Higgs at $e^+ e^-$ colliders

Daniel Jeans, KEK

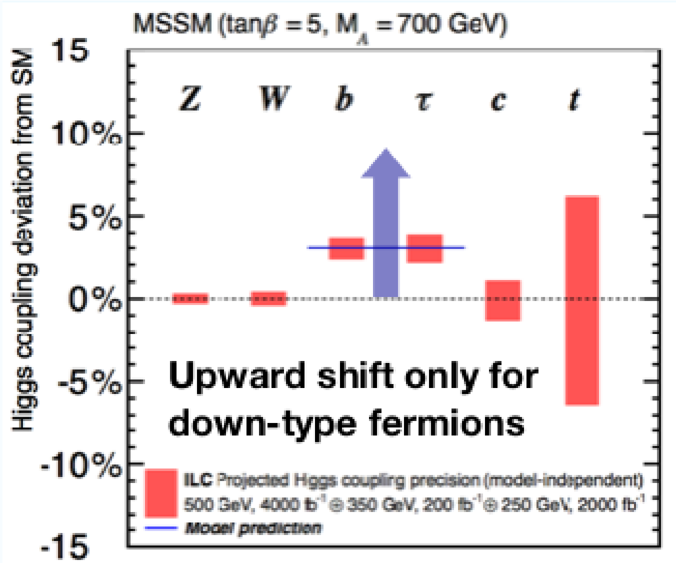
IAS High Energy Physics, Jan 2020

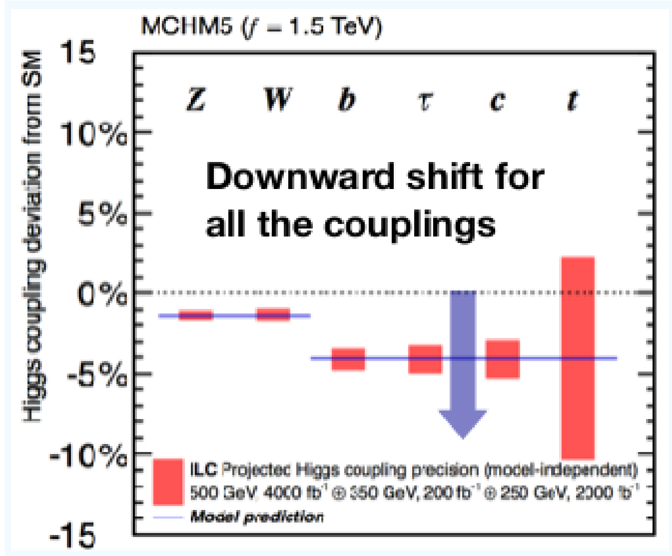
why measure the Higgs?

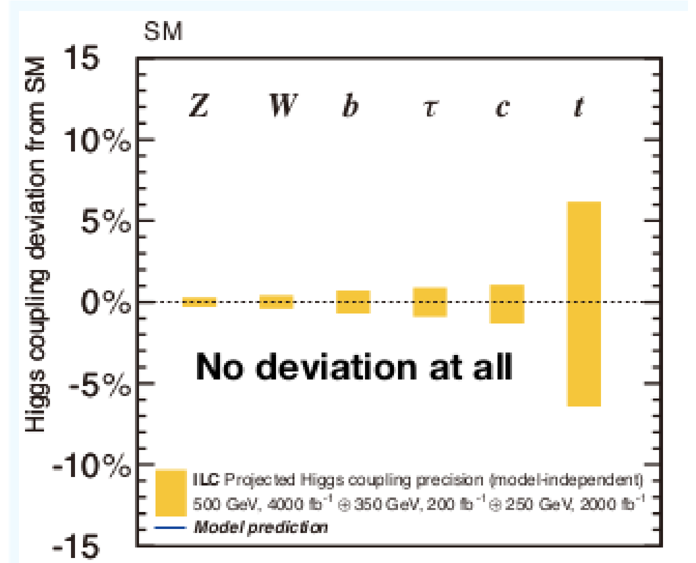
a new symmetry
e.g. SUSY

a deeper structure
e.g. composite Higgs

SM-like
multi-verse ?







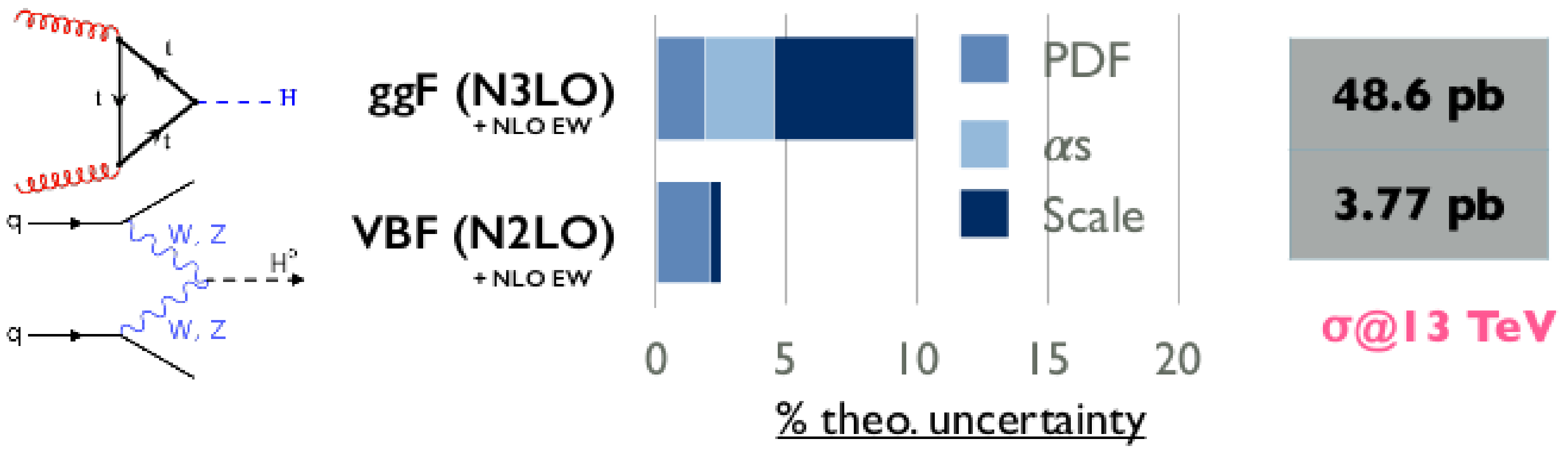
deeper physics leaves fingerprints on Higgs
few-% deviations for TeV-scale new physics

why a **lepton** collider ?

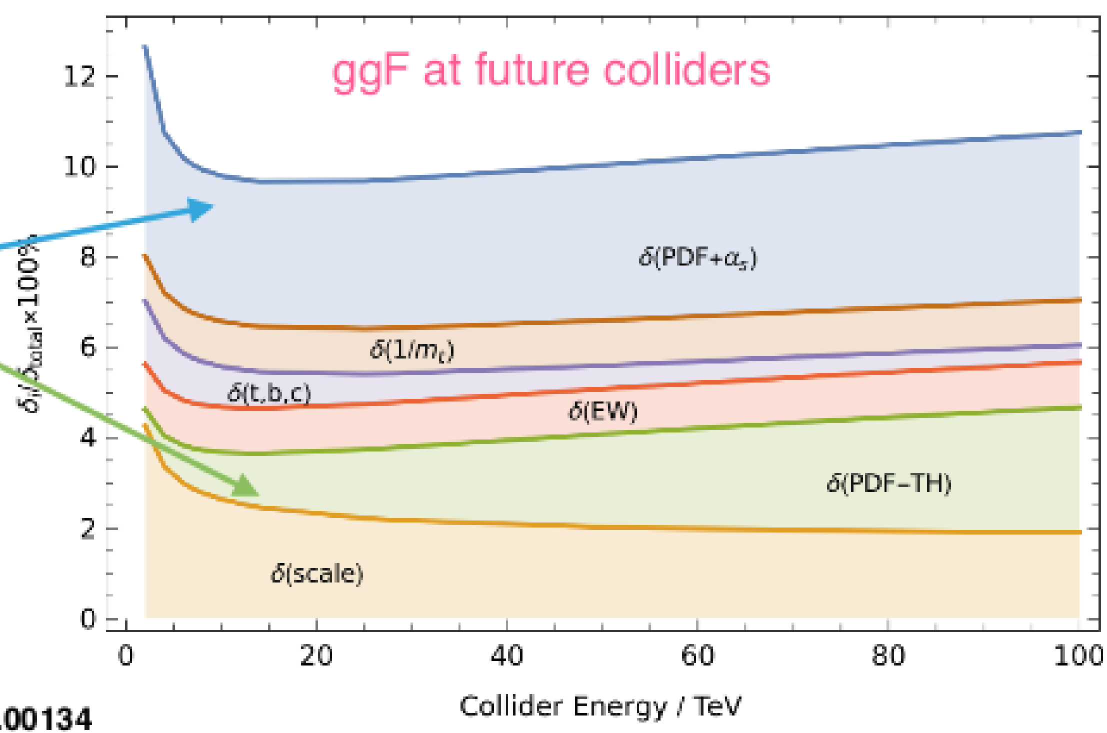
advantage of $e^+ e^-$

elementary & colourless

Higgs



PDF uncertainty significantly limitation to theory accuracy



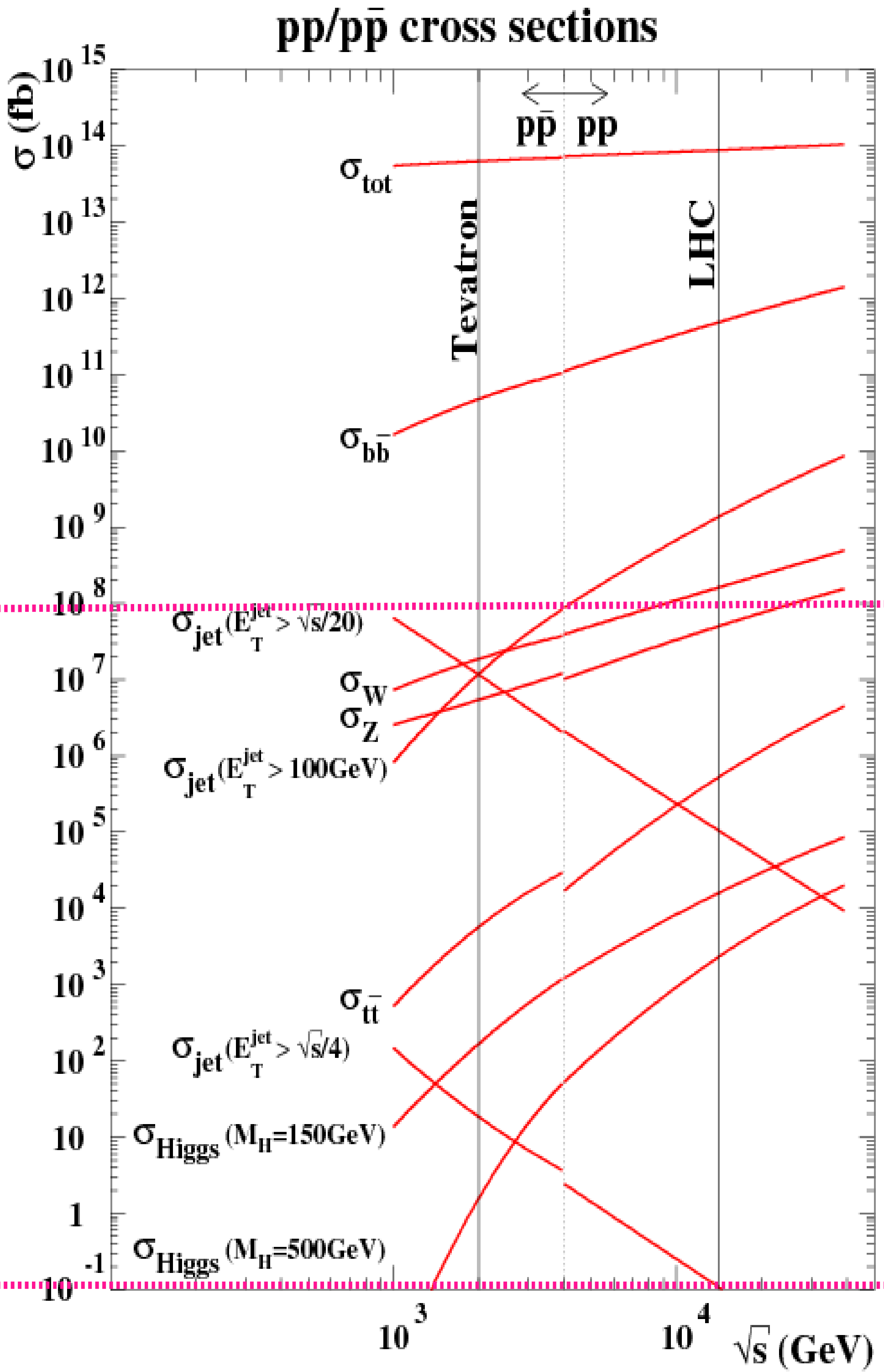
M. Cepeda et al. [HL/HE WG2 group], arXiv:1902.00134

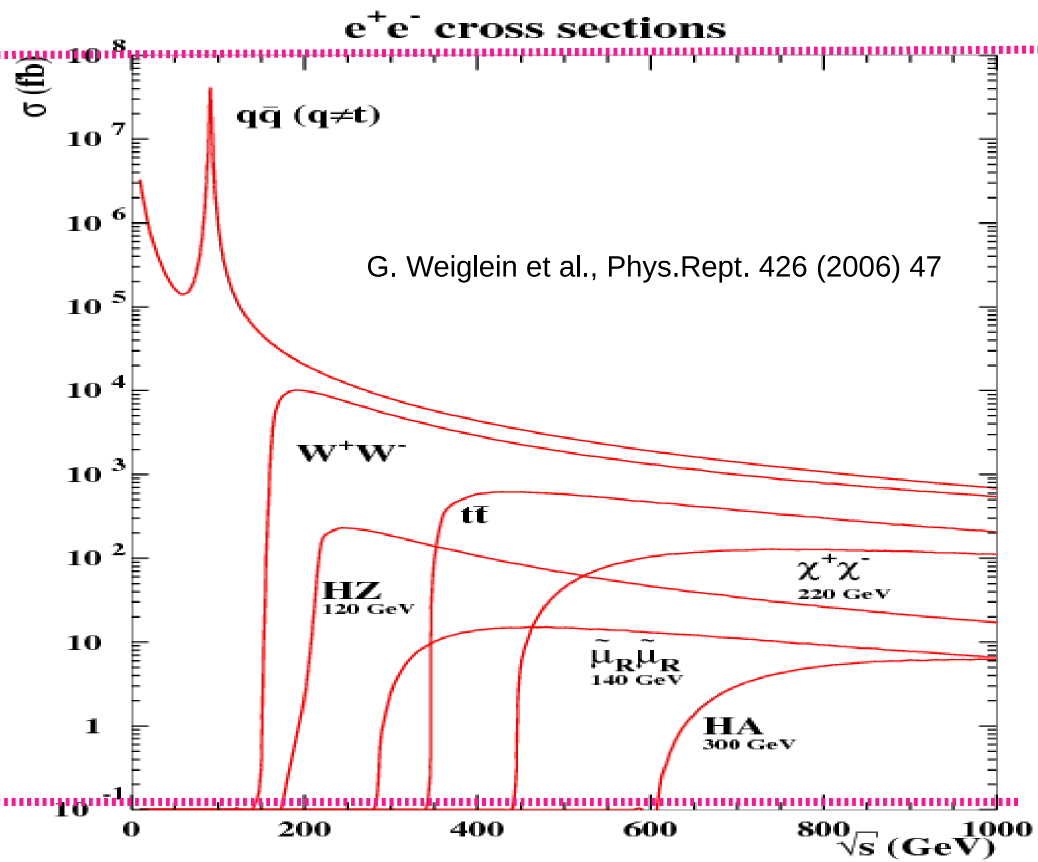
Maria Ubiali, HC2019

advantage of $e^+ e^-$

elementary & colourless

modest backgrounds,
"democratic" production
→ loose or no triggers
→ S/B ~ 1 for main decays





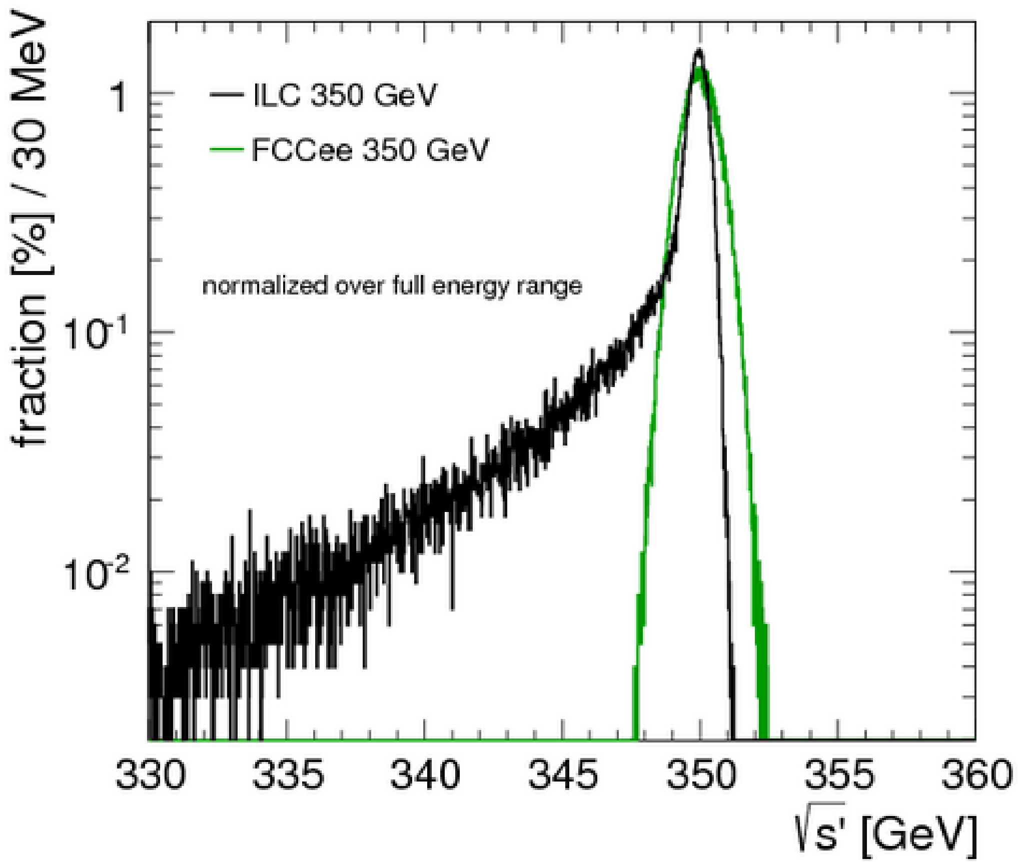
G. Weiglein et al., Phys.Rept. 426 (2006) 47

advantage of $e^+ e^-$

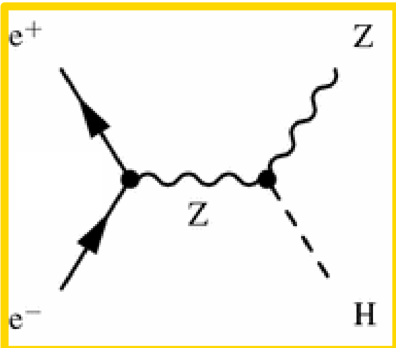
elementary & colourless

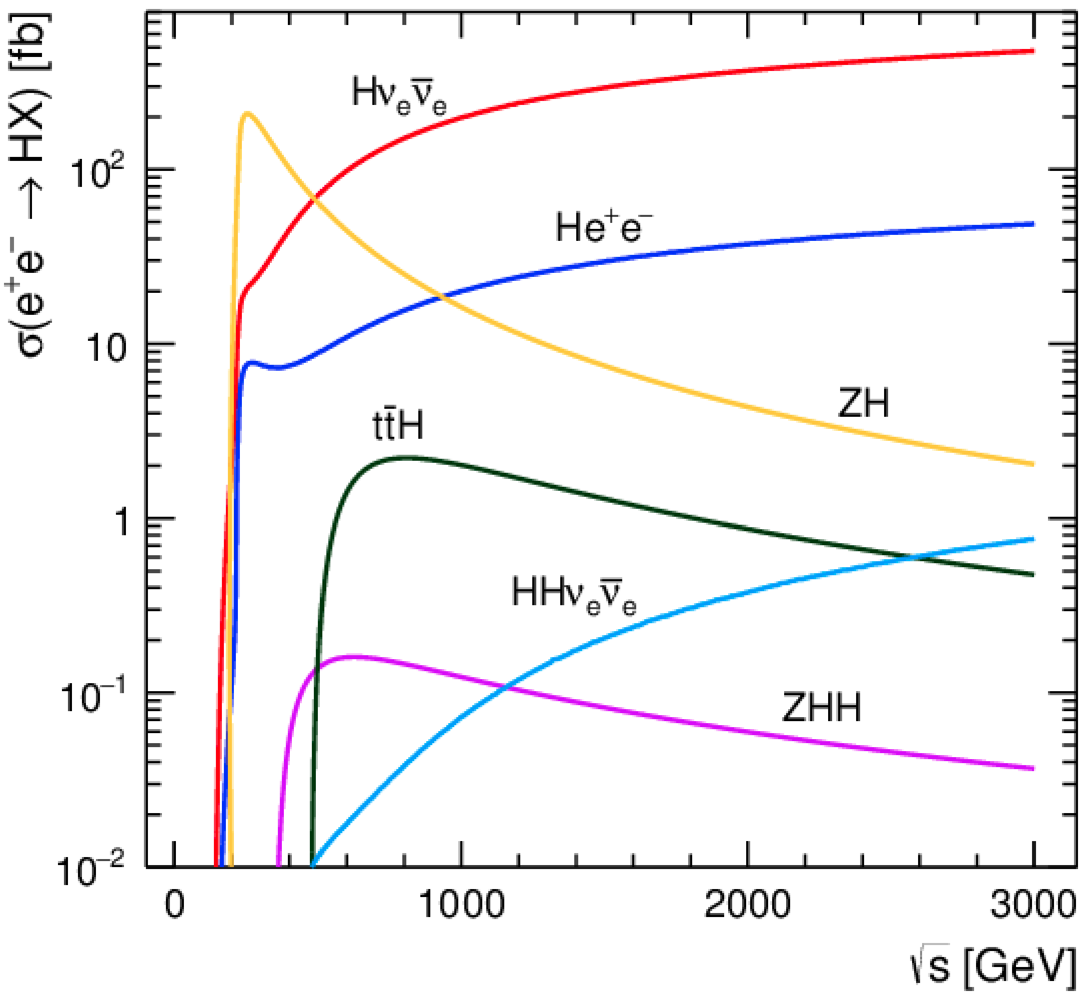
modest backgrounds

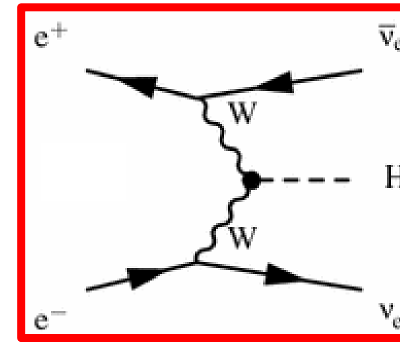
precisely known & tune-able
initial state
four-momentum,
+ spin at linear colliders

