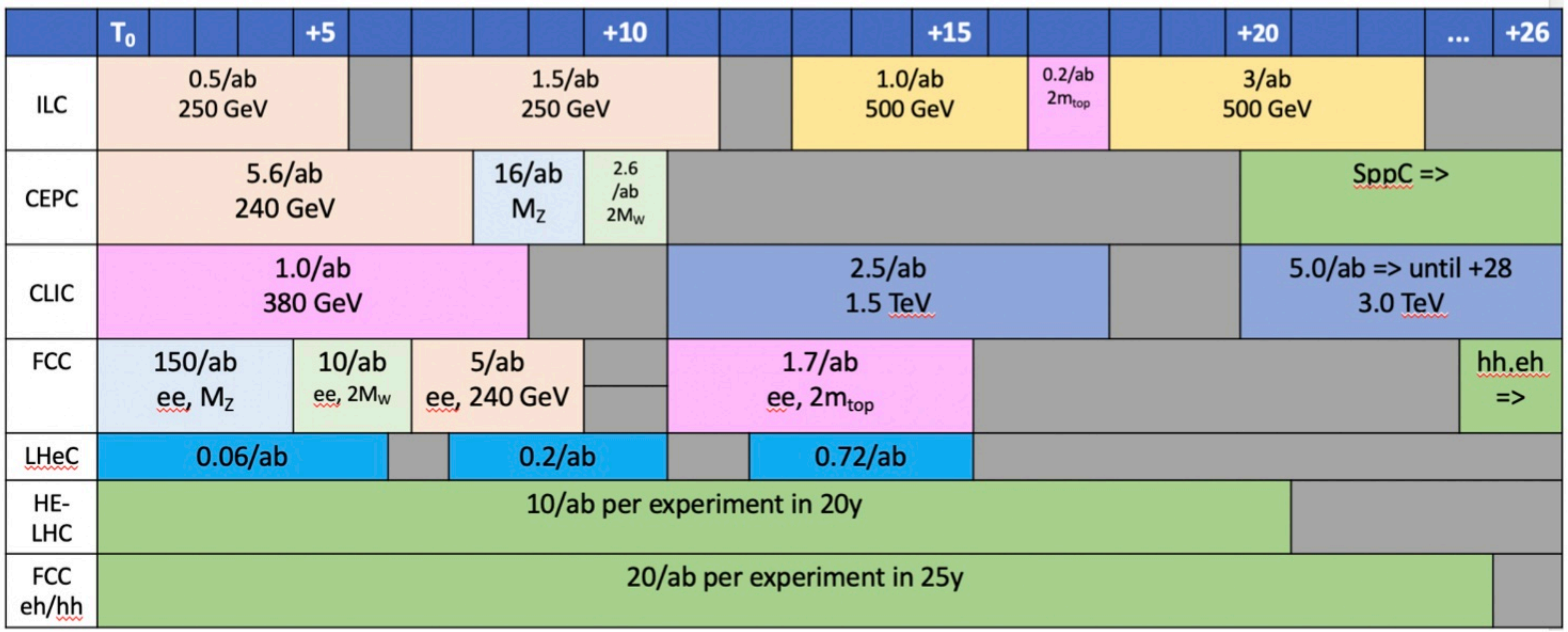
Introduction to e+e- Physics & Simulation



Junping Tian (U. Tokyo)

MCnet Beijing School for Event Generators, June 28-July 2, 2021

plan

(i) Mini-intro to future e+e- experiments

Lecture 1

(ii) Higgs Property Measurements

(iii) New Particle Searches

(iv) Top-quark & EW Measurements

Lecture 2

(v) Global Interpretation in SM EFT

focus will be on experimental concepts “why / what / how”
please learn theoretical concepts “why” from other lectures

(iii) New Particles Searches at e+e-

what we would like to measure here:
unlike Higgs/EW/Top physics, there are infinite number of possible searches of new particles, completely up to your (theorists') imagination

a lot searches ongoing at LHC, here some complementary searches at e+e-

(1) Dark matter particles
- Higgs Portal
- Mono-photon

(2) Extra scalar particles

(3) Supersymmetric Particles
- EWkinos
- s-tau

(4) …

as usual, selection is always biased

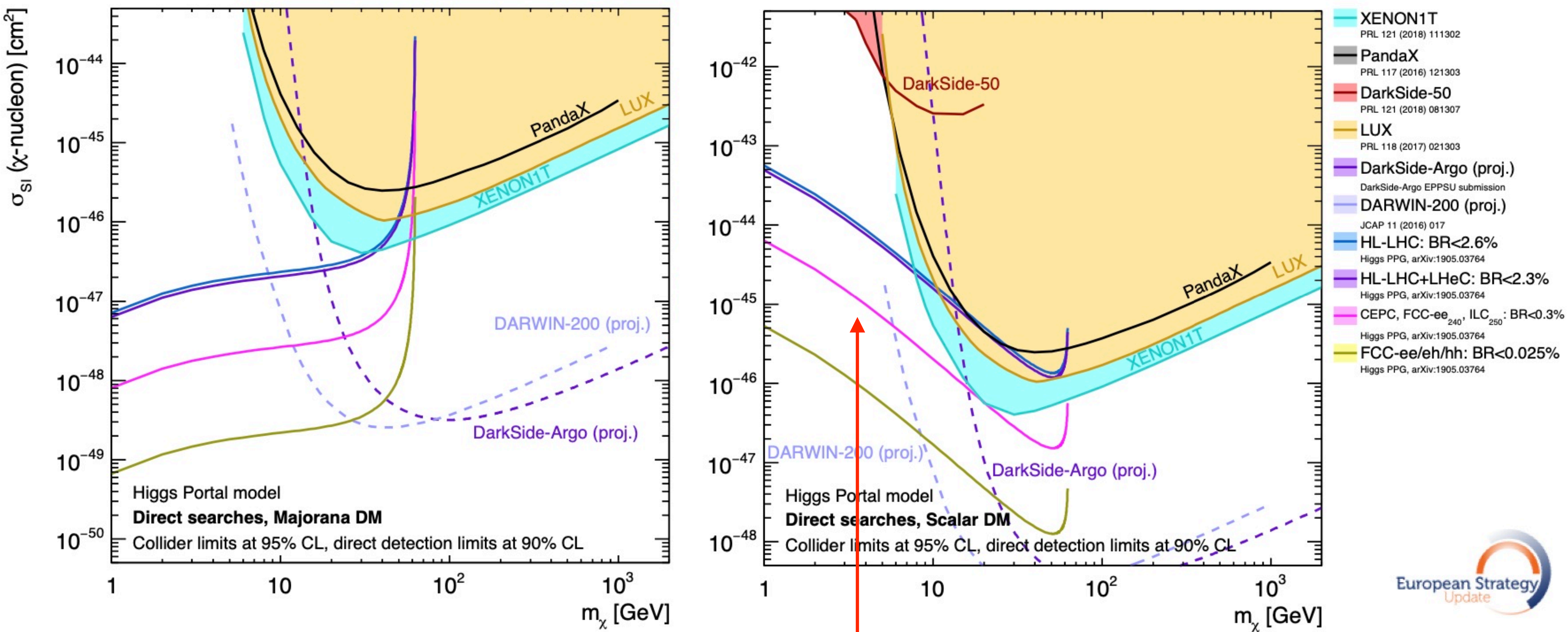
(iii-1) Dark Matter / Dark Sectors at e+e-

$$\epsilon\, B_{\mu\nu} \hat{F}^{\mu\nu} \;, \qquad \epsilon\, |\varphi|^2 |\hat{S}|^2 \;, \qquad \epsilon\, L^\dagger \cdot \varphi \hat{N} \;,$$

gauge portal

Higgs portal

neutrino portal

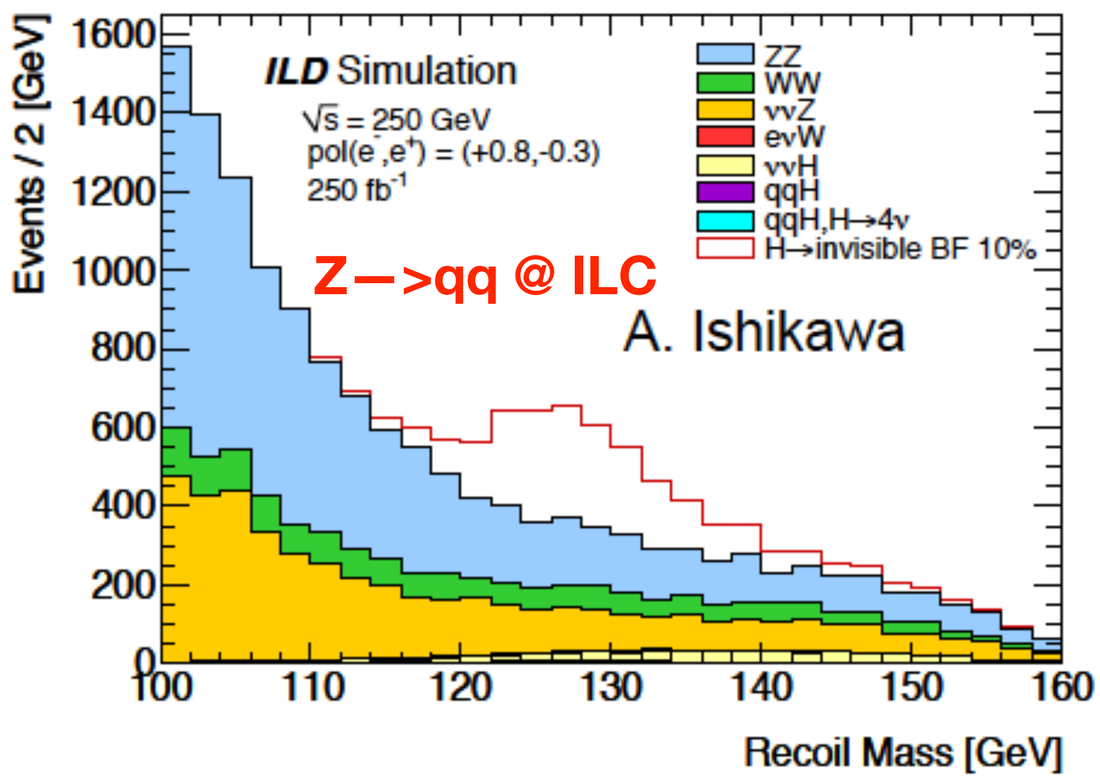


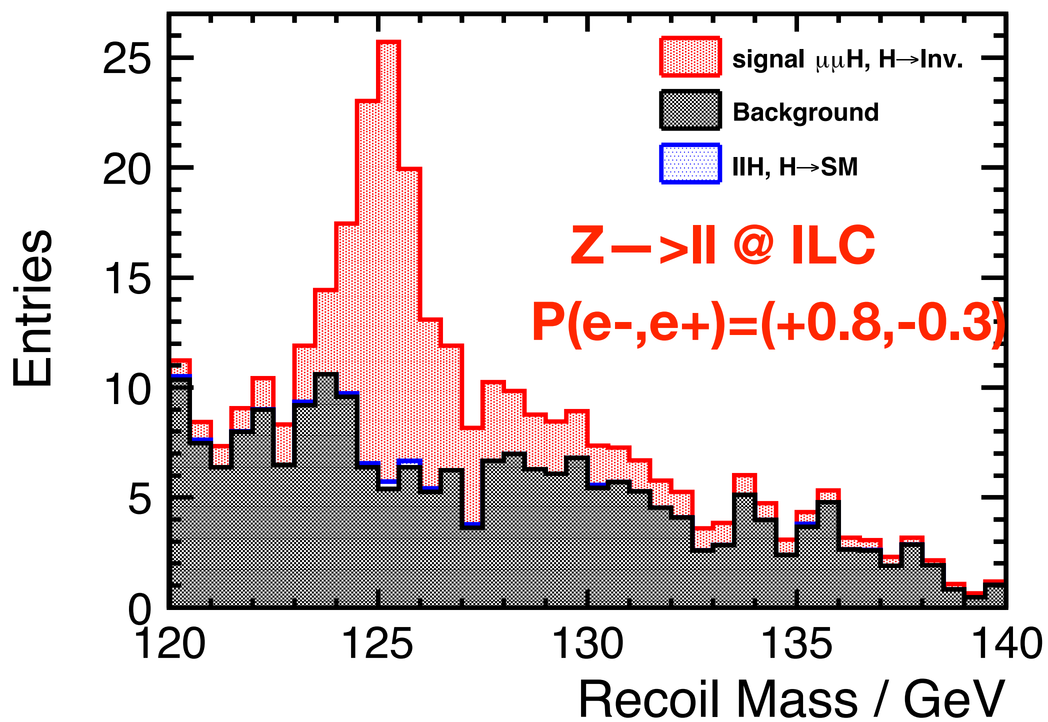
[ESU, arXiv:1910.11775]

BR(H—>invisible)

Higgs —> invisible at e+e-

$$e^+ + e^- \to ZH \to l^+l^-/q\bar{q} + \text{Missing}$$

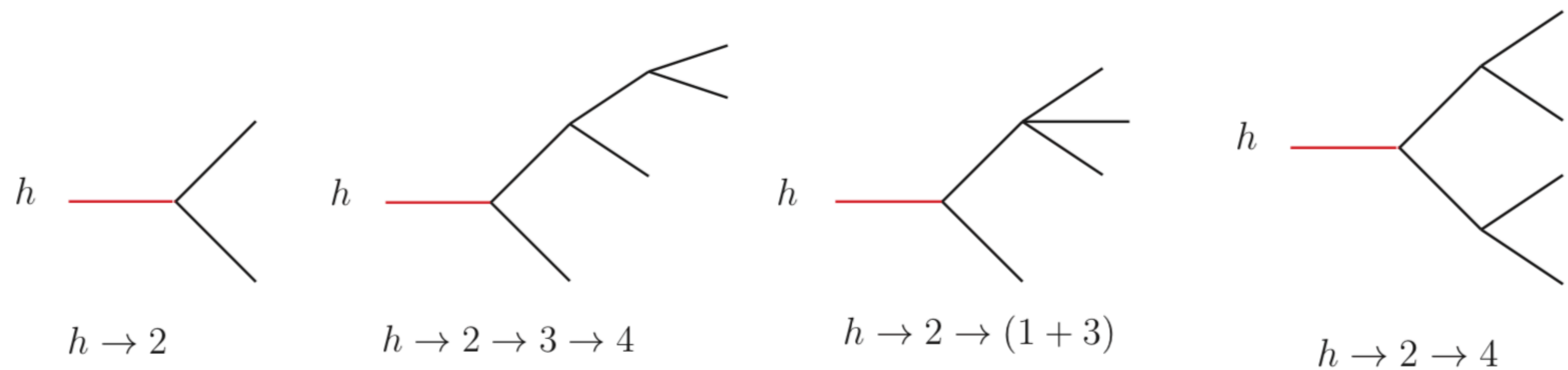


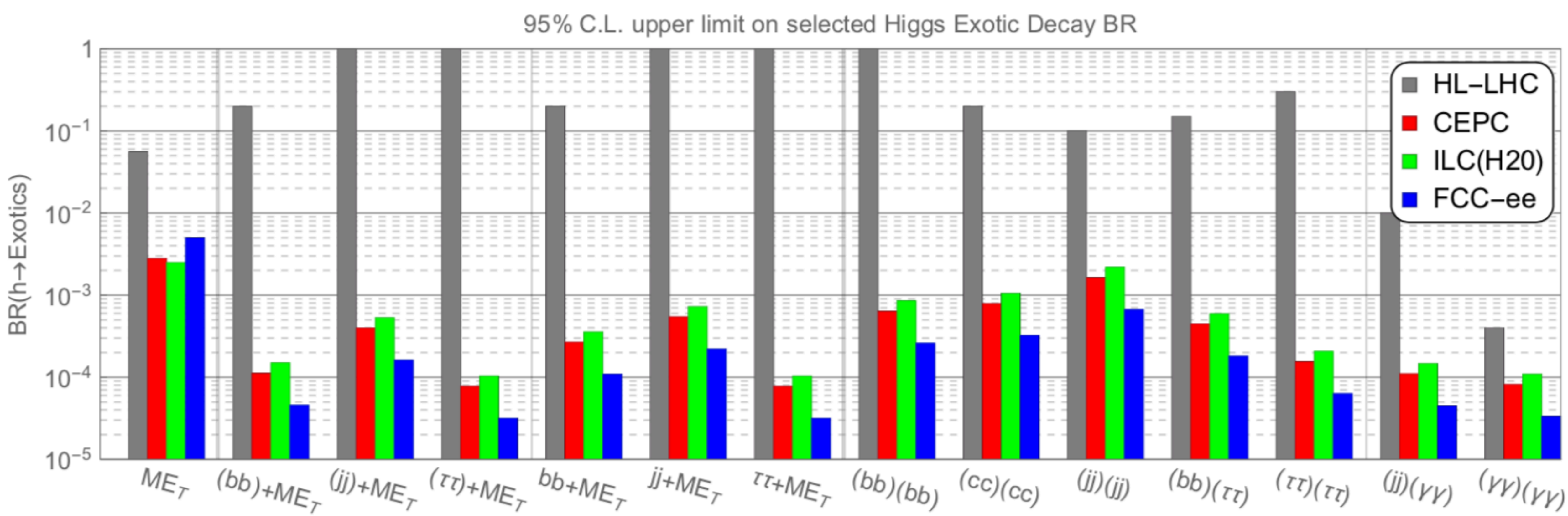


- recoil technique: Higgs mass fully reconstructed even it decays invisibly
- right-handed beam polarization helps: much lower background
- **BR(H—>inv.) < 0.3% (C.L.95)**

Higgs exotic decays at e+e-

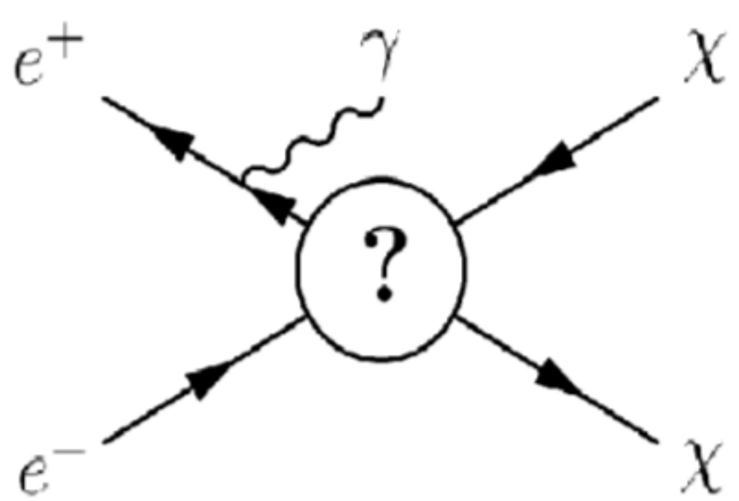
[Liu, Wang, Zhang, arXiv:1612.09284]



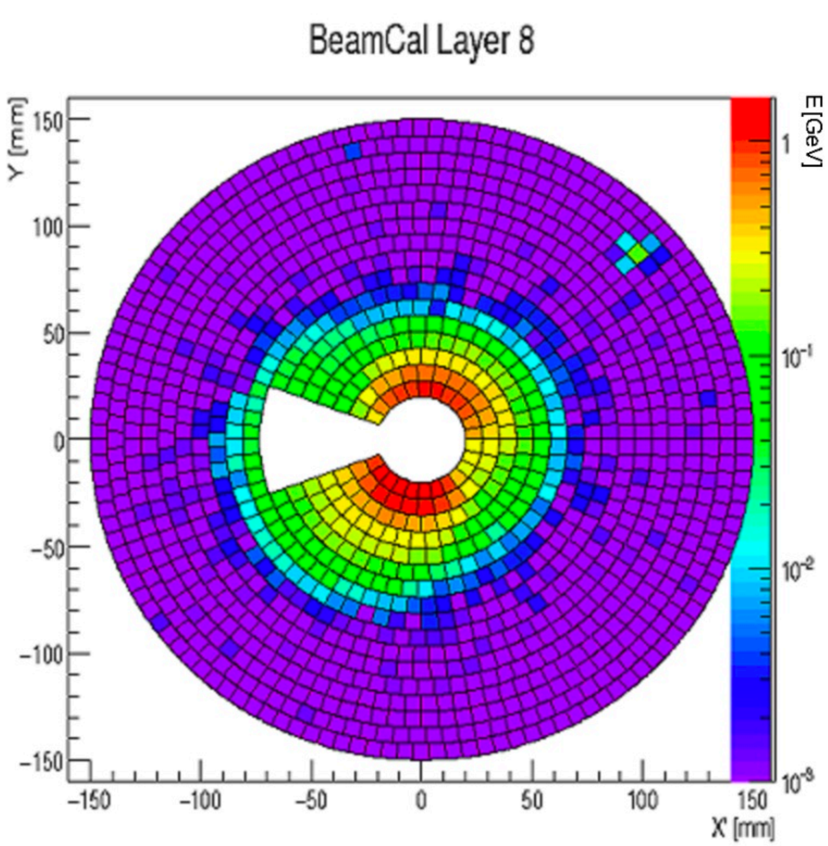


- many modes need to be studied with more realistic analyses

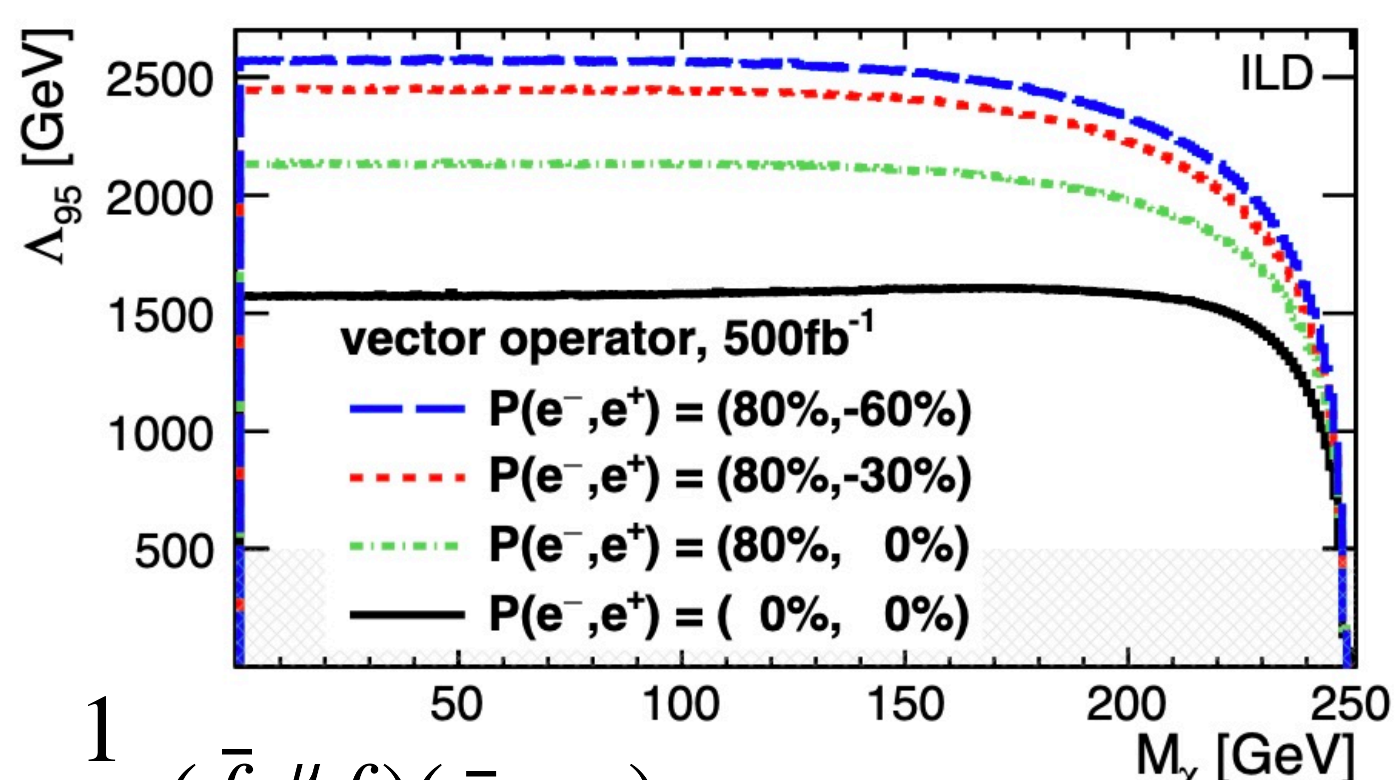
WIMP pair production: mono-photon search



