Future Circular e+e- Colliders



F. Bedeschi

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Outline

Current physics landscape
Current directions
FCC-ee
Key measurements
Current status
Conclusions



Higgs properties SM-like.





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After HL-LHC precision level of several %





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Higgs properties SM-like.

After HL-LHC precision level of several %

• Deviation from SM: $\delta \sim v^2/M^2$

M scale of new physics

 $\blacksquare M \sim 1 - 10 \text{ TeV} \quad \Rightarrow \delta \sim 6 - 0.06\%$





Higgs properties SM-like.

After HL-LHC precision level of several %

• Deviation from SM: $\delta \sim v^2/M^2$ v = 246 GeV

M scale of new physics

 $\blacksquare M \sim 1 - 10 \text{ TeV} \quad \Rightarrow \delta \sim 6 - 0.06\%$





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

A Ju	TLAS SUSY Sear	rches*	- 95%	6 CI	_ Lov	ver Limits						ATLAS Preliminary $\sqrt{s} = 13$ TeV
	Model	S	ignatur	e j	<i>L dt</i> [fb ⁻) Mas	ss limit					Reference
s	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\ell}_1^0$	0 e, µ mono-jet	2-6 jets 1-3 jets	E_T^{miss} E_T^{miss}	36.1 36.1	 <i>q</i> [2×, 8× Degen] <i>q</i> [1×, 8× Degen] 	0.43	0.9	1.55		m(x̂1)<100 GeV m(q̂) m(k̂1)=5 GeV	1712.02332 1711.03301
ie Searche	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{q} \tilde{\chi}_1^0$	0 <i>c</i> , <i>µ</i>	2-6 jets	E_T^{miss}	36.1	Ř Ř		Forbidden	0.95-1.6	2.0	m($\tilde{\chi}_{j}^{0}$)<200 GeV m($\tilde{\chi}_{j}^{0}$)=900 GeV	1712.02332 1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_{1}^{0}$	3 e, μ ee, μμ	4 jets 2 jets	E_T^{miss}	36.1 36.1	Ř Ř			1.2	.85	m($\tilde{\chi}_{1}^{0}$)<800 GeV m($\tilde{\chi}_{1}^{0}$)=50 GeV	1706.03731 1805.11381
clusi	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_{1}^{0}$	0 e, μ SS e, μ	7-11 jets 6 jets	E_T^{miss}	36.1 139	Î Î			1.15	8.1	$m(\tilde{\chi}_{1}^{0}) < 400 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_{1}^{0}) = 200 \text{ GeV}$	1708.02794 ATLAS-CONF-2019-015
11	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow d\tilde{\chi}_{1}^{0}$	0-1 e,μ SS e,μ	3 <i>b</i> 6 jets	E_T^{miss}	79.8 139	iğ ğ			1.25	2.25	m(x̃_1^0)<200 GeV m(g)-m(x̃_1^0)=300 GeV	ATLAS-CONF-2018-041 ATLAS-CONF-2019-015
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 {\rightarrow} b \tilde{V}_1^0 / t \tilde{V}_1^+$		Multiple Multiple Multiple		36.1 36.1 139	δ ₁ Forbidden δ ₁ δ ₁	Forbidden Forbidden	0.9 0.58-0.82 0.74		m(i m(\tilde{X}_1^0)=21	$m(\tilde{k}_1^0)=300 \text{ GeV}, BR(b\tilde{k}_1^0)=1$ $\tilde{k}_1^0=300 \text{ GeV}, BR(b\tilde{k}_1^0)=BR(k\tilde{k}_1^0)=0.5$ $300 \text{ GeV}, m(\tilde{k}_1^0)=300 \text{ GeV}, BR(k\tilde{k}_1^0)=1$	1708.09266, 1711.03301 1708.09266 ATLAS-CONF-2019-015
