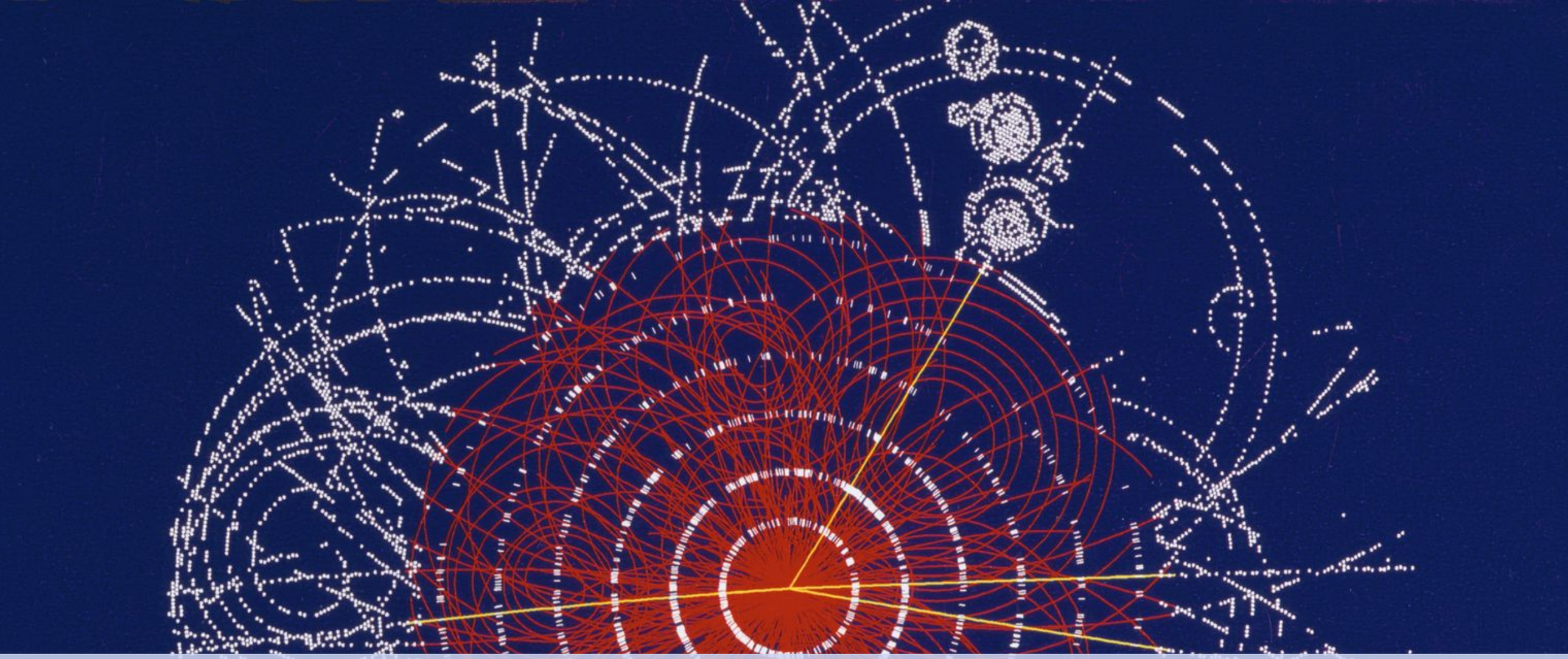

THE HIGGS AS A WINDOW ONTO PHYSICS BEYOND THE STANDARD MODEL (II)

Jessie Shelton
Illinois Center for the Advanced Studies of the Universe, UIUC
SLAC Summer Institute, August 2021

FIRST-ORDER PHASE TRANSITIONS

- In SM, EW phase transition is a cross-over

- Strongly first-order phase transitions:
  - necessary ingredient for electroweak baryogenesis
  - stochastic GW background
  - require BSM physics not far from EW scale

FIRST-ORDER PHASE TRANSITIONS

- New physics that drives EWPT first order must generically be fairly strongly coupled to Higgs
  - large exotic branching ratios when decays are kinematically possible; narrow sliver of parameter space still open
  - most surviving parameter space has heavy new physics: good prospects at future colliders

[Kozaczuk, Ramsey-Musolf, JS; Carena, Liu, Wang; Curtin, Meade, Yu; …]

SM+SINGLET

- potential for a general real singlet extension of SM:

$$V = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2} a_1 |H|^2 S + \frac{1}{2} a_2 |H|^2 S^2$$
$$+ b_1 S + \frac{1}{2} b_2 S^2 + \frac{1}{3} b_3 S^3 + \frac{1}{4} b_4 S^4$$

- Z_2 symmetry $S \to -S$: S is stable
- General case: S decays through Higgs mixing

SM+SINGLET

- potential for a general real singlet extension of SM:

$$V = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2} a_1 \underbrace{|H|^2}_{\mathcal{O}(\theta)} S + \frac{1}{2} a_2 |H|^2 S^2$$

$$+ \underbrace{b_1 S}_{\mathcal{O}(\theta)} + \frac{1}{2} \underbrace{b_2}_{-\frac{1}{2} a_2 v^2 + m_s^2 + \mathcal{O}(\theta^2)} S^2 + \frac{1}{3} b_3 S^3 + \frac{1}{4} b_4 S^4$$

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$\mathcal{O}(\theta)$

$Br(h \to ss)$

$\mathcal{O}(\theta)$

$$-\frac{1}{2} a_2 v^2 + m_s^2 + \mathcal{O}(\theta^2)$$

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$\mathcal{O}(\theta)$ $\quad$ $Br(h \to ss)$

$$+ b_1 S + \frac{1}{2} b_2 S^2 + \frac{1}{3} b_3 S^3 + \frac{1}{4} b_4 S^4$$

$\mathcal{O}(\theta)$

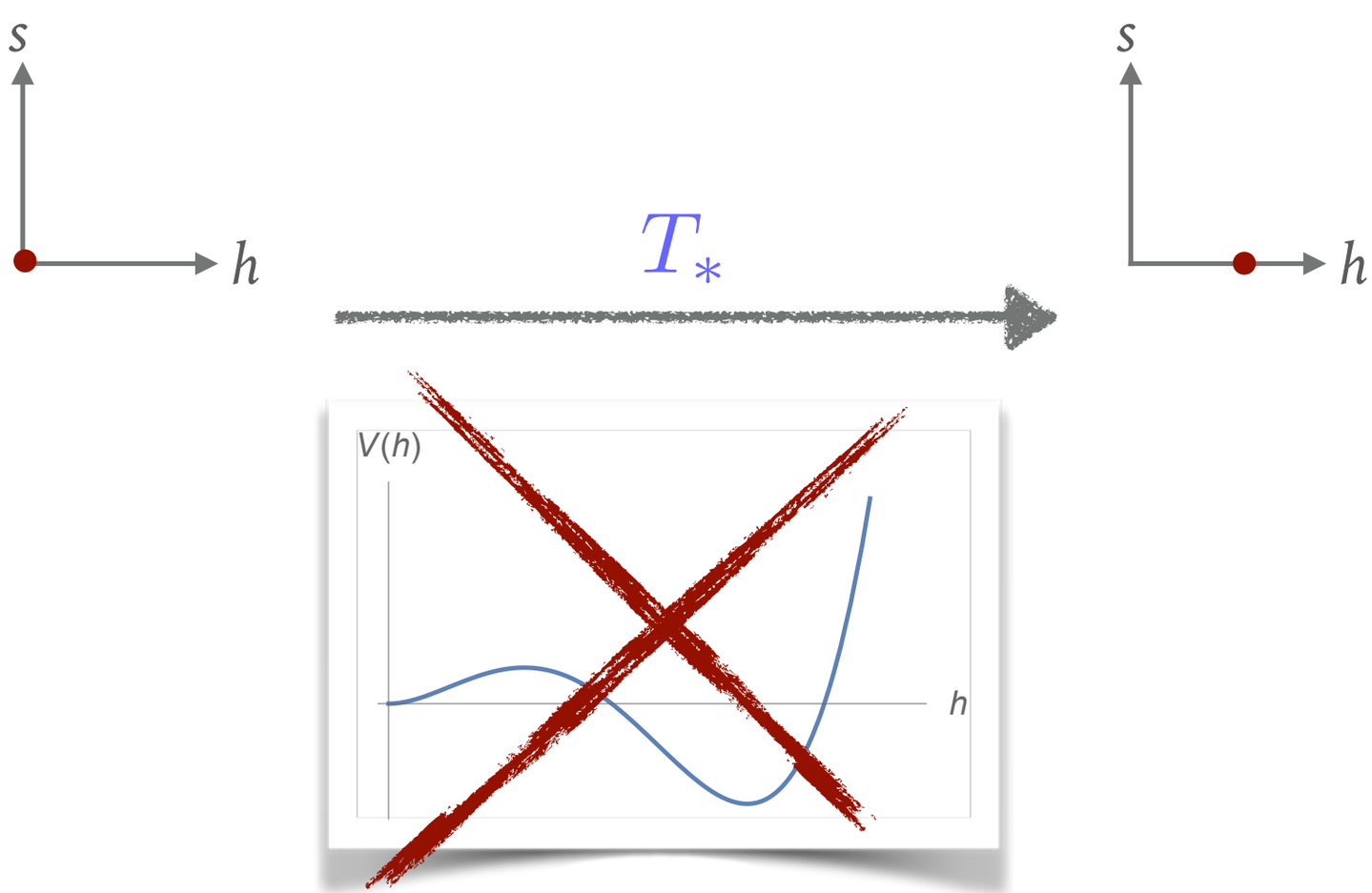
$$-\frac{1}{2} a_2 v^2 + m_s^2 + \mathcal{O}(\theta^2)$$

$$\{a_2, b_3, b_4; m_s, \cos\theta\}$$

- Z_2 symmetry $S \to -S$: S is stable
- General case: S decays through Higgs mixing