- reach of **$m_\chi \sim \sqrt{s} / 2$**
- precise forward EM calorimeter is crucial for tagging the ISR photon or vetoing Bahbah background —> **"~4π detector"**
- **polarized beam** is very useful to suppress irreducible t-channel neutrino background



BeamCal: $0.3 - 2.5^\circ$

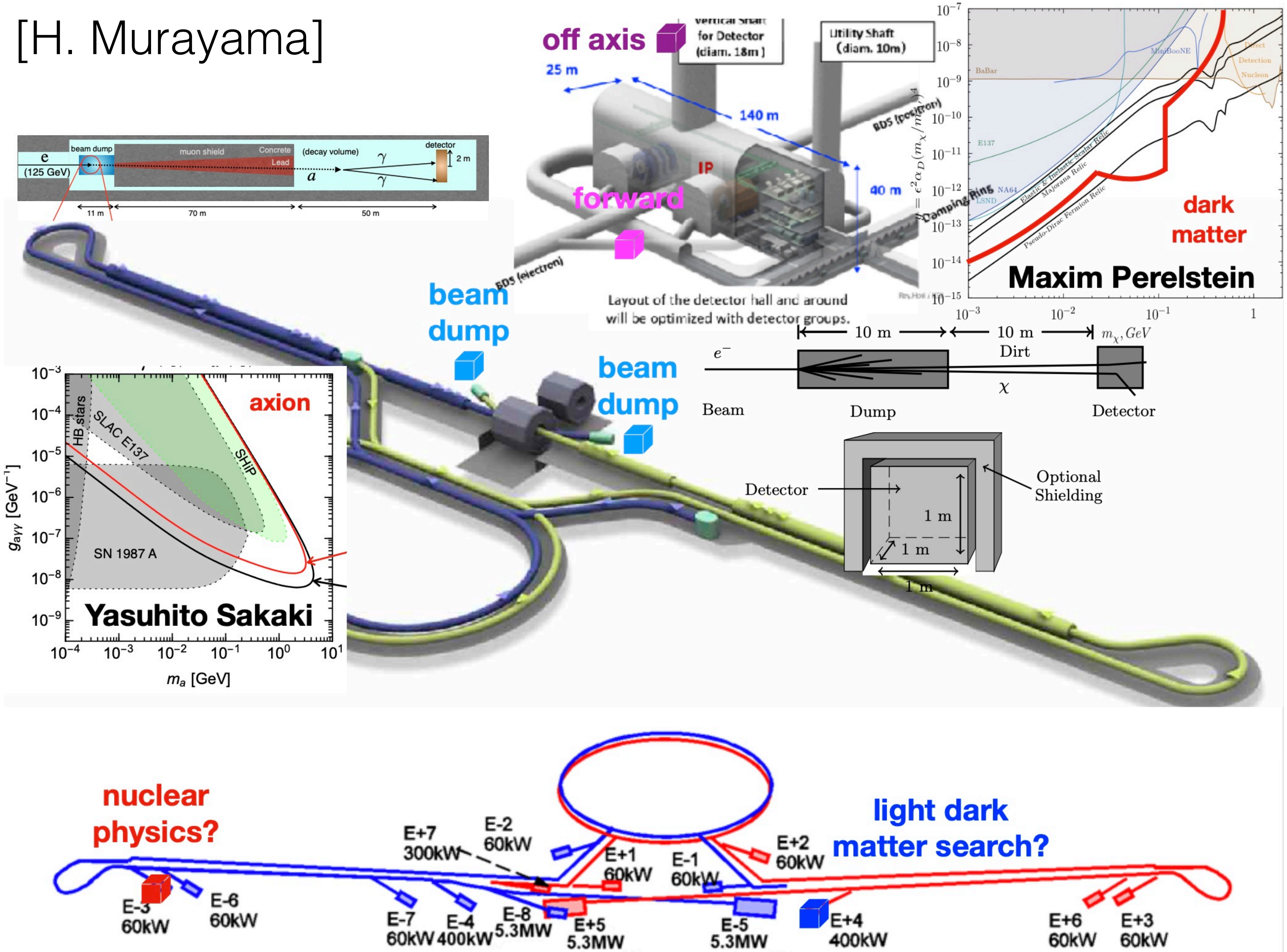


$$\frac{1}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{\chi}\gamma_\mu \chi)$$

[Habermehl et al, 2001.03011]

emerging: dark matter at beam dump / fixed target

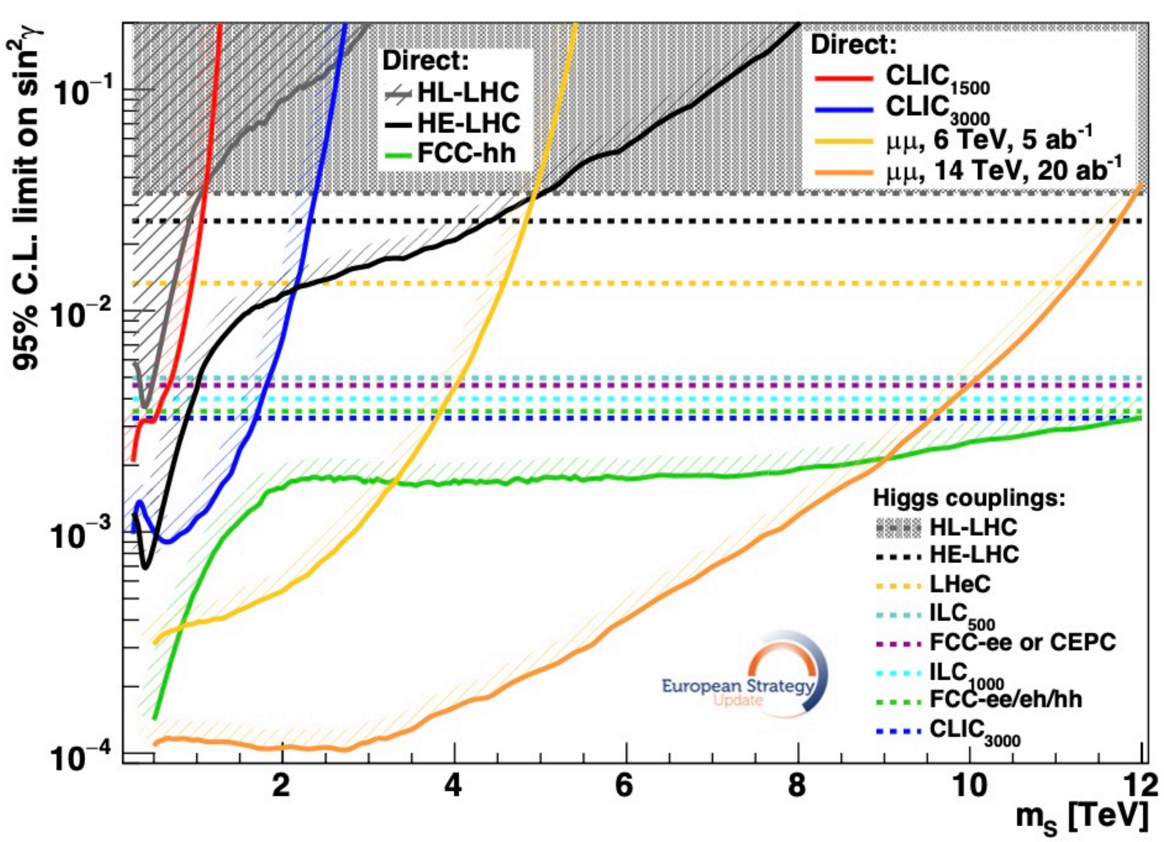
[H. Murayama]



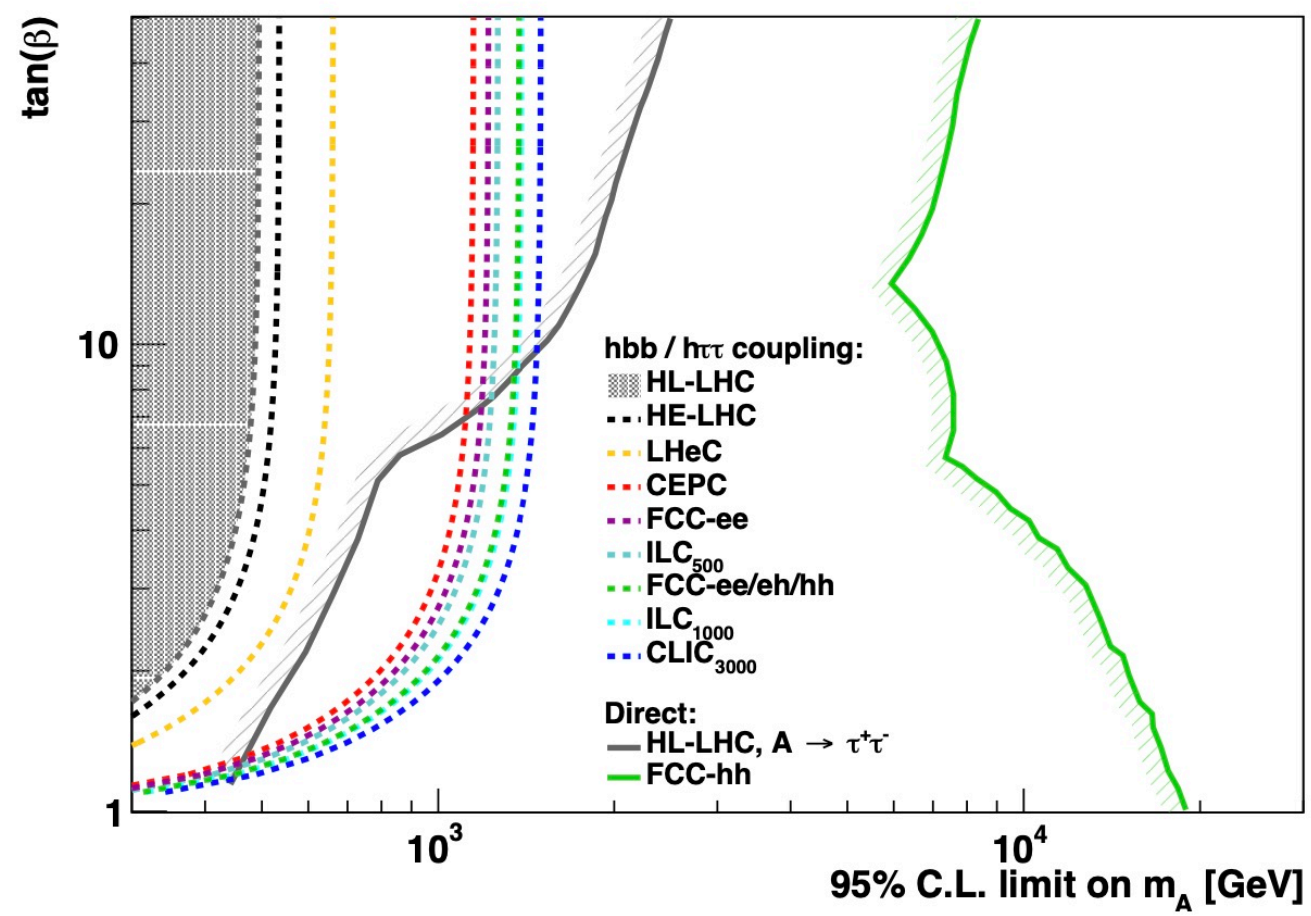
- long lived; axion; ALPs; feebly interacting particles…

(iii-2) Extra Scalars

- pair production: e+e- —> H^+H^- / HA, reach $m_A \sim \sqrt{s} / 2$
- Z-associated production: e+e- —> Z+S
- indirectly search by Higgs couplings
- light extra scalars are still plausible



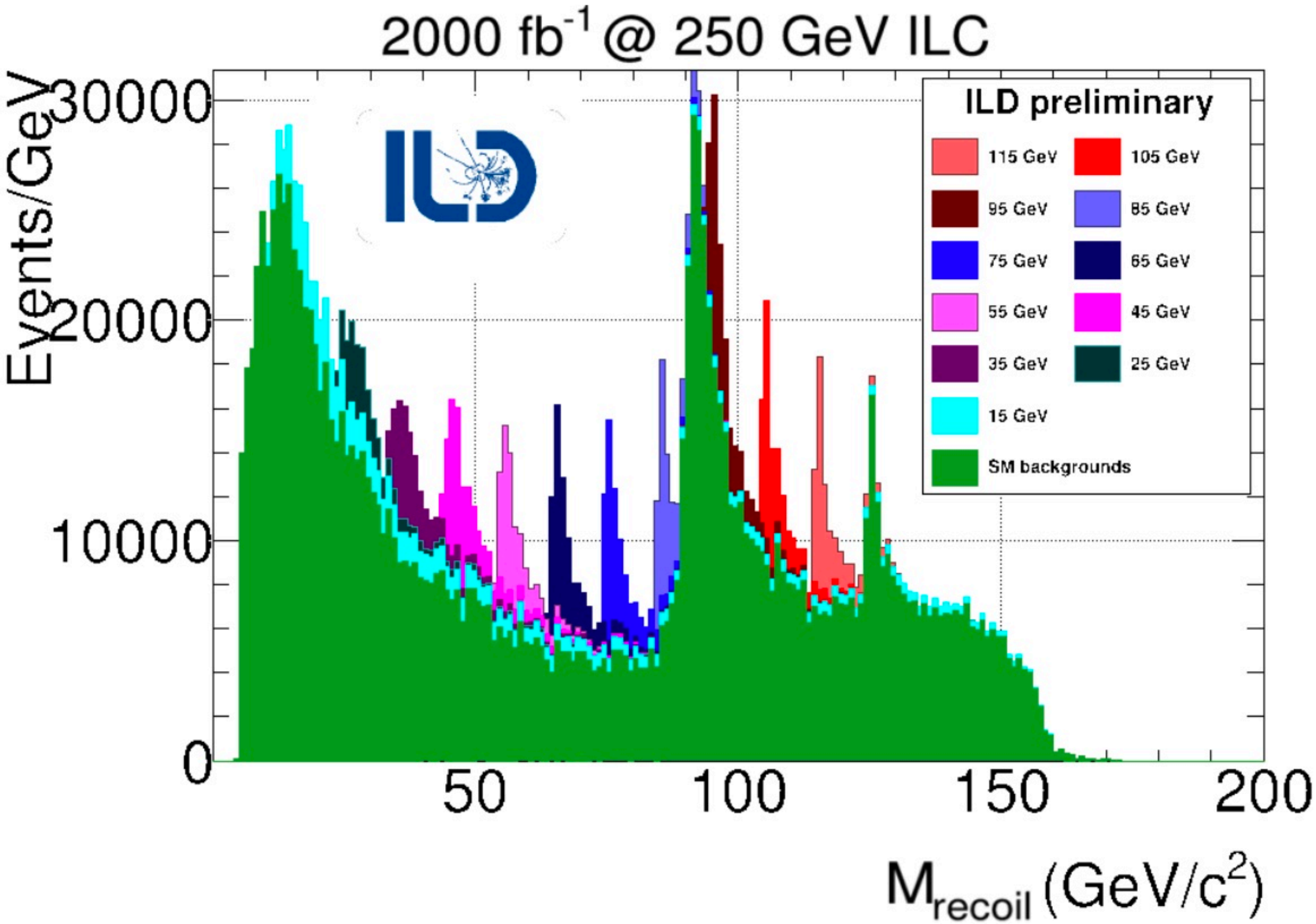
extra singlet



extra doublet

(iii-2) Extra Scalars

- recoil mass technique very useful

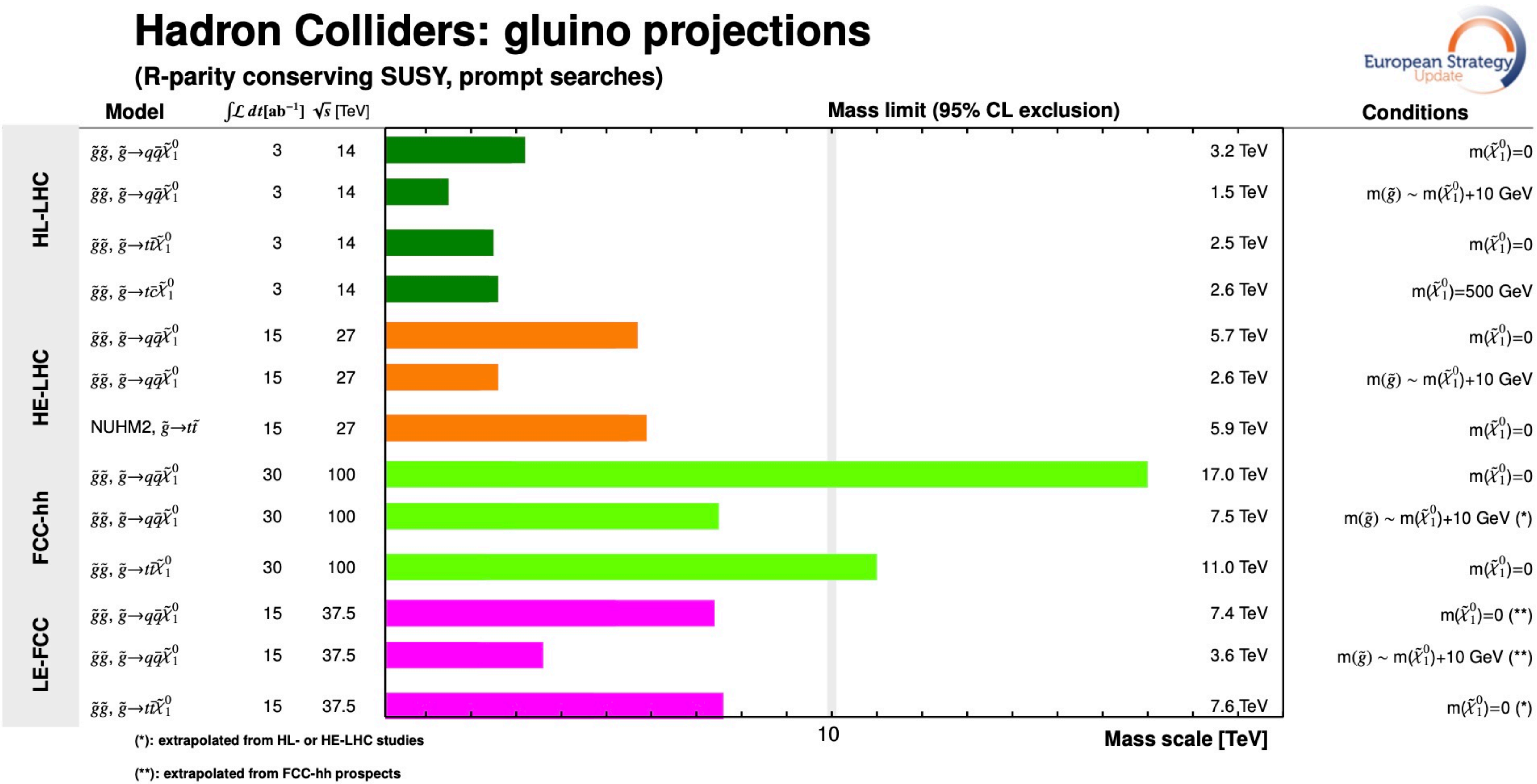


[Wang et al, 1902.06118]

- how to combine indirect / direct sensitivities?

