Non-resonant/EFT Higgs pair phenomenology

(+ some random musings on Higgs pair production)

José Francisco Zurita

Why di-(multi) Higgs?

After EWSB : $V = \frac{1}{2}m_h^2\, h^2 + \lambda v h^3 + \frac{1}{4}\tilde{\lambda} h^4$

SM : $\tilde{\lambda} = \lambda = \frac{m_h^2}{2v^2} \approx 0.13$ ⇒ **<u>ANY</u>** deviation implies BSM!

Also important for the vacuum (meta)-stability!

This is valid for all Higgs couplings

hh production is fixed in the SM! ⇒ **<u>Multi-front campaign</u>**

Current status reviewed in B. Di Micco, M. Goutzevitch, J. Mazitelli, C. Vernieri et al, arXiV 1910.00012, Review in Physics (2020) 100045

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Reviews in Physics

Available online 2 August 2020, 100045

In Press, Journal Pre-proof

REVIEWS IN PHYSICS

Higgs boson potential at colliders: status and perspectives

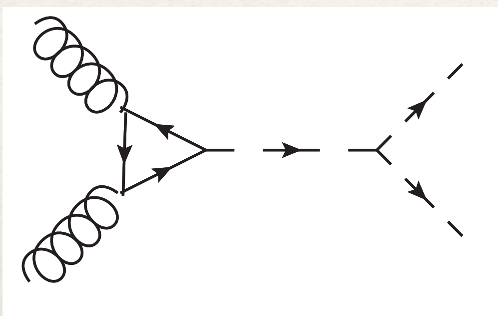
Biagio Di Micco [a], Maxime Gouzevitch [b], Javier Mazzitelli [c], Caterina Vernieri [d]

Show more

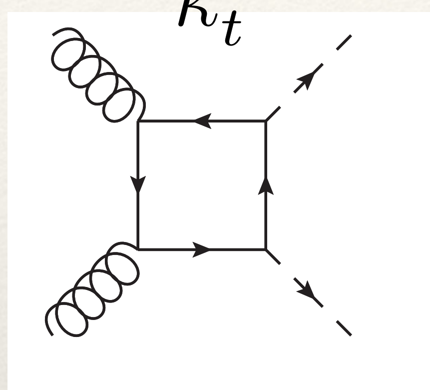
BSM effects in di-(SM)Higgs production

1) Anomalous couplings (hhh, hff, hhff, hhgg,). Other couplings affect VBF, ttHH (e.g:hhVV)

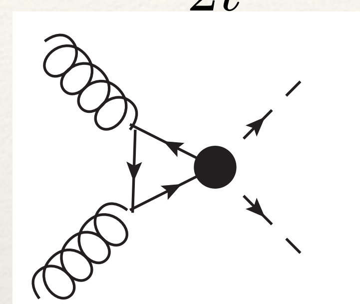
$\kappa_t \kappa_\lambda$

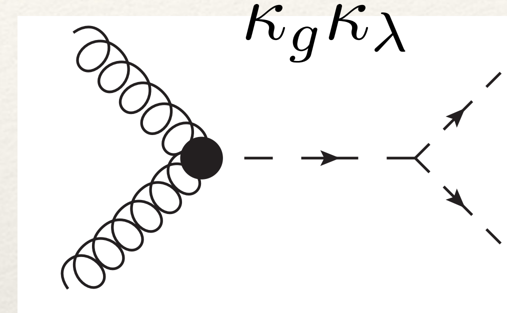


κ_t^2

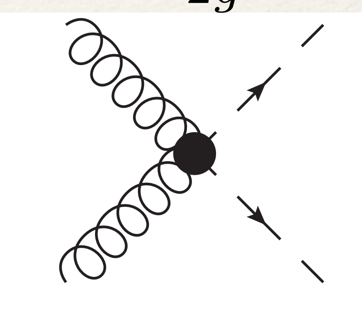


κ_{2t}





κ_{2g}



2) New particles (colored!) running on loops. Different scaling of triangles and boxes. Appear naturally in Composite Models, SUSY, RS (see e.g: Kribs, Martin, 1207.4996; Dawson, Ismail, Low, 1504.05596; Batell, McCullough, Stolarski, Verhaaren 1508.01208, Huang, Joglekar, Li, Wagner 1711.05743).

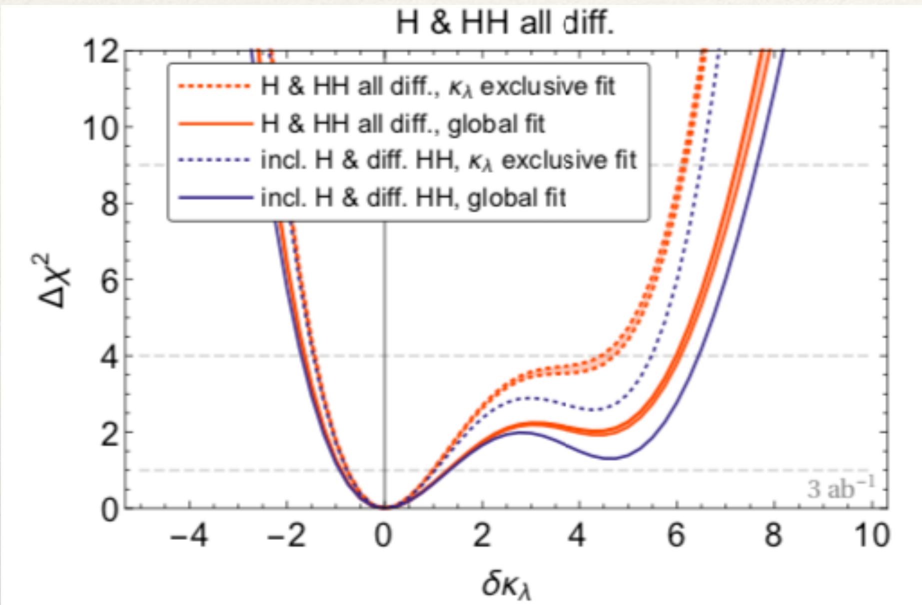
3) New resonances, H->hh, [featured in M. M. Mühlleitner's talk in previous session]. (see also: Robens, Stefaniak, Wittbrodt, 1908.08554, Basler, Dawson, Englert, Mühlleitner, 1812.03542).

4) Chain decays Y->H X (see e.g: Kang, Ko, Li 1504.04128, Blanke, Kast, Thompson, Westhoff, 1901.07758)

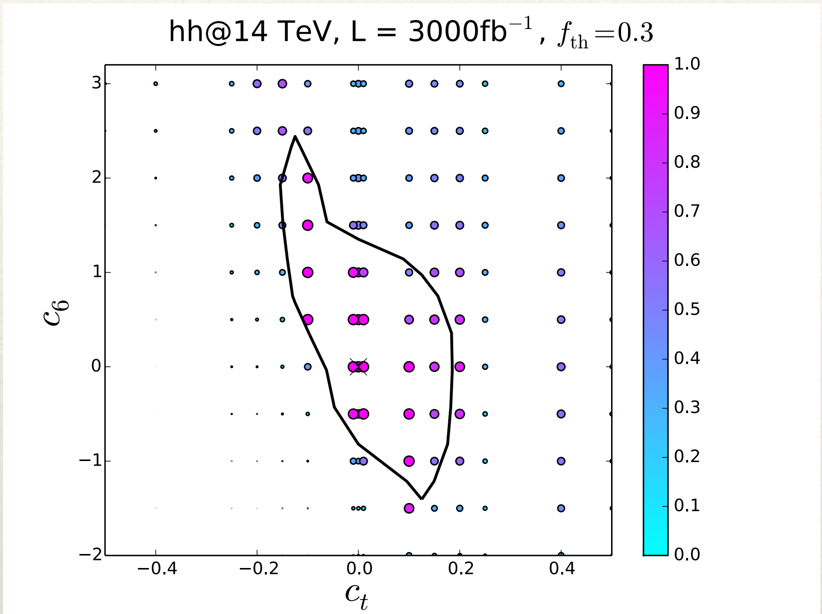
5) Exotic Higgs decays for hh. Mostly FCC/SPPC territory due to bounds on h-> exotic. (see e.g: Banerjee, Batell, Spannowsky 1608.0861).

