Identifying Exclusive Displaced Hadronic Signatures in the Forward region of the LHC

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Based on: X.C.Vidal, Y.Tsai, JZ, arXiv:1910.05225, JHEP 2001 (2020) 115

STEALTH@LHCb , 19.02.2020

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The Quest for New Physics

- Electroweak naturalness (hierarchy) problem solved by New Physics (NP) at the TeV scale.

- Other fundamental questions (dark matter, CP asymmetry, neutrino masses, flavor, etc) can also be solved if the NP scale, Λ_{NP} is around the TeV scale.

- No New Physics at the LHC yet! (modulo flavour anomalies…)

  - 1) *collider-phobic* (axions, dark photons, sub-GeV dark matter, sterile neutrinos, …): "we'll need <another kind of experiment> " (e.g: FASER, MATHUSLA, ADMX, DUNE)

  - 2) Λ_{NP} higher than expected:
    - → "let's build a new collider!" [BSM-doer, energy]
    - → "let's compute more loops!" [QCD-doer, precision]

  - 3) $\Lambda_{NP} \sim$ 0.1-1 TeV, but it operates in *stealth mode*: heavy mediators, tiny couplings, compressed spectra, sequestered sectors, large backgrounds, …)

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↓

Ideal territory for LHCb to explore!

BSM≠Flavor @ LHCb?

- LHCb is usually considered *only good for flavour physics*. ATLAS&CMS have more luminosity and larger geometrical acceptance (central), so that's the ideal playground to hunt for new heavy degrees of freedom.

- But LHCb has several other advantages compared to ATLAS&CMS!!! e.g: trigger on soft objects, accurate vertex reconstruction, hadronic ID, precise mass resolution ($\Delta m \sim 50$ MeV for $m \lesssim 10$ GeV), charged track reconstruction…

Can LHCb probe New Physics (besides flavor)?

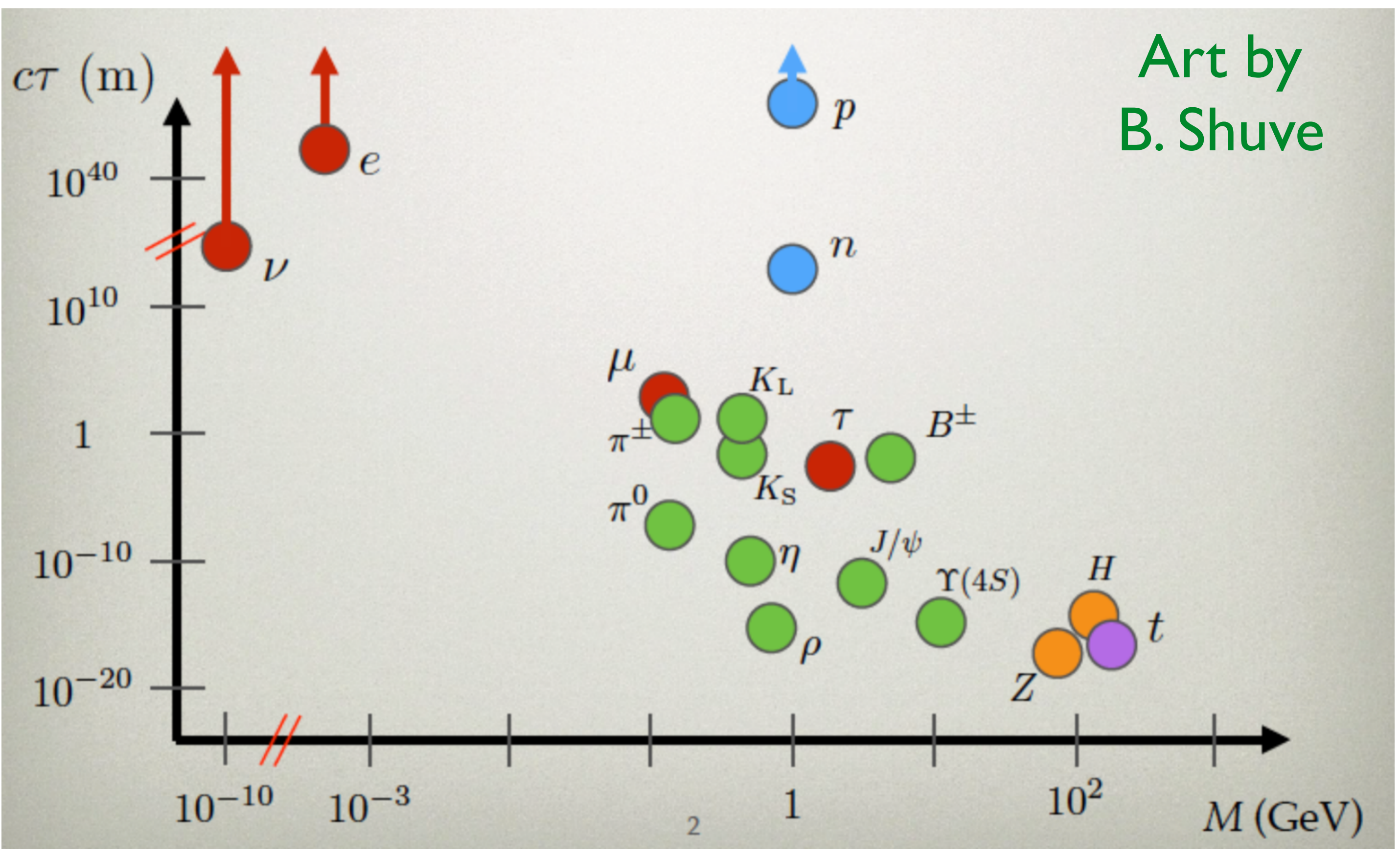
- Some examples: dark photons (P. Ilten, Y. Soreq, J. Thaler, M. Williams, W. Xue: 1603.08926), axions (X. C. Vidal, A Mariotti, D. Redigolo, F. Sala, K. Tobioka: 1810.09452), sterile neutrinos (Antusch, Cazzato, Fischer, 1706.05990), …