rks ion	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 {\rightarrow} b \tilde{\ell}_2^0 {\rightarrow} b h \tilde{\ell}_1^0$	0 <i>e</i> , <i>µ</i>	6 <i>b</i>	E_T^{miss}	139	b ₁ Forbidden	0.23-0.48		0.23-1.35	Δ	$m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0})=130 \text{ GeV}, m(\tilde{\chi}_{1}^{0})=100 \text{ GeV}$ $\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0})=130 \text{ GeV}, m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$	SUSY-2018-31 SUSY-2018-31
squa	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow Wb \tilde{\chi}_1^0$ or $t \tilde{\chi}_1^0$	0-2 e, µ	0-2 jets/1-2	$b E_T^{miss}$	36.1	Ĩ1		1.0	6		$m(\tilde{x}_1^0)=1 \text{ GeV}$	1506.08616, 1709.04183, 1711.11520
pro	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$	$1 e, \mu$	3 jets/1 b	ET T	139	Ĩ ₁	0.44-0	.59	11121		m(X ⁰ ₁)=400 GeV	ATLAS-CONF-2019-017
ge	$T_1T_1, T_1 \rightarrow T_1 bv, T_1 \rightarrow TG$	$1\tau + 1e,\mu,\tau$	2 jets/1 0	Emiss	36.1	11 2		0.95	1.16		m(r ₁)=800 GeV	1803.10178
34	$t_1 t_1, t_1 \rightarrow c t_1 / c c, c \rightarrow c t_1$	0 e,μ	mono-jet	E_T^{miss}	36.1	\tilde{t}_1 \tilde{t}_1	0.46 0.43	0.65			$m(\tilde{x}_1)=0$ GeV $m(\tilde{x}_1,\tilde{x})-m(\tilde{x}_1^0)=50$ GeV $m(\tilde{x}_1,\tilde{x})-m(\tilde{x}_1^0)=5$ GeV	1805.01649 1711.03301
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 e. µ	4 b	E_T^{miss}	36.1	ī,		0.32-0.88		r	$n(\tilde{\chi}_{1}^{0})=0$ GeV, $m(\tilde{\tau}_{1})-m(\tilde{\chi}_{1}^{0})=180$ GeV	1706.03986
1	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, µ	1 <i>b</i>	E_T^{miss}	139	Ĩ ₂	Forbidden	0.86		m	$(\tilde{t}_{1}^{0})=360 \text{ GeV}, m(\tilde{t}_{1})-m(\tilde{t}_{1}^{0})=40 \text{ GeV}$	ATLAS-CONF-2019-016
	$\hat{x}_1^{\pm}\hat{x}_2^0$ via WZ	2-3 e, μ ee, μμ	≥ 1	E_T^{miss} E_T^{miss}	36.1 139	$ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} $ $ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} $ 0.205		0.6			$m(\tilde{x}_{1}^{0})=0$ $m(\tilde{x}_{1}^{+})-m(\tilde{x}_{1}^{0})=5 \text{ GeV}$	1403.5294, 1806.02293 ATLAS-CONF-2019-014
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ via WW	2 c, µ		E_T^{miss}	139	\hat{X}_{1}^{\pm}	0.42				m($\tilde{\chi}_{1}^{0}$)=0	ATLAS-CONF-2019-008
***	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via Wh	0-1 <i>e</i> , μ	$2 b/2 \gamma$	E_T^{miss}	139	$\tilde{X}_{1}^{\pm}/\tilde{X}_{2}^{0}$ Forbidden		0.74			m(\tilde{t}_{1}^{0})=70 GeV	ATLAS-CONF-2019-019, ATLAS-CONF-2019-XYZ
W:	$\hat{X}_1^* \hat{X}_1^+$ via $\hat{\ell}_L / \hat{\nu}$	2 e, µ		E_T^{mass}	139	\hat{X}_{1}^{a}		1.0	£		$m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{*})+m(\tilde{\chi}_{1}^{0}))$	ATLAS-CONF-2019-008
