

সাহা ইনস্টিটিউট অফ নিউক্লিয়ার ফিজিক্স মাहা इंस्टिट्यूट ऑफ न्युक्लियर फिजिक्स Saha Institute of Nuclear Physics An Institution of Basic Research and Training in Physical and Biophysical Sciences under Dept. of Atomic Energy, Govt. of India

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Physics Prospects of Future circular Colliders

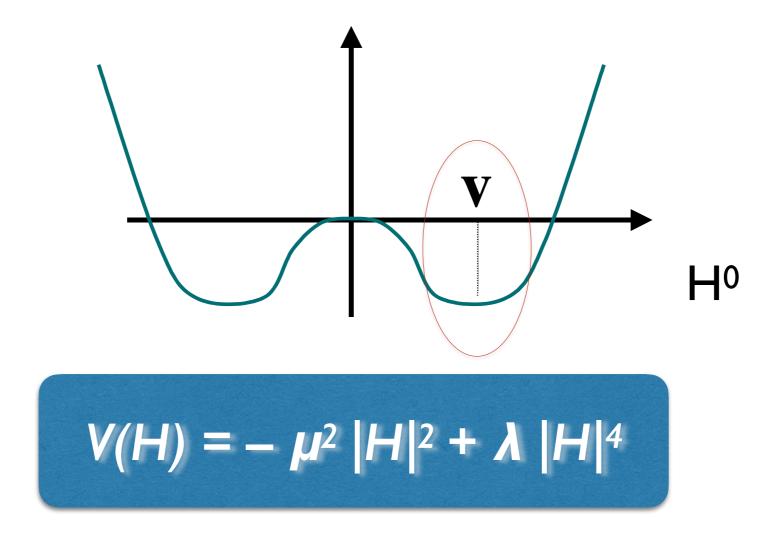
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For recent overviews of progress in the study of the FCC physics potential, see

- the Physics-Experiments-Detector sessions at the 2023 FCC week, https://indico.cern.ch/event/1202105/timetable/
- the presentations at the 2023 FCC Phenomenology Workshop, https://indico.cern.ch/event/1278845/timetable/

Of several opens questions in HEP (origin of DM, of neutrino masses, ...), one underlies our current understanding as embodied by the Standard Model, and can <u>only</u> be addressed by colliders Of several opens questions in HEP (origin of DM, of neutrino masses, ...), one underlies our current understanding as embodied by the Standard Model, and can <u>only</u> be addressed by colliders



Where does this come from?

a historical example: superconductivity

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

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- 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 we would still lack a deep understanding of the relevant dynamics.
- 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
 - EW symmetry breaking (and thus m_{H} and $\lambda)$ determined by the parameters of SUSY breaking

So far, no conclusive signal of physics beyond the SM

Model	ℓ , γ Jets† E_{T}^{mi}	^{ss} ∫£ dt[fb	¹] Limit	5	3.2 – 37.0) fb ⁻¹	Reference
ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH high $\sum p_T$ ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell v$ 2UED / RPP	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	36.7 37.0 3.2 3.6 36.7 s 36.1	M _D M _S M _{th} M _{th} M _{th} G _{KK} mass G _{KK} mass KK mass	7.75 TeV 8.6 TeV 8.9 TeV 8.2 TeV 9.55 TeV 4.1 TeV 1.75 TeV 1.6 TeV	n = 2 n = 3 HLZ NLO n = 6 $n = 6, M_D = 3 \text{ TeV, rot BH}$ $n = 6, M_D = 3 \text{ TeV, rot BH}$ $k/\overline{M}_{Pl} = 0.1$ $k/\overline{M}_{Pl} = 1.0$ Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	ATLAS-CONF-2017-06 CERN-EP-2017-132 1703.09217 1606.02265 1512.02586 CERN-EP-2017-132 ATLAS-CONF-2017-05 ATLAS-CONF-2016-10
SSM $Z' \rightarrow \ell \ell$ SSM $Z' \rightarrow \tau \tau$ Leptophobic $Z' \rightarrow bb$ Leptophobic $Z' \rightarrow tt$ SSM $W' \rightarrow \ell v$ HVT $V' \rightarrow WV \rightarrow qqqq$ mode HVT $V' \rightarrow WH/ZH$ model B LRSM $W'_R \rightarrow tb$ LRSM $W'_R \rightarrow tb$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	36.1 3.2 s 3.2 s 36.1 36.7 36.1 s 20.3	Z' mass Z' mass Z' mass W' mass V' mass V' mass V' mass W' mass W' mass	4.5 TeV 2.4 TeV 1 5 TeV 2.0 TeV 5.1 TeV 3.5 TeV 2.93 TeV 1.92 TeV 1.76 TeV	$\Gamma/m = 3\%$ $g_V = 3$ $g_V = 3$	ATLAS-CONF-2017-02 ATLAS-CONF-2017-02 1603.08791 ATLAS-CONF-2016-01 1706.04786 CERN-EP-2017-147 ATLAS-CONF-2017-05 1410.4103 1408.0886
Cl qqqq Cl llqq Cl uutt	$\begin{array}{cccc} - & 2 j & - \\ 2 e, \mu & - & - \\ 2 (SS) / \ge 3 e, \mu \ge 1 b, \ge 1 j & Yes \end{array}$	36.1	Λ Λ Λ	4.9 TeV	21.8 TeV η ⁻ _{LL} 40.1 TeV η ⁻ _{LL} C _{RR} = 1 Π	1703.09217 ATLAS-CONF-2017-02 1504.04605
Axial-vector mediator (Dirac DM) Vector mediator (Dirac DM) $VV_{\chi\chi}$ EFT (Dirac DM)		s 36.1	m _{med} 1. M _* 700 GeV	1 5 TeV 2 T • V	$\begin{array}{l} g_q {=} 0.25, g_\chi {=} 1.0, m(\chi) < 400 \; {\rm GeV} \\ g_q {=} 0.25, g_\chi {=} 1.0, m(\chi) < 480 \; {\rm GeV} \\ m(\chi) < 150 \; {\rm GeV} \end{array}$	ATLAS-CONF-2017-06 1704.03848 1608.02372
Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen	$\begin{array}{cccc} 2 \ e & \geq 2 \ j & - \\ 2 \ \mu & \geq 2 \ j & - \\ 1 \ e, \mu & \geq 1 \ b, \geq 3 \ j & \text{Yes} \end{array}$	3.2	LQ mass 1.1 LQ mass 1.05 1 LQ mass 640 GeV		$egin{array}{lll} eta = 1 \ eta = 1 \ eta = 1 \ eta = 0 \end{array}$	1605.06035 1605.06035 1508.04735
VLQ $TT \rightarrow Ht + X$ VLQ $TT \rightarrow Zt + X$ VLQ $TT \rightarrow Wb + X$ VLQ $BB \rightarrow Hb + X$ VLQ $BB \rightarrow Zb + X$ VLQ $BB \rightarrow Wt + X$ VLQ $QQ \rightarrow WqWq$	$\begin{array}{c c} 0 \text{ or } 1 e, \mu \geq 2 \text{ b}, \geq 3 \text{ j} & \text{Ye}; \\ 1 e, \mu \geq 1 \text{ b}, \geq 3 \text{ j} & \text{Ye}; \\ 1 e, \mu \geq 1 \text{ b}, \geq 1 \text{ J}/2 \text{ j} & \text{Ye}; \\ 1 e, \mu \geq 2 \text{ b}, \geq 3 \text{ j} & \text{Ye}; \\ 2/\geq 3 e, \mu \geq 2/\geq 1 \text{ b} & -1 \\ 1 e, \mu \geq 1 \text{ b}, \geq 1 \text{ J}/2 \text{ j} & \text{Ye}; \\ 1 e, \mu \geq 4 \text{ j} & \text{Ye}; \end{array}$	s 36.1 s 36.1 s 20.3 20.3 s 36.1	T mass 1.16 T mass 1 B mass 700 GeV B mass 790 GeV	2 T ₂ V Te V 35 TeV	$\begin{aligned} \mathcal{B}(T \to Ht) &= 1\\ \mathcal{B}(T \to Zt) &= 1\\ \mathcal{B}(T \to Wb) &= 1\\ \mathcal{B}(B \to Hb) &= 1\\ \mathcal{B}(B \to Zb) &= 1\\ \mathcal{B}(B \to Wt) &= 1 \end{aligned}$	ATLAS-CONF-2016-10- 1705.10751 CERN-EP-2017-094 1505.04306 1409.5500 CERN-EP-2017-094 1509.04261
Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited quark $b^* \rightarrow Wt$ Excited lepton ℓ^* Excited lepton ν^*	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	36.7 13.3	q* mass q* mass b* mass b* mass t* mass v* mass	6.0 TeV 5.3 TeV 2.3 TeV 1 5 TeV 3.0 TeV 1.6 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $f_g = f_L = f_R = 1$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	1703.09127 CERN-EP-2017-148 ATLAS-CONF-2016-06 1510.02664 1411.2921 1411.2921
LRSM Majorana v Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$ Monotop (non-res prod) Multi-charged particles Magnetic monopoles	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	36.1 20.3	Nº mass H ^{±±} mass 870 GeV H ^{±±} mass 400 GeV spin-1 invisible particle mass 657 GeV multi-charged particle mass 785 GeV monopole mass 1	2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing DY production DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ $a_{non-res} = 0.2$ DY production, $ q = 5e$ DY production, $ g = 1g_D$, spin 1/2	1506.06020 ATLAS-CONF-2017-05 1411.2921 1410.5404 1504.04188 1509.08059

†Small-radius (large-radius) jets are denoted by the letter j (J).

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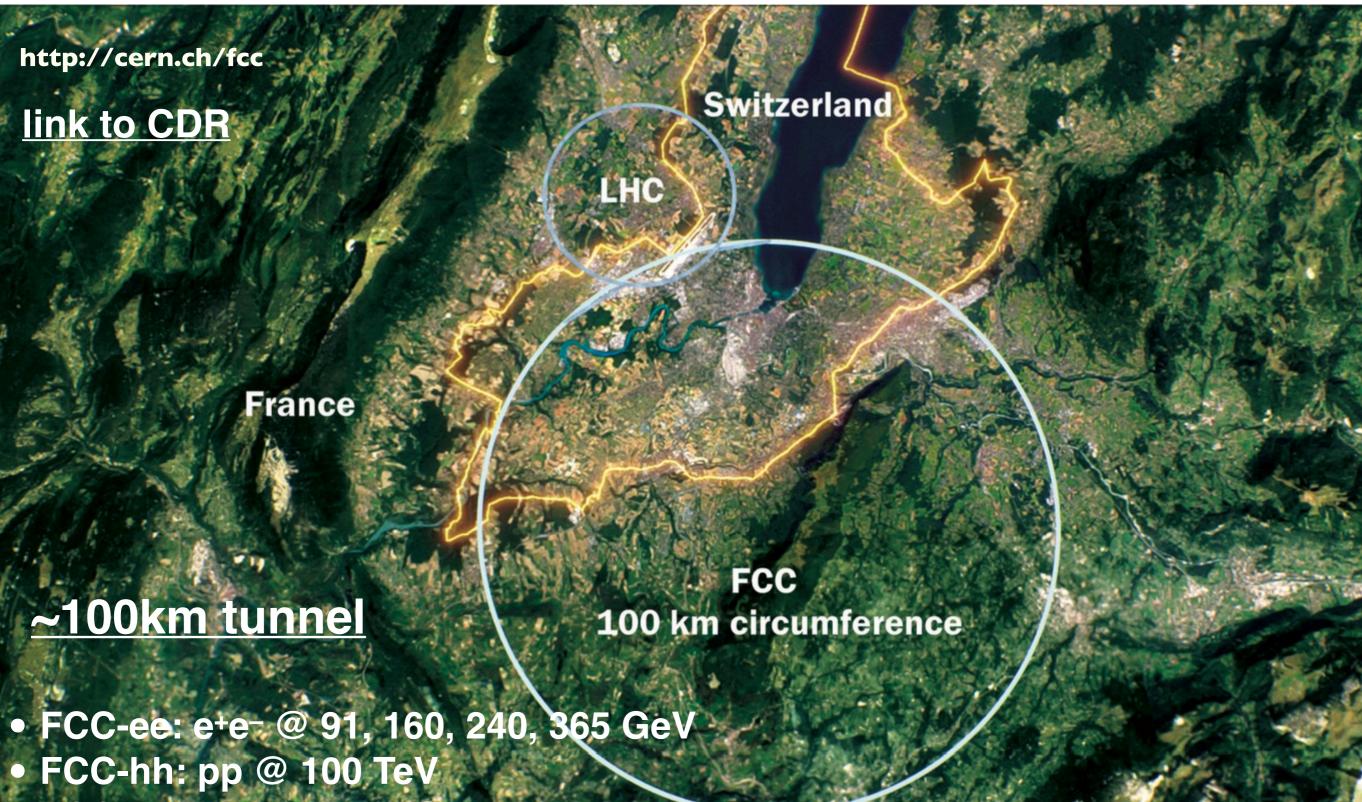
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These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:

