EXOTIC HIGGS DECAYS

6TH REDLHC MEETING, MADRID 9-11 MAY 2022

INTRODUCTION

- Searching for decays of the Higgs boson to light new particles is a key branch of the ongoing, extensive LHC Higgs characterisation program
- In many models, the Higgs mediates the leading interaction between the SM and BSM at the energy scale probed by LHC experiments ➔ Higgs Exo Decays can be the leading signal to new physics
- The current SM Higgs measurements still leave Br(H ➔ untagged)<16% at 95% CL, ATLAS-CONF-2021-053 , assuming $|\kappa_V|$<=1

  ➔ There is ample room for interestingly large exotic BRs and a strong motivation for direct searches for h➔BSM decays

  ➔ *Many* recent experimental results and theory developments: the panorama for h ➔ aa/ss, h ➔ LLP is already wide, but should be expanded!

- **This talk is based on "Exotic Higgs Decays", M.C, S. Gori, V. Martinez Outschoorn, J. Shelton, arXiv:2111.12751 (Submitted to Annual Reviews in Nuclear and Particle Physics)**
  - Here I will focus on the current experimental overview (and be necessarily very short on analysis details)

BENCHMARK SCENARIOS

SM+s

- Higgs-mixed scalar boson, s, with renormalizable couplings to the SM Higgs
  - **h→ss**
- Scalar and PseudoScalar typically have similar sensitivity (experimental strategies insensitive to CP properties of s)
  - If a mixes with 2HDM, **h→Za**
- Preferential decay to heaviest SM particle accessible: rich phenomenology, many final states
  - BR(s→SM)? PLB 823:136758 (2021) for m_s<20 GeV, and LHC Higgs WG above

SM+ALP

- New axion particle, a, with derivative couplings to the Higgs
  - **h→aa , h→Za**
- Large set of final states: **a→ff, a→gg, a→γγ** (photons and gluons particularly interesting)
- m_a<10 GeV —> collimated products (photon-jet-like signatures)

SM+v

- Z_D: new vector boson, a kinetically mixed dark photon
  - Introduce two parameters: ε (kinetic mixing between dark gauge boson and the SM hyper charge gauge boson B), κ (quartic interaction between dark scalar s and Higgs)
- **h→$Z_D Z_D$, h→ZZ_D**
- Also Non-Minimal models (eg: dark SUSY)

PROMPT AND DISPLACED SIGNATURES!!

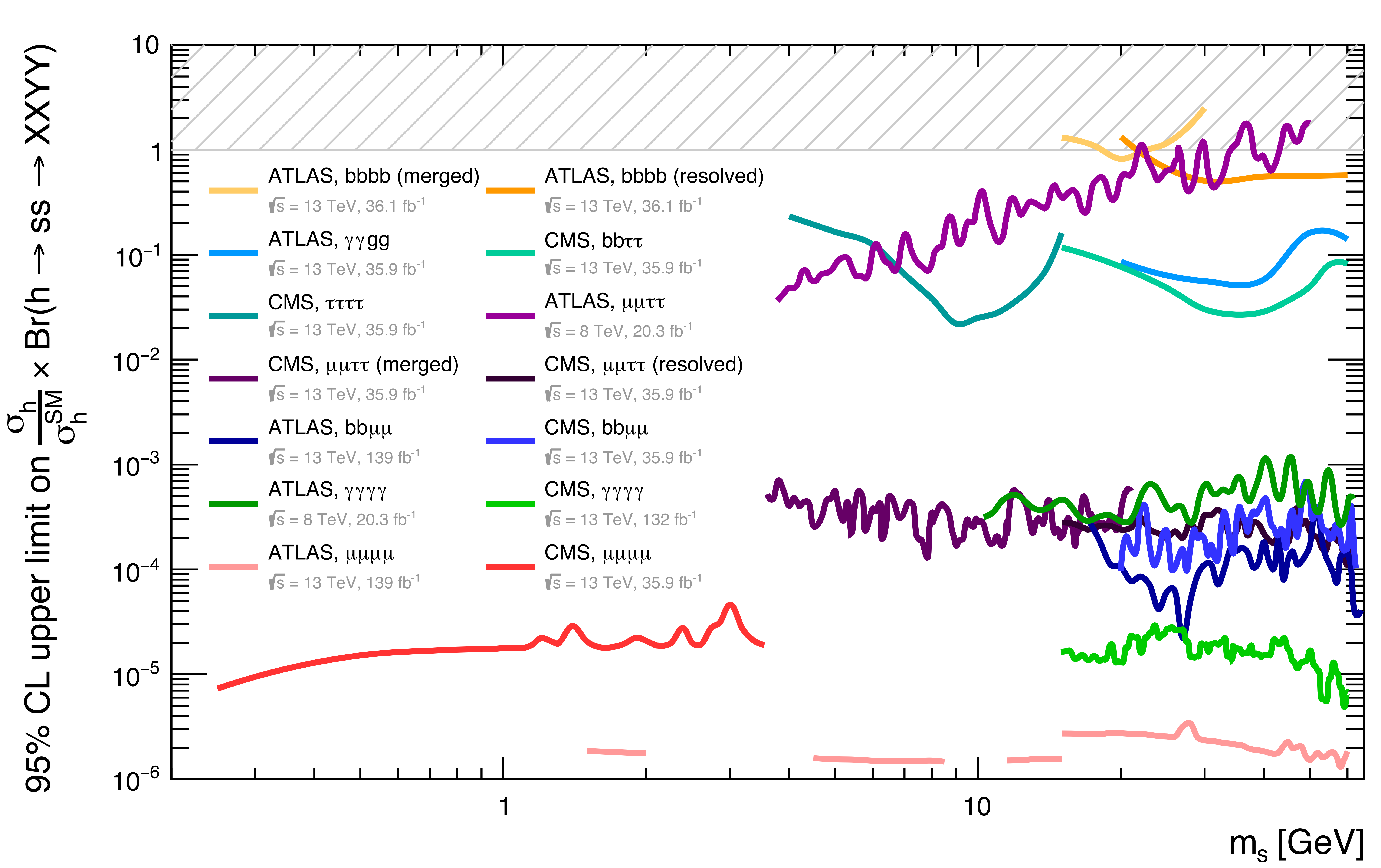
PROMPT SEARCHES

- Large phase space covered, many final states probed for h→ss/aa/vv
  - Channels with leptons or photons: easier trigger, target ggF (benefit from cross section)
  - Purely hadronic final states are difficult trigger at low mass: exploit VH
  - Ad-hoc **identification and reconstruction techniques** developed in many cases for low p_t or overlapping objects
- Results In terms of h→Za/Zv sparse still
- Few ALP interpretations!
- In general not trivial to extrapolate between models (acceptance)

