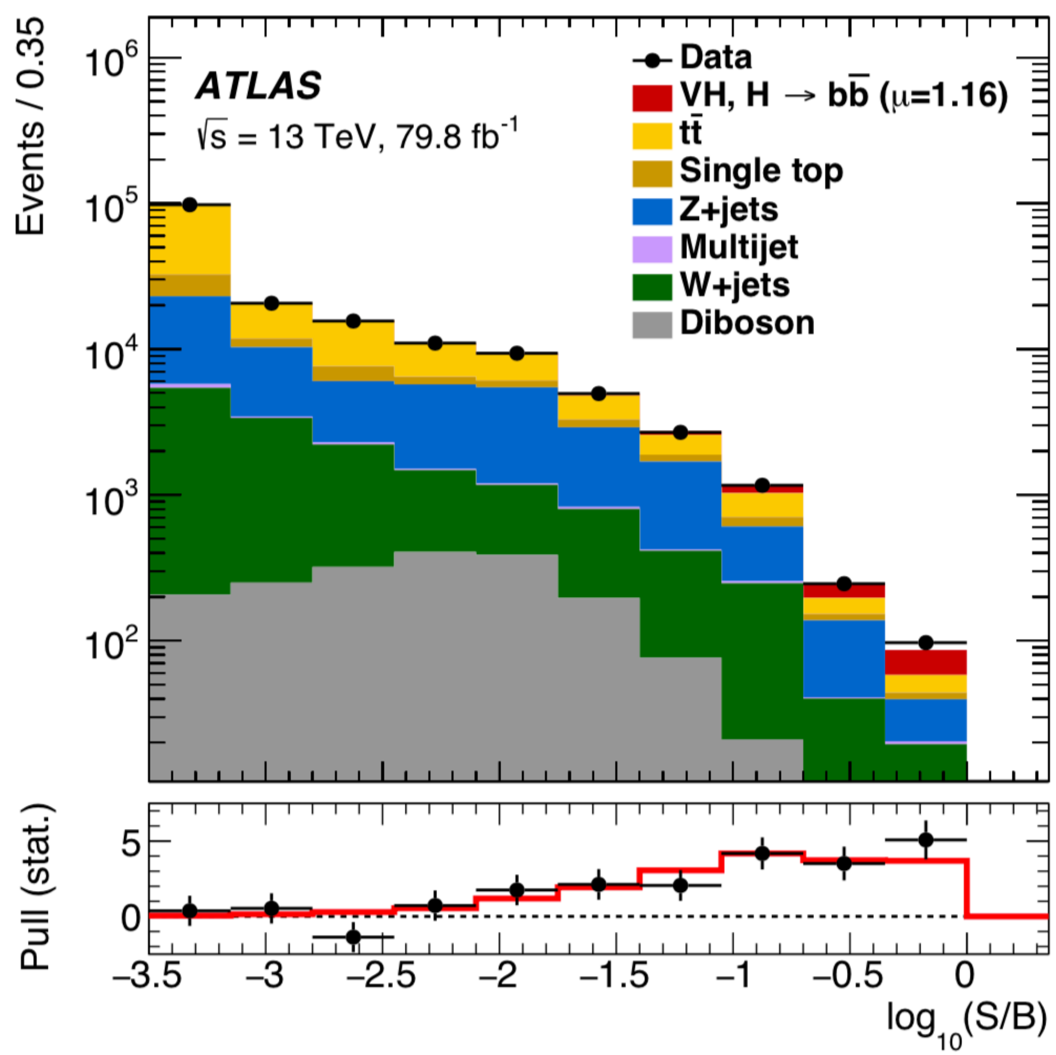
common: Higgs factory with $O(10^6)$ Higgs events

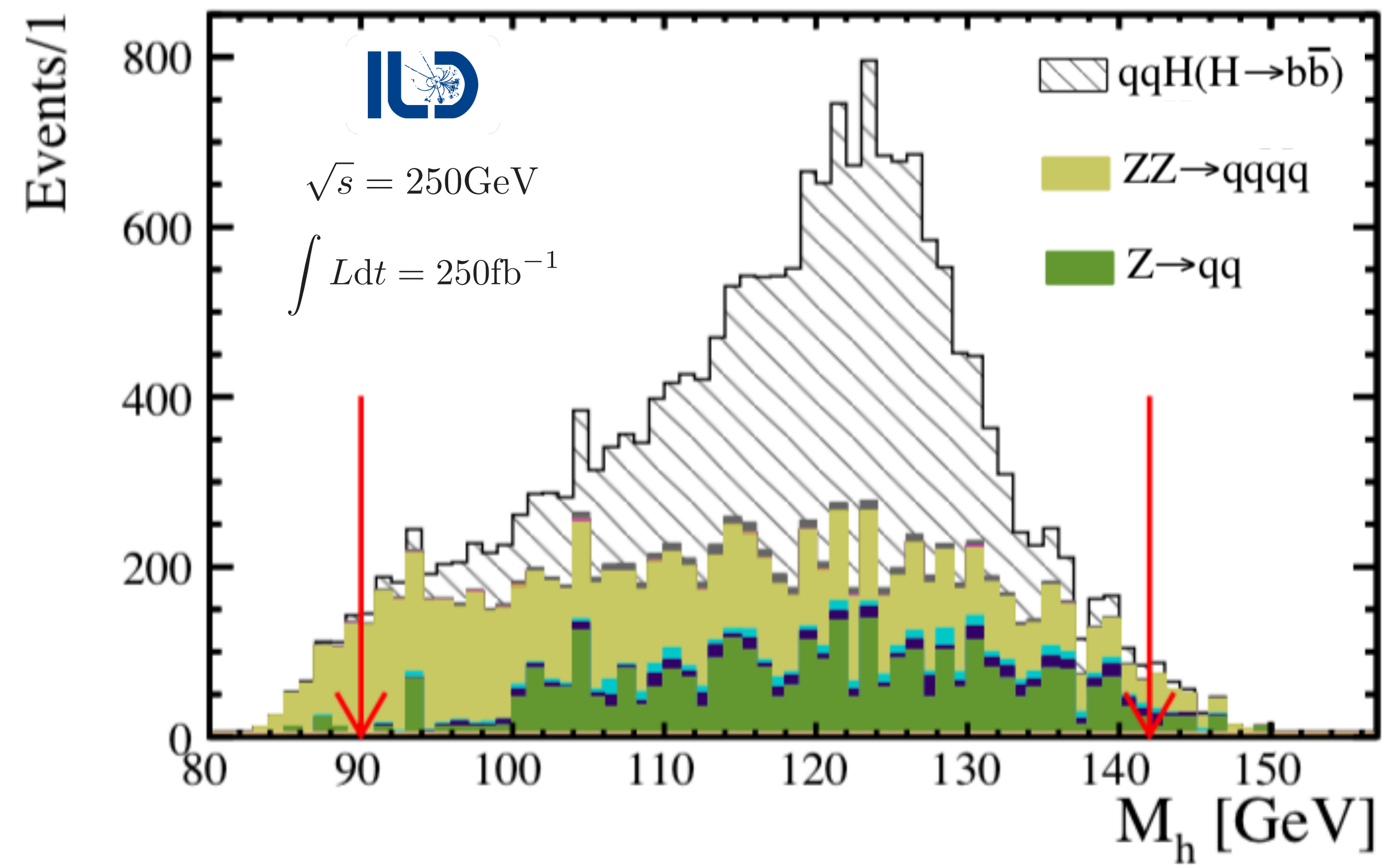
differ in energy reach, luminosity, polarization, project readiness

statistics vs S/B: example on H→bb discovery

LHC (super Higgs factory #10⁸)

e+e- (Higgs factory #10⁶)