Anomalous couplings

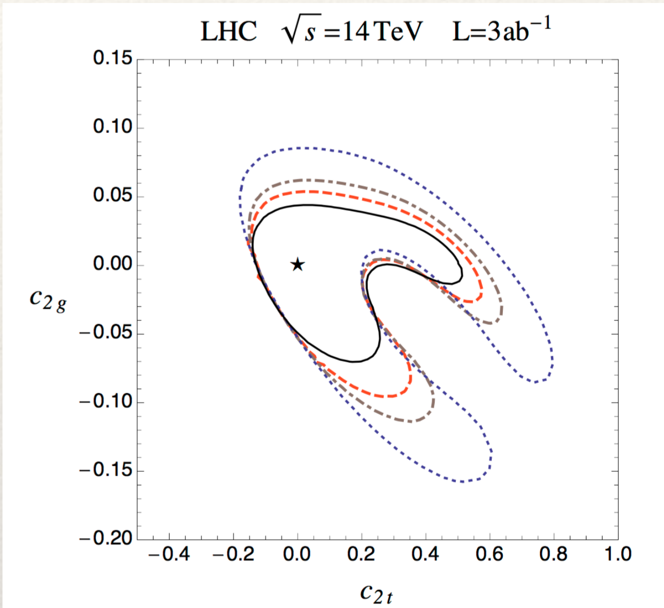
- They can be free parameters (à la “kappa-framework”*), or arise from Lagrangian coefficients (complete model or EFT** construction).



Di Vita, Grojean, Panico, Riembau, Vantalon, 1704.01953



Goertz, Papaefstathiou, L. L. Yang, JZ, 1410.3471



Azatov, Contino, Panico, Son 1502.00539

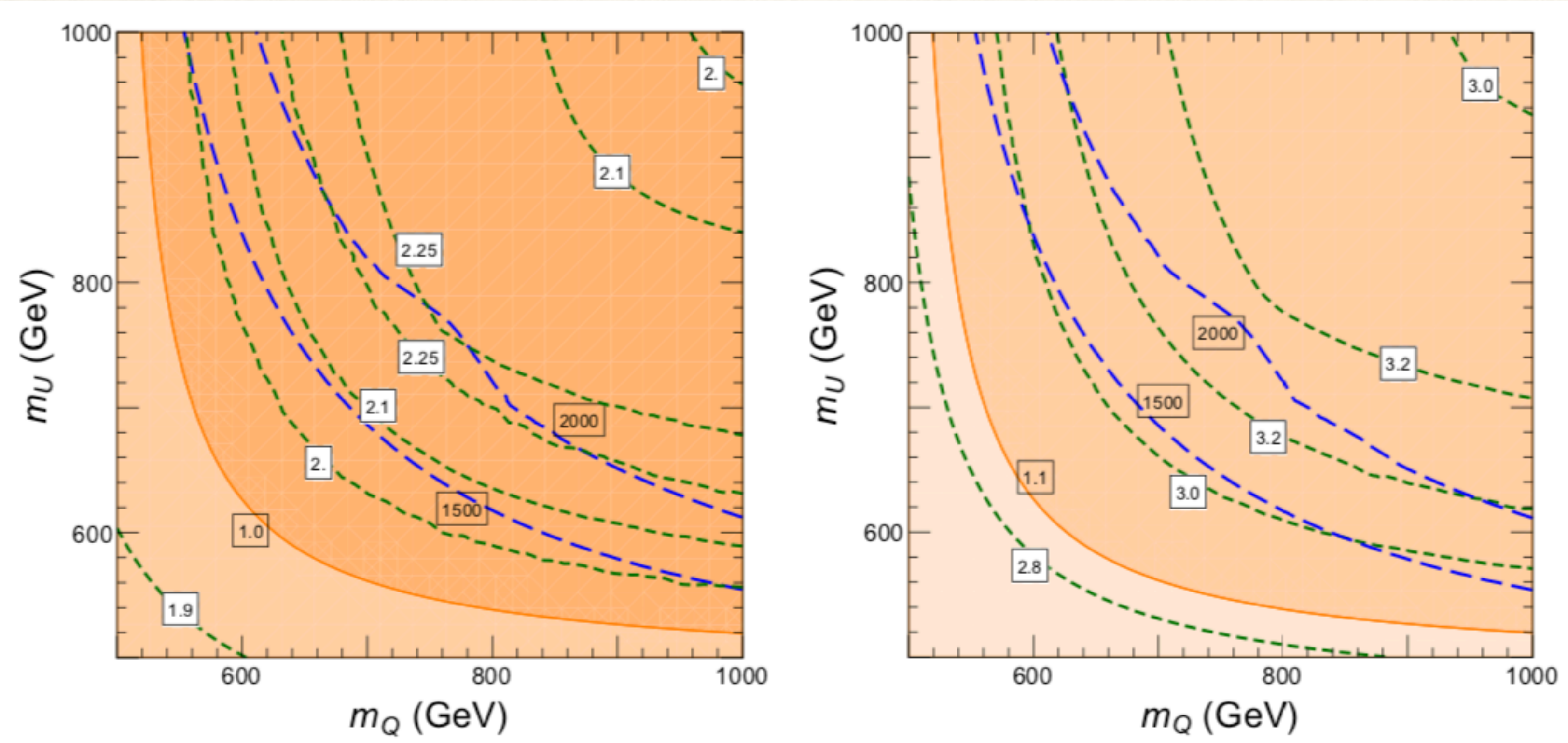
Beware of correlations between different couplings! (c_6 only [-0.9, 1.7] 95% C.L @ HL-LHC, fth=0.3).

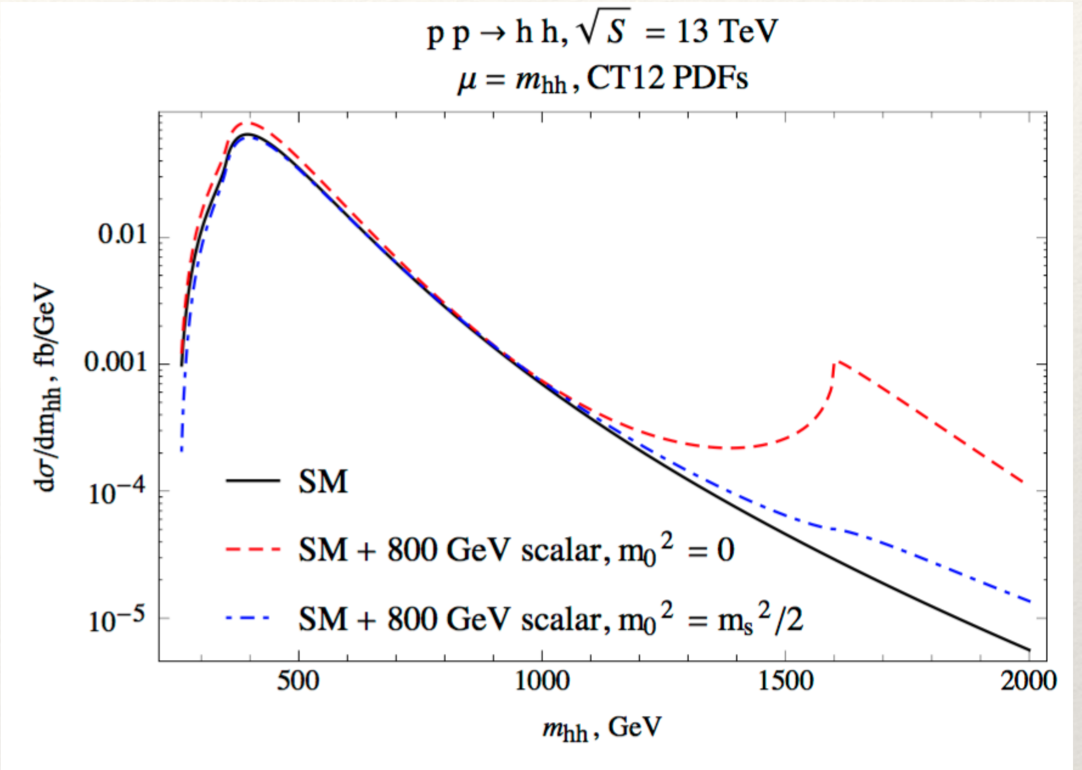
Global fit including differential information on h and hh production to resolve flat directions