Decay	Mode	Reference	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (fb^{-1})	m (GeV)	Interpretations
			$h \to ss/aa/vv$			
$eeee$ (r)	ggF	CMS (79)	13	137	4-8, 11.5-62.5	SM+v, SM+ALP
(r)	ggF	ATLAS (80)	13	139	15-60	SM+s, SM+v
$ee\mu\mu$ (r)	ggF	CMS (79)	13	137	4-8, 11.5-62.5	SM+v, SM+ALP
(r)	ggF	ATLAS (80)	13	139	15-60	SM+v
$\mu\mu\mu\mu$ (m)	ggF	D0 (81)	1.96	4.2	0.21-3	SM+s, SM+v
(r)	ggF	CMS (78)	13	35.9	0.25-8.5	SM+s, dark SUSY
(r)	ggF	CMS (79)	13	137	4-8, 11.5-60	SM+v, SM+ALP
(m/r)	ggF	ATLAS (80)	13	139	1.2-2, 4.4-8, 12-60	SM+s, SM+v
$\mu\mu\tau\tau$ (m/r)	ggF	D0 (81)	1.96	4.2	3.6-19	SM+s
(m/r)	ggF	ATLAS (82)	8	20.3	3.7-50	SM+s
(m/r)	ggF	CMS (83)	13	35.9	3.6-21	SM+s
(r)	ggF	CMS (84)	13	35.9	15-62.5	SM+s
$\tau\tau\tau\tau$ (m)	ggF	CMS (77)	13	35.9	4-15	SM+s
$bb\mu\mu$ (r)	ggF	ATLAS (85)	13	139	18-60	SM+s
(r)	ggF	CMS (86)	13	35.9	20-62.5	SM+s
$bb\tau\tau$ (r)	ggF	CMS (87)	13	35.9	15-60	SM+s
$bbbb$ (m)	Zh	ATLAS (88)	13	36.1	15-30	SM+s
(r)	Wh/Zh	ATLAS (76)	13	36.1	20-60	SM+s
$\gamma\gamma\gamma\gamma$ (r)	ggF	ATLAS (89)	8	20.3	10-62	SM+s
(r)	ggF	CMS (90)	13	132	15-60	SM+s
$\gamma\gamma gg$ (r)	VBF	ATLAS (91)	13	36.7	20-60	SM+s
			$h \to Za/Zv$			
gg (m)	ggF	ATLAS (92)	13	139	0.5-4	SM+s
ss (m)	ggF	ATLAS (92)	13	139	1.5-3	SM+s
ee (r)	ggF	CMS (79)	13	137	4-8, 11.5-35	SM+v
(r)	ggF	ATLAS (80)	13	139	15-55	SM+v
$\mu\mu$ (r)	ggF	CMS (79)	13	137	4-8, 11.5-35	SM+v
(r)	ggF	ATLAS (80)	13	139	15-30/15-55	SM+s, SM+v

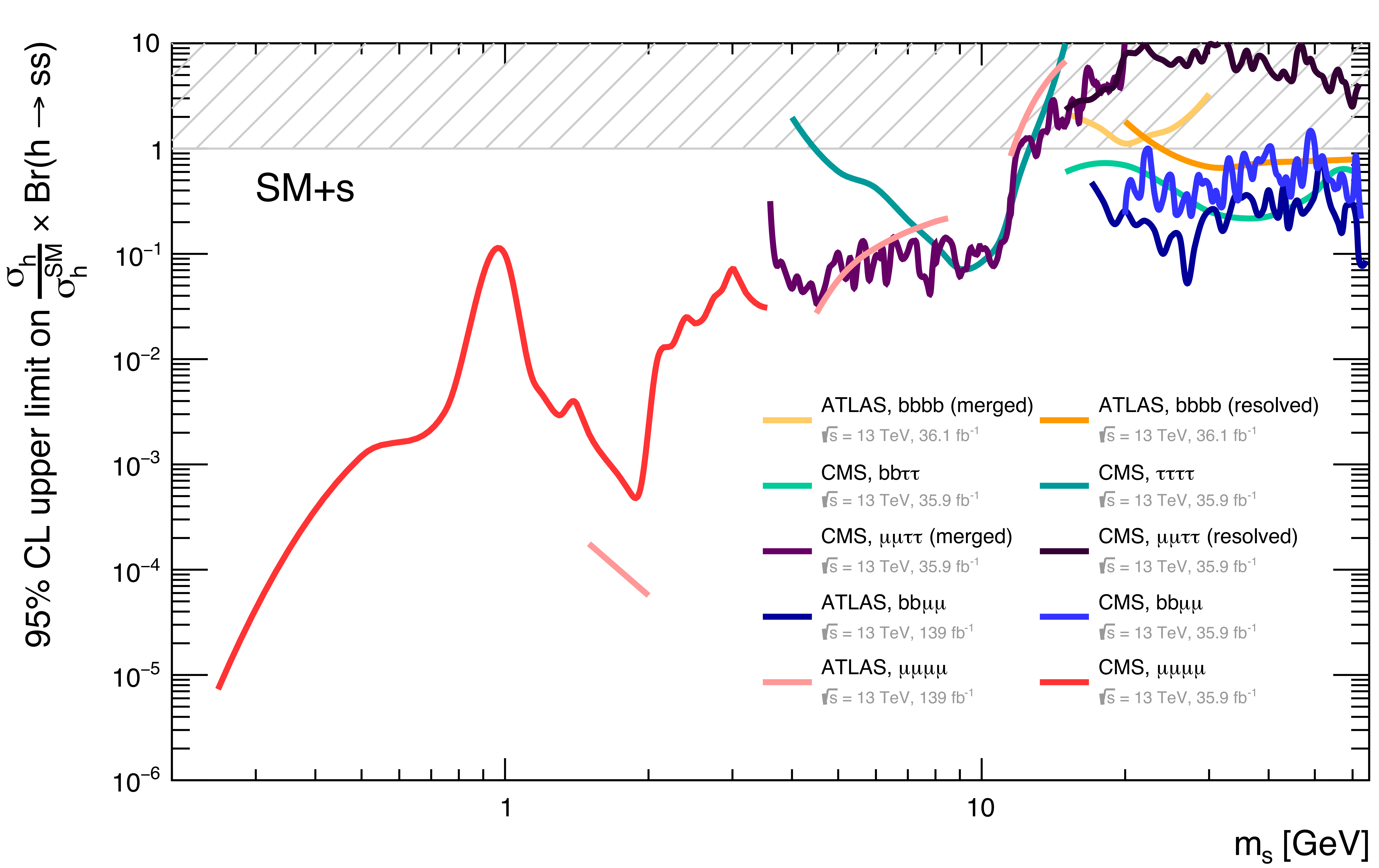
Br(h→ss→XXYYY)

- Wide mass range probed
- In terms of **Br(h→ss→XXYYY)** the reach of the all channels can be compared
- Analysis not sensitive to parity: **h→ss** and **h→aa**
- **Limited by statistics (and not all analysis already with full Run2!)**
- Additional channels, and improved reco/id techniques can also improve coverage during Run3



SM+s

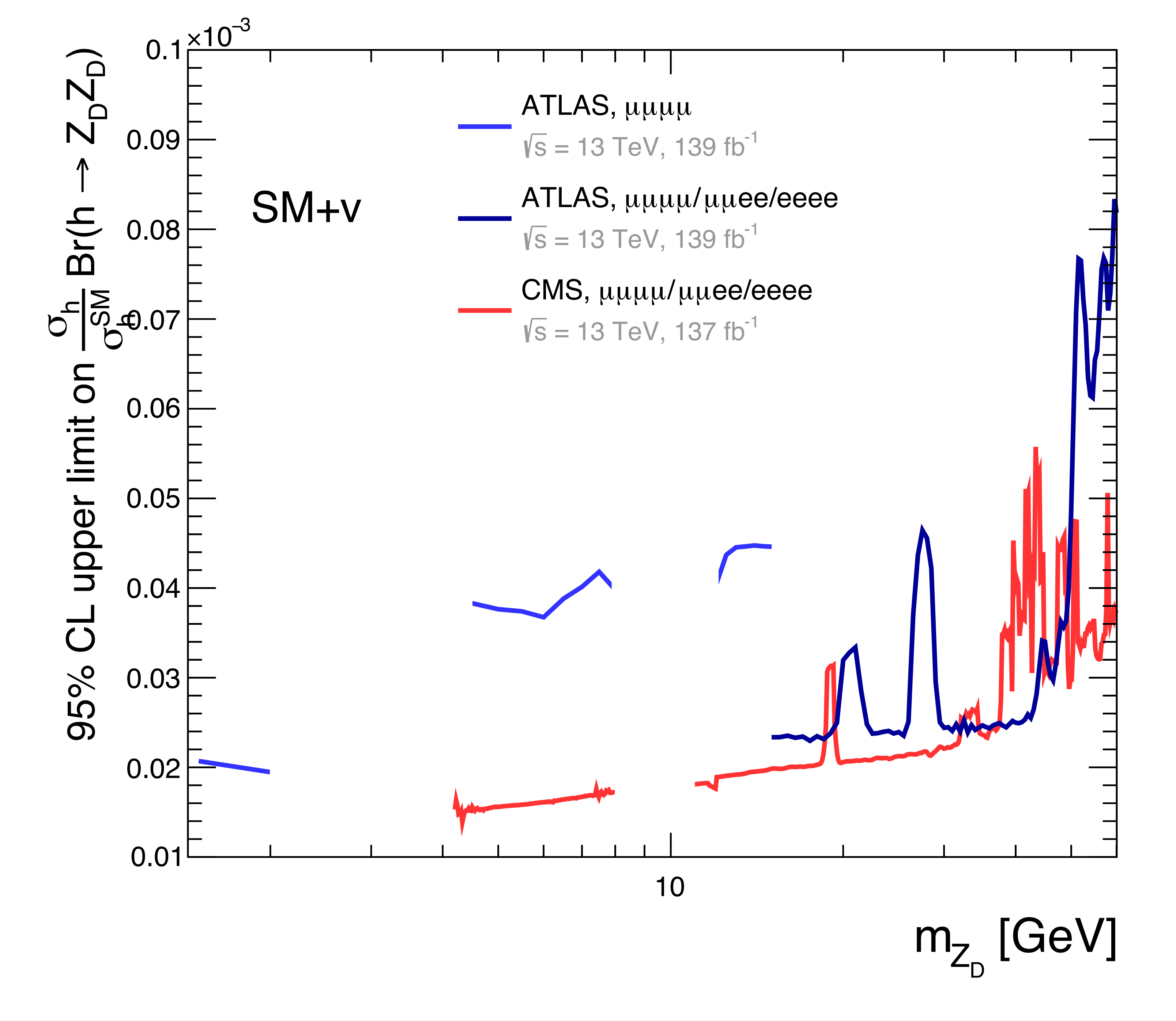
- Incorporating the model-dependent decay branching ratio BR(s→SM)
- Searches focus on the heaviest particles kinematically allowed in the decay: three distinct mass ranges: $<2m_\tau$, $2m_\tau$-$2m_b$, $>=2m_b$
- Hadronic topologies challenging experimentally at low mass (low momentum for bs and taus)
- Overall, limits are at 10% for a very large mass range
- Possible gain with combination



