

# Electroweak (SM, BSM) @Granada

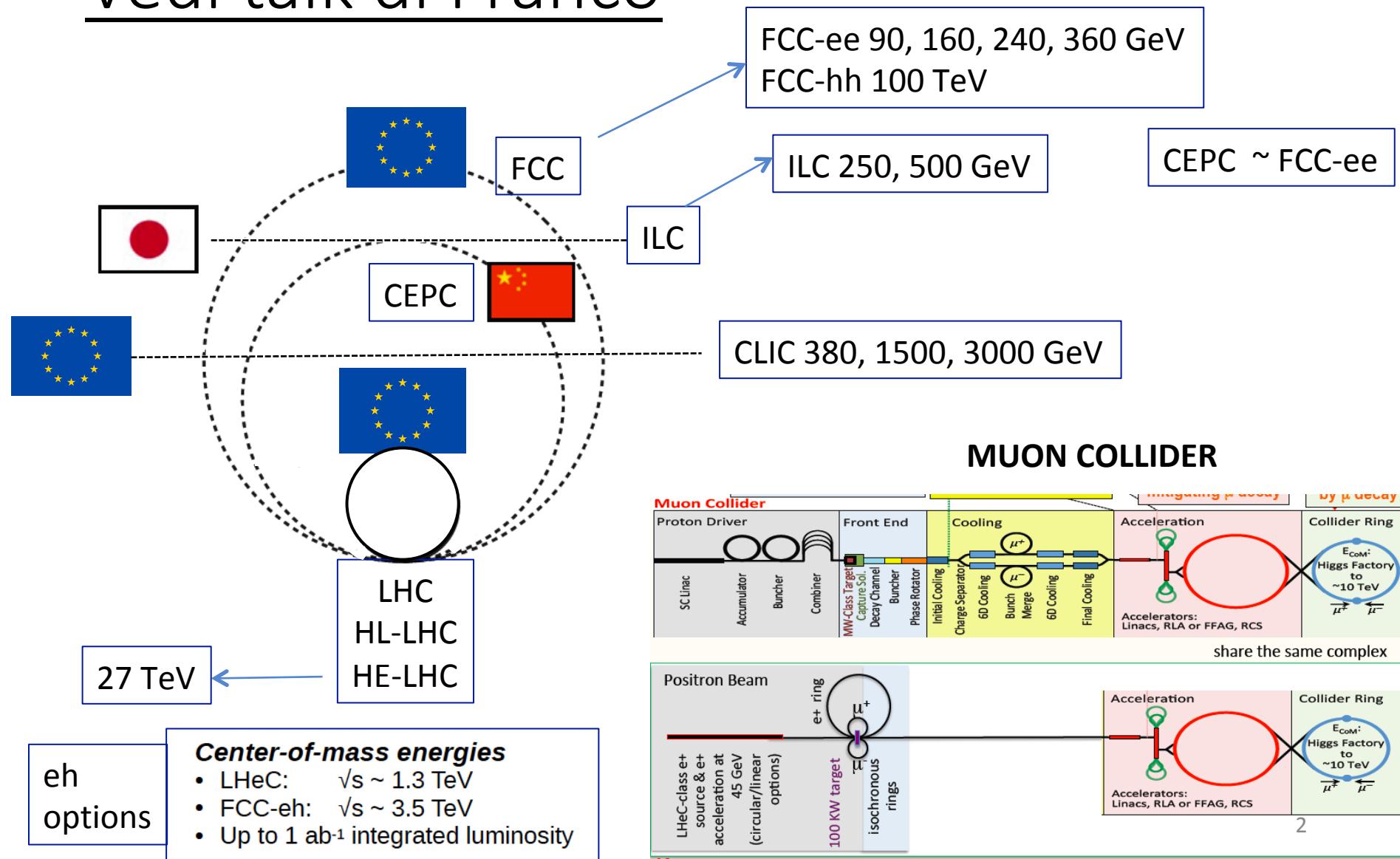
Roberto Tenchini

INFN Pisa

Pisa, 10 Giugno 2019

# Quali strumenti per le misure ?

## Vedi talk di Franco

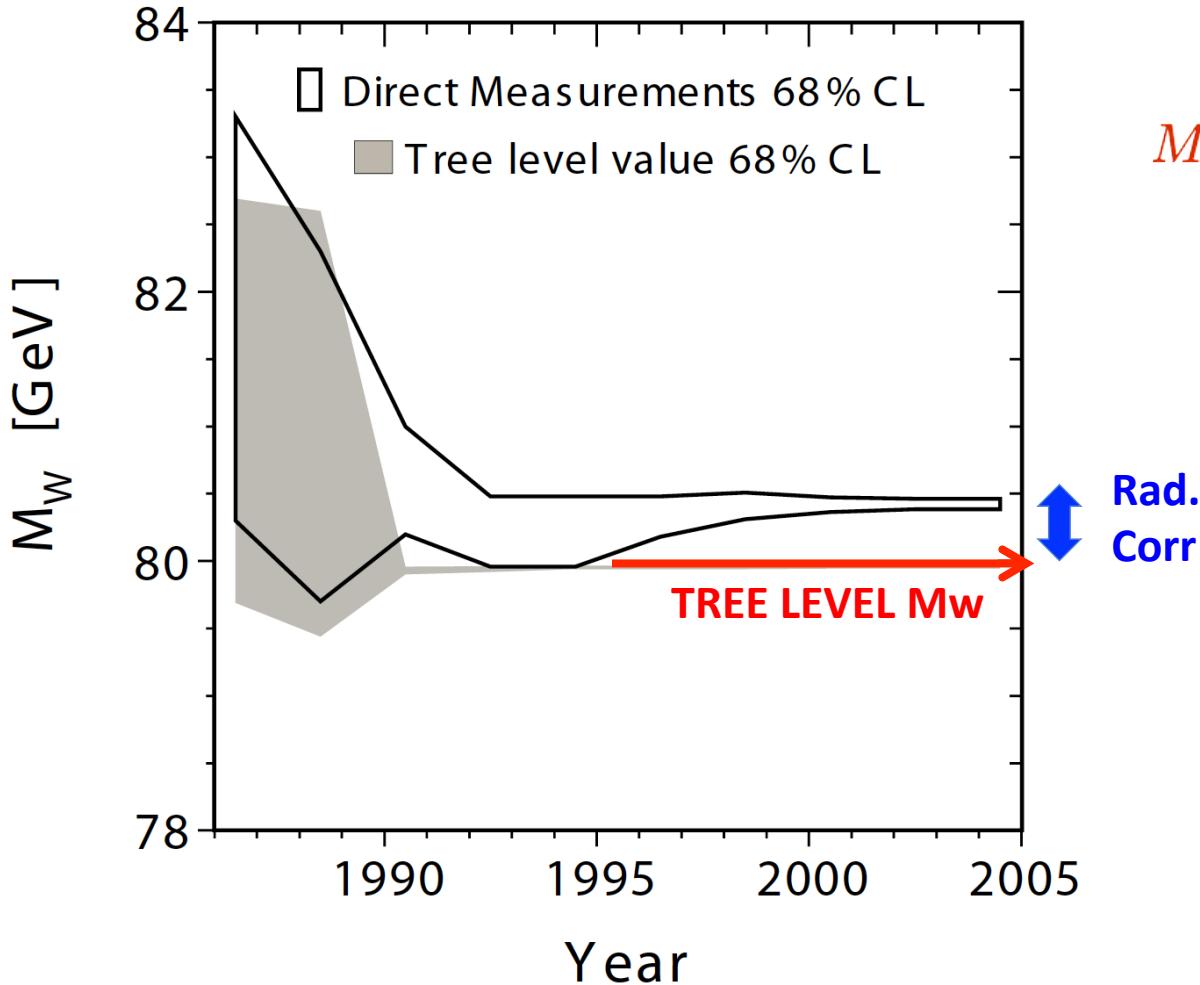


# Come ho organizzato il (breve ?) talk

- Impatto misure di precisione elettrodeboli, focalizzato alla parte  $e^+e^-$ 
  - assumo che fisica pp, e.g. Higgs, sia ben nota grazie a LHC
- Confronto sensitività vari progetti nel settore elettrodebole utilizzando un linguaggio comune (EFT)
- Confronto progetti model dependent (specifici benchmark BSM)

QUESTA NON E' UNA REVIEW ESAUSTIVA DEI LAVORI PRESENTATI A GRANADA

# Motivation: Fertile Ground



**TREE LEVEL SM**

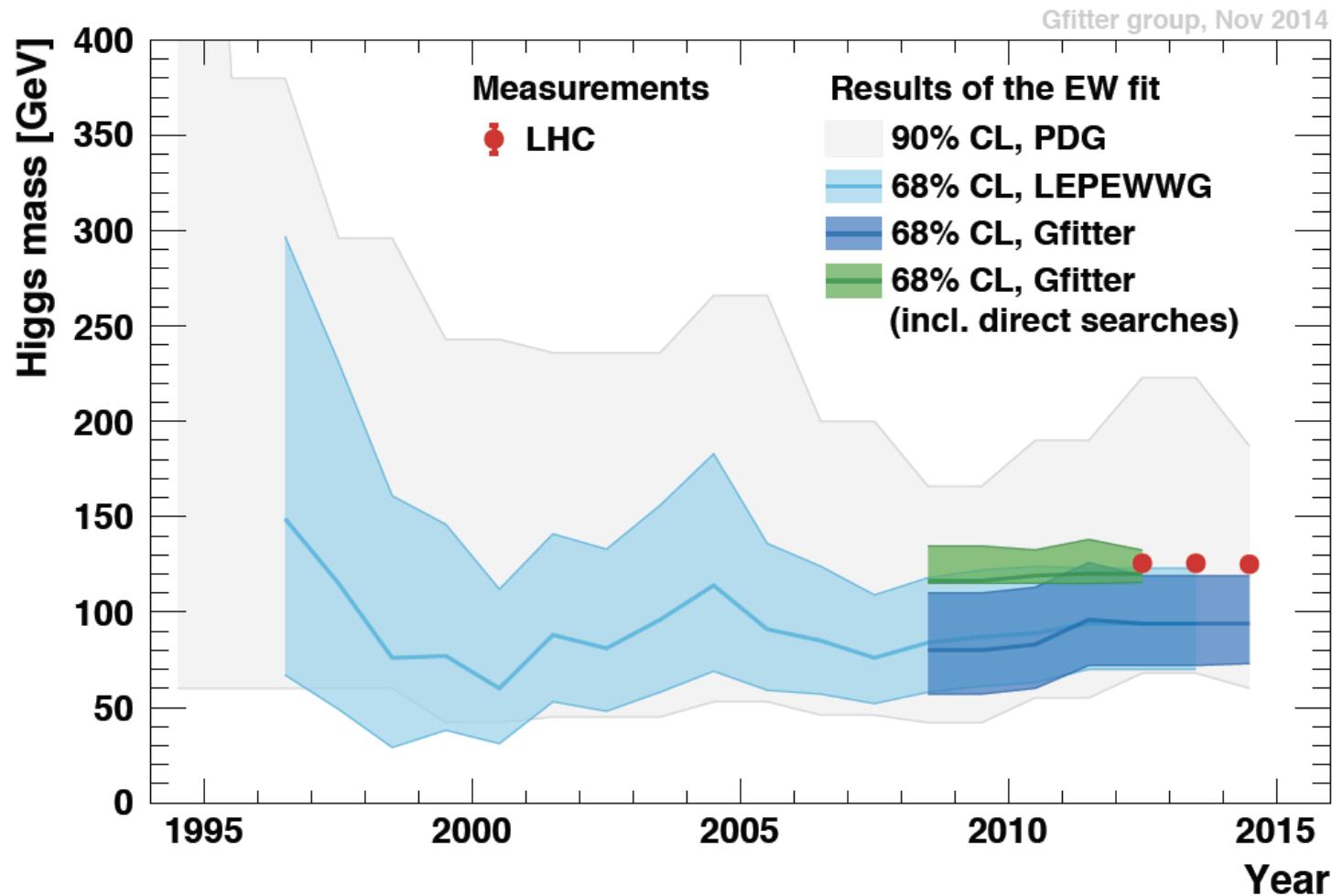
$$M_W^2 \left( 1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi \alpha_{EM}}{\sqrt{2} G_F}$$

**LOOP LEVEL SM**

~ 500 MeV.

