Perspectives at Particle Accelerators



# **Outline**

<u>F. Bedeschi, INFN</u> Pisa, November 7, 2019

Current physics landscape
Current directions
Higgs factories e+eCurrent status and comments
Key measurements and comparisons
Scenarios under discussion by ESG
INFN position

Pisa, November 7, 2019

# Current physics landscape



## Higgs properties SM-like.

After HL-LHC precision level of several %



# Current physics landscape



## No (additional) signs of BSM physics.

#### After intensive searches at LHC $\rightarrow M_{NP} > 1 \text{ TeV}$

#### ATLAS SUSY Searches\* - 95% CL Lower Limits

	Model	s	Signature	e ∫⊥	<i>C dt</i> [fb <sup>-1</sup>	Mass limit				смѕ		36 fb <sup>-1</sup> (13 TeV)
dusive Searches	$q\bar{q}, \bar{q} \rightarrow q\bar{k}_{1}^{0}$ $\bar{g}\bar{g}, \bar{g} \rightarrow q\bar{q}\bar{k}_{1}^{0}$ $\bar{g}\bar{g}, \bar{g} \rightarrow q\bar{q}\ell(\ell)\bar{k}_{1}^{0}$ $\bar{g}\bar{g}, \bar{g} \rightarrow q\bar{q}\ell(\ell)\bar{k}_{1}^{0}$	0 e, μ mono-jet 0 e, μ 3 e, μ ce, μμ 0 e, μ SS e, μ	2-6 jets 1-3 jets 2-6 jets 4 jets 2 jets 7-11 jets 6 jets	$E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$	36.1 36.1 36.1 36.1 36.1 36.1 36.1 36.1		Heavy Gauge Bosons	$\begin{array}{l} \text{SSM Z'}(t) \\ \text{SSM Z'}(q\bar{q}) \\ \text{LFVZ', RR(e\mu) = 10\% } \\ \text{SSM W'(Q\bar{q})} \\ \text{SSM W'(Q\bar{q})} \\ \text{SSM W'(Tv) } \\ \text{LRSM W_{n}(N_{n}), M_{n_{n}} = 0.5M_{m_{n}} \\ \text{LRSM W_{n}(Tv_{n})} \end{array}$	$M_Z$ $M_Z$ $M_{II}$ $M_{III}$ $M_{III}$ $M_{III}$ $M_{III}$ $M_{III}$	1803-06292 (21) 1806-00843 (2j) 1807-01122 (ep) 1808-11133 (1 + E <sup>max</sup> ) 1806-00843 (2j) 1807-11421 (1 + E <sup>max</sup> ) 1807-1116 (21 + 2j) 1811-00806 (2 <b>x</b> + 2j)	45 27 44 52 33 4 4 44 35	
pul	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow d\tilde{\chi}_1^0$	0-1 e,μ SS e,μ	3 <i>b</i> 6 jets	$E_T^{miss}$	79.8 139	ğ ğ		Axigluon, Coloron, $cot\theta = 1$ scalar LQ (pair prod.), coupling to 1 <sup>st</sup> gen. fermions, $\beta = 1$	Mc Muq	1806.00843 (2j) 1811.01197 (2e+ 2j)	6.1	
rks ion	$\begin{split} & \bar{b}_1 \bar{b}_1,  \bar{b}_1 {\rightarrow} b \bar{\chi}_1^0 / d \bar{\chi}_1^+ \\ & \bar{b}_1 \bar{b}_1,  \bar{b}_1 {\rightarrow} b \bar{\chi}_2^0 {\rightarrow} b b \bar{\chi}_1^0 \end{split}$	0 e, µ	Multiple Multiple Multiple 6 b	$E_T^{\rm miss}$	36.1 36.1 139 139	b1         Forbidden         0	Leptoquarks	scalar LQ (pair prod.), coupling to 1 <sup>st</sup> gen. fermions, $\beta = 0.5$ scalar LQ (pair prod.), coupling to 2 <sup>rd</sup> gen. fermions, $\beta = 1$ scalar LQ (pair prod.), coupling to 2 <sup>rd</sup> gen. fermions, $\beta = 0.5$ scalar LQ (pair prod.), coupling to 3 <sup>rd</sup> gen. fermions, $\beta = 1$ , $\lambda = 1$	MLQ MLQ MLQ MLQ MLQ	1811.01197 (2e + 2j; e + 2j + E <sub>7</sub> <sup>tran</sup> )           1808.05082 (2μ + 2j)           1808.05082 (2μ + 2j; μ + 2j + E <sub>7</sub> <sup>tran</sup> )           1810.0806 (2r + 2j)           1810.0806 (2r + 2j)           1006.03472 (2r + b)	127 153 129 2	