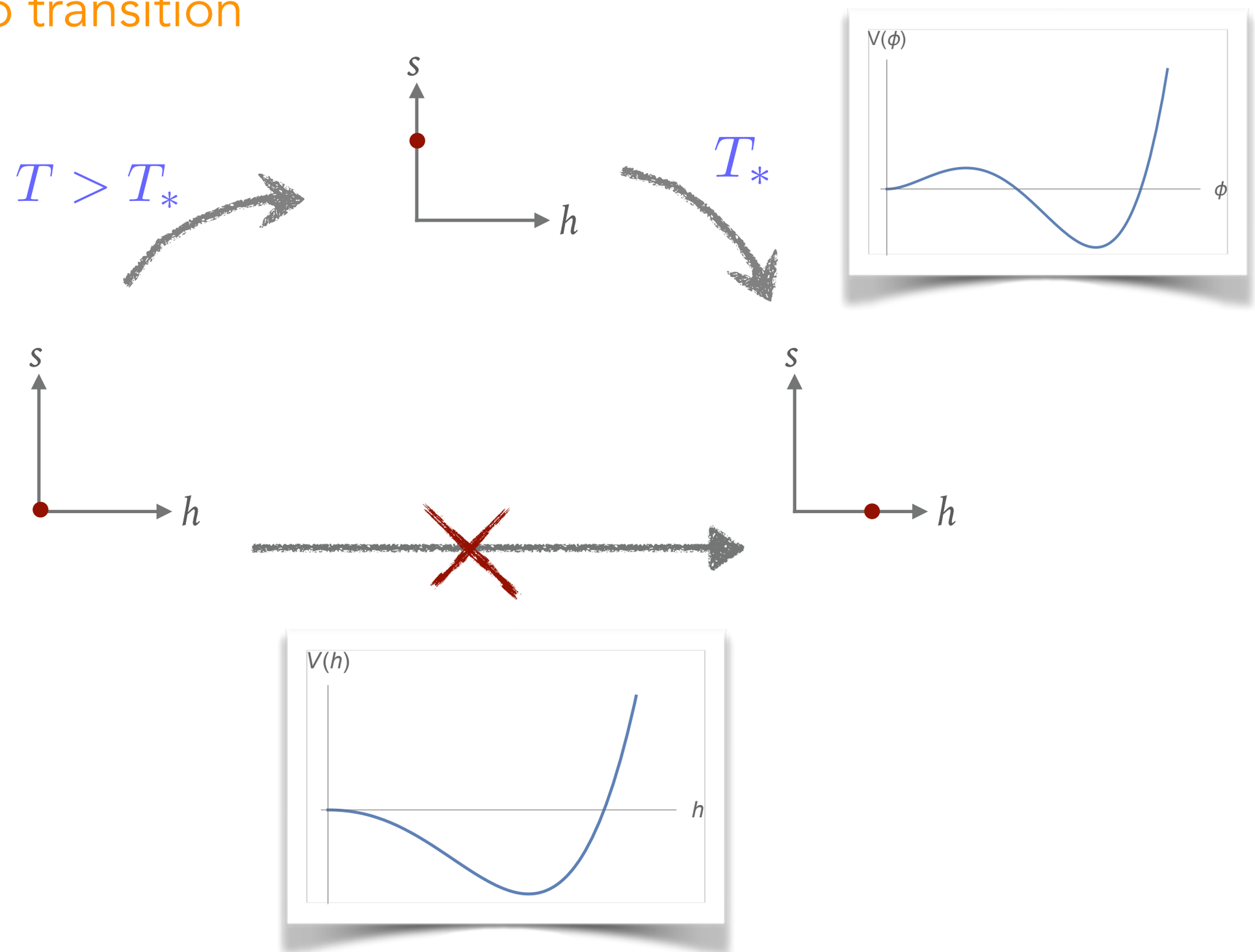
SINGLET-ASSISTED PHASE TRANSITIONS

- First order: new cubic terms (tree or loop)
  - strongly first order: $\frac{v(T_*)}{T_*} \gtrsim 1$
  - but adding cubic terms in pure *h* direction results in unacceptable changes to SM-like Higgs properties



SINGLET-ASSISTED PHASE TRANSITIONS

- two-step transition



TWO-STEP PHASE TRANSITION

- Consistency conditions for this scenario:
  - vacuum stability, $V(0, h_0, T = 0) < V(s_0, 0, T = 0)$
  - singlet vacuum is a local minimum at *T**

$$m_h^2(s_0, 0, T_*) > 0$$

  - system is in singlet vacuum, not symmetry-preserving vacuum before transition to EW vacuum

$$V(s_0, 0, T > T_*) < V(0, 0, T > T_*)$$

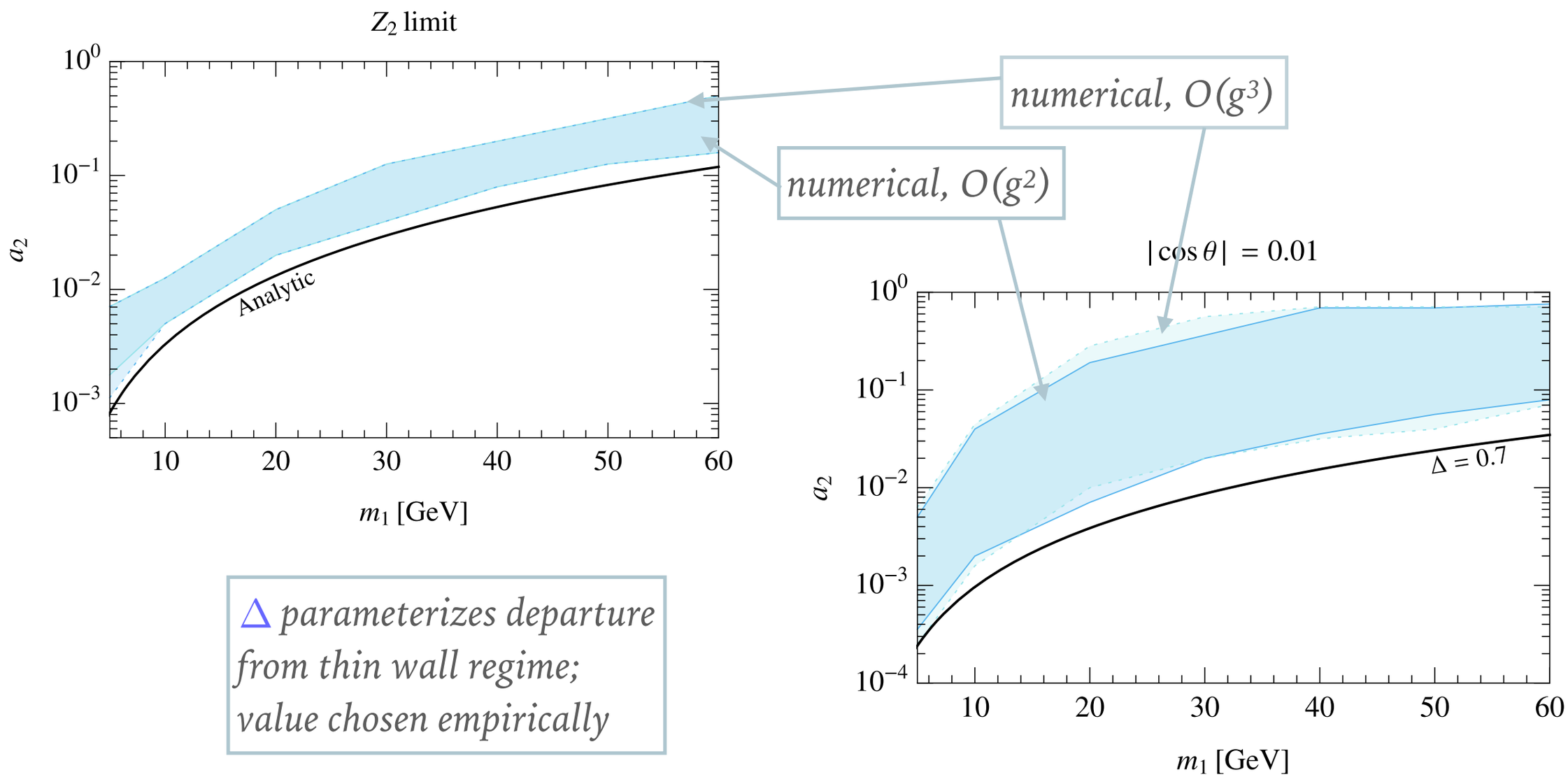
  - EW vacuum is energetically preferred at critical temp *T**

$$V(s_0, 0, T_*) > V(0, h_0, T_*)$$

  - phase transition successfully completes

MINIMUM BRANCHING RATIOS

- With $\cos\theta \ll 1$, potential at $O(g^2)$, above conditions can be combined to give (semi-)analytical lower bound on a_2:

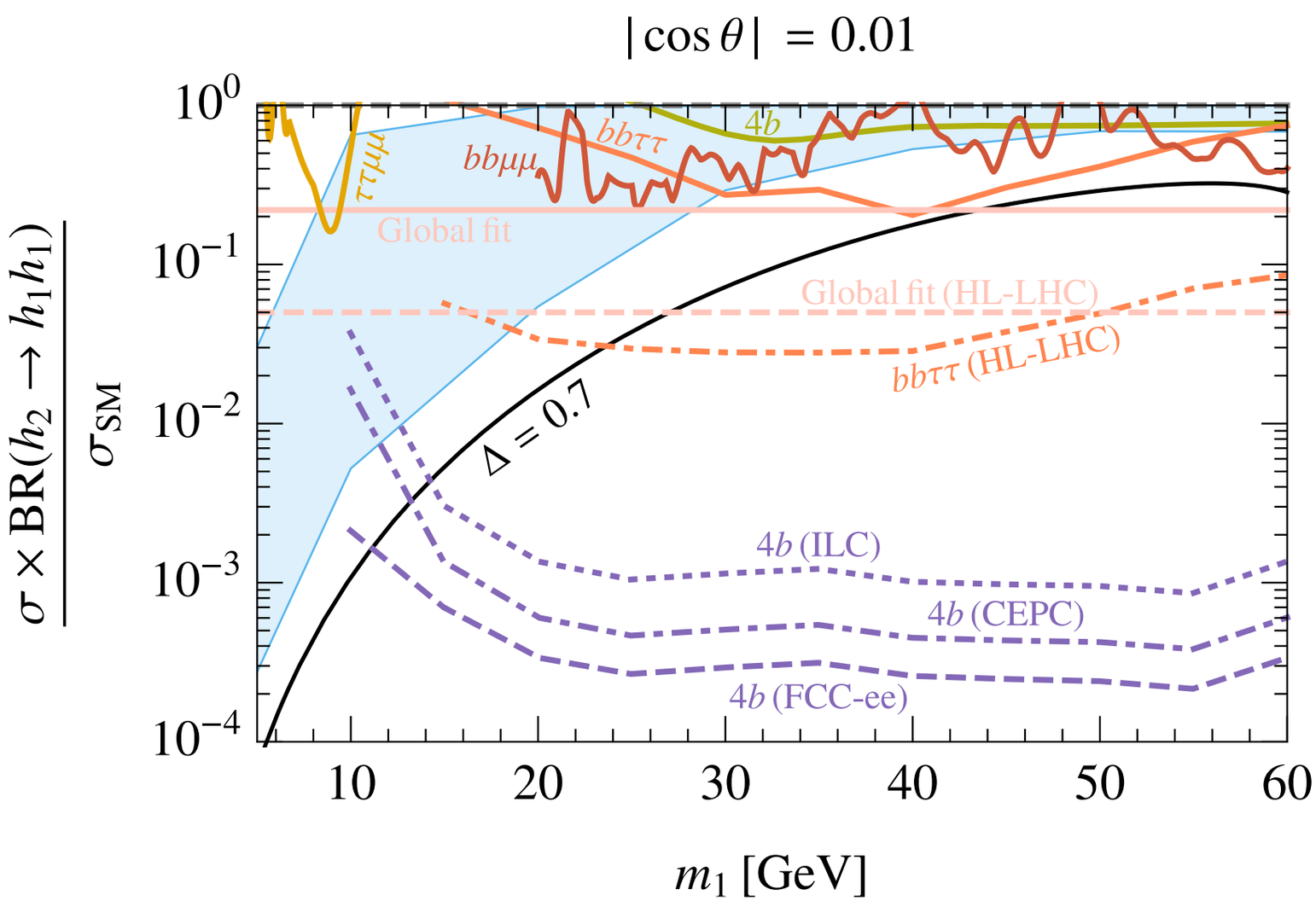


Δ parameterizes departure from thin wall regime; value chosen empirically

[Kozaczuk, Ramsey-Musolf, JS]

VISIBLE SIGNALS OF FIRST-ORDER PHASE TRANSITIONS

- Visible decays:



forecasts:

HL/HE WG2

CMS-PAS-FTR-18-035

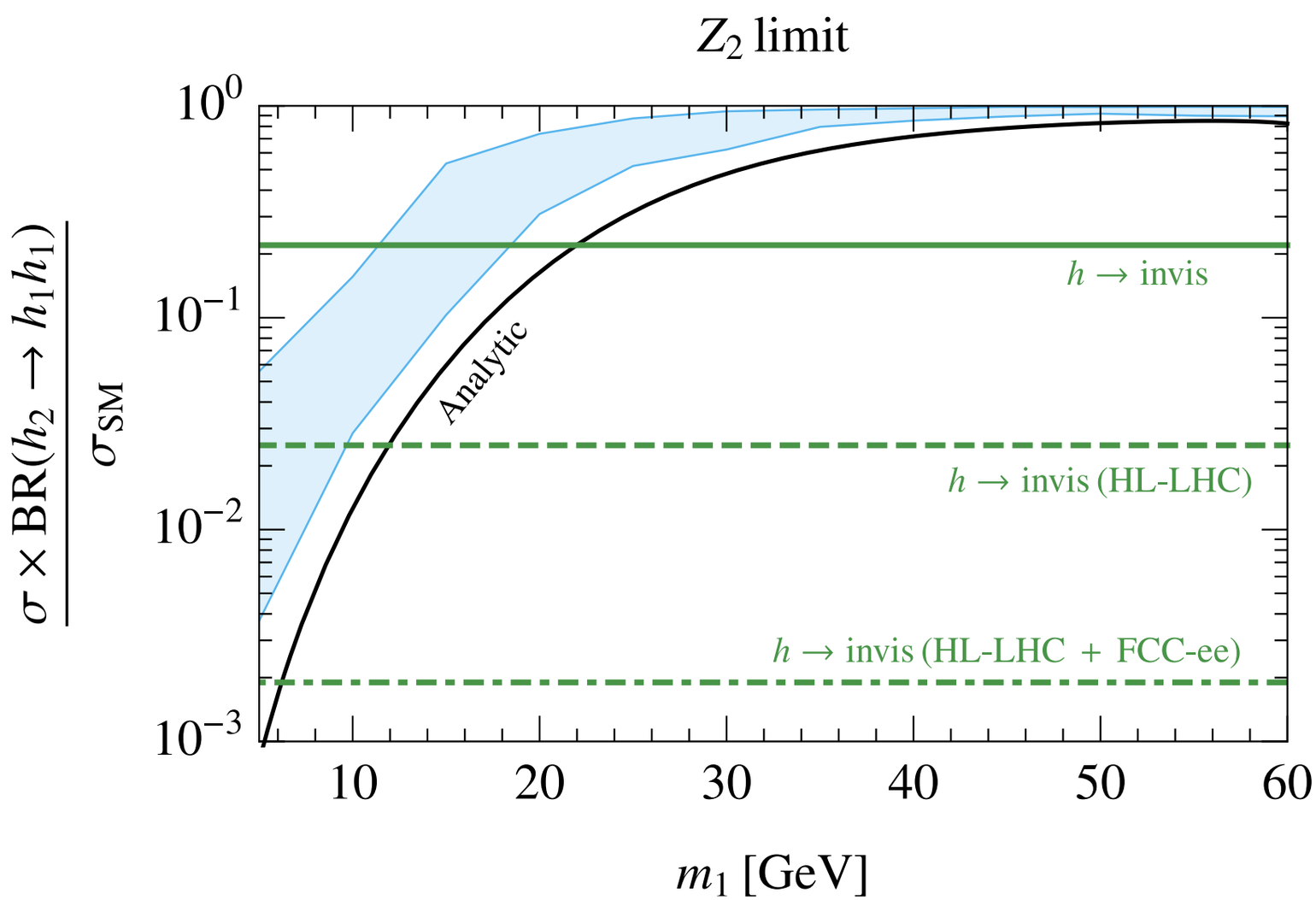
Liu, Wang, Zhang

- Low mass: more work needed (predictions, sensitivities)

[Kozaczuk, Ramsey-Musolf, JS]

FIRST-ORDER PHASE TRANSITIONS AND EXO H DECAYS

- Invisible decays:



forecasts:

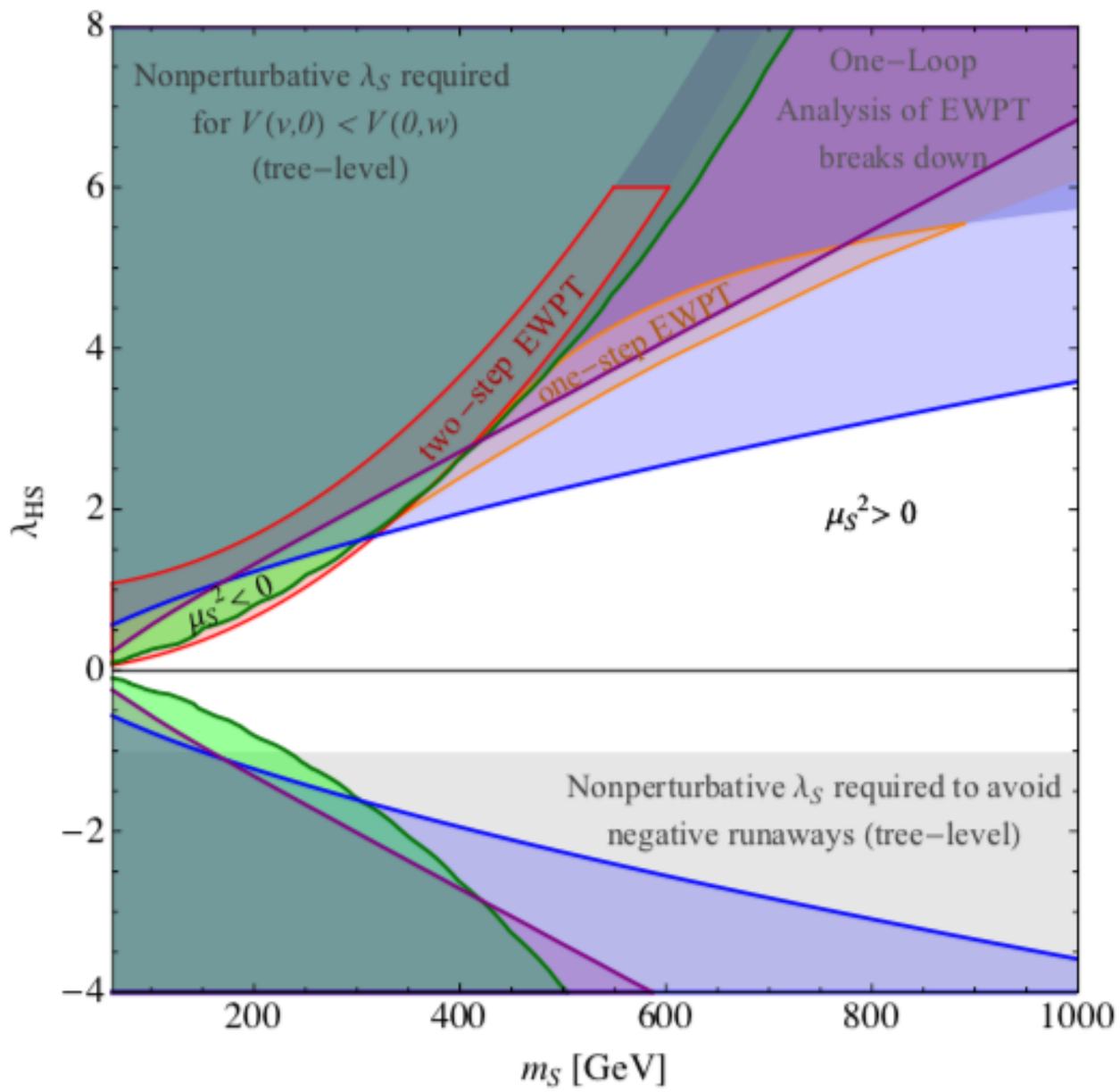
HL/HE WG2

de Blas et al.

