Searches for rare decays of the Higgs boson into light pseudoscalars at CMS

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Why look for h → aa/ss?

- Searching for decays of the Higgs boson to light new particles is a key branch of the ongoing, extensive LHC Higgs characterization 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 a relatively large Br(H ➔ untagged)<16% at 95% CL (assuming $|k_V|<1$, Nature 607 (2022) 60-68)

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

  ➔ *Many* experimental results: the panorama for h ➔ aa/ss, h ➔ LLP is already wide, and being expanded!

  ➔ Wide range of final states to probe

  ➔ Large room for innovation: new analysis techniques, detector developments

EXTENSIVE THEORETICAL LANDSCAPE

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!!

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PROMPT SEARCHES

- Focusing on prompt searches (see the displaced talk by **Petar Maksimovic!!**)
- 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

STATUS IN 2021! What has changed since then?

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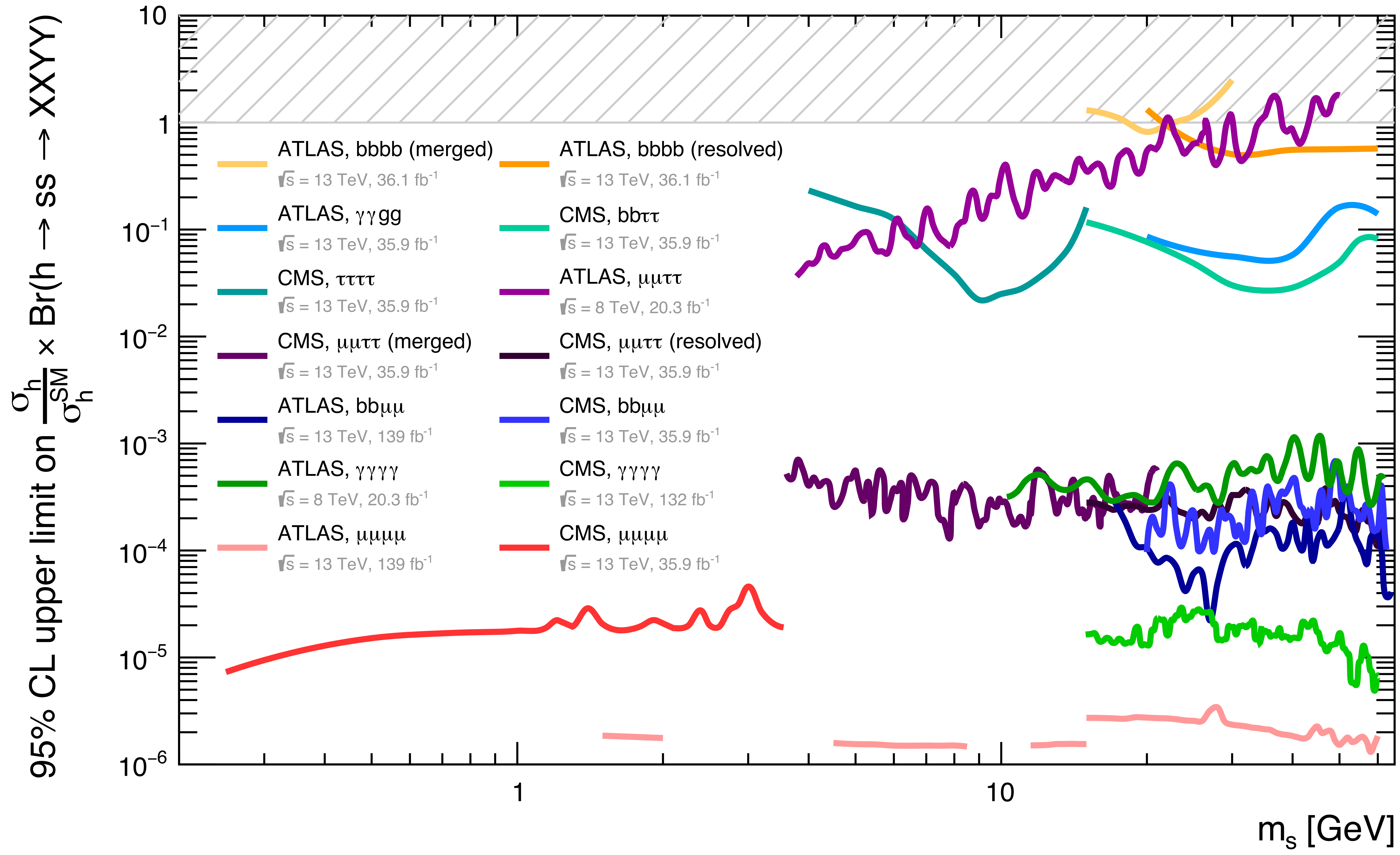
Br(h→ss→XXYYY)

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

Status of ATLAS+CMS searches for h->ss in 2021



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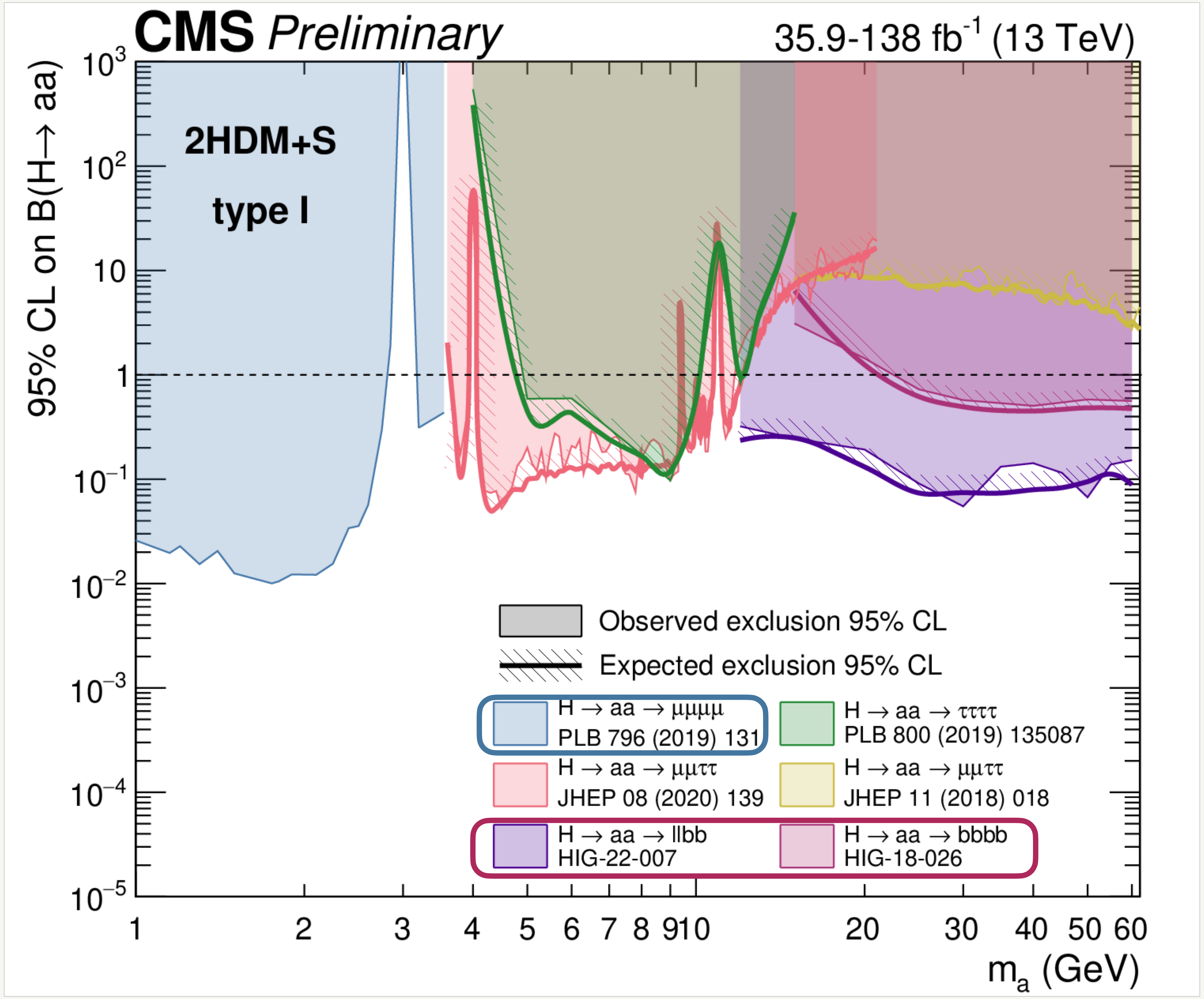
CMS Updates

- Let's focus only on CMS
- Updates to our results on SM+s prompt since the review
  - bb$\tau\tau$ and bb$\mu\mu$ (full Run2, now published: Eur. Phys. J. C 84 (2024) 493)
  - 4b full Run2: accepted in JHEP, arXiv:2403.10341)
  - 4μ: new full Run2 result in Winter 2024
    - In this summary plot still only 2016: now full Run2 now available! : the main focus of today's talk
- Other results in SM+ALP (Merged diphoton, very low mass Phys. Rev. Lett. 131 (2023) 101801) and several displaced searches