Requires 0.5%  
precision to probe

# Misura indiretta+diretta → progresso nella comprensione



# Misure a collider e+e- circolare (FCC-ee/CEPC) di rilevanza per fit globali elettrodeboli

## **TeraZ ( $5 \times 10^{12} Z$ )**

From data collected in a lineshape energy scan:

- Z mass (key for jump in precision for ewk fits)
- Z width (jump in sensitivity to ewk rad corr)
- $R_i$  = hadronic/leptonic width ( $\alpha_s(m_Z^2)$ , lepton couplings)
- peak cross section (invisible width,  $N_\nu$ )
- $A_{FB}(\mu\mu)$  ( $\sin^2\theta_{eff}$ ,  $\alpha_{QED}(m_Z^2)$ , lepton couplings)
- Tau polarization ( $\sin^2\theta_{eff}$ , lepton couplings,  $\alpha_{QED}(m_Z^2)$ )
- $R_b, R_c, A_{FB}(bb), A_{FB}(cc)$  (quark couplings)

## **OkuWW ( $10^8 WW$ )**

From data collected around and above the WW threshold:

- W mass (key for jump in precision for ewk fits)
- W width (first precise direct meas)
- $R^W = \Gamma_{had}/\Gamma_{lept}$  ( $\alpha_s(m_Z^2)$ )
- $\Gamma_e, \Gamma_\mu, \Gamma_\tau$  (precise universality test )
- Triple and Quartic Gauge couplings (jump in precision, especially for charged couplings)

## **Higgs – Top**

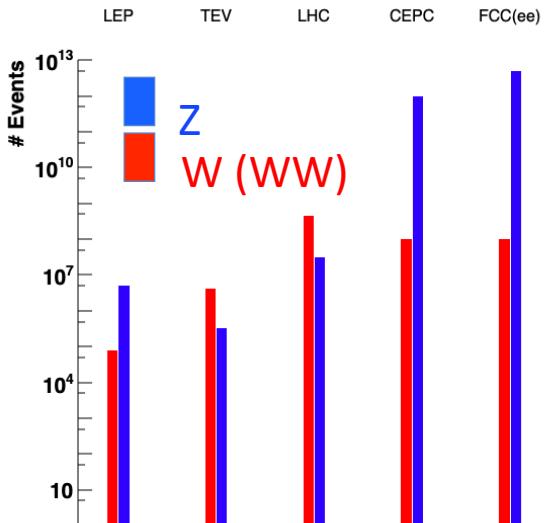
Dati a 240 – 360 GeV :

- Higgs mass
- Top mass
- *Higgs couplings and top couplings included in EFT global fits*

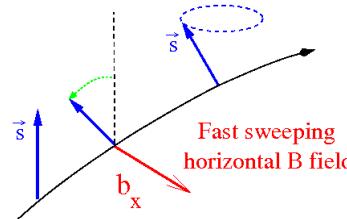
**Tipicamente la precisione di queste misure può essere migliorata di 1 o 2 ordini di grandezza rispetto ad oggi**

# Ingredienti per O(10) in precisione

## Statistica

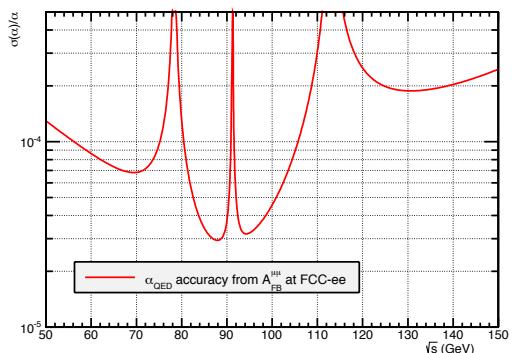


## Sistematici: nuove tecniche



Esempio: dedicare un  
bunch alla calibrazione  
continua in energia

## Sistematici: nuove misure



direct measurement of  $\alpha_{\text{QED}}(m_Z^2)$

## Teoria: miglioramento dei calcoli

BU-HEPP-18-04, CERN-TH-2018-145, IFJ-PAN-IV-2018-09, KM-18-003  
MITP/18-052, MPP-2018-143, SI-HEP-2018-21

### Standard Model Theory for the FCC-ee: The Tera-Z

Report on the 1<sup>st</sup> Mini workshop: Precision EW and QCD calculations in the FCC studies: methods and tools, 12-13 January 2018, INFN Roma

<https://indico.cern.ch/event/759759/>

A. Blondel<sup>1</sup>, J. Gómez<sup>2</sup>, J. Gómez-Román<sup>3,4</sup> (editors),

S. Bondu<sup>5</sup>, A. Boughezale<sup>6</sup>, C.M. Carloni Calame<sup>7</sup>, I. Dubovsky<sup>8,9</sup>,

Ya. Dydnytska<sup>10</sup>, S. Eidelman<sup>11</sup>, P. Ekelin<sup>12</sup>, K. Grzanka<sup>13</sup>, T. Hahn<sup>14</sup>, T. Hahn<sup>15</sup>,

J. Hahn<sup>16</sup>, J. Hahn<sup>17</sup>, P. Heslot<sup>18</sup>, P. Heslot<sup>19</sup>, J. Heshmati<sup>20</sup>, N. Inoue<sup>21</sup>,

S. Kramnik<sup>22</sup>, S. Krasznahorkay<sup>23</sup>, R. Sadykov<sup>19</sup>, M. Skrzypek<sup>24</sup>, D. Stöckinger<sup>21</sup>, J. Usovitsch<sup>22</sup>,

B.F.L. Ward<sup>12,13</sup>, S. Weinzierl<sup>19</sup>, G. Yung<sup>25</sup>, S.A. Yost<sup>26</sup>

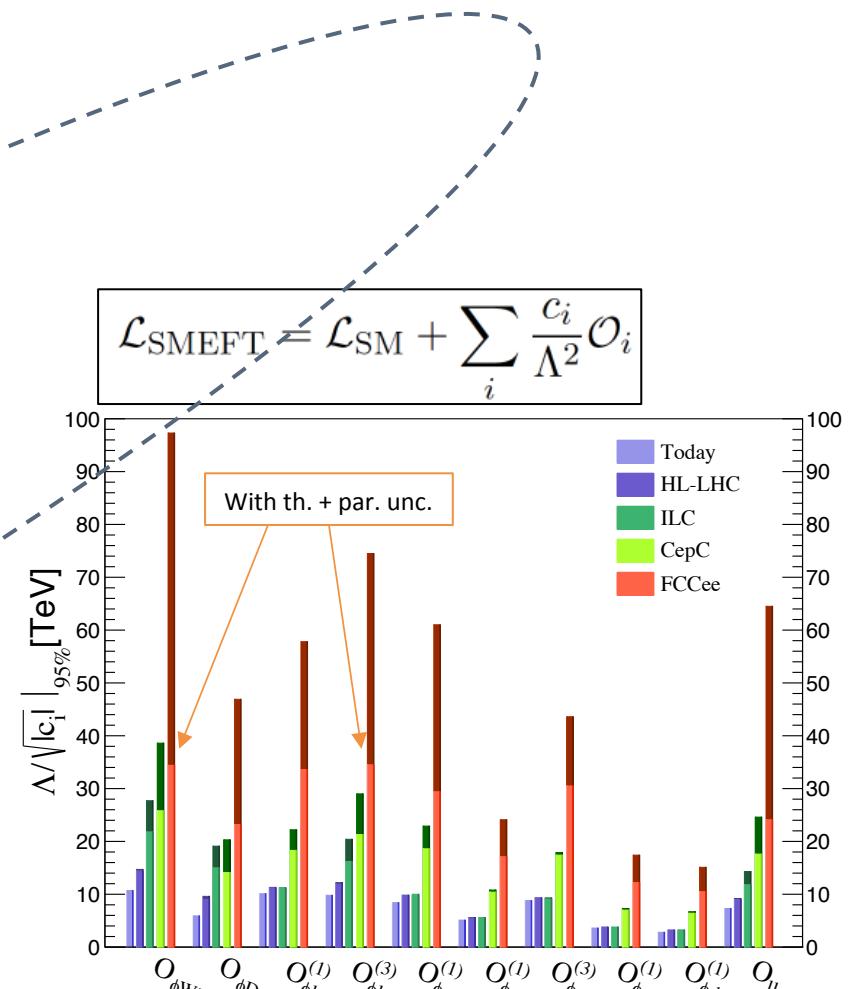
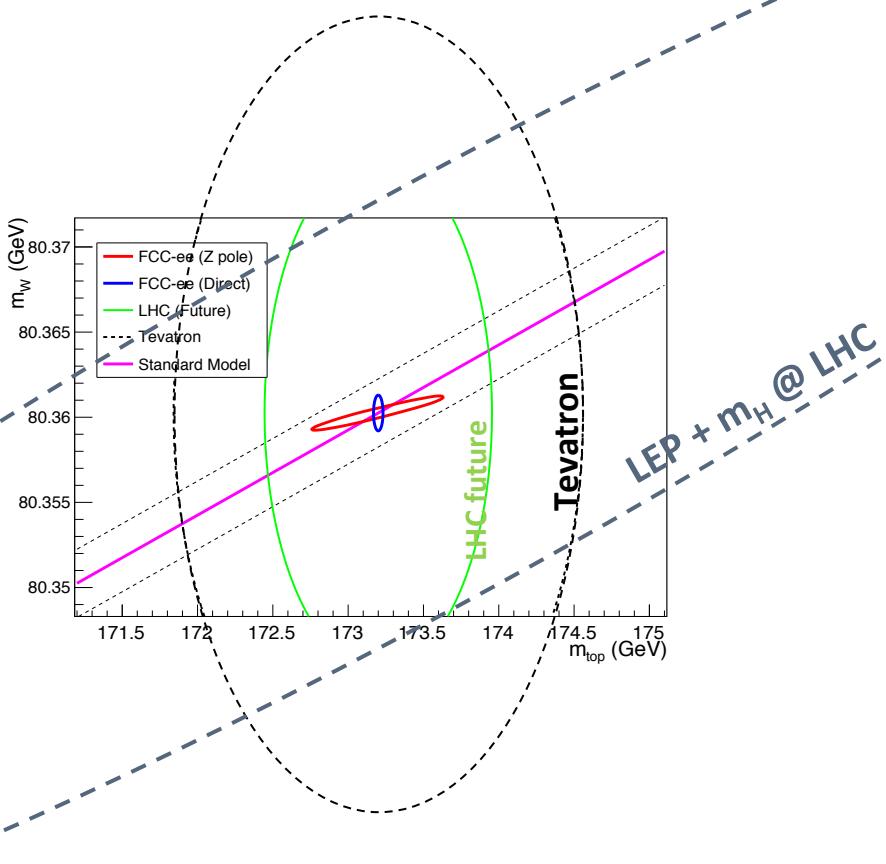
arXiv:1809.01890 [hep-ph] 22 Sep 2018

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Teórica, Universidad de Valencia, 46100 Valencia, Spain and Ayerbejón National Academy of Sciences,  
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<sup>8</sup>II Institute for Theoretical Particle Physics Universität Hamburg, 22761 Hamburg, Germany, <sup>9</sup>Istituto Nazionale di

3 loop calculation, will  
provide the needed precision

# ewk fit and sensitivity to new physics

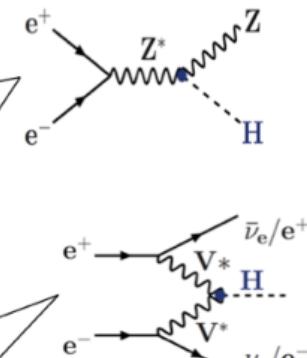
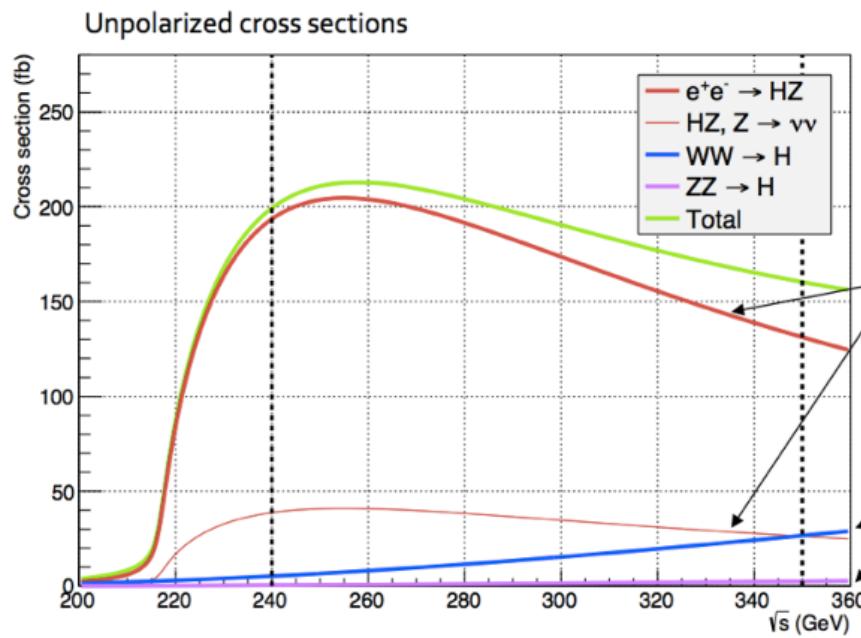
## Esempio da FCC-ee



Jorge de Blas  
LHCPh 2017

# The Higgs program at $\sqrt{s}=240$ and 350 GeV

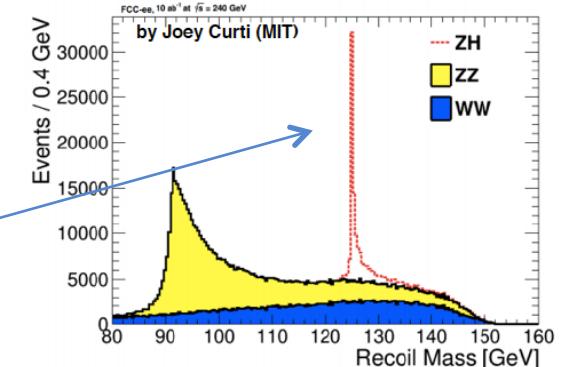
	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab <sup>-1</sup> )	5	1.5
Number of Higgs bosons from $e^+e^- \rightarrow HZ$	1,000,000	200,000
Number of Higgs bosons from fusion process	25,000	40,000



Combining  
Higgstrahlung and  
Vector Boson Fusion  
at the two centre-of-  
mass energies