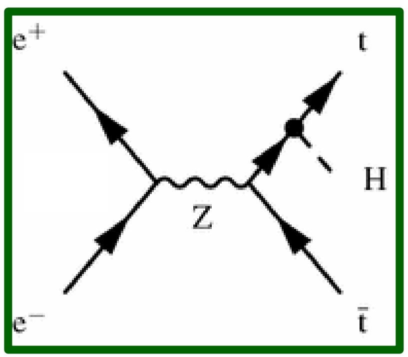


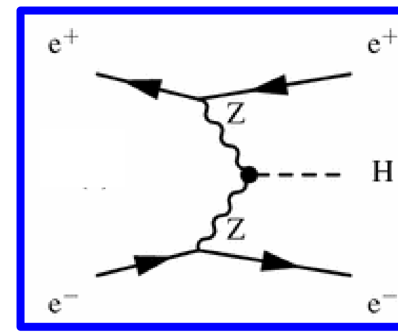
Higgs production in electron-positron collisions

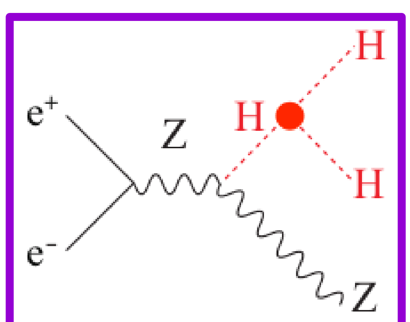


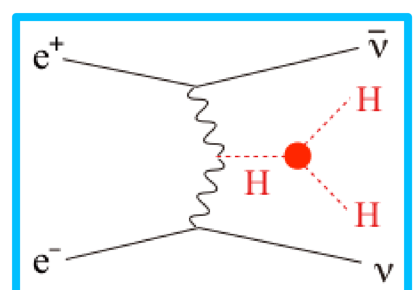








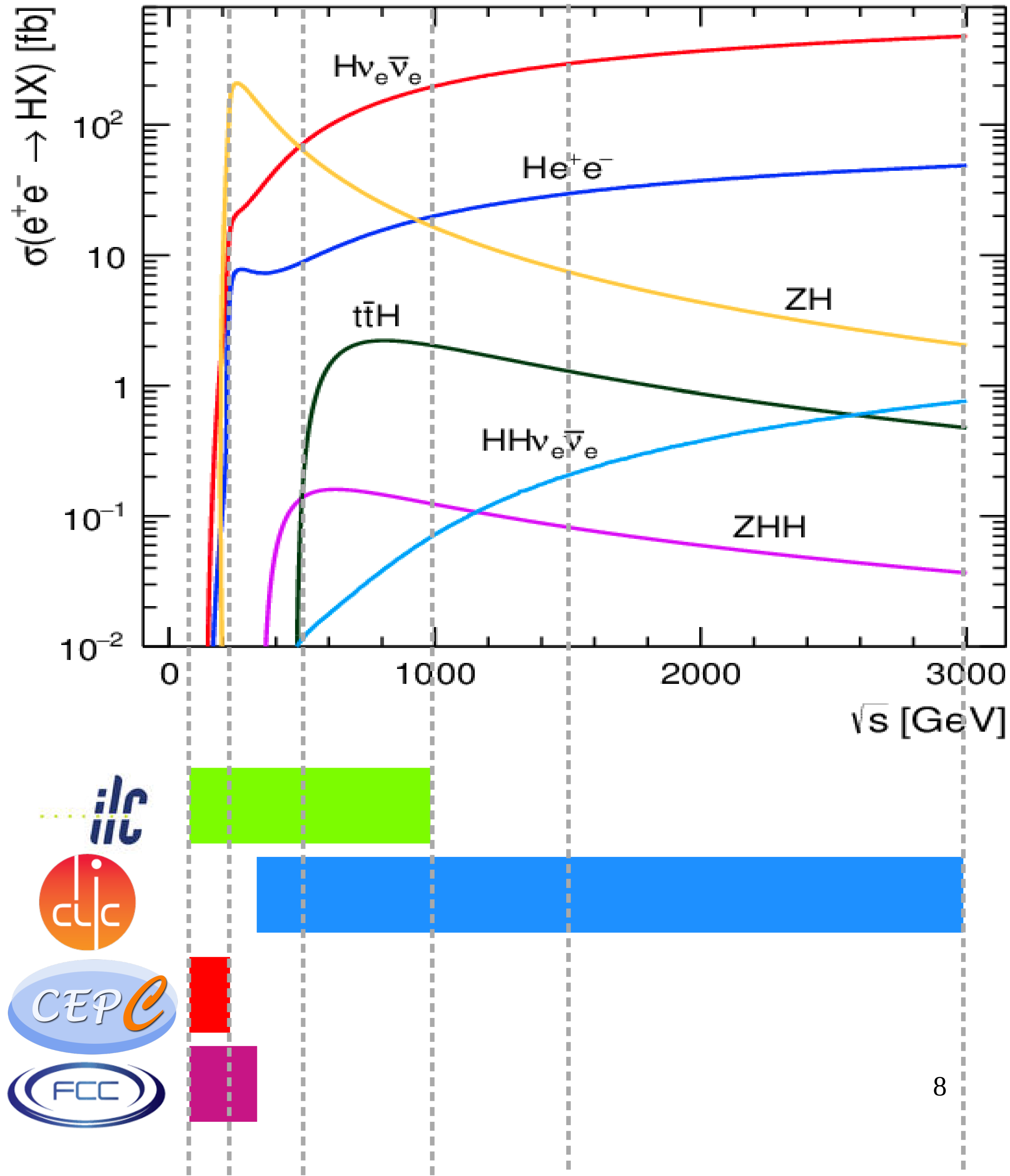




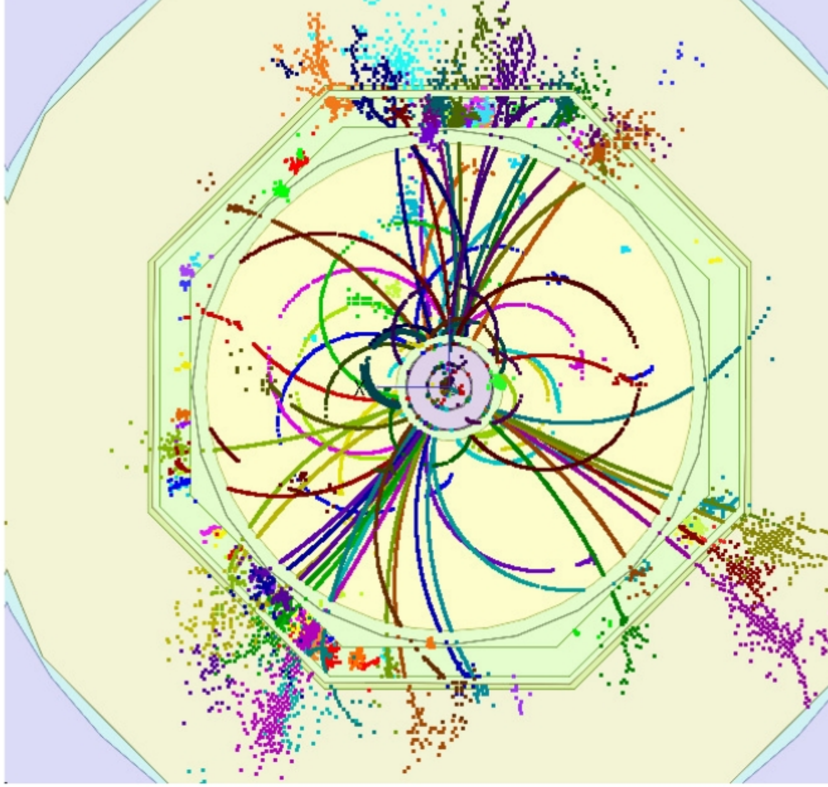
four $e^+ e^-$ collider proposals

contrasting
- geometries,
- technologies,
- energies, and
- luminosities

experimental projections at various levels:
- full simulation,
- fast simulation,
- dephes,
- MC-level...



typical detector performance requirements



charged track momentum resolution

$dp_T / p_T \sim$ few x $10^{-5}\, p_T$

→"recoil" H mass measurement

charged track impact parameter resolution

$\sigma_{d0} \sim 5\ \mu m$

→ identification of b, c, and τ decays

hadronic jet energy resolution

$\sigma_E / E \sim 3 \rightarrow 5\ \%$ over wide energy range

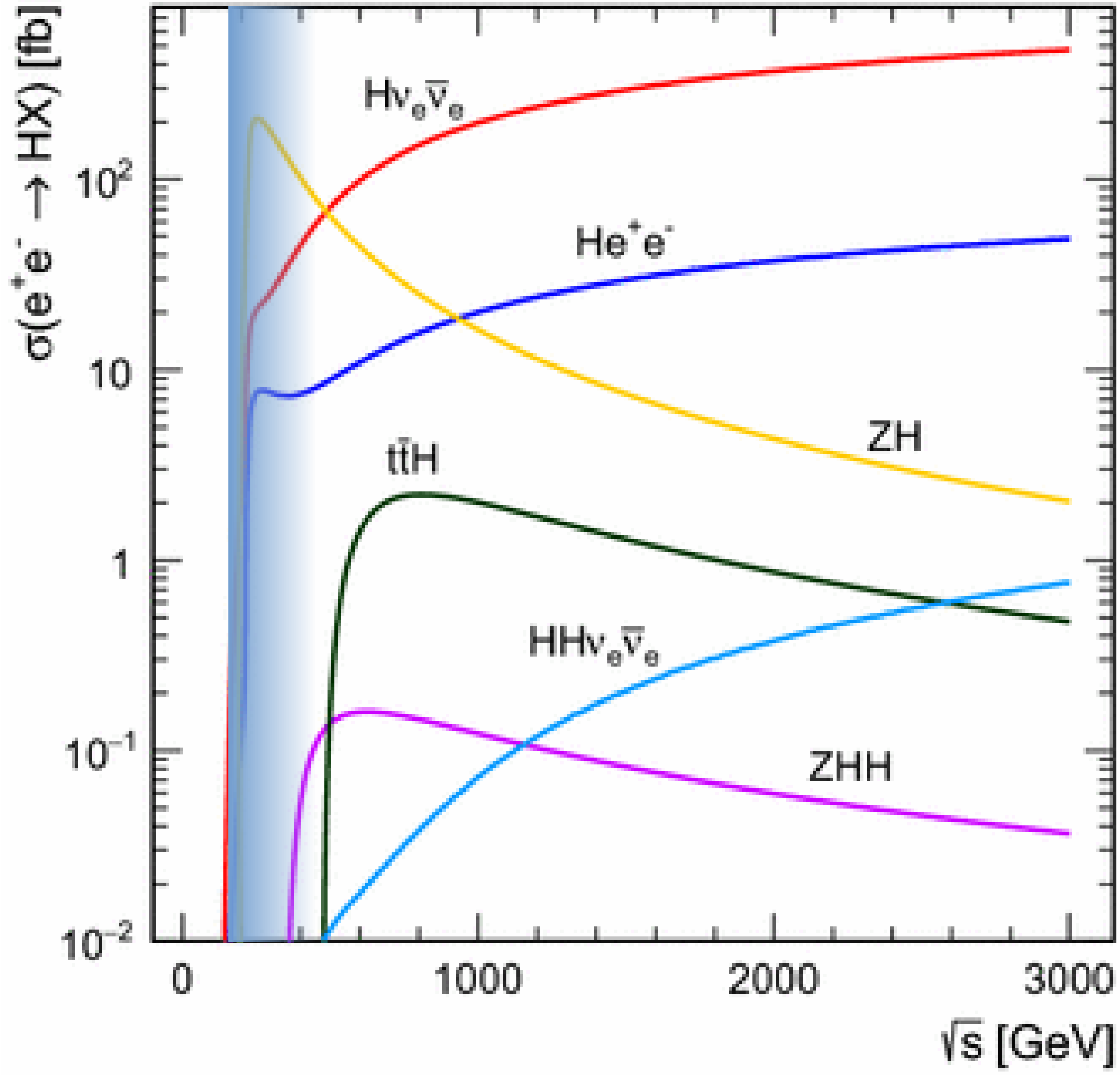
→ exploitation of hadronic final states; distinguish W, Z, H

none of these are met by today's LHC detectors, by factors of ~2 → ~40

covers almost 4π solid angle

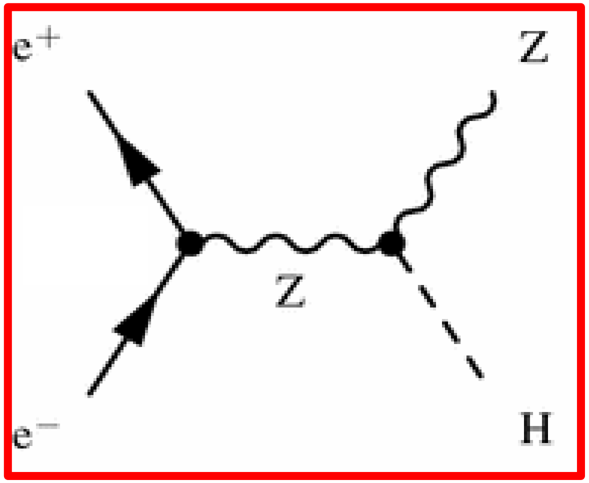
→ important for "missing momentum" searches

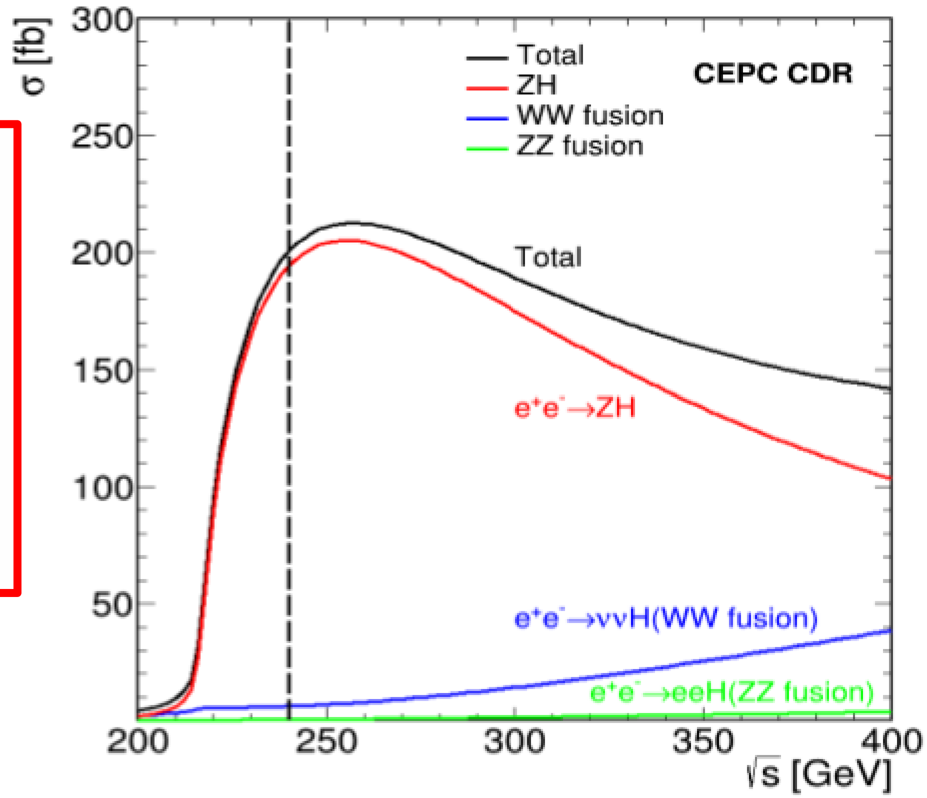
√s ~ 240+ GeV

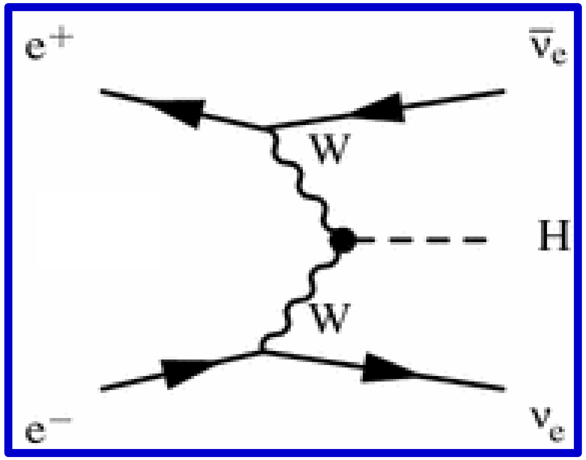


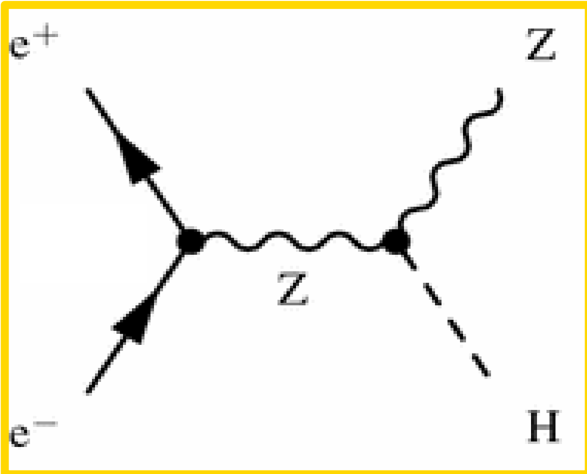
σ(e⁺e⁻ → HX) [fb]
10²
10
1
10⁻¹
10⁻²
0
1000
2000
3000
√s [GeV]
Hν_eν̄_e
He⁺e⁻
ZH
tt̄H
HHν_eν̄_e
ZHH

