Future Circular e+e- Colliders



F. Bedeschi

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<u>Outline</u>

Current physics landscape
Current directions
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Current physics landscape



Higgs properties SM-like. After HL-LHC precision level of several % Granada 2019 $k_F \frac{m_F}{V}$ or $\sqrt{k_V \frac{m_V}{V}}$ $\sqrt{s} = 14 \text{ TeV}$, 3000 fb⁻¹ per experiment ATLAS and CMS ATLAS and CMS LHC Run 1 Total Statistical **HL-LHC** Projection Experimental ⁰∕₀ Uncertainty [%] Theory 10^{-1} Tot Stat Exp Th κ_{v} **1.8** 0.8 1.0 1.3 onc **1.7** 0.8 0.7 1.3 nposite Higgs (MCHM5) 10^{-2} 1.5 0.7 0.6 1.2 = 1.5 TeV) 2.5 0.9 0.8 2.1 N b τ С ATLAS+CMS **3.4** 0.9 1.1 3.1 SM Higgs boson 10^{-3} **3.7** 1.3 1.3 3.2 $[M, \varepsilon]$ fit **1.9** 0.9 0.8 1.5 68% CL 4.3 3.8 1.0 1.7 95% CL 10^{-4} 9.8 7.2 1.7 6.4 ed Higgs coupling precision (model-independer 000 fb⁻¹ ⊕ 350 GeV, 200 fb⁻¹ ⊕ 250 GeV, 2000 fb⁻¹ 10^{-1} 10^{2} 10 diction 1 0.04 0.06 0.08 0.1 0.12 0.14 Particle mass [GeV] Expected uncertainty ILC Physics WG, '15 arXiv:1506.05992 2 F. Bedeschi, INFN-Pisa

Current physics landscape

Overview of CMS EXO results



♦ No (additional) signs of BSM physics. ■ After intensive searches at LHC → M_{NP} > 1 TeV

