Is the Higgs boson a portal to new dark sector states?

Dark scalar reinterpretation of searches for Higgs boson decays into long-lived particles (LLPs) at the LHC, arXiv:2509.02564

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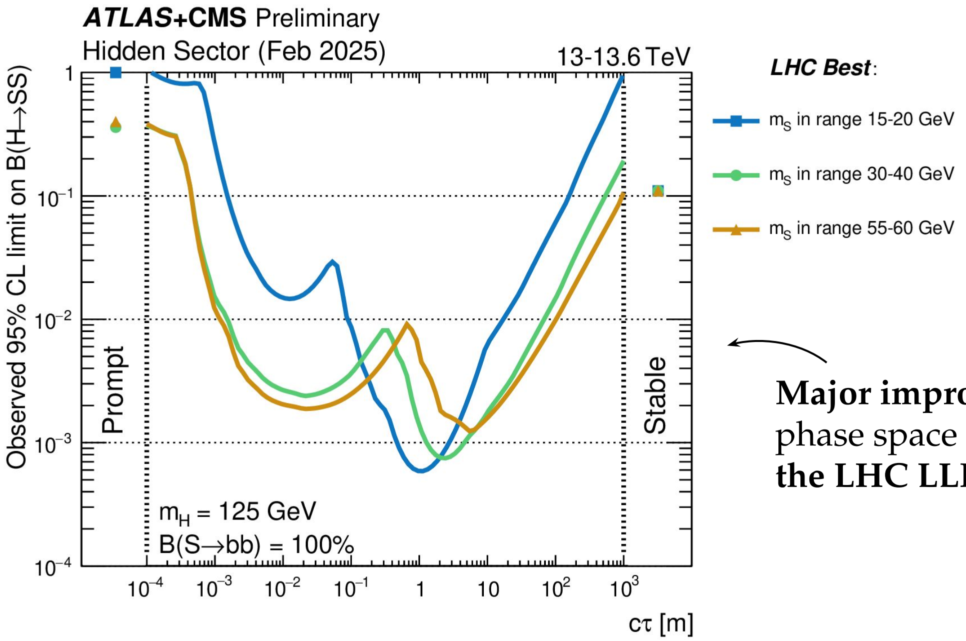
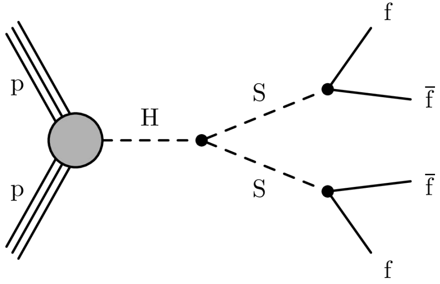
Setting the scene: Is the Higgs a portal to new dark sector states?

The landscape of LLP searches at the LHC for H → XX, where X is an LLP, is difficult to navigate

- No standard interpretation across searches and experiments
  - Scalar: H → SS, vector: H → $Z_D Z_D$, or in terms of final states, e.g assuming B(X→bb) = 100%





Major improvement in assessment of phase space coverage of S→bb, **thanks to the LHC LLP Summaries** (ATLAS, CMS)

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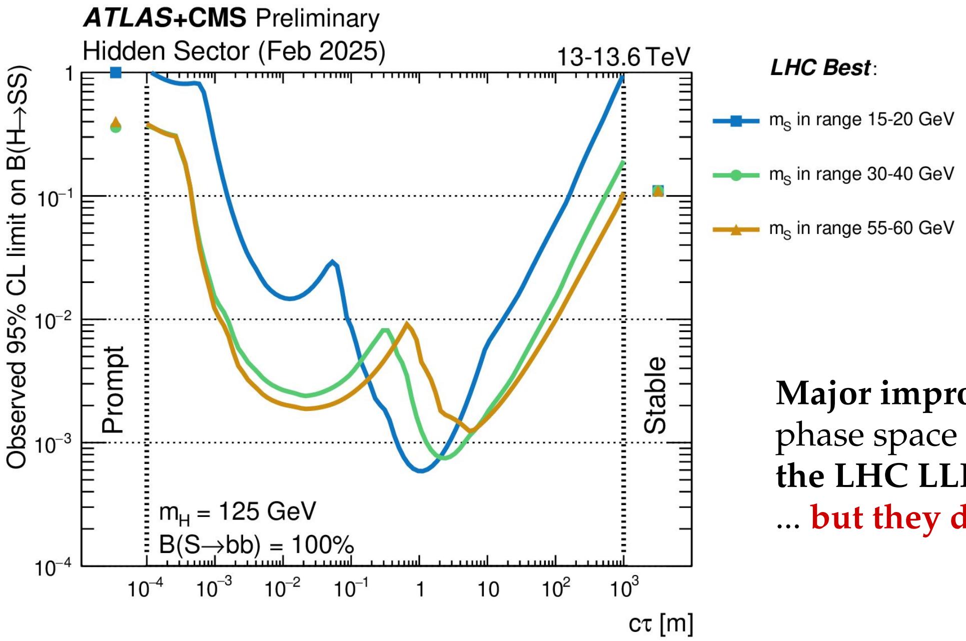

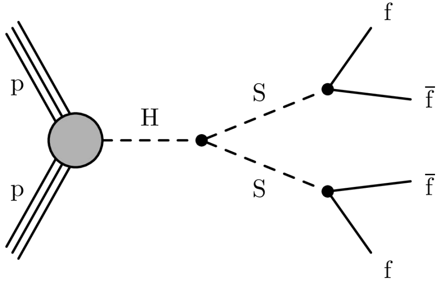

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… **but they don't tell the full story**

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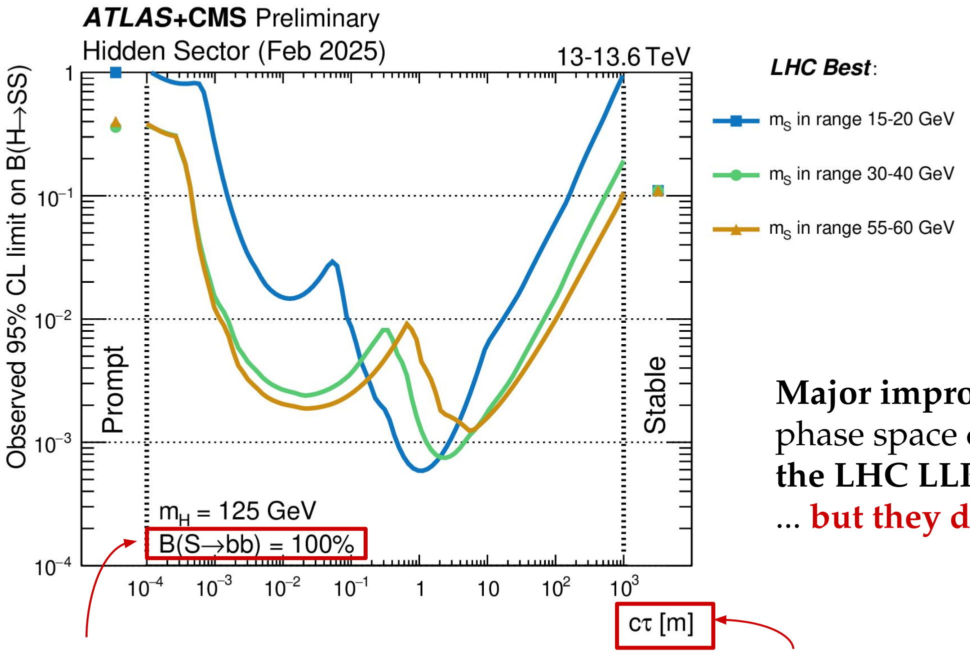

