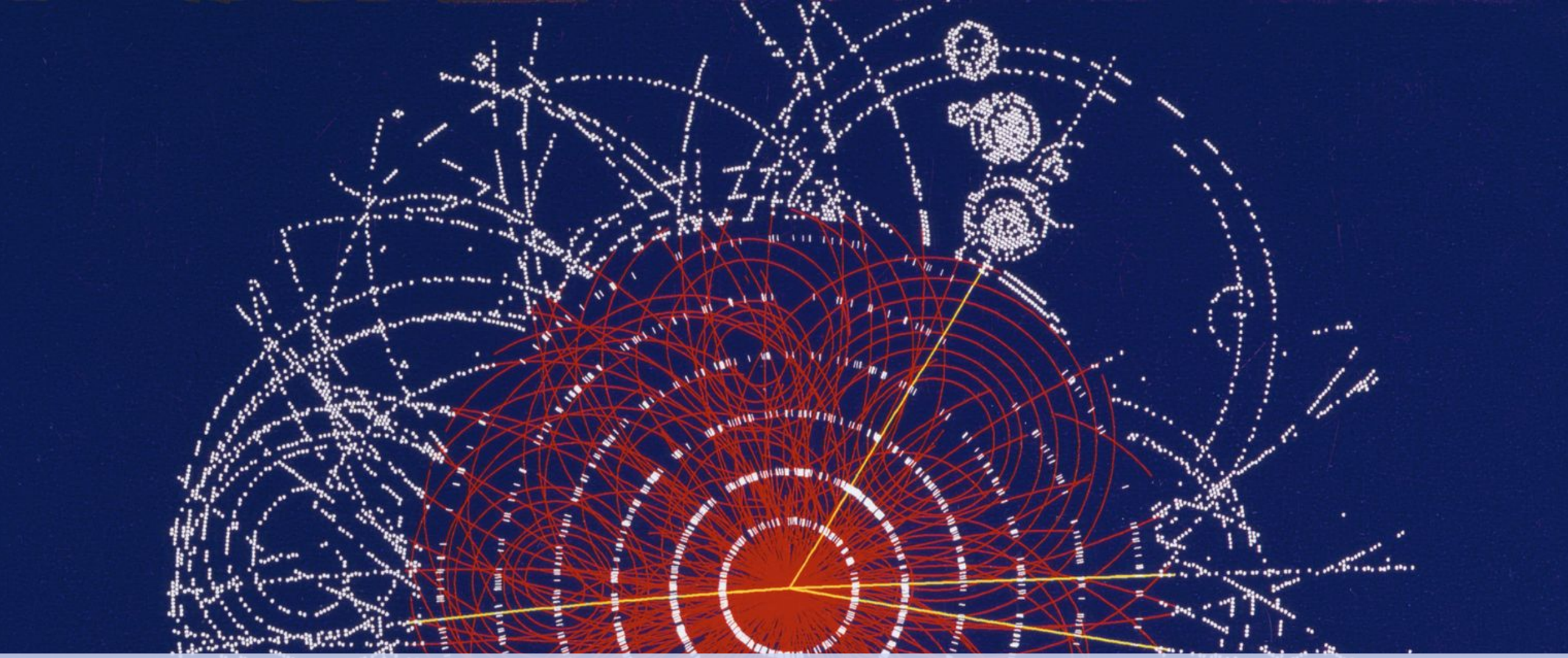
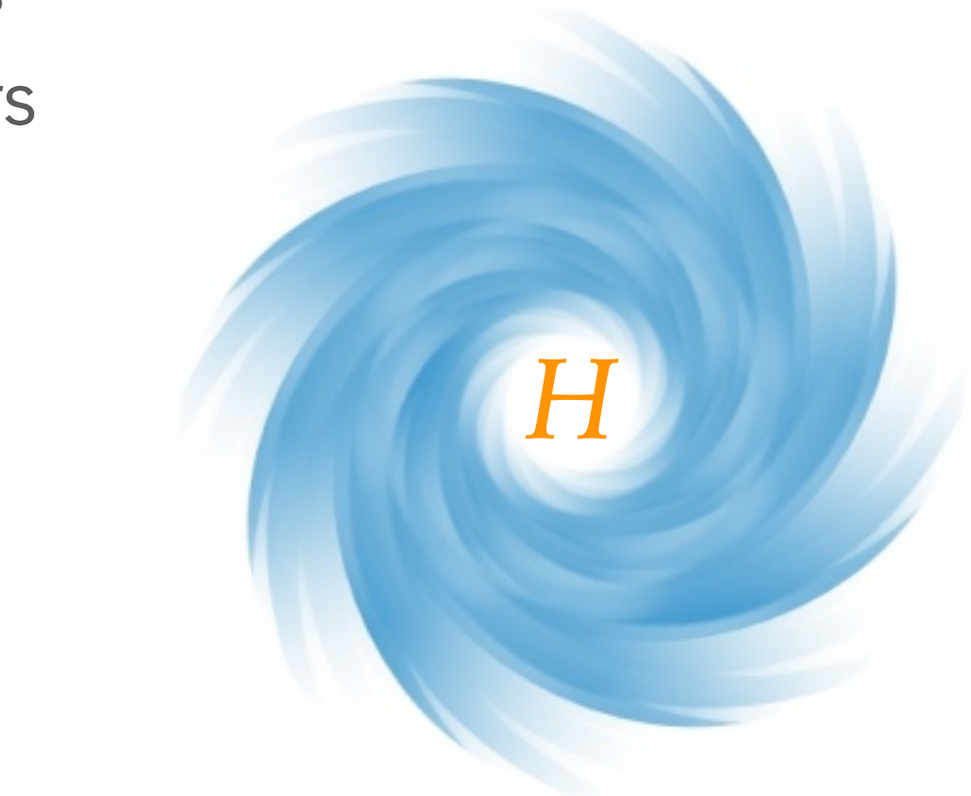


THE HIGGS AS A WINDOW ONTO PHYSICS BEYOND THE STANDARD MODEL (I)

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

THE HIGGS PORTAL

- Structure of SM gauge interactions limits the total SM singlet operators that one can construct
  - $\mathcal{L}_{SM}$: $\bar{f}\gamma^\mu D_\mu f$, $\bar{Q}_L H d_R$, ...
  - Currents: $\bar{f}_i \gamma^\mu f_i$
  - Neutrino portal: $H L_L$
  - Hypercharge portal: $B_{\mu\nu}$
  - Higgs portal, $|H|^2$

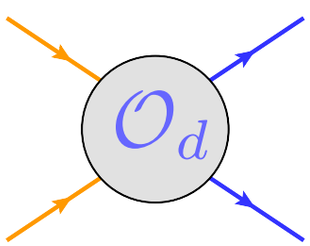


THE HIGGS PORTAL

- Higgs is thus particularly sensitive window onto to new physics
  - Quantum sensitivity to new physics: hierarchy problem

see lecture by Nate Craig

  - Effective field theory: leading place in SM where we may expect to see evidence of SM singlet new physics coupling to the SM

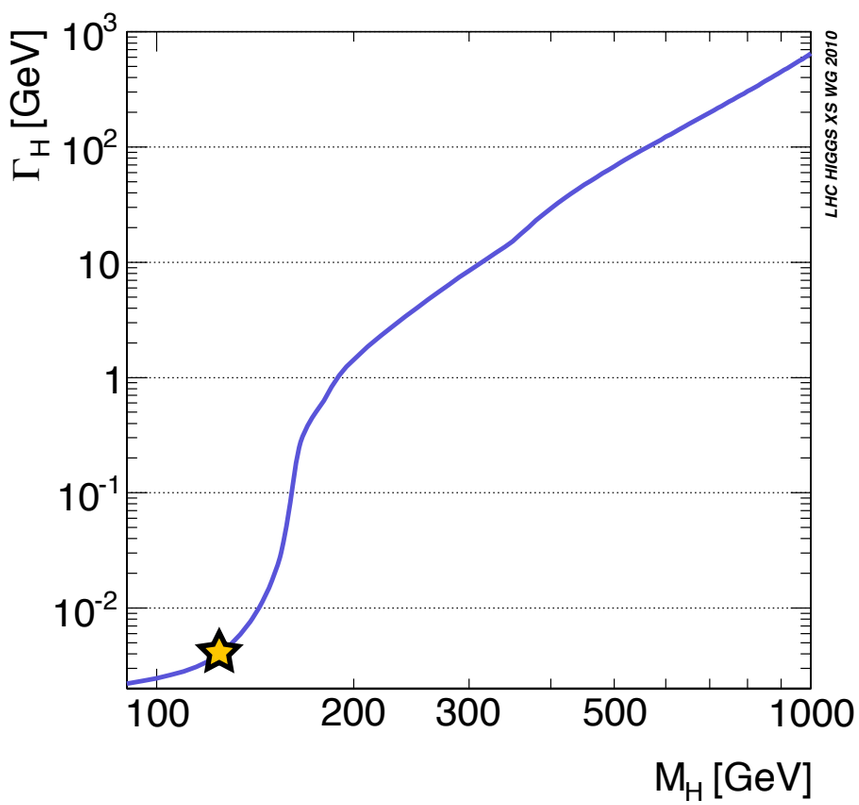


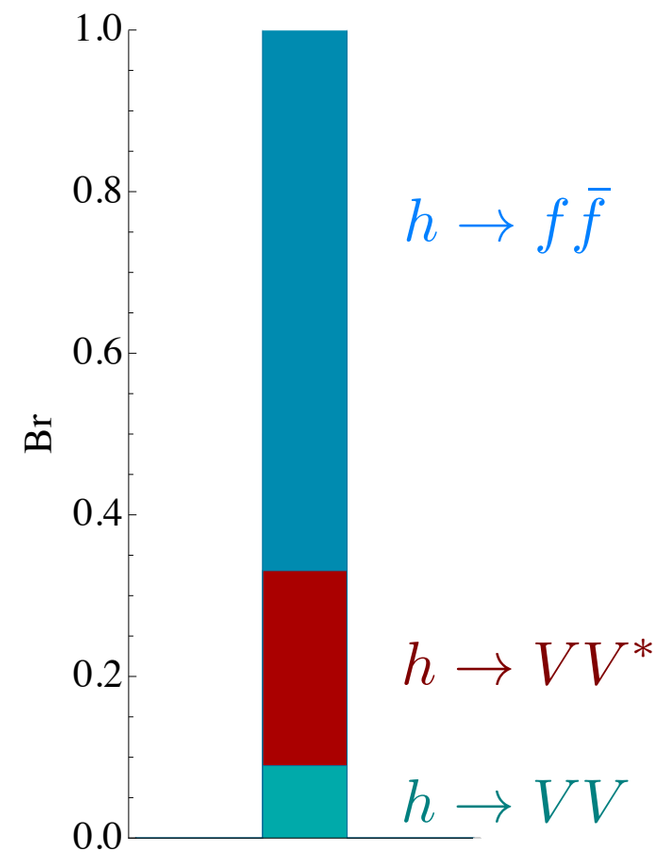
$$|\mathcal{M}|^2 \propto \Lambda^{-2(d-4)}$$

$$\frac{1}{\Lambda^{d-4}}\mathcal{O}_{BSM}\mathcal{O}_{SM}$$

THE HIGGS PORTAL

- Practically: Higgs portal has enhanced accidental sensitivity for light new physics (<$m_h/2$): suppressed SM decay modes





