Summary: Electroweak Session

Conveners: Keith Ellis and Beate Heinemann
Scientific Secretaries: Fabio Maltoni and Aleandro Nisati
Open Symposium towards updating the European Strategy for Particle Physics
May 13-16, 2019, Granada, Spain
General Considerations
What and Why?

Problems vs Mysteries

Problems:
- Dark Matter
- Baryogenesis
- Strong CP
- Fermion mass spectrum & mixing

Mysteries:
- Cosmological Constant
- EW hierarchy
- Black Hole information paradox
- very Early Universe

Plausible EFT solutions exist

Challenge or outside EFT paradigm

R. Rattazzi
Simplicity vs Naturalness

I. The SM is valid up to $\Lambda_{UV} \gg TeV$
   - B, L and Flavor: beautifully in accord with observation
   - Higgs mass & C.C. hierarchy point beyond naturalness
     - multiverse
     - cosmological relaxation, Nnaturalness, ...
     - failure of EFT ideology (UV/IR connection)

II. Naturalizing New Physics appears at $\Lambda_{UV} \sim 1$ TeV
   - Constraints on B, L, Flavor & CP met by clever model building

R. Rattazzi
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

\[
\epsilon \equiv \frac{m_h^2|_{\text{exp}}}{\Delta m_h^2|_{\text{max}}}
\]

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
What else do we learn from Higgs?

Many problems of particle physics today relate to Higgs observables

BH, Y. Nir, arXiv:1905.00382
## Collider Schedules: starting from $T_0$

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<tr>
<th></th>
<th>$T_0$</th>
<th>+5</th>
<th>+10</th>
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<td>1.5/ab 250 GeV</td>
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NB: number of seconds/year differs: ILC $1.6 \times 10^7$, FCC-ee & CLIC: $1.2 \times 10^7$, CEPC: $1.3 \times 10^7$
Big Questions

1. How well can the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?

2. How do precision electroweak observables inform us about the Higgs boson properties and/or BSM physics?

3. What progress is needed in theoretical developments in QCD and EWK to fully capitalize on the experimental data?

4. What is the best path towards measuring the Higgs potential?
Question 1: How well can the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?
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
Higgs Boson studies at future particle colliders

- Preliminary Version -

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4University of Utrecht, Utrecht, The Netherlands

Abstract

This document aims to provide an assessment of the potential of future colliding beam facilities to perform Higgs boson studies. The analysis follows the simulations made by the proponents of future colliders to the European Strategy Update process, and takes as its point of departure the results expected at the completion of the LHC program. This report presents quantitatively results on many aspects of Higgs physics for future collider projects using uniform methodologies for all proposed machine projects to allow ready comparisons. This report is still preliminary and is distributed for the purposes of discussion at the Open Symposium in Garvagh (12-15/05/2004).

arXiv:1905.03764

1 Introduction
2 Methodology
3 The Higgs boson couplings to fermions and vector bosons
3.1 The Higgs framework
3.2 Results from the Higgs framework studies and comparison
3.3 Effective field theory description of Higgs boson couplings
3.4 Results from the EFT framework studies
3.5 Impact of Standard Model theory uncertainties in Higgs calculations
4 The Higgs boson self-coupling
5 Rare Higgs boson decays
6 Sensitivity to Higgs CP
7 The Higgs boson mass and full width
8 Future studies of the Higgs sector, post-European Strategy
8.1 Higgs prospects at the muon collider
8.2 Higgs physics at multi-TeV $e^+e^-$ colliders
8.3 What and Why: Higgs prospect studies beyond this report
9 Summary

M. Cepeda
Comments on Higgs@FC Analysis

- Different simulation/analysis program for each proposal, varying from full simulation to parametric modelling (GUINEAPIG, CLICdet, WHIZARD, DELPHES)

- Lepton colliders: profit from the recoil mass method to obtain a precise ZH cross section measurement in a model independent way, regardless of the decay

- High energy hadron colliders: probing the Higgs boson at high $p_T$ enhances the sensitivity to new physics (not captured in the analyses presented in this report)

- Circular colliders: precision EWK program at MZ and MW

- Linear colliders: polarized beams and potential to go to higher energies

- Generally assumed progress in systematic uncertainties over the next decades (experimental and theoretical)

- We should not over-interpret 20% differences between projected sensitivities. In many cases, these are likely not significant.

M. Cepeda
Interpretation of Higgs Measurements

- **SMEFT and \( \kappa \)**
  \[
  (\sigma \cdot \text{BR})(i \rightarrow H \rightarrow f) = \frac{\sigma_i^{\text{SM}} \kappa_i^2 \cdot \Gamma_i^{\text{SM}}}{\Gamma_H^{\text{SM}} \kappa_H^2} \rightarrow \mu_i^f \equiv \frac{\sigma \cdot \text{BR}}{\sigma_{\text{SM}} \cdot \text{BR}_{\text{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}
  \]

  *\( \kappa \)-framework*: phenomenological parameterization of NP in single Higgs processes but not adequate for a systematic exploration/interpretation of BSM deformations in SM measurements

### Pros
- Compact parameterization of NP in single Higgs processes
- Does not require any BSM calculation per se
- Info easily applicable to several interesting NP scenarios (e.g. CH, MSSM)
- Theory constraints (e.g. gauge invariance, custodial) not implicit

