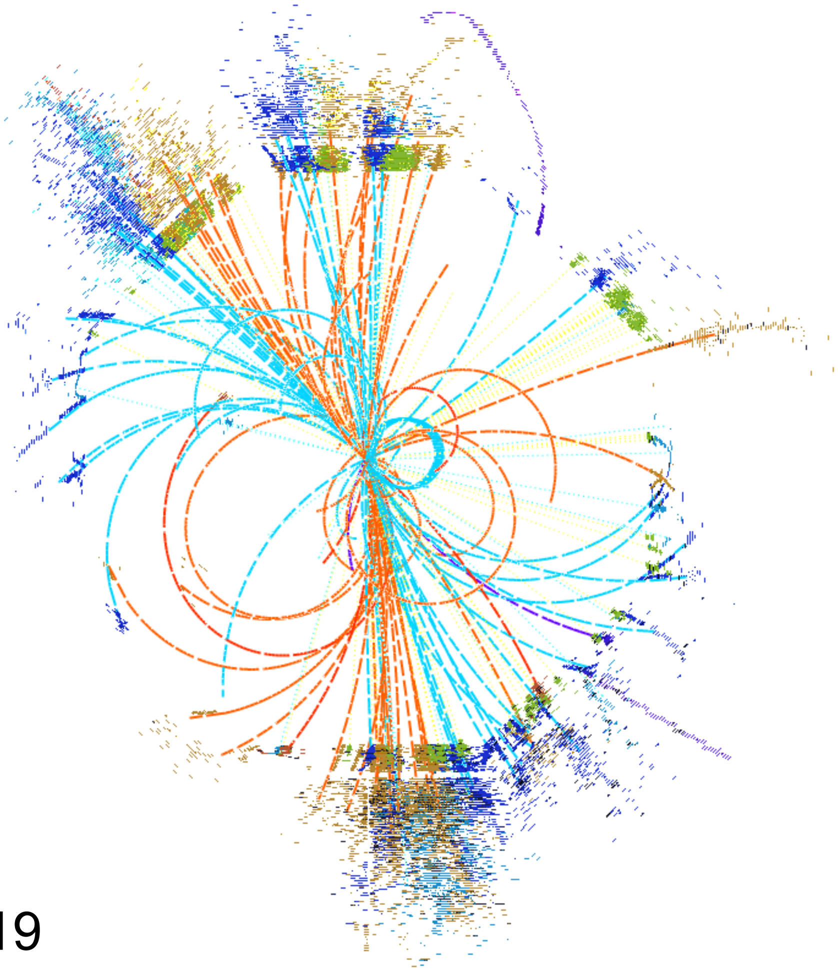
Beyond the Standard Model at future colliders

Philipp Roloff (CERN)

CLIC Detector and Physics
Collaboration Meeting



27/08/2019
CERN, Geneva

Introduction and caveats

- **This talk:** mainly highlights from the BSM sessions at the Open Symposium in Granada (and some updates afterwards in view of the briefing book)

- Impossible to cover every model or signature, several representative cases for each thematic area

- Projections have very different levels of sophistication (theory-level studies → DELPHES → full detector simulations)

- Sensitivity to new physics (usually 95% CL. limits), no characterisation of potential discoveries discussed

Topics in BSM

Conveners: Gian Giudice, Paris Sphicas

1.) **Electroweak symmetry breaking and new resonances**
Andrea Wulzer (th.), Juan Alcaraz (exp.)
Composite Higgs, top partners, particles associated with EW symmetry breaking, heavy Z' and W'

2.) **Supersymmetry**
Andreas Weiler (th.), Monica D'Onofrio (exp.)
Collider searches, motivations for supersymmetry after the LHC, unexplored corners, new models

3.) **Extended Higgs sectors and high-energy flavour dynamics**
Veronica Sanz (th.), Ph. R. (exp.)
Two Higgs doublets, singlets, new particles accompanying the Higgs, leptoquarks, particles related to flavour dynamics at the EW scale, rare top decays

4.) **Dark Matter**
Matthew McCullough (th.), Caterina Doglioni (exp.)
Collider searches, simplified models, comparisons with direct/indirect searches

5.) **Feebly-interacting particles**
Gilad Perez (th.), Gaia Lanfranchi (exp.)
Long-lived particles, high-handed neutrinos at the EW scale, dark photons at colliders, dark scalar / relaxion, ALPs at colliders

The big questions

1.) To what extend can we tell whether the Higgs boson is fundamental or composite?
→ EWSB/new resonances, SUSY

2.) Are there new interactions or new particles around or above the electroweak scale?
→ EWSB/new resonances, SUSY, Ext-H/FlavourDyn, DM, FIPs

3.) What cases of thermal-relic particles are still unprobed and can be fully covered by future collider searches?
→ DM, SUSY, FIPs

4.) To what extend can current or future accelerators probe feebly-interacting sectors?
→ FIPs, SUSY

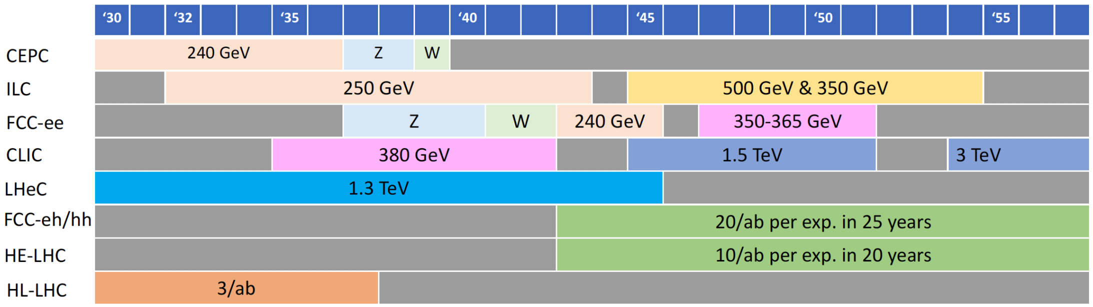
Collider parameters

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{inst}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]
HL-LHC	pp	14 TeV	-	2	5	6.0	12
HE-LHC	pp	27 TeV	-	2	16	15.0	20
FCC-hh	pp	100 TeV	-	2	30	30.0	25
FCC-ee	ee	M_Z	0/0	2	100/200	150	4
		$2M_W$	0/0	2	25	10	1-2
		240 GeV	0/0	2	7	5	3
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5
							(+1)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5
		350 GeV	±80/±30	1	1.6	0.2	1
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5
							(+1)
CEPC	ee	M_Z	0/0	2	17/32	16	2
		$2M_W$	0/0	2	10	2.6	1
		240 GeV	0/0	2	3	5.6	7
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8
		1.5 TeV	±80/0	1	3.7	2.5	7
		3.0 TeV	±80/0	1	6.0	5.0	8
							(+4)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25

pp colliders

e^+e^- colliders

ep colliders



+ LE-FCC: pp, 15 ab^{-1} at $\sqrt{s}$ = 37.5 TeV

arXiv:1905.03764

Direct vs. indirect

Direct searches: tuned for specific models (or classes of models)

Precision measurements: important complementary information

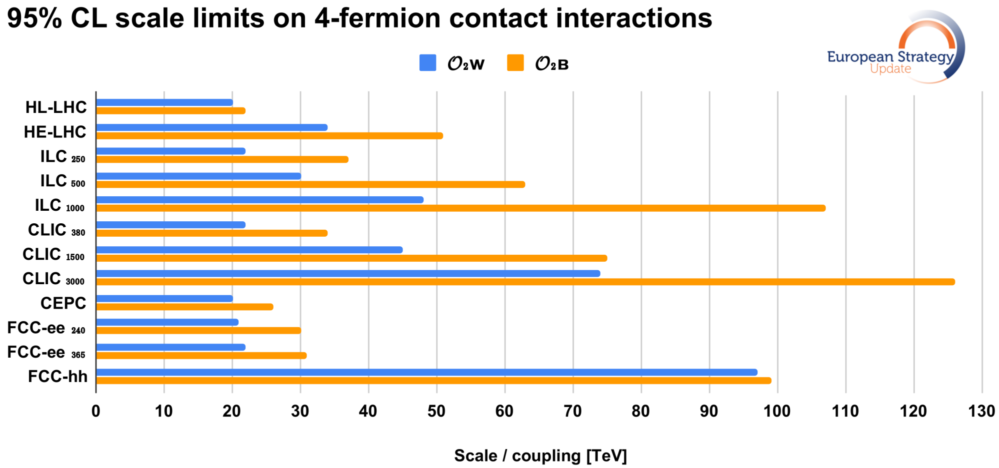
Standard Model Effective Field Theory: contributions from new physics expressed by dimension-6 operators

$$
\begin{aligned}
\mathcal{L}^{d=6}_{universal} \; = \;& c_H \frac{g_*^2}{m_*^2} \mathcal{O}_H \\
+ \;& \frac{1}{g_*^2 m_*^2} \left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B} \right] \\
+ \;& \frac{1}{m_*^2} \left[c_W \mathcal{O}_W + c_B \mathcal{O}_B \right] \\
+ \;& c_{y_t} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_t} + c_{y_b} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_b} \\
+ \;& \ldots
\end{aligned}
$$

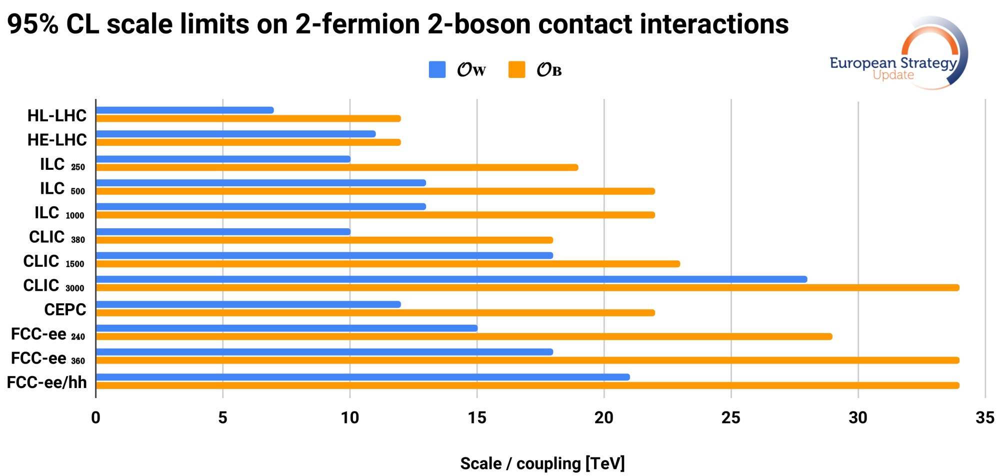
- c_H term → *Scaling all Higgs couplings by a common factor*
- c_{2W}, c_{2B} terms → *4-fermion contact ints., W', Z' resonances*
- c_W, c_B terms → *2 fermion–2 boson contact interactions, S parameter*
- c_{y_t}, c_{y_b} terms → *Modify top and bottom Yukawa couplings*
- + … → *And much, much more…*

(→ see also talk by Jiayin Gu)

Contact interactions



- Projected limits from di-fermion final states ($e^+e^- \rightarrow f\bar{f}$, Drell-Yan with neutral and charged currents)
- Sensitivity increases significantly with $\sqrt{s}$



- New physics effects in the interaction between gauge and Higgs sectors
- O_W dominated by $e^+e^- \rightarrow ZH$ at CLIC (→ see talk by Matthias Weber), $pp \rightarrow WZ$ at FCC-hh
- Largest sensitivity in e^+e^- collisions at lower $\sqrt{s}$ (and on O_B in general) from oblique parameter S