Recoil mass: Higgs events are tagged decay independent

$$\sigma(ZH) \sim g_{HZZ}^2$$

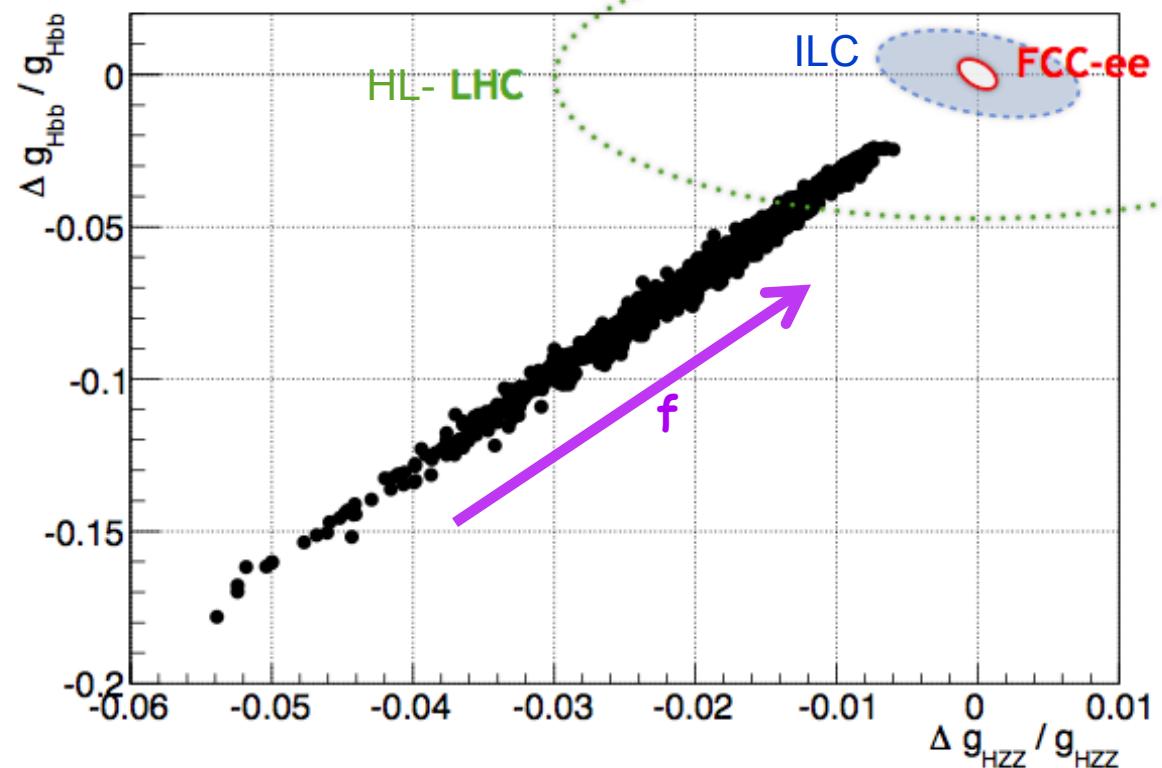


# Higgs couplings e sensitivita' a nuova fisica

Esempio: sensitivita' degli accoppiamenti del bosone di Higgs a Z e b quark a deviazioni dovute a Composite Higgs Models (4HDM)

Models → black points  
Ellipses → exp reach

$f$  = compositeness scale  
 $0.75 \leq f \text{ (TeV)} \leq 1.5$



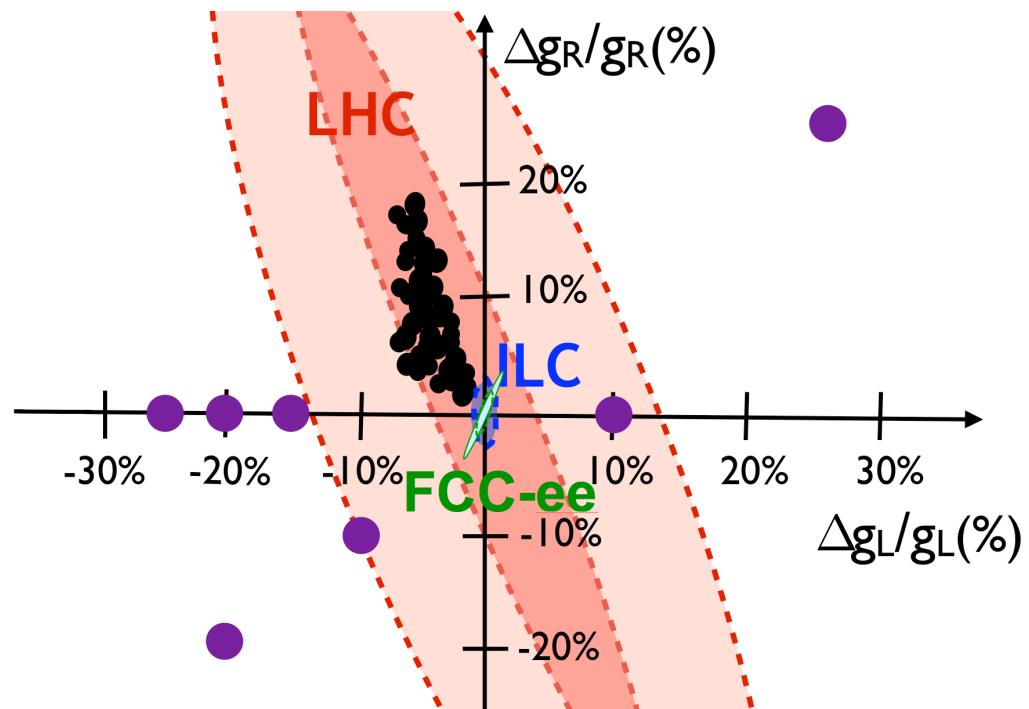
Deviations for HZZ and Hbb couplings in the 4DCHM  
compared with the relative precision expected at HL-LHC, ILC, FCC-ee

(DeCurtis, Redi, Tesi JHEP 1204(2012)042;  
Barducci et al. JHEP 1309(2013)047)  
(Janot EPS Proc.1510.09056)

# Run a $> 350$ GeV per misura massa top e top couplings

Esempio: sensitivita' agli accoppiamenti del quark top al bosone Z in vari scenari di nuova fisica confrontato con le precisioni di presenti e futuri acceleratori

[*Frascati Phys. Ser.* 60 (2015) 28-57]



Produzione ttZ recentemente osservata a LHC  
ATLAS Collaboration, JHEP 11 (2015) 172  
CMS Collaboration, JHEP 01 (2016) 096

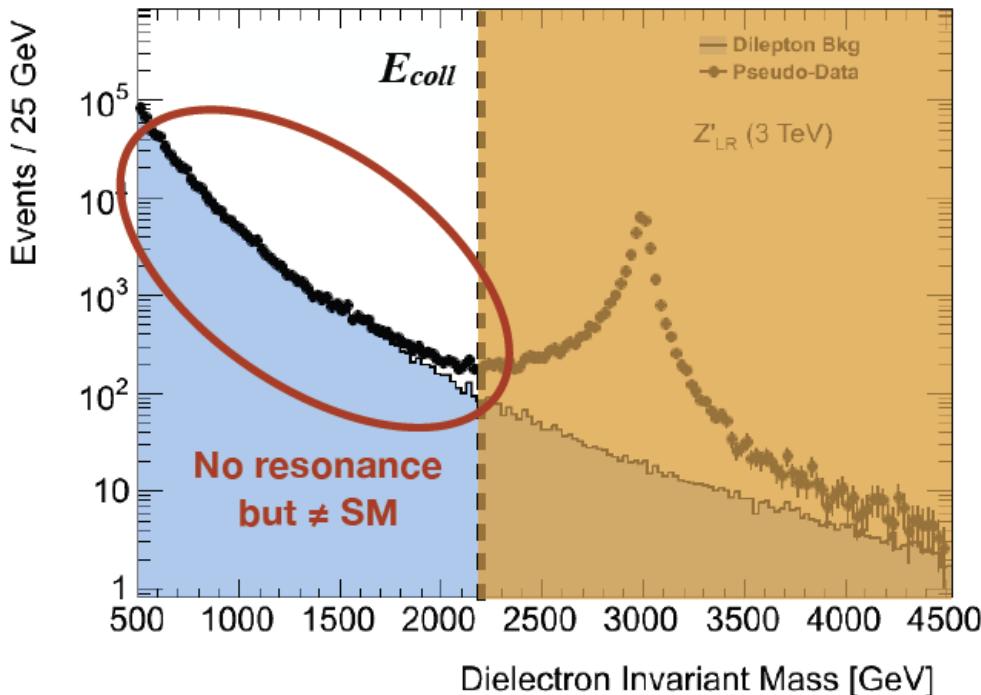
Granada: confronto  
progetti utilizzando uno  
schema basato su  
lagrangiane effettive

# Effective Field Theory description of New Physics

- BSM Effective Field Theories (EFT) are, by construction, a formalism for indirect tests of new physics

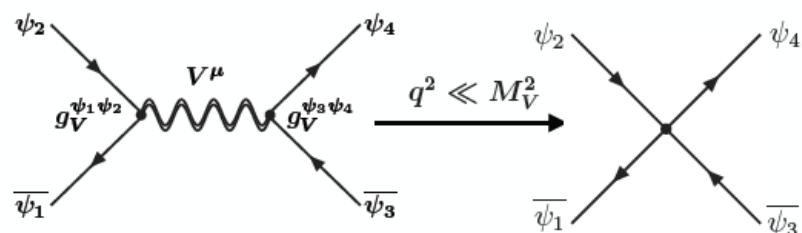
## What indirect searches look for

(e.g  $Z'$  effects in dilepton spectrum)



If  $E_{coll} < M_{Z'}$ , one can still test **virtual effects** of NP looking for “deformations” in SM measurements

For  $E_{coll} \ll M_{Z'}$ , these low-energy effects can be well described by effective interactions



In general, the whole set of such possible deformations can be studied with minimal reference to the nature of the UV theory

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{Z'} + \mathcal{L}_{\text{SM}-Z'} \xrightarrow{q^2 \ll M_V^2} \mathcal{L}_{\text{Eff}}$$

- The dimension 6 SMEFT:

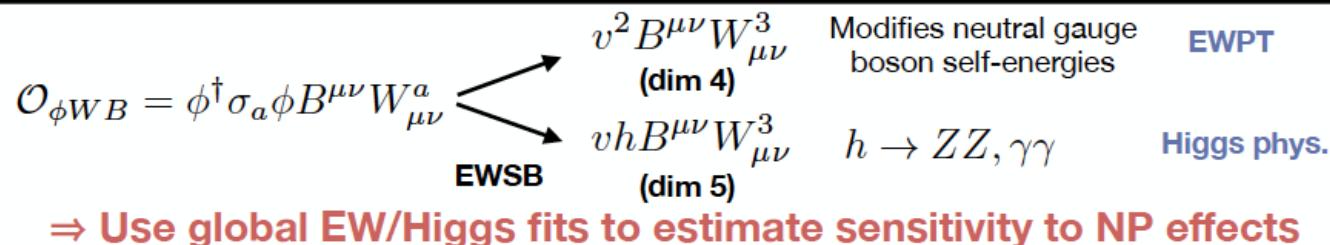
$$\mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \dots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \quad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

$\Lambda$ : Cut-off of the EFT

Effects  
suppressed by     $q = v, E < \Lambda$

- LO new physics effects “start” at dimension 6: **59 B & L preserving operators**  
[B.Grzadkowski, M.Iskrynski, M.Misiak, J.Rosiek, JHEP 1010 \(2010\) 085](#) (2499 counting flavor)
- SMEFT describes correlations of new physics effects in different types of observables, e.g.



Under these hypotheses we'll perform a fit to the future projections at each collider for

Single Higgs boson processes

EWPO: W and Z properties

Diboson production (aTGC)

(Top production)

# Higgs (and EW) physics at Future Colliders

- Inputs included in the fits (from ESU documents and Refs. therein):

	Higgs	aTGC	EWPO	Top EW
<b>FCC-ee</b>	Yes ( $\mu$ , $\sigma_{ZH}$ ) (Complete with HL-LHC)	Yes (aTGC dom.) <small>Warning</small>	Yes	Yes (365 GeV, Ztt)
<b>ILC</b>	Yes ( $\mu$ , $\sigma_{ZH}$ ) (Complete with HL-LHC)	Yes (HE limit) <small>Warning</small>	LEP/SLD (Z-pole) + HL-LHC + W (ILC)	Yes (500 GeV, Ztt)
<b>CEPC</b>	Yes ( $\mu$ , $\sigma_{ZH}$ ) (Complete with HL-LHC)	Yes (aTGC dom) <small>Warning</small>	Yes	No
<b>CLIC</b>	Yes ( $\mu$ , $\sigma_{ZH}$ )	Yes (Full EFT parameterization)	LEP/SLD (Z-pole) + HL-LHC + W (CLIC)	Yes
<b>HE-LHC</b>	Extrapolated from HL-LHC	N/A → LEP2	LEP/SLD + HL-LHC ( $M_W$ , $\sin^2\theta_W$ )	-
<b>FCC-hh</b>	Yes ( $\mu$ , $BR_i/BR_j$ ) Used in combination with FCCee/eh	From FCC-ee	From FCC-ee	-
<b>LHeC</b>	Yes ( $\mu$ )	N/A → LEP2	LEP/SLD + HL-LHC ( $M_W$ , $\sin^2\theta_W$ )	-
<b>FCC-eh</b>	Yes ( $\mu$ ) Used in combination with FCCee/hh	From FCC-ee	From FCC-ee + $Z_{uu}$ , $Z_{dd}$	-

# EFT studies at future colliders

## Presentation of SMEFT fit results

- Compare Future Collider sensitivity to deformations of Higgs couplings in a basis-independent way
  - Project EFT fit results into (pseudo) observable quantities

$$g_{HX}^{\text{eff}} \equiv \frac{\Gamma_{H \rightarrow X}}{\Gamma_{H \rightarrow X}^{\text{SM}}} \quad \text{Effective Higgs couplings}$$

Similar definition as  $\kappa$  modifiers, but different interpretation, e.g.

$$\frac{\Gamma_{ZZ^*}}{\Gamma_{ZZ^*}^{\text{SM}}} \simeq 1 + 2\delta c_Z - 0.15 c_{ZZ} + 0.41 c_{Z\square} + \dots \quad (\text{EW } Vff, hVff)$$