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\bar{c}_H}{2v^2}(\partial^\mu|H|^2)^2 - \frac{\bar{c}_6}{v^2}v|H|^6 + \left\{-\frac{\bar{c}_u}{v^2}y_u|H|^2\bar{Q}_L H^c u_R - \frac{\bar{c}_d}{v^2}y_d|H|^2\bar{Q}_L H d_R - \frac{\bar{c}_l}{v^2}y_l|H|^2\bar{L}_L H e_R + \text{ h.c.}\right\}$$
$$+ \frac{\alpha_s\bar{c}_g}{4\pi v^2}|H|^2 G^a_{\mu\nu}G^{\mu\nu}_a + \frac{g'^2\,\bar{c}_\gamma}{v^2}|H|^2 B_{\mu\nu}B^{\mu\nu} + \frac{ig\,\bar{c}_{HW}}{v^2}(D^\mu H)^\dagger\sigma_k(D^\nu H)W^k_{\mu\nu}$$
$$+ \frac{ig'\,\bar{c}_{HB}}{v^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} + \frac{ig\,\bar{c}_W}{2v^2}(H^\dagger\sigma_k\overleftrightarrow{D}^\mu H)D^\nu W^k_{\mu\nu} + \frac{ig'\,\bar{c}_B}{2v^2}(H^\dagger\overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$$ **

* $\mathcal{L} \supset -\frac{m_h^2}{2v}\kappa_\lambda h^3 - \frac{m_h^2}{8v^2}\kappa_{hh}h^4 + \left(\kappa_g\frac{h}{v} + \kappa_{2g}\frac{h^2}{2v^2}\right)G^a_{\mu\nu}G^{\mu\nu}_a - \sum_{f=b,t,\tau,\ldots}\frac{m_f}{v}\bar{f}_L f_R\left(\kappa_f\frac{h}{v} + \kappa_{2f}\frac{h^2}{v^2}\right)$

Colored states running around…





$m_{\tilde{t}_1} = 500$ GeV   Huang, Joglekar, Li, Wagner 1711.05743   Dawson, Ismail, Low 1504.05596

- New states induce large deviations in inclusive cross section and differential distributions.
- Vector-like quarks (Composite Higgs, Little Higgs) do not affect m_{hh} distribution significantly

  But coloured scalars and chiral fermions do! Dawson, Ismail, Low 1504.05596
- Complementarity with direct searches for top-partners (e.g: stops in MSSM).

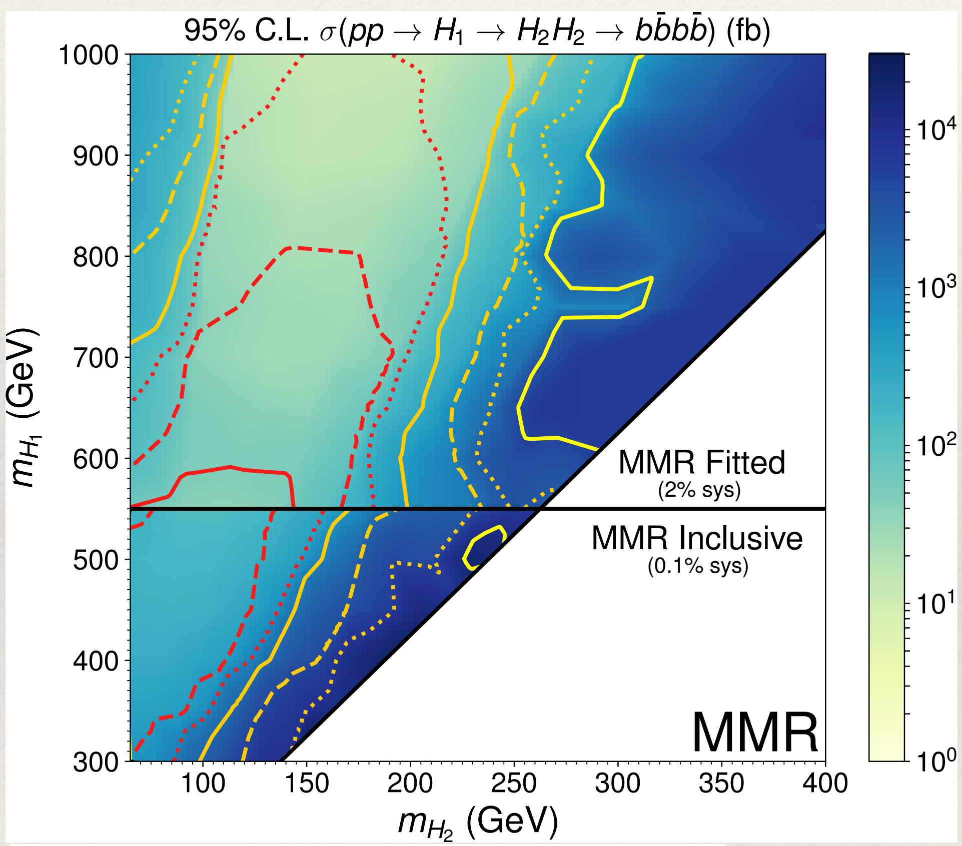
Bonus track!

Di-Higgs is much bigger than SM hh, or H->hh, or new coloured particles in loops!

- H -> AA -> 4b (no SM-Higgs involved) (Barducci, Mimasu, No, Vernieri, JZ)
- H -> A A, A->hh, A->x x, X=Dark Matter (Blanke, Kast, Thompson, Westhoff, JZ)
- h -> S S -> $K^+ K^-$ $K^+ K^-$ (Cid Vidal, Tsai, JZ)