dip	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau X_1^{\prime}$	27	O linte	Entro	139	7 [7], 7R,LJ 0.16-0.3	0.12-0.39				$m(\mathcal{X}_{1}^{*})=0$	ATLAS-CONF-2019-018
	$\ell_{1,R}\ell_{1,R}, \ell \rightarrow \ell \chi_1$	2 e, µ 2 e, µ	> 1	Emiss	139	i 0.256		0.7			$m(\tilde{\ell}_1)=0$ $m(\tilde{\ell}_1)-m(\tilde{\ell}_1^0)=10 \text{ GeV}$	ATLAS-CONF-2019-008 ATLAS-CONF-2019-014
	ĤĤ Ĥ→hĜ/ZĜ	0 e. u	> 3 h	Emiss	36.1	R 0.13-0.23		0.29-0.88			$BB(\tilde{X}^0 \rightarrow h\tilde{C})=1$	1806.04030
		4 e, µ	0 jets	$E_T^{\rm miss}$	36.1	ii 0.3					$BR(\tilde{x}_1^0 \rightarrow ZG)=1$	1804.03602
-lived icles	Direct $\tilde{X}_1^+ \tilde{X}_1^-$ prod., long-lived \tilde{X}_1^+	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$\hat{\chi}_{1}^{\pm}$ $\hat{\chi}_{1}^{\pm}$ 0.15	0.46				Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
ong	Stable g R-hadron		Multiple		36.1	ğ				2.0		1902.01636,1808.04095
24	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\ell}_1^{\prime\prime}$		Multiple		36.1	ĝ [r(ĝ) =10 ns, 0.2 ns]				2.05 2.4	m(X ⁰ ₁)=100 GeV	1710.04901.1808.04095
	LFV $pp \rightarrow \tilde{v}_{\tau} + X$, $\tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$	$e\mu,e au,\mu au$			3.2	\widetilde{P}_{T}				1.9	λ'_{311} =0.11, $\lambda_{132/133/233}$ =0.07	1607.08079
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e. µ	0 jets	E_T^{miss}	36.1	$\hat{\chi}_{1}^{\pm}/\hat{\chi}_{2}^{0} = [\lambda_{133} \neq 0, \lambda_{12k} \neq 0]$		0.82	1.33		$m(\tilde{\chi}_1^0)=100 \text{ GeV}$	1804.03602
ΡV	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qqq$	4	-5 large- <i>R</i> je Multiple	ets	36.1 36.1	ğ [m(X ⁺ ₁)=200 GeV, 1100 GeV] ğ [X' ₁₁₂ =2e-4, 2e-5]		1.0	1.3	1.9 2.0	Large J ⁰ ₁₁₂ m($\tilde{\ell}_1^0$)=200 GeV, bino-like	1804.03568 ATLAS-CONF-2018-003
œ	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$		Multiple		36.1	g (X ₃₂₃ =20-4, 10-2)	0.5	5 1.0)5		m(k))=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{i}_1 \tilde{i}_1, \tilde{i}_1 \rightarrow \delta s$ $\tilde{i}_1 \tilde{i}_1, \tilde{i}_1 \rightarrow q \ell$	2 e,μ 1 μ	2 jets + 2 b DV		36.1 136	$\begin{array}{ccc} i_1 & [qq, m_3] \\ \hline i_1 & \\ \hline i_1 & [1e-10 < i'_{_{234}} < 1e-8, 3e-10 < i'_{_{234}} \end{array}$	<30-9)	1.0	0.4-1.45		$BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$ $BR(\tilde{t}_1 \rightarrow g\mu) = 100\%, \cos\theta_i = 1$	1710.05744 ATLAS-CONF-2019-006
_												
									1			l
*Only a pheno	a selection of the available mas omena is shown. Many of the l	s limits on i imits are ba	new state ised on	s or	1	0-1			1		Mass scale [TeV]	
simpl	fied models, c.f. refs. for the a	ssumptions	made.									