Higgs production near threshold

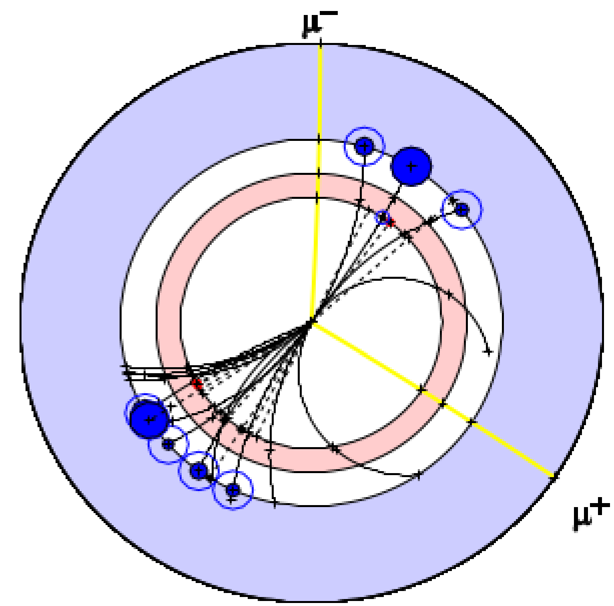








Higgs-strahlung

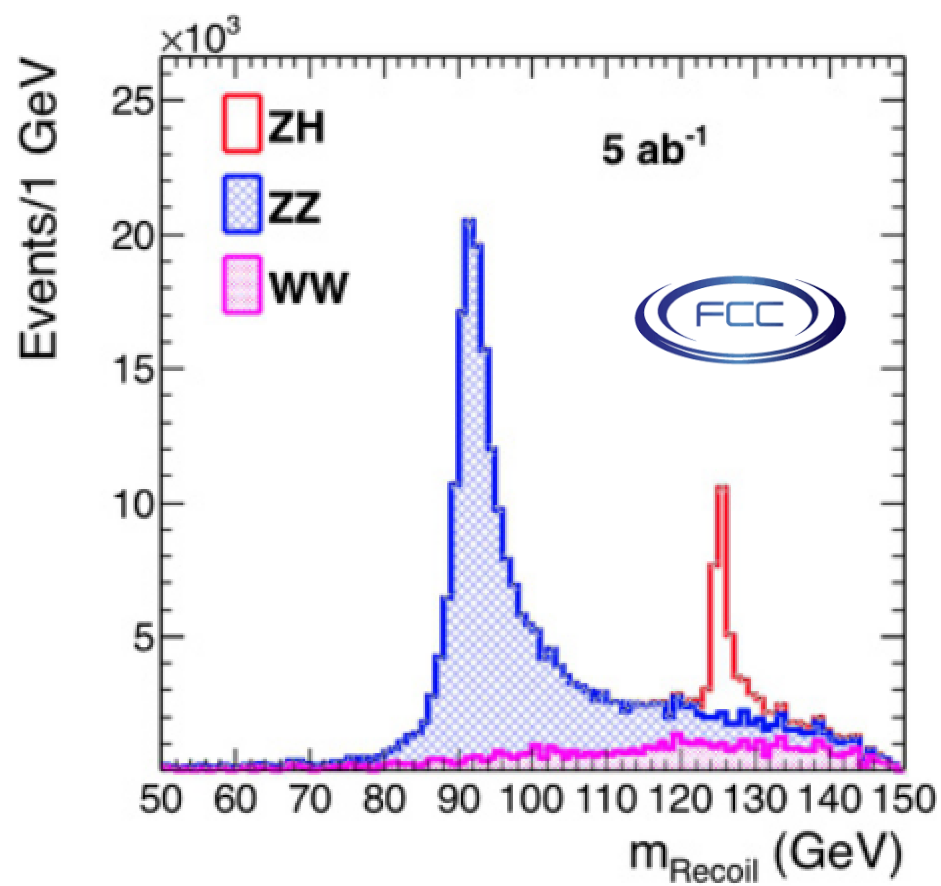


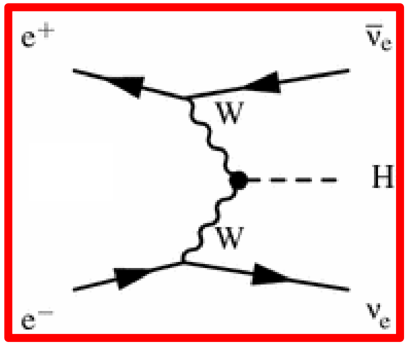
key to model-independent
measurement of Higgs couplings

known initial 4-mom
+ measured Z 4-mom
→ invariant mass of recoil 4-mom
"recoil mass"

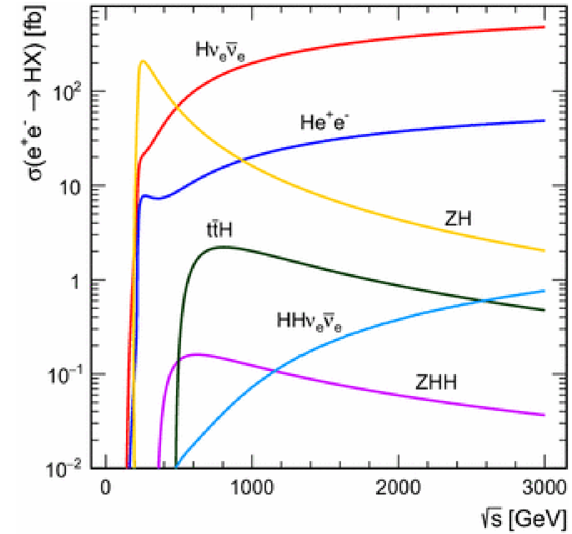
detect Higgs boson
without reconstructing its decay

measure σ($e^+ e^-$ → Z H),
independent of Higgs decay



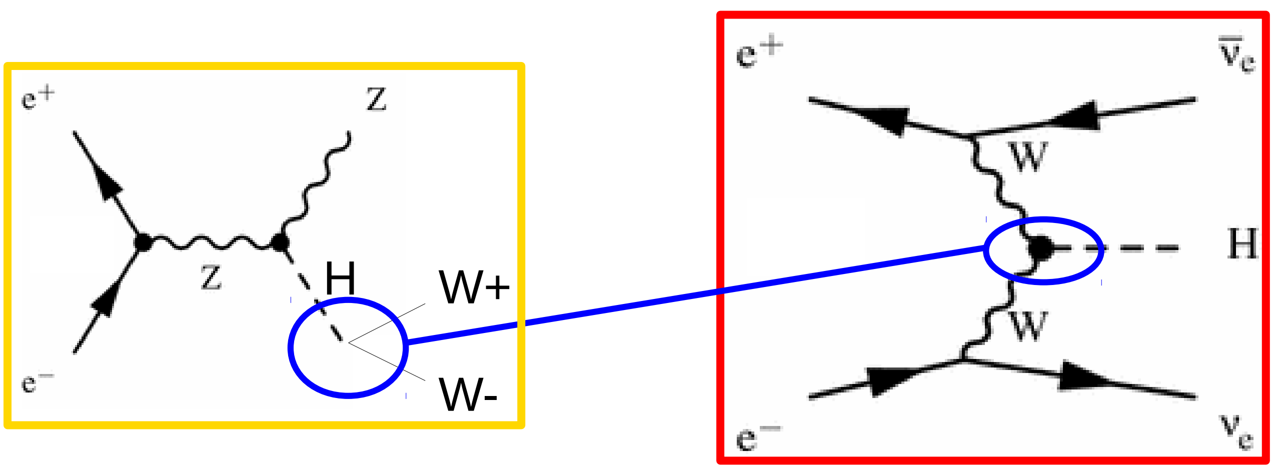


WW-fusion



dominant Higgs production process > ~500 GeV

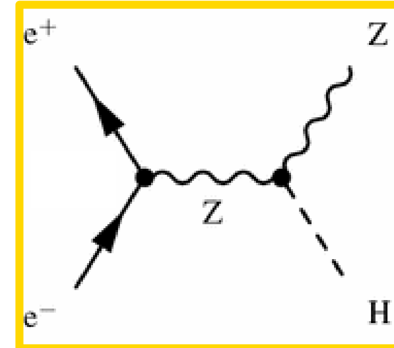
cannot fully reconstruct the final state,
but can be linked to Higgs-strahlung process
via the H → WW coupling



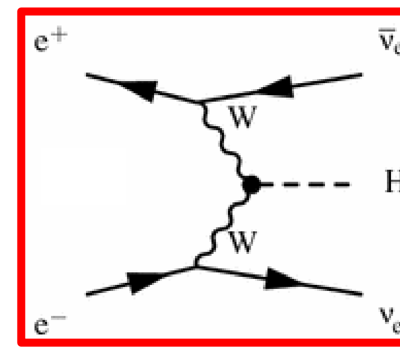
measurements

$\sigma\ (e^+ e^- \rightarrow Z\ H) \sim g_{HZZ}^2$

$\sigma\ (e^+ e^- \rightarrow Z\ H) \times BR\ (H \rightarrow XX) \sim g_{HZZ}^2\, g_{HXX}^2 / \Gamma_H$



$\sigma\ (e^+ e^- \rightarrow \nu_e\, \nu_e\ H) \times BR\ (H \rightarrow XX) \sim g_{HWW}^2\, g_{HXX}^2 / \Gamma_H$

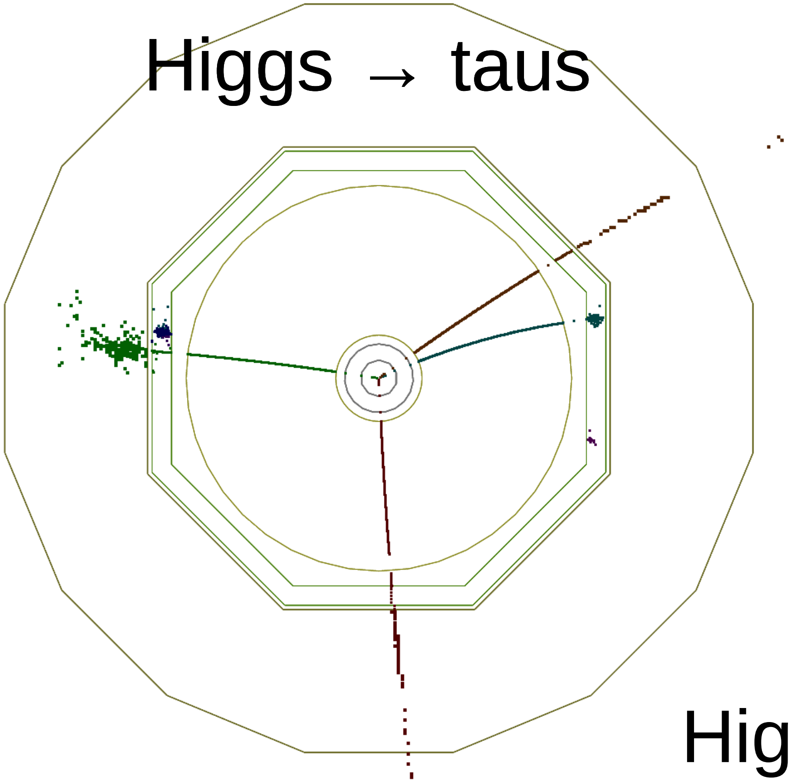


XX = any decay: bb, cc, tau tau, invisible, unexpected, ...

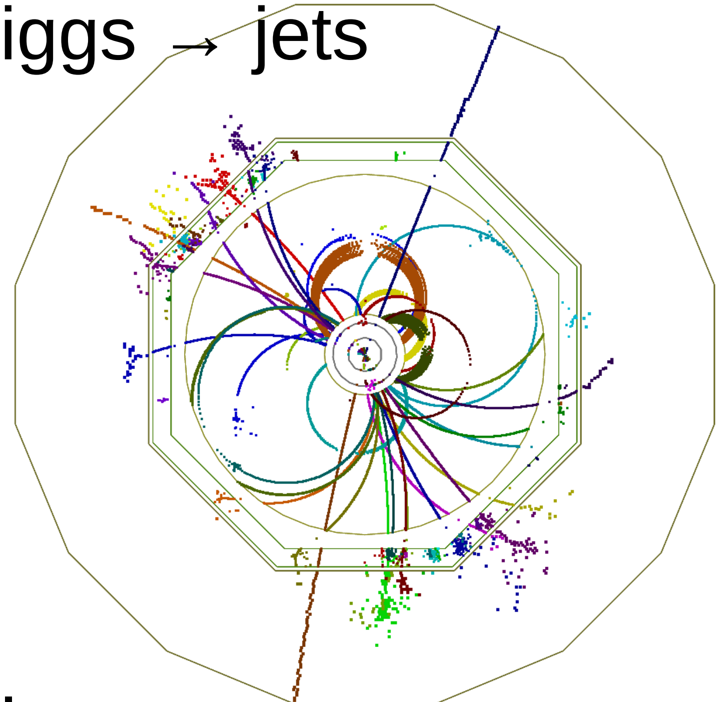
interpret in global SM-EFT fit

→ Higgs coupling constants & total decay width

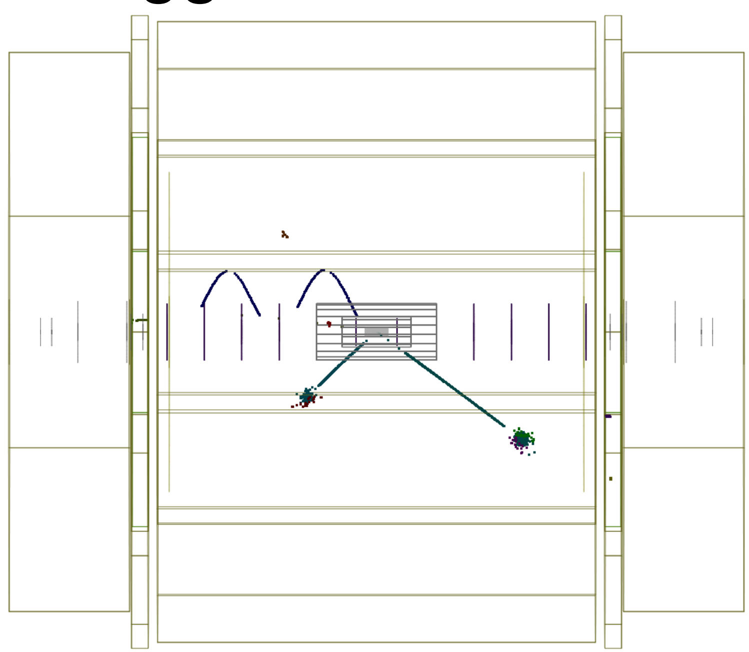
Higgs → taus



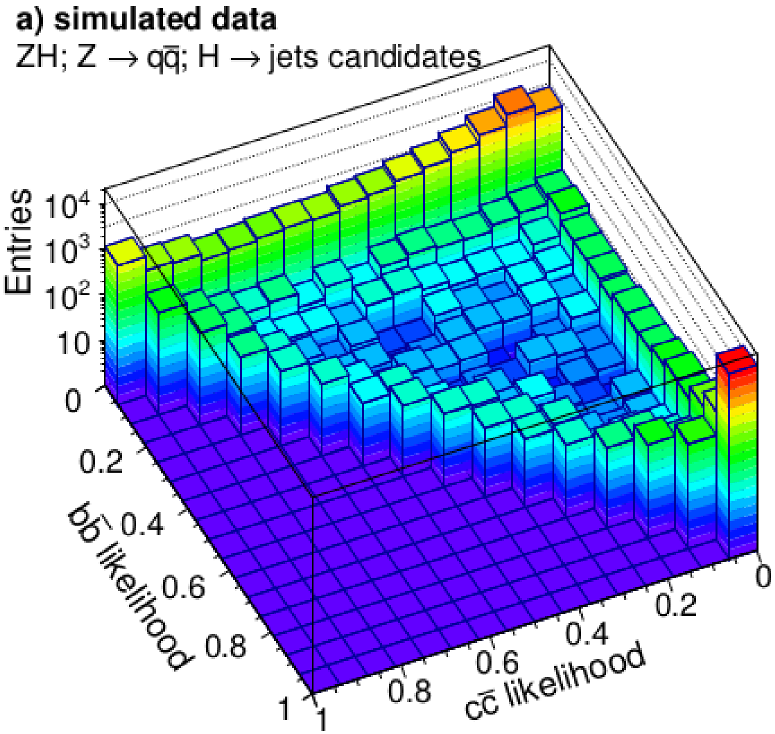
Higgs → jets



Higgs → invisible



quark flavour in hadronic Higgs decays

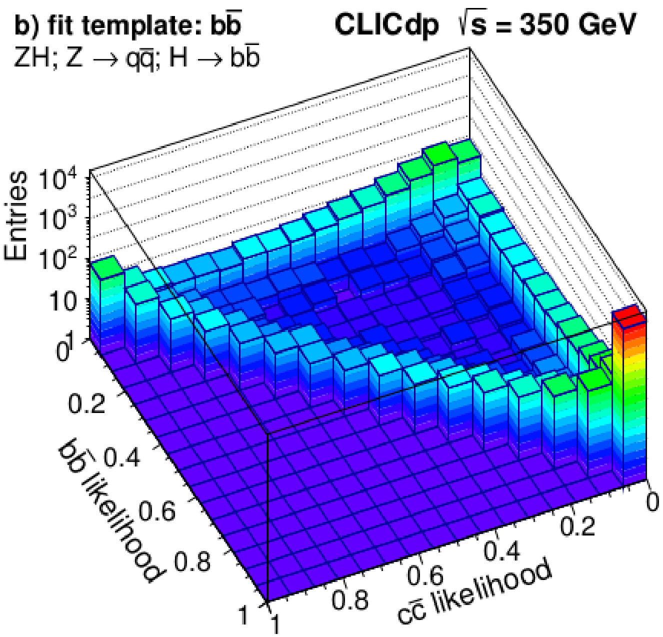


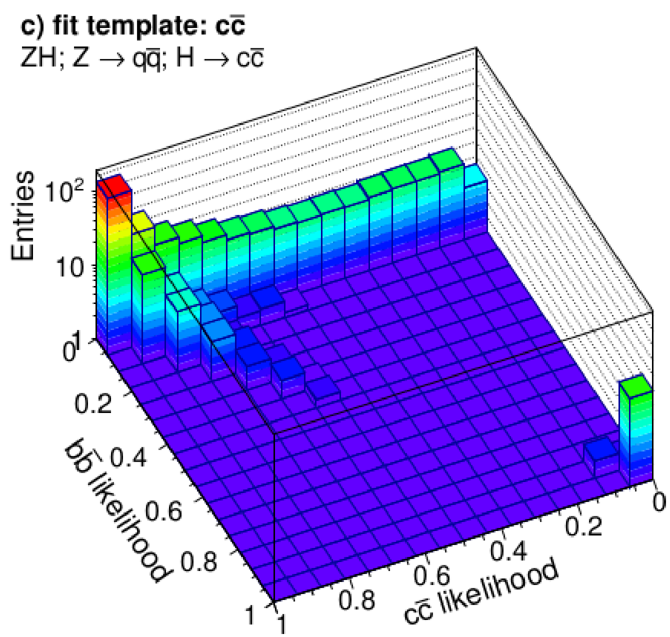
favourable experimental conditions
→ low backgrounds/pileup/underlying event
→ small/tiny beam spot
→ low radiation

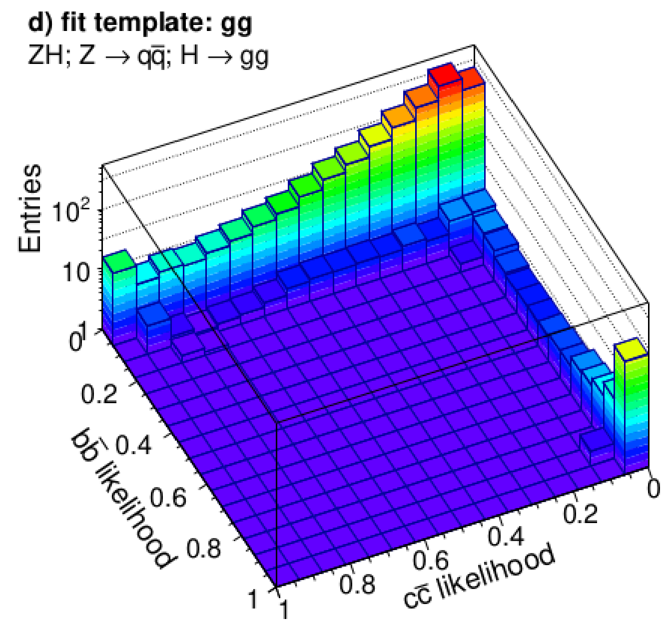
enable detectors & reconstruction
with excellent performance

arXiv:1608.07538

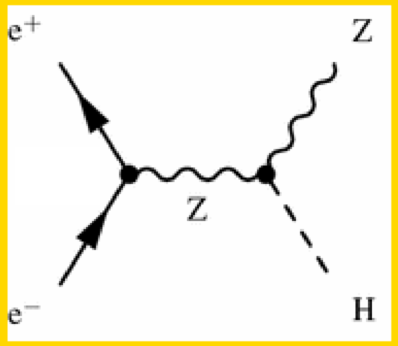
H → bb **H → cc** **H → gg**





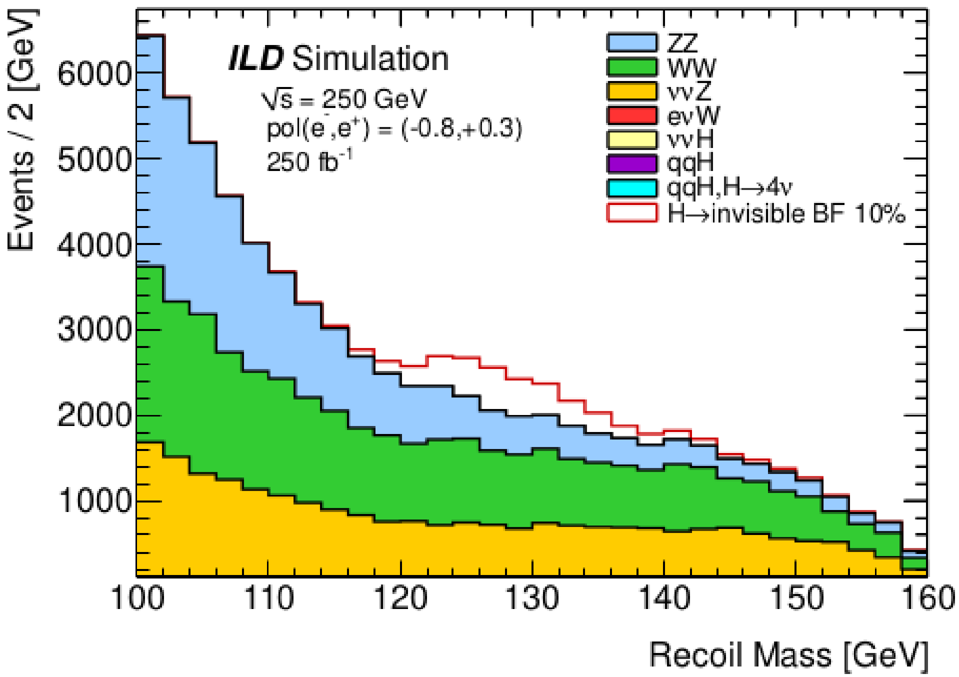


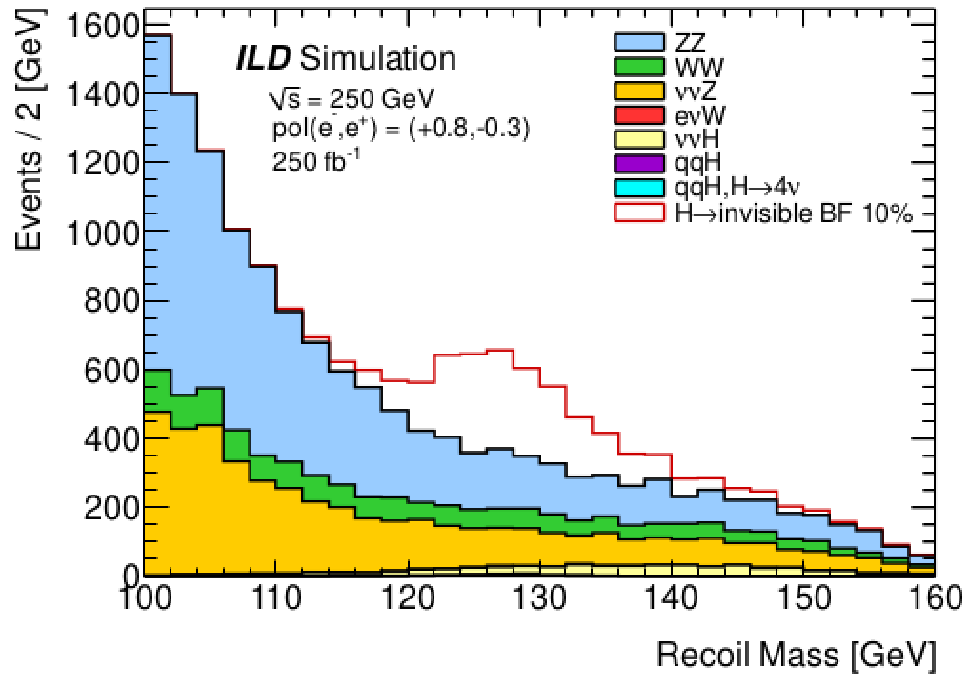
Higgs decay to invisible final states



dark matter particles?