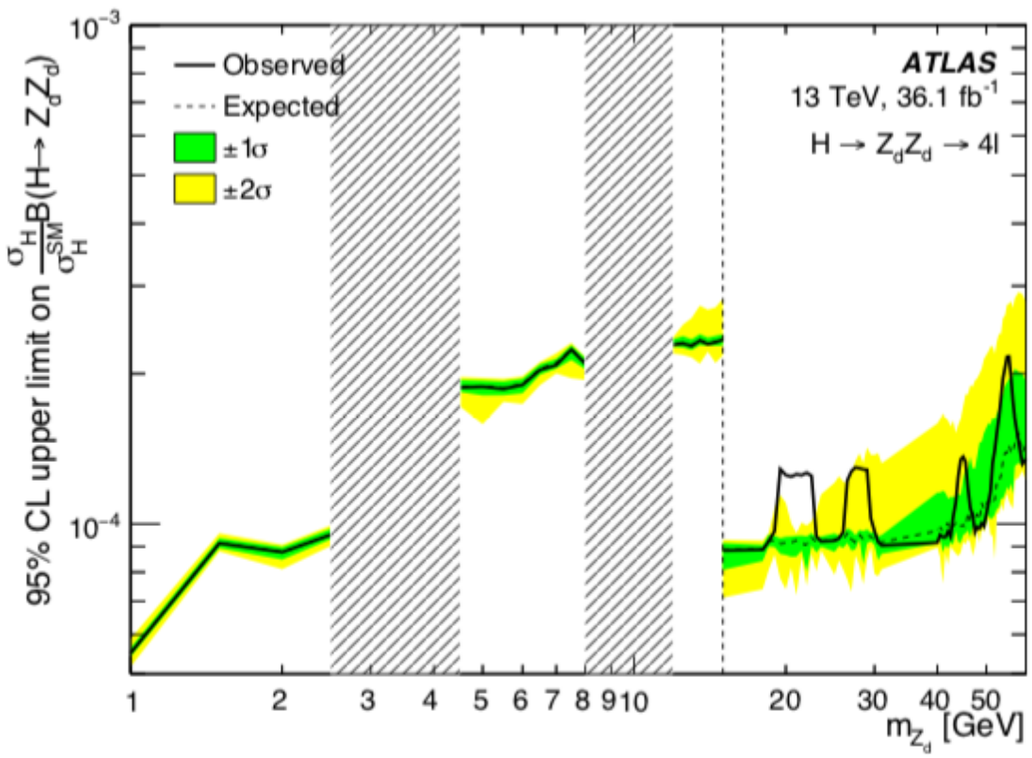
$$\Gamma_h(125\ \text{GeV}) = 4.1\ \text{MeV}$$

THE HIGGS PORTAL

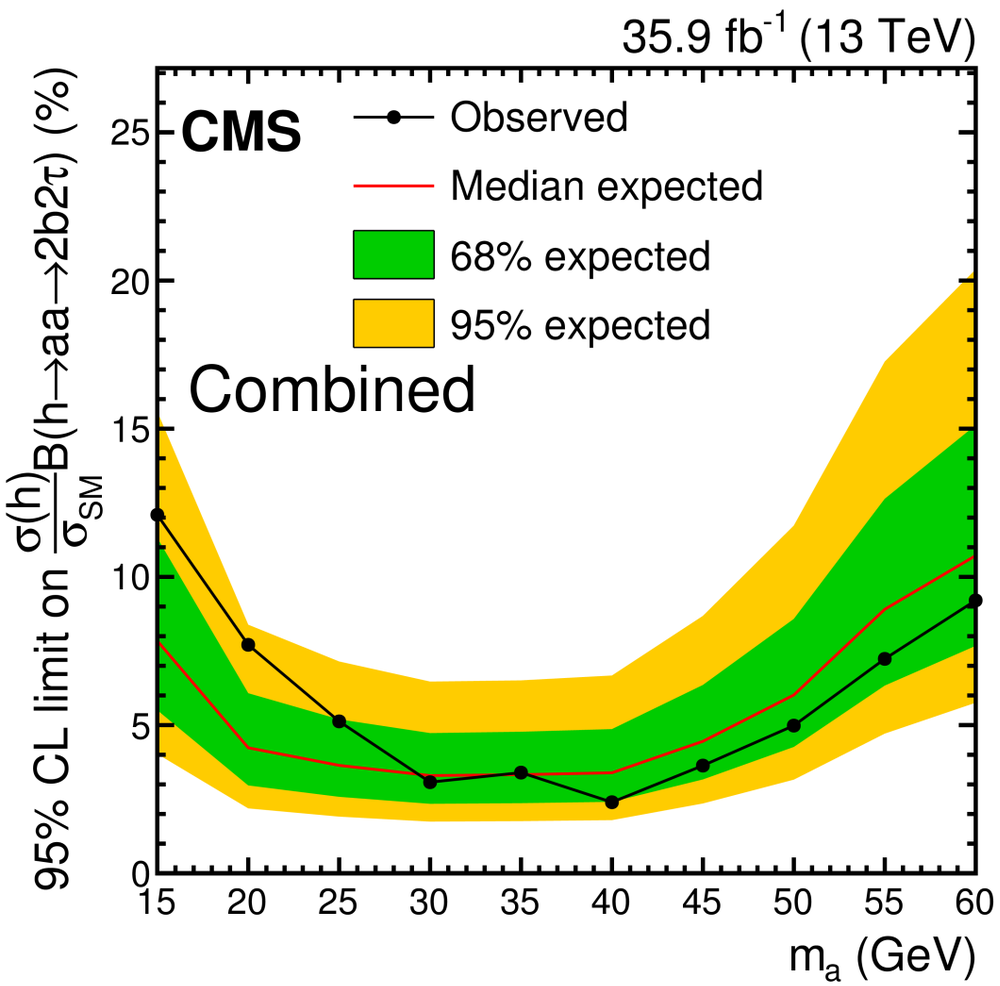
- The LHC as a Higgs factory
  - Higgs production cross-section at 13 TeV: ~50 pb
  - Integrated luminosity, ~35/fb (expect more public results to come soon!)
    - → 10^6 Higgs bosons served
    - If: reasonable reconstruction efficiency, good *S/B*: statistics for branching fractions ~10^{-5}
  - this is like the kinematic limit: best possible reach
    - But getting to this limit is often challenging: Higgs is light

EXOTIC HIGGS DECAYS

- Easy vs hard final states:



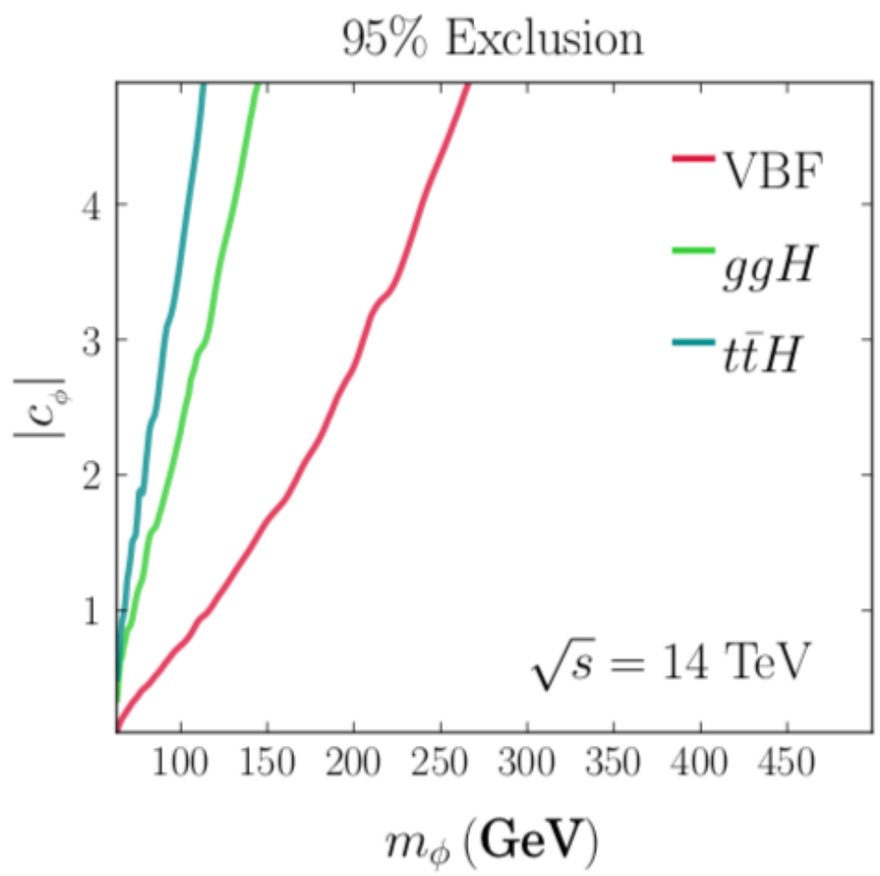
(a) $H \rightarrow Z_d Z_d$



THE HIGGS PORTAL

- For physics heavier than $m_h/2$, life is much harder at LHC (gg pdfs, large backgrounds)

see lectures by Marumi Kado



- at e+e-, deviations in Higgs properties may be easier to pin down

[Craig, Lou, McCullough, Thallapillal (2014)]

WHY NEW PHYSICS?

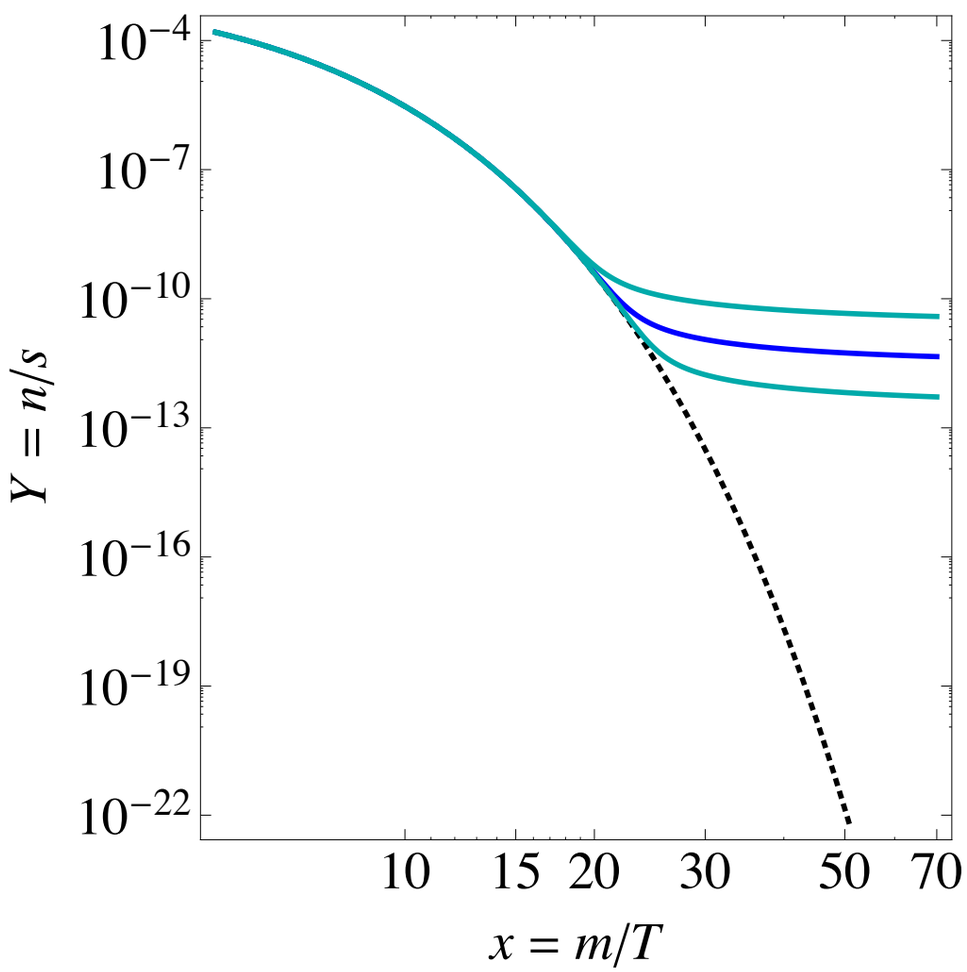
- Why SM singlet new physics near the weak scale?
  - co-responsible for generating it
  - stabilize it
  - thermal dark matter
  - ...why not?
- these essential motivations have not changed much, but the specific models and their resulting signatures have