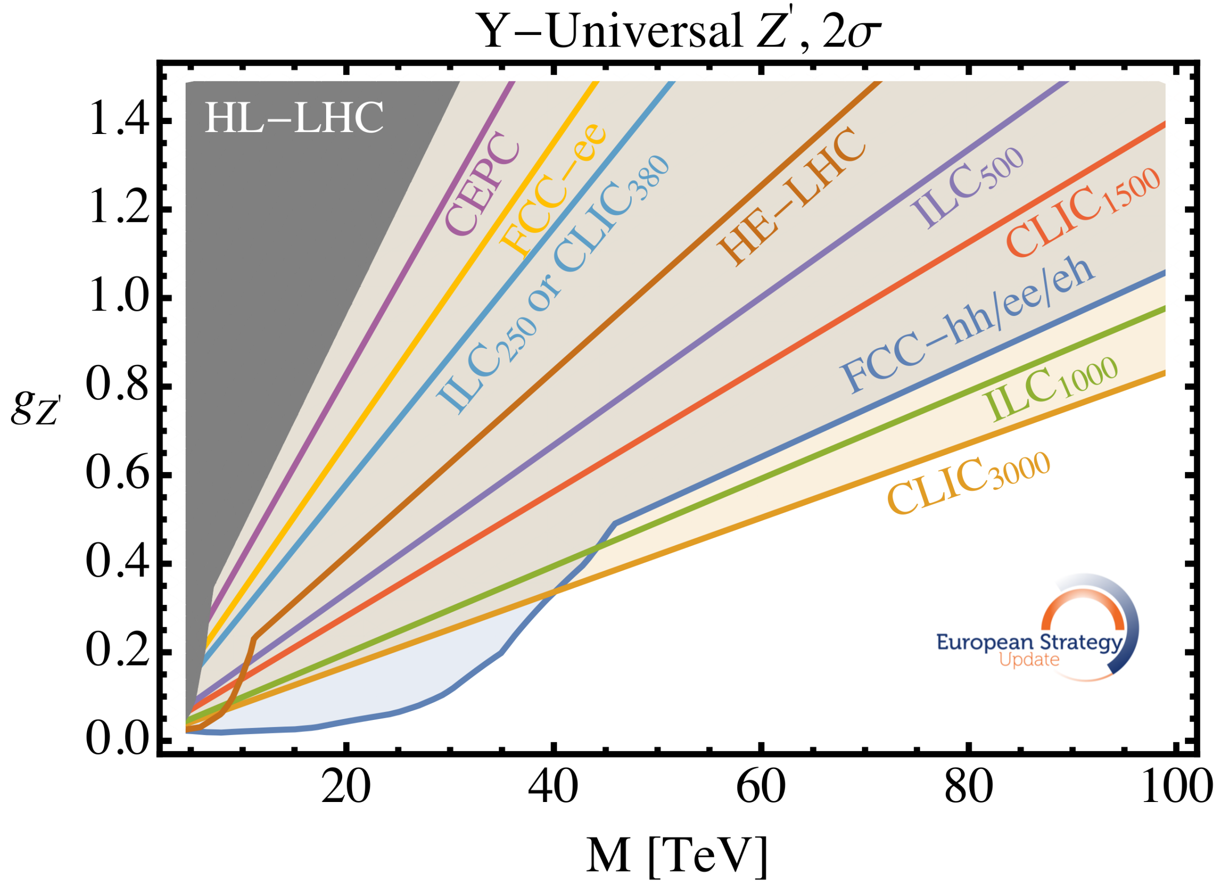
Y-Universal Z’

• New neutral gauge boson Z’ with mass M and charges to SM particles equal to hypercharge

$$\frac{c_{2B}}{\Lambda^2} = \frac{g_{Z'}^2}{g'^4 M_{Z'}^2}$$

• Direct reach inferior to the indirect one for high $g_{Z'}$

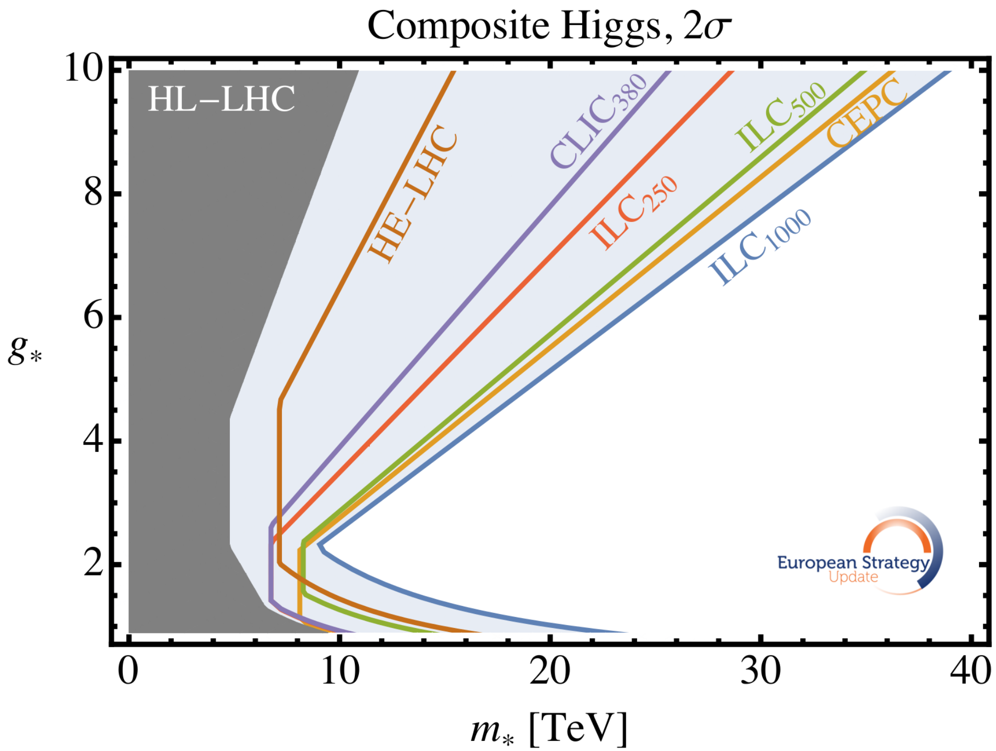
• <u>NB:</u> $g_{Z'} > 1.5 \rightarrow$ width exceeds 0.3 M



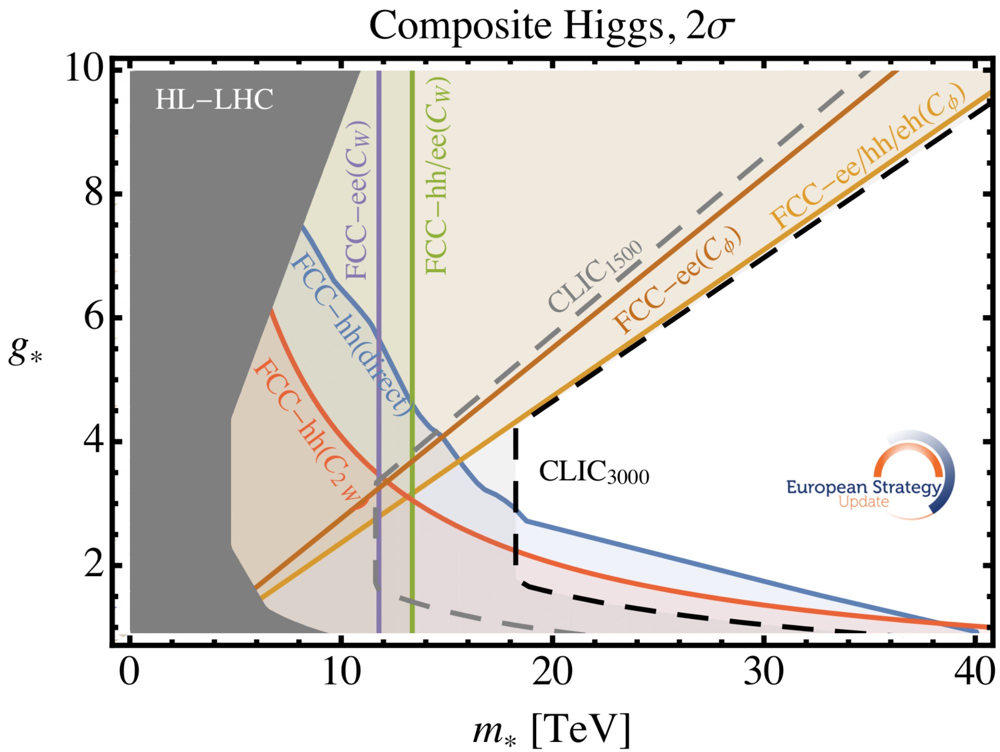
Composite Higgs (1)

m_*: mass scale
g_*: coupling

$$\frac{c_\phi}{\Lambda^2} \sim \frac{g_*^2}{m_*^2}, \quad \frac{c_W}{\Lambda^2} \sim \frac{1}{m_*^2}, \quad \frac{c_{2W}}{\Lambda^2} \sim \frac{1}{g_*^2 m_*^2}$$



Higgs factories (including 380 GeV CLIC) significantly better than HL-LHC



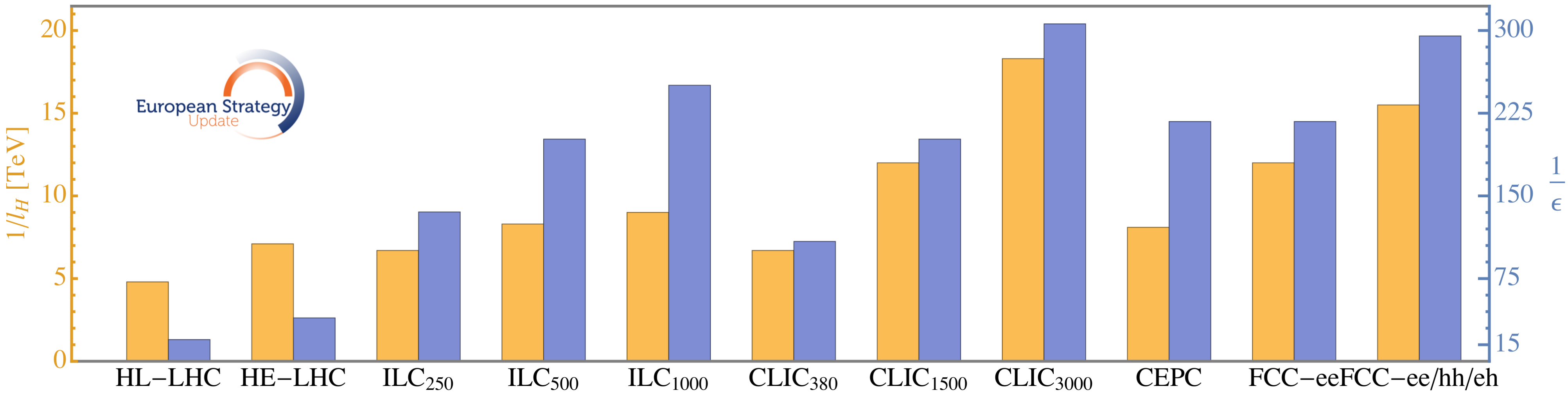
FCC-all and 3 TeV CLIC similar

Composite Higgs (2)

