Beyond the Standard Model (at colliders)

Open Symposium on the Update of European Strategy for Particle Physics

Gian Giudice and Paris Sphicas
For the BSM group
J. Alcaraz, C. Doglioni, G. Lanfranchi, M. D'Onofrio, M. McCullough,
G. Perez, P. Roloff, V. Sanz, A. Weiler, A. Wulzer

May 16, 2019

- **Introduction**
  - **Some cautionary comments**
  - **The big questions (& some smaller questions)**
- **The [partial] answers to the Big Questions**
  - **And some answers to the Smaller Questions**
- **Outlook**

Introduction

Generalities, some cautionary comments

Introduction – some cautionary comments

- **BSM space is huge. As in Huge.**
  - Impossible to cover everything. (IMPOSSIBLE)
- **We are not providing an exhaustive list of reach for each and every model/parameter hypothesis.**
  - Rather, concentrate(d) on wide comparisons that cover the essence of each thematic area
- **Caution: inputs used have had very different levels of detail, simulation/precision and analysis maturity.**
  - From full simulation to DELPHES to scaling by Lumi…
- **We have looked at the easy part: the "reach" of the various options.**
  - This means mostly "limits". In some cases, also discovery.
  - Next level: FTC [Future To-be-defined Collider] observes excess in jets+MET → What next? Another major issue.
    - Characterization of new signals → next Strategy Update.

The Big Questions (BQs)

- **The four big questions for BSM (@colliders):**
  - To what extent can we tell whether the Higgs is fundamental or composite?
  - Are there new interactions or new particles around or above the electroweak scale?
  - What cases of thermal relic WIMPs are still unprobed and can be fully covered by future collider searches?
  - To what extent can current or future accelerators probe feebly interacting sectors?

Topics in BSM

1) Electroweak breaking dynamics and resonances (EWSB/NewR)

Andrea Wulzer (CERN) & Juan Alcaraz (CIEMAT)

Composite Higgs, top partners, particles associated with EW symmetry breaking, heavy Z' and W'

2) Supersymmetry (SUSY)

Andreas Weiler (TUM) & Monica D'Onofrio (Liverpool)

Collider searches, motivations for supersymmetry after the LHC, unexplored corners, new models

3) Extended Higgs sectors & High-energy flavor dynamics (Ext-H/FD)

Veronica Sanz (Sussex) & Philipp Roloff (CERN)

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 (DM)

Matthew McCullough (CERN) & Caterina Doglioni (Lund)

Collider searches, simplified models, comparisons with direct/indirect searches

5) Feebly-interacting particles (FIPs)

Gilad Perez (Weizmann) & Gaia Lanfranchi (INFN, Frascati)

Long-lived particles, right-handed neutrinos at the EW scale, dark photons at colliders, dark scalar/relaxion, ALPs at colliders

The Big Questions (BQs)

- **The four big questions for BSM (@colliders):**
  - To what extent can we tell whether the Higgs is fundamental or composite?
    - EWSB/NewReson, SUSY
  - Are there new interactions or new particles around or above the electroweak scale?
    - EWSB/NewReson, SUSY, Ext-H/FlavorDyn, DM, FIPs
  - What cases of thermal relic WIMPs are still unprobed and can be fully covered by future collider searches?
    - DM, FIPs, SUSY
  - To what extent can current or future accelerators probe feebly interacting sectors?
    - FIPs, SUSY

EFTs, and the world of direct vs indirect

- **BSM searches: direct ones, where one can use specific models (or classes of models, e.g. SUSY); *important info also from precision measurements*.**
  - **Maximal expression of our ignorance: "SM is an EFT" → write down all possible dim-6 operators and see what new things we would see or what we would learn from limiting size of terms**

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

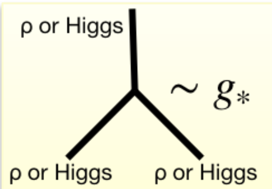
- c_H term → *Scaling all Higgs couplings by a common factor*
- c_{2W}, c_{2B} terms → *4-fermion contact ints., W', Z' resonances*
- c_W, c_B terms → *2 fermion–2 boson contact interactions, S parameter*
- c_{y_t}, c_{y_b} terms → *Modify top and bottom Yukawa couplings*
- + … → *And much, much more…*

Partial Answers to the Big Questions (I)

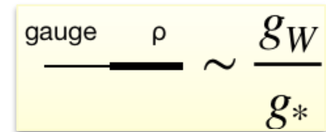
Is the Higgs fundamental?

Higgs Compositeness?

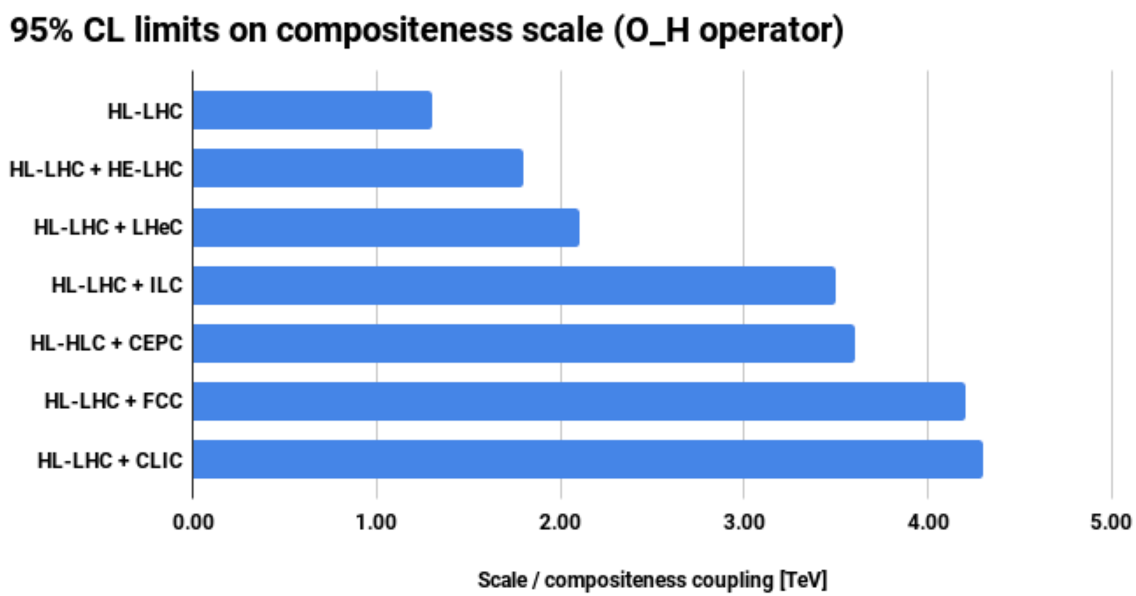
- **Using fits from EWK/Higgs group (arXiv:1905.03764)**
  - **Connection between notations:**



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

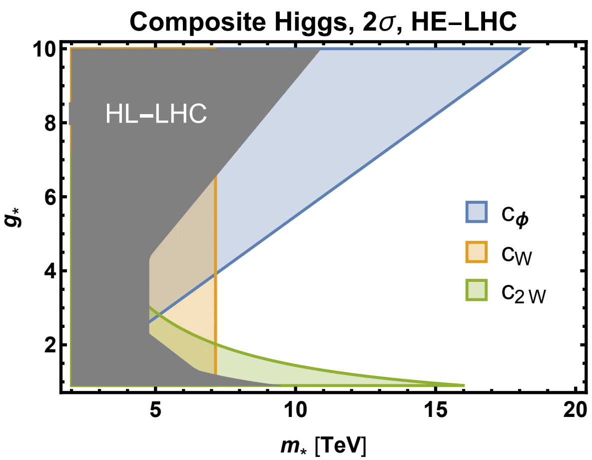


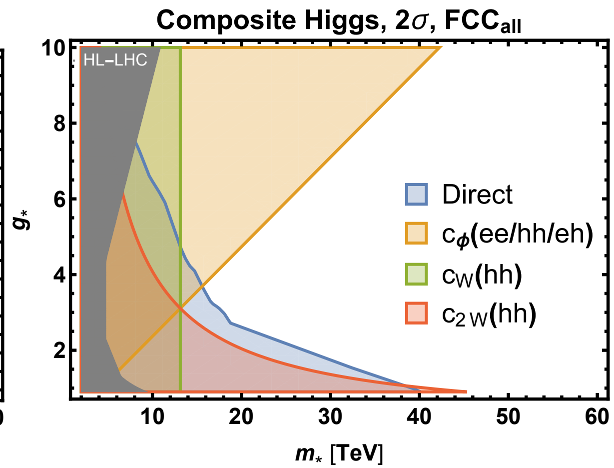
  - **Deviations ~1% in Higgs couplings for mass/coupling ~2 TeV**

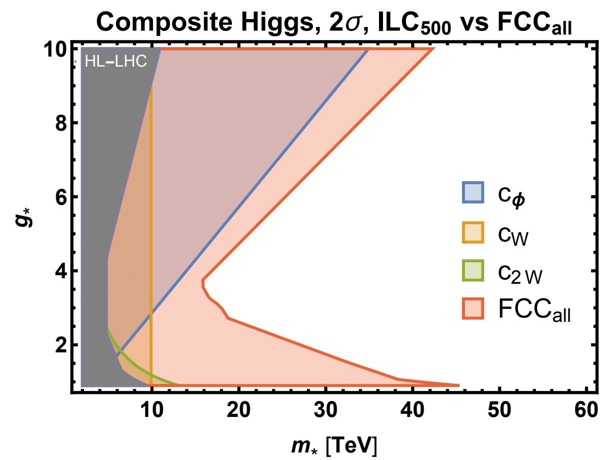


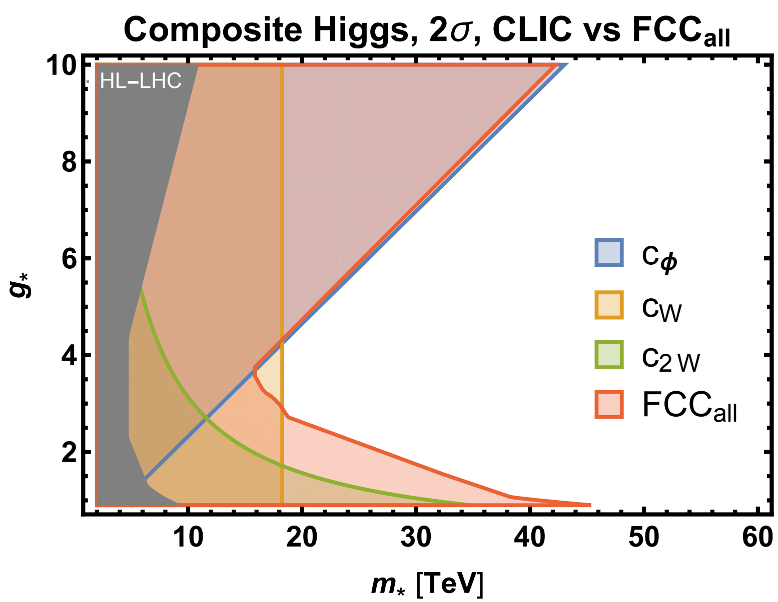
Maximum sensitivities from CLIC and FCC(ee+eh+hh)

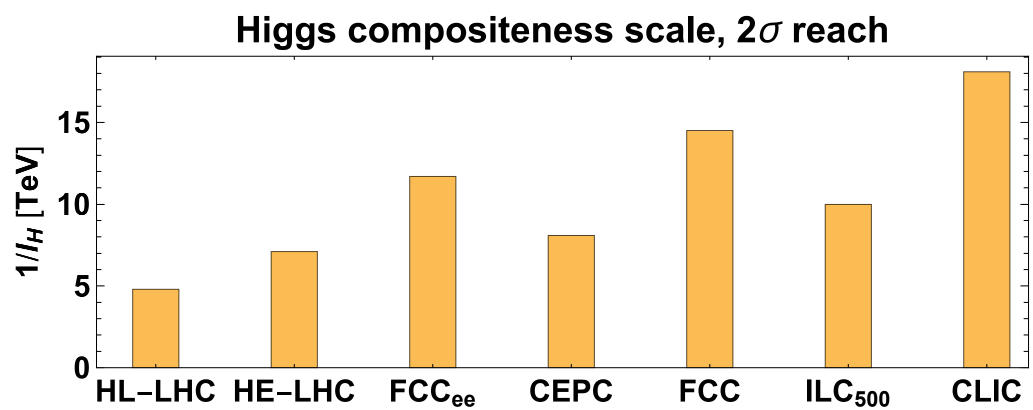
Higgs Compositeness?