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	Signature ∫£ dt [fb ⁻	Mass limit		смѕ	36 fb ⁻¹ (13 TeV)
ches	$\tilde{q}\tilde{q}, \tilde{\eta} \rightarrow q \tilde{k}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{q} \tilde{k}_{1}^{0}$	$\begin{array}{cccc} 0 \ e, \mu & 2\text{-}6 \ \text{jets} & E_T^{\text{mins}} & 36.1 \\ \text{mono-jet} & 1\text{-}3 \ \text{jets} & E_T^{\text{mins}} & 36.1 \\ 0 \ e, \mu & 2\text{-}6 \ \text{jets} & E_T^{\text{mins}} & 36.1 \end{array}$	i [2x, 8x Degen] i [1x, 8x Degen] 0.43 i λ i	SSM Z'(<i>ll</i>) SSM Z'(<i>q</i> q̃) LFV Z', BR(<i>e</i> μ) = 10% SSM W'(<i>lv</i>)	(c. 1803.06292 (2/) (c. 1806.00843 (2)) (c. 1806.01122 (eµ) (c. 1802.01122 (eµ)) (c. 1803.11138 (+ Fg ^{mm}))	45 27 44 52
nclusive Seal	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{q}(\ell \ell) \tilde{\chi}_1^0$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q q W Z \tilde{\chi}_1^0$	$\begin{array}{llllllllllllllllllllllllllllllllllll$	www.www.	SSM W('(q2)) SSM W('(ru') IRSM Wa(IMa), Ma, = 0.5Ma, IRSM Wa(IMa), Ma, = 0.5Ma, Axigluon, Coloron, cot9 = 1	(a) 100(00843 (2)) (a) 100(11421 (r + E(r ^m)) (100(11421 (r + E(r ^m)) (100(1162 (r + 2)) (100(10086 (2 + 2)) (100(10084 (2))	33) 4 44 35 61
h	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow i \tilde{\ell} \tilde{\chi}_{1}^{0}$ $\tilde{b}_{1}\tilde{b}_{1}, \tilde{b}_{1} \rightarrow b \tilde{\chi}_{1}^{0} / i \tilde{\chi}_{1}^{+}$	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	8 k Forbidden 0	scalar LQ (pair prod.), coupling to 1 st gen. fermions, $\beta = 1$ scalar LQ (pair prod.), coupling to 1 st gen. fermions, $\beta = 0.5$ scalar LQ (pair prod.), coupling to 2 st gen. fermions, $\beta = 1$	(a) 1811.01197 (2e + 2j) (b) 1811.01197 (2e + 2j; e + 2j + E ^{mm}) (c) 1810.05082 (2µ + 2j)	144 127 153
quarks uction	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 \rightarrow b h \tilde{\chi}_1^0$ $\tilde{b}_1 \tilde{b}_1, \tilde{h} \rightarrow W h \tilde{\chi}_1^0 \text{ or } \tilde{\chi}_1^0$	Multiple 139 $0 e, \mu = 6 h = E_T^{miss}$ 139 $0-2 e, \mu = 0-2 \text{ jets}/1-2 h E_T^{miss}$ 36.1	b1 Forbidden 50 b1 Forbidden 0.23-0.48 0.23-0.48	scalar LQ (pair prod.), coupling to 2^{rd} gen. fermions, $\beta = 0.5$ scalar LQ (pair prod.), coupling to 3^{rd} gen. fermions, $\beta = 1$ scalar LQ (single prod.), coup. to 3^{rd} gen. ferm., $\beta = 1, \lambda = 1$	L ₀ 1808.05082 (2μ+2j; μ+2j + E ^{tim}) L ₀ 1811.00806 (2τ+2j) 1.0 L ₀ 1806.03472 (2τ+b) 0.74	129
3rd gen. so direct prod	$ \begin{array}{l} \bar{t}_1 \bar{t}_1, \bar{t}_1 \rightarrow W \hat{k}_1^0 \\ \bar{t}_1 \bar{t}_1, \bar{t}_1 \rightarrow \bar{\pi}_1 \hat{k}_2, \bar{\pi}_1 \rightarrow \tau \hat{G} \\ \bar{t}_1 \bar{t}_1, \bar{t}_1 \rightarrow \bar{c} \tilde{k}_1^0 / \bar{c} \bar{c}, \bar{c} \rightarrow c \tilde{k}_1^0 \end{array} $	$\begin{array}{cccc} 1 \ e, \mu & 3 \ {\rm jets}^{1/1} \ b & E_T^{\rm miss} & 139 \\ 1 \ \tau + 1 \ e, \mu, \tau & 2 \ {\rm jets}^{1/1} \ b & E_T^{\rm miss} & 36, 1 \\ 0 \ e, \mu & 2 \ c & E_T^{\rm miss} & 36, 1 \\ 0 \ e, \mu & {\rm mono-jet} & E_T^{\rm miss} & 36, 1 \end{array}$	I 0.44-0.59 I Image: Constraint of the state of the sta	excited light quark (qq), $h = m_a^*$ excited light quark (qq), $h_z = f = f = 1, h = m_a^*$ excited b quark, $f_z = f = f = 1, h = m_a^*$ excited electron, $f_z = f = f = 1, h = m_a^*$ excited electron, $f_z = f = f = 1, h = m_a^*$	 (; 1260,0043; 2)) (; 1711,0452; (γ + j) (; 1711,0452; (γ + j) (; 1811,03052; (γ + 2e) (; 1811,03052; (γ + 2p) 	6 55 18 39 38
	$\hat{i}_2 \hat{i}_2, \hat{i}_2 \rightarrow \hat{i}_1 + h$ $\hat{i}_2 \hat{i}_2, \hat{i}_2 \rightarrow \hat{i}_1 + Z$ $\hat{c}^{\pm} \hat{c}^0, \hat{c}_2 \rightarrow \hat{v}_2$	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	i₁ i₂ Forbidden tutt	quark compositeness $(q\bar{q}), \eta_{1,LRR} = 1$ Λ_1^{i} quark compositeness $(ll), \eta_{1l,RR} = 1$ Λ_2^{i} quark compositeness $(q\bar{q}), \eta_{n,RR} = 1$ Λ_2^{i}	1803.08030 (2j) 1812:10443 (2/) 1803.08030 (2)	12.8 20 17.5
EW direct	$ \begin{array}{l} x_{1}x_{2} \forall \mathbf{u} \ \mathbf{W} \times \\ x_{1}^{2} \mathbf{x}^{2} \forall \mathbf{u} \ \mathbf{W} \\ \mathbf{x}^{2} \mathbf{x}^{2} \forall \mathbf{u} \ \mathbf{W} \\ \mathbf{x}^{2} \mathbf{x}^{2} \forall \mathbf{u} \ \mathbf{W} \\ \mathbf{x}^{2} \mathbf{x}^{2} \mathbf{x}^{2} \forall \mathbf{u} \ \mathbf{x}_{L} \\ \mathbf{x}^{2} \mathbf{x}^{2} \mathbf{x}^{2} \mathbf{x}^{2} \\ \mathbf{x}_{L} \mathbf{x}_{L} \mathbf{x}_{L} \in \mathcal{L}_{L}^{2} \\ \mathbf{B} \mathbf{B}, \mathbf{B} \rightarrow \mathbf{h} \mathbf{G} \mathbf{Z} \mathbf{G} \end{array} $	$\begin{array}{cccc} c_{r,\mu} & c_{r,\mu} & c_{r,\mu} & 30.1\\ c_{r,\mu} & \rho_{r,\mu} & 139\\ 2c_{r,\mu} & \rho_{r,\mu}^{rais} & 139\\ 0-1c_{r,\mu} & 2h^2 2\gamma & \rho_{r,\mu}^{rais} & 139\\ 2c_{r,\mu} & \rho_{r,\mu}^{rais} & 139\\ 2c_{r,\mu} & 0jots & \rho_{r,\mu}^{rais} & 36,1\\ 0c_{r,\mu} & 0jots & \rho_{r,\mu}^{rais} & 36,1\\ \end{array}$	1/1/3 0.205 0.6 3 and 1 K1 0.215 0.42 K1	ADD (ij) HLZ, $n_{tot} = 3$ ADD GBH (ij), $n_{tot} = 6$ M ADD GBH (ij), $n_{tot} = 6$ M R5 Ga(dit, g), $kM_{tot} = 0.1$ M R5 Ga(dit), $kM_{tot} = 0.1$ M	<pre> B12121044 [2/] B12121044 [2/] B12210443 [2/] B12210443 [2/] B1210443 [2/] B120308030 [2]) B10308030 [2]) B10308030 [2]) B10308030 [2]) B10308030 [2]) B10308030 [2]) B10308030 [2]) B10008030 [2]) B100808030 [2]) B1080808030 [2]) B108080800 [2] B108080800 [2] B108080800 [2] B1080808000 [2] B108080800 [2] B108080</pre>	31 31 99 99 82 18 41
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, $\tilde{g} \rightarrow qq \tilde{\xi}_1^0$	Disapp. trk 1 jet $E_7^{\rm miss}$ 36.1 Multiple 36.1 Multiple 36.1	k ² / ₁ 0.46 k ² / ₁ 0.15 δ [righ =10 ns, 0.2 ns]	RS QBH (µ), $n_{exp} = 1$ M RS QBH (µ), $n_{exp} = 1$ M non-rotating BH, $M_{exp} = 4$ TeV, $n_{exp} = 6$ M split-UED, $\mu \ge 4$ TeV	n 1803.08030 (2)) n 1802.01122 (ep) 1805.0013 (c 7/(t y)) 1805.0013 (t + E;"")	59 36 97