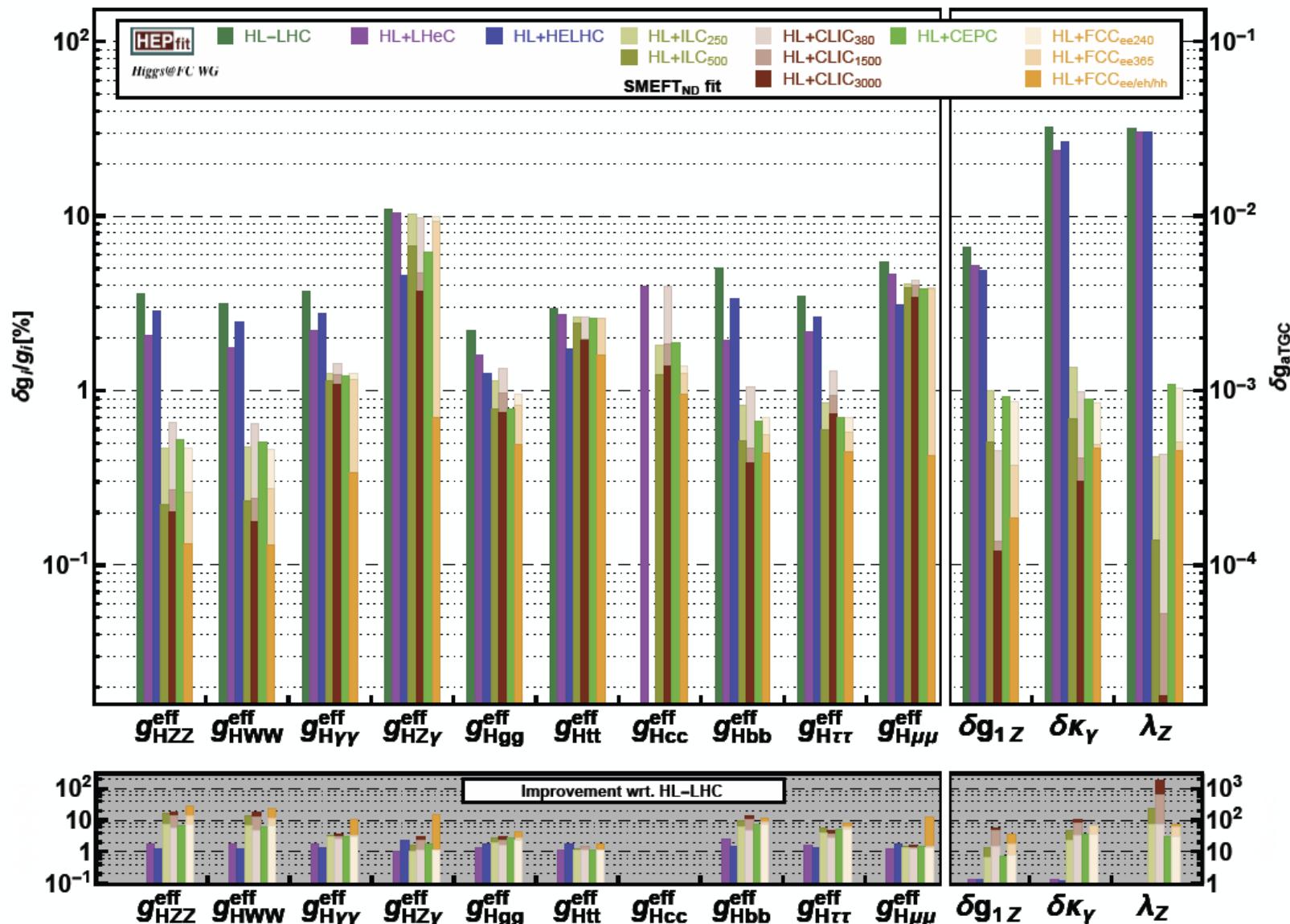
Only these are described in  $\kappa$ -framework

più informazione su  
arXiv:1905.03764

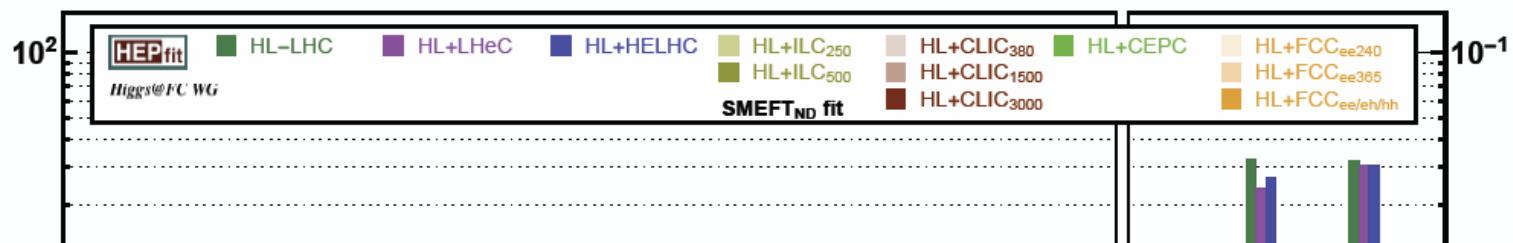
- Not enough to match EFT d.o.f : Add also aTGC
- Similarly, for EW interactions, project results into effective  $Zff$  couplings defined from EWPO, e.g.

$$\Gamma_{Z \rightarrow e^+ e^-} = \frac{\alpha M_Z}{6 \sin^2 \theta_w \cos^2 \theta_w} (|g_L^e|^2 + |g_R^e|^2), \quad A_e = \frac{|g_L^e|^2 - |g_R^e|^2}{|g_L^e|^2 + |g_R^e|^2}$$

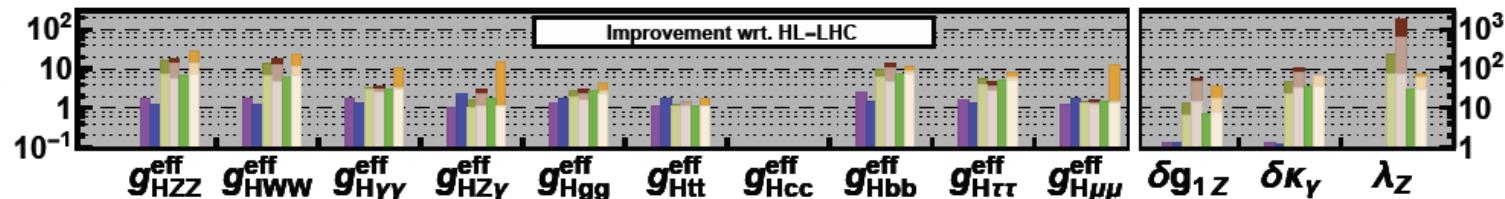
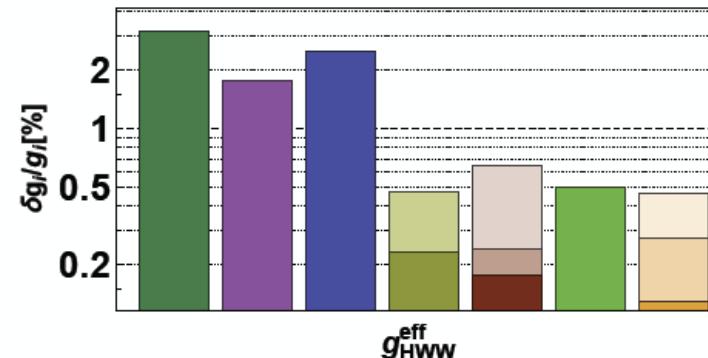
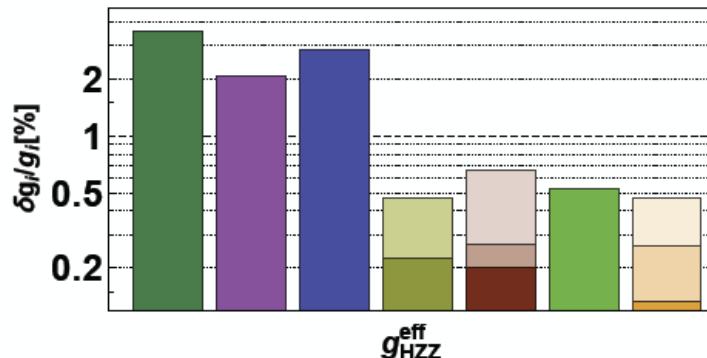
# Global fit results



