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PRECISION HIGGS PHYSICS AT FUTURE e+e- COLLIDERS

Opportunities at Future High Energy Colliders

IFT Madrid, Spain

11.06.-05.07. 2019

A LOT OF FLOWERS IN THE GARDEN

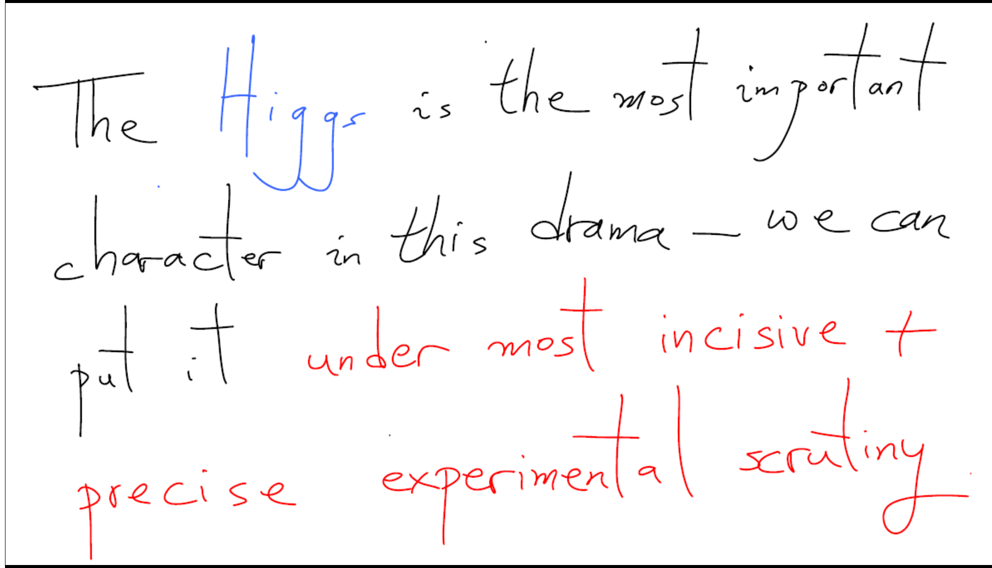
WHICH ONE TO CHOSE?

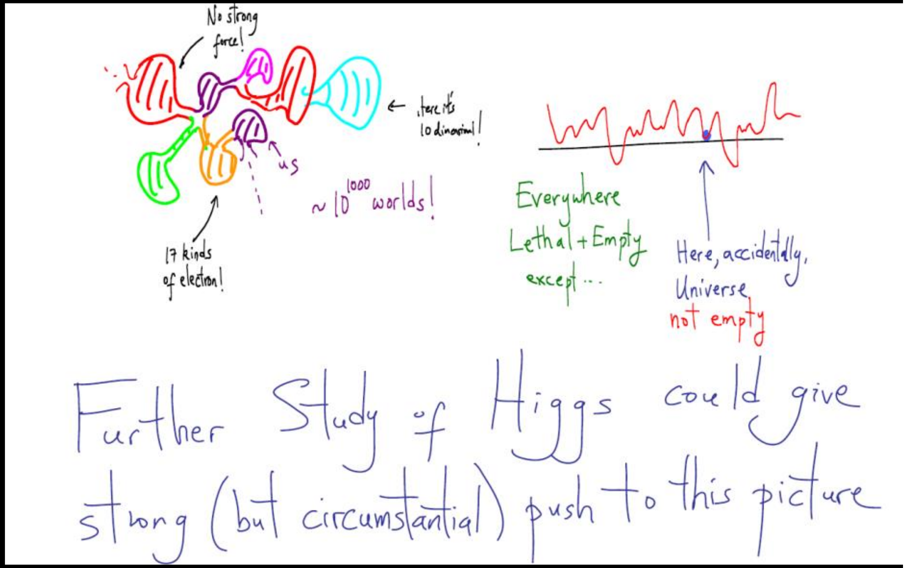
- To what extent are the linear and circular e+e- colliders complementary?
- To what extent are they synergistic with the HL- LHC?
- How might the results from the HL-LHC affect the opportunities with these other future machines?
- Is there a need for more than one future collider?

The above will be discussed from the perspective of Higgs physics

WHY HIGGS?

- The only new physics at LHC
- The only fundamental scalar
- The only self-coupled particle
- No analogy in nature (solid state)





N. Arkani Hamed, CEPC WS 2019,
https://indico.ihep.ac.cn/event/7389/session/0/contribution/18/material/slides/0.pdf

WHY HIGGS?

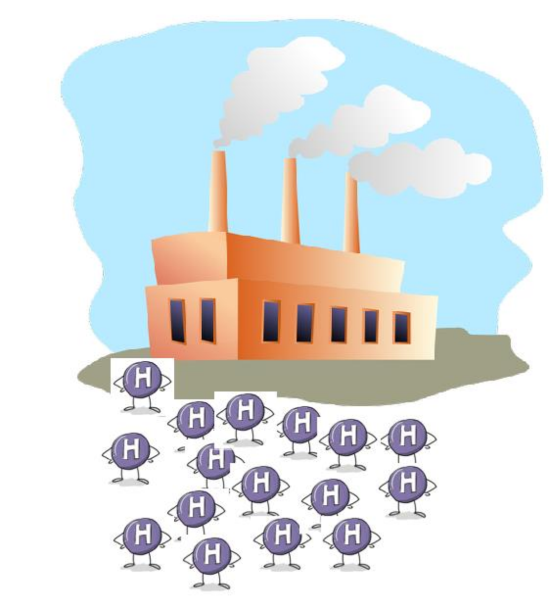
- The only new physics at LHC
- The only fundamental scalar
- The only self-coupled particle
- No analogy in nature (solid state)

The Higgs is the most important character in this drama — we can put it under most incisive + precise experimental scrutiny

- What is the origin of EWSB?
- Light scalar naturalness?
- Higgs as a portal to BSM (DM, CPV, compositeness, etc.)

N. Arkani Hamed, CEPC WS 2019,
https://indico.ihep.ac.cn/event/7389/session/0/contribution/18/material/slides/0.pdf

WHY HIGGS?

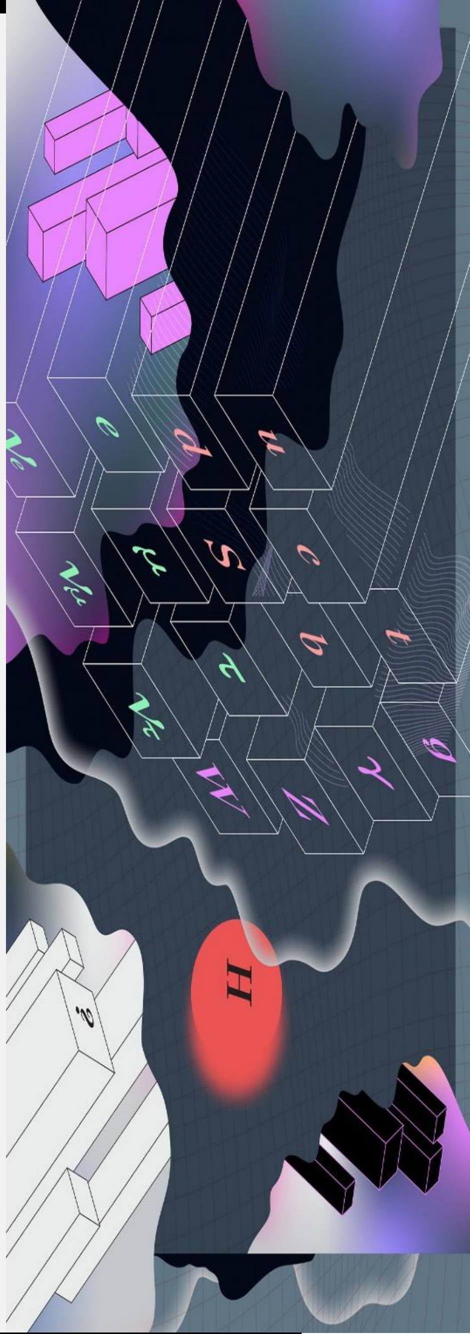


It's no wonder that all future e+e- colliders are foreseen to be Higgs factories

		Higgs
ILC 250	0.5	10^6
CLIC 380/1.4/3	0.18/0.71/2.31	10^6
CEPC 250	1	10^6
FCCee 240/365	1.02/0.22	10^6

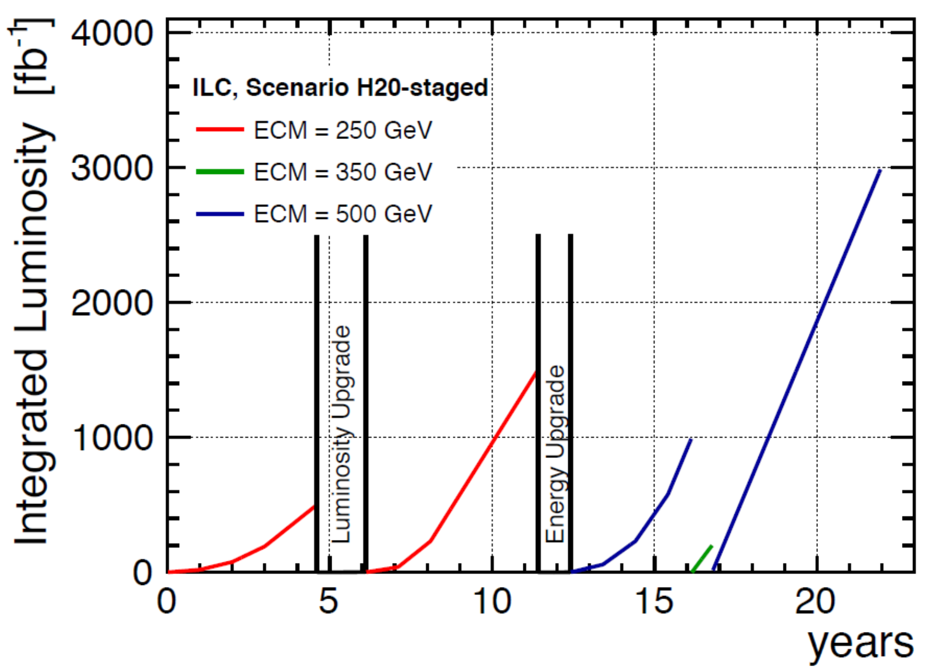
OVERVIEW

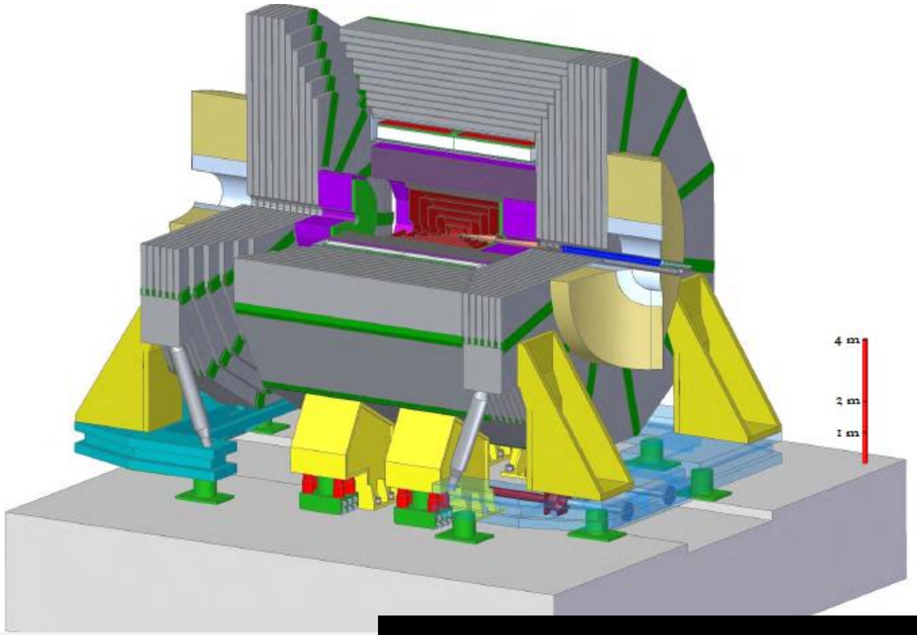
- e+e- projects in brief
- Higgs production mechanisms
- Higgs width
- Higgs couplings
- Self-coupling
- Higgs as a portal to BSM
- Can we answer the questions from the beginning?



ILC

- e^+e^- centre-of-mass energy
  - first stage: 250 GeV
  - tunable
  - upgrades: 500 GeV, 1 TeV
  - further options:
    running at Z pole & WW threshold
- luminosity at 250 GeV:
  - 1.35×10^{34} /cm^2 /s
  - upgrade 2.7×10^{34} /cm^2 /s (cheap)
  - upgrade 5.4×10^{34} /cm^2 /s (expensive)
- beam polarisation
  - $P(e^-) \geq \pm 80\%$
  - $P(e^+) = \pm 30\%$,
    at 500 GeV upgradable to 60%
- total length (250 GeV): 20.5 km





ILD Detector

- 3.5 T field
- Optimized for CM energies 90 GeV - 1 TeV
- Si/gaseous tracking
- Particle flow calorimetry
- Mature design and available technologies

CLIC

- Three energy stages: 380GeV, 1.5TeV (one drive-beam complex) and 3TeV (two drive-beam complexes)

- Possibilities for future higher-energy beams from novel accelerator techniques

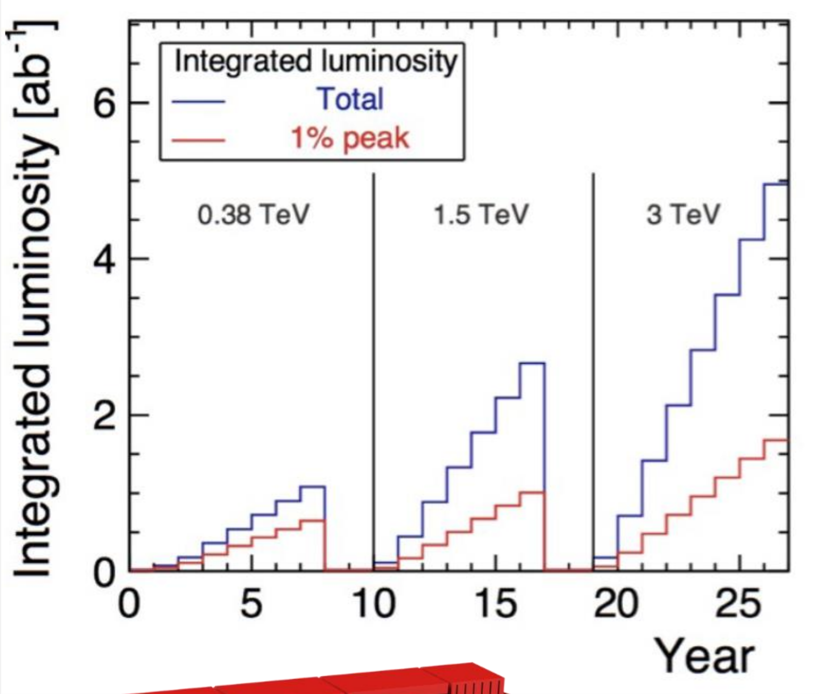
- Electron polarisation:

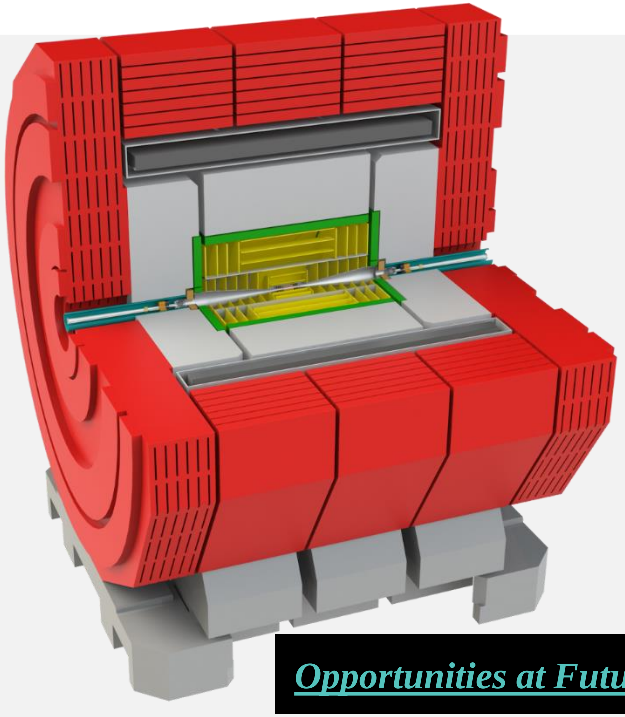
–enhances Higgs production at high-energy stages

–provides additional observables sensitive to NP

–helps to characterise new particles in case of discovery

Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{int}$ [ab^{-1}]	$P(e^-) = -80\%$ $\mathscr{L}_{int}$ [ab^{-1}]	$P(e^-) = +80\%$ $\mathscr{L}_{int}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0	0.5	0.5
2	1.5	2.5	2.0	0.5
3	3.0	5.0	4.0	1.0





CLIC det

- 4 T field
- Ultra low-mass VTX
- All Si tracking
- Particle flow calorimetry
- Time-stamped readout
- Ready for construction (det&acc) 2026

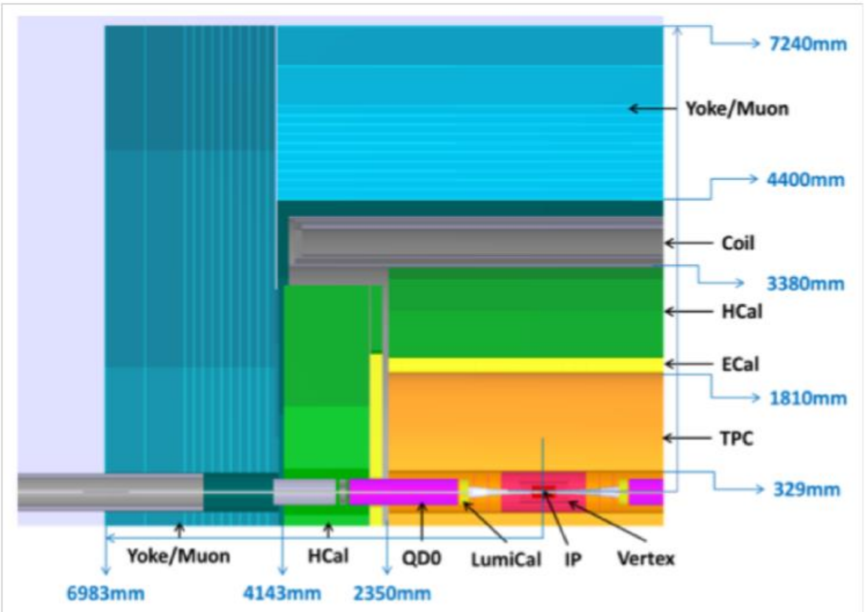
CEPC

Higgs factory √s = 240 GeV 7 yrs → 1M H, 1B Z, 100M W

Z factory √s = 91.2 GeV → 10^{11} – 10^{12} Z bosons

WW threshold scans ~ √s = 161 GeV → 10^{7}W

- 100 km tunel infrastructure
- 91.2 GeV, 161 GeV, Higgs production threshold
- Integrated luminosity 5.6 ab^{-1} at 240 GeV
- Also Z and W boson factory (as FCCee)
- As FCC, foreseen to be used for 100 TeV pp collisions



CEPC Detector

- 3 T field
- ILD based
- Si/gaseous tracking
- Particle flow calorimetry
- New at the market, ongoing optimization and R&D

FCCee

~100 km tunnel infrastructure

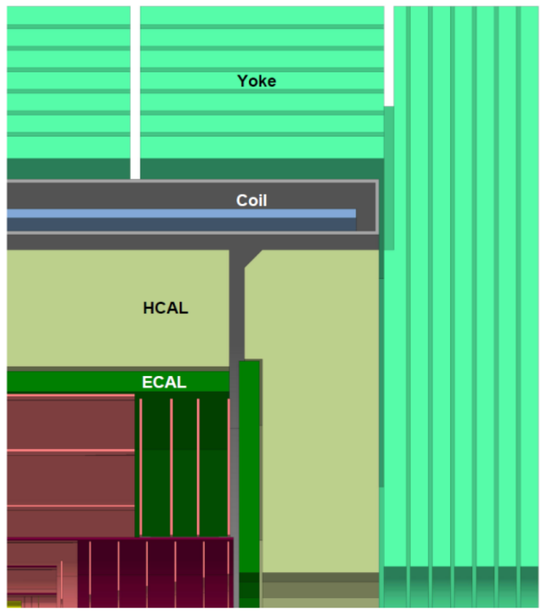
e^+e^- collider *(FCC-ee)*,$\sqrt{s}$=90-365 GeV, L~10^{35} - 4x10^{36}, L_{int}=1-48 ab^{-1}/yr

for H, Z as potential first step

HE-LHC with *FCC-hh* technology

p-e *(FCC-he)* option, $\sqrt{s}$=3.5 TeV, L~10^{34}

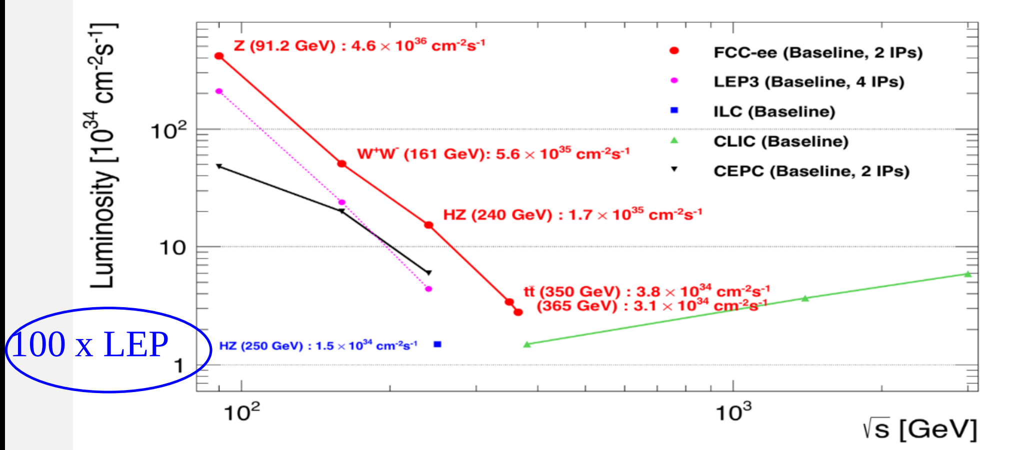
working point	nominal luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	total luminosity (2 IPs)/ yr half luminosity in first two years (Z) and first year (ttbar) to account for initial operation	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	48 ab^{-1}/year		
W	25	6 ab^{-1}/year	10 ab^{-1}	1 - 2
H	7.0	1.7 ab^{-1}/year	5 ab^{-1}	3
machine modification for RF installation & rearrangement: 1 year				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	0.2 ab^{-1}	1
top later (365 GeV)	1.4	0.34 ab^{-1}/year	1.5 ab^{-1}	4



CLD

- 2 T field
- CLICdet based
- Si tracking
- Particle flow calorimetry
- New at the market, ongoing optimization and R&D

FIRST CONCLUSIONS



Is there any benefit of having (so) many future options?

Competiveness gives added value

- Nobody is starting from tabula rasa – knowledge transfer (i.e. ILD (TESLA) is mother of all detectors)
- There is large community circulating between experiments (with every new project pushing forward the limits in R&D)
- Preserving the 'future projects' community over a time span of a two decades

Who has more (statistics)?

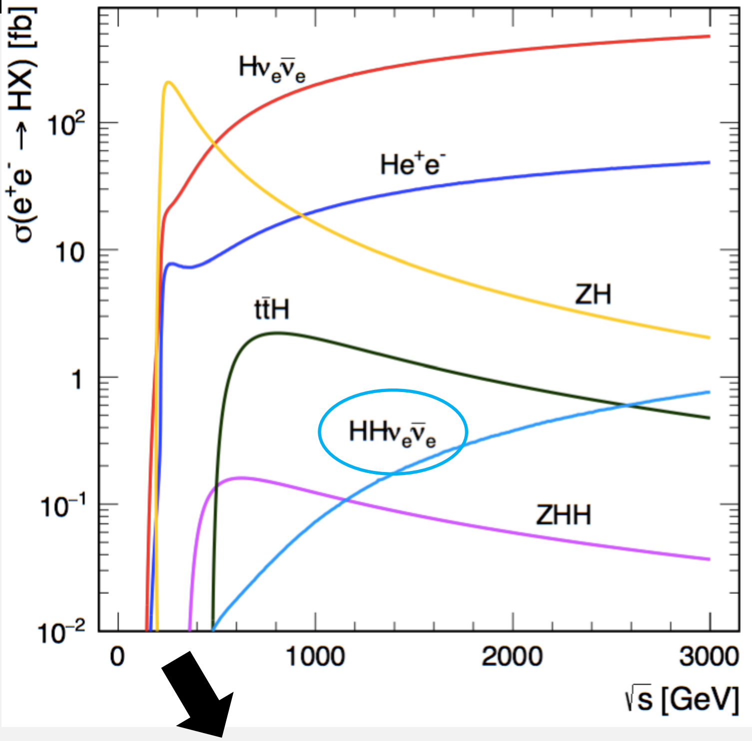
It's a luminosity run

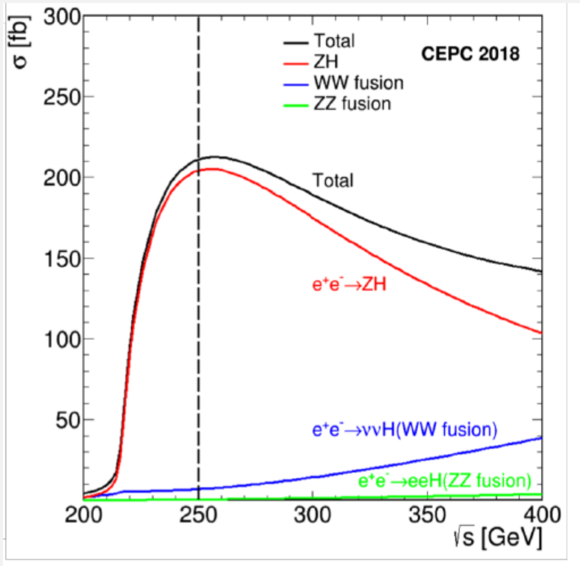
- It is clear that it is a run for statistical precision
- One should not forget about systematics, including theoretical uncertainties (the advanced level of these details is lacking in most experiments)
- BUT, other aspects are also important:
  - Extensibility of the physics span - flexibility to accommodate other options (pp, hh, ep, gamma gamma, plasma….)
  - Flexibility to accommodate changes in scenario (i.e. unexpected HL-LHC discovery),
  - Technological feasibility and cost,
  - Politics (it's a game of power, as well),
  - …

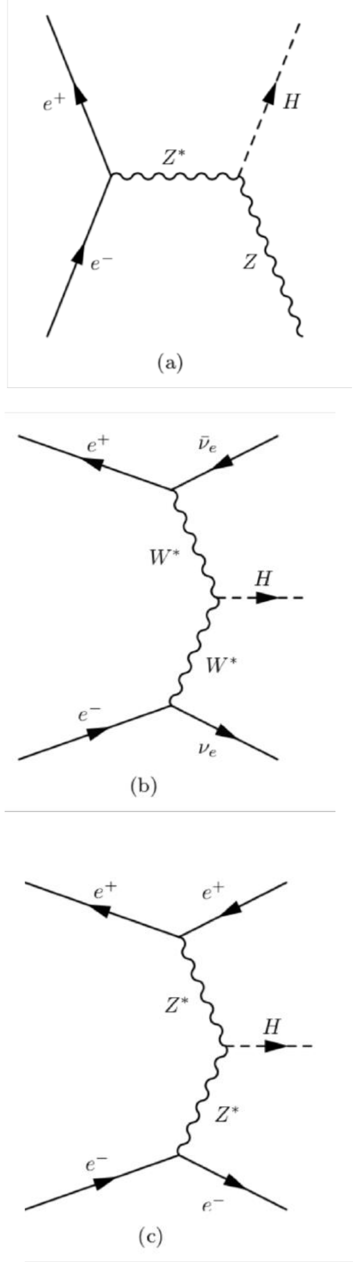
HIGGS PRODUCTION MECHANISMS

- Higgsstrahlung is a unique feature of particle-antiparticle collisions (i.e. e+e- colliders)
- It facilitates g_{HZZ} measurement in a model-independent way*
- Higgs invisible width can be determined from the recoil mass
- Most of the Higgs couplings can be determined with a better precision than at HL-LHC only from HZ
- Linear colliders foreseen as staged machines benefit from additional statistics from WW-fusion (clear example is CLIC with ~ 3M Higgs bosons at all stages)
- Double Higgs production at higher energies