RPV	$\begin{split} LFV & pp \rightarrow \hat{\gamma}_t + X, \hat{\gamma}_t \rightarrow q\mu e \tau / \mu \tau \\ X_1^2 \tilde{X}_1^2 (X_2^2 \rightarrow WW) / Z \ell \ell \ell v_{tr} \\ \tilde{g} \tilde{g}, \tilde{g} \rightarrow qq \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq q \\ \tilde{n}_t \tilde{r} \rightarrow k \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow ths \\ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs \\ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs \\ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q\ell \end{split}$	$\begin{array}{c} e_{\mu,er+\mu r} & 3.2 \\ 4 \ e, \mu & 0 \ \text{jets} k_T^{\text{min}} & 36.1 \\ 4 \ e, \mu & 0 \ \text{jets} k_T^{\text{min}} & 36.1 \\ Multiple & 36.1 \\ Multiple & 36.1 \\ 2 \ \text{jets} \ 2 \ b & 36.7 \\ 2 \ e, \mu & 2 \ b & 36.7 \\ 1 \ \mu & \text{DV} & 136 \end{array}$	$ \begin{array}{c} \mathbf{F}_{1} & & & \\ \mathbf{K}_{1}^{2}/\mathbf{K}_{2}^{2} & \left[\mathbf{A}_{01} \neq 0, \mathbf{A}_{01} \neq 0 \right] \\ \mathbf{K}_{1}^{2}/\mathbf{K}_{2}^{2} & \left[\mathbf{A}_{01} \neq 0, \mathbf{A}_{11} \neq 0 \right] \\ \mathbf{K}_{1}^{2} & \left[\mathbf{K}_{1}^{2} \geq \mathbf{A}, 2, \mathbf{S} \right] \\ \mathbf{K}_{1}^{2} & \left[\mathbf{K}_{1}^{2} \geq \mathbf{A}, 2, \mathbf{S} \right] \\ \mathbf{K}_{1}^{2} & \left[\mathbf{K}_{1}^{2} \geq \mathbf{A}, 1, \mathbf{S} \right] \\ \mathbf{K}_{1}^{2} & \left[\mathbf{K}_{1}^{2} = \mathbf{A}, 1, \mathbf{S} \right] \\ \mathbf{K}_{1}^{2} & \left[\mathbf{K}_{1}^{2} = \mathbf{K}, 1, \mathbf{S} \right] \\ \mathbf{K}_{1}^{2} & \left[\mathbf{K}_{1}^{2} = \mathbf{K}, \mathbf{K}, \mathbf{S} \right] \\ \mathbf{K}_{1}^{2} & \left[\mathbf{K}_{1}^{2} = \mathbf{K}, \mathbf{K}, \mathbf{S} \right] \\ \mathbf{K}_{1}^{2} & \left[\mathbf{K}_{1}^{2} = \mathbf{K}, \mathbf{K}, \mathbf{K} \right] \\ \mathbf{K}_{1}^{2} & \left[\mathbf{K}_{1}^{2} = \mathbf{K}, \mathbf{K}, \mathbf{K} \right] \\ \mathbf{K}_{1}^{2} & \left[\mathbf{K}_{1}^{2} = \mathbf{K}, \mathbf{K}, \mathbf{K} \right] \\ \mathbf{K}_{1}^{2} & \left[\mathbf{K}_{1}^{2} = \mathbf{K}, \mathbf{K}, \mathbf{K} \right] \\ \mathbf{K}_{1}^{2} & \left[\mathbf{K}_{1}^{2} = \mathbf{K}, \mathbf{K}, \mathbf{K} \right] \\ \mathbf{K}_{1}^{2} & \left[\mathbf{K}, K$	$ \begin{array}{llllllllllllllllllllllllllllllllllll$	1712.02345 (≥ 1) + E ^(m)) 1806.00843 (2)) 1900.10553 (0,14 + ≥ 3) + E ^(m)) 1901.01553 (0,14 + ≥ 3) + E ^(m)) 1911.01553 (0,14 + ≥ 3) + E ^(m)) 1912.02345 (≥ 1) + E ^(m)) 1810.1006 (4) 1910.01553 (4)	18 26 14 154
*Only phei simp	a selection of the available ma nomena is shown. Many of the plified models, c.f. refs. for the a	ss limits on new states or 1 limits are based on assumptions made.	0 ⁻¹ 5	string resonance	uncertainties are not included).	7.7 10 10.0 mass scale [TeV] January 2019
od	osobi I EC1	0 Tronto			3	E Dodogoh; INEN Digo