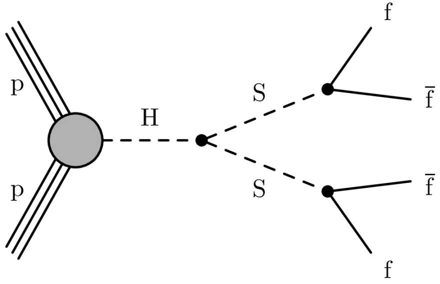

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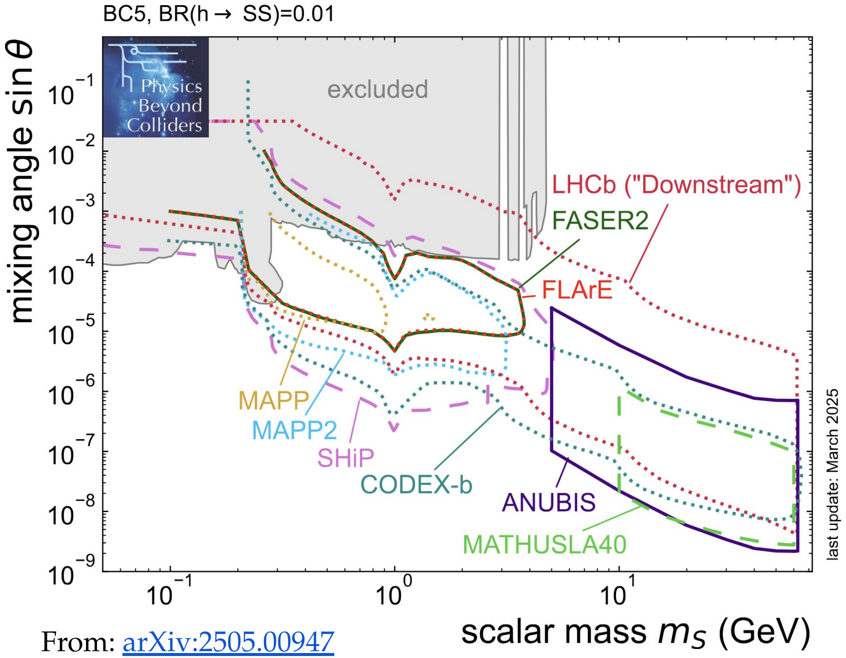
What's the interplay between decay modes?
(they are relevant for m < 15 GeV)

Other communities use mixing parameters
(e.g sinθ)

Setting the scene: Is the Higgs a portal to new dark sector states?

No HL-LHC extrapolations are available for *state-of-the-art* LHC Run 2 and Run 3 results

- **Difficult to compare** LHC constraints with those from other experiments



From: arXiv:2505.00947

Where are the LHC constraints and HL-LHC projections in the BC5 plane?

(This was asked at the LHC BSM Working Group: kickoff meeting)

The methodology

In arXiv:2509.02564, accepted for publication in JHEP, I addressed these questions through a **reinterpretation of selected LHC searches within the Physics Beyond Collider (PBC) BC5 model**, using HEPData

HEPData

Repository for publication-related High-Energy Physics data

This reinterpretation **accounts for the main effect,** which is the impact of the **model's branching fraction**

- This offers a major advantage: it **avoids re-running the many analyses** performed by the experimental collaborations (a full re-anlysis would require significant time and resources!)
    - Implemented in a conservative way, so the **resulting limits are weaker constraints than those from a full re-analysis.**

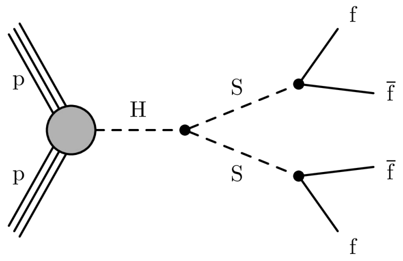
I am not speaking on behalf of any collaboration

- Results are based on **public information in HEPData**

BC5 model

"Scalar portal" benchmark physics case, **BC5**: J. Phys. G: Nucl. Part. Phys. 47 010501

$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H \, ,$$



Free parameters: sinθ, m(S), and λ

- λ controls the production rate, via H→SS
- **m(S)** controls B(S)
- **sinθ** controls **τ**(S), e.g if sinθ decreases, then **τ**(S) increases

$$\theta = \frac{\mu v}{m(\text{h})^2 - m(\text{S})^2} \, , \quad \Gamma(\text{S}) = \Gamma(\text{S})_{\text{SM}} \sin^2\theta \, ,$$