Today: <u>displaced</u>, <u>light</u> (1-2 GeV) <u>exclusive</u> hadronic resonances $H \to SS \to K^+K^-K^+K^-$.

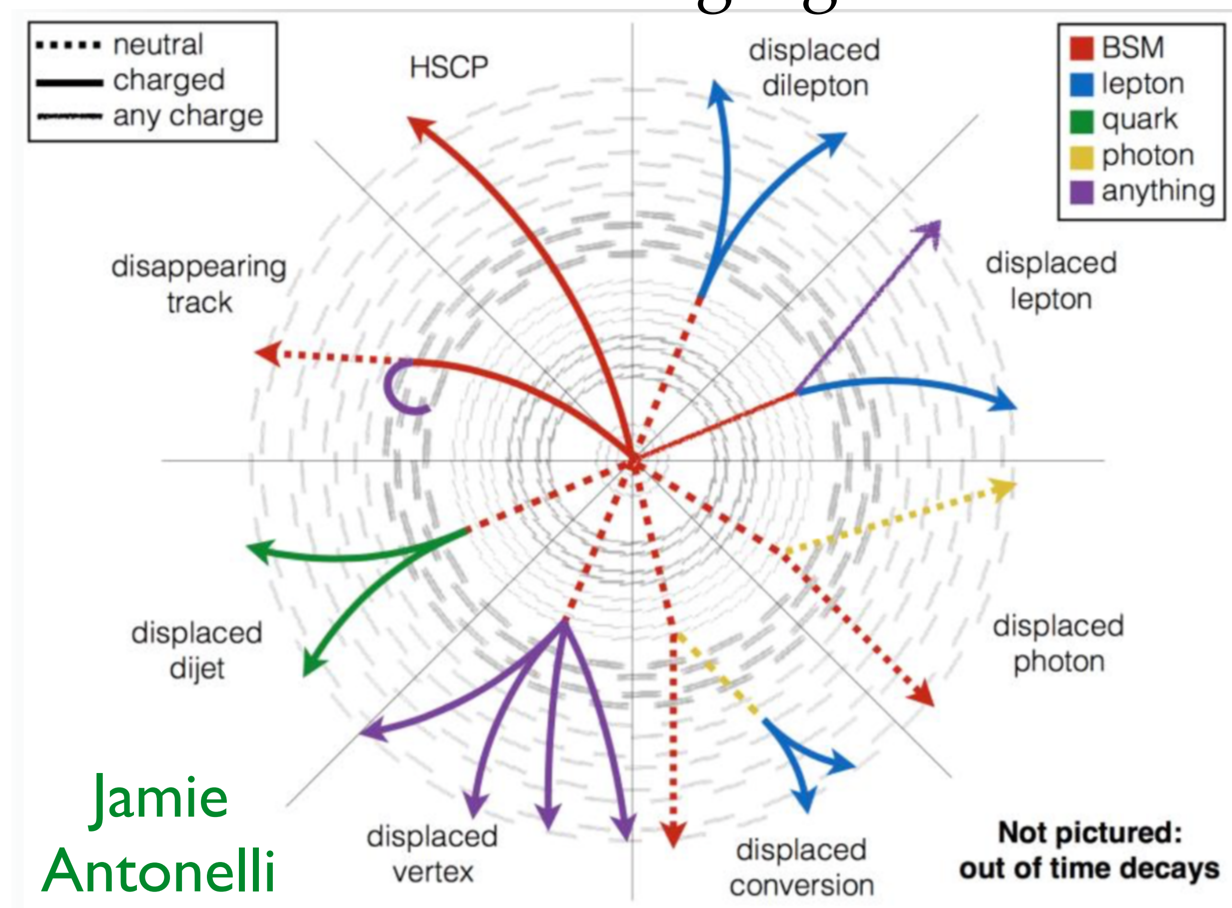
Long-Lived Particles

- LLPs: BSM states with macroscopic lifetimes (ns), theoretically well motivated.

Exist in the SM!



A lot of interesting signatures!



large cτ, small Γ

- Large mass hierarchies
- Compressed spectra
- Small couplings

EW Baryogenesis
Dark Matter
Hierarchy Problem
Neutrino Masses

BSM Models: RH neutrinos, dark QCD, stealth SUSY, Neutral Naturalness, Higgs Portal, Z′ Portal, Hidden Valleys, …

Models ⟷ **Signatures**

MATHUSLA Physics case
Curtin et al, 1806.07396

LLP@LHC White Paper:
Alimena et al, 1903.04497

Portals into New Physics

- How to couple light degrees of freedom to the SM while being consistent with all possible constraints (e.g: LEP, Tevatron, EDMs, LHC, flavor…)?
- Idea: add new particle weakly coupled to the SM via a portal term.