Higgs Compositeness? + New question

- **Corollary question: is it "natural"?**

$$(m_H^2)_{Phys.} = \int_0^\infty F_{true}(E; g_{true}) = \int_0^{\Lambda_{UV}} (\ldots) + \int_{\Lambda_{UV}}^\infty (\ldots)$$

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{126\,\text{GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{UV}}{500\,\text{GeV}}\right)^2$$

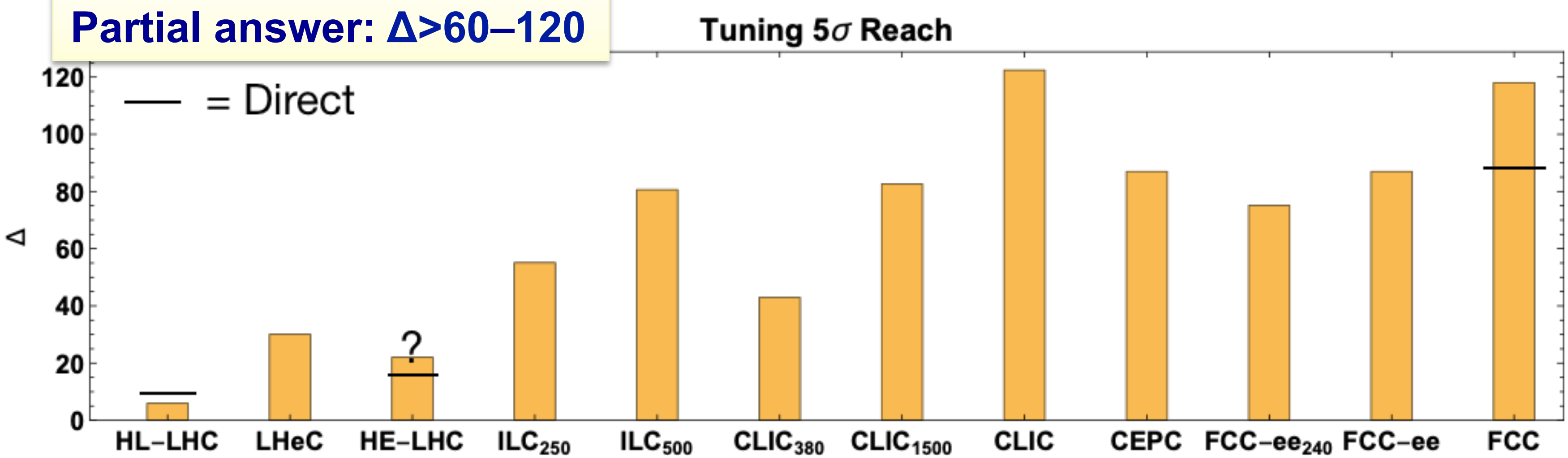
SM Contribution

$$\delta m_H^2 = \frac{3y_t^2}{8\pi^2}{\Lambda_{UV}}^2$$

HL-LHC: gets to Λ_{SM}~2TeV → Δ>10

$$\Delta > \left(\frac{M_{T.P.}}{500\,\text{GeV}}\right)^2 > \frac{1}{\xi} \qquad \frac{c_\phi}{\Lambda^2} = \frac{g_*^2}{m_*^2} = \frac{\xi}{v^2} \Rightarrow \frac{1}{\xi} = \frac{1}{v^2}\left(\frac{c_\phi}{\Lambda^2}\right)^{-1}$$

Partial answer: Δ>60–120



Partial Answers to the Big Questions (II)

Are there new interactions or new particles around or above the electroweak scale?

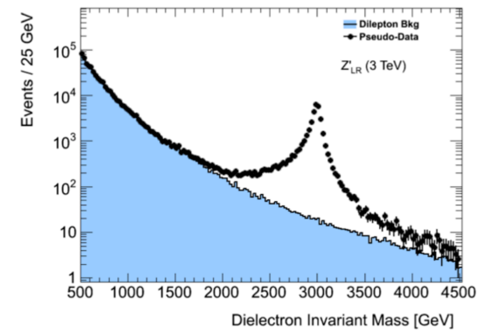
New resonances/particles/forces?

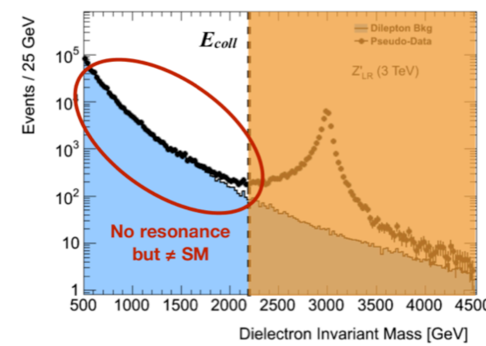
Seeing the peak. Reach:

- M < √s for lepton colliders
- M ≲ 0.3-0.5 √s in hadron colliders for couplings ~ weak couplings

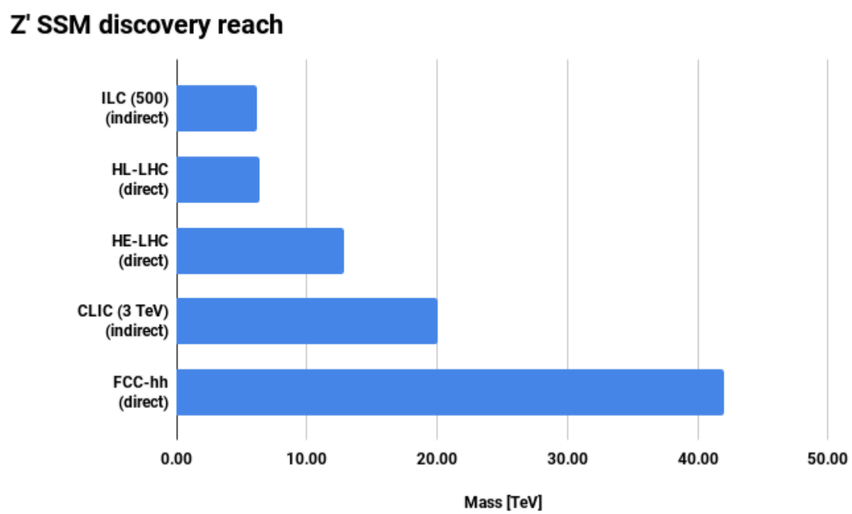
Deviations in high-M tails:

- Better suited for lepton colliders; sensitive to [mass/coupling] ≫ √s
- Hadron colliders relevant for $g_{Z'} > g_{SM}$ couplings: [mass/coupling] ≫ 0.5√s



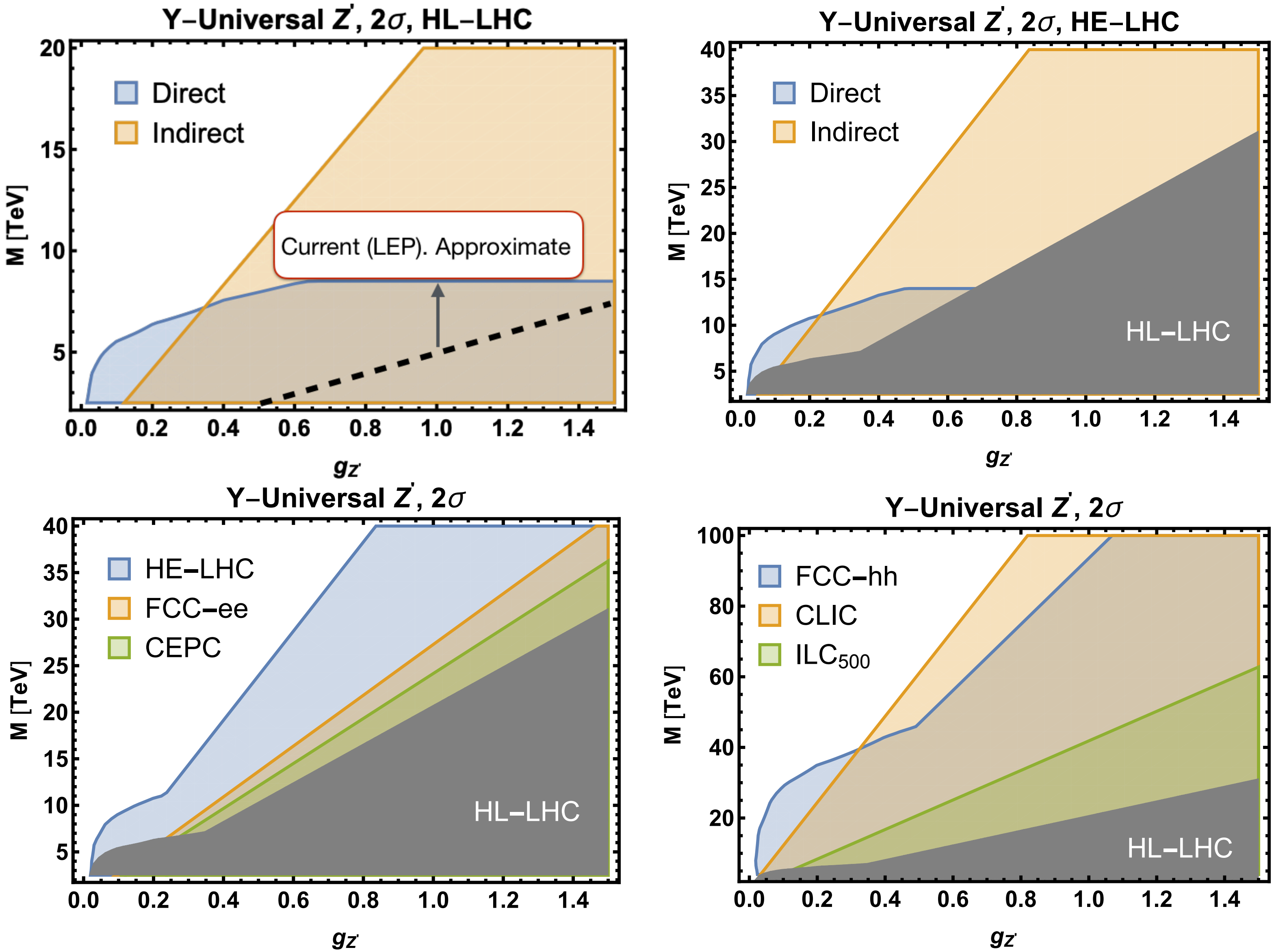


Courtesy: J. De Blas

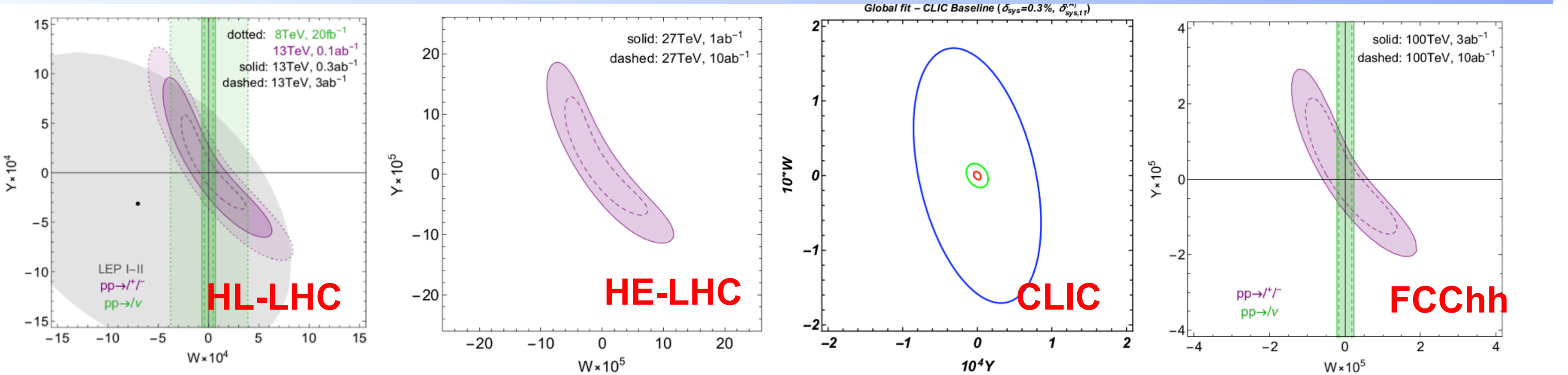


In what follows: using very simple model as example.
Universal Z'. Clearly, many models with flavor dependence etc.

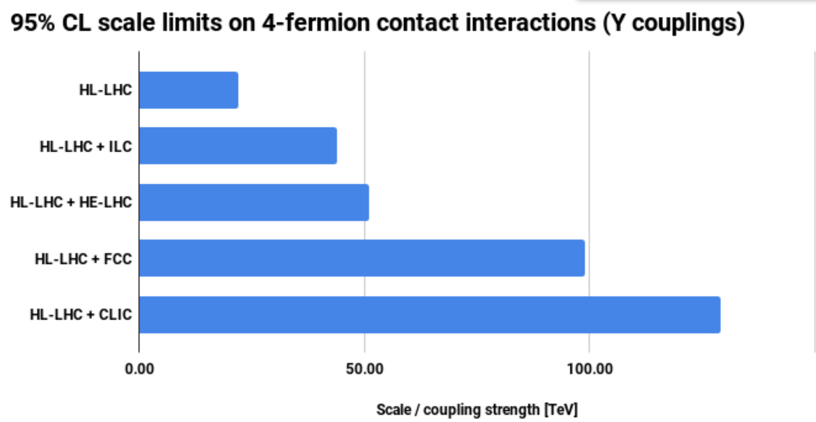
New resonances/particles/forces?

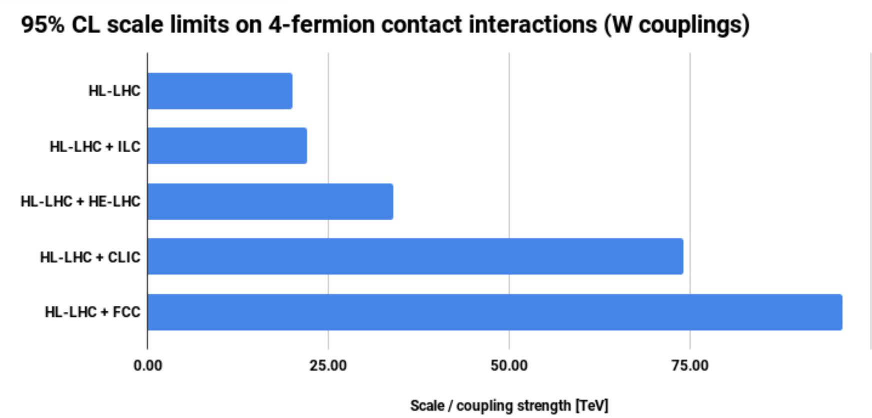


Contact Interactions



$$\frac{g^2 W}{m_W^2}, \frac{g'^2 Y}{m_W^2} \rightarrow \Delta\left(\left[\frac{\text{coupling}}{\text{Scale}}\right]^2\right)$$





Sensitivity for ee colliders enhanced for couplings ≳ 1
(weak couplings → direct searches become more sensitive)
Searches for W' & charged fermion currents more effective at hadron colliders

Extended Scalar Sectors?