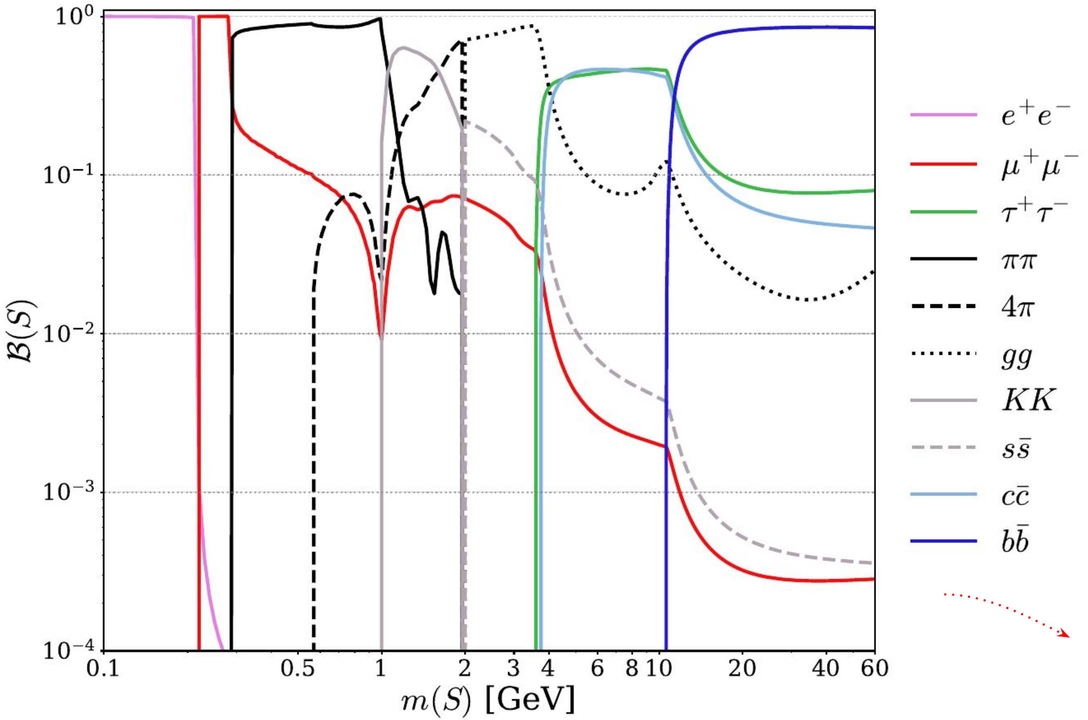
B(S) and *Γ*(S) provided by Maksym Ovchynnikov (co-author of arXiv:1904.10447), **thanks!**

Setting **λ = 0 forbids H→SS** (it is not discussed in this work)

BC5 model

The new light scalar, S, features Yukawa-like couplings

- B(S) to light leptons is suppressed (otherwise leptonic searches drive all constraints)

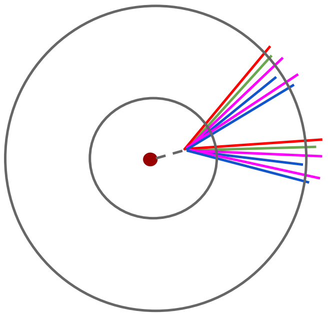


B(S →*μμ*) <0.1%

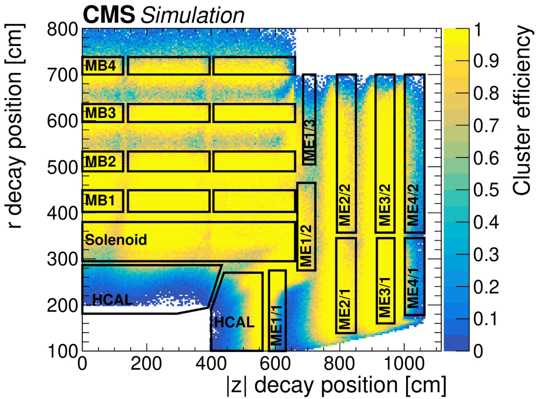
Selected LHC searches in hadronic final states

Broad set of searches targeting different m(S) and final states

- S→bb from the envelope of 'best constraints' from ATLAS and CMS, the so-called **'LHC LLP Summaries'**
  - **m(S) ≥ 15 GeV**
- **S→ gg, ss, cc, ττ, KK, ππ** using muon detector showers, **arXiv:2402.01898**
  - **m(S) < 15 GeV**



Displaced jets/vertices

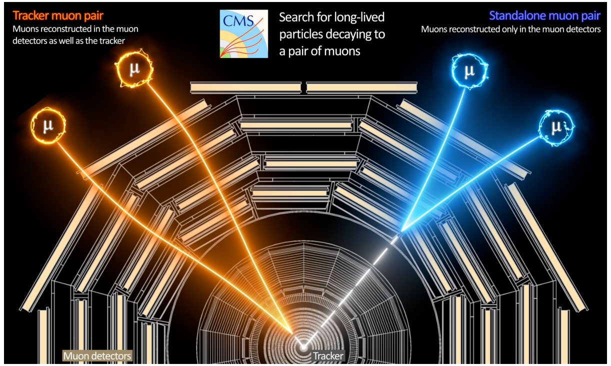


Muon detector showers

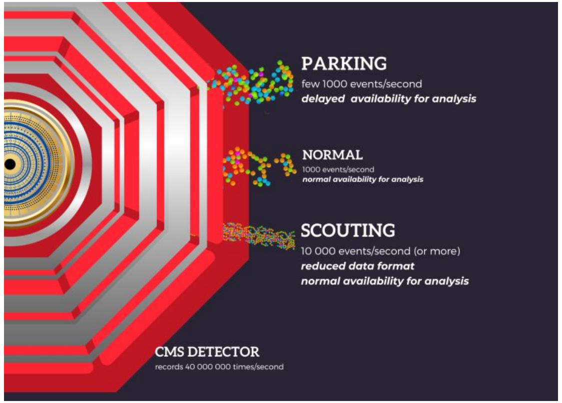
Selected LHC searches in leptonic final states

Broad set of searches targeting different m(S) and final states

- $S \to \mu\mu$ from displaced vertices using the inner tracker or only the muon system, **arXiv:2402.14491**
  - **m(S) ≥ 10 GeV**
- $S \to \mu\mu$ at high-level trigger, the so-called "scouting datastream", **arXiv:2112.13769**
  - **m(S) < 10 GeV**



Displaced dimuons (tracker or muon system)



CMS data taking strategies

From B(H→$Z_D Z_D$) to B(H→SS); S→$\mu\mu$

Displaced dimuon searches are typically interpreted in the **Hidden Abelian Higgs Model** (HAHM, arXiv:1412.0018), predicting **H→$Z_D Z_D$** with **B(Z_D→$\mu\mu$) ~ 30-10%**