full detector simulation

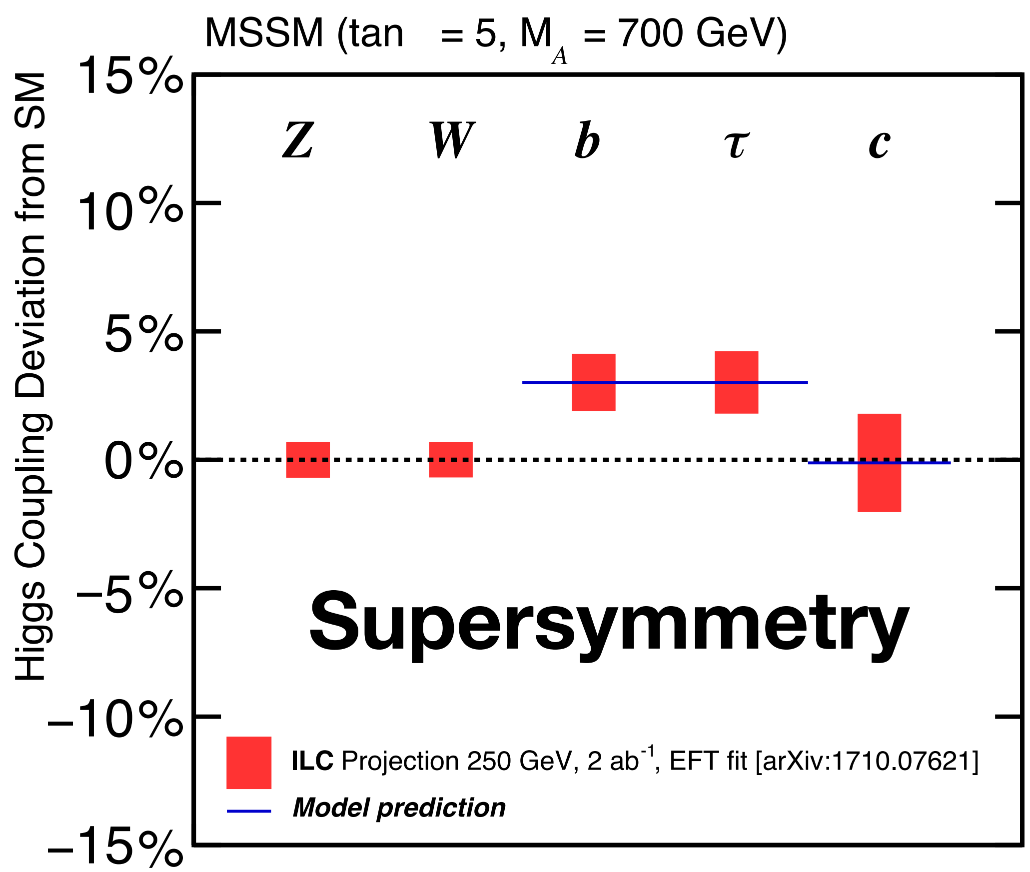
# of Higgs produced: ~4,000,000 ~400

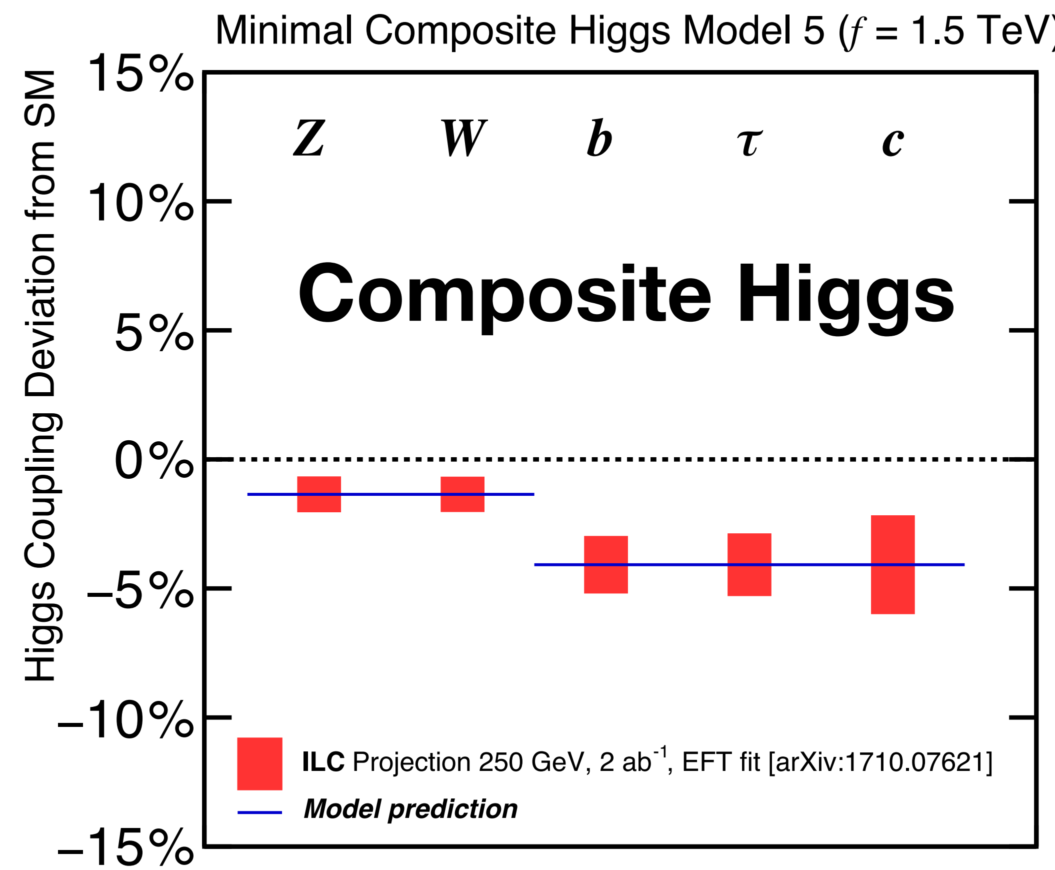
significance: 5.4σ 5.2σ

[ATLAS, 1808.08238; CMS, 1808.08242]

[Ogawa, PhD Thesis (Sokendai)]

goal of Higgs precision measurements @ e+e-

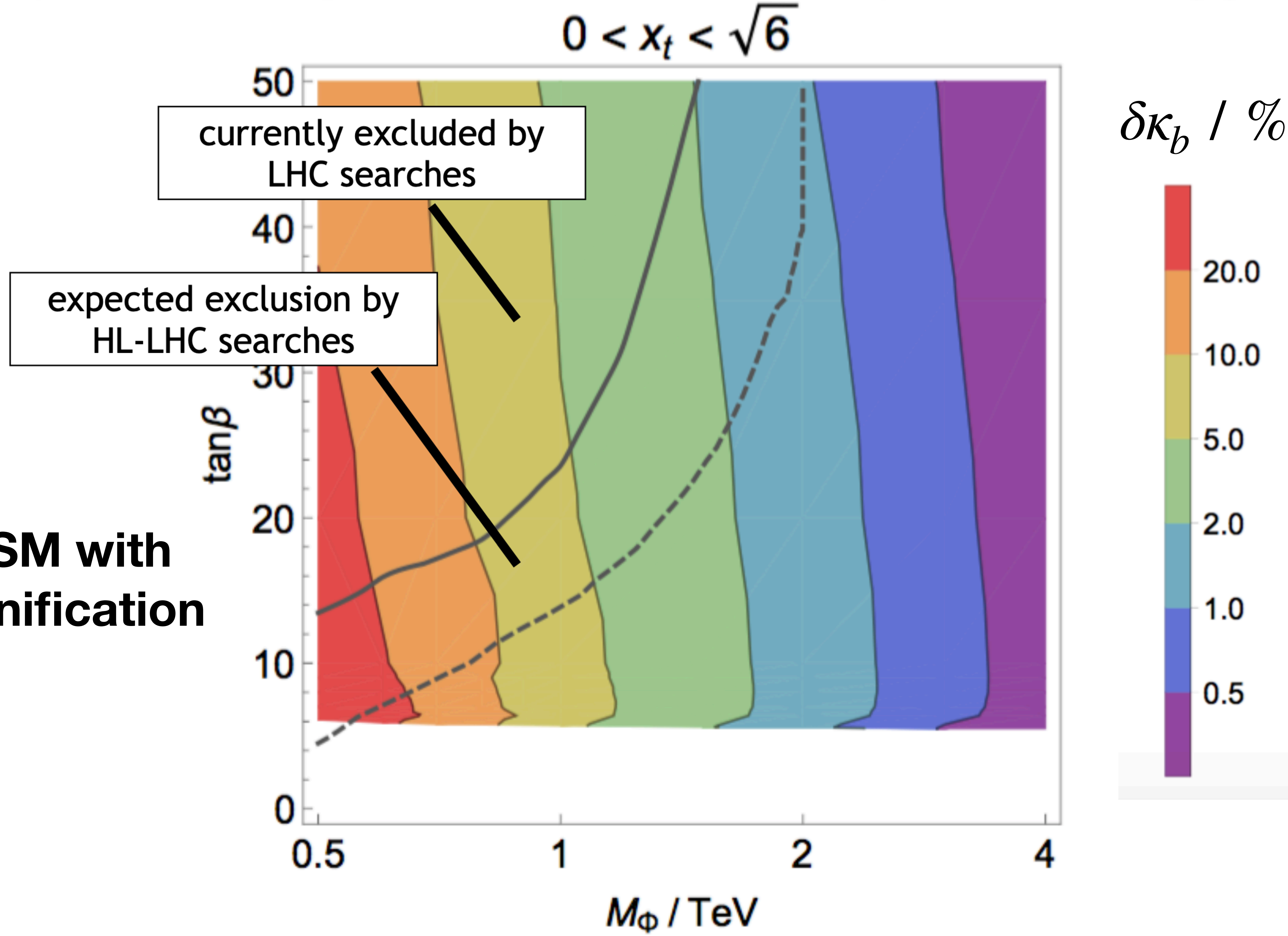




- ☑ to *see* new physics effects from deviation w.r.t. SM
  - ⇨ need 1% or below sensitivity for m_{BSM}~1TeV
- ☑ to *identify the* underling BSM model from deviation pattern
  - ⇨ need meas. as model-independent as possible