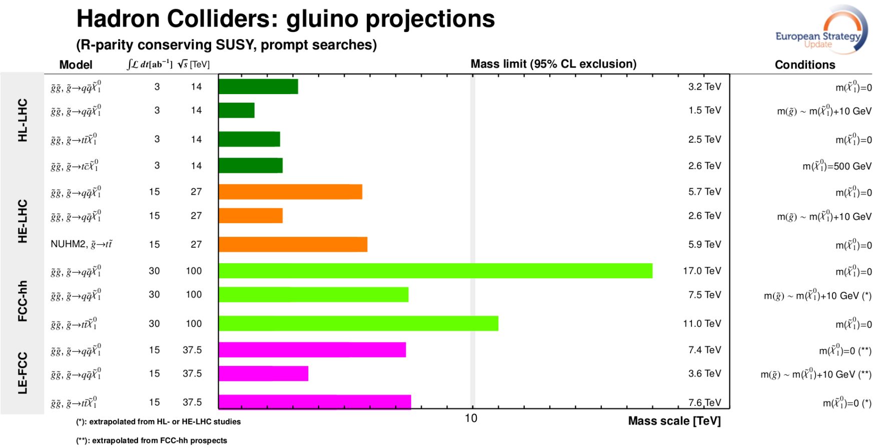
m_*: mass scale
g_*: coupling

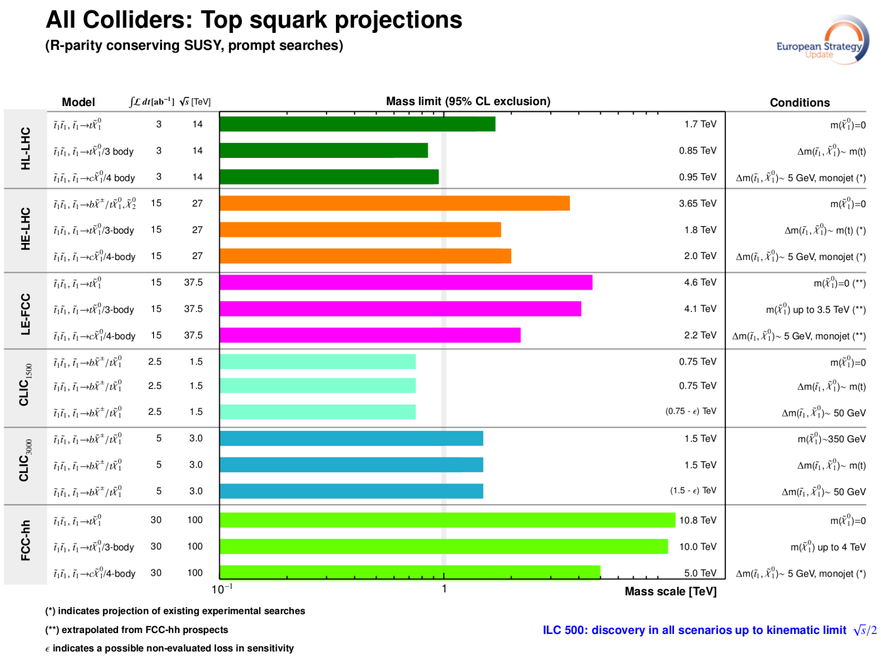
$$\frac{c_\phi}{\Lambda^2} \sim \frac{g_*^2}{m_*^2}, \qquad \frac{c_W}{\Lambda^2} \sim \frac{1}{m_*^2}, \qquad \frac{c_{2W}}{\Lambda^2} \sim \frac{1}{g_*^2 m_*^2}$$

Inverse Higgs length: $1 / \ell_H = m_*$
→ $1 / \ell_H$ = 10 - 20 TeV is 4 orders of magnitude below the size of the proton!



Strongly-interacting SUSY



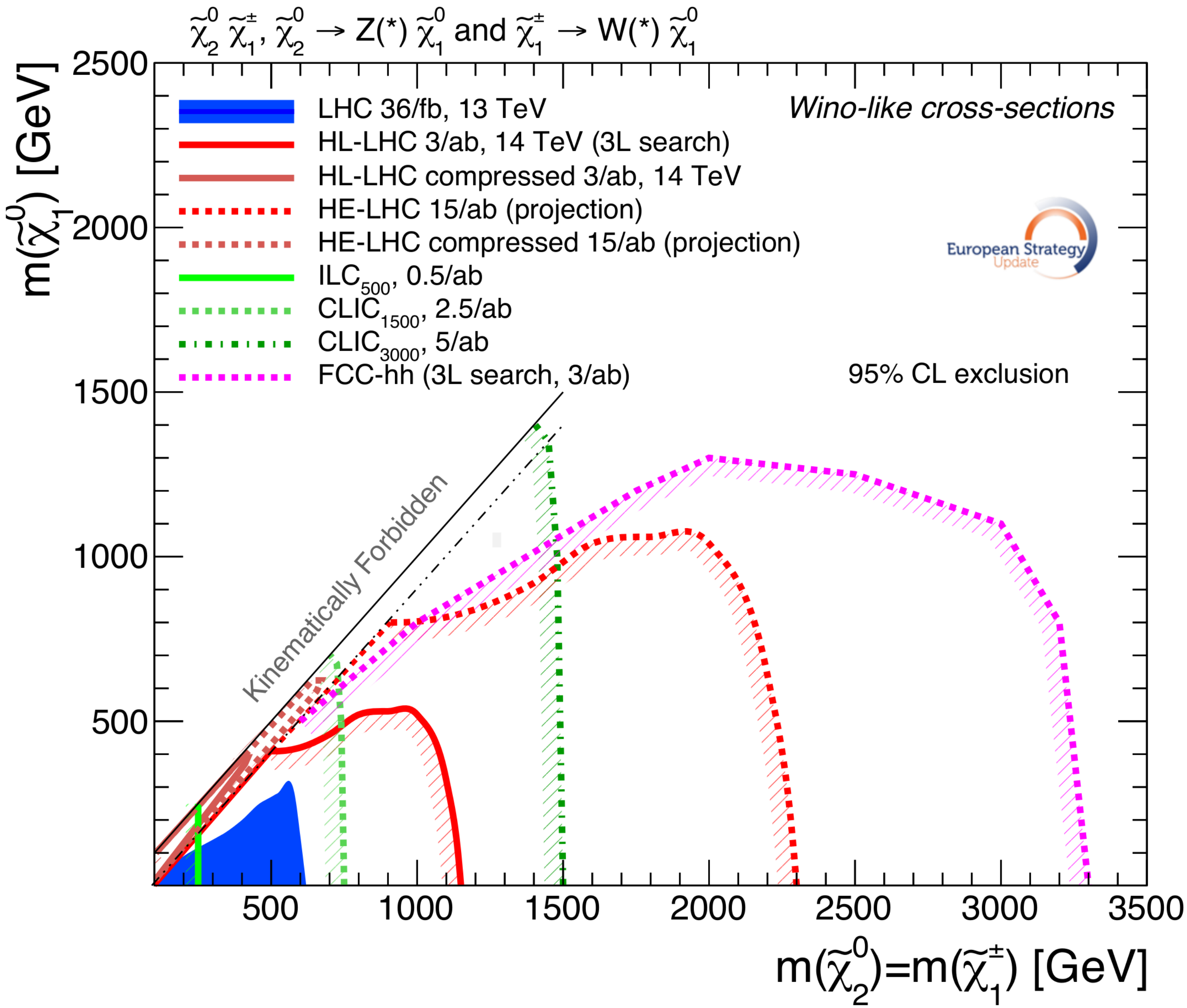


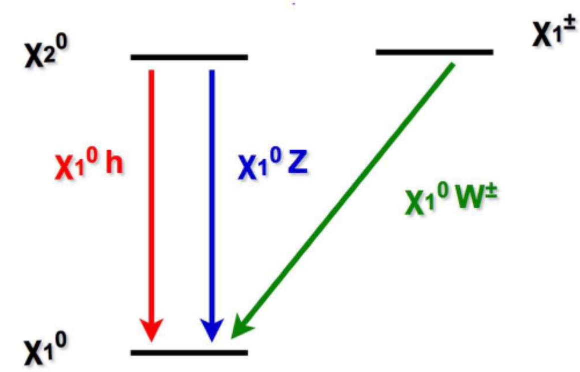
- Mainly purview of hadron colliders:
  FCC-hh : HE-LHC : HL-LHC ≈ 6x : 2x : 1
- CLIC at 3 TeV exceeds HL-LHC for top squarks for heavier LSP
- Powerful probes on the role of naturalness in the Higgs sector

Fine-tuning parameter: $1 / \varepsilon = \Delta m_H^2 / m_H^2$

ϵ	High-scale mediation	Low-scale mediation
stop	$5 \times 10^{-5} \left(\frac{10\ \mathrm{TeV}}{m_{\tilde{t}}}\right)^2$	$2 \times 10^{-3} \left(\frac{10\ \mathrm{TeV}}{m_{\tilde{t}}}\right)^2$
gluino	$7 \times 10^{-6} \left(\frac{17\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^2$	$6 \times 10^{-3} \left(\frac{17\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^2$

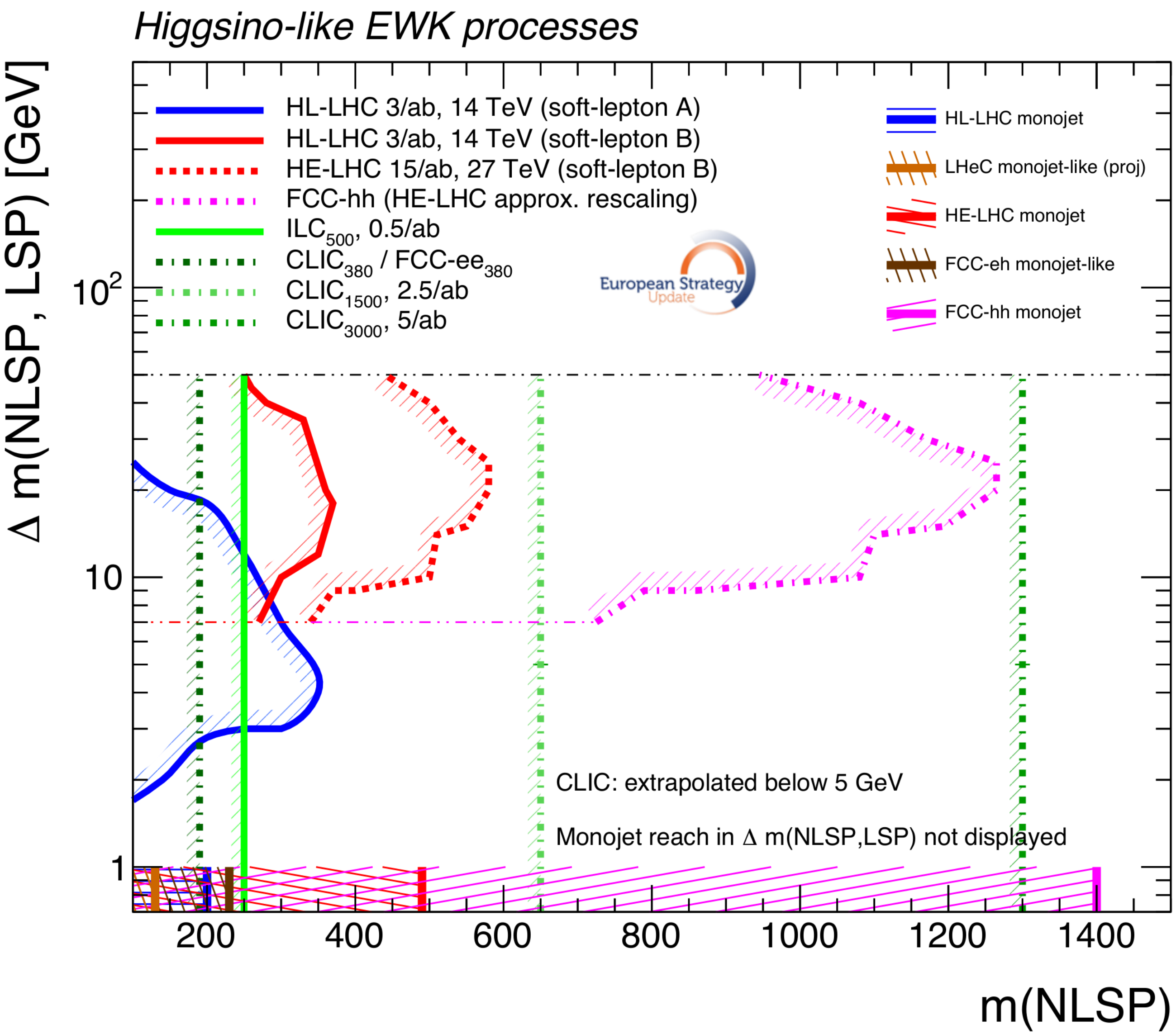
EW SUSY: Wino

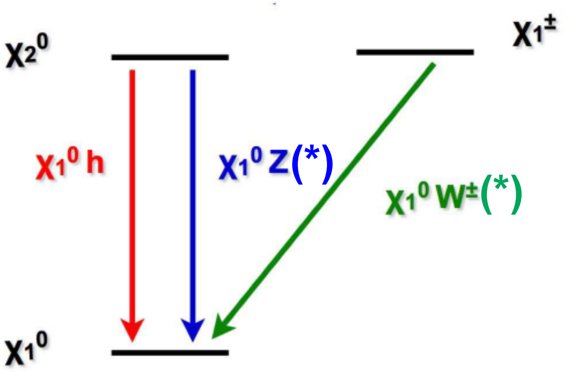




- **LSP is Bino-like:** lightest chargino and next-to-lightest neutralino are Wino-like
- Lepton colliders cover entire kinematic plane
- Hadron colliders reach the highest masses in case of a low-mass LSP