### Cons
- Not usable beyond single Higgs processes
  - Does not distinguish the source of NP (interpreted only as mod. of SM-like H couplings)
  - Only for total rates, no kinematics (Energy, angular dependence), no polarization
- Theory constraints (e.g. gauge invariance, custodial) not implicit

For heavy New Physics (NP) the formalism of Effective Field Theories (EFT) provides a suitable framework for systematic studies of indirect sensitivity to BSM effects in EW/Higgs/Top/Flavour/…

Include BSM in kappa via:

\[
\Gamma_H = \frac{\Gamma_H^{\text{SM}} \cdot \kappa_H^2}{1 - (\text{BR}_{\text{inv}} + \text{BR}_{\text{unt}})}
\]

J. De Blas
Higgs width and/or untagged decays

Unique feature of lepton-lepton colliders:
- Detecting the Higgs boson without seeing decay: “recoil method”
- Measure ZH cross section with high precision without assumptions on decay
- Often interpreted as quasi-direct measurement of width

\[
\frac{\sigma(e^+e^- \rightarrow ZH)}{BR(H \rightarrow ZZ^*)} = \frac{\sigma(e^+e^- \rightarrow ZH)}{\Gamma(H \rightarrow ZZ^*)/\Gamma_H} \approx \left[ \frac{\sigma(e^+e^- \rightarrow ZH)}{\Gamma(H \rightarrow ZZ^*)} \right]_{SM} \times \Gamma_H
\]

In kappa-framework:

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

=> Will probe width with 1-2% precision

arXiv:1905.03764
EFT analysis

Some remarks on current analysis
- Uses Higgs inclusive cross sections
- Makes use of polarization
- Does not explore differential distribution
  - Underestimates power of colliders, particularly for $h^h$
- Includes electroweak measurements as available at various colliders
  - aTGCs, W, Z and top properties

---

**Project EFT fit results into (pseudo) observable quantities**

\[
g_{\text{H}X}^\text{eff} = \frac{g_{\text{H}X}}{\Gamma_{\text{H}X}} \equiv \frac{g_{\text{H}X}^\text{eff}}{\Gamma_{\text{H}X}}
\]

Effective Higgs couplings

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

\[
\frac{\Gamma_{ZZ}}{\Gamma_{ZZ}} \approx 1 + 2 \delta c_{ZZ} - 0.15 c_{ZZ} + 0.41 c_{ZZ} + \ldots \quad (\text{EW } t^f, h^f)
\]

Only these are described in $\kappa$-framework

---

### Table: Project EFT fit results into (pseudo) observable quantities

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<th>aTGC</th>
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<th>Top EW</th>
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<td>Yes (aTGC dom.)</td>
<td>Yes</td>
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<tr>
<td>ILC</td>
<td>Yes ($\mu, \sigma_2h$) (Complete with HL-LHC)</td>
<td>Yes (HE limit)</td>
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<tr>
<td>CEPC</td>
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<td>Yes (aTGC dom.)</td>
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<td>From FCC$\mathrm{ee}$ + Z$\nu$, Z$\nu\nu$</td>
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J. De Blas
Comparison of Colliders: EFT

Effective Higgs couplings
- Constraints approach 0.1% precision for gauge bosons
- Major improvement w.r.t. HL-LHC for many colliders for fermions

Trilinear gauge couplings
- Will achieve precision $10^{-3}$-$10^{-4}$
- About 2-3 orders of magnitude better than LEP

arXiv:1905.03764
## Improvements w.r.t. HL-LHC

### Kappa-framework

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<th>LHCb/C*</th>
<th>HL-LHC</th>
<th>IL-2500</th>
<th>CLIC-3000</th>
<th>CLIC-5000</th>
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(\*) $|\kappa_\gamma| \leq 1$ applied for hadron colliders
\((**)\) Not requiring $|\kappa_\gamma| \leq 1$
\((*)\) Not measured in HL-LHC

### EFT-framework

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\(\delta_{\text{Br}_{1\tau}} \times 10^2 \) |

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SMEFT ND
\((*)\) not measured in HL-LHC

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M. Cepeda
# of “largely” improved H couplings (EFT)

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13 quantities in total

NB: number of seconds/year differs: ILC 1.6x10⁷, FCC-ee & CLIC: 1.2x10⁷, CEPC: 1.3x10⁷
# of “largely” improved H couplings (EFT)

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13 quantities in total

NB: number of seconds/year differs: ILC 1.6x10^7, FCC-ee & CLIC: 1.2x10^7, CEPC: 1.3x10^7
# of “largely” improved H couplings (EFT)

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13 quantities in total

NB: number of seconds/year differs: ILC 1.6x10⁷, FCC-ee & CLIC: 1.2x10⁷, CEPC: 1.3x10⁷
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13 quantities in total

NB: number of seconds/year differs: ILC $1.6 \times 10^7$, FCC-ee & CLIC: $1.2 \times 10^7$, CEPC: $1.3 \times 10^7$
# of “largely” improved H couplings (kappa)

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</table>

12 quantities in total  

NB: number of seconds/year differs: ILC $1.6\times10^7$, FCC-ee & CLIC: $1.2\times10^7$, CEPC: $1.3\times10^7$
Invisible H decays: $H \rightarrow E_T^{\text{miss}}$

Direct searches dominate sensitivity:
- HL-LHC will have sensitivity to ~2.6%
- $e^+e^-$ colliders improve to ~0.3%
- FCC-hh probes below SM value: ~0.025%
Question 2:
How do precision electroweak observables inform us about the Higgs boson properties and/or BSM physics?
What can HL-LHC do?