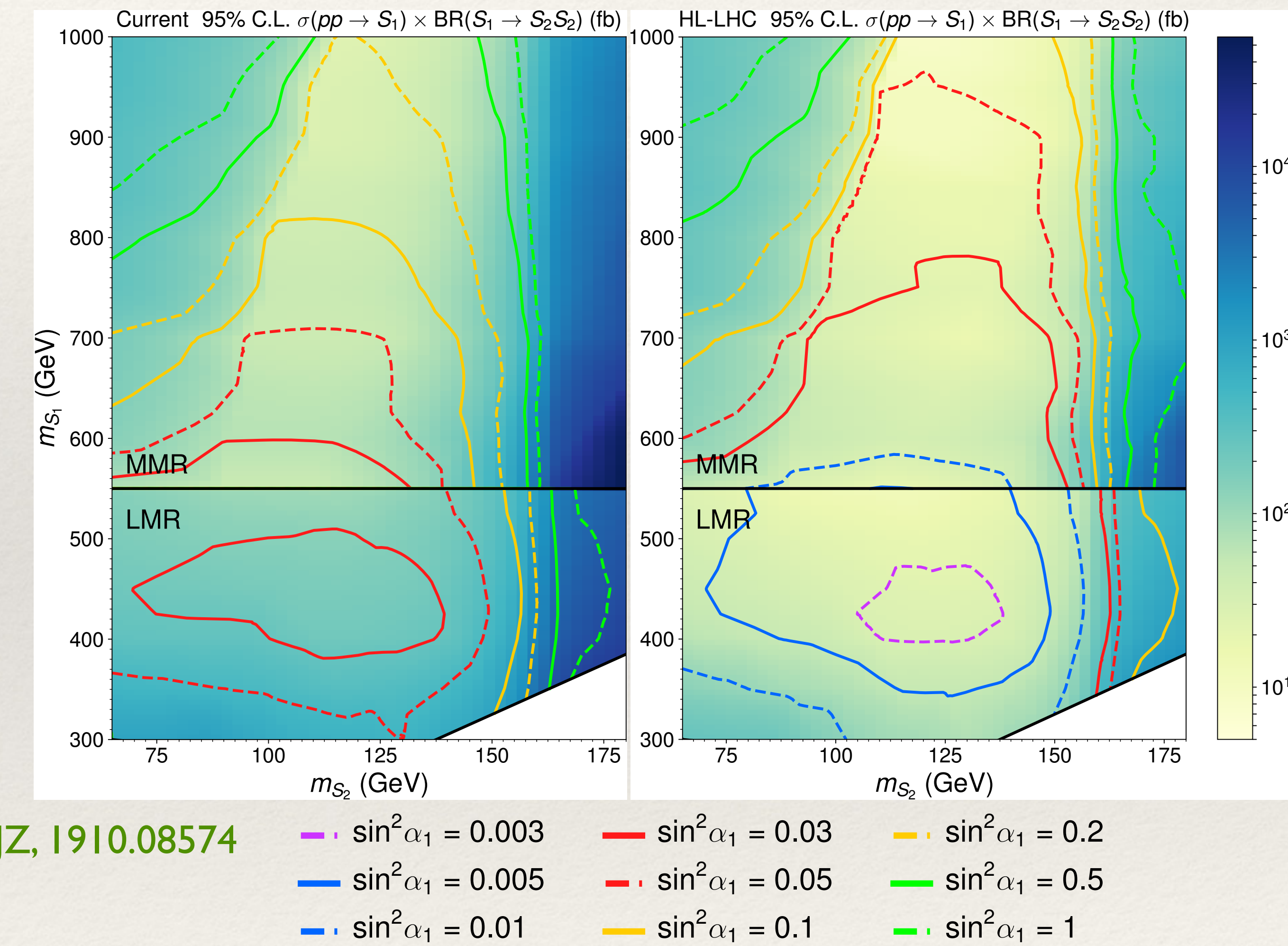
Higgs-to-Higgs decays

- Reinterpretation of CMS H->hh-> 4b study, 1806.03548 in a model independent manner.
- $H_1 \to H_2 H_2 \to 4b$ [no SM-Higgs involved! (not here: projections for HE-LHC, FCC-hh)
- Applied to other models (Two singlet scalars, 2HDM, 2HDM+s/a)



$\sigma(pp \to H_1 \to H_2H_2 \to b\bar{b}b\bar{b}) = \hat{\sigma}_{H_1} \times \kappa^2 \times \mathrm{BR}$

Barducci, Mimasu, No, Vernieri, JZ, 1910.08574



- Successfully reapplied by T. Robens to Two Real Singlet Model (TRSM), Robens, Stefaniak, Wittbrodt, 1908.08554

di-Higgs + MET?

M. Blanke, S. Kast, J. Thompson, S. Westhoff, 1901.07758

- HH is theoretically very well motivated: explore the scalar potential, understand the stability of our vacuum state, probe electroweak baryogenesis, etc. A large experimental effort has gone into studying several final states, techniques for Higgs reconstruction (in resolved and boosted regimes).

- The DMWG has explored several X+MET searches (X=h,Z,j,t,W, …) but not yet X=h h.

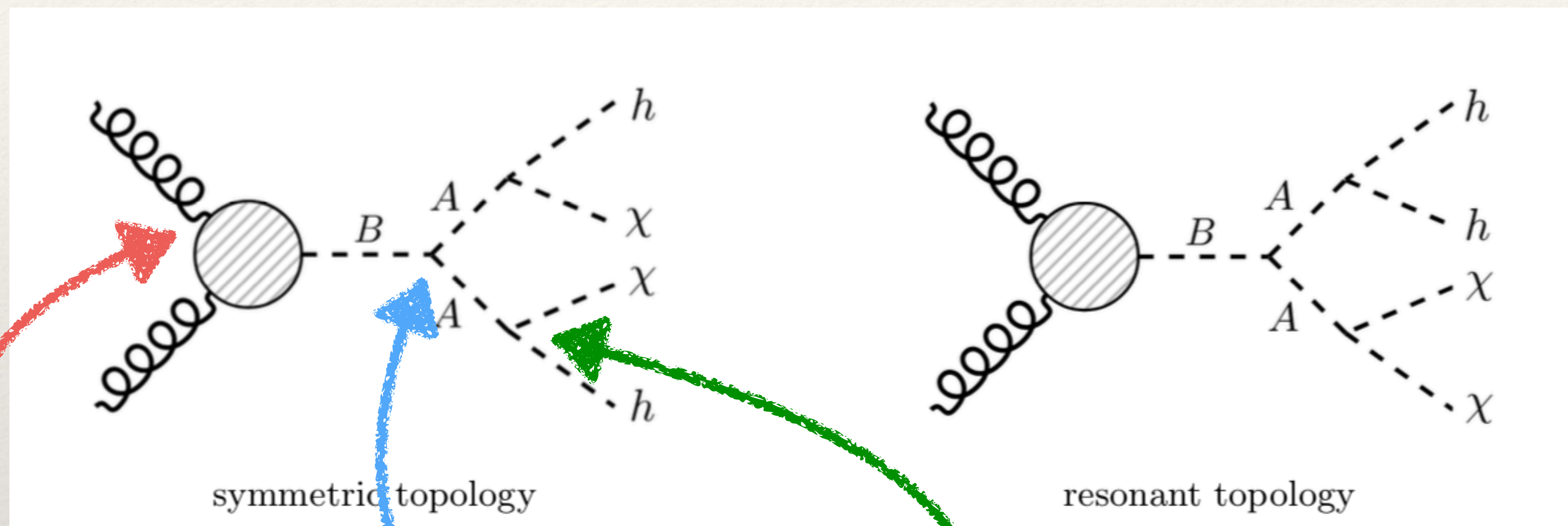
- Current experimental analysis from ATLAS (1806.03040) and CMS (1709.08946) look only for a concrete scenario: a massless invisible particle (goldstino DM: $\tilde{H} \to h\tilde{G}$).

- Signature occurs in complete models, e.g: the pseudo-scalar Portal (No:1509.01110), MSSM (Bernreuther, et al 1805.11637), NMSSM (Titterton, Ellwanger, Flaecher, Moretti, Shepherd-Themistocleous:1807.10672), Little Higgs (Chen, Lin, Wu, Yu: 1804.00405).

- Our goals:
  - devise simplified models for hh+MET based on signal topology (going beyond massless DM)
  - provide a flexible, model-independent framework for recasting (connect to complete models)
  - explore the discovery prospects at HL-LHC (note that hh+MET could be the discovery mode!)

Simple simplified models

- 3 scalar singlets: B, A, χ (DM) stable due to a Z_2 symmetry.
- 2 topologies: B is Z_2 even, χ is Z_2 odd and A is Z_2 odd (even) in model I (II).