- precision \Rightarrow higher statistics, better detectors and experimental conditions
- sensitivity (to elusive signatures) \Rightarrow ditto
- •extended energy/mass reach ⇒ higher energy

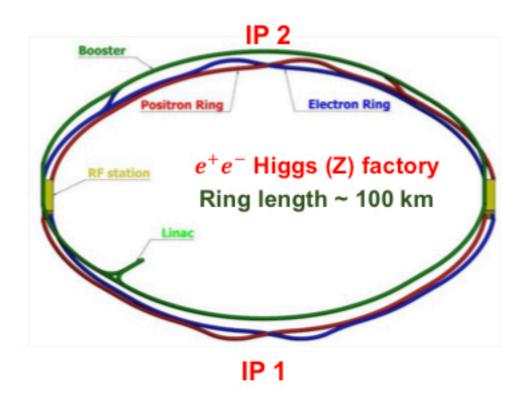
Future Circular Collider

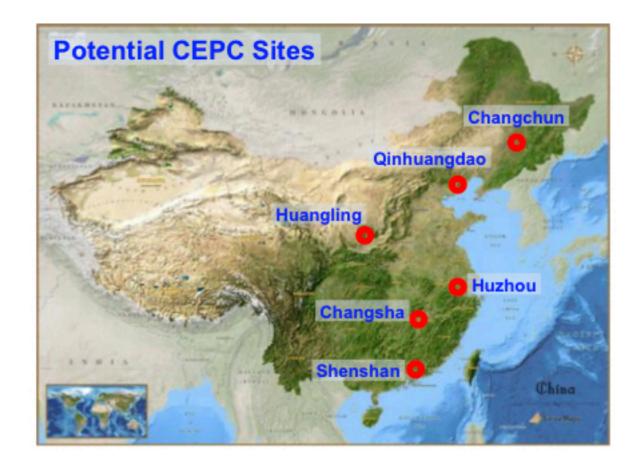


FCC-eh: ебодек ротек @ 3.5 ТеV

Circular electron-positron Collider

- □ The CEPC aims to start operation in 2030's, as a Higgs (Z / W) factory in China.
- □ To run at $\sqrt{s} \sim 240$ GeV, above the ZH production threshold for ≥1 M Higgs; at the Z pole for ~Tera Z; at the W⁺W⁻ pair and possible $t\bar{t}$ pair production thresholds.
- Higgs, EW, flavor physics & QCD, probes of physics BSM.
- □ Possible *pp* collider (SppC) of $\sqrt{s} \sim 50-100$ TeV in the far future.





link to CDR

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- <u>Provide firm Yes/No answers</u> 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?

(1) guaranteed deliverables: Higgs properties

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

	Model	$b\overline{b}$	$c\overline{c}$	gg	WW	au au	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [40]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD $[42]$	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD $[42]$	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD $[42]$	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [44]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity $[45]$	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
$\overline{7}$	Little Higgs w. T-parity $[46]$	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion $[47]$	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [48]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

5 – 10 %

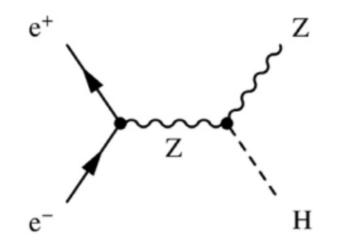
> 10%

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

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

The absolutely unique power of $e^+e^- \rightarrow ZH$ (circular or linear):

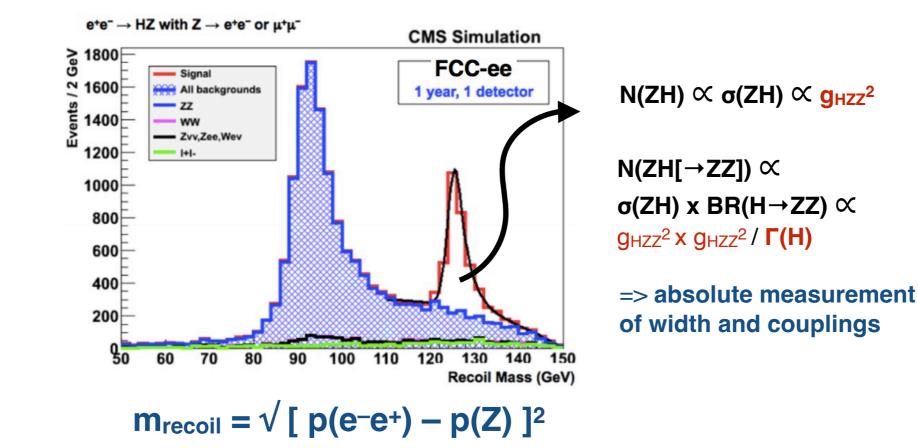
- the model independent absolute measurement of HZZ coupling, which allows the subsequent:
 - sub-% measurement of couplings to W, Z, b, τ
 - % measurement of couplings to gluon and charm



 $p(H) = p(e^-e^+) - p(Z)$

=> [p(e⁻e⁺) – p(Z)]² peaks at m²(H)

reconstruct Higgs events independently of the Higgs decay mode!



<u>The absolutely unique power of pp \rightarrow H+X:</u>

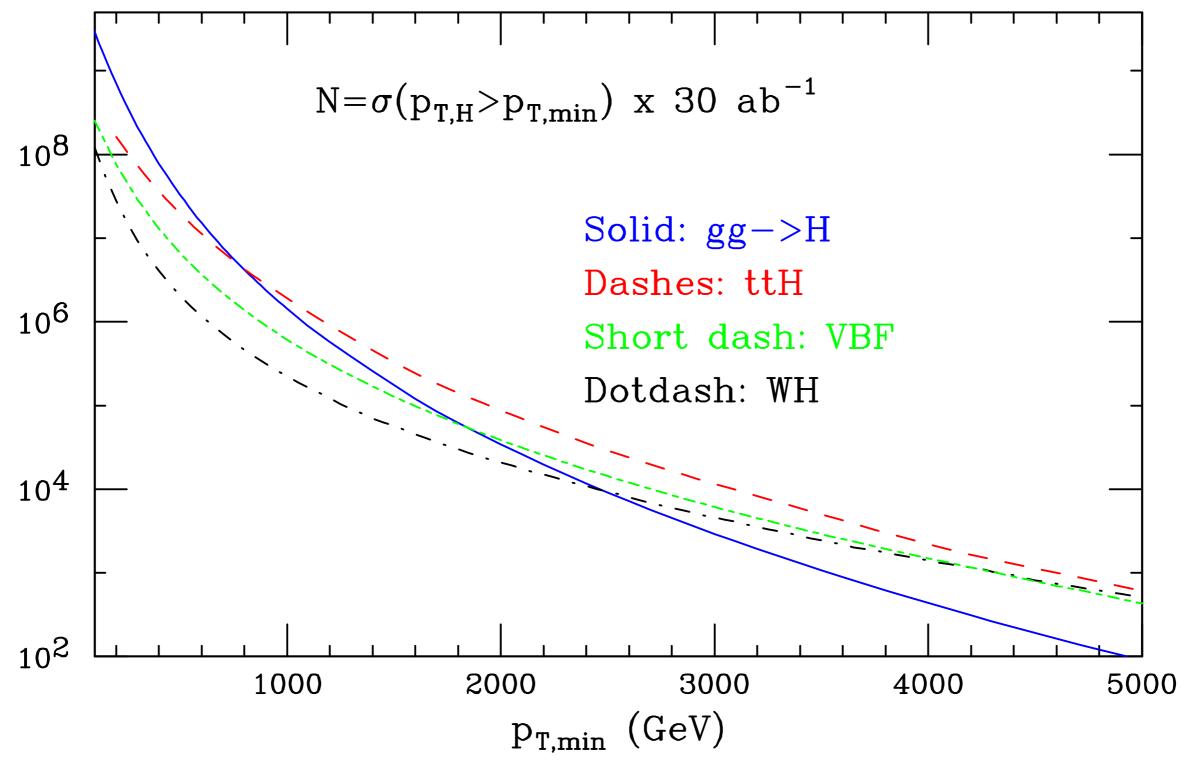
- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR(H \rightarrow ZZ*), allows
 - the sub-% measurement of rarer decay modes
 - the ~5% measurement of the Higgs trilinear selfcoupling
- the huge dynamic range (eg pt(H) up to several TeV), which allows to
 probe d>4 EFT operators up to scales of several TeV
 - search for multi-TeV resonances decaying to H, or extensions of the Higgs sector

	gg→H	VBF	WH	ZH	ttH	HH
N ₁₀₀	24 x 10 ⁹	2.1 x 10 ⁹	4.6 x 10 ⁸	3.3 x 10 ⁸	9.6 x 10 ⁸	3.6 x 10 ⁷
N100/N14	180	170	100	110	530	390

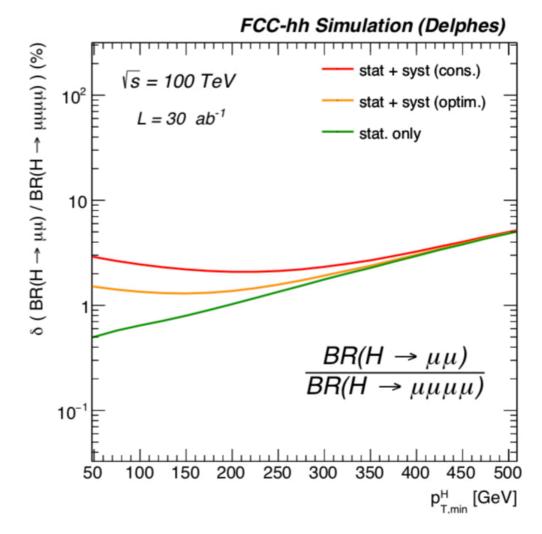
 $N_{100} = \sigma_{100 \text{ TeV}} \times 30 \text{ ab}^{-1}$

