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Oltre LHC: la fisica al Future Circular Collider (FCC)

Michelangelo L. Mangano CERN TH Department



Why we need a future circular collider ?



... because there are many fundamental questions in our understanding of Nature, and thus of particle physics, which cannot be answered with the <u>current</u> accelerators and experiments



... in particular, once we understand <u>how</u> something works, it's time to understand <u>why</u>



... and, in general, what we know and give for granted today may need revision once new evidence emerges, triggering new scientific revolutions



... therefore, we will always need a "future" experimental facility, to continue the endless exploration of nature at the most fundamental level

The discussion about, and study of, post-LHC colliders began well before the LHC even started



The open questions

- what's the origin of **dark matter** in the Universe ?
- what's the origin of the matter/antimatter **asymmetry**?
- what's the origin of **neutrino masses**?

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- are there additional **fundamental interactions**, too weak to have been observed so far? • are there **new families** of quarks and leptons ?
- quarks & leptons: are they elementary, or composite of other more fundamental particles ?

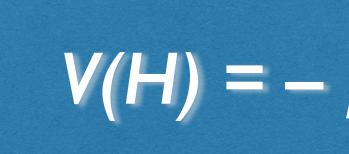
Answers to these questions imply the existence of new physics beyond the Standard Model

The opportunities

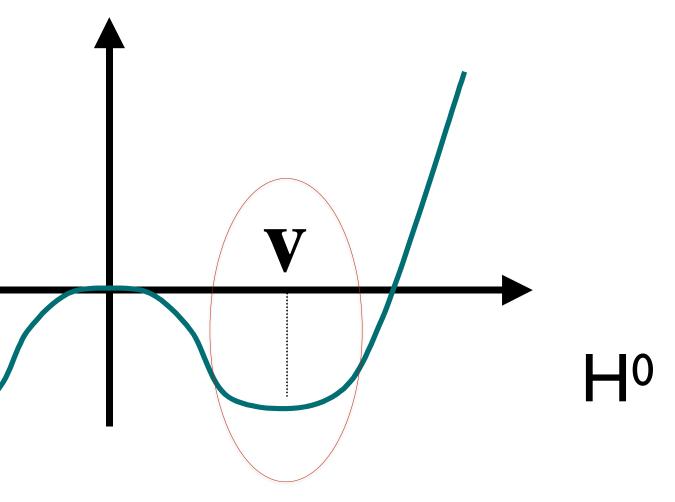
- For none of these questions, the path to an answer is unambiguously defined.
- Two examples:
 - DM: could be anything from fuzzy 10^{-22} eV scalars, to O(TeV) WIMPs, to multi-M_{\odot} primordial BHs, passing through axions and sub-GeV DM • a vast array of expts is needed, even though most of them will end up empty-handed...
 - Neutrino masses: could originate anywhere between the EW and the GUT scale • we are still in the process of acquiring basic knowledge about the neutrino sector: mass hierarchy, majorana nature, sterile neutrinos, CP violation, correlation with mixing in the charged-lepton sector ($\mu \rightarrow e\gamma$, $H \rightarrow \mu \tau$, ...): as for DM, *a broad range of options* to explore, to find the right clues
- We cannot objectively establish a hierarchy of relevance among the fundamental questions. The hierarchy evolves with time (think of GUTs and proton decay searches!) and is likely subjective. It is also likely that several of the big questions are tied together and will find their answer in a common context (eg DM and hierarchy problem, flavour and nu masses, quantum gravity/ inflation/dark energy, ...)



But there is one central question to the progress of HEP, which can <u>only</u> be addressed by colliders







$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$

Where does this come from?



The SM Higgs mechanism (*á la Weinberg*) provides the *minimal* set of *ingredients* required to enable a consistent breaking of the Electroweak symmetry (EWSB).

Where these ingredients come from, what possible additional infrastructure comes with them, whether their presence is due to purely anthropic or more fundamental reasons, we don't know, the SM doesn't tell us ...



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a historical example: superconductivity

- we would still lack a deep understanding of the relevant dynamics.

• The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But

• For superconductivity, this came later, with the identification of e-e- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and we must look beyond.



examples of possible scenarios

- **BCS-like**: the Higgs is a composite object
- Supersymmetry: the Higgs is a fundamental field and • $\lambda^2 \sim g^2 + g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one
 - parameter less than SM!)
 - potential is fixed by susy & gauge symmetry
 - parameters of SUSY breaking

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• EW symmetry breaking (and thus m_H and \lambda) determined by the
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Other important open issues on the Higgs sector

- $H^{\pm}, A^{0}, H^{\pm\pm}, \dots, EW$ -singlets,)?
 - Do all SM families get their mass from the **<u>same</u>** Higgs field?
 - fermions (down-type quarks and charged leptons)?
 - Do Higgs couplings conserve flavour? $H \rightarrow \mu \tau$? $H \rightarrow e \tau$? $t \rightarrow Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- What happens at the EW phase transition (PT) during the Big Bang?
 - what's the order of the phase transition?
 - are the conditions realized to allow EW baryogenesis?

the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, which can only rely on the LHC and on a future generation of colliders

• Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g.

• Do $I_3 = I/2$ fermions (up-type quarks) get their mass from the <u>same</u> Higgs field as $I_3 = -I/2$



The LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

In search of the origin of known departures from the SM

- Dark matter, long lived particles
- Neutrino masses
- Matter/antimatter asymmetry of the universe

<u>To explore alternative extensions of the SM</u>

- New gauge interactions (Z', W') or extra Higgs bosons
- Additional fermionic partners of quarks and leptons, leptoquarks, ...
- **Composite nature of quarks and leptons**
- Supersymmetry, in a variety of twists (minimal, constrained, natural, RPV, ...)
- **Extra dimensions**
- New flavour phenomena
- unanticipated surprises ...