3 <sup>rd</sup> gen. squa direct product	$ \begin{split} \tilde{\imath}_1 \tilde{\imath}_1 \cdot \tilde{\imath}_1 \rightarrow W b \tilde{k}_1^0 \text{ or } t \tilde{k}_1^0 \\ \tilde{\imath}_1 \tilde{\imath}_1 \cdot \tilde{\imath}_1 \rightarrow W b \tilde{k}_1^0 \\ \tilde{\imath}_1 \tilde{\imath}_1 \cdot \tilde{\imath}_1 \rightarrow \tilde{\imath}_1 b v, \tilde{\imath}_1 \rightarrow \tau \tilde{G} \\ \tilde{\imath}_1 \tilde{\imath}_1 \cdot \tilde{\imath}_1 \rightarrow c \tilde{k}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{k}_1^0 \end{split} $	0-2 e,μ 1 e,μ 1 τ + 1 e,μ,τ 0 e,μ 0 e,μ	0-2 jets/1-2 <i>b</i> 3 jets/1 <i>b</i> τ 2 jets/1 <i>b</i> 2 <i>c</i> mono-jet	$b E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$	36.1 139 36.1 36.1 36.1	<i>i</i> <sub>1</sub> 0.44-0.59 <i>i</i> <sub>1</sub> 0.44 <i>i</i> <sub>1</sub> 0.46 <i>i</i> <sub>1</sub> 0.46 <i>i</i> <sub>1</sub> 0.43	Excited Fermions	excited light quark (qg), $\Lambda = m_q^*$ excited light quark (qy), $f_s = f = f = 1, \Lambda = m_q^*$ excited b quark, $f_s = f = f = 1, \Lambda = m_q^*$ excited b quark, $f_s = f = f = 1, \Lambda = m_q^*$ excited encore, $f_s = f = 1, \Lambda = m_p^*$	$M_q \cdot M_q \cdot M_b \cdot M_b \cdot M_\mu \cdot$	1806 00843 (2) 1711 04652 (γ + j) 1711 04652 (γ + j) 1811 03052 (γ + 2φ) 1811 03052 (γ + 2φ)	6 55 18 39 38	
	$\tilde{t}_{2}\tilde{t}_{2}, \tilde{t}_{2} \rightarrow \tilde{t}_{1} + h$ $\tilde{t}_{2}\tilde{t}_{2}, \tilde{t}_{2} \rightarrow \tilde{t}_{1} + Z$ $\tilde{\chi}_{1}^{\pm}\chi_{2}^{0}$ via $WZ$	1-2 e,μ 3 e,μ 2-3 e,μ	4 b 1 b	$E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$	36.1 139 36.1	<i>i</i> <sub>2</sub> <	Contact teractions	quark compositeness (qq), $\eta_{LIRR} = 1$ quark compositeness (qt), $\eta_{UIRR} = 1$ quark compositeness (qq), $\eta_{LIRR} = -1$	Λ <sup>+</sup> <sub>LL/RR</sub> Λ <sup>+</sup> <sub>LL/RR</sub> Λ <sup>-</sup> <sub>LL/RR</sub>	1803.08030 (2) 1812.10443 (2) 1803.08030 (2)	1	2.8 20 17.5
EW direct	$ \begin{array}{l} \tilde{\chi}_1^+\tilde{\chi}_1^0 & \text{via } W W \\ \tilde{\chi}_1^+\tilde{\chi}_2^0 & \text{via } W h \\ \tilde{\chi}_1^+\tilde{\chi}_1^0 & \text{via } \tilde{\chi}_1/\tilde{\mu} \\ \tilde{\tau}_1^+\tilde{\tau}_1^+\tau - \tilde{\chi}_1^0 \\ \tilde{\tau}_{1,\mathbf{R}}^+\tilde{\tau}_1^-\tilde{\chi}_1^{-1}\tilde{\chi}_1^0 \\ H\tilde{H}, H \rightarrow hG/ZG \end{array} $	ee, μμ 2 e, μ 0-1 e, μ 2 e, μ 2 τ 2 e, μ 2 e, μ 2 e, μ 4 e, μ	≥ 1 2 <i>b</i> /2 γ 0 jets ≥ 1 ≥ 3 <i>b</i> 0 jets	$E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$ $E_T^{miss}$	139 139 139 139 139 139 139 139 36.1 36.1	λ <sub>T</sub> /λ <sub>T</sub> 0.205           δ <sup>1</sup> / <sub>1</sub> 0.42           λ <sup>2</sup> / <sub>1</sub> 0.16-0.3           δ <sup>1</sup> / <sub>1</sub> 0.16-0.3           1         0.256           β         0.13-0.23           β         0.3	a Dimensions	quark compositeness ( <i>U</i> ), $\eta_{uzym} = -1$ ADD (ij) HLZ, $n_{eD} = 3$ ADD ( $n_{eV}$ , <i>U</i> ) HLZ, $n_{eD} = 3$ ADD $\eta_{eV}$ , <i>U</i> ) HLZ, $n_{eD} = 6$ ADD QBH (ij), $n_{eD} = 6$ ADD QBH ( $e\mu$ ), $n_{eD} = 6$ RS $G_{ost}(40, g_{eV})$ , $MM_{eP} = 01$ RS $G_{ost}(10, eV_{eV})$ , $MM_{eP} = 01$	Л <sub>Ц,яя</sub> М <sub>5</sub> М <sub>5</sub> М <sub>0</sub> ен Моен Моен Моек	1812 10443 (27) 1803 0030 (2) 1812 10443 (27, 24) 1712 02345 (2 ij + F;***) 1803 0030 (2) 1803 0122 (2) 1803 0122 (2) 1805 0043 (2) 1805 00422 (2) 1805 00422 (2) 1805 00422 (2)	91 99 82 56 18 425	2
Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^+$ Stable $\tilde{g}$ R-hadron Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$	Disapp. trk	t 1 jet Multiple Multiple	$E_T^{\rm miss}$	36.1 36.1 36.1	$\tilde{\lambda}_{1}^{\pm}$ 0.46 $\tilde{\lambda}_{1}^{\pm}$ 0.15 $\tilde{g}$ [r( $\tilde{g}$ ) =10 ns. 0.2 ns]	Extr	$\label{eq:rescaled} \begin{array}{l} NS \ OB(\mathbf{r}), \ Ares = 1\\ RS \ OB(\mathbf{r}), \ Ares = 1\\ RS \ OB(\mathbf{r}), \ Ares = 1\\ On \ rotat = 1\\ On \ rotat = 1\\ Split-UED, \ \mu \geq 4 \ TeV \end{array}$	м <sub>авн</sub> М <sub>авн</sub> М <sub>ан</sub> 1/R	1805-8030 (EV) 1803-8030 (EV) 1802-80112 (eµ) 1805-80013 (E 7/(f, V)) 1803-11133 (f + E <sup>rm</sup> <sub>2</sub> )	59 36 9.7 29	
RPV	$\begin{split} & LFV \; pp \rightarrow \$, t \mathrel{\times} \$, \neg e\mu / e\tau / \mu \tau \\ & \tilde{k}_1^+ \tilde{k}_1^- \tilde{k}_2^0 \longrightarrow WW/ZUUV_{PV} \\ & \tilde{k}_2^* , \tilde{k}_2^- \rightarrow WW/ZUUV_{PV} \\ & \tilde{k}_2^* , \tilde{k}_1^- \rightarrow WW/ZUUV_{PV} \\ & \tilde{k}_1^* , \tilde{k}_1^- \rightarrow \tilde{k}_2^* \\ & \tilde{k}_1^* , \tilde{k}_1^- \rightarrow \tilde{k}_2^* \\ & \tilde{k}_1^* , \tilde{k}_1^- \rightarrow \tilde{k}_2^* \end{split}$	eμ, eτ,μτ 4 e, μ 4 e, μ 4	0 jets 4-5 large- <i>R</i> jet Multiple 2 jets + 2 b 2 b DV	$E_T^{miss}$	3.2 36.1 36.1 36.1 36.1 36.7 36.1 136	$ \begin{split} \tilde{r}_{1} & \tilde{k}_{1}^{2} \left[ \tilde{k}_{12}^{2} + 0, \tilde{k}_{12} \neq 0 \right] \\ \tilde{k}_{1}^{2} \left[ \tilde{k}_{12}^{2} - 200 \text{ GeV} + 100 \text{ GeV} \right] \\ \tilde{g} & [\tilde{k}_{12}^{2} - 20 + 2, 9, 0] \\ \tilde{g} & [\tilde{k}_{12}^{2} - 20 + 4, 10 - 2] \\ \tilde{g} & [\tilde{k}_{12}^{2} - 20 + 4, 10 - 2] \\ \tilde{f}_{1} & [\tilde{g}_{1}, \tilde{h}_{1}^{2} - 10 + 3, 9 - 10 + 3, 4] \\ \tilde{f}_{1} & [1 - 10 - 2, \frac{1}{2}, \frac{1}{2} - 10 + 3, 9 - 10 - 3, \frac{1}{2}, \frac{1}{2} - 3, 9 - 10 - 3, \frac{1}{2} - 10 + 3, \frac{1}{2} - $	er Dark Matter	(axia)-lvector mediator ( $\chi\chi$ ), $g_{i} = 0.25$ , $g_{out} = 1$ , $m_{s} = 1$ GeV (axia)-lvector mediator ( $\eta\chi$ ), $g_{i} = 0.25$ , $g_{out} = 1$ , $m_{s} = 1$ GeV scalar mediator (+ $tt\bar{t}\bar{t}$ ), $g_{-1} = 2g_{out} = 1$ , $m_{s} = 1$ GeV scalar mediator (+ $tt\bar{t}\bar{t}$ ), $g_{i} = 1$ , $g_{out} = 1$ , $m_{s} = 1$ GeV scalar mediator (+ $tt\bar{t}\bar{t}$ ), $g_{i} = 1$ , $g_{out} = 1$ , $m_{s} = 1$ GeV complex sc. med. (dark QCD), $m_{us} = 5$ GeV, $c\tau_{xu} = 25$ mm Type III Seesaw, $B_{i} = B_{i}$ .	M <sub>read</sub> M <sub>read</sub> M <sub>read</sub> M <sub>be</sub> M <sub>be</sub>	1712.02345 (≥ 1j + E <sub>2</sub> <sup>mm</sup> ) 1806.00843 (2j) 1901.01553 (0, 1t + ≥ 3j + E <sub>2</sub> <sup>mm</sup> ) 0.29 1901.01553 (0, 1t + ≥ 3j + E <sub>2</sub> <sup>mm</sup> ) 0.3 1712.02345 (≥ 1j + E <sub>2</sub> <sup>mm</sup> ) 1810.10099 (4j) 1708.02967 (> 3t) 0.84	18 26 14 154	
*Only	a selection of the available mas: oomena is shown. Many of the lir	s limits on mits are ba	new states	s or	1(		Othe	string resonance	Msigma Ms	0.1	7.7 .0 10. nass scale [TeV]	0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
simp	lified models, c.f. refs. for the as	sumptions	made.				Se	lection of observed exclusion limits at 95% C.L. (the	ory un	certainties are not included).		January 2019