ATLAS SUSY Searches* - 95% CL Lower Limits

	Model	S	ignatur	e ∫.	L dt [fb ⁻	Mass limit				CMS		36 fb ⁻¹ (13 TeV)
		0	O.C.into	emiss				SSM Z'(tt)	M _z ,	1803.06292 (21)	4.5	
	$\bar{q}\bar{q}, \bar{q} \rightarrow q\chi_1$	mono-jet	1-3 jets	Eniss	36.1	q [2×, 6× Degen.] q̃ [1×, 8× Degen.] 0,43	s	SSM Z'(qq)	Mz	1806.00843 (2 j)	2.7	
les	$\tilde{a}\tilde{a} \rightarrow a\tilde{a}\tilde{\chi}^{0}$	0 e. u	2-6 iets	Emiss	36.1	ř	oso	$LFVZ'$, $BR(e\mu) = 10\%$	Mz	1802.01122 (eµ)	4.4	
arcl	88,8-9901		,	-7		Ē	a B	SSM W((tv)	M	$1803.11133 (l + E_T^{max})$	52	
Sei	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell \ell)\tilde{\chi}_{1}^{0}$	3 e, µ	4 jets		36.1	Ř	jau	55M W(qq)	M	1800.00843 (2) 1807 11421 (T + Eminn)	3.3	
é		ee,µµ	2 jets	E_T^{miss}	36.1	<i>B</i>	5	LRSM $W_0(IN_0), M_{H_0} = 0.5M_{H_0}$	M// M	1803, 11421 (1 + 27) / 1803 11116 (21 + 2i)	44	
usi	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_{1}^{0}$	0 e, µ	7-11 jets	E_T^{miss}	36.1	8	fea	LR SM $W_R(\tau N_R)$, $M_{N_R} = 0.5M_{W_R}$	Mar.	1811.00806 (2 τ + 2j)	3.5	
ncl	-0	55 e, µ	6 jets	- miss	139	8		Axigluon, Coloron, $cot\theta = 1$	Mc	1806.00843 (2 j)	6.1	
-	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t l \tilde{\chi}_{1}^{\prime \prime}$	0-1 e,μ SS e μ	3 b 6 iets	E_T^{mass}	139	8						
		00 (1)4	0 1010		100	8		scalar LQ (pair prod.), coupling to 1^{st} gen. fermions, $\beta = 1$	MLQ	1811.01197 (2e+ 2j)	1.44	
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^+$		Multiple		36.1	b ₁ Forbidden	ark	scalar LQ (pair prod.), coupling to 1 gen. termions, $\beta = 0.5$	MLQ	1811.01197 (2e+ 2j; e + 2j + E _T ====)	152	
			Multiple		139	b ₁ Forbidden Forbidden	nbo	scalar LO (pair prod.), coupling to 2 rd gen. fermions, $\beta = 1$ scalar LO (pair prod.), coupling to 2 rd gen. fermions, $\beta = 0.5$	MLQ M	$1808,05082 (2\mu + 2j)$ $1808,05082 (2\mu + 2j; \mu + 2j + E^{mins})$	129	
	777,00,000	0.4.4	e 1.	rmiss	120	Eashiddan	ept	scalar LQ (pair prod.), coupling to 3^{rd} gen. fermions, $\beta = 1$	Mo	1811.00806 (2 τ + 2j) 1.0	2	
ks on	$b_1b_1, b_1 \rightarrow bx_2 \rightarrow bbx_1$	0ε,μ	00	L_T	139	δ ₁ 0.23-0.48	-	scalar LQ (single prod.), coup. to 3^{rd} gen. ferm., $\beta = 1, \lambda = 1$	MLo	1806.03472 (2 τ + b) 0.74		
luct	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ or $t \tilde{\chi}_1^0$	0-2 e, µ	0-2 jets/1-2	b Emiss	36.1	ĩ,						
rod	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow Wb \tilde{\chi}_1^0$	$1 e, \mu$	3 jets/1 b	E_T^{miss}	139	ī ₁ 0.44-0.59		excited light quark (qg) , $\Lambda = m_q^2$	M _q .	1806.00843 (2j)	6	
ct p	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$	$1\tau + 1e,\mu,\tau$	2 jets/1 b	E_T^{miss}	36.1	Ĩ ₁	ted	excited light quark $(qq), f_s = f = 1, h = m_q$	Mq [*]	$1711.04052 (\gamma + j)$ 1711.04652 ($\gamma + i$)	1.0	
3 ^{rr} dire	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / c \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$	0 e, µ	2 c	E_T^{miss}	36.1	č 7 0.46	Exci	excited electron, $f_5 = f = f' = 1, \Lambda = m_a^*$	M	1811.03052 (y + 2e)	3.9	
		0 e, µ	mono-jet	E_T^{miss}	36.1	i 0.46 i 0.43		excited muon, $f_s = f = f' = 1$, $\Lambda = m_{\mu}^*$	M _a .	1811.03052 (γ + 2μ)	3.8	
	The Real of the	1.2	4.6	r.miss	26.1	7						
	$\tilde{i}_1\tilde{i}_2, \tilde{i}_2 \rightarrow \tilde{i}_1 + \tilde{i}_1$ $\tilde{i}_2\tilde{i}_2, \tilde{i}_2 \rightarrow \tilde{i}_1 + Z$	3 e. u	4 U 1 h	E ^{miss}	139	T Forbidden	t a	quark compositeness ($q\ddot{q}$), $\eta_{LL,R,R} = 1$	$\Lambda^+_{LL/RR}$	1803.08030 (2 j)	Ľ	2.8
	****	0.0	10				actio	quark compositeness (ℓℓ), η _{LL/RR} = 1	Λ _{1,191}	1812.10443 (21)		20
	$\chi_1^*\chi_2^*$ via WZ	2-3 e, µ ee, µµ	> 1	Eniss	36.1 139	$\chi_1^*/\chi_2^* = 0.205$	ler S	quark compositeness (qq), $\eta_{LURR} = -1$ quark compositeness (H), $\eta_{LURR} = -1$	Λ _{LL/RR}	1803.06030 (2)		31