** Theory warning: level of accuracy <1% requires incorporation of loop-corrections → loss of strict model-independence*



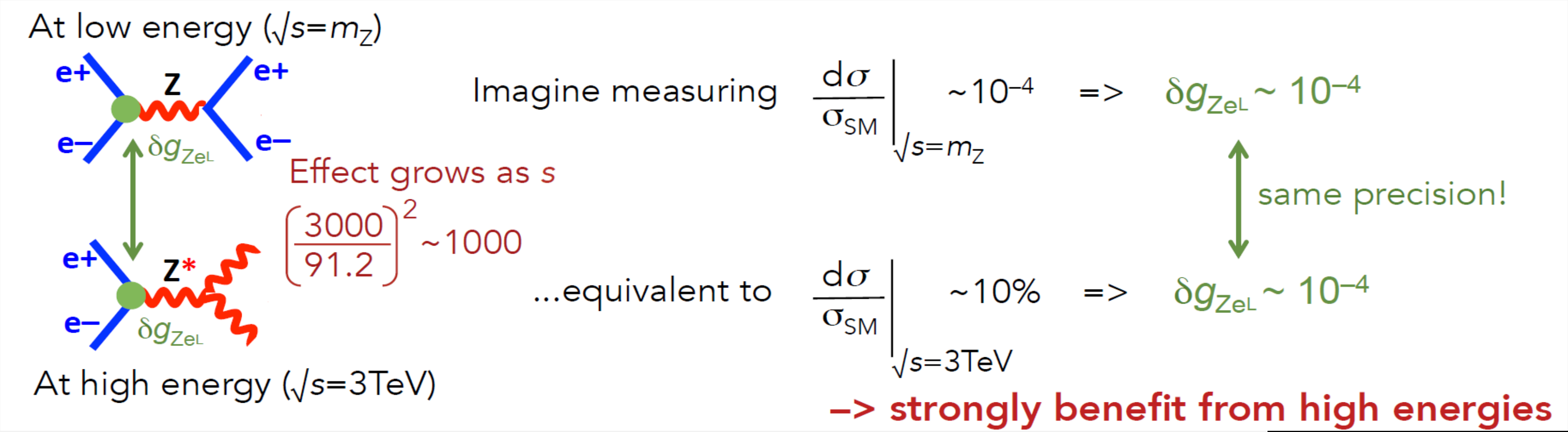




High-energy benefits

- Clear advantage from rising cross-section for WW-fusion – access to rare Higgs decays
- ttH production, suitable i.e. for CPV study in the Higgs sector
- Multiple-Higgs production → self-coupling measurement
- Precision Higgs physics as a portal to BSM
- Less precise determination of the observable at high energy leads to the same precision on coupling as at low energy

Decay mode	Branching ratio
$H \to b\bar{b}$	56.1%
$H \to WW^*$	23.1%
$H \to gg$	8.5%
$H \to \tau^+\tau^-$	6.2%
$H \to c\bar{c}$	2.8%
$H \to ZZ^*$	2.9%
$H \to \gamma\gamma$	0.23%
$H \to Z\gamma$	0.16%
$H \to \mu^+\mu^-$	0.021%
Γ_H	4.2 MeV

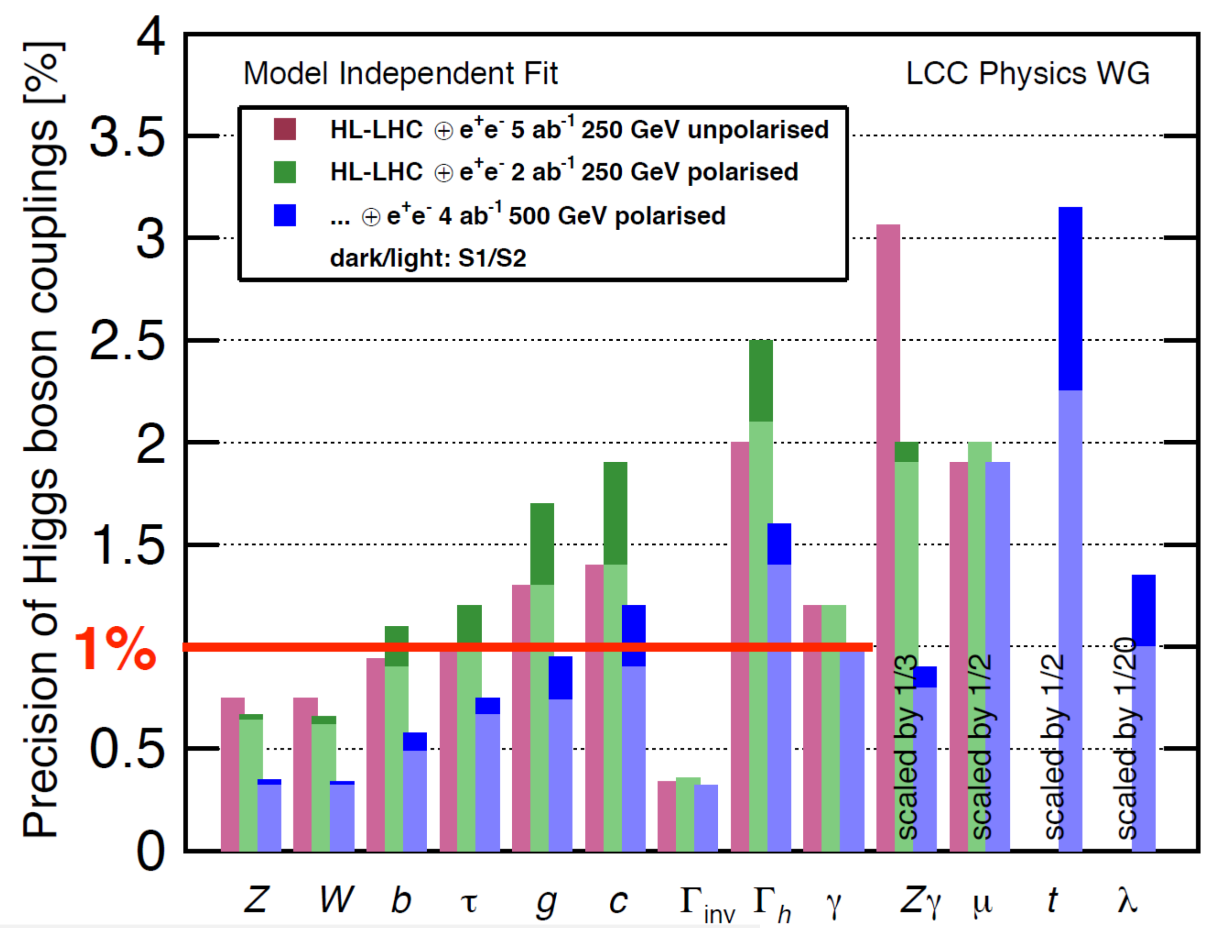


Example taken from A.Robson, CEPC WS Oxford 2019, https://indico.cern.ch/event/783429/contributions/3306678/

Polarization benefits

- Chiral nature of charge currents results in significant sensitivity of WW-fusion cross-section on polarization scheme (though *L* can be changed)
- Better precision with smaller statistics
- Enhanced precision at all energies

Polarisation	Scaling factor		
$P(e^-) : P(e^+)$	$e^+e^- \to ZH$	$e^+e^- \to H\nu_e\bar{\nu}_e$	$e^+e^- \to He^+e^-$
Unpolarised	1.00	1.00	1.00
−80% : 0%	1.12	1.80	1.12
−80% : +30%	1.40	2.34	1.17
−80% : −30%	0.83	1.26	1.07
+80% : 0%	0.88	0.20	0.88
+80% : +30%	0.69	0.26	0.92
+80% : −30%	1.08	0.14	0.84



HIGGS WIDTH

Statistical accuracy of 1-2%

- Being less than 5 MeV, Higgs decay width can not be *directly* measured at any proposed e+e- collider
- Can be determined from individual decays (quasi-direct measurement), i.e. H→WW decays in WW-fusion, H→ZZ in HZ)

$$\sigma(\mathrm{ee} \to \mathrm{ZH}) \cdot \mathrm{BR}(\mathrm{H} \to \mathrm{ZZ}) \propto \frac{g^4_{\mathrm{HZ}}}{\Gamma}$$

- In a combination of measurements:

$$\frac{\sigma(\mathrm{ee}\to\mathrm{ZH})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{WW})\cdot\sigma(\mathrm{ee}\to\mathrm{ZH})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{bb})}{\sigma(\mathrm{ee}\to\nu\nu\mathrm{H})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{bb})}$$

$$\propto \frac{g^2_{\mathrm{HZ}}\cdot \cancel{g^2_{\mathrm{HW}}}}{\Gamma} \cdot \frac{g^2_{\mathrm{HZ}}\cdot \cancel{g^2_{\mathrm{Hb}}}}{\cancel{\Gamma}} \cdot \frac{\cancel{\Gamma}}{\cancel{g^2_{\mathrm{HW}}}\cdot \cancel{g^2_{\mathrm{Hb}}}} = \frac{g^4_{\mathrm{HZ}}}{\Gamma}$$

- The ultimate precision is reached in a global fit, (model-independent or in the LHC-style, so called κ-framework):

$$\Gamma_H = \frac{\Gamma_H^{SM} \cdot \kappa_H^2}{1-(BR_{inv}+BR_{unt})}$$

- Or in a global (model-dependent) EFT fit (assumes the new physics scale $\Lambda >> M_H$)

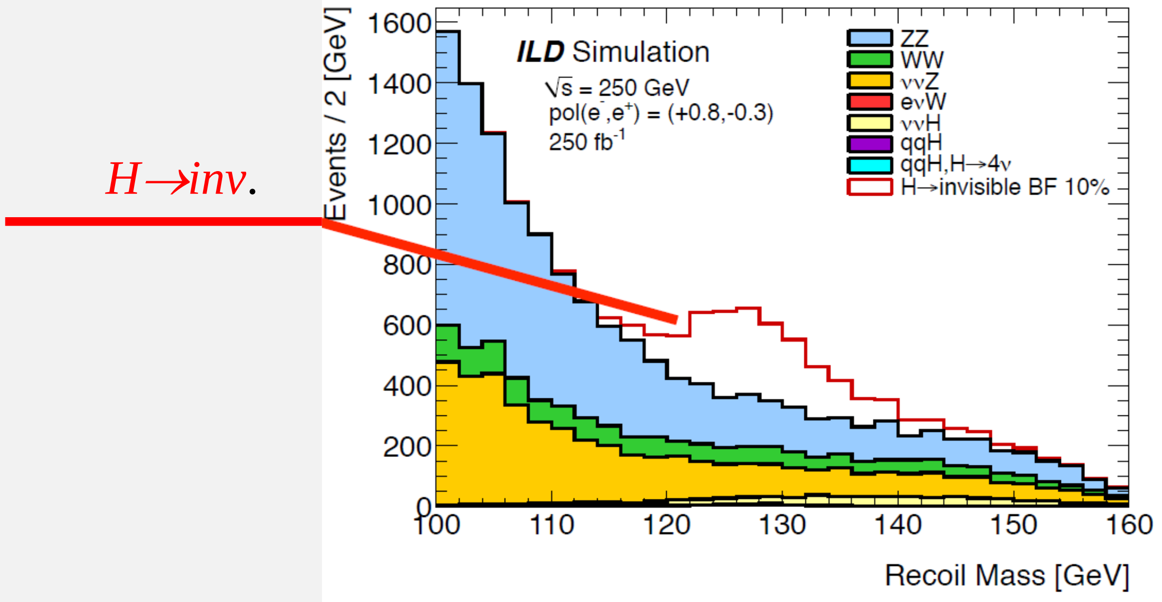
Collider	δΓ$_H$ (%) from Ref.	Extraction technique standalone result	δΓ$_H$ (%) kappa-3 fit
ILC$_{250}$	2.4	EFT fit [3]	2.4
ILC$_{500}$	1.6	EFT fit [3, 11]	1.1
CLIC$_{350}$	4.7	κ-framework [85]	2.6
CLIC$_{1500}$	2.6	κ-framework [85]	1.7
CLIC$_{3000}$	2.5	κ-framework [85]	1.6
CEPC	3.1	$\sigma(ZH, \nu\bar{\nu}H)$, BR($H \to Z, b\bar{b}, WW$) [90]	1.8
FCC-ee$_{240}$	2.7	κ-framework [1]	1.9
FCC-ee$_{365}$	1.3	κ-framework [1]	1.2

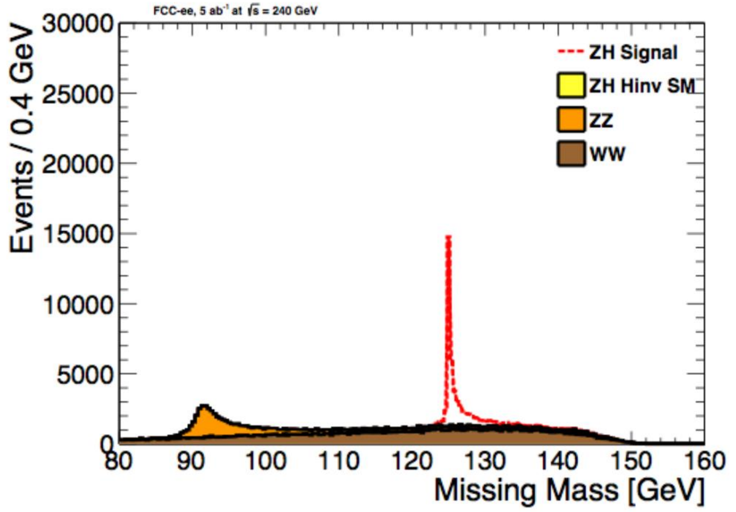
arXiv:1905.03764

HIGGS TO INVISIBLE

Portal to Dark Matter

- Looking at the recoil mass under the condition that nothing observable is recoiling against the *Z* boson (only one Z per event)
- Access to DM particles in the Higgs portal models





$\delta(\sigma_{ZH} x BR(H\to inv.))$ /CL	ILC250	CLIC	FCCee	CEPC
	0.9%/90%	0.97%/95%	0.3%/95%	0.3%/95%

Higgs physics at CLIC, Eur. Phys. J. C 77 475 (2017)
ILC Higgs White Paper, arXiv: 1310.0763
X. Shi, Higgs White Paper Group, Higgs Physics at CEPC, arXiv: 1810.09037
P. Giacomeli, The Higgs Boson at FCCee, ICHEP2018

COMPARISONS BETWEEN FUTURE EXPERIMENTS

Devil is in details

How objective can we compare?