- W and top mass are key parameters of the SM
- Motivation for low PileUp run: 200 pb-1 of Low PU data (μ~2) at 14 TeV
  - 5-10 weeks of running —> ~3MeV (stat only)
  - Exp syst assumed to be at same level of Stat uncertainty
  - PDF unc ~4MeV with ultimate PDF
- Goal Δm(W)~6MeV (extended coverage+combination+ultimate PDF)
  - PDF syst can go down to ~2MeV with LHeC PDF set

**W mass:**
- goal is ~6 MeV
- PDF precision important

**Top mass:**
- Several methods explored
- Precision range: 0.2-1.2 GeV
- Relation to pole mass unclear for most precise methods
Top precision at Future Colliders

Top Mass

Collider plans:
- FCC-ee plans 5y run at $\sqrt{s} \approx 2m_{top}$ after 9y run at 240 GeV
- CEPC currently not planning on top programme
- CLIC 1st stage at 380 GeV includes top programme
- ILC plans run at $\sqrt{s} \approx 2m_{top}$ after about 15y

Threshold scans give well-defined $m_{TOP}$

Current uncertainty $\sim 400$ MeV from Tevatron/LHC
CLIC/FCC/ILC all expected to achieve:
- 15-20 MeV statistical
- 10-20 MeV systematic $O(25)$ MeV

But presently uncertainty from theory is larger: 30 MeV ($\alpha_s$), 40 MeV (HO). This will be reduced by the measurements at Z-pole.
Electroweak Observables at Future Colliders

**ILC:**
- “Giga-Z” running not part of baseline but maybe later

**Precision EWK Observables**

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<th>CEPC</th>
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<td>$\Gamma_Z$ [MeV]</td>
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LHeC can measure $\sin^2 \theta_W$ as a function of energy.

LHeC: Mw to 10 MeV but can measure PDFs allowing HL-LHC to halve PDF uncertainty and achieve O(5 MeV) Mw.
ILC/CLIC: Mw to 5 MeV similar to HL-LHC/TeV average.
Oblique parameters

Characterise Improvements via Oblique Parameters

S & T determined much better for experiments at Mz (FCC, CEPC) but W & Y much better at CLIC that has highest energy range

Will probe fine tuning:

- Dibosons at CLIC: $< 1 \times 10^{-5}$
- EWPT at FCCee: $< 2.5 \times 10^{-5}$

0.1 has sensitivity to Higgs TGC x20 SM

R. Rattazzi

M. Lancaster
EWK observables in EFT: improvement factor

<table>
<thead>
<tr>
<th>Observable</th>
<th>ILC250</th>
<th>ILC500</th>
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Indirect constraints on Composite Higgs

Indirect constraints in CH models

Simplified CH benchmark: 1 coupling (g) - 1 scale (m)

\[
\begin{align*}
\frac{c_{\phi,6.3T}}{\Lambda^2} &= \frac{g_\phi^2}{m_\phi^2}, \\
\frac{c_{Y_\phi}}{\Lambda^2} &= \frac{1}{m_\phi^2}, \\
\frac{c_T}{\Lambda^2} &= \frac{1}{16\pi^2} \frac{1}{m_\phi^2}, \\
\frac{c_{\gamma,\phi}}{\Lambda^2} &= \frac{1}{16\pi^2} \frac{1}{m_\phi^2}, \\
\frac{c_{\phi,\phi}}{\Lambda^2} &= \frac{g_\phi^2}{m_\phi^2}, \\
\frac{c_{3W,3G}}{\Lambda^2} &= \frac{1}{16\pi^2} \frac{1}{m_\phi^2}.
\end{align*}
\]

J. de Blas
Question 4:
What is the best path towards measuring the Higgs potential?
Electroweak potential

**HEATING UP THE STANDARD MODEL**

EW sym. restored at \( T \gtrsim 130 \text{ GeV} \)
through a smooth crossover

\[
V(\phi) \quad \phi
\]

\( T_c \)

No departure from thermal equilibrium

**First-order EW phase transition**

\[
V(\phi) \quad \phi
\]

Barrier separates 2 degenerate minima
2 phases can coexist

Nucleation, expansion and collision of Higgs bubbles

> Framework for EW baryogenesis !

> Stochastic bgd of gravitational waves detectable at LISA !

G. Servant
1\textsuperscript{st} order phase transition: how to observe?

Gravitational Waves from a first-order phase transition.

What makes the EW phase transition 1\textsuperscript{st-order}?