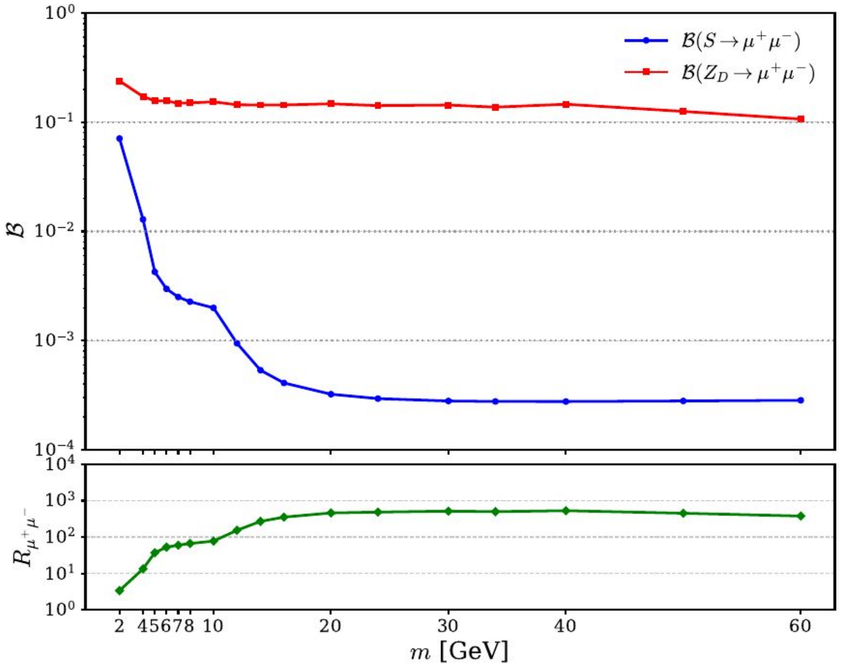
To reinterpret B(H→$Z_D Z_D$) as B(H→SS) one can **rescale the 95% CL published limits** by:

$$R_{\mu\mu} = \mathcal{B}(\mathrm{Z_D} \to \mu^+\mu^-)/\mathcal{B}(\mathrm{S} \to \mu^+\mu^-)\,,$$

Main assumptions:

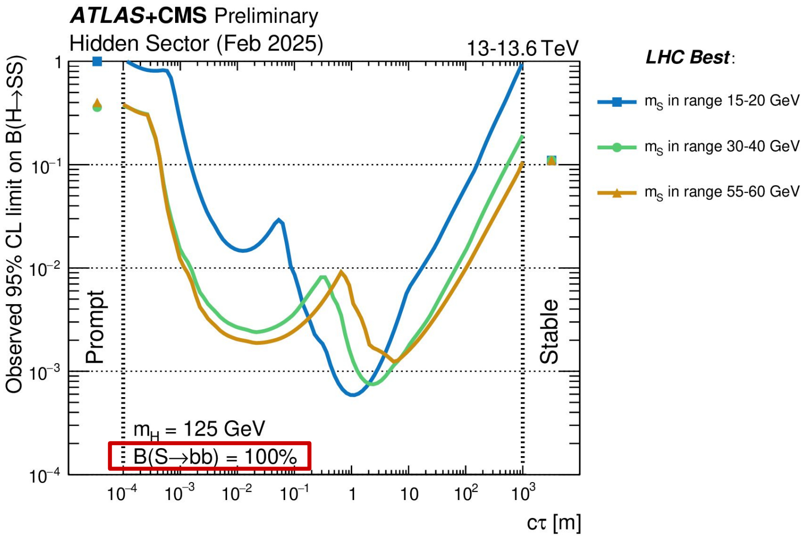
- Similar efficiencies for Z_D and S models (validated up to 20% in arXiv:2205.08582)
- Differences between HAHM and BC5 in the fraction of 4μ events have a negligible impact on the efficiency
  - Since this fraction is small, the effect is subdominant

As a result, factor of ~5-700x weakening of limits for m(Z_D) > 2 GeV



From B(H→XX) to B(H→SS); S→bb

For hadronic searches, it's common to interpret **H → XX under the assumption of B(X) = 100% into a single final state** (especially in CMS). This is also the choice in the LLP Summaries, shown below:



Rescale the published 95% CL limits on B(H → XX) by "1/B(S)^2" to get limits on BC5

- B(S) accounts for the **final state in the original interpretation**, plus any **other final states with similar signal efficiencies**

For m(S)≥15 GeV: $$1/\mathcal{B}(S \rightarrow b\bar{b})^2$$

From B(H→XX) to B(H→SS); S→gg, ss, cc, $\tau\tau$, KK, and ππ

For m(S)<15 GeV

- The dominant **S decay mode depends on m(S)**
- **QCD background increases dramatically**
  - Displaced vertex results (ATLAS and CMS) are not competitive
  - Constraints come from **high-multiplicity hit cluster searches in the muon system**, **arXiv:2402.01898**

The search sensitivity is **largely independent of the LLP decay mode and mass**

- There is only a mild dependence on whether the shower is primarily hadronic (b^-b^+, d^-d^+, $K^{\pm}K^{\mp}$, K^0K^0, $\pi^{\pm}\pi^{\pm}$), electromagnetic ($\pi^0\pi^0$, γγ, $e^{\pm}e^{\mp}$), or mixed ($\tau^{\pm}\tau^{\mp}$)
- One can define **"R factors"**:

$$R_{\pi\pi} = 1/\mathcal{B}(\mathrm{S} \to \pi\pi, 4\pi)^2 \,,$$

$$R_{KK,4\pi} = 1/\mathcal{B}(\mathrm{S} \to KK, 4\pi)^2 \,,$$

$$R_{gg,s\bar{s}} = 1/\mathcal{B}(\mathrm{S} \to gg, s\bar{s})^2 \,,$$

$$R_{c\bar{c},\tau\tau} = 1/\mathcal{B}(\mathrm{S} \to gg, s\bar{s}, c\bar{c}, \tau_\mathrm{h}\tau_\mathrm{h})^2 \,,$$

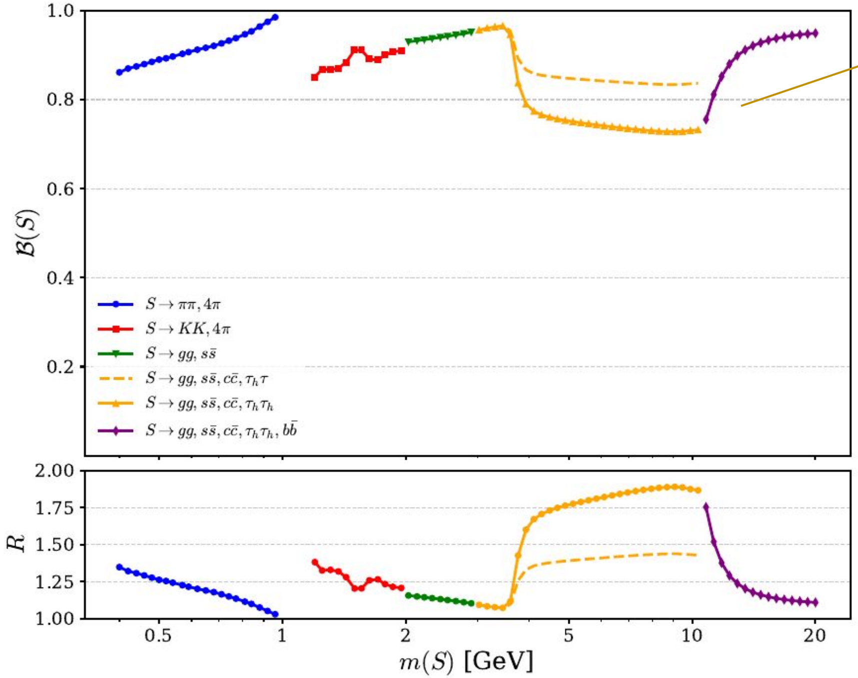
$$R_{b\bar{b}} = 1/\mathcal{B}(\mathrm{S} \to gg, s\bar{s}, c\bar{c}, \tau_\mathrm{h}\tau_\mathrm{h}, b\bar{b})^2 \,,$$