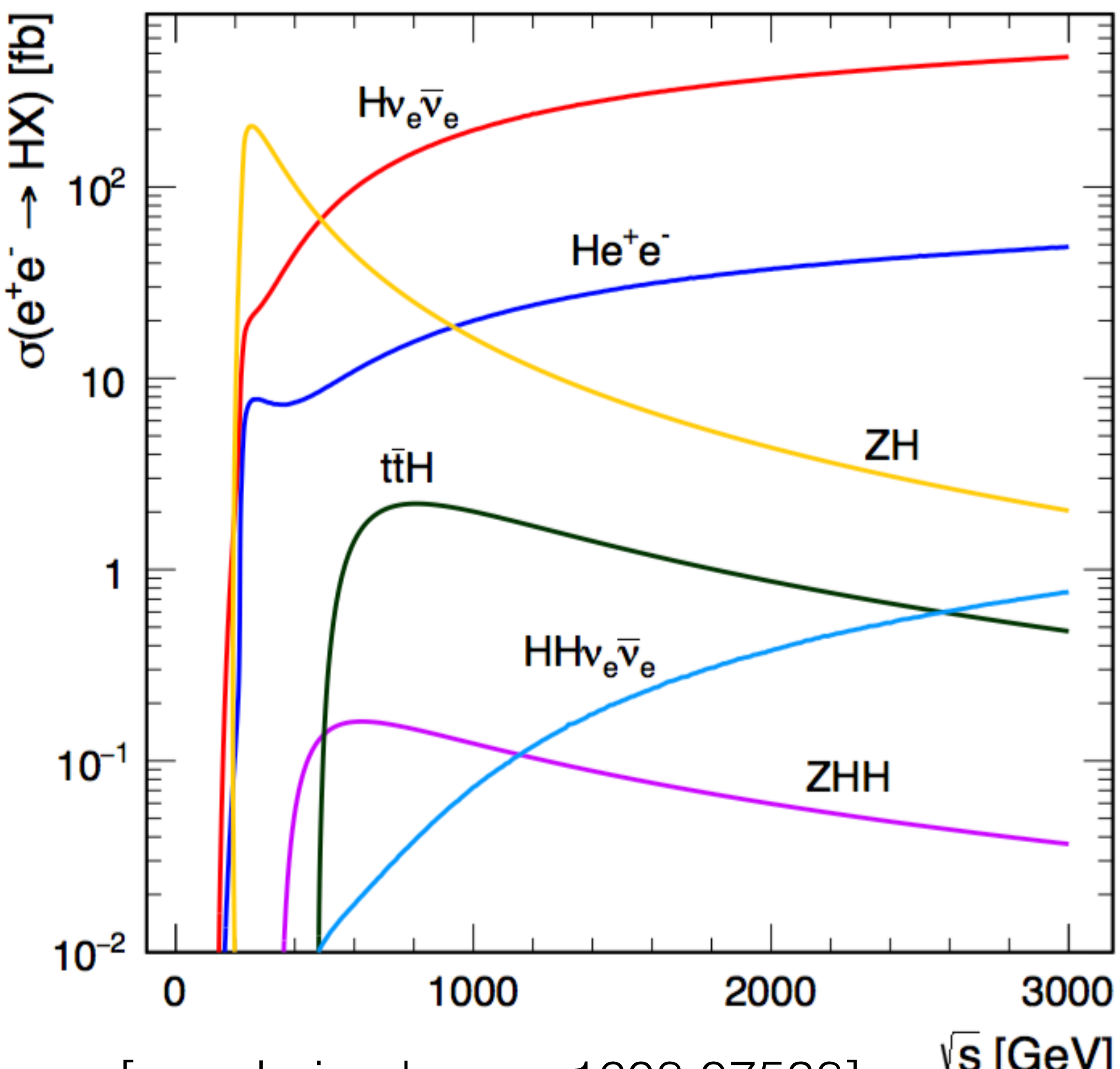
complementarity: direct NP search & precision Higgs coup.

MSSM with b-τ unification

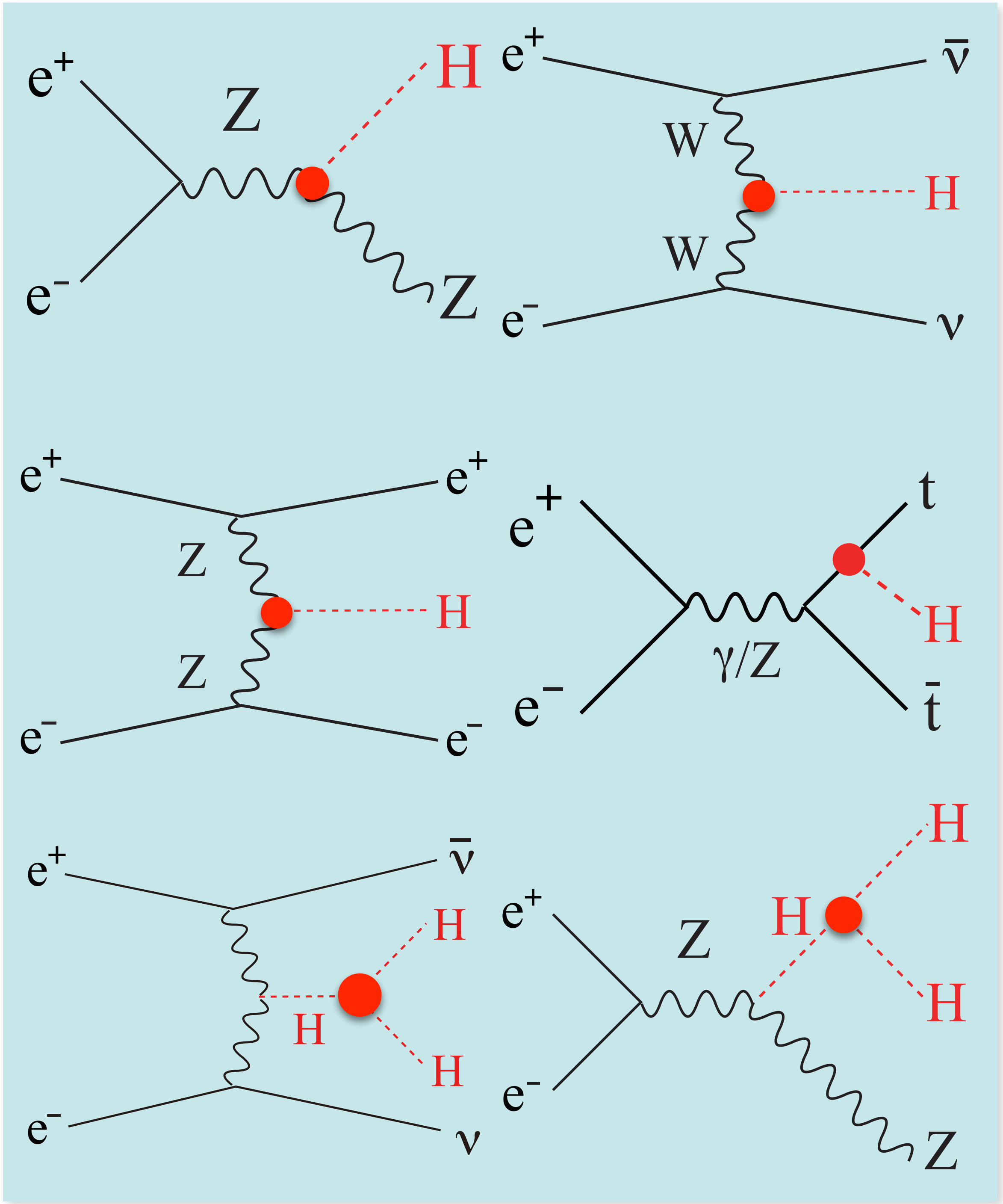


[Wells, Zhang, arXiv:1711.04774]

Higgs productions at e+e-



[unpolarized case; 1608.07538]



- two apparent thresholds: $\sqrt{s}$ ~ 250 GeV for ZH, ~500 GeV for ZHH & ttH
- + another threshold for t t-bar, important for Higgs sector as well

Highlight a few measurements @ e+e-

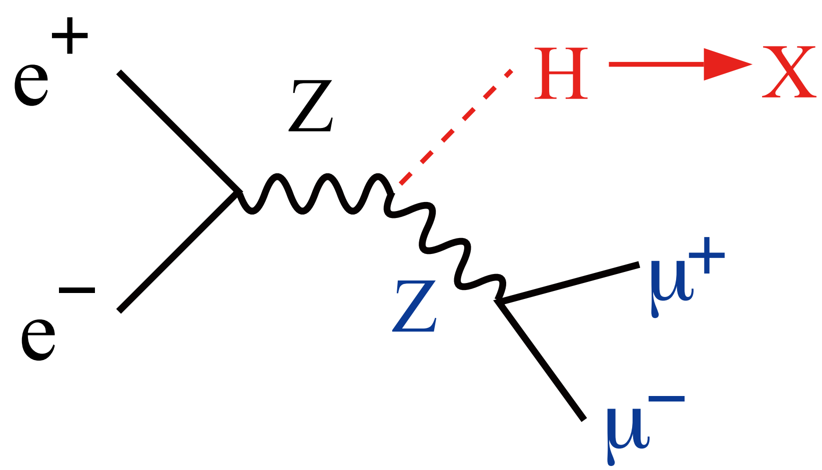
caution:
bias in selection

- m_H, CP
- σ_{ZH}
- Br(H→bb / cc / gg)
- Br(H→Invisible / Exotic)
- total width Γ_H
- Higgs self-coupling

note the important synergy with LHC on BR(H→γγ/γZ/μμ)