- One (experiment) needs not only to have, but also to RECONSTRUCT and IDENTIFY events of interest (sometimes with a rather small effective cross-sections),
- … in a FULL detector SIMULATION,
- … against ALL BACKGROUNDS (usually calls for machine learning methods)
- There is a SYSTEMATICS, too,
- + uncertainties from THEORY
- + theoretical assumptions for various model-dependent methods
- Naturally (they appeared first), linear collider experiments are more advanced w.r.t the level of details

Simulation Studies

ILC analyses based on

- Whizard (ME) + Pythia 6 (PS & hadronisation) MC
- including beam energy spectrum & ISR
- full, Geant4-based simulation of the detectors
- gauged against test beam performance of prototypes
- inclusion of machine and full SM background
- in some cases full sim analyses are extrapolated to other center-of-mass energies

J. List, ECFA HIggs@FutureColliders, 2019

Comparison between different approaches is possibly only if the set of theoretical assumptions is known (i.e. in the κ-framework: signal corresponds to only one state, no overlapping resonances, zero width approximation, no change in tensor structure of the couplings, only overall strength, implies assumption that the observed state is a CP-even scalar, …)

HIGGS COUPLINGS

Situation at LHC (HL-LHC, and pp in general)

- No absolute measurement of the production cross-section (like ZH at e+e- colliders)
- Higgs couplings come in combination:

$$\sigma(H) \times \mathrm{BR}(H \to a + b) \sim \frac{\Gamma_{\mathrm{prod}} \Gamma_{\mathrm{decay}}}{\Gamma_{\mathrm{tot}}}$$

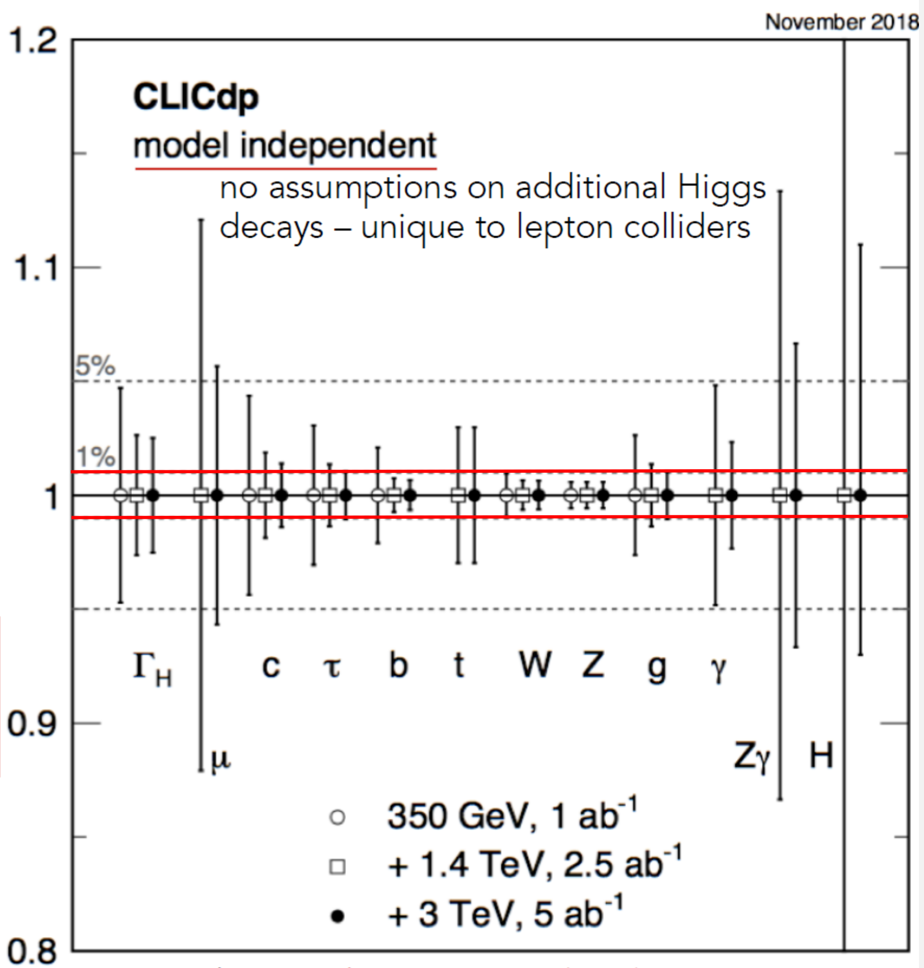
- Only ratio of couplings can be directly determined (i.e. $g^2_{H\tau\tau}/g^2_{HWW}$)

e+e- colliders

- Absolute measurement of the ZH cross-section
- Absolute measurement of the Higgs BRs
- Nearly model-independent determination of the Higgs total width and couplings

HIGGS COUPLINGS

Model independent approach, precision better than 1% for most couplings*



Based on Eur. Phys. J. C 77 475 (2017)
updated to new luminosity scenario arXiv:1812.01644

Statistical uncertainties are shown for 5 ab^{-1}@240 GeV and 1.5 ab^{-1}@365 GeV (from FCC-ee CDR)

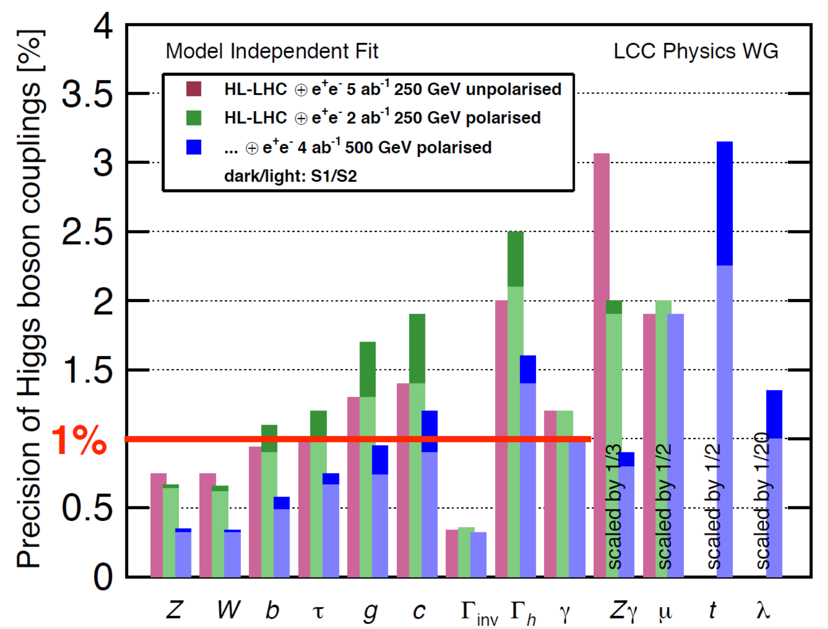
in %	FCC-ee 240 GeV	+FCC-ee 365 GeV	+HL-LHC
δg_{HZZ}	0.25	0.22	0.21
δg_{HWW}	1.3	0.47	0.44
δg_{Hbb}	1.4	0.68	0.58
δg_{Hcc}	1.8	1.23	1.20
δg_{Hgg}	1.7	1.03	0.83
$\delta g_{H\tau\tau}$	1.4	0.8	0.71
$\delta g_{H\mu\mu}$	9.6	8.6	3.4
$\delta g_{H\gamma\gamma}$	4.7	3.8	1.3
δg_{Htt}			3.3
$\delta \Gamma_H$	2.8	1.56	1.3

COMBINATION WITH HL-LHC

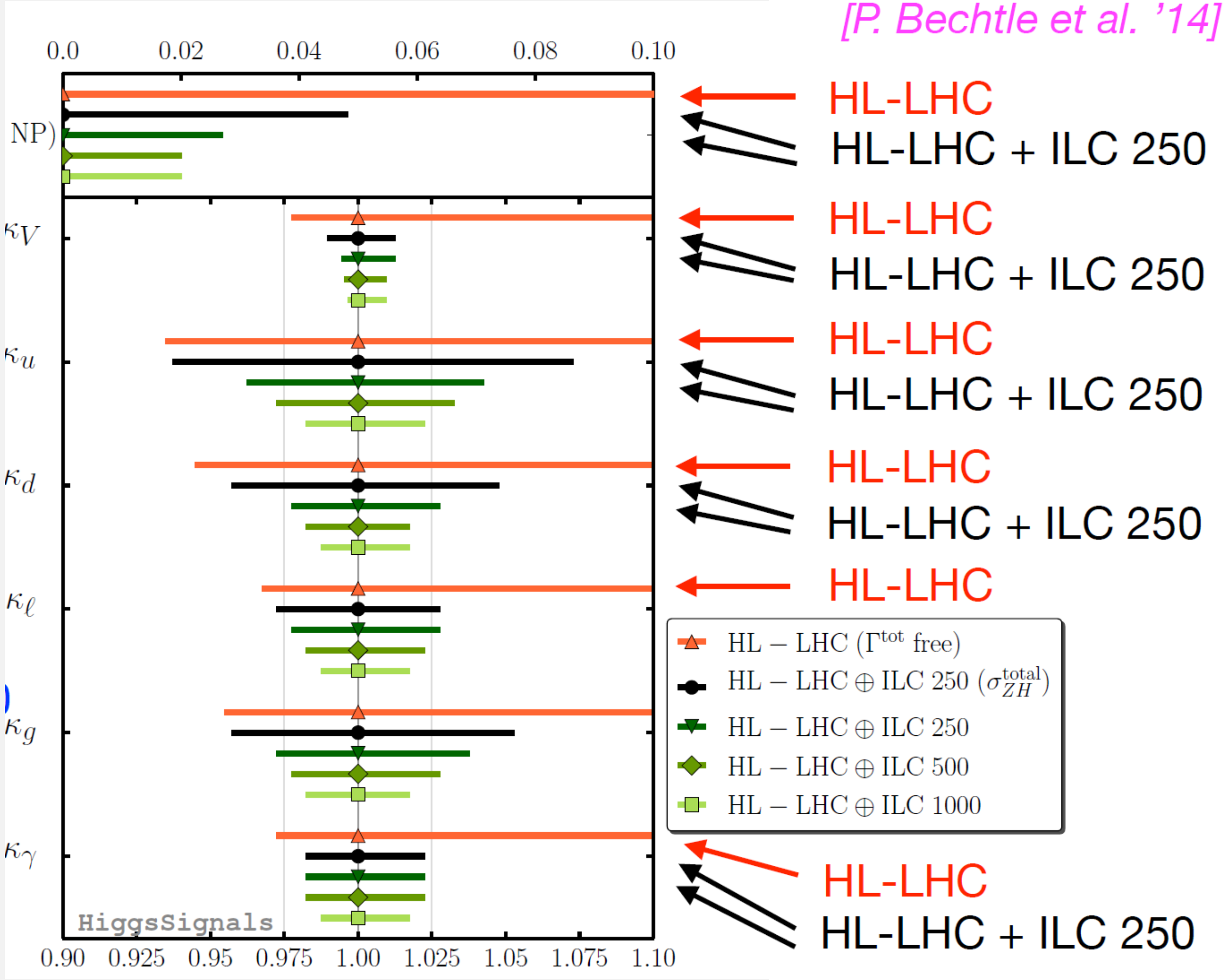
To what extent future e+e- experiments are synergistic with the HL- LHC?

Evident synergy

- An example: ILC250 with 250 fb^{-1}
- Already the single measurement of the HZ cross section at ILC 250 yields a very large improvement of the HL-LHC accuracies



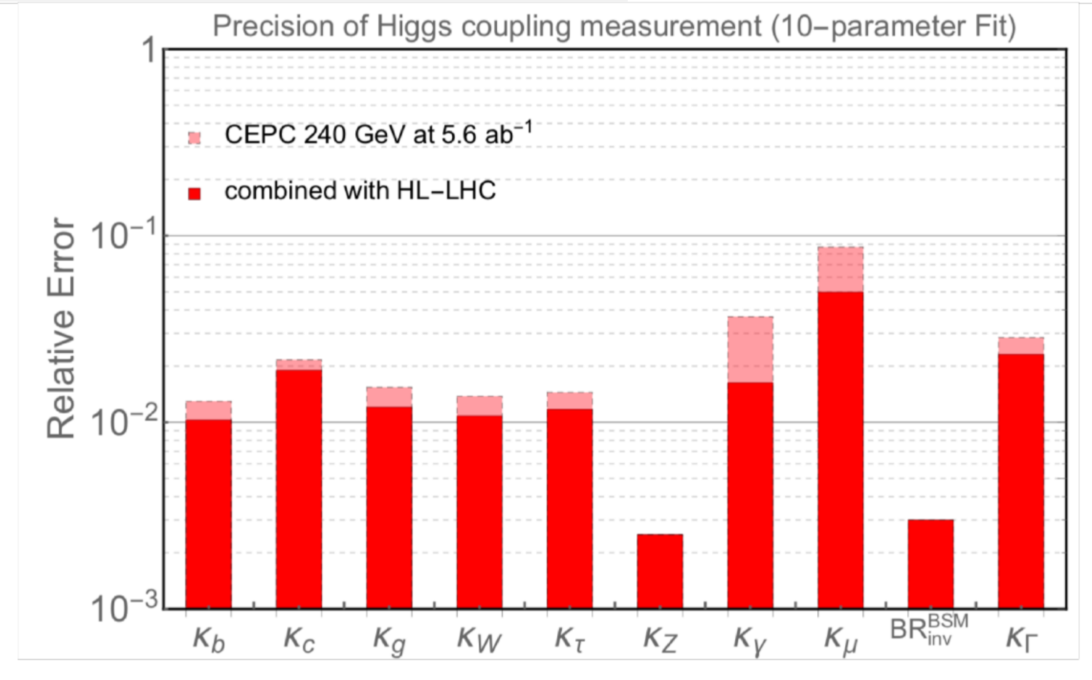
[P. Bechtle et al. '14]



COMBINATION WITH HL-LHC

Some conclusions

- e+e- linear collider and circular colliders statistical accuracy is comparable (i.e. CLIC and FCCee) w.r.t. the Higgs width and couplings measurements
- Any future Higgs factory will significantly improve the HL-LHC accuracy on Higgs couplings
- The other way around is doesn't hold



X. Shi, Higgs White Paper Group, Higgs Physics at CEPC, arXiv: 1810.09037

THEORY EXPECTATIONS

How well do we need to know Higgs couplings?