measurements of Higgs-strahlung sensitive to *any* Higgs decay:
[visible/invisible]; [standard/exotic]



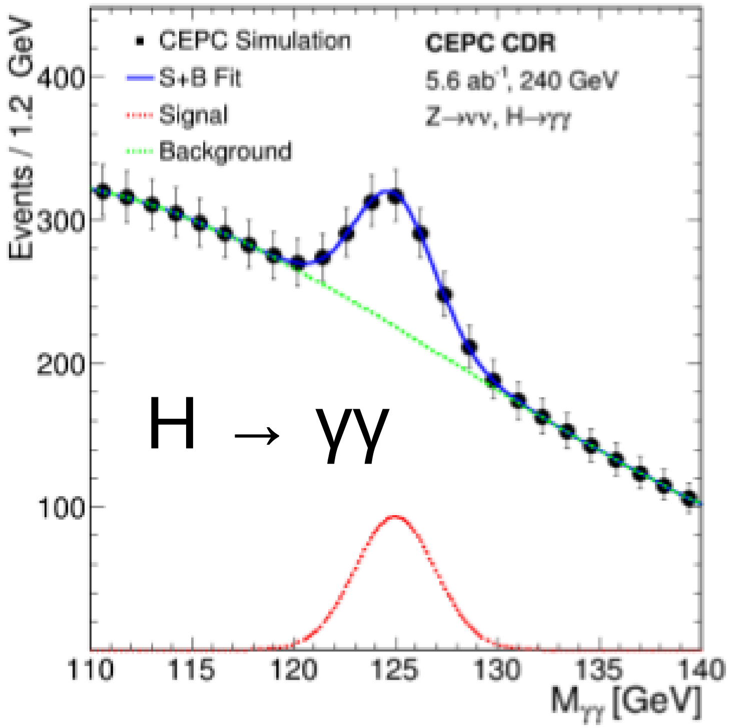


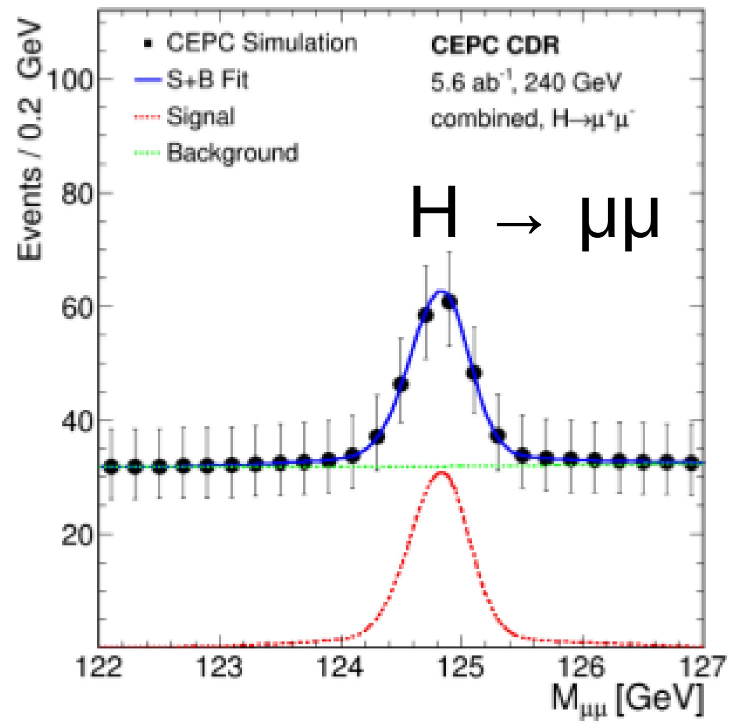
background suppression
by beam polarisation

arXiv:1909.07537

rare Higgs decays

measurement of rare Higgs decays statistically limited



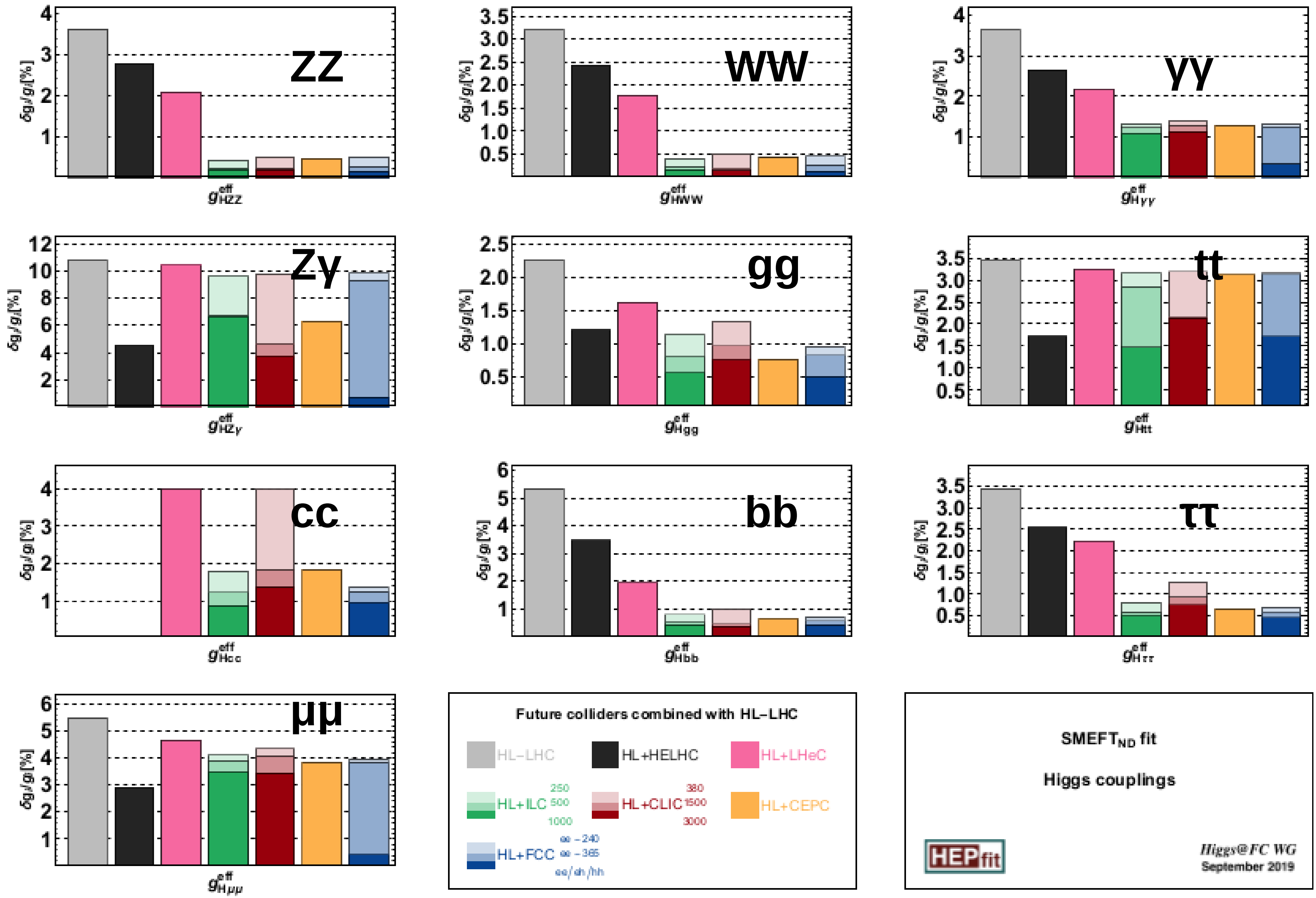


IHEP-CEPC-DR-2018-02

complementarity between LHC and LC,
precise (HL-)LHC measurement of *e.g.* BR (H → μμ) / BR (H → ZZ)
combined with a LC's g_{HZZ} measurement

projected coupling precisions in SM-EFT fit

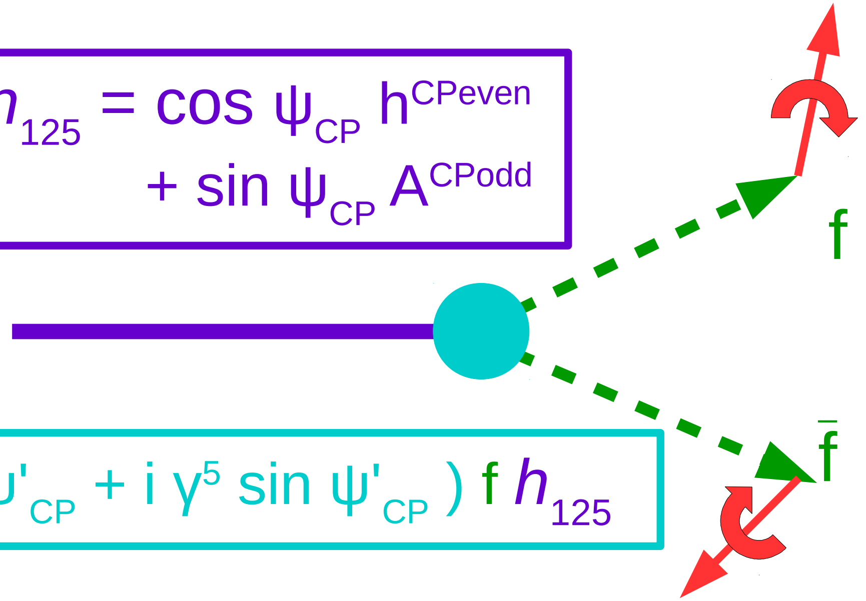
CERN-ESU-004



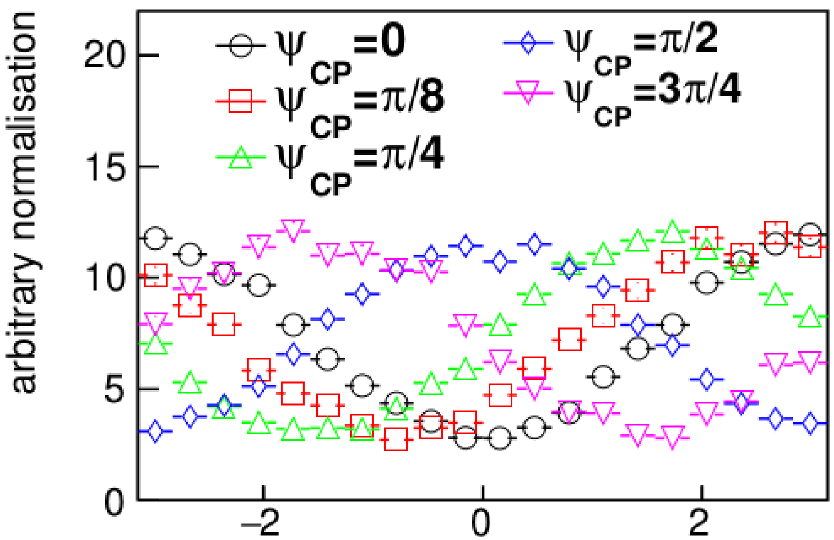
CP violation in Higgs sector

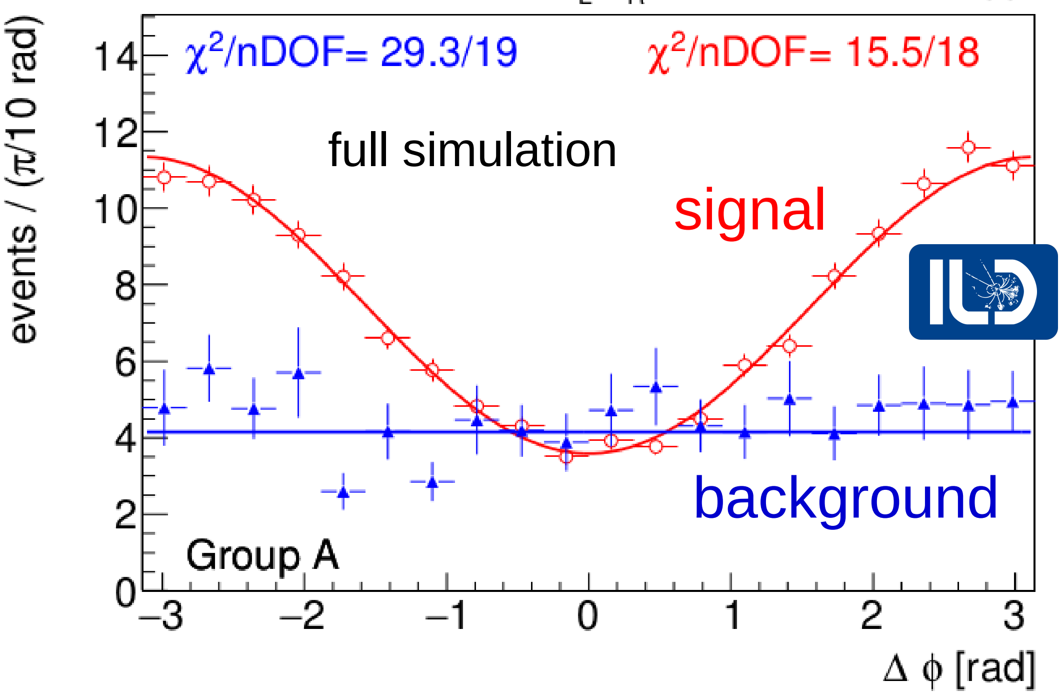
spin correlations between
tau leptons from Higgs decay

$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$



$g\,\bar{f}\,(\cos\psi'_{CP} + i\,\gamma^5 \sin\psi'_{CP})\, f\, h_{125}$





arXiv:1804.01241

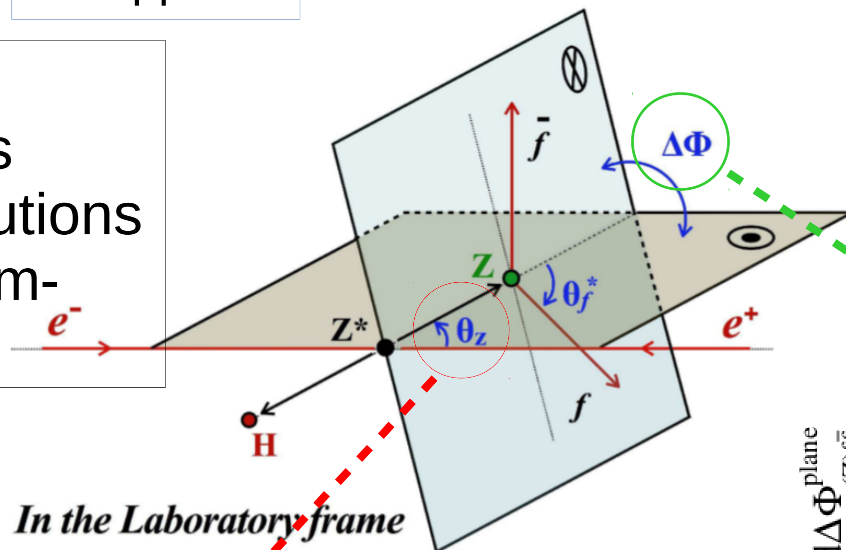
at ILC250, measure ψ_{CP} to ~4°

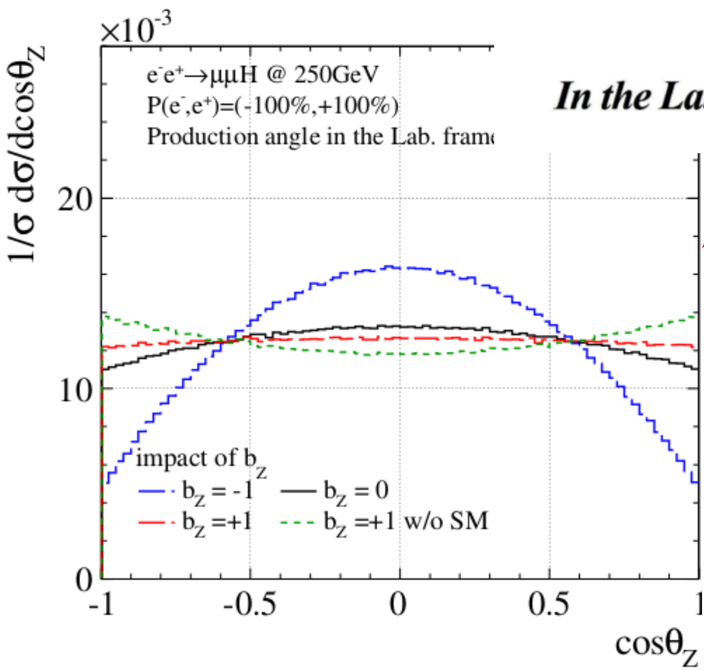
CP violation in Higgs sector : HVV coupling

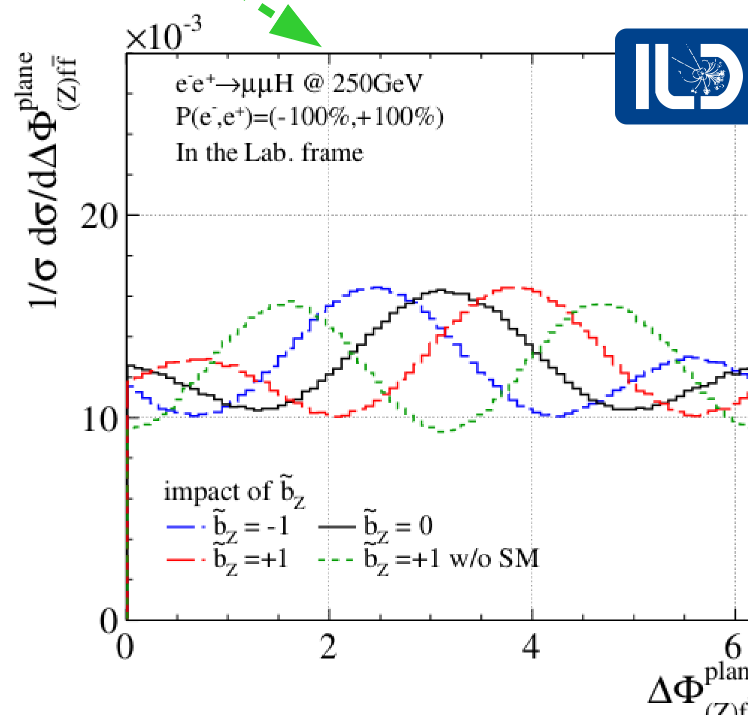
$$\mathscr{L}_{ZZH} = M_Z^2\underbrace{\left(\frac{1}{v}+\frac{a_Z}{\Lambda}\right)}_{\text{“kappa”}}Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu}H$$

[%/TeV]–level sensitivity on a_Z/Λ, b_Z/Λ, $\tilde{b}_Z/\Lambda$

combination of e.g. 250+500 GeV helps disentangle contributions thanks to momentum-dependence