So far, no conclusive signal of physics beyond the SM

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2022

	Model	<i>ℓ</i> , γ	Jets†	E ^{miss} T	∫£ dt[fb	-1]
Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP	$\begin{array}{c} 0 \ e, \mu, \tau, \gamma \\ 2 \ \gamma \\ - \\ 2 \ \gamma \\ 2 \ \gamma \\ \end{array}$ multi-channel 1 e, μ	1 – 4 j 	Yes – – – Yes J Yes	139 36.7 139 3.6 139 36.1 139 36.1 36.1	M _D M _s M _{th} M _{th} G _{KK} mass G _{KK} mass g _{KK} mass g _{KK} mass KK mass
Gauge bosons	$\begin{array}{l} \operatorname{SSM} Z' \to \ell\ell \\ \operatorname{SSM} Z' \to \tau\tau \\ \operatorname{Leptophobic} Z' \to bb \\ \operatorname{Leptophobic} Z' \to tt \\ \operatorname{SSM} W' \to \ell\nu \\ \operatorname{SSM} W' \to \tau\nu \\ \operatorname{SSM} W' \to tb \\ \operatorname{HVT} W' \to WZ \to \ell\nu qq \operatorname{mode} \\ \operatorname{HVT} W' \to WZ \to \ell\nu \ell'\ell' \operatorname{mod} \\ \operatorname{HVT} W' \to WH \to \ell\nu bb \operatorname{mode} \\ \operatorname{HVT} Z' \to ZH \to \ell\ell/\nu\nu bb \operatorname{mode} \\ \operatorname{HVT} Z' \to ZH \to \ell\ell/\nu\nu bb \operatorname{mode} \\ \operatorname{LRSM} W_R \to \mu N_R \end{array}$	$1 e, \mu$ 1τ $e B 1 e, \mu$ $de I C 3 e, \mu$ $e B 1 e, \mu$	_ 2 b ≥1 b, ≥2 J _ ≥1 b, ≥1 J 2 j / 1 J 2 j (VBF) 1-2 b, 1-0 j 1-2 b, 1-0 j 1 J	Yes Yes Yes Yes Yes	139 36.1 139 139 139 139 139 139 139 139 139 80	Z' mass Z' mass Z' mass Z' mass W' mass W' mass W' mass W' mass W' mass W' mass Z' mass Z' mass
CI	Cl qqqq Cl ℓℓqq Cl eebs Cl μμbs Cl tttt	- 2 e, μ 2 e 2 μ ≥1 e,μ	2 j _ 1 b 1 b ≥1 b, ≥1 j	- - - Yes	37.0 139 139 139 36.1	Λ Λ Λ Λ
MQ	Axial-vector med. (Dirac DM) Pseudo-scalar med. (Dirac DM) Vector med. Z'-2HDM (Dirac D Pseudo-scalar med. 2HDM+a	l) 0 e, μ, τ, γ	1 – 4 j 2 b	Yes Yes Yes	139 139 139 139	m _{med} m _{med} m _{med}
ГQ	Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Vector LQ 3 rd gen	$\begin{array}{c} 2 \ e \\ 2 \ \mu \\ 1 \ \tau \\ 0 \ e, \mu \\ \geq 2 \ e, \mu, \geq 1 \ \tau \\ 0 \ e, \mu, \geq 1 \ \tau \\ 1 \ \tau \end{array}$		-	139 139 139 139 139 139 139 139	LQ mass LQ mass LQ ^u mass LQ ^u mass LQ ^d mass LQ ^d mass LQ ^v mass
Vector-like fermions	$\begin{array}{l} VLQ \ TT \to Zt + X \\ VLQ \ BB \to Wt/Zb + X \\ VLQ \ T_{5/3} \ T_{5/3} T_{5/3} \to Wt + X \\ VLQ \ T \to Ht/Zt \\ VLQ \ T \to Ht/Zt \\ VLQ \ Y \to Wb \\ VLQ \ B \to Hb \\ VLL \ \tau' \to Z\tau/H\tau \end{array}$	1 e,μ 1 e,μ	≥1 b, ≥1 j ≥1 b, ≥3 j ≥1 b, ≥1 j 2b, ≥1j, ≥1	Yes Yes Yes	139 36.1 139 36.1 139 36.1 139 139	T mass B mass T _{5/3} mass T mass Y mass B mass τ' mass
Excited fermions	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton ℓ^* Excited lepton ν^*	- 1 γ - 3 e, μ 3 e, μ, τ	2 j 1 j 1 b, 1 j - -		139 36.7 139 20.3 20.3	q* mass q* mass b* mass ℓ* mass v* mass
Other	Type III Seesaw LRSM Majorana ν Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$ Multi-charged particles Magnetic monopoles	2,3,4 e, μ 2 μ 2,3,4 e, μ (SS) 2,3,4 e, μ (SS) 3 e, μ , τ -	- - - -	Yes Yes 	139 36.1 139 139 20.3 139 34.4	N ⁰ mass N _R mass H ^{±±} mass H ^{±±} mass H ^{±±} mass multi-charged particle monopole mass
		$\sqrt{s} = 13 \text{ TeV}$	√s = 13 full da			10 ⁻¹

*Only a selection of the available mass limits on new states or phenomena is shown. †Small-radius (large-radius) jets are denoted by the letter j (J).

