Identifying Exclusive Displaced Hadronic Signatures at LHCb

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X.C. Vidal, YT, J. Zurita JHEP 01 (2020) 115

A. Pierce, B. Shakya, YT, Y. Zhao Phys.Rev.D 97 (2018) 9, 095033

Energy Frontier in Particle Physics,
NCTS, Oct 5, 2020

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The Quest for New Physics

New physics exists (dark matter, naturalness problems, neutrino mass)

No new physics at the LHC yet! (modulo flavor anomalies…)

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=> build higher energy colliders / compute more loops (precision measurement)

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new physics is within TeV, but operates in a “stealth” mode?
(tiny coupling, compressed spectra & soft, large backgrounds,…)

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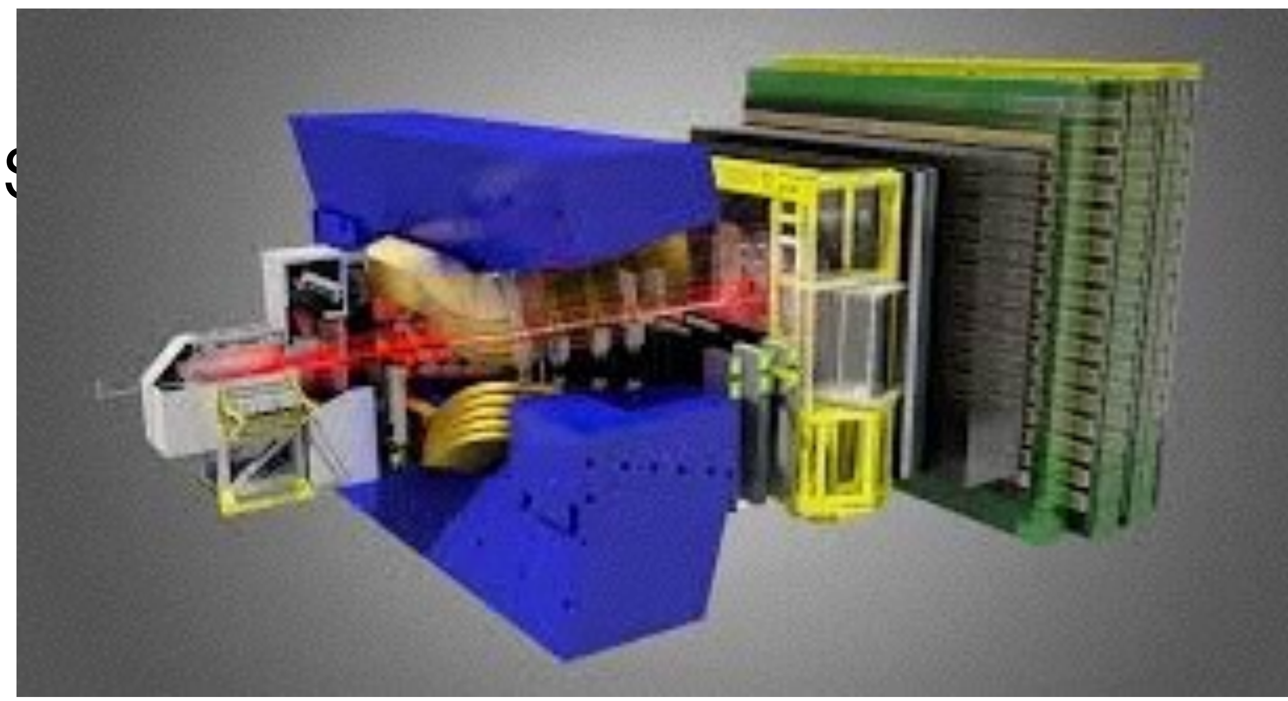
No new physics [...] or anomalies…)



LHCb is a powerful machine to study the "Stealth Physics"!

new physics is within TeV, but operates in a "stealth" mode?
(tiny coupling, compressed spectra & soft, large backgrounds,…)

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LHCb is not only about flavor physics

Several advantages comparing to ATLAS/CMS

e.g., trigger on soft objects, low pileup, accurate vertex reconstruction, precise mass resolution ($\Delta m \sim< 50\,\mathrm{MeV}$), hadronic ID, charge track reconstruction, …

Can LHCb probes new physics (besides flavor)?

Some examples: dark photons (P. Ilten, Y. Soreq, J. Thaler, M. Williams, W. Xue: 1603.08926), sterile neutrinos (Antusch, Cazzato, Fischer: 1706.05990), Confining Hidden Valley (Pierce, Shakya, YT, Zhao: 1708.05389), axions (X. C. Vidal, A Mariotti, D. Redigolo, F. Sala, K. Tobioka:1810.09452)

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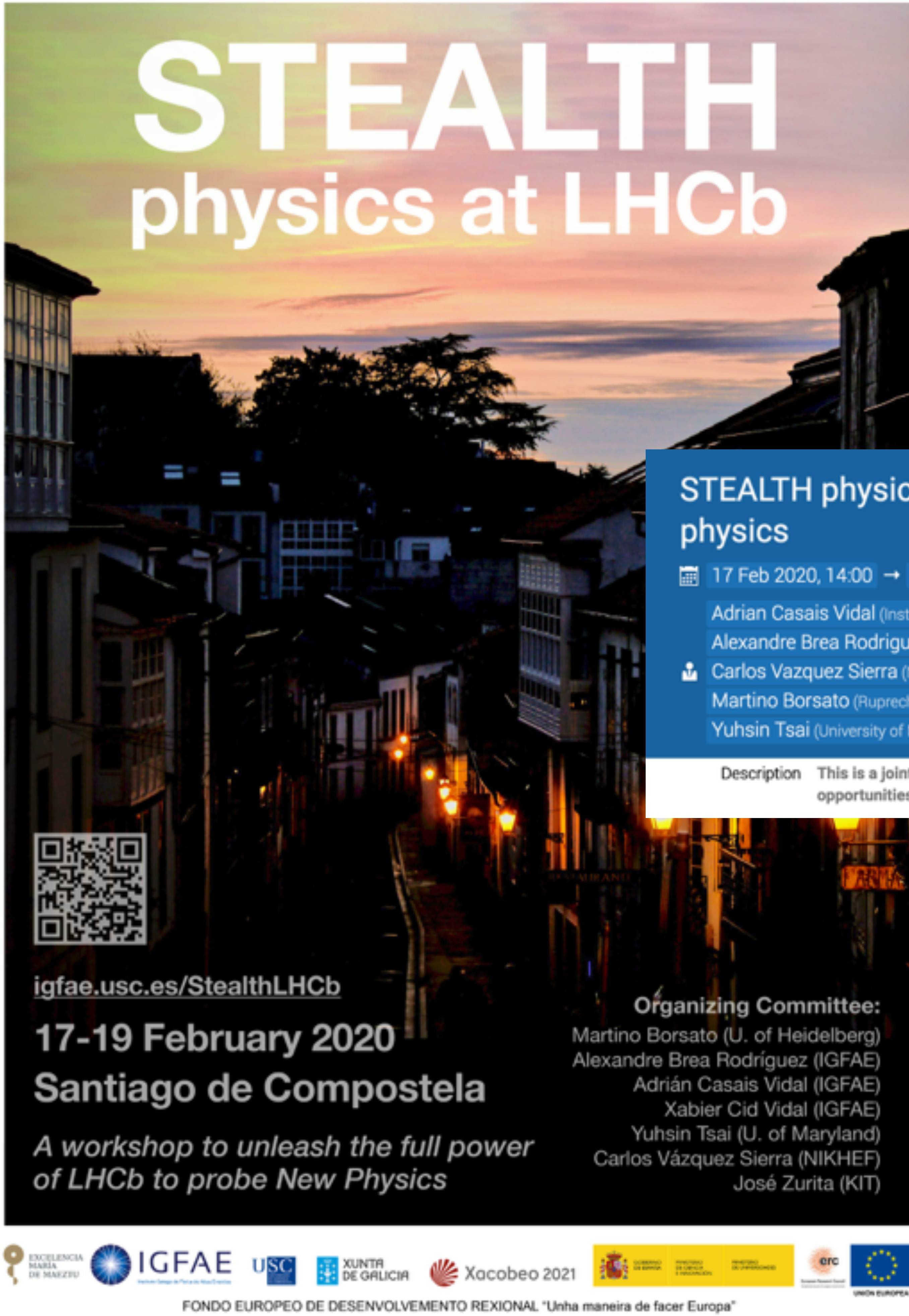


STEALTH physics at LHCb: unleashing the full power of LHCb to probe new physics

17 Feb 2020, 14:00 → 19 Feb 2020, 18:30 Europe/Zurich

Adrian Casais Vidal (Instituto Galego de Física de Altas Enerxías (ES)), Alexandre Brea Rodriguez (Universidade de Santiago de Compostela (USC), IGFAE), Carlos Vazquez Sierra (Nikhef National institute for subatomic physics (NL)), José Francisco Zurita (KIT), Martino Borsato (Ruprecht Karls Universitaet Heidelberg (DE)), Xabier Cid Vidal (Instituto Galego de Física de Altas Enerxías), Yuhsin Tsai (University of Maryland)