Some conclusions

- In many BSM models one expects only % level deviations from the SM couplings for BSM particles in the TeV range
- Example, 2HDM-type model in decoupling limit

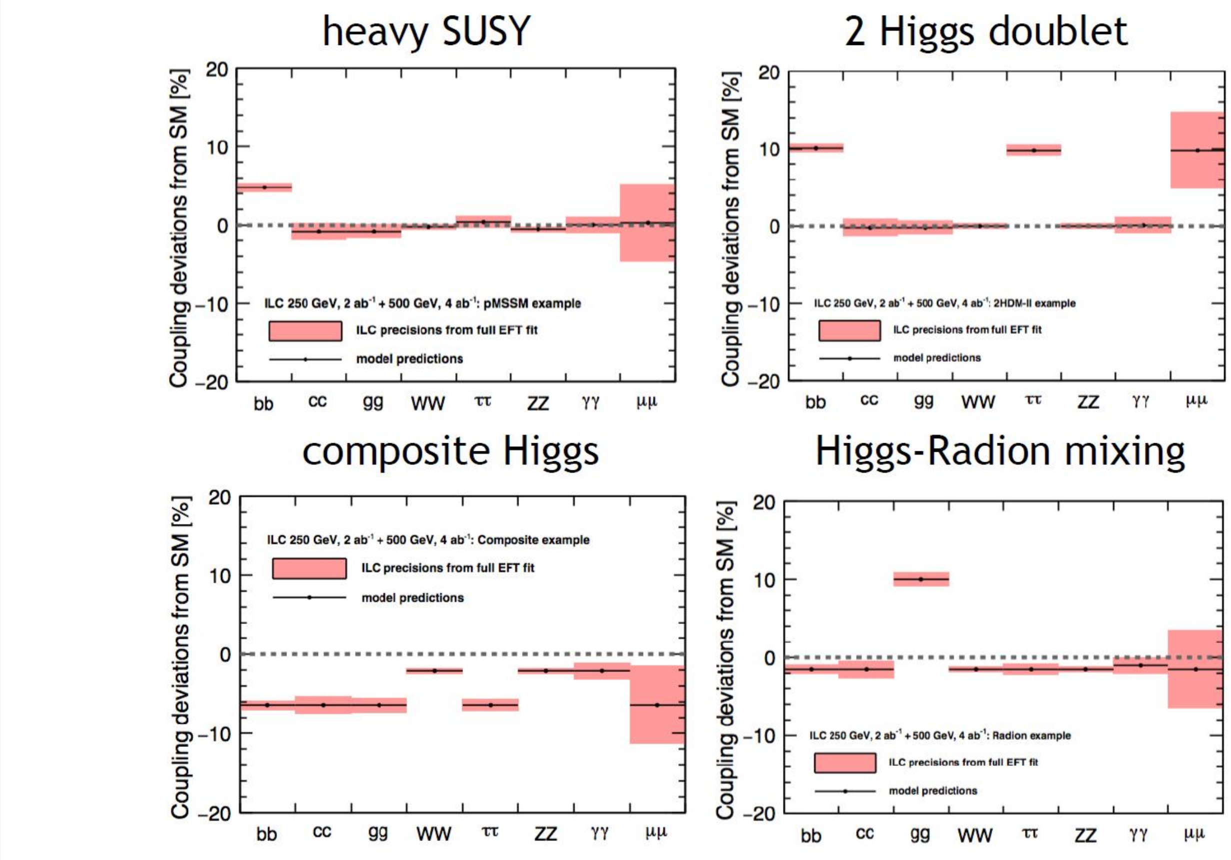
$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 0.3\% \left(\frac{200\ {\rm GeV}}{m_A}\right)^4$$

$$\frac{g_{htt}}{g_{h_{\rm SM}tt}} = \frac{g_{hcc}}{g_{h_{\rm SM}cc}} \simeq 1 - 1.7\% \left(\frac{200\ {\rm GeV}}{m_A}\right)^2$$

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ {\rm GeV}}{m_A}\right)^2 .$$

The models below are outside the HL-LHC reach

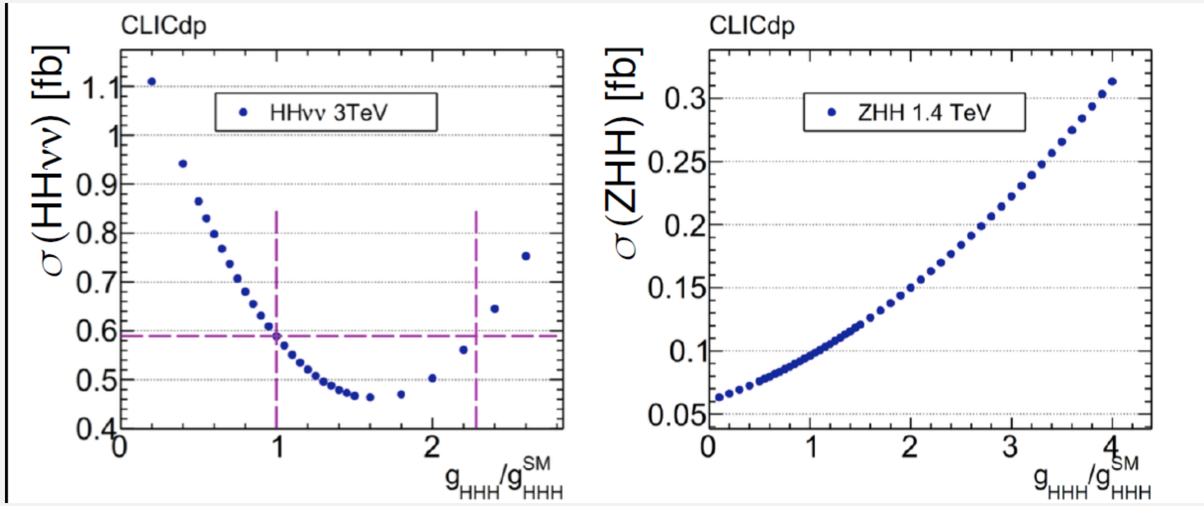
[T. Barklow et al. '17]



Percent order accuracy on Higgs couplings offers access to various BSM scenarios

HIGGS SELF-COUPLING

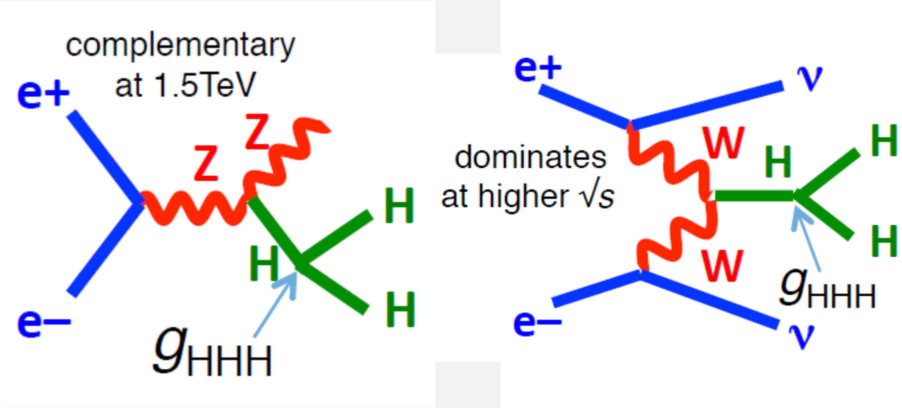
- High energy (>1 TeV) e+e- collider is superior in determination of the Higgs self-coupling
- Intermediate energy (1.4(5) TeV) at CLIC provides complementarity to 3 TeV option with ZHH production
- Different behavior of ZHH and double-Higgs production in WW-fusion, for non-SM values of triple Higgs couplings



Double Higgs and self-coupling:

	1.4TeV	3TeV
$\sigma(HH\nu_e\bar{\nu}_e)$	>3σ EVIDENCE $\frac{\Delta\sigma}{\sigma}$ = 28%	>5σ OBSERVATION $\frac{\Delta\sigma}{\sigma}$ = 7.3%
σ(ZHH)	>5σ OBSERVATION	
g_{HHH}/g_{HHH}^{SM}	1.4TeV: –34%, +36% rate-only analysis	1.4 + 3TeV: –7%, +11% differential analysis

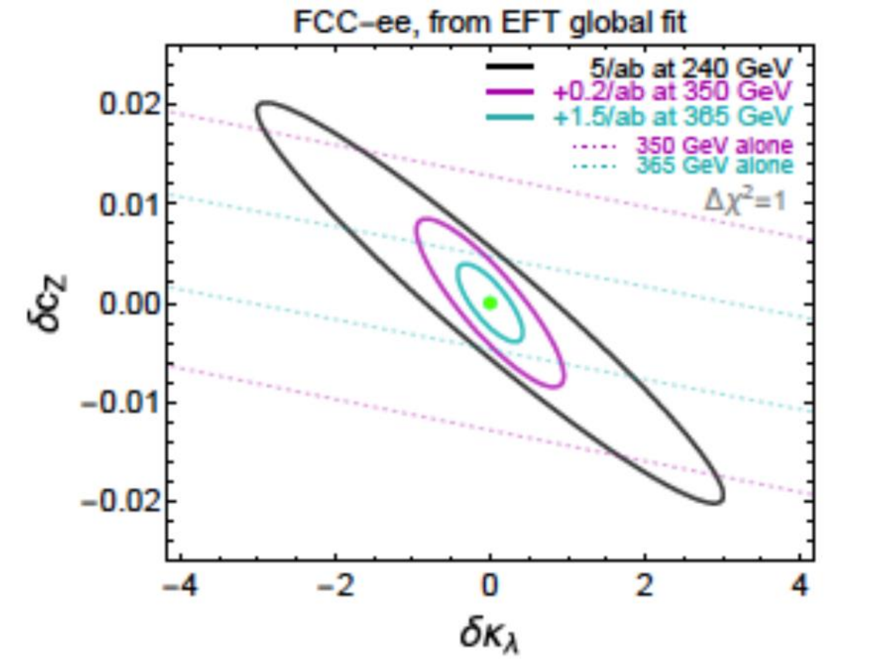
arXiv:1901.05897



A.Robson, CEPC WS Oxford 2019,
https://indico.cern.ch/event/783429/contributions/3306678/

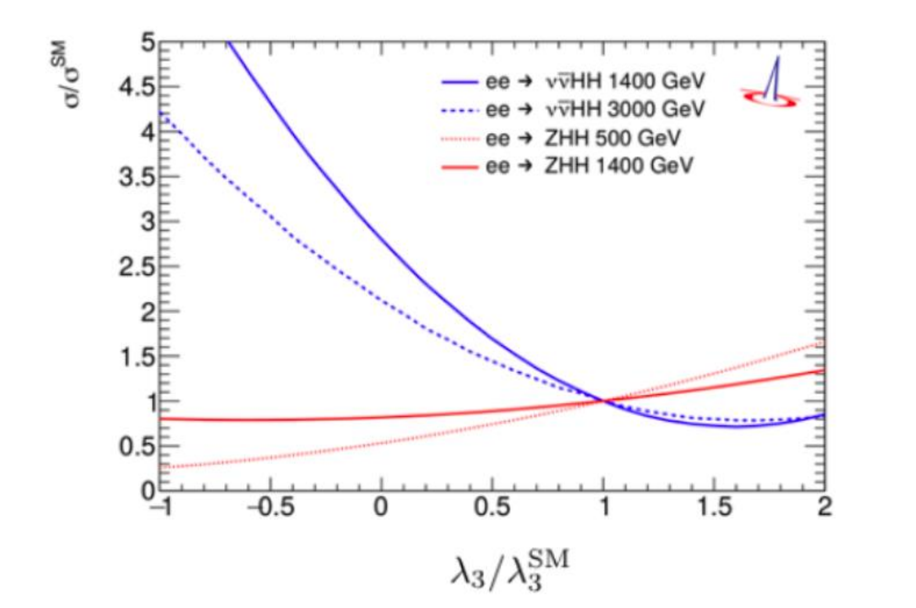
HIGGS SELF-COUPLING

- Global model-independent fit gives stand-alone precision for FCCee of ±40%
- Combination with HL-LHC reduces the uncertainty to ±35%



P. Giacomeli, The Higgs Boson at FCCee, ICHEP2018 /

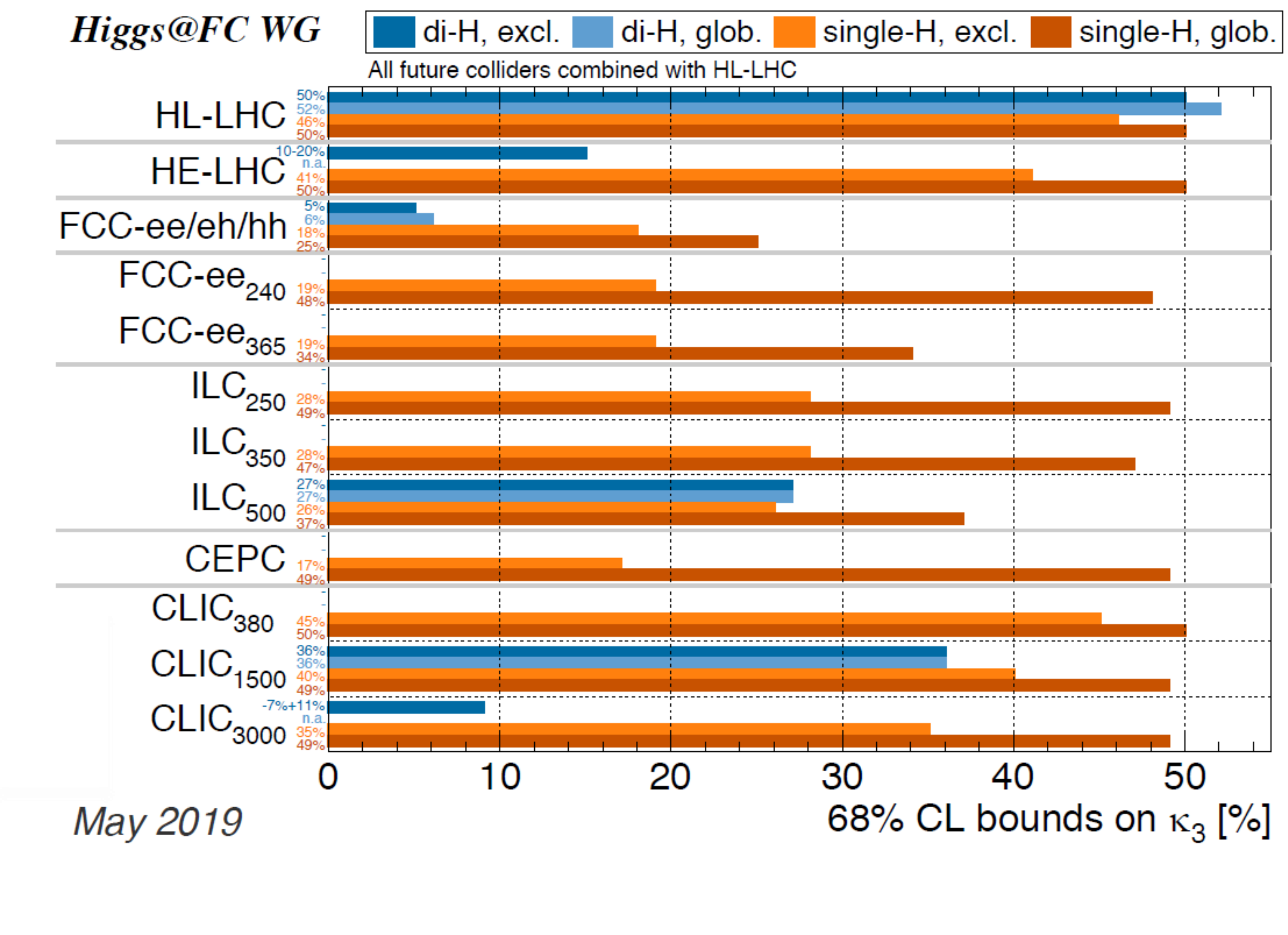
A word from theory (1)