ATLAS Preliminary

 $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$

 $\sqrt{s} = 8, 13 \text{ TeV}$

Limit Reference **11.2 TeV** *n* = 2 2102.10874 **8.6 TeV** *n* = 3 HLZ NLO 1707.04147 **9.4 TeV** *n* = 6 1910.08447 **9.55 TeV** $n = 6, M_D = 3$ TeV, rot BH 1512.02586 $k/\overline{M}_{Pl} = 0.1$ 4.5 TeV 2102.13405 2.3 TeV $k/\overline{M}_{Pl} = 1.0$ 1808.02380 $k/\overline{M}_{Pl} = 1.0$ 2.0 TeV 2004.14636 $\Gamma/m = 15\%$ 1804.10823 3.8 TeV Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$ 1.8 TeV 1803.09678 5.1 TeV 1903.06248 2.42 TeV 1709.07242 2.1 TeV 1805.09299 4.1 TeV $\Gamma/m = 1.2\%$ 2005.05138 6.0 TeV 1906.05609 ATLAS-CONF-2021-025 5.0 TeV 4.4 TeV ATLAS-CONF-2021-043 4.3 TeV $g_V = 3$ 2004.14636 340 GeV ATLAS-CONF-2022-005 $g_V c_H = 1, g_f = 0$ 3.3 TeV $g_V = 3$ 2207.00230 3.2 TeV $g_V = 3$ 2207.00230 $m(N_R) = 0.5 \text{ TeV}, g_L = g_R$ 5.0 TeV 1904.12679 **21.8 TeV** η_{LL} 1703.09127 35.8 TeV η_{LL}^- 2006.12946 1.8 TeV $g_{*} = 1$ 2105.13847 2.0 TeV $g_{*} = 1$ 2105.13847 $|C_{4t}| = 4\pi$ 2.57 TeV 1811.02305 $g_q=0.25, g_{\chi}=1, m(\chi)=1 \text{ GeV}$ 2.1 TeV 2102.10874 $g_q=1, g_{\chi}=1, m(\chi)=1 \text{ GeV}$ 376 GeV 2102.10874 $\tan\beta=1, g_Z=0.8, m(\chi)=100 \text{ GeV}$ 3.1 TeV 2108.13391 $\tan\beta=1, g_{\chi}=1, m(\chi)=10 \text{ GeV}$ ATLAS-CONF-2021-036 560 GeV 1.8 TeV $\beta = 1$ 2006.05872 1.7 TeV $\beta = 1$ 2006.05872 $\mathcal{B}(\mathrm{LQ}_3^u o b au) = 1$ $\mathcal{B}(\mathrm{LQ}_3^u o t au) = 1$ 1.2 TeV 2108.07665 1.24 TeV 2004.14060 $\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1$ 1.43 TeV 2101.11582 $\mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1$ 1.26 TeV 2101.12527 1.77 TeV $\mathcal{B}(LQ_3^V \to b\tau) = 0.5$, Y-M coupl. 2108.07665 1.4 TeV SU(2) doublet ATLAS-CONF-2021-024 1.34 TeV SU(2) doublet 1808.02343 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ 1807.11883 1.8 TeV SU(2) singlet, $\kappa_T = 0.5$ ATLAS-CONF-2021-040 1.85 TeV $\mathcal{B}(Y \to Wb) = 1, c_R(Wb) = 1$ 1812.07343 SU(2) doublet, $\kappa_B = 0.3$ 2.0 TeV ATLAS-CONF-2021-018 898 GeV SU(2) doublet ATLAS-CONF-2022-044 6.7 TeV only u^* and d^* , $\Lambda = m(q^*)$ 1910.08447 5.3 TeV only u^* and d^* , $\Lambda = m(q^*)$ 1709.10440 3.2 TeV 1910.0447 3.0 TeV $\Lambda = 3.0 \text{ TeV}$ 1411.2921 1.6 TeV $\Lambda = 1.6 \text{ TeV}$ 1411.2921 910 GeV 2202.02039 $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 3.2 TeV 1809.11105 DY production 350 GeV 2101.11961 DY production ATLAS-CONF-2022-010 1.08 TeV DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ 400 GeV 1411.2921 DY production, |q| = 5e1.59 TeV ATLAS-CONF-2022-034 mass DY production, $|g| = 1g_D$, spin 1/2 2.37 TeV 1905.10130 10

Mass scale [TeV]



Why can't we find an answer to those "origin" questions with the LHC and other experiments?

- Is the mass scale of new physics beyond the LHC reach ?
- Is the mass scale within LHC's reach, but the manifestations of new physics are elusive to the direct search?

- To address both possibilities, we need a future circular collider to increase the: • precision \Rightarrow higher statistics, better detectors and experimental conditions
- sensitivity (to elusive signatures) \Rightarrow ditto
- energy/mass reach ⇒ higher energy

Future Circular Collider

LHC

http://cern.ch/fcc

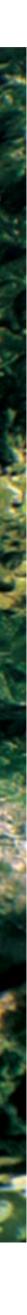
France

100km tunnel

e+e- @ 91, 160, 240, 365 GeV
pp @ 100 TeV
e60Gev P50Tev @ 3.5 TeV

Switzerland

FCC 100 km circumference



What a future circular collider can offer

- Guaranteed deliverables:
 - best possible precision and sensitivity
- Exploration potential:

 - exploit both direct (large Q^2) and indirect (precision) probes enhanced mass reach for direct exploration at 100 TeV
 - E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector
- Provide firm Yes/No answers to questions like:
 - is there a TeV-scale solution to the hierarchy problem?
 - is DM a thermal WIMP?

• ...

- could the cosmological EW phase transition have been 1st order? • could baryogenesis have taken place during the EW phase transition? • could neutrino masses have their origin at the TeV scale?