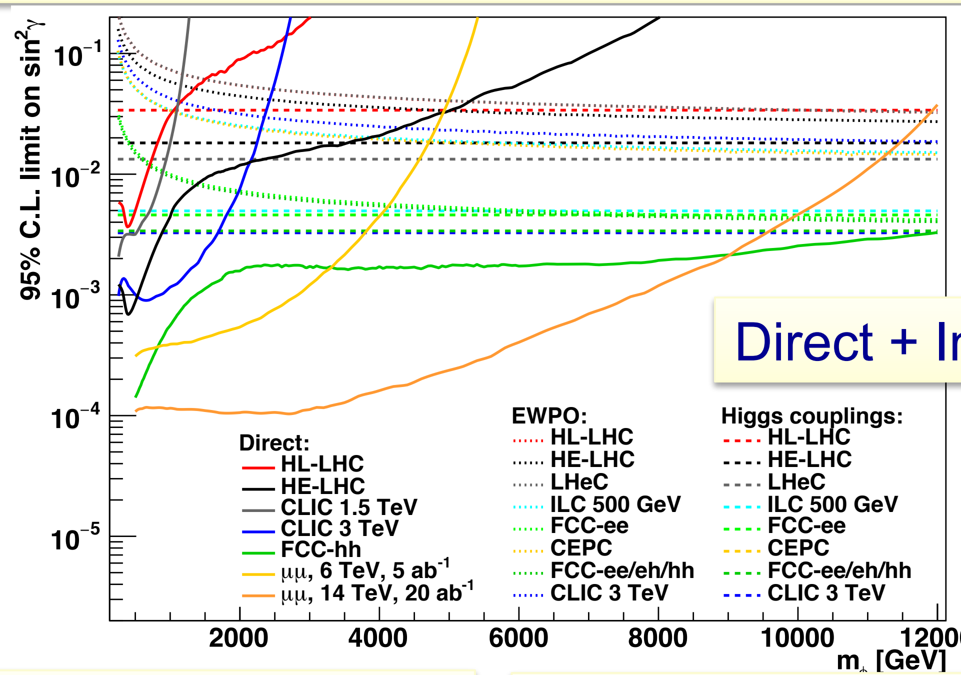
$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 - \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 + \lambda_{HS}|H|^2 S^2$$

h & S can mix
$h = h_0 \cos\gamma + S \sin\gamma$
$\varphi = S \cos\gamma - h_0 \sin\gamma$

Indirect: H couplings + EWK PO

Direct searches: pp: main LHC result ZZ; hadron colliders: extrap in $\sqrt{s}$; $e^+e^- \to \nu\nu\varphi$; $\varphi \to hh \to bbbb$

Facility	$\sin^2\gamma$ lim (95% CL)
HL-LHC	0.034
LHeC	0.013
HE-LHC	0.018
ILC 250	0.0073
ILC 500	0.0050
CLIC 380	0.0093
CLIC 1.5	0.0048
CLIC 3	0.0033
CEPC	0.0046
FCCee 240	0.0053
FCC-ee	0.0046
FCC-all	0.0034



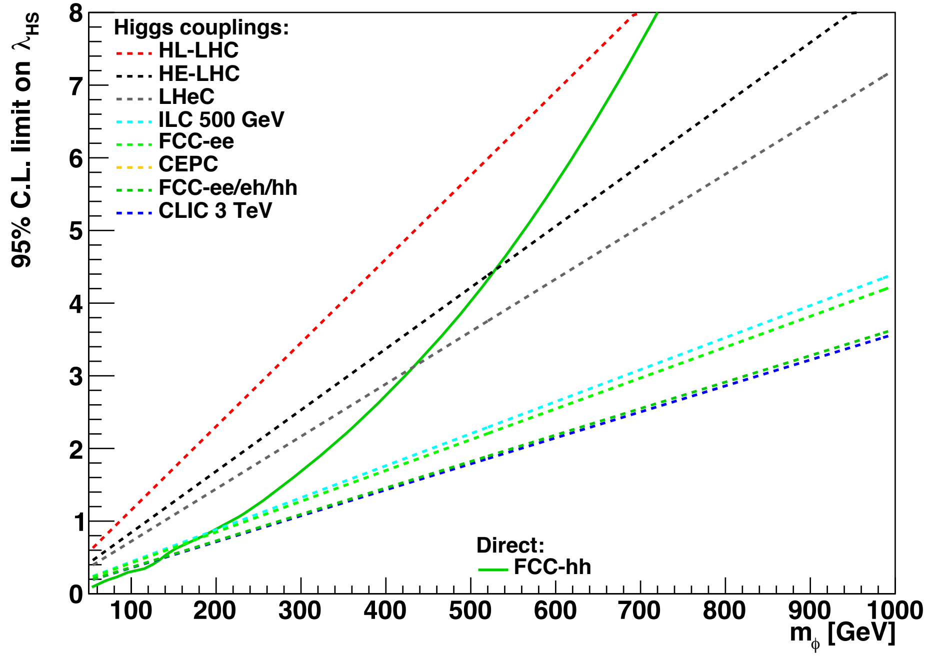
Direct + Indirect

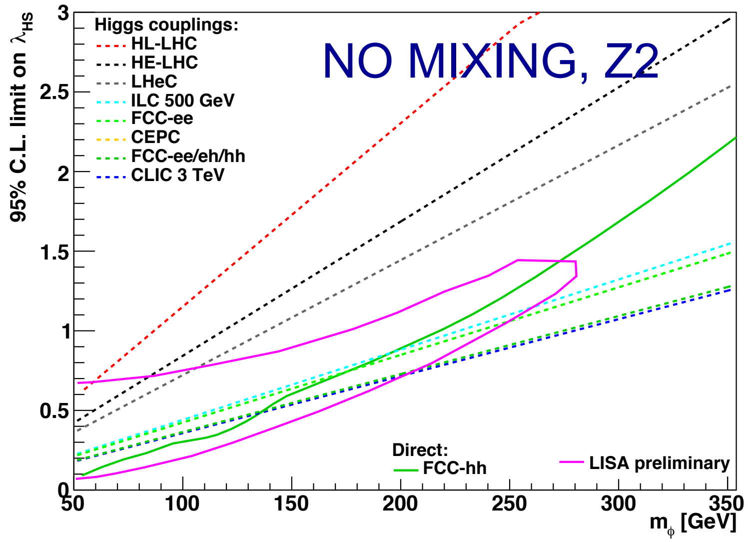
Direct & indirect: provide complementary info (HL-LHC, HE-LHC & CLIC)

Direct reach at FCC-hh better than precision H couplings for m_φ<12 TeV

Extended Scalar Sectors? (zero mixing)

- **Corollary question: is it a first-order phase transition?**





Direct search: VBF φφjj, φ→MET

Indirect info more powerful;
CLIC3.0 = FCC-all

Large area where first-order PT is possible [green] can be probed; not completely, though.

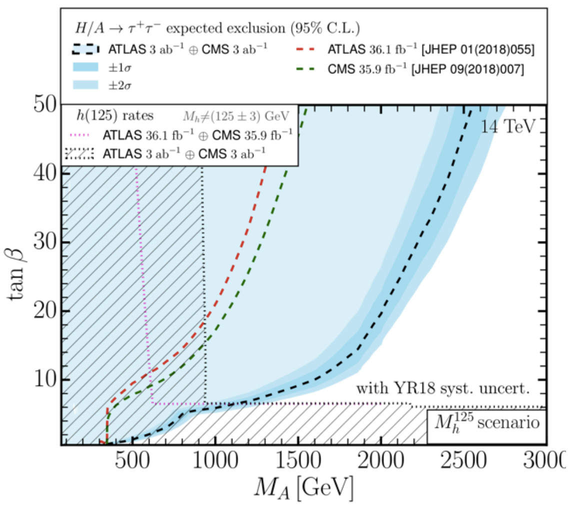
Extended Scalar sectors: MSSM

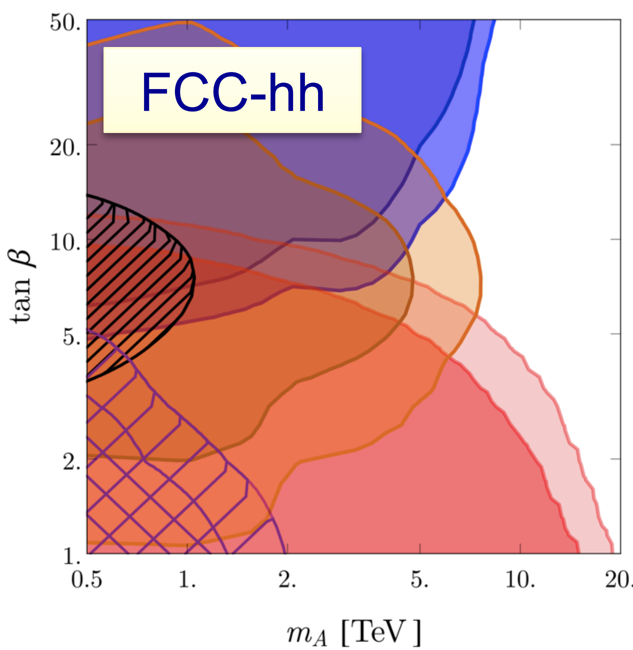
Hadron colliders

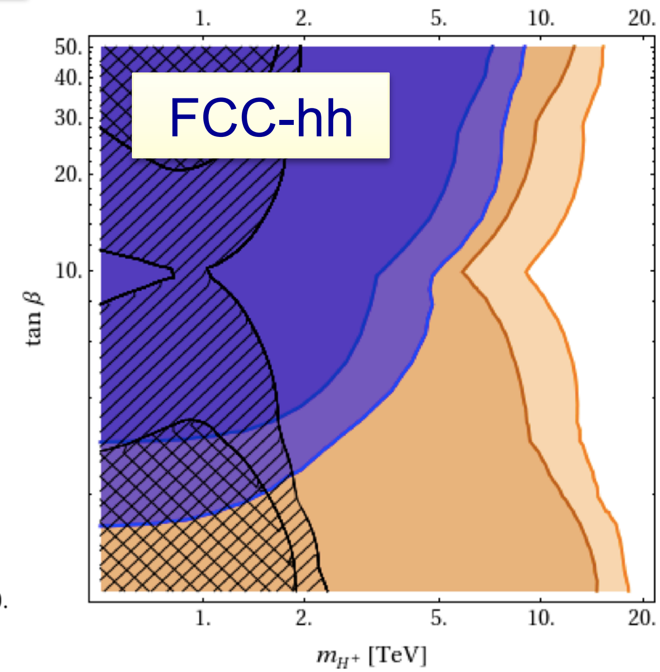
pp → bbH^0/A → bbττ (large tanβ)
pp → bbH^0/A → ttbb (int. tanβ)
pp → ttH^0/A → tttt (low tanβ)

pp → btH$^{\pm}$ → bbτν
pp → btH$^{\pm}$ → tbtb

LHC+HL-LHC



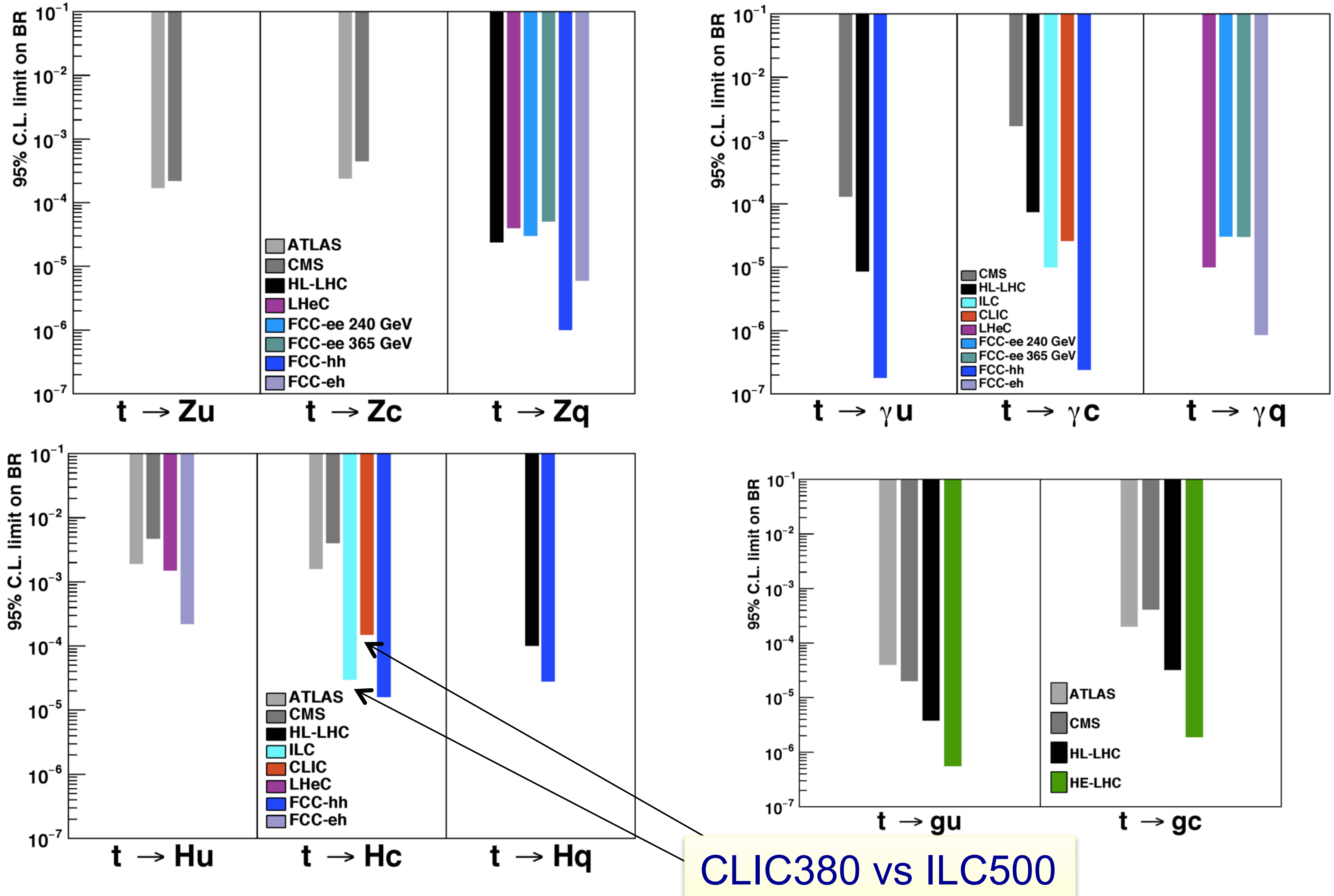




Indirect info also probes additional h bosons (e.g. $\kappa_b \sim m_Z^2/m_A^2$)