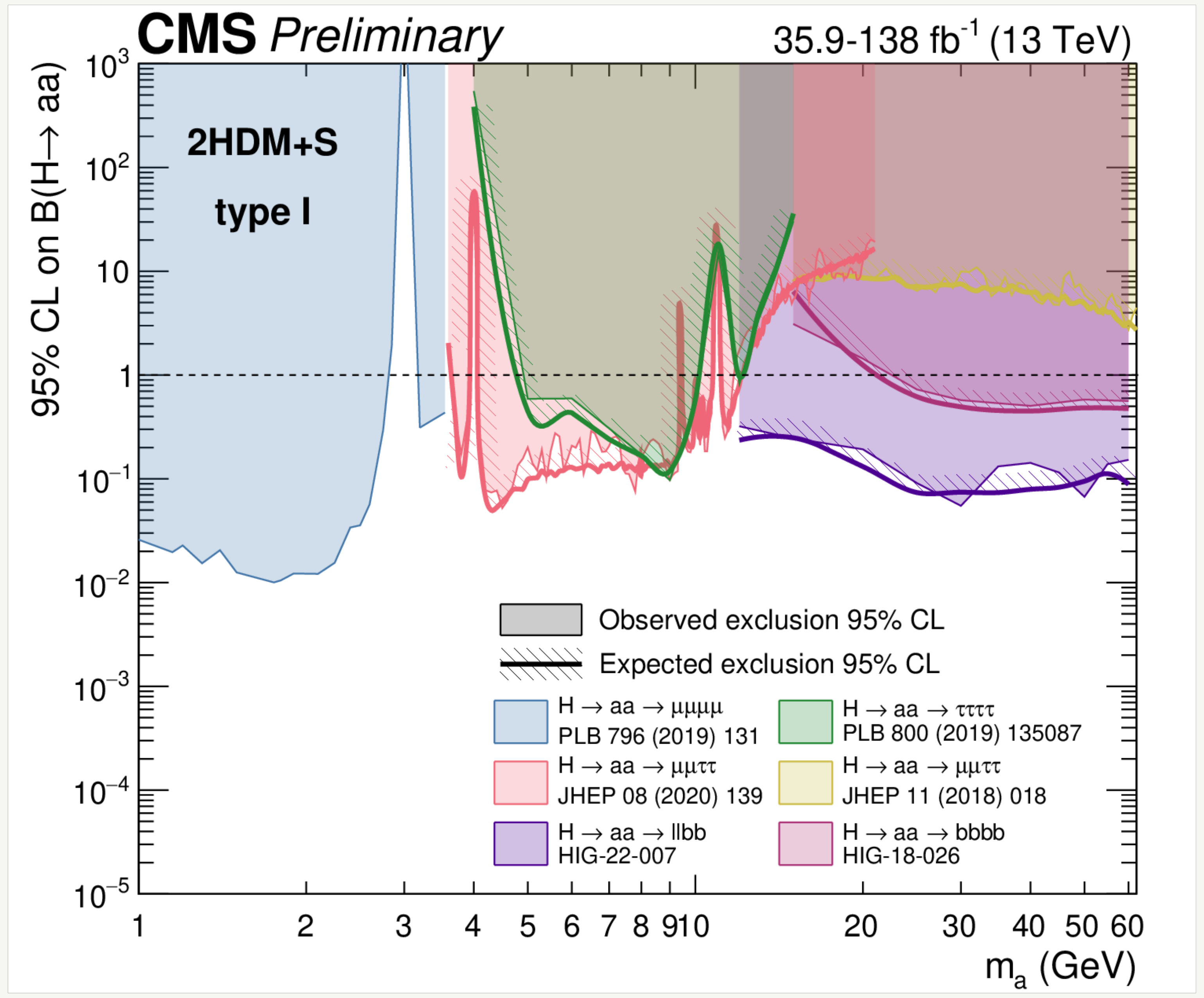


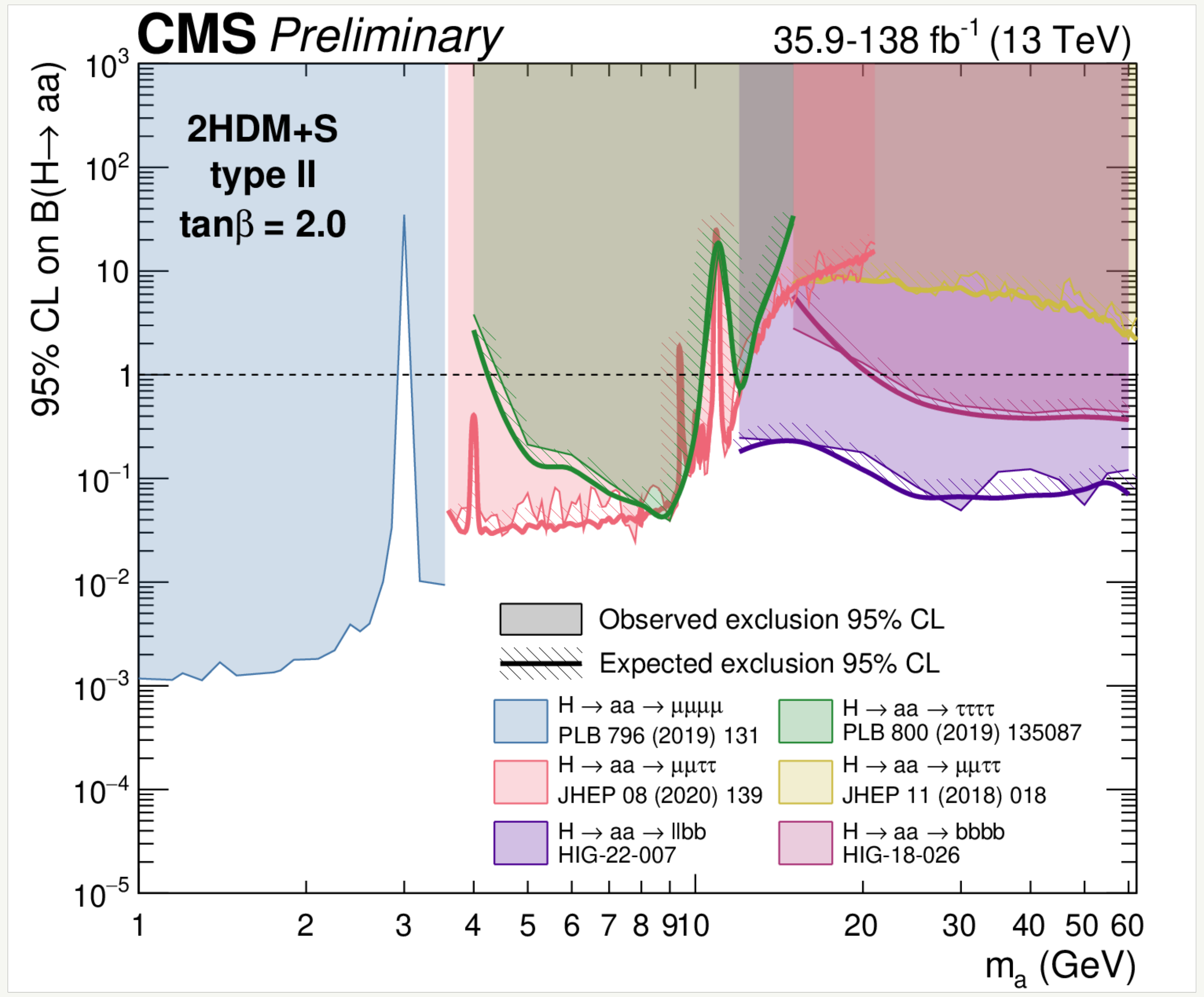
2HDM+S: TypeI-IV

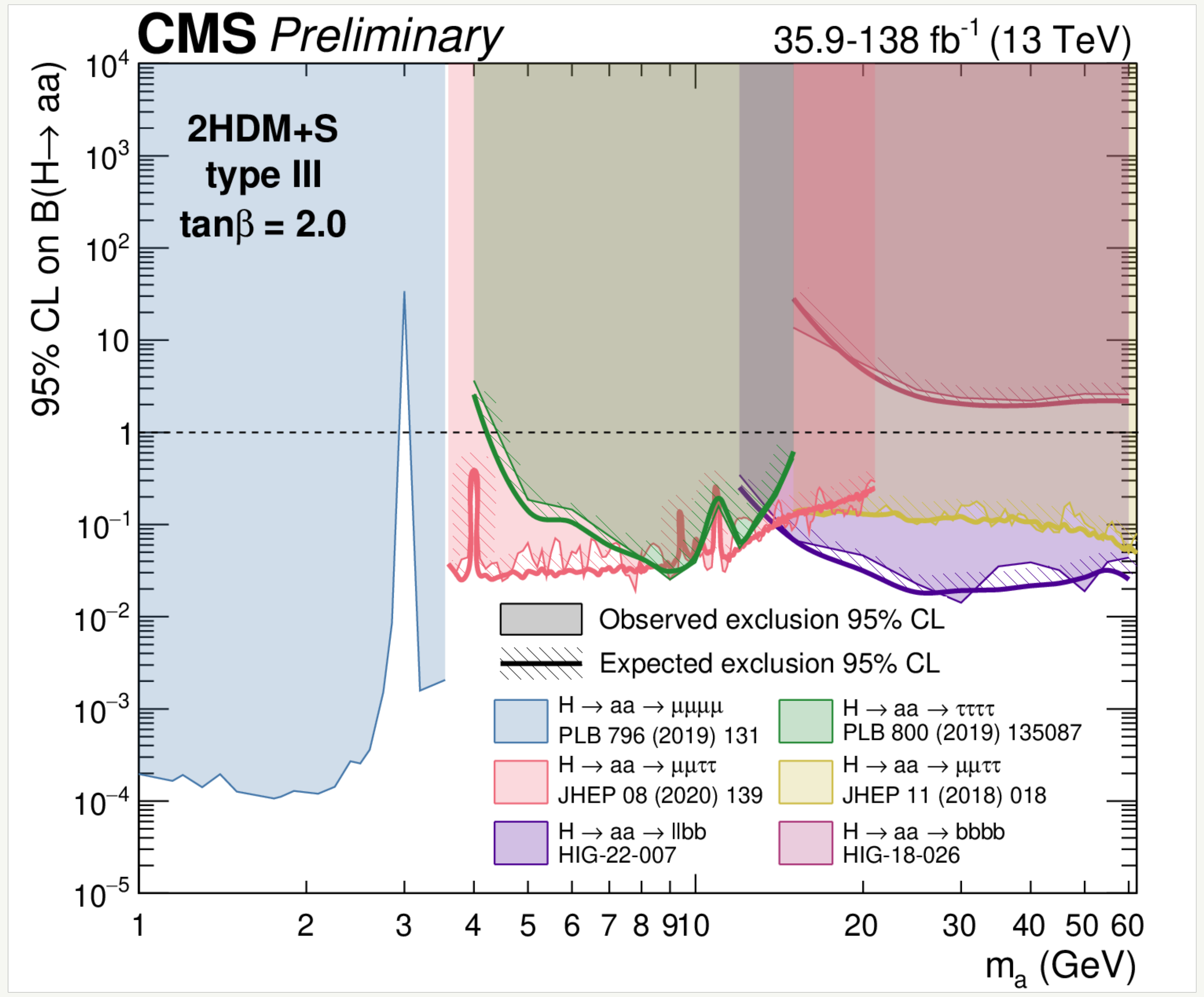
- Specific benchmark scenarios

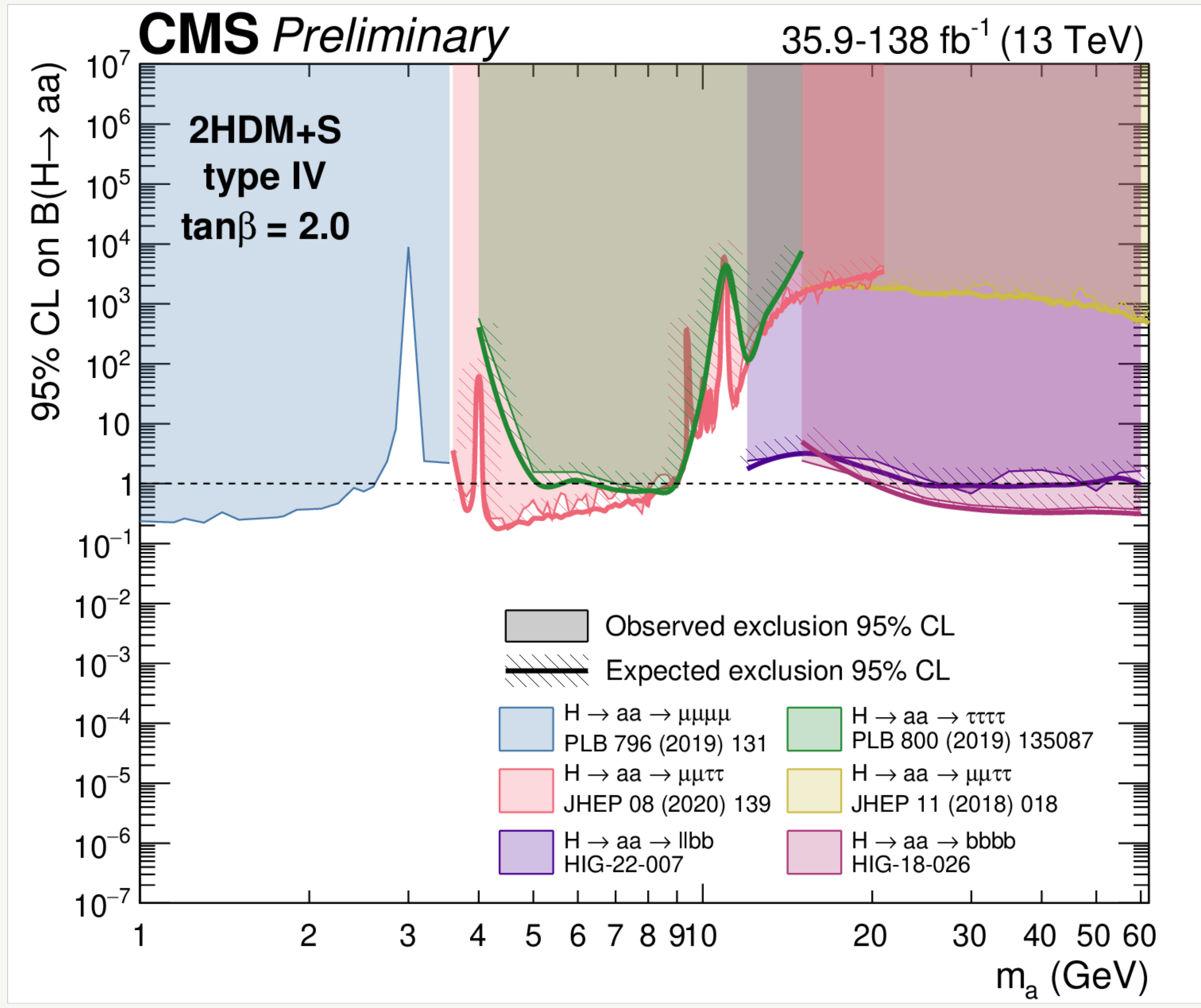
Model	2HDM I	2HDM II	2HDM III	2HDM IV
u	H_2	H_2	H_2	H_2
d	H_2	H_1	H_2	H_1
e	H_2	H_1	H_1	H_2

- Incorporating the model-dependent decay branching ratio BR(s→SM)
- Interplay between the decays will also be discussed by Alexis Kalogeropoulos tomorrow!
  - **Searches focus on the heaviest particles kinematically allowed in the decay: three distinct mass ranges: <$2m_\tau$, $2m_\tau$-$2m_b$, >=$2m_b$**
  - **Lowest mass reach in 4μ.**







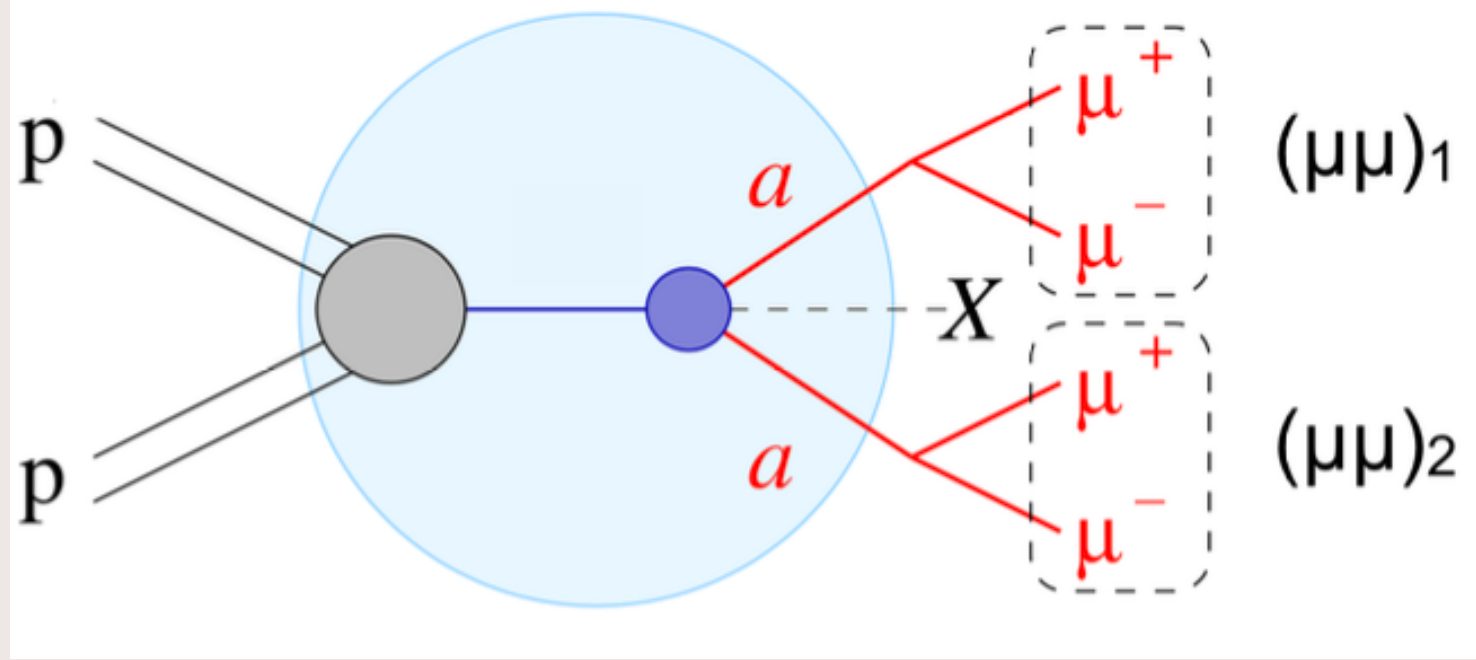


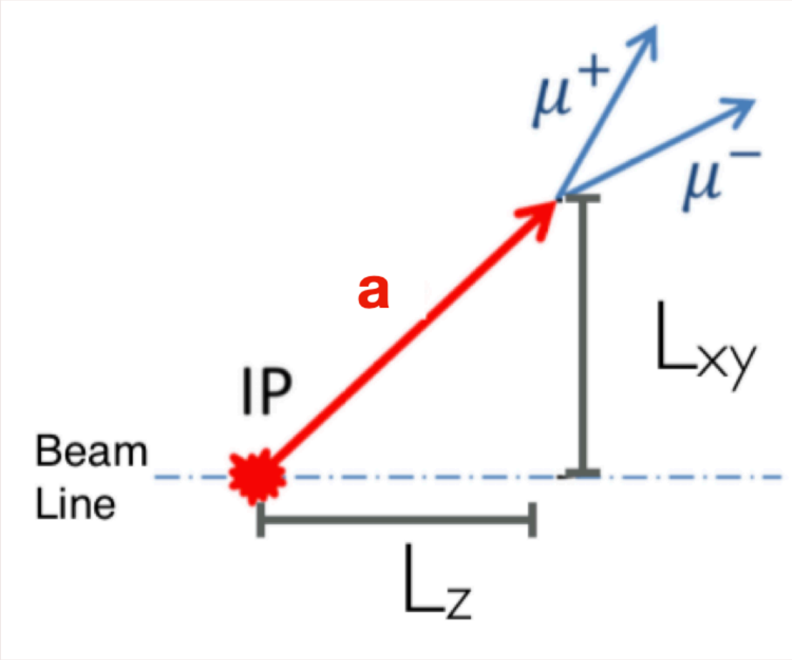
March 2023 Summaries

Let’s focus on the new results…

Pair production of new bosons decaying to 4μ

- Model independent search in the 4μ final state
- Probe very low masses: **0.21 < m_a< 60 GeV**
- **Big improvement wrt to 2016 search:** extended dimuon mass range, expanded fiducial volume from phase1 pixel upgrade, extended interpretations
- **New developed trigger with alternative muon reconstruction for 2018**
  - Use only muon detector independently on PV reconstruction
  - Sensitive to both prompt and displaced muons





CMS-PAS-HIG-21-004

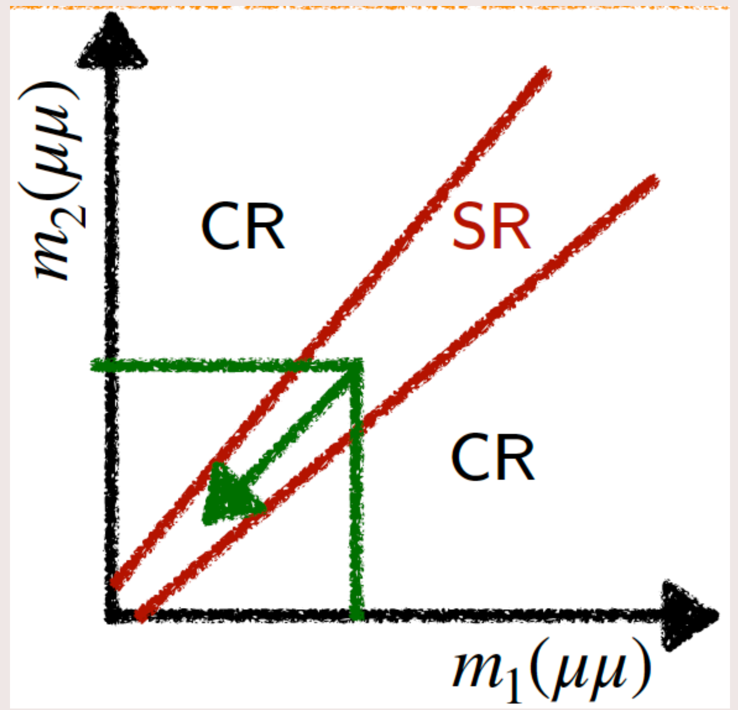
Results are interpreted in various models: ALP, NMSSM, Vector Portal Model, Dark SUSY