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{portal} + \mathcal{L}_{\mathcal{NP}}$$

Encodes interaction of SM fields and new particles

Field	Lagrangian	Phenomenology
Scalar S:	$\mathcal{L}_S \supset \mu S H^\dagger H + \lambda S^2 H^\dagger H$	Exotic Higgs decays
Vector A′:	$\mathcal{L}_{A'_\mu} \supset \epsilon F'_{\mu\nu} B_{\mu\nu}$	Dark photon / Z′
Fermion N:	$\mathcal{L}_N \supset y_{ai}(L_a H) N^i$	HNL (ν masses)
Pseudoscalar a:	$\mathcal{L}_a \supset a\left(\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4f_\gamma} + \frac{G_{\mu\nu}\widetilde{G}^{\mu\nu}}{4f_g}\right) + \frac{\partial^\mu a}{f_f}\bar{f}_i\gamma^\mu\gamma^5 f^i$	ALPs

Physics Beyond Colliders Report, Beacham et al, 1901.09966

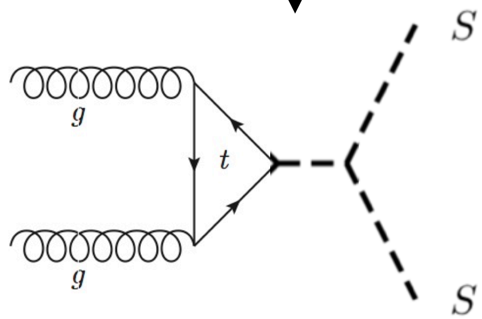
LHC pheno: H→SS→hadrons

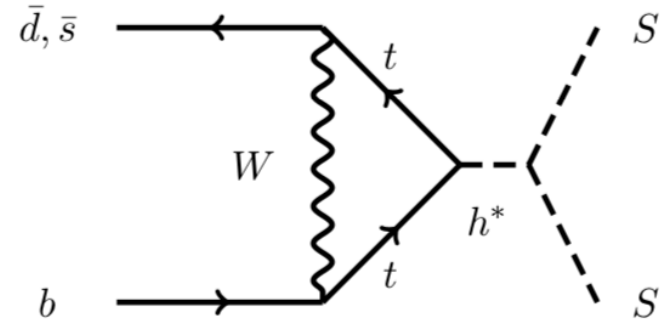
Production:

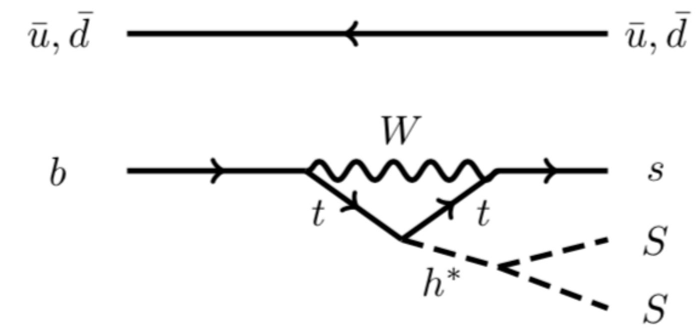
This talk

conventional (rare B-decays)

Guaranteed XS!
54.61 pb@14 TeV
Anastasiou et al, 1602.00695



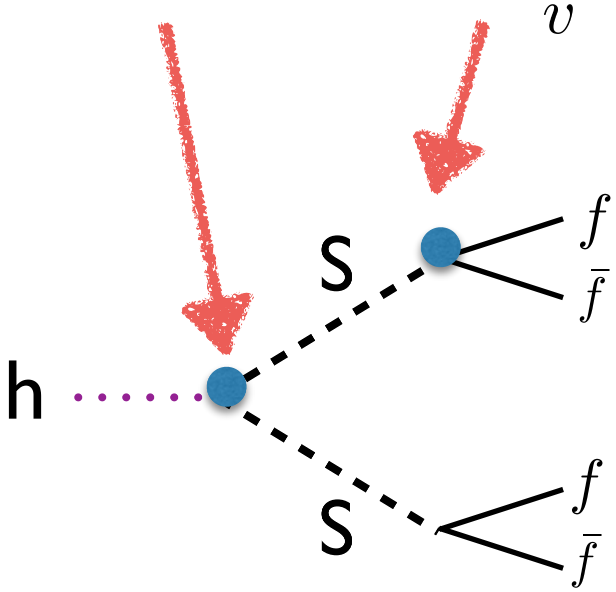




Discussed in talks by Ruth and Maria.

Decay:

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

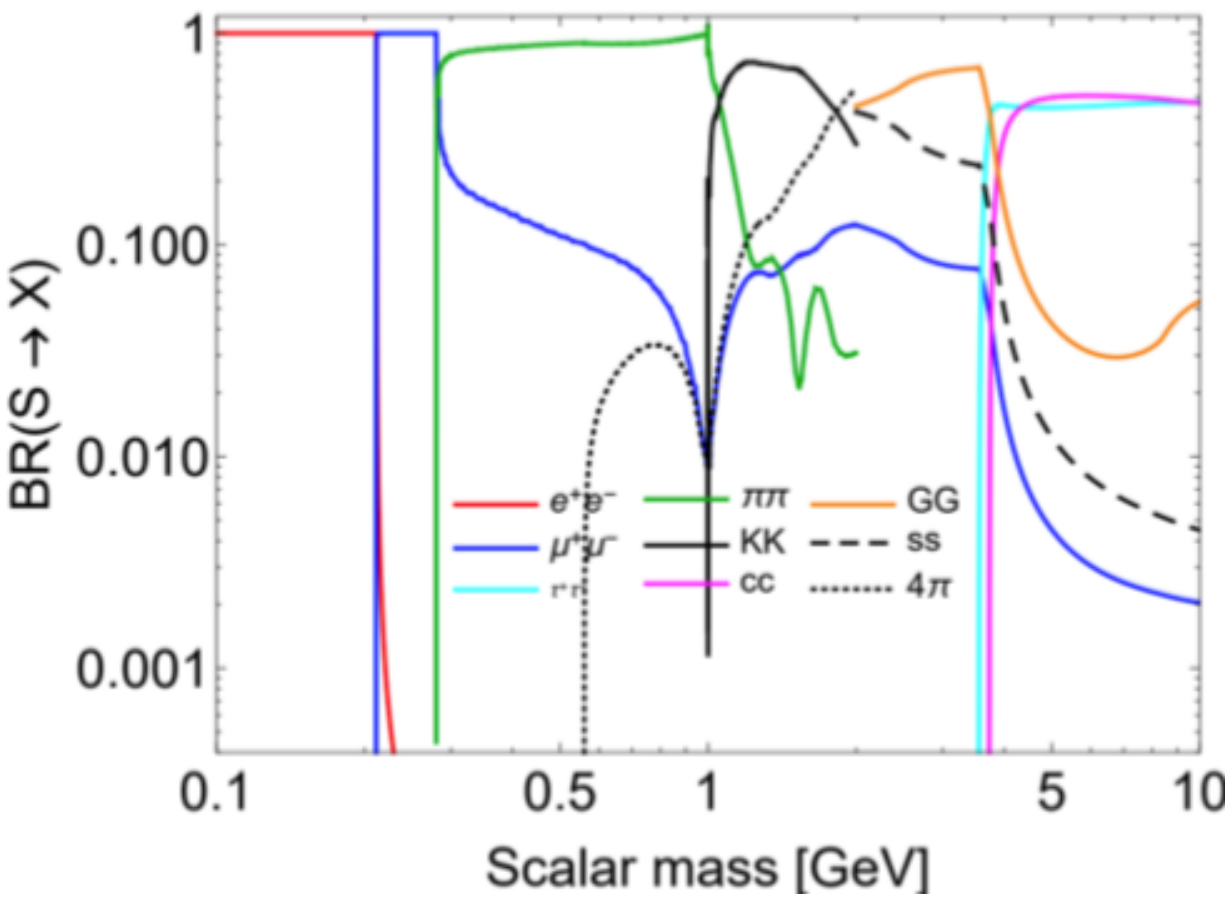


- BR(h→SS) driven by λ_{SSh} : can be sizable!
- cτ driven by h-S mixing θ, constrained by h decays.
- Displaced jet searches: ATLAS (1811.07370, 1902.03094, 1909.01246), CMS (1811.07991) and even LHCb (1705.07332) do not apply if mS ≤5-10 GeV (direct search).
- Higgs to BSM (*invisible Higgs decays*) 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



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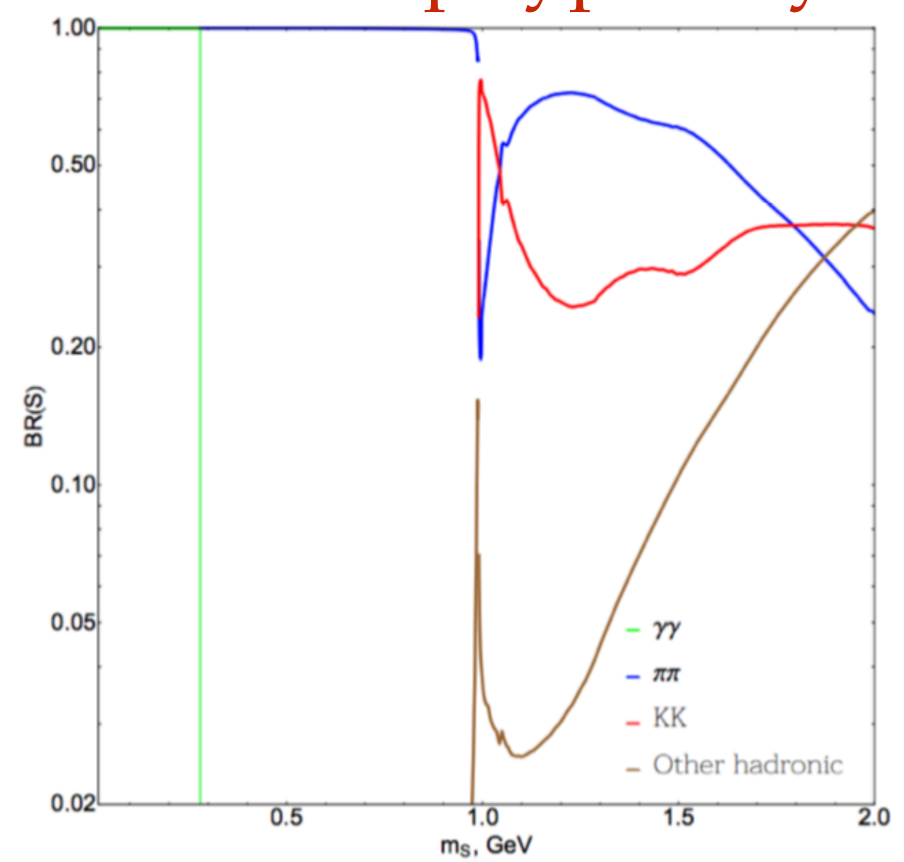


I. Boiarska, K. Bondarenko, A. Boyarsky, V. Gorkavenko, M. Ovchynnikov, and A. Sokolenko, *Phenomenology of GeV-scale scalar portal*, arXiv:1904.10447.