# Global fit results



## Sensitivity to deviations in $HVV$ couplings



# Global fit results

## Improvement with respect to HL-LHC

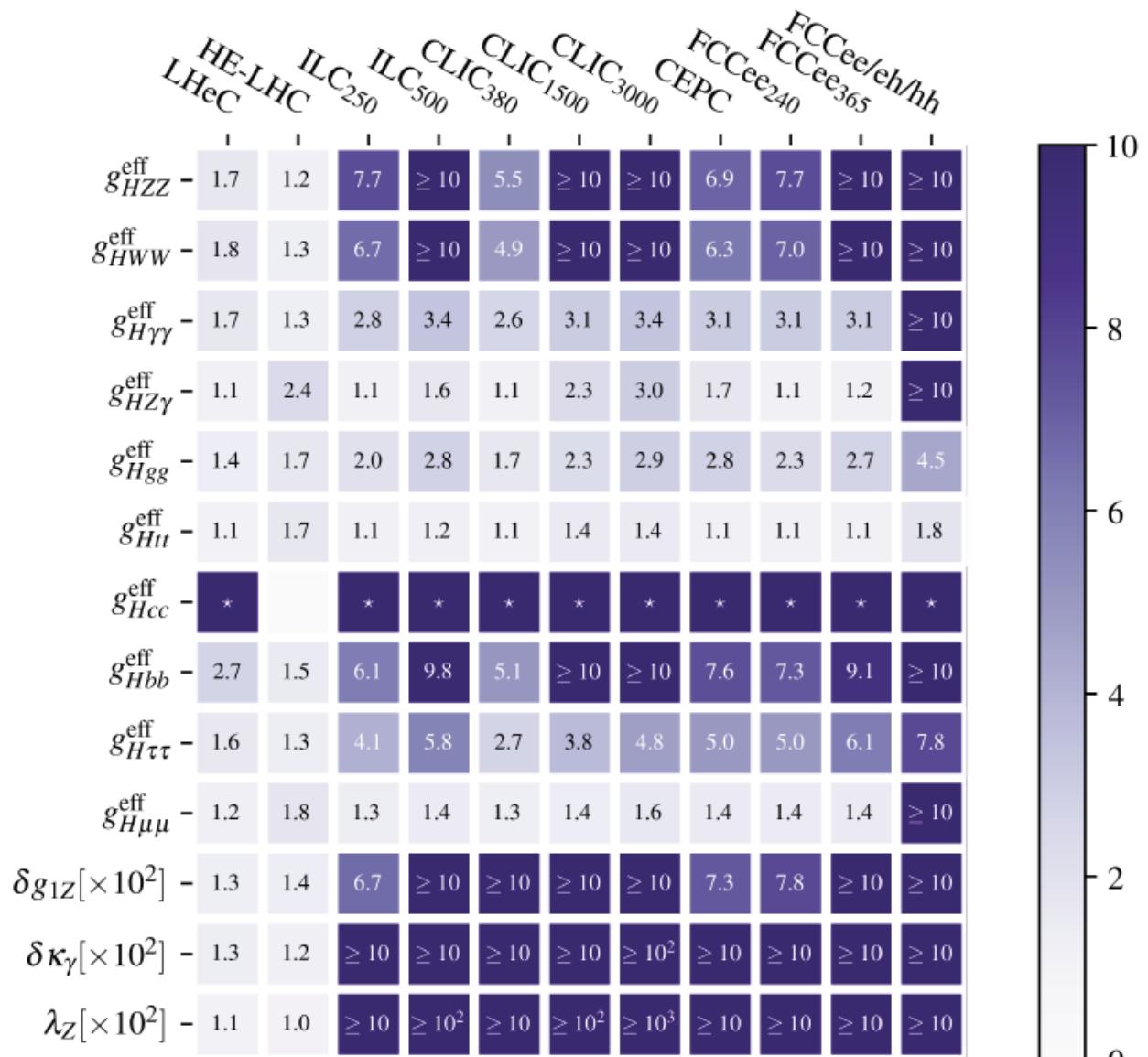


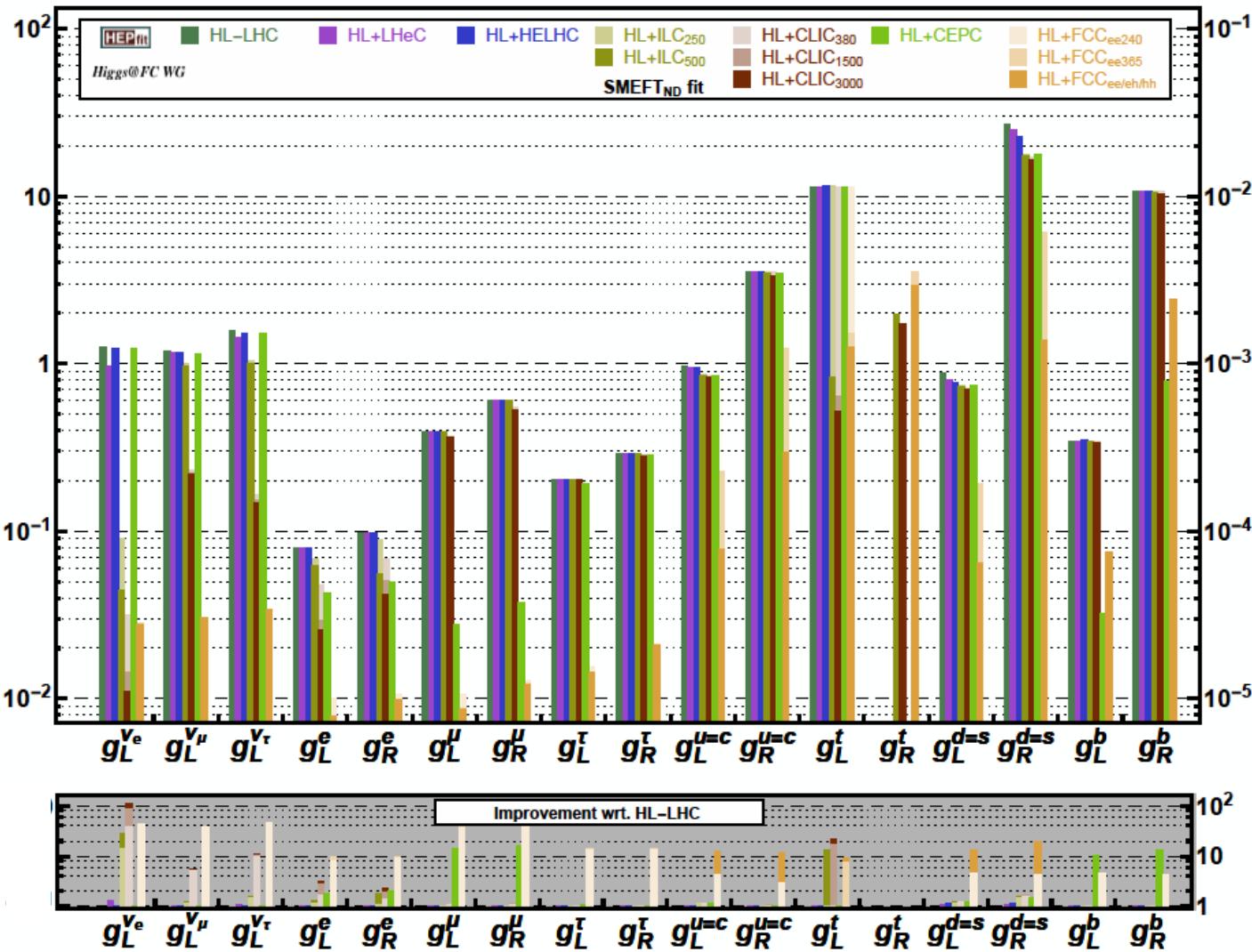
Fig. by M. Cepeda

SMEFT ND

(\*) not measured at HL-LHC

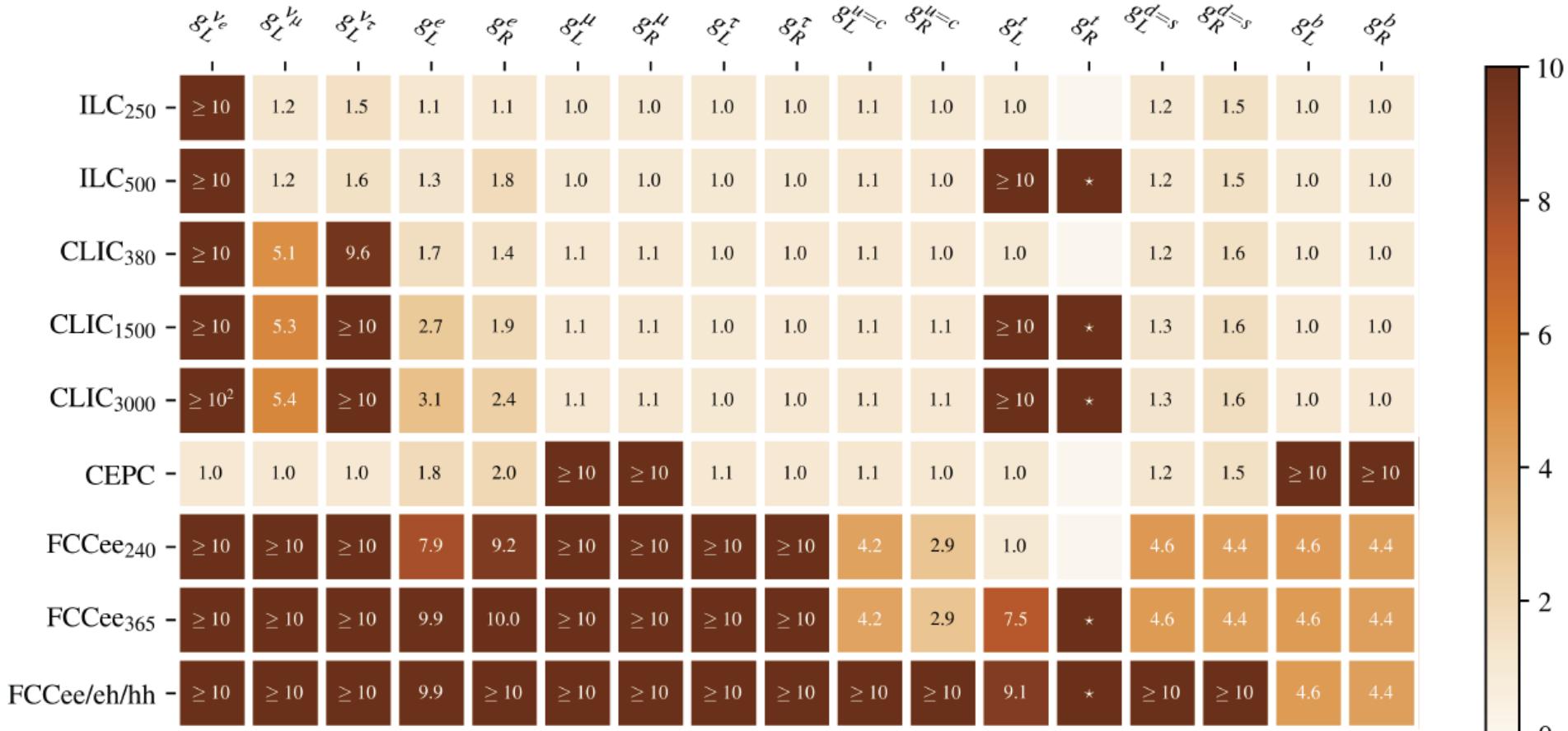
## Global fit results

## The other “half” of the 30+ EFT parameters: EW Zff couplings



# Global fit results

## Improvement with respect to HL-LHC



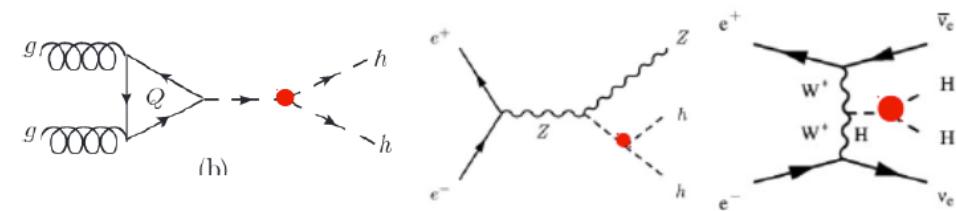
-WARNING: CEPC EWPO ~ FCCee EWPO (except 365 GeV: top).

Difference due to current status of EWPO projections (Flav. Non-univ, sys,...)

# Measurement of Higgs Self-Coupling

## Di-Higgs processes at hadron colliders:

- $\sigma(HH) \approx 0.01 \times \sigma(H)$
- Important to use differential measurements

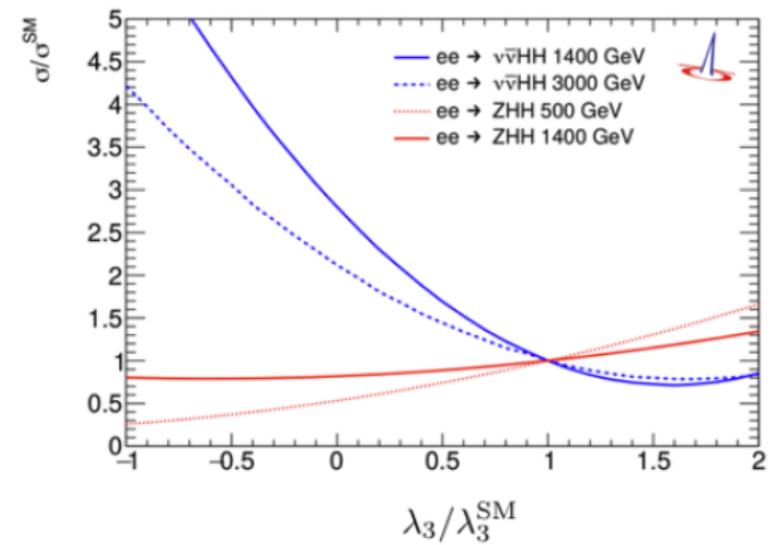
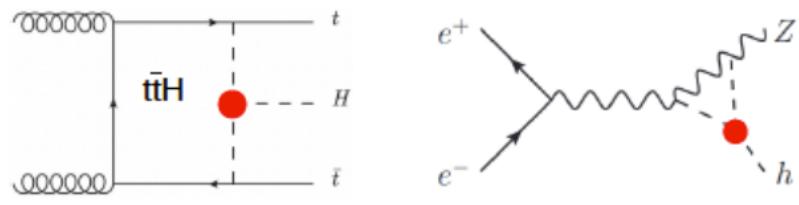


## Di-Higgs processes at lepton colliders

- ZHH or VBF production complementary

## Single-Higgs production sensitive through loop effects, e.g. for $\kappa_\lambda = 2$ :

- Hadron colliders: ~3%
- Lepton colliders: ~1%



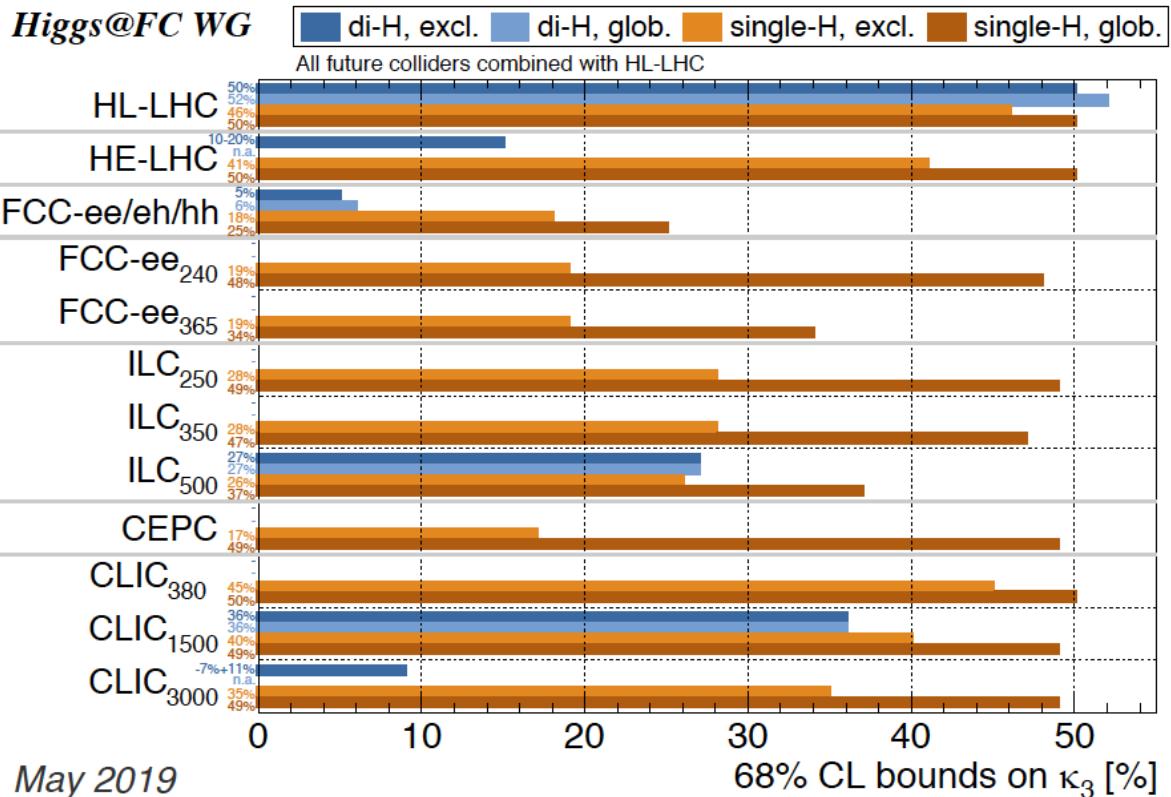
# Sensitivity to $\lambda$ : via single-H and di-H production

## Di-Higgs:

- HL-LHC: ~50% or better?
- Improved by HE-LHC (~15%), ILC<sub>500</sub> (~27%), CLIC<sub>1500</sub> (~36%)
- Precisely by CLIC<sub>3000</sub> (~9%), FCC-hh (~5%),
- Robust w.r.t other operators

## Single-Higgs:

- Global analysis: FCC-ee365 and ILC500 sensitive to ~35% when combined with HL-LHC
  - ~21% if FCC-ee has 4 detectors
- Exclusive analysis: too sensitive to other new physics to draw conclusion



Confronto progetti model  
dependent (specifici  
benchmark BSM)



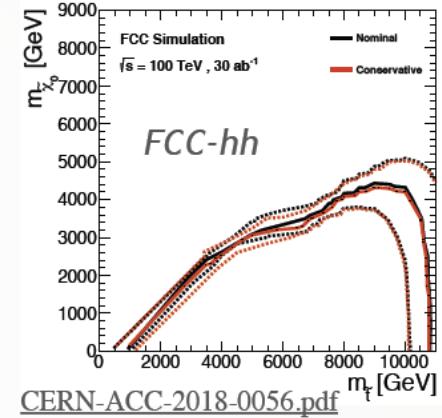
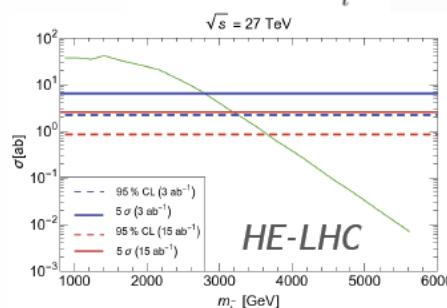
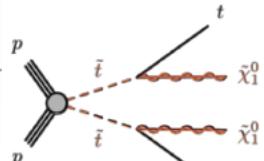
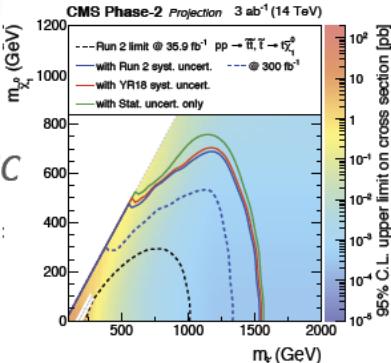
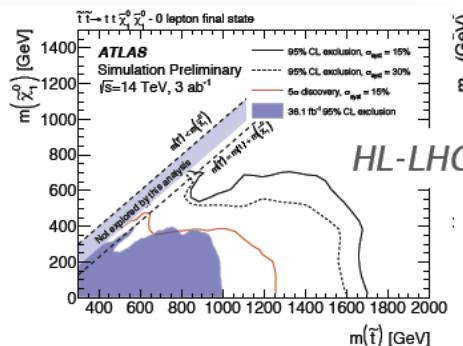
(taken from  
Symmetry  
Magazine)