- $O(1)$ modifications to the Higgs potential
- Extra EW-scale scalar(s) coupled to the Higgs

G. Servant
Higgs Potential: measurement of self-coupling

- Higgs potential: $V(\Phi) = \frac{1}{2} \mu^2 \Phi^2 + \frac{1}{4} \lambda \Phi^4$

- Approximation around the v.e.v:
  
  $$V(\Phi) \approx \lambda \cdot v^2 \cdot h + \lambda \cdot v \cdot h^3 + \frac{1}{4} \lambda \cdot h^4$$

  mass term self-coupling terms

- $\lambda$ known from v.e.v and Higgs mass: $\lambda = \frac{m_H^2}{2 \cdot v^2} \approx 0.13$

- BSM effects could change $\lambda \Rightarrow$ define deviation of tri-linear term: $\kappa_\lambda = \frac{\lambda_{\text{BSM}}}{\lambda_{\text{SM}}}$
  
  - no quartic terms considered here
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: $\sim 3\%$
- Lepton colliders: $\sim 1\%$
Sensitivity to $\lambda$: via \textbf{single-H} and \textbf{di-H} production

\textbf{Di-Higgs:}
- HL-LHC: $\sim$50% or better?
- Improved by HE-LHC ($\sim$15%), ILC$_{500}$ ($\sim$27%), CLIC$_{1500}$ ($\sim$36%)
- Precisely by CLIC$_{3000}$ ($\sim$9%), FCC-hh ($\sim$5%),
- Robust w.r.t other operators

\textbf{Single-Higgs:}
- \textbf{Global} analysis: FCC-ee365 and ILC500 sensitive to $\sim$35% when combined with HL-LHC
- $\sim$21% if FCC-ee has 4 detectors
- \textbf{Exclusive} analysis: too sensitive to other new physics to draw conclusion

### Higgs@FC WG

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</tbody>
</table>

All future colliders combined with HL-LHC

\textit{May 2019}
Question 3: What progress is needed in theoretical developments in QCD and EWK to fully capitalize on the experimental data?
Theoretical Uncertainties: production

Production at hadron colliders
- For HL-LHC uncertainties expected to be improved by factor 2 w.r.t. current
- HE-LHC: another factor of 2
- FCC-hh: well below 1%

Requires e.g.
- Improved PDFs
- Higher precision calculations
- Improved non-perturbative aspects
- ...

$ggf$: many small sources of uncertainties that add up

Improving substantially on any of the current sources of uncertainty represents a major theoretical challenge that should be met in accordance with our ability to utilise said precision and with experimental capabilities. The... It is obvious that the future precision of experimental measurement of Higgs boson properties will challenge the theoretical community. Achieving a significant improvement of our current theoretical understanding of the Higgs boson and its interactions will inspire us to push the boundaries of our capabilities to predict and extract information. New ways of utilising...

+ extreme kinematics [boosted, off-shell...]

F. Caola
Theoretical Uncertainties: partial widths

**Higgs: parametric uncertainties**

<table>
<thead>
<tr>
<th>Decay</th>
<th>Partial width [keV]</th>
<th>current unc. $\Delta \Gamma/\Gamma$ [%]</th>
<th>future unc. $\Delta \Gamma/\Gamma$ [%]</th>
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<tr>
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<td>&lt;0.4 1.4 0.4</td>
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</tr>
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<td>$H \rightarrow W^+W^-$</td>
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<td>0.4</td>
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<tr>
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<td>1.0 0.5</td>
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<td>0.3 0.5</td>
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<tr>
<td>$H \rightarrow \gamma\gamma$</td>
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<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>6.3</td>
<td>5.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

---

**F. Caola**

- <= very hard but doable at $M_Z$
- <= OK at $e^+e^-$ threshold scan
- <= OK

\[ \delta \alpha_s = 0.0002 \]
\[ \delta m_t = 50 \text{ MeV} \]
\[ \delta m_b = 13 \text{ MeV} \]
\[ \delta m_c = 7 \text{ MeV} \]
\[ \delta m_H = 10 \text{ MeV} \]
Theory uncertainties for EWK physics

ILC and FCC-ee have great potential for high-precision Z, WW, and Higgs physics

Can theory provide the necessary precision?

Optimists: “Yes. No show-stoppers seen, great progress can be anticipated.”

Sceptics: “Enormous challenge! Conceptual progress difficult to extrapolate.”

Some warnings:

- Produce solid and conservative uncertainty estimates!
- Always combine experimental and theoretical uncertainties!
- Employ different theoretical strategies and exp. analyses as much as possible!
  (e.g. for $\alpha_s$, $\Delta\alpha_{\text{had}}$)

The greatest challenges: (+ many more very demanding tasks)

- **Z:**
  - full EW 2-loop calculation for off-shell $e^+e^- \rightarrow f\bar{f}$
  - theoretically sound concept of pseudo-obervables
  - massive 3-loop calculations for $1 \rightarrow 2$ decays and $\mu$ decay

- **WW:**
  - NNLO threshold EFT calculation for $e^+e^- \rightarrow WW$

- **Higgs:**
  - full EW 2-loop calculation for off-shell $e^+e^- \rightarrow ZH$
  - massless 4-/5-loop QCD calculations for $1 \rightarrow 2$ decays

Certainly takes another generation of bright minds!