(iii-3) Supersymmetric particles

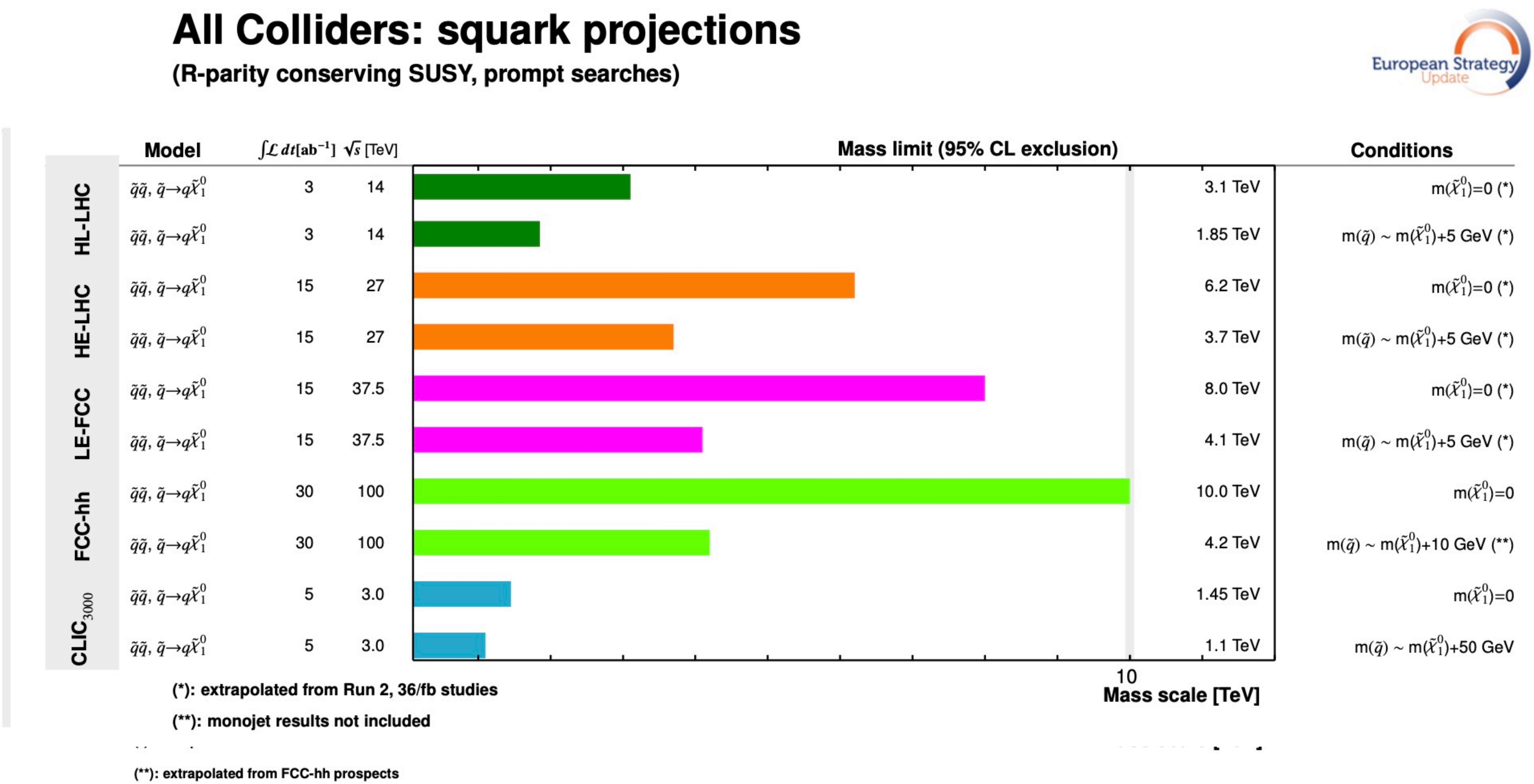
- LHC: good at searching colored particles



- what if “neutral naturalness”?

(iii-3) Supersymmetric particles

- LHC: good at searching colored particles

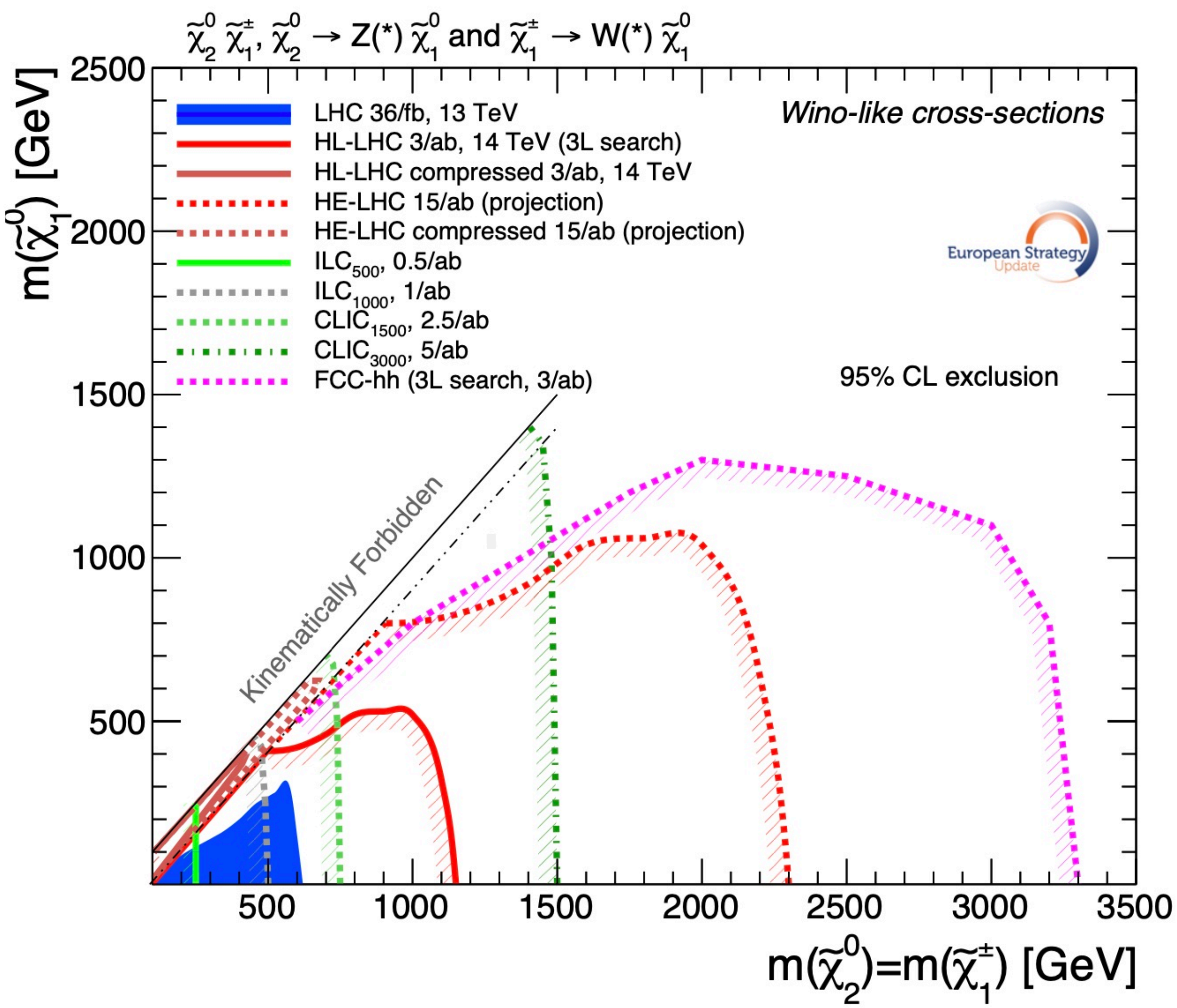


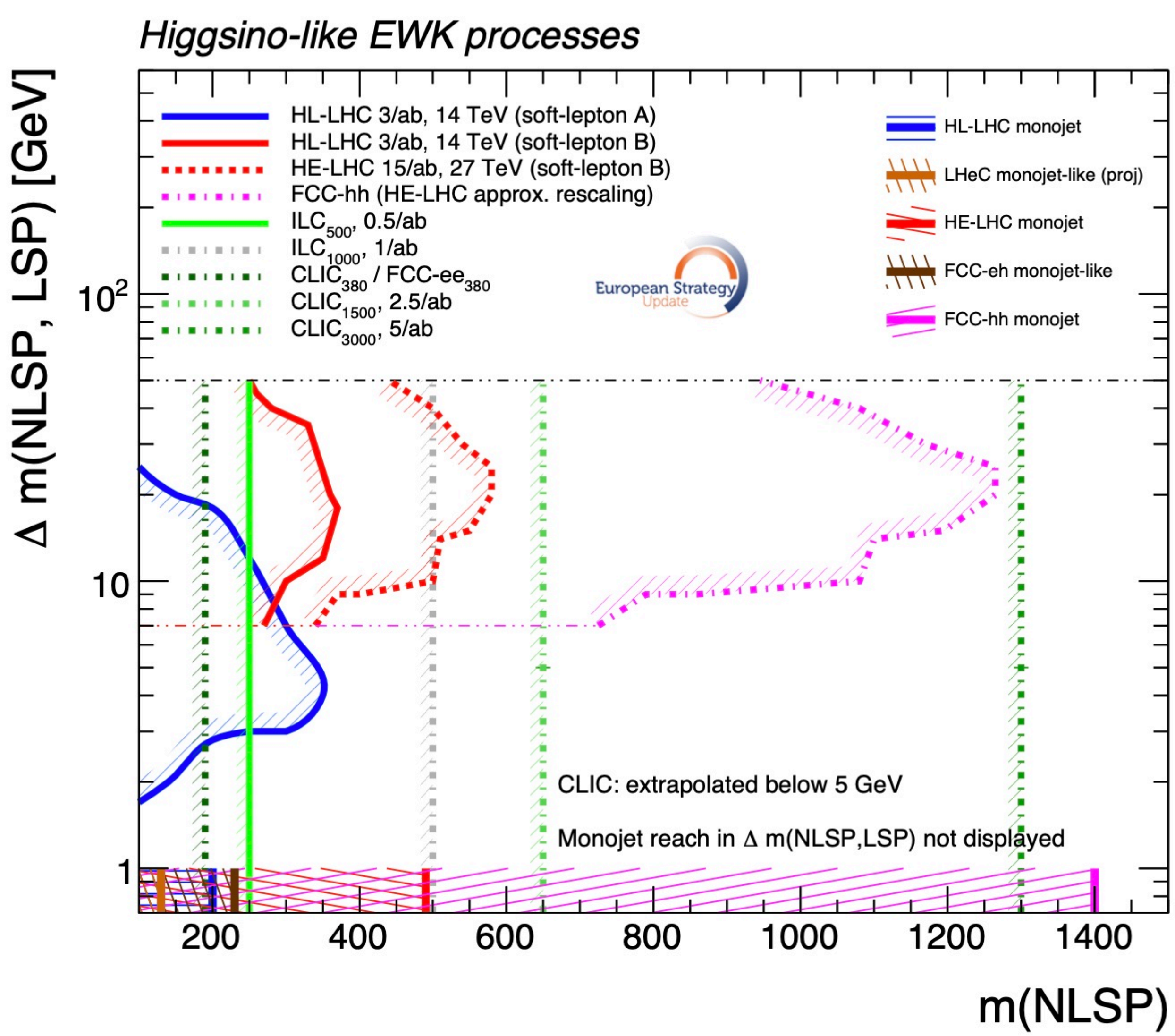
- what if “neutral naturalness”?

(iii-3) Supersymmetric particles: EWkinos

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

- e+e- searches can be very competitive for “compressed” spectrum
- cover almost full region up to **m ~ √s / 2** and **Δm as low as <1GeV**

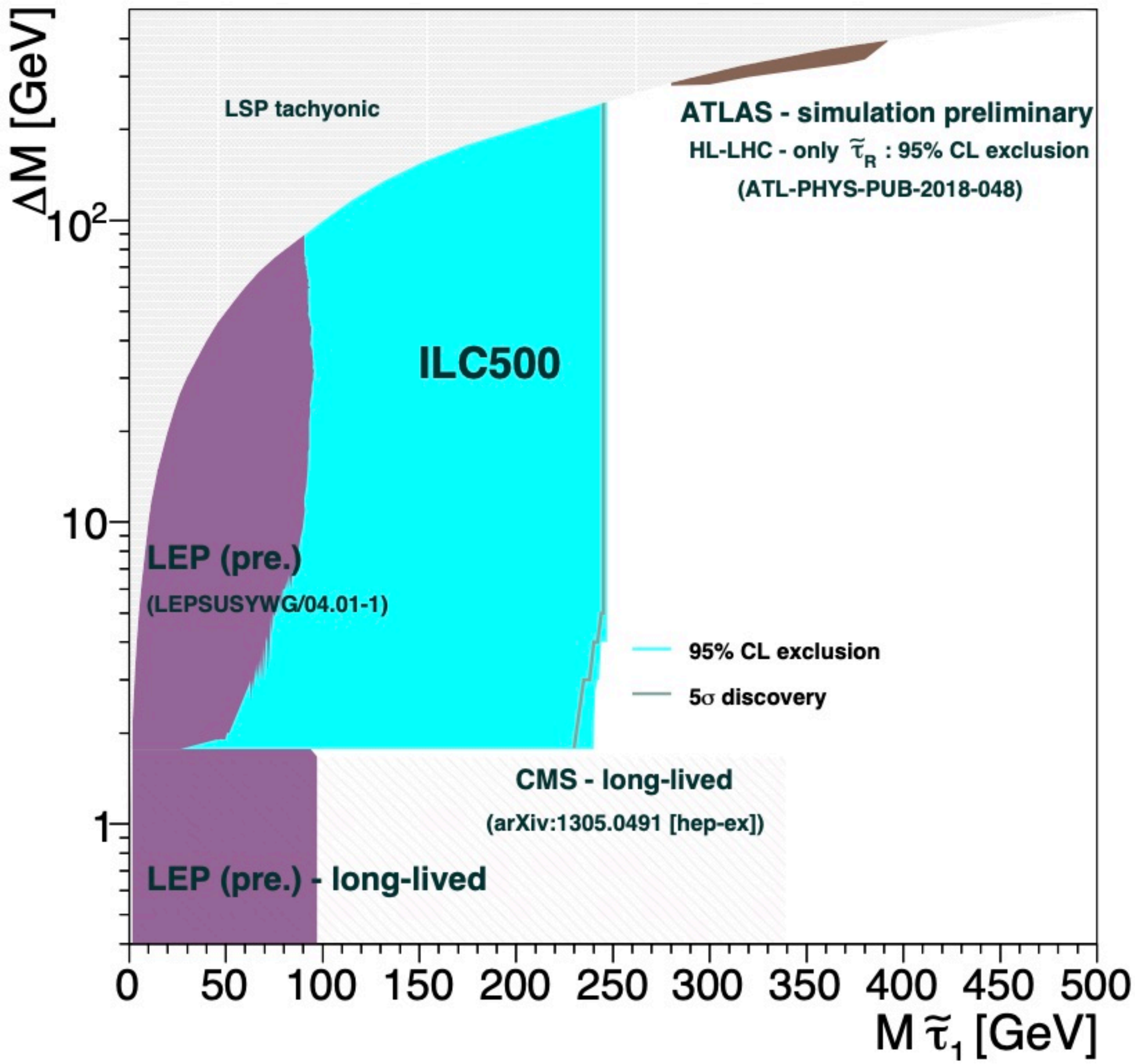




- e+e-: still lots of room to explore, e.g. disappearing tracks for extremely low Δm

(iii-3) Supersymmetric particles: s-tau

$$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$$



[Berggren et al, 2105.08616]

(iv) Top-quark and EW measurements

what we would like to measure here:

- mass & width of t, Z, W; α_S
- chiral couplings between fermion and Z/W: g_L, g_R for each flavor
- triple / quartic gauge couplings
- 4-f contract interactions
- BR, A_{LR}, A_{FB}

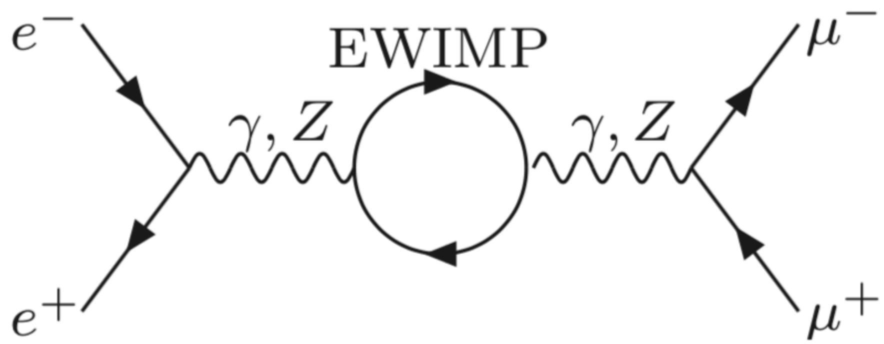
many analyses are extension of LEP/SLC; challenges are often from precision theory calculations as well as control of experimental systematics;

[Freitas et al, 1906.05379; 2012.11642]

(1) top-quark mass
(2) strong coupling α_S
(3) left-right asymmetry
(4) 4-fermion interactions
(5) …

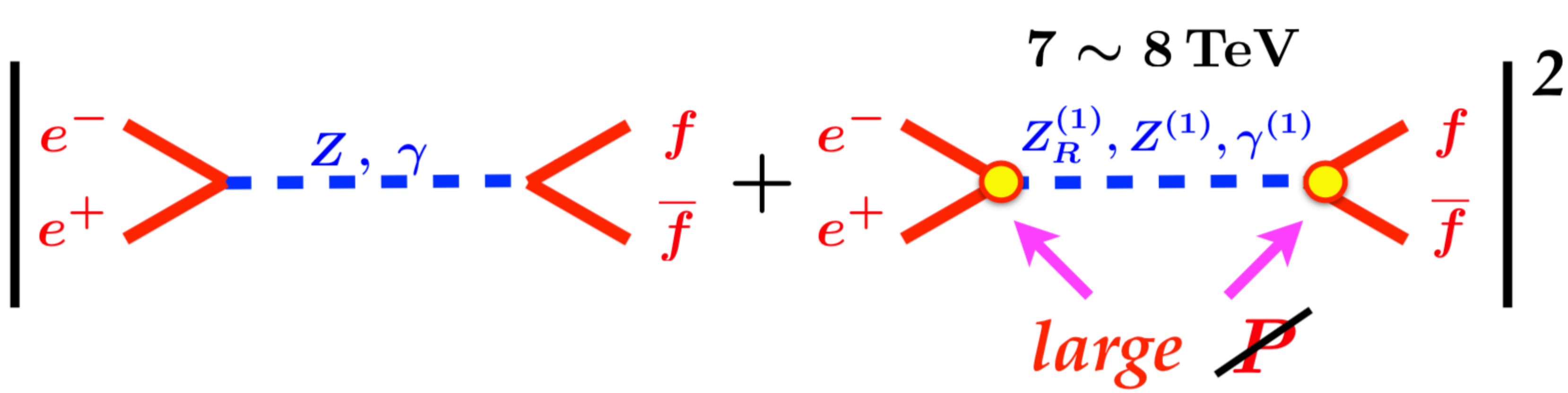
as usual, selection is always biased

indirect discovery by e+e- -> 2-fermion



- search for electroweak charged WIMP via oblique correction, M ~ 200 GeV

[Harigaya, Ichikawa, Kundu, Matsumoto, Shirai, Satoshi, 1504.03402]

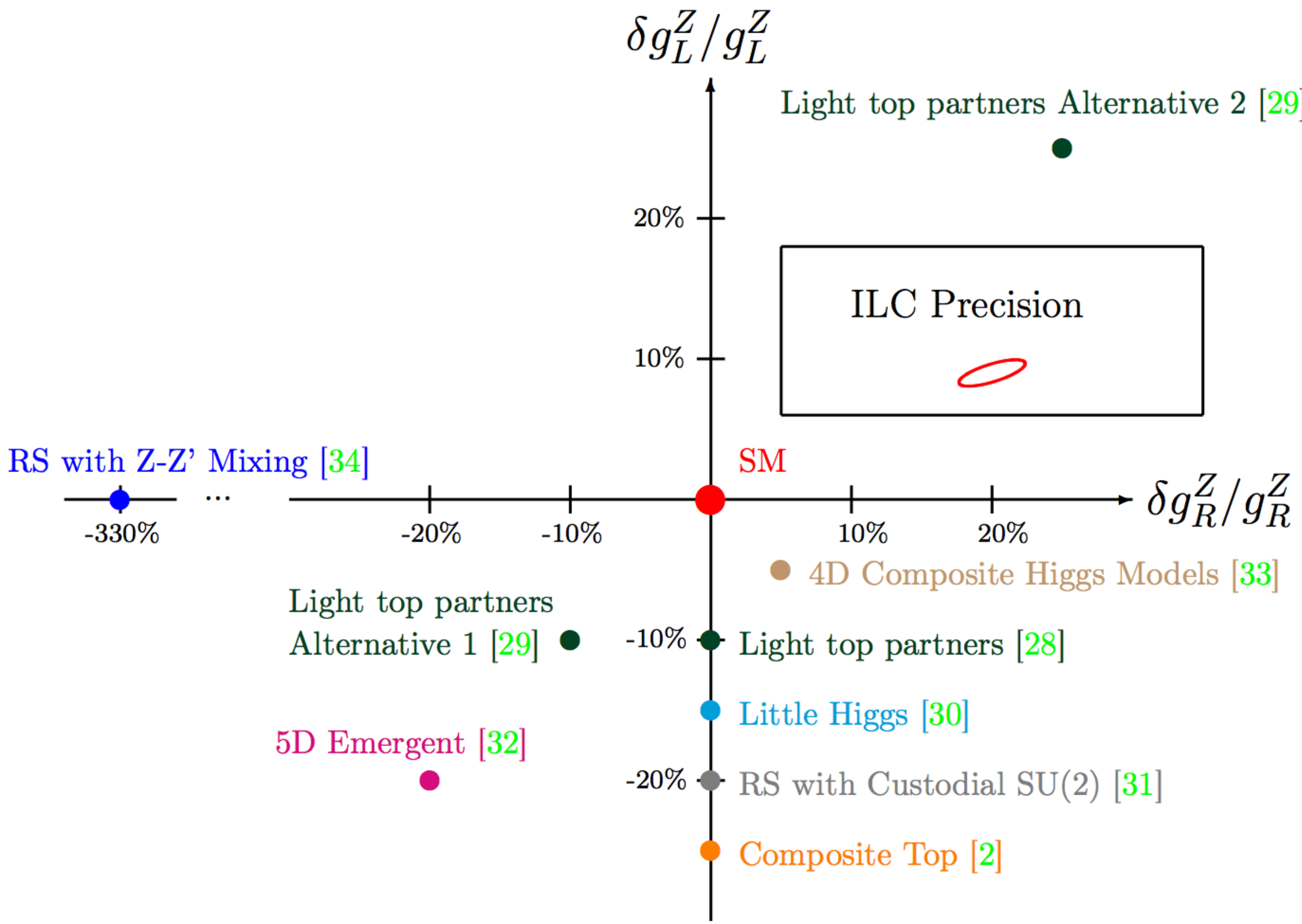


[Funatsu, Hatanaka, Hosotani, Orikasa, 1705.05282]