#### **Overview of CMS EXO results**

F. Bedeschi, INFN-Pisa

- 3

# Current physics landscape



Higgs properties SM-like.

- At current precision level of several %
- No (additional) signs of BSM physics.
  - After intensive searches at LHC
- ... but SM is an insufficient description
  - Prevalence of matter over anti-matter.
    - Not explained by current values of CKM elements
  - ▶ Neutrinos have masses not acquired in the SM.
  - Compelling evidence for the existence of dark matter in the Universe with no candidate particle(s) in the SM.
- What new next accelerator to go beyond SM?

# **Current directions**



#### ICFA statement - Tokyo, March 2019:

"ICFA confirms the international consensus that the highest priority for the next global machine is a "Higgs Factory" capable of precision studies of the Higgs boson.

ICFA notes with satisfaction the great progress of the various options for Higgs factories proposed across the world. All options will be considered in the European Strategy for Particle Physics Update and by ICFA.

#### ICFA report – LP2019, Toronto, August 2019:

Worldwide effort for e+e- Higgs Factory must not fail!

- Linear or Circular
- Asia or Europe (or elsewhere?)

#### Recent comments on ESPPU preparations (B. Vachon – LP2019)

- Emerging consensus for the importance of a "Higgs factory" to fully explore properties of the Higgs, EW sector, etc.
- > Need to prepare a clear path towards highest energy.

5

# EU strategy update



Input documents from all communities by Dec. 2018
 Open symposium to discuss everything in Granada 2019
 <a href="https://indico.cern.ch/event/808335/">https://indico.cern.ch/event/808335/</a>

After Granada a "Briefing Book" was produced

Supposedly to summarize everything for the group of people who will draft the report for the CERN Council

http://cds.cern.ch/record/2691414

Some parts of this book are debatable – Will point them out during the talk.





# The planned machines

# Higgs factories

Difficult



- *e+e* linear
  - ILC – CLIC
- e+e- circular
  - -FCC-ee
  - CepC
  - $\mu + \mu$  circular

- **Requirement:** high luminosity *O*(10<sup>34</sup>) at the Higgs energy scale
- Usually, compared to the LHC which is, as a machine :
- 27 km long

8

- SC magnets (8T)
- 150 MW power total
- ~ 10 years to build
- Cost "1 LHC Unit" \*



F. Bedeschi, INFN-Pisa



- 168 MW site power (~9MW beams)
- Cost est. 5.9 BCHF (klystrons + 1.4 BCHF)

# Linear Colliders *e+e-* Higgs Factories



#### Advantages:

- Based on mature technology (Normal Conducting RF, SRF)
- Mature designs: ILC TDR, CLIC CDR and test facilities
- Polarization (ILC: 80%-30%; CLIC 80% 0%)
- Expandable to higher energies (ILC to 0.5 and 1 TeV, CLIC to 3 TeV)
- → Well-organized international collaboration (LCC) → "we're ready"
- Wall plug power ~130-170 MW (i.e. <= LHC)</p>

#### Pay attention to:

- Cost more than LHC ~(1-1.5) LHC
- LC luminosity < ring (e.g., FCC-ee), upgrades at the cost:</p>
  - e.g. factor of 4 for ILC: x2 Nbunches and 5 Hz  $\rightarrow$  10 Hz
- Limited LC experience (SLC), two-beam scheme (CLIC) is novel,
   klystron option as backup
- Wall plug power may grow >LHC for lumi / E upgrades

# Challenges of Linear Colliders Higgs Factories



#### Notes from the briefing book:

- The world record for positron production rates is still held by the SLC positron source. LCs require much higher positron production rates than SLC (CLIC about 20 times more, ILC baseline about 40 times, ILC upgrade about 160 times).

#### Notes from the briefing book:

- ATF2 has achieved the scaled ILC vertical spot size of  $\sim 40$  nm, albeit with a relaxed optics and at roughly 1/10 of the design bunch charge; the charge was reduced to mitigate wakefield effects.









Luminosity Dilution by Beamstrahlung

The limits are set by:Cost

- ILC TDR 1 TeV 17 B\$
- CLIC CDR 3 TeV 18.3BCHF
- Electric power required
- Total length

7. SHILTSEV, Granada 2019

(complication of) Beamstrahlung

3.0





#### Key facts:

- 100 km tunnel, three rings (e-, e+, booster)
- SRF power to beams 100 MW (60 MW in CepC)
- Total site power <300MW (tbd)</p>
- Cost est. FCCee 10.5 BCHF (+1.1BCHF for tt)
  - ("< 6BCHF" cited in the CepC CDR)



Fisica Nuclea

# e<sup>+</sup>e<sup>-</sup> Ring Higgs Factories

#### Advantages:

- Based on mature technology (SRF) and rich experience
  - $\blacksquare \rightarrow$  lower risk
- High(er) luminosity and ratio luminosity/cost;
  - Up to 4 IPs, EW factories
- > 100 km tunnel can be reused for a pp collider in the future
- Fransverse polarization ( $\tau \sim 18$  min at tt) for E calibration O(100keV)
- CDRs addressed key design points, may be ready for ca 2039 start
- Very strong and broad Global FCC Collaboration

# Challenges of e<sup>+</sup>e<sup>-</sup> Ring HF's

#### Power limited regime

 Synchrotron radiation power from both beams limited to 100 MW (P/η=total site power)
 → current I is set by power



## Notes from the briefing book:

There are no major technical obstacles for their (all Higgs factories) realization, however more effort is required before construction of any of them could start.

Dete Not everybody agrees on this flattening beam-ocan parameter  $\varsigma_y$ , ocan function at the IP  $\beta_y^*$  and power

Beam life ~18 min requires full energy booster ring

**A SHILTSEV, Granada 2019** 

Lumino

# FCC integrated program

#### **Implementation studies in Geneva basin:**



#### baseline position was established considering:

- minimum risk for construction, fastest and cheapest construction
- efficient connection to CERN accelerator complex
  - Total construction duration 7 years
  - First sectors ready after 4.5 years



M. BENEDIKT, Granada 2019

F. Bedeschi, INFN-Pisa





FCC integrated project plan is fully integrated with HL-LHC exploitation and provides for seamless further continuation of HEP in Europe.