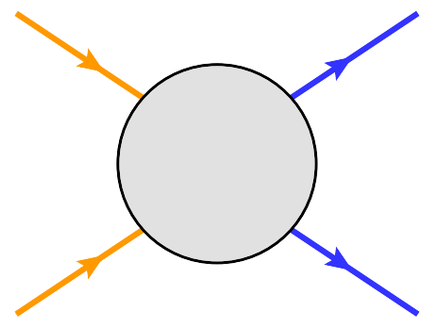
SOME THERMAL RELIC NUMEROLOGY

- Many (many, many) ideas for particle DM
- best motivation for DM with terrestrially accessible mass scales and interactions:
  - a particularly simple class of models: WIMPs and their relatives
  - these particles are thermal relics: once a part of hot, dense plasma in the early universe, then left equilibrium as universe expanded and cooled
- equilibrium number densities:
  - relativistic: $n_i \propto g_i T^3$
  - non-relativistic: $n_i \propto g_i T^3 \left(\frac{m}{T}\right)^{3/2} e^{-m/T}$

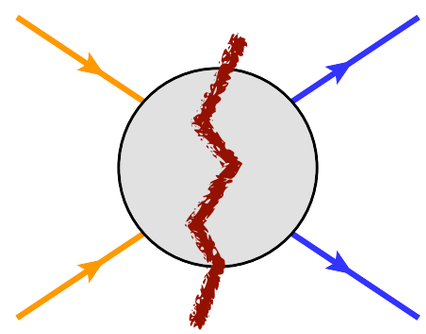
SOME THERMAL RELIC NUMEROLOGY

- Thermal freezeout:





$n\langle\sigma v\rangle > H$



$n\langle\sigma v\rangle \ll H$

SOME THERMAL RELIC NUMEROLOGY

- Estimate when freezeout happens:

$$n\langle\sigma v\rangle \approx H$$

- Today,

$$0.2 = \Omega_{DM} = \frac{\rho_{DM}}{\rho_c} = \frac{m n_{DM}}{\rho_c} = \frac{m}{\rho_c}\frac{T_0^3}{T_{fo}^3} n_{fo}$$

$$= \frac{m}{\rho_c}\frac{T_0^3}{T_{fo}^3}\frac{H_{fo}}{\langle\sigma v\rangle}$$

measured!

measured! $\rho_c = \dfrac{3H_0^2}{8\pi G_N}$

$$\left(\frac{\Omega_{DM}}{0.2}\right) \approx \left(\frac{x_{fo}}{20}\right)\left(\frac{\text{pb}}{\langle\sigma v\rangle}\right)$$

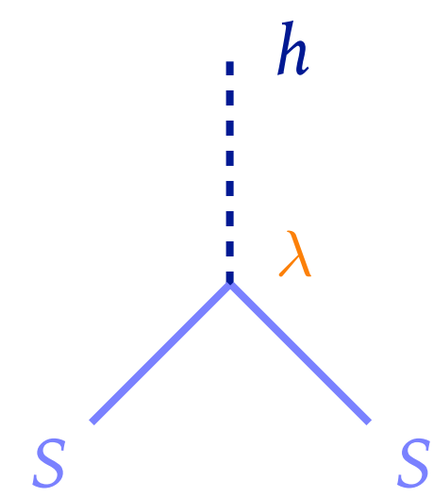
HIGGS PORTAL DARK MATTER

- scalar singlet model:

$$\mathcal{L}_{int} = -\frac{\lambda}{2} S^2 |H|^2 - \frac{1}{2} m_s^2 S^2 - \frac{\lambda_s}{4!} S^4$$

unimportant for standard thermal history

Obtaining the observed relic abundance fixes λ as a function of m_s

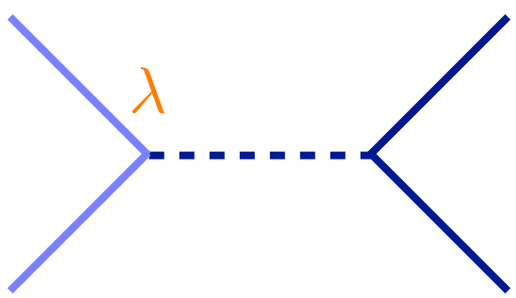


very predictive!

[Silveira, Zee]

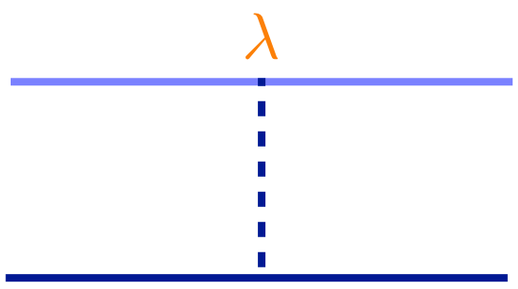
HIGGS PORTAL DARK MATTER

- Indirect detection:

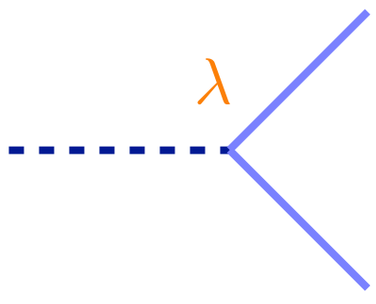


s-wave component of annihilation cross-section means appreciable indirect detection signals in DM-rich environments today

- Direct detection:

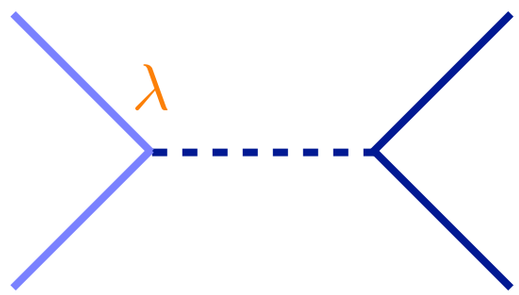


- Collider production:



HIGGS PORTAL DARK MATTER

- Indirect detection:



s-wave component of annihilation cross-section means appreciable indirect detection signals in DM-rich environments today

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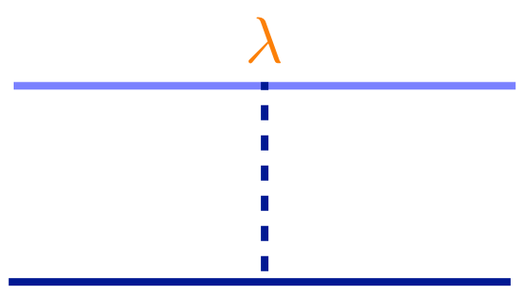
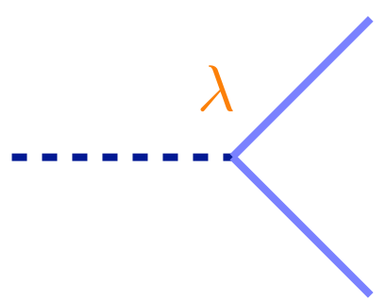


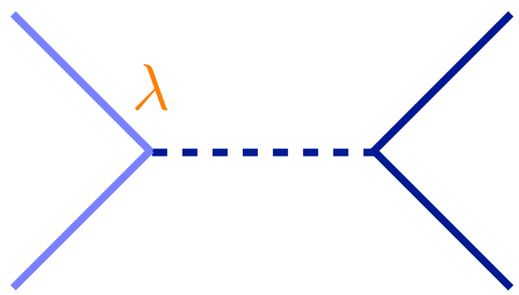
DM-nucleon cross-section is both spin- and velocity-independent: unsuppressed coherent nuclear scattering

- Collider production:



HIGGS PORTAL DARK MATTER

- Indirect detection:



s-wave component of annihilation cross-section means appreciable indirect detection signals in DM-rich environments today

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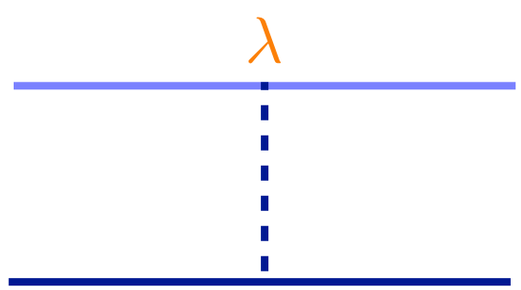
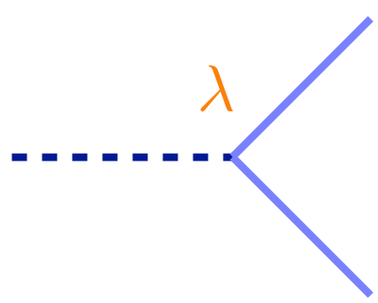


DM-nucleon cross-section is both spin- and velocity-independent: unsuppressed coherent nuclear scattering

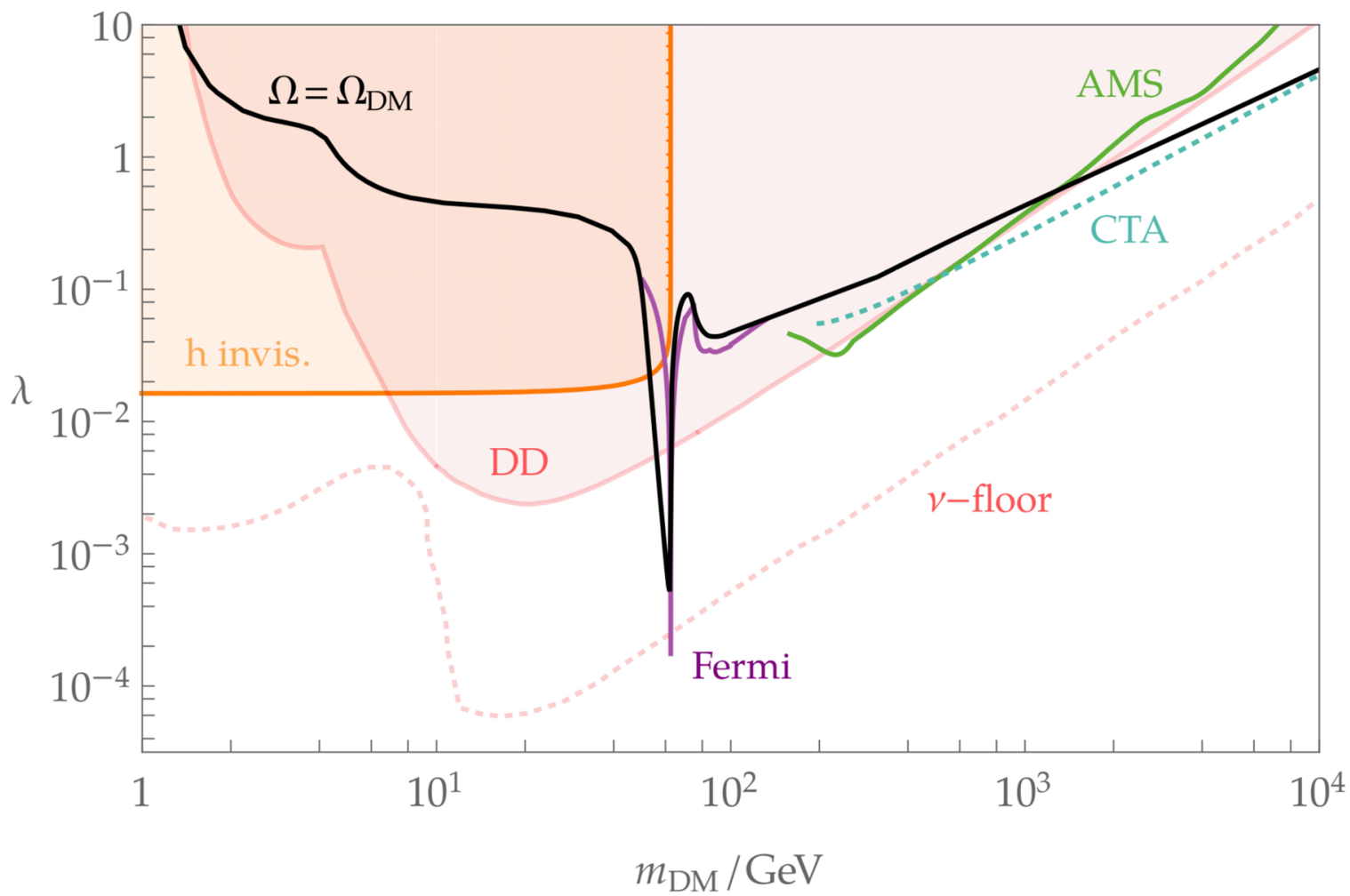
- Collider production:



Sensitivity depends on whether or not Higgs can decay into DM pairs

HIGGS PORTAL DARK MATTER

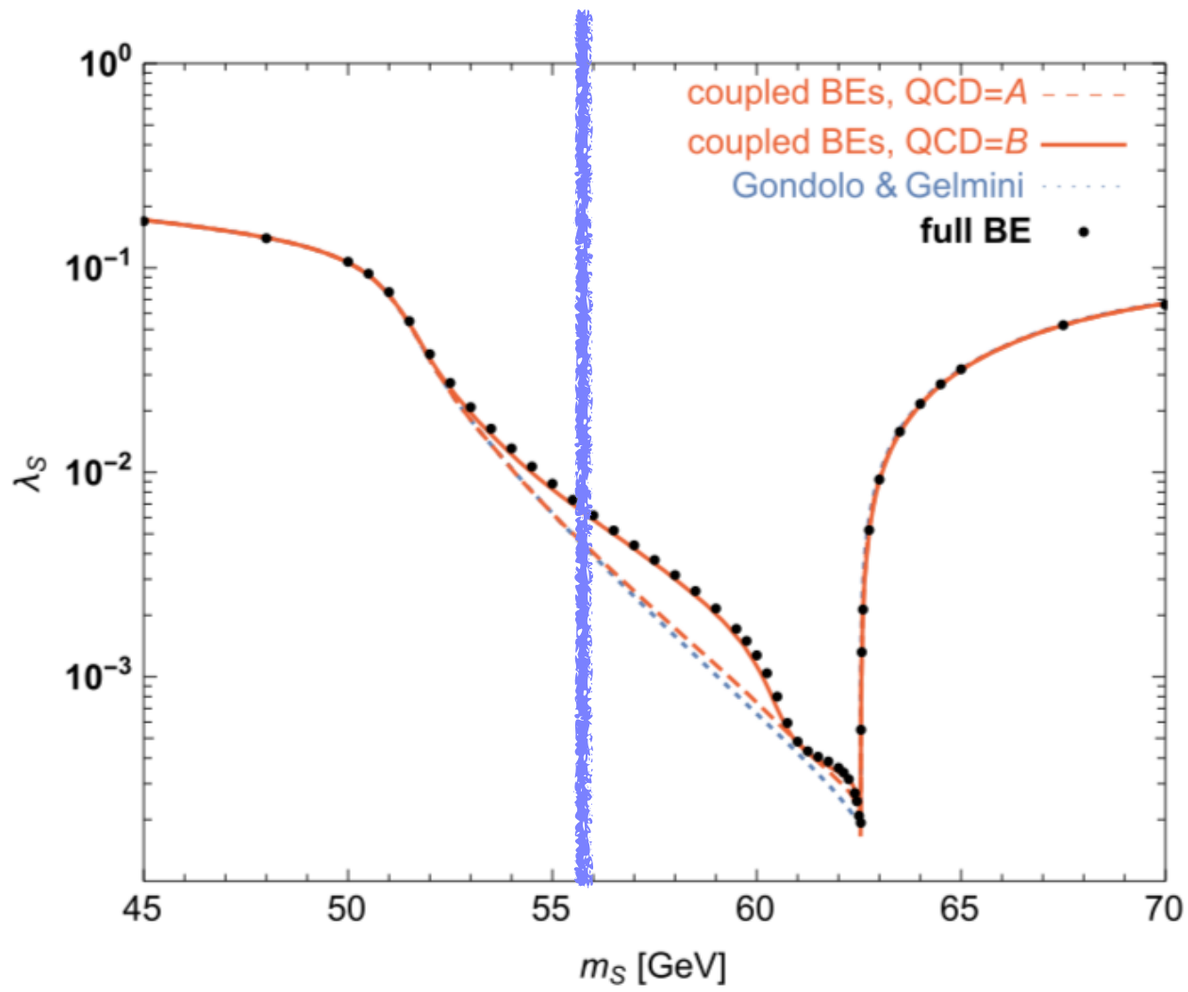
- Collected constraints on minimal HPDM:



[Hardy (2018)]

RESONANT REGIME

- Finely-tuned viable region near $m_h/2$:

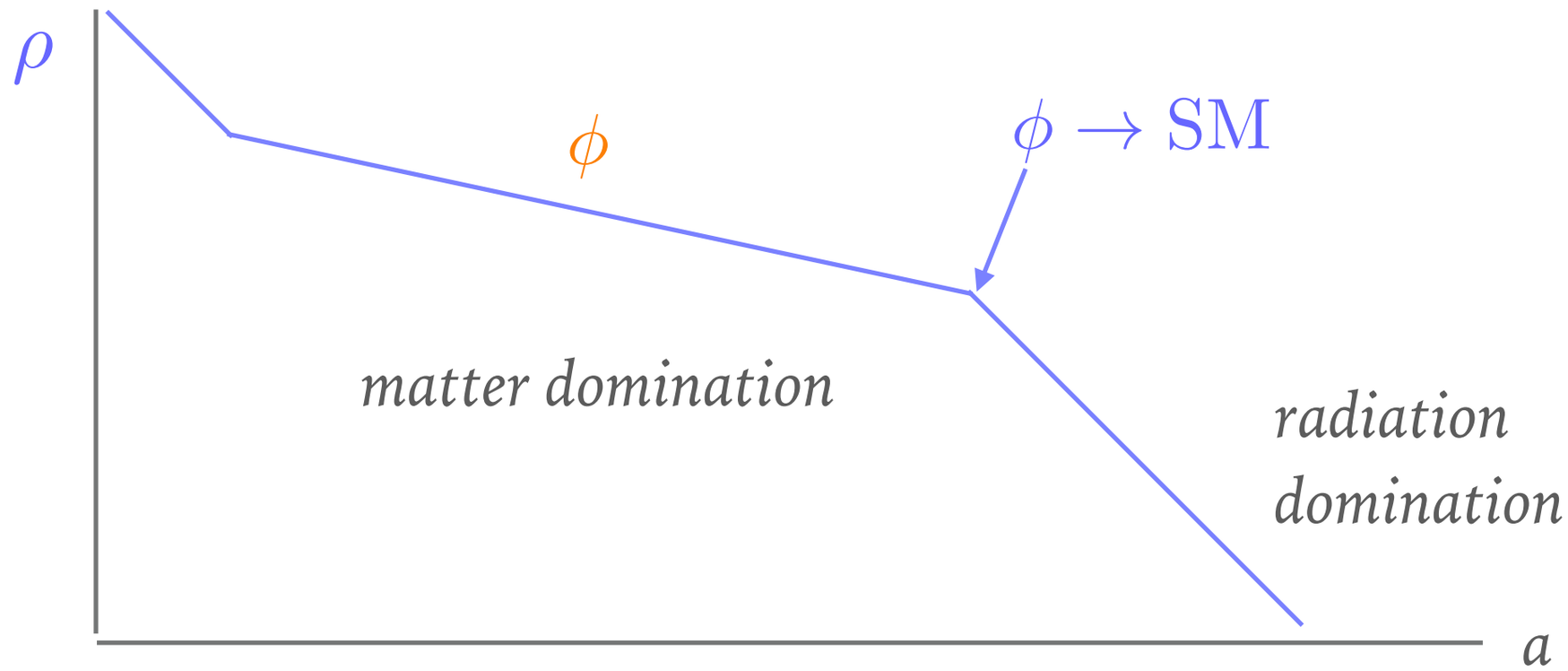


- next generation direct detection (indirect detection)

[Binder, Bringmann, Gustafsson, Hryczuk (2017)]

NON-MINIMAL COSMOLOGY?

- Early matter-dominated era: dilute DM abundance

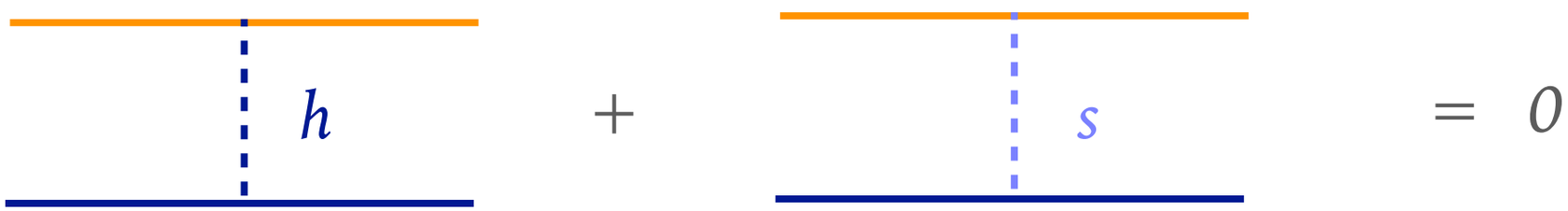


- entropy dump depends on properties of decaying metastable field
  - parametrically separate DM-Higgs coupling from present-day relic abundance

NON-MINIMAL PARTICLE MODELS

- Global symmetry to suppress DD cross section:

$$S \to \Phi = S e^{ia/f_a}$$

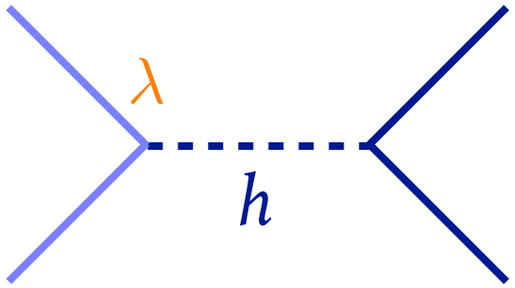


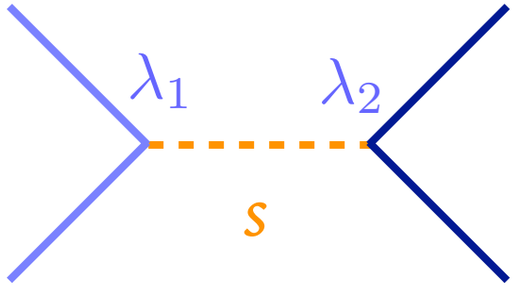
- leading DD cross-section at one loop
- Higgs decays, ID still constraining at lower DM masses
- signals, constraints depend on properties of new heavy BSM scalar S

[Gross, Lebedev, Toma]