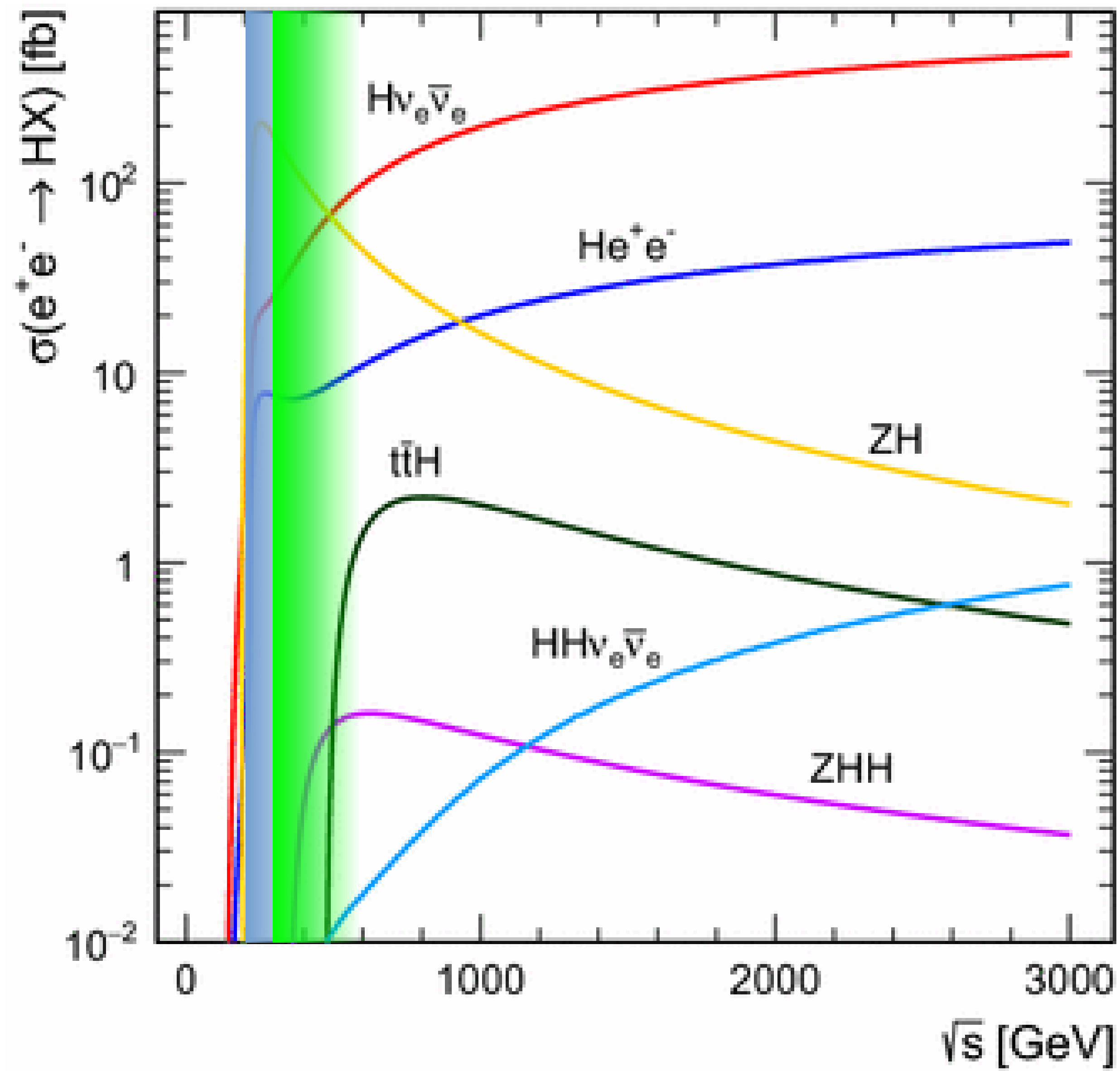




can, and must, dig much deeper than “kappa”

arXiv:1712.09772

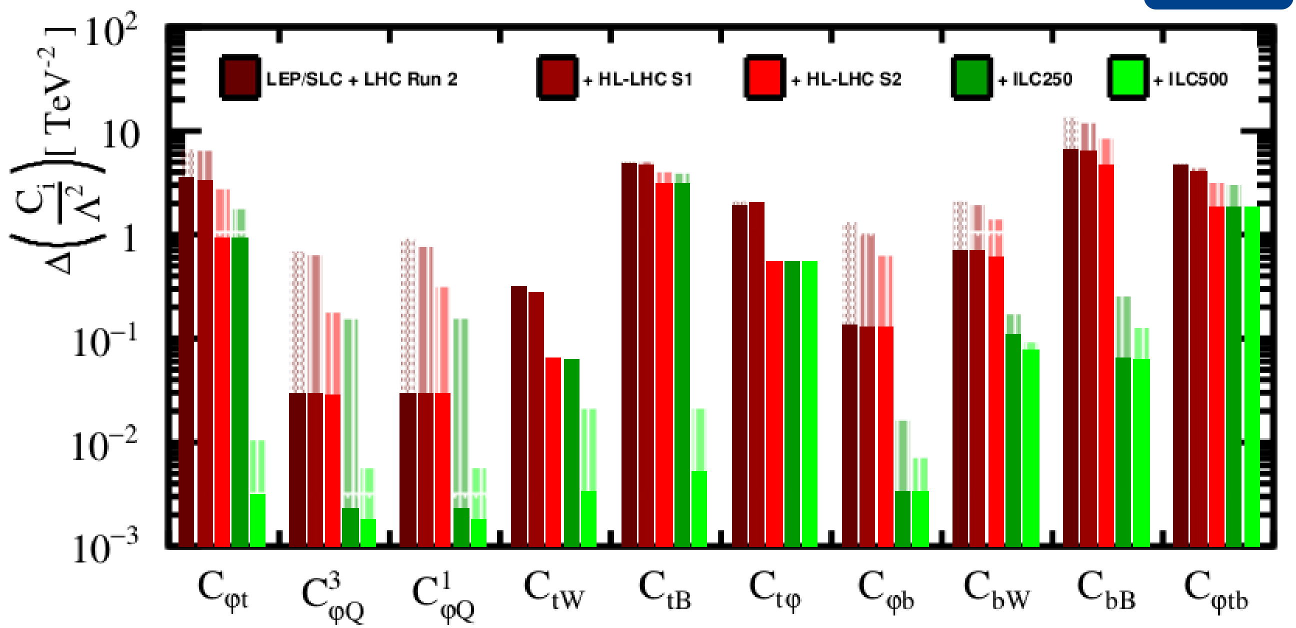
√s ~ 350+ GeV



$\sigma(e^+e^- \to HX)$ [fb]
10^2
10
1
10^{-1}
10^{-2}
0
1000
2000
3000
√s [GeV]
$H\nu_e\bar{\nu}_e$
He^+e^-
ZH
$t\bar{t}H$
$HH\nu_e\bar{\nu}_e$
ZHH

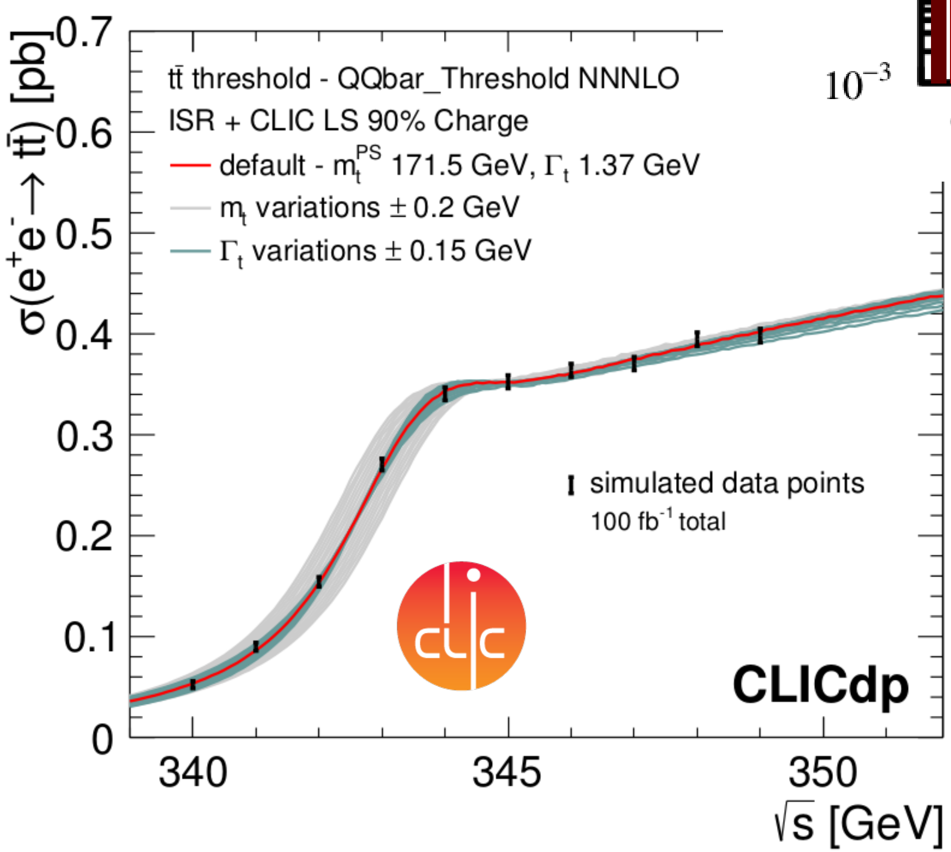
Higgs is not alone, and is in a close relationship with top

top electroweak couplings

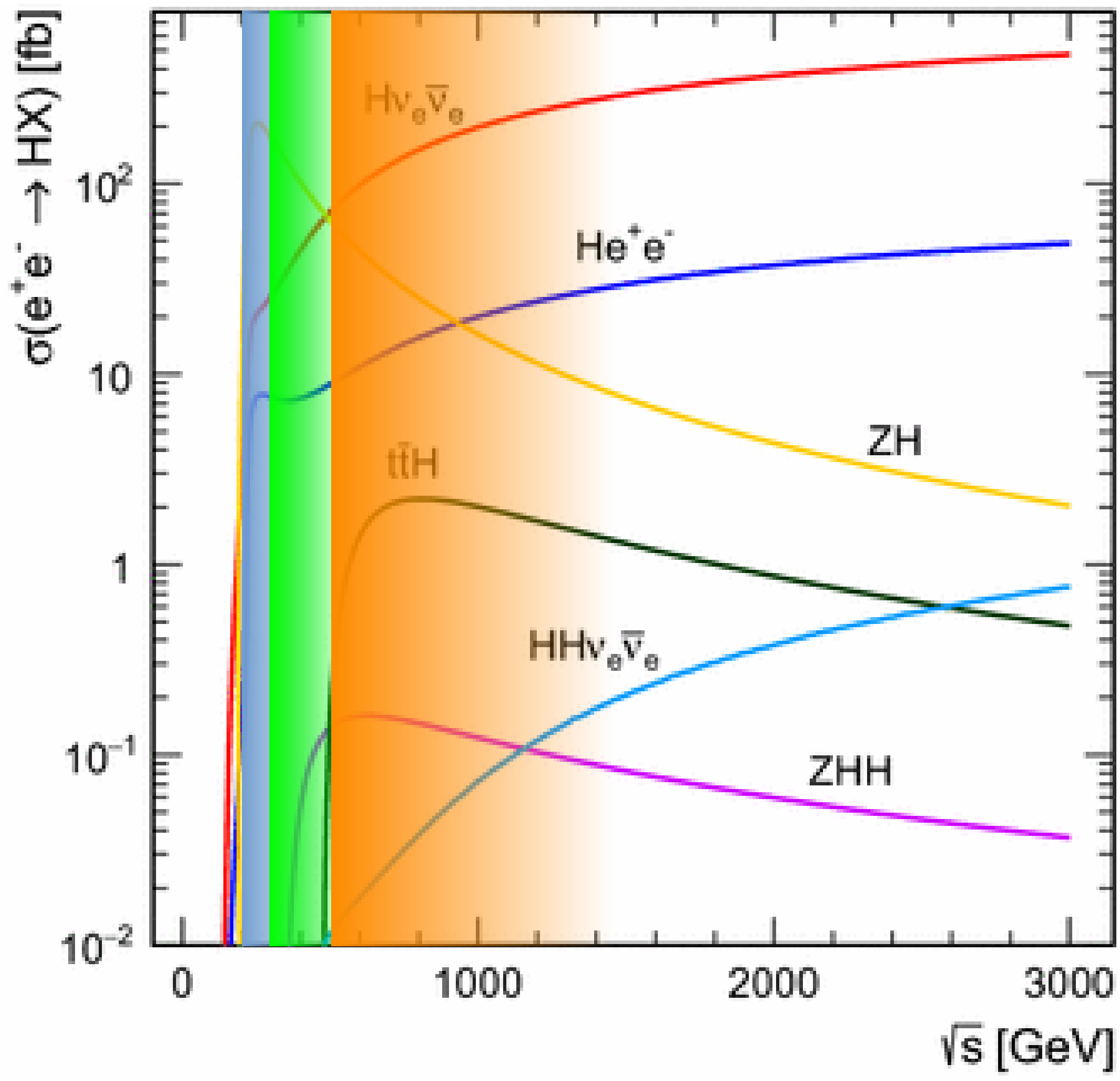


arXiv:1907.10619

top mass & width



√s ~ 500+ GeV



$\sigma(e^+e^- \to HX)$ [fb]
10^2
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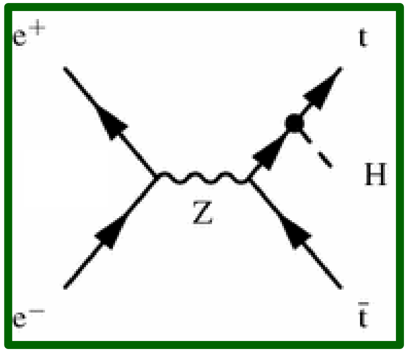
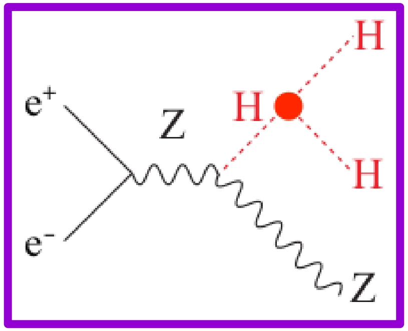
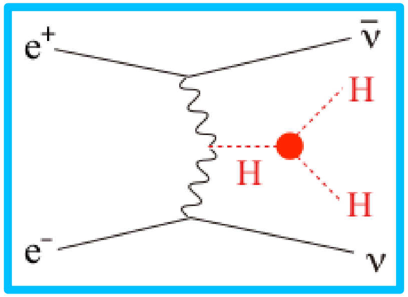
√s [GeV]
$H\nu_e\bar{\nu}_e$
He^+e^-
ZH
$t\bar{t}H$
$HH\nu_e\bar{\nu}_e$
ZHH

500/550 GeV opens direct access to



top Yukawa coupling



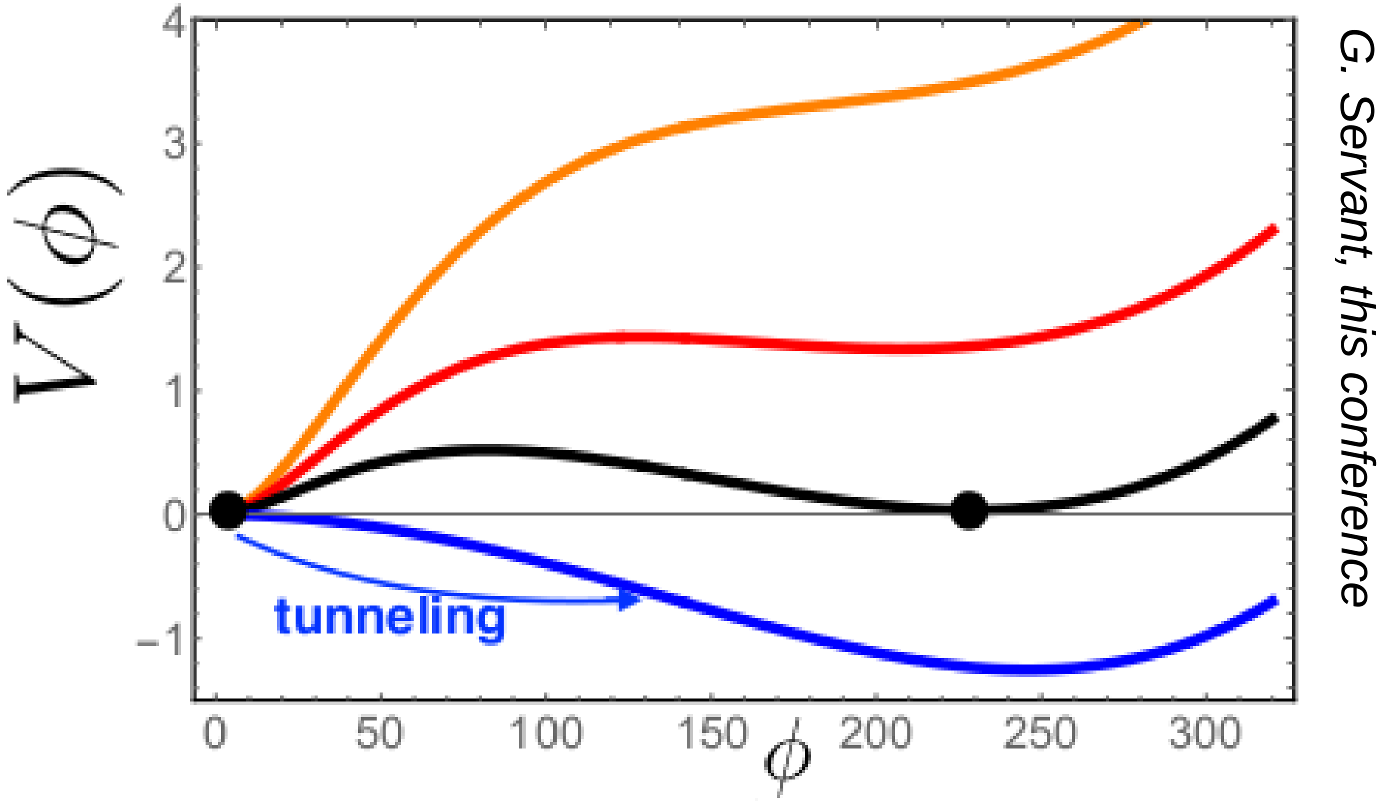


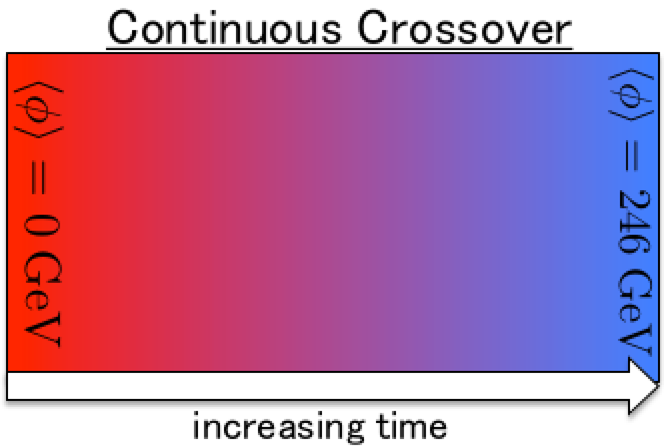
Higgs self-interaction

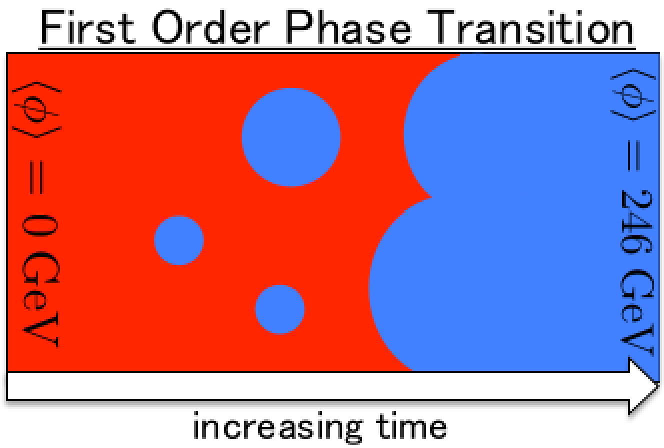
→ shape of Higgs potential

→ EW phase transition

higgs self-coupling



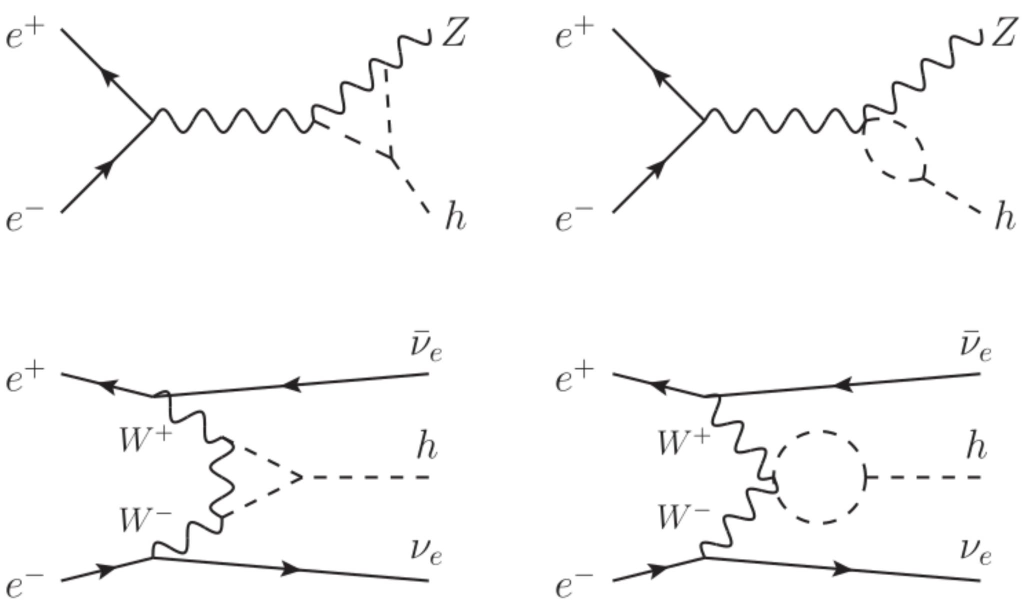


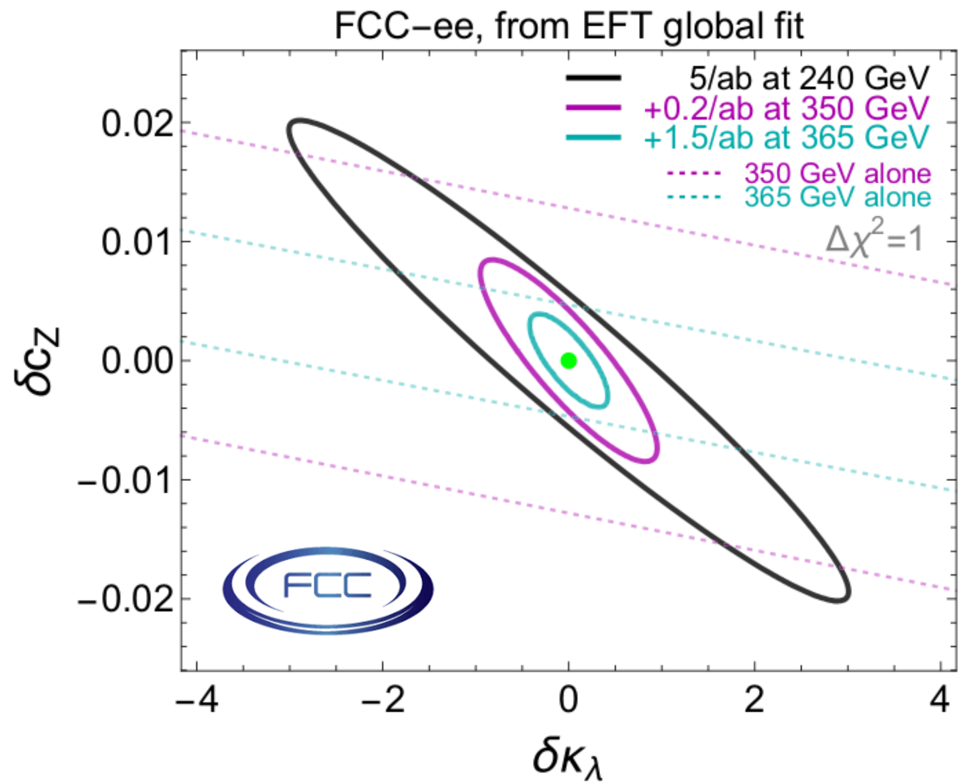


higgs self-coupling

indirect : loop corrections modify Higgs production x-sec, in an energy dependent way

cross-section measurements at well-spaced energy points provides some sensitivity to the self-coupling