- search for Z' via interference, e.g. in Gauge Higgs Unification, large deviation with SM for M(Z') ~ 7-8 TeV

top-quark EW chiral couplings

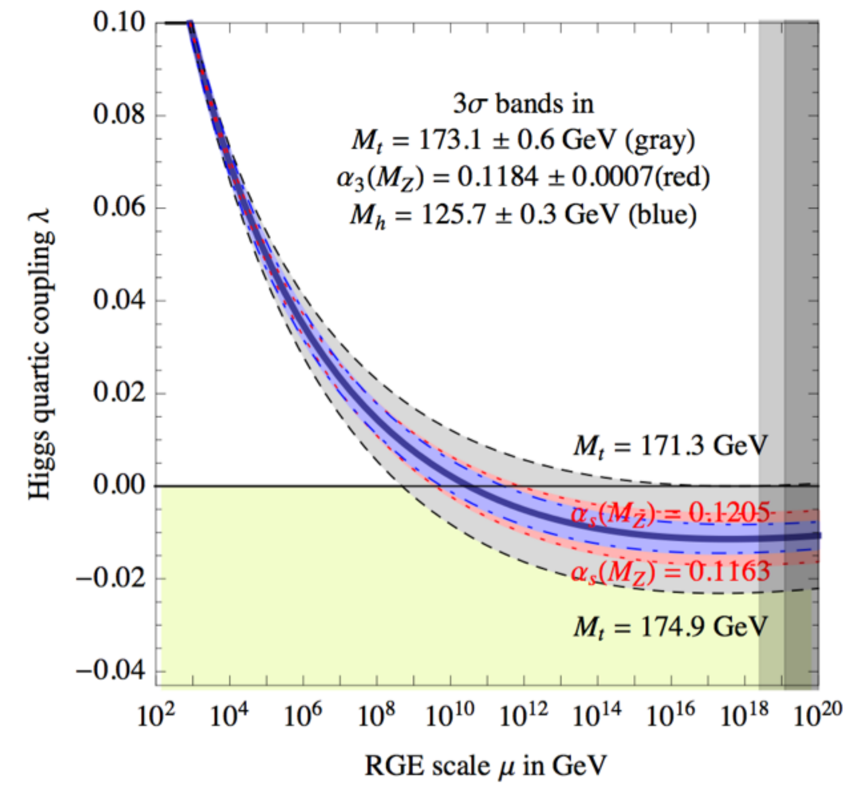
Eur.Phys.J. C75 (2015) no.10, 512



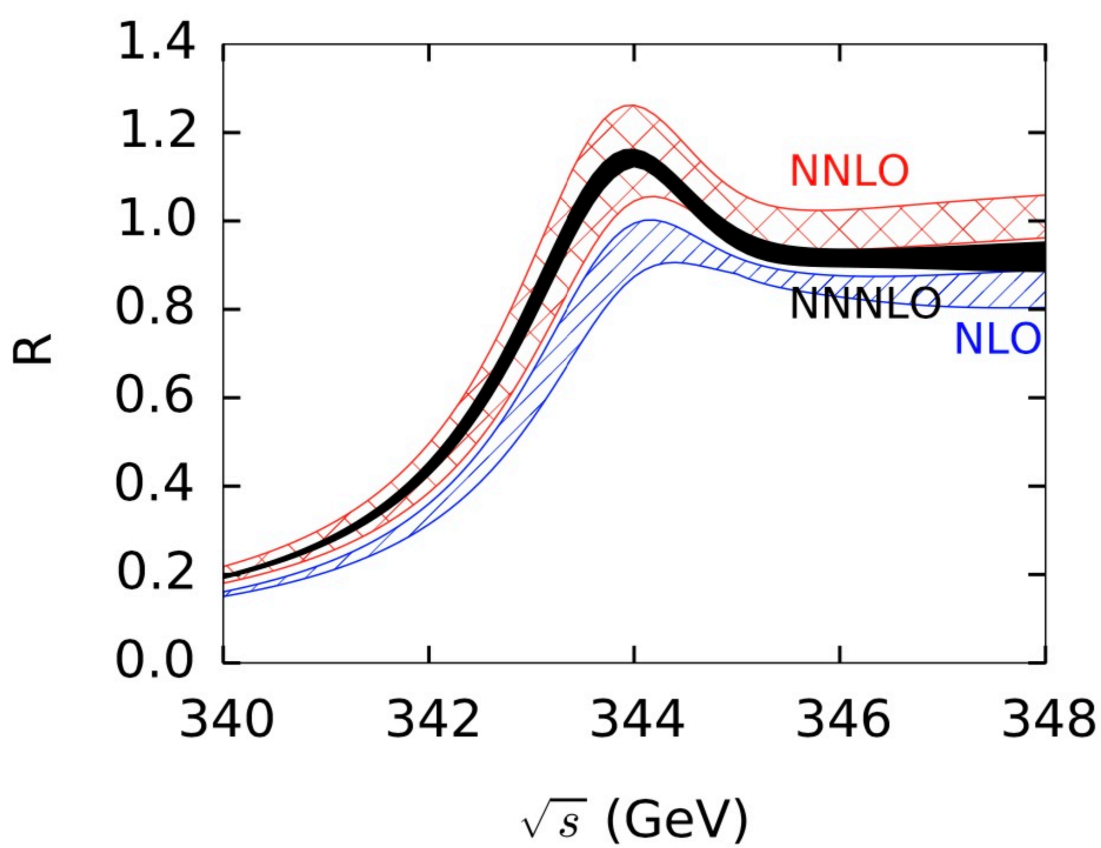
- great sensitivities to discover/distinguish various composite models

(iv-1) top-quark mass

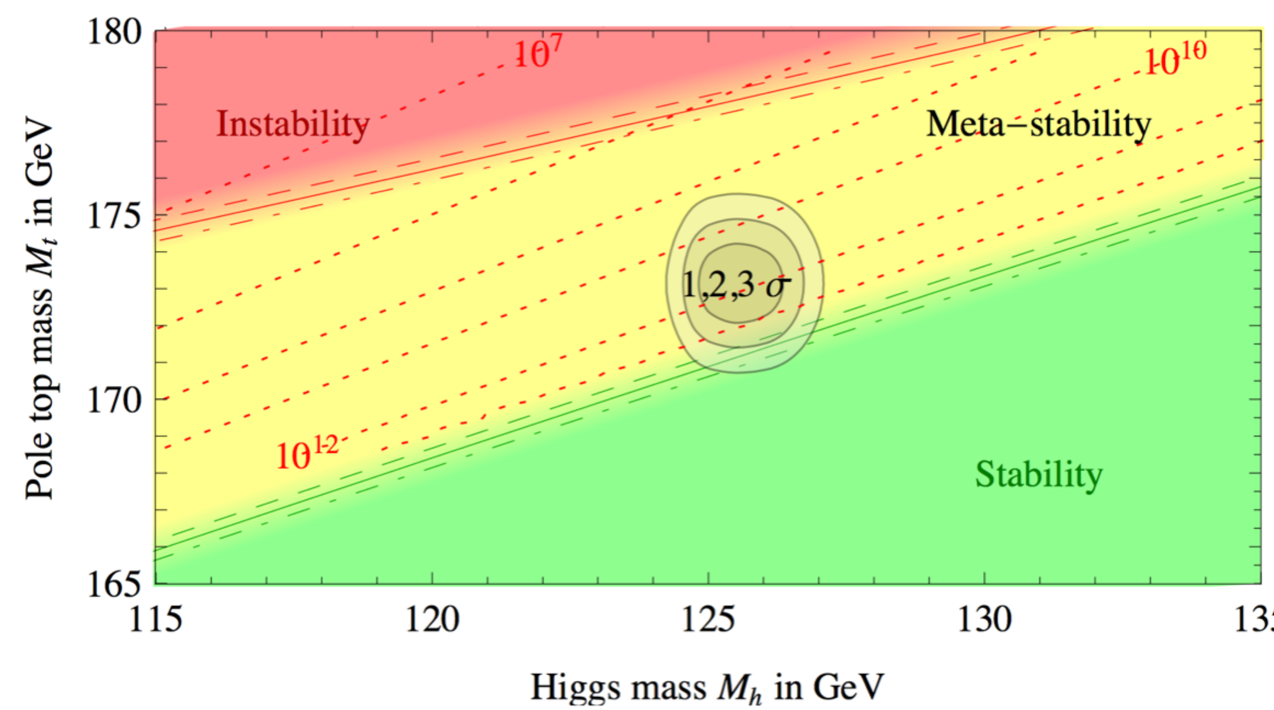
- **vacuum stability**: whether Higgs self-coupling λ runs to negative or not at high scale
- need to measure **short-distance mass**, unlike MC mass at LHC
- at e+e-: use top-pair **threshold scan** to measure m_t, much lower theory error



[Beneke et al, 1312.4791]



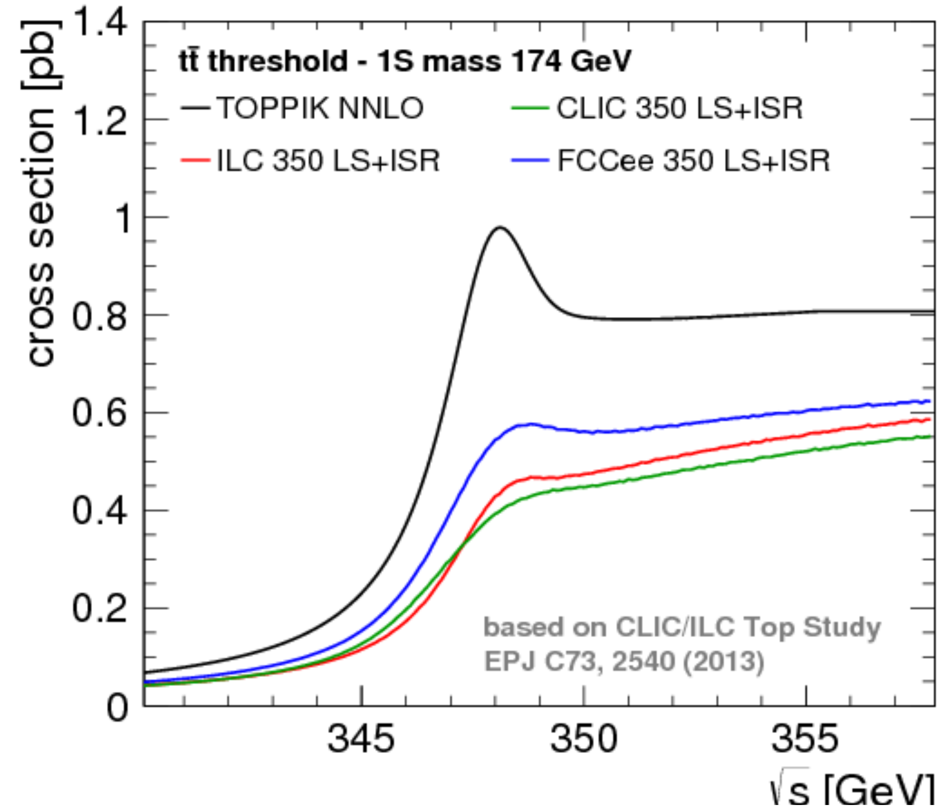
[Degrassi et al, JHEP 1208 (2012) 098]



(iv-1) top-quark mass

$e^+e^- \to t\bar{t}$ at $\sqrt{s} \sim 350$ GeV

- important to include **beamstrahlung & ISR** in this analysis
- open: any impact on measurement if including possible new physics?
- need also improved input $\boldsymbol{\alpha_s}$



today:

$$\delta m_t^{\overline{\text{MS}}} = [\quad]_{\text{exp}} \oplus [50\text{ MeV}]_{\text{QCD}} \oplus [10\text{ MeV}]_{\text{mass def.}} \oplus [70\text{ MeV}]_{\alpha_s}$$

$$> 100\text{ MeV}$$

future:

$$[20\text{ MeV}]_{\text{exp}}$$
$$\oplus [30\text{ MeV}]_{\text{QCD}} \quad \text{(h.o. resummation)}$$
$$\oplus [10\text{ MeV}]_{\text{mass def.}}$$
$$\oplus [15\text{ MeV}]_{\alpha_s} \quad (\delta\alpha_s \lesssim 0.0002)$$

$$\lesssim 50\text{ MeV}$$

[A. Freitas]

(iv-2) α_S measurement at e+e-

- α_S: d'Enterria, Skands, et al. '15
  - Electroweak precision ($R_\ell = \Gamma_Z^{had}/\Gamma_Z^{\ell}$):

    $\alpha_S = 0.120 \pm 0.003$ PDG '18

    $\rightarrow$ No (negligible) non-perturbative QCD effects

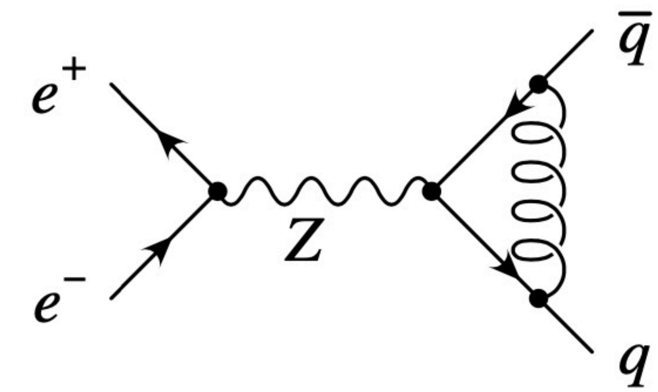
    FCC: $\delta R_\ell \sim 0.001$

    $\Rightarrow \quad \delta\alpha_S < 0.0001$

    Theory input: N^3LO EW corr. + leading N^4LO

    to keep $\delta_{th} R_\ell \lesssim \delta_{exp} R_\ell$

    Caviat: R_ℓ could be affected by new physics



[A. Freitas]

(iv-3) Left-right asymmetries A_f (f=e/μ/τ/b/c)

$$e^+e^- \to Z \to f\bar{f}$$ **@ Z-pole**

- polarized beam

for electron

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = A_e$$

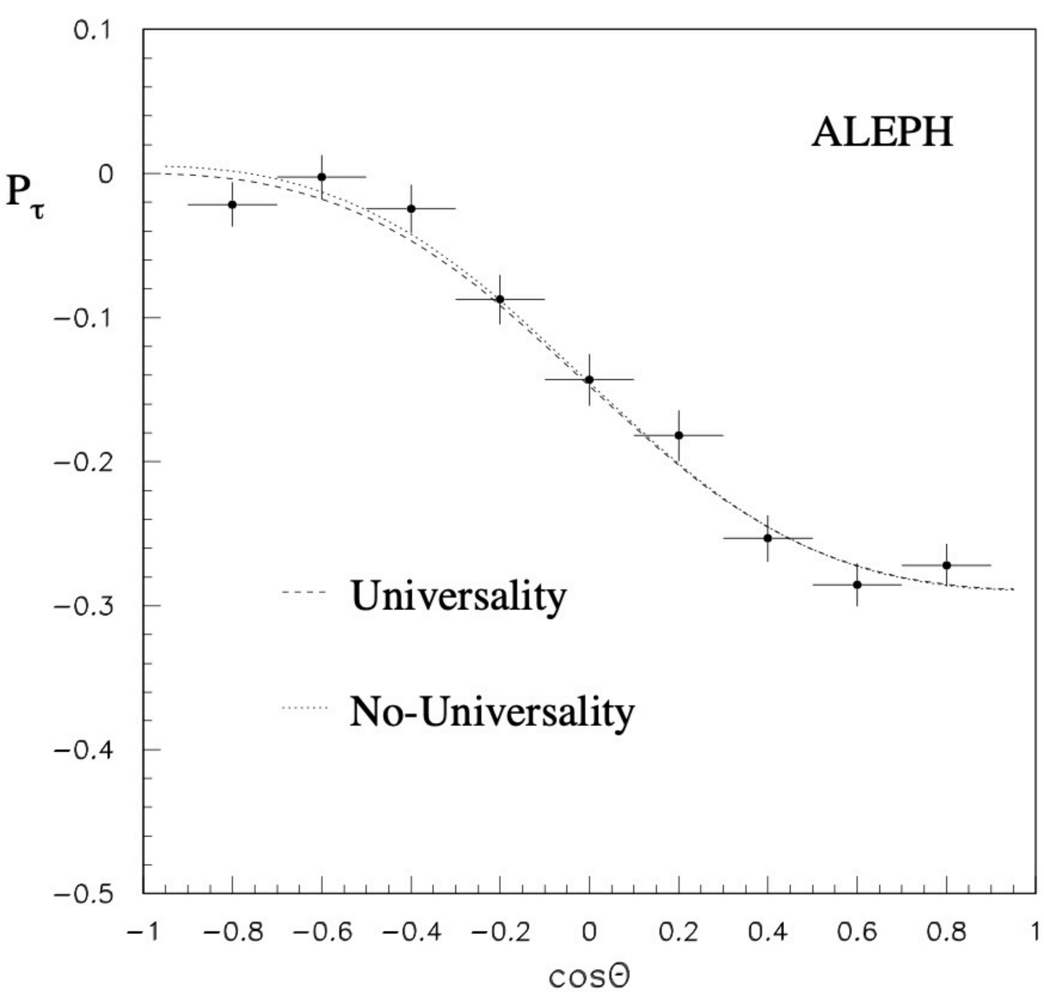
for other fermion

$$A_{LRFB} = \frac{\sigma_{LF} - \sigma_{LB} - \sigma_{RF} + \sigma_{RB}}{\sigma_{LF} + \sigma_{LB} + \sigma_{RF} + \sigma_{RB}} = \frac{3}{4}A_f$$

(iv-3) Left-right asymmetries A_f (f=e/μ/τ/b/c)

$$e^+e^- \to Z \to f\bar{f}$$ **@ Z-pole**

- unpolarized beam



$$A_{FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4} A_e A_f$$

$$P_\tau(\cos\theta) = -\frac{A_\tau(1+\cos^2\theta) + 2A_e\cos\theta}{(1+\cos^2\theta) + \frac{8}{3}A^\tau_{FB}\cos\theta}$$

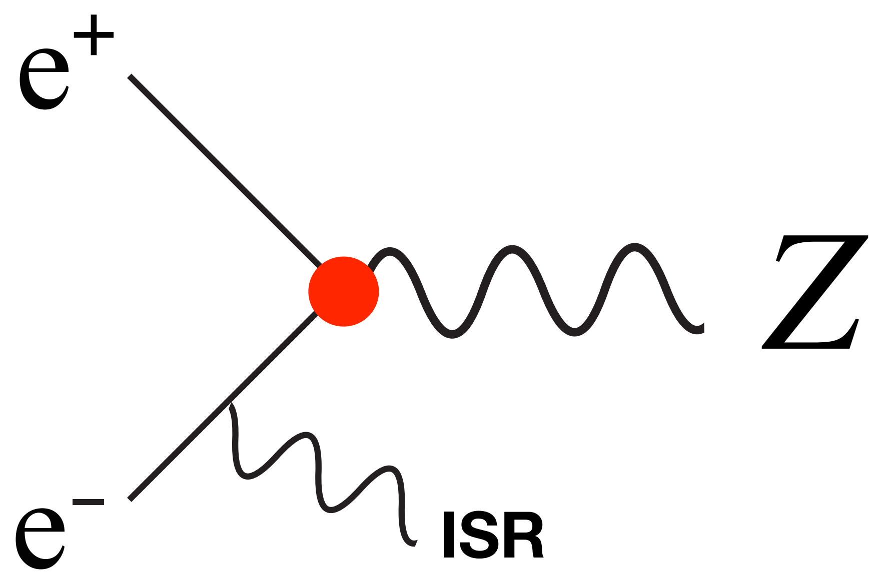
$$\approx A_\tau + \frac{2\cos\theta}{1+\cos\theta^2} A_e$$

[ALEPH, Eur.Phys.J.C20:401-430,2001]

- open: can we measure $\mathbf{A_s}$, $\mathbf{A_u}$, $\mathbf{A_d}$?

(iv-3) new idea: radiative return

radiative return



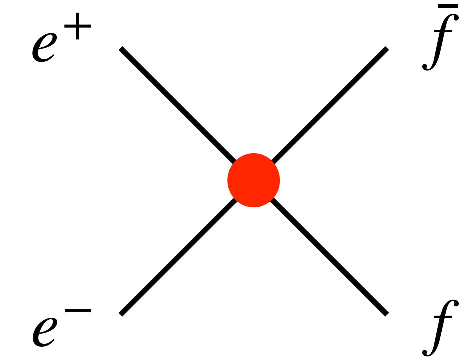
- a free gift by ISR: Higgs factory is meantime a Z factory
- lots of theory issues & sys. errors to be explored