[Kozaczuk, Ramsey-Musolf, JS]

FIRST-ORDER PHASE TRANSITIONS AND HEAVY SCALARS

- Heavier singlets are harder to probe:



estimated sensitivity from Zh coupling at future e+e-

100 TeV estimated sensitivity from Higgs triple coupling

100 TeV estimated sensitivity from VBF production of *SS*

[Curtin, Meade, Yu]

LIGHT SCALARS AND THE HIERARCHY PROBLEM

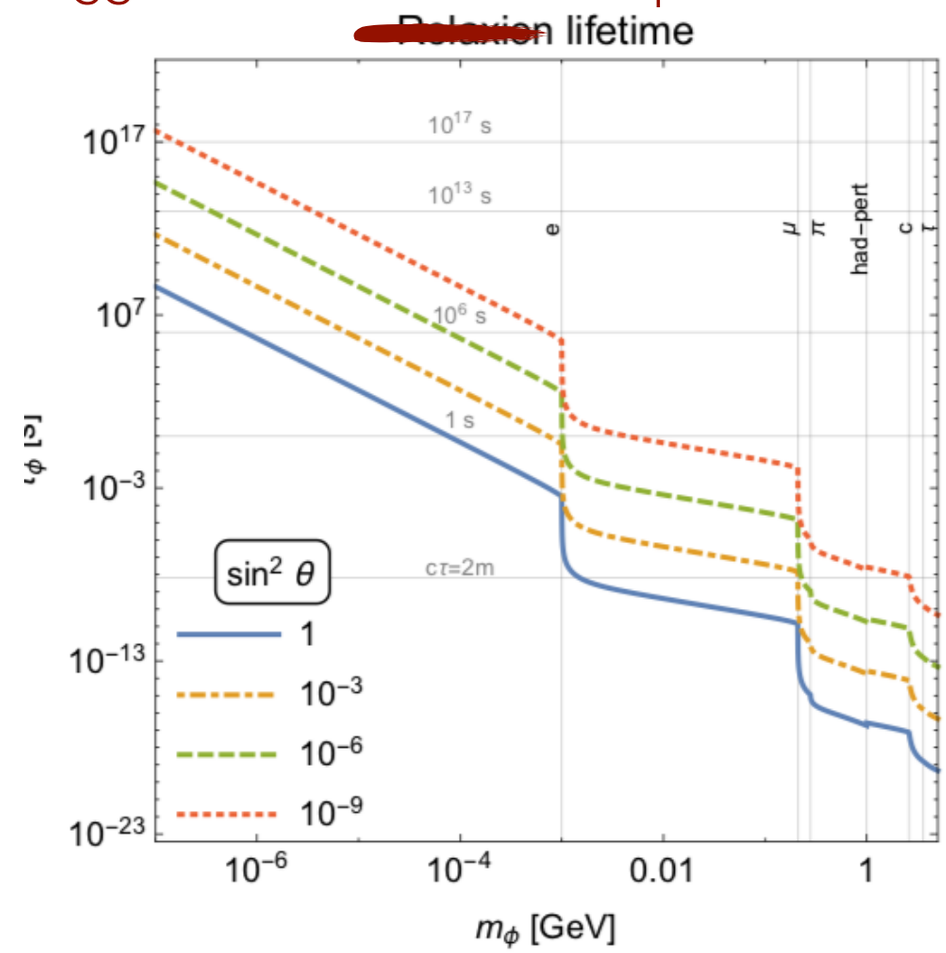
- A light scalar mixing with the Higgs can be a prediction of relaxion solution to hierarchy problem

see lecture by Nate Craig

  - final relaxion vev will often spontaneously break CP, allowing for relaxion-Higgs mixing
  - A light Higgs-mixed scalar can easily become long-lived

$$\Gamma(m) \propto m \sin^2\theta \frac{m_f^2}{v^2}$$

Higgs-mixed fundamental spin-zero field

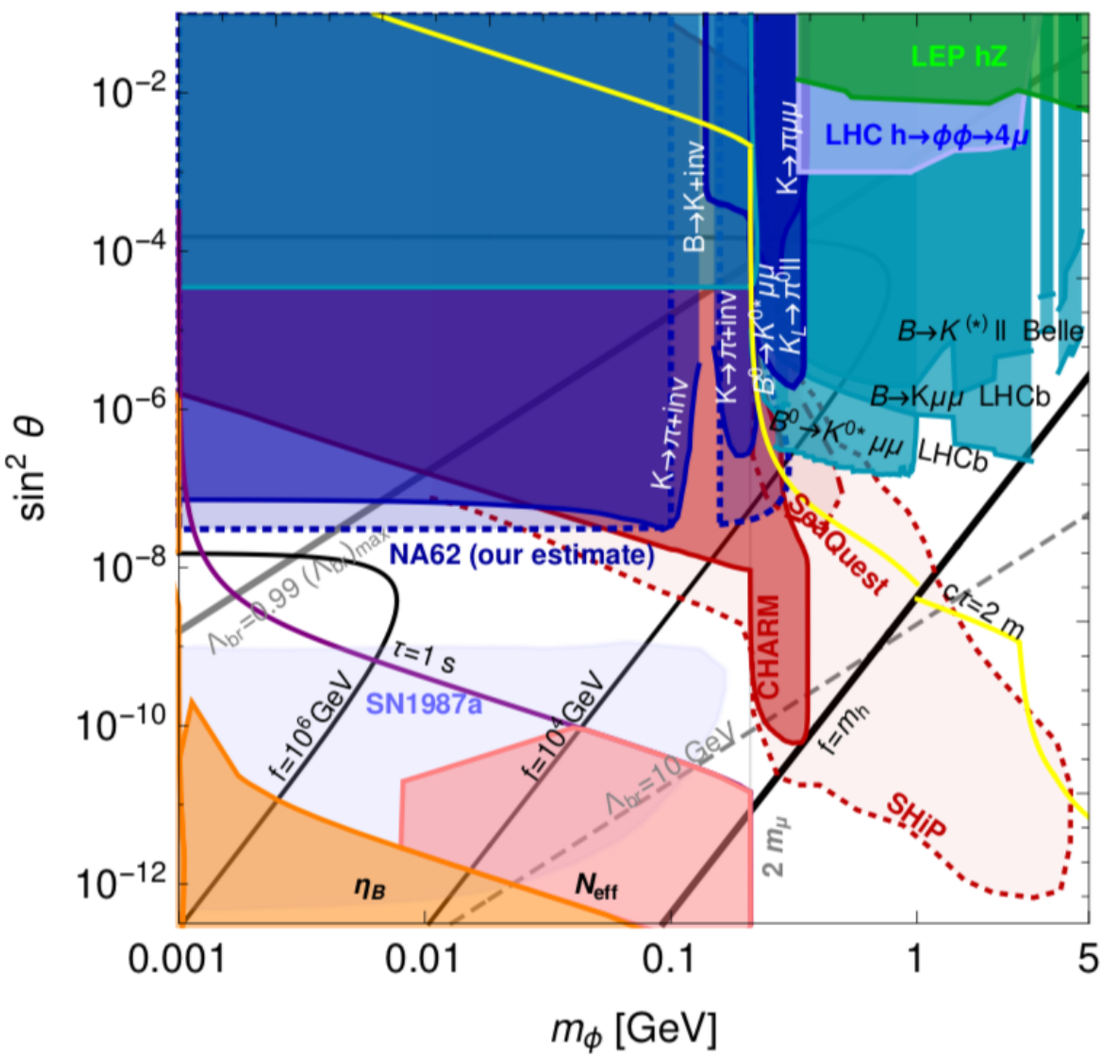


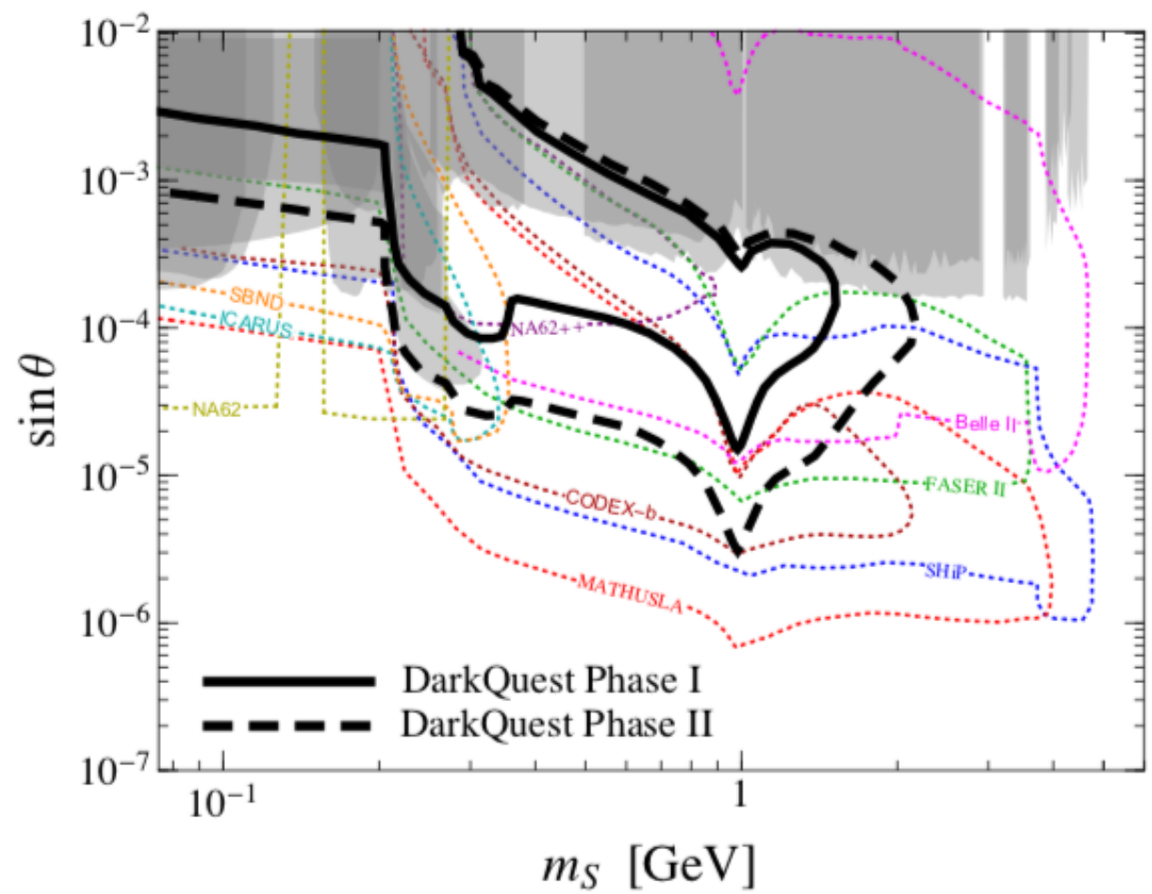
[Flacke, Frugiuele, Fuchs, Gupta, Perez]