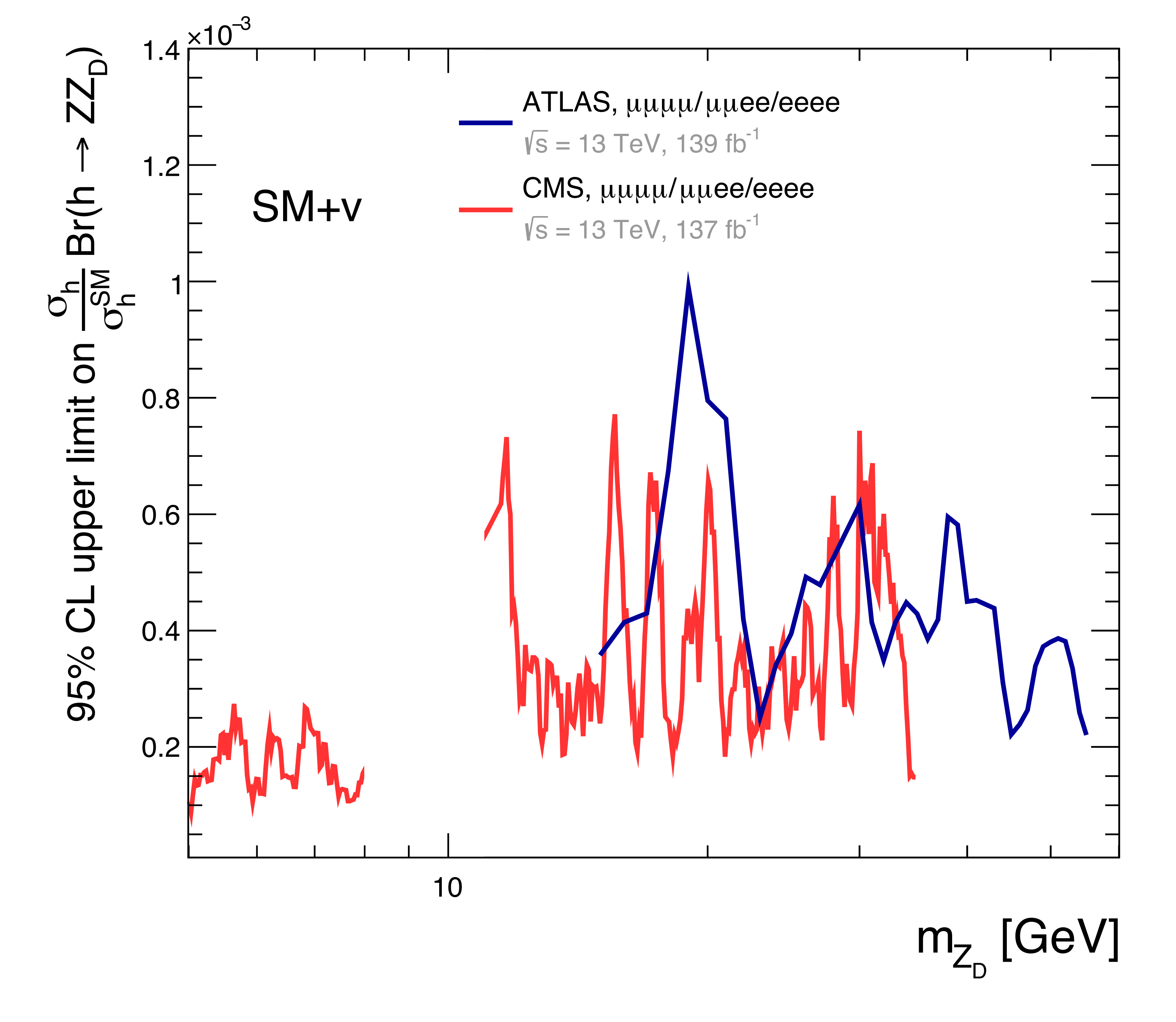
SM+v

- 4mu, 4e, 2mu2e final states . Down to 4 GeV
  - At low mass, only 4mu (down to 1.2 GeV)
- Limits also presented as a function of κ and ε
- Improving the sensitivity (beyond the statistics gain in Run3) can be done by:
  - extending the search to very low mass in the muon channels (done in CMS for Dark SUSY models, dedicated reconstruction, down to 0.25 GeV)
  - improving background modelling techniques in the J/ψ , Y region
  - incorporating more consistently electrons would improve sensitivity