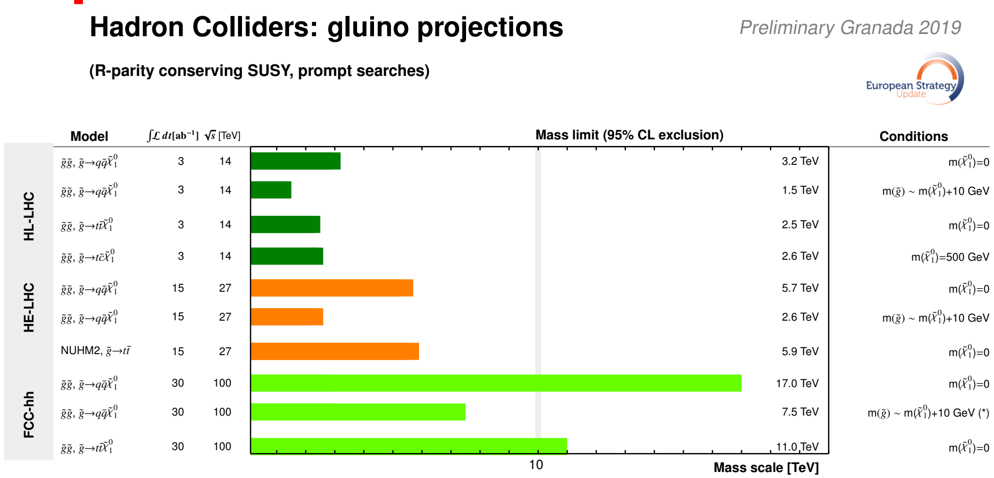
H^0/A: exclusion limits > 5 TeV
(20 TeV at low tan β)
H$^{\pm}$: exclusion limits ~10 - 15 TeV

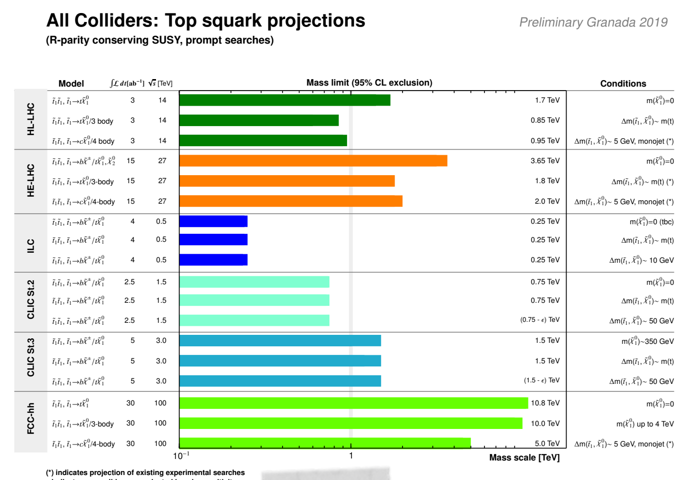
Flavor Dynamics (FCNC)



Extra particles at ~ TeV? SUSY has many…

- **Corollary questions:**
  - If {SUSY} which masses (and mass differences) of strongly- or weakly coupled super-partners can we reach?
  - Is nature fundamentally fine-tuned? If the solution is SUSY, how well can we test this?
  - Is dark matter a thermal SUSY WIMP?
- **Strongly-interacting SUSY (gluinos and squarks): the purview of hadron colliders**





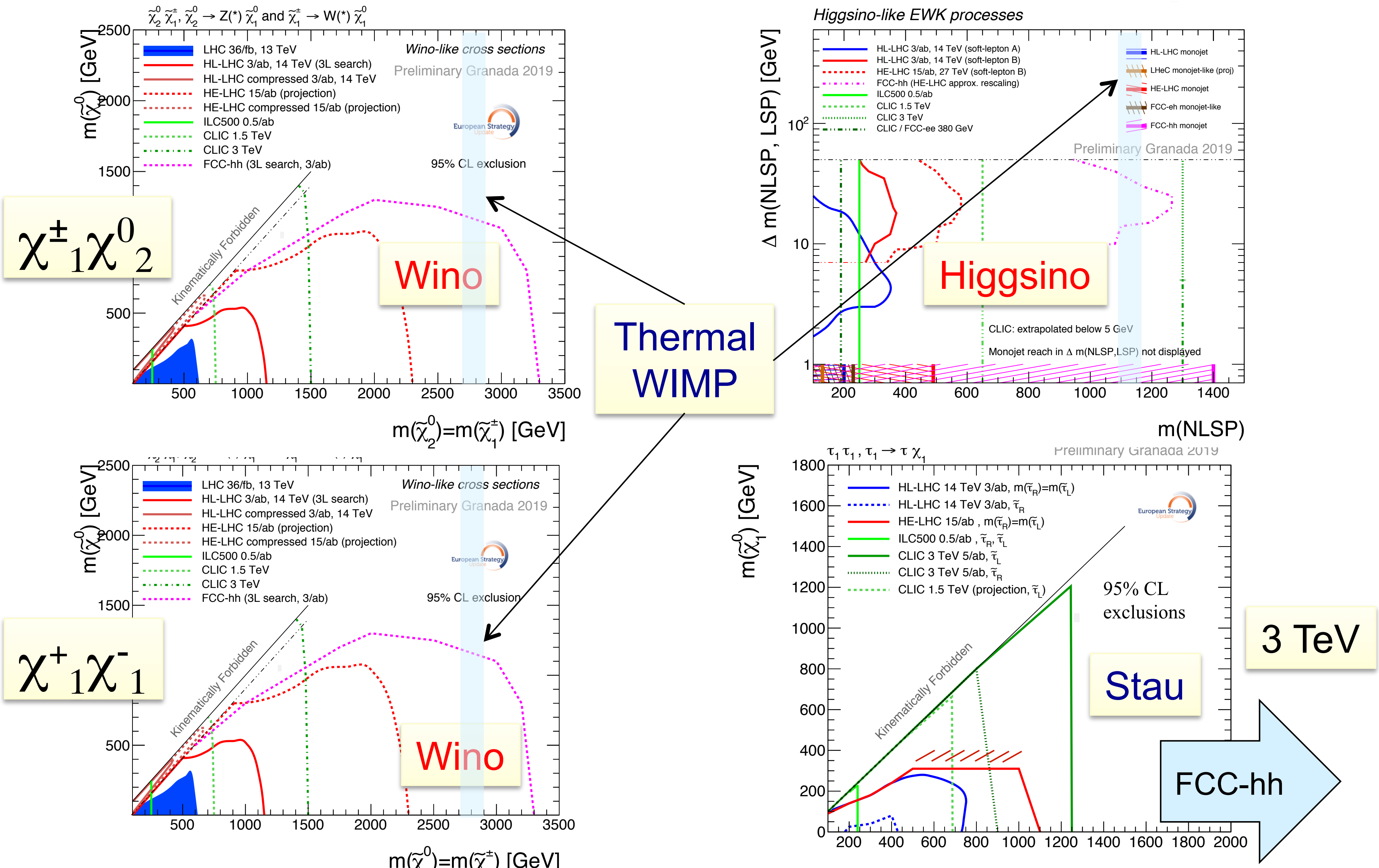
HE-LHC: ~ 2 x $M_{HL\text{-}LHC}$
FCChh: ~ 5 x $M_{HL\text{-}LHC}$

Canonical signature: $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \to t\tilde{\chi}_0$

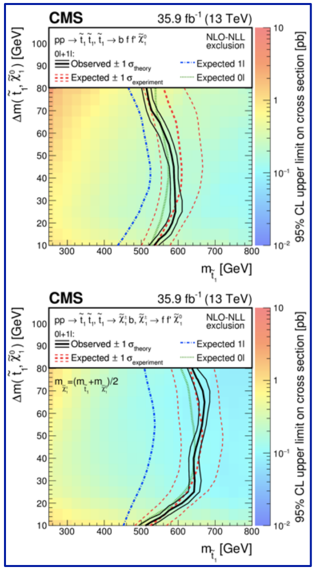
ILC_{500}: $m_{stop} > 250$ GeV
$CLIC_{3000}$: $m_{stop} > 1500$ GeV

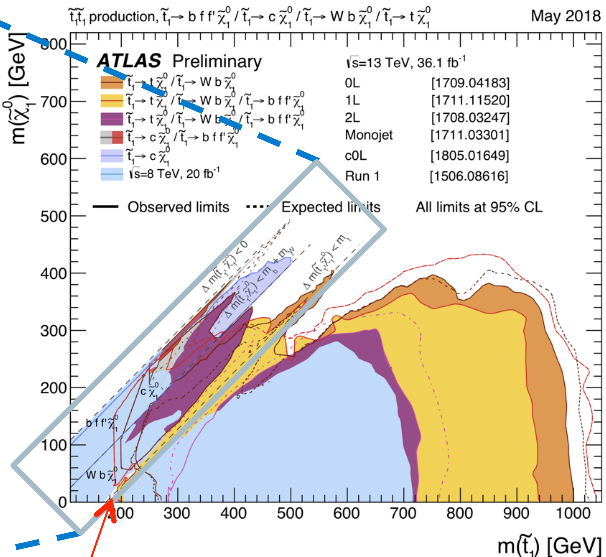
FCC_{HH} : HE-LHC : HL-LHC ≈ **6 x : 2 x : 1**

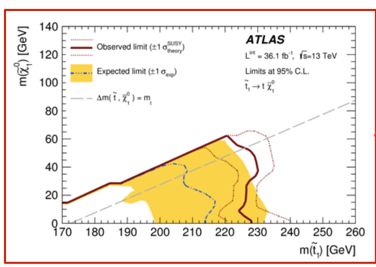
SUSY: EWK sector

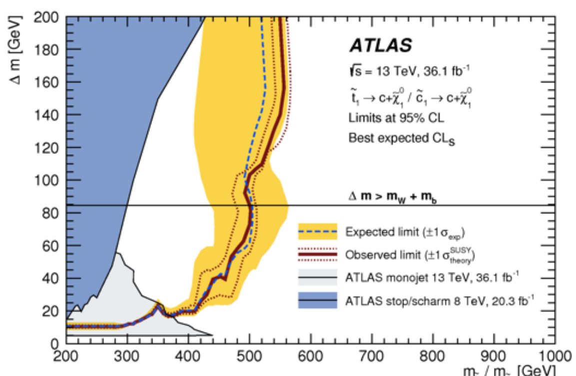


SUSY: any “holes”?

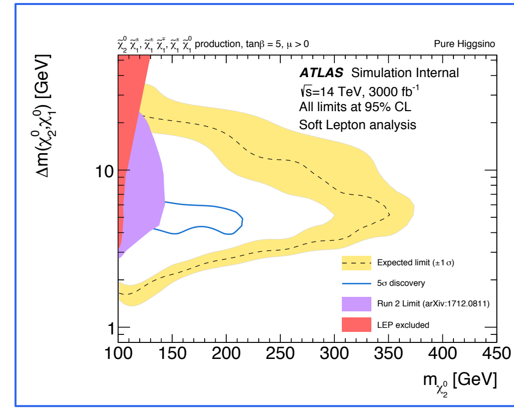


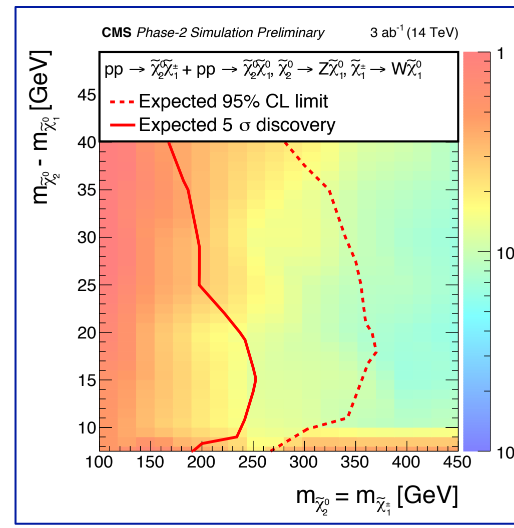






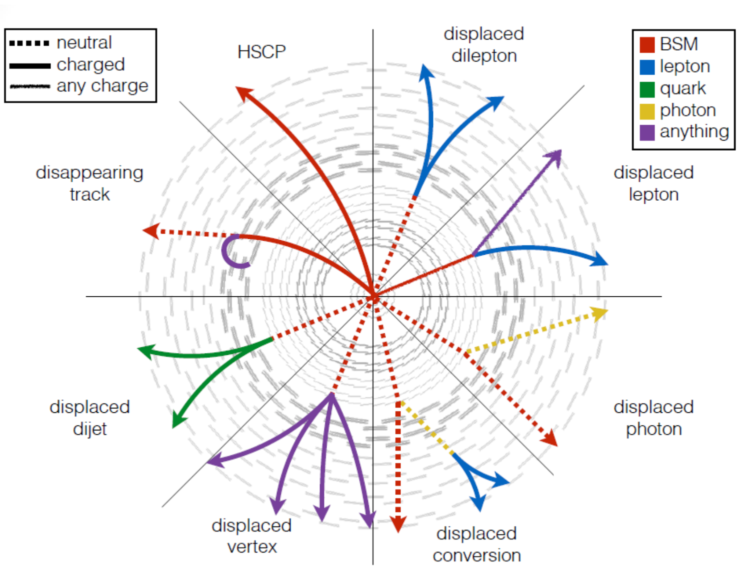
–:
Info only from LHC (& only for stop).
+:
based on data!