18

Istituto Nazionale di Fisica Nucleare

## **CEPC-SppC:** site studies



1) Qinhuangdao, Hebei **ProvinceCompleted 2014**) 2) Huangling, Shanxi **Province** (Completed 2017) 3) Shenshan, Guangdong **Province(Completed 2016)** 4) Baoding (Xiong an), Hebei Province (Started **August 2017)** 5) Huzhou, Zhejiang **Province (Started March** 2018) 6) Chuangchun, Jilin **Province (Started May** 2018)

7) Changsha, Hunan Province (Started Dec. 2018)



#### F. Bedeschi, INFN-Pisa







# Schedules





# Luminosity comparison





Higgs production

Istituto Nazionale di Fisica Nucleare



# Physics at FCC-ee



Higgs factory  $\blacktriangleright 10^6 \text{ e+e-} \rightarrow \text{HZ}$ **EW & Top factory** > 3x10<sup>12</sup> e+e-  $\rightarrow$  Z  $\rightarrow$  10<sup>8</sup> e+e-  $\rightarrow$  W+W-;  $> 10^6 \text{ e}+\text{e}- \rightarrow \text{tt}$ Flavor factory > 5x10<sup>11</sup> e+e- $\rightarrow$  bb, cc  $\rightarrow 10^{11} e^+e^- \rightarrow \tau^+\tau^-$ Potential discovery of NP  $\triangleright$  ALPs, RH v's, ...



24

# Higgs total width



Higgs recoil provides model independent  $L = 5 \text{ ab}^{-1}$ measurement of coupling to Z IDEA: Higgs recoil  $\Delta$  E/E = .136%  $\sigma(\text{HZ}) \propto g^2_{\text{HZ}}$ 18000 ww 1000 Z\* 2000 0000 8000 6000 4000 Critical: 2000 120 Beam energy spread: SR+BS Recoil mass (GeV) Higgs recoil mass with 0.136% beam spread Detector resolution eHrec Entries 126.4 Mean etectors RMS 2 34 Beam only 2.372 IDEA Total width combining with CLD 500 E decays in specific channels 400 <sup>300</sup>  $\sigma(ee \to ZH) \cdot BR(H \to ZZ) \propto \frac{g_{HZ}^4}{r}$ 200 100 E Recoil mass (GeV)

25

# Higgs coupling fits



Kappa framework

$$(\boldsymbol{\sigma} \cdot \mathbf{BR})(i \rightarrow \mathbf{H} \rightarrow f) = \frac{\boldsymbol{\sigma}_i \cdot \boldsymbol{\Gamma}_f}{\boldsymbol{\Gamma}_H},$$

$$\kappa_{H}^{2} \equiv \sum_{j} rac{\kappa_{j}^{2} \Gamma_{j}^{\mathrm{SM}}}{\Gamma_{H}^{\mathrm{SM}}}$$

Extension

 $\Gamma_{H} = \frac{\Gamma_{H}^{\text{SM}} \cdot \kappa_{H}^{2}}{1 - (BR_{inv} + BR_{unt})}$ BRinv measured at FCC-ee BRunt 100% correlated with  $\Gamma_{H}$ 

 $(\boldsymbol{\sigma} \cdot \mathbf{BR})(i \to \mathbf{H} \to f) = \frac{\boldsymbol{\sigma}_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_i^{SM} \kappa_i^2} \to \mu_i^f \equiv \frac{\boldsymbol{\sigma} \cdot \mathbf{BR}}{\boldsymbol{\sigma}_{SM} \cdot \mathbf{BR}_{SM}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_i^2}$ 

## EFT framework

Leading order NP effects weighted sum of all dim-6 operators  $O = O_{SM} + \delta O_{NP} \frac{1}{\Lambda^2}$   $\rightarrow$  59 B&L conserving operators

Includes interference with SM operators

Simultaneous fit of Higgs, EWPO, aTGC, topEW

Fit results projected into effective Higgs couplings

$$g_{HX}^{\rm eff~2}\equiv\frac{\Gamma_{H\rightarrow X}}{\Gamma_{H\rightarrow X}^{\rm SM}}$$

# Higgs coupling fits





# **Triple Higgs**





# Higgs coupling comparison

 $g_{HZZ}^{\text{eff}}$  -



**Improvement factors** relative to HL-LHC

## Notes from the briefing book:

- As Higgs factories, all the four contenders have a similar reach, as established during the Open Symposium.
  - Debatable ...



29



## EWK with Circular e+e-

## Outstanding program of precision EWK measurements



## EWK examples





#### INFN Istituto Nazionale di Fisica Nucleare

## NP sensitivity from EFT fits

From exclusive fits

Reach to several 10's TeV

Theory uncertainties
Parametric~ exp. precision
Theory precision need
3 loop Z pole
2 loop WW



# S, T parameters (Peskin–Takeuchi)





INF

Istituto Nazionale di Fisica Nucleare

# Note from briefing book



..... about 5x10<sup>12</sup> Z bosons will be recorded for FCC-ee within four years. For the linear colliders, ILC and CLIC, within a few years a sample of a few 10<sup>9</sup> Z bosons could be recorded. In addition, a significant improvement for some of the Z boson properties can also

be achieved using Z bosons durin energies; those numbers are also

- ► Issues for LC:
  - x 10 in beam energy spread
     Much longer collection time
     HF physics relies on statistics



# Heavy flavors



## Large heavy flavor production at Z pole

\_

Particle production $(10^9)$	$B^0$	$B^-$	$B_s^0$	$\Lambda_b$	$c\overline{c}$	$\tau^- \tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	400	400	100	100	800	220



## Direct NP search example: HNL

NuTeV

Seesaw

NuTeV

Seesaw

HNL mass (GeV)

1

HNL mass (GeV)

BAU

BAU

FCC-ee

36

FCC-ee



HNL mix with active neutrino's ► Fully reconstructable decay with W  $\blacktriangleright$  Small mixing  $\rightarrow$  long lifetime

10<sup>-10</sup>

10-1

BBN



FCC-ee

Seesaw

HNL mass (GeV)

10<sup>-10</sup>

10

BBN

. . . . . .