$h \to Z_D Z_D$



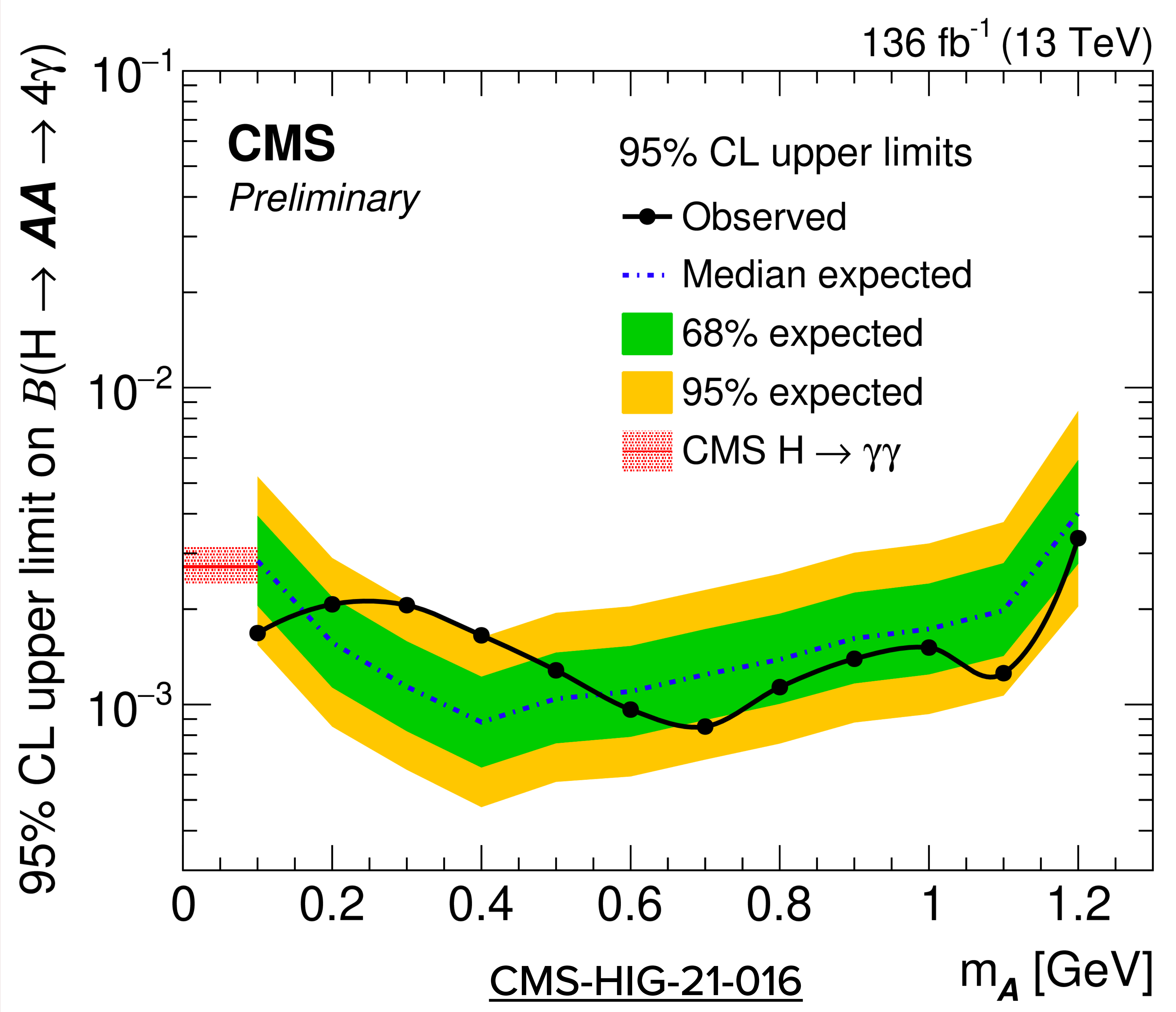
$h \to Z Z_D$



SM+ALP

- Fewer searches interpreted in SM+ALP scenarios
- In the benchmark in *Bauer M, Neubert M, Thamm A. JHEP 12:044 (2017)* (with appreciable fermionic Brs and enhanced Brs to photons and gluons when compared to SM+S), the current searches can be reinterpreted to give Br≈10%
- Strong case for more direct searches in photons and jets topologies

  ➔ A recent CMS result (public only after the review was submitted) probes h➔aa➔4γ for *very* low masses. It exploits merged diphoton, with an specific reconstruction using ML.



LONG LIVED DECAYS

- **Wide field of techniques for reconstructing displaced signatures**
  - Large impact parameter tracks and Displaced Vertices (DVs) in the Inner Detector (ID) or the Muon Spectrometer (MS)
  - Displaced hadronic jets or photons in the calorimeter
  - Displaced signals from jets or leptons in the muon system