Each **R factor** accounts for the B(S) that are kinematically accessible in an m(S) range

From B(H→XX) to B(H→SS); S→gg, ss, cc, $\tau\tau$, KK, and $\pi\pi$

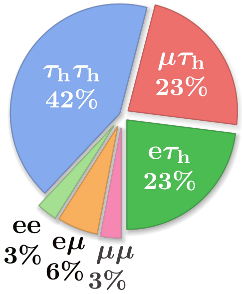
Rescale the published 95% CL limits on B(H → XX) by the corresponding "R factor"

- In most cases it is a small correction (~25%)



The largest correction is $R_{cc,\tau\tau}$

- It accounts for S → $\tau_h\tau_h$, where both τ must decay hadronically



https://tikz.net/sm_decay_piechart/

A more aggressive choice would be to consider S → $\tau_h\tau$

- It would improve the constraints at m(S) = 7 GeV by 28%

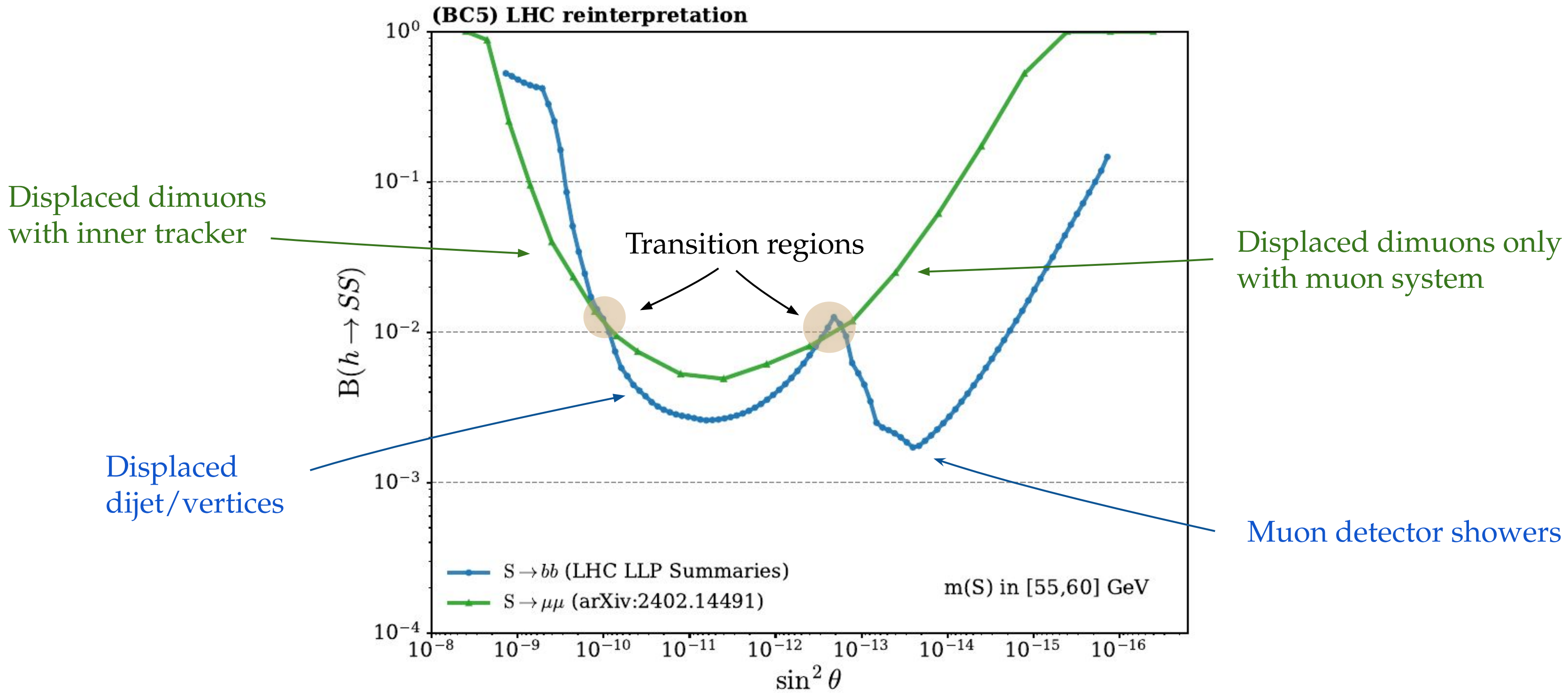
Using $R_{\mu\mu}$, R_{bb}, $R_{cc,\tau\tau}$, $R_{gg,ss}$, $R_{KK,4\pi}$, $R_{\pi\pi}$, and the published limits, **one can reinterpret all considerd searches**

Results: High mass

m(S) = [55, 60] GeV

Constraints driven by S → μμ (in tracker and muon system), **and S → bb** (displaced dijet/vertices and muon detector showers)

- **S → μμ** useful in challenging areas of the phase space ("transition regions", and at small cτ)