 $10 \text{ cm} < c\tau < 100 \text{ cm}$  $10^{12} Z$ 



F. Bedeschi, INFN-Pisa

## FCCee summary



Huge potential of physics from FCC-ee (or CepC) Study Higgs x10 better than HL-LHC EWPO x10-100 better than LEP Direct sensitivity to new physics Indirect sensitivity to NP in the 10's TeV range Large potential for HF studies complementary to LHC-b/Belle II Can match right time scale immediately after HL-LHC Setup infrastructure for highest energy with FCC-hh Gain time for high field magnet development Same infrastructure could be used for a multi TeV muon collider Significant activity on detector concepts is in progress

# ESG main scenarios



#### 5 basic options for the future being explored by ESG

	2020-2040	2040-2060	2060-2080			
		1st gen technology	2nd gen technology			
CLIC-all	HL-LHC	CLIC380-1500	CLIC3000 / other tech			
CLIC-FCC	HL-LHC	CLIC380	FCC-h/e/A (Adv HF magnets) / other tech			
FCC-all	HL-LHC	FCC-ee (90-365)	FCC-h/e/A (Adv HF magnets) / other tech			
LE-to-HE-FCC-h/e/A HL-LHC		LE-FCC-h/e/A (low-field magnets)	FCC-h/e/A (Adv HF magnets) / other tech			
LHeC-FCC-h/e/A	HL-LHC + LHe	C LHeC	FCC-h/e/A (Adv HF magnets) / other tech			

## CERN funding:

First 3 scenarios: 10-13% CERN budget in 2025-2045

Civil engineering assumed outside of CERN budget

- ► 4<sup>th</sup> scenario: ~20% CERN budget in 2025-2045
- ► 5<sup>th</sup> scenario is within the regular CERN budget

Last 2 scenarios assume that an e+e- collider is built outside of Europe

# Comments under discussion



## Agreed by many at INFN:

- We think that the ESPP update should be based on significant jump in precision and broad exploration potential
- We believe that, out of the five proposed scenarios, the FCC-all option is the best one in this respect.
- In the FCC-ee phase electroweak physics will be studied with unprecedented precision not only in the sector related to the newly discovered scalar boson, but also in the Z, W and top quark sectors.
- The FCC-hh phase would guarantee in the best way direct broad exploration of new territories.

# Comments under discussion



## What if Asia builds e+e- first:

- Option (FCC) robust against any decision taken in other geographical regions.
- Should ILC (or other e+e- colliders) start construction in the next decade or so, then CERN could directly proceed to FCC-hh, presumably starting with low-field magnets.
- Otherwise the FCC-ee would be the first step.
- Moreover FCC is the infrastructure that provides the most flexible tool for our research in the next decades, including the possibility of having <u>at least two detectors operating</u>, which is mandatory in case of discovery or evidence of some anomaly.