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!

José Zurita

Search strategy

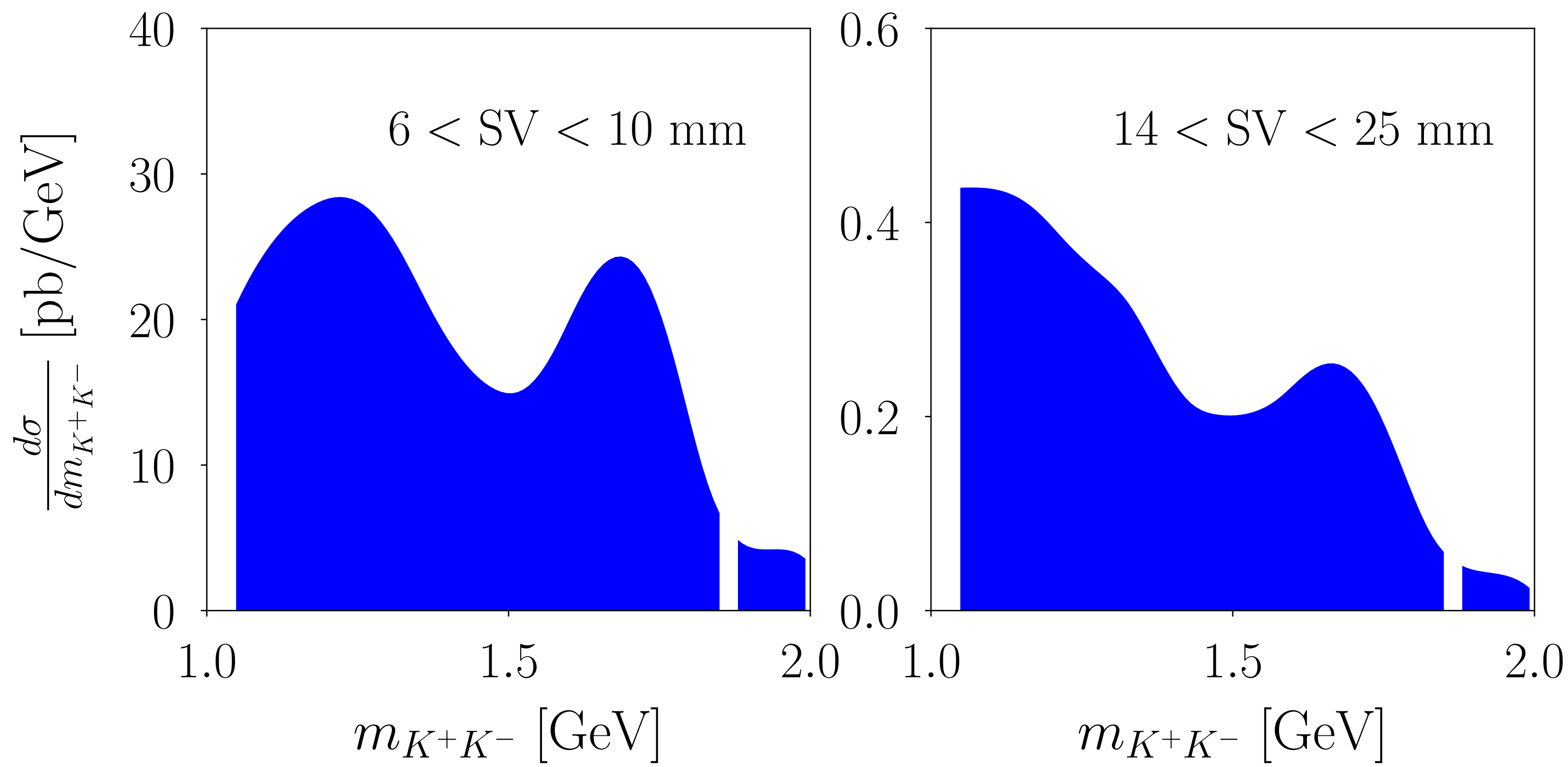
- Select $K^{\pm}$ within LHCb ($2<\eta<5$), pT > 0.5 GeV.
- Reconstruct S: $d(K^+, K^-) < 0.1$ mm, pT(S) > 10 GeV.
- S vertex must point to PV with IP < 0.1mm and $2<\varrho<25$, $z<400$ mm with $\varrho=(x^2+y^2)^{1/2}$.
- Isolation: No track with $2<\eta<5$, pT > 0.25 GeV, IP > 0.1 mm has $d(\text{track}, K^{\pm}) < 0.1$ 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->$p\pi$).
- 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	$< 10^{-6}$