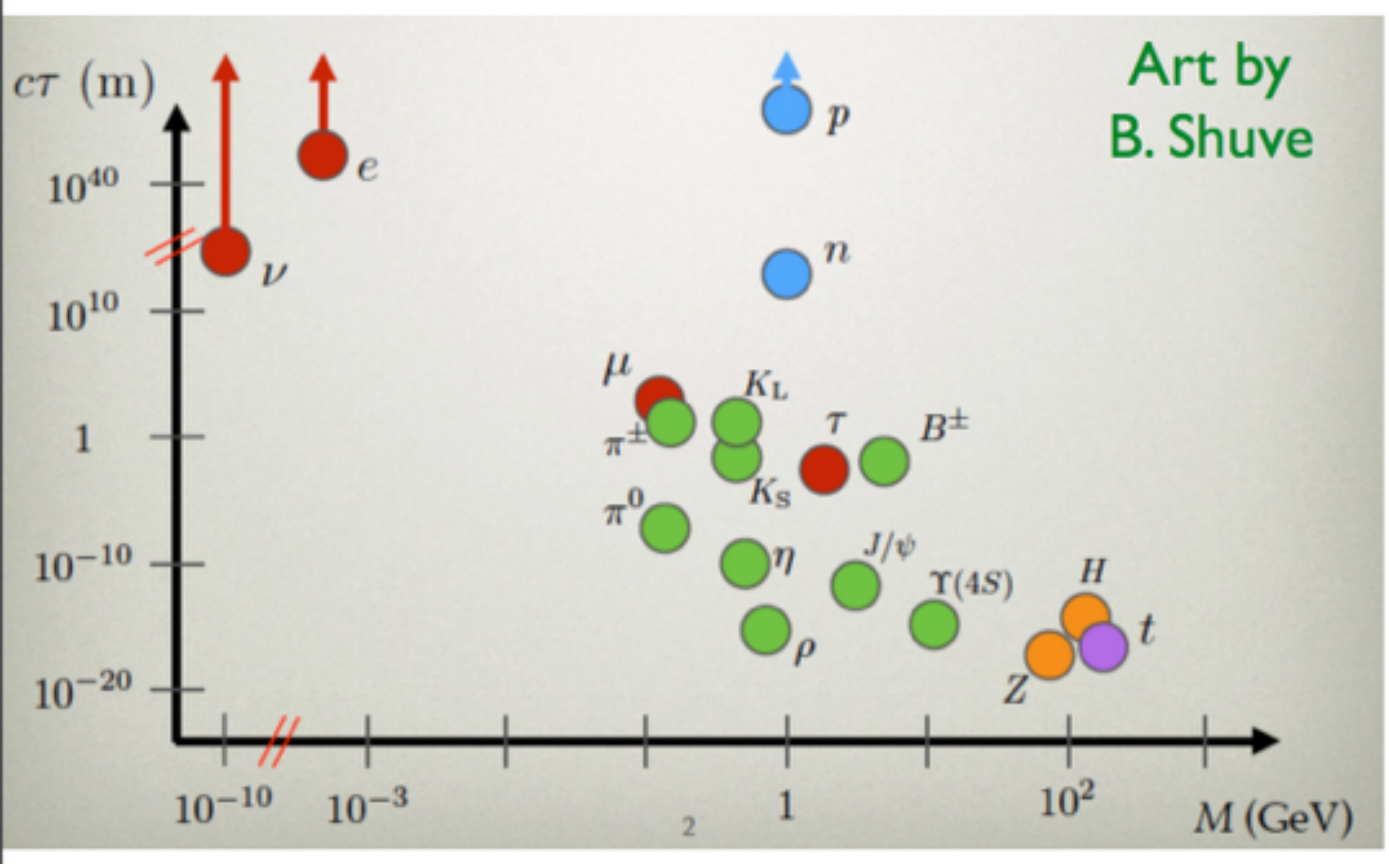
Description: This is a joint theory and experimental LHCb workshop hold in Santiago de Compostela (Spain), to trigger a fruitful discussion and lo
opportunities at LHCb concerning STEALTH physics.

https://indico.cern.ch/event/849862/timetable/

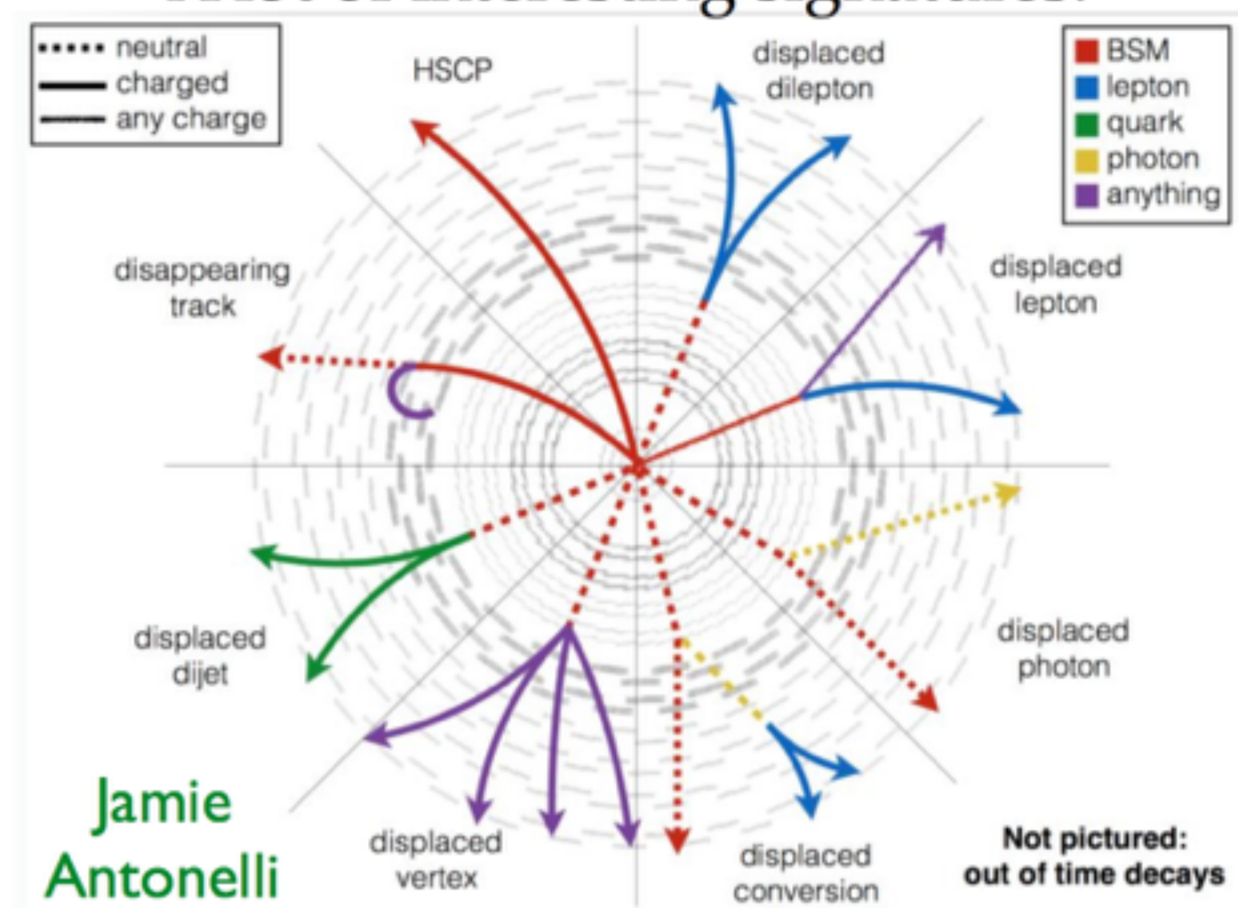
Long-Lived Particles (LLPs)

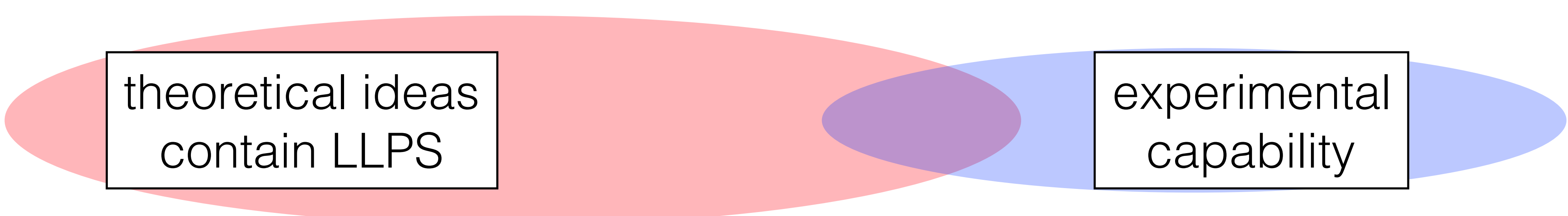
BSM states with macroscopic lifetimes (> ns), theoretically well motivated

Exist in the SM!



A lot of interesting signatures!