# LHC BSM exclusion

	Model	1.7	Jets†	Emiss	[L dt[fb	-1]	Limit		-		Reference
Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD OBH ADD BH high $\sum pT$ ADD BH multiget RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW \rightarrow qqqq$ Bulk RS $g_{KK} \rightarrow WW \rightarrow qqqq$ Bulk RS $g_{KK} \rightarrow tt$	$0 e, \mu$ $2 \gamma$ $-$ $\geq 1 e, \mu$ $-$ $2 \gamma$ multi-chann $0 e, \mu$ $1 e, \mu$ $1 e, \mu$	1 - 4 j - 2 j $\geq 2 j$ $\geq 3 j$ - 3 j el 2 J $\geq 1 b, \geq 1 J b$ $\geq 2 b, \geq 3$	Yes - - - - 2j Yes j Yes	36.1 36.7 37.0 3.2 3.6 36.7 36.1 139 36.1 36.1	Mo Ms Ms Ma Ma Grac mass Grac mass Grac mass Grac mass Grac mass Grac mass Grac mass		4.1 TeV 2.3 TeV 1.6 TeV 1.8 TeV 1.8 TeV	7.7 TeV 8.6 TeV 8.9 TeV 8.2 TeV 9.55 TeV	$\begin{array}{l} n=2\\ n=3\ \text{HLZ NLO}\\ n=6\\ n=6,\ M_D=3\ \text{TeV, rot BH}\\ n=6,\ M_D=3\ \text{TeV, rot BH}\\ k/\overline{M}_{PI}=0.1\\ k/\overline{M}_{PI}=1.0\\ k/\overline{M}_{PI}=1.0\\ \Gamma/m=15\%\\ \text{Terr}(1,1),\ \text{S}(A^{(1,1)}\to tr)=1 \end{array}$	1711.03301 1707.04147 1703.09127 1606.02265 1512.02566 1707.04147 1808.02380 ATLAS-CONF-2019-00 1804.10823 1803.09678
Gauge bosons	$\begin{array}{l} \text{SSM } Z' \to \ell\ell \\ \text{SSM } Z' \to \tau\tau \\ \text{Leptophobic } Z' \to bb \\ \text{Leptophobic } Z' \to bt \\ \text{SSM } W' \to \ell \nu \\ \text{SSM } W' \to \tau\nu \\ \text{HVT } V' \to WZ \to qqqq \text{ model } B \\ \text{HVT } V' \to WH/ZH \text{ model } B \\ \text{LRSM } W_R \to bb \\ \text{LRSM } W_R \to \mu N_R \end{array}$	2 e, µ 2 τ - 1 e, µ 1 r, β 0 e, µ multi-chann 2 µ	- 2 b ≥ 1 b, ≥ 1J, - 2 J el el 1 J	- 2j Yes Yes Yes -	139 36.1 36.1 139 36.1 139 36.1 36.1 36.1 80	Z' mass Z' mass Z' mass Z' mass W' mass W' mass V' mass V' mass W <sub>R</sub> mass W <sub>R</sub> mass		5.1 TeV 2.42 TeV 3.0 TeV 3.0 TeV 3.7 TeV 3.6 TeV 2.93 TeV 3.25 TeV 5.0 TeV	n Nev	$\label{eq:gv} \begin{split} &\Gamma/m = 1\% \\ &g_V = 3 \\ &g_V = 3 \\ &m(N_R) = 0.5 \text{ TeV}, g_L = g_R \end{split}$	1903.06248 1709.07242 1805.09299 1804.10823 CERN-EP-2019-100 1801.06992 ATLAS-CONF-2019-00 1712.06518 1807.10473 1904.12679
G	Cl qqqq Cl <i>ttq</i> q Cl <i>tttt</i>		2 j  ≥1 b, ≥1 j	- Yes	37.0 36.1 36.1	A A A		2.57 TeV		21.8 TeV η <sub>LL</sub> 40.0 TeV η <sub>LL</sub>  C <sub>trl</sub> = 4π	1703.09127 1707.02424 1811.02305
MQ	Axial-vector mediator (Dirac DM) Colored scalar mediator (Dirac D $VV_{\chi\chi}$ EFT (Dirac DM) Scalar reson. $\phi \rightarrow t\chi$ (Dirac DM)	0 e, μ M) 0 e, μ 0 e, μ 0-1 e, μ	1 - 4 j 1 - 4 j $1 J, \le 1 j$ 1 b, 0-1 J	Yes Yes Yes	36.1 36.1 3.2 36.1	m <sub>med</sub> m <sub>med</sub> M. m <sub>g</sub>	700 GeV	55 TeV 1.67 TeV 3.4 TeV		$\begin{array}{l} g_{q} = 0.25,  g_{\chi} = 1.0,  m(\chi) = 1   \mathrm{GeV} \\ g = 1.0,  m(\chi) = 1   \mathrm{GeV} \\ m(\chi) < 150   \mathrm{GeV} \\ y = 0.4,  \lambda = 0.2,  m(\chi) = 10   \mathrm{GeV} \end{array}$	1711.03301 1711.03301 1608.02372 1812.09743
ro	Scalar LQ 1 <sup>st</sup> gen Scalar LQ 2 <sup>nd</sup> gen Scalar LQ 3 <sup>rd</sup> gen Scalar LQ 3 <sup>rd</sup> gen	1,2 e 1,2 μ 2 τ 0-1 e, μ	≥ 2 j ≥ 2 j 2 b 2 b	Yes Yes - Yes	36.1 36.1 36.1 36.1	LQ mass LQ mass LQ <sup>*</sup> <sub>3</sub> mass LQ <sup>*</sup> <sub>3</sub> mass	1 1.03 Te 970 GeV	s TeV 56 TeV		$\begin{array}{l} \beta = 1 \\ \beta = 1 \\ \mathcal{B}(\mathrm{L}Q_3^\nu \rightarrow b\tau) = 1 \\ \mathcal{B}(\mathrm{L}Q_3^\nu \rightarrow t\tau) = 0 \end{array}$	1902.00377 1902.00377 1902.08103 1902.08103
quarks	$ \begin{array}{l} VLQ \ TT \rightarrow Ht/Zt/Wb + X \\ VLQ \ BB \rightarrow Wt/Zb + X \\ VLQ \ BT \rightarrow Wt/Zb + X \\ VLQ \ T_{5/3} \ T_{5/3}   \ T_{5/3} \rightarrow Wt + X \\ VLQ \ Y \rightarrow Wb + X \\ VLQ \ Q \rightarrow Hb + X \\ VLQ \ QQ \rightarrow WqWq \end{array} $	multi-chann multi-chann $2(SS)/\geq 3 e,$ $1 e, \mu$ $0 e, \mu, 2 \gamma$ $1 e, \mu$	el el $\mu \ge 1 \text{ b}, \ge 1 \text{ j}$ $\ge 1 \text{ b}, \ge 1$ $\ge 1 \text{ b}, \ge 1$ $\ge 4 \text{ j}$	Yes j Yes j Yes Yes	36.1 36.1 36.1 36.1 79.8 20.3	T mass B mass T <sub>5/2</sub> mass Y mass B mass Q mass	1.3 1.3 1.21 690 GeV	TeV TeV 1.64 TeV 1.85 TeV eV		$\begin{array}{l} SU(2) \text{ doublet} \\ SU(2) \text{ doublet} \\ \mathcal{B}(T_{5/3} \rightarrow Wt) = 1, \ c(T_{5/3}Wt) = 1 \\ \mathcal{B}(Y \rightarrow Wb) = 1, \ c_{R}(Wb) = 1 \\ \kappa_{B} = 0.5 \end{array}$	1808.02343 1808.02343 1807.11883 1812.07343 ATLAS-CONF-2018-02/ 1509.04261
fermions	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton $t^*$ Excited lepton $\gamma^*$	- 1 γ - 3 e,μ 3 e,μ,τ	2j 1j 1b,1j -		139 36.7 36.1 20.3 20.3	q* mass q* mass b* mass r* mass y* mass		6. 5.3 Te 2.6 TeV 3.0 TeV 1.6 TeV	TeV V	only $u^{\circ}$ and $d^{\circ}, \Lambda = m(q^{\circ})$ only $u^{\circ}$ and $d^{\circ}, \Lambda = m(q^{\circ})$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	ATLAS-CONF-2019-00 1709.10440 1805.09299 1411.2921 1411.2921
Other	Type III Seesaw LRSM Majorana $v$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Multi-charged particles Magnetic monopoles	1 e,μ 2 μ 2,3,4 e,μ (S 3 e,μ,τ - -	≥ 2 j 2 j S) - - -	Yes - - - -	79.8 36.1 20.3 36.1 36.1 34.4	N <sup>o</sup> mass Na mass H <sup>ss</sup> mass H <sup>ss</sup> mass multi-charged particle mass monopole mass	560 GeV 870 GeV 400 GeV 1.22	3.2 TeV eV 2.37 TeV		$\begin{array}{l} m(W_R)=4.1 \ \text{TeV}, g_1=g_R \\ \mbox{DY production} \\ \mbox{DY production}, \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \$	ATLAS-CONF-2018-021 1809.11105 1710.09748 1411.2921 1812.03673 1905.10130
*Only †Smi	Magnetic monopoles VS = 8 TeV pa y a selection of the available all-radius (large-radius) jets	= 13 TeV rtial data e mass lim are denoi	$\sqrt{s} = 13$ full d hits on new ted by the	<mark>3 TeV</mark> ata v states letter j	34.4 s or pher (J).	10 <sup>-1</sup>	1_T	2.37 TeV		DY production, $ g  = 1_{gD}$ , spin 1/2 Mass scale [TeV]	1905.10130