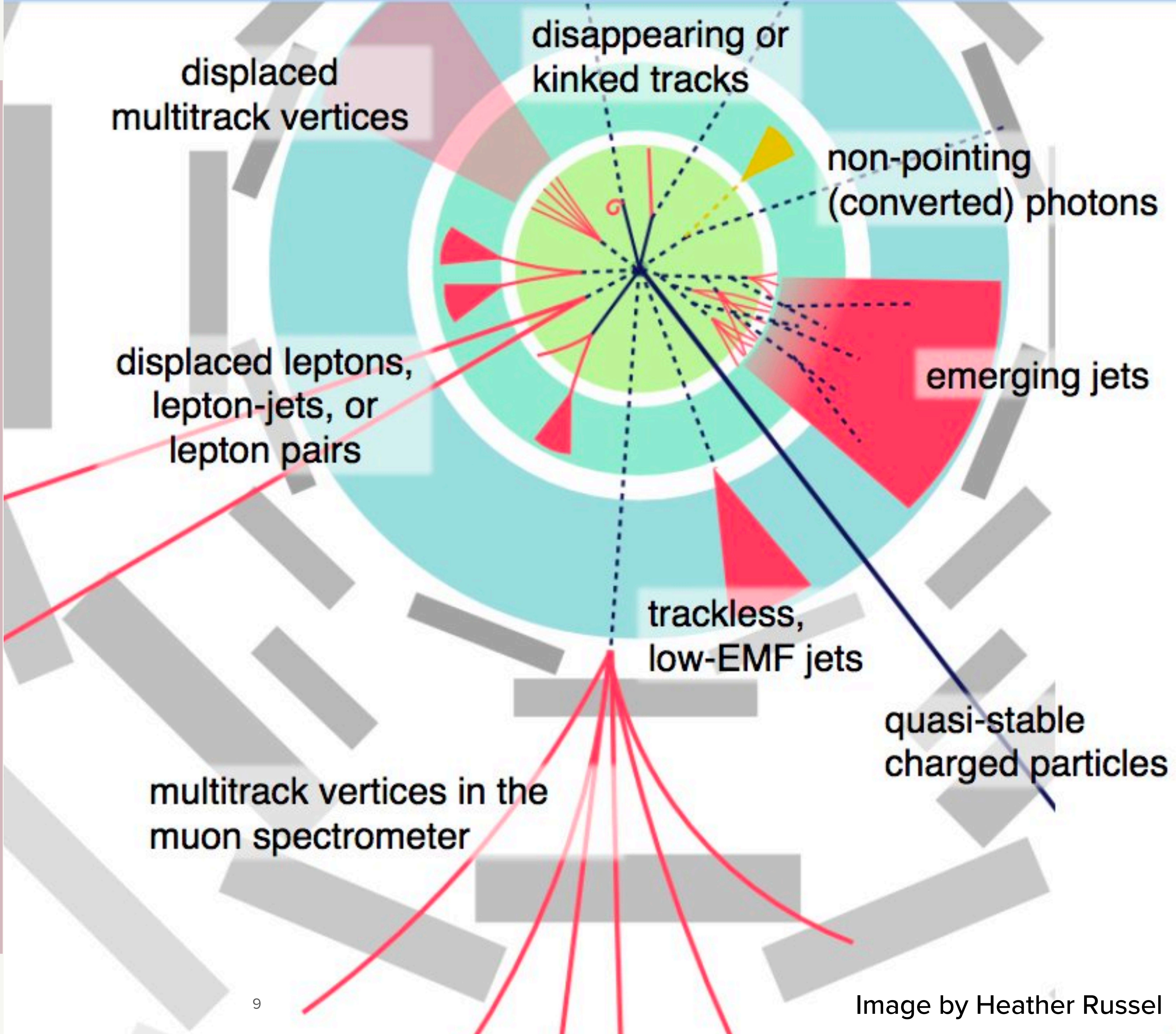


Image by Heather Russel

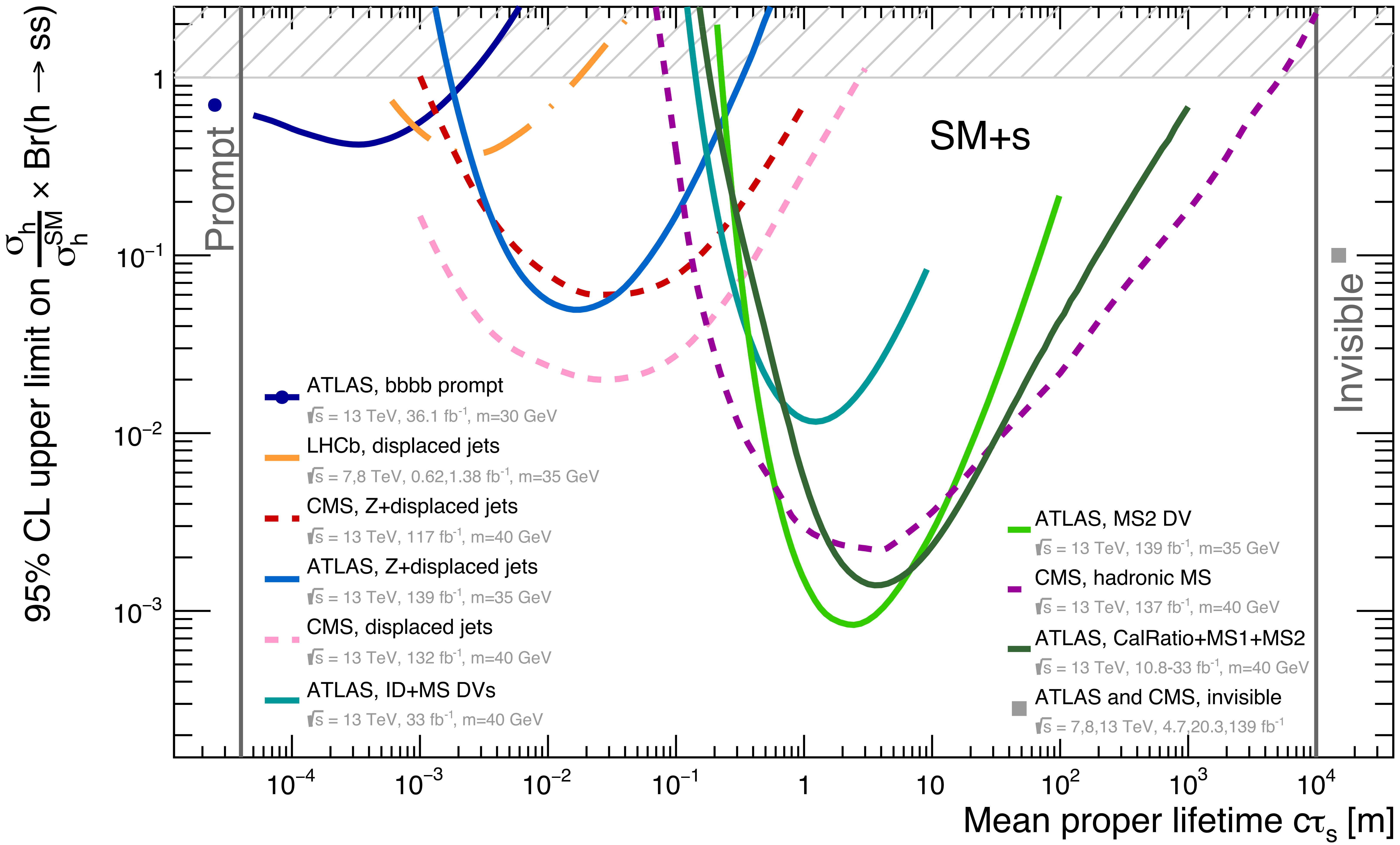
SM+s

- Leptonic or hadronic signatures:
  - h → ss → XX YY
  - h → s + X → YY + X
- Triggering strategies key
  - Scouting
  - Dedicated trigger algorithms (interesting developments in progress for the future)
- LHCb , ATLAS and CMS
- Longest lifetimes profit from distinctiveness of the signal and the few SM backgrounds: sensitivity is limited by the size of the detector
- Large range of masses and lifetimes probed already

Decay	Mode	Reference	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (fb^{-1})	m (GeV)	$c\tau$ (m)
SM+s: $h \to ss$ or $s + X$, s long-lived						
$bbbb$	Wh/Zh	ATLAS (76) prompt reinterp.	13	36.1	20-60	$10^{-4} - 10^{-2}$
$bbbb$ $cccc$ $ssss$	ggF	LHCb (94) disp. jets	7,8	2.0	25-50	$10^{-3} - 10^{-1}$
$bbbb$ $dddd$	Zh	CMS (95) Z+disp. jets	13	117	15-55	$10^{-3} - 1$
$bbbb$	Zh	ATLAS (96) Z+disp. jets	13	139	16-55	$10^{-3} - 1$
$bbbb$ $dddd$	ggF	CMS (97) disp. jets	13	132	15-55	$10^{-3} - 10$
$bbbb$ $cccc$ $\tau\tau\tau\tau$	ggF	ATLAS (98) CalRatio	13	10.8, 33.0	5-55	$10^{-1} - 10^{3}$
$bbbb$ $cccc$ $\tau\tau\tau\tau$	ggF	ATLAS (99) ID+MS DVs	13	33.0	8-55	$10^{-1} - 10$
$bbbb$ $dddd$ $\tau\tau\tau\tau$	ggF	CMS (100) hadronic MS	13	137	14-55 7-55 7-55	$10^{-1} - 10^{4}$
$bbbb$ $cccc$ $\tau\tau\tau\tau$	ggF	ATLAS (101) MS1+MS2 DV	13	36.1	5-40	$10^{-1} - 10^{3}$
$bbbb$ $cccc$ $\tau\tau\tau\tau$	ggF	ATLAS (102) MS2 DV	13	139	5-55	$10^{-1} - 10^{2}$
$e\mu$+X $\mu\mu$+X ee+X	ggF	CMS (103) disp. leptons	13	113-118	30-50	$10^{-3} - 10^{1}$