 $N_{14} = \sigma_{14 \text{ TeV}} \times 3 \text{ ab}^{-1}$

H at large рт

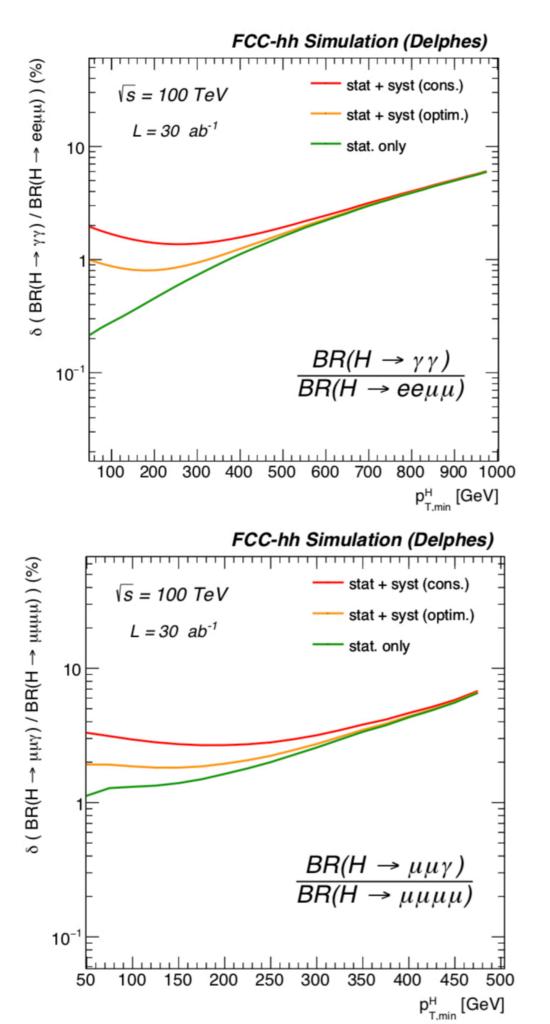


- Hierarchy of production channels changes at large p_T(H):
 - $\sigma(ttH) > \sigma(gg \rightarrow H)$ above 800 GeV
 - $\sigma(VBF) > \sigma(gg \rightarrow H)$ above [800 GeV



Normalize to BR(4I) from ee => sub-% precision for absolute couplings

Future work: explore in more depth data-based techniques, to <u>validate and</u> <u>then reduce</u> the systematics in these ratio measurements, possibly moving to lower pt's and higher stat

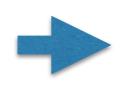


Higgs couplings after FCC-ee / hh

	HL-LHC	FCC-ee	FCC-hh
δΓΗ / ΓΗ (%)	SM	1.3	tbd
δg _{HZZ} / g _{HZZ} (%)	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
δg _{Hττ} / g _{Hττ} (%)	1.9	0.74	tbd
δg _{Hµµ} / g _{Hµµ} (%)	4.3	9.0	0.65 (*)
δд _{Нүү} / д _{Нүү} (%)	1.8	3.9	0.4 (*)
δg _{Htt} / g _{Htt} (%)	3.4	~10 (indirect)	0.95 (**)
δд _{HZγ} / g _{HZγ} (%)	9.8	—	0.9 (*)
бдннн / дннн (%)	50	~44 (indirect)	3.5
BR _{exo} (95%CL)	$BR_{inv} < 2.5\%$	< 1%	BR _{inv} < 0.025%

NB

BR(H→ZY,YY) ~O(10⁻³) ⇒ O(10⁷) evts for Δ_{stat} ~% BR(H→µµ) ~O(10⁻⁴) ⇒ O(10⁸) evts for Δ_{stat} ~%

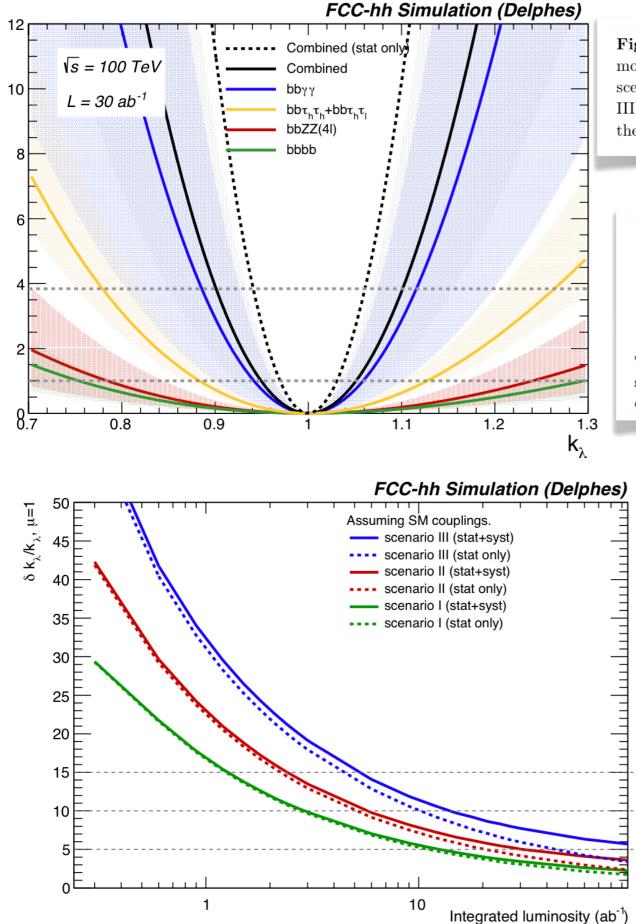


pp collider is essential to beat the % target, since no proposed ee collider can produce more than O(10⁶) H's

* 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

The Higgs self-coupling at FCC-hh https://arxiv.org/abs/2004.03505



-2∆ In L

Figure 13. Expected negative log-Likelihood scan as a function of the trilinear self-coupling modifier $\kappa_{\lambda} = \lambda_3 / \lambda_3^{\text{SM}}$ in all channels, and their combination. The solid line corresponds to the scenario II for systematic uncertainties. The band boundaries represent respectively scenario I and III. The dashed line represents the sensitivity obtained including statistical uncertainties only, under the assumptions of scenario I.

		Syst	scenarios	5
	@68% CL	scenario I	scenario II	scenario III
s	stat only	2.2	2.8	3.7
δ_{μ}	stat + syst	2.4	3.5	5.1
S	stat only	3.0	4.1	5.6
$\delta_{\kappa_{\lambda}}$	stat + syst	3.4	5.1	7.8

Table 7. Combined expected precision at 68% CL on the di-Higgs production cross- and Higgs self coupling using all channels at the FCC-hh with $\mathcal{L}_{int} = 30 \text{ ab}^{-1}$. The symmetrized value $\delta = (\delta^+ + \delta^-)/2$ is given in %.

- I. Target det performance: LHC Run 2 conditions
- II. Intermediate performance
- III. Conservative: extrapolated HL-LHC performance, with today's algo's (eg no timing, etc)

Expected precision on the Higgs self-coupling as a function of the integrated luminosity.

3-5 ab⁻¹ are sufficient to get below the 10% level

=> within the reach of the first 5yrs of FCC-hh running, in

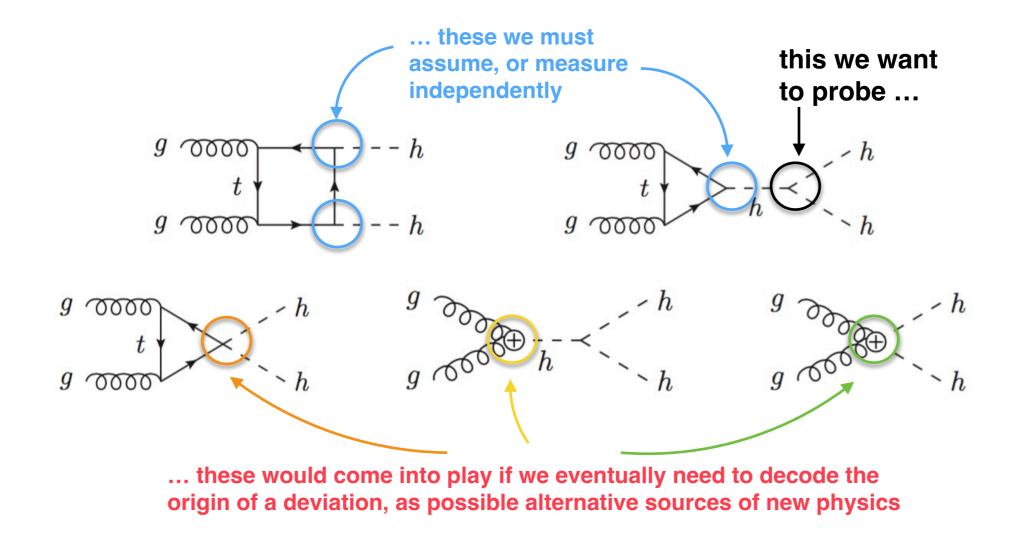
the <u>"low" luminosity / low pileup</u> phase

=> the 10% precision threshold can be reached within the timescale of a similar measurement by CLIC @ 3 TeV

Extracting Higgs self-coupling from HH at FCC:

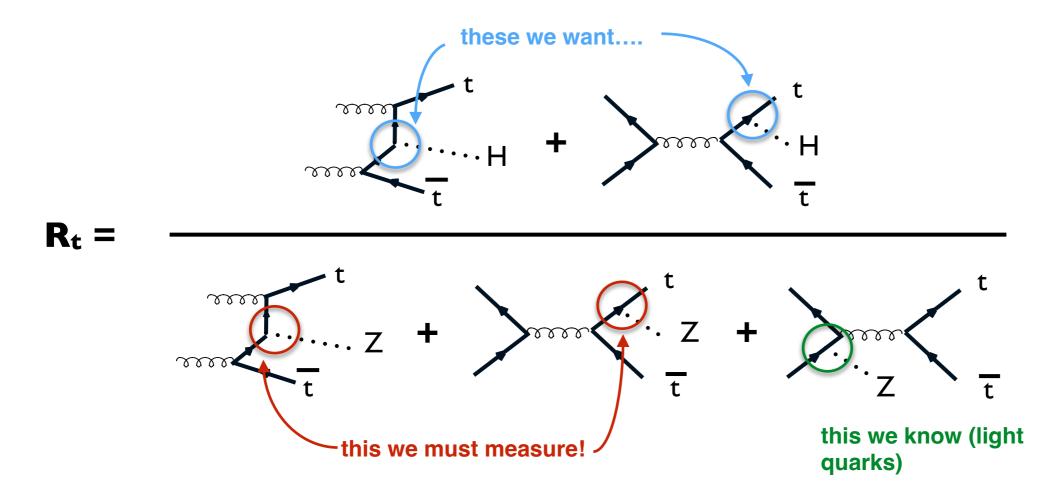
the power of ee/hh synergy & complementarity

At FCC-hh we can precisely measure HH rate ... but, to interpret this as H selfcoupling:



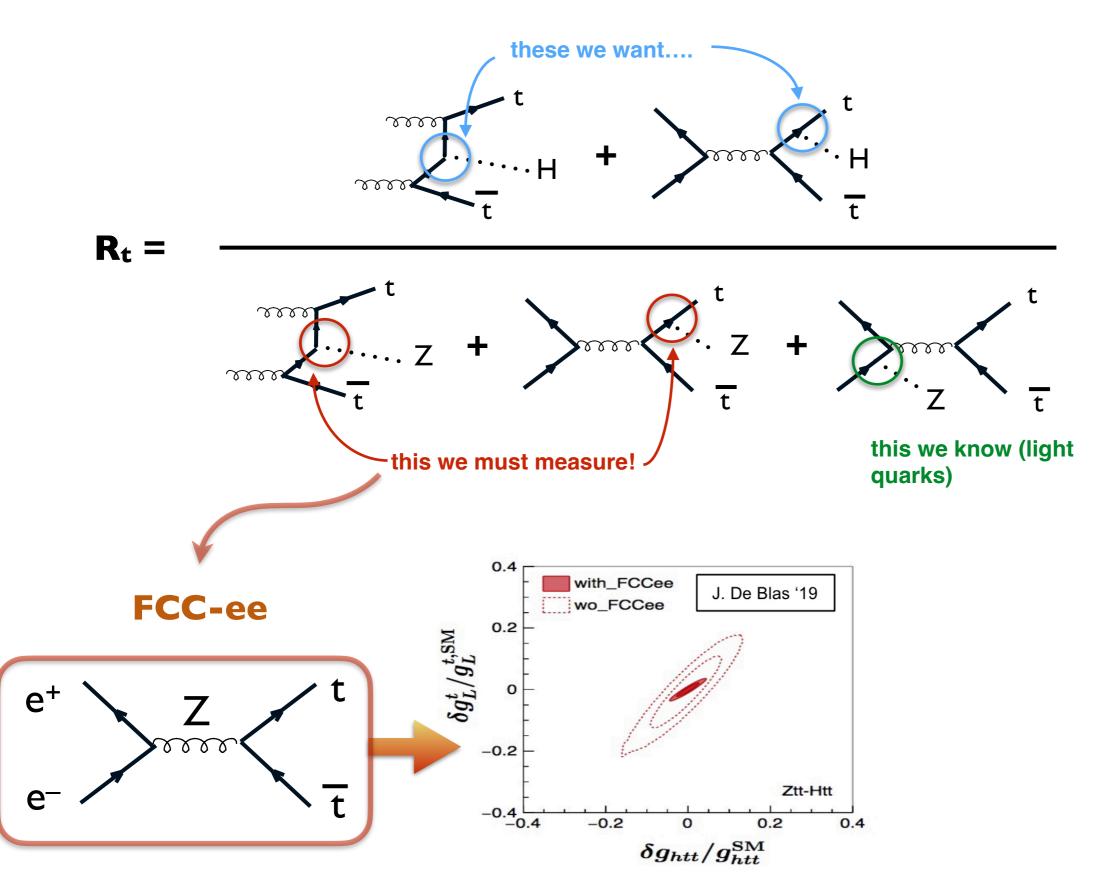
Direct measurement of ttH coupling: from $R_t = \sigma(ttH)/\sigma(ttZ)$

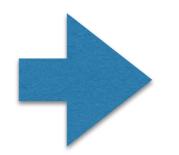
FCC-hh can measure R_t with $\Delta R_t/R_t < 2\%$ but:



Direct measurement of ttH coupling: from $R_t = \sigma(ttH)/\sigma(ttZ)$

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FCC-ee is a necessary pre-requisite to fully exploit the precision potential of FCC-hh

(1) guaranteed deliverables: EW&flavour observables

The absolutely unique power of **Circular** e⁺e⁻:

e+e- → Z	e+e- → WW	т(←Z)	b(←Z)	c(←Z)	e+e- → tt
5 10 ¹²	10 ⁸	3 10 ¹¹	1.5 10 ¹²	10 ¹²	10 ⁶

=> O(10⁵) larger statistics than LEP at the Z peak and WW threshold

Flavour statistics from Z decays:

S. Monteil, FCC PED Week 2023

Working point Lumi. /	IP $[10^{34} \text{ cm}^{-2}]$.	s ⁻¹] Total	lumi. (2 IP	s) Run t	ime	Physics go	al
Z first phase	100	26	ab^{-1} /year	2			
Z second phase	200	52	ab^{-1} /year	2		$150 {\rm ~ab^{-1}}$	
	0		0				
Particle production (10	⁹) B^0 / \overline{B}^0	$B^+ \ / \ B^-$	$B^0_s \ / \ \overline{B}^0_s$	$\Lambda_b \;/\; \overline{\Lambda}_b$	$c\overline{c}$	$ au^-/ au^+$	
Belle II	27.5	27.5	n/a	n/a	65	45	
FCC-ee	300	300	80	80	600	150	

Additional bonus wrt B factory: (i) Lorentz boost (ii) B hadrons not accessible at the Y(4S,5S) thresholds

EW param @ FCC-

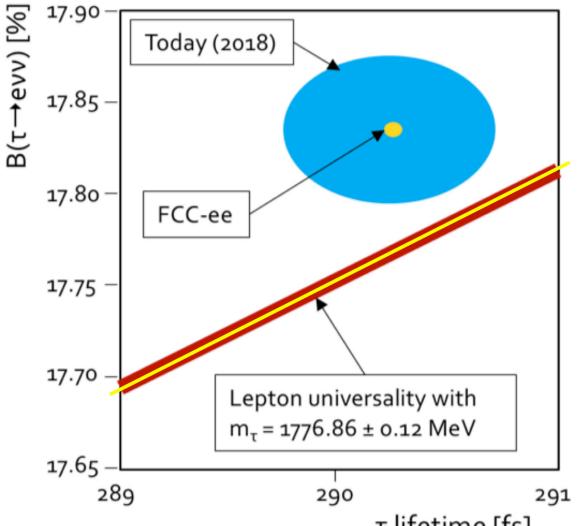
Improvement wrt curre uncertainties:

stat precision ~ 10-1 • with exptl syst ~ > 1

Currently limited by TH systematics => work ongoing

	Observable	present value ± error	FCC-ee stat.	FCC-ee syst.	:
W parameters	m _Z (keV)	91186700±2200	5	100	•
@ FCC-ee	$\Gamma_{\rm Z}$ (keV)	2495200±2300	8	100	•
	R_l^Z (×10 ³)	20767±25	0.06	0.2-1.0	·
	α_{s} (m _Z) (×10 ⁴)	1196±30	0.1	0.4-1.6	
	R_{b} (×10 ⁶)	216290±660	0.3	<60	·
	$\sigma_{\rm had}^{0}$ (×10 ³) (nb)	41541±37	0.1	4	
	N_{ν} (×10 ³)	2991±7	0.005	1	
provement wrt current total certainties:	$\sin^2 \theta_{W}^{eff}$ (×10 ⁶)	231480±160	3	2-5	•
	$1/\alpha_{QED}(m_Z)$ (×10 ³)	128952±14	4	Small	•
stat precision ~ 10-1000 smaller with exptl syst ~ > 10-50 smaller	$A_{\rm FB}^{b,0}$ (×10 ⁴)	992±16	0.02	1-3	•
	$A_{\rm FB}^{{\rm pol}, \tau}$ (×104)	1498±49	0.15	<2	,
<pre>irrently limited by TH stematics =></pre>	m _W (MeV)	80350±15	0.6	0.3	•
ork ongoing	$\Gamma_{\rm W}$ (MeV)	2085±42	1.5	0.3	-
	$\alpha_s (m_W) (\times 10^4)$	1170±420	3	Small	
	$N_{\nu}(\times 10^3)$	2920±50	0.8	Small	
	m _{top} (MeV)	172740±500	20	Small	;
	$\Gamma_{\rm top}$ (MeV)	1410±190	40	Small	
	$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2±0.3	0.08	Small	
crucial for ttH and HHH couplings at FCC-hh	ttZ couplings	±30%	▶ 0.5 – 1.5%	Small	-

Flavour probes: eg lepton universality in tau decays



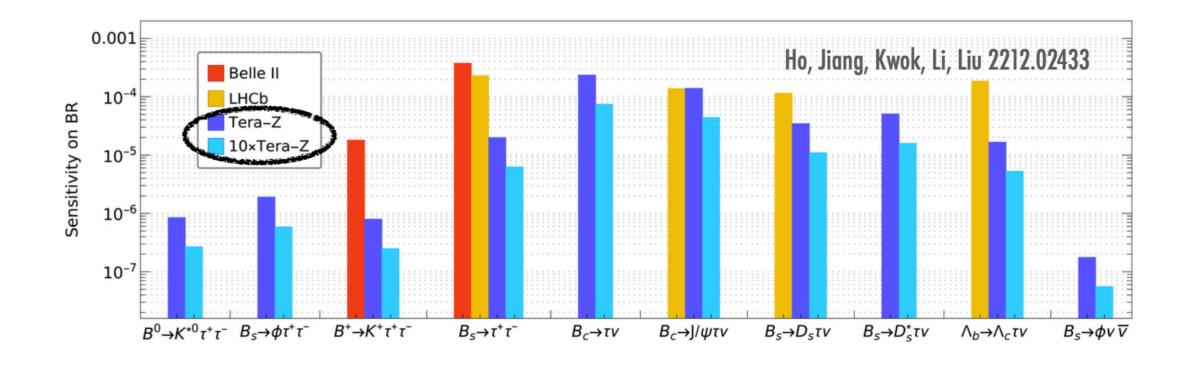
Lorentz boost crucial!

τ lifetime [fs]

[Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
	m _τ [MeV]	Threshold / inv. mass endpoint	1776.86 ± 0.12	0.004	0,04-0,1	Mass scale
	→ τ _τ [fs]	Flight distance	290.3 ± 0.5 fs	0.001	0.04	Vertex detector alignment
	Β(τ→evv) [%]	Selection of τ⁺τ , identification of final	17.82 ± 0.05	0.0001	0.000	Efficiency, bkg,
	Β(τ→μνν) [%]	state	17.39 ± 0.05	0.0001	0.003	Particle ID

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For details about the potential of the flavour programme at the Z pole, see Jernej's <u>overview</u> at the 2023 FCC week

Flavour Programme Jernej F. Kamenik

- 1 Leptonic and semileptonic b decays
- 2 Rare leptonic and semileptonic b decays
- 3 CPV in b decays and mixing
- 4 Tau physics
- 5 Charm physics
- 6 Flavour @ high-pT