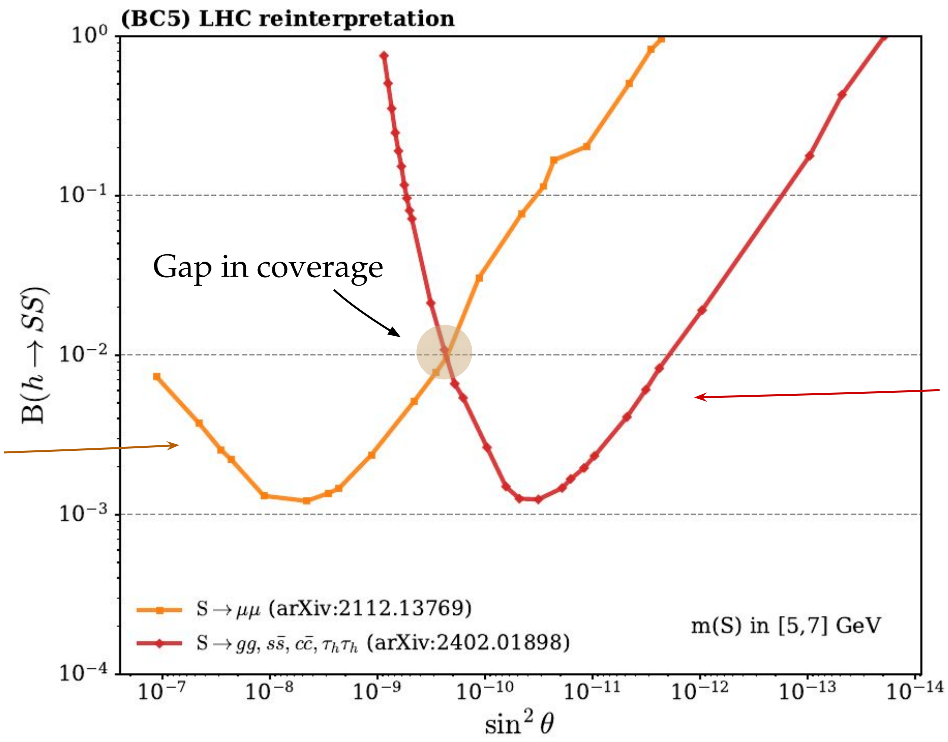
Results: Low mass

m(S) = [5, 7] GeV

Constraints driven by S → μμ (with scouting data) and **S → gg, ss, cc, ττ** (muon detector showers)

- Strategies clearly complement each other in phase space coverage, except for the gap around $\sin^2\theta \sim 10^{-9}$ to 10^{-10}

Displaced dimuons with scouting dataset



Muon detector showers

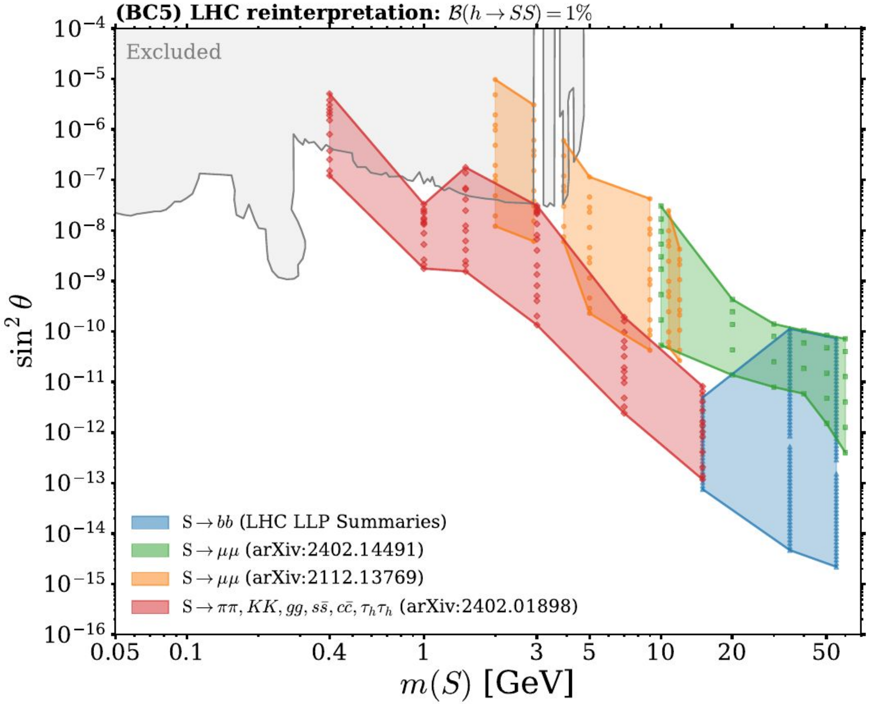
Other m(S) values are in the paper

Results: LHC constraints in dark scalar portal ("BC5")

B(H→SS) = 1%

Now in 2D: [m(S), $\sin^2\theta$]

- **LHC covers phase space that is uncovered by other experiments** (in gray)
- **Searches for S → $\mu\mu$, S → $\mu\mu$** (with scouting data), S → bb, and S → gg, ss, cc, $\tau\tau$, KK, $\pi\pi$ **complement each other** (and they are needed to explore the BC5 plane!)

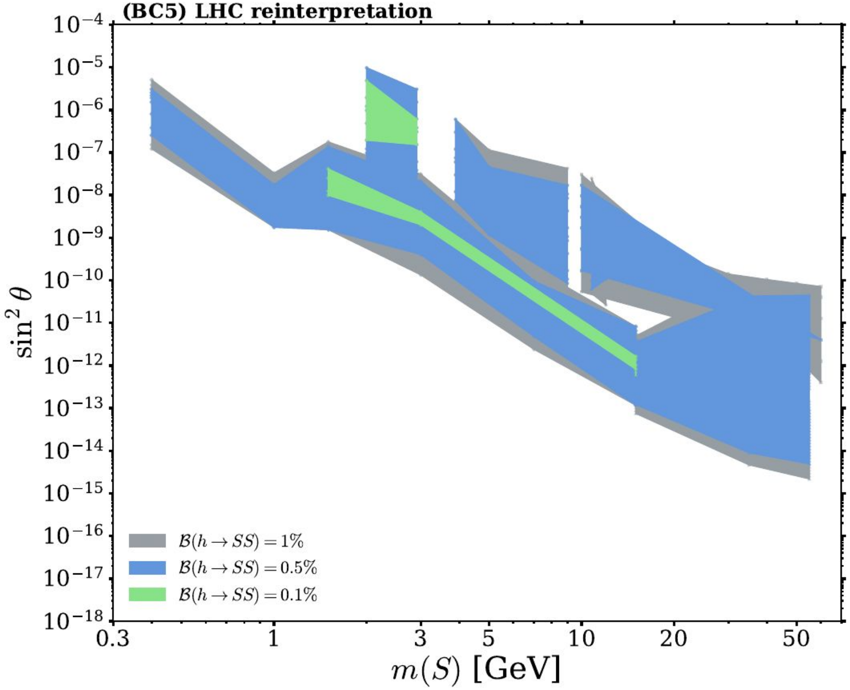


Results: LHC constraints in dark scalar portal ("BC5")

B(H→SS) = 0.1%

The benchmark **B(H→SS) = 1%** is driven by the expected precision on B(H → Invisible) ~ 2% at HL-LHC

- Well motivated **BSM theories also predict smaller B(H→SS)**
  - At **B(H→SS) = 0.1%** (green), most of the **parameter space remains unconstrained**