- **Two ways to “naturalize” a light Higgs at the TeV scale:**
  - i. Internal symmetries (SUSY: fermions  $\leftrightarrow$  bosons)
  - ii. **Global symmetries (Little Higgs models, holographic Higgs,...):**
    - Higgs gets “composite” due to fundamental interactions that manifest at higher scale (similar to QCD  $\rightarrow$  pion)
    - This can be described in a general framework (Strong Interacting Light Higgs: SILH)

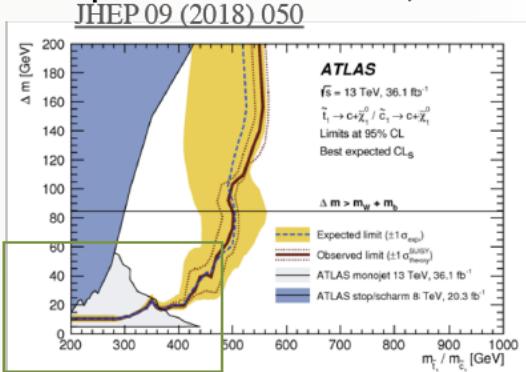
# Hadron collider prospects

## Analyses for large and medium $\Delta M$ (stop, N1)

<https://arxiv.org/pdf/1812.07831.pdf>



## Compressed scenarios, small $\Delta M = m_{\text{stop}} - m_{\text{LSP}}$ :

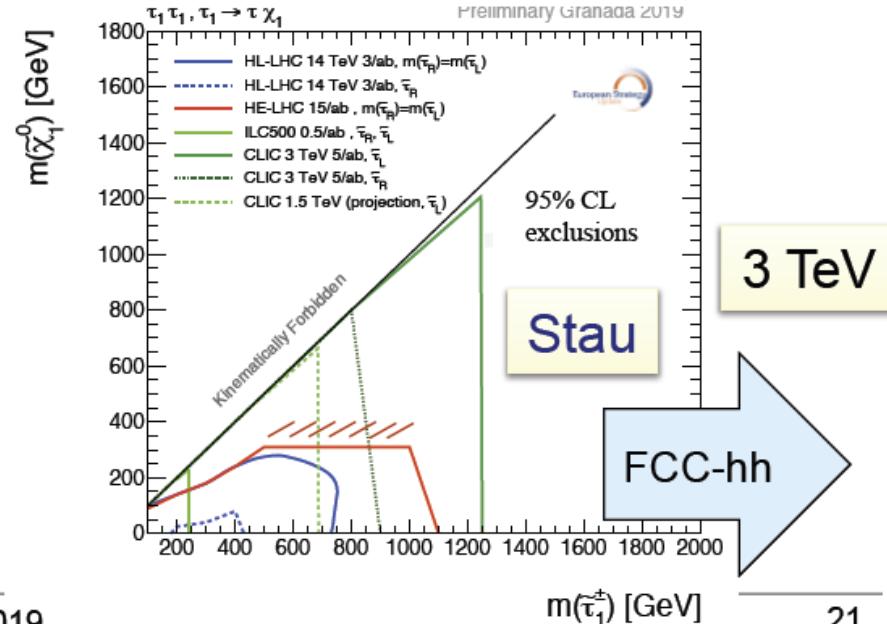
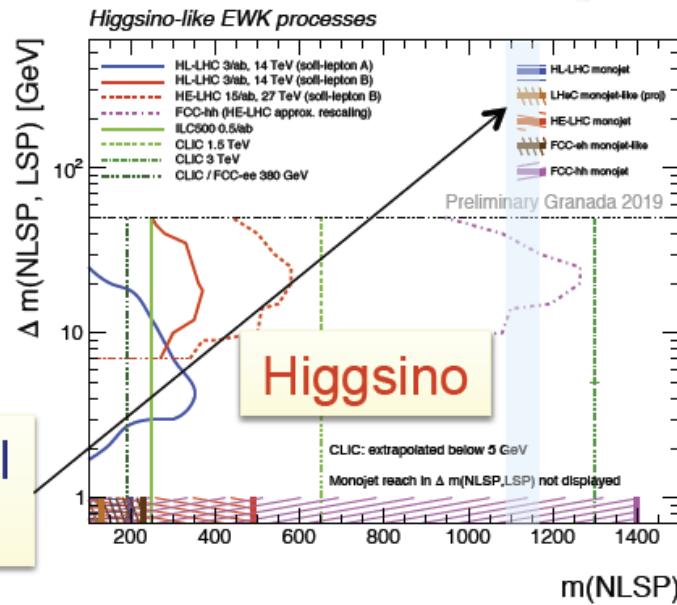
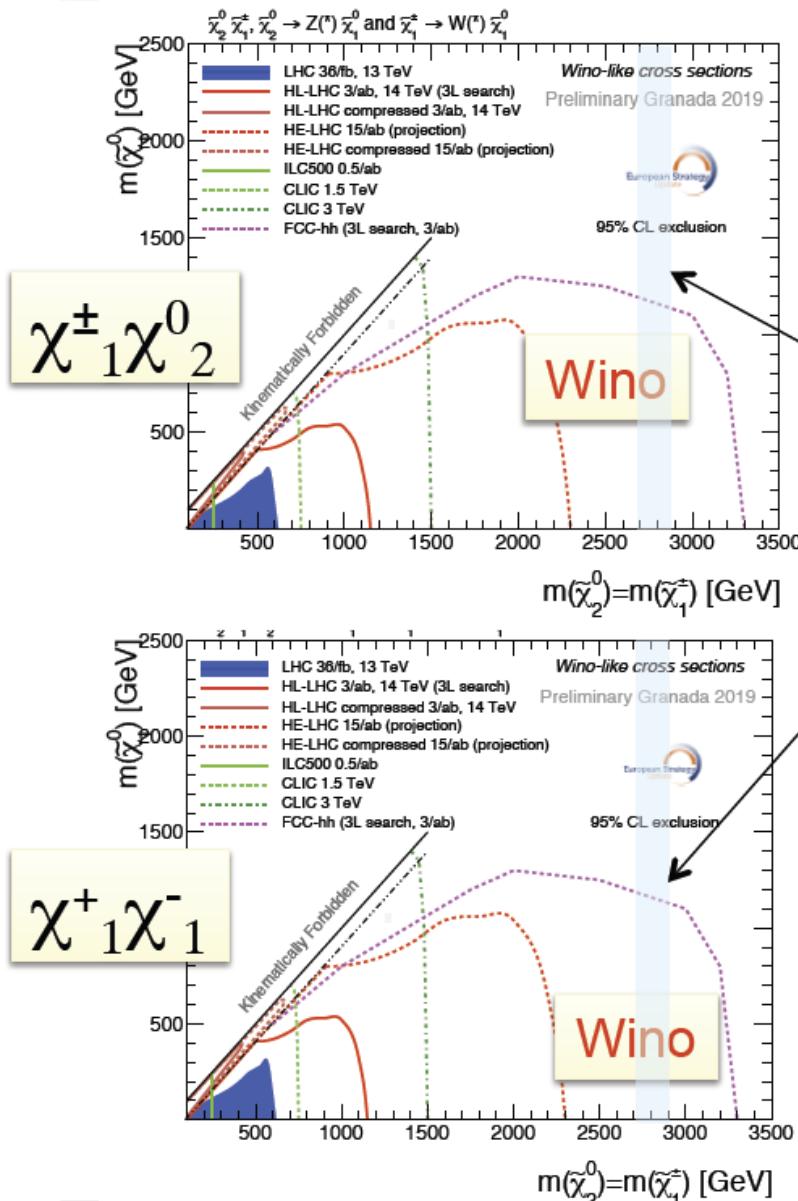


Good potential from analyses:  
**(1) monojet ( $\Delta M \sim 2 - 10$  GeV)** →  
**(2) soft leptons**

Projections with [ColliderReachTool](#):  
**HL-LHC → 0.95 TeV;**  
 [confirmed by theorists' studies]  
**HE-LHC → 2 TeV;**  
**FCC-hh → 5 TeV**

→ Might be conservative: e.g. recoil-jet pt thresholds can be adjusted

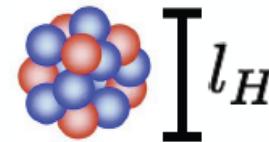
# SUSY: EWK sector



# A Composite Higgs?

Andrea Wulzer

The Composite Higgs Picture:



## Composite Sector

$m_*$  Resonances ( $\rho$ )

Higgs (light pNGB)

Typical CS Mass:  $m_* \simeq 1/l_H$

Typical CS Coupling:  $g_* \in [1, 4\pi]$

## Elementary Sector

SM gauge fields:  $W_\mu^\alpha, B_\mu$

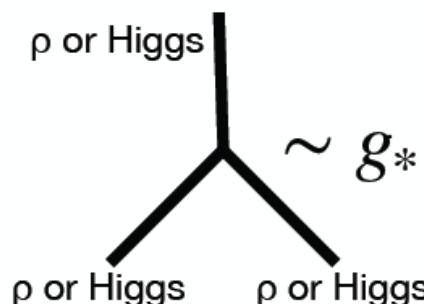
Coupled by gauging.

SM fermions:  $\{t_L, b_L\}, t_R, \dots$

Coup. by partial comp.

[interesting t/b-related phenomenology  
not discussed here, striking at CLIC!]

$$g = g_W$$



$$\text{gauge} \quad \rho \sim \frac{g_W}{g_*}$$

# A Composite Higgs?

Results: HL-LHC [notice the improvement w.r.t. current knowledge]