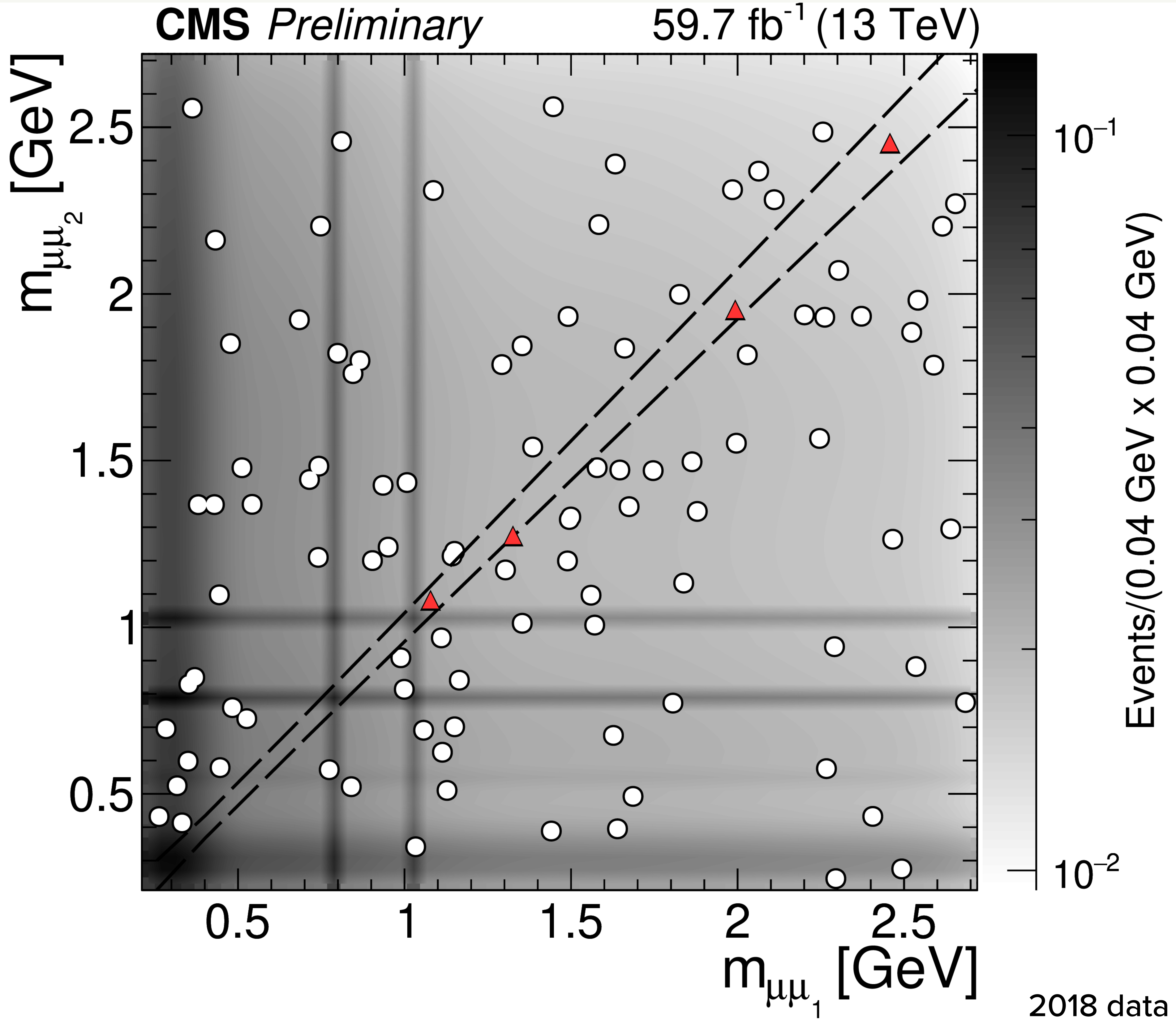
Analysis Strategy

- Selection:
  - 2 $\mu^+\mu^-$ pairs, < 60 GeV, valid common vertex
  - identical mass for m1 and m2

$$|m_1 - m_2| < f\left(\frac{m_1 + m_2}{2}\right)$$

- Below the ϒ Peak (<9 GeV):
  - Background Dominated by QCD events, especially bb
  - Double semileptonic decay or decay via resonances (η,ω,φ, J/ψ(1S),ψ(2S))
  - Data driven from control sample (2D template)





2018 data

Analysis Strategy

- Selection:
  - 2 $\mu^+\mu^-$ pairs, < 60 GeV, valid common vertex
  - identical mass for m1 and m2

$$|m_1 - m_2| < f\left(\frac{m_1 + m_2}{2}\right)$$

- Below the ϒ Peak (<9 GeV):
  - Background Dominated by QCD events, especially bb
  - Double semileptonic decay or decay via resonances (η,ω,φ, J/ψ(1S),ψ(2S))
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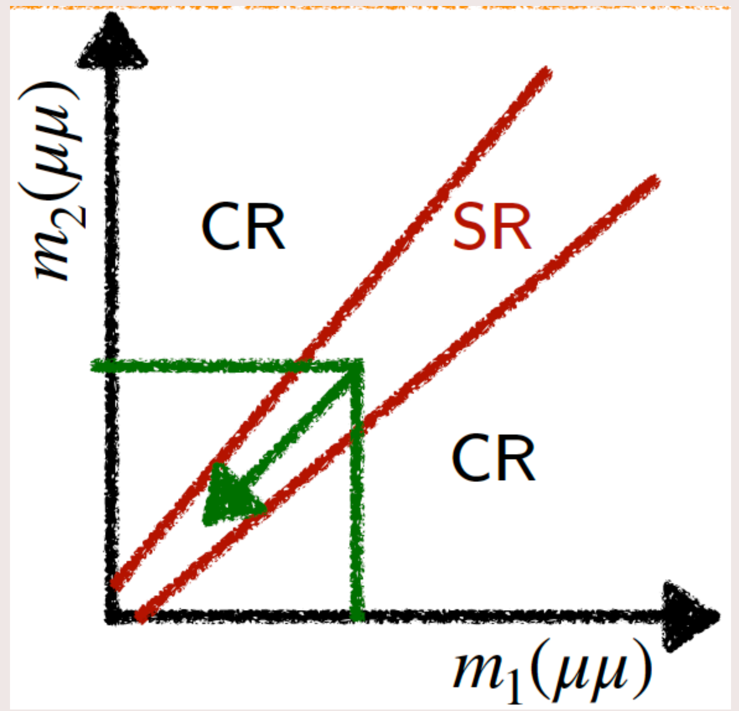
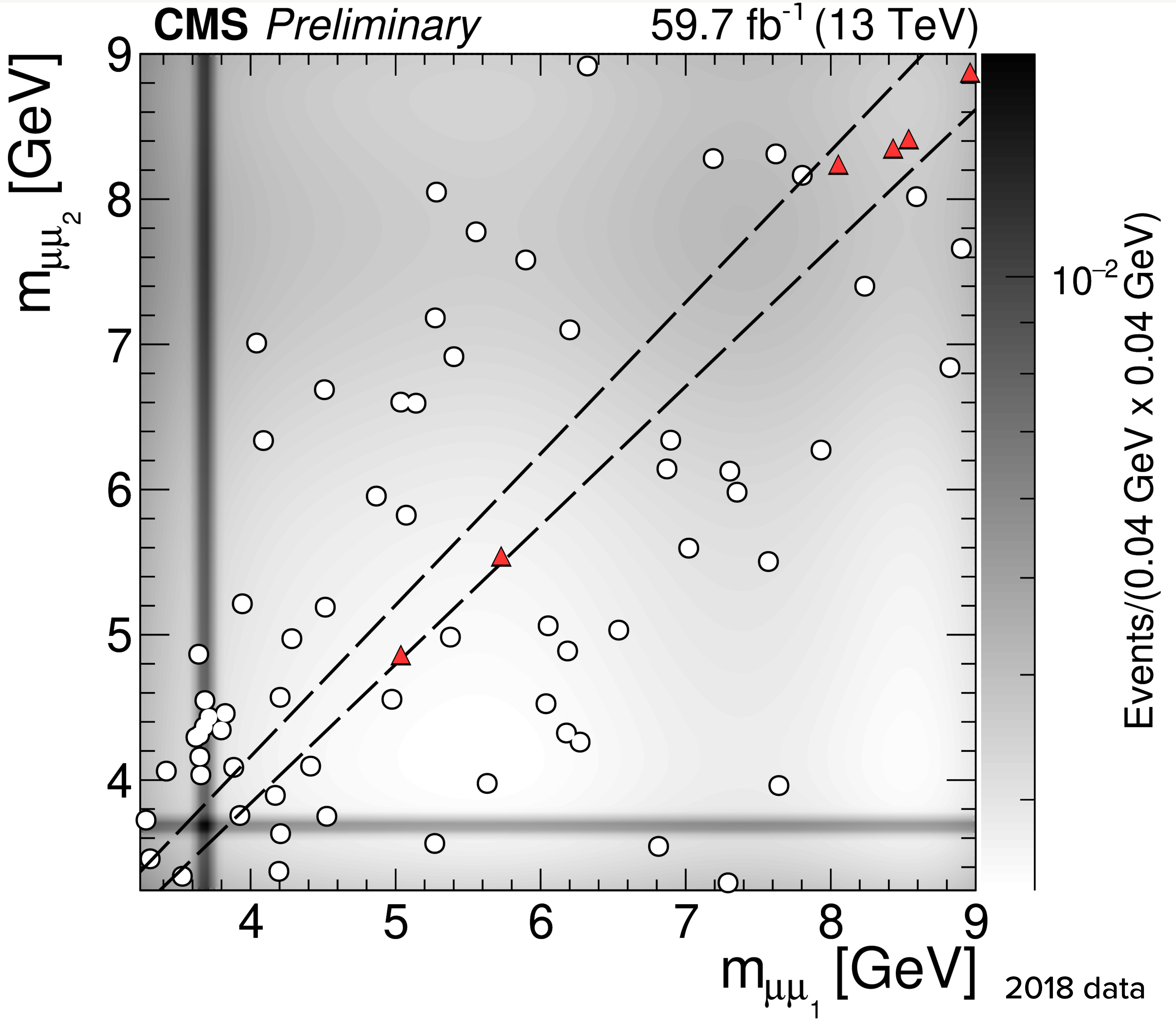


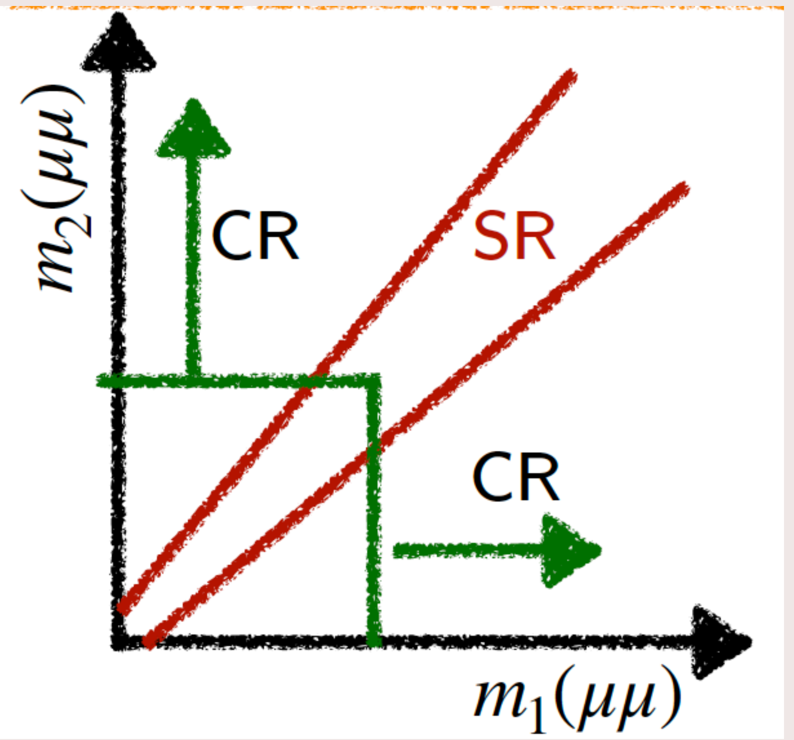


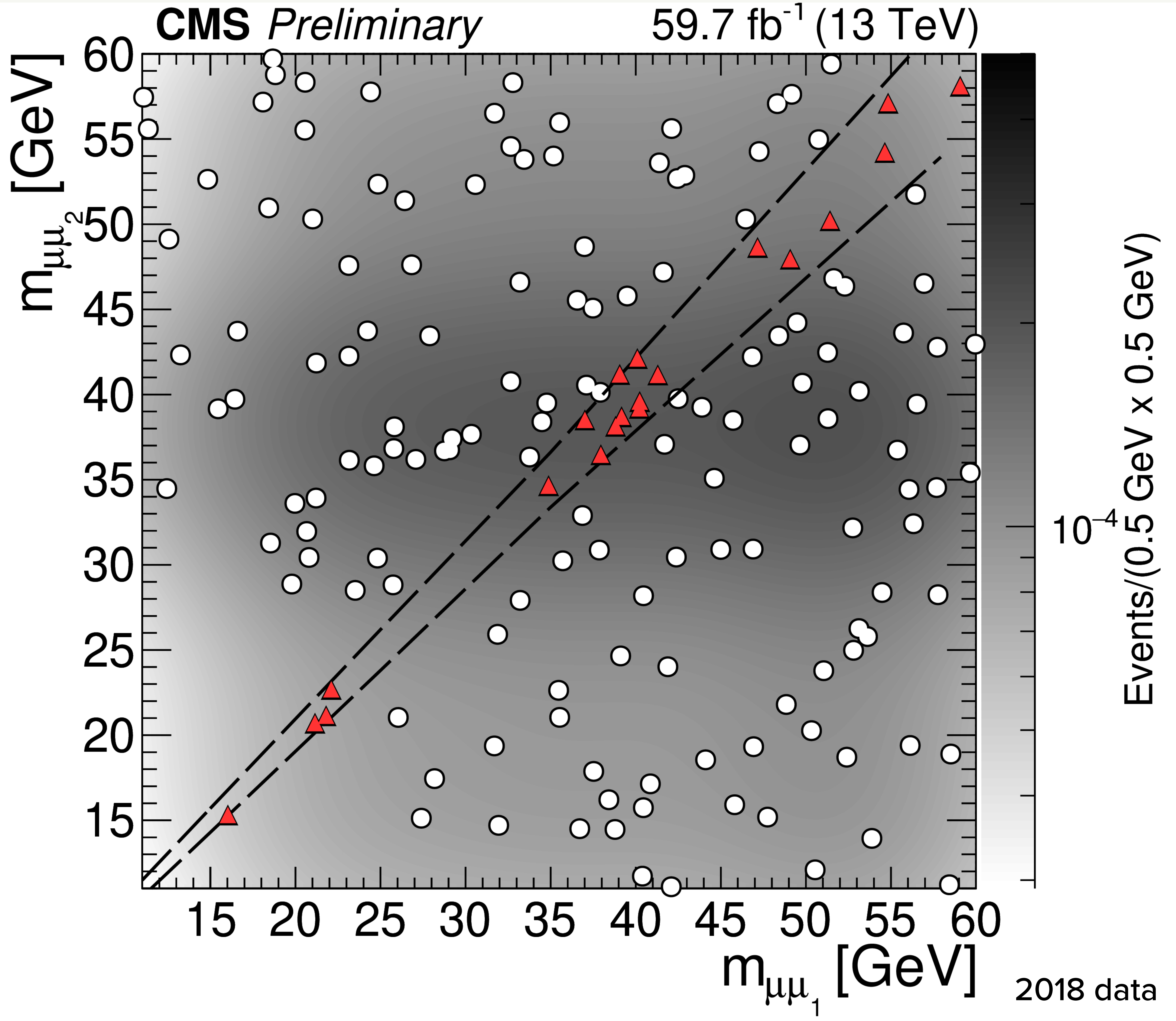
Analysis Strategy

- Selection:
  - 2 $\mu^+\mu^-$ pairs, < 60 GeV, valid common vertex
  - identical mass for m1 and m2