S. Dittmaier
1. How well can the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?
   - Current colliders: ~1-3% for 3rd gen fermions and gauge bosons, 4% to μ, 50% to itself
   - Future colliders: factors of ~2-10 better (!) + $\kappa_c \sim 2\%$ + model-independent $\sigma(ZH)$

2. How do precision electroweak observables inform us about the Higgs boson properties and/or BSM physics?
   - Important to make sure precision H measurements ($\delta g_Z$) not limited by these
   - Themselves probe new physics in interesting and complementary way

3. What progress is needed in theoretical developments in QCD and EWK to fully capitalize on the experimental data?
   - A lot of progress needed! Plan exists but lots of work/people needed!!
   - In some cases, new ideas are needed => and unclear when/if new ideas come

4. What is the best path towards measuring the Higgs potential?
   - Di-Higgs and single Higgs production are sensitive to derivative $d^3V/d^3\phi$ near minimum
   - Seems conceivable to determine it with sufficient precision to test 1st order EWΦT
Conclusions
Conclusions I

1. Measuring H coupling at the level of few% or better very interesting!!
   - Naturalness vs simplicity tested: complementary to LHC direct searches
   - Many important questions are related to Higgs boson

2. Significant advances in theory needed to exploit data from all (!) colliders

3. HL-LHC probes many H couplings to few % level
   - Absolute values model dependent, ratios of couplings model-independent

4. All ee colliders achieve major (and comparable) improvements in their first stage already in probing Higgs sector compared to HL-LHC:
   - At least half of couplings get improved by factor 5 or more
   - W/Z effective couplings and $BR(H \rightarrow invisible)$ even probed to $\sim 3 \times 10^{-3}$
   - Model-independent total cross section measurement $\Rightarrow$ access to width, untagged BR
   - Clean environment to study H if/when anomalies are seen to understand underlying physics

5. Higher energy stages of ee and hadron colliders important
   - Excellent sensitivity to high-scale physics, e.g. CLIC3000 and FCC-hh
   - FCC-hh/eh improves rare Higgs couplings by large factor compared to FCC-ee
Conclusions II

6. Electroweak precision measurements important for Higgs programme and NP tests
   - Oblique parameters
     - Circular colliders have naturally an extensive programme on EWPO at Z-pole (also $\Gamma_Z$)
     - CLIC at high energy and FCC-hh excellent reach
   - Precision top and W programme important for EFT analysis and theor. Uncertainties
     - Top requires $\sqrt{s} \geq 350$ GeV
   - Tera-Z programme at FCC-ee (and potentially CEPC) impressive
     - Giga-Z programme at ILC (incl. polarisation) not part of baseline plan => needs follow-up

7. Higgs self-coupling sensitivity interesting for electroweak phase transition:
   - di-Higgs process probes $\kappa_\lambda$ to 50% at HL-LHC => Improvements from HE-LHC (~15%), ILC$_{500}$ (~27%), CLIC$_{3000}$ (~9%), FCC-hh (~5%)
   - Single Higgs production also sensitive through loop effects

8. A few other interesting submissions for non-collider/low-energy measurements:
   - Not covered here but will include in briefing book
Backup Slides
<table>
<thead>
<tr>
<th>#</th>
<th>Title</th>
<th>Submitter</th>
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<tbody>
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<td>29</td>
<td>CEPC Input to the ESPP 2018 - Physics and Detector</td>
<td>Manqi Ruan</td>
</tr>
<tr>
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<td>Further searches of the Higgs scalar sector</td>
<td>Rubbia Secretariat</td>
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<tr>
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<td>The Physics Beyond Colliders Study at CERN</td>
<td>Claude Vallee</td>
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<td>Particle physics applications of the AWAKE acceleration scheme</td>
<td>Matthew Wing</td>
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<td>The International Linear Collider. A Global Project</td>
<td>Juan Fuster Verdú</td>
</tr>
<tr>
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<td>Future strategies for the discovery and the precise measurement of the Higgs self coupling</td>
<td>Patrick Janot</td>
</tr>
<tr>
<td>92</td>
<td>PROSPECT OF THE IN2P3 COMMUNITY INVOLVED IN THE ILC PROJECT</td>
<td>Marc Winter</td>
</tr>
<tr>
<td>99</td>
<td>Synergies between a U.S.-based Electron-Ion Collider and the European research in Particle Physics</td>
<td>Daniel Boer</td>
</tr>
<tr>
<td>100</td>
<td>Precision calculations for high-energy collider processes</td>
<td>Thomas Kurt Gehrmann</td>
</tr>
<tr>
<td>101</td>
<td>Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders</td>
<td>Alain Blondel</td>
</tr>
<tr>
<td>114</td>
<td>Monte Carlo event generators for high energy particle physics event simulation</td>
<td>Mike Seymour</td>
</tr>
<tr>
<td>118</td>
<td>The MUonE experiment</td>
<td>Clara Matteuzzi</td>
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<td>120</td>
<td>Muon Colliders</td>
<td>Nadia Pastrone</td>
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<td>131</td>
<td>Enhancing the LBNF/DUNE Physics Program</td>
<td>Roberto Petti</td>
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<tr>
<td>135</td>
<td>Future Circular Collider - The Integrated Programme (FCC-int)</td>
<td>Michael Benedikt</td>
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<tr>
<td>136</td>
<td>Future Circular Collider - The High-Energy LHC (HE-LHC)</td>
<td>Michael Benedikt</td>
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<tr>
<td>145</td>
<td>The Compact Linear e$^+e^-$ Collider (CLIC): Physics Potential</td>
<td>Philipp Roloff</td>
</tr>
<tr>
<td>152</td>
<td>The physics potential of HL-LHC</td>
<td>Michelangelo Mangano</td>
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<td>159</td>
<td>Exploring the Energy Frontier with Deep Inelastic Scattering at the LHC</td>
<td>Max Klein</td>
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<tr>
<td>160</td>
<td>The physics potential of HE-LHC</td>
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<tr>
<td>163</td>
<td>Quantum Chromodynamics: Theory - Input for the European Particle Physics Strategy Update</td>
<td>Francesco Hautmann</td>
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</table>