NON-MINIMAL PARTICLE MODELS

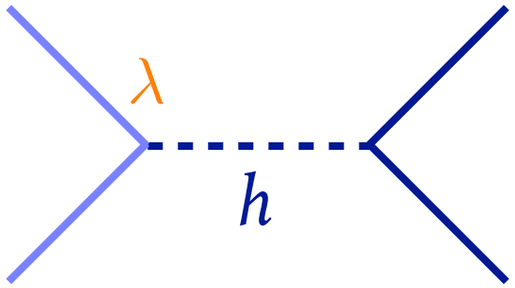
- Introducing new mediators gives new flexibility in how DM talks to the SM
  - Higgs-mixed scalar: same issues as minimal HPDM

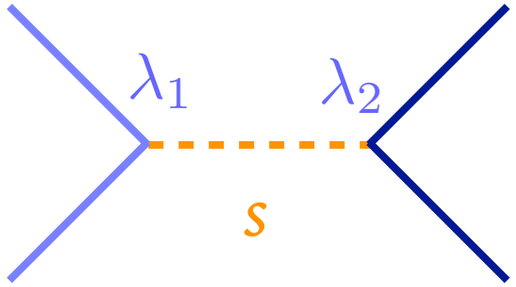


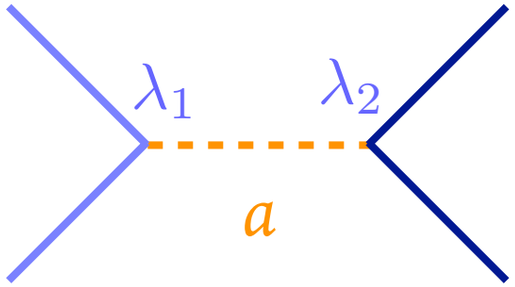


NON-MINIMAL PARTICLE MODELS

- Introducing new mediators gives new flexibility in how DM talks to the SM
  - Higgs-mixed scalar: same issues as minimal HPDM
  - pseudo-scalar: parametrically suppress DD signal, nuclear cross-section is velocity-suppressed and spin-dependent (fermionic DM)
- UV-complete $a\bar{f}\gamma^5 f$?
  - simple: mix with A^0 in 2HDM model



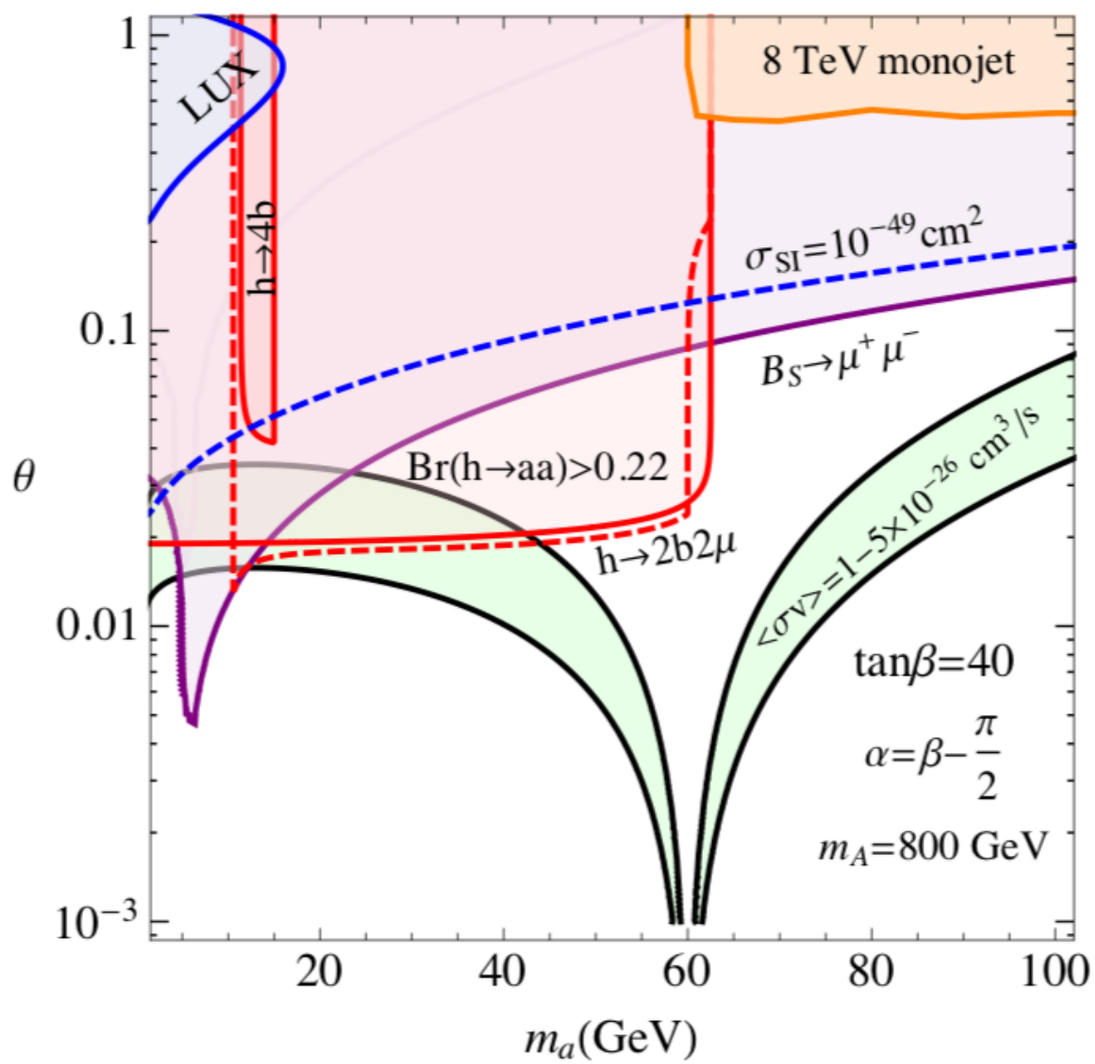




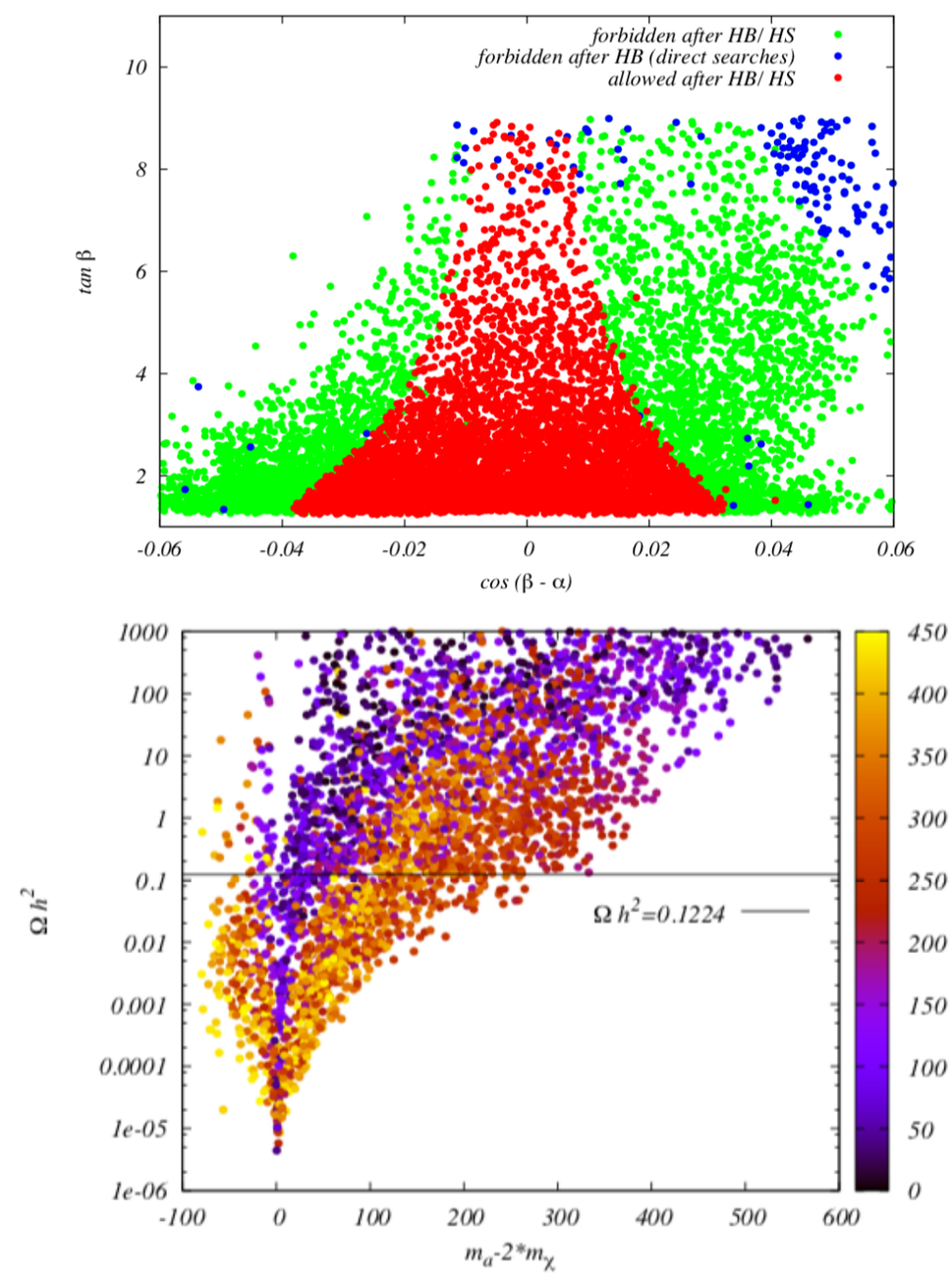
see lectures by Nausheen Shah

NON-MINIMAL PARTICLE MODELS

- 2HDM+*a*:



[Ipek, McKeen, Nelson (2014)]

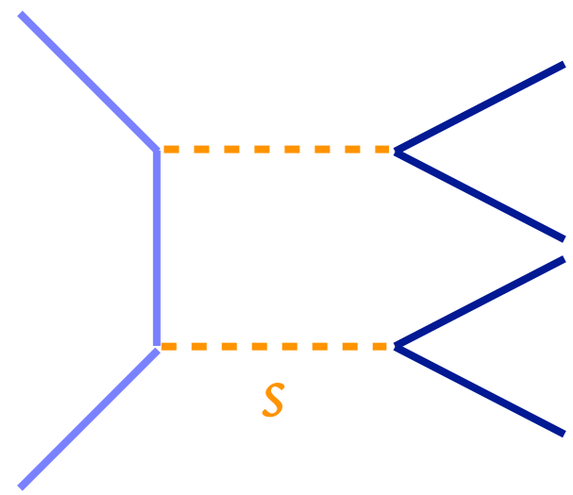


[Robens (2021)]

NON-MINIMAL PARTICLE MODELS

- Secluded annihilations:

relic abundance constraint fixes DM-mediator coupling



small SM coupling lets mediator decay

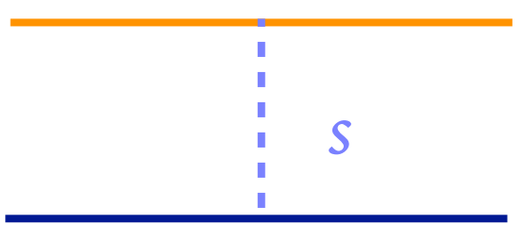
- Astrophysical signatures of WIMPy DM more or less unchanged
- terrestrial signatures parametrically suppressed