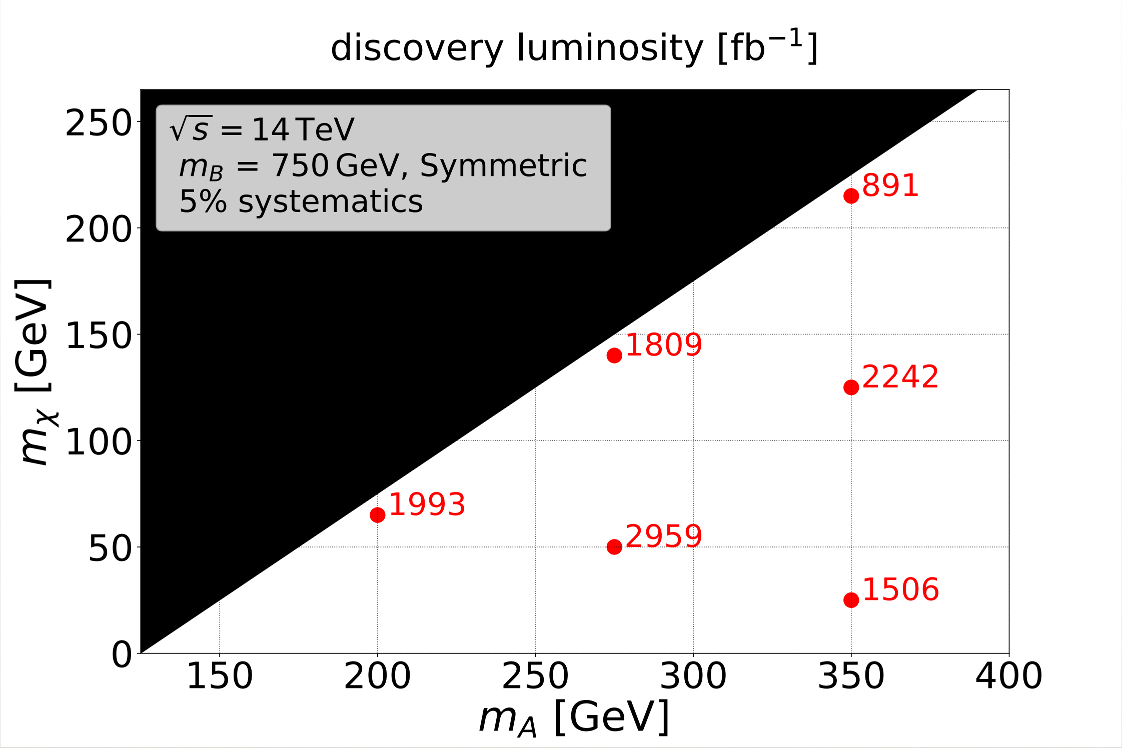


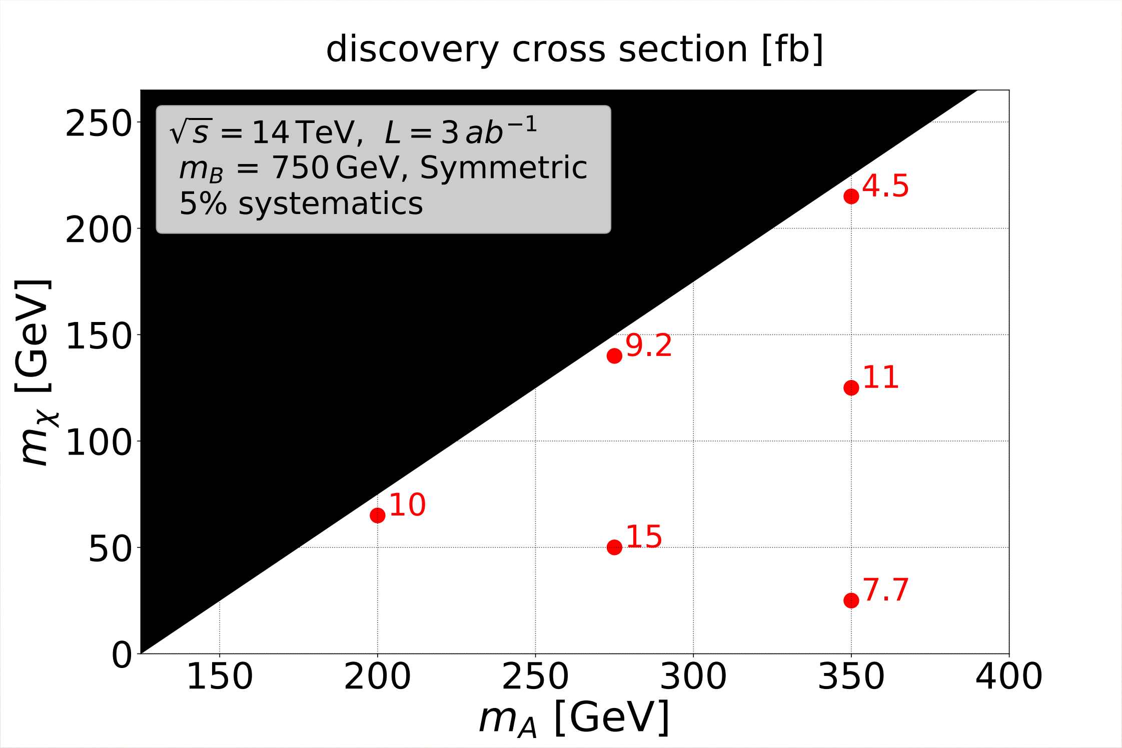
M. Blanke, S. Kast, J. Thompson, S. Westhoff, 1901.07758

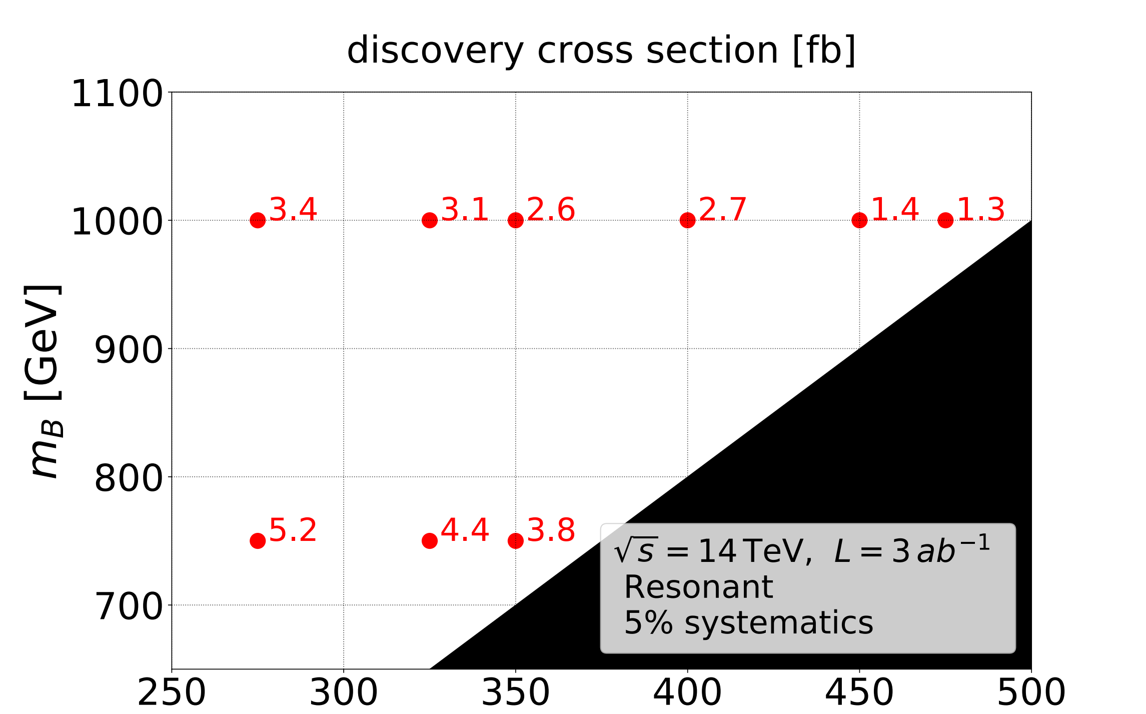
$$\mathcal{L} = \frac{C_{Bgg}}{\Lambda} B G^a_{\mu\nu} G^{\mu\nu\, a} + \frac{m_{BAA}}{2} BAA + \lambda_{A\chi HH} A\chi H^\dagger H.$$

- Model I has 6 free params: m_A, m_S, m_χ, σ(gg ->S), Br(S->AA), Br(A->hχ).
- We set BR(S->AA)=1, BR(A->hχ)=1 and compute C_{sgg} integrating out a 1 TeV VL top-partner.
- The most general V(S,A,H,χ) has more free params. We keep those relevant for our signal.