All submissions, see https://indico.cern.ch/event/765096/contributions/
Session 1
- Talk 1: Prospects for Higgs and EW measurements at HL-LHC (Patrizia Azzi, INFN Padova)
- Talk 2: QCD uncertainties on Higgs and EWK measurables (Fabrizio Caola, Oxford)
- Talk 3: Theoretical Perspective on direct and indirect searches for new physics (Riccardo Rattazzi, EPFL)

Session 2 (joint with accelerator track)
- Talk 4: Overview and technical challenges of proposed Higgs factories (Daniel Schulte, CERN)
- Talk 5: Capability of future machines for precision Higgs physics (Maria Cepeda, CIEMAT)
- Long Discussion

Session 3
- Talk 6: Electroweak Precision Measurements at future experiments (Mark Lancaster, Manchester)
- Talk 7: Precision Electroweak calculations (Giga-Z,WW, Higgs BRs, etc) (Stefan Dittmaier, Freiburg)
- Talk 8: The Higgs potential and its cosmological histories (Geraldine Servant, DESY)

Session 4
- Talk 9: Path towards measuring the Higgs potential (E. Petit, CPPM Marseille)
- Talk 10: Interpretation of Higgs and EWK data in EFT framework (Jorge de Blas, Padova)
- Long Discussion
Some observations:

- HL-LHC achieves precision of ~1-3% in most cases
- In some cases model-dependent
- Proposed $e^+e^-$ and $ep$ colliders improve w.r.t. HL-LHC by factors of ~2 to 10
- Initial stages of $e^+e^-$ colliders have comparable sensitivities (within factors of 2)
- $ee$ colliders constrain $BR \rightarrow untangled$ w/o assumptions
- Access to $\kappa_c$ at ee and eh

arXiv:1905.03764
High $p_T$ Higgs

\[ L = L_{SM} + \frac{1}{\Lambda^2} \sum_k O_k + \cdots \]

\[ O = | \langle f | L | i \rangle |^2 = O_{SM} \left[ 1 + O(\mu^2/\Lambda^2) + \cdots \right] \]

For H decays, or inclusive production, $\mu \sim O(\nu, m_H)$

\[ \delta O \sim \left( \frac{\mu}{\Lambda} \right)^2 \sim 6\% \left( \frac{\text{TeV}}{\Lambda} \right)^2 \quad \Rightarrow \text{precision probes large } \Lambda \]

e.g. $\delta O=1\% \Rightarrow \Lambda \sim 2.5 \text{ TeV}$

For H production off-shell or with large momentum transfer $Q$, $\mu \sim O(Q)$

\[ \delta O \sim \left( \frac{Q}{\Lambda} \right)^2 \quad \Rightarrow \text{kinematic reach probes large } \Lambda \]

even if precision is low

e.g. $\delta O=15\%$ at $Q=1 \text{ TeV} \Rightarrow \Lambda \sim 2.5 \text{ TeV}$
High $p_T$ Higgs at Hadron Colliders

**Powerful probe of new physics**
- Complementary to precision measurements of incl. $\sigma$
- $\delta O=15\%$ at $p_T(H)>1000$ GeV probes similar NP scale as $\delta O=1\%$ at rest ($M. Mangano$)
- HE-LHC: $\delta O \sim 5\%$ at 500 GeV
- FCC-hh: $\delta O \sim 2\%$ at 1 TeV
- Not captured by EFT it presented here!
Theoretical Uncertainties

Comparison of SM Theory uncertainties in Higgs calculations

Impact of SM theory uncertainties

Color code:
- No intrinsic unc.
- Full Th. unc.
- No Th. unc.
- No Parametric unc.
EFT: Detailed look at W and Z coupling

**Sensitivity to deviations in HVV couplings**

- **WARNING:** HE improvement relies on improvement of theory uncertainties
- **WARNING:** LHeC achieves <1% precision for some H rates. However, in EFT framework precision on HVV requires extra info (e.g. aTGC, angular). Results in current fit limited by LEP2 precision of aTGC (e.g. 10x LEP2 precision would bring LHeC HVV down to 0.7%)
- Lepton colliders can achieve ~per-mille accuracy. (Difference is how long it may take to get there.)
EFT: Detailed Look at 3rd generation

Sensitivity to deviations in $Hff$ ($3\text{rd}$ fam) couplings

- 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
EFT: Detailed look at 2\textsuperscript{nd} gen. and rare decays

*Sensitivity to deviations in $Hff$ (2nd fam.) couplings and rare decays*

- Rare decays statistically limited at Lepton Colliders: sub-percent precision at FCC-ee/eh/hh via hh ratios of BR
Measurements that probe Higgs couplings at ~1% level probe naturalness beyond LHC searches

<table>
<thead>
<tr>
<th>Model</th>
<th>LHC direct searches</th>
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<tbody>
<tr>
<td>soft</td>
<td>$\epsilon \lesssim 0.01$</td>
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<tr>
<td>Super-soft</td>
<td>$\epsilon \lesssim 0.1$</td>
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<tr>
<td>Hyper-soft</td>
<td>n.a.</td>
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R. Rattazzi
Measuring Naturalness with EWK prec. obs.