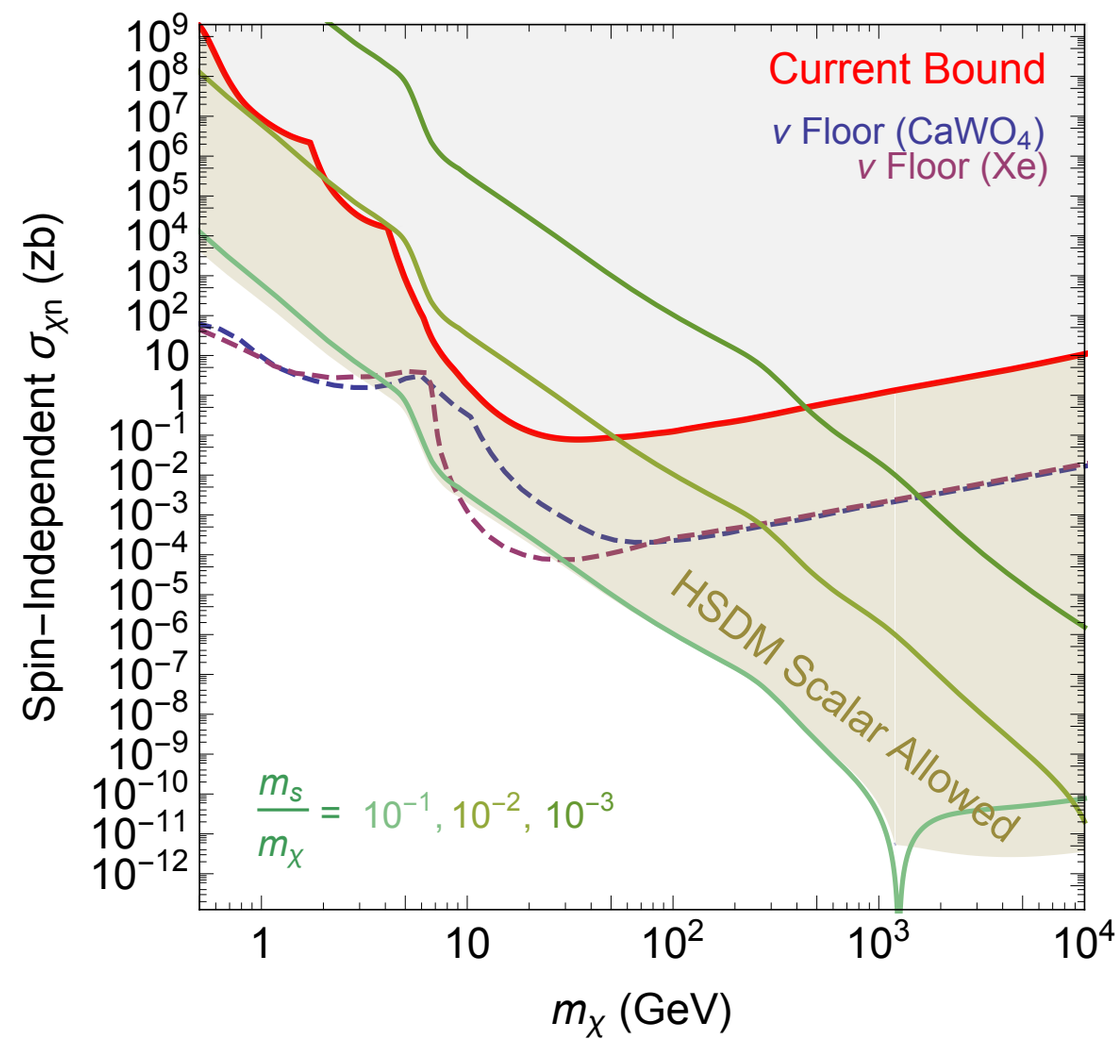
[Pospelov, Ritz, Voloshin]

NON-MINIMAL PARTICLE MODELS

- thermalization floor: SM-mediator couplings large enough for single temperature to describe the whole system

  - Higgs-mixed scalar mediator
  - DD cross-section depends on mediator mass

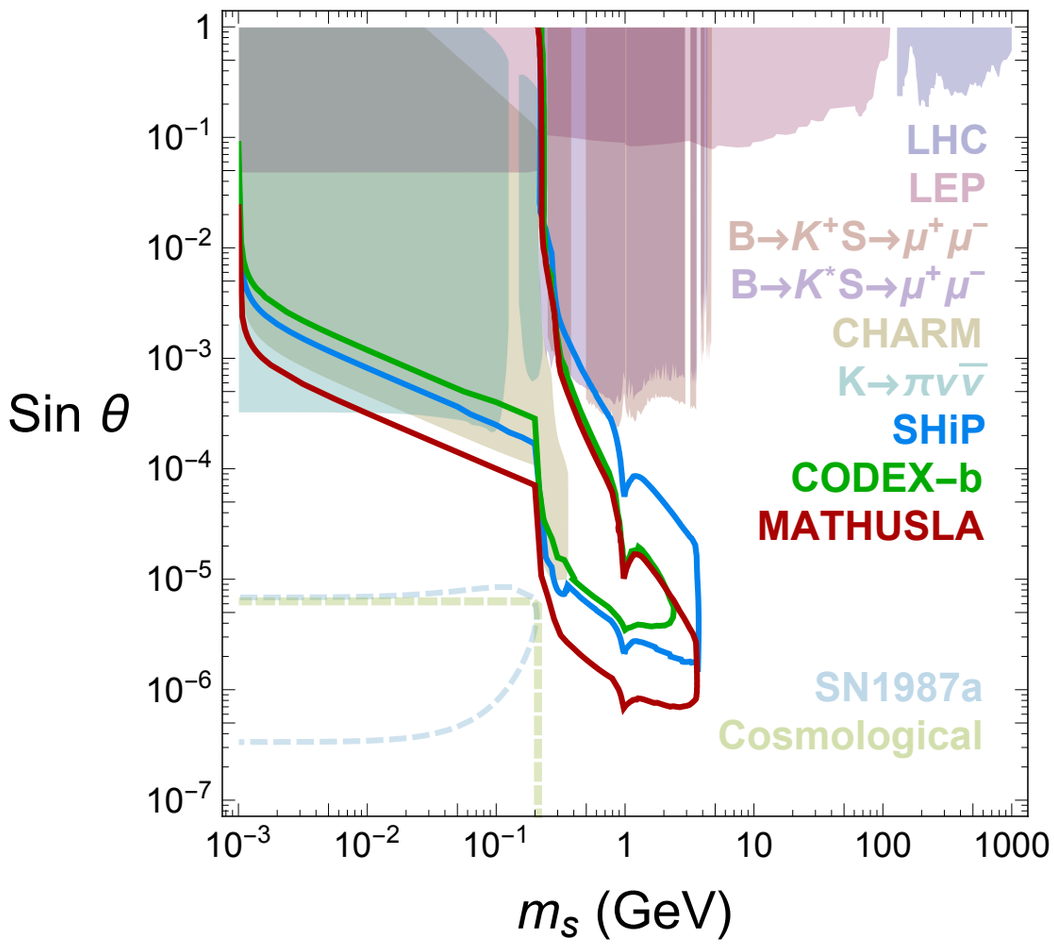


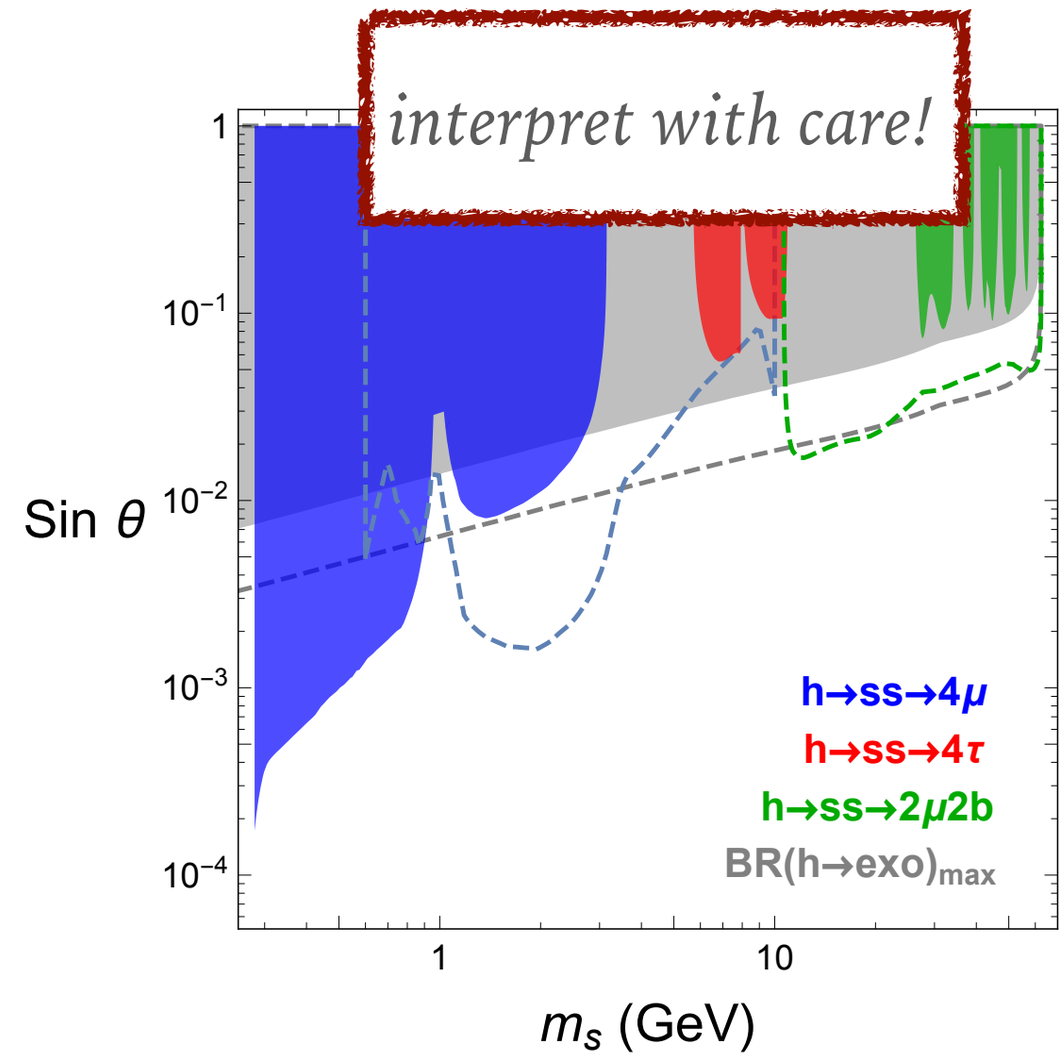


[Evans, Gori, JS (2017)]

A LIGHT HIGGS-MIXED SCALAR

- direct production probes different combination of model couplings than on-shell Higgs decays:





[Evans, Gori, JS (2017)]

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 parameter space has heavy new physics: good prospects at future colliders

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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SM+SINGLET

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$\mathcal{O}(\theta)$

$Br(h \to ss)$

$\mathcal{O}(\theta)$

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

- Z_2 symmetry $S \to -S$: S is stable
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$$V = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2} a_1 |H|^2 S + \frac{1}{2} a_2 |H|^2 S^2$$