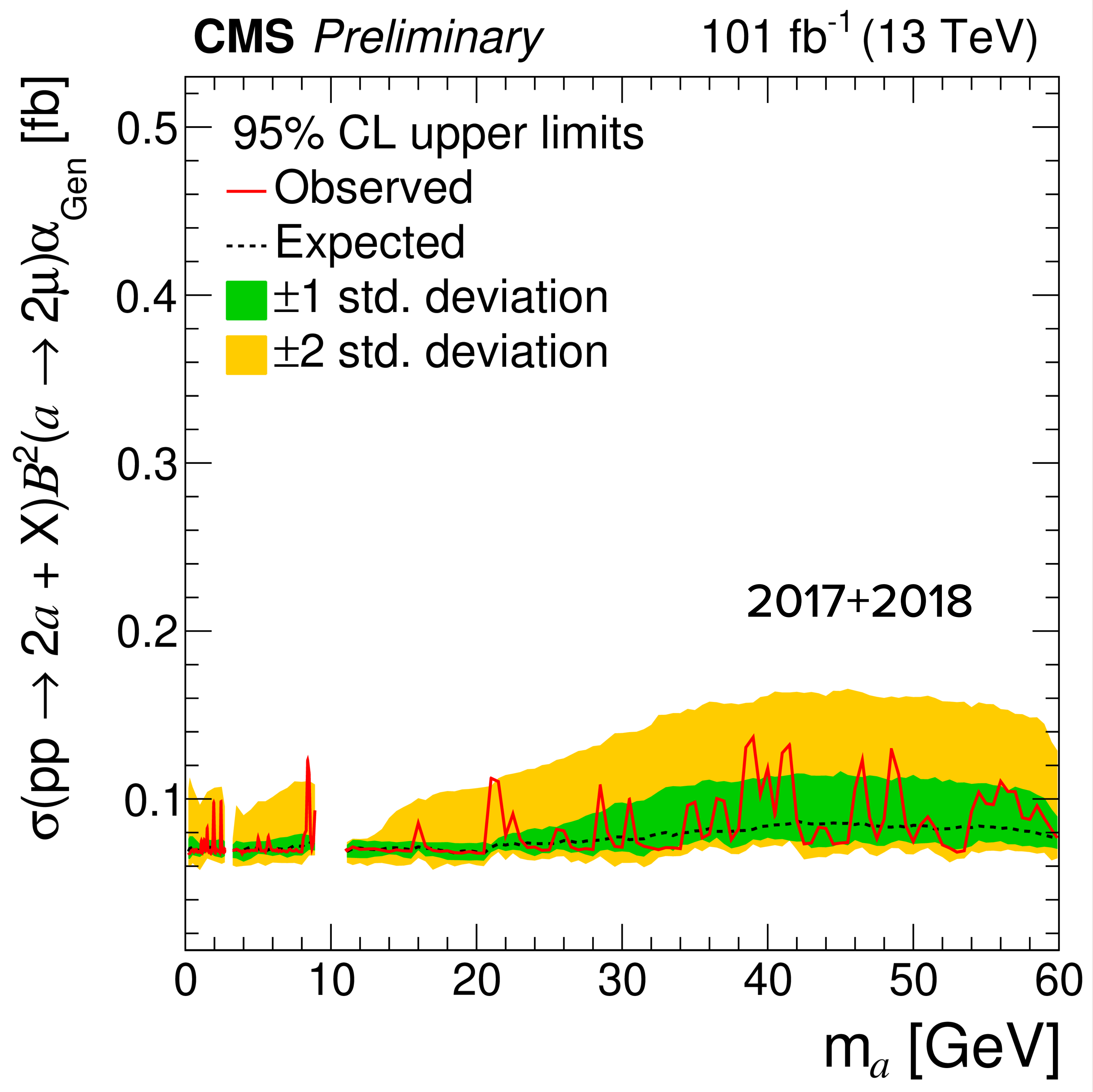
$$|m_1 - m_2| < f\left(\frac{m_1 + m_2}{2}\right)$$

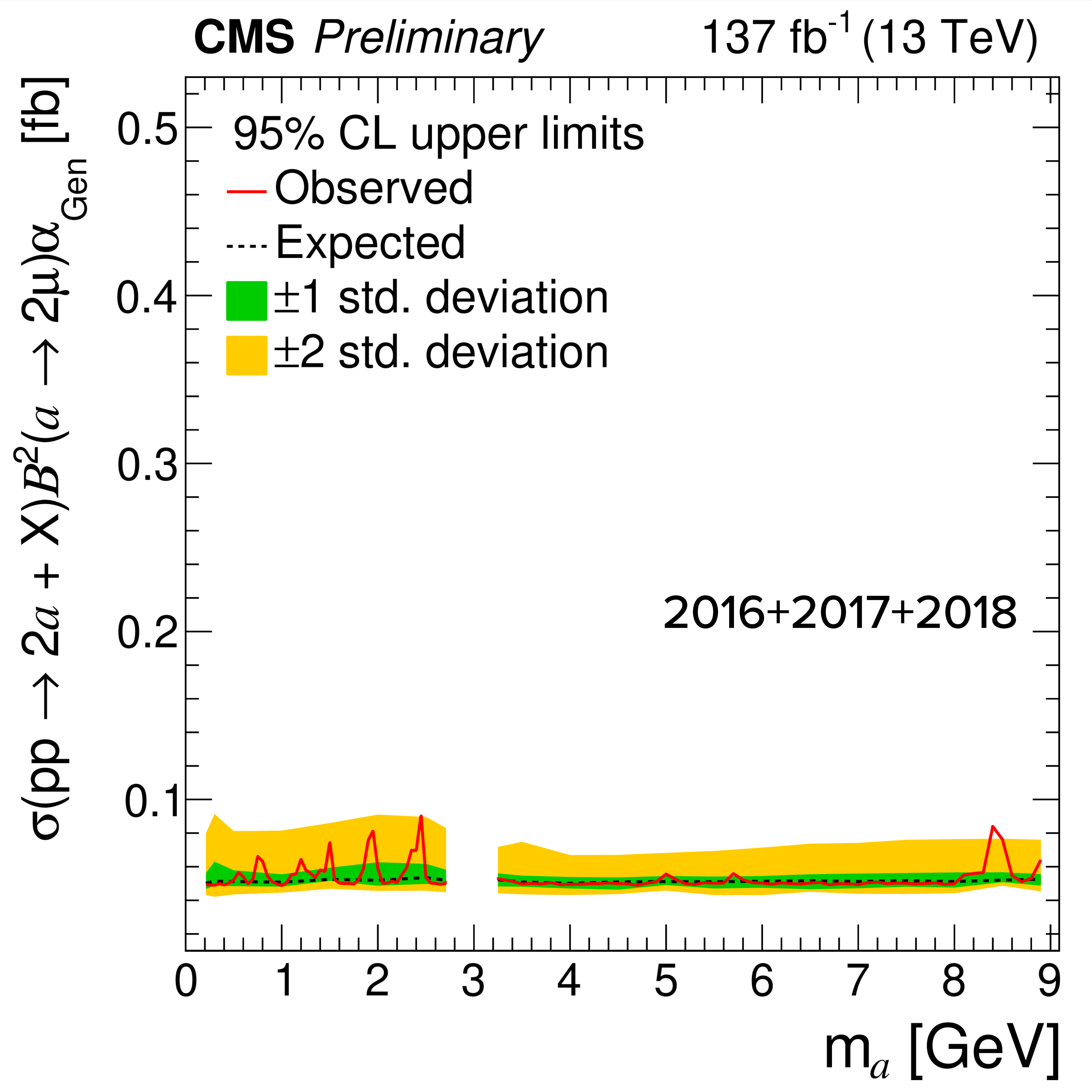
- Above the ϒ Peak (>11 GeV):
  - Background: ZZ, ttbar, DY (QED radiation)
  - Gaussian KDE method
  - Norm from data





Model Independent Results



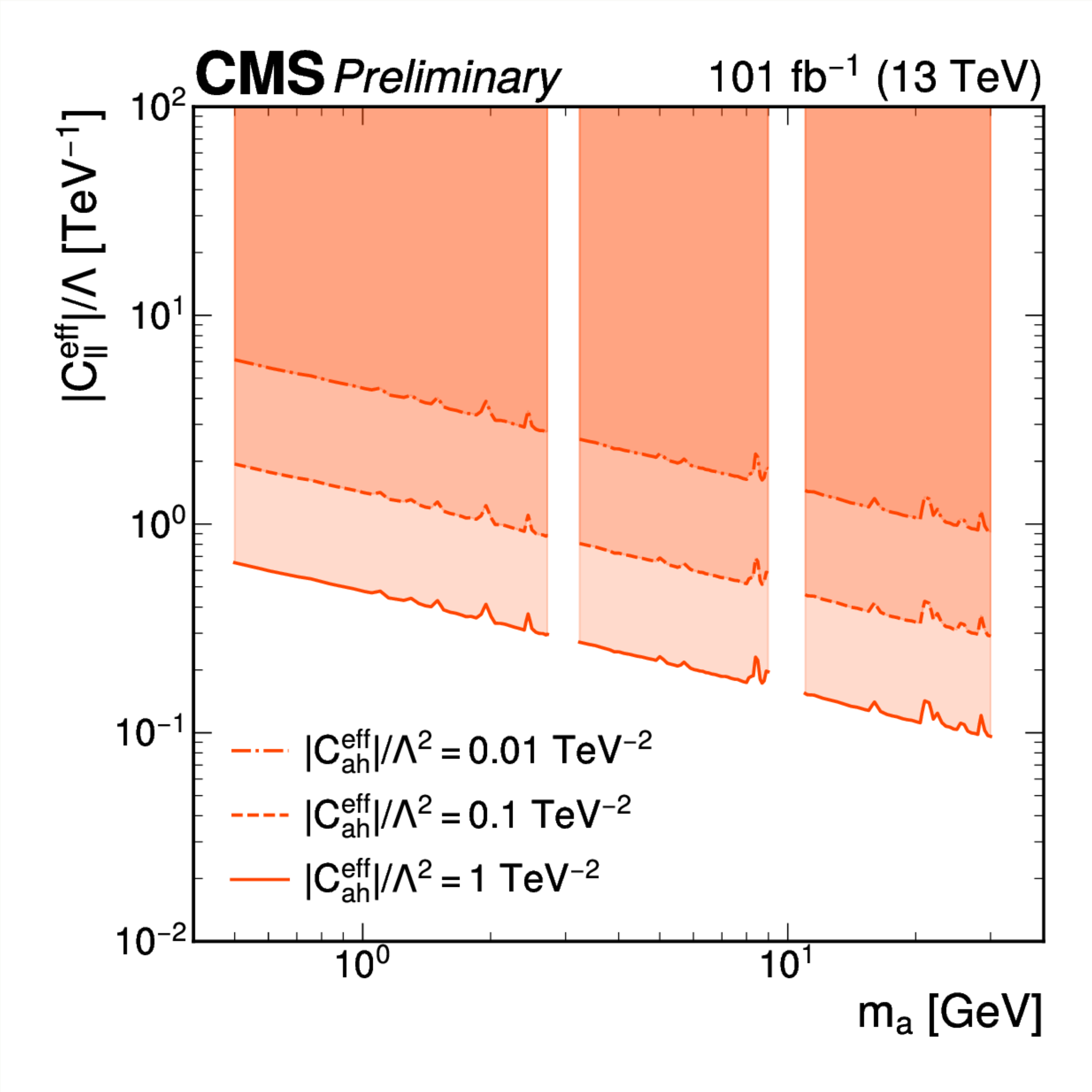


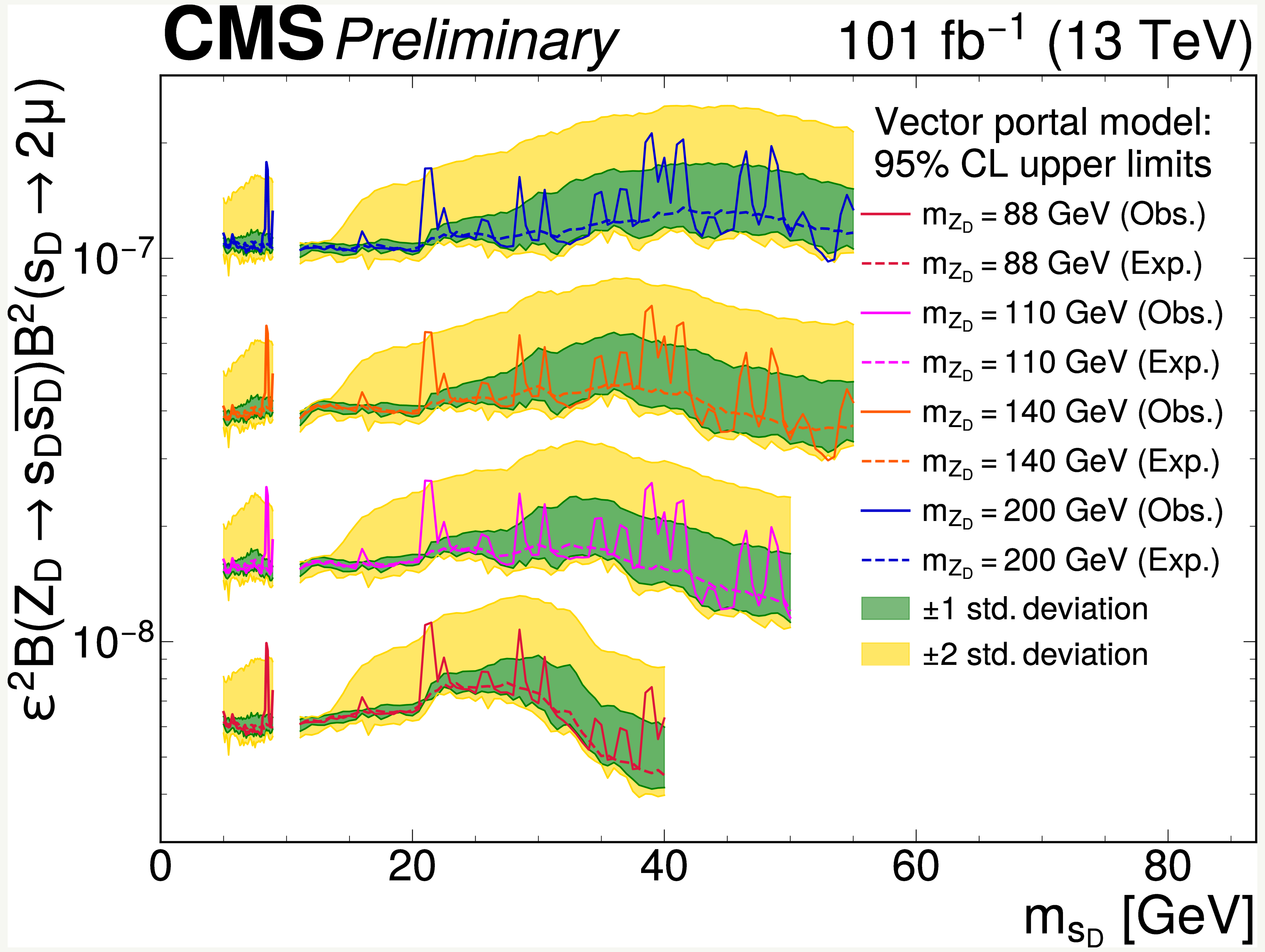
Observed events in the SR consistent with the SM expectation. Limits set on the xsec*Br