High energy (double)Higgs production is the most sensitive to deviations of the Higgs self-coupling

HIGGS SELF-COUPLING

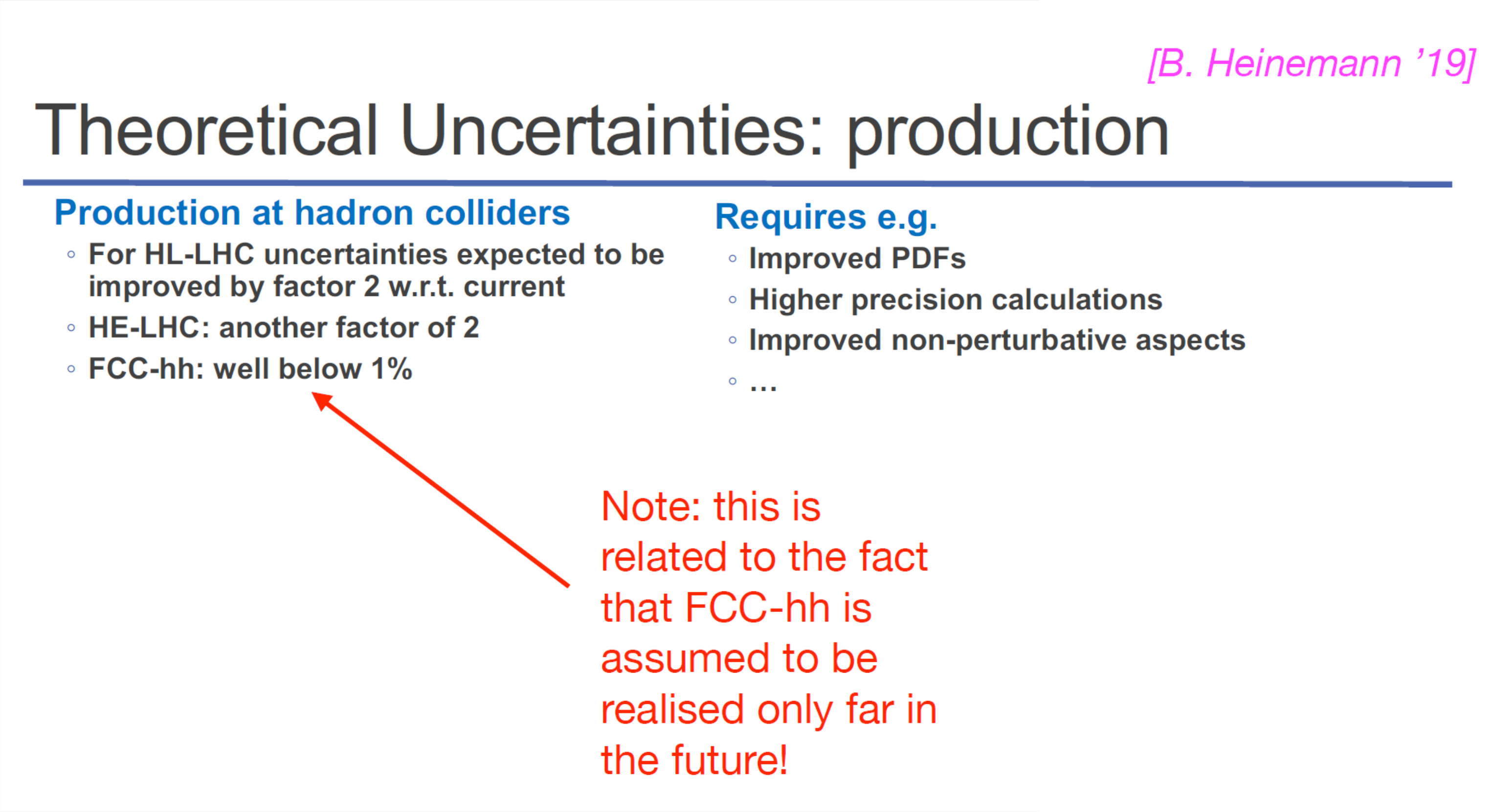
- Low energy e+e- colliders (single Higgs production) uncertainty in combination with HL-LHC:
  - ILC250 and FCCee365, ±35%
- Double-Higgs production:
  - HL-LHC: ~ ±50%
  - ILC500 ~ ± 27%
  - CLIC3000 ~ ± 9%
  - FCC-hh ~ ± 5%



A word from theory (2)

- Precision measurement of couplings at hadron colliders are limited by the systematic (theoretical) uncertainties
- This is also a reason for the fact that the Higgs coupling projections for HE-LHC show only relatively small improvements over HL-LHC
- FCC-hh projections, in particular when taken separately, depend on a wild guesses of drastic reduction of theory uncertainties

Georg Weiglein, QU Future Facilities Platform — Higgs Meeting, Hamburg, 05 / 2019



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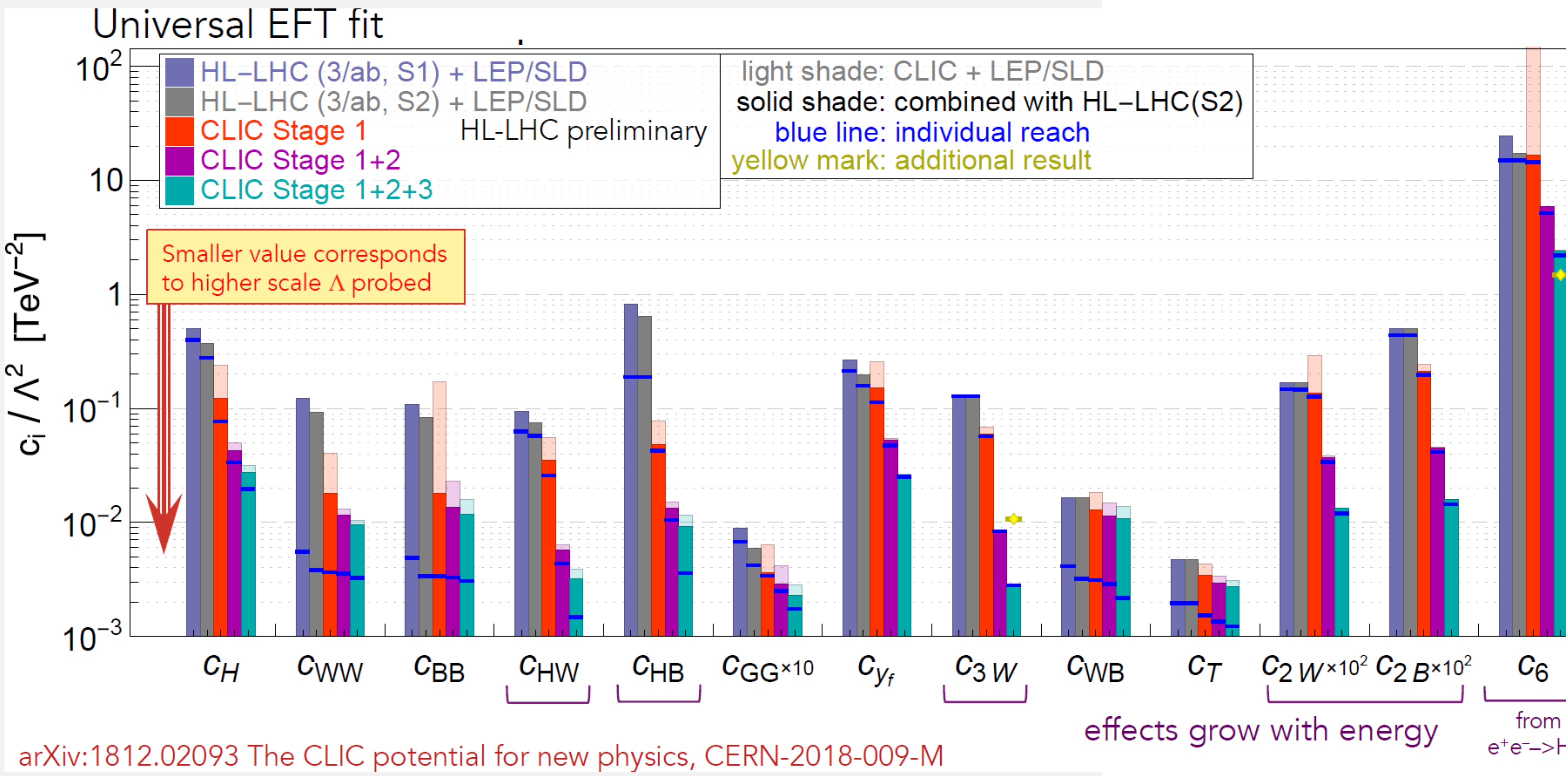
HIGGS AS A PORTAL TO BSM

- BSM physics can manifest itself in the Higgs sector in several ways:
  - Contribution from the higher order operators (EFT approach)
  - Higgs compositeness
  - Multiple Higgses
  - CPV in the Higgs sector
- BSM interpretation of Higgs



High energy Higgs production is the most sensitive to contributions from the 6D operators in the EFT approach, and thus can probe the highest NP scale Λ

HIGGS AS A PORTAL TO BSM

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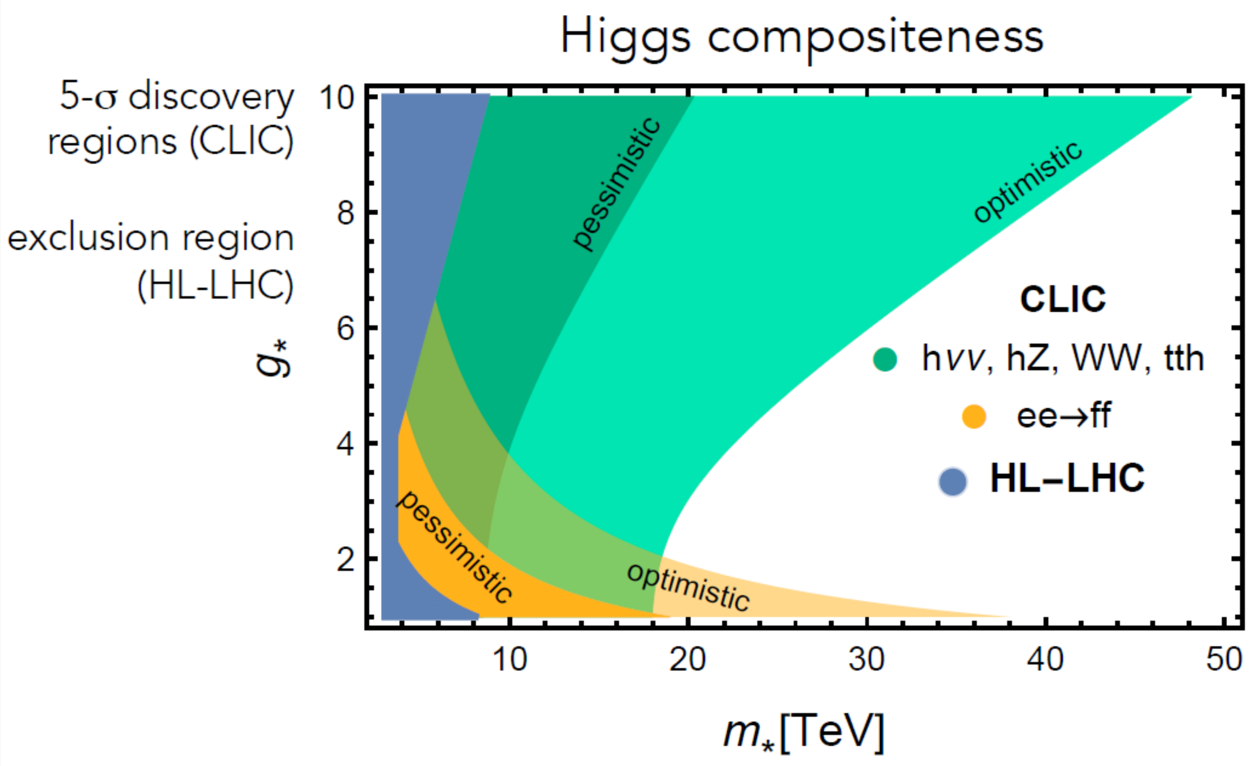

arXiv:1812.02093 The CLIC Potential for New Physics
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The scale of compositeness can be probed significantly further from the high-energy collider kinematic limit

HIGGS AS A PORTAL TO BSM

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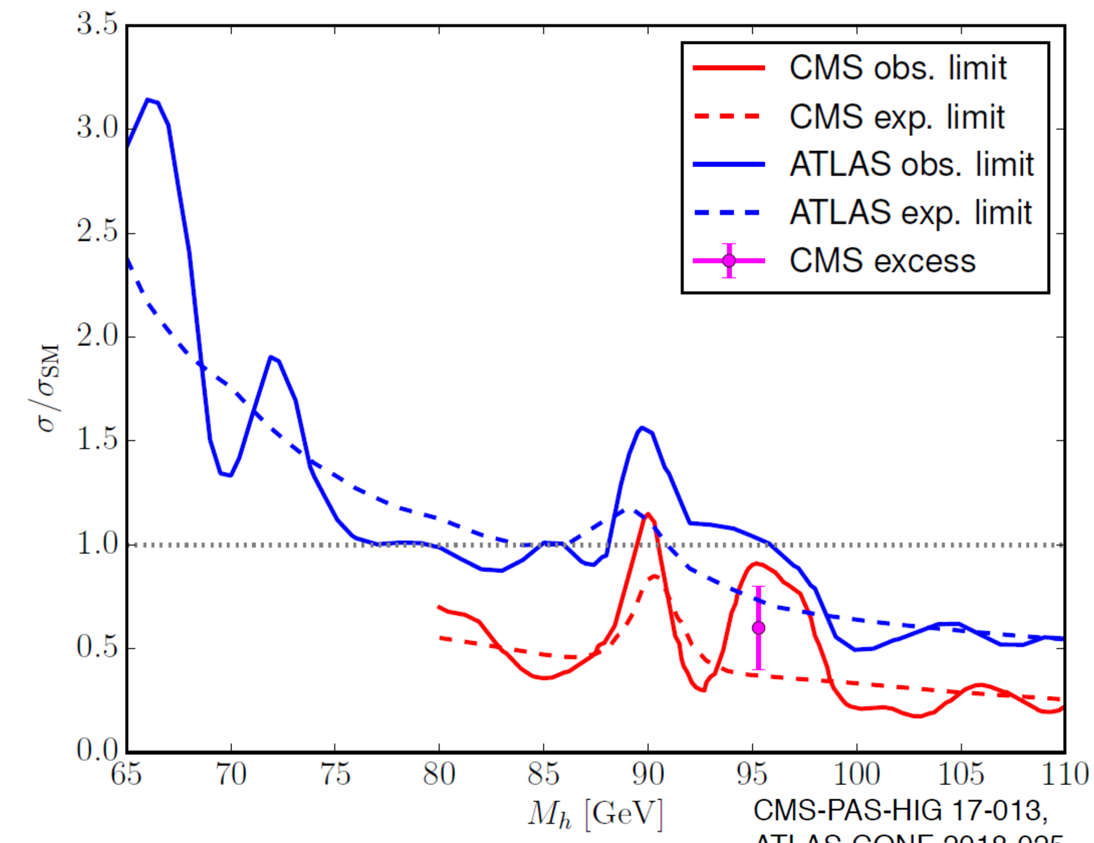