INFN Istituto Nazionale di Fisica Nucleare

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

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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 \triangleright 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.



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 \triangleright 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.

Higgs factories



• e+e- linear

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

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

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

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

Higgs factories

Difficult



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6

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F. Bedeschi, INFN-Pisa

Luminosity comparison





Bedeschi, LFC19, Trento

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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)

Circular e+e- Higgs Factories



SHILTSEV, Granada 2019

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 - ("< 6BCHF" cited in the CepC CDR)</p>



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✤ Higgs factory
> $10^6 e^+e^- \rightarrow HZ$





★ Higgs factory
> 10⁶ e+e- → HZ
★ EW & Top factory
> 3x10¹² e+e- → Z
> 10⁸ e+e- → W+W- ;
> 10⁶ e+e- → tt





Higgs factory $> 10^6 \text{ e+e-} \rightarrow \text{HZ}$ **EW & Top factory** \rightarrow 3x10¹² e+e- \rightarrow Z $\rightarrow 10^8 \text{ e}+\text{e}- \rightarrow \text{W}+\text{W}-;$ $> 10^6 \text{ e+e-} \rightarrow \text{tt}$ Flavor factory \rightarrow 5x10¹² e+e- \rightarrow bb, cc \succ 10¹¹ e+e- \rightarrow τ + τ -





Higgs factory \rightarrow 10⁶ e+e- \rightarrow HZ **EW & Top factory** > 3x10¹² e+e- \rightarrow Z $> 10^8 \text{ e}+\text{e}- \rightarrow \text{W}+\text{W}-;$ $> 10^6 \text{ e}+\text{e}- \rightarrow \text{tt}$ Flavor factory \rightarrow 5x10¹² e+e- \rightarrow bb, cc \rightarrow 10¹¹ e+e- \rightarrow τ + τ -

Potential discovery of NP

 \triangleright ALPs, RH v's, ...



Higgs production





Higgs production





Higgs total width



 $L = 5 ab^{-1}$

Higgs recoil provides model independent measurement of coupling to Z

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





Higgs total width



 $L = 5 ab^{-1}$

Higgs recoil provides model independent measurement of coupling to Z

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



Critical:

- Beam energy spread: SR+BS
- Tracking resolution





Higgs total width



 $L = 5 ab^{-1}$

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Critical:

Beam energy spread: SR+BS

Tracking resolution

Total width combining with decays in specific channels

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







Kappa framework

ork

$$(\sigma \cdot BR)(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H},$$

$$\kappa_H^2 \equiv \sum_j \frac{\kappa_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$$

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



Kappa framewo

Extension

ork

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

Sulua al F $\mathbf{\nabla}\mathbf{\nabla}$ BRunt 100% correlated with $\Gamma_{\rm H}$



Kappa framework

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Extension

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EFT framework

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Extension

BRinv measured at FCC-ee BRunt 100% correlated with $\Gamma_{\rm H}$

EFT framework

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

Includes interference with SM operators

Simultaneous fit of Higgs, EWPO, aTGC, topEW

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

Fit results projected into effective Higgs couplings $g_{HX}^{\text{eff 2}} \equiv \frac{\Gamma_{H \to X}}{\Gamma_{H \to X}^{\text{SM}}}$



Collider	HL-LHC	ILC_{250}	$\operatorname{CLIC}_{380}$	$CEPC_{240}$	$\text{FCC-ee}_{240 \rightarrow 365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years		$11.5^{\ 5}$	8	7	3+1+4
$g_{\rm HZZ}$ (%)	1.5 / 3.6	$0.29 \ / \ 0.47$	$0.44 \ / \ 0.66$	$0.18 \ / \ 0.52$	0.17 / 0.26
$g_{\rm HWW}$ (%)	1.7 / 3.2	1.1 / 0.48	$0.75 \ / \ 0.65$	$0.95 \ / \ 0.51$	0.41 / 0.27
g_{Hbb} (%)	3.7 / 5.1	1.2 / 0.83	$1.2 \ / \ 1.0$	$0.92 \ / \ 0.67$	0.64 / 0.56
$g_{\rm Hcc}$ (%)	SM / SM	2.0 / 1.8	4.1 / 4.0	2.0 / 1.9	1.3 / 1.3
g_{Hgg} (%)	2.5 / 2.2	$1.4 \ / \ 1.1$	1.5 / 1.3	1.1 / 0.79	0.89 / 0.82
$g_{\mathrm{H}\tau\tau}$ (%)	1.9 / 3.5	$1.1 \ / \ 0.85$	1.4 / 1.3	1.0 / 0.70	0.66 / 0.57
$g_{\mathrm{H}\mu\mu}$ (%)	4.3 / 5.5	4.2 / 4.1	4.4 / 4.3	3.9 / 3.8	3.9 / 3.8
$g_{\rm H\gamma\gamma}$ (%)	1.8 / 3.7	$1.3 \ / \ 1.3$	1.5 / 1.4	$1.2 \ / \ 1.2$	1.2 / 1.2
$g_{\mathrm{HZ}\gamma}$ (%)	11. / 11.	11. / 10.	11. / 9.8	6.3 / 6.3	10. / 9.4
$g_{\rm Htt}$ (%)	3.4 / 2.9	2.7 / 2.6	2.7 / 2.7	2.6 / 2.6	2.6 / 2.6
$g_{\rm HHH}$ (%)	50. / 52.	28. / 49.	45. / 50.	17. / 49.	19. / 34.
$\Gamma_{\rm H}$ (%)	SM	2.4	2.6	1.9	1.2
BR_{inv} (%)	1.9	0.26	0.63	0.27	0.19
BR_{EXO} (%)	SM (0.0)	1.8	2.7	1.1	1.0