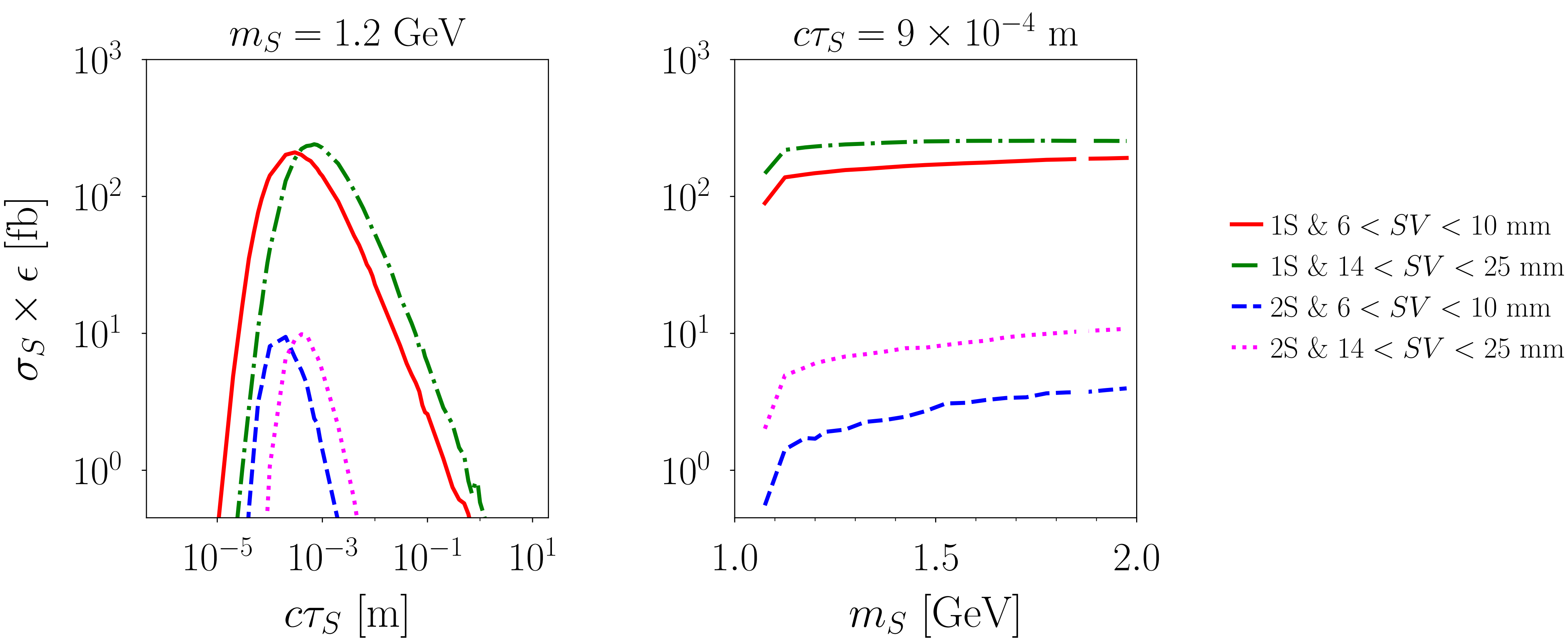
Table 1. Description of the different signal regions in terms of the tracker geometry. See main text for details.

Results

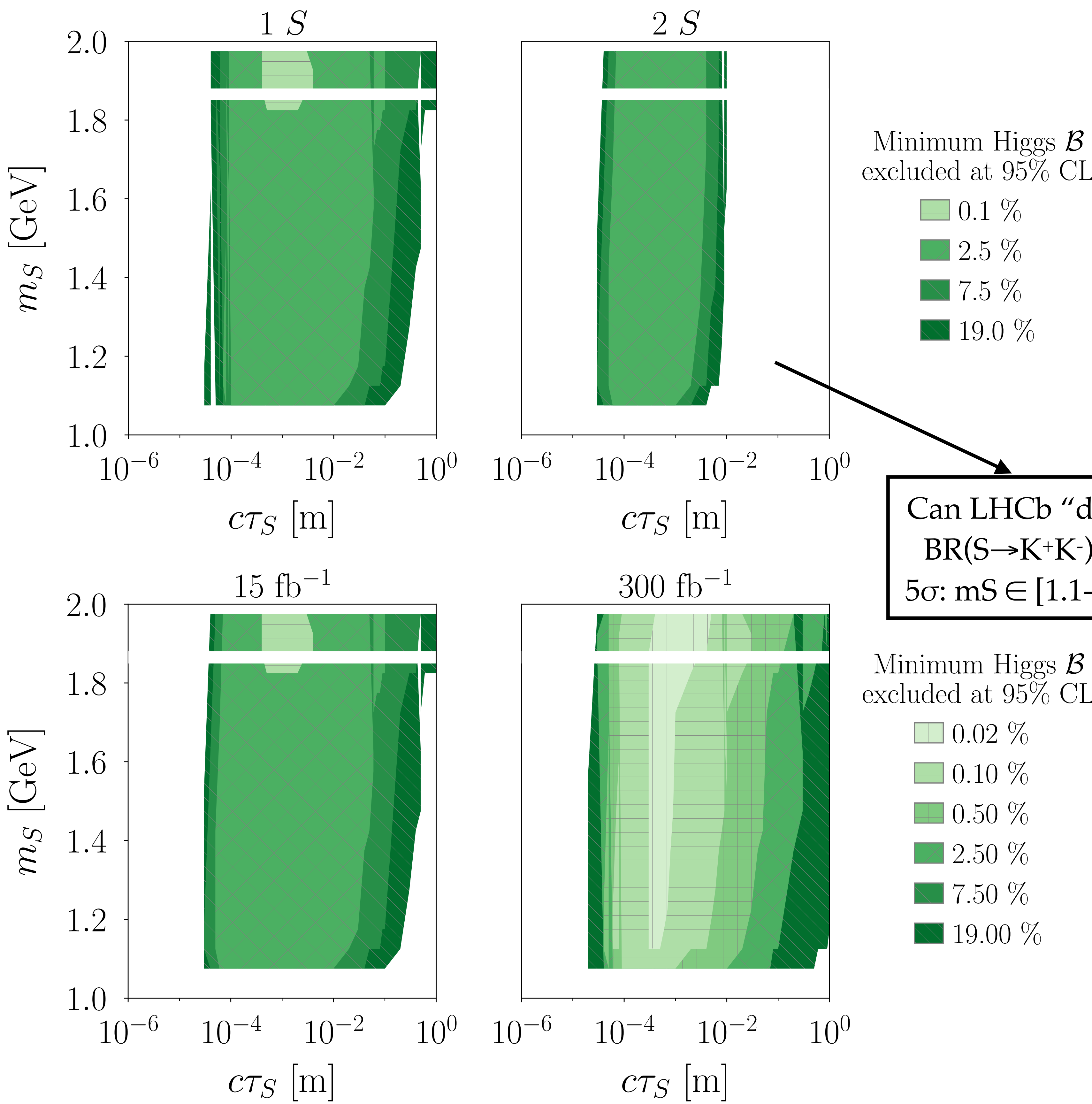
Bgd:



Signal:



Higgs BR limits



Can LHCb "discover" the Higgs? For BR(S→K⁺K⁻)=0.1, BR(H→SS)=0.19, 5σ: mS ∈ [1.1-2] GeV, cτ ∈ 0.1-1.5 mm

Hadrophilic Higgs Portal

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

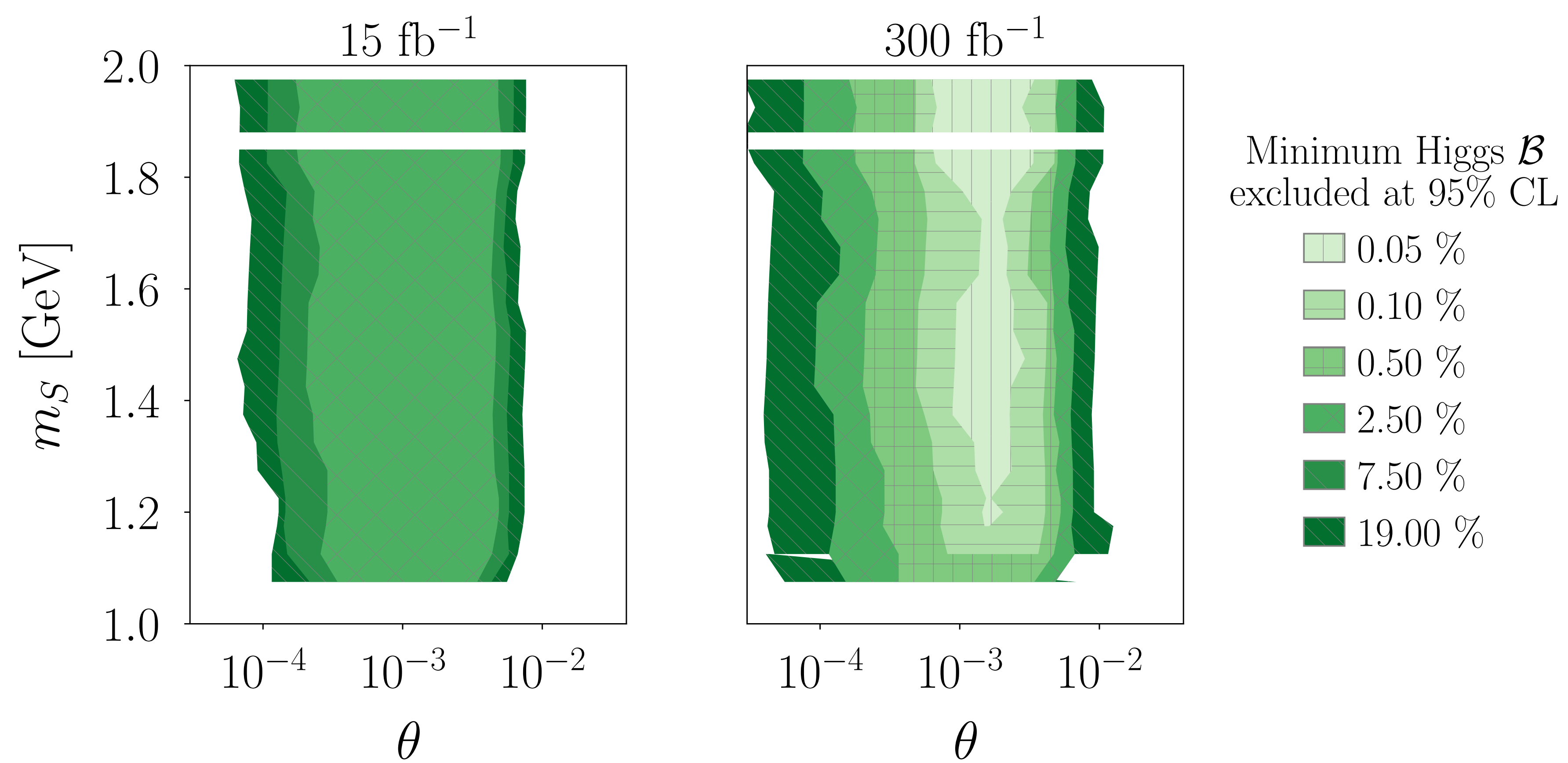
1S: σ(H) * BR(H→SS) * 2 BR(S→KK)

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).