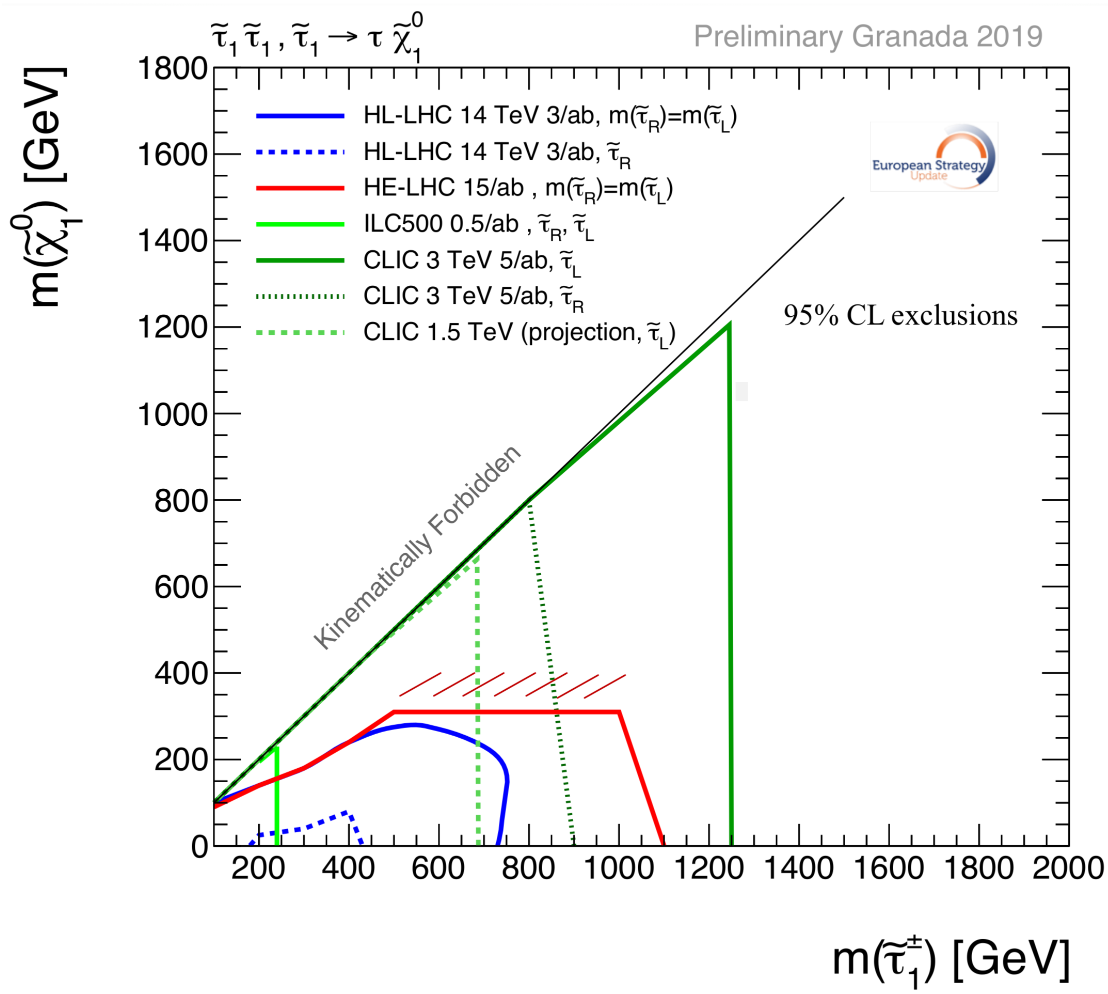
EW SUSY: Higgsino

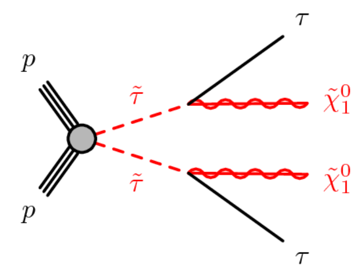




- **LSP Higgsino-like:** ΔM(NLSP, LSP) ~ O(GeV)
- **LSP pure Higgsino:** ΔM(NLSP, LSP) ~ 160 MeV → targeted by disappearing track analysis (see later)

EW SUSY: staus



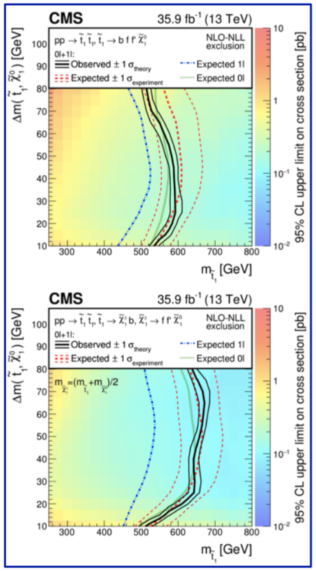


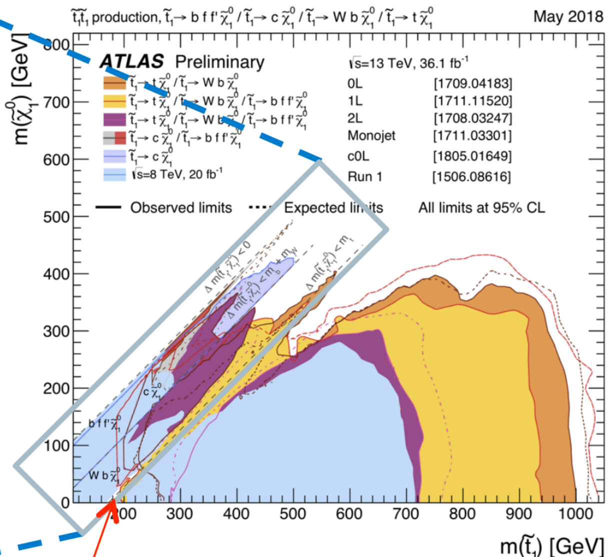
- Mixing of RH and LH component
→ large impact on cross section

- FCC-hh might push limit to 3 - 4 TeV for low LSP mass (boosed tau reconstruction to be studied)

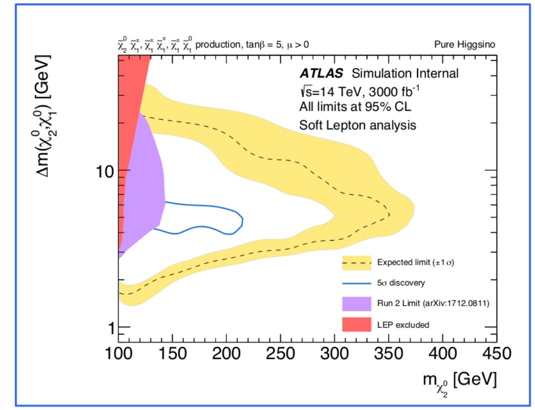
- Lepton colliders cover large part of kinematic plane for LH stau
→ see talk by Ulrike Schnoor

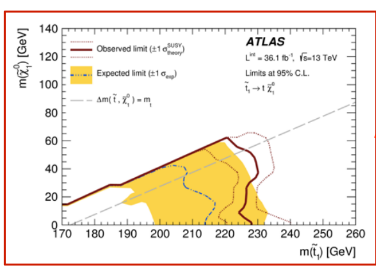
SUSY: unexplored corners?

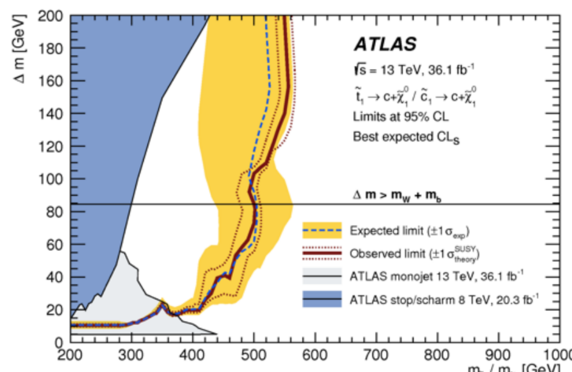


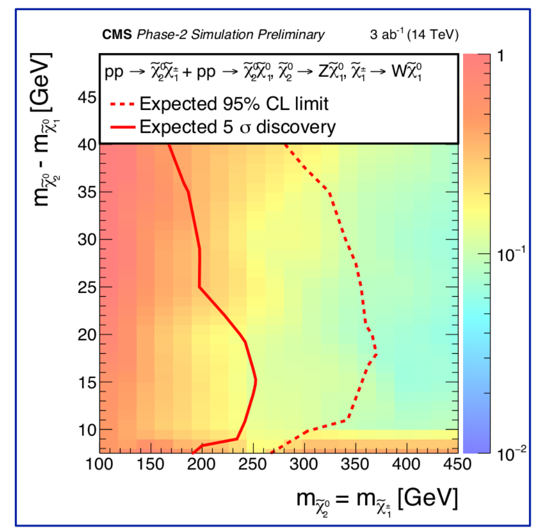


–:
Info only from LHC (& only for stop).
+:
based on data!





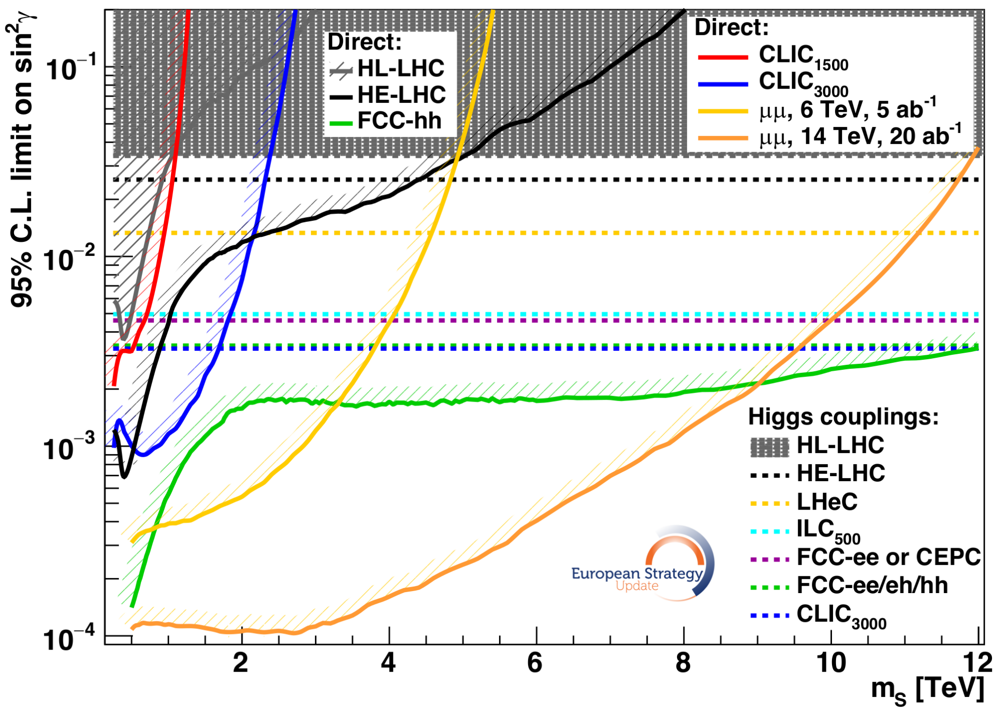




Indeed, after LHC, there will be holes [in low mass regions]; closing or looking at how to close them at HL-LHC; for EWKinos, some regions will remain difficult @ pp.