	$\bar{v}^{\pm}\bar{v}^{\mp}$ via WW	20.11		Emiss	130	F [±] 0.42	-	dan territoria de la construcción d	/IL/RR			
	$\hat{x}_{1}^{\dagger}\hat{x}_{1}^{0}$ via Wh	0-1 e, µ	2 b/2 y	Emiss	139	$\tilde{\chi}^{\pm}_{\pm}/\tilde{\chi}^{0}_{\pm}$ Forbidden		ADD (jj) HLZ, $n_{ED} = 3$	M ₅	1803.08030 (2 j)	1	2
Sct <	$\hat{\chi}_{1}^{\pm}\hat{\chi}_{1}^{\mp}$ via $\tilde{\ell}_{L}/\tilde{\nu}$	2 e, µ		E_T^{miss}	139	X		ADD $(\gamma\gamma, tt)$ HLZ, $n_{ED} = 3$	Ms	1812.10443 (2γ, 2ℓ)	9.1	
目間	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_{1}^{0}$	2 τ		E_T^{miss}	139	$\tilde{\tau} = [\tilde{\tau}_L, \tilde{\tau}_{R,L}] = 0.16-0.3 = 0.12-0.39$		ADD G_{ixx} emission, $n = 2$	Mo	$1712.02345 (\geq 1j + E_T^{max})$	9.9	
	$\tilde{\ell}_{1,R}\tilde{\ell}_{1,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	2 e, µ	0 jets	E _T miss cmiss	139	Ĩ	suo	ADD QBH (jj), $n_{ED} = 0$ ADD OBH (au), $n_{em} = 6$	Мовн	1803.08030 (2j) 1802.01122 (eu)	56	
	00 0 · 0 · 0	2 e, µ	≥1	ET	139	7 0.256	ensi	RS $G_{xx}(a\bar{a}, a\bar{a}), k/\overline{M}_{ex} = 0.1$	MonH M-	1806.00843 (2i)	18	
	$HH, H \rightarrow hG/ZG$	0 e, μ 4 e, μ	$\ge 3 b$ 0 iets	Emiss	36.1	H 0.13-0.23	in the second se	RS $G_{xx}(tt)$, $k/\overline{M}_{P1} = 0.1$	Mar	1803.06292 (21)	4.25	
_			.,	1			E	RS $G_{xx}(\gamma\gamma)$, $k/\overline{M}_{Pl} = 0.1$	MGer	1809.00327 (2 y)	4.1	
es es	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^+$	Disapp. trk	1 jet	E_T^{mass}	36.1	λ [±] 0.46	Ĕ	RS QBH (jj), $n_{ED} = 1$	Мовн	1803.08030 (2 j)	5.9	
d-li ticl	Stable & P. hadron		Multiple		26.1	a 0.10		RS QBH ($e\mu$), $n_{ED} = 1$	Мовн	1802.01122 (eµ)	3.0	
pa la	Motoctable & R. hadron, & varX ⁰		Multiple		36.1	8 P [r(P) =10 ns. 0.2 ns]		split-UED, $u \ge 4$ TeV	Ман 1/R	$1803.11133 (l + E^{intra})$	29	
-					00.1				-			
	LFV $pp \rightarrow y_{\tau} + X, y_{\tau} \rightarrow e\mu/e\tau/\mu\tau$	еµ,ет,µт А с. и	0 inte	L'IDİSS	3.2	ν _τ		(axial-)vector mediator ($\chi\chi$), $g_{\rm q}$ = 0.25, $g_{\rm DM}$ = 1, m_{χ} = 1 GeV	Mmed	$1712.02345 (\ge 1j + E_T^{mins})$	1.8	
	$\chi_1 \chi_1 / \chi_2 \rightarrow W W / Z U U U V V$ $\tilde{\mu} \tilde{\mu} \rightarrow a a \tilde{\nu}^0 \tilde{\nu}^0 \rightarrow a a a$	4 ε, μ	-5 large- <i>R</i> ir	ets	36.1	$X_1/X_2 = [A_{(3)} \neq 0, A_{12k} \neq 0]$ $\tilde{\sigma} = [m(\tilde{X}^0) - 200 \text{ GeV} + 1100 \text{ GeV})$	tter	(axial-)vector mediator ($q\bar{q}$), $g_q = 0.25$, $g_{DM} = 1$, $m_\chi = 1$ GeV	Mmed	1806.00843 (2 j)	2.6	
>	$gg, g \rightarrow qqq ; \lambda \rightarrow qqq$		Multiple		36.1	g (X'_112=2e-4, 2e-5]	Mat	scalar mediator $(+t/tt)$, $g_q = 1$, $g_{DM} = 1$, $m_\chi = 1$ GeV	Mened	$1901.01553 (0, 1\ell + \ge 3j + E_T^{minis}) 0.29$		
R	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$		Multiple		36.1	ğ [X''_323=2e-4, 1e-2] 0.55	ark	scalar mediator (fermion portal), $\lambda_x = 1$, $m_x = 1$ GeV	Mened	1901.01335 (0, 12 + 2 5) + E _T / 0.3	14	
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$		2 jets + 2 b	6	36.7	<i>ī</i> ₁ [<i>qq</i> , <i>bs</i>] 0.42 0.61	-	complex sc. med. (dark QCD), $m_{m_x} = 5 \text{ GeV}$, $c_{\tau_{N_x}} = 25 \text{ mm}$	M.	1810.10069 (4 i)	154	
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e, µ	2 b		36.1	\tilde{I}_1 (10.10 c k' = 10.8 20.10 c k' = 20.0)	_		- ADE			
		ſμ	DV		136	1 [10-10< x _{23k} <10-0, 30-10< x _{23k} <30-0]	F	Type III Seesaw, $B_{\mu} = B_{\mu} = B_{\tau}$	M _{Sigma}	1708.07962 (≥ 3ℓ) 0.84		
							8	string resonance	M ₅	1806.00843 (2j)	7.7	
								-	1	0.1	LO 10.0	· · · · · · · · · · · · · · · · · · ·
Only a	a selection of the available mass	s limits on	new state	es or	1	0-1					nass scale [TeV]	
simpl	ified models, c.f. refs. for the as	sumptions	made.				S	election of observed exclusion limits at 95% C.L. (theo	ory un	certainties are not included).		January 2019