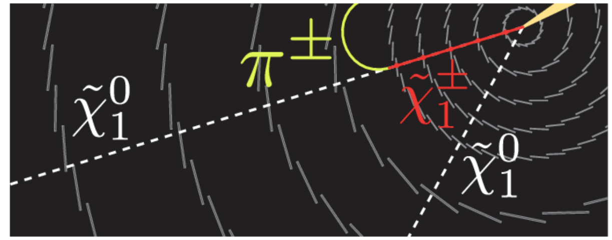


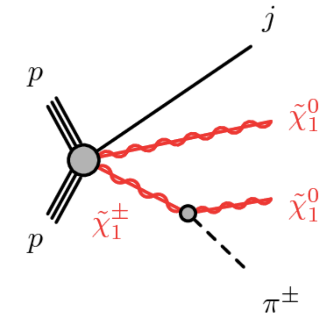
Indeed, after LHC, there will be holes [in low mass regions]; closing or looking at how to close them at HL-LHC; for EWKinos, some regions will remain difficult @ pp.

Long-lived SUSY?

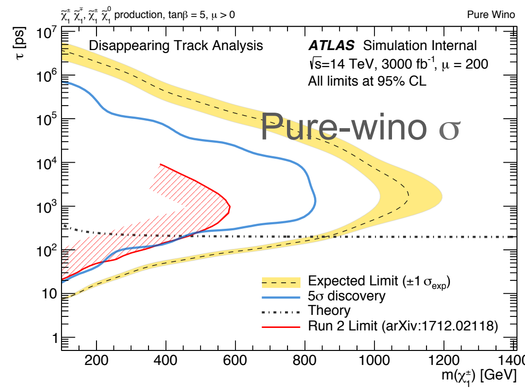


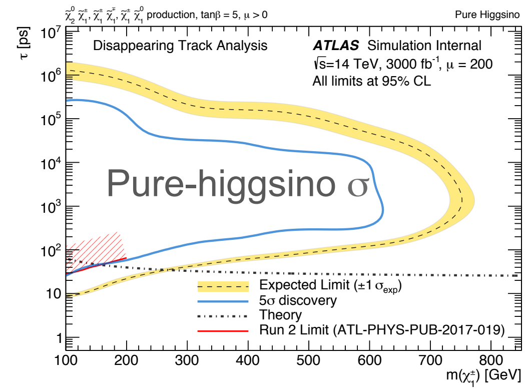
Charged stub + photon

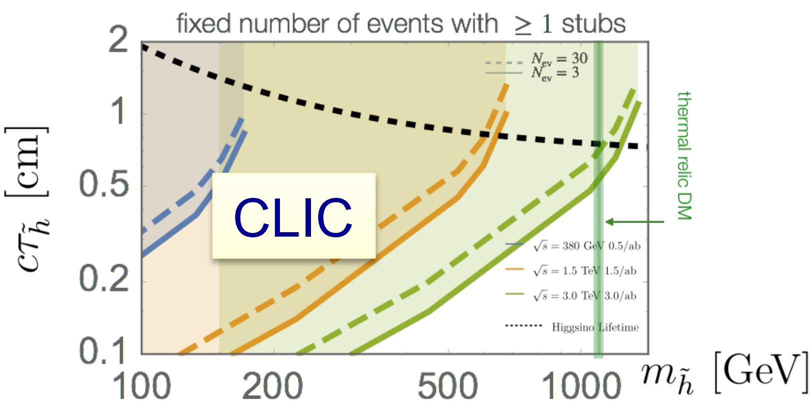




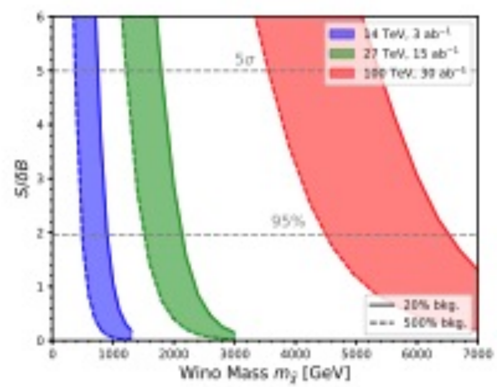
HL-LHC

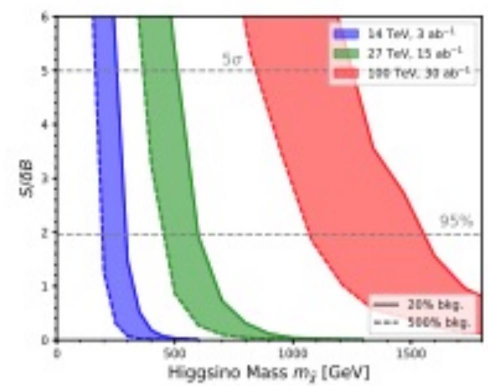






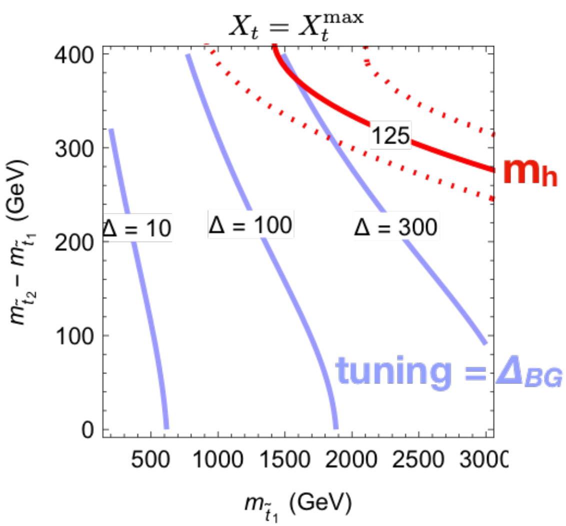
CLIC



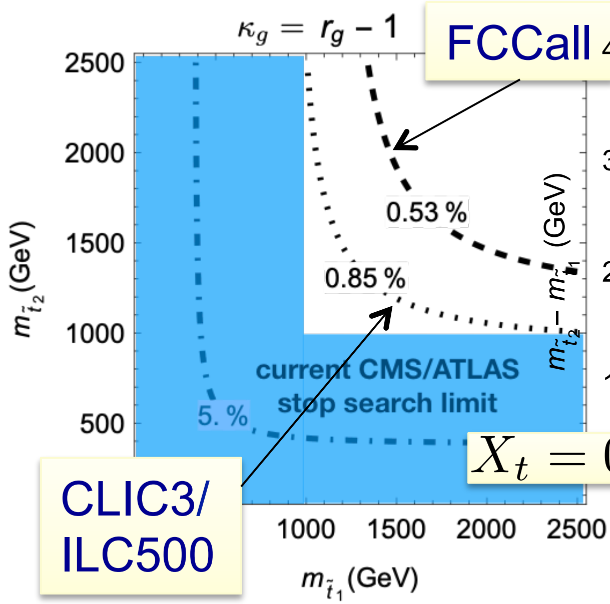


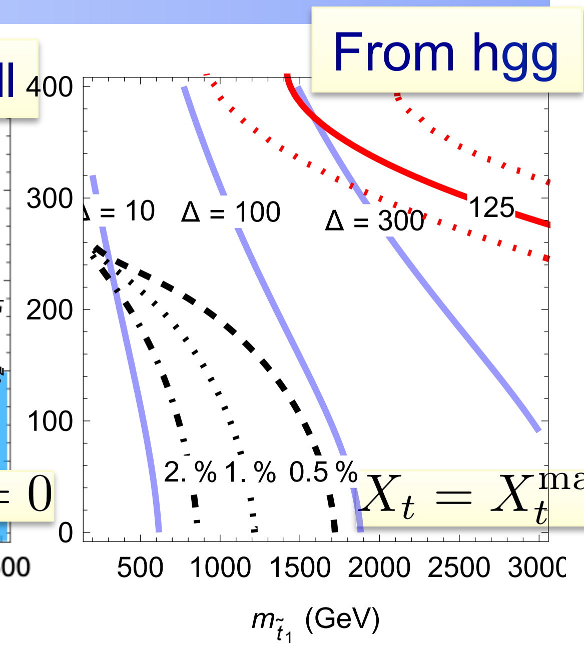
SUSY: what does it mean?

- **Corollary question: is SUSY natural?**



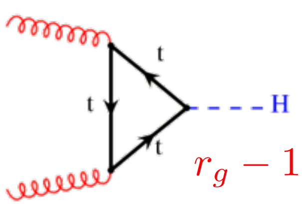
MSSM: already unnatural





For X_t^{max}: m_h already beyond reach of κ_g

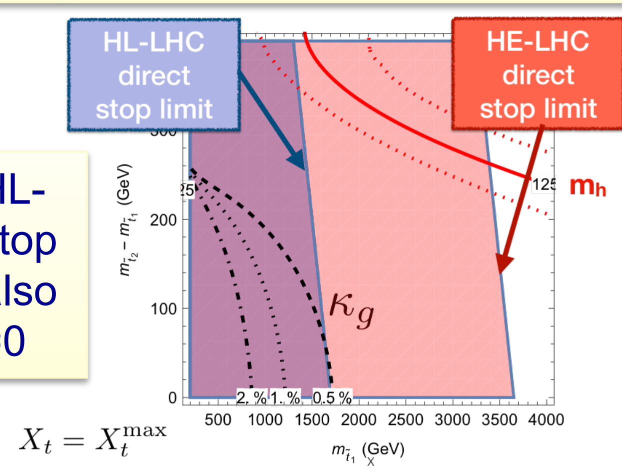
- **What do we learn from indirect information?**



$$\frac{\delta\mathcal{O}_{\rm SUSY}}{\mathcal{O}_{SM}} \sim \frac{m^2_{\rm SM}}{m^2_{\rm SUSY}}$$

$$r_g - 1 \approx \frac{1}{4}\frac{m_t^2}{m_{\tilde{t}_1}^2} \approx 0.7\% \left(\frac{1\,\text{TeV}}{m_{\tilde{t}_1}^2}\right)^2$$

With HL-LHC stop limit: also for X_t=0



Partial Answers to the Big Questions (III)

What cases of thermal relic WIMPs are still unprobed and can be fully covered by future collider searches?

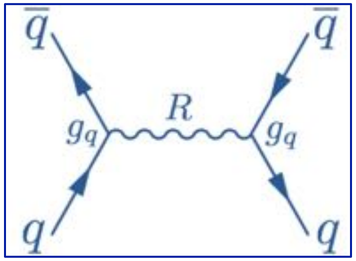
Thermal relic WIMPs

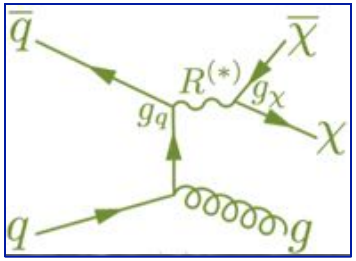
- **Motivation for direct, indirect and collider searchers:**

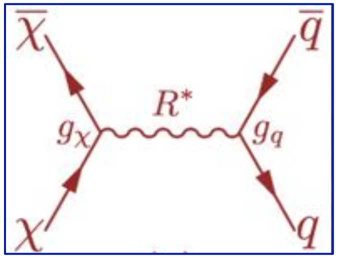
$$\Omega_{\rm DM}h^2 \sim 0.12 \times \left(\frac{M_{\rm DM}}{2\ {\rm TeV}}\right)^2 \left(\frac{0.3}{g_{\rm eff}}\right)^4 \Longrightarrow M_{DM} \sim \mathcal{O}(\text{few GeV}) \to \mathcal{O}(10\text{'s TeV})$$

  - **WIMP miracle has moved upwards – to ~TeV.**
- **Focus of BSM group: GeV–TeV region; two classes**
  - **Classic electroweak WIMP candidates (SUSY inspired)**
    - **Winos and Higgsinos (and linear combinations…)**
  - **Simplified models with mediator particles**
    - **Axial-vector simplified models**
    - **Scalar simplified models**