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

ATLAS Preliminary

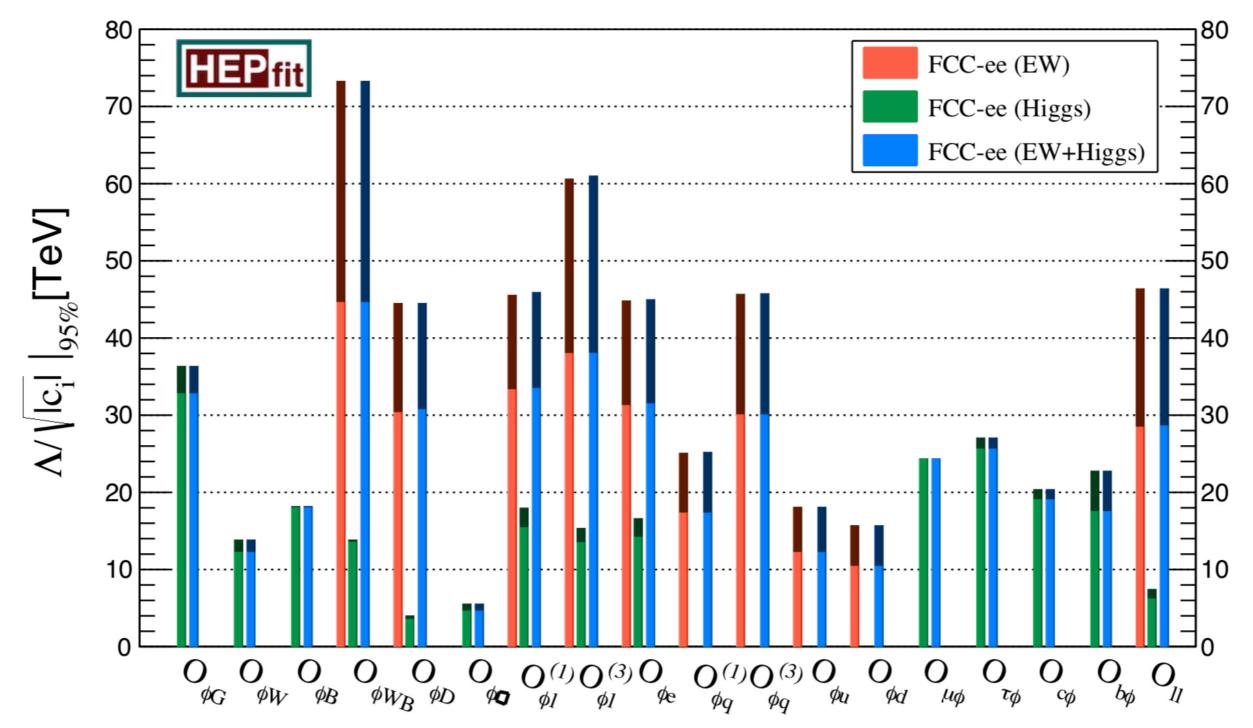
ATLAS SUSY Searches* - 95% CL Lower Limits