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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.

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> Need to prepare a clear path towards **highest energy**.

Higgs factories



e+e-linear

- -ILC
- -CLIC
- e+e- circular
 - FCC-ee
 - CepC
 - μ + μ circular

Requirement: high luminosity *O*(10³⁴) at the Higgs energy scale

Usually, compared to the LHC – which is, as a machine :

• 27 km long

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

Luminosity comparison





F. Bedeschi, INFN-Pisa

Circular e+e- Higgs Factories



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 7.4 (tunnel)+ 3.1 BCHF (machine (+1.1BCHF for tt)
 - ("< 6BCHF" cited in the CepC CDR)



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Physics at FCC-ee



★ Higgs factory
> 10⁶ e+e- → HZ
★ EW & Top factory
> $3x10^{12}$ e+e- → Z
> 10⁸ e+e- → W+W- ;
> 10⁶ e+e- → tt

Flavor factory

> $5 \times 10^{12} \text{ e}+\text{e}- \rightarrow \text{bb, cc}$ > $10^{11} \text{ e}+\text{e}- \rightarrow \tau + \tau$ -

Potential discovery of NP
ALPs, RH v's, ...



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Higgs production

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Higgs total width

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 $L = 5 ab^{-1}$

Higgs recoil provides model independent measurement of coupling to Z

 $\succ \sigma(\text{HZ}) \propto g^2_{\text{HZ}}$



Critical: Beam energy spread: SR+BS Tracking resolution Total width combining with decays in specific channels

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





F. Bedeschi, INFN-Pisa

Higgs coupling fits



Kappa framework

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

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

 $(\boldsymbol{\sigma} \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \to \mu_i^f \equiv \frac{\boldsymbol{\sigma} \cdot \mathrm{BR}}{\boldsymbol{\sigma}_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$

Extension

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

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

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









Outstanding program of precision EWK measurements





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



Heavy flavors



Large heavy flavor production at Z pole

Belle II $27.5 \ 27.5 \ n/a \ n/a \ 65$	45	
FCC- <i>ee</i> 400 400 100 100 800	220	_



Direct NP search example: HNL

Inverted hierarchy



◆ HNL mix with active neutrino's
 > Fully reconstructable decay with W
 > Small mixing → long lifetime









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

 $0.01 \text{ cm} < c\tau < 500 \text{ cm}$ 10^{13} Z

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Accelerators



The planned machines

FCC integrated program

Implementation studies in Geneva basin:



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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-ee + FCC-hh





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

CEPC-SppC: site studies



Qinhuangdao, Hebei
 ProvinceCompleted 2014)
 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)