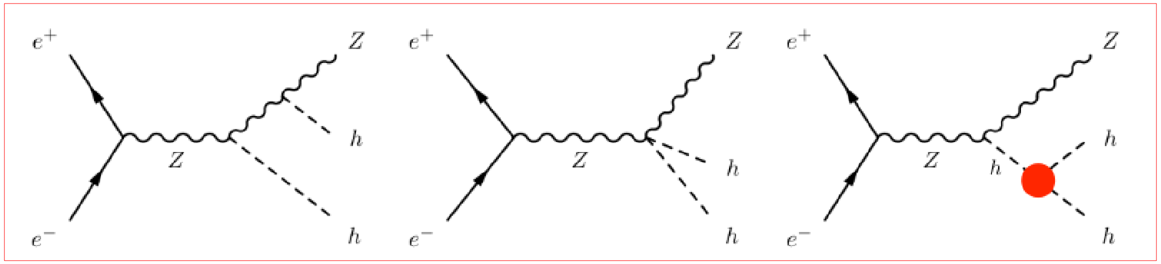


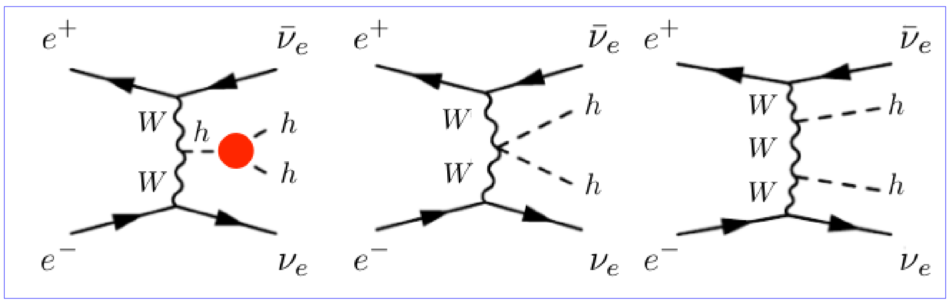


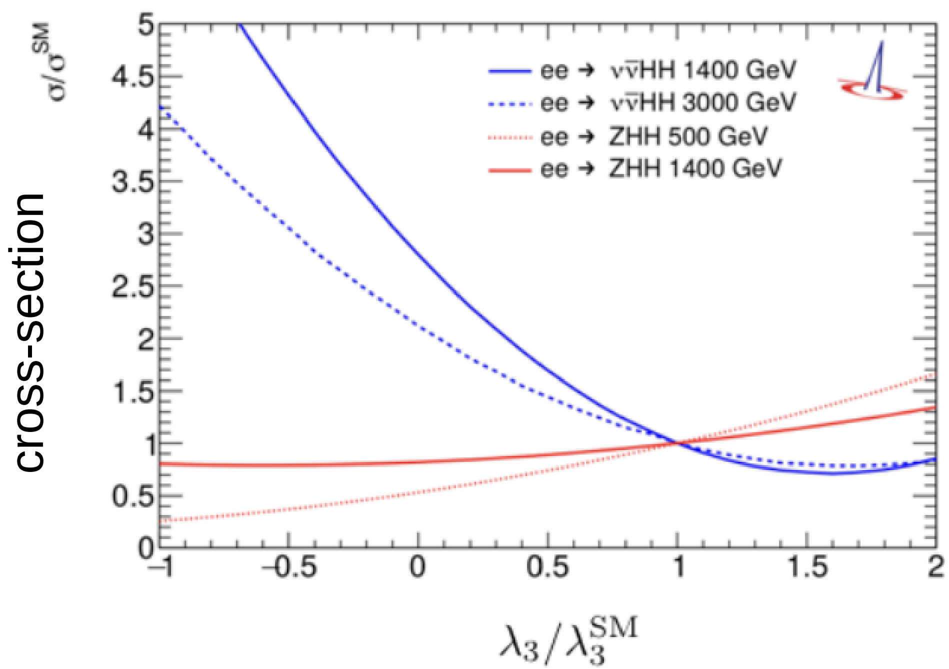
Eur. Phys. J. Special Topics 228, 261 (2019)

higgs boson self-coupling

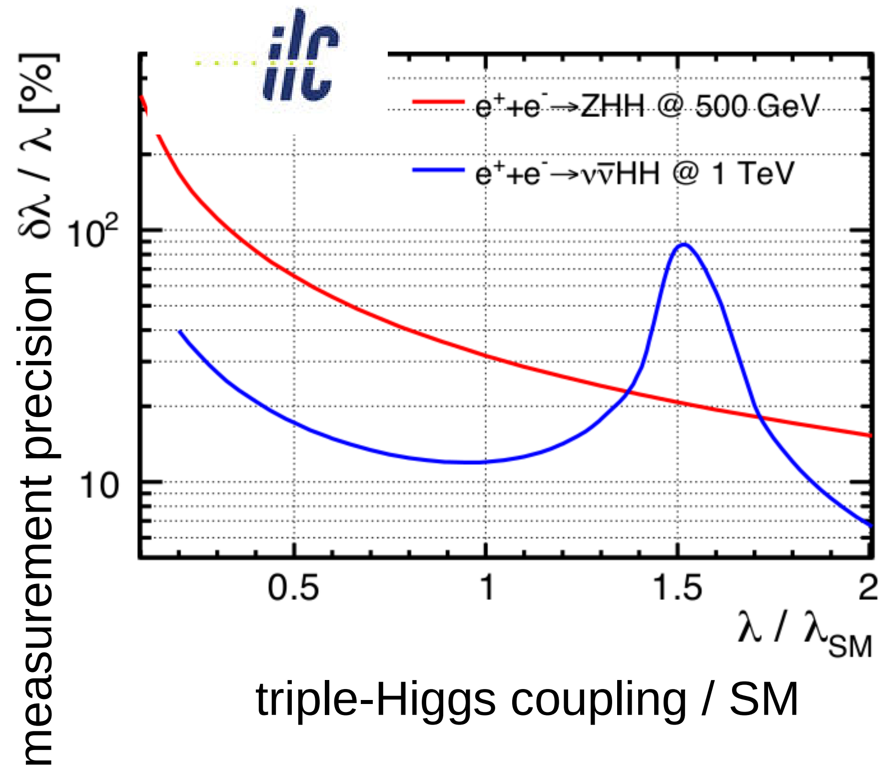
at energies > 500 GeV, *direct* access to di-Higgs production



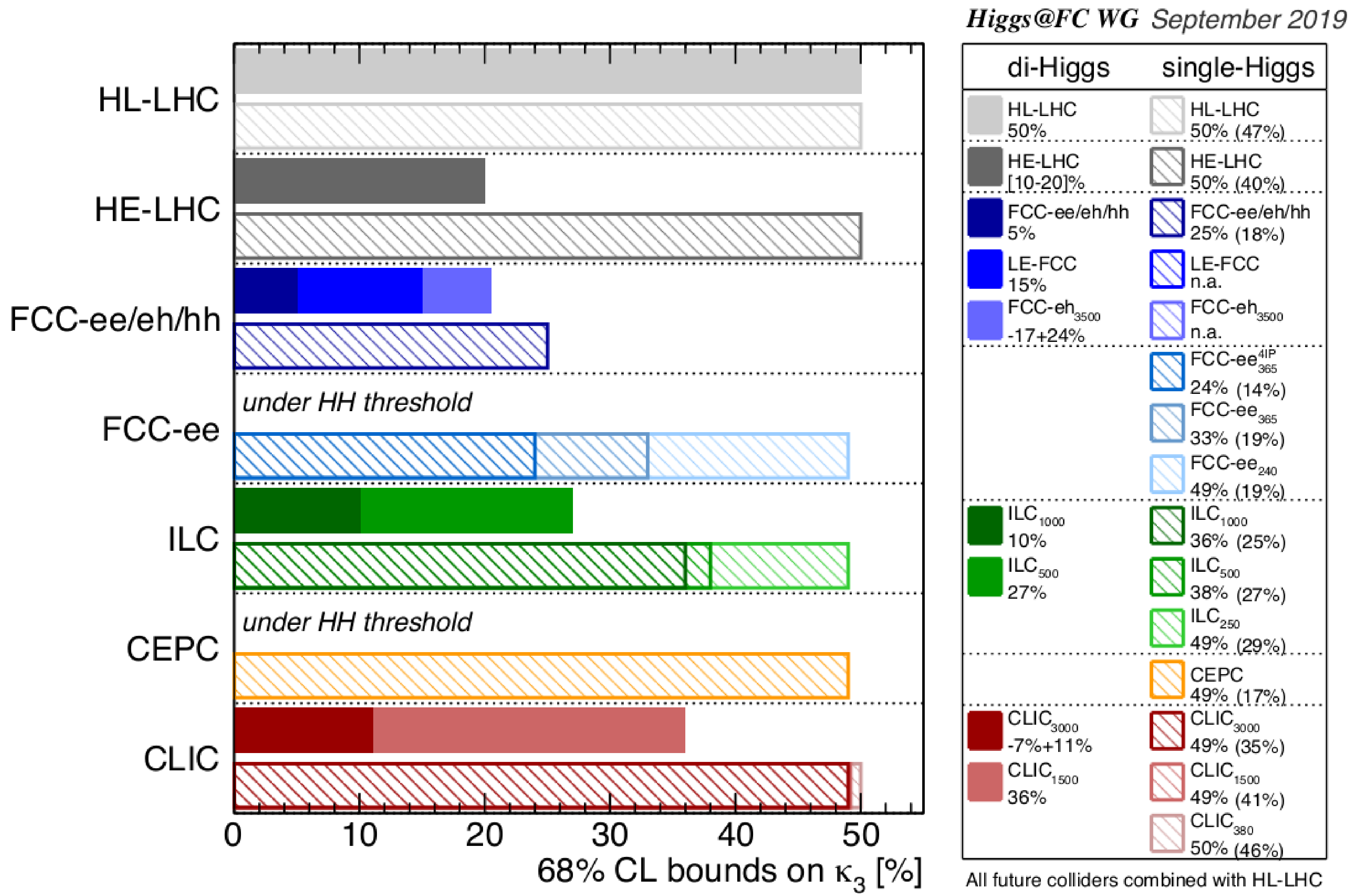




triple-Higgs coupling / SM



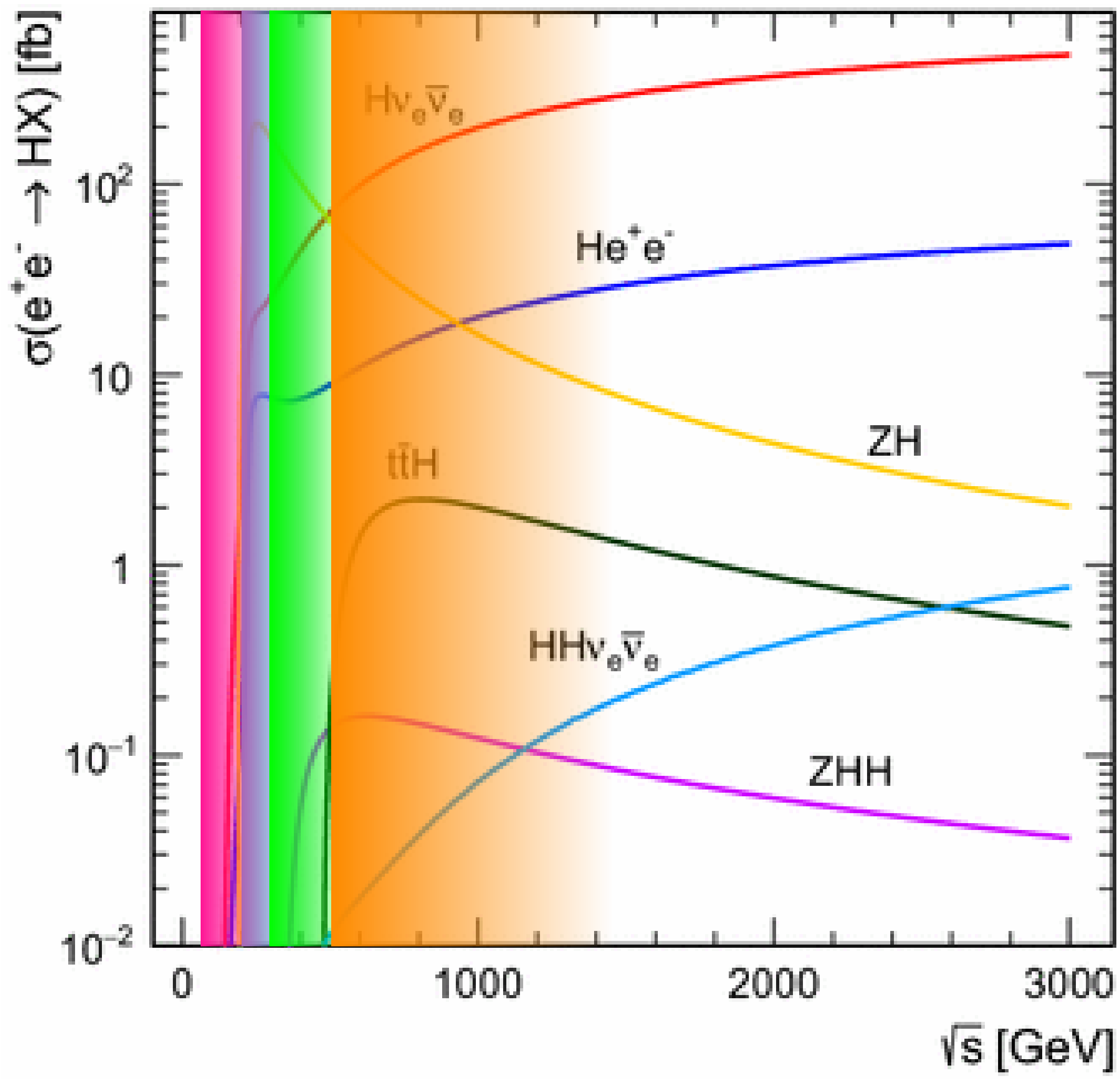
triple-Higgs coupling / SM



indirect approach : ~20~50 %
direct approach : ~10~35 %

→ test for consistency of approaches

√s ~ 91, 161+ GeV



$\sigma(e^+e^- \to HX)$ [fb]
10^2
10
1
10^{-1}
10^{-2}
0
1000
2000
3000
√s [GeV]
$H\nu_e\bar{\nu}_e$
He^+e^-
ZH
$t\bar{t}H$
$HH\nu_e\bar{\nu}_e$
ZHH

Higgs mechanism intertwined with entire EW sector

improved measurements of W, Z, t are an essential ingredients to more precisely constrain EWSB & Higgs

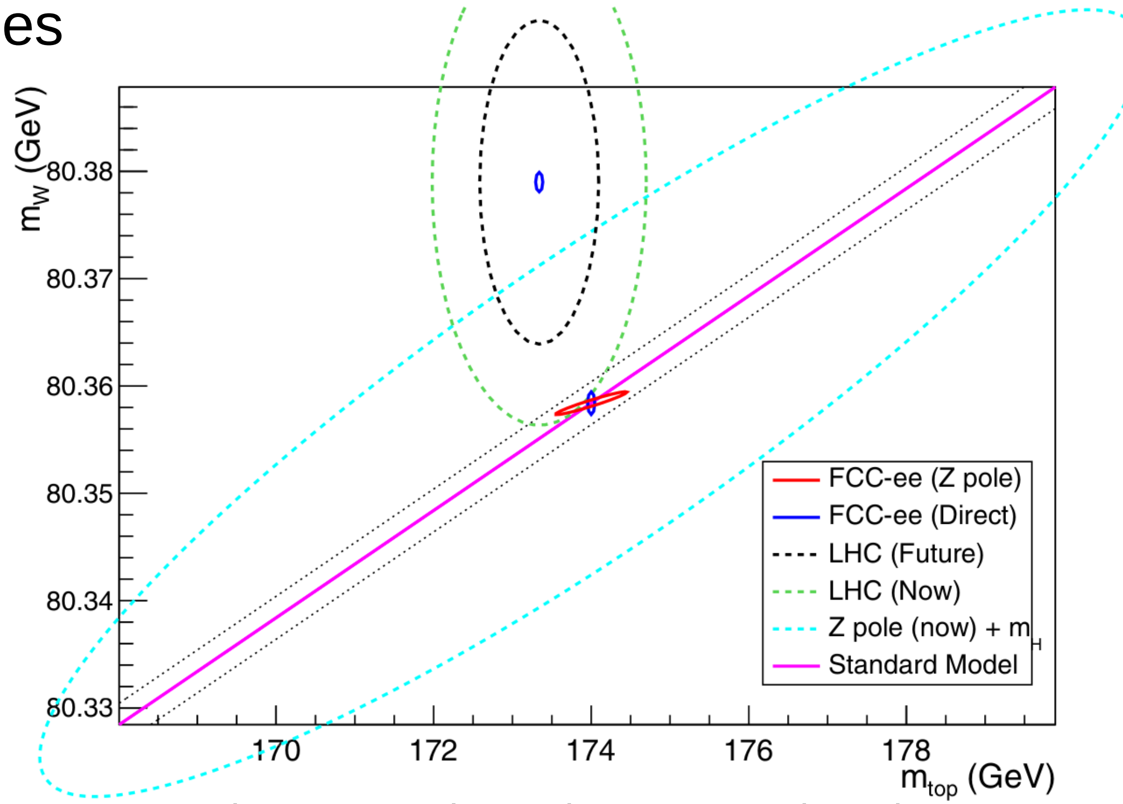
Z
→ on-resonance @ 91 GeV
→ radiative returns at higher energies