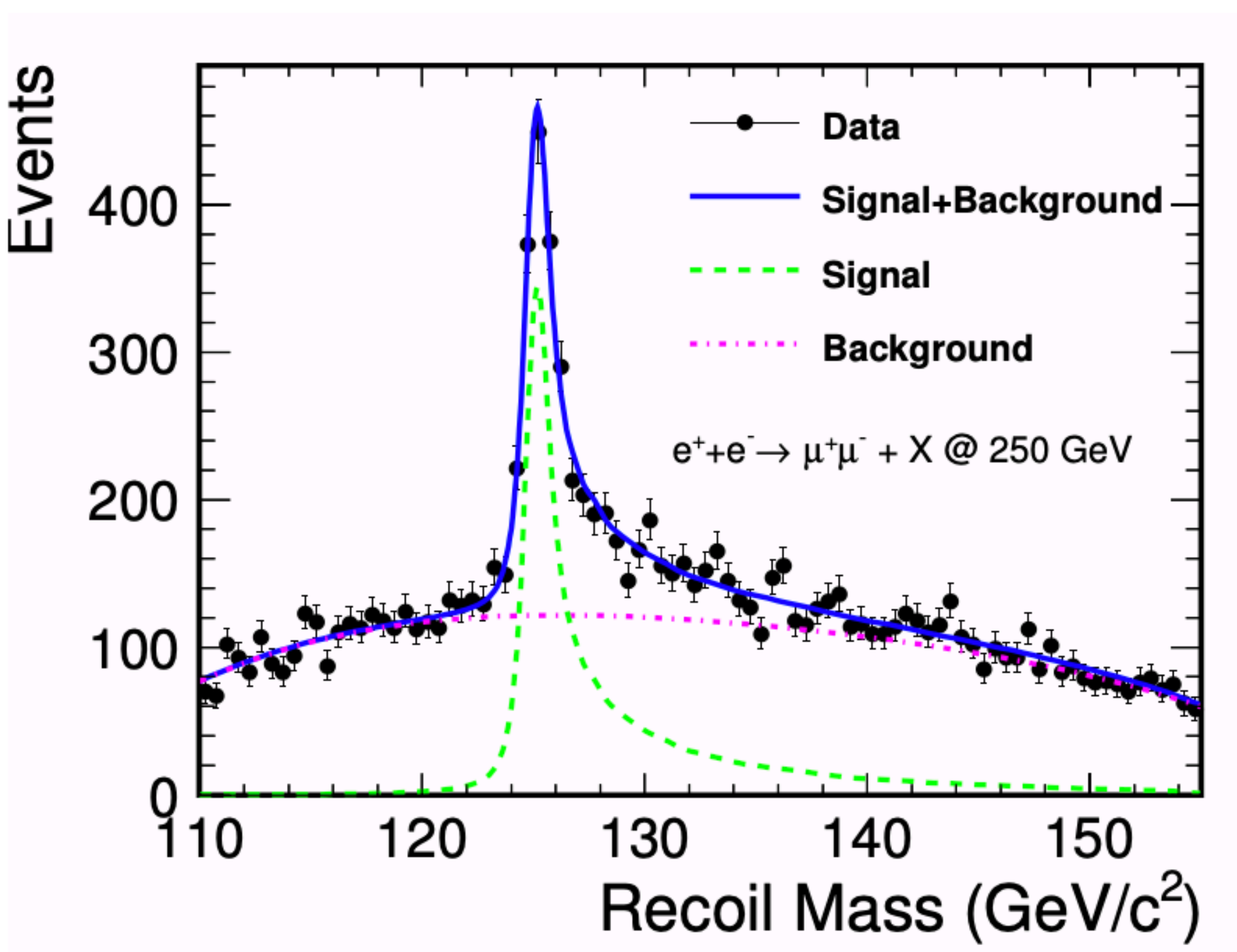
unless stated, most features are common for e+e-

recoil mass technique: m_H & inclusive σ_{ZH}



$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

- well defined initial states at e+e-
- Higgs is tagged without looking into H decay
- inclusive cross section of $e^+e^- \to ZH$
- key to determining absolute Higgs couplings

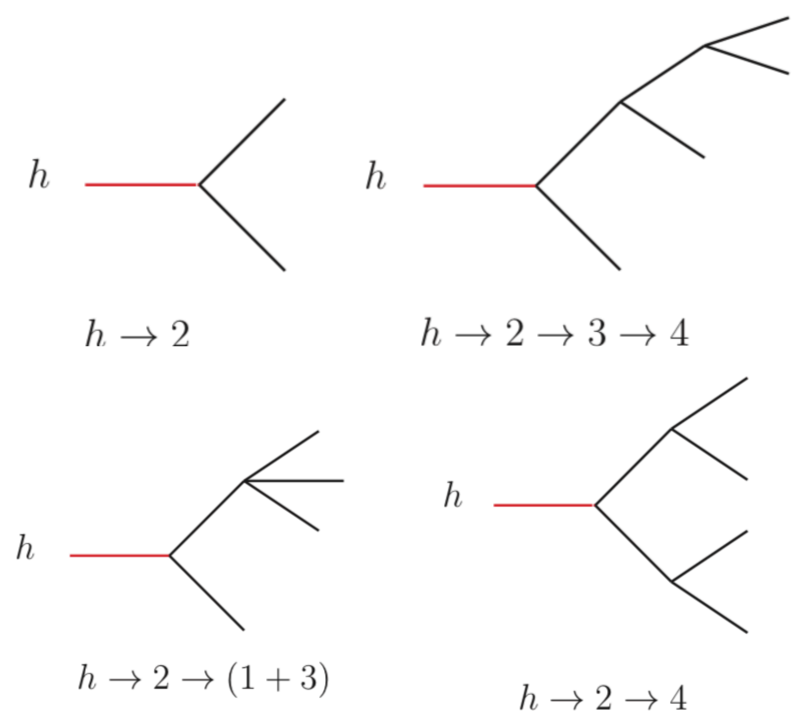


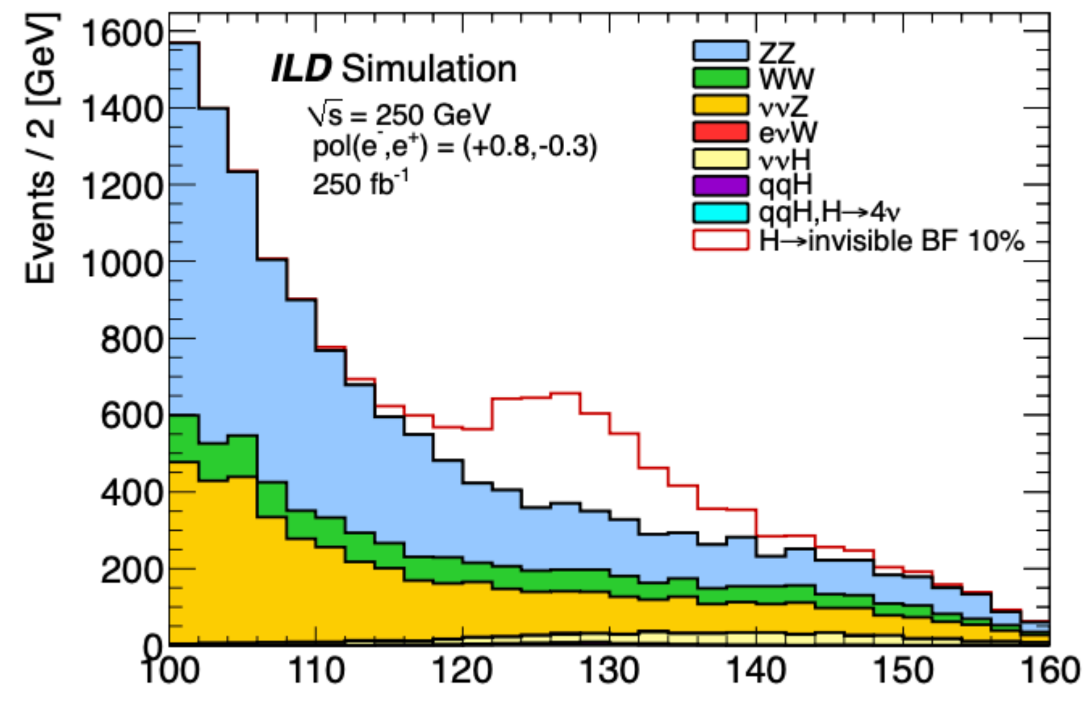
[Yan et al, arXiv:1604.07524]

[ESG]	Δm_H / MeV	$\delta\sigma_{ZH}$
CEPC	5.9	0.5%
FCC-ee240	11	0.5%
ILC250	14	L:1.1%; R:1.1%
CLIC380	78 (23)	L:1.5%; R:1.8%