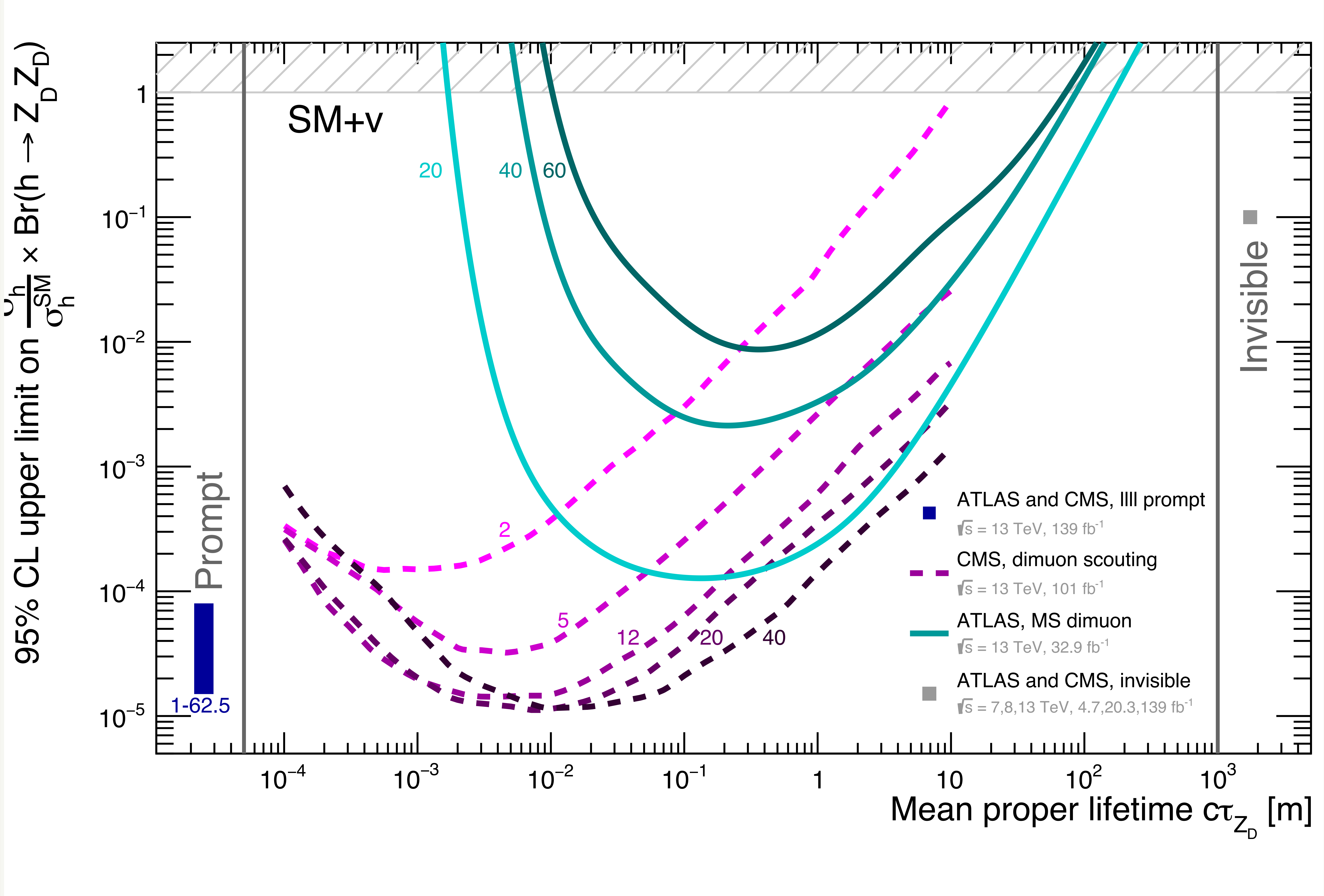
SM+s

- Summary of h→ss LLP searches with different techniques with m_s =30-40 GeV
  - Wide range of cτ
- s decay dominated by Br(s→bb)≈85% , Br(s→cc)≈5%, Br(s→ττ)≈8%
- The original experimental results include either directly the combination of final states or individual results in b,c,τ decays: results converted to $\sigma/\sigma_h\times$ Br(h→ss) for comparison



SM+v

- $h \to Z_D Z_D$, 4Mu or 2Mu+X, using displaced muons and scouting strategies (very low mass accessible!)
- Other analysis target Dark Susy (displaced calorimeter jets, displaced lepton-jets)
- Results still coming (eg CMS-EXO-21-006, m_s muons full Run2, better sensitivity at in sensitivity at high cτ)



Conclusions

- The Higgs Boson is an excellent laboratory in which to look for new physics. Does the Higgs have new interactions? Surprises in the decay can lead us to new particles that couple only feebly to the SM.
- Many developments (theo and exp) in prompt and displaced h->ss/aa/vv in the last years
- On the experimental side: huge advances, with many recent results, and more to come. Broad range of masses, lifetimes, and final states covered. Direct searches reach typically surpass the Br(BSM) limits set by SM decays
  - Still substantial gaps in coverage: very few ALP searches; final states with photons and jets not really covered yet; the mass and lifetime coverage varies with the final state; cascade decays and decays to two different masses ($s_1 s_2$) not yet extensively explored
  - Comparing and recasting results is in general difficult
- Exciting area experimentally speaking, with opportunities to develop new triggering and reconstruction techniques at the LHC and specially with the HL-LHC upgrade, as well as future colliders and experiments
- I did not cover the theoretical and phenomenological developments in this talk. They continues to be crucial to understand the implications of these analyses for physics beyond the SM and to set priorities for future efforts.
  - For the details: "Exotic Higgs Decays", M.C, S. Gori, V. Martinez Outschoorn, J. Shelton, arXiv:2111.12751

BACKUP

Run3 and HL-LHC

O(10^8) Higgs bosons. Beyond the gain from the added luminosity, detector upgrades to tracker, trigger and timing and new analysis strategies promise to greatly improve the reach (eg: prompt decays to hadronic modes below the percent level, new phase spaces open for displaced decays. Note Br(BSM)<4% 95%CL, from couplings.

Dedicated LLP Experiments

Mathusla, CODEXb: far away from interaction point, shielded, no trigger limitations. Low bg, extended $c\tau$ range covered. Low angle as limitation. Especially interesting for cases with topologies with many soft LLPs (difficult to trigger at LHC)

Future e+e-

O(10^6) Higgs bosons. Exploit the clean signatures and reconstruction. B(Inv)<0.3% (JHEP 01:139 (2020)). exotic branching ratios of 10^{-4} for a number of signatures, wide mass range (Chin. Phys. C 41:063102 (2017), from ee→ZH, Z→ll)

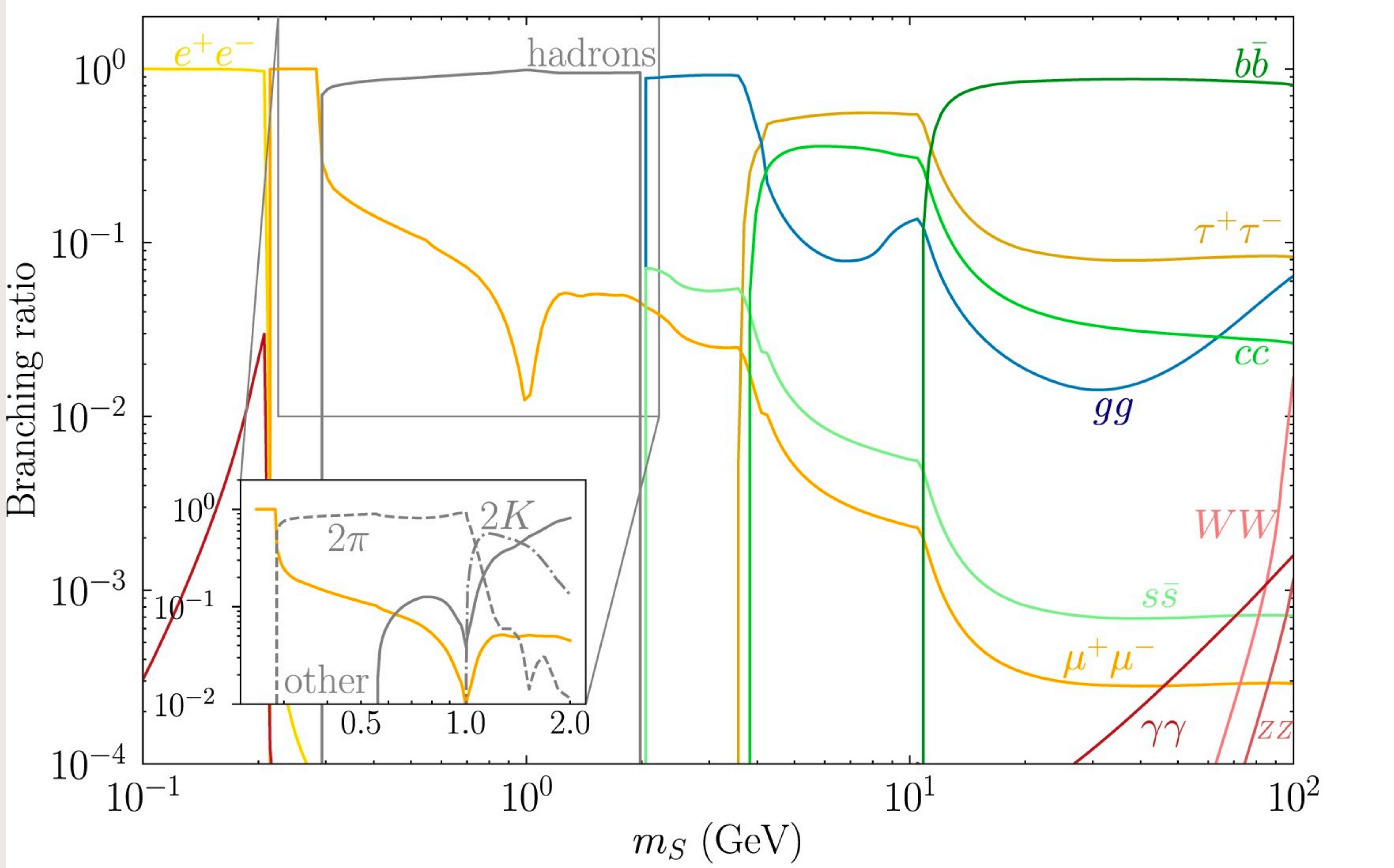
Future pp

O(10^9) Higgs bosons → very rare decays accessible. Some examples: B(BSM<1%) , B(Inv)<2.5 10^{-4} below the 4Nu threshold (JHEP 01:139 (2020)). $h \to Z_D Z_D$ down to 10^{-7} (JHEP 02:157, 2015)

Muon Colliders

O(10^8) Higgs bosons → reach down to 10^{-7} as well (arXiv:2103.14043, Symmetry 13:851 2021)

Br(s→SM)



[Gershtein Y, Knapen S, Redigolo D. Phys. Lett. B 823:136758 (2021)]

- For m_s<20 GeV we use the prediction in PLB 823:136758 (2021): includes decays to hadrons, particularly pions and kaons
- For ms>=20 GeV, we use the prediction of the [LHC Higgs WG (arXiv:1610.07922, YR4 BSM Width without NLO corrections)]
- The predictions differ at the 30% for hadronic decay modes at 20 GeV

H→Inv

Current experimental reach for Invisible Higgs decays already at 10%!