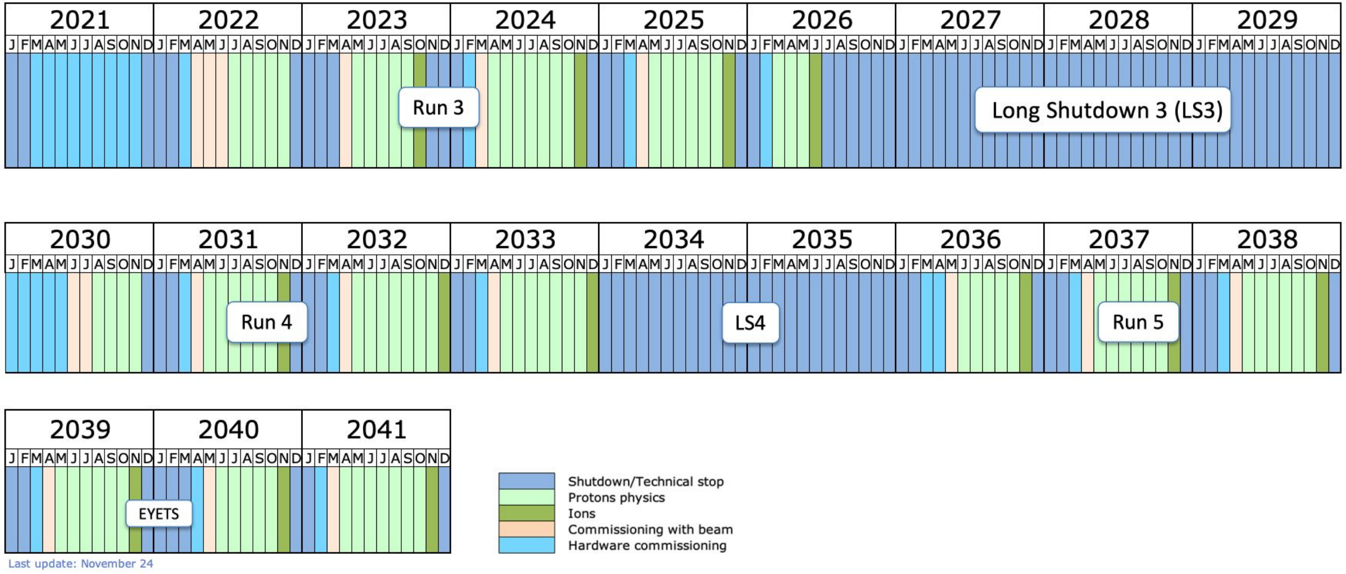


This highlights the **need for further <u>R&D at the HL-LHC</u>** to minimize the gaps in experimental coverage and **maximize discovery potential**

HL-LHC: What to expect?

HL-LHC: **3 ab^{-1} of data with upgraded detectors**

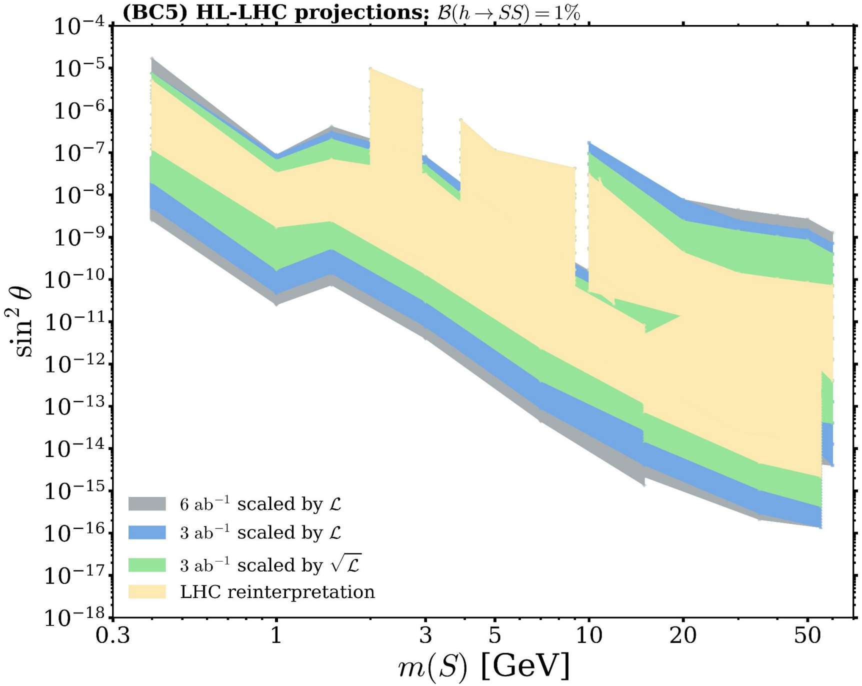
- These upgrades are expected to significantly enhance the BSM discovery potential, also for LLP searches
- **It's not trivial to do HL-LHC extrapolations for LLP searches** (field subject to lots of R&D!)
  - E.g early Run 3 searches by ATLAS and CMS have already demonstrated **increased sensitivity significantly exceeding the scaling by √L** wrt Run 2 search, see [1, 2, 3]



HL-LHC: What to expect?

B(H→SS) = 1%

Extrapolation of current bounds, "LHC reinterpretation", under <u>three HL-LHC scenarios</u>



3 ab^{-1} scaled by √L

- Backgrounds scale with L and no improvements in signal efficiency at HL-LHC

3 ab^{-1} scaled by L

- Backgrounds can be reduced to negligible levels thanks to HL-LHC upgrades, and new developments in analysis techniques

6 ab^{-1} scaled by L

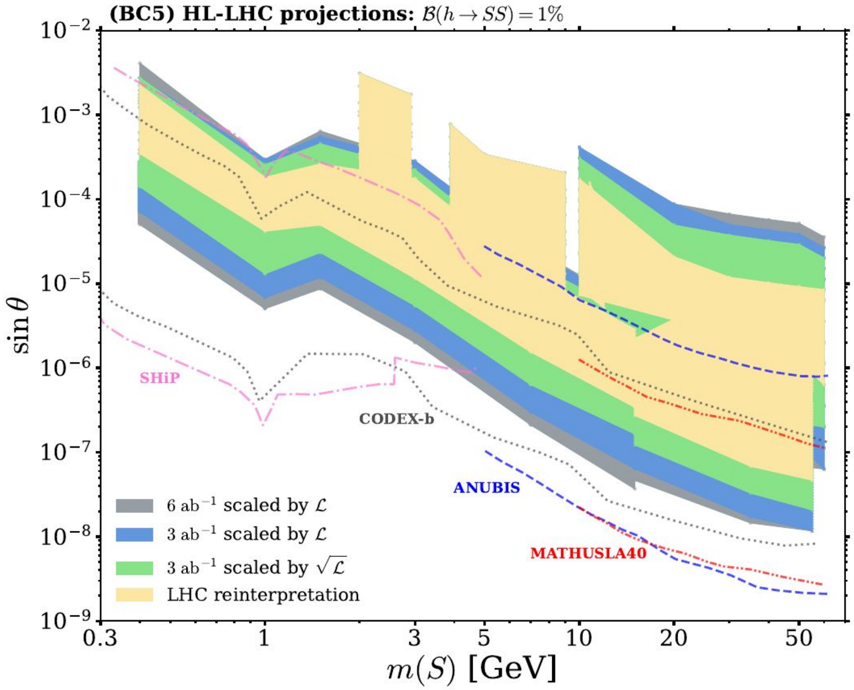
- Adds doubled signal efficiencies (e.g., from improved trigger algorithms), or a combination of ATLAS and CMS datasets

All upper limits are assumed to scale equally. However, in practice, **some search strategies have <u>greater R&D potential than others</u>** (this should be kept in mind when interpreting the projections)

HL-LHC: What to expect?