Extended Higgs sectors: SM + real scalar singlet

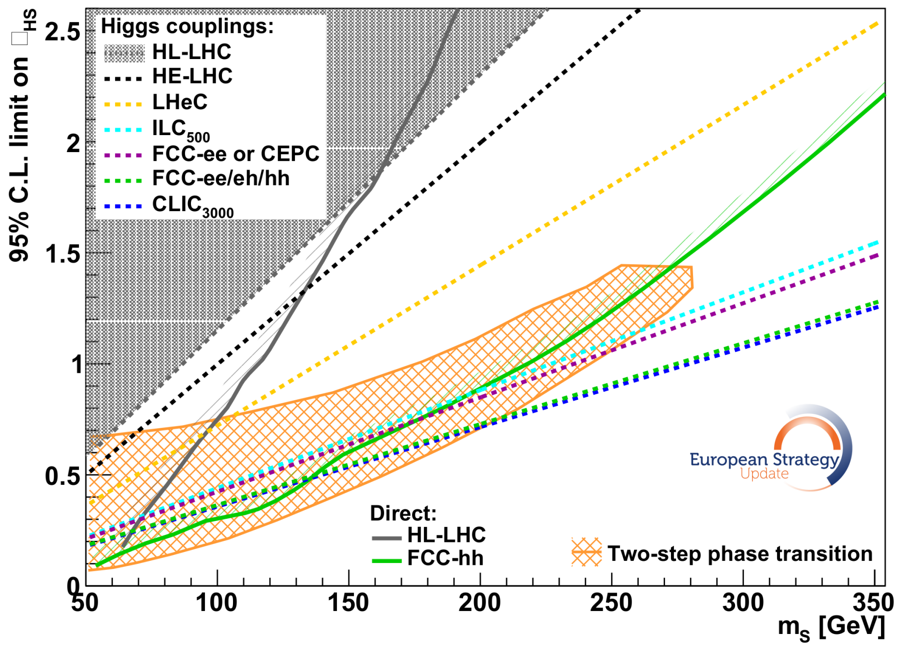
$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 - \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 + \lambda_{HS}|H|^2 S^2$$



- H & S can mix: $\sin^2\gamma$
- **Direct searches:** $S \rightarrow ZZ$ in pp and $S \rightarrow HH$ in e^+e^- give the best sensitivity
- **Indirect searches:** sensitivity from c_ϕ (overall scaling of the Higgs couplings)
- Direct & indirect proves provide complementary information
- Direct reach at FCC-hh better than precision Higgs couplings for m_S < 12 TeV

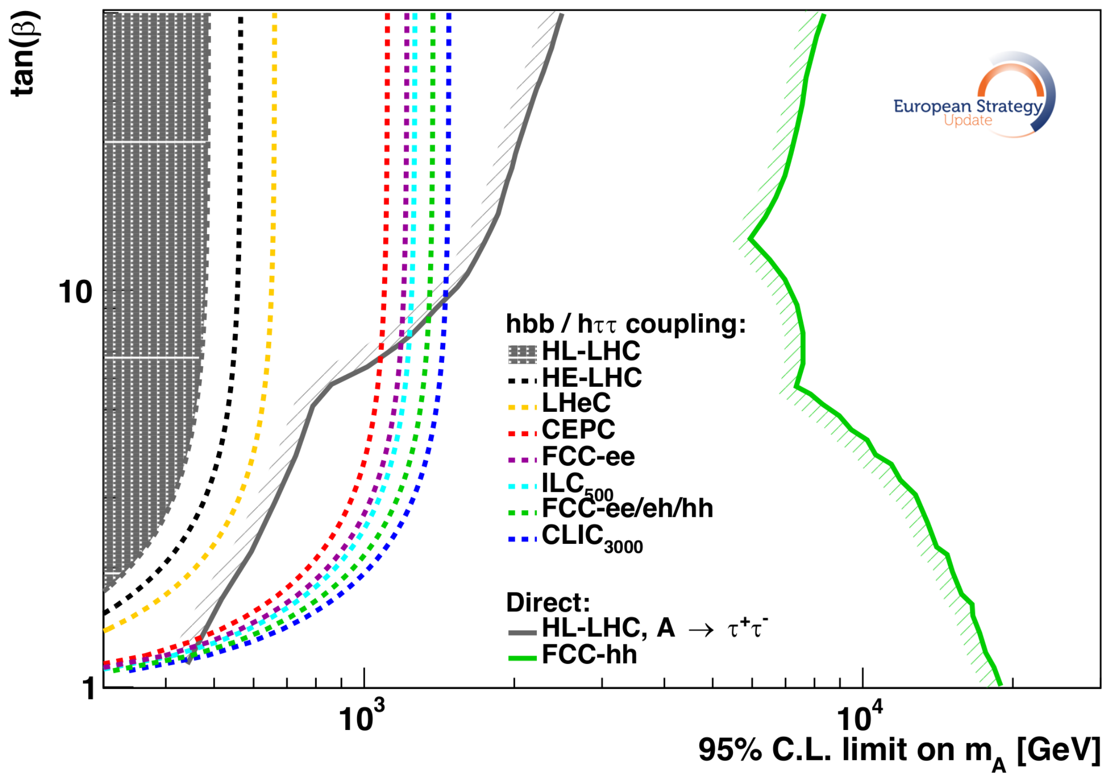
No mixing limit

$$V_0 = -\mu^2 |H|^2 + \lambda |H|^4 - \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 + \lambda_{HS} |H|^2 S^2$$



- No mixing → limit on portal coupling λ_{HS}
- **Direct searches:** S escapes undetected, event selection using VBF jets: pp → SSjj
- **Indirect searches:** sensitivity from c_ϕ (overall scaling of the Higgs couplings)
- FCC-all or 3 TeV CLIC would cover most of the region compatible with two-step phase transition (where the singlet supports the Higgs in delivering a strong first-order phase transition)
- Strong first-order phase transitions could lead to sizeable gravitational wave signals at future experiments like LISA

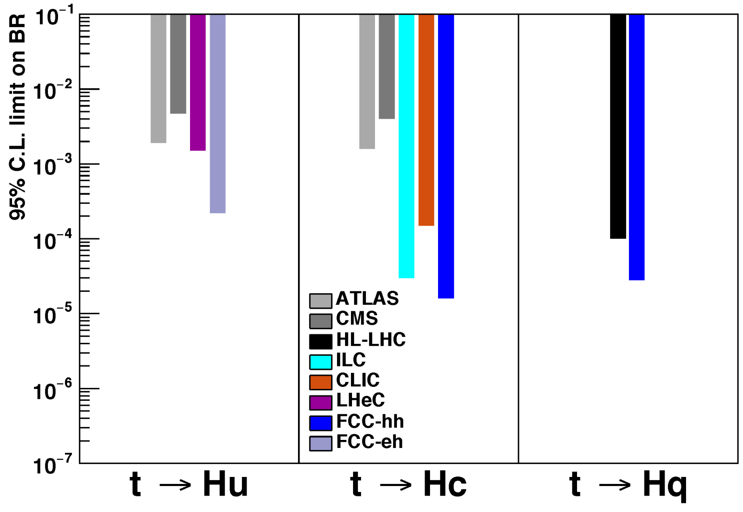
Heavy neutral scalars in minimal SUSY

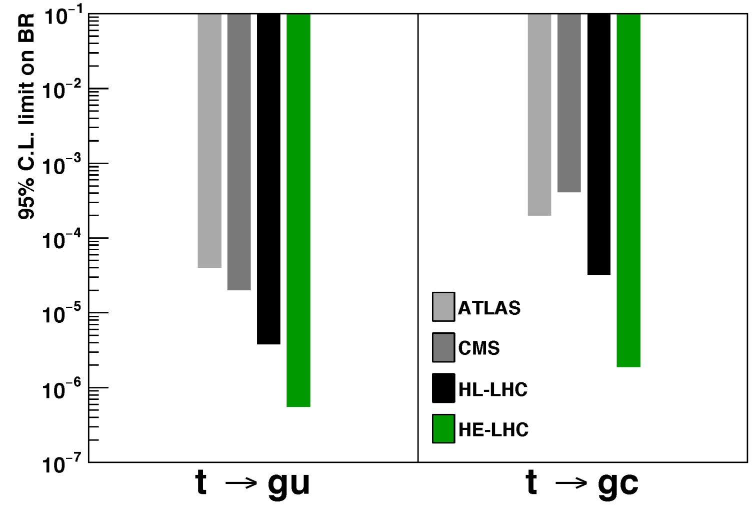


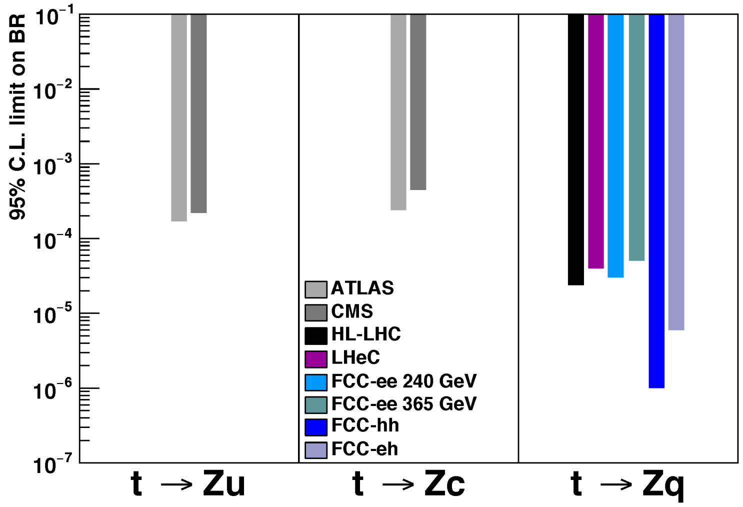
Example: CP-odd scalar A

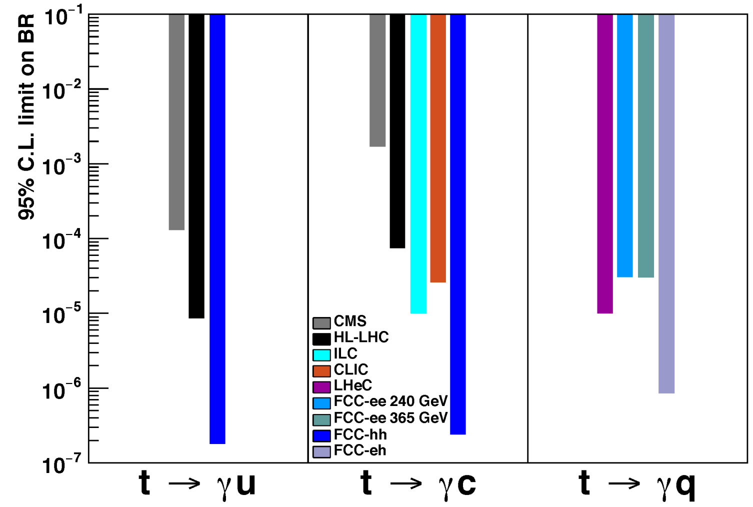
- Mass reach generally close to $\sqrt{s}$ / 2 at lepton colliders
- HL-LHC sensitive to heavy neutral scalars up to 2.5 TeV for tan β > 50 using $\tau^+\tau^-$
- Exclusion limits > 5 TeV at FCC-hh (20 TeV at low tan β)
- Indirect sensitivity from g_{hbb} or $g_{h\tau\tau}$ (further improvement from global fit)