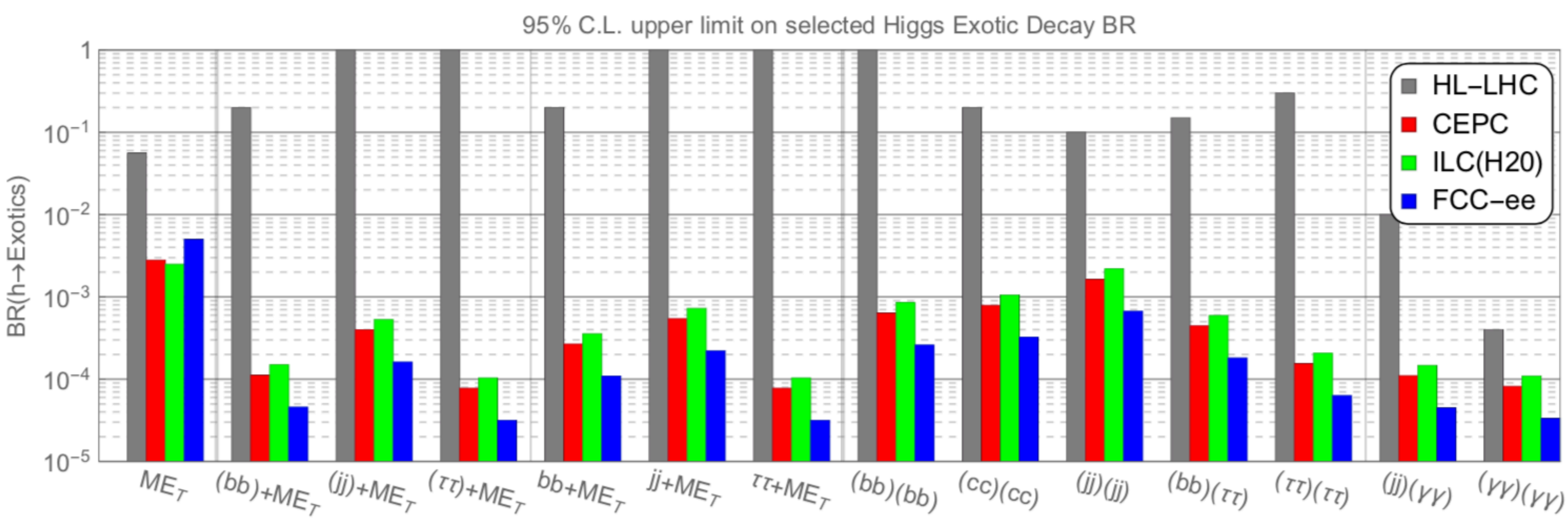
Higgs decays to invisible or exotic

- recoil technique allows Higgs to be fully reconstructed even if it decays invisibly





[Ishikawa, arXiv:1909.07537]

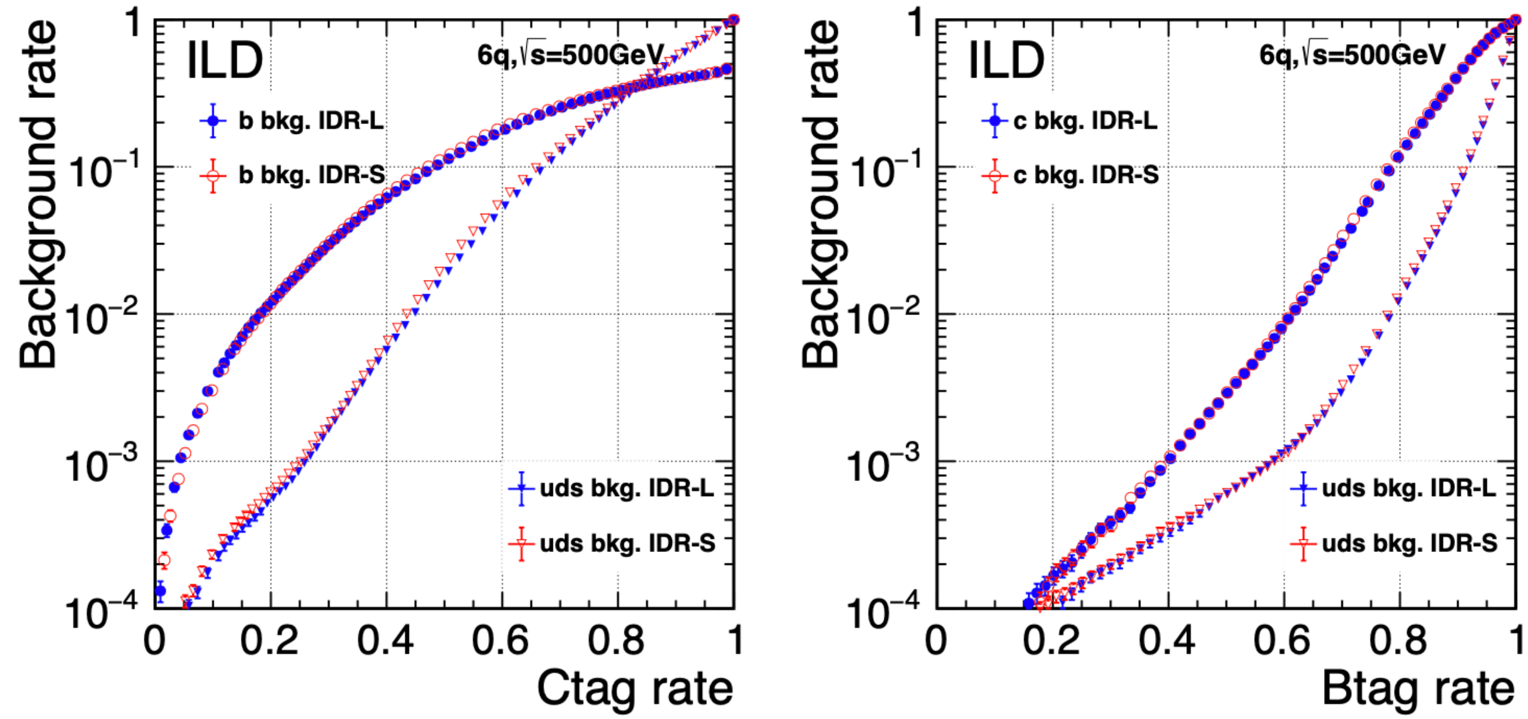


BR~O(0.1%)

[Liu, Wang, Zhang, arXiv:1612.09284]

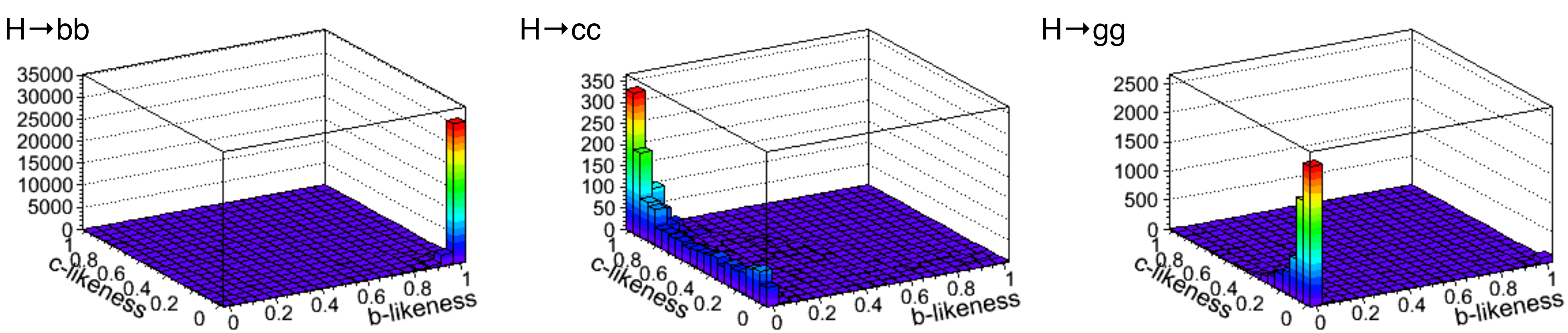
Higgs decays to bb, cc and gg

- clean environment at e+e- allows excellent b- and c-tagging performance
- b-tag eff. typically > 80%
- c-tag eff. typically > 50%
- H→bb/cc/gg separation



[ILD IDR, arXiv:2003.0116]

e+e- → ZH, H→2-jet: b-likeness vs c-likeness



[Ono, et. al, Euro. Phys. J. C73, 2343]