W
→ pair production @ 161+ GeV

top quark
→ pair production @ 350+ GeV

luminosities many *orders of magnitude* beyond LEP, SLC

+ significantly longer energy lever arm



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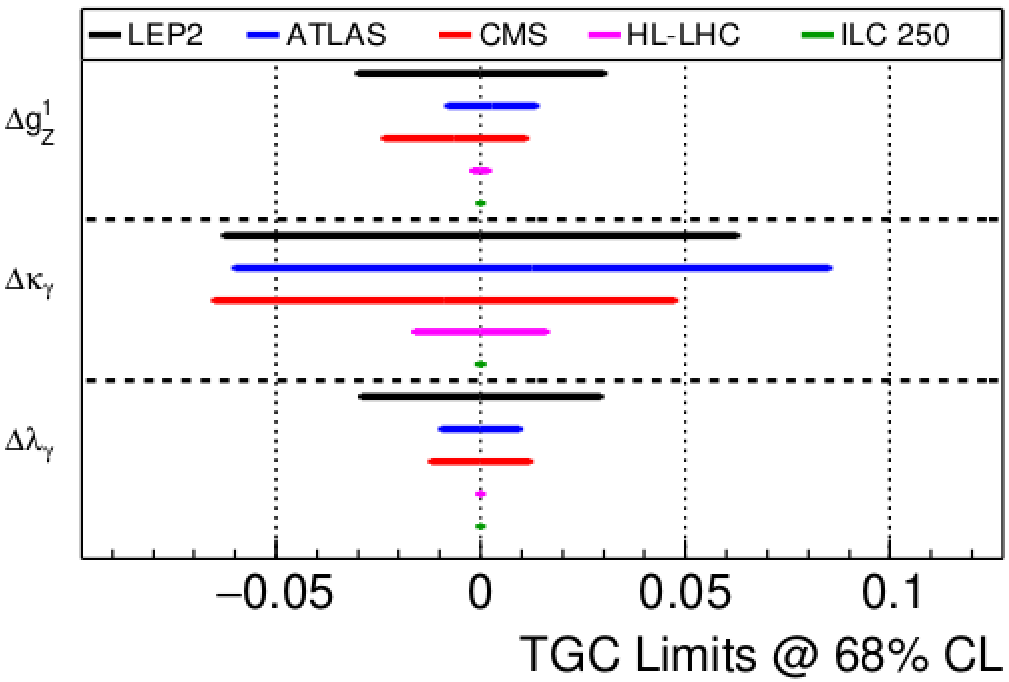
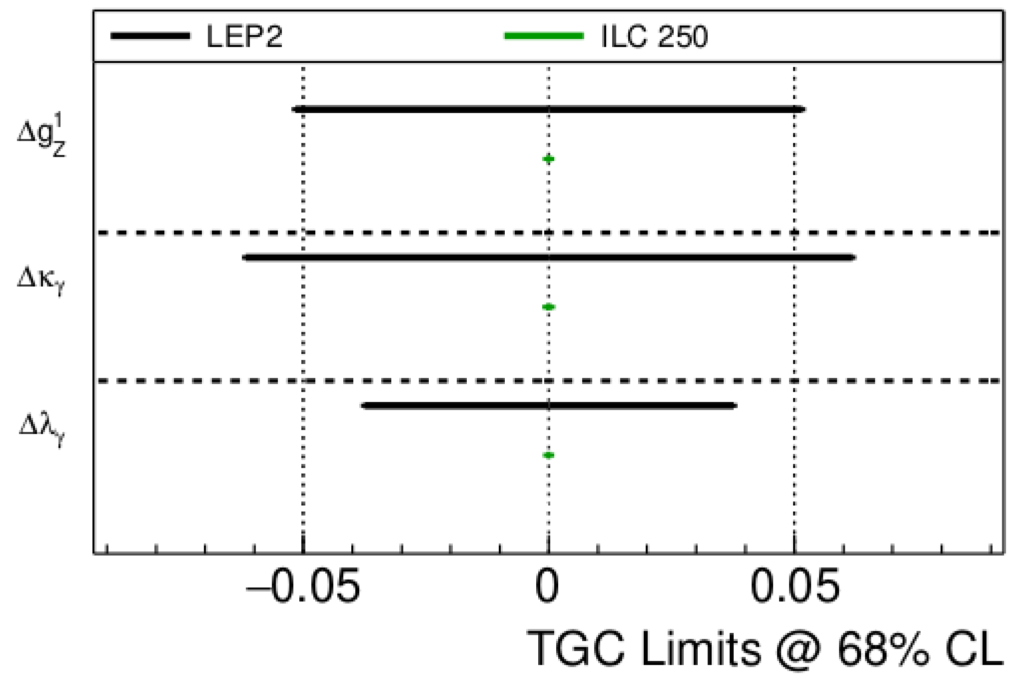
Anomalous triple-gauge couplings

single parameter



simultaneous fit

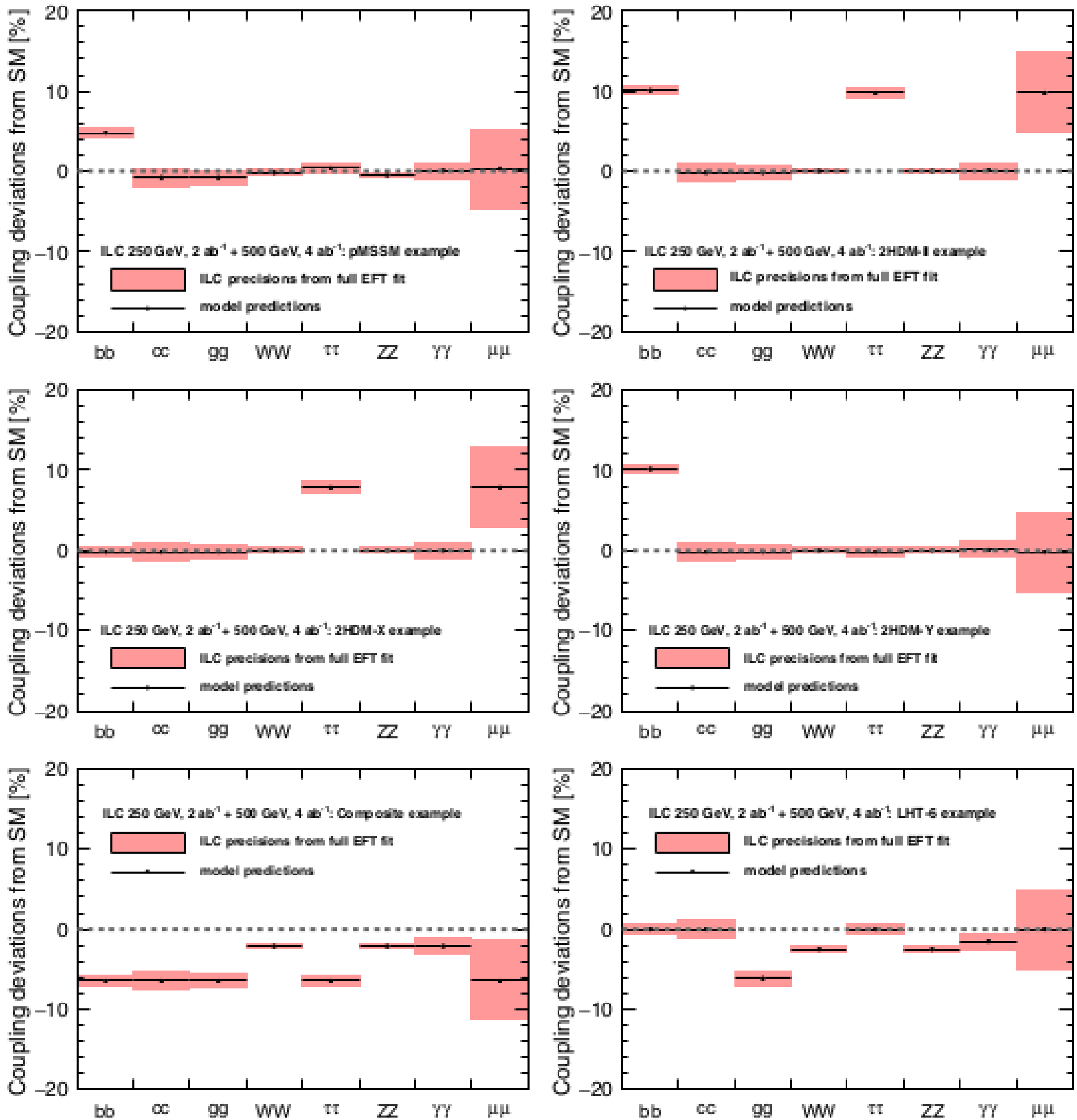


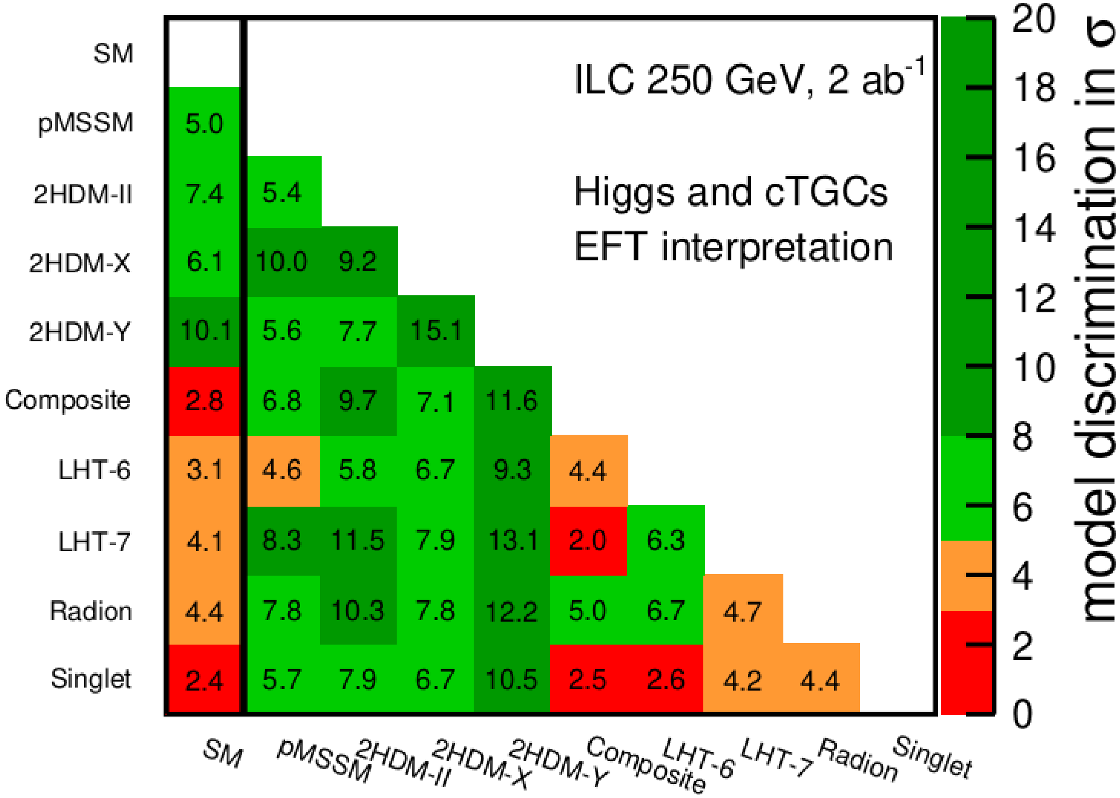
arXiv:1710.07621

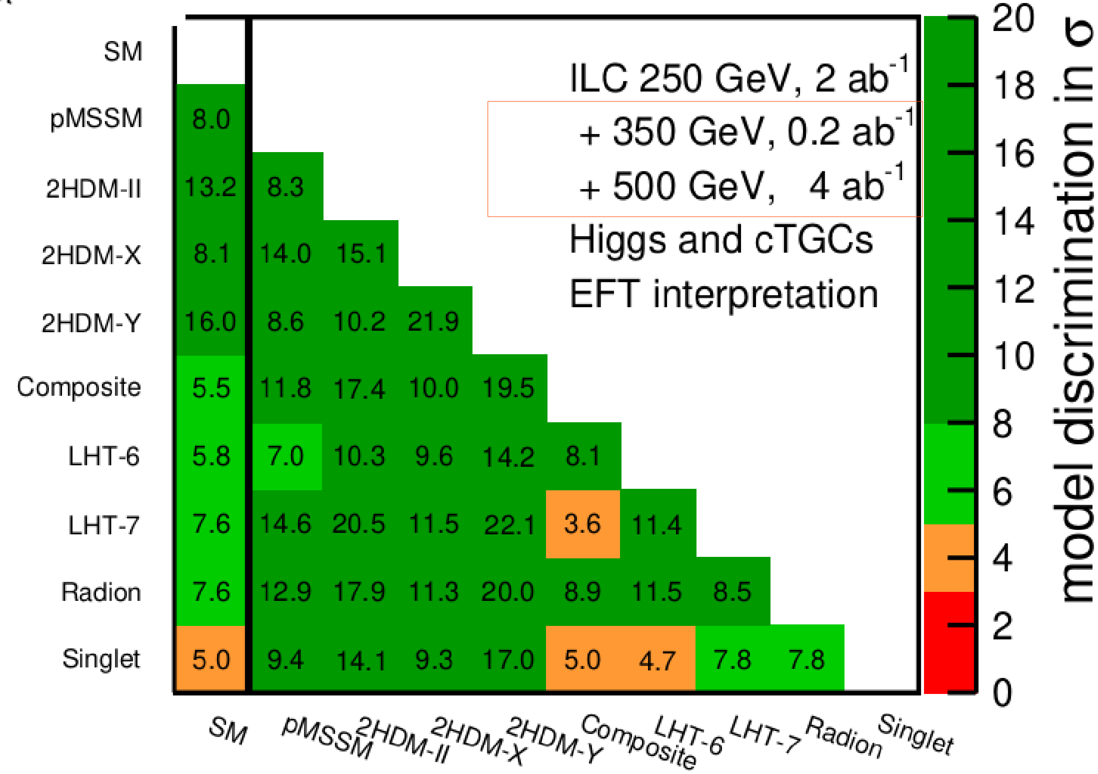
precision EW measurements needed to fully interpret our measurements of Higgs

Summary

arXiv:1708.08912




ILC 250 GeV, 2 ab-1
Higgs and cTGCs
EFT interpretation
model discrimination in σ
20 18 16 14 12 10 8 6 4 2 0
SM
pMSSM 5.0
2HDM-II 7.4 5.4
2HDM-X 6.1 10.0 9.2
2HDM-Y 10.1 5.6 7.7 15.1
Composite 2.8 6.8 9.7 7.1 11.6
LHT-6 3.1 4.6 5.8 6.7 9.3 4.4
LHT-7 4.1 8.3 11.5 7.9 13.1 2.0 6.3
Radion 4.4 7.8 10.3 7.8 12.2 5.0 6.7 4.7
Singlet 2.4 5.7 7.9 6.7 10.5 2.5 2.6 4.2 4.4
SM pMSSM 2HDM-II 2HDM-X 2HDM-Y Composite LHT-6 LHT-7 Radion Singlet


ILC 250 GeV, 2 ab-1
+ 350 GeV, 0.2 ab-1
+ 500 GeV, 4 ab-1
Higgs and cTGCs
EFT interpretation
model discrimination in σ
20 18 16 14 12 10 8 6 4 2 0
SM
pMSSM 8.0
2HDM-II 13.2 8.3
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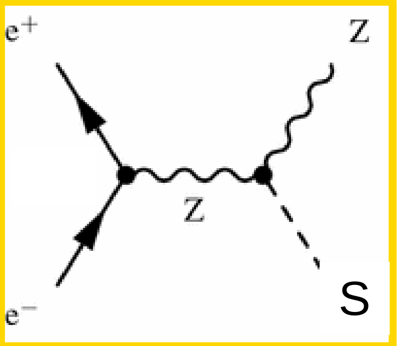
SM pMSSM 2HDM-II 2HDM-X 2HDM-Y Composite LHT-6 LHT-7 Radion Singlet

A future electron – positron Higgs-factory will
precisely map the Higgs sector, in concert with the HL-LHC,
over the next ~30 years

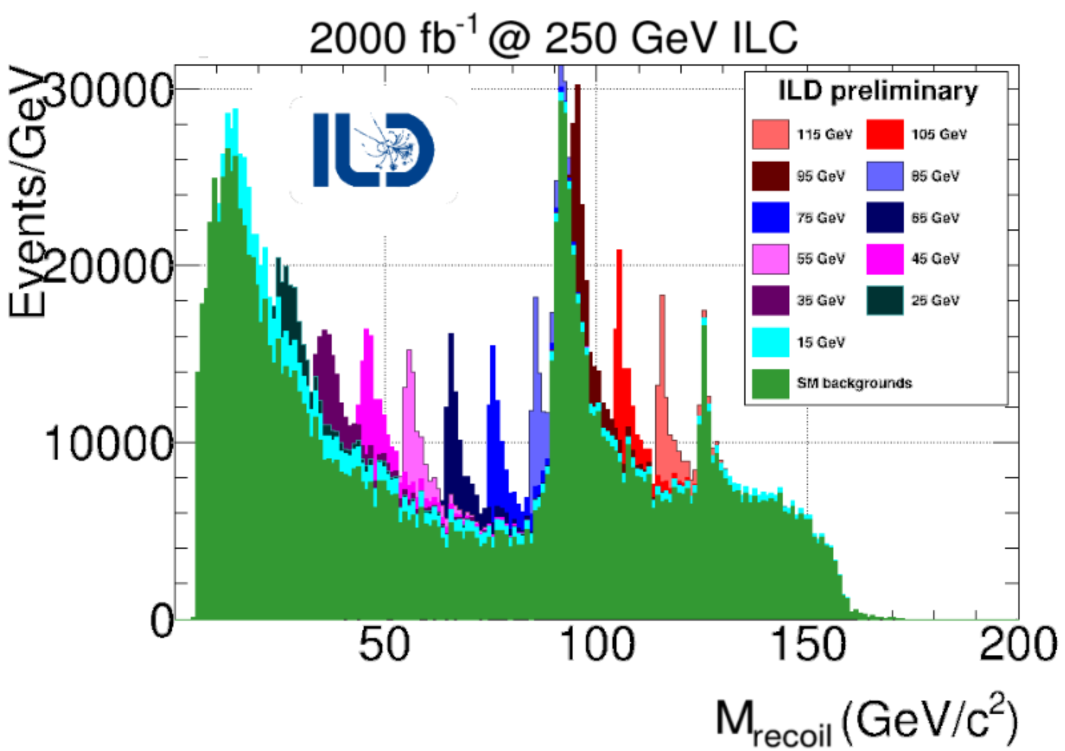
Several contrasting proposals on the table,
using different technologies,
which have rather similar power to probe the Higgs

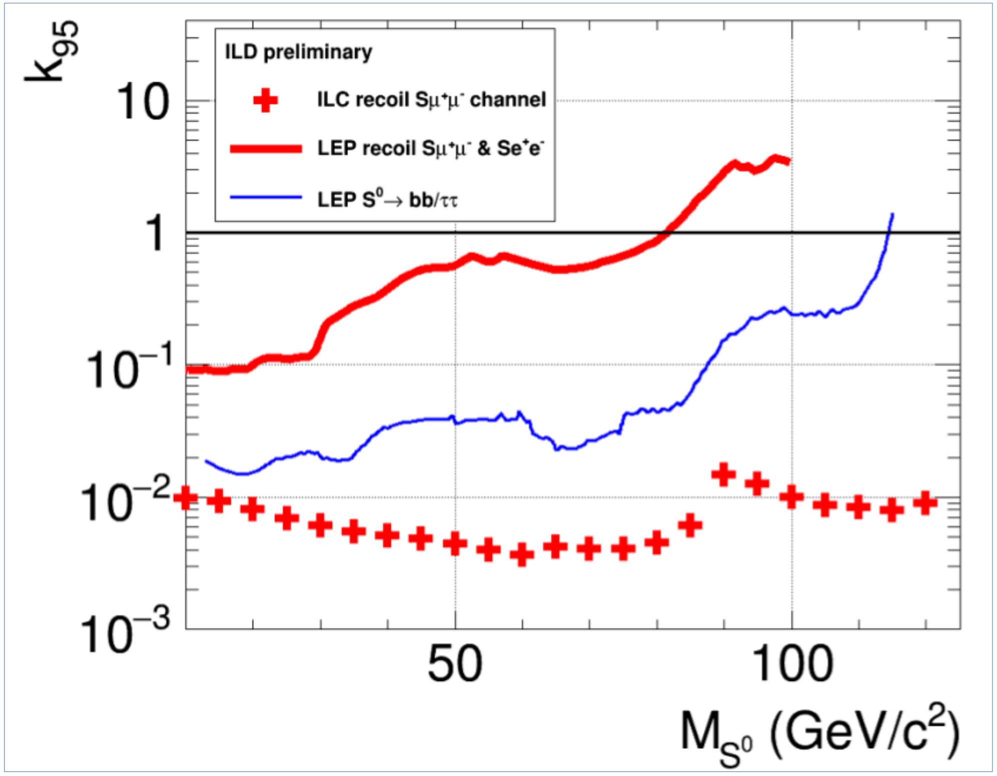
The “Higgs print” will point the way to physics beyond the SM

additional light scalars



search for additional light scalars,
produced via Higgs-strahlung





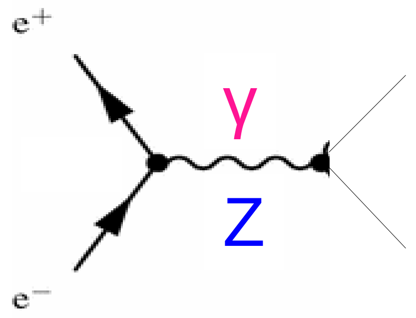
PoS(ICHEP2018)630

beam polarisation

longitudinal beam polarisation, possible at linear H factories, offers an additional measurement dimension

→ disentangle Z and γ contributions

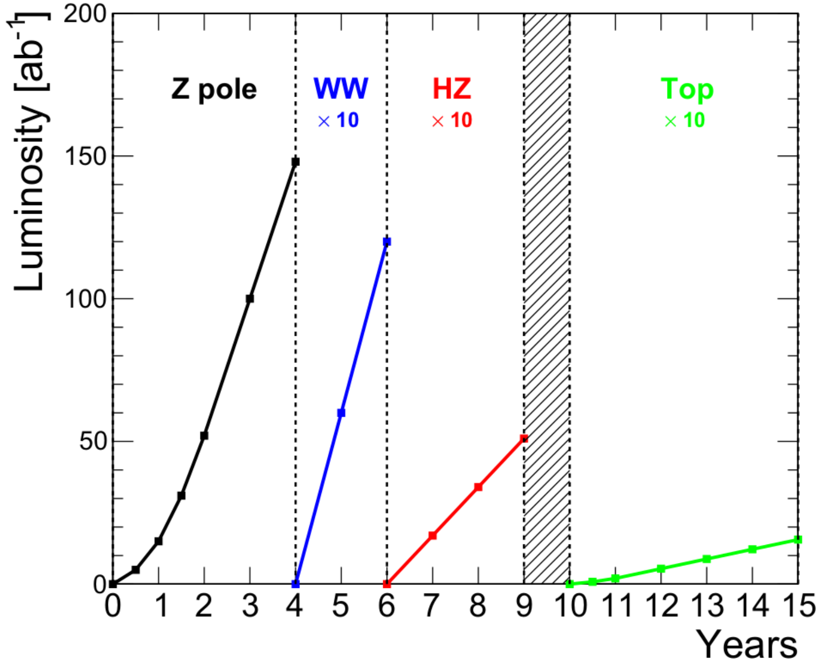
e.g. HZZ *vs.* HZγ couplings
2-fermion: left-right asymmetries of Z