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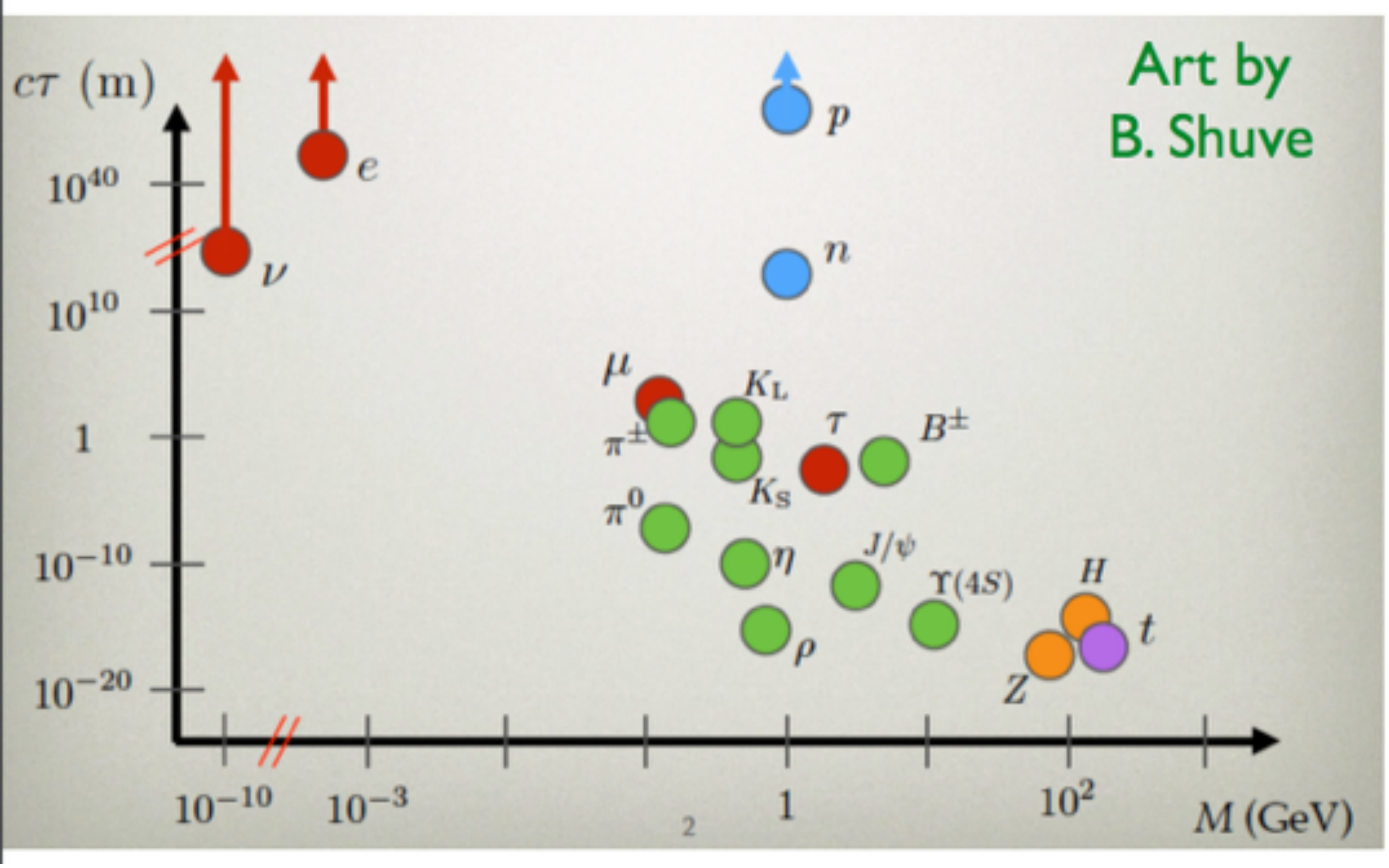

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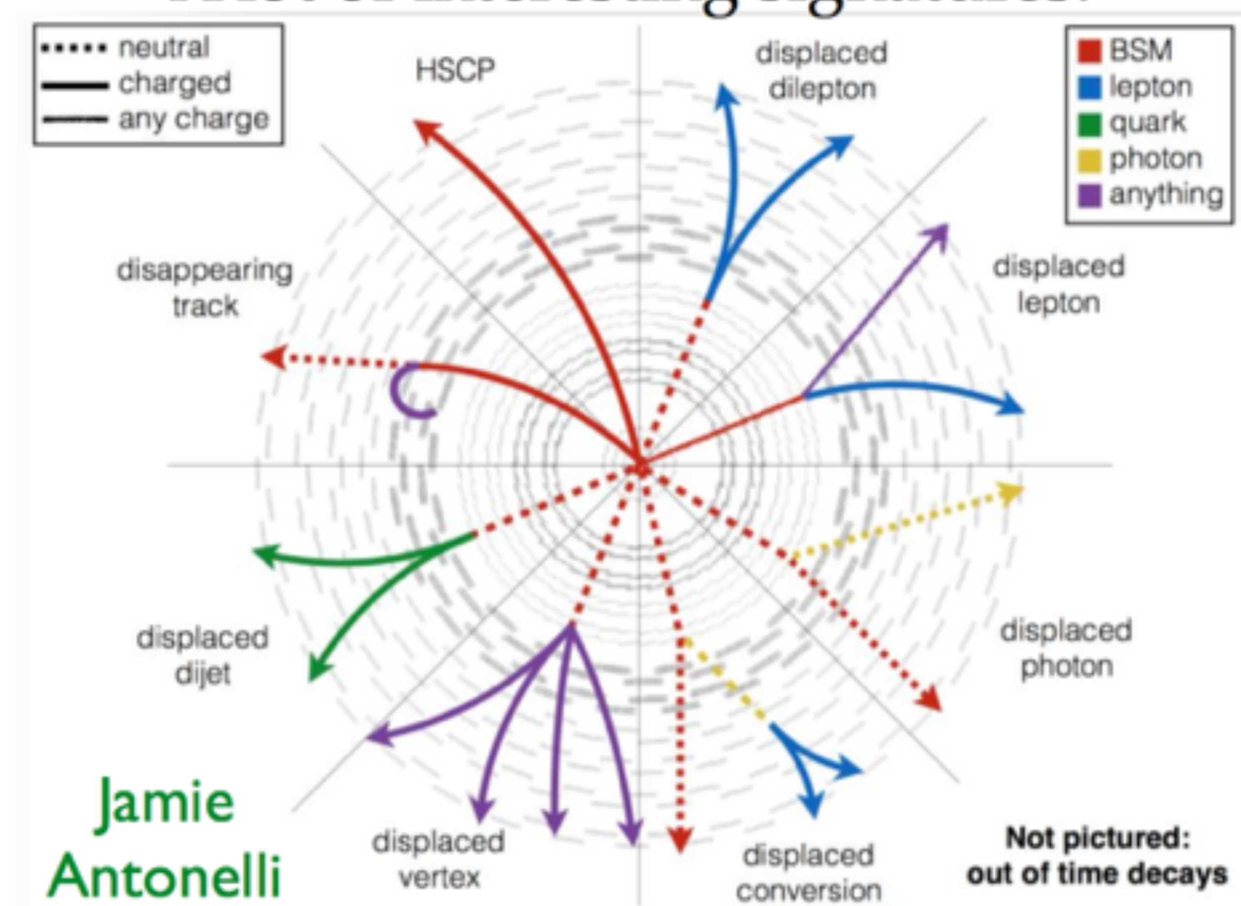