(iv-4) 4-fermion contact interaction

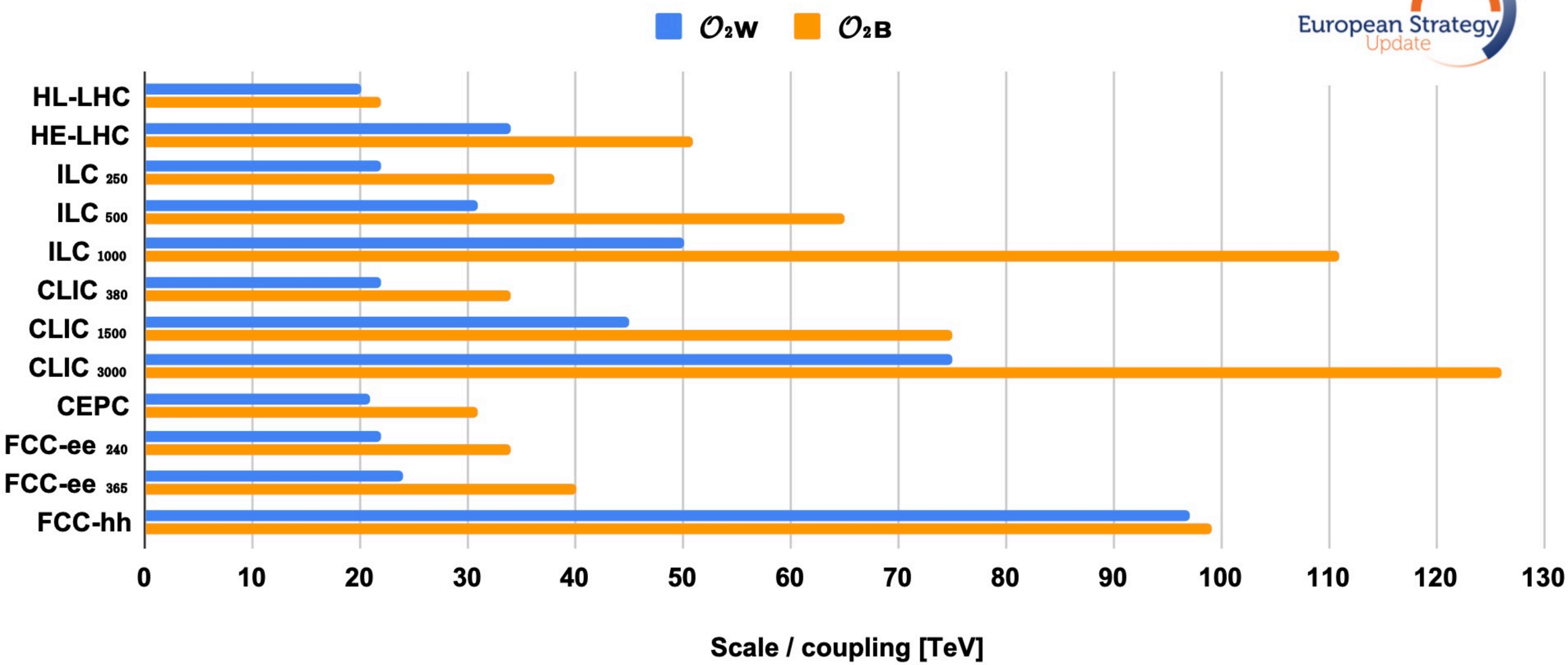
$$O_{2W} = (D^\mu W_{\mu\nu})^i (D_\rho W^{\rho\nu})^i$$

$$O_{2B} = (\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu})$$

equation of motion



95% CL scale limits on 4-fermion contact interactions

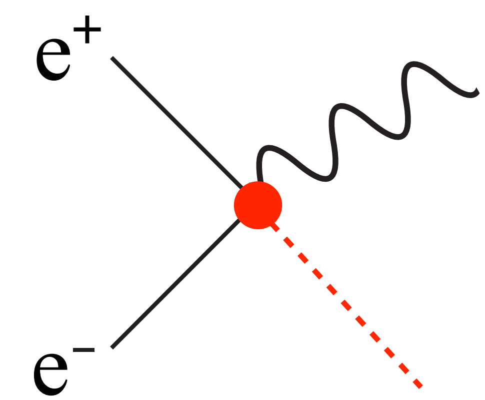


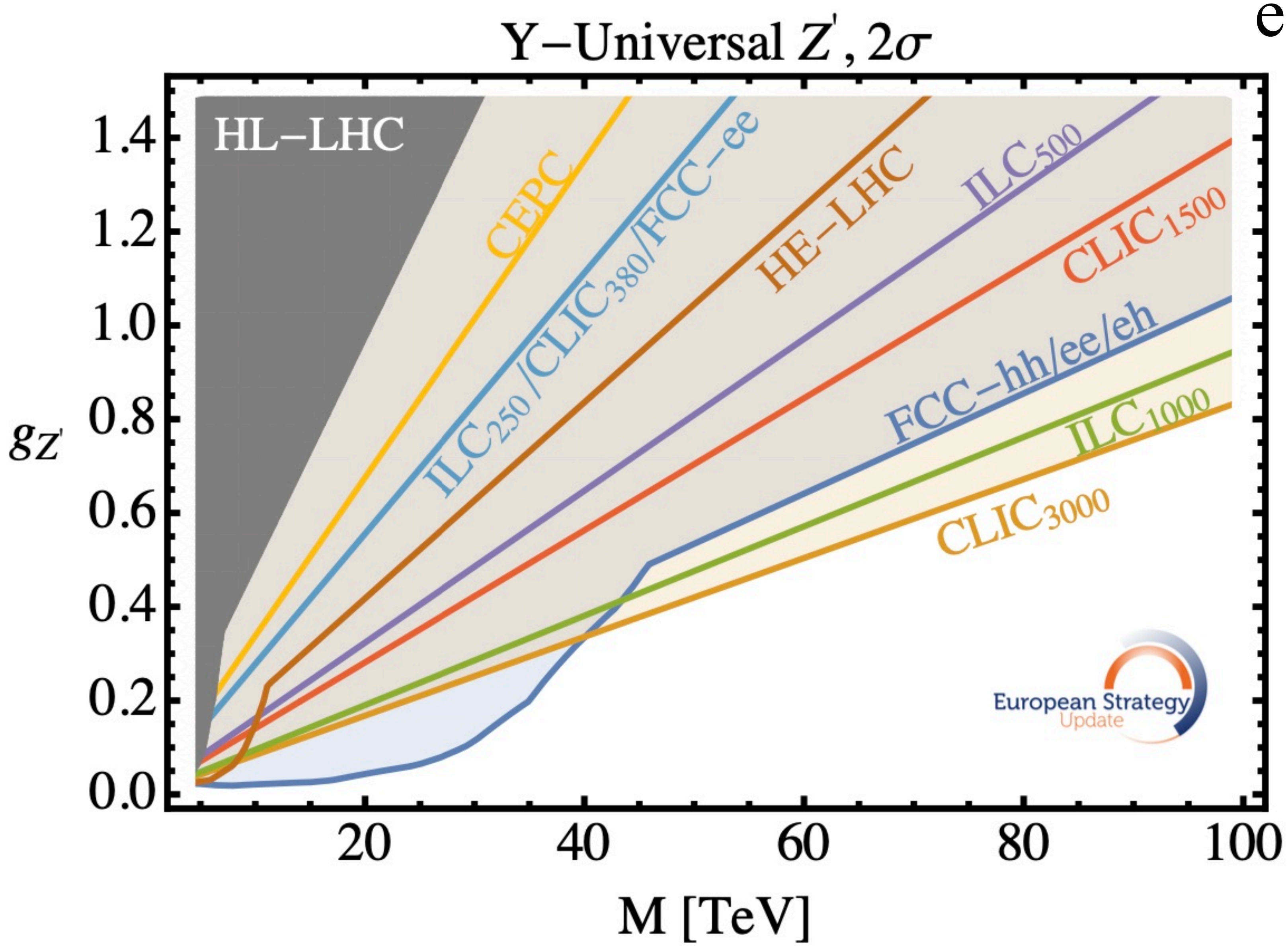
- high energy e+e- sensitive to very high scale; your model?

(iv-4) 2-fermion 2-boson contact interaction

$$O_W = i\left(H^\dagger \sigma^i \overleftrightarrow{D}^\mu H\right)(D^\nu W_{\mu\nu})^i$$

equation of motion





- high energy e+e- sensitive to very high scale; your model?

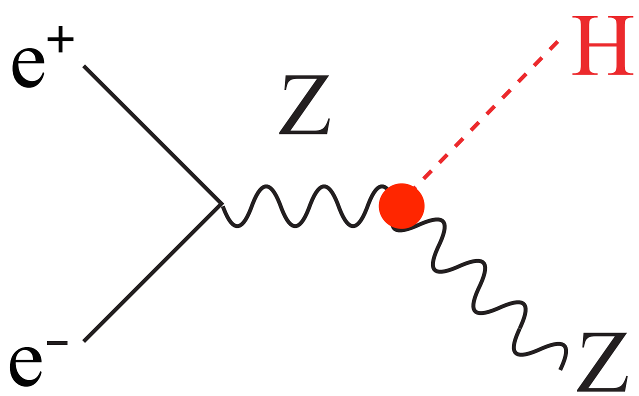
(v) Global Interpretation in SMEFT

tribute to our dear colleague

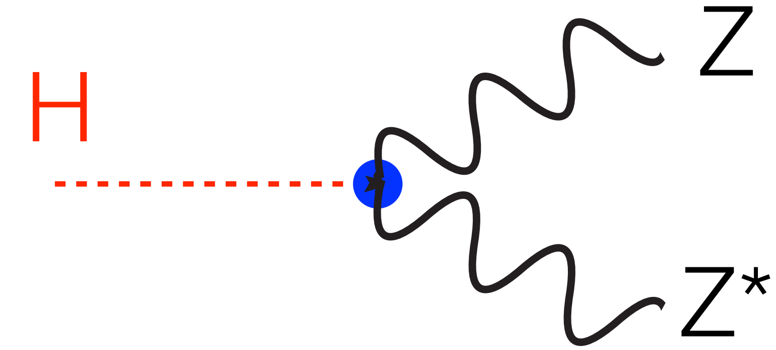
Cen Zhang (张岑)

question from last lecture in kappa formalism:

$$\frac{\sigma(e^+e^- \to Zh)}{SM} = \frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2 \qquad \textbf{?}$$



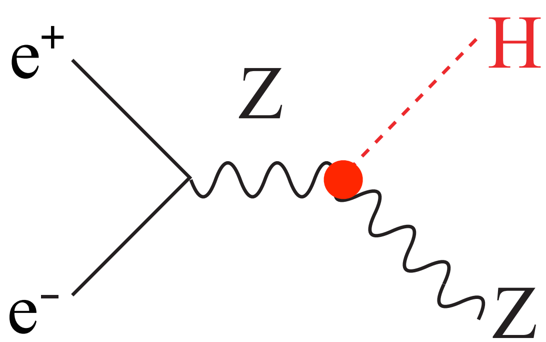
$\propto \quad \kappa_Z^2 \; ? \quad \propto$

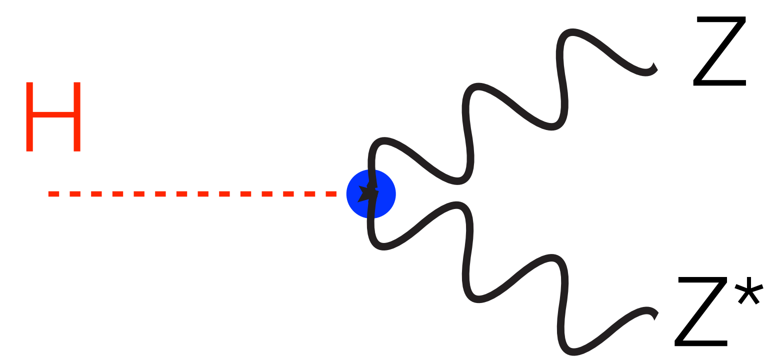


- BSM territory: can deviations be represented by single κ_Z?
- How to include radiative corrections in kappa formalism?

the answer is model dependent

$$\delta\mathcal{L} = (1+\eta_Z)\frac{m_Z^2}{v}hZ_\mu Z^\mu + \zeta_Z\frac{h}{2v}Z_{\mu\nu}Z^{\mu\nu}$$





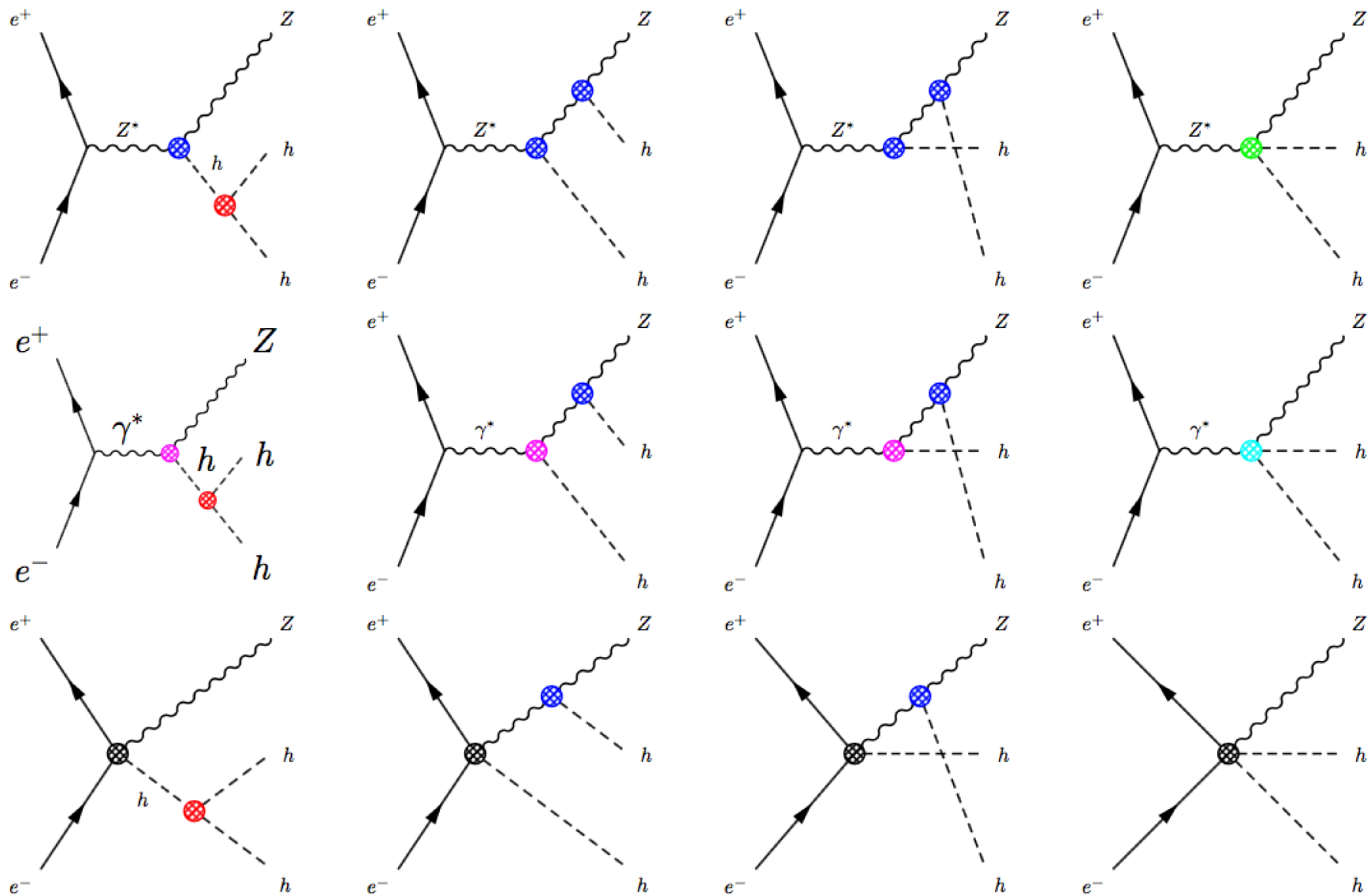
$$\sigma(e^+e^- \to Zh) = (SM)\cdot (1+2\eta_Z+(5.5)\zeta_Z)$$

$\neq$

$$\Gamma(h \to ZZ^*) = (SM)\cdot (1+2\eta_Z-(0.50)\zeta_Z)$$

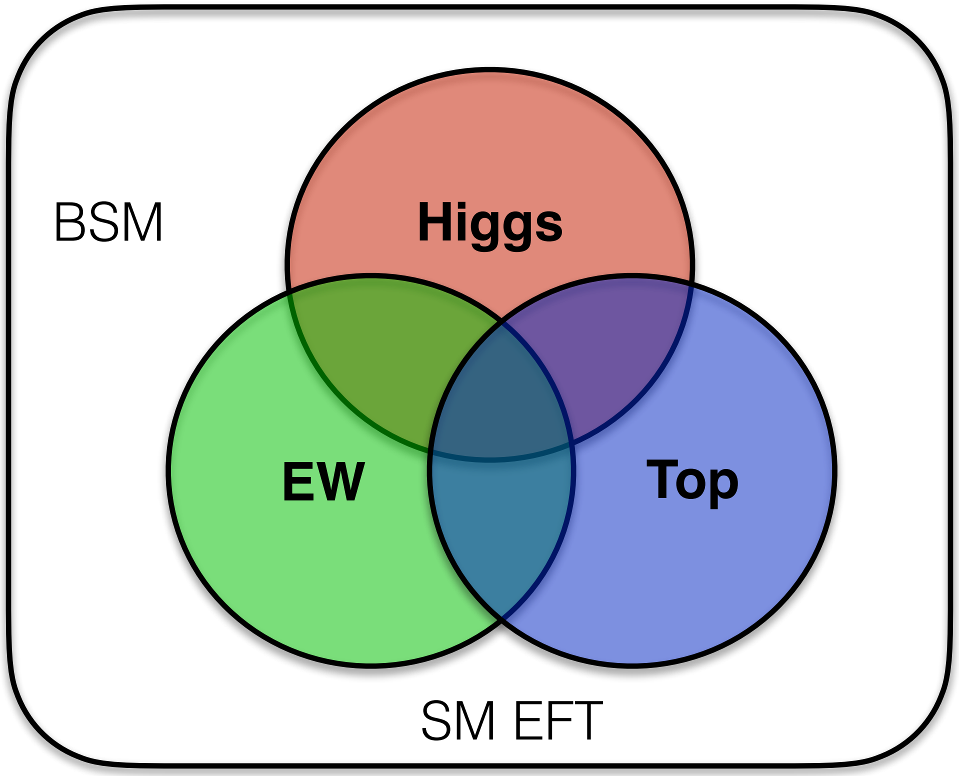
- BSM can induce new Lorentz structures in hZZ
- need a better, more theoretical sound framework

how do we determine λ_{hhh} model-independently?



$$e^+e^- \to Zhh$$

new opportunities



- analyses are used to be pursued alone looking for new physics effects
- but they are all related: gauge symmetries & Higgs field nature of W/Z longitudinal modes
- a new category of analyses are emerging: explore every channel one can think of, likely all are useful in a global interpretation

new strategy: SM Effective Field Theory

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

$$= \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{d_i-4}} O_i$$

- most general BSM effects represented by $d_i>4$ operators
  - more model-independent formalism
- well-defined quantum field theory respecting SM SU(3)xSU(2)xU(1) gauge symmetries
  - can include radiative corrections consistently
- unifying BSM effects in Higgs, W/Z, top, 2-fermion physics
  - global view in searching for BSM

SM Effective Field Theory: some simplifications

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

$$= \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{d_i-4}} O_i$$

the new particle searches at LHC Run 2 suggest ***Λ>500*** GeV

simplify the analysis up to dimension-**6** operators

there are ***84*** of such operators for 1 fermion generation

assuming B / L conservation & CP even, there are ***59***

- there exists a smaller but complete set relevant to Higgs coupling determination at e+e-

global SMEFT fit @ e+e-

(Barklow, Fujii, Jung, Peskin, JT, arXiv:1708.09079)

$$
\begin{aligned}
\Delta\mathcal{L} = &\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\
&+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\
&+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\
&+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L) \\
&+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .
\end{aligned}
$$

“Warsaw” basis,
Grzadkowski et al,
arXiv:1008.4884

Φ: higgs field
W, B: SU(2), U(1) gauge
L, e: left/right electron

- 10 operators modifying couplings for h/Z/W/γ
- in total, 23 parameters (see backup slides)

next: highlight a few important implications

(v-1) absolute Higgs couplings (unique role of inclusive σ_{Zh})

$$\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi)$$

$$\frac{c_H}{2}\partial^\mu h \partial_\mu h \longrightarrow$$ renormalize kinetic term of SM Higgs field

$h \longrightarrow (1-c_H/2)h$

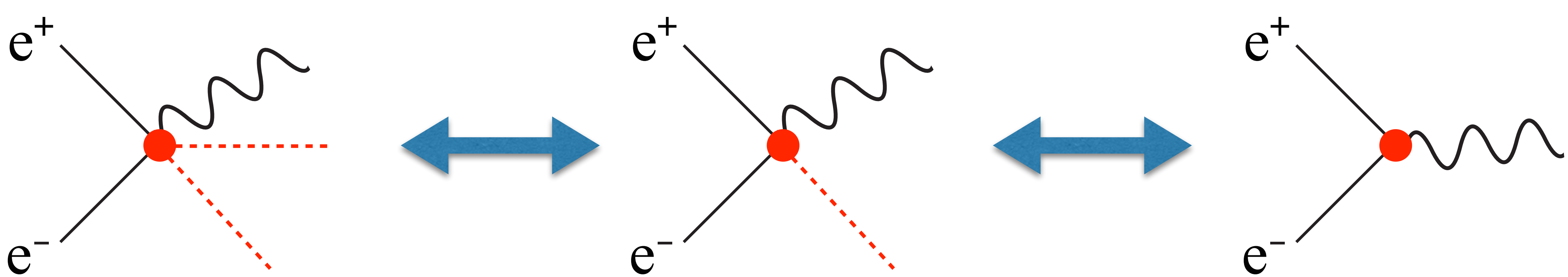
$\longrightarrow$ **shift all SM Higgs couplings by $-c_H/2$**

- c_H can not be determined by any BR or ratio of couplings

- c_H has to rely on inclusive cross section of $e^+e^- \to Zh$, enabled by recoil mass technique at e+e-

(v-2) Higgs couplings are related to W-/Z- couplings (EWPOs)

$$i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu L) \quad +(c'_{HL},\, c_{HE})$$



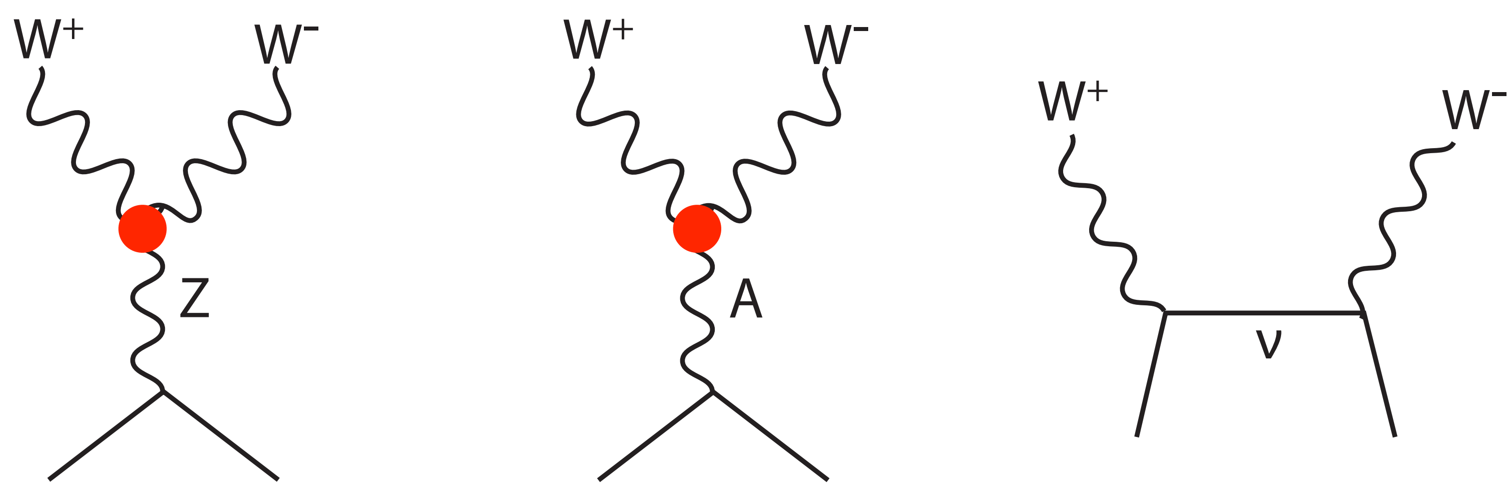
$e^+e^- \to Zhh$ $e^+e^- \to Zh$ Z-pole

- Higgs coupling encoded in EWPOs at Z-pole: $\boldsymbol{A_{LR}}$, $\boldsymbol{\Gamma_l}$
- Z coupling helped by Higgs meas. at high $\sqrt{s}$: $\boldsymbol{\delta\sigma \sim s/m^2_Z}$