→ enhance or suppress subsets of diagrams

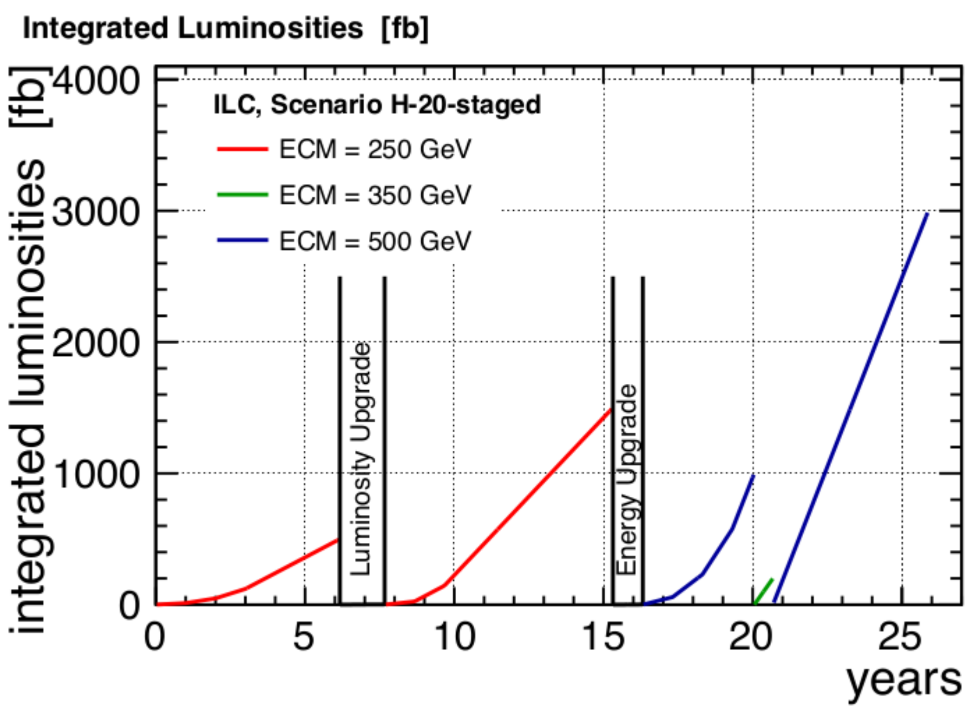
→ combining different polarisations:
doubles the number of independent measurements

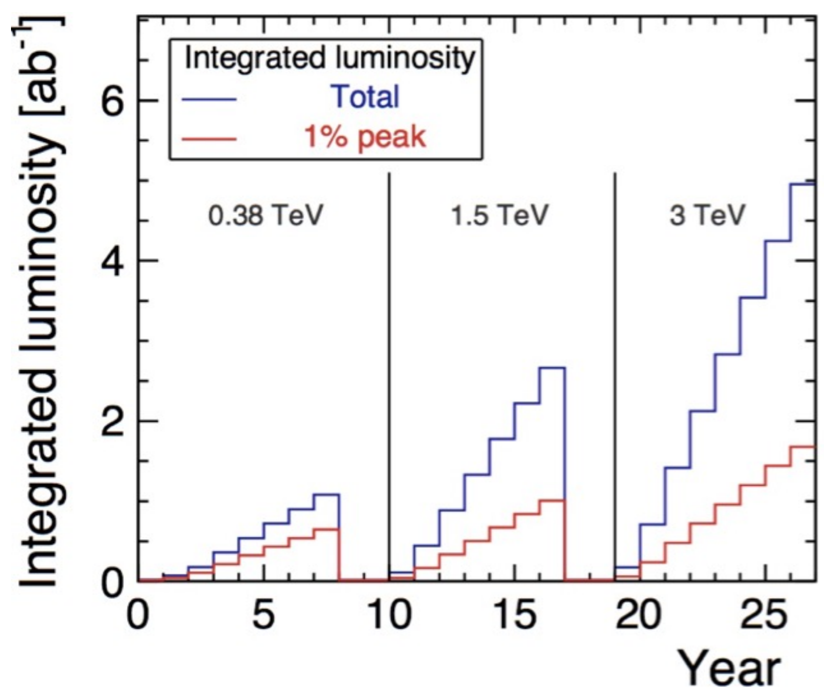
+ probe chiral nature of any new particles, interactions

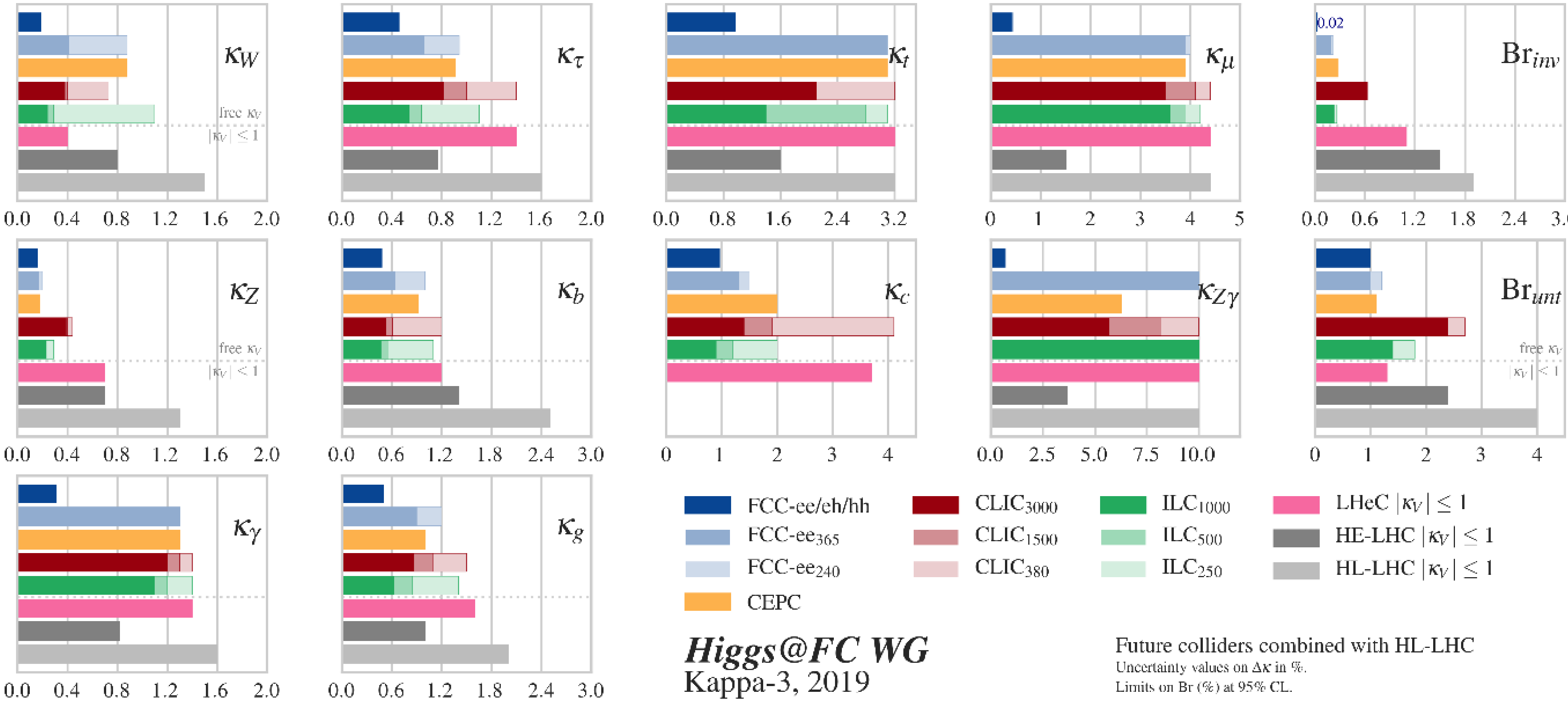


staged operation

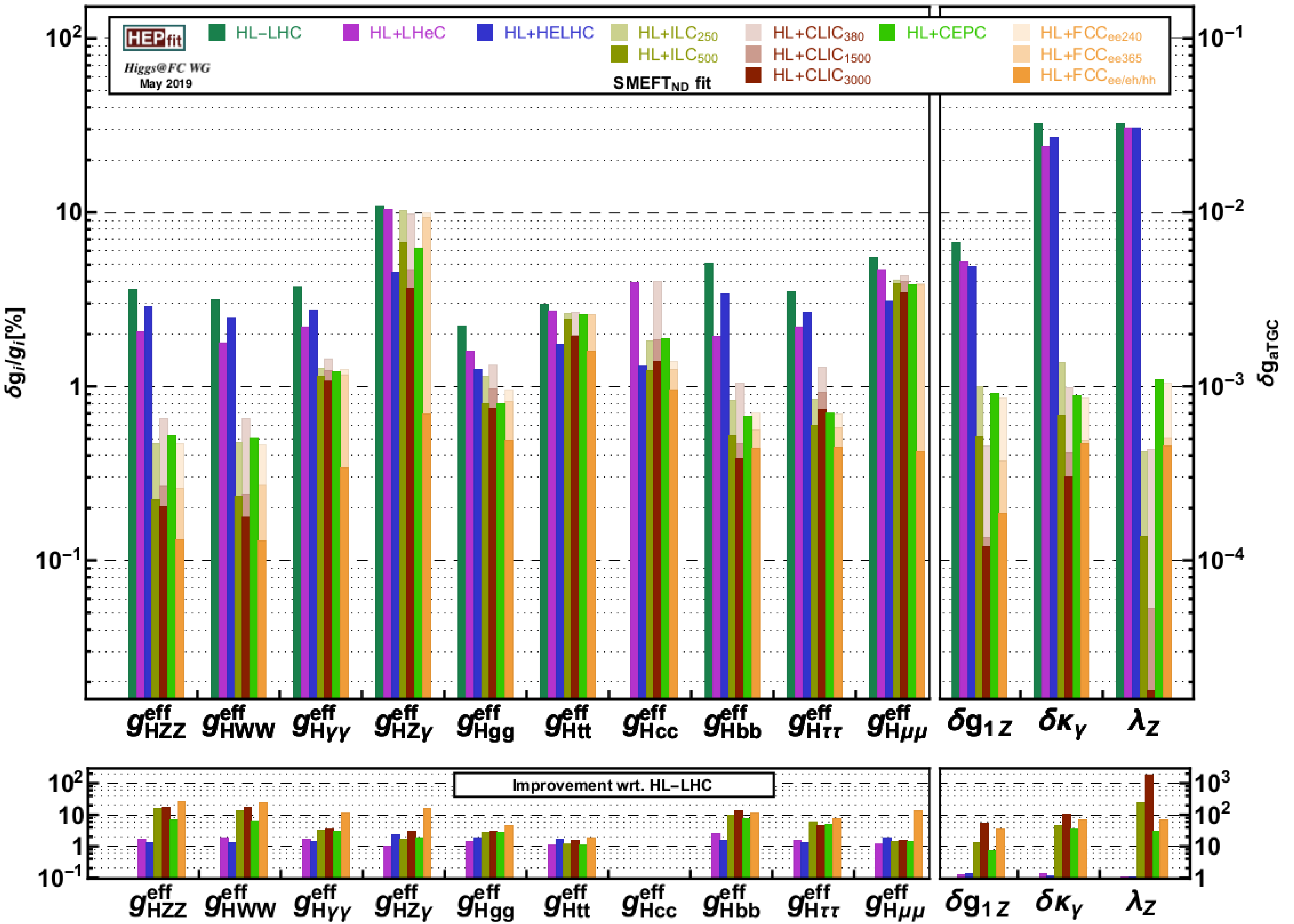
Operation mode	$\sqrt{s}$ (GeV)	L per IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158–172	10	1	2.6	2×10^7 (†)







arXiv:1905.03764



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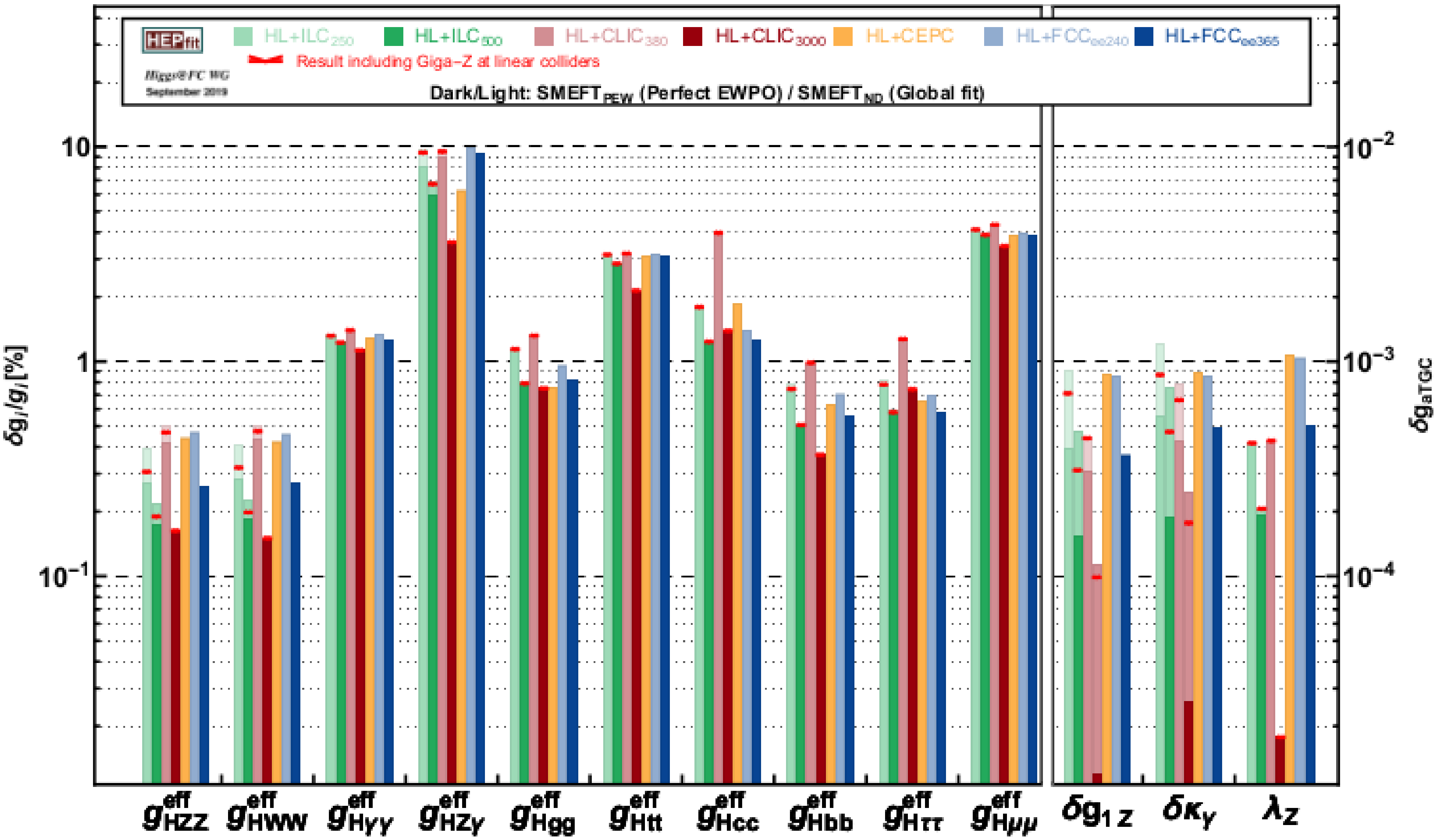
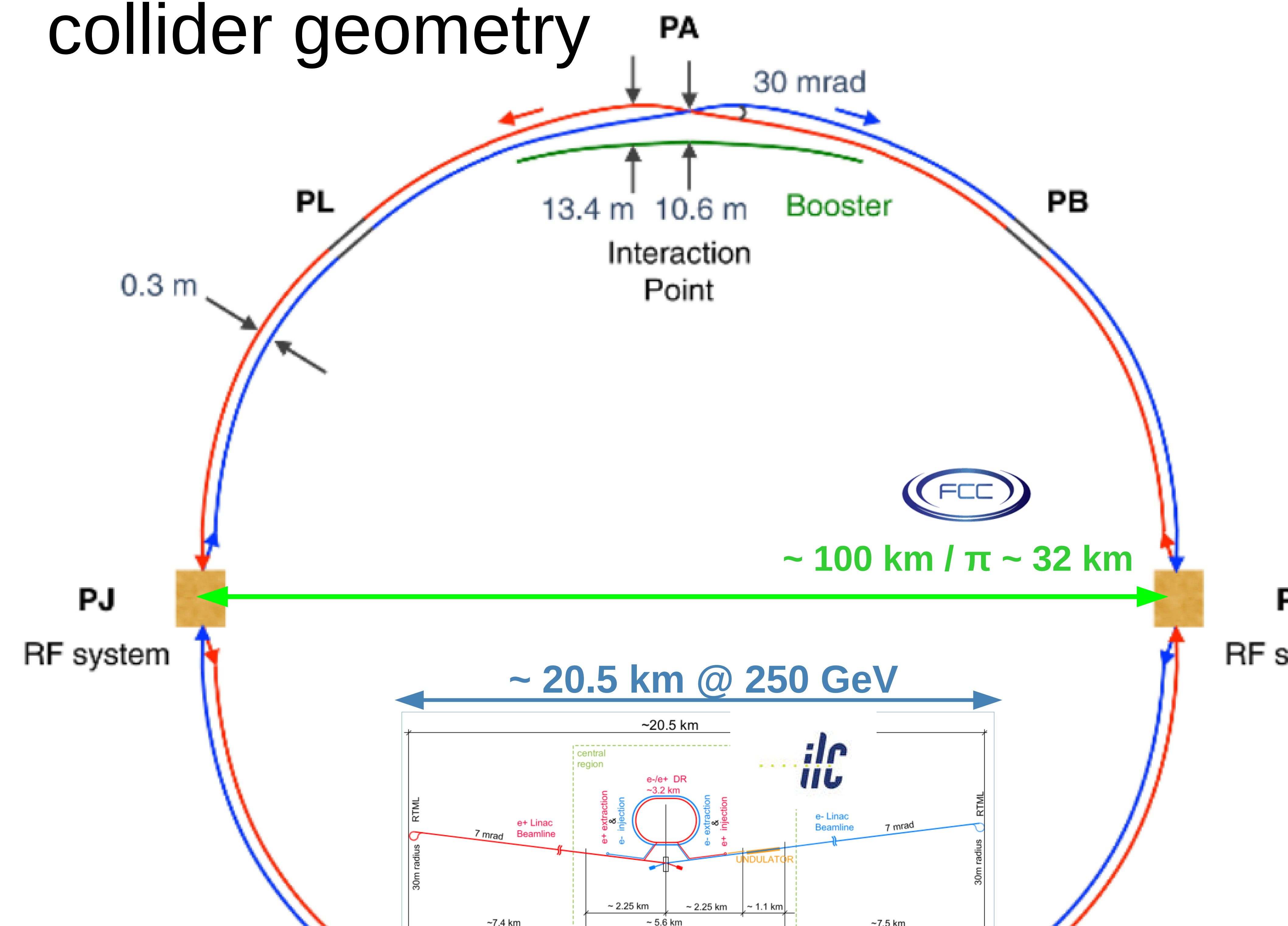
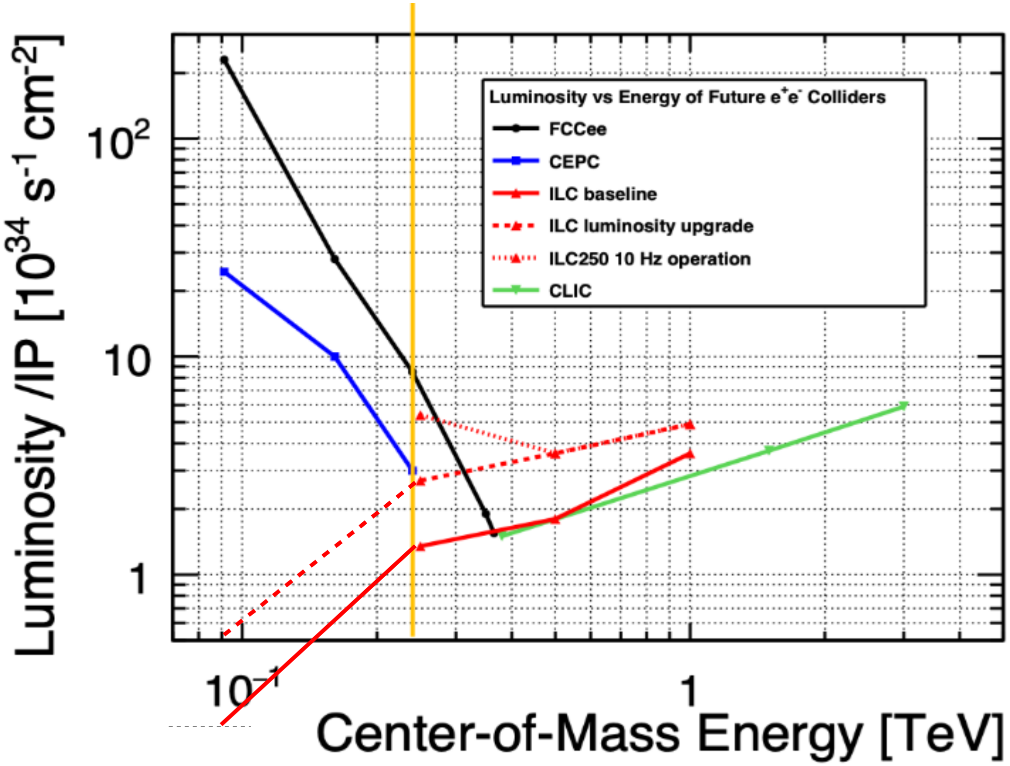


arXiv:1905.03764

collider geometry





Collider performance