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

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

$\mathcal{O}(\theta)$

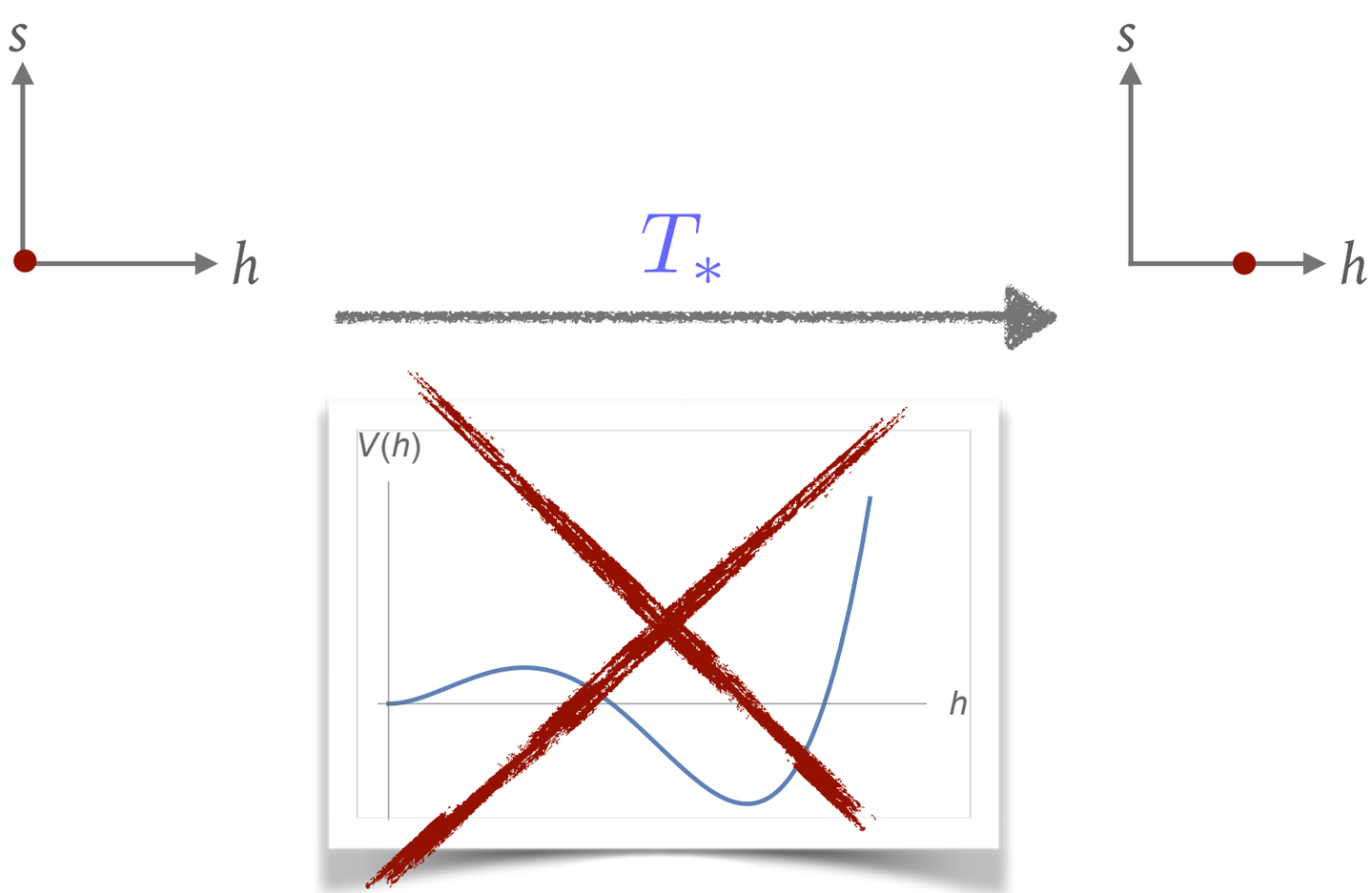
$$-\frac{1}{2} a_2 v^2 + m_s^2 + \mathcal{O}(\theta^2)$$

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

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

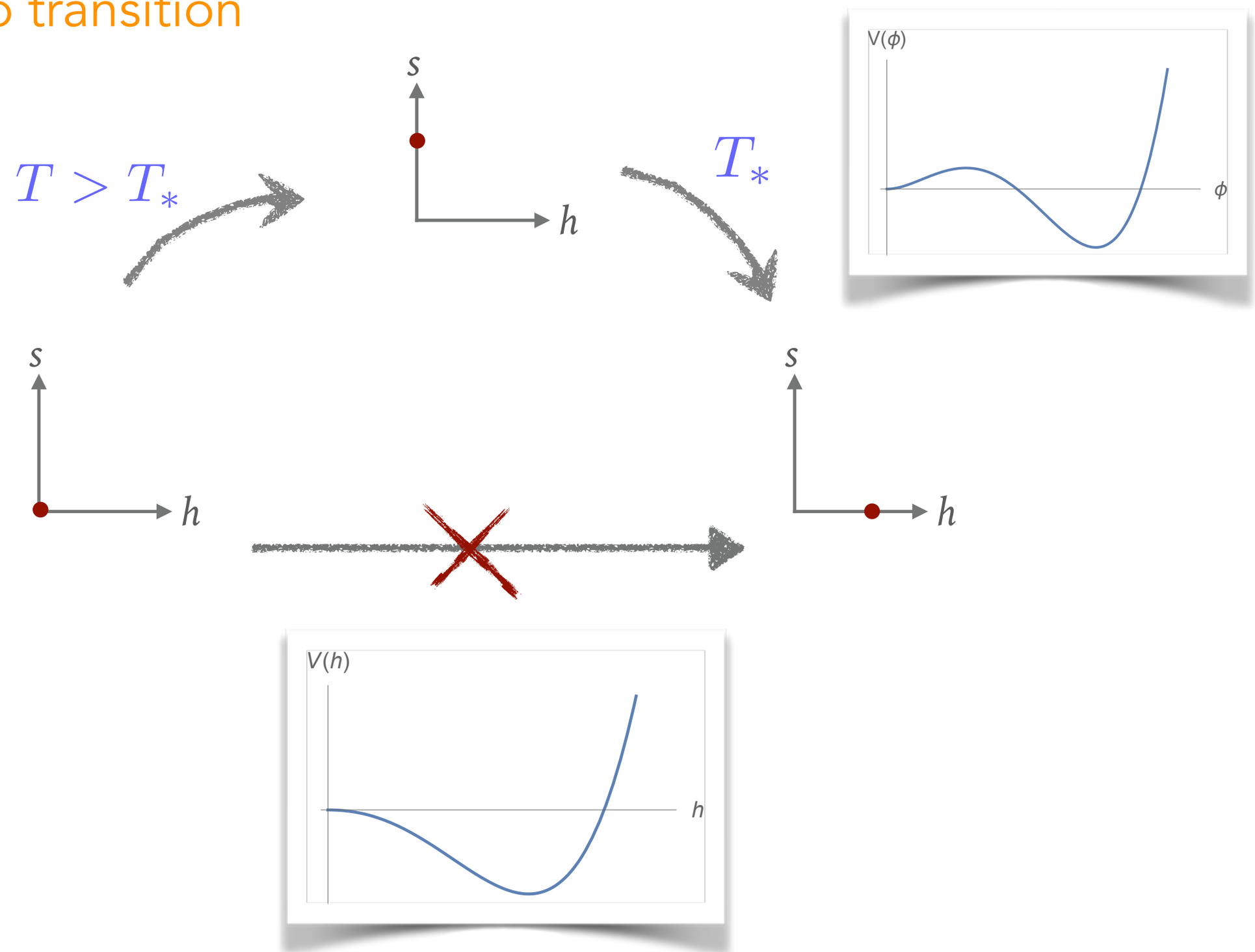
SINGLET-ASSISTED PHASE TRANSITIONS

- 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**

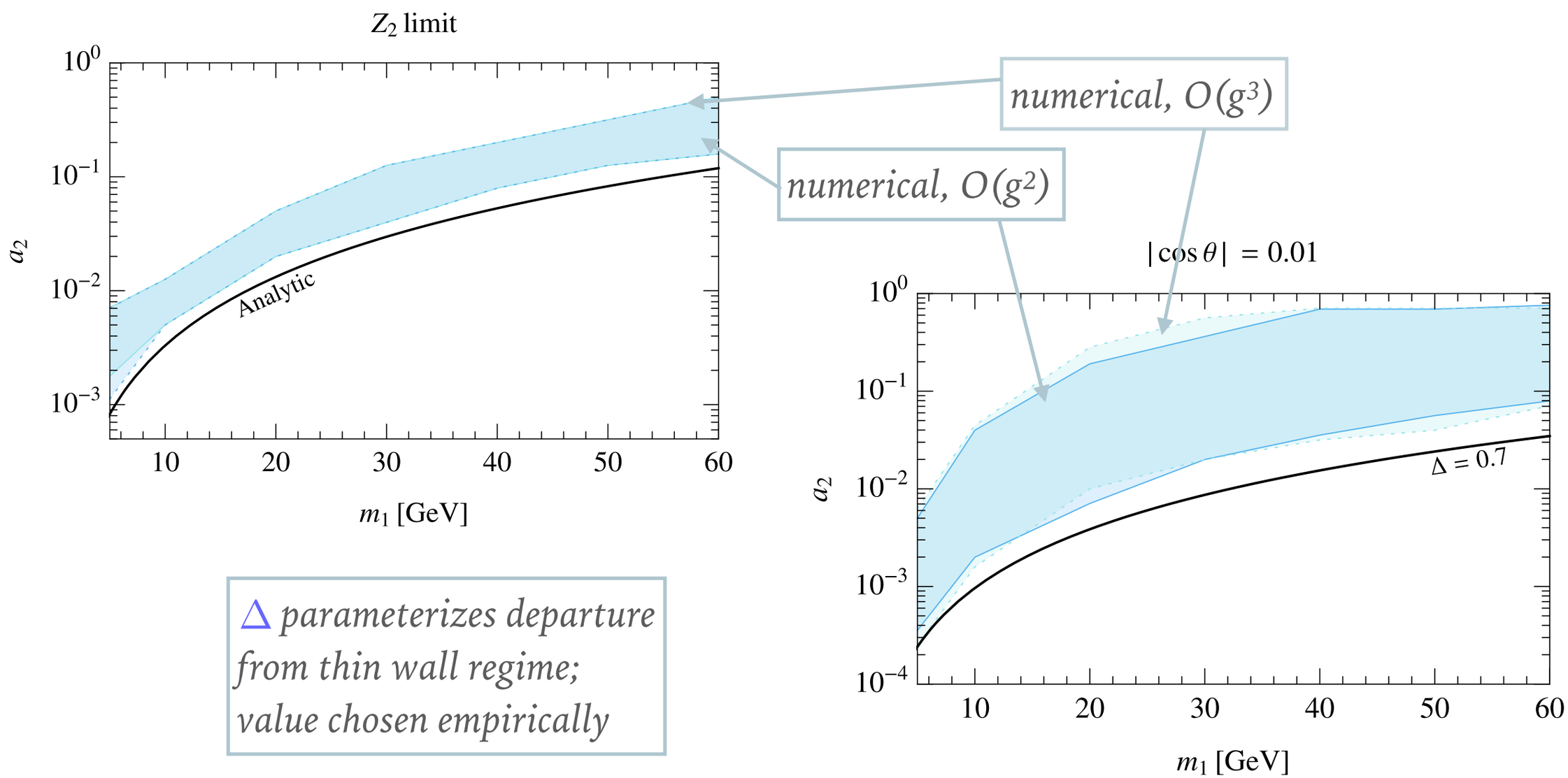
$$V(s_0, 0, T_*) > V(0, h_0, T_*)$$

  - phase transition successfully completes

MINIMUM BRANCHING RATIOS

need to say allowed by all exp searches (except exo H)