## Composite Higgs, $2\sigma$ , HL-LHC

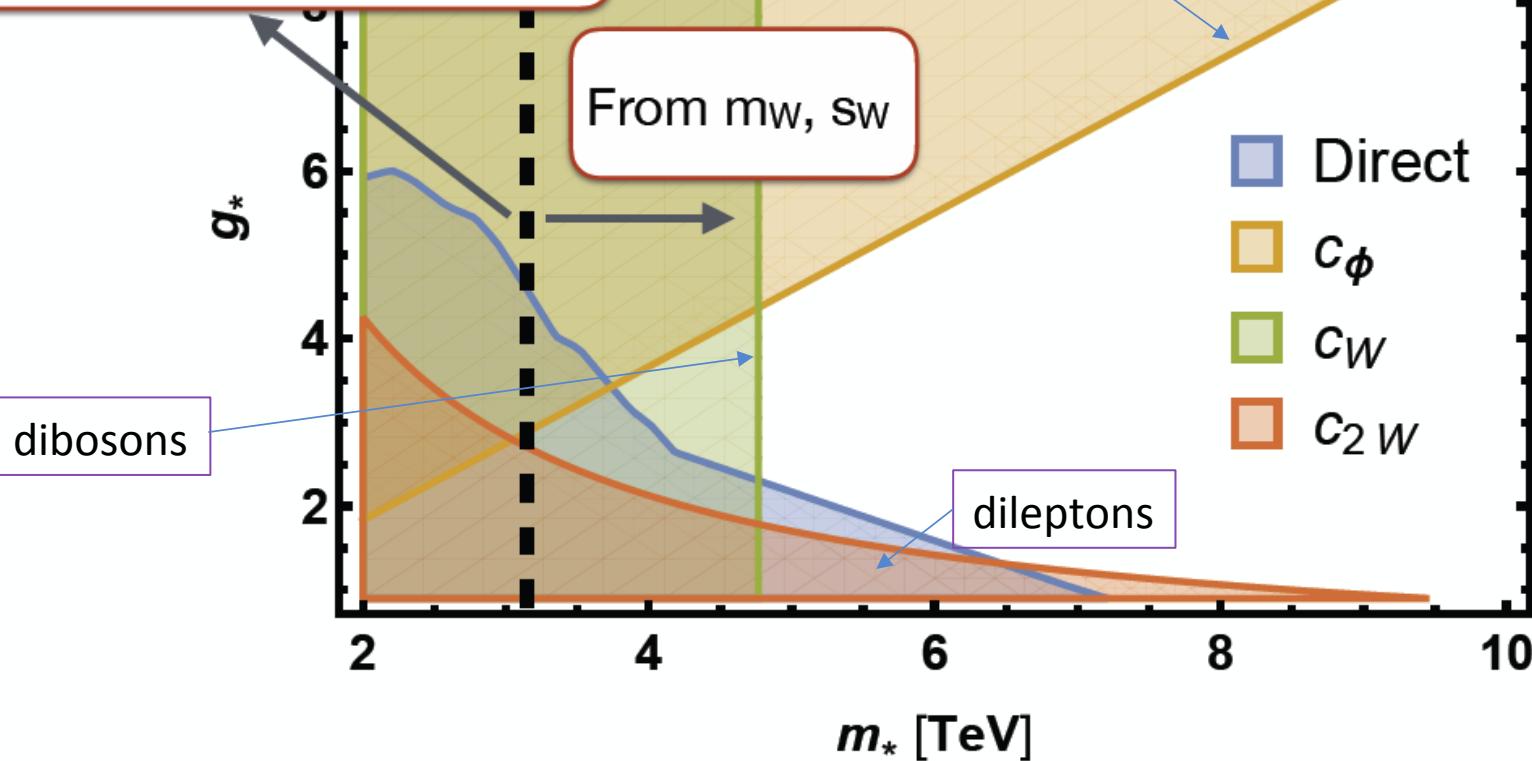
Preliminary, Granada 2019



Current (LEP). Approximate

From  $m_W, s_W$

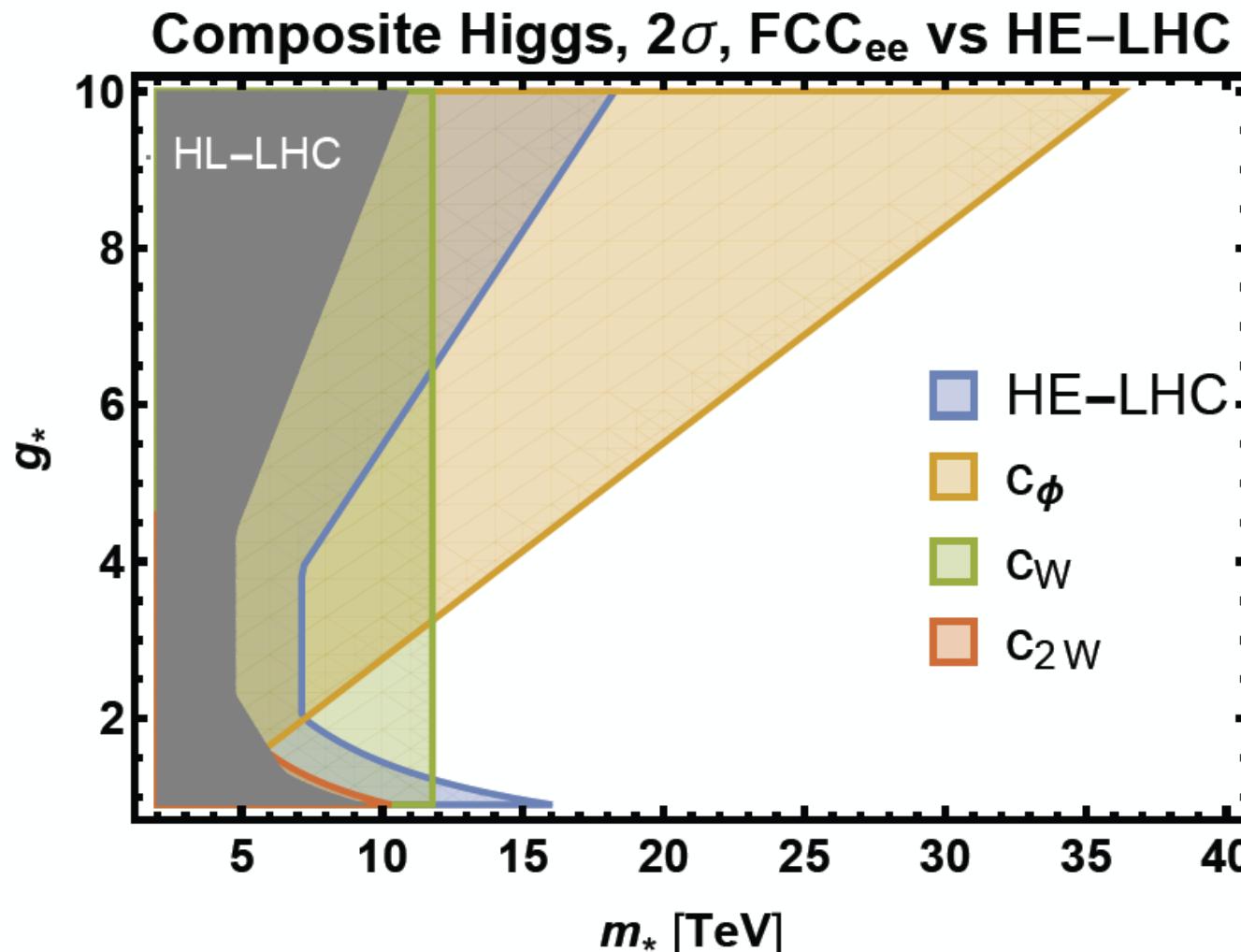
Higgs couplings



$$\frac{c_\phi}{\Lambda^2} = \frac{g_*^2}{m_*^2}$$
$$\frac{c_W}{\Lambda^2} = \frac{1}{m_*^2}$$
$$\frac{c_{2W}}{\Lambda^2} = \frac{1}{g_*^2 m_*^2}$$

# A Composite Higgs?

Results: HE-LHC vs FCC-ee

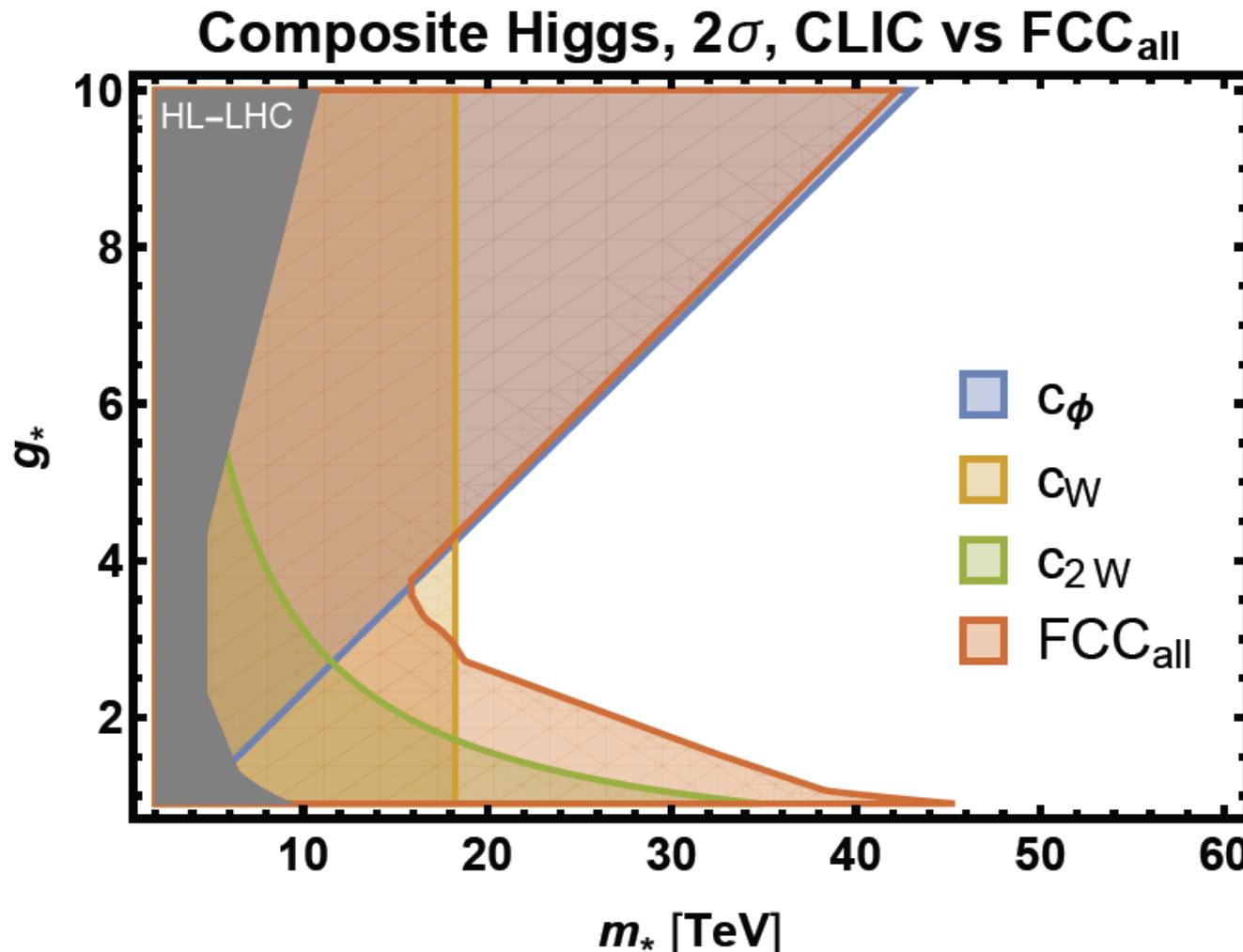


Preliminary, Granada 2019



# A Composite Higgs?

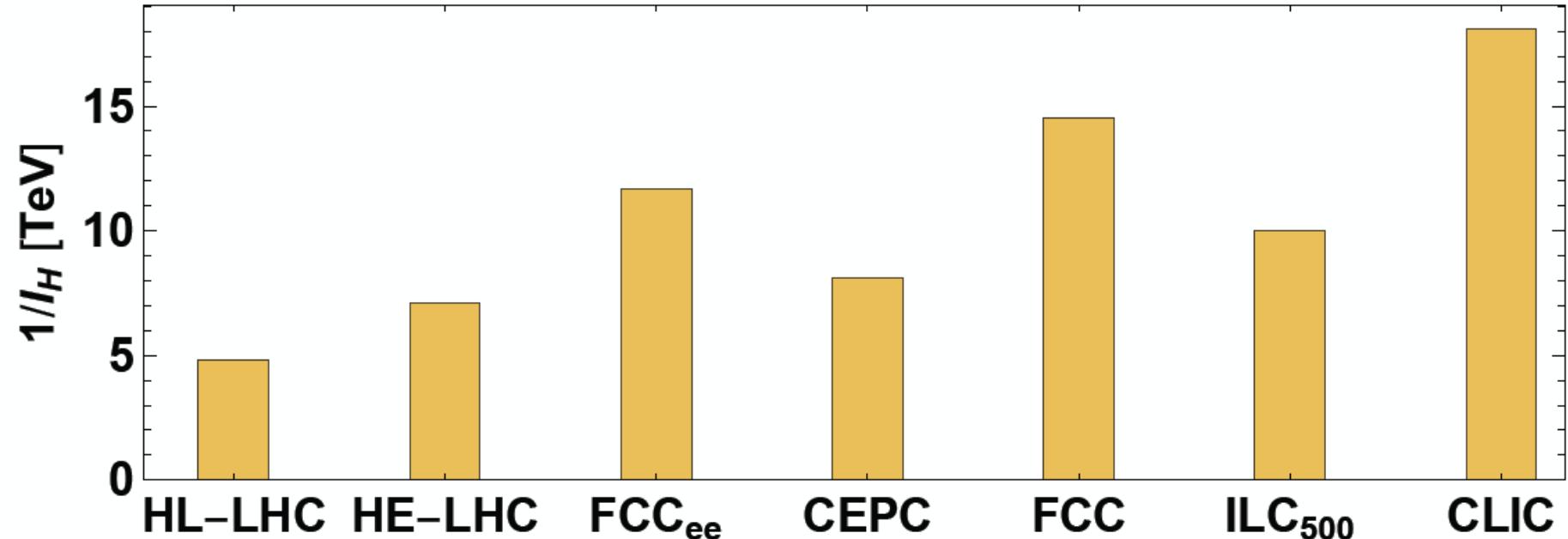
Results: FCC-hh vs CLIC



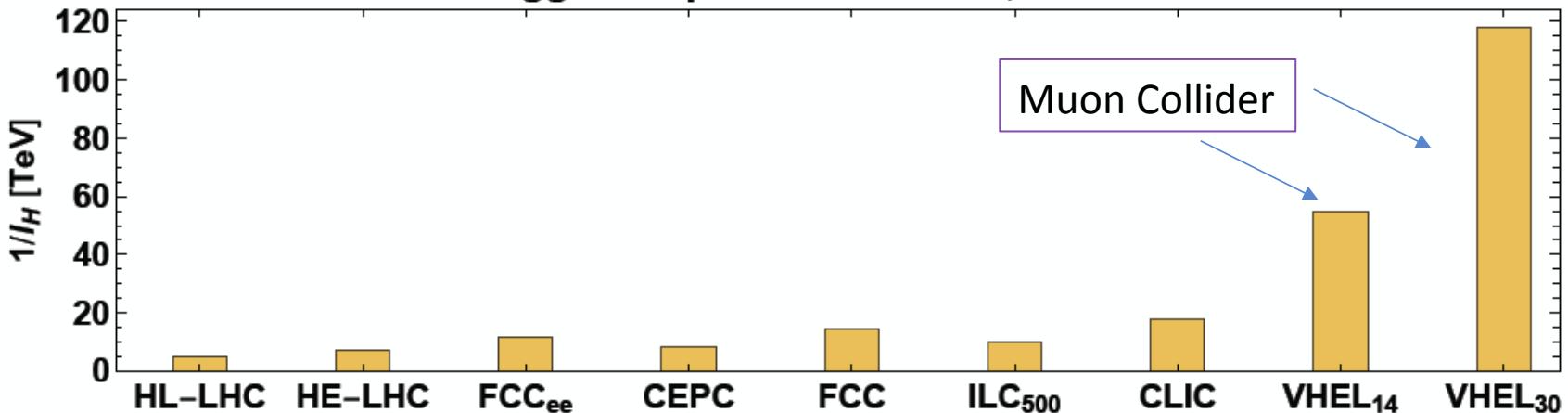
Preliminary, Granada 2019



# Higgs compositeness scale, $2\sigma$ reach



# Higgs compositeness scale, $2\sigma$ reach

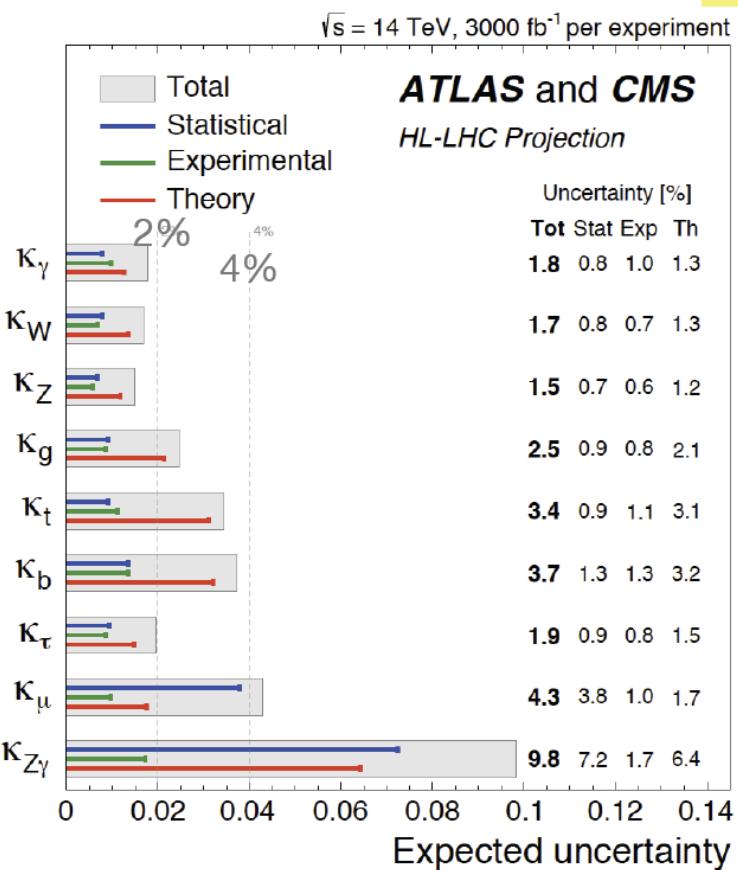


# Conclusioni (personalì)

- La conoscenza del settore elettrodebole puo' essere migliorata di almeno un ordine di grandezza rispetto ad oggi, entrando nella scala 10 – 100 TeV
- Il successo dello SM richiede esplorazione a largo spettro
  - Higgs factory → Electroweak factory
- L'alternanza di macchine leptoniche adroniche non è ripetizione: è necessità
- Prima o poi i fasci di elettroni lasceranno il passo a fasci di mu o nuove tecniche di accelerazione nei test di precisione dello SM