# $\mu^+\mu^-$ Collider progress



Ionization cooling of muons: Demonstrated in MICE @ RAL 4D emittance change O(10%)NC RF 50 MV/m in 3 T field Developed and tested at Fermilab Rapid cycling HTS magnets Record 12 T/s – built and tested at FNAL First RF acceleration of muons J-PARC MUSE RFQ 90 KeV  $\bullet$  US MAP Collaboration  $\rightarrow$  Int'l Low emittance (no cool) concept 45 GeV e<sup>+</sup>+e<sup>-</sup> $\rightarrow$   $\mu^+\mu^-$ : CERN fixed target







# High Energy $\mu^+\mu^-$ Colliders

#### Advantages:

- μ's do not radiate / no beamstrahlung

   acceleration in rings
   low cost & great power efficiency

   \* ~ x7 energy reach vs pp
   \* New positron driven approach
   \* Key to success:
  - Test facility to demonstrate performance implications
    - muon production and 6D cooling,
    - study LEMMA e+-45 GeV + e- at
    - design study of acceleration, detec background and neutrino radiation



F. Bedeschi, INFN-Pisa

Istituto Nazional di Fisica Nuclear

# Circular pp Colliders



HE-LHC 27 TeV

V. SHILTSEV, Granada 201

#### 

## Key facts: HE-LHC / FCC-hh\* / SppC\*

- \* follow up after e+e- Higgs factories
- Large tunnel -27 / 100 / 100 km
- ► SC magnets 16 / 16 / 12 T
- High Lumi / pileup O(1035) / O(500)
- ➢ Site power (MW) −200 / 500? / ?
- ➢ Cost (BCHF) −7.2 / 17.1 / ?
- Unexplored possibility:
  - FCC with conventional magnets



stituto Nazionalo li Fisica Nuclearo

# **HE-LHC** timeline



## Timeline dominated by magnet R&D/Production



46

# What if just 12 T magnets



## Somewhat faster - Similar cost - 21 TeV

	2020					2025				2030			2035		2040	
Design & Parameters Opt.																
Superconductor Nb <sub>3</sub> Sn	Develo	op. & p	ilots	Protot	ypes	Conntruction	1									
Magnet Eng & Proto			Model	s		Prototypes										
Industrialization					1st gei	neration	2nd ge	ener.co	st opt.							
Construction								Pre-se	ries	Series.						
Installation & HW Comm.																

#### Cost scaled from 2019 HE-LHC study. If it is of real interest the study could be done

L. ROSSI, Granada 2019

Domain	Cost MCHF	Comments	Wrt HE-LHC
Collider	4500	2400 for Magnets	-500
Injectors	500 ÷ 1100	New optimization TBD	0 ÷ -600
Tech Infr.+C.E.	900 ÷ 1100	Probably is less (< P <sub>syn</sub> )	? (-200?)
ТОТ	6100 ÷ 6700	(LHC2008 was 3400)	Cost should be optimized as upgrade

# Other comparisons



# *F1* "Technology *F2* "Energy Efficiency" Readiness" : Green - TDR *F2* "Energy Efficiency" Green : 100-200 MW

 Yellow
 - CDR
 Yellow
 : 200-400 MW

 Red
 - R&D
 Red
 : > 400 MW

F3 "Cost" :
 Green : < LHC</li>
 Yellow : 1-2 x LHC
 Red : > 2x LHC

# Other comparisons



Higgs Factories	Readiness	Power-Eff.	Cost
ee Linear 250 GeV			
ee Rings 240GeV/tt			
μμ Collider 125 GeV			*

V. SHILTSEV, Granada 2019

## Beamstrahlung



8	$\left(\underline{E}_{CM}\right)$	$N^2$
$\bullet O_{BS}$	$\left( \sigma_z \right)$	$\sigma_x$

	Unit	IL	CLIC	
$\sqrt{s}$	GeV	500	1000	3000
L	10 <sup>34</sup> cm <sup>-2</sup> s <sup>-1</sup>	1.5	4.3	5.9
$\Upsilon_{av}$		0.15	0.20	4.9
$\delta_{B}$	%	3.7	10	28
nγ		1.7	2.0	2.1



 $\blacktriangleright$  ILC  $\overline{240 \sim 1.6\%}$ 

50

# Luminosity issues



## Physics reach driven by luminosity

Success driven by luminosity!

Luminosity relies on complex/sensitive magnetic optics