• study of Higgs and top quark properties, and exploration of EWSB phenomena, with the

Direct vs indirect discovery



The serendipitous value of precision measurements: a few history lessons

- Tycho Brahe (1546-1601) spent his life measuring planets' positions more and more precisely Johannes Kepler (1571-1630) used those data to extract a "phenomenological"
 - interpretation, based on his 3 laws
 - Isaac Newton (1643-1727) discovered the underlying "theoretical" foundation of Kepler's laws ... but it all started from Brahe's precision data!
- Newton's law became the new Standard Model for planetary motions. Precision measurements of the Uranus orbit, in the first half of the XIX century, showed deviations from this "SM": was it a break-down of the SM, or the signal of a new particle planet?
 - <u>assuming</u> the validity of the SM, interpreting the deviations as due to perturbations by a yet unknown planet, Neptun was discovered (1846), implicitly giving stronger support to Newton's SM
- Precision planetary measurements continued throughout the XIX century, revealing yet another SM deviation, in Mercury's motion. This time, it was indeed a beyond SM (BSM) signal: Einstein's theory of General Relativity!! Mercury's data did not motivate Einstein to formulate it, but once he had the equations, he used those precise data to confirm its validity! 20



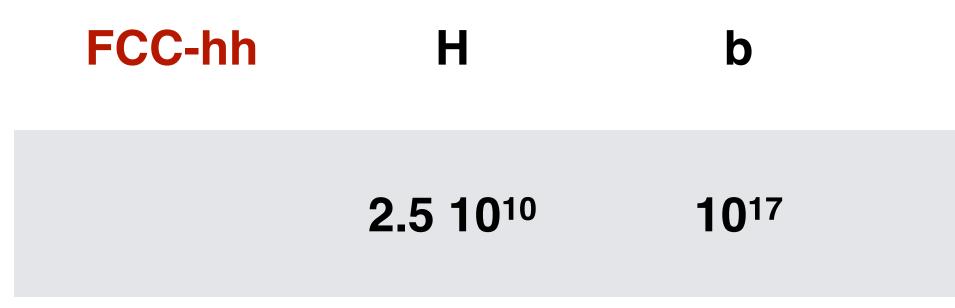


Event rates at FCC: examples

e+e- collisions: very clean experimental environment, every single event is recorded and later analyzed, small backgrounds, high experimental precision and small systematic uncertainties

FCC-ee	Н	Ζ	W	t	т(←Z)	b(←Z)	c(←Z)
	10 ⁶	5 10 ¹²	10 ⁸	106	3 10 ¹¹	1.5 10 ¹²	10 ¹²

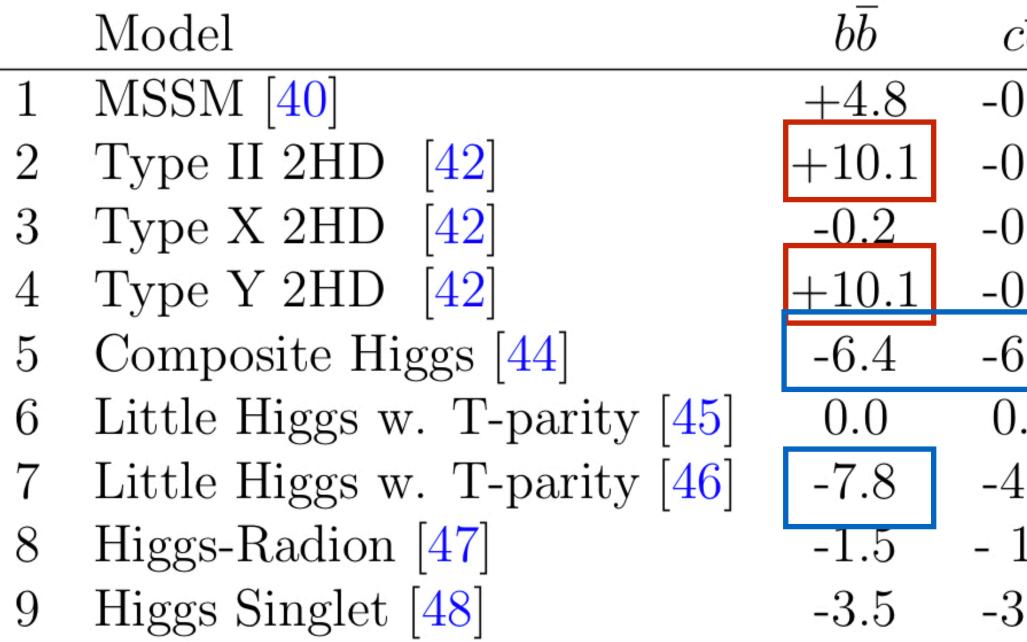
pp collisions: very high energies, very large production rates, sensitivity to extremely rare processes and potential to directly observe new partiles of very large mass



t	W(←t)	τ(←W←t)
10 ¹²	10 ¹²	10 ¹¹

How precise do we need Higgs measurements to be?

Coupling deviations for various BSM models, likely to remain unconstrained by direct searches at HL-LHC



(sub)-% precision must be the goal to ensure 3-5 σ evidence of deviations, and to cross-correlate coupling deviations across different channels

https://arxiv.org/pdf/1708.08912.pdf

$c\overline{c}$	gg	WW	au au	ZZ	$\gamma\gamma$	$\mu\mu$
0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

3: when the b coupling is modified, BR deviations are smaller than the uare of the coupling deviation. Eg in model 5, the BR to b, c, tau, mu e practically SM-like