backup

# HL-LHC Higgs measurement projections

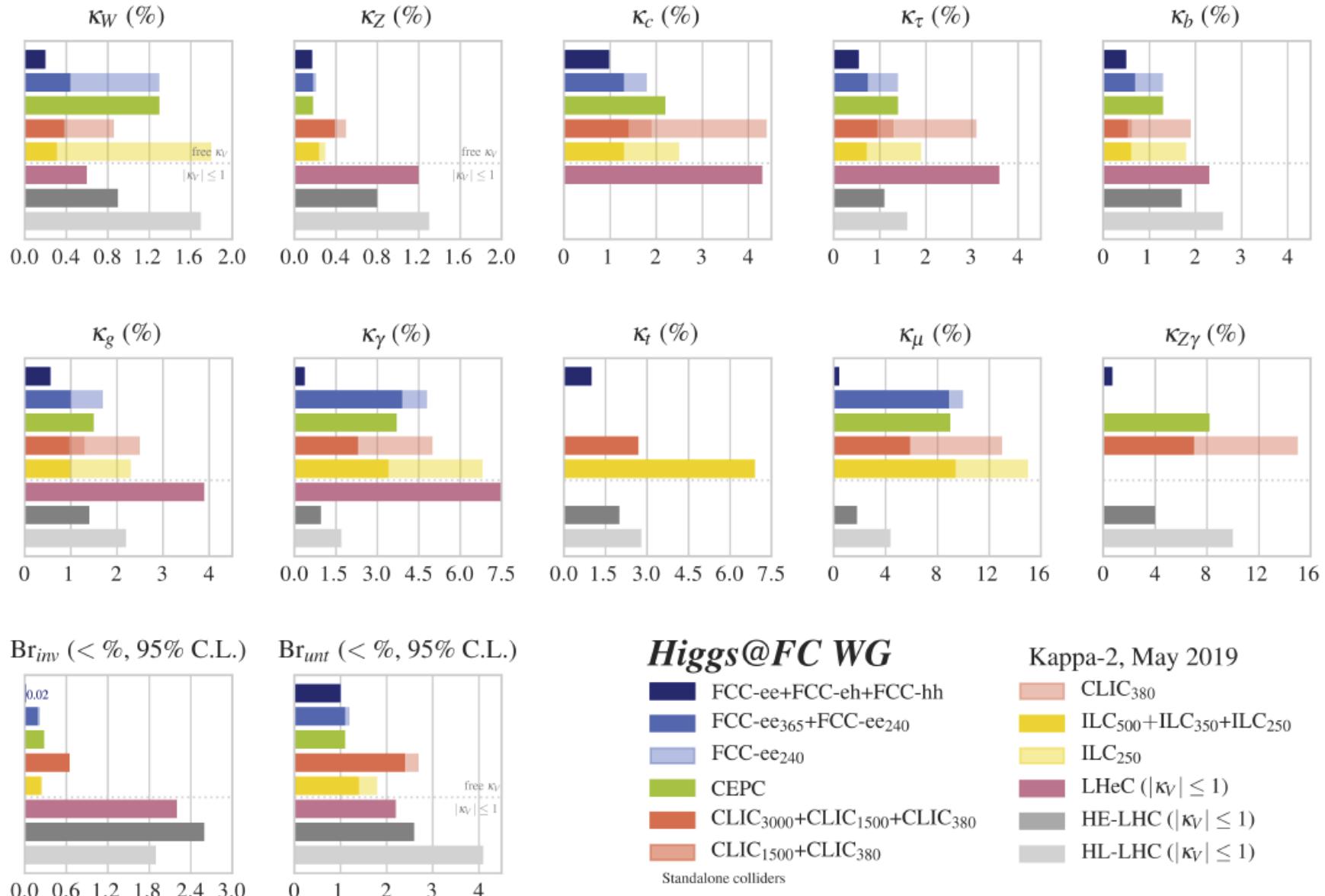


## Some remarks:

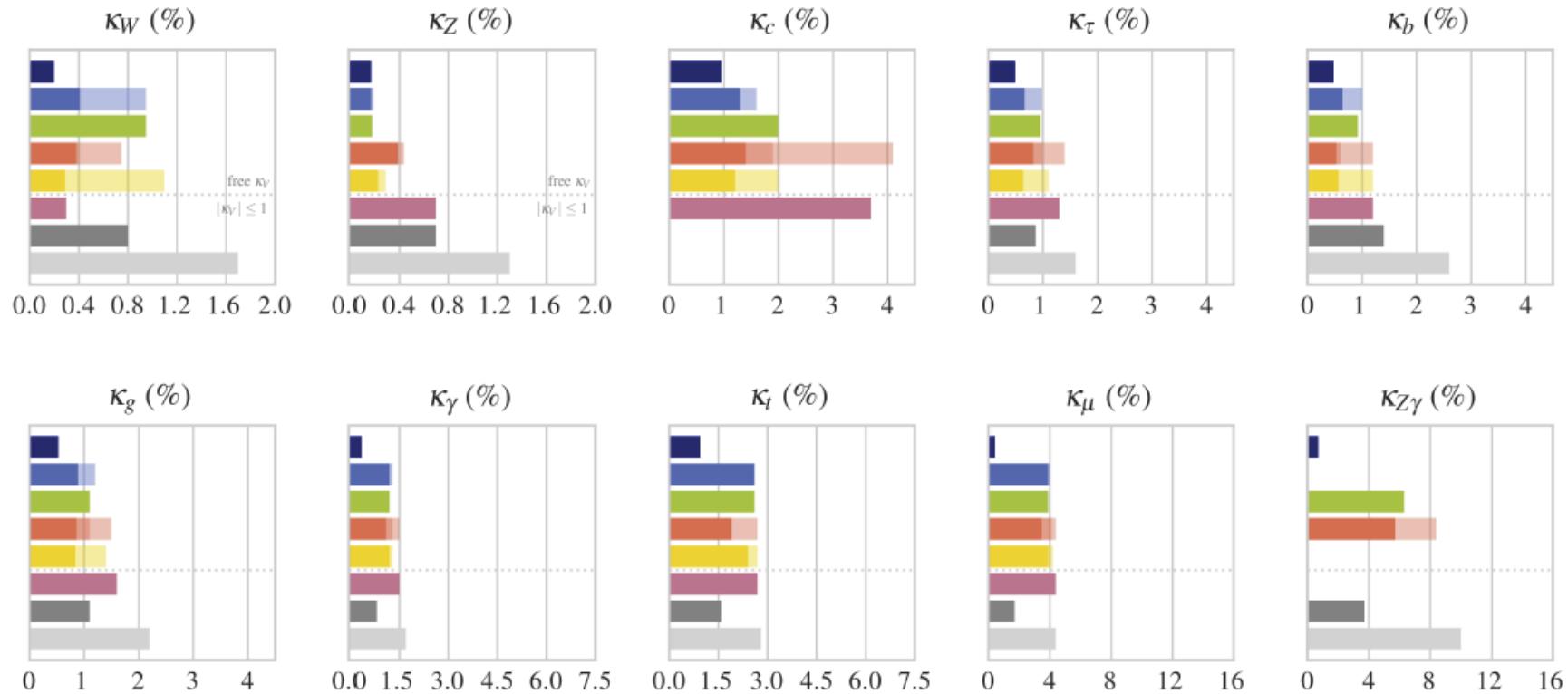
- Combination benefits from extensive analysis experience of ATLAS and CMS since 2012 Higgs discovery
- Precision dominated by theoretical uncertainties for most decay modes
  - Scaled by factor 2 compared to present uncertainties
- Measurement of absolute couplings model-dependent
  - Measure also ratios to reduce model-dependence

P. Azzi

# Kappa-2: allowing BSM and Invisible

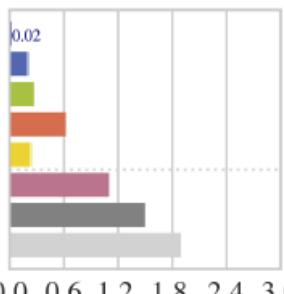


# Kappa-3: +HL-LHC

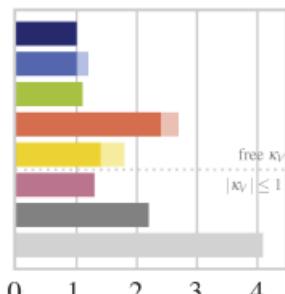


modified version (x-scale) of the plot in the report for illustration purposes

$\text{Br}_{inv} (< \%, 95\% \text{ C.L.})$



$\text{Br}_{unt} (< \%, 95\% \text{ C.L.})$

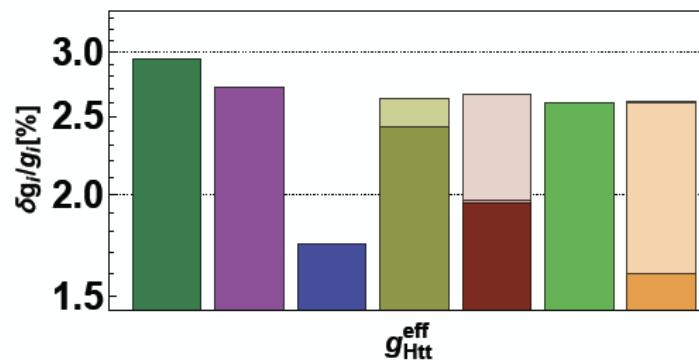
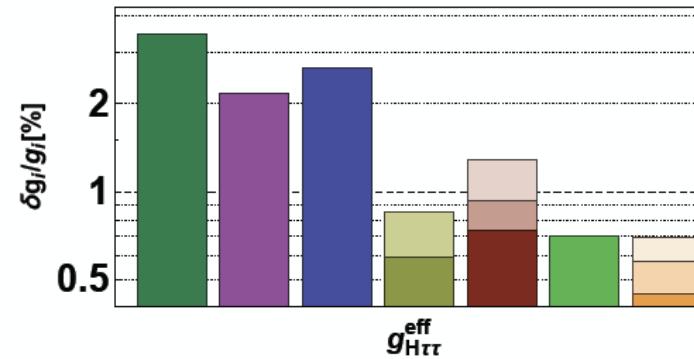
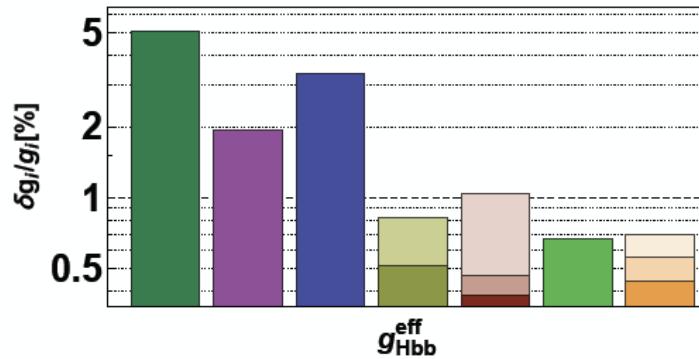


**Higgs@FC WG**

- FCC-ee+EEC-eh+FCC-hh
  - FCC-ee<sub>365</sub>+FCC-ee<sub>240</sub>
  - FCC-ee<sub>240</sub>
  - CEPC
  - CLIC<sub>3000</sub>+CLIC<sub>1500</sub>+CLIC<sub>380</sub>
  - CLIC<sub>1500</sub>+CLIC<sub>380</sub>
  - All future colliders combined with HL-LHC
- Kappa-3, May 2019
- CLIC<sub>380</sub>
  - ILC<sub>500</sub>+ILC<sub>350</sub>+ILC<sub>250</sub>
  - ILC<sub>250</sub>
  - LHeC ( $|\kappa_V| \leq 1$ )
  - HE-LHC ( $|\kappa_V| <= 1$ )
  - HL-LHC ( $|\kappa_V| <= 1$ )

# Global fit results

## Sensitivity to deviations in $Hff$ (3rd fam) couplings



- e<sup>+</sup>e<sup>-</sup> coll: Tau and Bottom Yukawa (0.5% - 1%)
- Top Yukawa not directly accessible to low-E lepton colliders.
- Accessible above 500 GeV (ILC, CLIC). Precision similar to HL-LHC.
- 1% precision possible at FCC-hh

**WARNING:** In all cases, ttH requires knowledge of, at least, other Top interactions

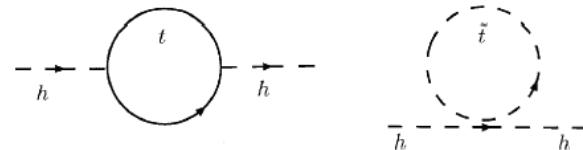
Model-Independent Top: Advantage for CLIC

# Measuring Naturalness

Hierarchy  
Paradox



**unavoidable** and **global** perspective  
on energy frontier exploration



In any model with calculable  $m_h$ :

$$m_h^2 = \sum_i \Delta m_i^2$$

fine tuning     $\epsilon \equiv \frac{m_h^2|_{exp}}{\Delta m_h^2|_{max}}$

offers a measure of where Nature stands in the negotiation  
between Simplicity and Naturalness

## Measures of fine tuning

- Direct searches: depends on top partner constraints in model (e.g. SUSY varieties, composite H, twin H)
  - LHC now:  $\epsilon \lesssim 10^{-2} - 1$
  - FCC-hh:  $\epsilon \lesssim 10^{-4} - 10^{-2}$  (if nothing)
- Higgs observables:  $\epsilon \sim \delta g/g$
- Electroweak precision:  $\epsilon \sim 10^2 \times \delta S/S$



**Higgs and EWK precision observables can test naturalness beyond direct searches**

R. Rattazzi