$ \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 $	March 2019 Model		Signatur	re l	<i>L dt</i> [fb⁻	1 Mass I	imit				$\sqrt{s} = 13 \text{ TeV}$ Reference
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	$ \begin{bmatrix} y \\ y \\ y \\ z \\$	$ \begin{aligned} $			•			· · ·					
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	$ \begin{bmatrix} 0 & 0 & -0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 $	Model Model Solution			2-6 jets 1-3 jets	E_T^{mass} E_T^{miss}	36.1 36.1		0.43 0.71	0.9 1.5	55	$m(\tilde{\chi}_{1}^{0}) < 100 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{\chi}_{1}^{0}) = 5 \text{ GeV}$	
$ \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 $	$k_{1}^{2} + a_{1}^{2}, \qquad (1)_{2}^{2} + a_{1}^{2}, a_{2}^{2}, a_{3}^{2}, a_{4}^{2}, a_{$	ĝġ, ğ→qq̄χ̃ ⁰	0 e,µ	2-6 jets		36.1	15c 100	Forbio	den 0.95-			
$ \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{bmatrix} b_{1} + a_{1}, & b_{1} + a_{2}, & b_{2} + b_{2} \\ b_{1} + a_{2}, & b_{2} + b_{2} \\ b_{1} + b_{2} + b_{2} + b_{1} \\ b_{1} + b_{2} + b_{1} + b_{2} \\ b_{1} + b_{2} + b_{1} + b_{2} \\ b_{1} + b_{2} + b_{2} + b_{1} \\ b_{1} + b_{2} + b_{1} + b_{2} \\ b_{1} + b_{2} + b_{2} + b_{1} \\ b_{1} $	$ \underbrace{\widetilde{\mathcal{G}}}_{\mathbf{Q}} \qquad \widetilde{g}_{\tilde{g}}, \check{g} \rightarrow q \bar{q}(\ell \ell) \check{\chi}_{1}^{0} $	З е,µ ее,µµ		$E_T^{ m miss}$		ישלי		1.2	1.85	m(ℓ̃ ₁)<800 GeV m(ĝ)-m(ℓ̃ ₁)=50 GeV	
$ \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{bmatrix} b_{1} + m_{1}^{2} & 0 & 0 & 0 \\ b_{1} + b_{1} + b_{2} + b_{2}^{2} & b_{2}^{2} & 0 \\ b_{1} + b_{2} + b_{2}^{2} & b_{2}^{2} & b_{2}^{2} & b_{2}^{2} \\ b_{1} + b_{2} + b_{2}^{2} & b_{2}^{2} & b_{2}^{2} & b_{2}^{2} \\ b_{1} + b_{2} + b_{2}^{2} + b_{2}^{2} & b_{1}^{2} & b_{2}^{2} & b_{2}^{2} & b_{2}^{2} \\ b_{1} + b_{2} + b_{2}^{2} + b_{2}^{2} & b_{1}^{2} & b_{2}^{2} & b_{2}^{2} & b_{1}^{2} \\ b_{1} + b_{1} + b_{1} + b_{2} + b_{2}^{2} & b_{2}^{2} & b_{1}^{2} & b$	$\tilde{g}_{\tilde{g}_{1}}$ $\tilde{g}_{\tilde{g}_{1}}$ $\tilde{g} \rightarrow q q W Z \hat{\chi}_{1}^{0}$	3 e,µ		$E_T^{\rm miss}$		100 YBC		0.98	1.8		
$ \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$	$\tilde{g}\tilde{g}, \tilde{g} \to t\bar{t}\tilde{\chi}_{1}^{(i)}$	0-1 e,μ 3 e,μ		E_T^{miss}		150 100		1.25	2.25	m(𝔅̃_1)<200 GeV m(𝔅)-m(𝔅̃_1)=300 GeV	
$ \begin{bmatrix} k \\ k$	$ \frac{1}{2} 1$	$ \frac{1}{2} \frac{1}{2} \int_{0}^{1} \int_{0}^{$	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 ightarrow b \tilde{\chi}_1^{1} / t \tilde{\chi}_1^{-}$		Multiple		36.1	δ ₁ For			$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\chi}_1^0)=200$ G	300 GeV, BR(bữ̃)=BR(tữ̃)=0.5	1708.09266
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	$ \begin{bmatrix} 5 \\ 1, 0, 1, 1, 1, 0, 0, 1 \\ 1, 1, 1, 1, 1, 0, 1, 1, 1, 0, 0, 1 \\ 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, $	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^{II} \rightarrow b h \tilde{\chi}_1^{II}$	0 e,µ	6 <i>b</i>	E_T^{miss}	139		23-0.48	0.23-1.35	$\Delta m \langle \tilde{\chi}_2^0 \rangle$	$(\tilde{\chi}_{1}^{0})=130 \text{ GeV}, m(\tilde{\chi}_{1}^{0})=100 \text{ GeV}$ $(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0})=130 \text{ GeV}, m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$	
$ \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 &$	$ \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 &$	$ \begin{bmatrix} 0 & 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1$	$\tilde{t}_1 \tilde{t}_1, Well-Tempered LSP$		Multiple		36.1	ζ ₁ ζ ₁	0.48-0.4	4	m($ar{k}_1^0$)=150 G	ieV, m $(\tilde{\chi}_1^1)$ -m $(\tilde{\chi}_1^0)$ =5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
$\frac{1}{2} \frac{1}{2}, \frac{1}{2}, -\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{2}, \frac{1}{4}, \frac$	$\frac{k_{1}^{2}k_{1}^{2}-k_{1}^{2}+k_{1}^{2}+k_{2}^{2}+k_{2}^{2}}{k_{1}^{2}} = \frac{k_{1}^{2}}{k_{1}^{2}} = \frac{k_{1}^{2}}{k_{1}^$	$ \frac{i_{1}i_{2}i_{2}-i_{1}+h}{i_{1}+h} = \frac{1-2 \iota_{\mu}}{4} + \frac{4}{h} + \frac{h^{2m}}{4} = 3.61 \frac{1}{4} = \frac{0.322438}{0.322438} $ $ \frac{\pi i_{1}i_{2}^{2} - (0.4 \vee m i_{2}) + m i_{1}^{2} - (1.6 \vee m i_{2}) + m i_{1}^{2} + m i_{2}^{2} + m i_{3}^{2} + $	$[\mathbf{u}]$ $[\mathbf{u}], [\mathbf{u}] \rightarrow \mathbf{u}$ $[\mathbf{u}], [\mathbf{u}] \rightarrow \mathbf{u}$	0 e,µ	2 c	$E_T^{\rm miss}$	36.1	<i>t</i> ₁ ē <i>τ</i> ₁	0.46			$m(\tilde{t}_1^0)=0 \text{ GeV}$ $m(\tilde{t}_1,\tilde{c})-m(\tilde{t}_1^0)=50 \text{ GeV}$	1805.01649 1805.01649
$ \begin{split} \tilde{\chi}_{1}^{2} \tilde{\chi}_{2}^{2} \eta \text{ arg} Z & \frac{2.3 c_{\mu}}{c_{\tau,\mu\mu}} & \frac{E_{\tau}^{2} \text{ in}}{E_{\tau}^{4} \text{ in}} & \frac{6.1}{2} & \frac{E_{\tau}^{2} \text{ in}}{E_{\tau}^{4} \text{ in}} & \frac{6.1}{30.1} & \frac{1}{E_{\tau}^{4} \text{ in}} & \frac{6.1}{30.1} & \frac{1}{E_{\tau}^{4} \text{ in}} & \frac{6.1}{30.1} & \frac{1}{E_{\tau}^{4} \text{ in}} & \frac{6.1}{30.2} & \frac{1}{2} & \frac{6.1}{30.1} & \frac{1}{E_{\tau}^{4} \text{ in}} & \frac{6.1}{30.2} & \frac{1}{2} & \frac{6.1}{30.1} & \frac{1}{E_{\tau}^{4} \text{ in}} & \frac{6.1}{30.1} & \frac{1}{E_{\tau}^{4} \text{ in}} & \frac{6.1}{30.2} & \frac{1}{2} & \frac{6.1}{30.1} & \frac{6.1}{2} & \frac{1}{2} & \frac{6.1}{30.1} & \frac{6.1}{30.15} & \frac{1}{2} & \frac{6.1}{30.15} & \frac{6.1}{30.15} & \frac{1}{30.15} & \frac{1}{30.15}$	$ \begin{split} \tilde{k}_{1}^{2} \tilde{k}_{2}^{2} \sqrt{n} WZ & \frac{23}{c_{\mu}} \sum_{\substack{c_{\mu}, \mu}} E_{\mu}^{2m} & 36.1 \\ \tilde{k}_{1}^{2} \tilde{k}_{2}^{2} 0.17 \\ \tilde{k}_{1}^{2} \tilde{k}_{1}^{2} \sqrt{n} WV & 2.c_{\mu} \\ \tilde{k}_{1}^{2} \sqrt{n} WV & 2.c_{\mu} \\ \tilde{k}_{1}^{2} \sqrt{n} WV & 2.c_{\mu} \\ \tilde{k}_{1}^{2} \tilde{k}$	$ \hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \text{ vi } \text{WZ} $ $ \hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \text{vi } \text{WZ} $ $ \hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \text{WZ} $ $ \hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \text{WZ} $ $ \hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \frac{\hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \frac{\hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \frac{\hat{k}_{1}^{+1} \hat{k}_{1}^{+1} \hat{k}_{1}^$	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	-	-	-				88	$m(\tilde{\chi}_1^0)$		
$ \frac{1}{2} 1$	$ \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 $	$ ilde{\chi}_1^- ilde{\chi}_2^0$ via WZ		>1			$\bar{\chi}_{1}^{\pm}/\bar{\chi}_{2}^{0}$ $\bar{\chi}_{-}^{\pm}/\bar{\chi}_{-}^{0}$ 0.17	0.6			$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\chi}_1^0)=10$ GeV	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{split} & \int_{1}^{\infty} $	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{2}^{0}$ via Wh	2 e,μ 0 -1 e,μ		E_T^{miss} E_T^{miss}	139 36.1	$ar{\chi}_1^{\pm}$ 0 $ar{\chi}_1^{\pm}/ar{\chi}_2^0$				$m(\bar{k}_{1}^{(i)})=0$ $m(\bar{k}_{1}^{(i)})=0$	ATLAS-CONF-2019-008 1812.09432
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{4 e, \mu} = 0 \text{ jets } E_T^{\frac{1}{2} \text{ is } 36.1} \\ \frac{\hat{H}}{R} = 0.3 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{0.3} = 0.29 \cdot 0.88 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/X\hat{G}}{BR(t_1^2 \rightarrow X\hat{G})^{-1}} = 1 \\ \frac{\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{H}, \hat{H} \rightarrow h\hat{H} \rightarrow h\hat{H}$	$\frac{\hat{n}\hat{n}, \hat{n} \rightarrow k_{0}^{2}/\hat{C}^{2}}{4 e, \mu} = \frac{2}{9} \frac{1}{9} \frac{k_{1}}{k_{1}}^{\frac{\mu}{\mu}} = \frac{3}{9} \frac{k_{2}}{k_{1}}^{\frac{\mu}{\mu}} = \frac{3}{9} \frac{k_{2}}{k_{1}}^{\frac{\mu}{\mu}} = \frac{3}{9} \frac{1}{9} \frac{k_{2}}{k_{1}}^{\frac{\mu}{\mu}} = \frac{3}{9} \frac{1}{9} 1$	$\begin{array}{c} \chi_1\chi_1 \text{ via } \ell_L/\tilde{\nu} \\ \chi_1\chi_1^- \tilde{\chi}_1^- \tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow \tilde{\tau}_1 \nu(\tau \tilde{\nu}), \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau(\nu \tilde{\nu}) \\ \chi_1^- \tilde{\chi}_1^- \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}_1 \tau(\nu \tilde{\nu}), \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau(\nu \tilde{\nu}) \end{array}$			E_T^{miss} E_T^{miss}			0.76	1.0	$\mathfrak{m}(\tilde{\chi}_{1}^{+})-\mathfrak{m}(\tilde{\chi}_{1}^{0})=100$	$\tilde{\chi}_{1}^{0} = 0, m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_{1}^{-}) + m(\tilde{\chi}_{1}^{0}))$	1708.07875
$ \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 $	Direct $\tilde{\chi}_{1}^{*} \tilde{\chi}_{1}^{*}$ prod., long-lived $\tilde{\chi}_{1}^{*}$ Disapp. trk 1 jet E_{T}^{*ives} 36.1 $\tilde{\chi}_{1}^{*}$ 0.15 Pure Higgsino ATL-PHYS-PUB-2017-019 Stable \tilde{g} R-hadron Multiple 36.1 \tilde{g} $\tilde{r}(\tilde{g}) = 10 \text{ ns. } 0.2 \text{ ns}$ 2.0 1902.01636,1908.04095 1902.01636,1908.04095 LFV $pp - \tilde{v}_{r}, k, \tilde{v}_{r} \rightarrow qp/\xi^{0}$ Multiple 36.1 \tilde{g} $\tilde{r}(\tilde{g}) = 10 \text{ ns. } 0.2 \text{ ns}$ 2.0 1.9 $d_{2,11}^{*}=0.11, d_{1,21,212,20}=0.07$ 1607.08079 $\tilde{\chi}_{1}^{*} \tilde{\chi}_{1}^{*} \tilde{\chi}_{0}^{*} \rightarrow qqq$ q, ℓ, ℓ, η 0 \tilde{g} $\tilde{r}(\tilde{g}) = 0.0 \text{ col} / 1.02 \text{ col} / 1.33$ $m(\tilde{\ell}_{1}^{*}) = 0.0 \text{ GeV}$ 1804.03560 $\tilde{\chi}_{1}^{*} \tilde{\chi}_{1}^{*} \tilde{\chi}_{1}^{*} qqq$ $4-5$ \tilde{g} $[m(\tilde{\chi}_{1}^{*}) = 200 \text{ GeV} / 1100 \text{ GeV}]$ 1.3 1.9 Large $A_{1,2}^{*}$ 1804.03568 $\tilde{\chi}_{1}^{*} - \chi_{1}^{*} \tilde{\chi}_{1}^{*} q \rightarrow dpq$ $4-5$ \tilde{g} $[m(\tilde{\chi}_{1}^{*}) = 0.65]$ 0.65 0.64 $m(\tilde{\chi}_{1}^{*}) = 200 \text{ GeV} / 100 \text{ GeV}$ 1804.03568 $\tilde{\chi}_{1}^{*} - \chi_{1}^{*} \tilde{\chi}_{1}^{*} q \rightarrow dpq$ $4-5$ \tilde{g} \tilde{g} $m(\tilde{\chi}_{1}^{*}) = 0.65$ 0.65 0.64 $m(\tilde{\chi}_{1}^{*}) = 200 Ge$	$\tilde{\ell}_{1,\mathbf{R}}\tilde{\ell}_{1,\mathbf{R}},\tilde{\ell}{\rightarrow}\ell\tilde{\chi}_{1}^{0}$			E_T^{miss} E_T^{miss}		ℓ ℓ 0.18	0.7			$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\ell})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$	
Stable \check{g} R-hadron, $\check{g} \rightarrow qq\check{\chi}_{1}^{0}$ Multiple 36.1 \check{x} 2.0 1902.01636,1808.04095 Metastable \check{g} R-hadron, $\check{g} \rightarrow qq\check{\chi}_{1}^{0}$ Multiple 36.1 \check{x} \check{x} 2.05 2.4 $m(\check{\chi}_{1}^{0})=100$ GeV 1710.04901,1808.04095 LFV $pp \rightarrow \check{v}_{\tau} + X, \check{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$ $e\mu, e\tau, \mu\tau$ 3.2 \check{v}_{τ} \check{v}_{τ} 1.9 $\mathscr{L}_{311}=0.11, \mathscr{L}_{122/13/233}=0.07$ 1607.08079 $\check{\chi}_{1}\check{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell vv$ $4 e, \mu$ 0 jets E_{T}^{mins} 36.1 $\check{\chi}_{1}^{i}\check{\chi}_{2}^{0}$ $I_{433} \neq 0, \mathscr{L}_{123} \neq 0$ 0.82 1.3 1.9 Large \mathscr{A}_{112} 1804.03602 $\check{g}_{\tilde{S}, \tilde{S} \rightarrow qq}\check{q}_{1}^{0}, \check{\chi}_{1}^{0} \rightarrow dpq$ $\mathcal{M}_{12}=2e-4, 2e-5$ 1.05 2.0 $m(\check{\chi}_{1}^{0})=200$ GeV, bino-like ATLAS-CONF-2018-003 $\check{g}_{1}\check{\chi}_{1}\check{\chi}_{1}\check{\chi}_{2}^{0} \rightarrow dps$ $Multiple$ 36.1 $\check{g}_{1}(\check{\chi}_{23}=2e-4, 1e-2)$ 0.55 1.05 $m(\check{\chi}_{1}^{0})=200$ GeV, bino-like ATLAS-CONF-2018-003 $\check{g}_{1}\check{\chi}_{1}\check{\chi}_{1}\check{\chi}_{2} = jes + 2b$ 36.7 $\check{f}_{1}(g, bs)$ 0.422 0.61 $0.421, 45$ 0.422 0.61 $0.42, 40.61$ $0.421, 45$ $0.421, 45$ <t< td=""><td>Definition Multiple 36.1 \bar{x} 2.0 1992.01836,1808.04095 Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_{10}^{0}$ Multiple 36.1 \bar{x} $(\bar{x}_{1}) = 10 \text{ ns. } 0.2 \text{ ns}$ 2.0 2.0 2.4 $m(\tilde{\chi}_{1}^{0}) = 100 \text{ ev}$ 1992.01836,1808.04095 LFV $pp \rightarrow \tilde{v}_{r} + X, \tilde{v}_{r} \rightarrow e\mu/er/\mu \tau$ $e\mu,er,\mu \tau$ 3.2 \bar{v}_{τ} \bar{v}_{τ} 1.9 $A'_{211}=0.11, A_{122(157238}=0.07)$ 1607.08079 $\tilde{\chi}_{1}^{-} \chi_{1}^{0} \tilde{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell er/\mu \tau$ $e_{\mu}\mu$ 0 jets E_{μ}^{mins} 36.1 $\tilde{\kappa}_{1}^{+} \chi_{2}^{+} = 0.00 \text{ ceV}$ 1.3 1.9 Large A'_{112} 1804.03568 $\tilde{\chi}_{1}^{-} \chi_{1}^{0} \tilde{\chi}_{1}^{0} \rightarrow dpq$ $A^{+5}_{1} \text{ large-} R$ jets 36.1 $\tilde{\kappa}_{1}^{+} (\chi_{12}^{-} = 2e-4, 2e-5]$ 1.05 2.0 $m(\tilde{\chi}_{1}^{0}) = 200 \text{ GeV}, \text{ bin-like}$ ATLAS-CONF-2018-003 $\tilde{\pi}_{1}^{-} \chi_{1}^{-} \chi_{1}^{0} \rightarrow dps$ $Multiple$ 36.1 $\tilde{\kappa}_{1}^{+} (\chi_{12}^{-} = 2e-4, 2e-5]$ 0.55 1.05 $m(\tilde{\chi}_{1}^{0}) = 200 \text{ GeV}, \text{ bin-like}$ ATLAS-CONF-2018-003 ATLAS-CONF-2018-003 ATLAS-CONF-2018-003 ATLAS-CONF-2018-003 ATLAS-CONF-2018-003 ATLAS-CONF-2018-003 ATLAS-CONF-2018-003 ATLAS-CONF-2018-003 ATLAS-CONF-201</td><td>p_{10}^{0} Stable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_{1}^{0}$ Multiple 36.1 \tilde{k} 2.0 1902.01636,1808.04095 Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_{1}^{0}$ Multiple 36.1 \tilde{k} 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$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	$ \tilde{\chi}_{1}^{-} \tilde{\chi}_{1}^{-} \tilde{\chi}_{1}^{0} \rightarrow qqq $ $ \tilde{\chi}_{1}^{-} \tilde{\chi}_{1}^{0} \tilde$	$\tilde{\chi}_{1}\tilde{\chi}_{1}/\tilde{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell\nu\nu \qquad 4 e,\mu \qquad 0 \text{ jets } E_{T}^{min} \qquad 36.1 \\ \tilde{\chi}_{1}^{*}/\tilde{\chi}_{2}^{0} \left[4x_{3} \neq 0, 4x_{4} \neq 0 \right] \qquad 0.82 \qquad 1.33 \qquad m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV} \\ \tilde{g}_{3}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qqq \qquad 4 e,\mu \qquad 0 \text{ jets } E_{T}^{min} \qquad 36.1 \\ \tilde{\chi}_{1}^{*}/\tilde{\chi}_{2}^{0} \left[4x_{3} \neq 0, 4x_{4} \neq 0 \right] \qquad 0.82 \qquad 1.33 \qquad m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV} \\ 1804.03602 \\ 1804.03568 \\ \text{ATLAS-CONF-2018-003} \\ \tilde{g}_{1}, \tilde{\chi}_{1} \rightarrow ds \qquad 2 \text{ jets } + 2 b \qquad 36.1 \\ \tilde{g}_{1}, \tilde{\chi}_{1} \rightarrow bs \qquad 2 \text{ jets } + 2 b \qquad 36.7 \\ \tilde{g}_{1}, \tilde{\chi}_{1} \rightarrow ds \qquad 2 \text{ jets } + 2 b \qquad 36.7 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} \rightarrow ds \qquad 2 \text{ jets } + 2 b \qquad 36.7 \\ \tilde{\chi}_{1}, \tilde{\chi}_{1} \rightarrow ds \qquad 2 \text{ jets } + 2 b \qquad 36.7 \\ \tilde{\chi}_{1}, \tilde{\chi}_{1} \rightarrow ds \qquad 2 \text{ jets } + 2 b \qquad 36.7 \\ \tilde{\chi}_{1}, \tilde{\chi}_{1} \rightarrow ds \qquad 2 \text{ jets } + 2 b \qquad 36.7 \\ \tilde{\chi}_{1}, \tilde{\chi}_{1} \rightarrow ds \qquad 2 \text{ jets } + 2 b \qquad 36.7 \\ \tilde{\chi}_{1}, \tilde{\chi}_{1} \rightarrow ds \qquad 2 \text{ jets } + 2 b \qquad 36.7 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} \rightarrow ds \qquad 2 \text{ jets } + 2 b \qquad 36.7 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 2 b \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} e, \mu \qquad 36.1 \\ \tilde{\chi}_{1}^{*}, \tilde{\chi}_{1} = \sqrt{2} $						\vec{K} $\tilde{g} = [\tau(\tilde{g}) = 10 \text{ ns}, 0.2 \text{ ns}]$		_		m($ ilde{\lambda}_1^0$)=100 GeV	
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\rightarrow qq q}$ $\frac{4.5 \text{ large-} R \text{ jets}}{M \text{ ultiple}} 36.1$ $\frac{\tilde{g}}{\tilde{g}, \tilde{\chi}_{112}^{0} \rightarrow qq q}$ $\frac{4.5 \text{ large-} R \text{ jets}}{M \text{ ultiple}} 36.1$ $\frac{\tilde{g}}{\tilde{g}, \tilde{\chi}_{112}^{0} \rightarrow qq q}$ $\frac{1.3 1.9}{1.05 2.0} m(\tilde{\chi}_{1}^{0}) = 200 \text{ GeV, bino-like}$ $\frac{1.3 1.9}{m(\tilde{\chi}_{1}^{0}) = 200 \text{ GeV, bino-like}}$ $\frac{1.3 1.9}{m(\tilde{\chi}_{1}^{0}) = 200 \text{ GeV, bino-like}}$ $\frac{1.4 1.05 2.0}{m(\tilde{\chi}_{1}^{0}) = 200 \text{ GeV, bino-like}}$ $\frac{1.13 1.9}{m(\tilde{\chi}_{1}^{0}) = 20 $			0 jets	Emiss		$\tilde{\tilde{\nu}}_{T}$ $\bar{\tilde{\nu}}_{T}^{\dagger}/\bar{\tilde{\nu}}_{T}^{0}$ [$\tilde{J}_{TT} \neq 0, \tilde{J}_{TT} \neq 0$]	0.8	1.33	1.9		
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$ 2 jets + 2 b 36.7 $\tilde{t}_1 [qq, bs]$ 0.42 0.61 1710.07171 $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow qt$ 2 e, μ 2 b 36.1 \tilde{t}_1 0.42 0.61 0.4-1.45 1710.0554	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qqq$, 4-5 large- <i>R</i> j		36.1	$ \begin{array}{c} \tilde{g} & [m(\tilde{\chi}_1^0) = 200 \text{ GeV}, 1100 \text{ GeV}] \\ \tilde{g} & [\tilde{\chi}_{112}^{\prime\prime} = 2e{-}4, 2e{-}5] \end{array} $		1.3		Large λ_{112}''	1804.03568
$\tilde{l}_1 \tilde{l}_1, \tilde{l}_1 \rightarrow q \ell$ 2 e, μ 2 b 36.1 \tilde{l}_1 0.4-1.45	$\vec{i}_{1}\vec{i}_{1}, \vec{i}_{1} \rightarrow q\ell = 2b \qquad 36.1 \\ 1_{\mu} \qquad DV \qquad 136 \qquad \vec{i}_{1} \qquad 0_{231k} < \mathbf{1e} - 8, 3e - 10 < \lambda'_{231k} < \mathbf{3e} - 9 \qquad 1.0 \qquad 1.6 \qquad 1.6 \qquad \mathbf{BR}(\vec{i}_{1} \rightarrow q\mu) = 100\%, \cos \theta \qquad 1710, 05544 \\ \mathbf{BR}(\vec{i}_{1} \rightarrow q\mu) = 100\%, \cos \theta \qquad 1710, 05544 \\ 1_{\mu} = 100, 1_{\mu} = 100,$	$\tilde{i}_{1}\tilde{i}_{1}, \tilde{i}_{1} \rightarrow qt \qquad 2e, \mu \qquad 2b \qquad 36.1 \\ 1\mu \qquad DV \qquad 136 \qquad \tilde{i}_{1} \qquad 0.4-1.45 \qquad 0.4-1$				ь				1.05		$m(\widetilde{\mathcal{X}}^0_1){=}200$ GeV, bino-like	
		phénomena is shown. Many of the limits are based on			2 b		36.1	ī,				$BR(\tilde{i}_1 \rightarrow q\mu) = 100\%$	1710.05544
implified models, c.f. refs. for the assumptions made.	@14 TeV									Contraction of the second	San States		1.0
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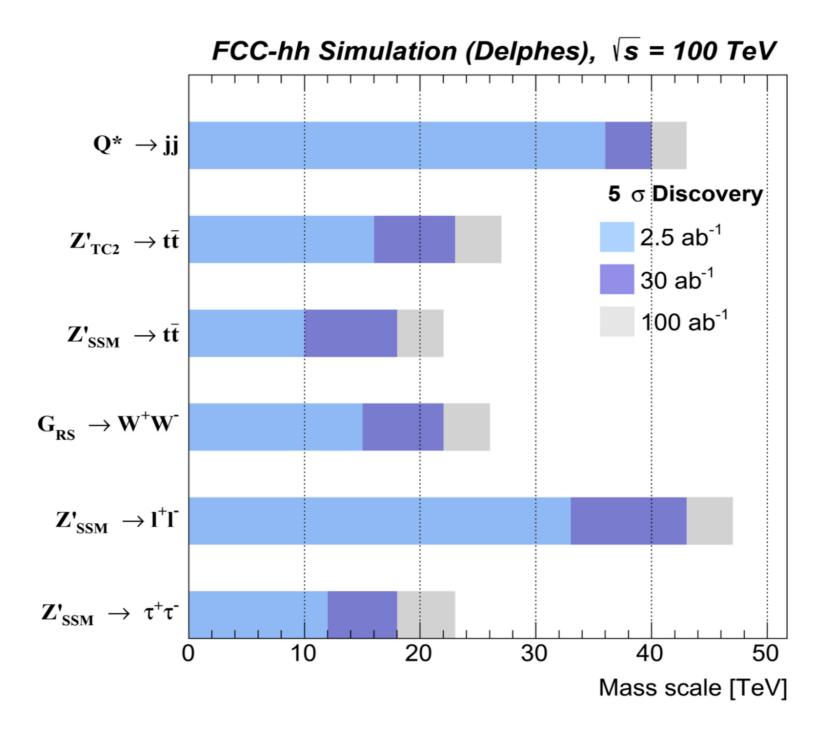
@100 TeV