Conclusions













LHC BSM exclusion

odel	τ,γ	Jets	T	L dt fb		Limit				Reference
$\bar{a}_{\mu\nu} + g/g$										menerenee
$ \begin{array}{l} \text{Korresonant } \gamma\gamma \\ \text{BH} \\ \text{High } \sum p\tau \\ \text{High } multiple \\ \text{Korreson} \\ \text{S} \; G_{KK} \rightarrow WW/ZZ \\ \text{S} \; G_{KK} \rightarrow WW \rightarrow qqqq \\ \text{S} \; g_{KK} \rightarrow tt \\ \end{array} $	$\begin{array}{c} 0 \ e, \mu \\ 2 \ \gamma \\ - \\ \geq 1 \ e, \mu \\ - \\ 2 \ \gamma \\ multi-channe \\ 0 \ e, \mu \\ 1 \ e, \mu \end{array}$	1 - 4 j - 2j $\ge 2j$ $\ge 3j$ - 0l 2 J $\ge 1 b, \ge 1J/2$	Yes - - - - Yes	36.1 36.7 37.0 3.2 3.6 36.7 36.1 139 36.1	Мо Ms Ma Ma Gec mass Gec mass gec mass gec mass		4.1 TeV 2.3 TeV 1.6 TeV 3.8 TeV	7.7 TeV 8.6 TeV 8.9 TeV 8.2 TeV 9.55 TeV	$\begin{array}{l} n=2 \\ n=3 \; \text{HLZ NLO} \\ n=6 \\ n=6, M_D=3 \; \text{TeV, rot BH} \\ n=6, M_D=3 \; \text{TeV, rot BH} \\ k/\overline{M}p=0.1 \\ k/\overline{M}p=1.0 \\ k/\overline{M}p=1.0 \\ r/m=15\% \end{array}$	1711.03301 1707.04147 1703.09127 1606.02265 1512.02586 1707.04147 1808.02380 ATLAS-CONF-2019-00 1804.10823
/ RPP	1 e,µ	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass		1.8 TeV	_	Tier (1,1), $\mathcal{B}(\mathcal{A}^{(1,1)} \rightarrow tt) = 1$	1803.09678
$\begin{array}{l} \mathcal{V} \to \ell\ell \\ \mathcal{V} \to \tau\tau \\ hobbic \mathcal{Z}' \to bb \\ hobbic \mathcal{Z}' \to tt \\ \mathcal{V}' \to \ell\nu \\ \mathcal{V} \to \tau\nu \\ \mathcal{V} \to \tau\nu \\ \mathcal{V} \to \tau\nu \\ \mathcal{W} \to \tau\nu \\ \mathcal{W} \to \eta Qq q \text{ model B} \\ \mathcal{W}_R \to tb \\ \mathcal{W}_R \to \mu N_R \end{array}$	2 e, µ 2 τ - 1 e, µ 1 r, µ 1 r, β 0 e, µ multi-channe 2 µ	- 2 b ≥ 1 b, ≥ 1J/2) - 2 J el al 1 J	- Yes Yes -	139 36.1 36.1 139 36.1 139 36.1 36.1 36.1 80	2' mass 2' mass 2' mass W' mass W' mass V' mass V' mass W _R mass W _R 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 5.0 TeV	eV.	$\label{eq:gv} \begin{split} &\Gamma/m = 1\% \\ &g_V = 3 \\ &g_V = 3 \\ &m(N_R) = 0.5 \text{ TeV}, g_L = g_R \end{split}$	1903.06248 1709.07242 1805.09299 1804.10823 CERN-EP-2019-100 1801.06992 ATLAS-CONF-2019-00 1712.06518 1807.10473 1904.12679
9	_ 2 e,μ ≥1 e,μ	2 j _ ≥1 b, ≥1 j	_ Yes	37.0 36.1 36.1	A A A		2.57 TeV		21.8 TeV η_{LL}^{-} 40.0 TeV η_{LL}^{-} $ C_{4t} = 4\pi$	1703.09127 1707.02424 1811.02305
ector mediator (Dirac DM) d scalar mediator (Dirac D EFT (Dirac DM) reson. $\phi \rightarrow t\chi$ (Dirac DM)	0 e,μ M) 0 e,μ 0 e,μ 0-1 e,μ	$\begin{array}{c} 1-4 \ j \\ 1-4 \ j \\ 1 \ J, \leq 1 \ j \\ 1 \ b, 0\text{-}1 \ J \end{array}$	Yes Yes Yes Yes	36.1 36.1 3.2 36.1	m _{ened} m _{ened} M _* m _p	700 GeV	55 TeV 1.67 TeV 3.4 TeV		$\begin{array}{l} g_{q} = 0.25, g_{\chi} = 1.0, m(\chi) = 1 \mathrm{GeV} \\ g = 1.0, m(\chi) = 1 \mathrm{GeV} \\ m(\chi) < 150 \mathrm{GeV} \\ y = 0.4, \ell = 0.2, m(\chi) = 10 \mathrm{GeV} \end{array}$	1711.03301 1711.03301 1608.02372 1812.09743
LQ 1 st gen LQ 2 nd gen LQ 3 rd gen LQ 3 rd 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 [°] mass LQ [°] mass	1 1.03 Tel 970 GeV	l TeV 56 TeV		$\begin{array}{l} \beta = 1 \\ \beta = 1 \\ \mathcal{B}(LQ_{3}^{\nu} \to b\tau) = 1 \\ \mathcal{B}(LQ_{5}^{d} \to t\tau) = 0 \end{array}$	1902.00377 1902.00377 1902.08103 1902.08103