Higgs coupling precision after FCC-ee / hh

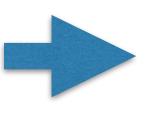
	HL-LHC	FCC-ee	FCC-hh
δГн / Гн (%)	SM	1.3	tbd
δgнzz / gнzz (%)	1.5	0.17	tbd
δднww / днww (%)	1.7	0.43	tbd
δд _{ньь} / д _{ньь} (%)	3.7	0.61	tbd
δg _{Hcc} / g _{Hcc} (%)	~70	1.21	tbd
δg _{Hgg} / g _{Hgg} (%)	2.5 (gg->H)	1.01	tbd
δgнττ / gнττ (%)	1.9	0.74	tbd
δg _{Hµµ} / g _{Hµµ} (%)	4.3	9.0	0.65 (*)
δg _{Hγγ} / g _{Hγγ} (%)	1.8	3.9	0.4 (*)
δg _{Htt} / g _{Htt} (%)	3.4	~10 (indirect)	0.95 (**)
δg _{HZγ} / g _{HZγ} (%)	9.8	—	0.9 (*)
бдннн / дннн (%)	50	~44 (indirect)	5
BR _{exo} (95%CL)	BR _{inv} < 2.5%	<1%	BR _{inv} < 0.025%

NB

BR(H \rightarrow Z γ , $\gamma\gamma$) ~O(10⁻³) \Rightarrow O(10⁷) evts for Δ_{stat} ~% BR(H \rightarrow µµ) ~O(10⁻⁴) \Rightarrow O(10⁸) evts for Δ_{stat} ~%

* From BR ratios wrt B($H \rightarrow ZZ^*$) @ FCC-ee

** From $pp \rightarrow ttH / pp \rightarrow ttZ$, using B(H \rightarrow bb) and ttZ EW coupling @ FCC-ee



pp collider is essential to beat the % target, since no proposed ee collider can produce more than O(10⁶) H's

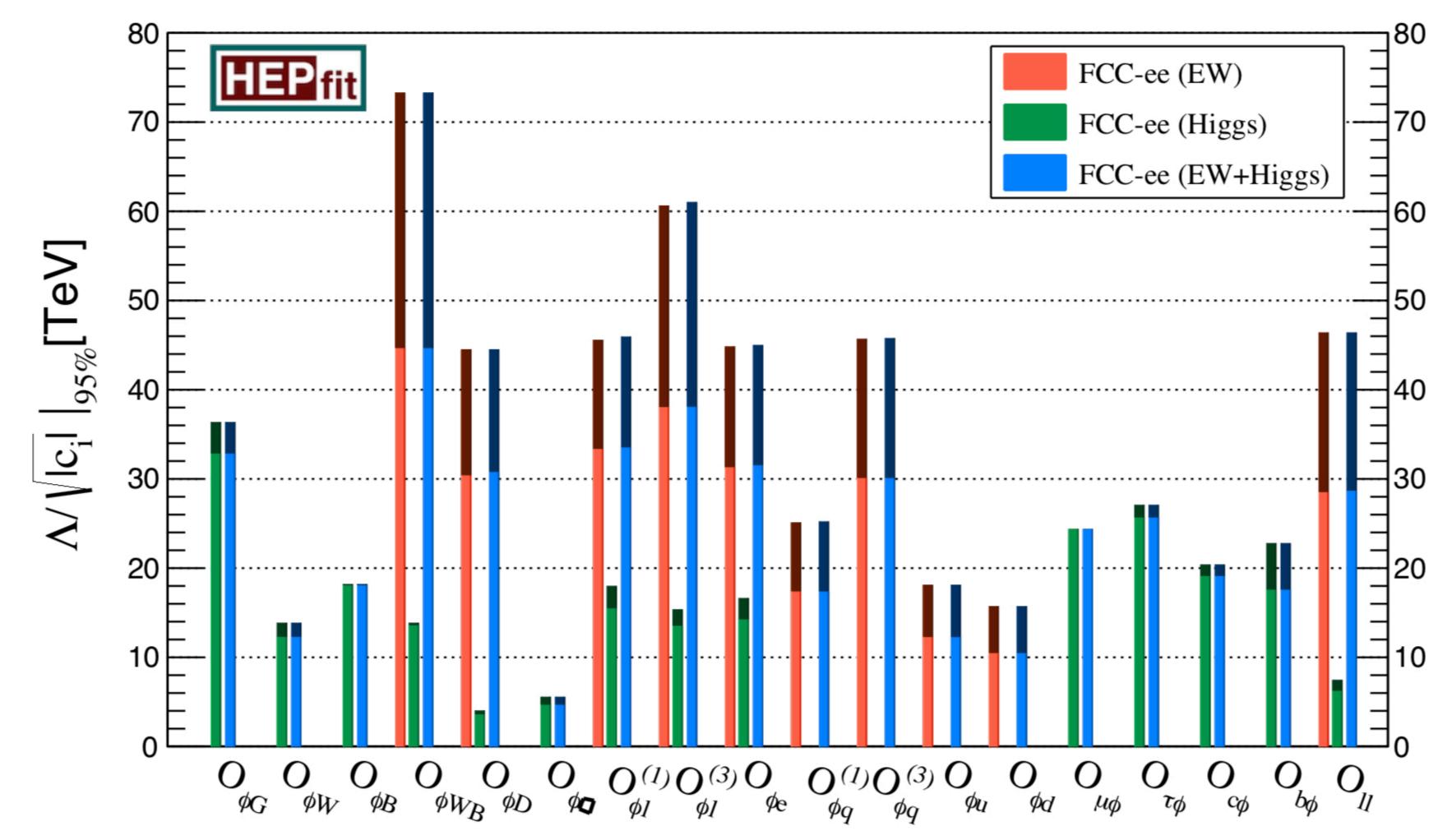
(2) Direct discovery reach at high mass: the power of 100 TeV