(v-2) Higgs couplings are related to W-/Z- couplings (TGCs)

$$\boxed{\frac{4gg'c_{WB}}{m_W^2}\Phi^\dagger t^a \Phi W^a_{\mu\nu}B^{\mu\nu}} \qquad +(c_{WW},\, c_{BB})$$

$e^+e^- \to WW$



$h \to ZZ$ $\qquad \zeta_Z \frac{h}{2v} Z_{\mu\nu}Z^{\mu\nu} \qquad \zeta_Z = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + s_w^4/c_w^2(8c_{BB})$

- longitudinal modes of W/Z are from Higgs fields
- higgs coupling helped by meas. of TGCs in $e^+e^- \to WW$

(v-3) Higgs couplings are related to themselves

$$\Delta\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 h^2 - (1+\eta_h)\overline{\lambda} v h^3 + \frac{\theta_h}{v} h \partial_\mu h \partial^\mu h$$
$$+(1+\eta_W)\frac{2m_W^2}{v}W_\mu^+ W^{-\mu} h + (1+\eta_{WW})\frac{m_W^2}{v^2}W_\mu^+ W^{-\mu} h^2$$
$$+(1+\eta_Z)\frac{m_Z^2}{v}Z_\mu Z^\mu h + \frac{1}{2}(1+\eta_{ZZ})\frac{m_Z^2}{v^2}Z_\mu Z^\mu h^2$$
$$+\zeta_W \hat{W}^+_{\mu\nu}\hat{W}^{-\mu\nu}\left(\frac{h}{v}+\frac{1}{2}\frac{h^2}{v^2}\right) + \frac{1}{2}\zeta_Z \hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}\left(\frac{h}{v}+\frac{1}{2}\frac{h^2}{v^2}\right)$$
$$+\frac{1}{2}\zeta_A \hat{A}_{\mu\nu}\hat{A}^{\mu\nu}\left(\frac{h}{v}+\frac{1}{2}\frac{h^2}{v^2}\right) + \zeta_{AZ}\hat{A}_{\mu\nu}\hat{Z}^{\mu\nu}\left(\frac{h}{v}+\frac{1}{2}\frac{h^2}{v^2}\right).$$

(SM structure: kappa like)

$$\eta_h = \delta\overline{\lambda} + \delta v - \frac{3}{2}c_H + c_6$$
$$\eta_W = 2\delta m_W - \delta v - \frac{1}{2}c_H$$
$$\eta_{WW} = 2\delta m_W - 2\delta v - c_H$$
$$\eta_Z = 2\delta m_Z - \delta v - \frac{1}{2}c_H - c_T$$
$$\eta_{ZZ} = 2\delta m_Z - 2\delta v - c_H - 5c_T$$

(Anomalous: new Lorentz structure)

$$\theta_h = c_H$$
$$\zeta_W = \delta Z_W \quad = (8c_{WW})$$
$$\zeta_Z = \delta Z_Z \quad = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + s_w^4/c_w^2(8c_{BB})$$
$$\zeta_A = \delta Z_A \quad = s_w^2\Big((8c_{WW}) - 2(8c_{WB}) + (8c_{BB})\Big)$$
$$\zeta_{AZ} = \delta Z_{AZ} \quad = s_w c_w\Big((8c_{WW}) - (1-\frac{s_w^2}{c_w^2})(8c_{WB}) - \frac{s_w^2}{c_w^2}(8c_{BB})\Big)$$

- hZZ/hWW/hγZ/hγγ highly related: SU(2)xU(1) gauge symmetries

(v-3) Higgs couplings are related to themselves (synergy w/ LHC)

two measurements from LHC (model independent)

$$R_{\gamma\gamma} = \frac{BR(h \to \gamma\gamma)}{BR(h \to ZZ^*)} \qquad R_{\gamma Z} = \frac{BR(h \to \gamma Z)}{BR(h \to ZZ^*)}$$

$$\delta\Gamma(h \to \gamma\gamma) = \mathbf{528}\, \delta Z_A - c_H \quad + \ldots$$

$$\delta\Gamma(h \to Z\gamma) = \mathbf{290}\, \delta Z_{AZ} - c_H \quad + \ldots$$

$$\delta\Gamma(h \to ZZ^*) = -0.50 \delta Z_Z \ - c_H \quad + \ldots$$

- loop induced h->γγ/γZ depend strongly on $c_{WW}/c_{WB}/c_{BB}$

- h → γγ/γZ at LHC can help higgs couplings at e+e-

(v-3) Higgs couplings are related to themselves (hWW/hZZ)

$$\Gamma(h \to ZZ^*) = (SM) \cdot (1 + 2\eta_Z - (0.50)\zeta_Z) \ ,$$

$$\Gamma(h \to WW^*) = (SM) \cdot (1 + 2\eta_W - (0.78)\zeta_W)$$

SM-like hVV

$$\eta_W = -\frac{1}{2} c_H$$

$$\eta_Z = -\frac{1}{2} c_H - c_T$$

custodial symmetry is broken by c_T -> constrained by EWPOs

$c_i \sim O(10^{-4}\text{-}10^{-3})$

anomalous hVV

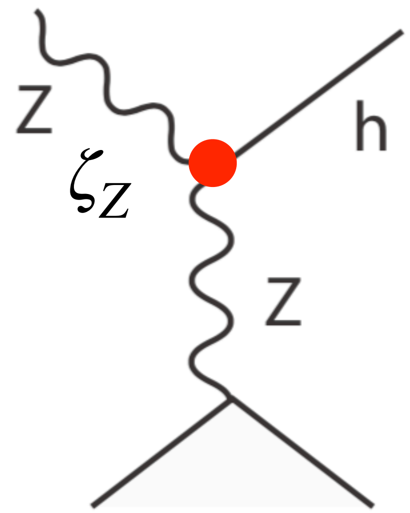
$$\zeta_W = (8c_{WW})$$

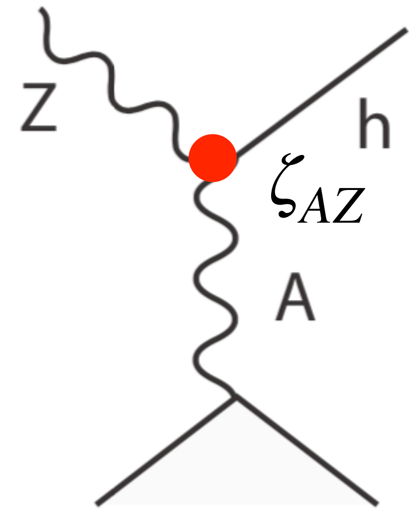
$$\zeta_Z = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + (s_w^4/c_w^2)(8c_{BB})$$

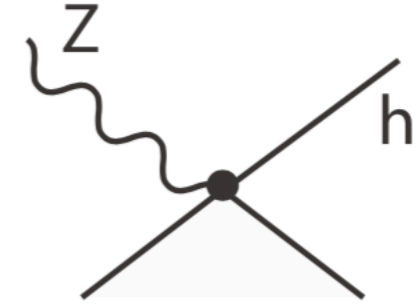
- hWW/hZZ ratio can be determined to <0.1%

- very important for physics case of any 250 GeV e+e-
- hWW can be determined as precisely as hZZ at 250 GeV; hence precision total width & other couplings

(v-4) role of beam polarizations (e+e- -> Zh)







$P(e^-,e^+)$			
(-1,+1)	$\frac{g}{\cos\theta_w}(\frac{1}{2}-\sin^2\theta_w)$	$g\sin\theta_w$	$\frac{g}{\cos\theta_w}(c_{HL}+c'_{HL})$
(+1,-1)	$\frac{g}{\cos\theta_w}(-\sin^2\theta_w)$	$g\sin\theta_w$	$\frac{g}{\cos\theta_w}(c_{HE})$

- sensitive to different couplings -> lift degeneracy
- A_{LR} in σ_{ZH} -> improve c_{WW}, $c_{HL}+c_{HL}'$ and c_{HE}
- large cancellation in **(+1,-1)** -> weaker dependence on c_{WW}

(v-4) role of beam polarizations (e+e- -> Zh)

√s=250 GeV

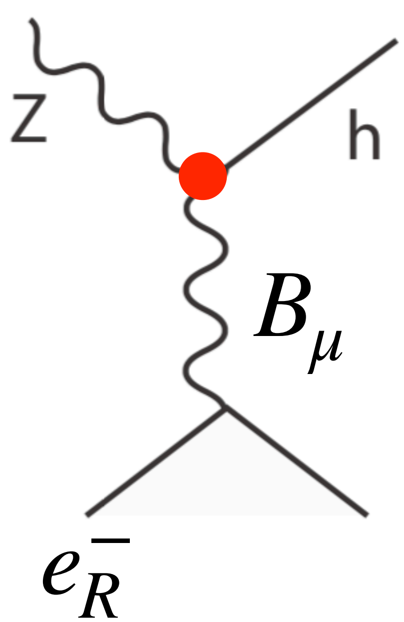
$$\delta\sigma_L = -c_H + 7.7(8c_{WW}) + \ldots$$

$$\delta\sigma_R = -c_H + 0.6(8c_{WW}) + \ldots$$

why?

$$\delta\sigma_0 = -c_H + 4.6(8c_{WW}) + \ldots$$

(8c_{WW}) ~ 0.16% from other meas.



contribution from

almost cancels out

$$\frac{g^2 c_{WW}}{m_W^2} \Phi^\dagger \Phi W^a_{\mu\nu} W^{a\mu\nu}$$

up to a difference in Z/γ propagator suppressed by $\frac{m_Z^2}{s}$

(v-4) role of beam polarizations (overall effects)

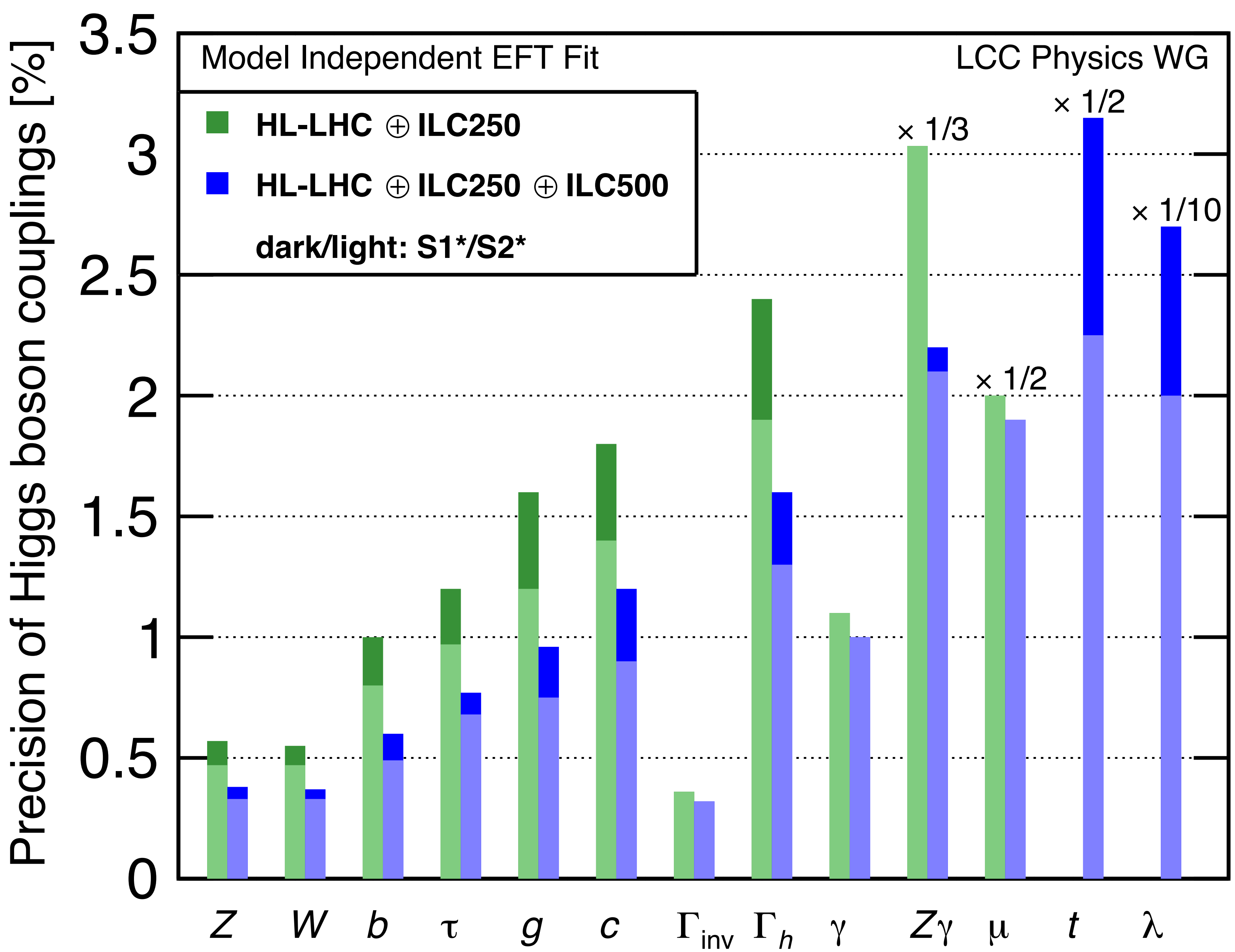
ILC250: 2 ab^{-1} **FCCee240: 5 ab^{-1}**

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

- 250 GeV e+e-: power of 2 ab^{-1} polarized ≈ 5 ab^{-1} unpolarized

(arXiv:1903.01629)

global SMEFT fit @ e+e-: Higgs coupling precisions



(arXiv:1903.01629)

#qualitative:

model independence,
hcc coupling

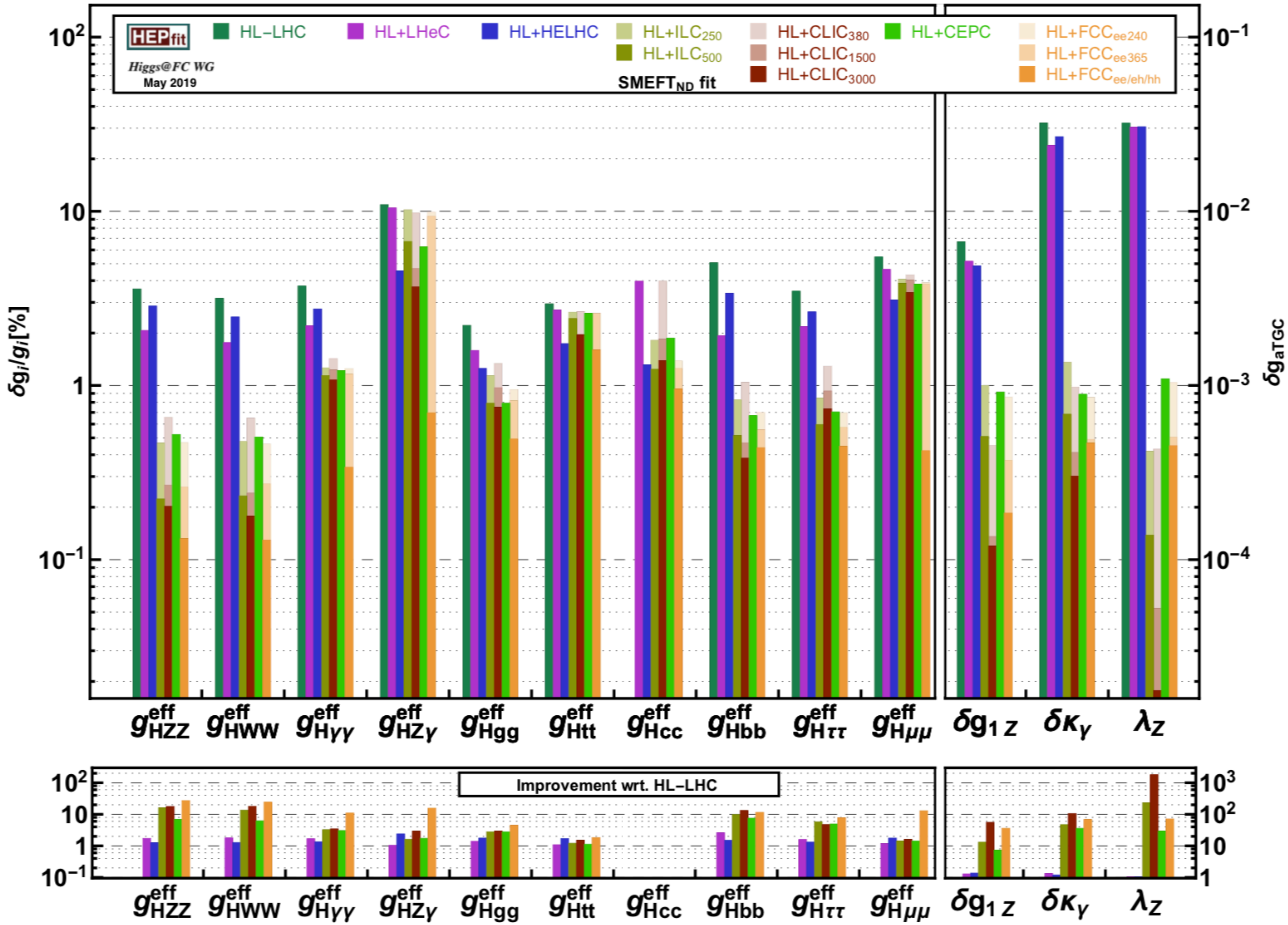
#quantitative (<~1%):

hZZ, hWW, hbb, h$\tau\tau$
h->invisible/exotic

#synergy:

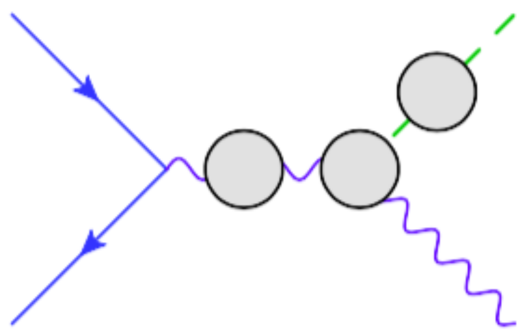
h$\gamma\gamma$, hγZ, h$\mu\mu$, htt, λ

precision at Higgs factories: European Strategy Update

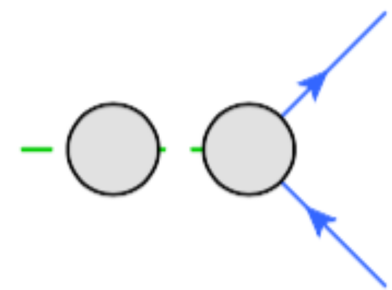


(Physics Briefing Book, arXiv:1910.11775)

(v-5) what happens at next leading order for SMEFT



WH,ZH



$H \to bb$

Zhang, et al,
arXiv:1804.09766,
1807.02121

- at e+e-, NLO ~ O(α), 1% level
- for NLO from W/Z/γ/H, operators constrained to ~<0.01, overall effect will be < 0.1%
- for NLO from top, operators would be much less constrained, currently ~ O(1) -> overall effect 1% -> potential impact in global fit on Higgs coupling precision

top-quark operators (added to previous SMEFT fit)

(no 4-fermion operators considered)

$$\mathcal{O}_{tH} = (\Phi^\dagger\Phi)(\bar{Q}t\tilde{\Phi}), \qquad \mathcal{O}_{Hq}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{Q}\gamma^\mu Q),$$

$$\mathcal{O}_{Hq}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}^a_\mu\Phi)(\bar{Q}\gamma^\mu\tau^a Q), \qquad \mathcal{O}_{Ht} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{t}\gamma^\mu t),$$

$$\mathcal{O}_{Htb} = i(\tilde{\Phi}^\dagger D_\mu\Phi)(\bar{t}\gamma^\mu b),$$

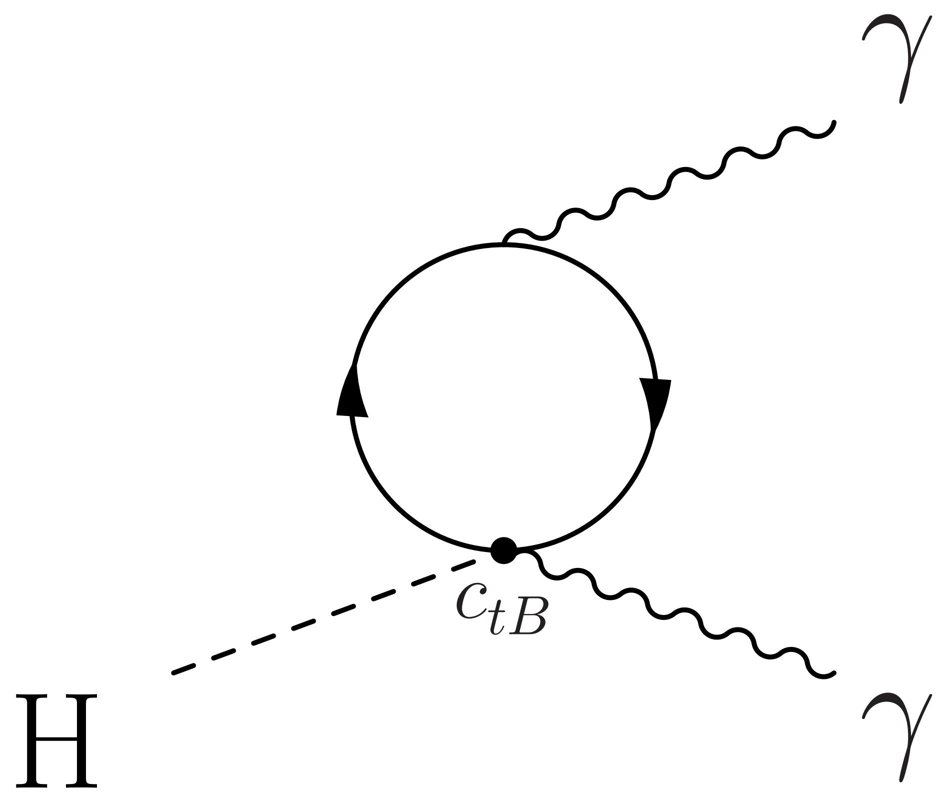
$$\mathcal{O}_{tW} = (\bar{Q}\sigma^{\mu\nu}t)\tau^a\tilde{\Phi}W^a_{\mu\nu}, \qquad \mathcal{O}_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\tilde{\Phi}B_{\mu\nu},$$

$$\Delta\mathcal{L}_{\rm top} = y_t\frac{c_{tH}}{v^2}\mathcal{O}_{tH} + \frac{c_{Hq}^{(1)}}{v^2}\mathcal{O}_{Hq}^{(1)} + \frac{c_{Hq}^{(3)}}{v^2}\mathcal{O}_{Hq}^{(3)} + \frac{c_{Ht}}{v^2}\mathcal{O}_{Ht} + \frac{c_{Htb}}{v^2}\mathcal{O}_{Htb} + \frac{c_{tW}}{v^2}\mathcal{O}_{tW} + \frac{c_{tB}}{v^2}\mathcal{O}_{tB}$$

some detailed understandings

$$\delta\Gamma(h \to \gamma\gamma) : + = -0.56c_{tH} + 1.2c_{HQ}^{(3)} - 0.04c_{Htb} + 33c_{tW} + 61c_{tB}$$