Flavour dynamics: FCNC





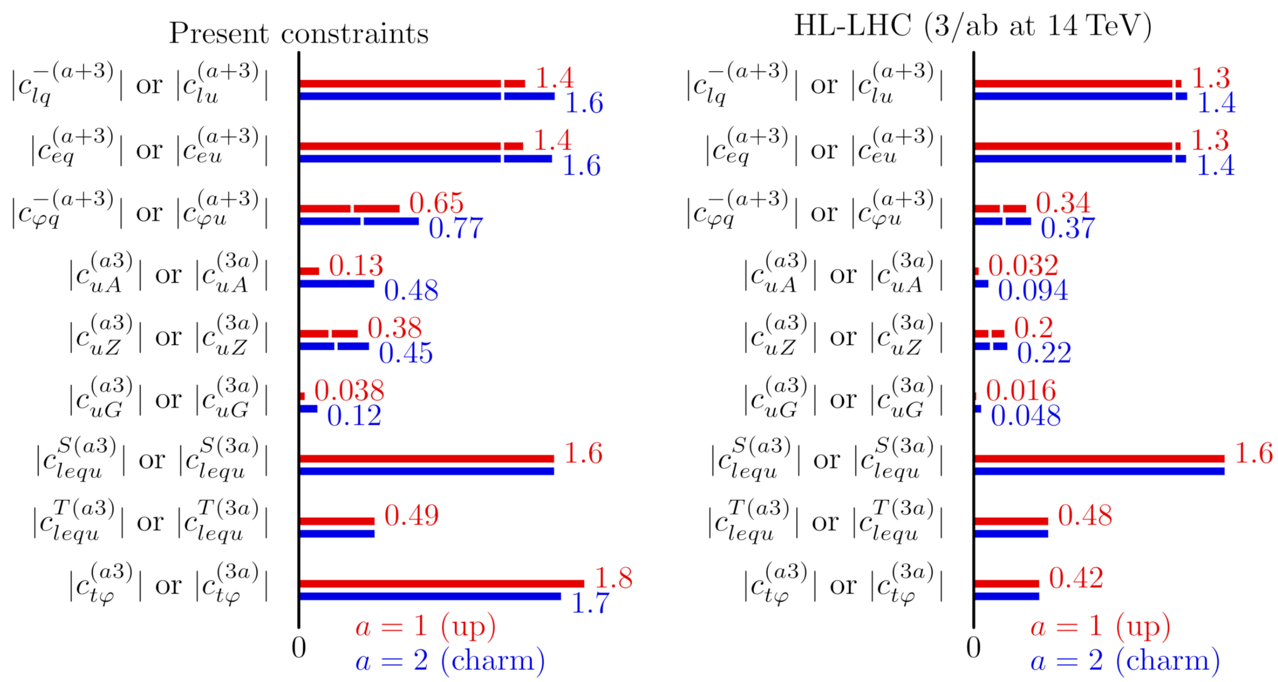




Top-quark FCNC: EFT for HL-LHC

Sensitivity to top-quark FCNC effects can be studied using EFT

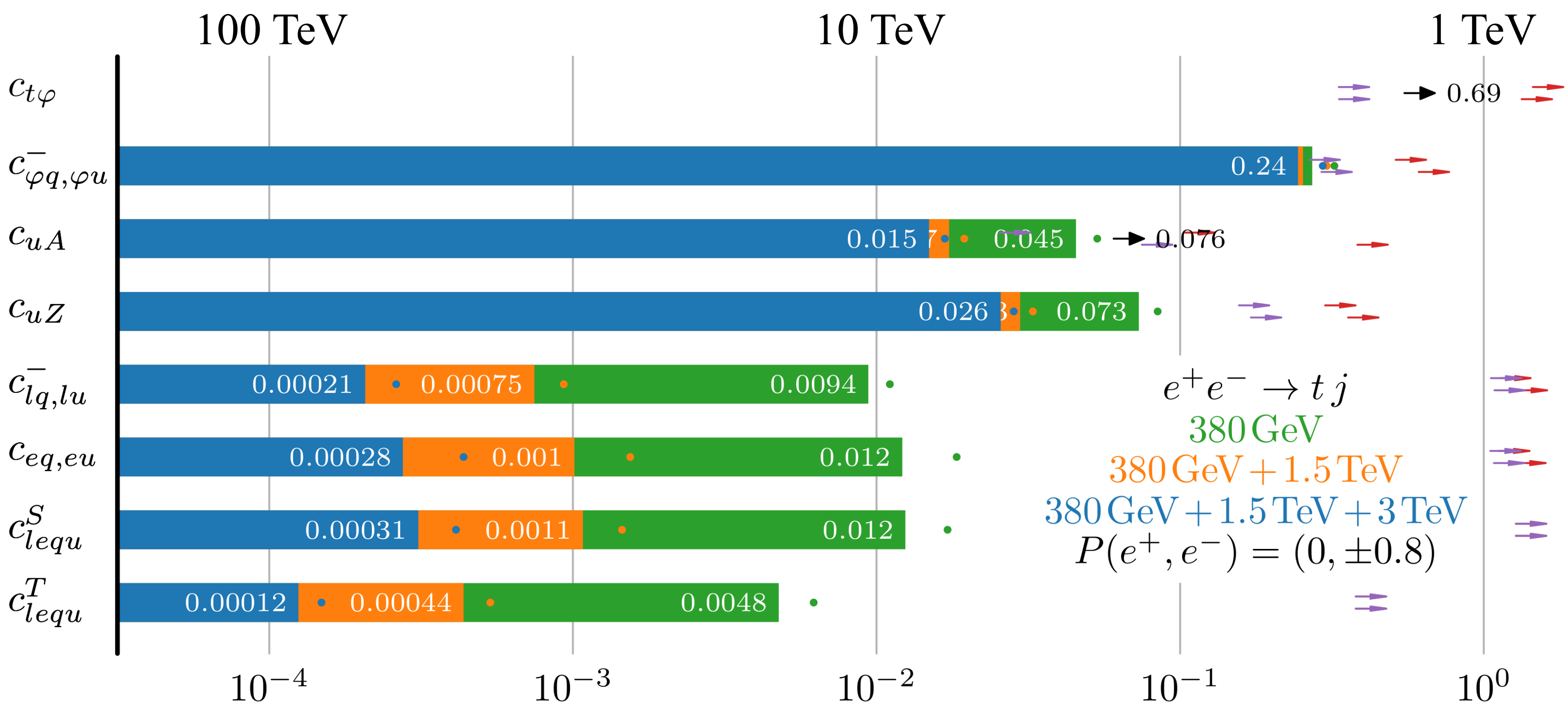
Input: limits on FCNC branching ratios, limits on $e^+e^- \rightarrow tj$ from LEP II



White marks: individual limits

Sec. 8.1 of CERN-LPCC-2018-06

Top-quark FCNC: $e^+e^- \rightarrow tj$ at CLIC



95% C.L. limits on top-quark FCNC operator coefficients

Black arrows: decays at CLIC (see slide X)
Red arrows: current LHC
Magenta arrows: HL-LHC projections
Dots: CLIC without beam polarisation

- The high-energy runs significantly improve the sensitivity for "four-fermion" operators
- $e^+e^- \rightarrow tj$ much more powerful than the decays at high-energy lepton colliders

CERN-2018-009-M

Dark Matter

Cosmology (thermal freeze-out mechanism) provides a strong motivation for direct, indirect and collider searches
→ DM masses from multi-keV to 100 TeV
→ Couplings to SM particles comparable or weaker than EW interactions

Focus on GeV - TeV mass range, two approaches:

1.) "Classic" electroweak WIMP candidates (SUSY inspired):
- Winos and Higgsinos

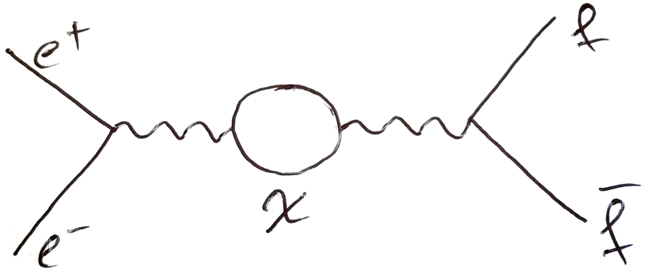
2.) Simplified models with mediator particles:
- Axial-vector simplified models
- Scalar simplified models

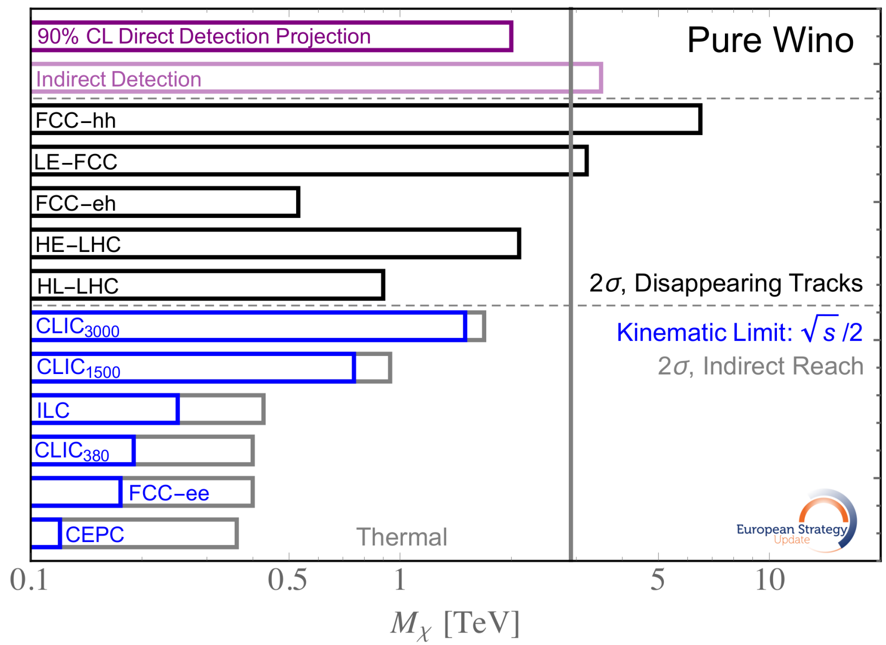
WIMPs: Wino and Higgsino

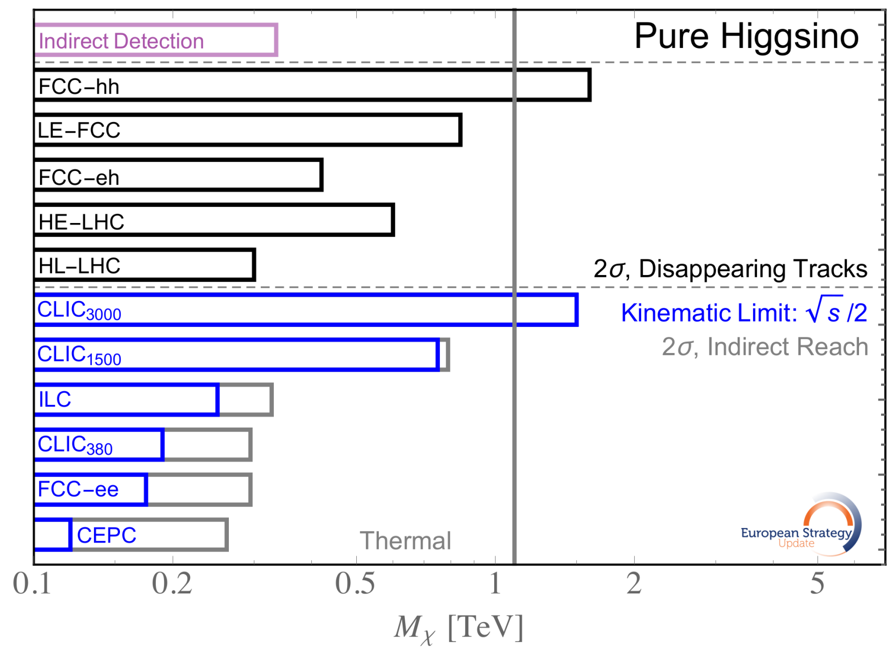
In SUSY terminology: "pure Wino" and "pure Higgsino" (spin ½ particles transforming as doublets or triplets under SU(2) symmetry)