Measurements that probe EWK observables at ~0.01% level probe naturalness beyond LHC searches

\[
\hat{S} \sim \frac{\alpha_w}{8\pi} \times \frac{g_*^2 v^2}{m_*^2} \times N \approx \frac{m_W^2}{m_*^2}
\]

In all cases \( \hat{S} \sim 10^{-2\div3} \times \epsilon \)

- few \( \times 10^{-2} \times \epsilon \) Comp Higgs
- few \( \times 10^{-3} \times \epsilon \) SUSY

\[
\frac{\hat{S}}{m_W^2} i \left( H^\dagger \sigma^a D^\mu H \right) (D^\nu W_{\mu\nu})^a
\]

need high energy/huge precision

- dibosons at CLIC \( < 1 \times 10^{-5} \)
- EWPT at FCCee, dibosons at Fcchh \( < 2.5 \times 10^{-5} \)

R. Rattazzi

<table>
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<tr>
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<td>Super-soft</td>
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<tr>
<td>Hyper-soft</td>
<td>n.a.</td>
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</tbody>
</table>
All new high-energy colliders are also higgs factories

- Cannot cover them all in detail, so focus on some

- Electron-positron colliders
  - Linear colliders
    - ILC and CLIC
  - Circular colliders
    - FCC-ee and CepC
    - (LEP 3)

- Hadron colliders
  - LHC, HL-LHC, HE-LHC, FCC-hh and SppC

- Lepton-hadron colliders
  - LHeC and FCC-eh

- Muon colliders
- Plasma colliders
  - LEP3 and “Low-field” magnets in FCC tunnel

Happens in any case

Not mature enough at this moment
More R&D needed
Muon colliders could come in if we fail to have another higgs factory

One in Europe, one in Asia
Higgs Factories

Energy dependence:

At low energies circular colliders trump
• Reduction at high energy due to synchrotron radiation

At high energies linear colliders excel
• Luminosity per beam power roughly constant

Note: The typical higgs factory energies are close to the cross over in luminosity
Linear collider have polarised beams (80% e^-, ILC also 30% e^+) and beamstrahlung
• All included in the physics studies
The picture is much clearer at lower or higher energies

D. Schulte
### Accelerators relevant to Higgs physics

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<tr>
<th>Collider</th>
<th>Type</th>
<th>$\sqrt{s}$</th>
<th>$P,%$</th>
<th>N(Det.)</th>
<th>$L_{\text{inst}} , [10^{14}] , \text{cm}^{-2} \cdot \text{s}^{-1}$</th>
<th>$L , [\text{ab}^{-1}]$</th>
<th>Time [years]</th>
<th>Refs.</th>
<th>Abbreviation</th>
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<td>[3, 11]</td>
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<td>$\pm 80/\pm 30$</td>
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<td>1.6</td>
<td>0.2</td>
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<td>500 GeV</td>
<td>$\pm 80/\pm 30$</td>
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<td>1.8/3.6</td>
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<td>(+1)</td>
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<td>1.5</td>
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<tr>
<td>HE-LHeC</td>
<td>$ep$</td>
<td>1.8 TeV</td>
<td>-</td>
<td>1</td>
<td>1.5</td>
<td>2.0</td>
<td>20</td>
<td>[11]</td>
<td>HE-LHeC</td>
</tr>
<tr>
<td>FCC-eh</td>
<td>$ep$</td>
<td>3.5 TeV</td>
<td>-</td>
<td>1</td>
<td>1.5</td>
<td>2.0</td>
<td>25</td>
<td>[1]</td>
<td>FCC-eh</td>
</tr>
</tbody>
</table>

*References:* [1], [2], [3], [10], [11], [12]
## Schedules: by calendar year

<table>
<thead>
<tr>
<th>Year</th>
<th>CEPC</th>
<th>ILC</th>
<th>FCC-ee</th>
<th>CLIC</th>
<th>LHeC</th>
<th>FCC-eh/hh</th>
<th>HE-LHC</th>
<th>HL-LHC</th>
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<tr>
<td>'30</td>
<td>240 GeV</td>
<td>250 GeV</td>
<td>Z</td>
<td>380 GeV</td>
<td>1.3 TeV</td>
<td></td>
<td></td>
<td>3/ab</td>
</tr>
<tr>
<td>'32</td>
<td>Z</td>
<td>500 GeV &amp; 350 GeV</td>
<td>W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'35</td>
<td>W</td>
<td></td>
<td>240 GeV</td>
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<td>'40</td>
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<td>350-365 GeV</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>'50</td>
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<td></td>
</tr>
<tr>
<td>'55</td>
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</tbody>
</table>
 HL-LHC inputs

Major focus on understanding realistic systematic uncertainties (benefits from Run-1 comb. experience)

- Whenever feasible present results as value ± stat ± syst_exp ± syst_theory [± syst_lumi]
- Baseline scenario defined as:
  - YR18(S2): based on synchronised estimates of ultimate performance for experimental and theory uncertainties, and applying guidelines as in previous slide