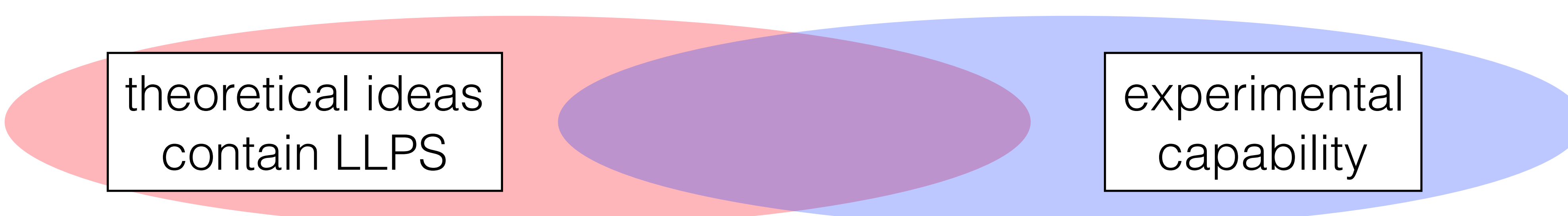

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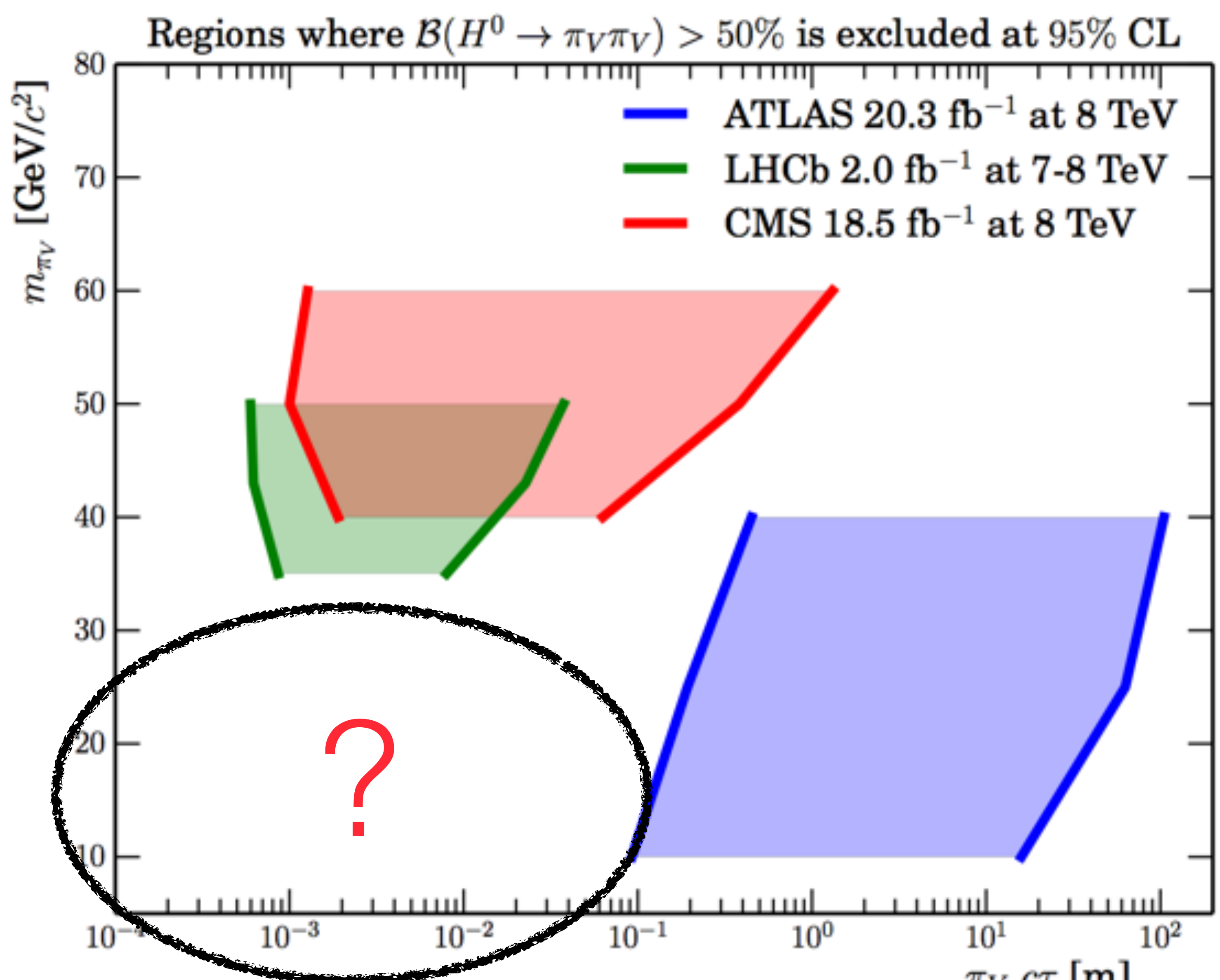
Long-Lived Particles

what LHCb's territory in LLP searches?

e.g., dark pion search



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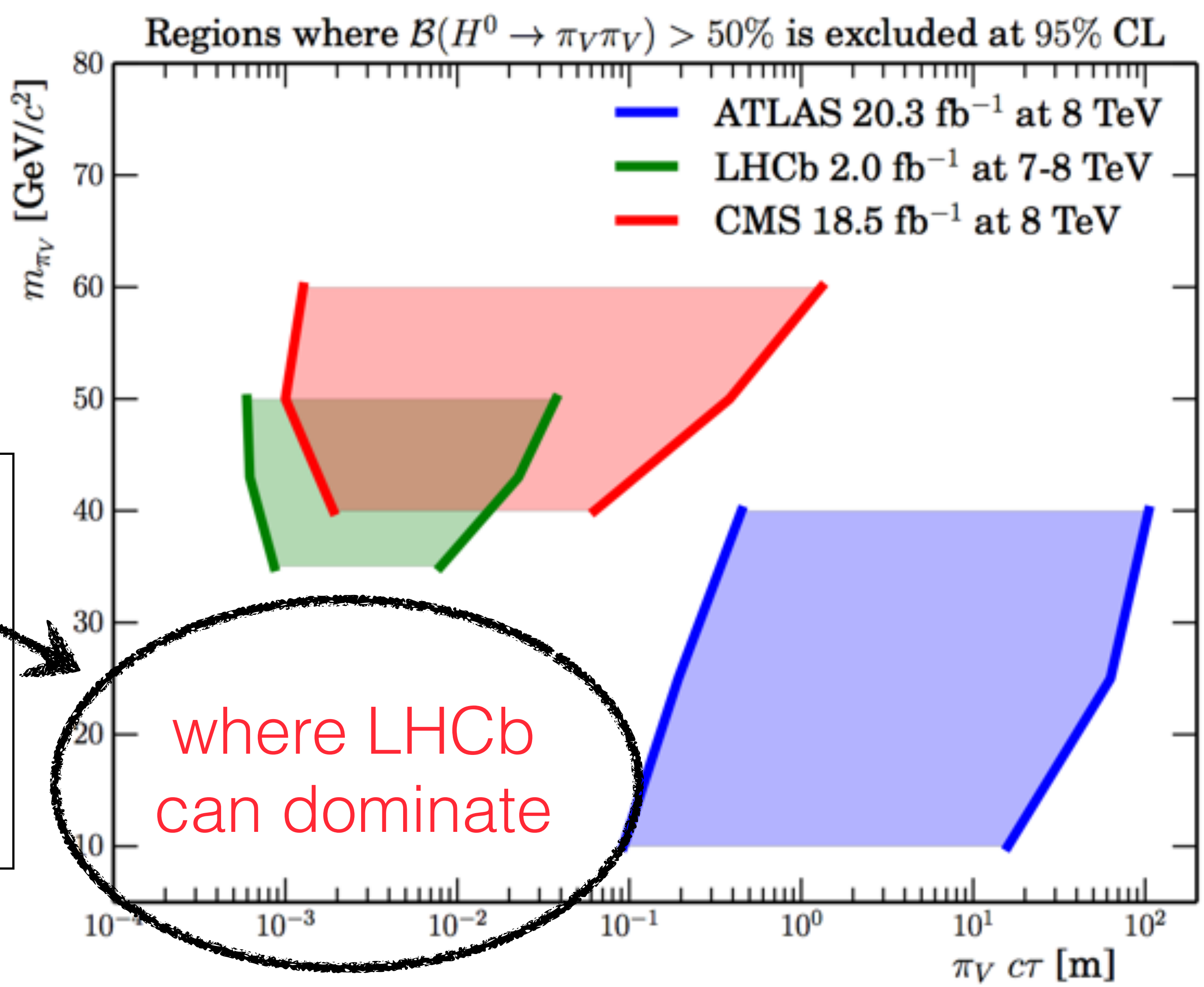

- vertex reconstruction
- mass reconstruction
- particle id (combinatorial bg)
- low pT threshold (soft signal)

LHCb = Particle spectrometer + High energy collision

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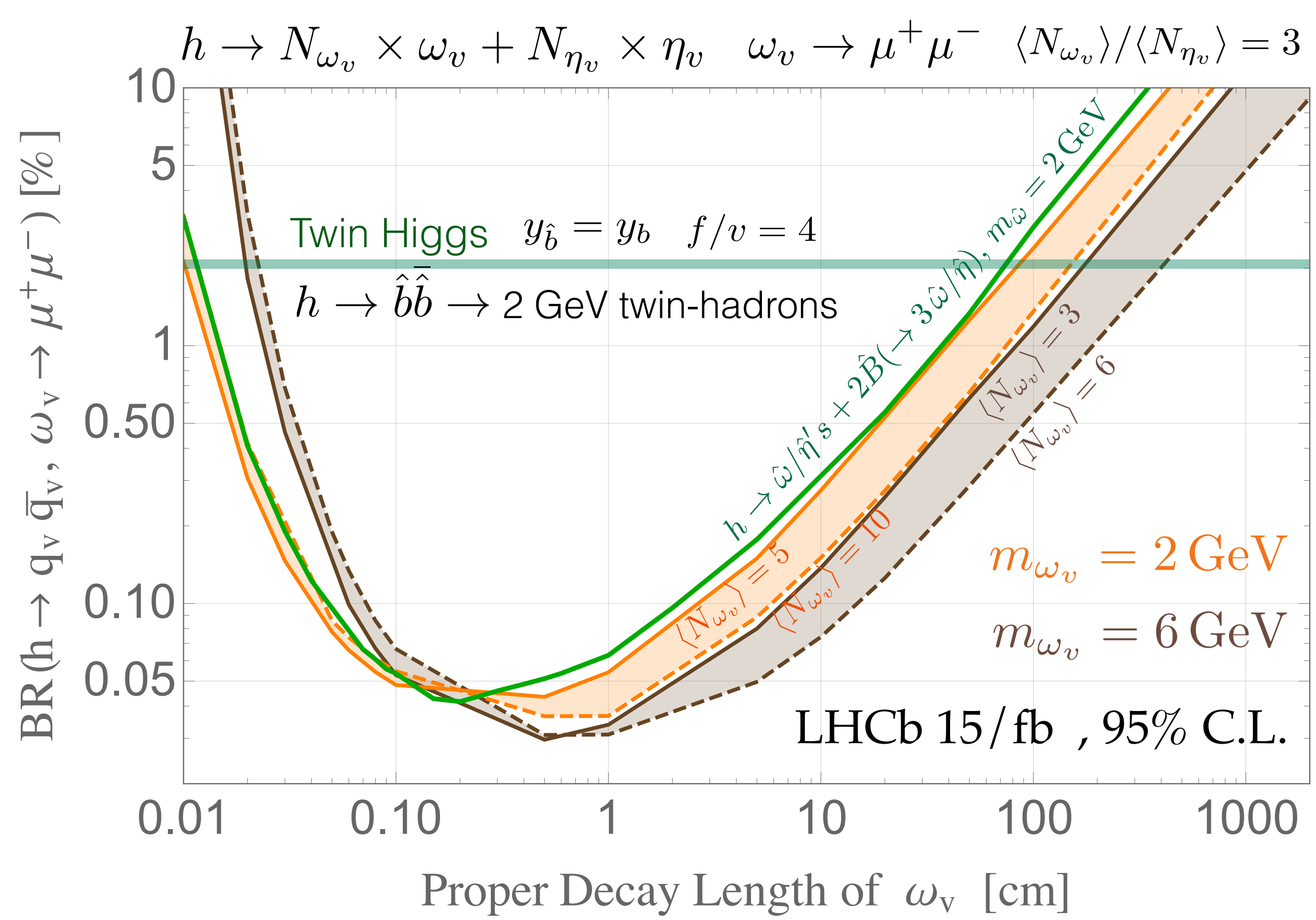
Example: dark shower signature from Hidden Valley models