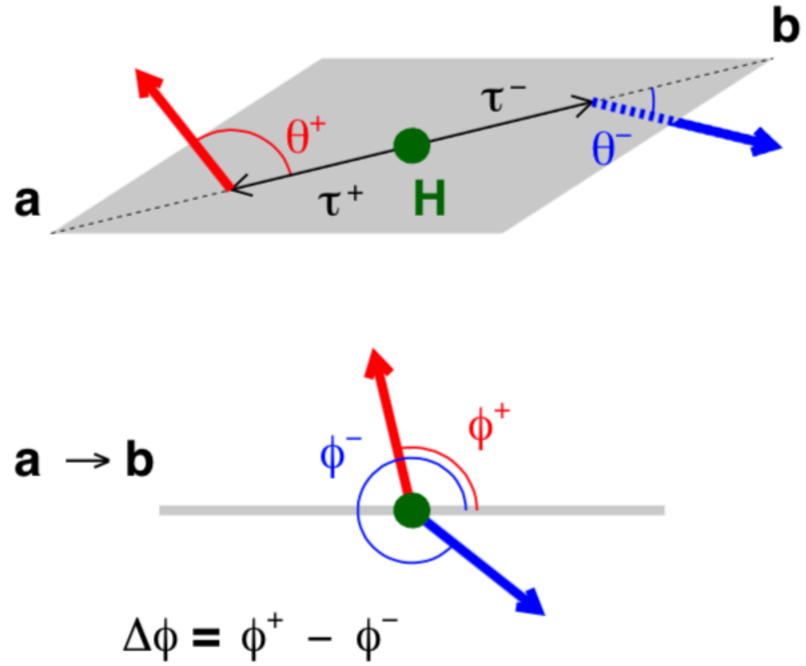
differential meas.: Higgs CP & anomalous couplings

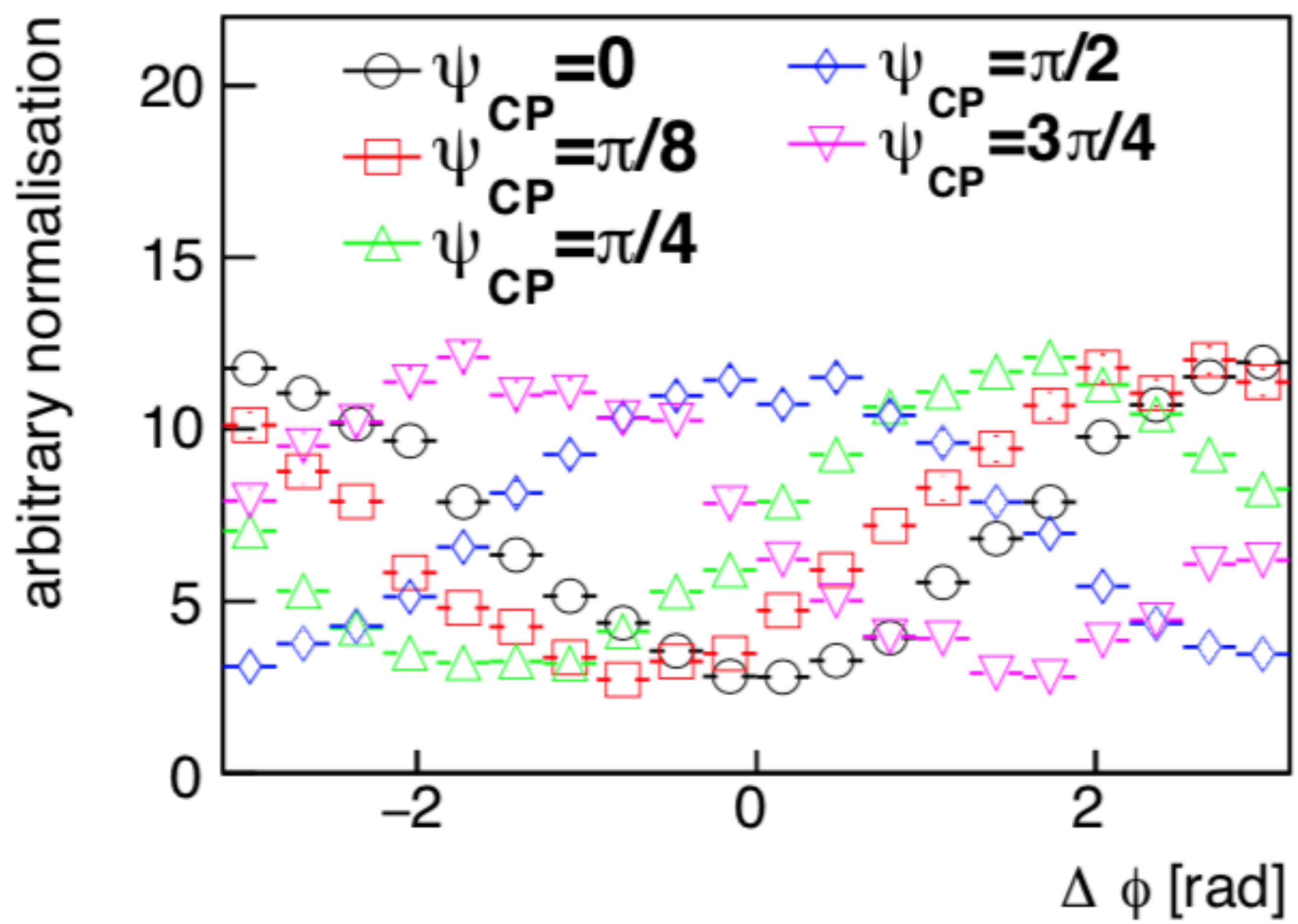
- through H→τ+τ-
  (or ttH)

$$\mathscr{L}_{Hff} = -\frac{m_f}{v} H\bar{f}(\cos\Phi_{CP} + i\gamma^5 \sin\Phi_{CP})f$$

(CP-odd)

$\Delta\Phi_{CP} \sim 4.3^\circ$ [Jeans, Wilson, 1804.01241]





CP sensitive observable (Δϕ): transverse spin correlation of two τ

differential meas.: Higgs CP & anomalous couplings

- through HZZ (or HWW)

$$\mathscr{L} = m_Z^2\left(\frac{1}{v} + \frac{a}{\Lambda}\right)HZ^\mu Z_\mu + \frac{b}{2\Lambda}HZ^{\mu\nu}Z_{\mu\nu} + \frac{\tilde{b}}{\Lambda}HZ^{\mu\nu}\tilde{Z}_{\mu\nu}$$

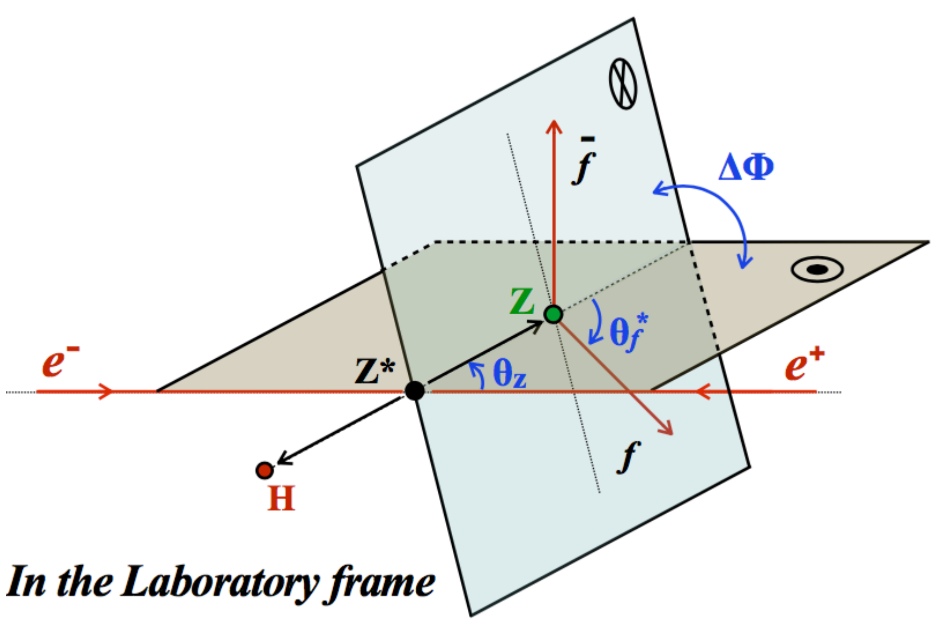
(CP-odd)