HL-LHC prospects







- All points within reach of HL-LHC (including 0.5 and 1 TeV benchmarks not shown here) and will not be excluded by any existing (inCheckMATE2) searches (MET + X, di-photon resonances).

- Discovery XS depend only on kinematics, plots useful for easy recasting!

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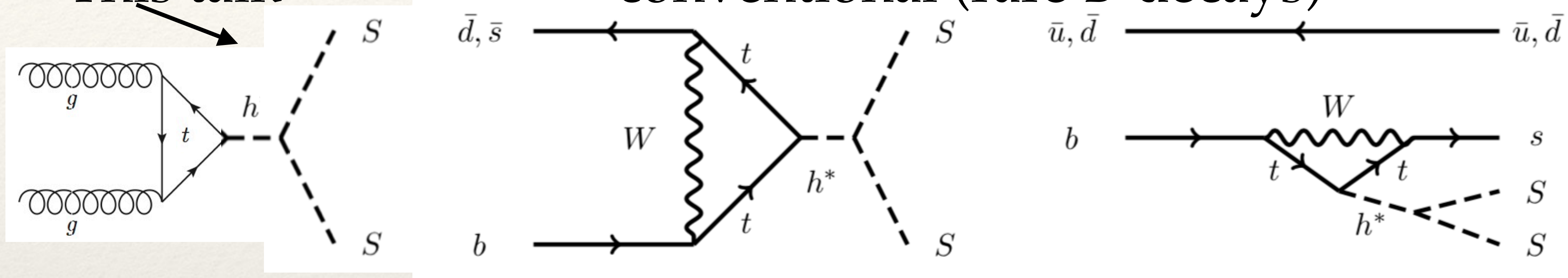
M. Blanke, S. Kast, J. Thompson, S. Westhoff, 1901.07758

LHC(b) pheno: H→SS→hadrons

Production:

This talk

conventional (rare B-decays)

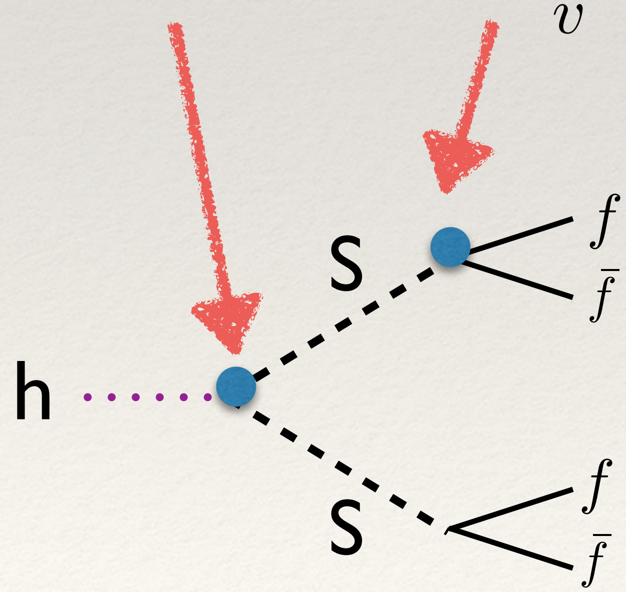


Guaranteed XS!
54.61 pb@14 TeV

Anastasiou et al, 1602.00695

Decay:

$$\mathcal{L} \supset -\lambda_{SSh} h S^2 - \sin\theta \frac{m_f}{v} S \bar{f} f$$

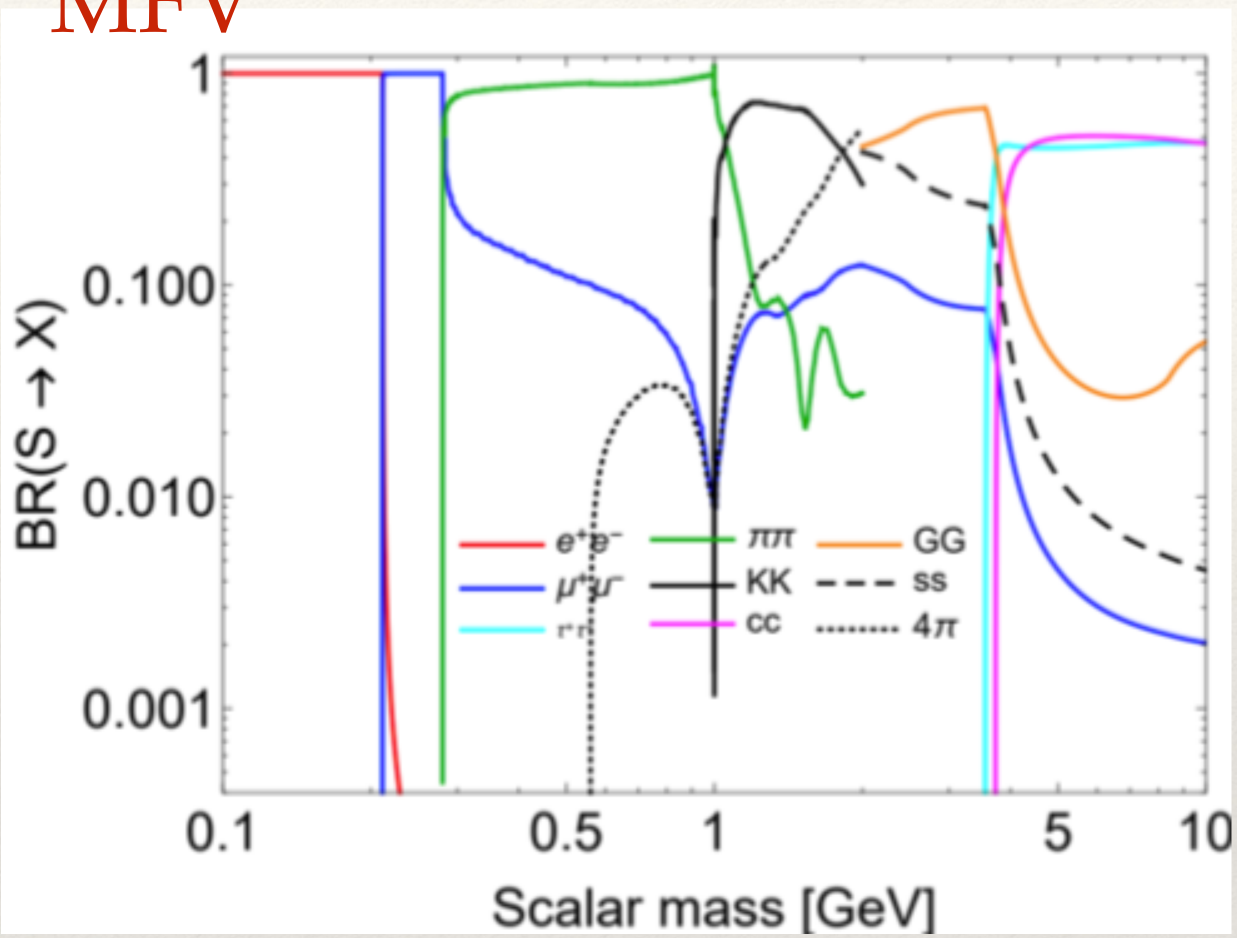


- BR(h→SS) driven by λ_{SSh} : can be sizable!
- cτ driven by h-S mixing θ, constrained by h decays.
- Displaced jet searches: ATLAS (1811.07370, 1902.03094, 1909.01246), CMS (1811.07991) and even LHCb (1705.07332) do not apply if mS ≲5-10 GeV (direct search).
- Higgs to BSM (*invisible Higgs decays*) bounds BR(h→SS), currently19% from CMS (1809.05937) and 26% from ATLAS (1904.05105). Proyected 2.5 % at the HL-LHC (1902.00134).
- cτ ≳ 1 m: MATHUSLA, FASER, CODEX-b, …

S→hadrons decays

Decays are model-dependent (actually, flavor structure dep.)