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_{\rm Int}$$



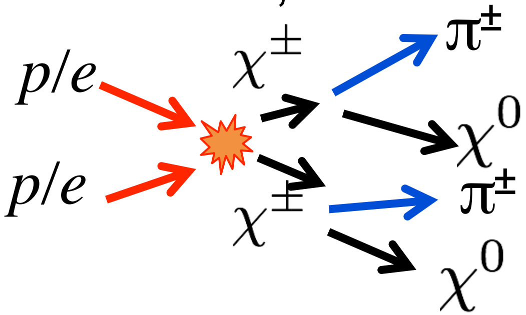




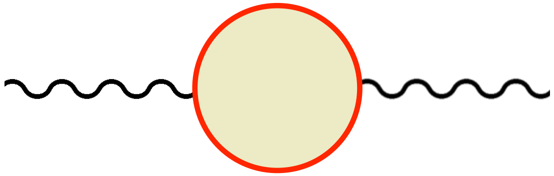
DM: Classic WIMPs

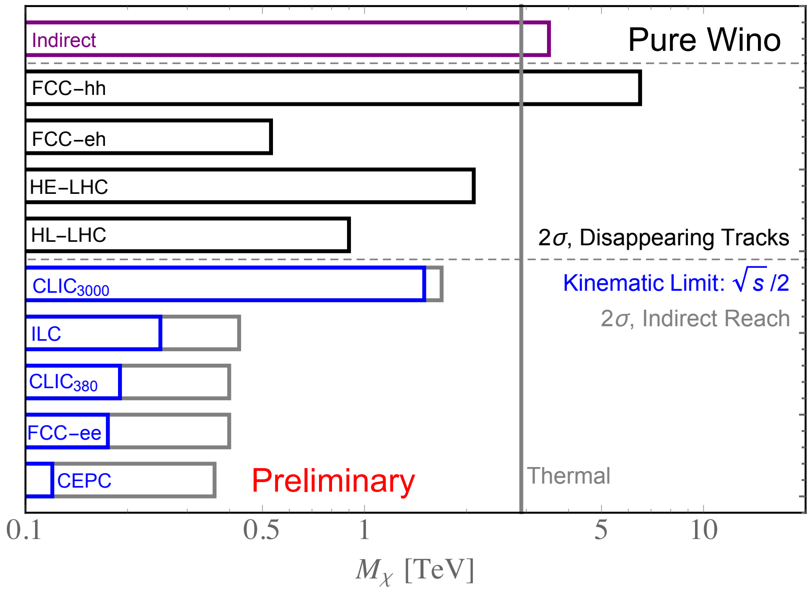
- **Two "extremes", pure Wino, pure Higgsino**
  - **Main "tools": disappearing track, propagator modifications**

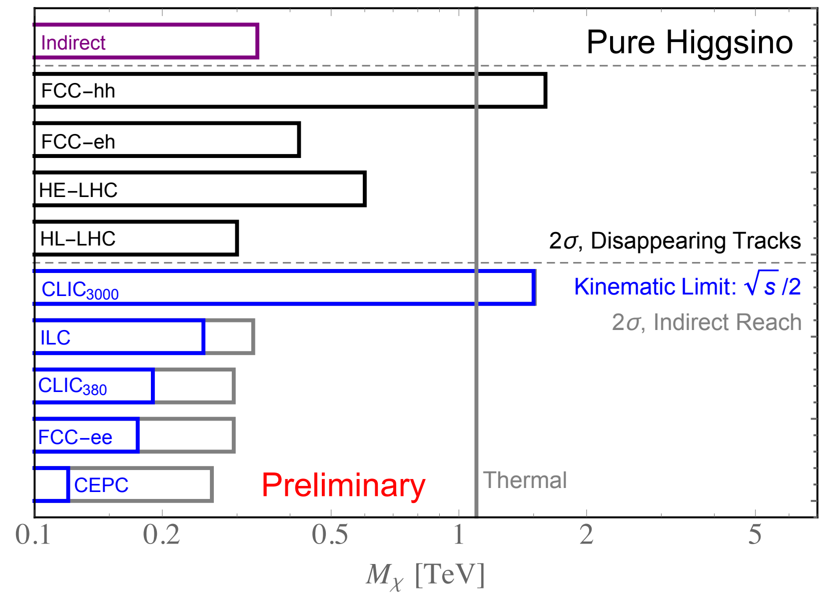
For small Δm, soft $\pi^{\pm}$...



EWKinos in loop change prop (W, Y parameters)

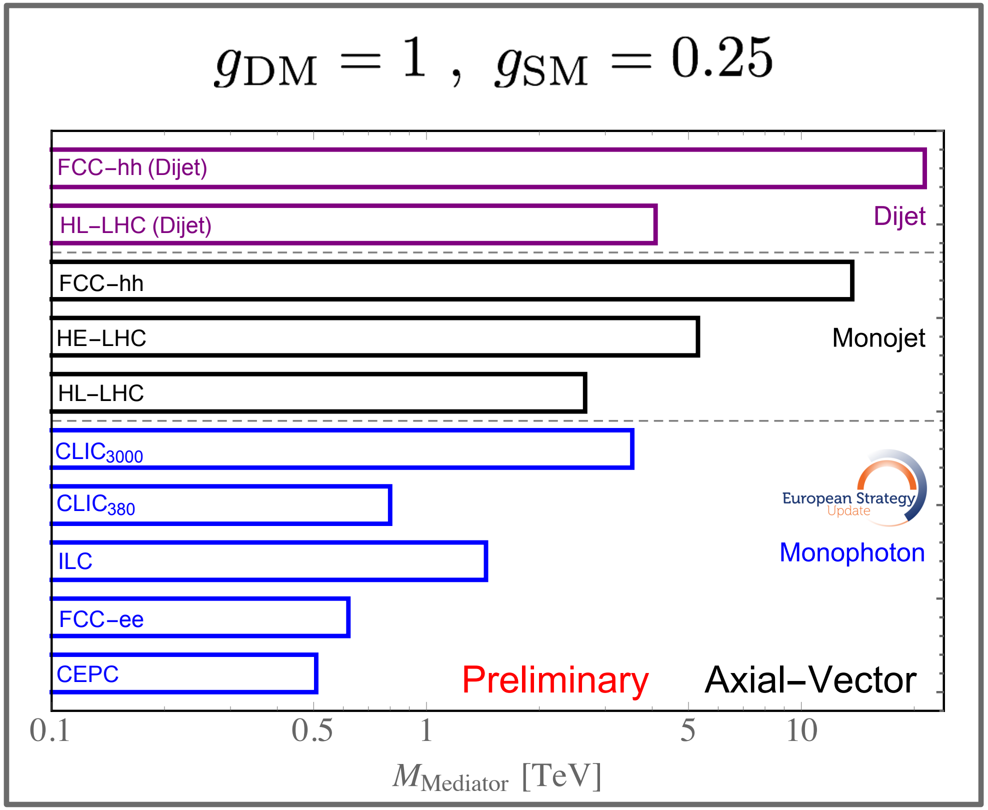


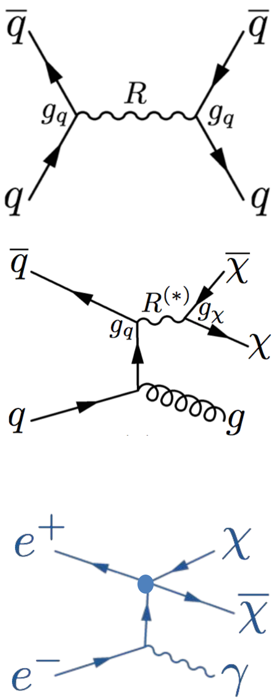




Simplified Models: axial vector

- **Light DM, m_χ=1GeV**





pp: assumes mediator couplings to quarks only.
- 750 GeV, HL-LHC
- 1.5 TeV, HE-LHC
- 3.9 TeV for FCC-hh

Dependence on couplings!

ee: assumes mediator couplings to leptons only. Also in EFT limit, so can be easily rescaled for modified couplings.

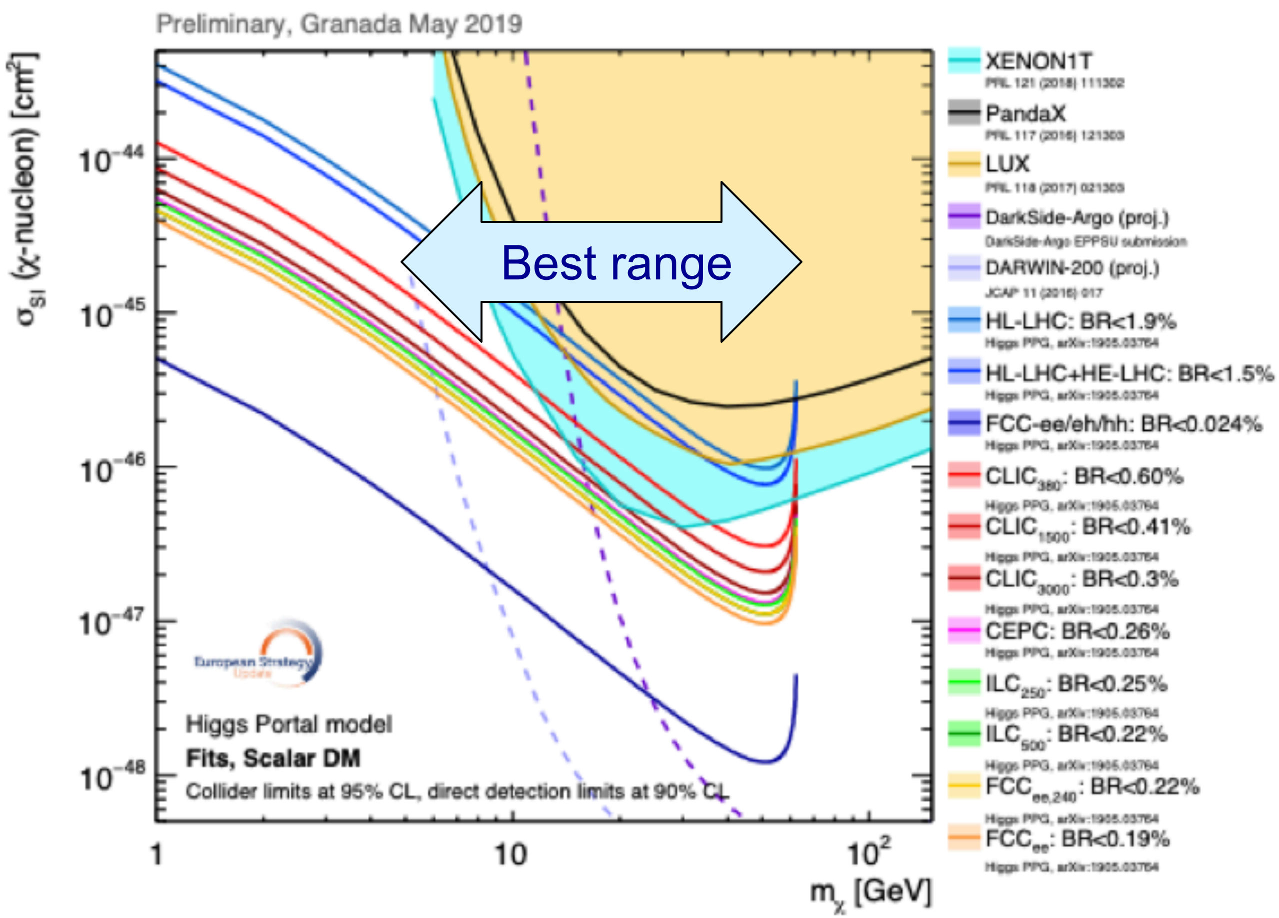
Note: taking EFT scale as free parameter, M_{DM} reach ~kinematic reach of collider.

Significant model dependence. UV models may have comparable quark and lepton couplings. If both present, can also use dilepton resonances.

SM scalar mediator: Higgs portal

A collider discovery will need confirmation from DD/ID for cosmological origin

A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction

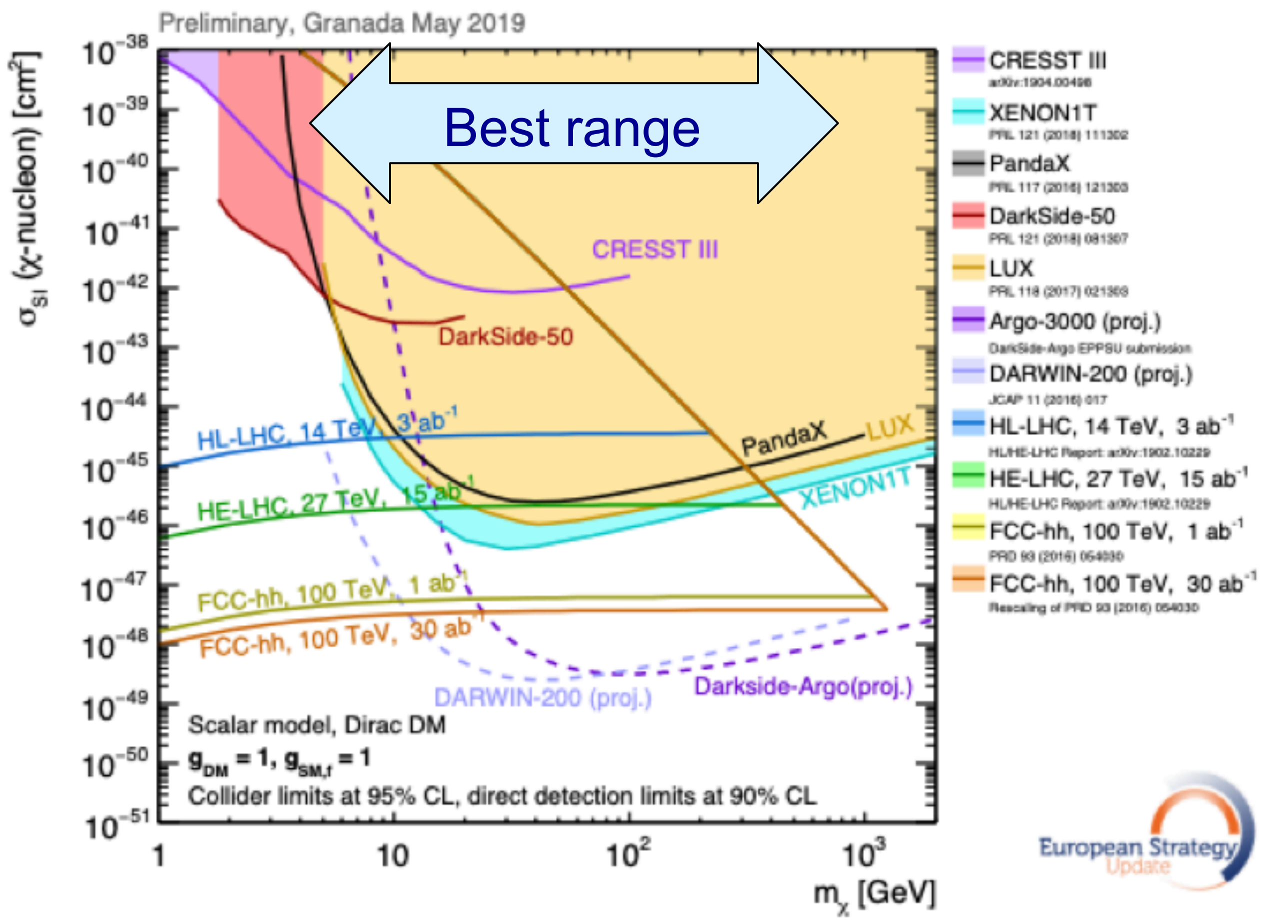


A future collider program that optimizes sensitivity to invisible particles coherently with DD/ID serves us well. Need maximum overlap with DD/ID!