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

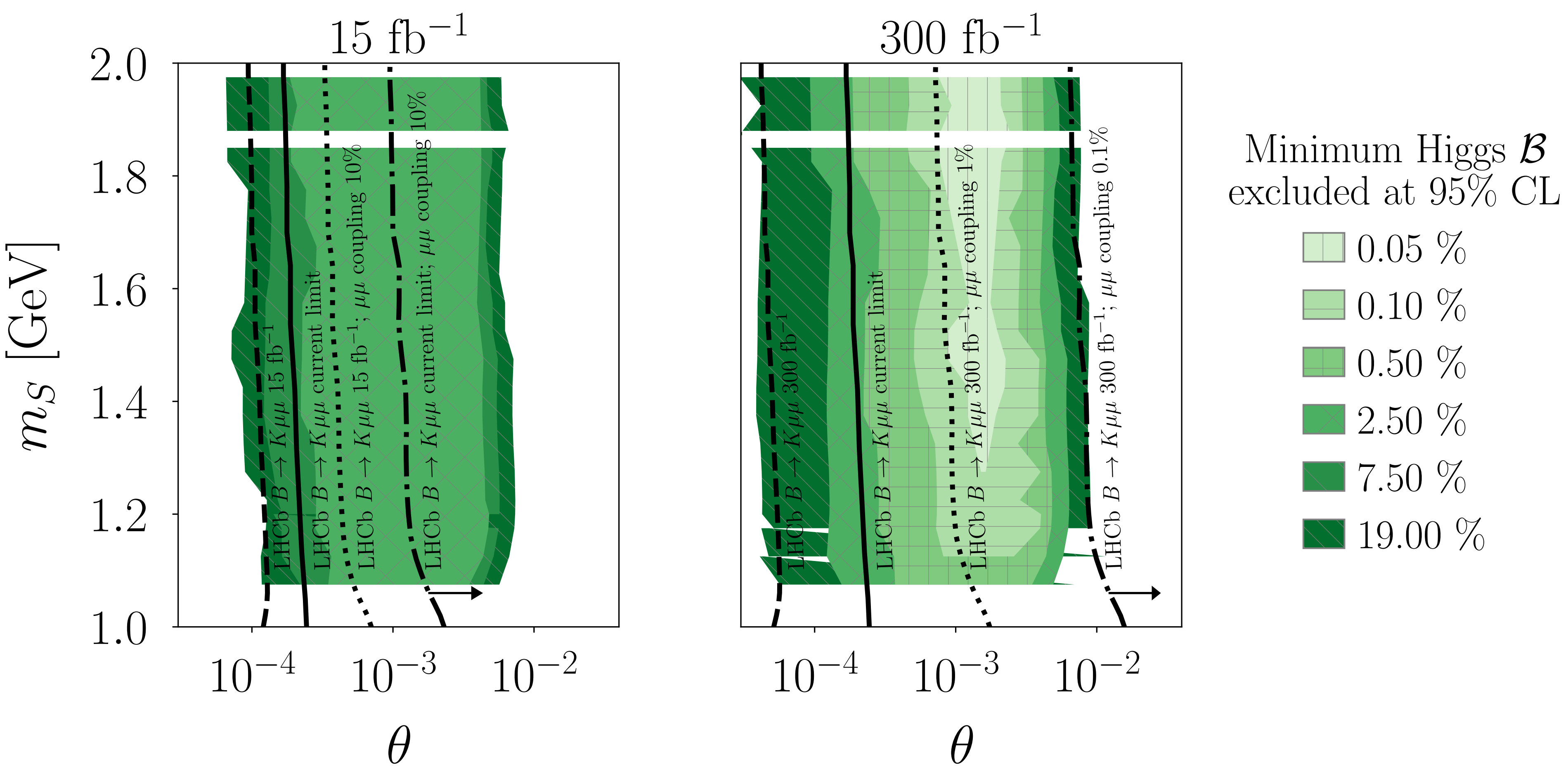
M. W. Winkler, arXiv:1809.01876



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!

Conclusions

- LHCb can probe New Physics that is stealth to ATLAS and CMS, for instance light mass resonances, hadronic final states, displaced particles, …
- We examined the LHCb prospects to test exotic Higgs decays, which complement the existing efforts of ATLAS/CMS via displaced jets and invisible Higgs decays, as well as those of dedicated detectors (FASER, MATHUSLA, CODEX-b, AL3X, etc).
- Even if an excess in displaced jets/inv Higgs is found, LHCb would still be necessary to characterise the New Physics signal.
- A similar strategy can be applied to other:
  - hadronic final states (DD, $\pi\pi$,…).
  - production modes (e.g: rare B-decays).
  - signatures: dark showers (multiple displaced vertexes in single event).

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- Next related workshops: May 25th-29th