Pierce, Shakya, YT, Zhao (2018)

Target on **SOFT** LLPs decays(pT cut > ~0.5 GeV only)

$$pp \to \text{mediator}^{(*)} \to q_v\,\bar{q}_v + X\,, \quad q_v\,\bar{q}_v \to N_{\pi_v} \times \pi_v + N_{\eta_v} \times \eta_v + N_{\omega_v} \times \omega_v \ldots$$

e.g., higgs decay into O(1-10) hidden hadrons, **average pT ~ few GeV**, some of them later decay into muons (hard to trigger at ATLAS/CMS, usually required pT >> 10 GeV in the search)



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Example: dark shower signature from Hidden Valley models

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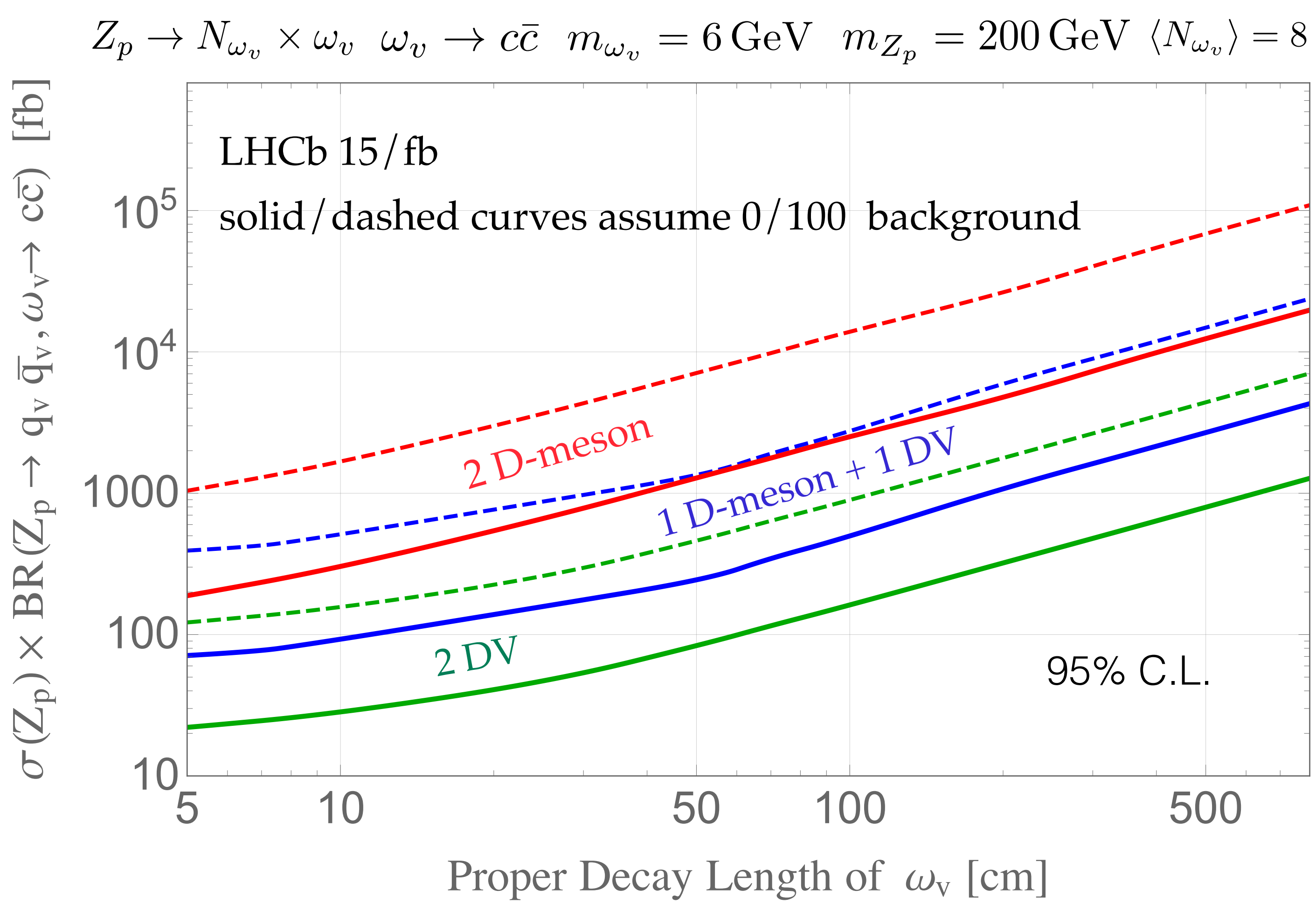
chance of having the search on hadronic final states?

usually suffer from **large hadronic background & mis-id of the final particles** => but LHCb is good at identifying hadrons!

detailed track reconstruction of hadrons from LLP decays is possible



e.g., 6 GeV LLPs have <pT>~ 10 GeV decay into D-mesons

This is why we want to study

GeV scale LLPs decay into SM hadrons

using exclusive searches at the LHCb
(instead of treating final states as jets)

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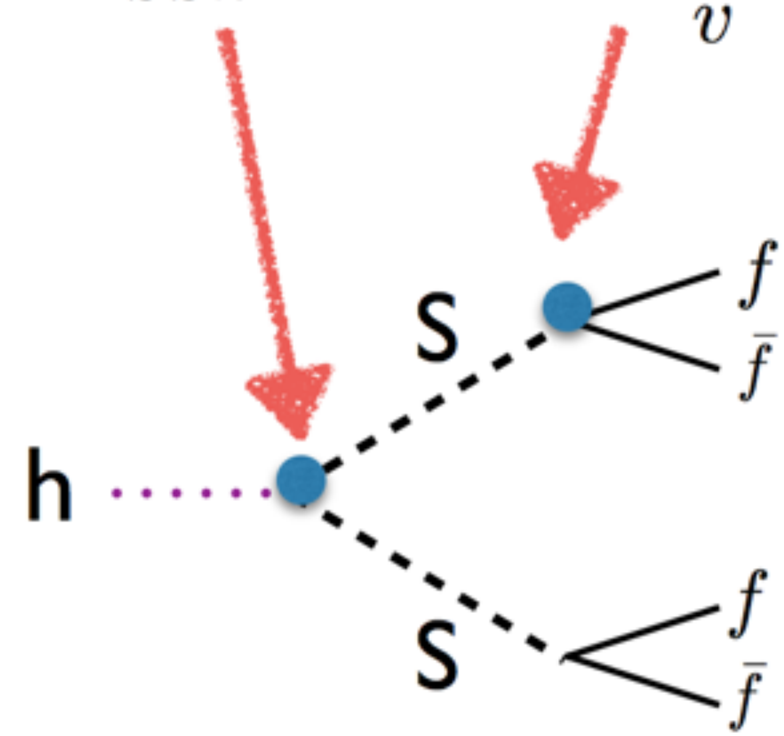
Scalar portal & exotic Higgs decays

use this as a benchmark model

$$\mathcal{L}_S \subset \mu S H^\dagger H + \lambda S^2 H^\dagger H$$

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



- BR($h \to SS$) driven by λ_{SSh} : can be sizable!
- $c\tau$ 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($h \to SS$), currently19% from CMS (1809.05937) and 26% from ATLAS (1904.05105). Proyected 2.5 % at the HL-LHC (1902.00134).
- $c\tau \gtrsim 1$ m: MATHUSLA, FASER, CODEX-b, …