Main techniques:

- Dark Matter in loops
- Disappearing tracks (→ see talk by Cecilia Ferrari)

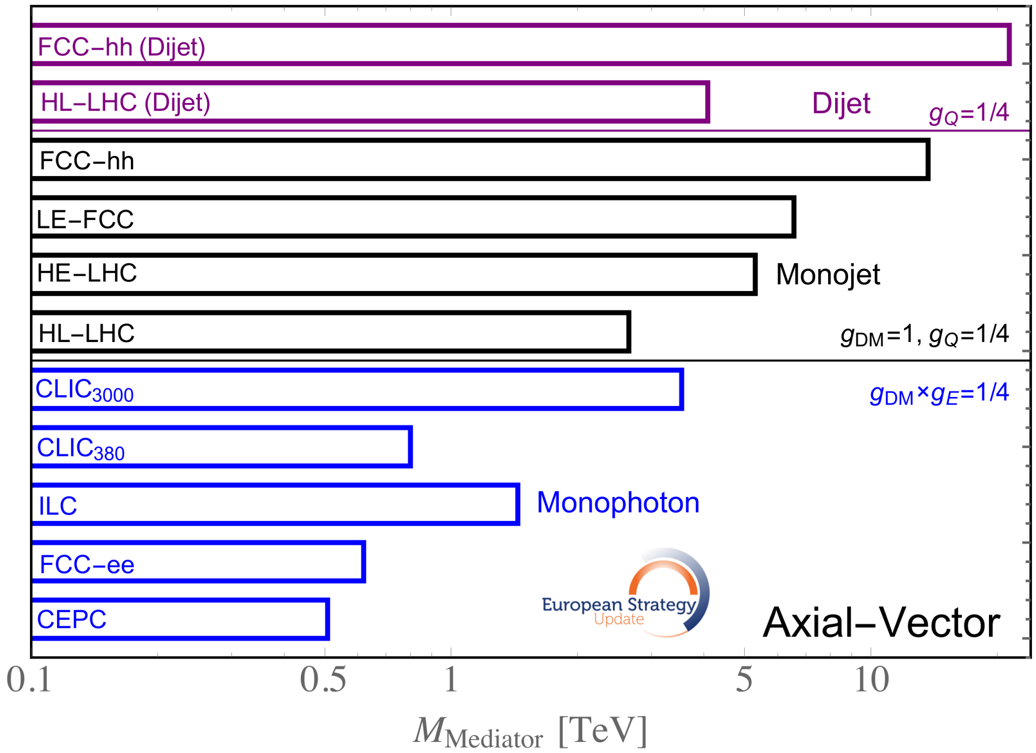


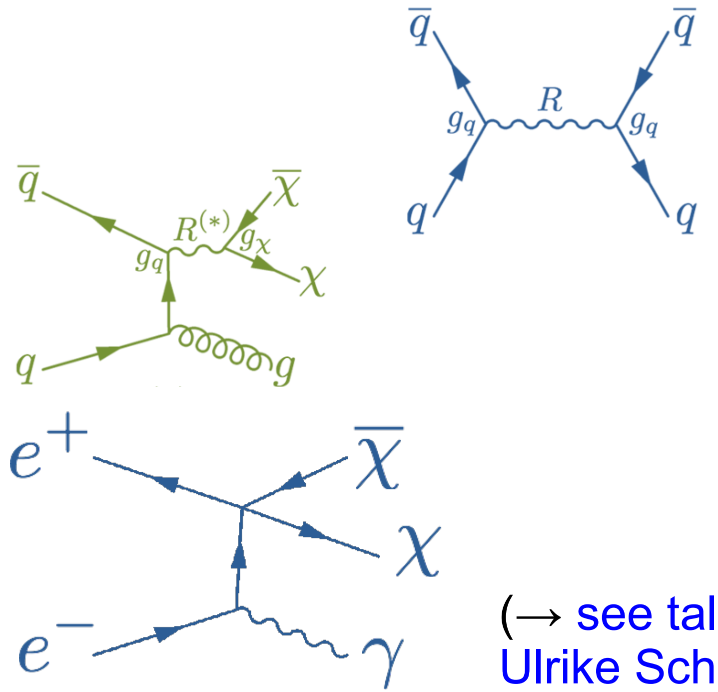




→ Thermal Wino within reach of FCC-hh and LE-FCC, thermal Higgsino within reach of FCC-hh and 3 TeV CLIC

Simplified models: axial vector



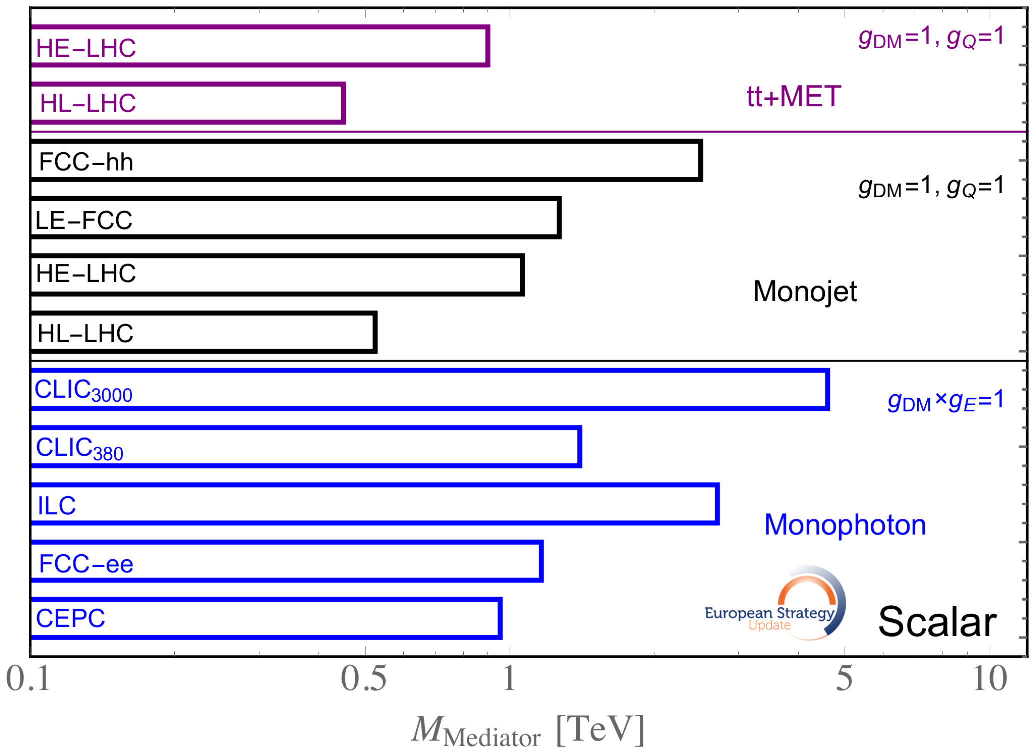


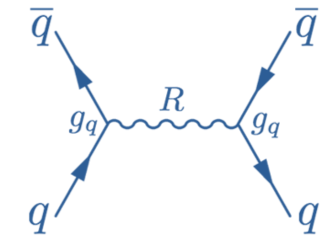
(→ see talk by Ulrike Schnoor)

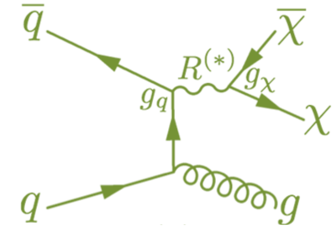
$$-Z'_\mu(g_{\rm DM}\,\bar\chi\gamma^\mu\gamma_5\chi + g_f\sum_f \bar f\gamma^\mu\gamma_5 f)$$

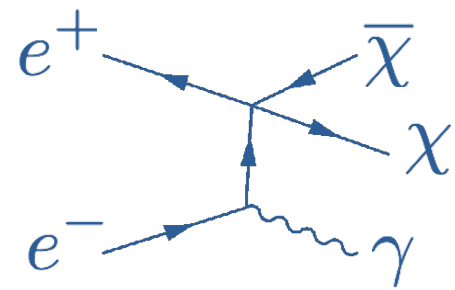
- Mediator is spin-1 particle (Z') coupled to an axial-vector current (reach of direct DM searches limited → interesting for colliders)
- pp colliders assume couplings to quarks only, e^+e^- colliders assume couplings to leptons only → projections not directly comparable

Simplified models: scalar









(→ see talk by Ulrike Schnoor)

$$\phi(g_{\text{DM}}\,\bar{\chi}\chi - g_f \sum_f y_f \bar{f} f/\sqrt{2})$$

y_f: Yukawa couplings

- Mediator is spin-0 particle (ϕ)
(reach of direct DM searches limited → interesting for colliders)
- pp colliders assume couplings to quarks only, e^+e^- colliders assume couplings to leptons only
→ projections not directly comparable