LIGHT SCALARS AND THE HIERARCHY PROBLEM

- Constraints on low-mass scalar parameter space dominated by production in meson decays

reminder: relation between Higgs branching ratios and direct production is model-dependent

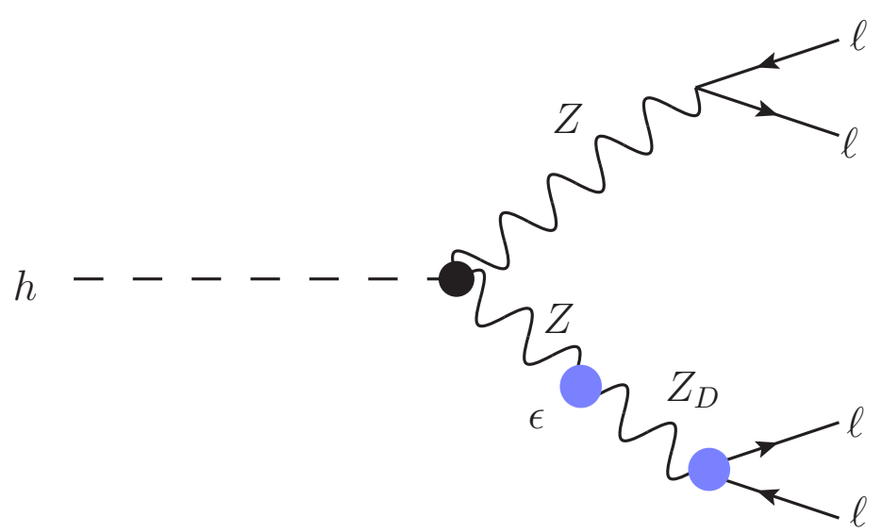


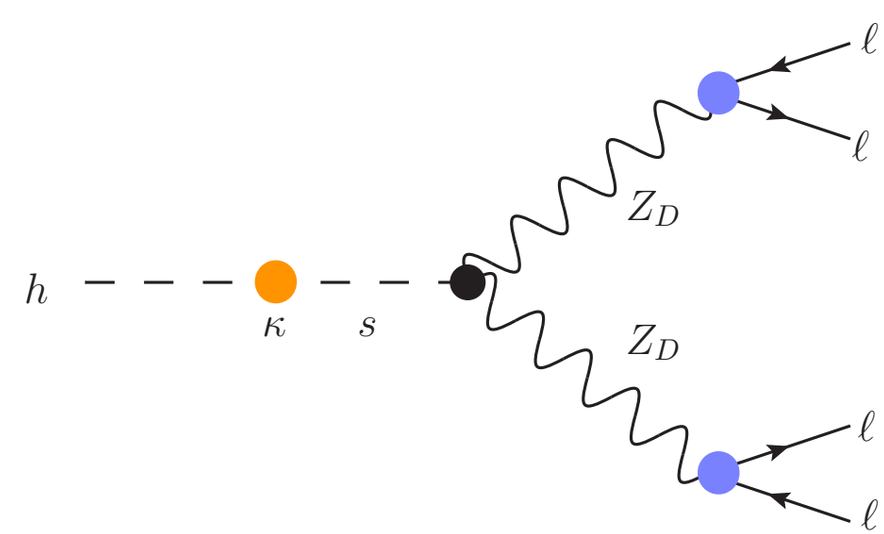


[Flacke, Frugiuele, Fuchs, Gupta, Perez; Batell, Evans, Gori, Rai]

LONG-LIVED PARTICLES IN DARK SECTORS

- dark sector: SM singlet particles that interact with each other (generally, more strongly than with SM)
- Example: dark photon with mass from a dark Higgs
- Separate production from decay: LLP signatures can become generic





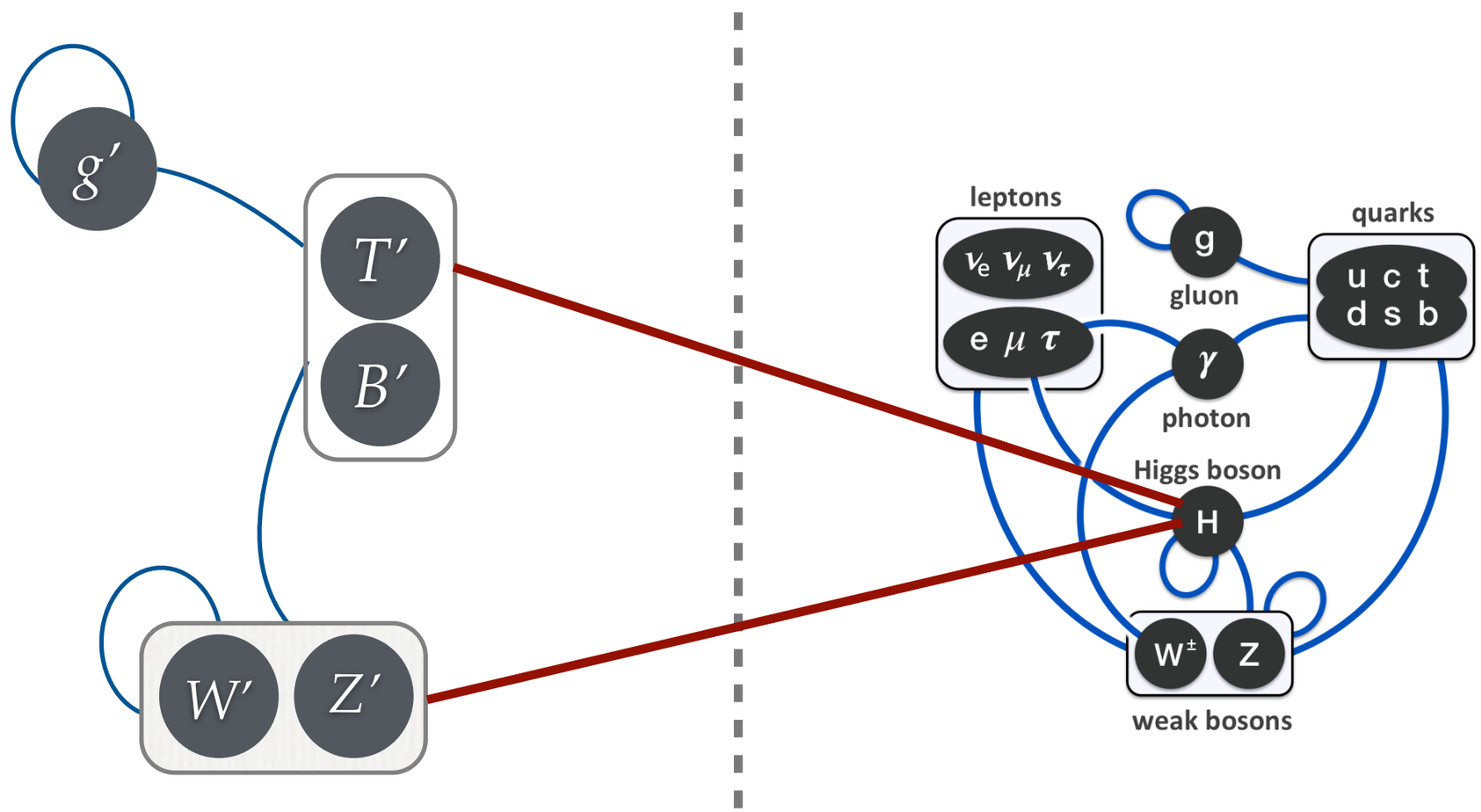
[Schabinger, Wells; Curtin, Essig, Gori, JS; …]

CONFINING DARK SECTORS AND COMPOSITE STATES

- What if dark sector has confining gauge interactions: for instance, a dark copy of QCD?
- Lightest dark states can be composite
- Composite states are described by higher-dimension operators than elementary states are
  - ex: dark meson $\tilde{\Lambda}^2\eta \leftrightarrow \bar{\psi}\gamma^5\psi$
  - ex: dark glueball $\widetilde{\Lambda}^3\phi \leftrightarrow \mathrm{Tr}\,\widetilde{G}_{\mu\nu}\widetilde{G}^{\mu\nu}$
  - Lifetime for composite dark state to decay into SM is parametrically longer than for elementary dark state

CONFINING DARK SECTORS AND THE HIERARCHY PROBLEM

- Neutral naturalness: dark QCD for the hierarchy problem
  - partners of SM particles neutral under SM forces, charged under (near-)mirror copy of SM gauge group