$h \to s/v + E_T^{miss}$					
Decay	Mode	Reference	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (fb^{-1})	Interpretations
$E_T^{miss} + \gamma$	VBF	CMS (114)	13	130	SM+v
	VBF	ATLAS (115)	13	139	SM+v
	Zh	CMS (110)	13	137	SM+v
	ggF, Zh	CMS (116)	8	19.4	Other
$E_T^{miss} + bb$	Zh	ATLAS (117)	13	139	NMSSM

$h \to E_T^{miss}$					
Decay	Mode	Reference	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (fb^{-1})	Br(H→Inv) UL
E_T^{miss}	VBF	ATLAS (118)	13	139	0.145 (0.103)
	VBF	CMS (119)	8, 13	19.7+140	0.18 (0.10)
	$Z(ll)h$	ATLAS (112)	13	139	0.18 (0.18)
	$Z(ll)h$	CMS (113)	13	137	0.29 (0.25)
	ggF	ATLAS (120)	13	139	0.34 (0.39)
	ggF, $V(qq)h$	CMS (121)	13	137	0.278 (0.253)
	tth	ATLAS (111)	13	139	0.40 (0.36)
	tth	CMS (122)	13	35.9	0.46 (0.48)
	Combination	ATLAS (111)	7, 8, 13	4.7+20.3+139	0.11 (0.11)
	Combination	CMS (123)	7, 8, 13	4.9+19.7+38.2	0.19 (0.15)

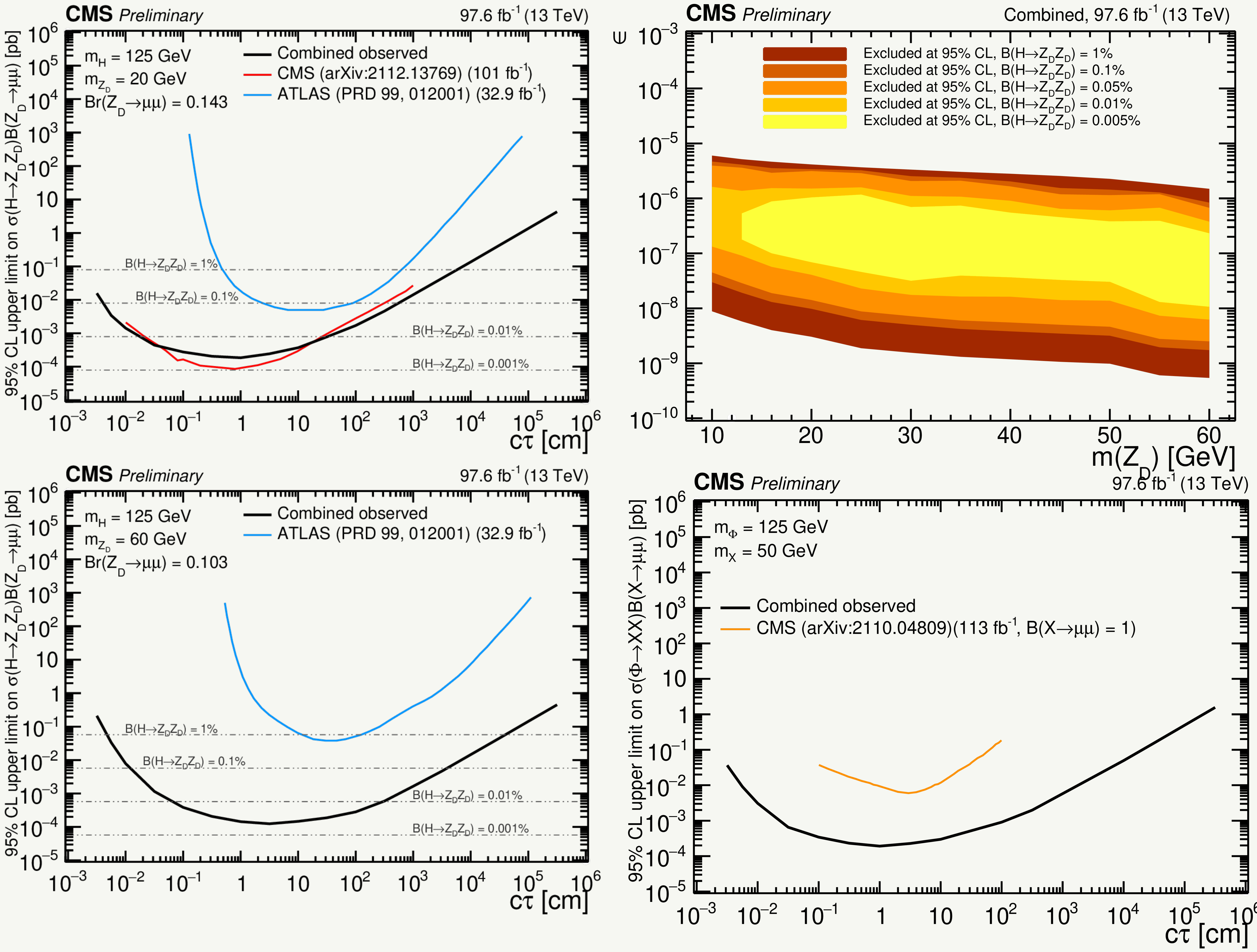
SM+v

- $h \rightarrow Z_D Z_D$, 4Mu or 2Mu+X, using displaced muons and scouting strategies (very low mass accessible!)
- Other analysis target Dark Susy (displaced calorimeter jets, displaced lepton-jets)
- Results still coming (eg CMS-EXO-21-006, Ms muons full Run2, better sensitivity at in sensitivity at high cτ)

Decay	Mode	Reference	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (fb^{-1})	m (GeV)	$c\tau$ (m)
SM+v: $h \to Z_D Z_D$ or $Z_D + X$, Z_D long-lived						
$\mu\mu\mu\mu$ $\mu\mu$+X	ggF	CMS (104) dimuon scouting	13	101	0.5-50	$10^{-4} - 10$
$\mu\mu + X$	ggF	CMS (105) disp. muons	13	97.6	10-60	$10^{-6} - 100$
$\mu\mu$+X	ggF	ATLAS (106) MS dimuon	13	32.9	20-60	$10^{-3} - 10^2$
SM+v: dark SUSY long-lived						
$\mu\mu$+X hh+X	ggF	ATLAS (107) disp. lepton-jets	13	36.1	$0.2 - 3.6$	$10^{-3} - 1$
hh+X	ggF	ATLAS (108) recast of (98)	13	10.8, 33.0	~ 0.4	$10^{-3} - 10^{-1}$
$\mu\mu\mu\mu$	ggF	CMS (78) disp. muons	13	35.9	0.25-8.5	0-1