ATLAS SUSY Searches* - 95% CL Lower Limits March 2019

М	arch 2019		-								$\sqrt{s} = 13$	3 TeV
	Model	S	Signatur	e ∫.	<i>L dt</i> [fb ⁻	·']	Mass limit				Reference	
	$\hat{q}\tilde{q},\tilde{q}\!\rightarrow\!q\tilde{\chi}^0_1$	0 e,μ mono-jet	2-6 jets 1-3 jets	$E_T^{ m miss} \ E_T^{ m miss}$	36.1 36.1	<i>q̃</i> [2×, 8× Degen.] <i>q̃</i> [1×, 8× Degen.]	0.43	0.9	1.55			
ar	ĝğ, ğ→qą̃X̃ ⁰	0 e,µ	2-6 jets	$E_T^{\rm miss}$	36.1	ř. B		Forbidden	0.95-1.6	2.0 $m(\tilde{x}_1^0) < 200 \text{ G}$ $m(\tilde{x}_1^0) = 900 \text{ G}$	GeV 1712.02332	
	$\widetilde{g}\widetilde{g}, \widetilde{g} \rightarrow q \overline{q}(\ell \ell) \breve{\chi}_1^0$	3 e,μ ee,μμ	4 jets 2 jets	$E_T^{ m miss}$	36.1 36.1	ř			1.4 1.2	85 m(ℓ ₁ ^a)<800 0 m(ğ)-m(ℓ ₁ ^a)=50 0	GeV 1706.03731 GeV 1805.11381	
clusiv	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 e,μ 3 e,μ	7-11 jets 4 jets	$E_T^{ m miss}$	36.1 36.1	те 25		0.98	1.		GeV 1708.02794	
μ	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{\chi}_{1}^{\Omega}$	0-1 e,μ 3 e,μ	3 <i>h</i> 4 jets	$E_T^{ m miss}$	79.8 36.1	12C 100			1.25	2.25 m(𝔅̃ ₁)<200 ⟨ m(𝔅̃)-m(𝔅̃)=300 ⟨	GeV ATLAS-CONF-2018-041	
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / \ell \tilde{\chi}_1^-$		Multiple Multiple Multiple		36.1 36.1 36.1	$egin{array}{ccc} egin{array}{ccc} eta_1 & Forb \ eta_1 & eta_1 \ eta_1 & eta_1 \end{array} \end{array}$	idden Forbidden Forbidden	0.9 0.58-0.82 0.7		$\begin{split} \mathbf{m}(\tilde{\chi}_{1}^{0}) = & 300 \text{ GeV}, \text{ BR}(b\tilde{\chi}_{1}^{0}) \\ & \mathbf{m}(\tilde{\chi}_{1}^{0}) = & 300 \text{ GeV}, \text{ BR}(b\tilde{\chi}_{1}^{0}) = & \text{BR}(b\tilde{\chi}_{1}^{-}) \\ & \mathbf{m}(\tilde{\chi}_{1}^{0}) = & 200 \text{ GeV}, \mathbf{m}(\tilde{\chi}_{1}^{+}) = & 300 \text{ GeV}, \text{ BR}(b\tilde{\chi}_{1}^{-}) \end{split}$	0.5 1708.09266	
squarks oduction	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 {\rightarrow} b \tilde{\chi}_2^0 {\rightarrow} b h \tilde{\chi}_1^0$	0 <i>e</i> , µ	6 <i>b</i>	$E_T^{\rm miss}$	139	$ar{b}_1$ Forbidden $ar{b}_1$	0.23-0.48	C	.23-1.35	$\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 0.000 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 0.0000 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 0.0000000000000000000000000000000000$	GeV SUSY-2018-31 GeV SUSY-2018-31	
3 rd gen. squ direct produ	$\begin{split} \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow Wh\tilde{\chi}_{1}^{0} \text{ or } \tilde{\chi}_{1}^{0} \\ \tilde{t}_{1}\tilde{t}_{1}, \text{ Well-Tempered LSP} \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow \tilde{\tau}_{1}b\nu, \tilde{\tau}_{1} \rightarrow \tau\tilde{G} \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow c\tilde{\chi}_{1}^{0} / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_{1}^{0} \end{split}$	0-2 e, μ 1 τ + 1 e,μ,τ 0 e, μ 0 e, μ	0-2 jets/1-2 Multiple τ 2 jets/1 b 2 c mono-jet	$E_T^{ m miss}$ $E_T^{ m miss}$	36.1 36.1 36.1 36.1 36.1	\tilde{t}_1 \tilde{t}_1 \tilde{t}_1 \tilde{t}_1 \tilde{t}_1 \tilde{t}_1 \tilde{t}_1 \tilde{t}_1	0.46 0.43	1.0 0.48-0.84 0.85	1.16	$\begin{split} m(\tilde{\chi}_{1}^{0}) =& 150 \text{ GeV}, \ m(\tilde{\chi}_{1}^{1}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ \tilde{\iota}_{1} \\ m(\tilde{\tau}_{1}) =& 800 \text{ GeV}, \\ m(\tilde{\tau}_{1}) =& 800 \text{ GeV}, \ m(\tilde{\tau}_{1}) =& 800 \text{ GeV}, \ m(\tilde{\tau}_{1}) =& 800 \text{ GeV}, \ m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) - m(\tilde{\chi}_{1}^{0}) =& 5 \text{ GeV}, \ m(\tilde{\chi}_{1}, \tilde{c}) + m(\tilde{\chi}_{1}, \tilde{c}) +$	≈ ĩ _L 1709.04183, 1711.11520 GeV 1803.10178 GeV 1805.01649 GeV 1805.01649	1520
	$\tilde{l}_2 \tilde{l}_2, \tilde{l}_2 \rightarrow \tilde{l}_1 + h$	1-2 e, µ	4 <i>b</i>	E_T^{miss}	36.1	ĩ ₂		0.32-0.88		$m(\tilde{\chi}_1^0)=0$ GeV, $m(\tilde{\iota}_1)-m(\tilde{\chi}_1^0)=180$ G		
	$\tilde{\chi}_1 \tilde{\chi}_2^0$ via WZ	2-3 e, μ ee, μμ	≥ 1	E_T^{miss} E_T^{miss}	36.1 36.1			0.6		$m(\tilde{\chi}_{1}^{r})-m(\tilde{\chi}_{1}^{r})=10$ C) ₌₀ 1403.5294, 1806.02293	