HL-LHC~600%

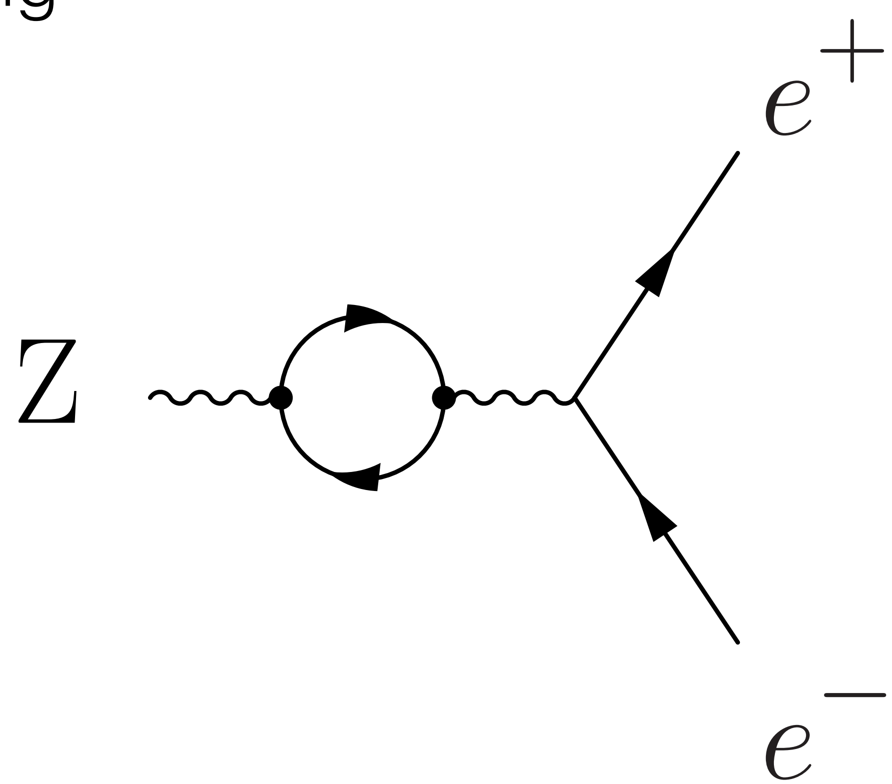


some detailed understandings

$$\delta A_l : += 0.05c_{HQ}^{(1)} - 0.2c_{HQ}^{(3)} + 0.1c_{Ht} + 1.8c_{tW} - 0.3c_{tB}$$

A_{LR}: left-right asymmetry in Z-e-e coupling

~1%



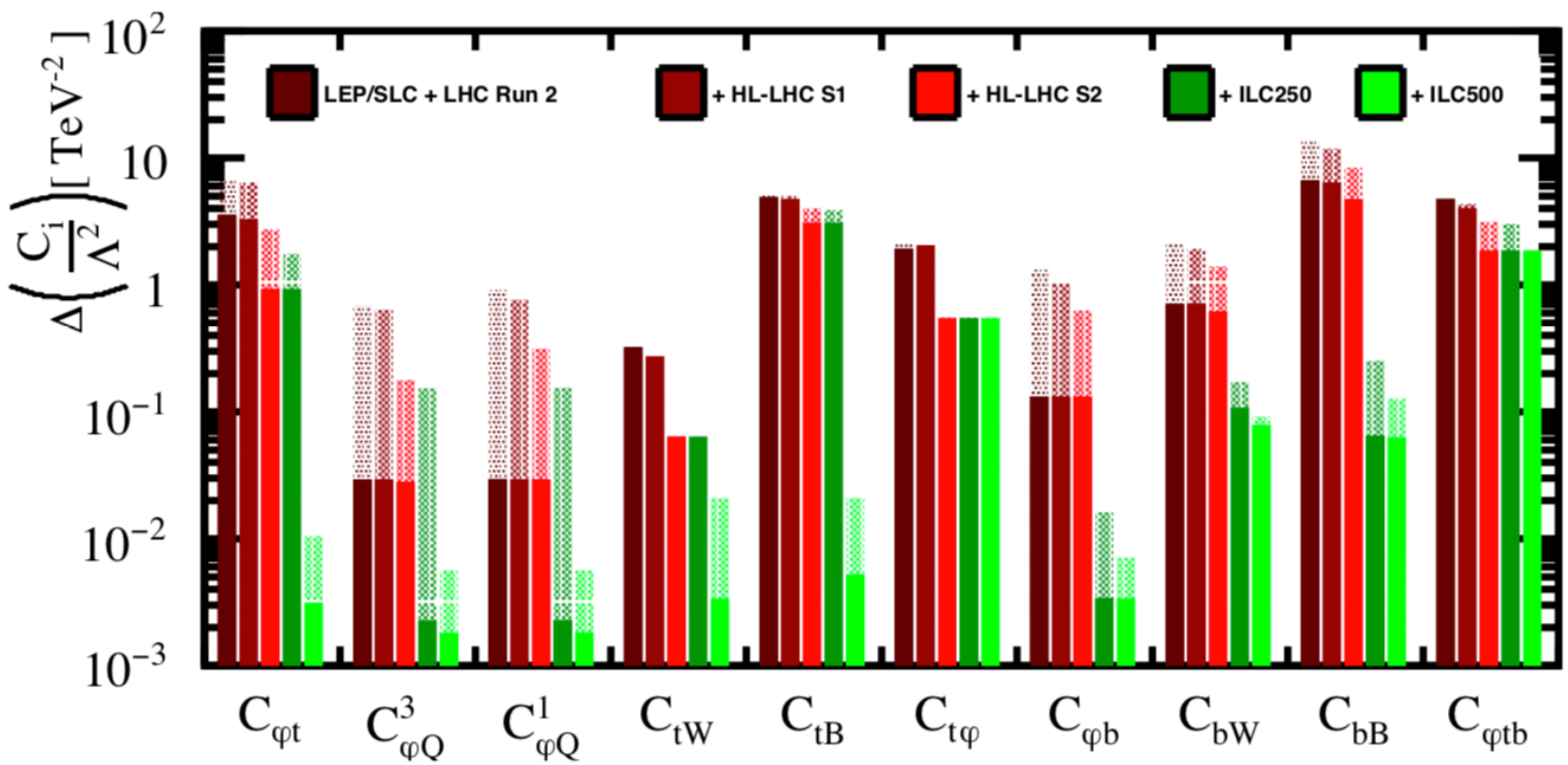
impact from top-EW operators: $\sqrt{s}$ = 250 GeV e+e-

- with the same set of observables (as previous global fit), at 250 GeV running only, the global fit will not converge at any of the Higgs factories
- e.g. Higgs couplings could not be determined unambiguously

impact from top-EW operators: ILC250 + LHC

- LHC will provide us valuable top data sets
- top operators will be constrained to some extent at (HL-)LHC

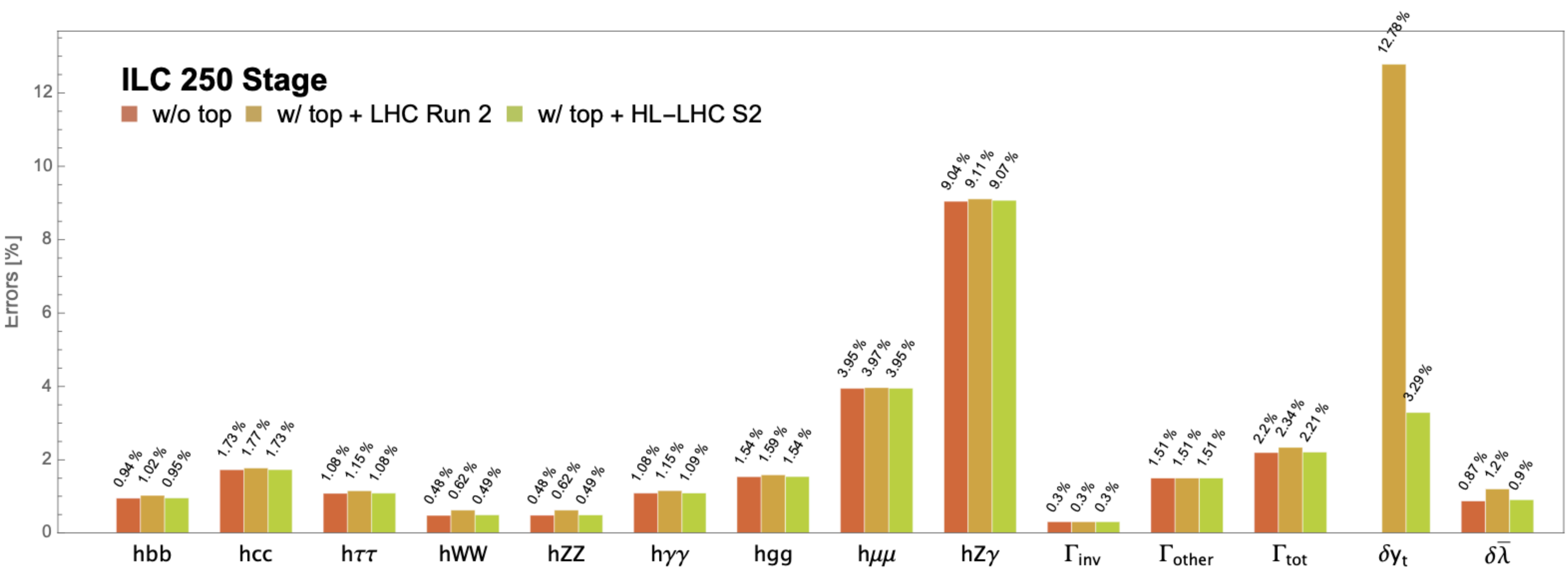
Process	observable
$pp \to t\bar{t}H$	cross section
$pp \to t\bar{t}Z/W$	cross section
$pp \to t\bar{t}\gamma$	fid. x-sec.
single-top (t-ch)	cross section
single-top (Wt)	cross section
single-top (tZq)	cross section
$t \to W^+b$	F_0, F_L
$e^-e^+ \to b\bar{b}$	R_b , A_{FBLR}^{bb}



[Durieux, et al, arXiv:1907.10619]

impact from top-EW operators: ILC250 + LHC

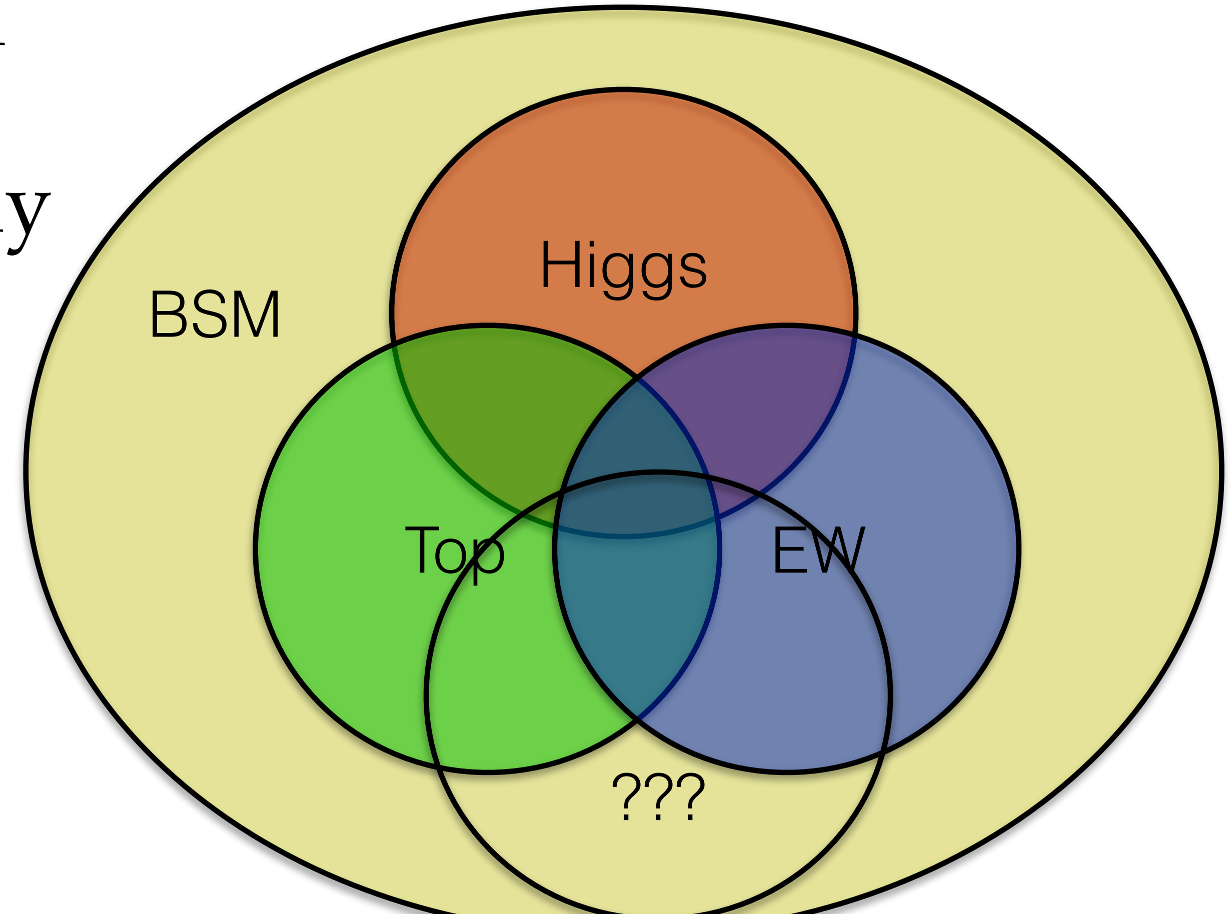
- with the help of LHC top data, Higgs coupling precisions @ ILC250 are almost restored
- note: top data from LHC Run 2 is not constraining enough



S.Jung, J.Lee, M.Perello, JT, M.Vos, arXiv:2006.14631

summary

- physics at future e+e- is very rich
- discover BSM directly & indirectly
- Higgs is unique but not alone
- in addition to a Higgs factory
    - HH factory
    - Z/W factory
    - Top-quark factory
    - flavor factories
    - in the end: new particles factory

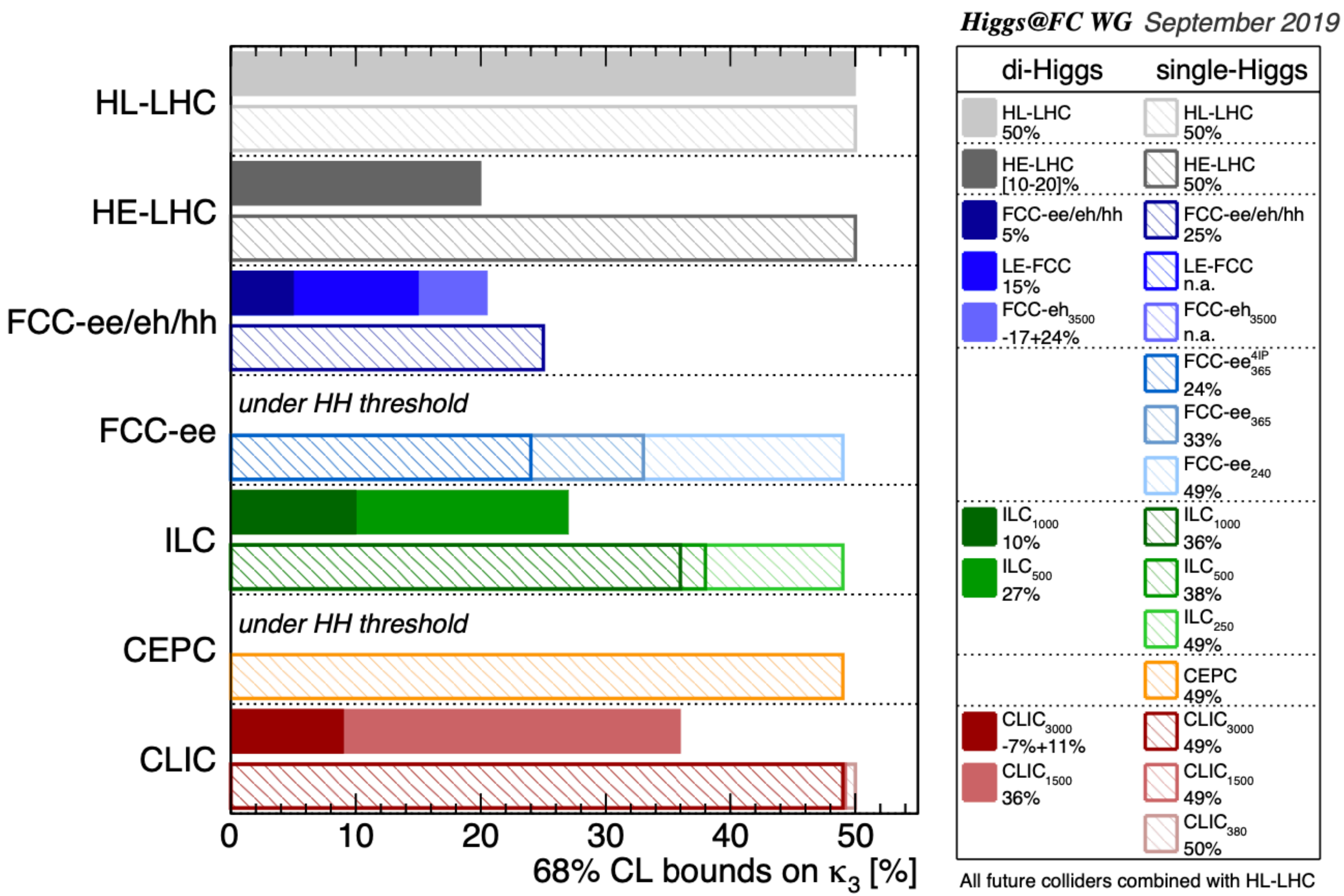


- let's get prepared for the realization

email me with questions: tian@icepp.s.u-tokyo.ac.jp

supplementary reading

λ_{hhh} by double / single Higgs processes



(Physics Briefing Book, arXiv:1910.11775)

benchmark BSM models

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [34]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [36]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [36]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [36]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [38]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [39]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [40]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [41]	-1.5	- 1.5	10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [42]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

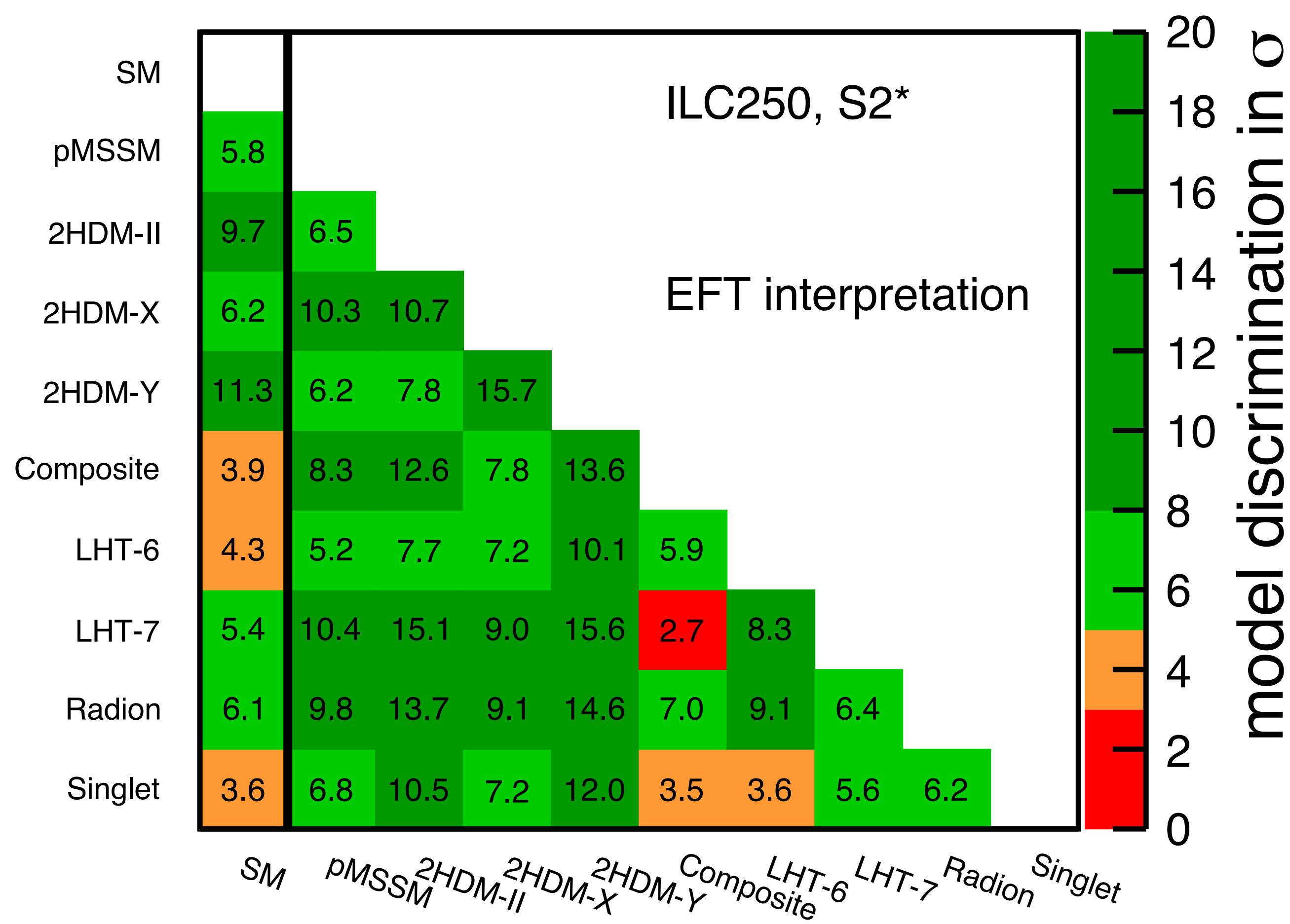
Table 4: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