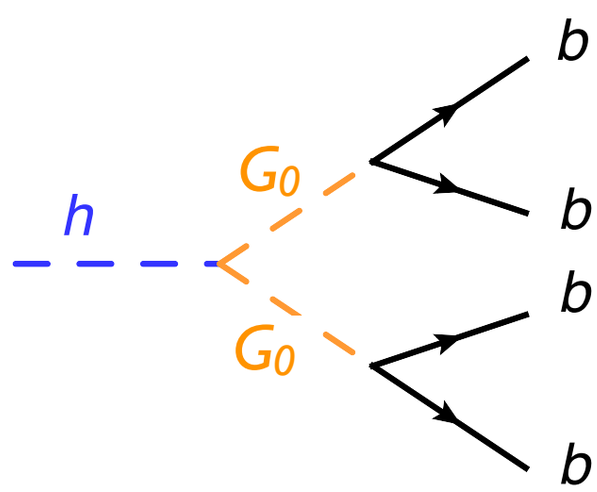


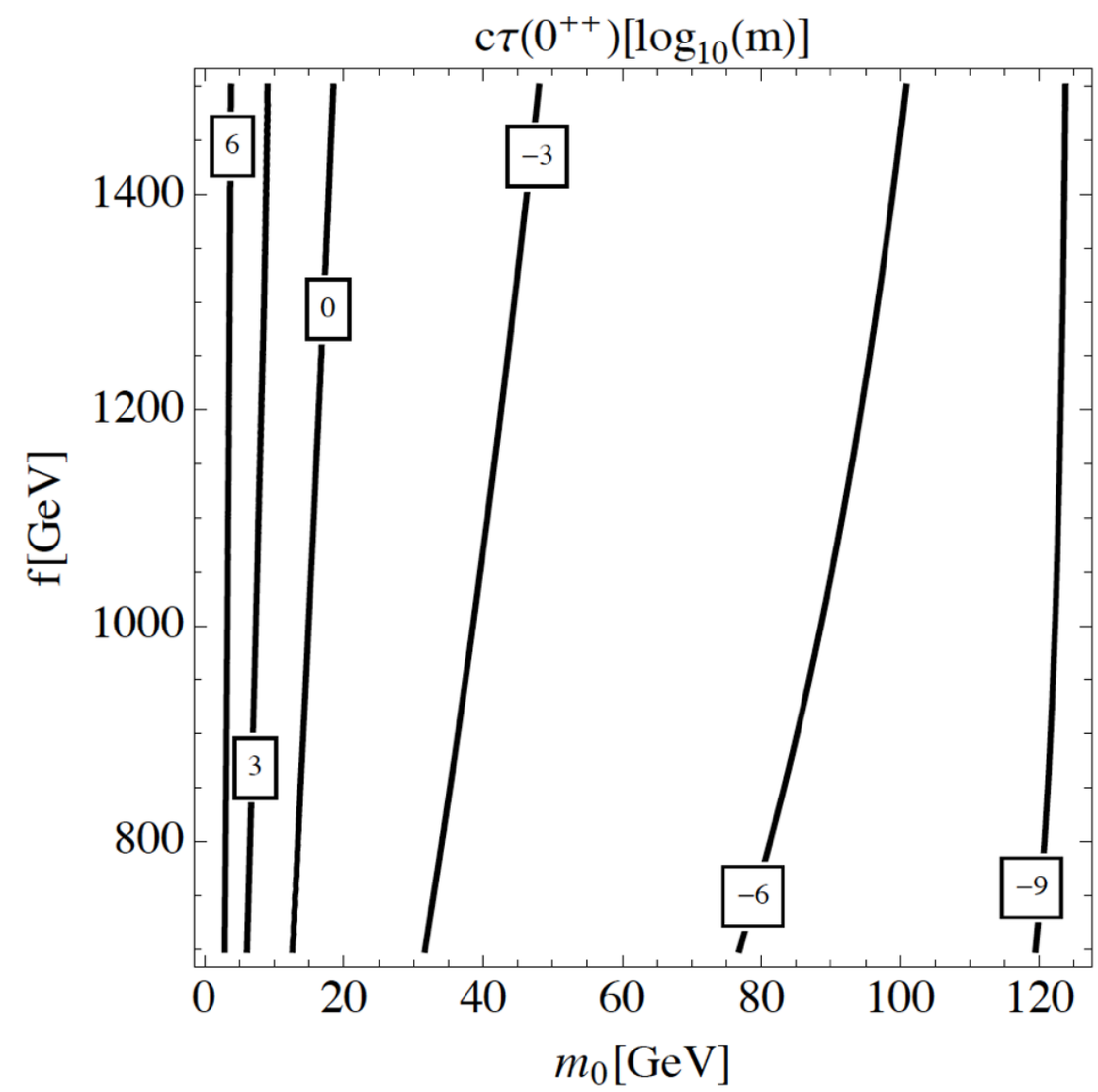
  - strength of Higgs coupling depends on amount of fine-tuning

see lecture by Nate Craig

HIGGS DECAYS TO LLPS

- Leading signature of neutral naturalness at LHC: Higgs decays to dark glueballs, i.e., composite dark scalar

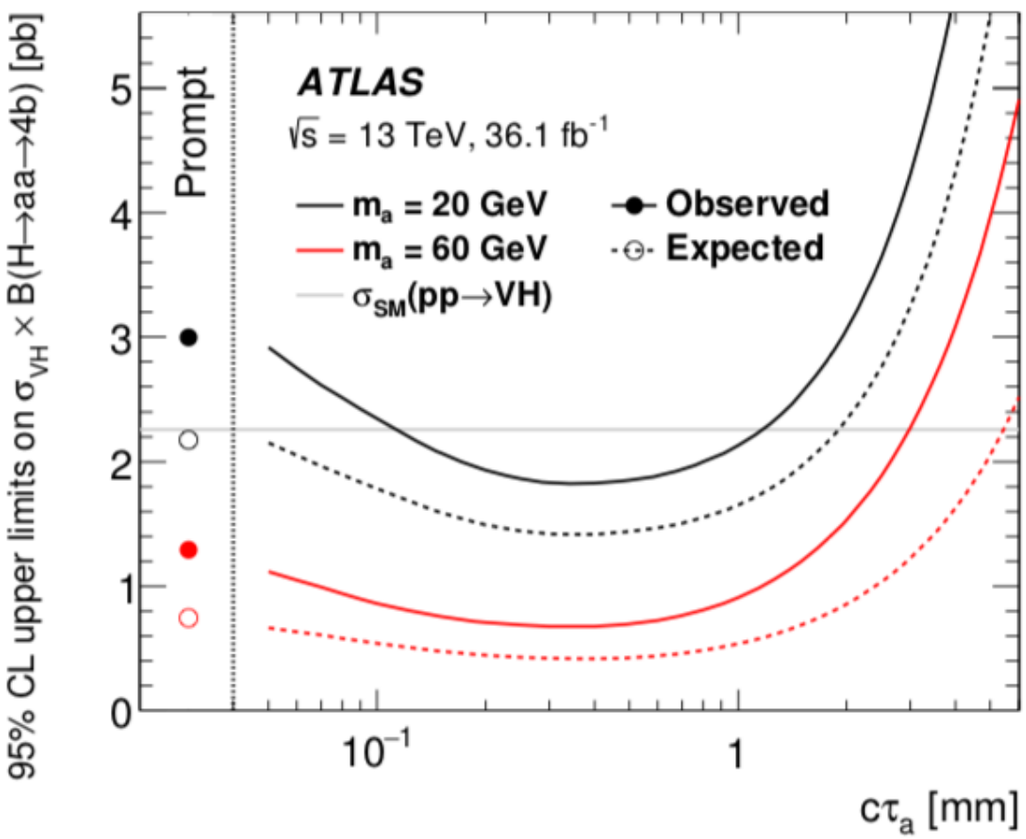


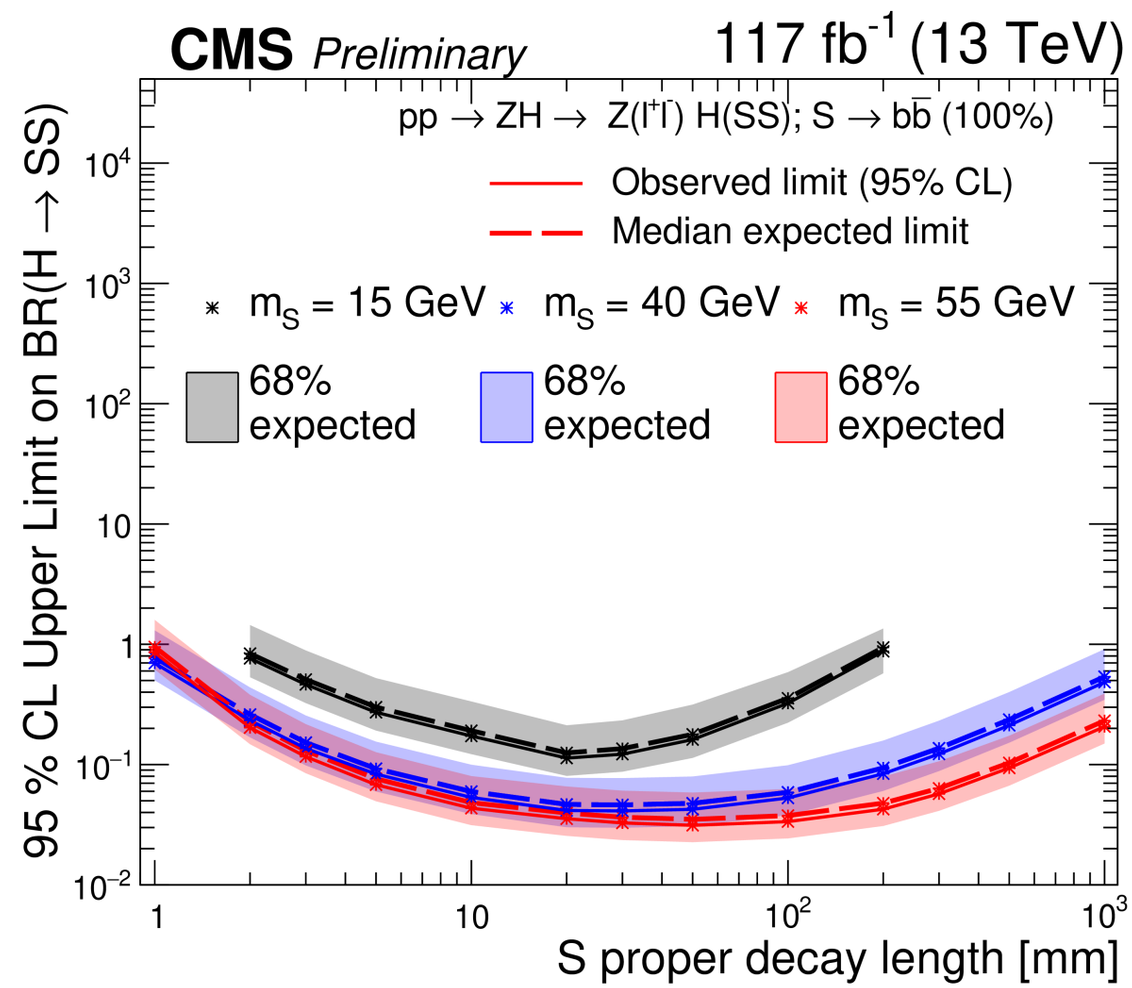


[Craig, Katz, Strassler, Sundrum]