<table>
<thead>
<tr>
<th>Object</th>
<th>WP</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Muons</td>
<td>reco+ID+ISO</td>
<td>0.1%(0.5%)</td>
</tr>
<tr>
<td>Electrons</td>
<td>reco+ID+ISO</td>
<td>0.5%</td>
</tr>
<tr>
<td>Taus</td>
<td>reco+ID+ISO</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>specific cases</td>
<td>2.5%</td>
</tr>
<tr>
<td>B-jet tag</td>
<td>30&lt;pt&lt;300GeV</td>
<td>-1%</td>
</tr>
<tr>
<td></td>
<td>pt&gt;300GeV</td>
<td>2-6%</td>
</tr>
<tr>
<td>c-jet tag</td>
<td></td>
<td>-2%</td>
</tr>
<tr>
<td>Light jets</td>
<td>L/M/T WP</td>
<td>5/10/15%</td>
</tr>
<tr>
<td>JES</td>
<td>abs/rel scale</td>
<td>0.1-0.2%(0.1-0.5%)</td>
</tr>
<tr>
<td>JEC</td>
<td>Pile-Up</td>
<td>0.2%</td>
</tr>
<tr>
<td>JEC</td>
<td>Flavor</td>
<td>0.75%</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td></td>
<td>1%</td>
</tr>
</tbody>
</table>
HL-LHC Sensitivity

**Expected significance** (SM) with and without systematics at HL-LHC

<table>
<thead>
<tr>
<th></th>
<th>Statistical-only ATLAS</th>
<th>Statistical-only CMS</th>
<th>Statistical + Systematic ATLAS</th>
<th>Statistical + Systematic CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HH \to bbb\bar{b}$</td>
<td>1.4</td>
<td>1.2</td>
<td>0.61</td>
<td>0.95</td>
</tr>
<tr>
<td>$HH \to b\tau\tau$</td>
<td>2.5</td>
<td>1.6</td>
<td>2.1</td>
<td>1.4</td>
</tr>
<tr>
<td>$HH \to b\gamma\gamma$</td>
<td>2.1</td>
<td>1.8</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>$HH \to bbVV(l\nu\nu)$</td>
<td>-</td>
<td>0.59</td>
<td>-</td>
<td>0.56</td>
</tr>
<tr>
<td>$HH \to bbZZ(4l)$</td>
<td>-</td>
<td>0.37</td>
<td>-</td>
<td>0.37</td>
</tr>
<tr>
<td><strong>combined</strong></td>
<td><strong>3.5</strong></td>
<td><strong>2.8</strong></td>
<td><strong>3.0</strong></td>
<td><strong>2.6</strong></td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td><strong>4.5</strong></td>
<td><strong>4.0</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Measurement of signal strength $\mu$ (SM):
  - $\sim 25\%$ ($30\%$) without (with) systematics
  - $\mu = 0$ (no SM HH signal) excluded at 95\% CL

- Measurement of $\kappa_x$:
  - 68\% CI of 50\%
  - 2nd minimum excluded at 99.4\% CL thanks to the $m_{hh}$ shape information

---

E. Petit
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 $E_{\text{coll}} < M_{Z'}$ one can still test virtual effects of NP looking for “deformations” in SM measurements.

For $E_{\text{coll}} \ll M_{Z'}$ 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.

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{Z'} + \mathcal{L}_{\text{SM}-Z'} \quad \xrightarrow{q^2 \ll M_{Z'}^2} \quad \mathcal{L}_{\text{Eff}} \]

J. De Blas
Fine-tuning constraints in BSM Models

**Soft Models** (SUSY with high scale mediation)

\[ \Delta m_h^2 \sim \frac{3y_i^2}{4\pi^2} \times m_T^2 \times \ln(\Lambda / m_t) \rightarrow m_T^2 \]

Natural range: LEP/Tevatron

LHC: \( \epsilon \lesssim 10^{-2} \) \( m_t \gtrsim 1 \) TeV

**HyperSoft Models** (Twin Higgs & Folded SUSY)

\[ \Delta m_h^2 \sim \frac{3\lambda_h}{16\pi^2} \times m_T^2 \]

\( \text{colored top partner} \)

Neutral twin top

\( \sqrt{\frac{4\pi^2}{3y_i^2}} \)

\( 1.5 \) TeV

\( 0.5 \) TeV

\( 0.1 \) TeV

**SuperSoft Models** (SUSY with low scale mediation & Composite Higgs)

\[ \Delta m_h^2 \sim \frac{3y_T^2}{4\pi^2} \times m_T^2 \]

\( \text{top partner} \)

\( 0.5 \) TeV

\( 0.1 \) TeV

LHC just got into the relevant grounds: \( \epsilon \lesssim 10^{-1} \)

- colored top partners out of LHC reach
- still tuning required by Higgs coupling data

Chacko, Goh, Harnik 2005
+ Burdman 2006

R. Rattazzi
Simplicity vs Naturalness

- **$10^{12}$ TeV**: High Scale SM: super simple & super un-natural
- **$10^4$ TeV**: Middle Options? just simpler and not yet super un-natural
- **$10^2$ TeV**: TeV Scale New Physics: not simple & almost natural
- **TeV**: perfect Flavor and CP, better Flavor and perfect EW

See also talk by R. Sundrum, HEFT 2016