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



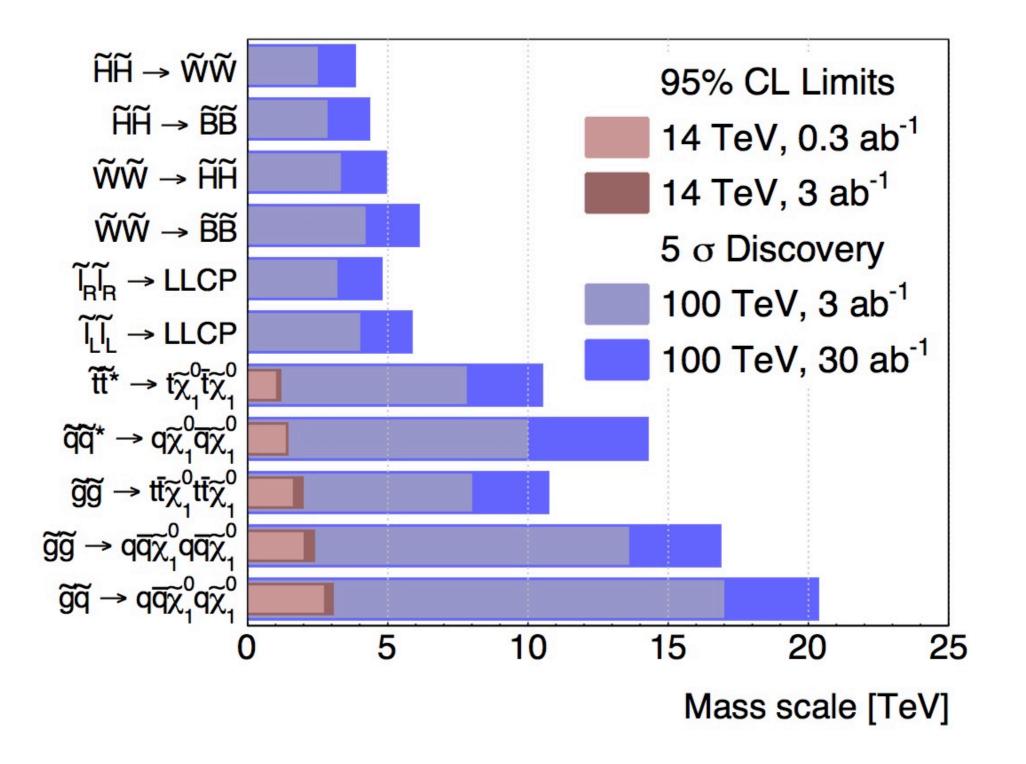
Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

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

SUSY reach at 100 TeV



15-20 TeV squarks/gluinos would require a lepton collider in the ECM range of 30-50 TeV

(2) **Direct discovery: the "low-mass-but-elusive"** scenarios — LLP, ALPs, HNL and exotic H decays

See e.g. LLP: Blondel, et al.. <u>https://doi.org/10.3389/fphy.2022.967881</u> HNL: Blondel et al., https: //<u>doi.org/10.1016/j.nuclphysbps.2015.09.304</u> FCC LLP working group: https://indico.cern.ch/category/5664/