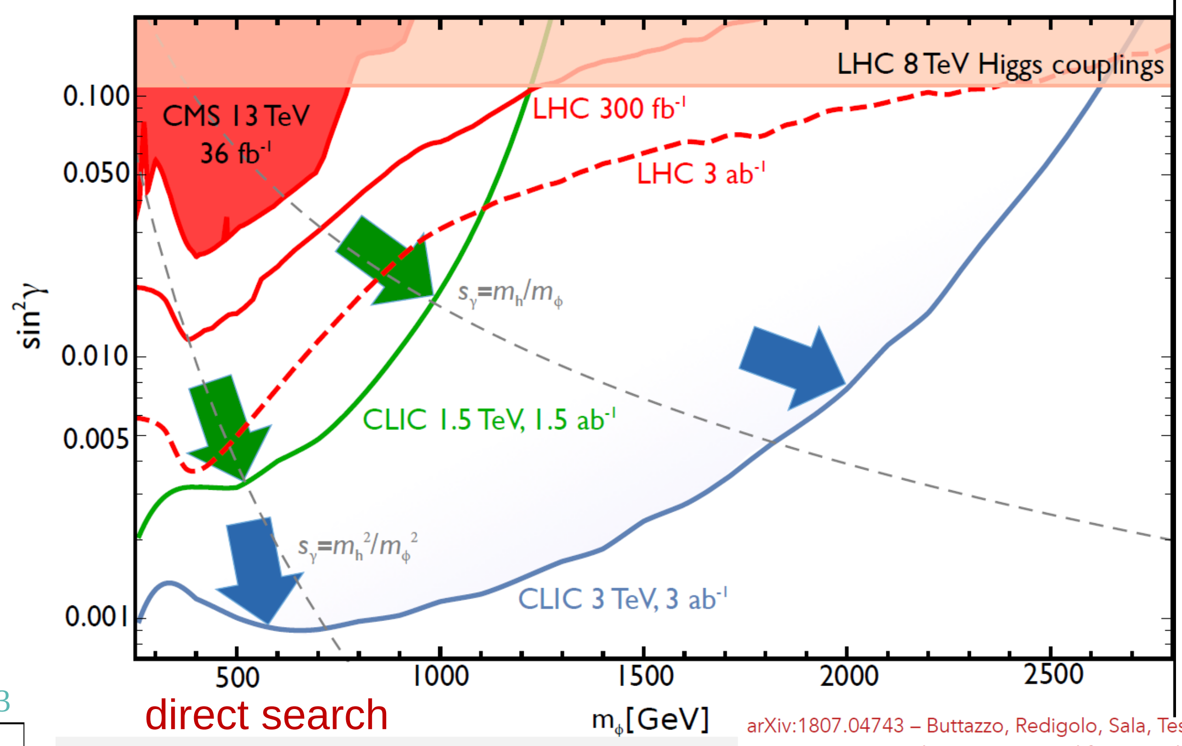
CMS-PAS-HIG 17-013,
ATLAS-CONF-2018-025

- In majority of BSM models, SM Higgs comes with additional Higgses (2HDM, SUSY in general, compositeness,..etc.)
- Can be a lighter scalar than SM Higgs – it is important to be capable of probing such states at future colliders
  - If SM Higgs is the lightest, other states are nearly mass-degenerated

HIGGS AS A PORTAL TO BSM

Multiple Higgses

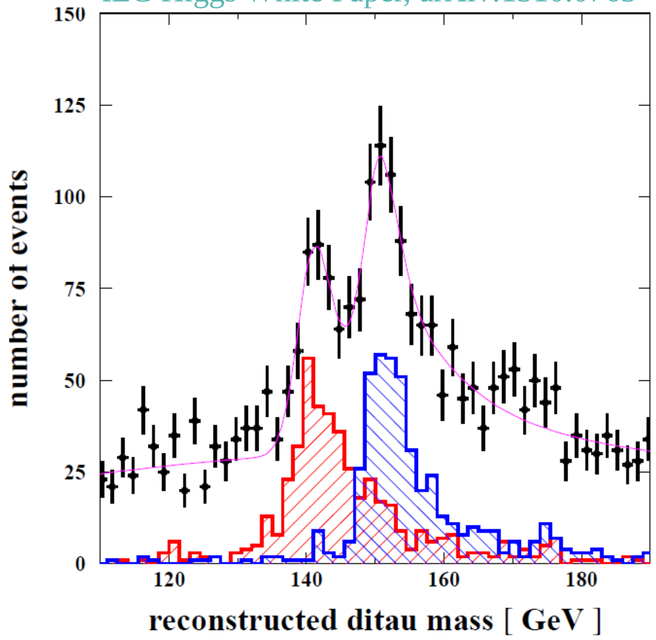
Real scalar singlet ϕ mixed with the SM-like Higgs via mixing angle γ



arXiv:1807.04743 – Buttazzo, Redigolo, Sala, Tesi
arXiv:1812.02093 The CLIC Potential for New Physics

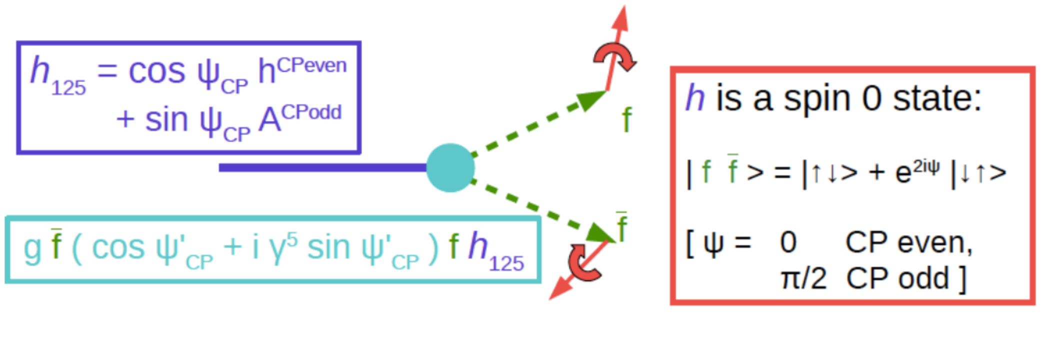
Direct HA production in 2HDM at ILC; A→ττ can be directly reconstructed as long as m_{HA} is not larger than available cm energy. Else, associated production i.e. bbA, ττA

ILC Higgs White Paper, arXiv:1310.0763

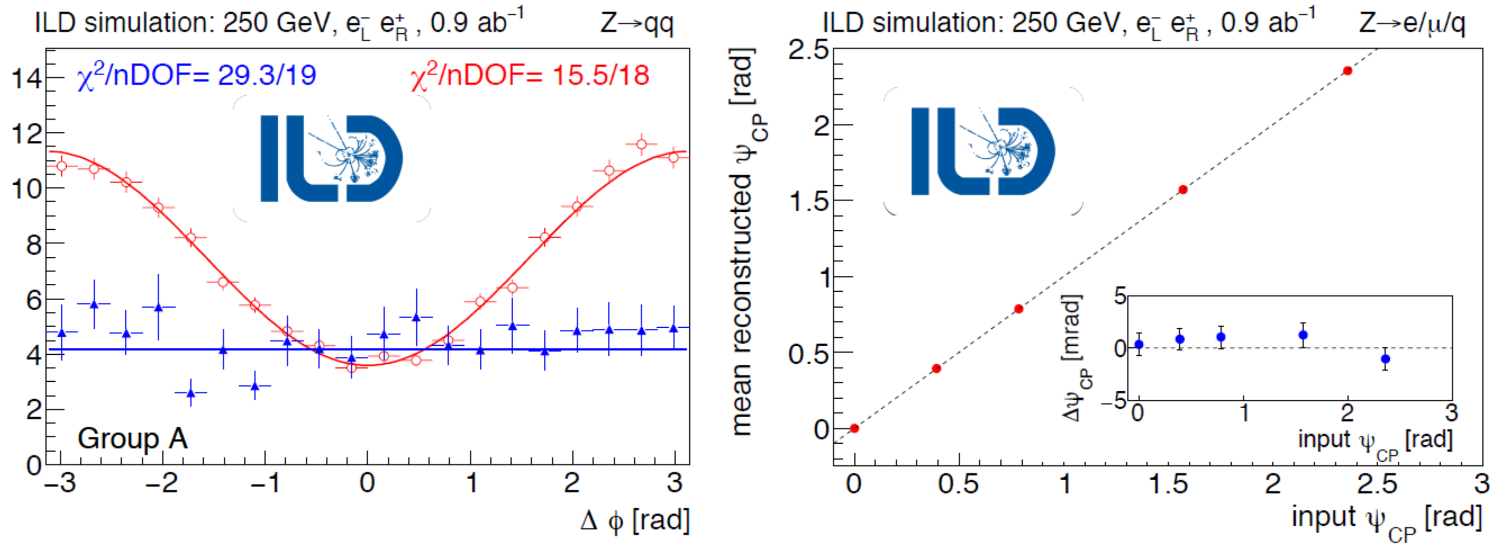


Again, it is pretty obvious that a high-energy collider can do more than 'just' a Higgs factory, also in a case of multiple Higgs bosons

CPV IN THE HIGGS SECTOR



- More difficult than just a spin/parity determination: Higgs can be a mixture of different CP eigenstates
- Can be addressed in HVV processes (i.e. H→ZZ→4l)
- Also in Higgs couplings to fermions
- Only lose bounds (at present) on a quantum superposition od different CP states
- Experimentally disfavored hypothesis on purely CP odd state



arXiv:arxiv:1804.01241

At ILC250 (polarized) CPV mixing angle can be determined with 70 mrad uncertainty

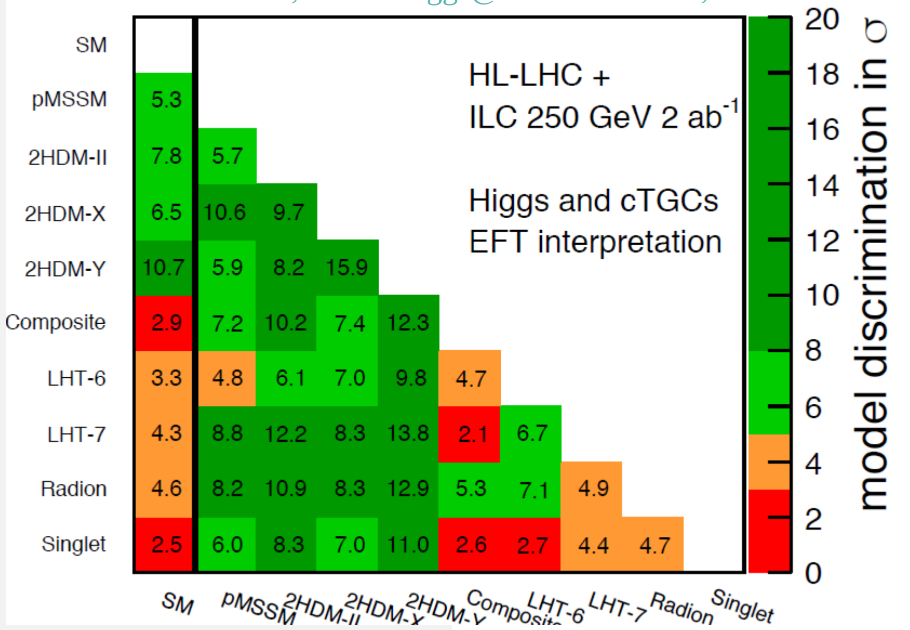
At FCCee, estimated uncertainty for the same decay channel is 174 mrad (FCCee CDR, 2018)

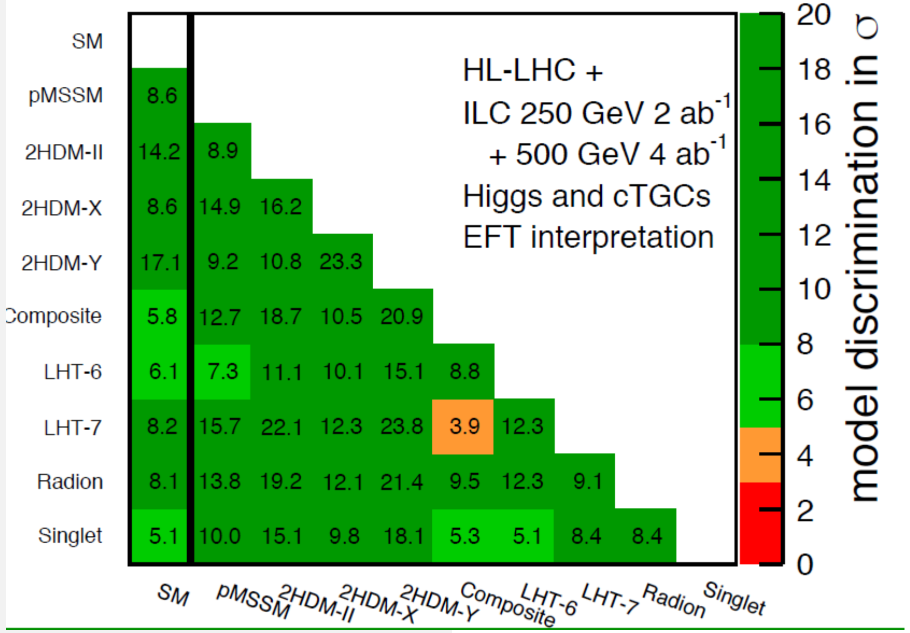
BSM INTERPRETATION OF HIGGS

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [36]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [35]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [35]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [35]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [37]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [38]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [39]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [40]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [41]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

- Impact of various BSM models on Higgs couplings to SM particles (arXiv:1708.08912)
- Unlikely to be tested at LHC or HL-LHC

J. List, ECFA HIggs@FutureColliders, 2019





- Substantial improvement at higher energies (linear e+e- colliders): @ILC a factor 2 in Higgs couplings precision with 500 GeV polarized beams
- Complementarity with HL-LHC

AN ATTEMPT TO ANSWER THE QUESTIONS*

- To what extent are the linear and circular e+e- colliders complementary?
- To what extent are they synergistic with the HL- LHC?
- How might the results from the HL-LHC affect the opportunities with these other future machines?
- Is there a need for more than one future collider?

***from the perspective of Higgs physics**

AN ATTEMPT TO ANSWER THE QUESTIONS*

- To what extent are the linear and circular e+e- colliders complementary?