B(H→SS) = 1%

In the timescale of HL-LHC, **there are proposed dedicated LLP experiments at CERN**



Projections from SHiP (approved), CODEX-b, MATHUSLA, and ANUBIS, all taken from arXiv:2505.00947, are overlaid:

- Proposed LLP experiments extend the reach in sin θ for m(S) > 0.4 GeV

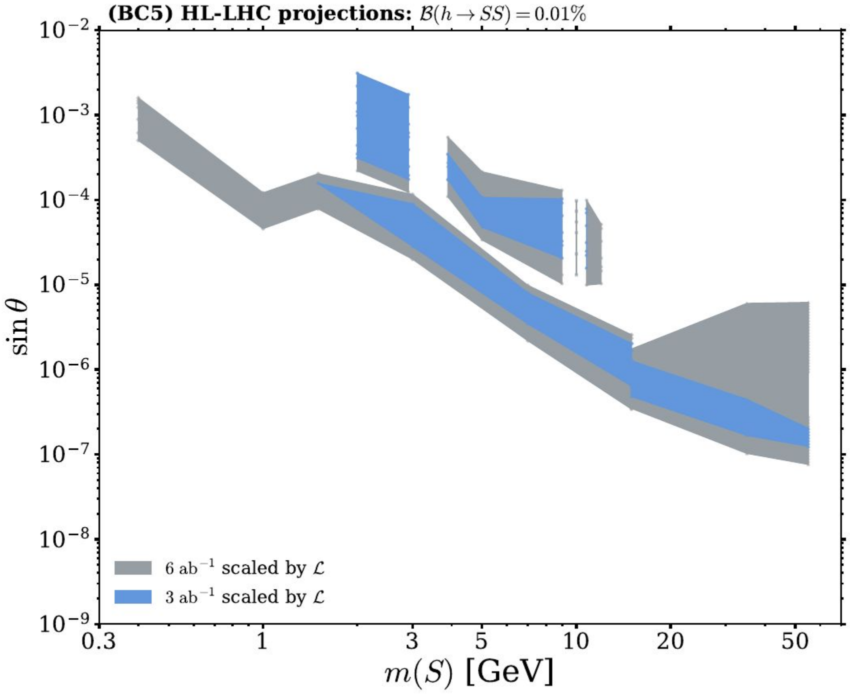
See Carlos Vázquez Sierra's talk for details on CODEX

HL-LHC: What to expect?

B(H→SS) = 0.01%

Let's take **B(H→SS) = 0.01%** (unexplored today) to illustrate the power of the large HL-LHC dataset

- In the 3 ab^{-1} scaled by √L scenario → **No new bounds** (not shown)
- The first constraints show up for 3 ab^{-1} scaled by L, and **especially for the 6 ab^{-1} scenario**

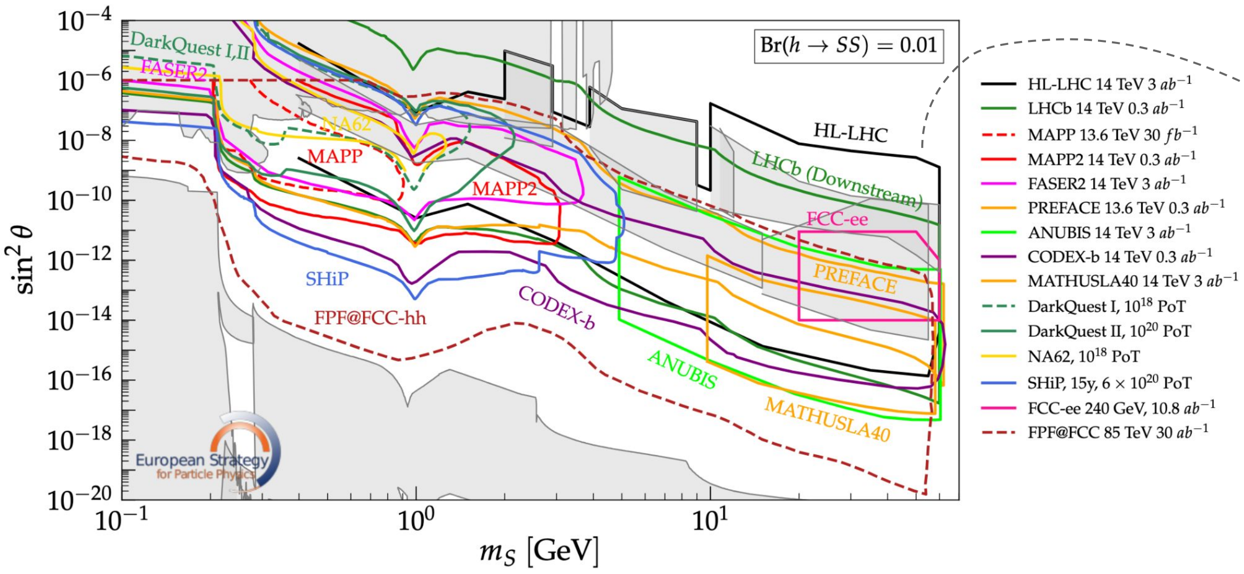


The strong dependence of the expected exclusion on the extrapolation assumptions manifests the importance of **background suppression in LLP searches**, **a key challenge for analyses at the HL-LHC**

Wrap up

Main results (arXiv:2509.02564):

- Searches for S → bb, S → gg, ss, cc, $\tau\tau$, KK, ππ, and S →$\mu\mu$ are needed to explore the BC5 plane
  - Highlighted the 'gaps' in the phase-space coverage from different searches
- HL-LHC extrapolations show:
  - Proposed LLP experiments at CERN (SHiP, CODEX-b, MATHUSLA, ANUBIS) extend the reach in sin θ in all considered scenarios
  - Background suppression will be key for ultimate sensitivity



Constraints from the LHC included in the ESPP 2026 Briefing Book, arXiv:2511.03883

Thanks!