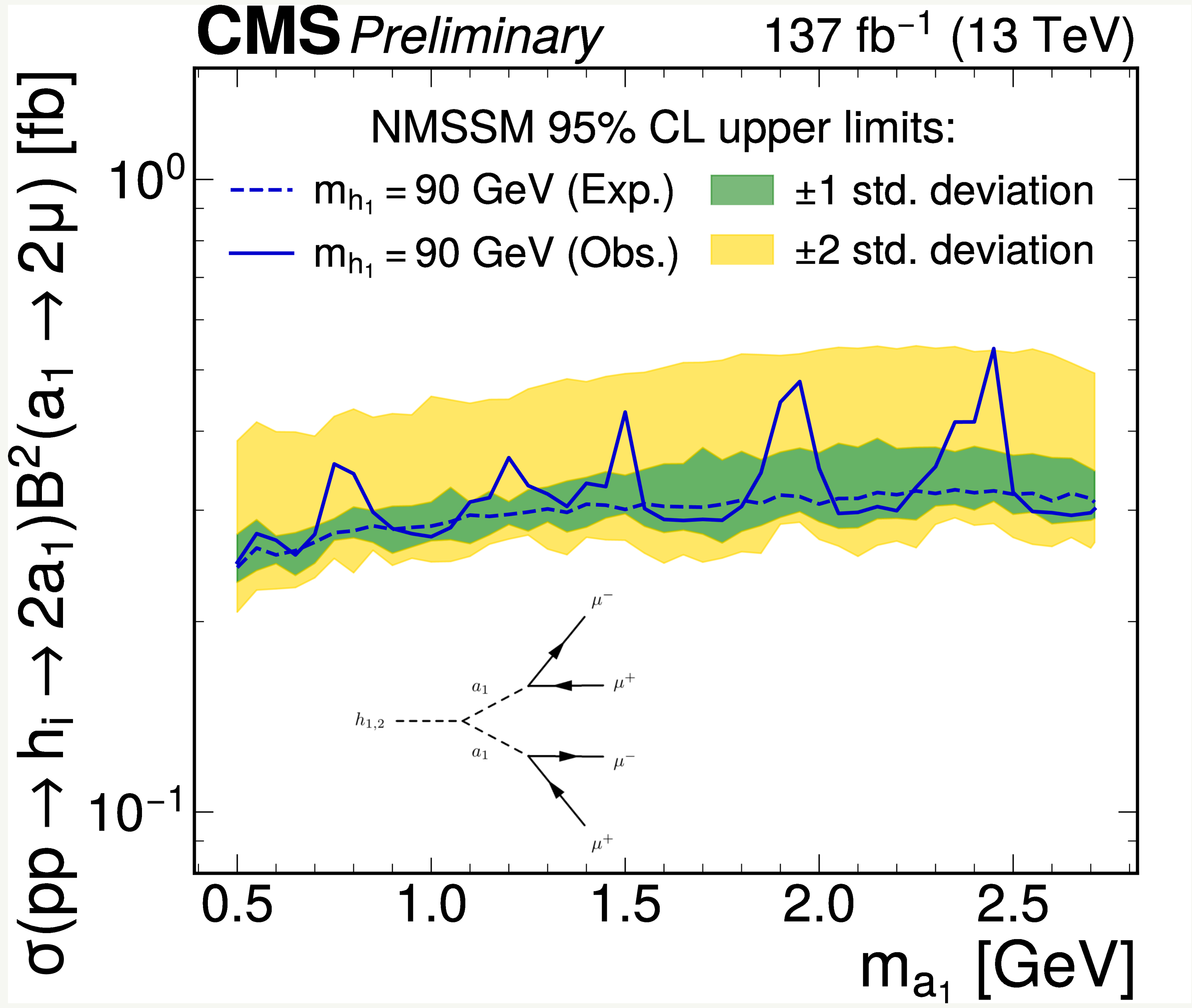
Model Specific Interpretations

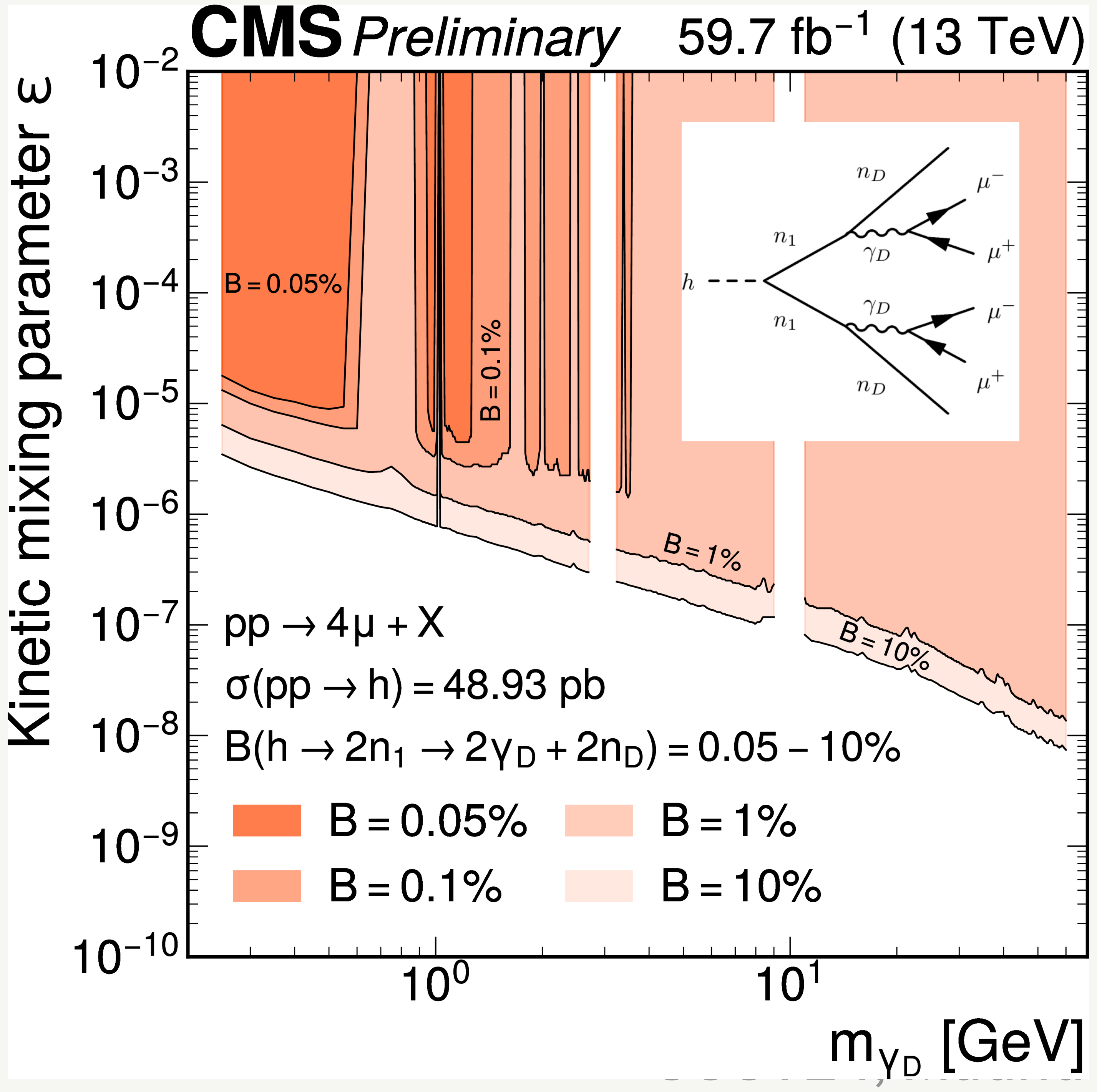
The results are also interpreted in the context of

- ALPs
- SM+v (Dark Boson)
- NMSSM
- Dark SUSY with non-negligible boson lifetimes of up to $c\tau_{\gamma_D} = 100\text{mm}$







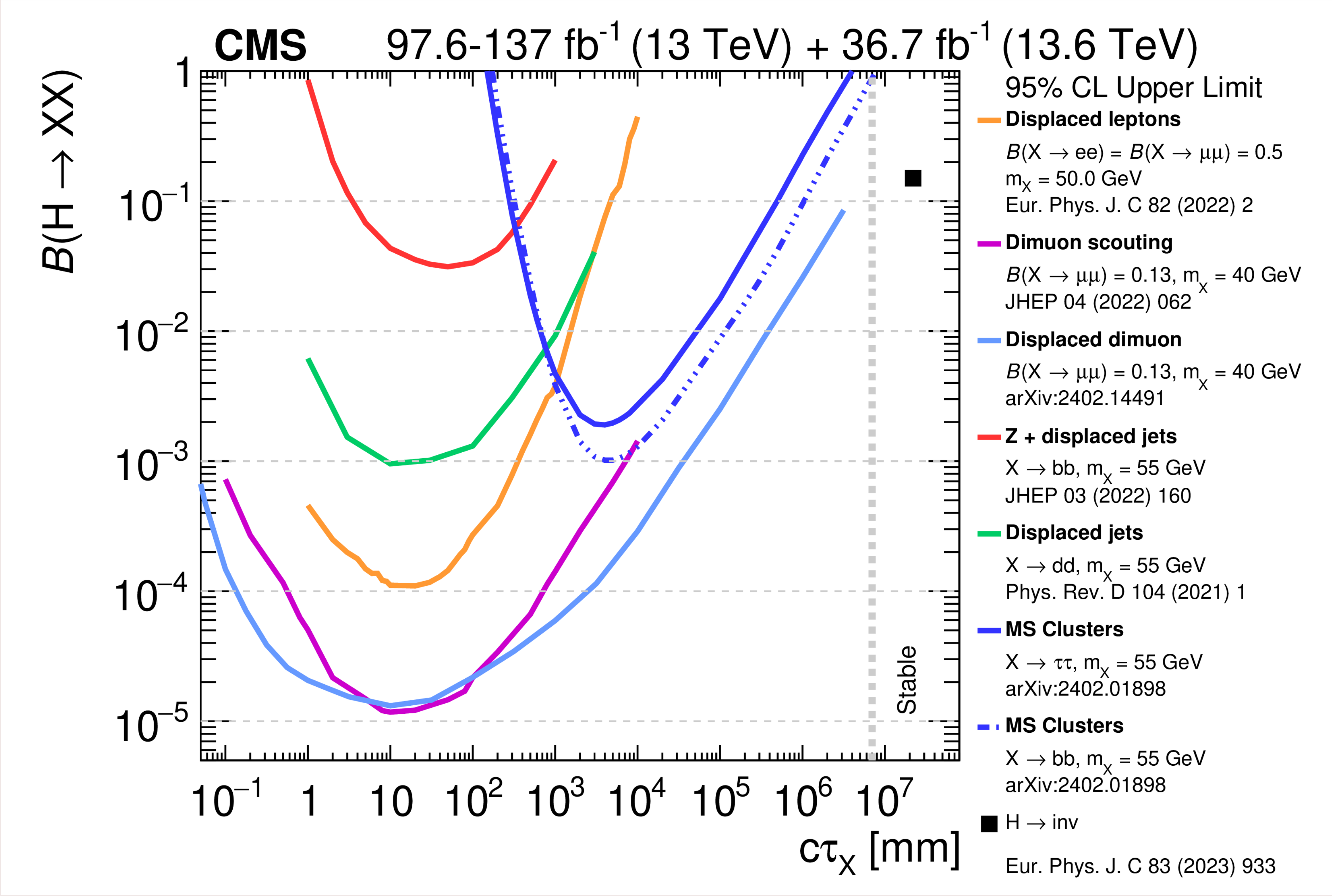


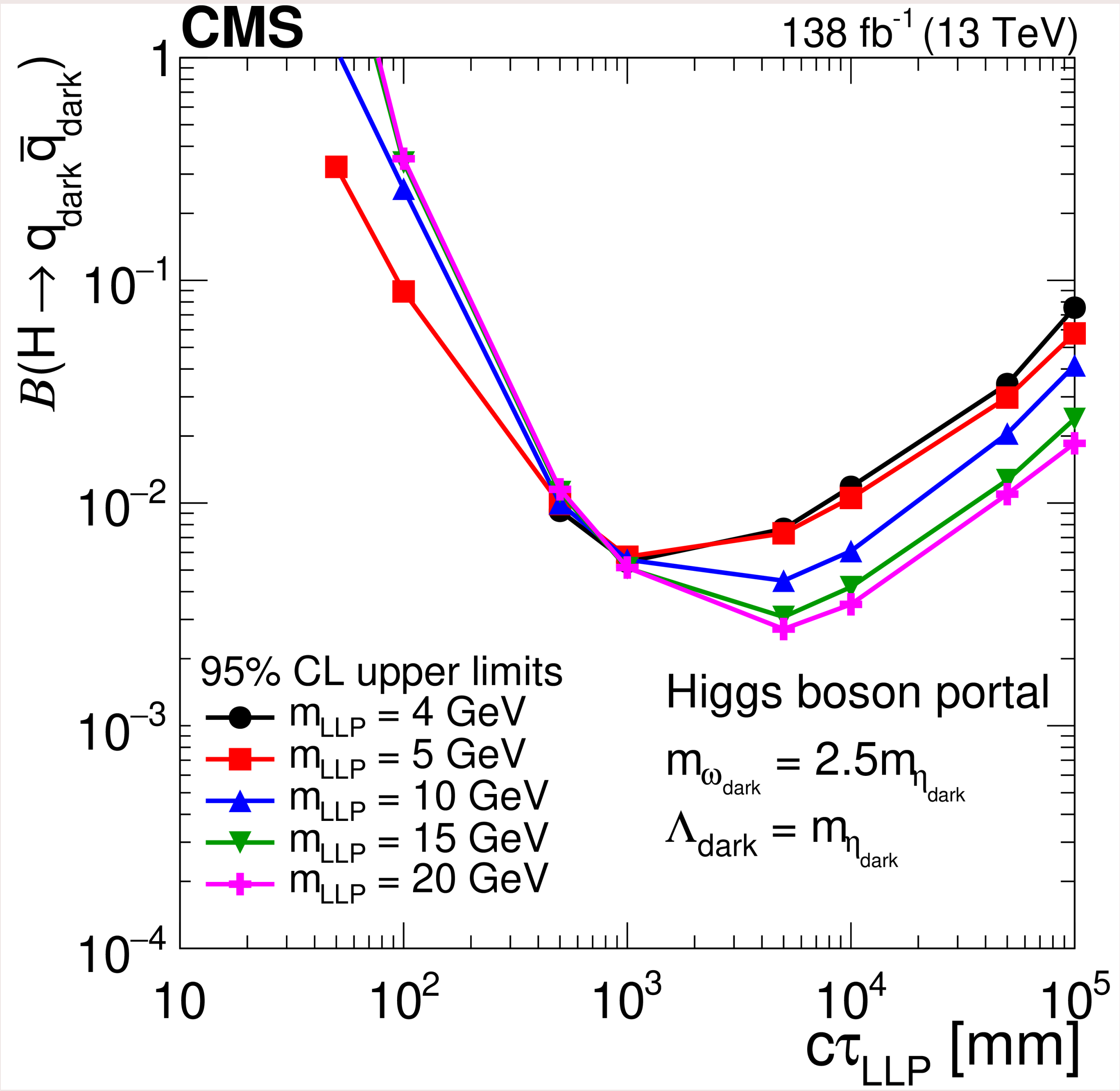
… and what else?

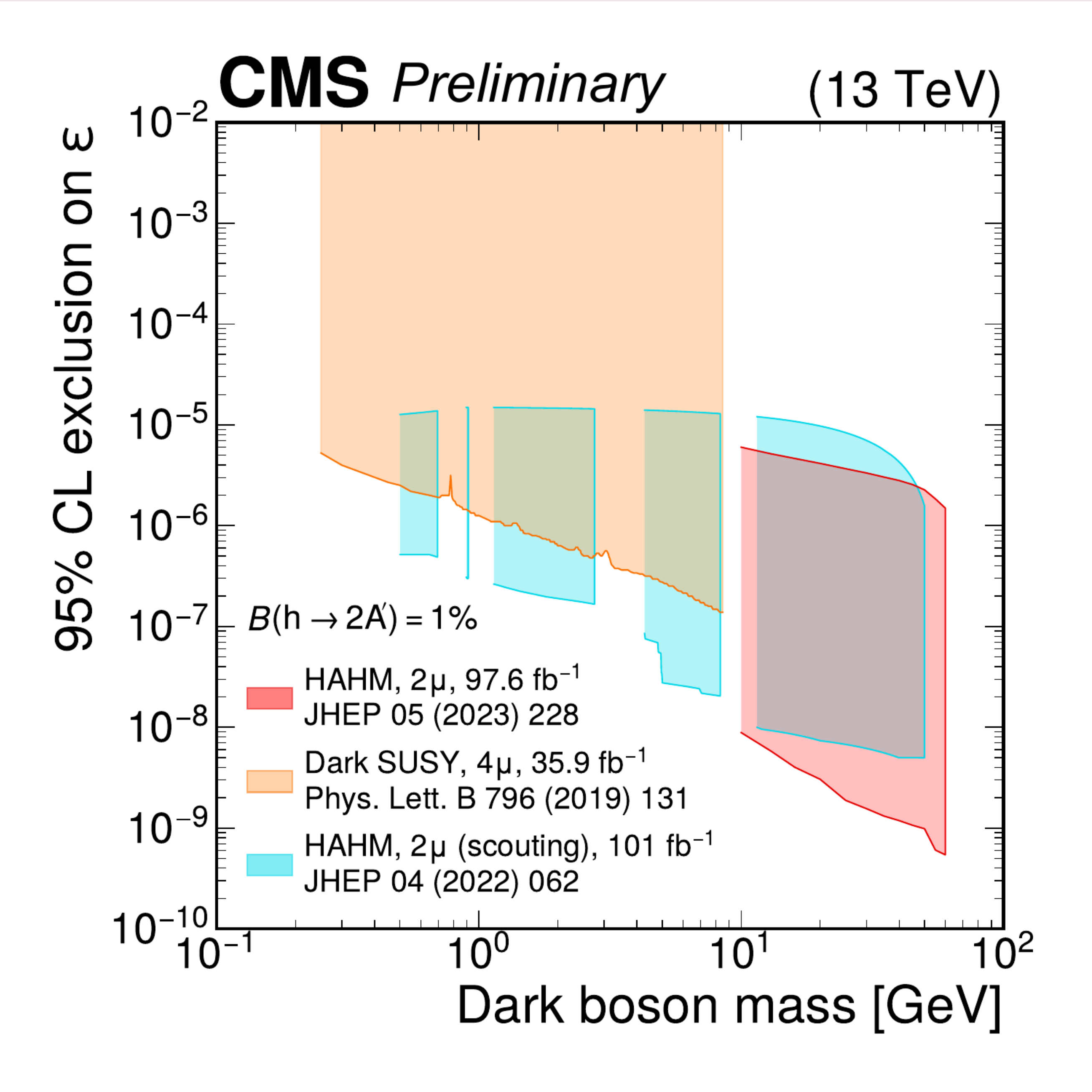
Beyond SM+S…

arXiv:2405.13778

- Looking for exotic Higgs decays goes beyond the traditional h->aa/ss searches
- Expanding to probe for decays to Dark Bosons, ALPs, Long Lived particles is one of the next frontiers
- See the displaced talk by Petar Maksimovic for more - and check out the “Dark sector searches with the CMS experiment” for a detailed account of the different interpretations