Newer Results

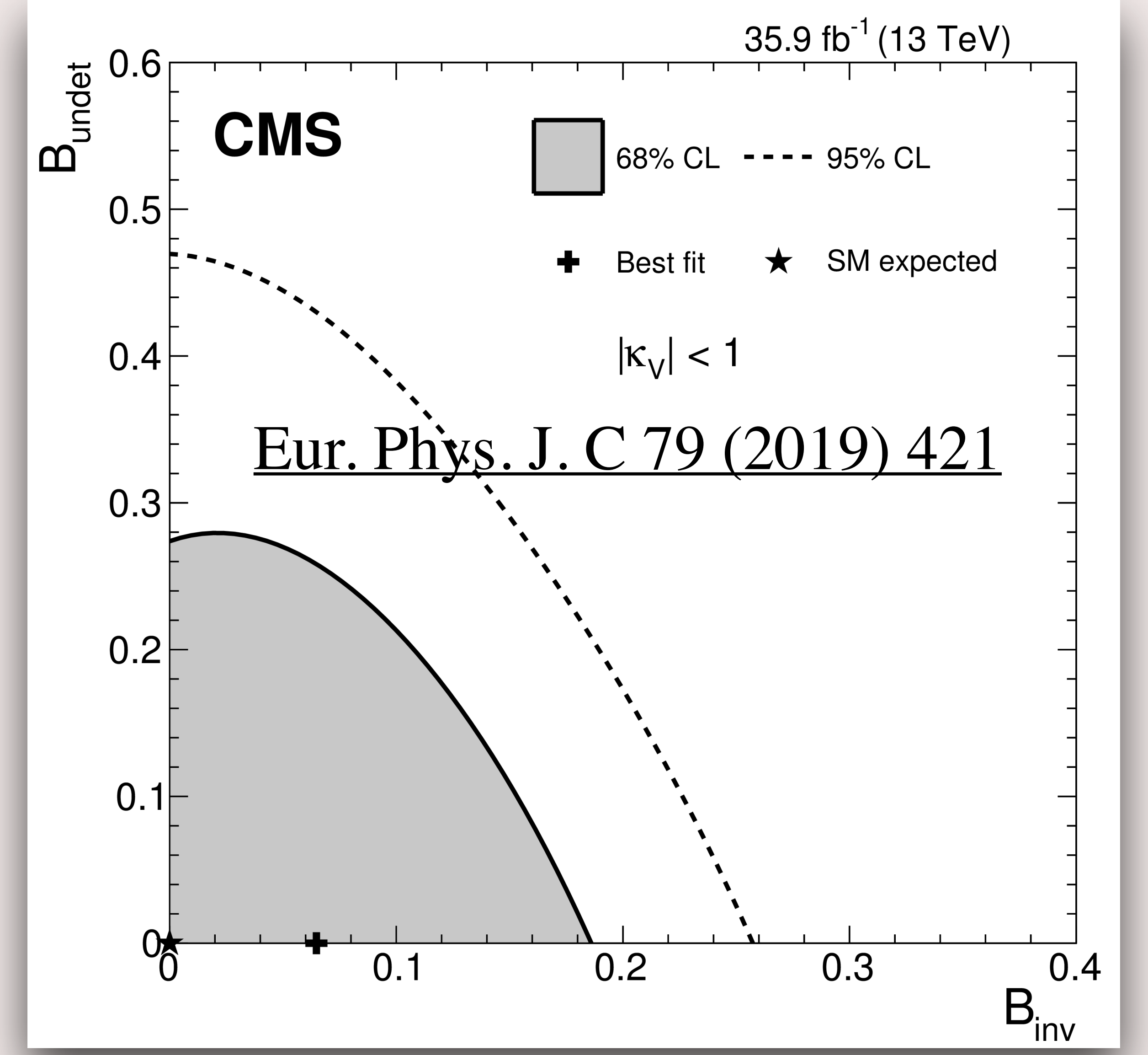
- Results up to Nov 21 included in the plots: newer searches coming
- Eg: CMS-EXO-21-006 (muon pair coming from a common Displaced Vertex, 2Mu+X topology)



How well we know BR(Higgs→BSM)?

- We derive constraints on the Exotic Higgs Branching ratio from the existing SM Higgs measurements

- Warning: since at LHC we have no direct measurement of the width, tto probe the BSM BR an additional constrain needs to be imposed. Usually, $\kappa_{W,Z} \leq 1$



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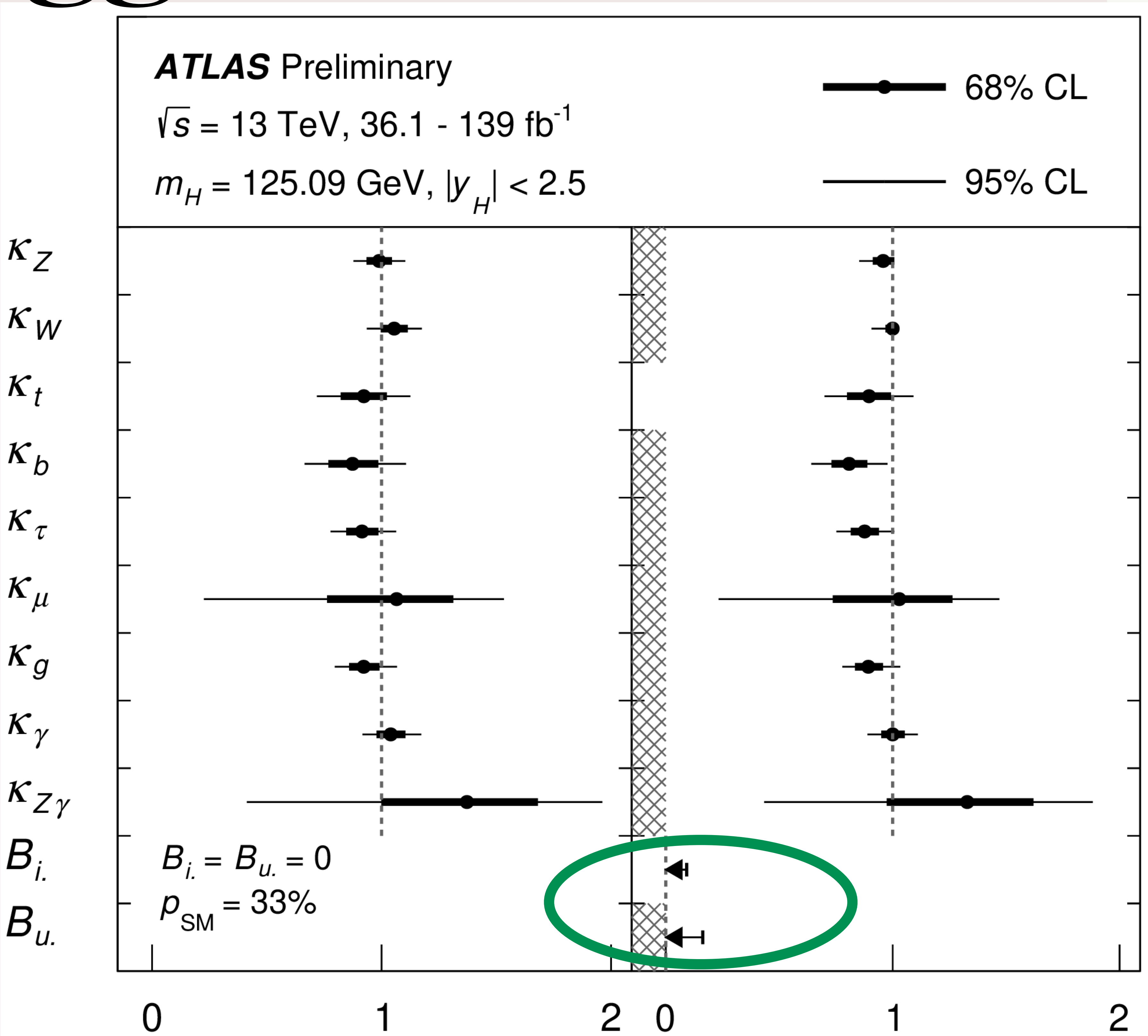

ATLAS-CONF-2021-053

$B_{inv} < 9\%$ and $B_{undet} < 16\%$ at 95% CL