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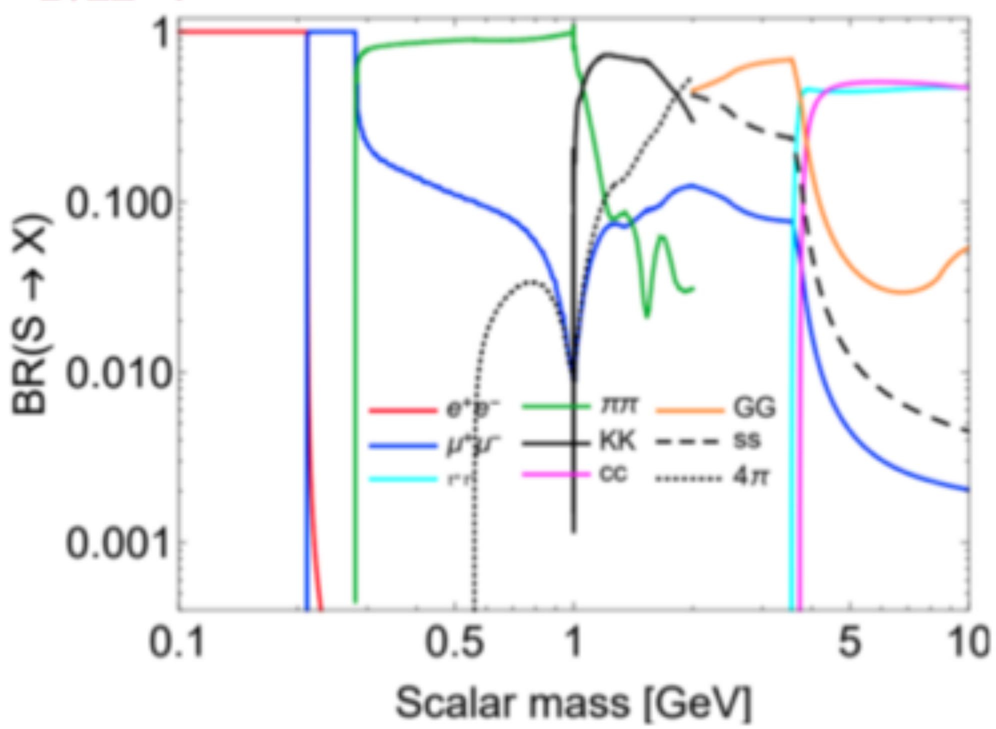
S -> Hadron Decays

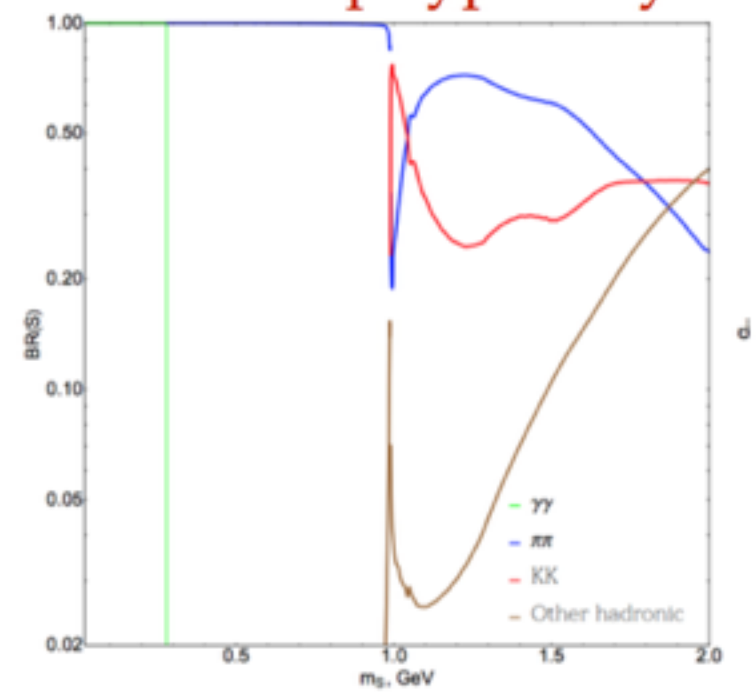
scalar decay is model dependent
need theory input in calculating the decay BR

MFV



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

up-type only



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

$B \to K^+ S$, $S \to \mu\mu$ strongly constrained by LHCb.

we don't know which model that Nature chooses
should design searches for every final states

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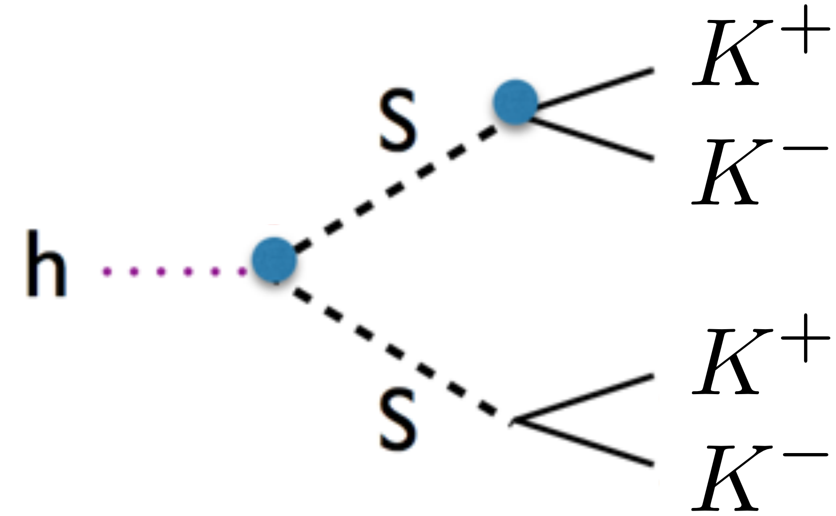
e.g., S > K+K- : Search Strategy



- 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.

slide from J. Zurita

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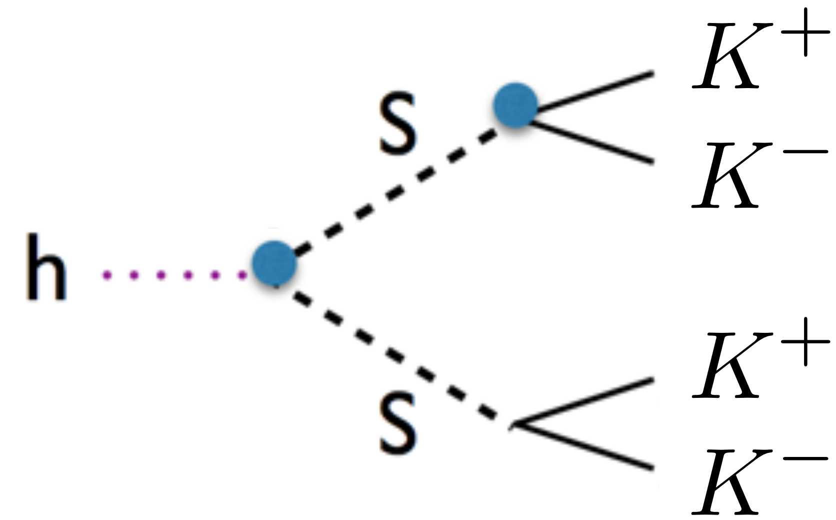