HIGGS DECAYS TO LLPS

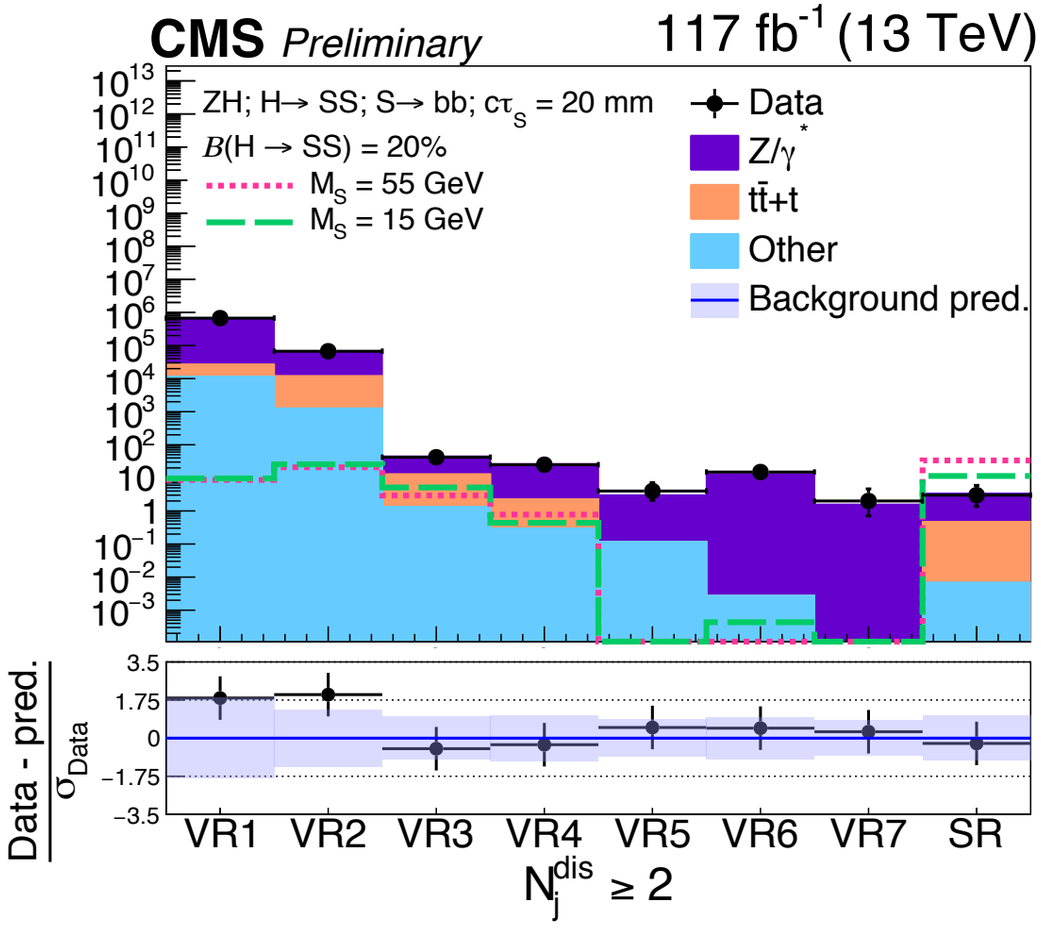
- LLPs at the main detectors are a double-edged sword:
  - clean signatures! SM backgrounds can be very low





HIGGS DECAYS TO LLPS

- But: LHC detectors, standard analysis pipelines not designed for such signals: much work to record, understand the data
  - backgrounds often (weird SM physics) x (weird detector response), typically need to data-drive estimaes

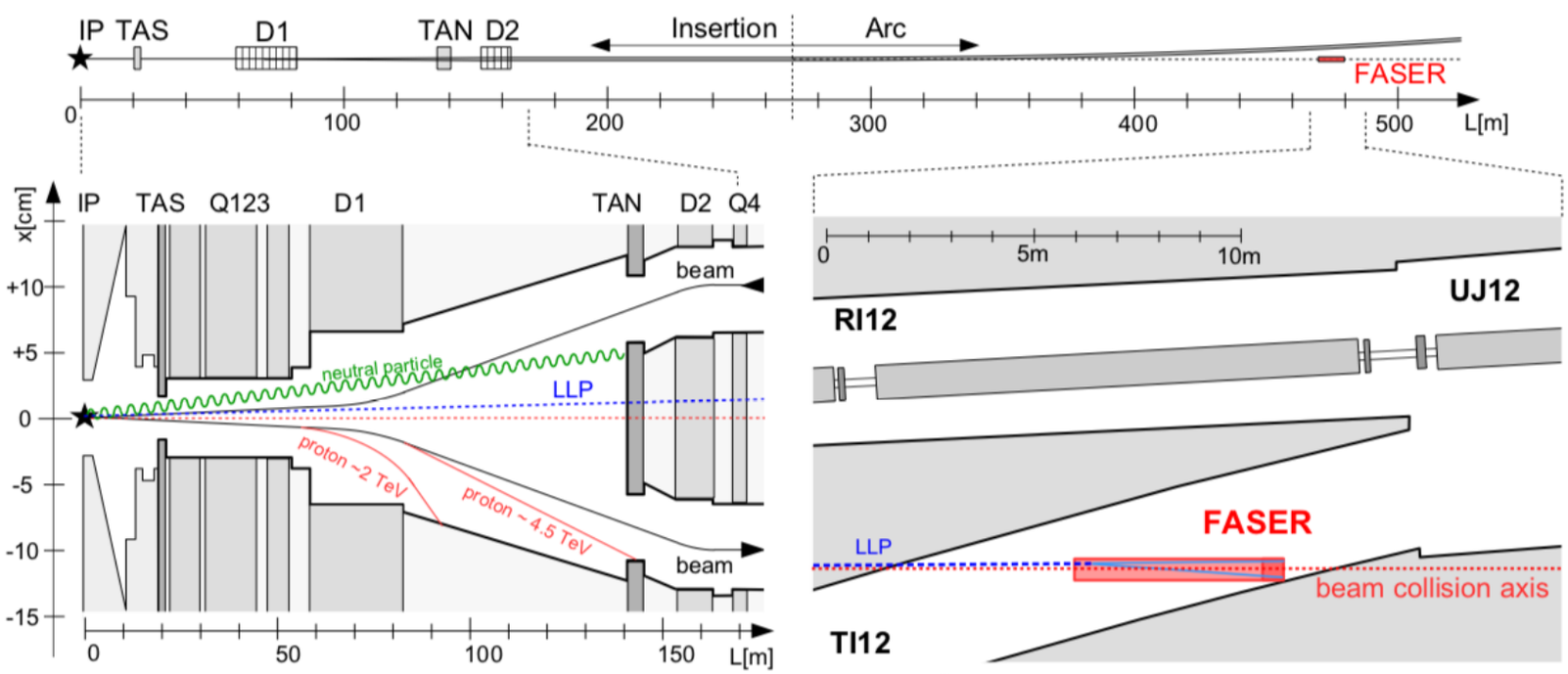


- Displaced jets from:
  - known SM LLPs (b, c, tau)
  - material interactions in tracker (nuclear interactions, photon conversions)
  - misidentification from imperfect track reconstruction

DEDICATED LONG-LIVED PARTICLE DETECTORS

- new detectors for LLPs produced at LHC:

FASER: dedicated forward detector near ATLAS interaction point



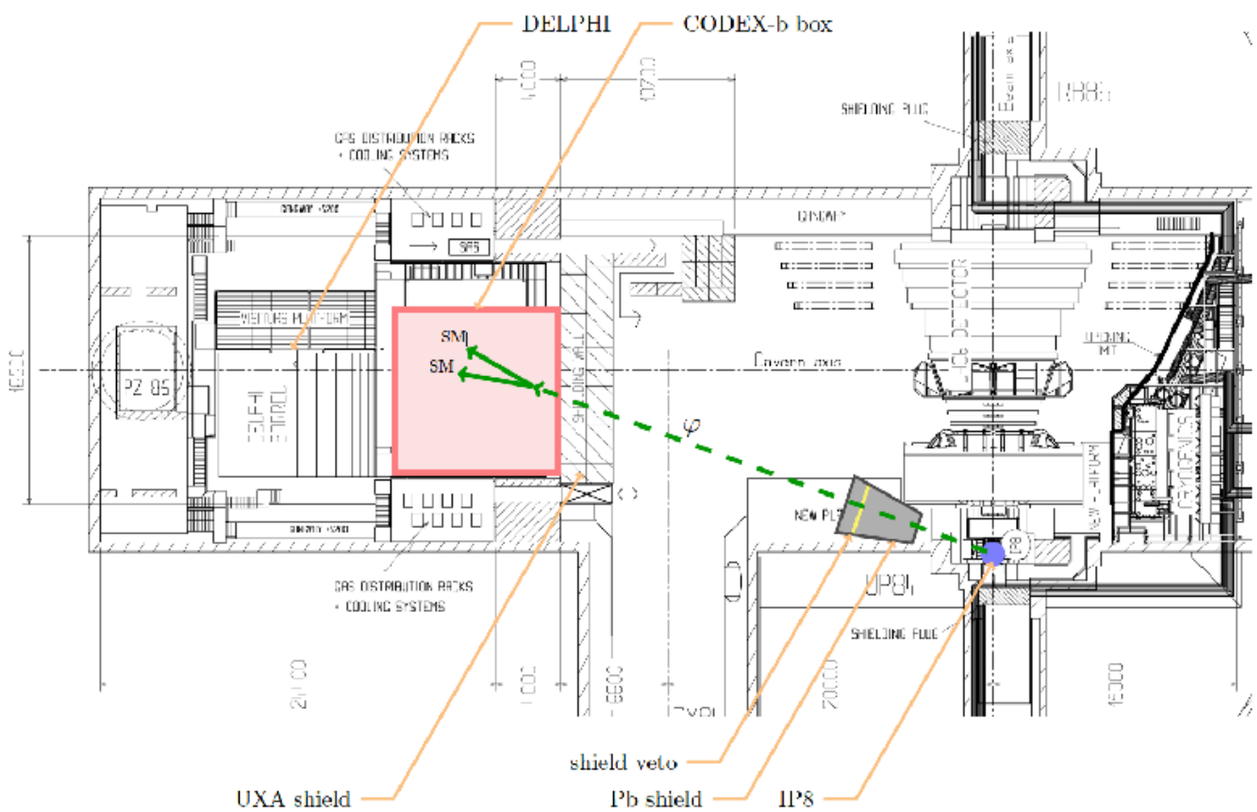
- in operation! Angular acceptance best suited for vector portal physics, interesting scalar portal reach in proposed Faser 2