BSM scalar mediator

A collider discovery will need confirmation from DD/ID for cosmological origin

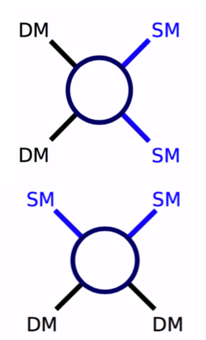
A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction



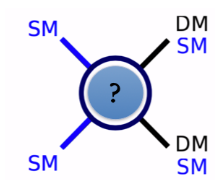
A future collider program that optimizes sensitivity to invisible particles coherently with DD/ID serves us well. Need maximum overlap with DD/ID!

DM: summary

- **Strengths in WIMP searches both in future lepton and hadron options:**
  - **Combined FCC program shows best sensitivity to benchmarks**
  - **Still, needs complementary experiments: DM ≠ WIMP (only)**
- **We can probe the thermal WIMP parameter region**
- **Large (& yet unknown) parts of phase space can be probed by precision environment/lower bkg in ee**



Synergies with DD/ID communities welcome (and necessary)



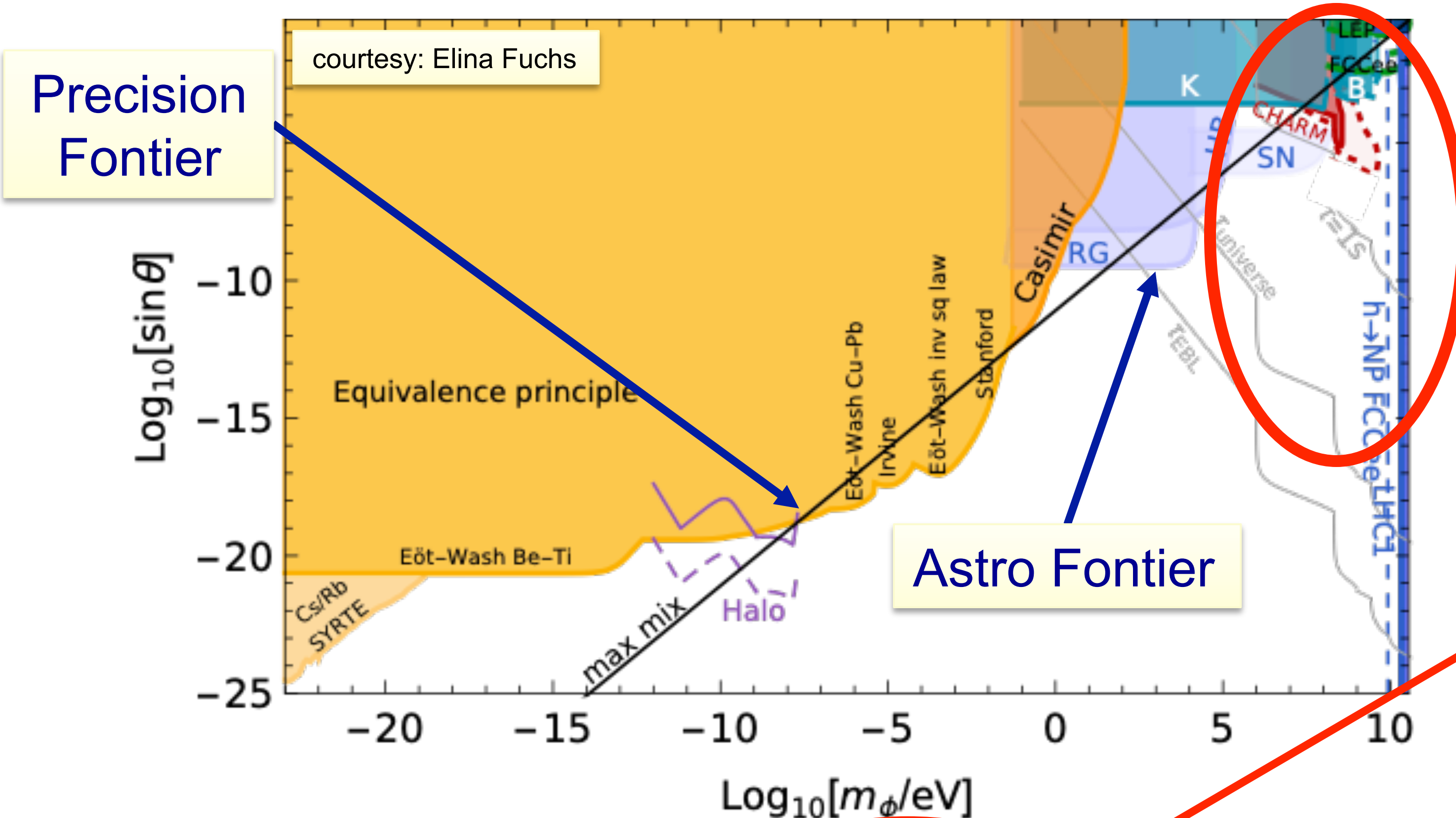
cosmological origin
DD/ID/astrophysics

nature of DM-SM interaction
colliders(/beam dumps)

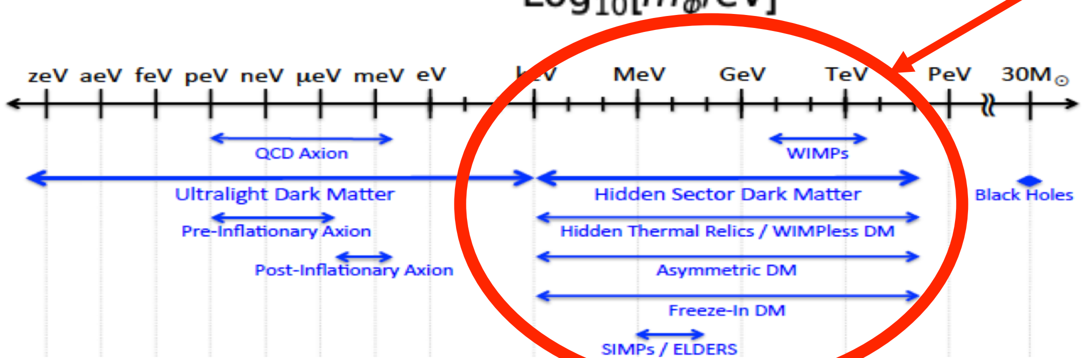
Partial Answers to the Big Questions (IV)

To what extent can current or future accelerators probe feebly interacting sectors?

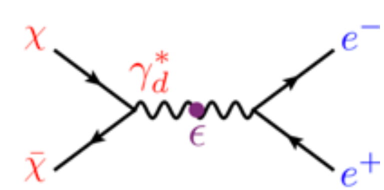
Feebly Interacting Particles (FIPs)



Accelerator Fontier



Plus: light DM, typically → light mediator, e.g. dark-photon



Feebly Interacting Particles (FIPs)

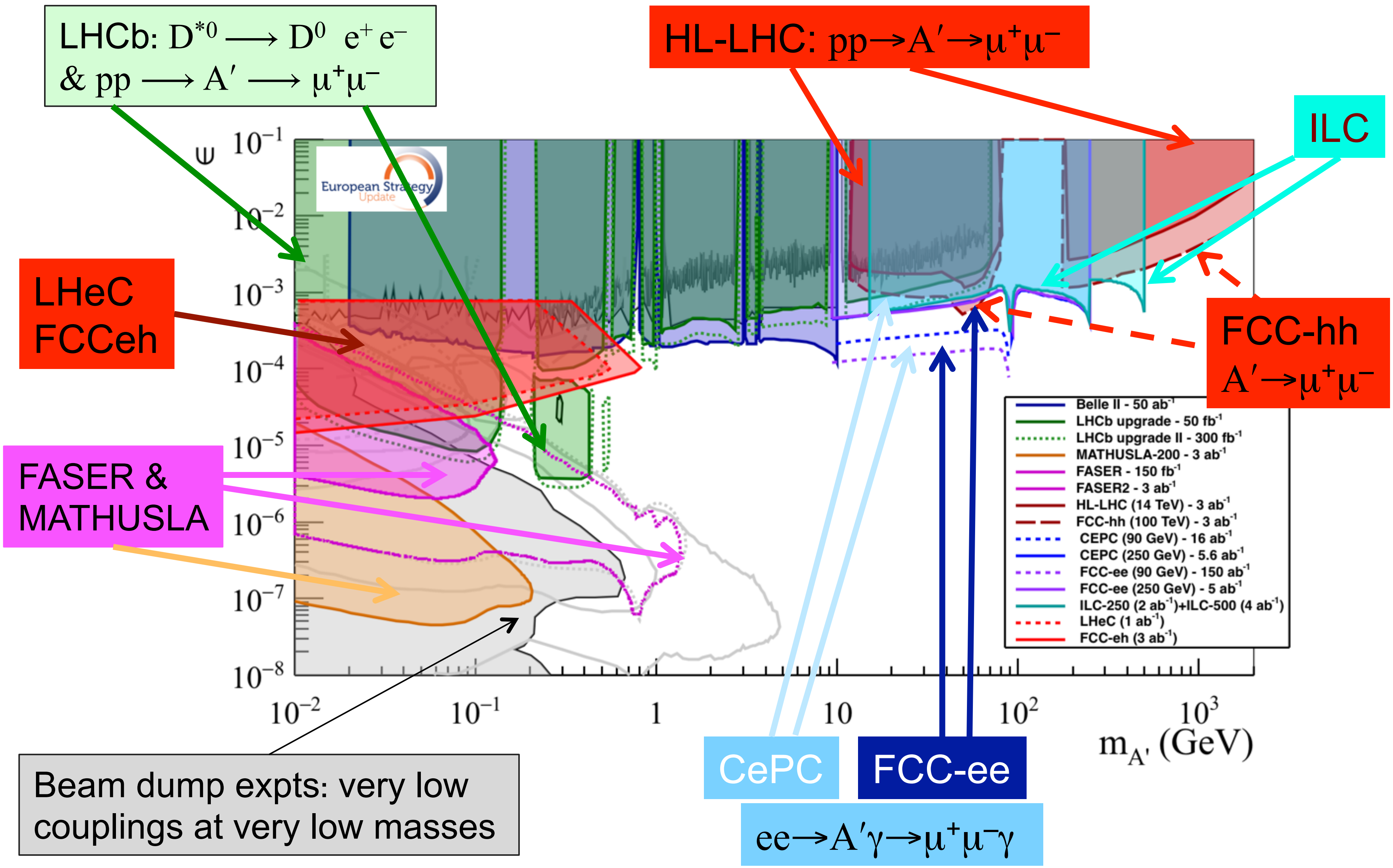
- **Very wide range of possibilities .AND. Models**
  - How to search for such broad class of models?
    - Simplified models
  - How to compare frontiers? Experiments?
    - Use benchmarks.
  - Simplified models: four "portals"

PBC report, arXiv:1901.09966

Portal	Coupling	
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$	
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$	(Relaxion toy model, mixes \w Higgs)
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$	
Sterile Neutrino, N	$y_N L H N$	

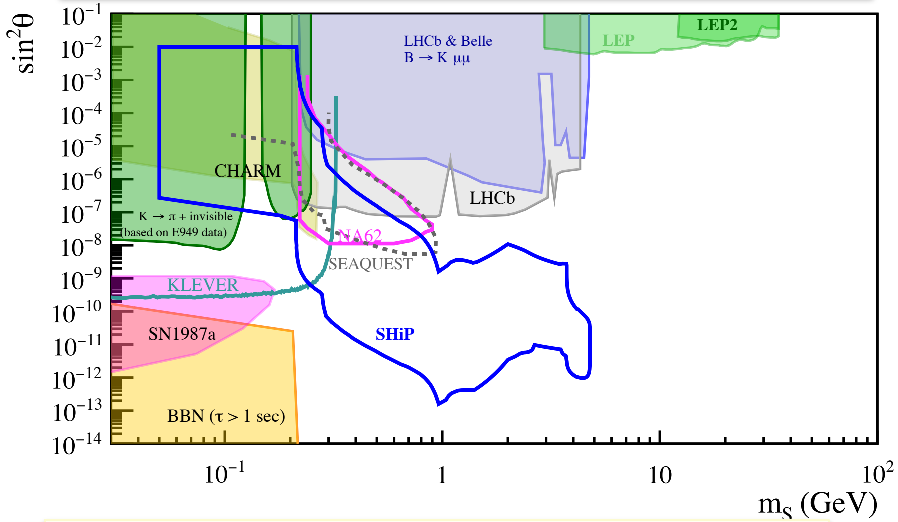
  - From portals: identify benchmark cases to evaluate experimental sensitivities. Common ground to compare machines/experiments and put them in worldwide context