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

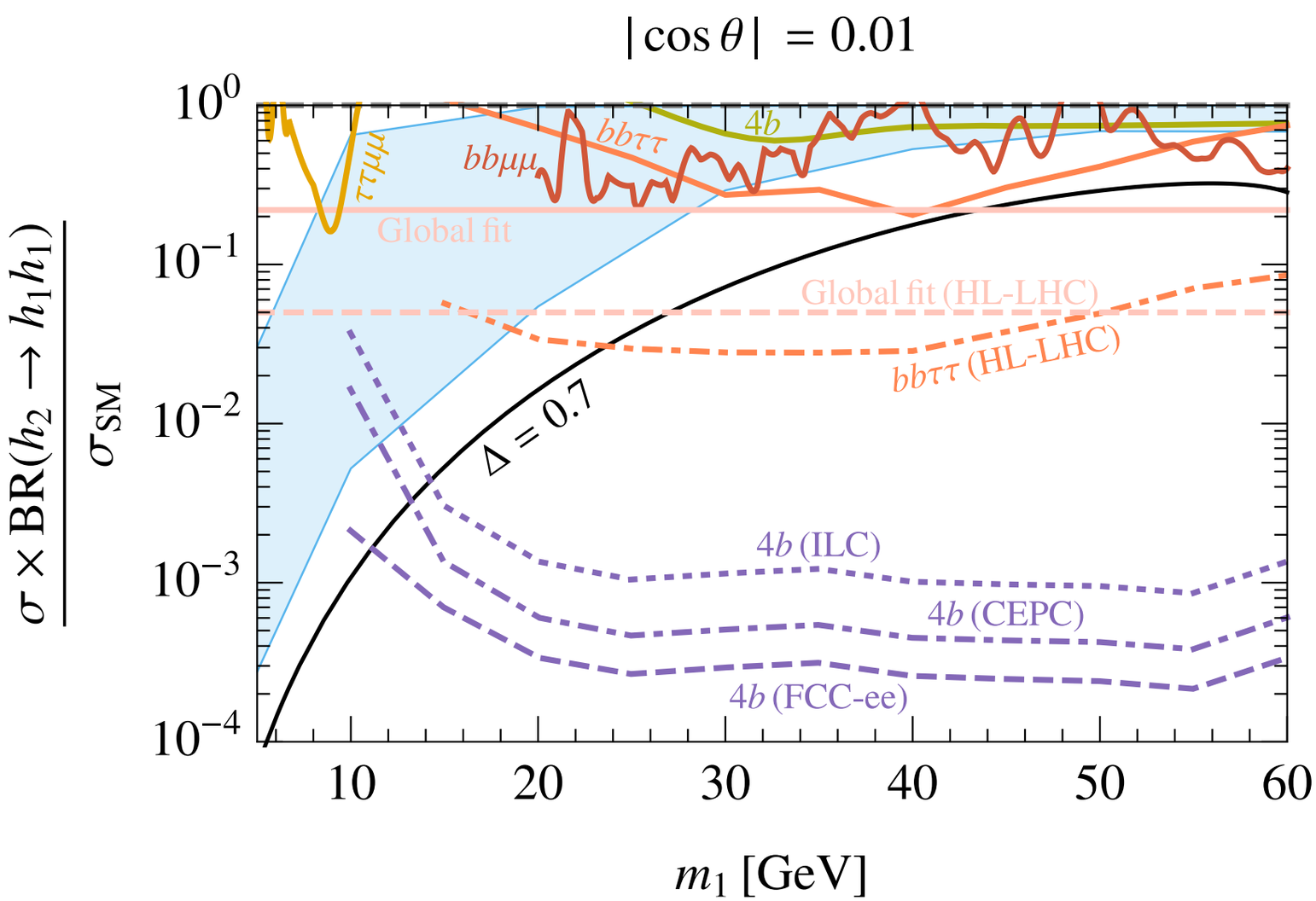


Δ parameterizes departure from thin wall regime; value chosen empirically

[Kozaczuk, Ramsey-Musolf, JS]

VISIBLE SIGNALS OF FIRST-ORDER PHASE TRANSITIONS

- Visible decays:



forecasts:

HL/HE WG2

CMS-PAS-FTR-18-035

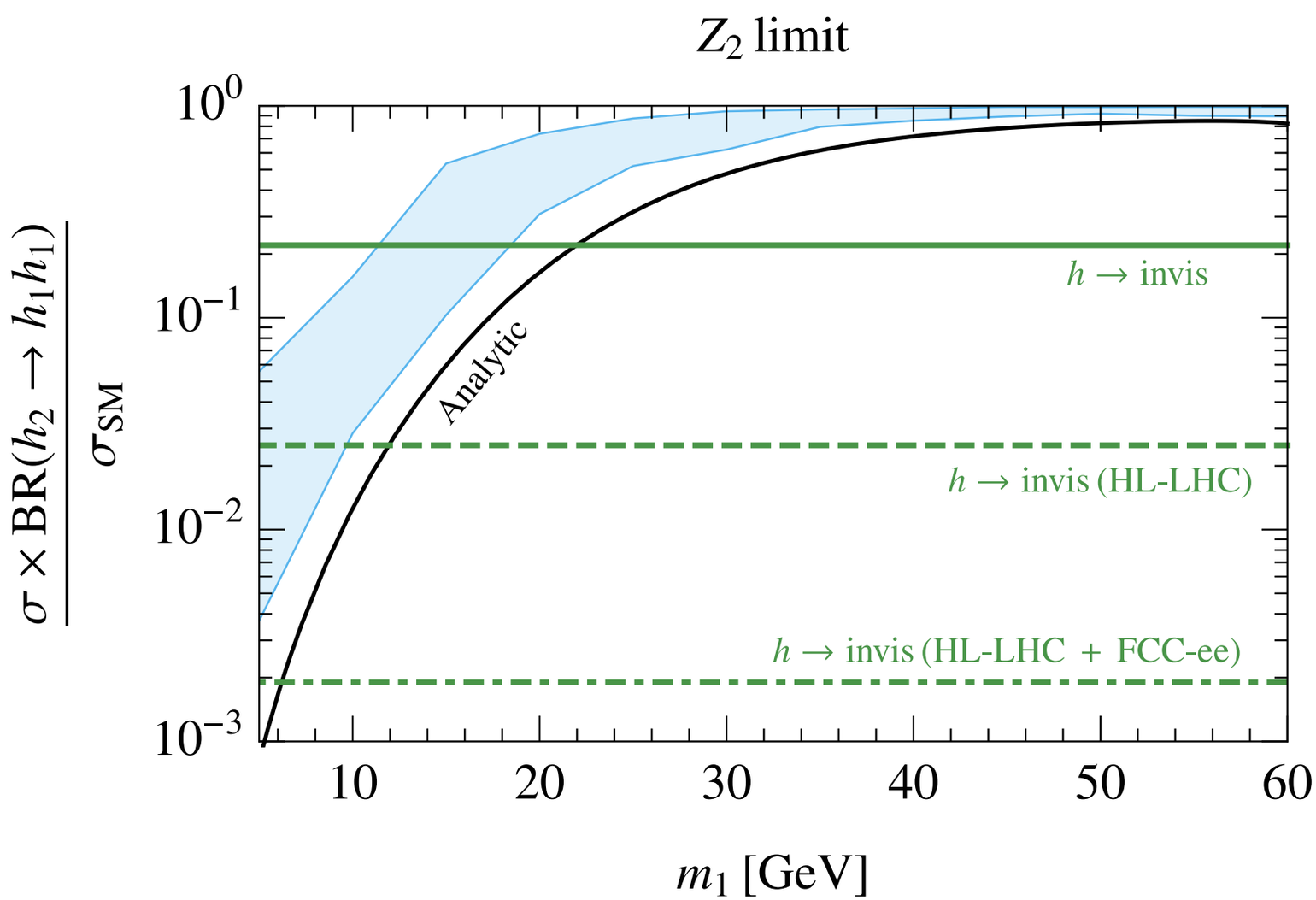
Liu, Wang, Zhang

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

[Kozaczuk, Ramsey-Musolf, JS]

FIRST-ORDER PHASE TRANSITIONS AND EXO H DECAYS

- Invisible decays:



forecasts:

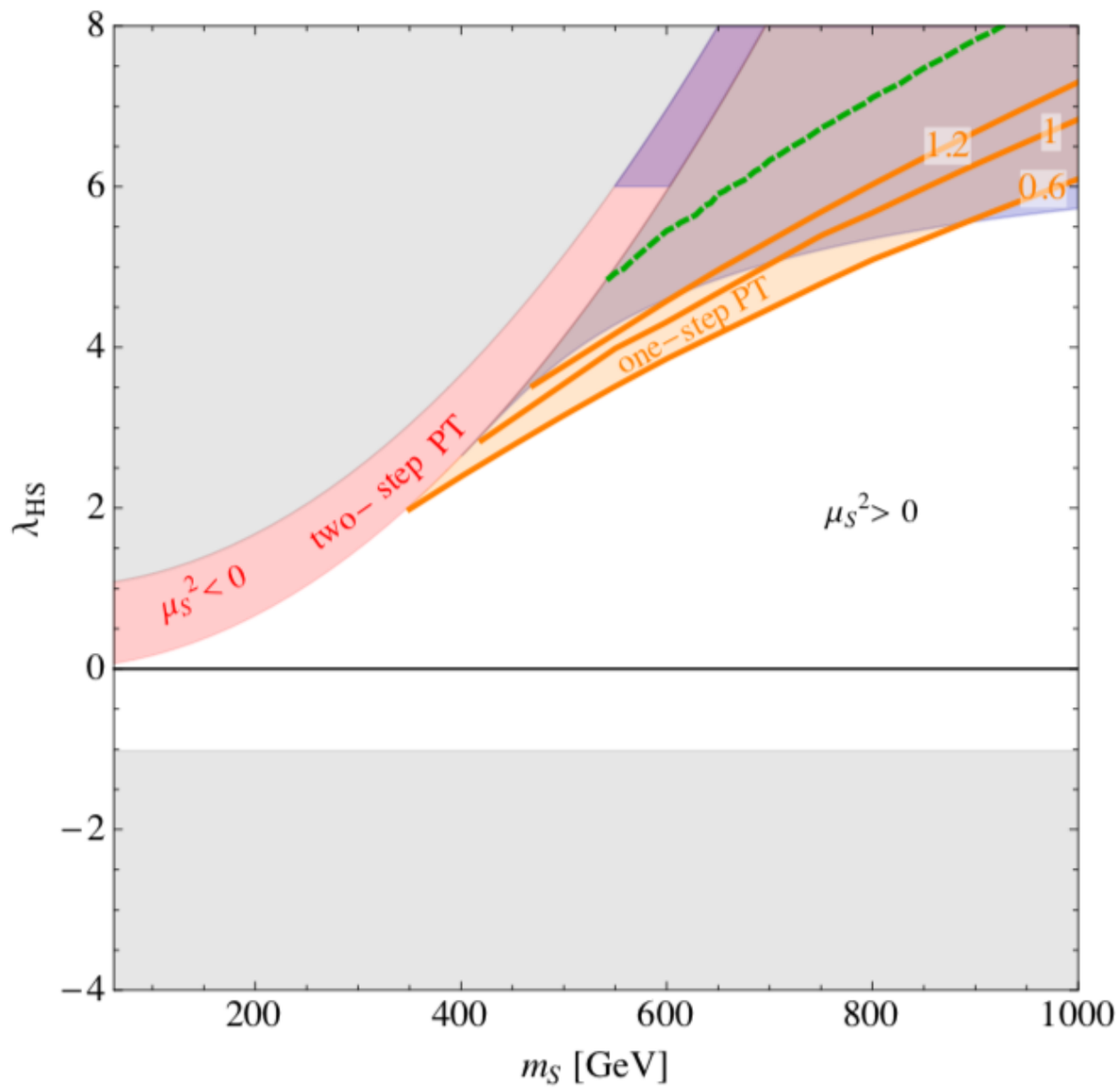
HL/HE WG2

de Blas et al.

[Kozaczuk, Ramsey-Musolf, JS]

FIRST-ORDER PHASE TRANSITIONS AND HEAVY SCALARS

- Heavier states:



[Curtin, Meade, Yu]