MFV



I. Boiarska, K. Bondarenko, A. Boyarsky, V. Gorkavenko, M. Ovchynnikov, and A. Sokolenko, *Phenomenology of GeV-scale scalar portal*, arXiv:1904.10447.

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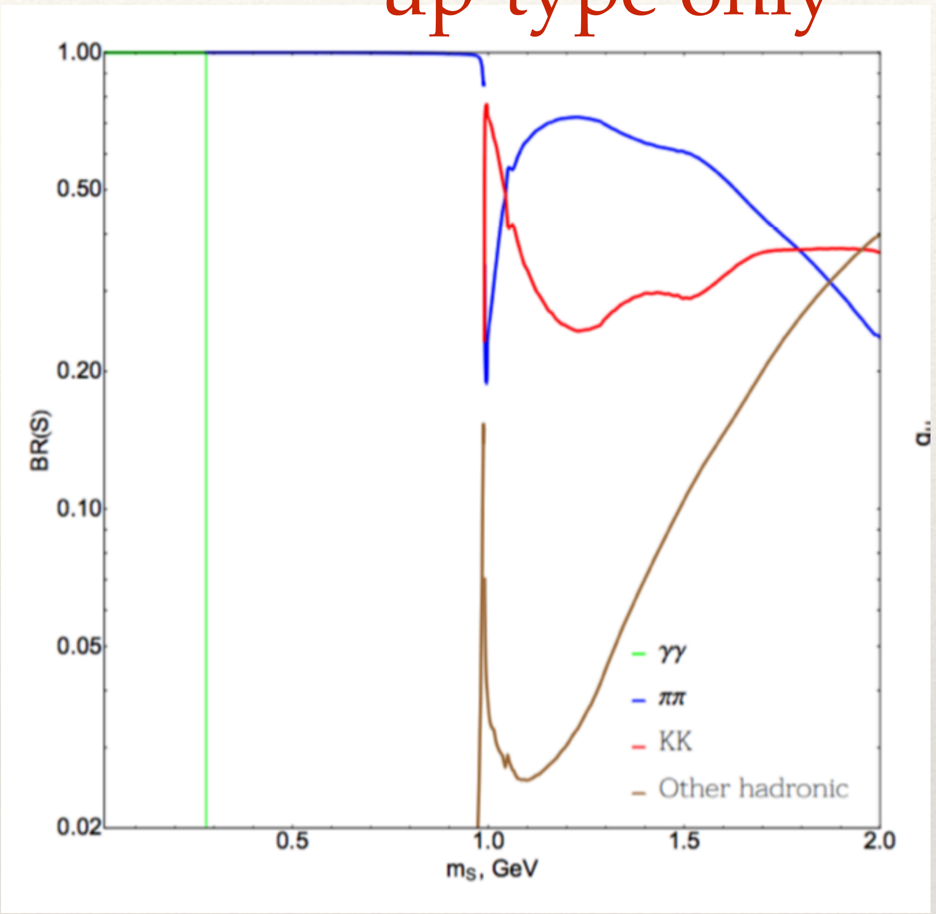


B. Batell, A. Freitas, A. Ismail, and D. Mckeen, *Probing Light Dark Matter with a Hadrophilic Scalar Mediator*, arXiv:1812.05103.

B→K⁺S, S→μμ strongly constrained by LHCb.

Hence we have no right to assume a specific flavour structure!

Search strategy

- Select $K^{\pm}$ within LHCb ($2<\eta<5$), pT > 0.5 GeV.
- Reconstruct S: $d(K^+, K^-) < 0.1$ mm, pT(S) > 10 GeV.
- S vertex must point to PV with IP < 0.1mm and $2<\varrho<25$, $z<400$ mm with $\varrho=(x^2+y^2)^{1/2}$.
- Isolation: No track with $2<\eta<5$, pT > 0.25 GeV, IP > 0.1 mm has d(track,$K^{\pm}$) < 0.1 mm.
- Mass vetoes:
  - $m_{KK} \in [1.85\text{-}1.88]$ GeV (D^0->KK), $m_{KK} \in [0.99\text{-}1.05]$ GeV (Φ->KK).
  - $m_{\pi\pi} \in [0.48\text{-}0.52]$ GeV (K_S^0->$\pi\pi$), $m_{KK} \in [1.11\text{-}1.12]$ GeV (Λ^0->pπ).
- Classify in signal regions according to #S, iso=yes/no, $\varrho \in [6\text{-}10]$ mm or $\in [14\text{-}25]$ mm.
- We focus on kaons, but the analysis applicable to any hadron (D^+D^-, $\pi^+\pi^-$, …)

Signal Region	ρ range (mm)	Isolation	Number of S	bg @ 15 fb^{-1} $m_S = [1, 2]$ GeV
a_1	$6 < \rho < 10$	no	1	7.85×10^6
a_2	$6 < \rho < 10$	yes	1	2.62×10^5
b_1	$14 < \rho < 25$	no	1	2.01×10^5
b_2	$14 < \rho < 25$	yes	1	3.43×10^3
c_1	both $6 < \rho < 10$	no	2	16.8
c_2	both $6 < \rho < 10$	yes	2	0.67
d_1	both $14 < \rho < 25$	no	2	$< 10^{-4}$
d_2	both $14 < \rho < 25$	yes	2	$< 10^{-6}$

Table 1. Description of the different signal regions in terms of the tracker geometry. See main text for details.