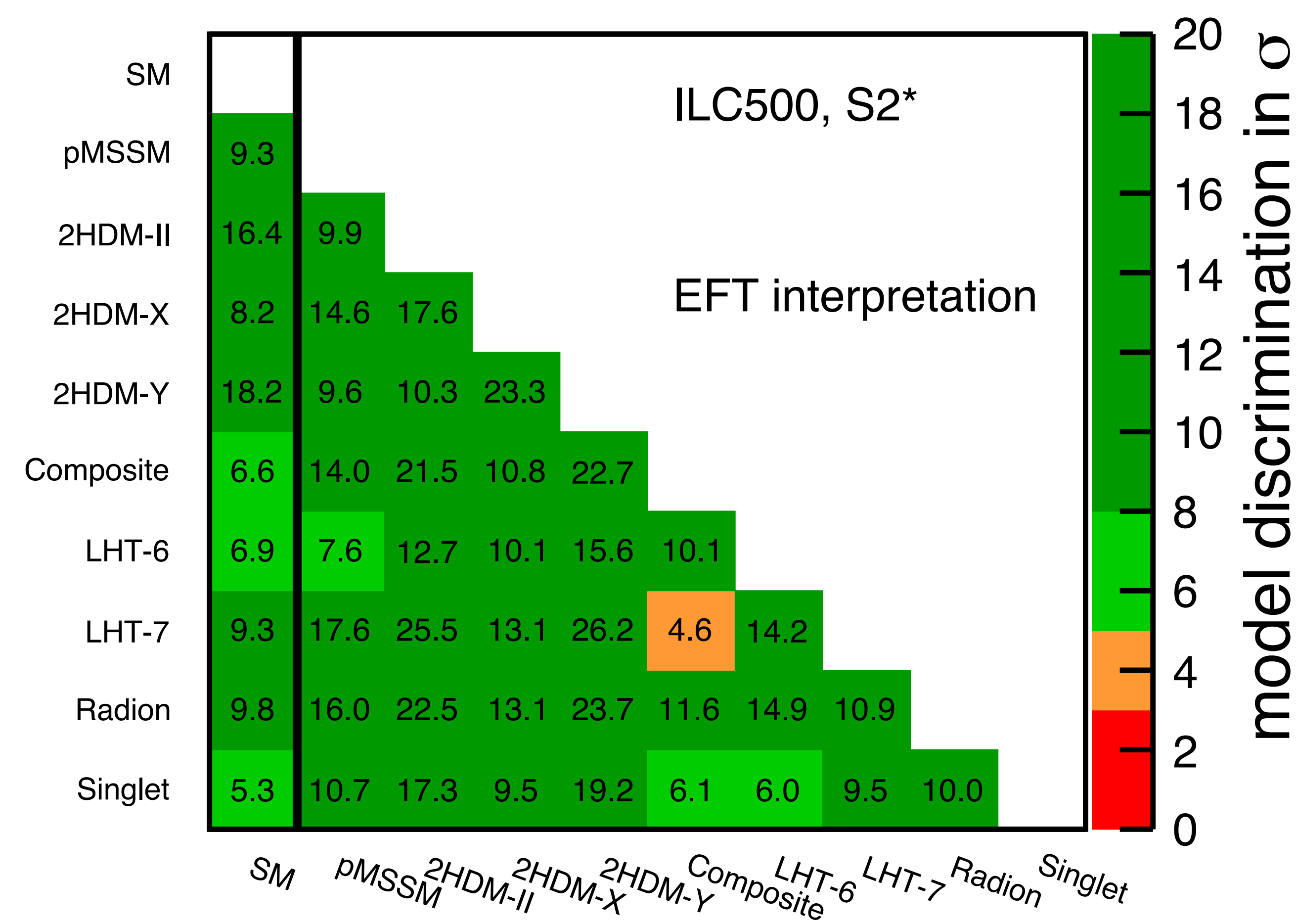
—> quantitative assessment for models discrimination

model parameters (chosen as escaping direct search at HL-LHC)

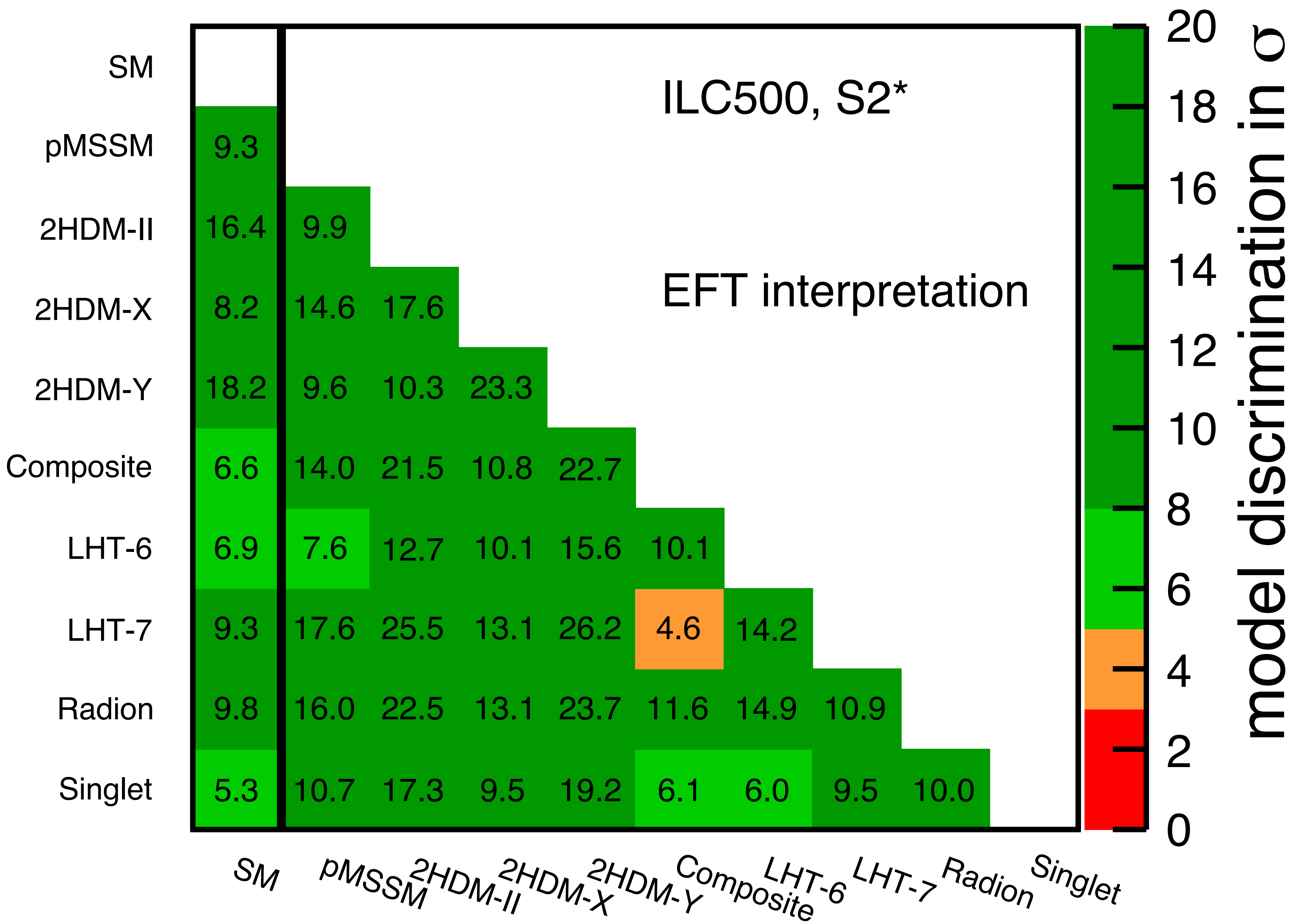
- a PMSSM model with b squarks at 3.4 TeV, gluino at 4 TeV
- a Type II 2 Higgs doublet model with $m_A = 600\ \mathrm{GeV}, \tan\beta = 7$
- a Type X 2 Higgs doublet model with $m_A = 450\ \mathrm{GeV}, \tan\beta = 6$
- a Type Y 2 Higgs doublet model with $m_A = 600\ \mathrm{GeV}, \tan\beta = 7$
- a composite Higgs model MCHM5 with $f = 1.2\ \mathrm{TeV}, m_T = 1.7\ \mathrm{TeV}$
- a Little Higgs model with T-parity with $f = 785\ \mathrm{GeV}, m_T = 2\ \mathrm{TeV}$
- A Little Higgs model with couplings to 1st and 2nd generation with $f = 1.2\ \mathrm{TeV}, m_T = 1.7\ \mathrm{TeV}$
- A Higgs-radion mixing model with $m_r = 500\ \mathrm{GeV}$
- a model with a Higgs singlet at $2.8\ \mathrm{TeV}$ creating a Higgs portal to dark matter and large λ for electroweak baryogenesis

BSM benchmark models discrimination at ILC250





effect of improvement from TGC, vvH, ZH at 500GeV



strategy to determine all the 23 parameters

- m_W and $\alpha(m_Z)$ -> g, g';
- G_F -> v; m_h -> λ; m_Z -> c_T;
- A_l and Γ_l -> c_{HL}+c_{HL}', c_{HE};
- Γ_W and Γ_Z -> c_W, c_Z;

- g_{1Z} -> c_{HL}'; κ_γ -> c_{WB}; κ_λ -> c_{3W};

- *BR(h->γγ)* and *BR(h->γZ)* -> c_{BB}, c_{WW};
- σ_{ZH} -> c_H; σ_{ZHH} -> c_6;
- *BR(h->bb/cc/gg/μμ/ττ)* -> y_b, y_c, c_g, y_μ, y_τ;
- *BR(h->invisible)* and *BR(h->other)*;
- c_{WW} is helped by A_{LR} in σ_{ZH}, angular meas., W-fusion;
- c_{HL}/c_{HL}'/c_{HE} are helped by A_{LR} in σ_{ZH}

simplifications of our analysis

- at tree level, and to linear order in D-6 coefficients
- ignore some possible D-6 corrections involving light leptons, e.g. 4-fermion operators
- avoid using observables that involve contact interactions that include quark currents (see more later)
- ignore the effects of CP-violating operators

$$\Delta\mathcal{L}_{CP} = +\frac{g^2\tilde{c}_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} + \frac{4gg'\tilde{c}_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}\widetilde{B}^{\mu\nu}$$
$$+\frac{g'^2\tilde{c}_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}\widetilde{B}^{\mu\nu} + \frac{g^3\tilde{c}_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_{\rho}\widetilde{W}^{c\rho\mu}$$

on-shell renormalization

- D-6 operators modify the SM expressions for precision electroweak observables, thus shift the appropriate values for the SM couplings —> g, g', v, λ free parameters
- D-6 operators also renormalize the kinetic terms of the SM fields —> rescale the boson fields

$$\mathcal{L} = -\frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu}\cdot(1-\delta Z_W) - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu}\cdot(1-\delta Z_Z) \\ -\frac{1}{4}A_{\mu\nu}A^{\mu\nu}\cdot(1-\delta Z_A) + \frac{1}{2}(\partial_\mu h)(\partial^\mu h)\cdot(1-\delta Z_h)\ ,$$

with

$$\begin{aligned} \delta Z_W &= (8c_{WW}) \\ \delta Z_Z &= c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + s_w^4/c_w^2(8c_{BB}) \\ \delta Z_A &= s_w^2\Big((8c_{WW}) - 2(8c_{WB}) + (8c_{BB})\Big) \\ \delta Z_h &= -c_H\ . \end{aligned}$$

$$\Delta\mathcal{L} = \frac{1}{2}\,\delta Z_{AZ}\,A_{\mu\nu}Z^{\mu\nu}\ ,\qquad \delta Z_{AZ} = s_w c_w\Big((8c_{WW}) - (1-\frac{s_w^2}{c_w^2})(8c_{WB}) - \frac{s_w^2}{c_w^2}(8c_{BB})\Big)$$

EFT input: EWPOs

Observable	current value	current σ	future σ	SM best fit value
$\alpha^{-1}(m_Z^2)$	128.9220	0.0178		(same)
G_F (10^{-10} GeV^{-2})	1166378.7	0.6		(same)
m_W (MeV)	80385	15	5	80361
m_Z (MeV)	91187.6	2.1		91188.0
m_h (MeV)	125090	240	15	125110
A_ℓ	0.14696	0.0013		0.147937
Γ_ℓ (MeV)	83.984	0.086		83.995
Γ_Z (MeV)	2495.2	2.3		2494.3
Γ_W (MeV)	2085	42	2	2088.8

EFT input: EWPOs (7)

$$\underline{\alpha(m_Z), G_F, m_W, m_Z, m_h,}\, A_{LR}(\ell), \Gamma(Z \to \ell^+\ell^-)$$

$$\delta e = \delta(4\pi\alpha(m_Z^2))^{1/2} = s_w^2 \delta g + c_w^2 \delta g' + \frac{1}{2}\delta Z_A$$

$$\delta G_F = \; -2\delta v + 2c'_{HL}$$

$$\delta m_W = \delta g + \delta v + \frac{1}{2}\delta Z_W$$

$$\delta m_Z = c_w^2 \delta g + s_w^2 \delta g' + \delta v - \frac{1}{2}c_T + \frac{1}{2}\delta Z_Z$$

$$\delta m_h = \frac{1}{2}\delta\overline{\lambda} + \delta v + \frac{1}{2}\delta Z_h$$

($\delta X = \Delta X / X$)

$$\overline{\lambda} = \lambda(1 + \frac{3}{2}c_6)$$

$$s_w^2 = \sin^2\theta_w = \frac{g'^2}{g^2 + g'^2}$$

$$c_w^2 = \cos^2\theta_w = \frac{g^2}{g^2 + g'^2}$$

⟶ δg, $\delta g'$, δv, $\delta\lambda$, c_T

EFT input: EWPOs (7)

$$\alpha(m_Z), G_F, m_W, m_Z, m_h, \underline{A_{LR}(\ell), \Gamma(Z \to \ell^+ \ell^-)}$$

$$\delta\Gamma_\ell = \delta m_Z + 2\frac{g_L^2 \delta g_L + g_R^2 \delta g_R}{g_L^2 + g_R^2}$$

$$\delta A_\ell = \frac{4 g_L^2 g_R^2 (\delta g_L - \delta g_R)}{g_L^4 - g_R^4}$$

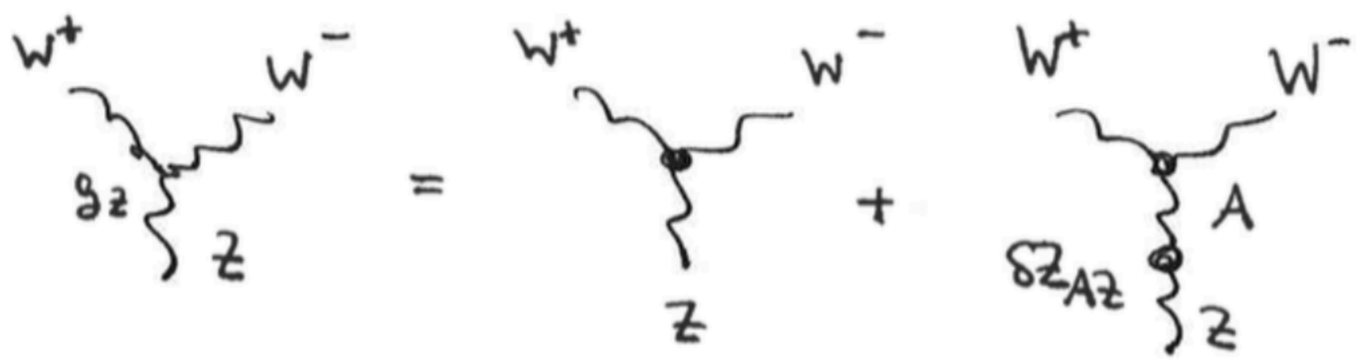
$$g_L = \frac{g}{c_w}\left[(-\frac{1}{2} + s_w^2)(1 + \frac{1}{2}\delta Z_Z) - \frac{1}{2}(c_{HL} + c'_{HL}) - s_w c_w \delta Z_{AZ}\right]$$

$$g_R = \frac{g}{c_w}\left[(+s_w^2)(1 + \frac{1}{2}\delta Z_Z) - \frac{1}{2}c_{HE} - s_w c_w \delta Z_{AZ}\right]$$

$\longrightarrow$ $c_{HL}+c'_{HL}$, c_{HE}

EFT input: TGC (3)

$$\Delta\mathcal{L}_{TGC} = ig_V\Big\{V^\mu(\hat{W}^-_{\mu\nu}W^{+\nu} - \hat{W}^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu \hat{V}^{\mu\nu} + \frac{\lambda_V}{m_W^2}\hat{W}^{-\rho}_\mu \hat{W}^+_{\rho\nu}\hat{V}^{\mu\nu}\Big\}$$

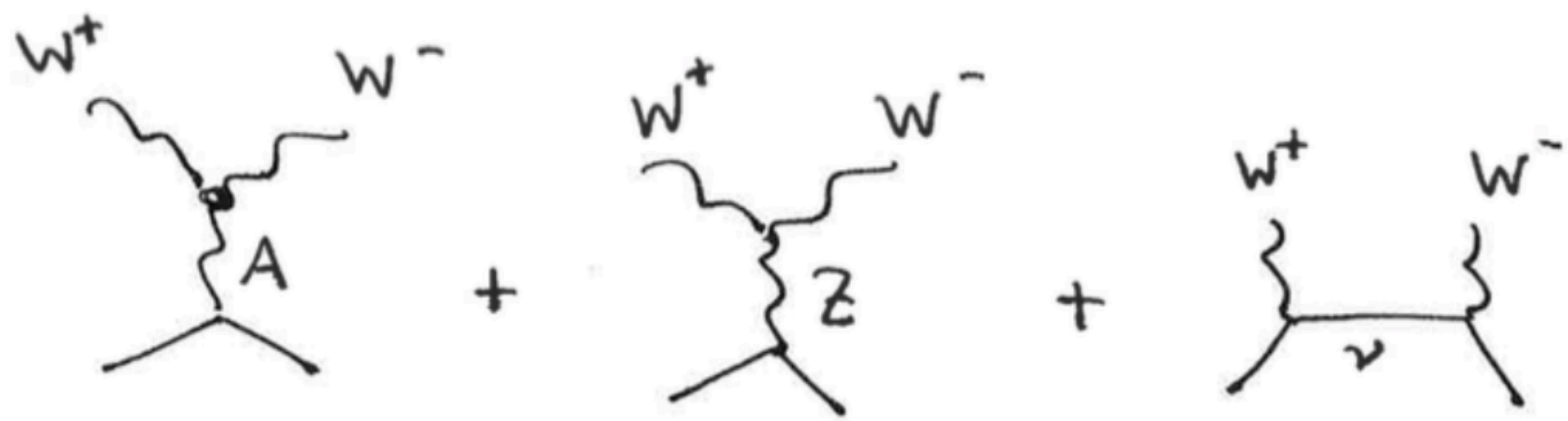


$$g_Z = gc_w(1 + \frac{1}{2}\delta Z_Z + \frac{s_w}{c_w}\delta Z_{AZ})$$

$$\kappa_A = 1 + (8c_{WB})$$

$$\lambda_A = -6g^2 c_{3W}$$

EFT input: TGC (3)



$$\delta g_{Z,eff} = \delta g_Z + \frac{1}{c_w^2}((c_w^2 - s_w^2)\delta g_L + s_w^2 \delta g_R - 2\delta g_W)$$
$$\delta\kappa_{A,eff} = (c_w^2 - s_w^2)(\delta g_L - \delta g_R) + 2(\delta e - \delta g_W) + (8c_{WB})$$
$$\delta\lambda_{A,eff} = -6g^2 c_{3W}$$

$$g_W = g\ (1 + c'_{HL} + \frac{1}{2}\delta Z_W)$$

EFT input: BR(h->γγ)/BR(h->ZZ*), BR(h->γZ)/BR(h->ZZ*)

(2: HL-LHC)

$$\delta\Gamma(h\to\gamma\gamma) = 528\,\delta Z_A - c_H + 4\delta e + 4.2\,\delta m_h - 1.3\,\delta m_W - 2\delta v$$

$$\delta\Gamma(h\to Z\gamma) = 290\,\delta Z_{AZ} - c_H - 2(1-3s_W^2)\delta g + 6c_w^2\delta g' + \delta Z_A + \delta Z_Z \\ +9.6\,\delta m_h - 6.5\,\delta m_Z - 2\delta v$$

$$\delta\Gamma(h\to ZZ^*) = 2\eta_Z - 2\delta v - 13.8\delta m_Z + 15.6\delta m_h - 0.50\delta Z_Z - 1.02 C_Z + 1.18\delta\Gamma_Z$$

$$\delta Z_A = s_w^2\Big((8c_{WW}) - 2(8c_{WB}) + (8c_{BB})\Big) \qquad \delta Z_{AZ} = s_w c_w\Big((8c_{WW}) - (1-\frac{s_w^2}{c_w^2})(8c_{WB}) - \frac{s_w^2}{c_w^2}(8c_{BB})\Big)$$

EFT coefficients

10: c_H, c_T, c_6, c_{WW}, c_{WB}, c_{BB}, c_{3W}, c_{HL}, c'_{HL}, c_{HE}

+ 4: g, g', v, λ

can already be determined,
except c_6, c_H

—> Higgs observables @ e+e-

EFT input: σ(e+e- —>Zh), σ(e+e- —> Zhh)

- c_H has to be determined by inclusive σ_{Zh} measurement
- c_6 has to be determined by double Higgs measurement

EFT input: BR(h—>XX)

$$\Delta\mathcal{L} = -c_{\tau\Phi}\frac{y_\tau}{v^2}(\Phi^\dagger\Phi)\overline{L}_3\cdot\Phi\tau_R + h.c.$$

- h couplings to b, c, τ, μ, g

$$\delta\mathcal{L} = \mathcal{A}\frac{h}{v}G_{\mu\nu}G^{\mu\nu}$$

- Γ(h->invisible), total decay width

note: beam polarizations provide several independent (redundant) set of σ,σxBR input, which are powerful to test EFT validity two more parameters: C_W, C_Z for Γ(h->WW*) and Γ(h->ZZ*)

$$\Gamma/(SM) = 1 + 2\eta_W - 2\delta v - 11.7\delta m_W + 13.6\delta m_h$$
$$-0.75\zeta_W - 0.88C_W + 1.06\delta\Gamma_W \ ,$$

$$C_W = \sum_X c'_X \mathcal{N}_X \ / \ \sum_X \mathcal{N}_X \ ,$$

(c'_X: contact interactions)

EFT input:

$$\Gamma_W = \frac{g^2 m_W}{48\pi}(\sum_X \mathcal{N}_X) \cdot (1 + 2\delta g + \delta m_W + \delta Z_W + 2C_W)$$

(similar for Z)