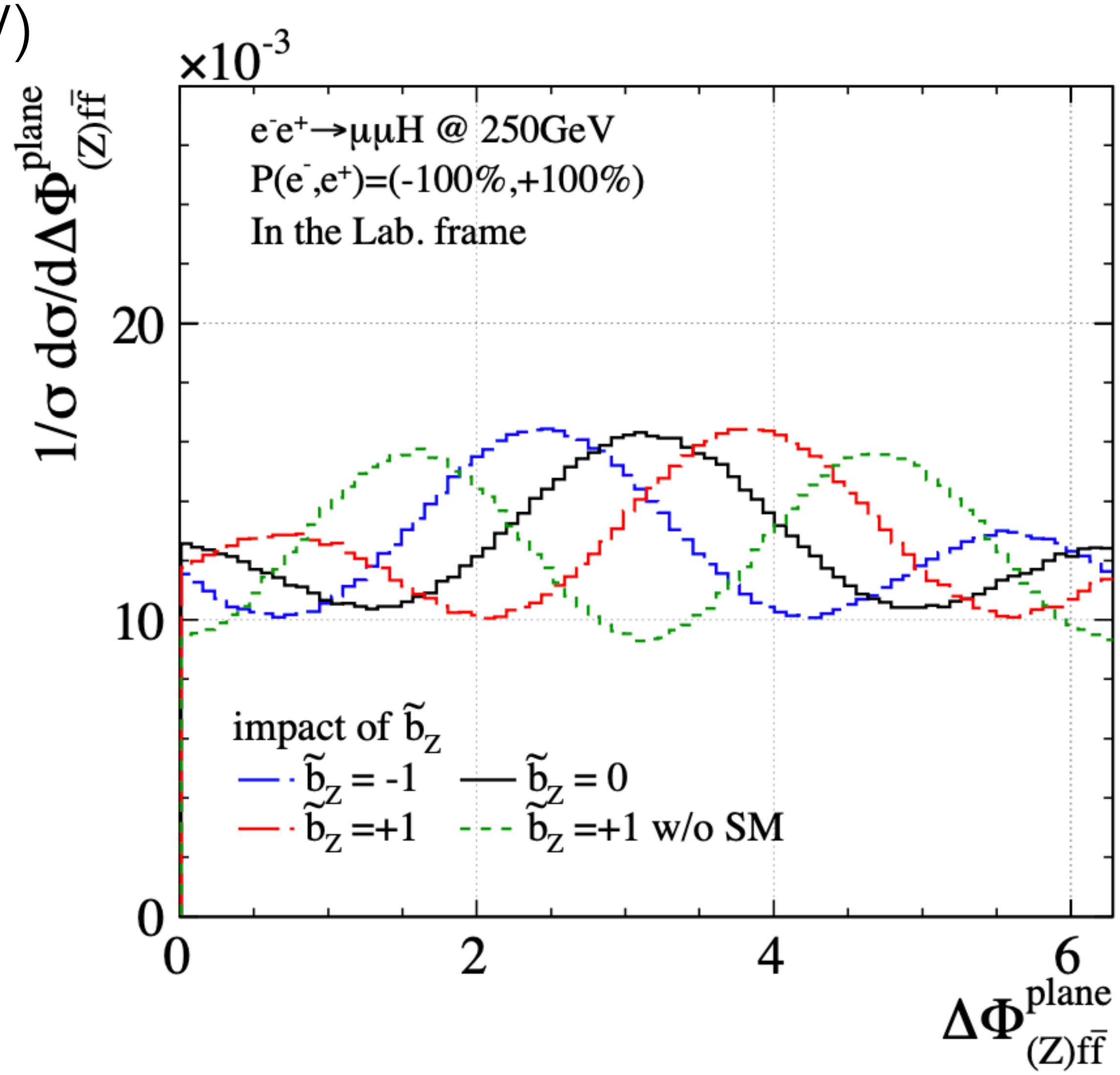
$\Delta\tilde{b} \sim 0.016$

(for Λ=1TeV)

[Ogawa, Fujii, JT, 1712.09772]

$$e^+ + e^- \to Zh \to f\bar{f}h$$





CP sensitive observable (Δϕ):
angle between Zh production plane & Z decay plane

Higgs total width Γ_H (4 MeV in SM)

- too small to be determined directly through line-shape (σ_D~O(500) MeV)
- unique method enabled by meas. of inclusive σ_{ZH} @ e+e-
  1. extraction of absolute HZZ coupling (given ***a theory formalism***)
  2. computation of partial width $\Gamma(H\to ZZ^*)$
  3. with meas. of $BR(H\to ZZ^*)$, total width is determined as

$$\Gamma_H = \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)}$$

(similar for $H\to WW^*$)

[ESG]

Collider	$\delta\Gamma_H$ [%] from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ [%] kappa-3 fit
ILC_{250}	2.3	EFT fit [3, 4]	2.2
ILC_{500}	1.6	EFT fit [3, 4, 14]	1.1
ILC_{1000}	1.4	EFT fit [4]	1.0
$CLIC_{380}$	4.7	κ-framework [98]	2.5
$CLIC_{1500}$	2.6	κ-framework [98]	1.7
$CLIC_{3000}$	2.5	κ-framework [98]	1.6
CEPC	2.8	κ-framework [103, 104]	1.7
FCC-ee_{240}	2.7	κ-framework [1]	1.8
FCC-ee_{365}	1.3	κ-framework [1]	1.1

$$\delta\Gamma_H \sim 1-2\,\%$$

tricky due to Step 1

From observables to couplings — Global Fit

- kappa formalism
  - useful to quantify the sensitivity to new physics effect from single measurement; but may miss important relations

eg. $$\mathscr{L} = (1+\eta_Z)\frac{m_Z^2}{v} H Z^\mu Z_\mu + \zeta_Z \frac{H}{2v} Z^{\mu\nu} Z_{\mu\nu}$$ (new Lorentz structure)

$$\delta\sigma(e^+e^- \to ZH) = 2\eta_Z + 5.5\zeta_Z$$
$$\delta\Gamma(H \to ZZ^*) = 2\eta_Z - 0.5\zeta_Z$$

can't be both represented by a single κ_Z

- SM Effective Field Theory formalism

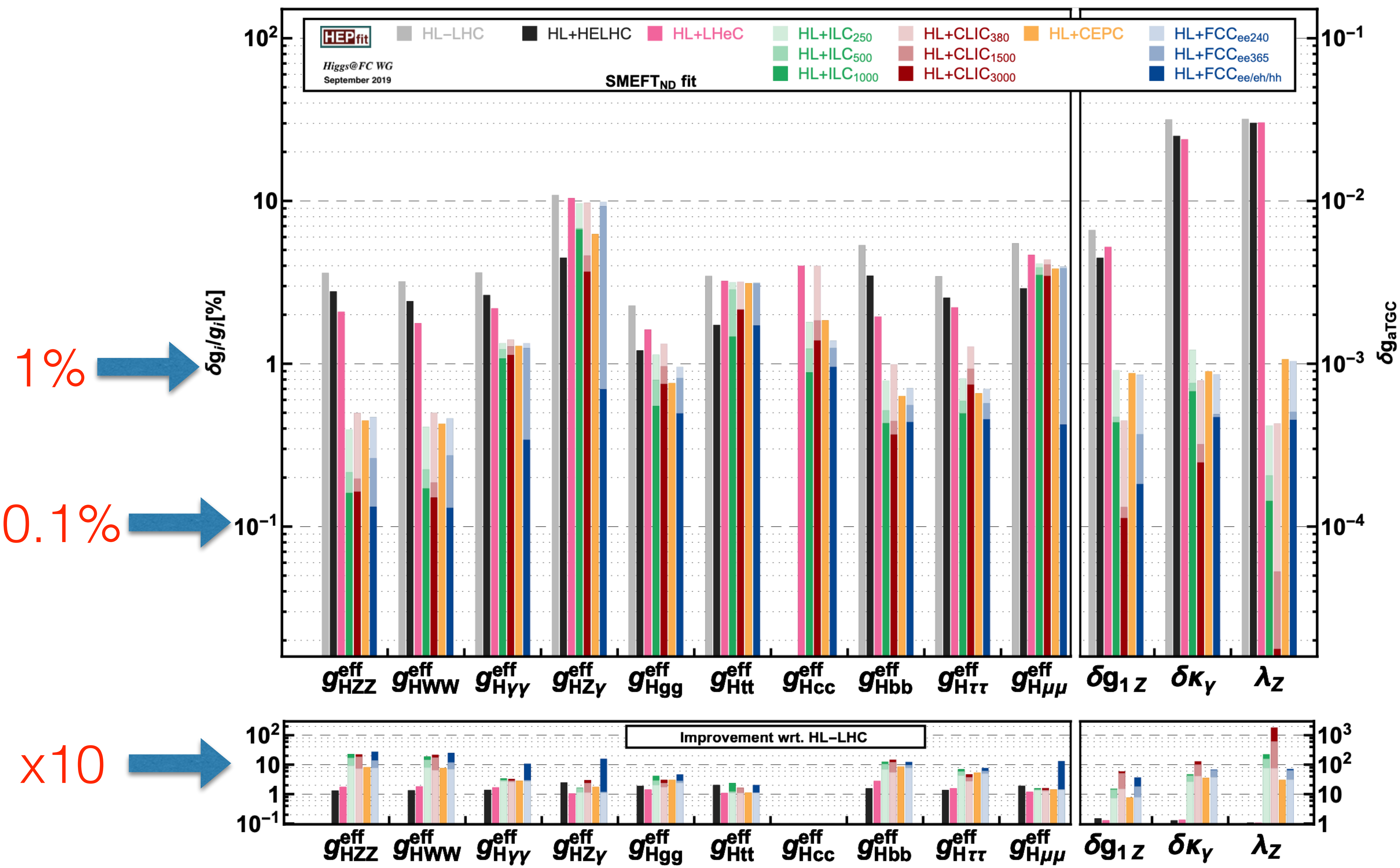
$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^{d_i-4}} O_i^{(d_i)}$$

  - represent most general BSM effects
  - respect SM gauges symmetries

17 D-6 ops related to Higgs can be determined simultaneously at e+e-

[Barklow et al, 1708.09079;1708.08912]