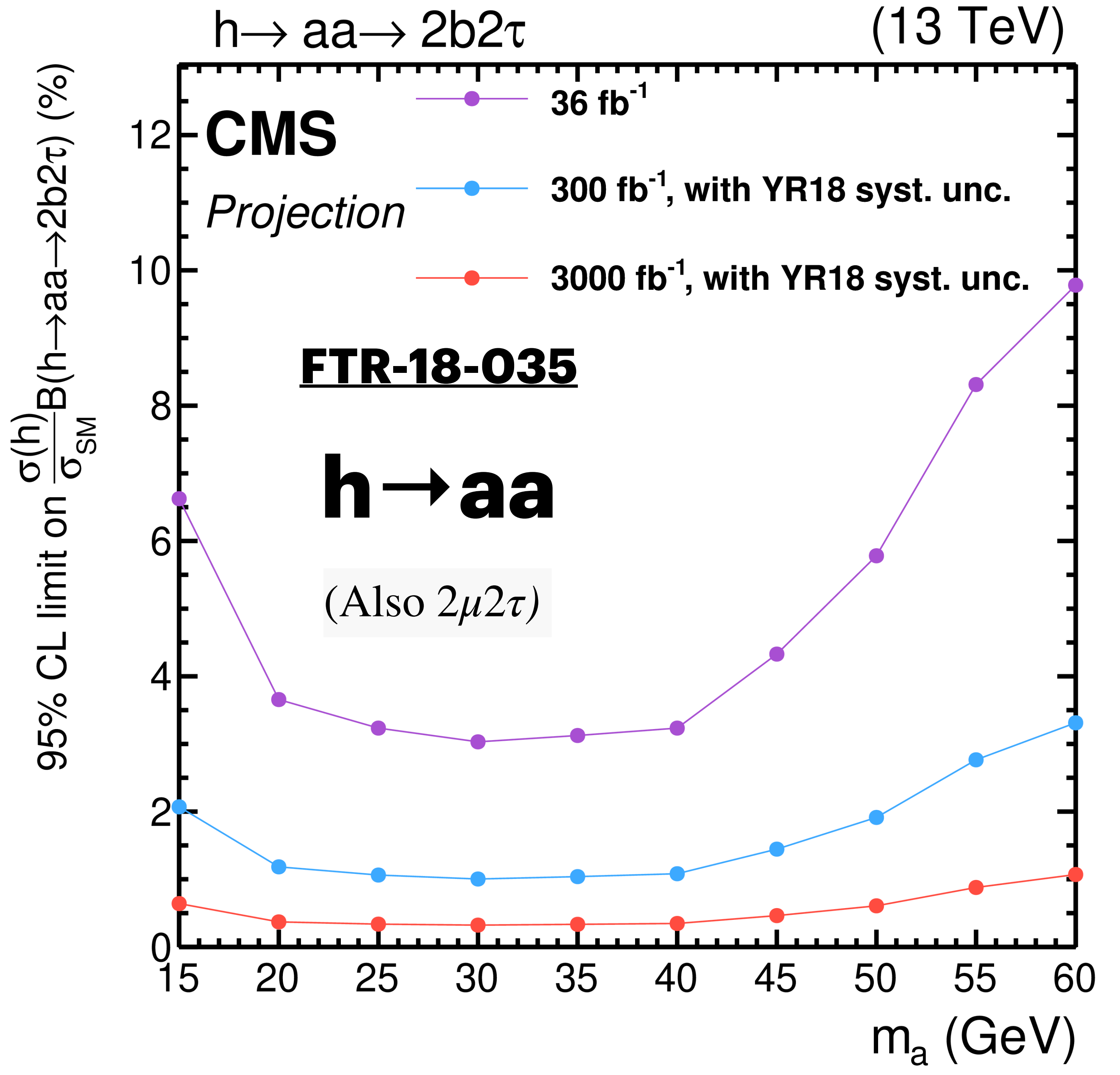
Thinking ahead…

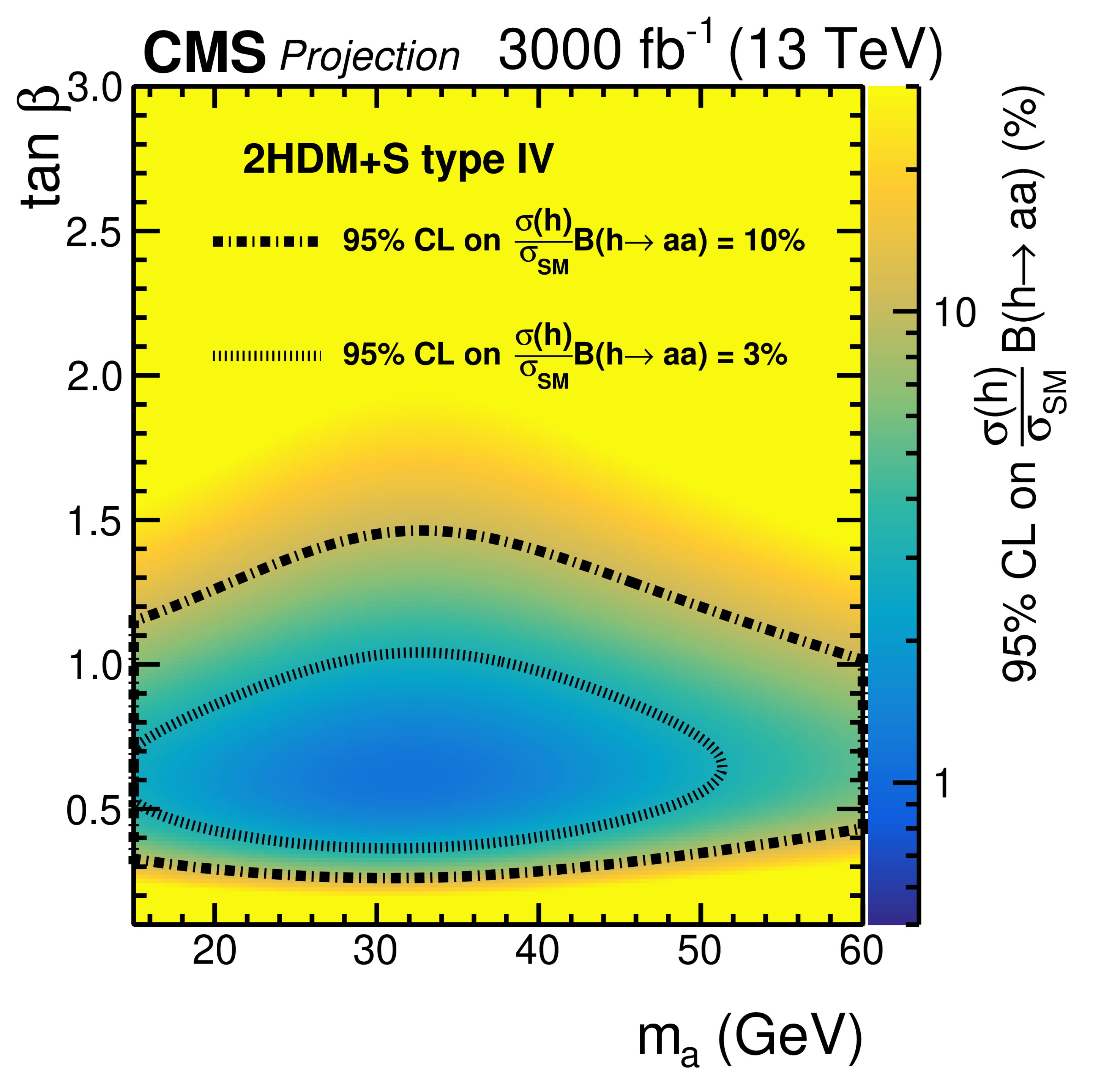
Run3 and HL-LHC

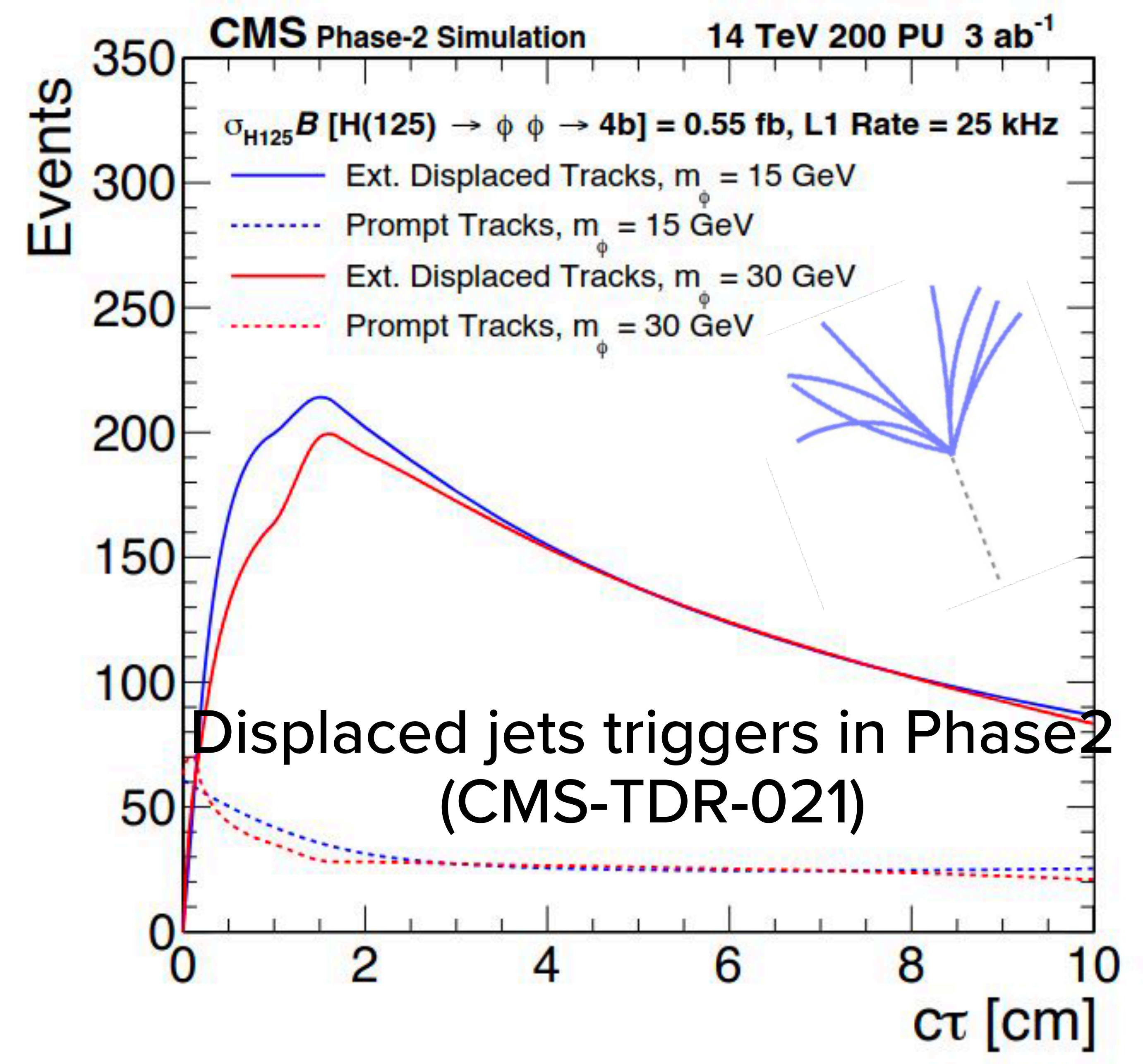
Statistically dominated, and still a lot of improvements on analysis techniques to come

Some projections available (the usual caveat applies that we can always do better with better analyses). Note the gain from luminosity at the end of Run3!!

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.





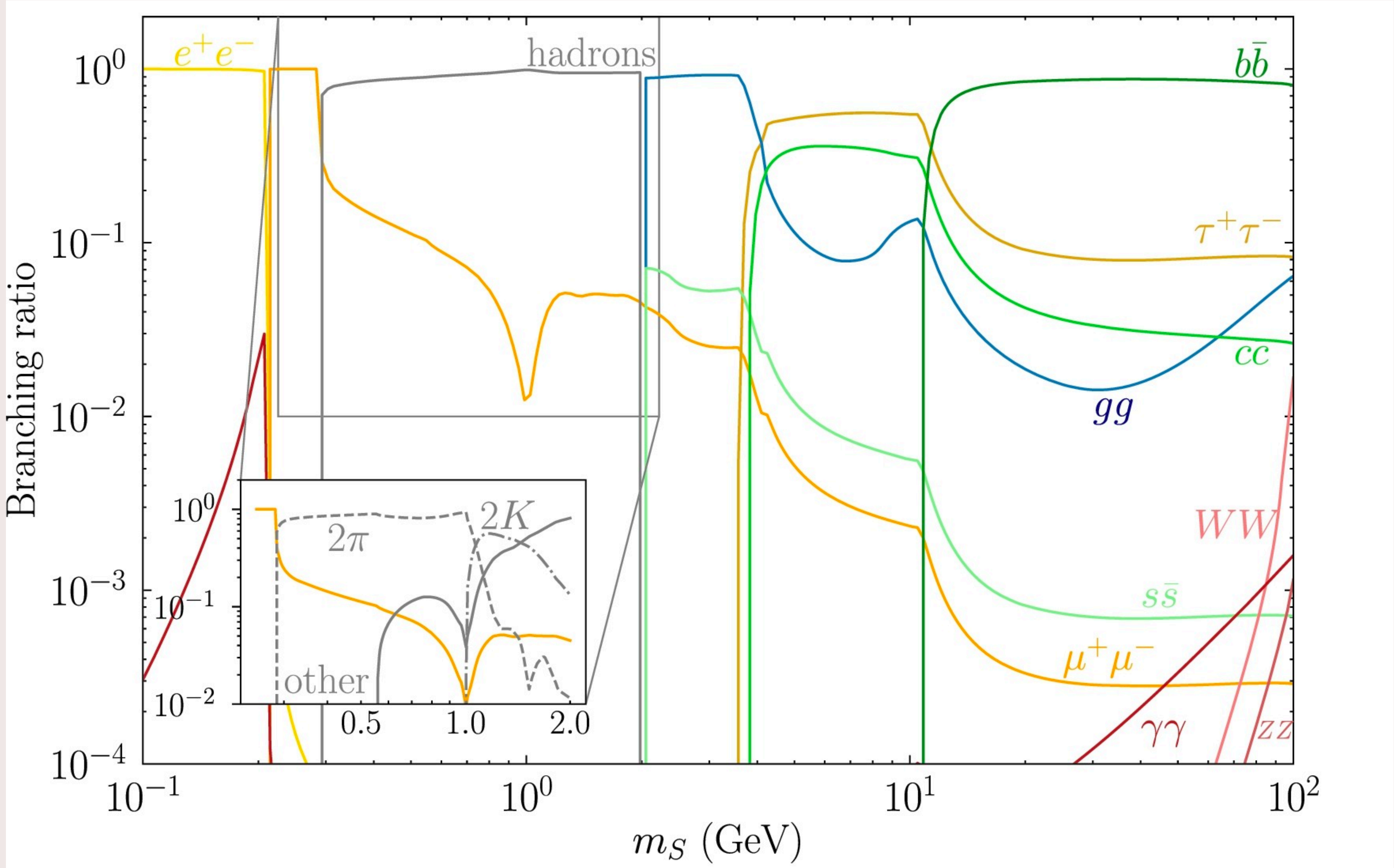


Conclusions

- 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 feebly to the SM.
- Many opportunities in prompt and displaced h->ss/aa/vv decays. 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 that we are working hard to cover!
  - 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
- As a proof of this progress:
  - update on 4μ final states (CMS-PAS-HIG-21-004), reaching down to 0.2 GeV and covering both model independent and model specific (ALPs, darksusy, nmssm, dark photon, 2HDM+s) interpretations
  - newly submitted result for the 4b final state (arXiv:2403.10341)
- Connection & coherence between prompt and long lived searches as a must for the future

BACKUP

Br(s→SM) ?