- *Well, not really. They cover more or less the same parameter space with similar precision (Higgs width, couplings).*
- *The real breakthrough comes with a high-energy (i.e. ≥1 TeV) e+e- collider (Higgs self-coupling, compositeness, BSM sensitivity of the Higgs sector).*
- *And also with a beam polarization (i.e. CPV, BSM).*

Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
$CLIC_{350}$	4.7	κ-framework [85]	2.6
$CLIC_{1500}$	2.6	κ-framework [85]	1.7
$CLIC_{3000}$	2.5	κ-framework [85]	1.6
CEPC	3.1	$\sigma(ZH, \nu\bar{\nu}H)$, BR$(H \to Z, b\bar{b}, WW)$ [90]	1.8
$FCC\text{-}ee_{240}$	2.7	κ-framework [1]	1.9
$FCC\text{-}ee_{365}$	1.3	κ-framework [1]	1.2

arXiv:1905.03764

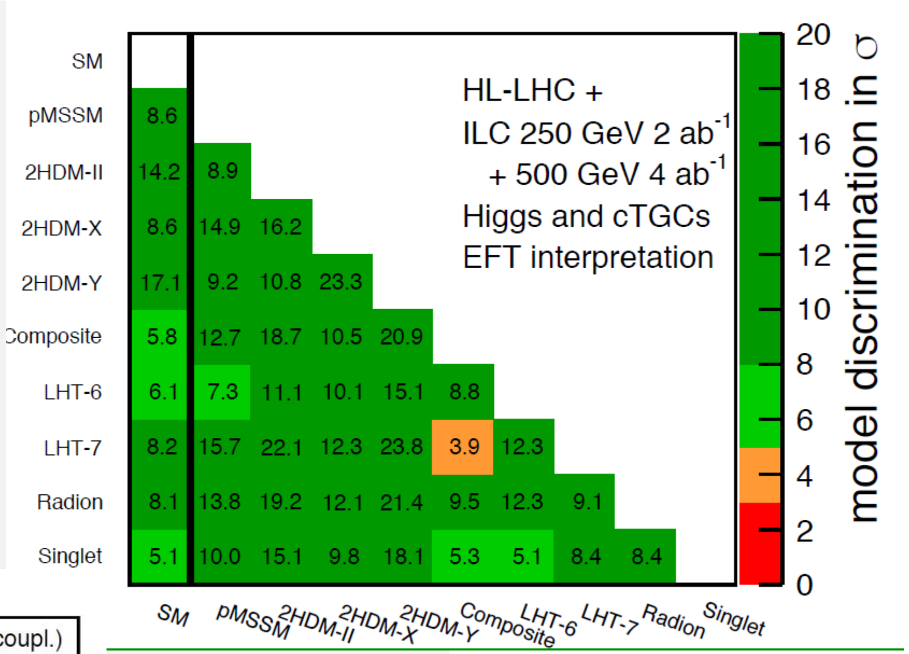
g_{HHH}/g_{HHH}^{SM} CLIC	1.4TeV: –34%, +36% rate-only analysis	1.4 + 3TeV: **–7%, +11%** differential analysis

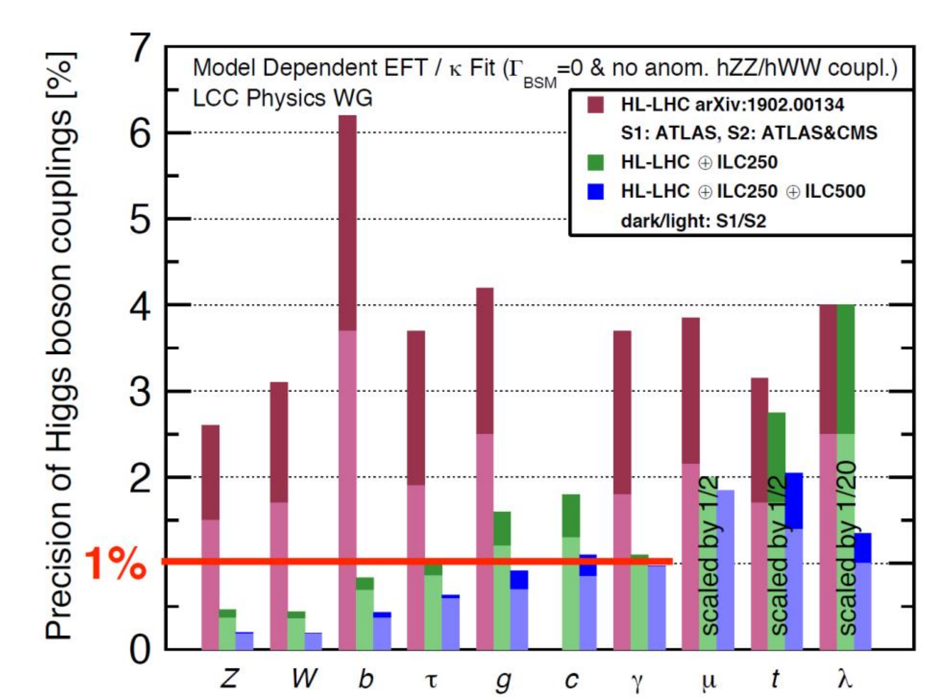
arXiv:1901.05897

Disclaimer: This is personal opinion of the speaker that can be extrapolated from the exhibited material. This is also a partial view based on future e+e- collider studies in Higgs physics.

AN ATTEMPT TO ANSWER THE QUESTIONS*

- **To what extent are they synergistic with the HL- LHC?**
  - *Absolutely, they are.*
  - ***All future e+e- projects** bring significant added value to the projected HL-LHC sensitivities in the Higgs sector…*
  - *… enabling discrimination of BSM models inaccessible at HL-LHC*





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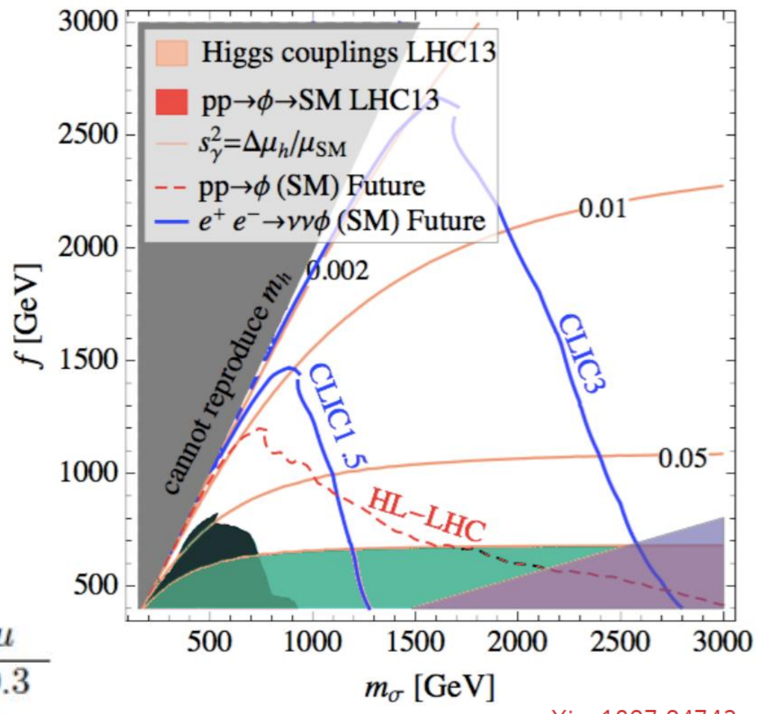
AN ATTEMPT TO ANSWER THE QUESTIONS*

- **How might the results from the HL-LHC affect the opportunities with these other future machines?**

  - *According to what we (theorists) can think of, future projects seem to be very well equipped to address even very exotic physics options.*
  - *Yet, one can always get surprised by Nature.*

Twin Higgs model:
S is SM singlet state from the twin sector; h–S mixing is of order v/f



arXiv: 1807.04743

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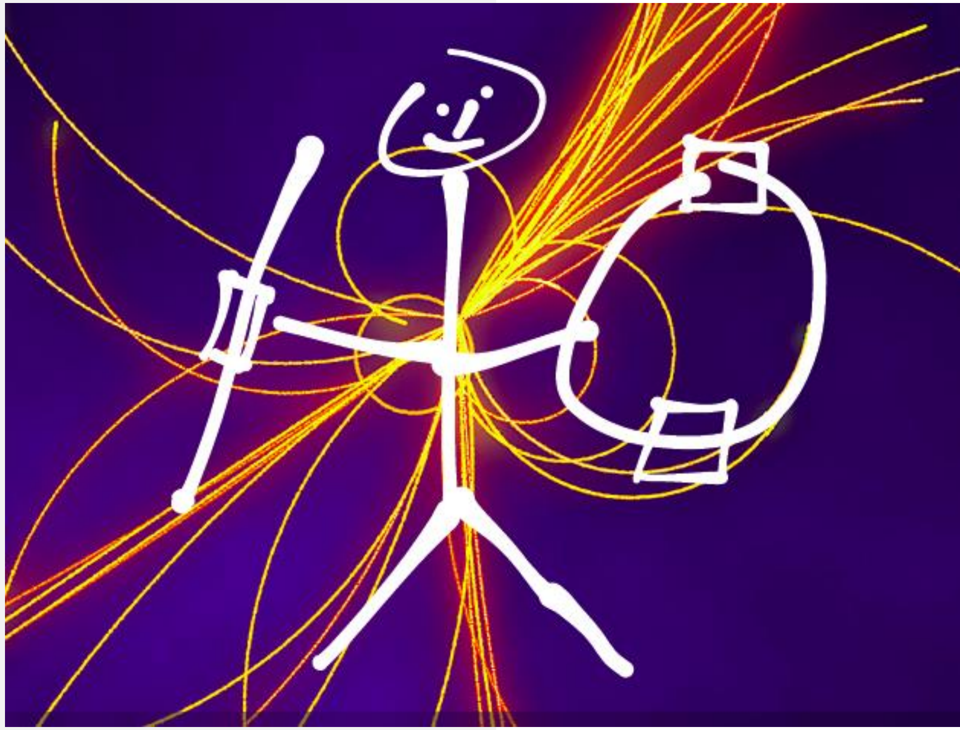
AN ATTEMPT TO ANSWER THE QUESTIONS*

- Is there a need for more than one future collider?



- *If we (the world) could afford it, a 'dream-combination' might be a TeV or a multi-TeV e+e- (linear) collider*
- *+ a 100 TeV hadron-collider, that comes at the moment with so many open issues:*
  - Accelerator & detector technologies vise
  - Huge pile-up
  - Systematics control and theoretical uncertainties
  - ….
- *NB: Added value of this, or any other combination, has to be justified with the adequate level of details, above the simple statistical scaling of precision.*

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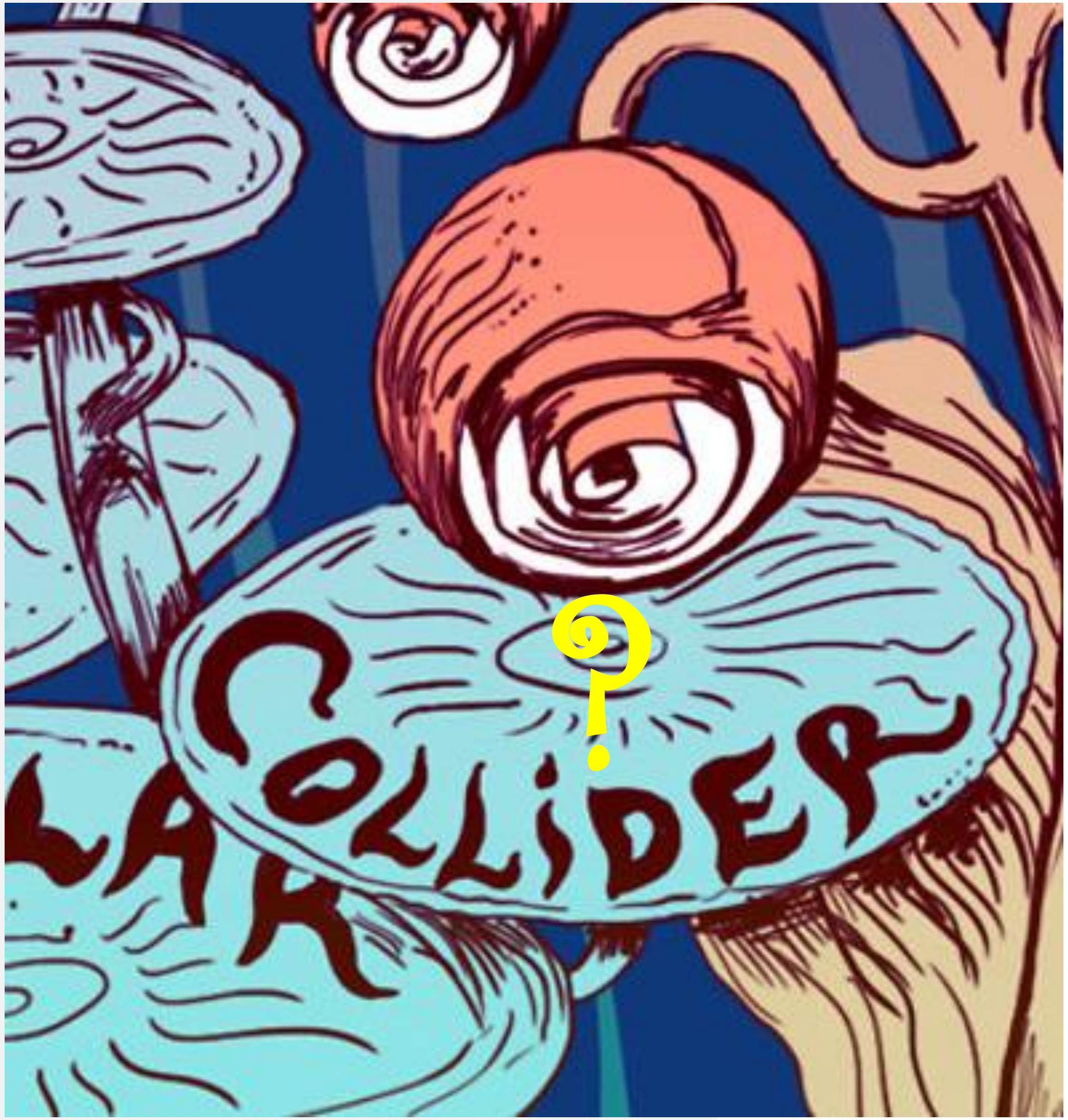
SUMMARY

- Future e+e- colliders will enable measurements in the Higgs sector (mass, width, couplings) far beyond HL-LHC precision
- Higher center of mass energy significantly extends sensitivity to the Higgs self-coupling, compositeness scale and BSM scenarios



THANK YOU