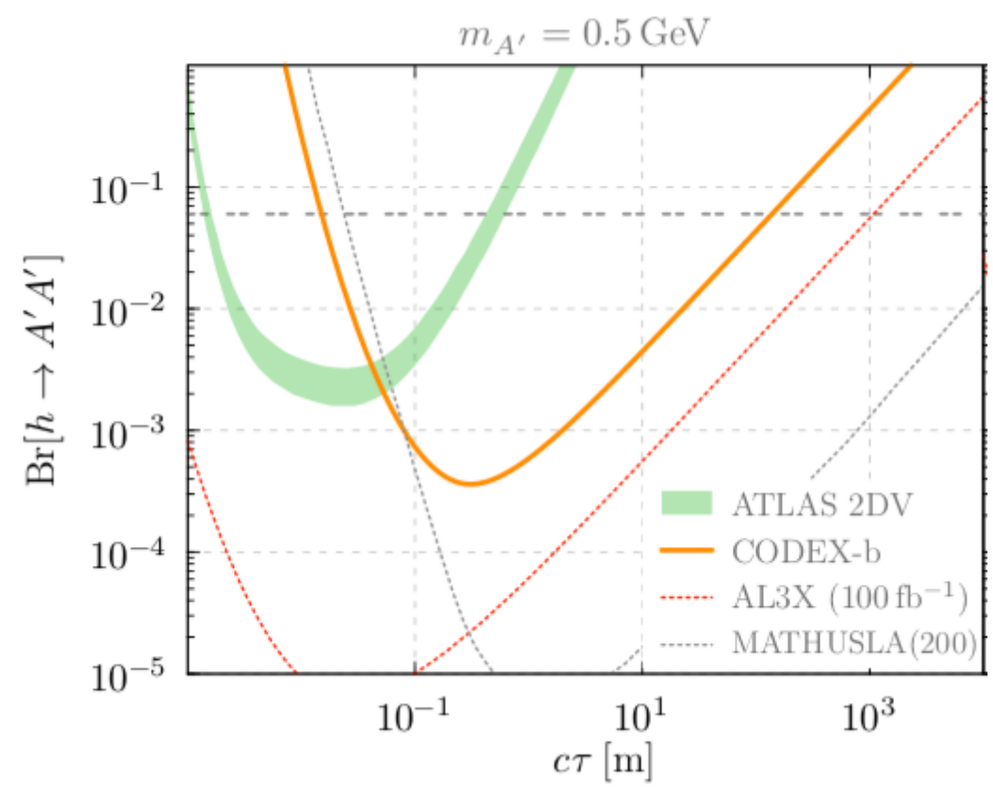
[Feng, Galon, Kling, Trojanowski; FASER collaboration]

DEDICATED LONG-LIVED PARTICLE DETECTORS

- new detectors for LLPs produced at LHC:

CODEX-b: proposed LLP detector near LHCb interaction point



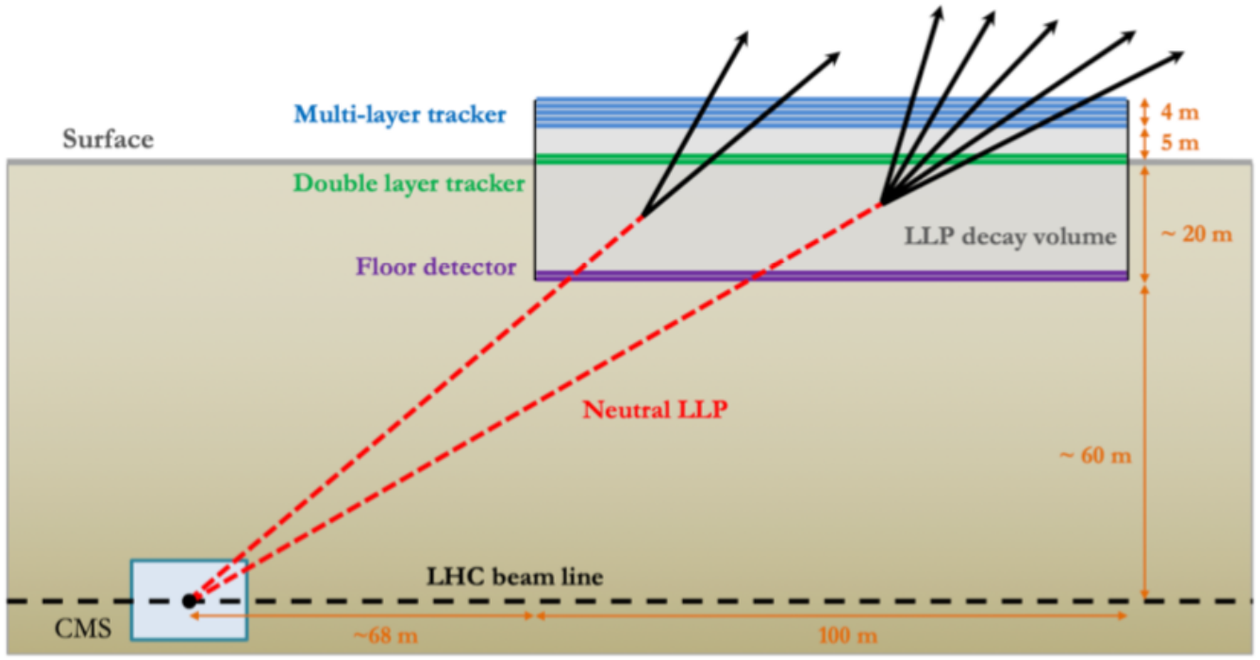


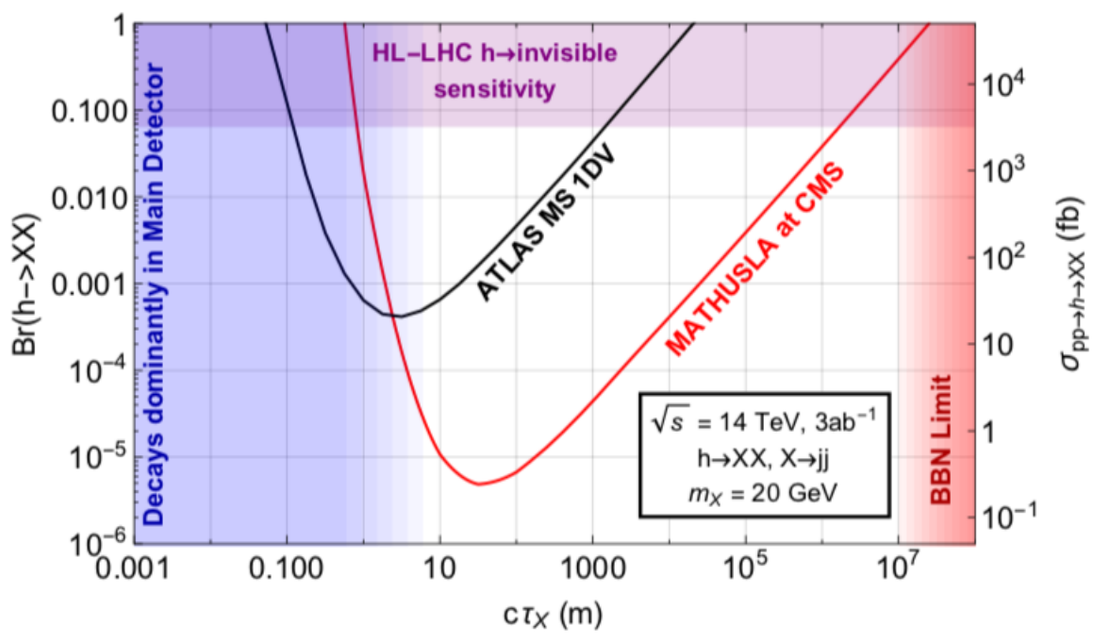
[Gligarov, Knapen, Papucci, Robinson; CODEX-b collaboration]

DEDICATED LONG-LIVED PARTICLE DETECTORS

- new detectors for LLPs produced at LHC:

MATHUSLA: proposed LLP detector near CMS interaction point





[Chou, Curtin, Lubatti; MATHUSLA collaboration]

FRONTIERS: HIGGS DECAYS INTO CONFINING HIDDEN SECTORS

- Confining hidden sectors are a generic possibility for new physics (explicit examples for DM, hierarchy problem)
- Higgs portal: production in SM Higgs decays a leading possibility
- Characteristic features of dark shower events:
  - variable and potentially large object multiplicity
  - non-SM-like distributions of energy, flavor
  - often non-isolated final state objects
  - hierarchy of lifetimes
- Detector-scale lifetimes for at least one species

[Strassler, Zurek; … ; Knapen, JS, Xu]

LOOKING FORWARD

- LHC is our first chance to study the Higgs boson directly
  - simultaneous advances in direct detection, intensity frontier experiments
- already learned enormous amounts about what our universe does and doesn't do
- HL-LHC: enormous Higgs sample, $\sim 10^8$!
  - many opportunties for finding new physics
  - advances in triggering capabilities will add more
- Complementary physics at future e+e- colliders