Hadrophilic Higgs Portal

In a given model, BR(H→SS), BR(S-→K+K-) need to be computed

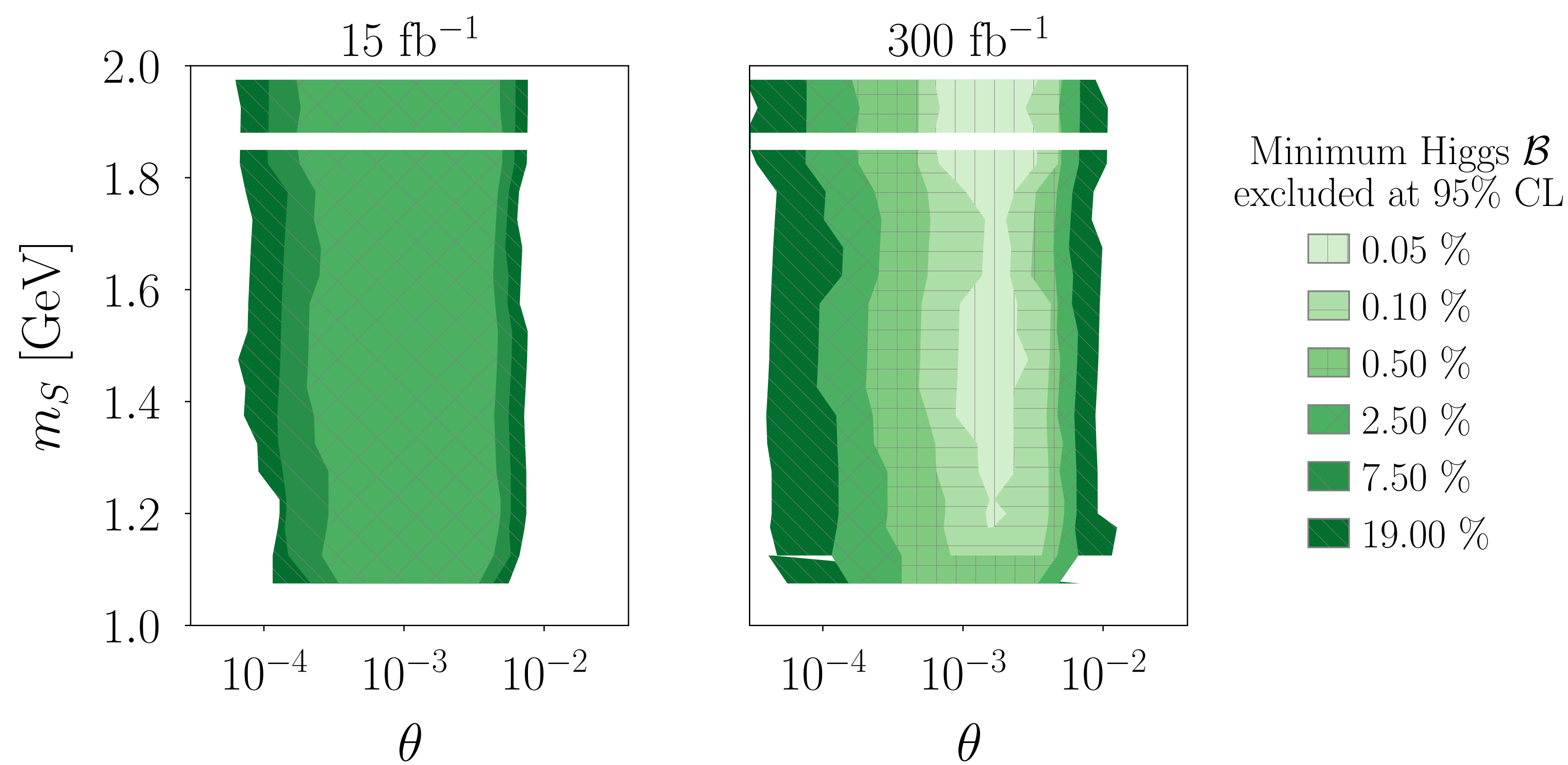
1S: σ(H) * BR(H→SS) * 2 BR(S→KK)

2S: σ(H) * BR(H→SS) * BR(S→KK)^2

We will compute BR(S→KK) (m_S) and set 2σ constrains on BR(H→SS).

$$\mathcal{L}_S^{\text{had}} = \frac{m_{q_i}}{M} S\bar{q}_i q_i + \alpha v \left(\frac{1}{2} h S^2 + \frac{1}{v} h^2 S^2\right) - \frac{\tilde{m}_S^2}{2} S^2$$

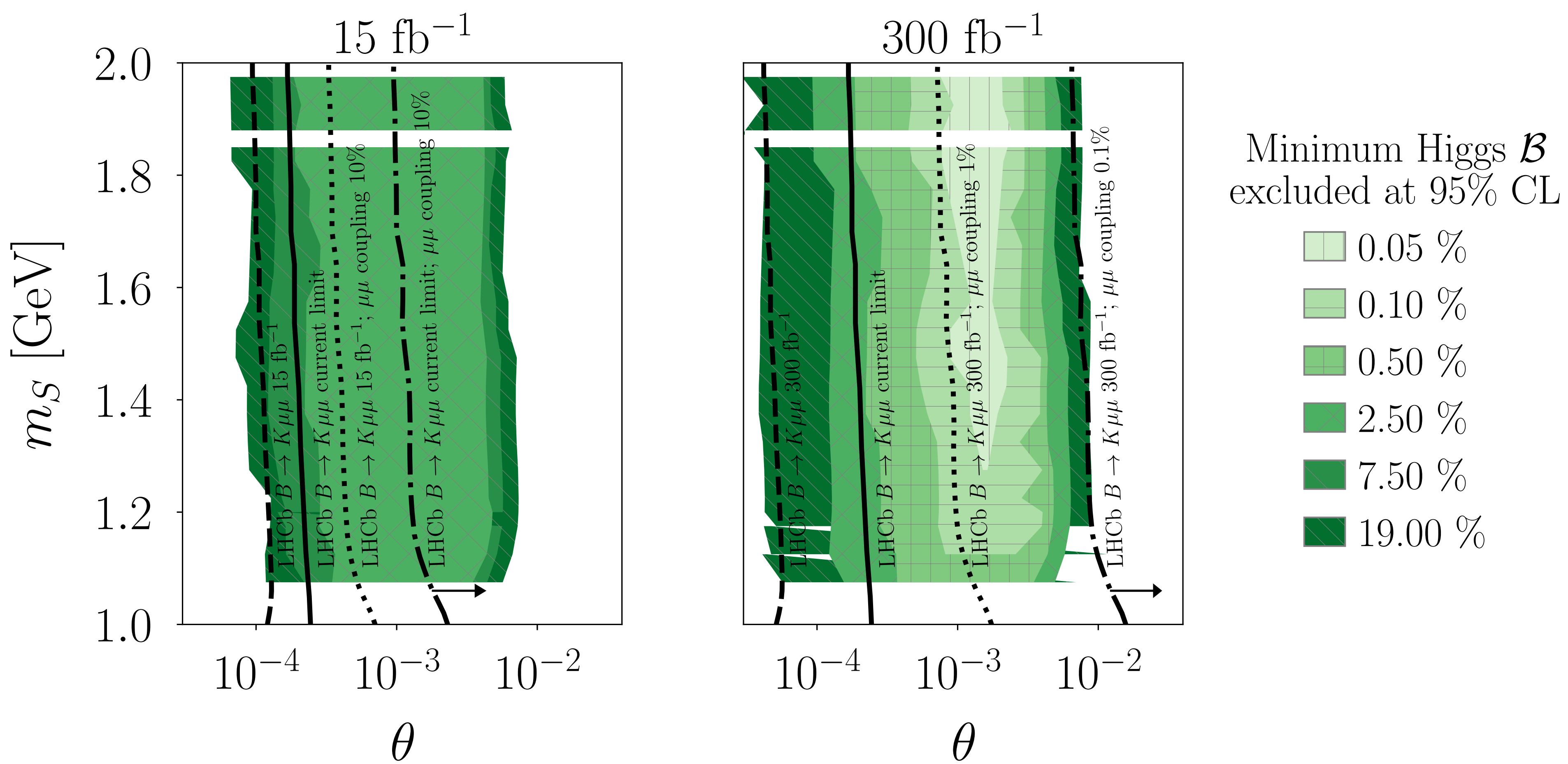
M. W. Winkler, arXiv:1809.01876



Higgs Portal

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{m_S^2}{2}S^2 - \theta\frac{m_f}{v}S\bar{f}f + 2\theta\frac{m_W^2}{v}SW^+W^- + \theta\frac{m_Z^2}{v}SZ^2 + \alpha(\frac{v}{2}S^2h + S^2h^2)$$

I. Boiarska, K. Bondarenko, A. Boyarsky, V. Gorkavenko, M. Ovchynnikov, and A. Sokolenko, arXiv:1904.10447.



Most of parameter space already excluded by LHCb B→Kμμ!
Leading signal here would be an excess in the B rare decay,
but the exclusive search is needed to identify the New Physics!

Outlook

- hh production is a guaranteed SM process, allowing for a direct probe of the h self-couplings.
- Main BSM effects: resonances, modified couplings, heavy coloured particles (EFT language appropiate)
- But di-Higgs phenomenology is larger than the previous items, including:
  - Additional (non-SM) scalars (Higgs-to-Higgs decays can probe additional parameter space!)
  - Dark Matter (hh + MET, can even be discovery channel!)
  - Long-lived light scalars
- Let's keep exploring the di-Higgs frontier!

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