EW direct	$\begin{split} &\tilde{\chi}_{1}^{\mp} \tilde{\chi}_{1}^{\mp} \text{ via } WW \\ &\tilde{\chi}_{1}^{\mp} \tilde{\chi}_{2}^{0} \text{ via } Wh \\ &\tilde{\chi}_{1} \tilde{\chi}_{1}^{-} \text{ via } \tilde{\ell}_{L} / \tilde{\nu} \\ &\tilde{\chi}_{1}^{\mp} \tilde{\chi}_{1}^{-} / \tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\tau}_{1} \nu (\tau \tilde{\nu}), \tilde{\chi}_{2}^{0} \rightarrow \tilde{\tau}_{1} \tau (\nu \tilde{\nu}) \end{split}$	2 e,μ 0 -1 e,μ 2 e,μ 2 τ	2 <i>b</i>	$E_T^{ m miss}$ $E_T^{ m miss}$ $E_T^{ m miss}$ $E_T^{ m miss}$	139 36.1 139 36.1		0.42	0.68 1.0 0.76	m	$\begin{split} &m(\tilde{\ell}_{1}^{0})\\ &m(\tilde{\ell}_{1}^{0})=0.5(m(\tilde{\ell}_{1}^{-})+m(\tilde{\ell}_{1}^{0}))\\ &m(\tilde{\ell}_{1}^{0})=0, \ m(\tilde{\tau},\tilde{\tau})=0.5(m(\tilde{\ell}_{1}^{-})+m(\tilde{\ell}_{1}^{+})-m(\tilde{\ell}_{1}^{0}))=100 \ \text{GeV}, \ m(\tilde{\tau},\tilde{\tau})=0.5(m(\tilde{\ell}_{1}^{-})+m(\tilde{\ell}_{1}^{0})) \end{split}$	$T_{1}=0$ ATLAS-CONF-2019-008 $T_{1}=0$ 1812.09432 $\tilde{\chi}_{1}^{0}$)) ATLAS-CONF-2019-008 $\tilde{\chi}_{1}^{0}$)) 1708.07875	
	$\tilde{\ell}_{1,\mathbf{R}}\tilde{\ell}_{1,\mathbf{R}},\tilde{\ell}{\rightarrow}\ell\tilde{\chi}_{1}^{0}$	2 e,μ 2 e,μ	0 jets ≥ 1	$E_T^{ m miss} \ E_T^{ m miss}$	139 36.1	ℓ ℓ 0.18		0.7		${f m}({f ilde r}_1^0) = {f s}$ ${f m}({f ilde r}_1^0) = {f s}$ ${f s}$)=0 ATLAS-CONF-2019-008 GeV 1712.08119	
	$\hat{H}\hat{H},\hat{H}{\rightarrow}h\tilde{G}/Z\tilde{G}$	0 e,μ 4 e,μ	$\ge 3 \ b$ 0 jets	E_T^{miss} E_T^{miss}	36.1 36.1	<i>ї</i> 1 0.13-0.23 <i>Н</i>	0.3	0.29-0.88		$\frac{BR(\tilde{\chi}_1^0 \to h\tilde{0})}{BR(\tilde{\chi}_1^0 \to Z\tilde{0})}$	j=1 1806.04030	
Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^+$ Stable \tilde{g} R-hadron	Disapp. trk	t 1 jet Multiple	$E_T^{\rm miss}$	36.1 36.1	$ \tilde{x}_{1}^{\pm} = 0.15 $	0.46			Pure V Pure Higg		
Lon	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$		Multiple		36.1	$\tilde{g} = [\tau(\tilde{g}) = 10 \text{ ns}, 0.2 \text{ ns}]$				2.0 2.05 2.4 $m(\tilde{x}_1^0)=100$ C		
RPV	$ \begin{array}{l} LFV \ pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau \\ \tilde{\chi}_{1}^{-}\tilde{\chi}_{1}/\tilde{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell\ell\nu\nu \\ \tilde{g}\tilde{g}, \ \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{0}, \ \tilde{\chi}_{1}^{0} \rightarrow qqq \\ \\ \tilde{t}\tilde{t}, \ \tilde{t} \rightarrow \tilde{\ell}_{1}^{0}, \ \tilde{\chi}_{1}^{0} \rightarrow tbs \\ \tilde{t}_{1}\tilde{t}_{1}, \ \tilde{t}_{1} \rightarrow bs \\ \tilde{t}_{1}\tilde{t}_{1}, \ \tilde{t}_{1} \rightarrow q\ell \end{array} $	еµ,ет,µт 4 е,µ 4 2 е,µ 1 μ	0 jets 4-5 large- <i>R</i> je Multiple Multiple 2 jets + 2 <i>b</i> DV		3.2 36.1 36.1 36.1 36.7 36.7 36.1 136	$ \begin{split} \tilde{v}_{\tau} \\ \bar{\chi}_{1}^{\pm} / \bar{\chi}_{2}^{0} & [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0] \\ \bar{g} & [m(\tilde{\chi}_{1}^{0}) = 200 \text{ GeV}, 1100 \text{ GeV} \\ \bar{g} & [\lambda_{112}'' = 2e{-}4, 2e{-}5] \\ \bar{g} & [\lambda_{323}'' = 2e{-}4, 1e{-}2] \\ \tilde{\ell}_{1} & [qq, bs] \\ \bar{\ell}_{1} & [1e{-}10{-}\lambda_{31k}' = {-}8, 3e{-}1] \end{split} $	0.5	0.82 1.0 5 1.0 0.61 1.0	1.33 1.3 5	1.9 $\lambda'_{311} = 0.11, \ \lambda_{132/133/233} = 0$ $m(\tilde{\chi}^0_1) = 100 \ 0$ 1.9 Large 1 2.0 $m(\tilde{\chi}^0_1) = 200 \ \text{GeV}, \ \text{binom}$ $m(\tilde{\chi}^0_1) = 200 \ \text{GeV}, \ \text{binom}$ $m(\tilde{\chi}^0_1) = 200 \ \text{GeV}, \ \text{binom}$	GeV 1804.03602 λ_{112}'' 1804.03568 -like ATLAS-CONF-2018-003 -like ATLAS-CONF-2018-003 1710.07171 20% 1710.05544	
^t Only phen simp	a selection of the available mas omena is shown. Many of the li lified models, c.f. refs. for the as	s limits on imits are ba	new state ased on	s or		0 ⁻¹			@14	Mass scale [Te	V]	0.4-1.45 .0 1.6
											@	100 TeV