$\begin{array}{l} T \rightarrow Ht/Zt/Wb + X\\ B \rightarrow Wt/Zb + X\\ f_{5/3}T_{5/3}T_{5/3} \rightarrow Wt + X\\ ' \rightarrow Wb + X\\ t \rightarrow Hb + X\\ Q \rightarrow WqWq \end{array}$	multi-channe multi-channe $2(SS)/\geq 3 e_{,\mu}$ $1 e_{,\mu}$ $0 e_{,\mu}, 2 \gamma$ $1 e_{,\mu}$	$ \begin{array}{l} \textbf{J} \\ \textbf{J} \\ \textbf{J} \\ \textbf{J} \\ \geq 1 \text{ b}, \geq 1 \text{ j} \\ \geq 1 \text{ b}, \geq 1 \text{ j} \\ \geq 1 \text{ b}, \geq 1 \text{ j} \\ \geq 4 \text{ j} \end{array} $	Yes Yes Yes Yes	36.1 36.1 36.1 36.1 79.8 20.3	T mass B mass T _{5/2} mass Y mass B mass Q mass	1.3 1.3 1.21 690 GeV	TeV TeV .64 TeV .64 TeV 1.85 TeV eV		$\begin{array}{l} SU(2) \mbox{ doublet} \\ SU(2) \mbox{ doublet} \\ \mathcal{B}(T_{3(2)} \rightarrow Wt) = 1, \ c_{1}(T_{5/2}Wt) = 1 \\ \mathcal{B}(Y \rightarrow Wb) = 1, \ c_{11}(Wb) = 1 \\ \kappa_{22} = 0.5 \end{array}$	1808.02343 1808.02343 1807.11883 1812.07343 ATLAS-CONF-2018-02 1509.04261
d quark $q^* \rightarrow qg$ d quark $q^* \rightarrow q\gamma$ d quark $b^* \rightarrow bg$ d lepton ℓ^* d lepton γ^*	- 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 (" mass y" mass		6. 5.3 Te 2.6 TeV 3.0 TeV 1.6 TeV	TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	ATLAS-CONF-2019-00 1709.10440 1805.09299 1411.2921 1411.2921
I Seesaw Majorana ν triplet $H^{\pm\pm} \rightarrow \ell \ell$ triplet $H^{\pm\pm} \rightarrow \ell \tau$ harged particles tilc monopoles	1 е, µ 2 µ 2,3,4 е, µ (S 3 е, µ, т – –	≥2j 2j 5) - - -	Yes - - - -	79.8 36.1 20.3 36.1 34.4	N ⁰ mass N ₈ mass H ¹¹ mass multi-charged particle mass monopole mass	560 GeV 870 GeV 400 GeV 5 1.22	3.2 TeV eV 2.37 TeV		$\begin{split} m(W_{\rm R}) &= 4.1 \text{TeV}, g_{\rm L} = g_{\rm R} \\ \text{DY production} \\ \text{DY production}, & \mathcal{B}(h_{\rm L^+}^{+*} \to \ell \tau) = 1 \\ \text{DY production}, & \mathcal{g} = 5 \epsilon \\ \text{DY production}, & \mathcal{g} = 1 g_D, \text{spin} 1/2 \end{split}$	ATLAS-CONF-2018-020 1809.11105 1710.09748 1411.2921 1812.03673 1905.10130
	H high Σpr H multijet $kc \rightarrow \gamma\gamma$ $S G_{KK} \rightarrow WW/ZZ$ $S G_{KK} \rightarrow WW \rightarrow qqqq$ $S g_{KK} \rightarrow WW \rightarrow qqqq$ $S g_{KK} \rightarrow tt$ (PPP) $\gamma \rightarrow \ell\ell$ $\gamma \rightarrow \tau\tau$ $r \rightarrow VVZ \rightarrow qqqq model E \gamma' \rightarrow \tau\tau\gamma \rightarrow WZ \rightarrow qqqq model BW_R \rightarrow tbW_R \rightarrow tbW_R \rightarrow thW_R \rightarrow t$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	H high Σρr ≥ 1 e, μ ≥ 2j - 32 Ma K multijet - ≥ 3j - 3.6 Ka S G _{KK} → WW/ZZ multichannel 36.1 S G _{KK} → WW/ZZ multichannel 36.1 S G _{KK} → WW → qqq 0 e, μ ≥ 1 b. ≥ 1J/2 Ves 36.1 S G _{KK} → WW → qqq 1 e, μ ≥ 1 b. ≥ 1J/2 Ves 36.1 S g _{KK} → tt 1 e, μ ≥ 1 b. ≥ 1J/2 Ves 36.1 Y → tr 2 e, μ 139 Y → tr 2 e, μ 56.1 V' → tv 1 e, μ ≥ 1 b. ≥ 1J/2 Ves 36.1 Nobic Z' → tt 1 e, μ ≥ 1 b. ≥ 1J/2 Ves 36.1 V' → tv 1 f Yes 36.1 V' → tv 1 f Yes 36.1 W → qqqq 1 f Yes 36.1 W → qqqq 1 f Yes 36.1 V' → tv 1 f Yes 36.1 W → qqqq 1 f Yes 36.1 W → qqqq model B 0 e, μ 2.1 ' → W/ J ZH qqqq model B 0 e, μ 2.1 ' → WH Midischarnel 36.1	H high ∑pr. ≥ 1 e, μ ≥ 2 j - 3.2 Ma. H multijet - ≥ 3 j - 3.6 Ma. S G _K → WW /ZZ multi-channel 36.1 Goc mass Goc mass S G _K → WW /ZZ multi-channel 36.1 Goc mass Goc mass S G _K → WW /4Z multi-channel 36.1 Goc mass Goc mass S G _K → WW /4Z 1 e, μ ≥ 1 b, ≥ 1//2 Ves 36.1 K mass Goc mass '' → tr 2 e, μ - 139 Z mass Z mass '' → tr 2 r - 39 W mass Y mass Y mass '' → tr 1 r - Yes 36.1 Z mass Y mass Y mass '' → tr 1 r - Yes 36.1 Y mass Y mass	H hgh Zpr $\geq 1, e, \mu$ ≥ 2 $=$ ≥ 2 <t< td=""><td><math display="block">\begin{split} & H hg D_{\mathcal{D}} r & \geq 1 e, \mu & \geq 2 & - & 3.2 \\ H Mall g t & mall channel & = & 33 & - & 36 \\ S G_{\mathcal{M}} \leftarrow WW / ZZ & mall channel & 36.1 \\ S G_{\mathcal{M}} \leftarrow WW / ZZ & mall channel & 36.1 \\ S G_{\mathcal{M}} \leftarrow WW / QZ & mall channel & 36.1 \\ S G_{\mathcal{M}} \leftarrow WW / QZ & mall channel & 36.1 \\ S G_{\mathcal{M}} \leftarrow W & 1 e, \mu & \geq 2 b, \geq 3 \} & Ves & 36.1 \\ S G Ms & MS & MS & MS & MS \\ S HPP & 1 e, \mu & \geq 2 b, \geq 3 \} & Ves & 36.1 \\ K Mass & MS & MS & MS & MS \\ S GV \leftarrow tt & 1 e, \mu & \geq 2 b, \geq 2 \} & Ves & 36.1 \\ S C MS & MS & MS & MS & MS \\ Mobb Z' \to tt & 1 e, \mu & \geq 1 b, \geq 1 \lambda/2 \} & Ves & 36.1 \\ C Mass & MS & MS & MS \\ M Mobb Z' \to tt & 1 e, \mu & \geq 1 b, \geq 1 \lambda/2 \} & Ves & 36.1 \\ V \to V \to V & V \to V & I e, \mu & I d = MS & MS \\ M M MS & MS & MS \\ M \to MS & MS & MS \\ M \to M M MS & MS & MS \\ M \to M M MS & MS & MS \\ M M MS & MS & MS \\ M M MS & MS \\ M \to M \\ M \\ M \to M \\ M \to M \\ M \\ M \to M \\ M \to M \\ M = M \\ M \\ M = M \\ M \\ M \\ M \to M \\ M \\ M = M \\ M \\ M \to M \\ M \\ M \\ M \to M \\ M \\ M \to M \\ /math></td><td>$\begin{split} & Holp Zpr & \geq l.e. \mu & \geq 2] & - & 32 & - & 32 & M_{a} & \qquad$</td></t<>	$\begin{split} & H hg D_{\mathcal{D}} r & \geq 1 e, \mu & \geq 2 & - & 3.2 \\ H Mall g t & mall channel & = & 33 & - & 36 \\ S G_{\mathcal{M}} \leftarrow WW / ZZ & mall channel & 36.1 \\ S G_{\mathcal{M}} \leftarrow WW / ZZ & mall channel & 36.1 \\ S G_{\mathcal{M}} \leftarrow WW / QZ & mall channel & 36.1 \\ S G_{\mathcal{M}} \leftarrow WW / QZ & mall channel & 36.1 \\ S G_{\mathcal{M}} \leftarrow W & 1 e, \mu & \geq 2 b, \geq 3 \} & Ves & 36.1 \\ S G Ms & MS & MS & MS & MS \\ S HPP & 1 e, \mu & \geq 2 b, \geq 3 \} & Ves & 36.1 \\ K Mass & MS & MS & MS & MS \\ S GV \leftarrow tt & 1 e, \mu & \geq 2 b, \geq 2 \} & Ves & 36.1 \\ S C MS & MS & MS & MS & MS \\ Mobb Z' \to tt & 1 e, \mu & \geq 1 b, \geq 1 \lambda/2 \} & Ves & 36.1 \\ C Mass & MS & MS & MS \\ M Mobb Z' \to tt & 1 e, \mu & \geq 1 b, \geq 1 \lambda/2 \} & Ves & 36.1 \\ V \to V \to V & V \to V & I e, \mu & I d = MS & MS \\ M M MS & MS & MS \\ M \to MS & MS & MS \\ M \to M M MS & MS & MS \\ M \to M M MS & MS & MS \\ M M MS & MS & MS \\ M M MS & MS \\ M \to M \\ M \\ M \to M \\ M \to M \\ M \\ M \to M \\ M \to M \\ M = M \\ M \\ M = M \\ M \\ M \\ M \to M \\ M \\ M = M \\ M \\ M \to M \\ M \\ M \\ M \to M \\ M \\ M \to M \\	$\begin{split} & Holp Zpr & \geq l.e. \mu & \geq 2] & - & 32 & - & 32 & M_{a} & \qquad $