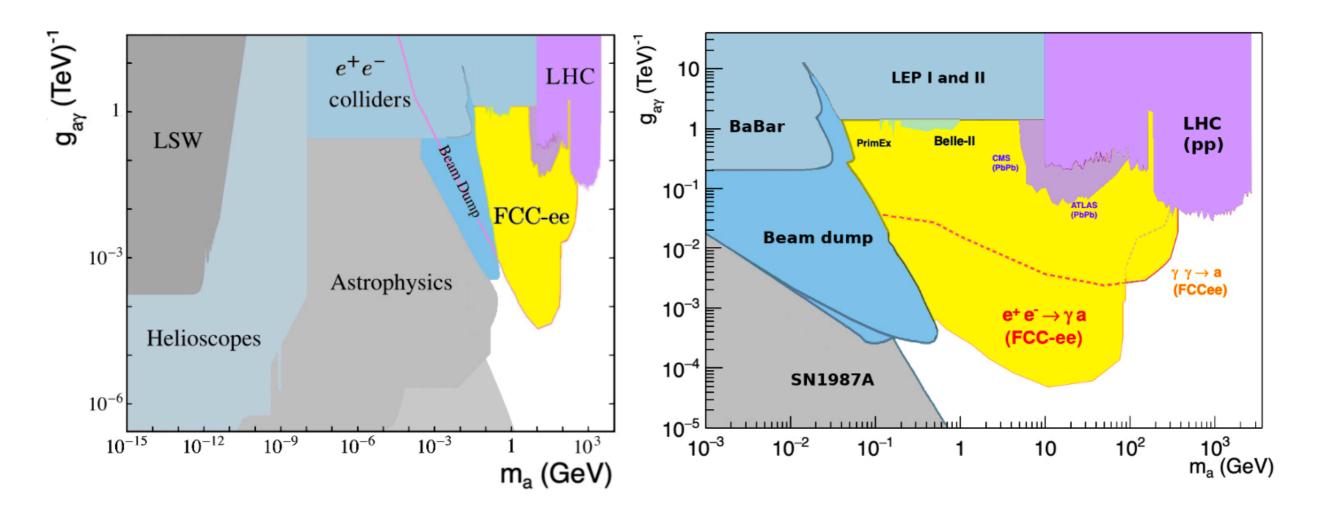
Axion-like particles

In the run at the Z pole, exploit possible channels such as

$$e^+e^- \rightarrow a\gamma \qquad e^+e^- \rightarrow e^+e^-a$$

with

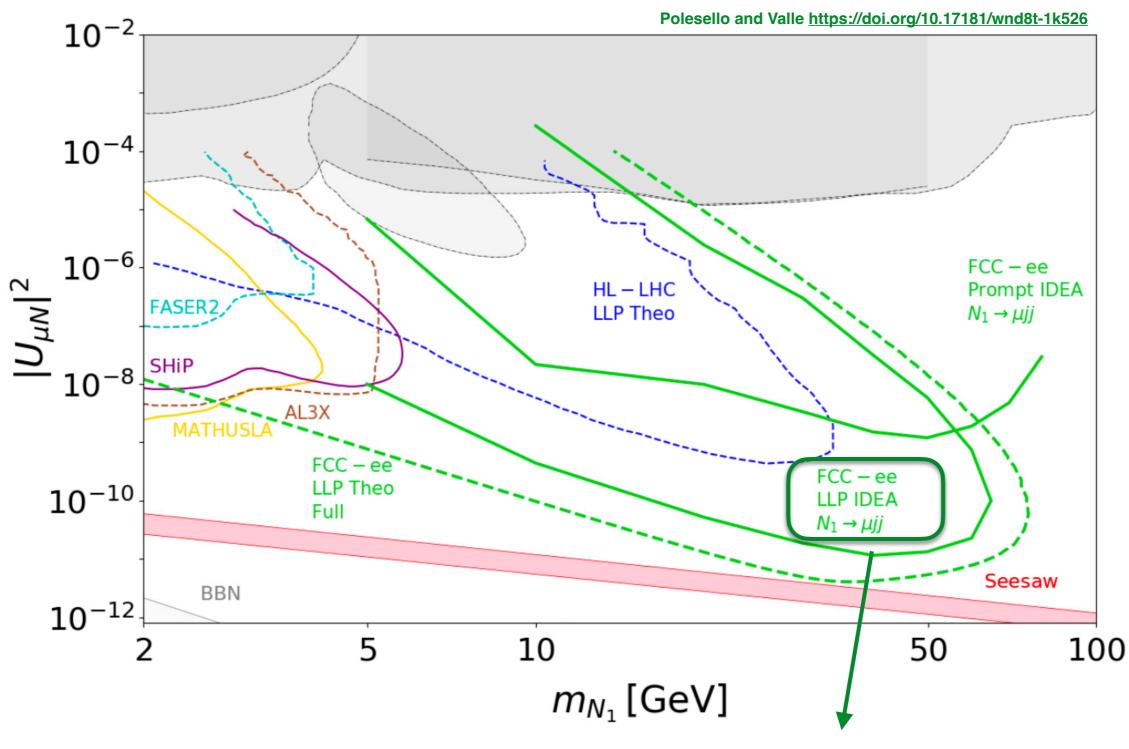
 $a \rightarrow \gamma \gamma$



P. Rebello-Teles et al, to appear

Heavy Neutral Leptons

 $e^+e^- \to Z \to \nu N \qquad N \to \ell W^* \to \ell j j$



dedicated search for decay lengths in the 1mm-2m range

(3) The potential for yes/no answers to important questions

WIMP DM theoretical constraints

For particles held in equilibrium by pair creation and annihilation processes, ($\chi \ \chi \leftrightarrow SM$)

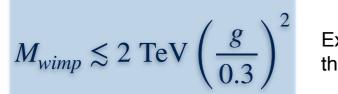
$$\Omega_{\rm DM} h^2 \sim rac{10^9 {
m GeV}^{-1}}{M_{
m pl}} rac{1}{\langle \sigma v
angle}$$

For a particle annihilating through processes which do not involve any larger mass scales:

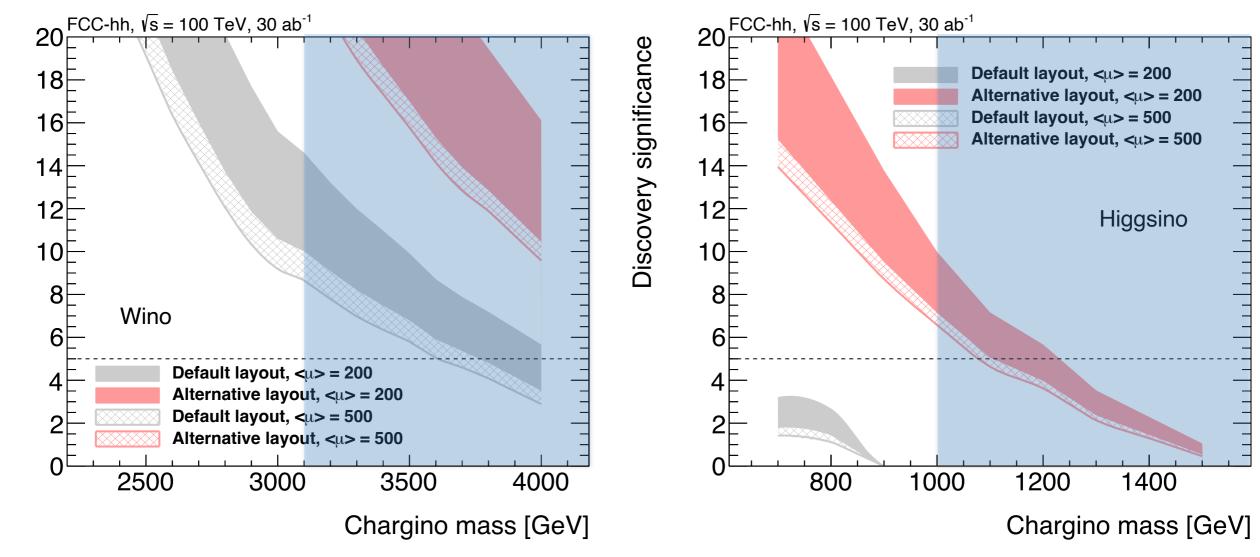
 $\langle \sigma v \rangle \sim g_{\rm eff}^4 / M_{\rm DM}^2$

Disappearing charged track analyses (at ~full pileup)

K. Terashi et al, https://cds.cern.ch/record/2642474



Excluded region for thermal WIMP DM



=> full coverage below the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

... and much more ...

- Countless studies of discovery potential for multiple BSM scenarios, from SUSY to heavy neutrinos, from very low masses to very high masses, LLPs, DM, etcetcetc, with plenty of opportunities for direct discovery even at FCCee 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

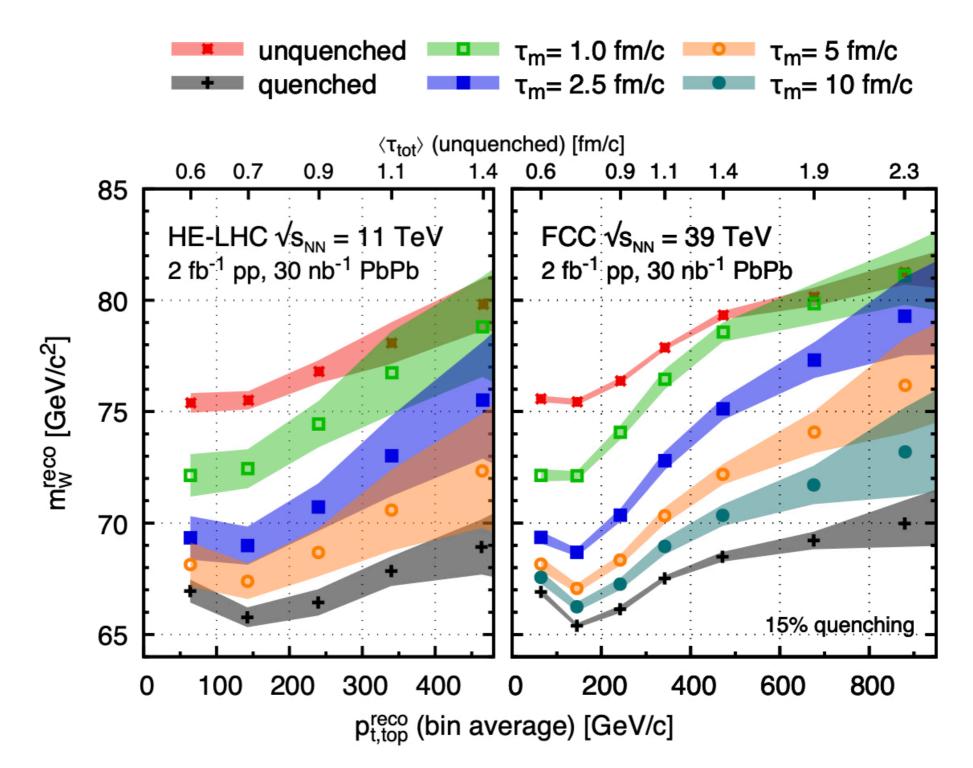
• Operations with heavy ions: new domains open up at 100 TeV in the study of high-T/high-density QCD. Broaden the targets, the deliverables, extend the base of potential users, and increase the support beyond the energy frontier community

Ex: medium modification of top-decay properties in PbPb @ FCC

Apolinario et al, https://arxiv.org/pdf/1711.03105.pdf

 $t \rightarrow bW \rightarrow bjj$

 $\tau_{top} = 0.15$ fm/c, τ_W (from top decay) = 0.09 fm/c ... both are increased if the top is boosted, modifying the time the final state jets spend inside the thermalized medium, subject to quenching



Final remarks

- The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.
- The exptl program possible at a future circular collider facility, combining a versatile high-luminosity e⁺e⁻ circular collider, with a follow-up pp collider in the 100 TeV range, offers unmatchable breadth and diversity: concrete, compelling and indispensable Higgs & SM measurements enrich a unique direct & indirect discovery potential
- The next 3-4 years, before the next review of the European Strategy for Particle Physics, will be critical to reach the scientific consensus and political support required to move forward