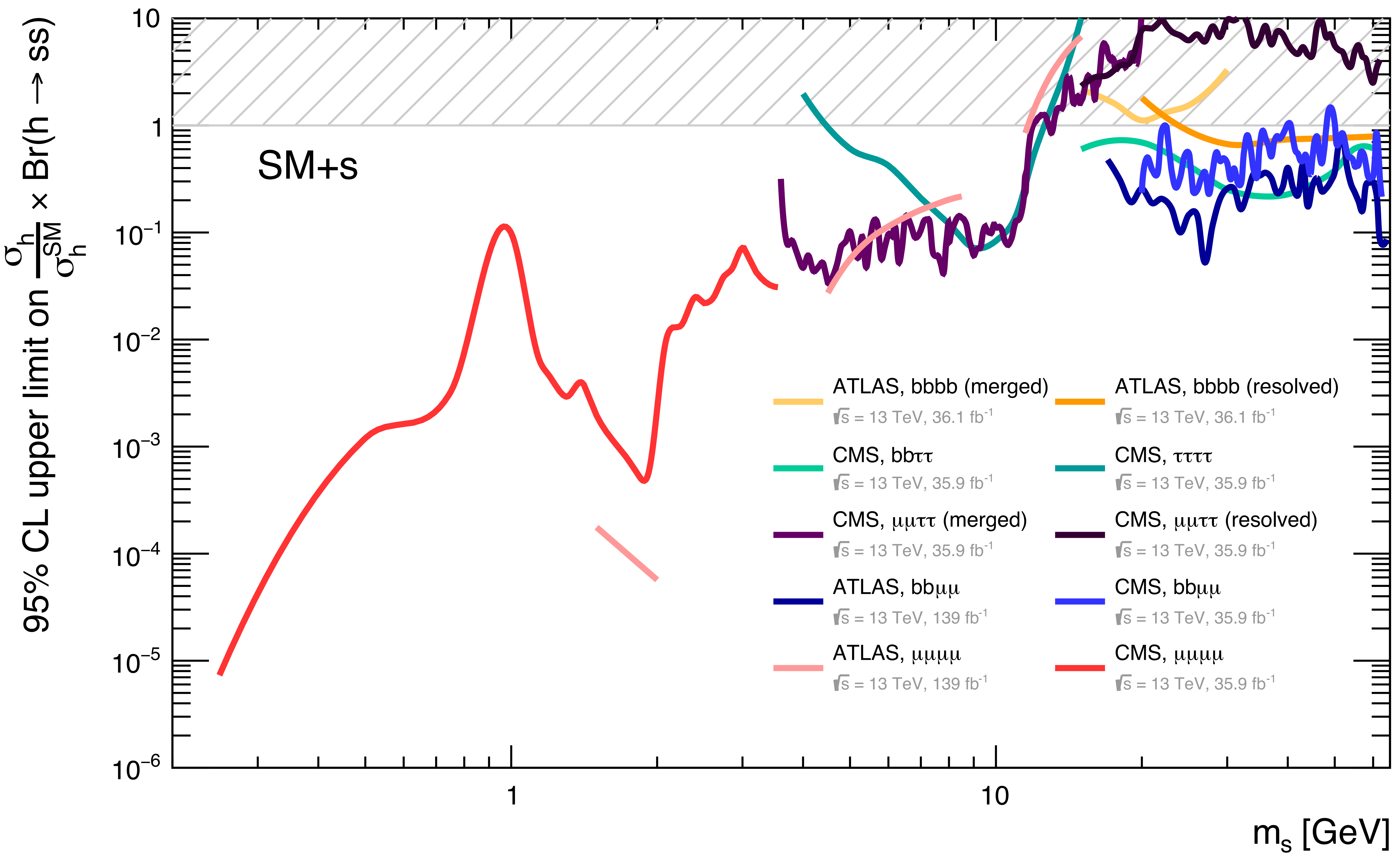
Gershtein Y, Knapen S, Redigolo D. Phys. Lett. B 823:136758 (2021)

- For m_s<20 GeV —> best prediction is in PLB 823:136758 (2021): includes decays to hadrons, particularly pions and kaons
- For ms>=20 GeV —> 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

SM+s

- Incorporating the model-dependent decay branching ratio BR(s→SM)
  - Interplay between the decays already discussed by Alexis this morning!
- **Searches focus on the heaviest particles kinematically allowed in the decay: three distinct mass ranges: <$2m_\tau$, $2m_\tau$-$2m_b$, >=$2m_b$**
- **Lowest mass reach in 4μ.**
- 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

Status of ATLAS+CMS searches for h->ss in 2021: only Run2



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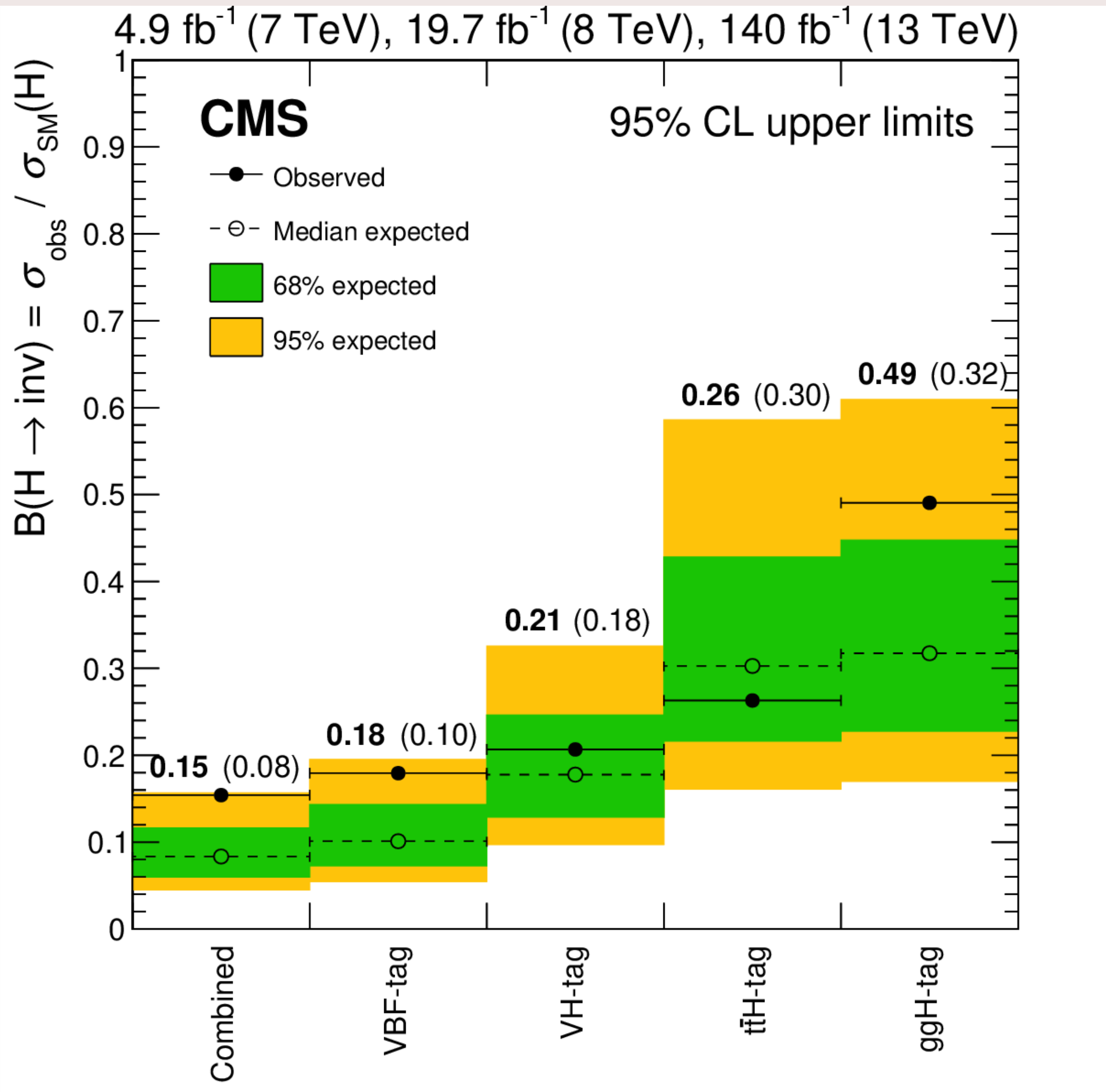
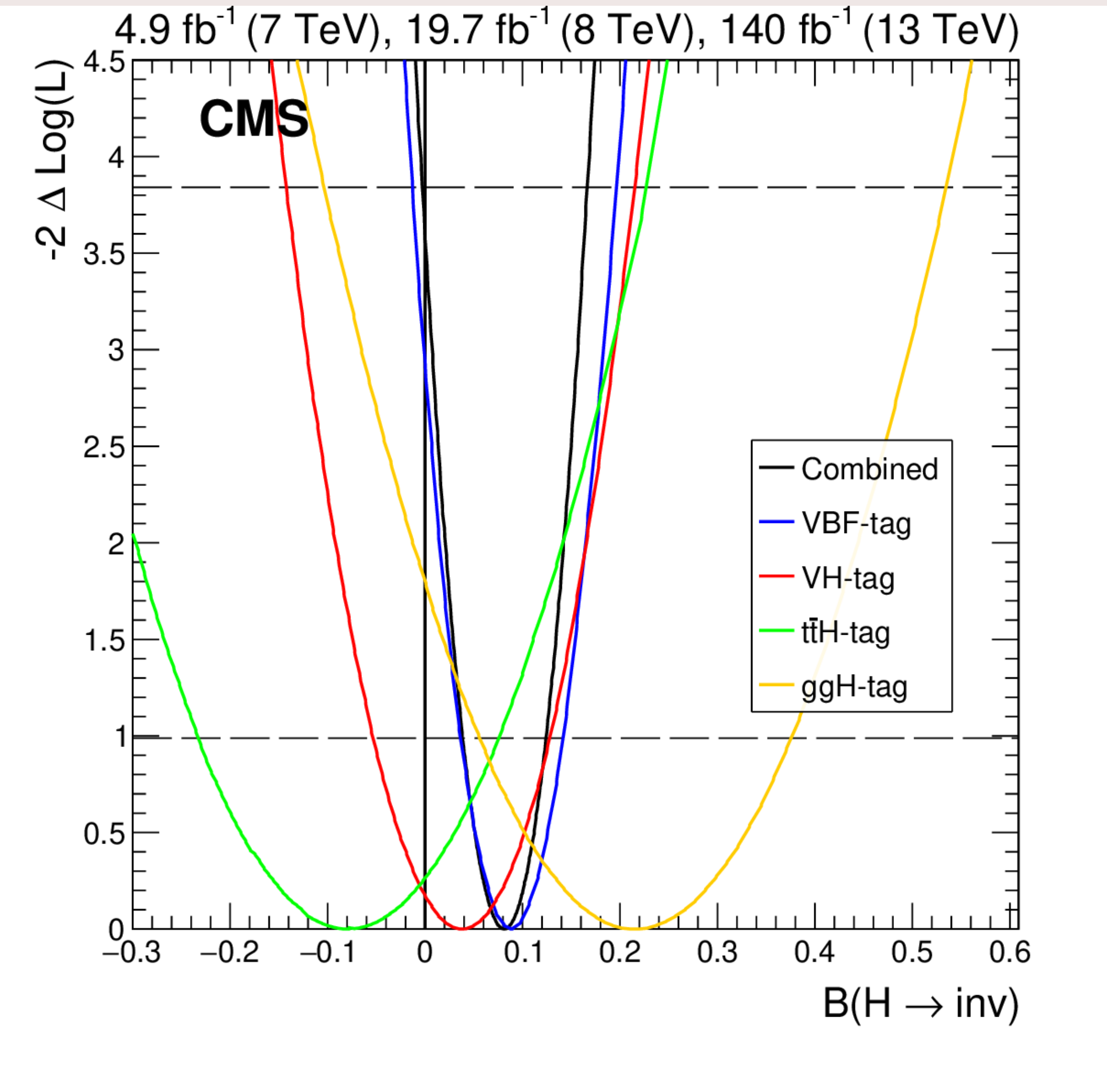
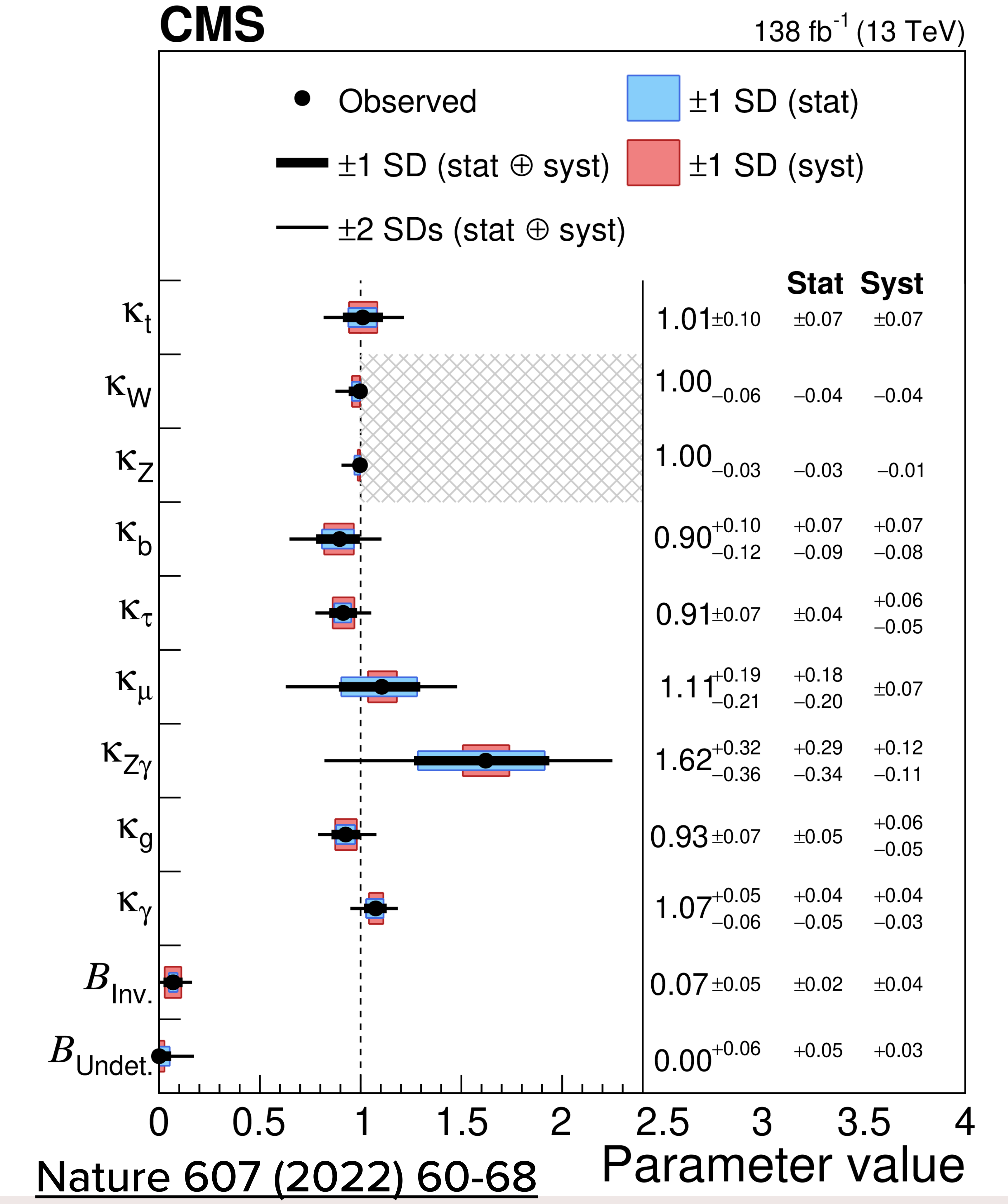
How well we know BR(Higgs→BSM)?