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F. Bedeschi, INFN-Pisa

Higgs coupling comparison

INF Istituto Nazionale di Fisica Nucleare

Improvement factors relative to HL-LHC

LHE-L	L. IL			Q.I.C	Clic	$\sum_{i=1}^{n} Q_{i}$	FCC		Ceeve	ha	
~eC ~	aC .	250	-500	380	1300	~000 `	чÇ.	240	365	~0h	10
g_{HZZ}^{eff} = 1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10	10
g_{HWW}^{eff} - 1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10	
$g_{H\gamma\gamma}^{\rm eff}$ - 1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1	3.1	≥ 10	- 8
$g_{HZ\gamma}^{\rm eff}$ - 1.1	2.4	1.1	1.6	1.1	2.3	3.0	1.7	1.1	1.2	≥ 10	
$g_{Hgg}^{\rm eff}$ - 1.4	1.7	2.0	2.8	1.7	2.3	2.9	2.8	2.3	2.7	4.5	
g_{Htt}^{eff} - 1.1	1.7	1.1	1.2	1.1	1.4	1.4	1.1	1.1	1.1	1.8	- 6
g_{Hcc}^{eff} - \star		*	*	*	*	*	*	*	*	*	
g_{Hbb}^{eff} - 2.7	1.5	6.1	9.8	5.1	≥ 10	≥ 10	7.6	7.3	9.1	≥ 10	- 4
$g_{H\tau\tau}^{\rm eff}$ - 1.6	1.3	4.1	5.8	2.7	3.8	4.8	5.0	5.0	6.1	7.8	
$g_{H\mu\mu}^{\rm eff}$ - 1.2	1.8	1.3	1.4	1.3	1.4	1.6	1.4	1.4	1.4	≥ 10	
$\delta g_{1Z}[imes 10^2]$ - 1.3	1.4	6.7	≥ 10	≥ 10	≥ 10	≥ 10	7.3	7.8	≥ 10	≥ 10	- 2
$\delta\kappa_{\gamma}[imes 10^2]$ - 1.3	1.2	≥10	≥ 10	≥ 10	≥ 10	$\ge 10^{2}$	≥ 10	≥ 10	≥ 10	≥ 10	
$\lambda_Z[imes 10^2]$ - 1.1	1.0	≥ 10	$\geq 10^2$	≥ 10	$\geq 10^2$	$\ge 10^{3}$	≥ 10	≥ 10	≥ 10	≥ 10	
SMEF	T ND		(*)	not m	neasure	d at H	L-LHO	7			- 0
		\mathbf{a})								

F. Bedeschi, INFIN-Pisa

e⁺e⁻ Ring Higgs Factories



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
- Transverse polarization ($\tau \sim 18$ min at tt) for E calibration O(100keV)

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- CDRs addressed key design points, mb ready for ca 2039 start
- Very strong and broad Global FCC Collaboration

Fisica Nuclear

Challenges of e⁺e⁻ 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

$$I = \frac{e\rho}{2C_{\gamma}E^4}P_T,$$

INF

$$\mathscr{L}\gamma^3 = \frac{3}{16\pi r_e^2 (m_e c^2)}$$

$$\left[\rho \frac{\xi_y P_T}{\beta_y^*} H(\beta_y^*, \sigma_z)\right]$$

Luminosity

SHILTSEV, Granada

- Determined by bend radius ρ , beam-beam parameter ξ_y , beta function at the IP β_y^* and power
- Beam life ~18 min requires full energy booster ring

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) \rightarrow "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:
 - 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





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Key facts:

- > 11 km main linac @ 380 GeV c.m.e.
- NC RF 72 MV/m, two-beam scheme
- ► 168 MW site power (~9MW beams)
- Cost est. 5.9 BCHF (klystrons + 1.4 BCHF)





Limits of Linear e^+e^- Colliders



Both ILC and CLIC offer staged approach to ultimate E



Luminosity Dilution by Beamstrahlung









Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)

Very optimistic!!!

D. SCHULTE, Granada 2019

Other comparisons



- F2 "Energy Efficiency" F1 "Technology **Readiness**": Green : 100-200 MW - TDR Green Yellow : 200-400 MW **CDR** Yellow : > 400 MW Red - **R&D** Red
 - F3 "Cost" :
 Green : < LHC
 Yellow : 1-2 x LHC
 Red : > 2x LHC

Other comparisons



Higgs Factories	Readiness	Power-Eff.	Cost
ee Linear 250 GeV			
ee Rings 240GeV/tt			
μ <mark>μ Collider 125 GeV</mark>			*

Comparison table



Project	Туре	Energy [TeV]	Int. Lumi. [a ⁻¹]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G\$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	рр	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Beamstrahlung



$\bullet \delta BS ? (ECM/\sigma_z)N2/\sigma_x2$

	Unit	IL	CLIC	
\sqrt{s}	GeV	500	1000	3000
L	10 ³⁴ cm ⁻² s ⁻¹	1.5	4.3	5.9
Υ_{av}		0.15	0.20	4.9
δ_{B}	%	3.7	10	28
nγ		1.7	2.0	2.1



► ILC 240 ~ 1.6%