Feebly-interacting particles

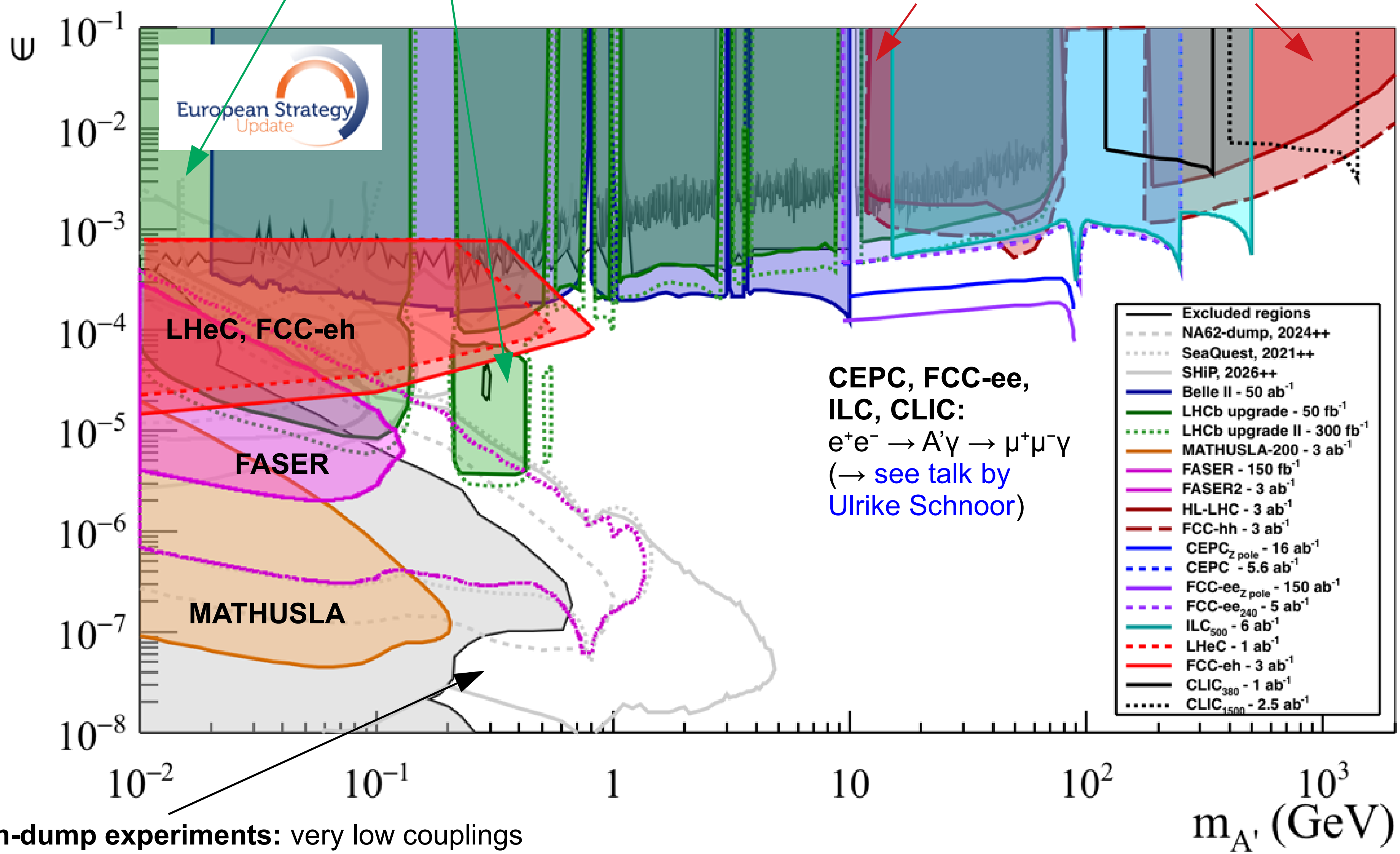
- Undetected particles feebly interacting with SM particles: part of Hidden or dark sector
- Masses and interactions of dark sector particles unknown, focus here on MeV to tens of GeV range → important motivation is Dark Matter
- Very wide range of theoretical models: simplified models (4 portals) to compare experiments from Physics Beyond Colliders study
- From portals: identify benchmarks to evaluate experimental sensitivity → common ground to compare machines / experiments

Portal	Coupling
Vector (Dark Photon, A_μ)	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$ ←
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$ ←
Fermion (Sterile Neutrino, N)	$y_N L H N$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$ ←

Dark Photons

LHCb: $D^{*0} \to D^0 A'$; $A' \to e^+e^-$ & $pp \to A' \to \mu^+\mu^-$

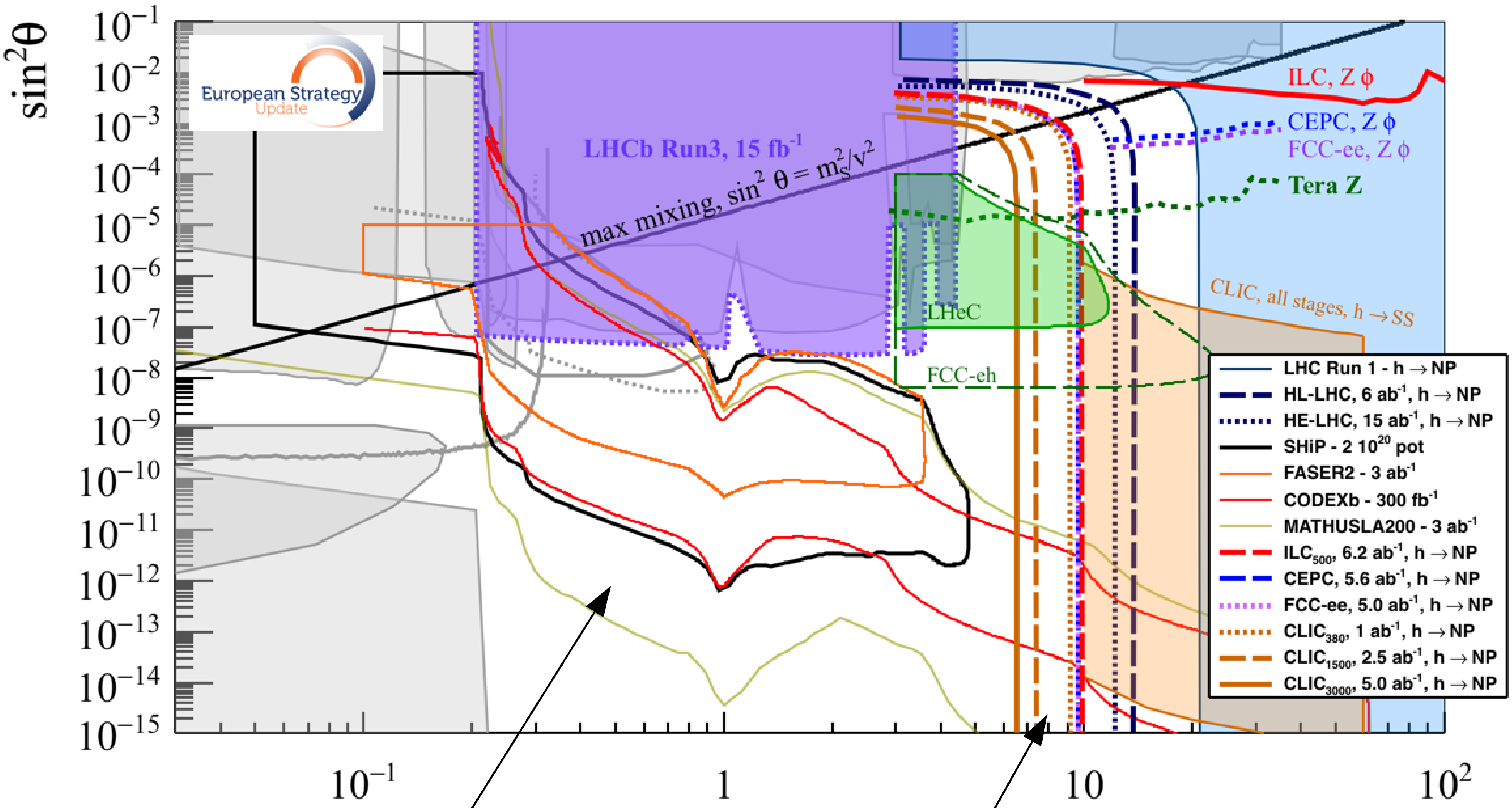
HL-LHC / FCC-hh: $pp \to A' \to \mu^+\mu^-$



CEPC, FCC-ee, ILC, CLIC:
$e^+e^- \to A'\gamma \to \mu^+\mu^-\gamma$
(→ see talk by Ulrike Schnoor)

Beam-dump experiments: very low couplings at very low masses

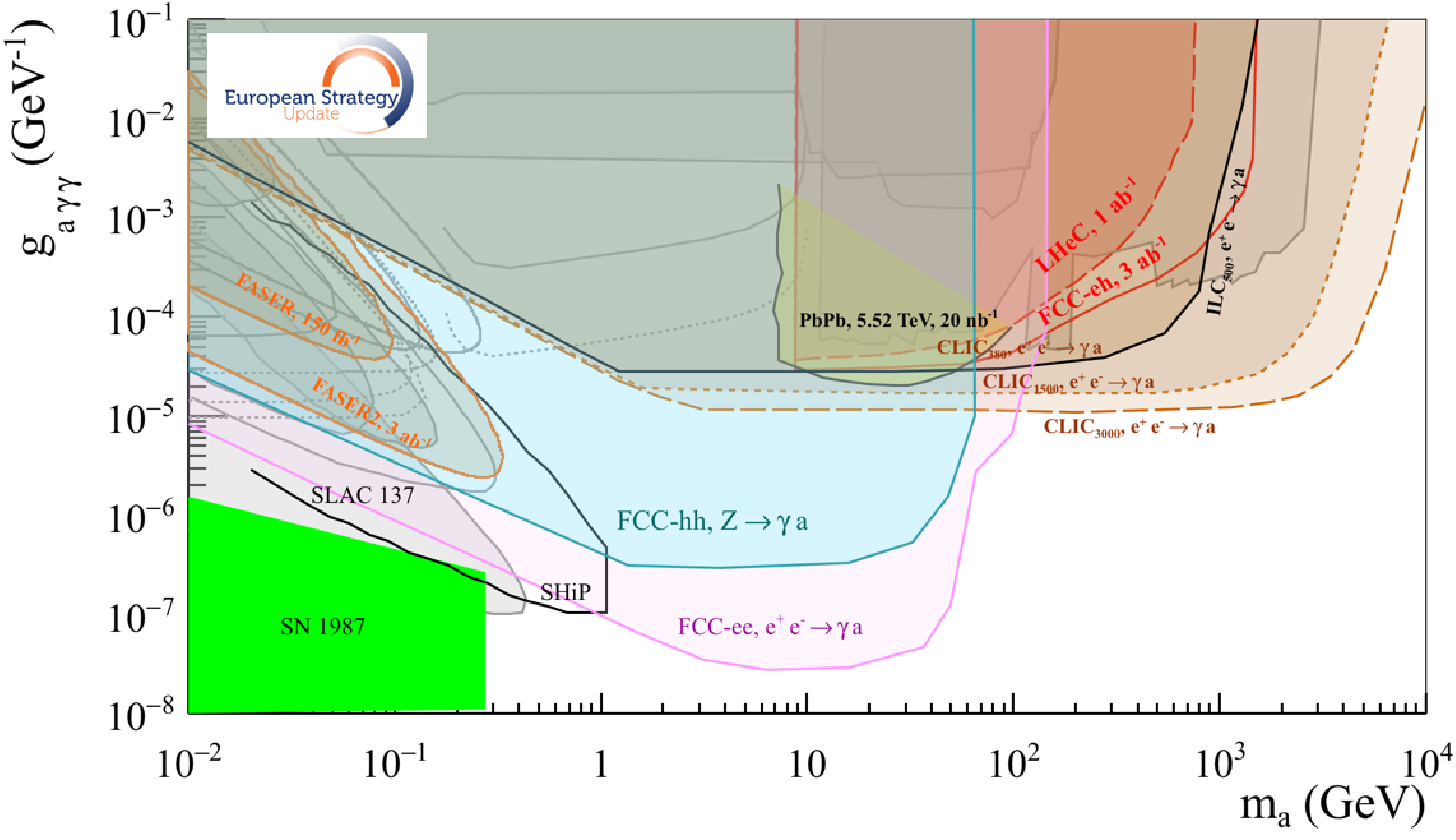
Dark scalar mixing with the Higgs



SHiP, MATHUSLA, FASER, CODEXb

Precision Higgs at colliders

ALPs coupled to photons



Summary

• Substantial improvement with respect to HL-LHC possible for all discussed physics topics

• Precision Higgs measurements are central for many BSM scenarios (e.g. composite Higgs models, extended Higgs sectors)

• Large amount of complementarity between direct and indirect searches (e.g. Higgs couplings, EW precision measurements at Z-pole, flavour sector, SM processes at highest energies) for new particles and interactions

• For feebly-interacting particles (including forms of Dark Matter), the reach of energy-frontier colliders is complemented by beam-dump and fixed target facilities at low masses

Thank you!

Backup slides

Heavy Neutral Lepton mixed with electron neutrino