FIPs: Vector Portal (Dark Photon)

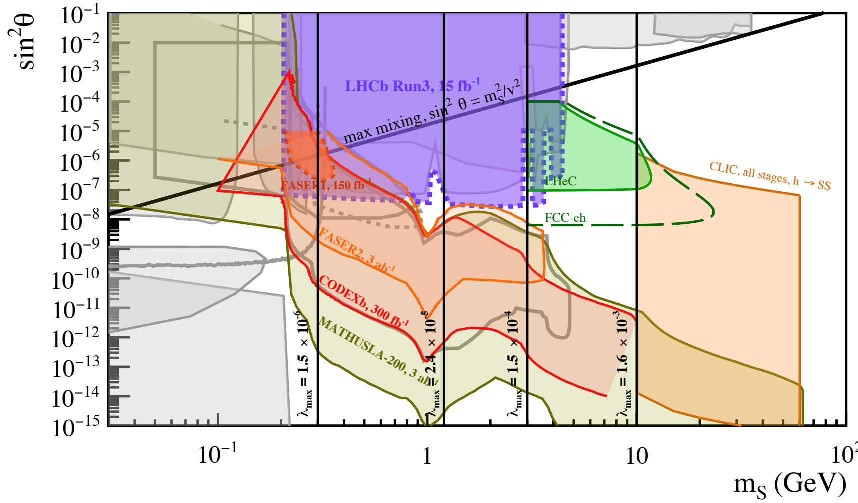


FIPS: Scalar Portal (Dark Higgs)

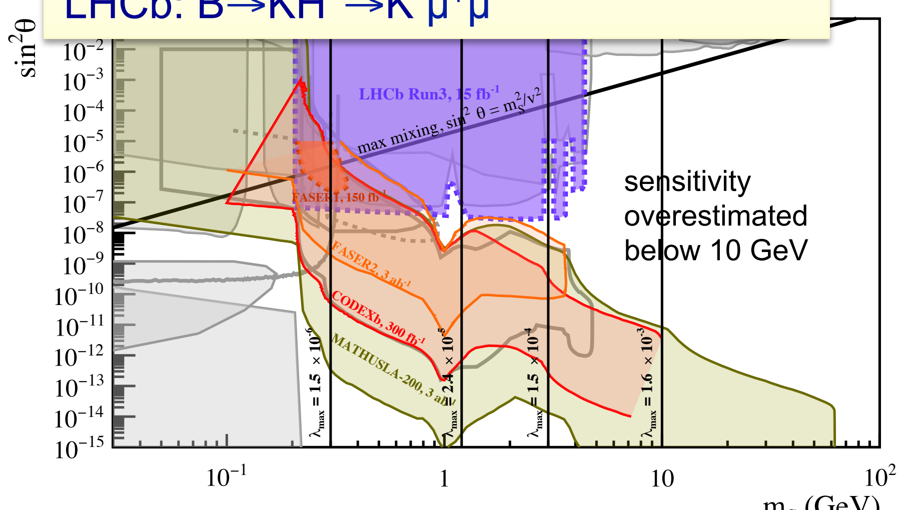
SHiP & beam-dump/fixed target expts



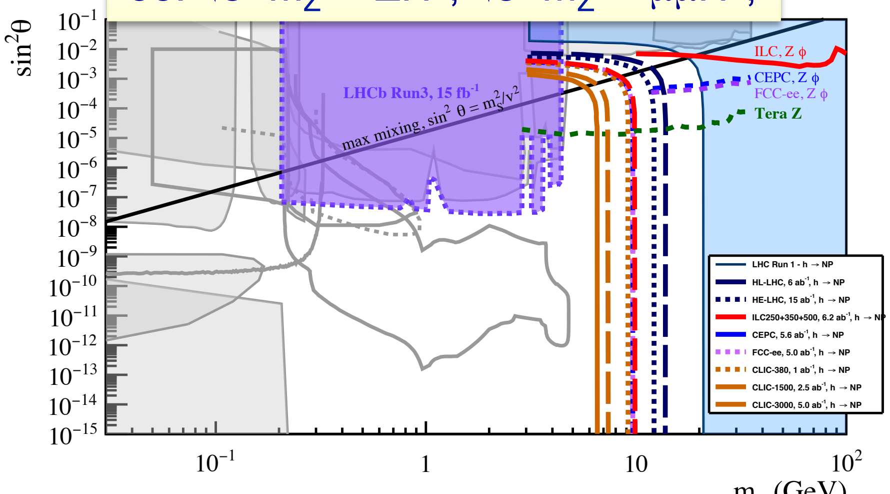
sensitivity overestimated below 10 GeV



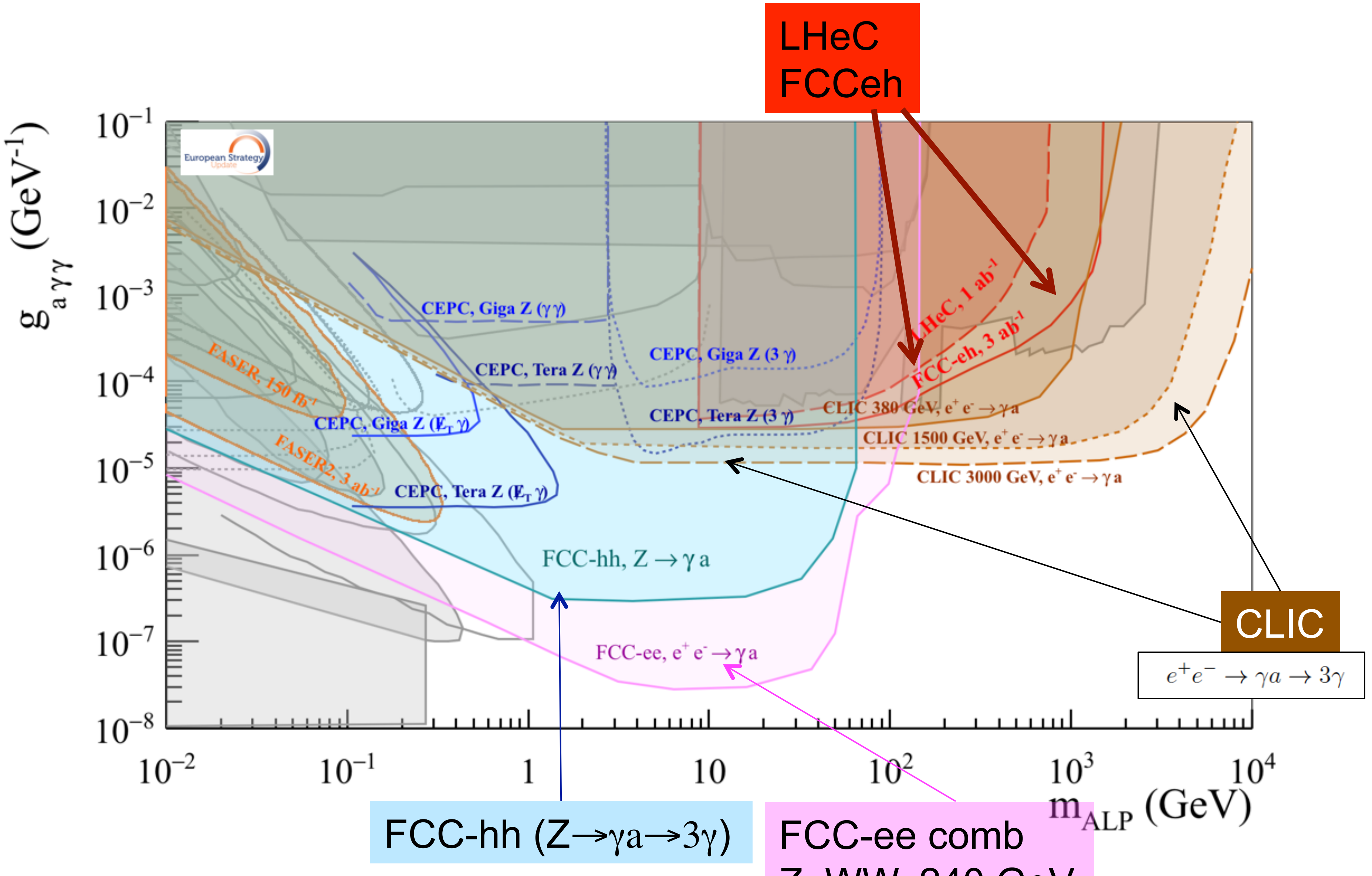
MATHUSLA, CODEX, FASER: H→SS;
LHCb: B→KH*→K $\mu^+\mu^-$



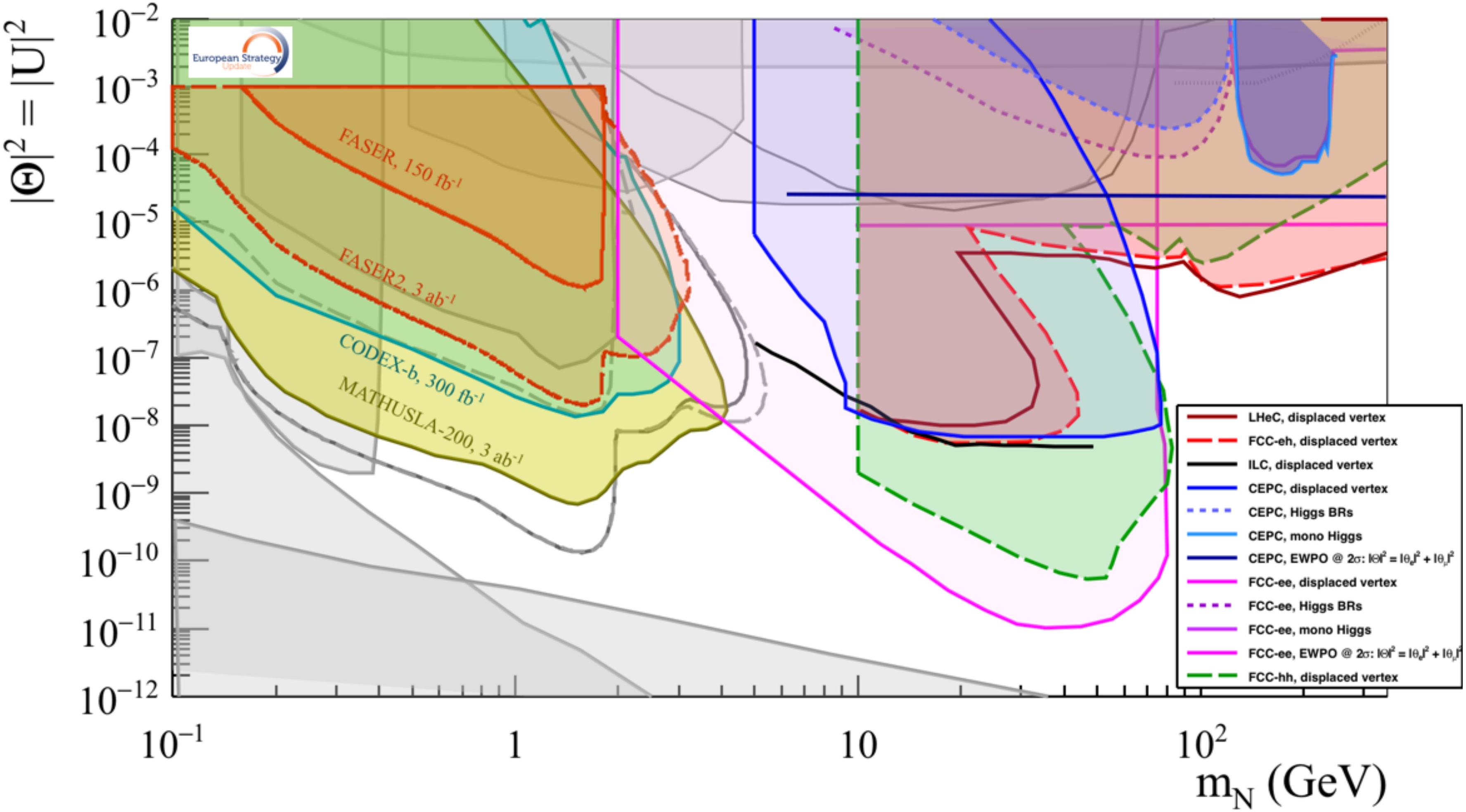
HL/HE-LHC: indirect Higgs;
ee: $\sqrt{s}>M_Z$→ ZH*; $\sqrt{s}=M_Z$→ μμH*;



FIPs: Pseudo-Scalar Portal (Axions, ALPs)



FIPs: Sterile Neutrinos



FIPs…

- FIPs represent a new paradigm that requires systematic exploration on multiple fronts
- FIP mass(es) can span several orders of magnitude
  - However, there are preferred regions for motivated models (Dark photon for thermal dark matter, relaxion in its natural region, right-handed neutrinos below EW scale down to the see-saw limit) that are within reach for accelerator-based experiments
- Beam dump and collider experiments: complementary in reach
  - Very significant reach in several places. Not exhaustive – but this is only the beginning.
    - Note: invisible counterpart in summary talk from DM group

Outlook

Some lessons learned

Summary/Outlook

- We are trying to provide a meaningful comparison between the different machines and experiments
  - And to see what we really learn in response to “big questions”
- We do learn a lot
  - But not everything we would like – answers, unfortunately, are not absolute. As expected, they are expressed in terms of reach in BSM energy/mass scale (and some extra parameters)
- Next step: condense detailed reviews into a super-short summary
  - And document the (much) longer story behind the Super Short Summary; suggestions welcome.
- We are very thankful to all the collaborations
  - For the effort put into submissions & accompanying materials
  - For answering our questions and for running some extra scenarios [or existing scenarios with different parameters, etc]
  - For participating in the discussion sessions and making insightful comments