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  - $m_{\pi\pi} \in [0.48-0.52]$ GeV ($K_S^0 \to \pi\pi$), $m_{KK} \in [1.11-1.12]$ GeV ($\Lambda^0 \to p\pi$).
- Classify in signal regions according to #S, iso=yes/no, $\varrho \in [6-10]$ mm or $\in [14-25]$ mm.
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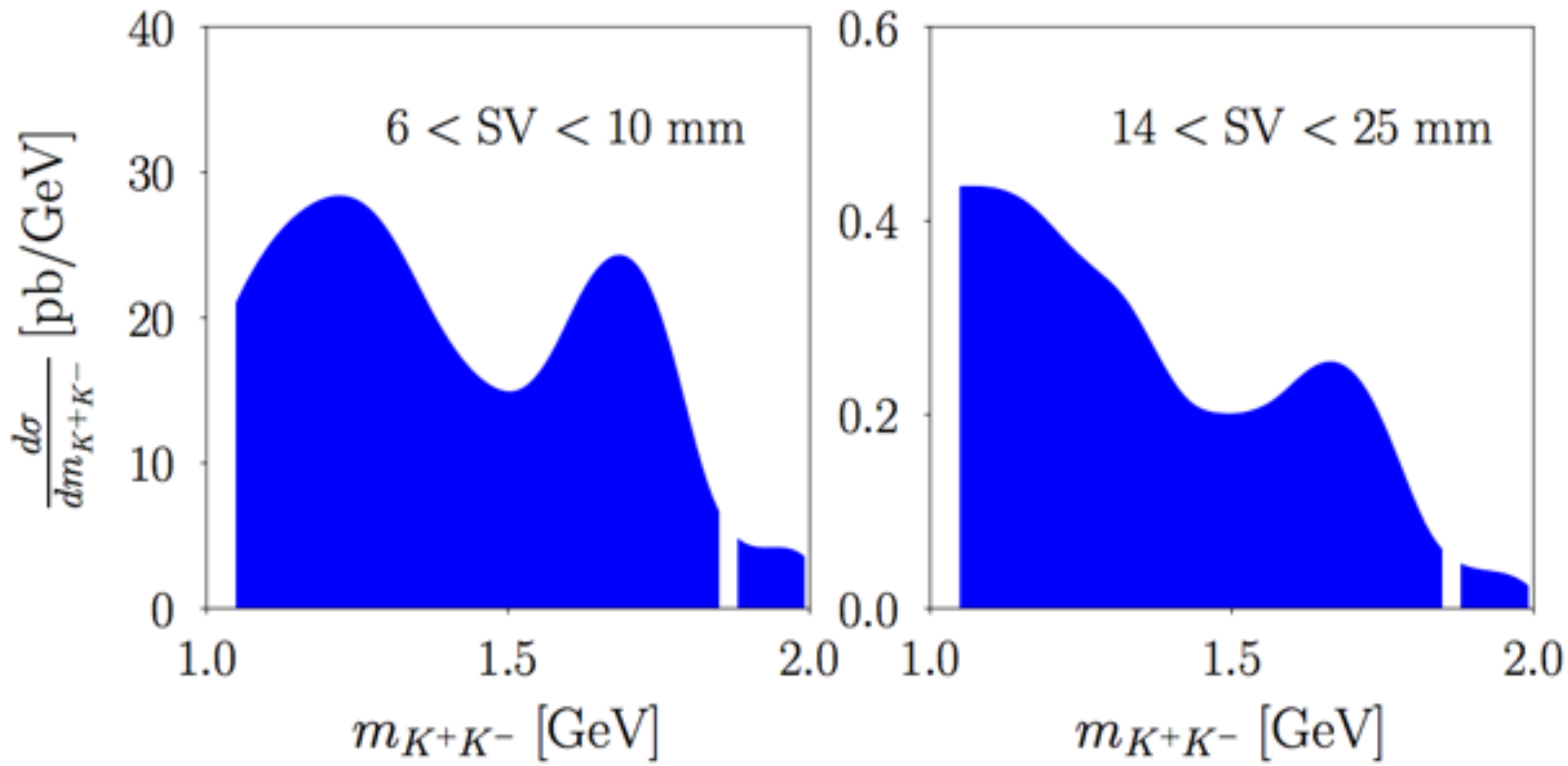
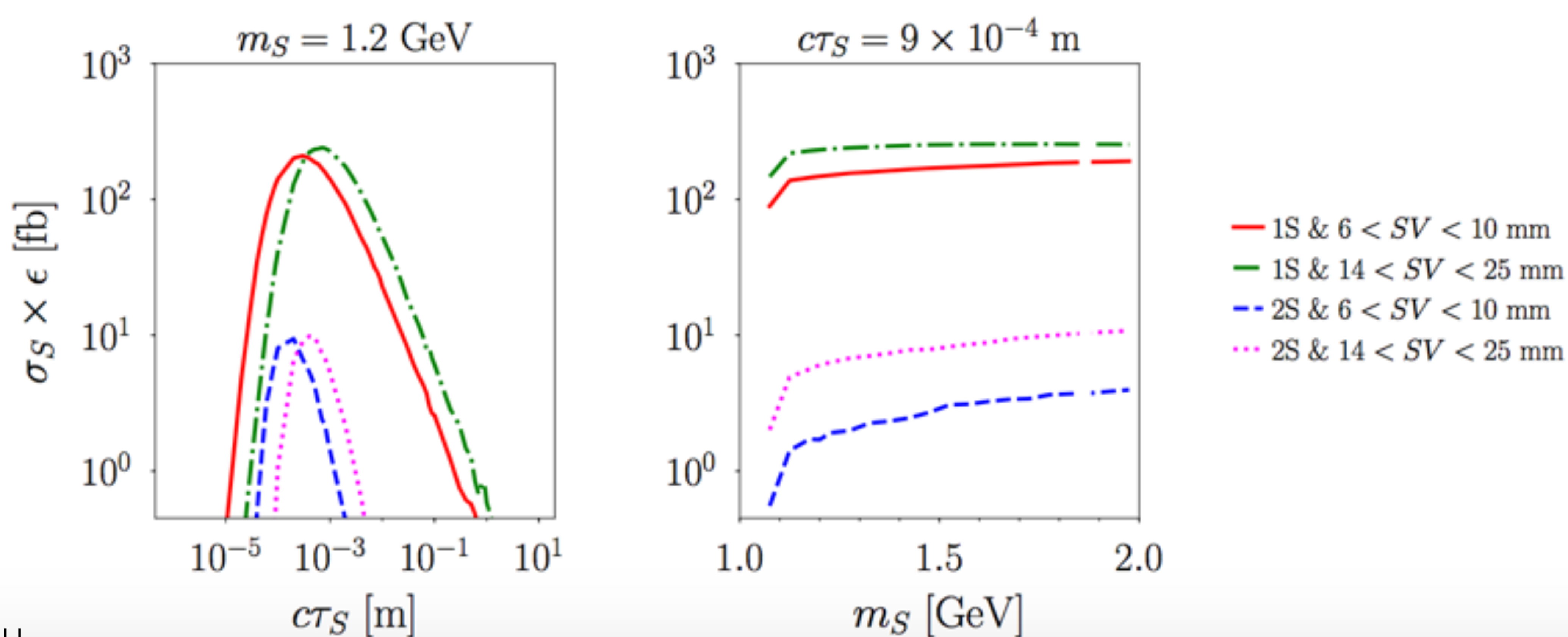
Results: Signal efficiency & background

Background



Signal

assume BR(h>ss)=19%
BR(s>K+K-)=100%



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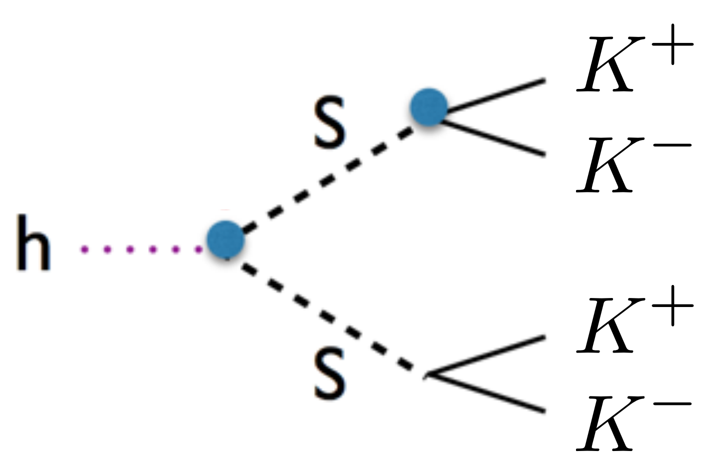
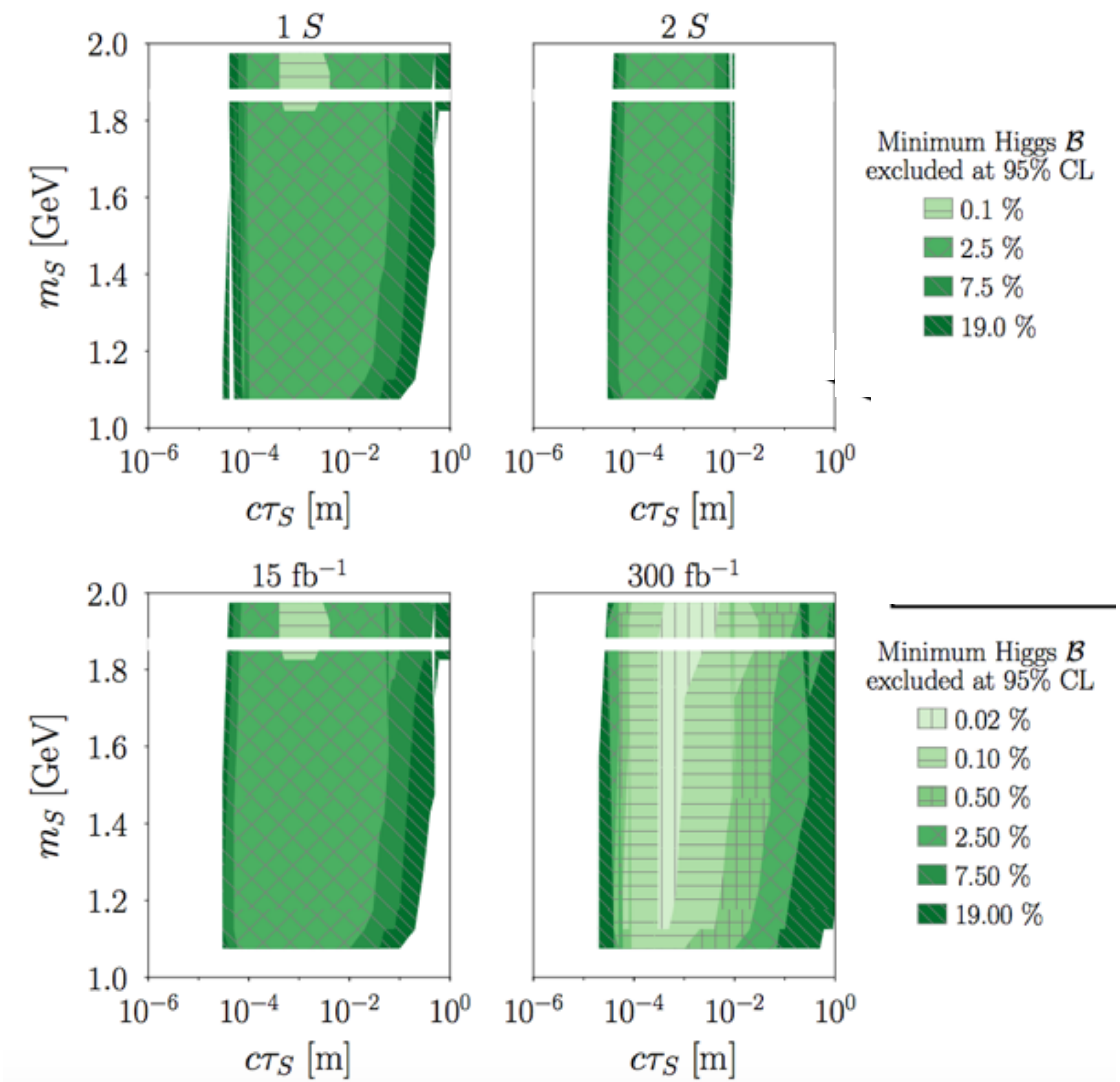
Higgs BR limits, BR(h > SS)

assume BR(s>K+K-)=100%





LHCb can be the "discovery machine" if BR(h>SS)~10% BR(S>KK)~20% lifetime ~ 0.1-1 mm