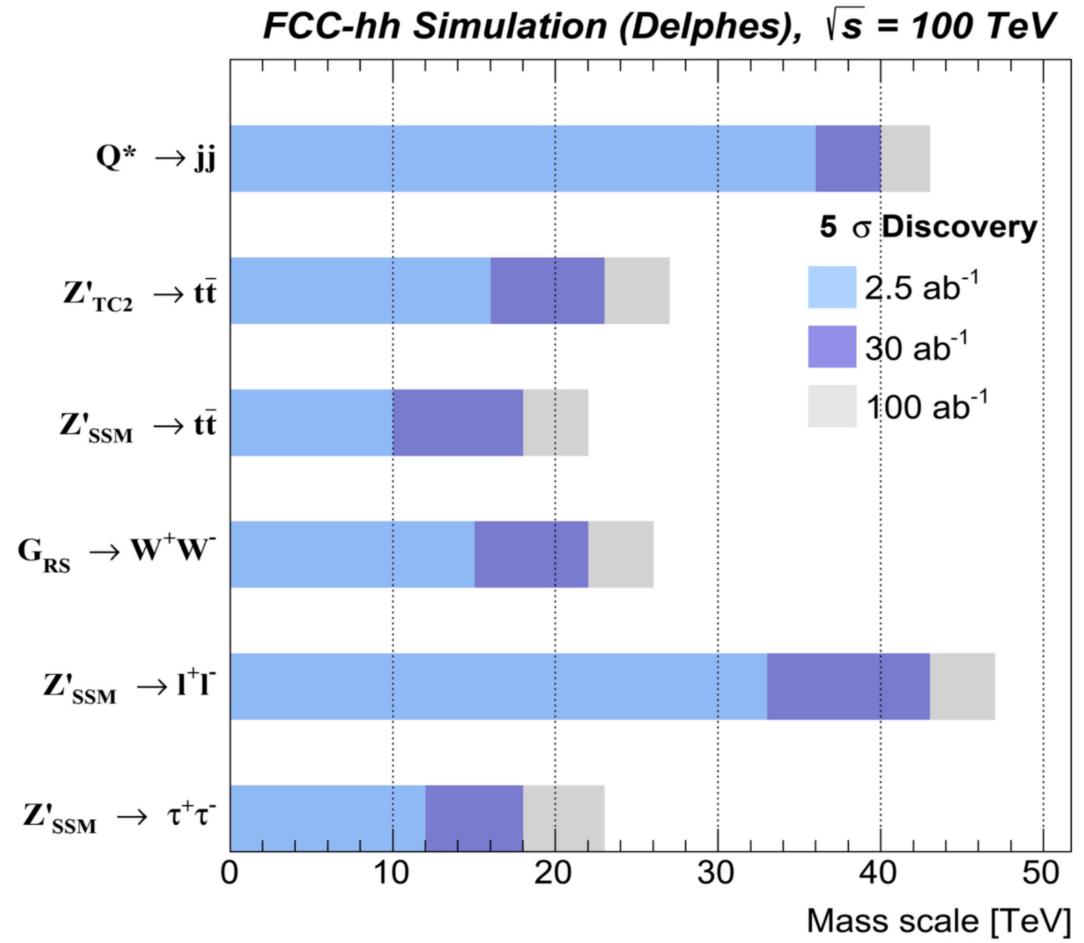
ATLAS Preliminary $\sqrt{s} = 13$ TeV

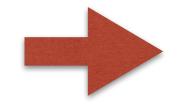
Global EFT fits to EW and H observables at FCC-ee



Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

s-channel resonances





100 TeV allow to directly access the mass scales revealed indirectly by precision EW and H measurements at the future e+e- factory

What more will come from FCC? Some examples

- Reduce by 5-10 the scale at which the elementary nature of quarks and leptons are tested Increase by 5-10 in mass the search for new fundamental forces
- Cover the full range of parameters for possible weakly interacting massive particles (WIMPs) as sources of dark matter
- Explore new scenarios for dark matter candidates (dark photons, axion like particles, ...)
- Countless studies of discovery potential for multiple BSM scenarios, from Supersymmetry to heavy neutrinos, from very low masses to very high masses, LLPs, DM, etcetcetc, with plenty of opportunities for direct discovery even at FCC-ee and FCC-eh
- Sensitivity studies to SM deviations in the properties of top quarks, flavour physics in Z decays: huge event rates offer unique opportunities, that cannot be matched elsewhere
- Operations with heavy ions: new domains open up at 100 TeV in the study of high-T/highdensity QCD. Broaden the targets, the deliverables, extend the base of potential users, and increase the support beyond the energy frontier community