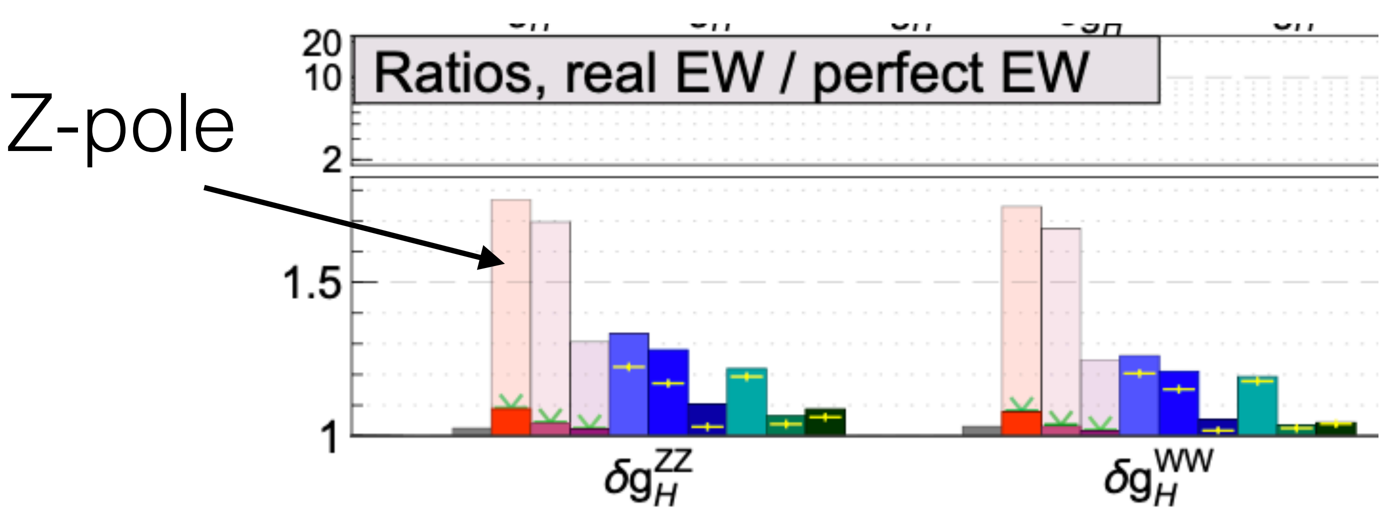
expected Higgs coupling precisions @ future e+e-



[global SMEFT fits by ESG]

global perspective for Higgs meas. @ future e+e-

- the same new physics that modifies Higgs properties may show somewhere else as well
  - combined probe with EWPO, $e^+e^- \to$ WW / 2-fermion
- great synergies with (HL-)LHC measurements
  - Higgs rare decays; Top-quark EW couplings; TGC / QGC; etc
- CEPC / FCC-ee: important role by *Z-pole run*, ~x2 better δg_{HVV}
- ILC/ CLIC: important role by *beam polarizations*, made up ∫L



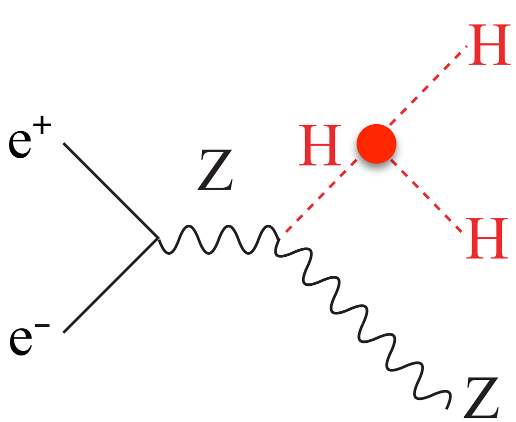
[de Blas et al, arXiv:1907.04311]

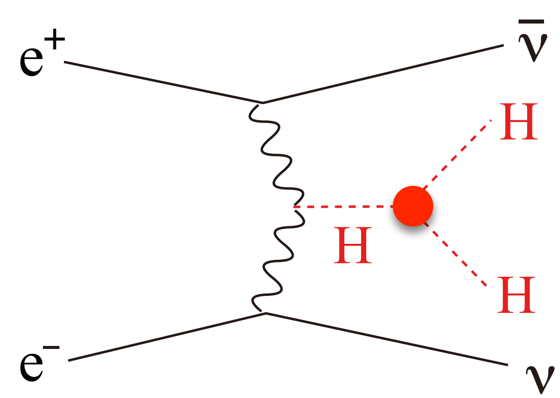
[ESG] $SMEFT_{ND}$	ILC250	CLIC380	CEPC	FCC-ee240
∫L•ab	2	1	5.6	5
δg_{HZZ}	0.39%	0.5%	0.45%	0.47%
δg_{Hbb}	0.78%	0.99%	0.63%	0.71%
$\delta g_{H\tau\tau}$	0.81%	1.3%	0.66%	0.69

Higgs self-coupling $\delta\lambda_{HHH}$

[Di Micco et al, arXiv:1910.00012]

- through double Higgs (ZHH ~500GeV; vvHH ≥1TeV)



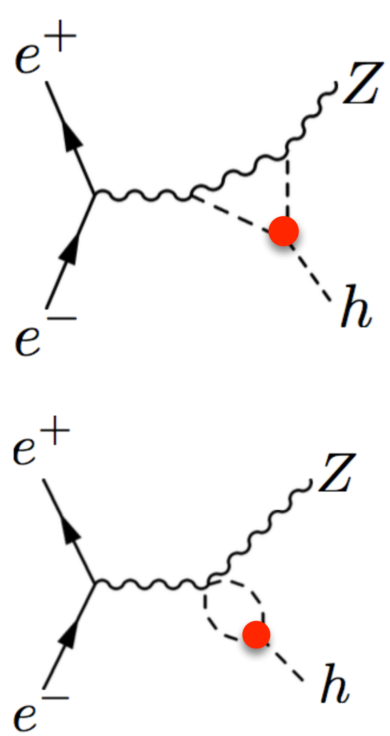


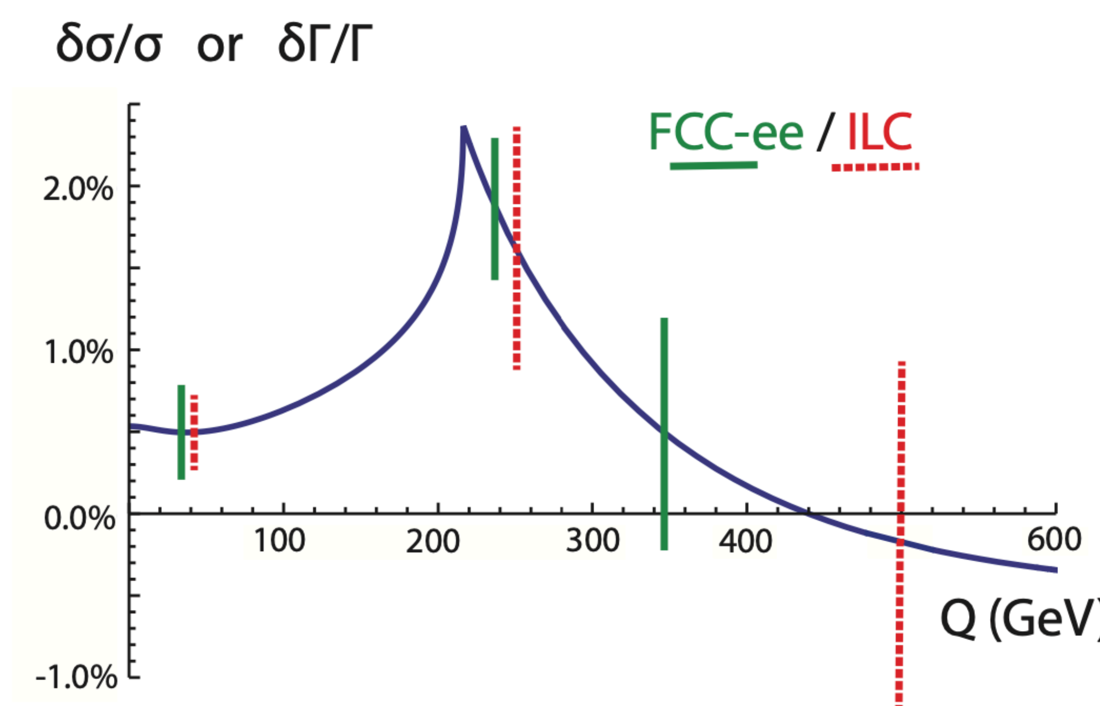
ILC500	ILC1000
27%	10%

CLIC1500	CLIC3000
36%	10%

- through single Higgs (need multiple Q^2 to identify λ_{HHH} effects)

[McCullough, 1312.3322]





(full SMEFT)

FCC-ee 240+365	44% 27% (4IP)
ILC 250+500	58%

(HL-LHC excluded)

summary

- future e+e- Higgs factories will add great opportunities on precision determination of Higgs properties, which will help reveal the nature of BSM physics
- recoil mass analysis is the key to model-independent meas. of absolute Higgs couplings & total width
- need a global perspective on Higgs physics (+EW / Top / BSM)
- all proposed e+e- are capable of reaching $\lesssim 1\%$ precision for many of the Higgs couplings
- when will any of them be realized?