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Apply the result to ``hadrophilic” Higgs portal

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

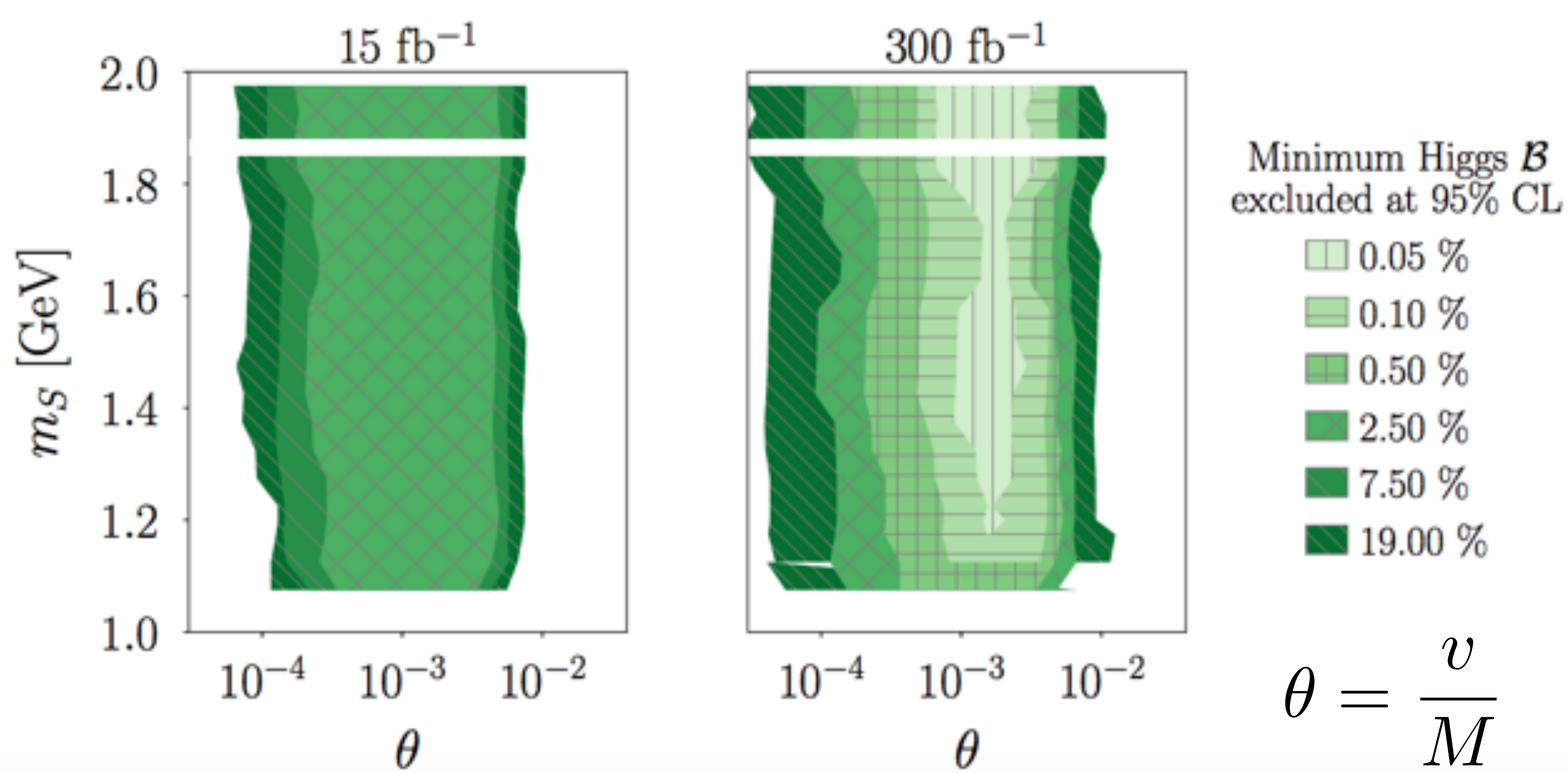
1S: σ(H) * BR(H→SS) * 2 BR(S→KK)

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



$$\theta = \frac{v}{M}$$

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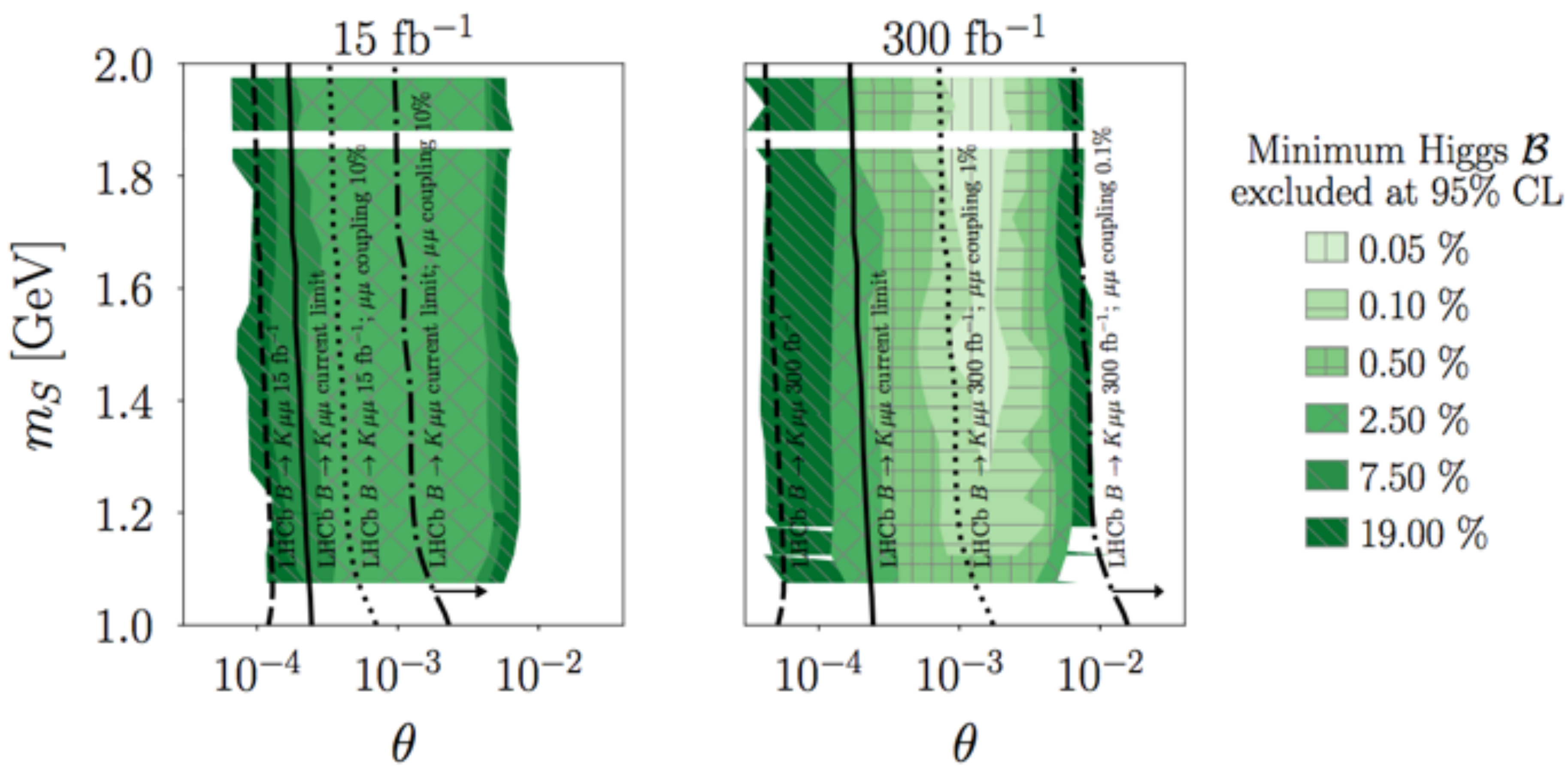
Apply the result to MFV Higgs portal

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

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!

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Conclusions

LHCb can probe new physics that is “stealth” to ATLAS/CMS

(light mass resonance, hadronic final states, displaced decays)

We examined the LHCb prospects to test light LLP decay into hadrons, which complement the existing efforts of ATLAS/CMS via displaced jets, as well as those of dedicated detectors (FASER, MATHUSLA, CODEX-b,…)

Even if an excess in displaced jets/inv Higgs is found, LHCb would still be necessary to characterize the New Physics signal

A similar strategy can be applied to other decays:

other hadronic final states (DD,pipi, …), rare B-decays into LLPs, dark showers, …

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