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EFT



Results limited only by statistics



Triple Higgs



No direct production @ FCC-ee

Sensitivity through loop effects





Triple Higgs



No direct production @ FCC-ee



EWK



Outstanding program of precision EWK measurements O(10-100) better than LEP precision

Substantially reduce parametric uncertainties in theory

Observable	Present value \pm error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error	
m _Z (keV)	$91,186,700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration	1
$\Gamma_{\rm Z}$ (keV)	$2,495,200 \pm 2300$	8	100	From Z line shape scan Beam energy calibration	
R_{ℓ}^{Z} (×10 ³)	$20,767\pm25$	0.06	0.2-1.0	Ratio of hadrons to leptons acceptance for leptons	
$\alpha_{\rm s} \ ({\rm m_Z}) \ (\times 10^4)$	1196 ± 30	0.1	0.4-1.6	From R_{ℓ}^{Z} above [43]	
R_b (×10 ⁶)	$216,290\pm 660$	0.3	< 60	Ratio of bb to hadrons stat. extrapol. from SLD [44]	
$\sigma_{\rm had}^0 \; (\times 10^3) \; ({\rm nb})$	$41,541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement	Z pole
N_{ν} (×10 ³)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement	
$\sin^2 \theta_W^{\text{eff}}$ (×10 ⁶)	$231,\!480\pm160$	3	2-5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration	
$1/\alpha_{\rm QED}~(m_Z)~(\times 10^3)$	$128,952\pm14$	4	Small	From $A_{FB}^{\mu\mu}$ off peak [34]	
$A_{FB}^{b,0}$ (×10 ⁴)	992 ± 16	0.02	1-3	b-quark asymmetry at Z pole from jet charge	
$A_{FB}^{pol,\tau}$ (×10 ⁴)	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics	
m _W (MeV)	$80,350 \pm 15$	0.5	0.3	From WW threshold scan Beam energy calibration	i
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration	WW
$\alpha_{\rm s} \ ({\rm m_W}) \ (\times 10^4)$	1170 ± 420	3	Small	From R_{ℓ}^{W} [45]	
N_{ν} (×10 ³)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns	
mtop (MeV)	$172,740 \pm 500$	17	Small	From tt threshold scan QCD errors dominate	1
Γ_{top} (MeV)	1410 ± 190	45	Small	From tt threshold scan QCD errors dominate	
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From tt threshold scan QCD errors dominate	
ttZ couplings	$\pm 30\%$	0.5-1.5%	Small	From $E_{CM} = 365 \text{ GeV run}$	





Outstanding program of precision EWK measurements



EWK examples





W mass/width $\rightarrow 0.5/1.2$ MeV resolution

WW threshold scan/ direct measurements check and improve

***** Top quark mass/width \rightarrow 17/45 MeV resolution

▶ tt threshold scan – N³LO, ISR and FCCee luminosity spectrum Bedeschi, LFC19, Trento
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EWK examples







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NP sensitivity from EFT fits





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

Particle production (10^9)	B^0	B^{-}	B_s^0	Λ_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

Very clean, well separated, pairs

Heavy flavors



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Direct NP search example: HNL



HNL mix with active neutrino's

➢ Fully reconstructable decay with W
➢ Small mixing → long lifetime



Direct NP search example: HNL

BAU

FCC-ee

Seesaw



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





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

Direct NP search example: HNL

Inverted hierarchy

NuTeV



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

10

² 10⁻⁹

10-11

10-10 - BBN

CHARN







SHIP

1

Seesaw

HNL mass (GeV)



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



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FCC-ee

Accelerators



The planned machines

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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

Bedeschi, LFC19, Trento

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.

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CEPC-SppC: site studies



 Qinhuangdao, Hebei ProvinceCompleted 2014)
 Huangling, Shanxi Province (Completed 2017)
 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)



CEPC







Huge potential of physics from FCC-ee (or CepC)

- Study Higgs x10 better than HL-LHC
- EWPO x10-100 better than LEP
- \rightarrow sensitivity to NP in the 10's TeV range
- Large potential for HF studies complementary to LHC-b/Belle II
- Direct sensitivity to new physics



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- 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