- We derive constraints on the Exotic Higgs Branching ratio from the existing SM Higgs measurements
- Since at LHC we have no direct measurement of the width, to probe the BSM BR an additional constrain needs to be imposed. Usually, $|\kappa_V| \leq 1$

Higgs Invisible: from direct searches Eur. Phys. J. C 83 (2023) 933

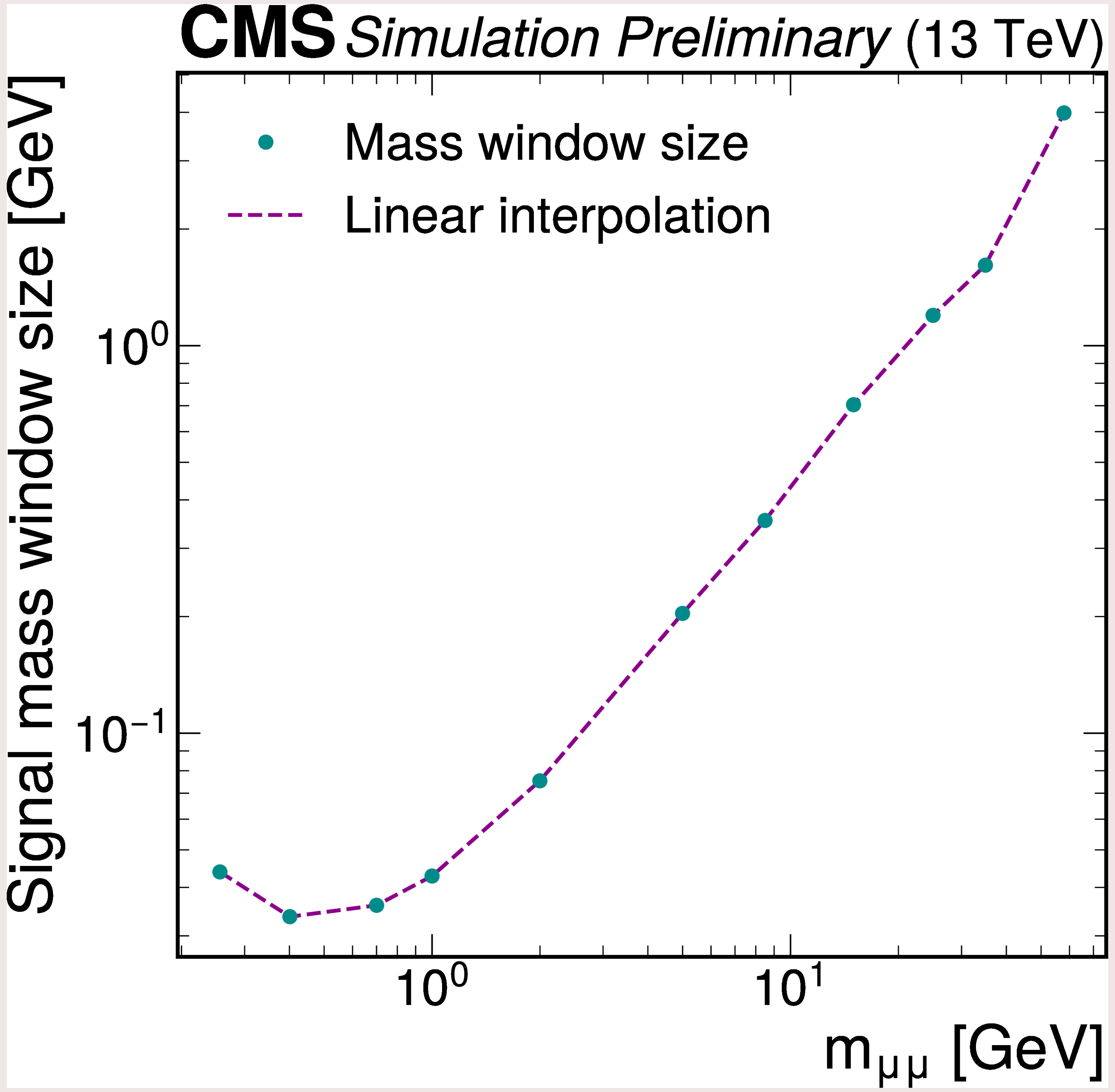






Nature 607 (2022) 60-68

Mass Window Size



The mass window size as a function of invariant dimuon mass. It is derived from a Crystal Ball function fitting to MC signal events to contain 90% of events. The wider mass window size below 0.4 GeV is due to deteriorating mass resolution for near-collinear dimuon in decays of low-mass boson.

Uncertainties in 4μ search

Source of uncertainty	Value 2017	Value 2018
Experimental signal uncertainties		
Integrated luminosity	2.3%	2.5%
Muon ID	$4 \times 0.6\%$	$4 \times 0.6\%$
Dimuon isolation	$2 \times 0.1\%$	$2 \times 0.1\%$
Reco. of close muons in tracker (signal mass < 9 GeV)	$2 \times 1.2\%$	$2 \times 1.2\%$
Reco. of close muons in muon system (signal mass < 9 GeV)	$2 \times 1.3\%$	$2 \times 1.3\%$
Muon HLT	0.9%	0.6%
Reconstruction of displaced track/vertex	—	$2 \times 0.5\%$
PU distribution	0.1%	0.05%
PU effect	2.3%	1.8%
Dimuon mass consistency	0.24%	0.24%
Experimental background uncertainties below J/ψ (0.21–2.72 GeV)		
Normalization	14.2%	10.1%
Systematic	6.6%	4.1%
Experimental background uncertainties above J/ψ and below Υ (3.24–9 GeV)		
Normalization	73.5%	12.3%
Systematic	5.9%	1.5%
Experimental background uncertainties above Υ (11–60 GeV)		
Normalization	6.9%	16.4%
Systematic	1.2%	2.3%
Shape	23.6%	36.7%
Theoretical signal uncertainties		
PDF + α_S + QCD scales	8%	8%
Higgs cross-section and BR[a]	3.8%	3.8%
NNLO Higgs p_T re-weighting[a]	2%	2%

[a]Uncertainty is not used in the vector portal model.

Selection for 4μ search

Selection	Additional information	Requirement 2017	Requirement 2018
Signal muon candidates		4 PF loose muons	$\geq$3 PF loose muons and $\leq$1 SA muon
p_T ($\|\eta\|$)	2 signal muons	$p_T > 13\,\text{GeV}$ ($\|\eta\| < 2.0$)	$p_T > 24\,\text{GeV}$ ($\|\eta\| < 2.0$)
	All 4 signal muons	$p_T > 8\,\text{GeV}$ ($\|\eta\| < 2.4$)	$p_T > 8\,\text{GeV}$ ($\|\eta\| < 2.4$)
Invariant mass	Each dimuon	$m_{\mu\mu_i} < 60\,\text{GeV}$	$m_{\mu\mu_i} < 60\,\text{GeV}$
Fitted dimuon vertex probability	Each dimuon	$P_{\mu\mu_i} > 0.15$	$P_{\mu\mu_i} > P(L_{xy}, \Delta R, N_{\text{SA}})$
Dimuon isolation	Each dimuon	$\text{Iso}_{\mu\mu_i} < 2.3\,\text{GeV}$ ($\Delta R < 0.4$)	$\text{Iso}_{\mu\mu_i} < 2.3\,\text{GeV}$ ($\Delta R < 0.4$)
Fiducial volume	Each dimuon	N/A	$L_{xy} < 16.0\,\text{cm}$ $L_z < 51.6\,\text{cm}$

Region	Quantity	Year 2017	Year 2018
Below J/ψ	Obs. events in CR	49	98
	Exp. events in SR	$2.62 \pm 0.32\,(\text{stat}) \pm 0.14\,(\text{syst})$	$4.34 \pm 0.44\,(\text{stat}) \pm 0.18\,(\text{syst})$
Above J/ψ, Below Υ	Obs. events in CR	2	66
	Exp. events in SR	$0.19 \pm 0.14\,(\text{stat}) \pm 0.01\,(\text{syst})$	$6.16 \pm 0.76\,(\text{stat}) \pm 0.09\,(\text{syst})$
Above Υ	Obs. events in CR	212	143
	Exp. events in SR	$18.10 \pm 1.23\,(\text{stat}) \pm 4.49\,(\text{syst})$	$13.81 \pm 1.16\,(\text{stat}) \pm 5.39\,(\text{syst})$

Search for Vh, h → aa → 4b

- One control region for each signal region
  - Lower number of b-tagged jets
- tt & V+jets background
  - Categorised in jet flavour (at particle level)
  - Shape estimated from simulation
  - Normalisation constrained by data in CR
- Multijet background
  - Inverted lepton isolation requirement
  - Sideband to extract normalisation

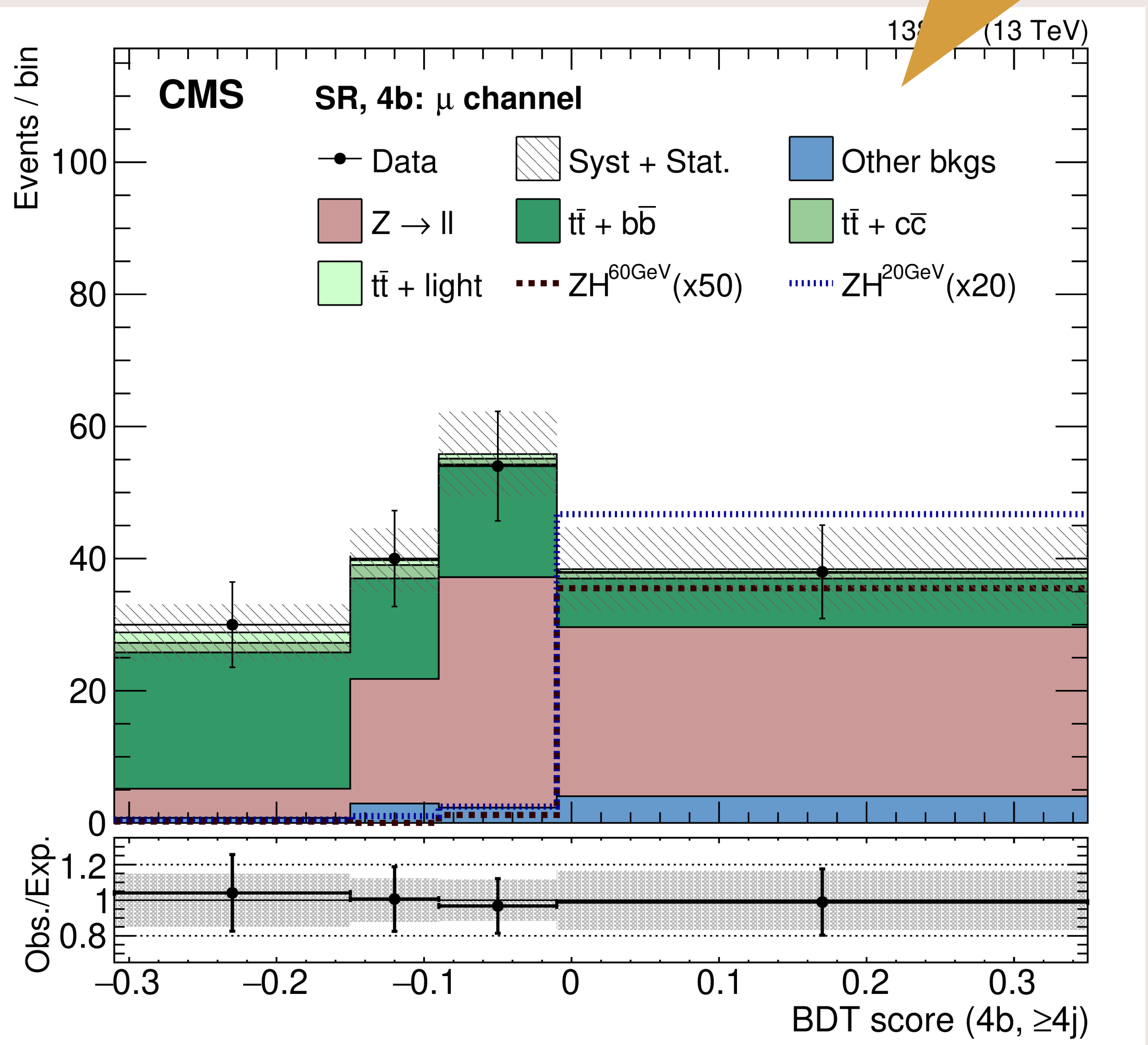
Label	(N_b, N_j)	Description
	WH channel	
SR (3b)	(3b, 3–4j)	3b signal region
SR (4b)	(4b, 4j)	4b signal region
CR (3b)	(2b, 3j)	$W/t\bar{t}$+jets control region
CR (4b)	(2b, 4j)	$t\bar{t}$+jets control region
	ZH channel	
SR (3b)	(3b, $\geq$3j)	3b signal region
SR (4b)	(4b, $\geq$4j)	4b signal region
CR (3b)	(2b, 3j)	DY control region
CR (4b)	(2b, 4j)	DY control region

SUBMITTED

Search for Vh, h → aa → 4b

- Probes the mass range 15 < m_a < 60 GeV
- Associated production: ZH and WH:
  - Leptonic decays of V: single and dilepton signatures
  - In WH: m_T> 50 GeV to suppress QCD
  - In ZH: consistency with Z mass to suppress ttbar
- Signal regions based on btagging and jet multiplicity:
  - 4b: resolved
  - 3b: boostd + failed reconstruction
- Data driven techniques to estimate backgrounds
- Selection and Signal extraction based on BDT

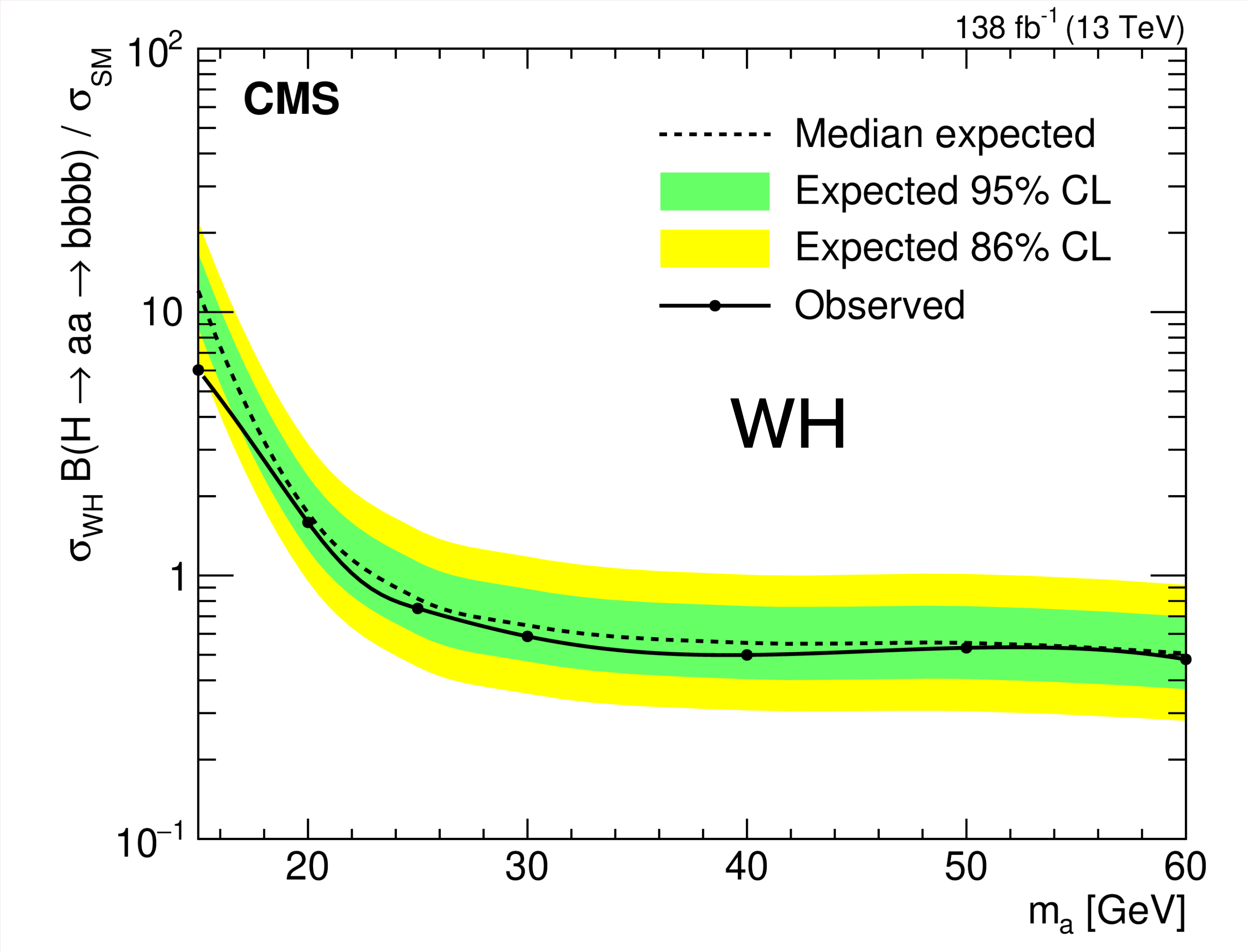
HIG-18-026, arXiv:2403.10341

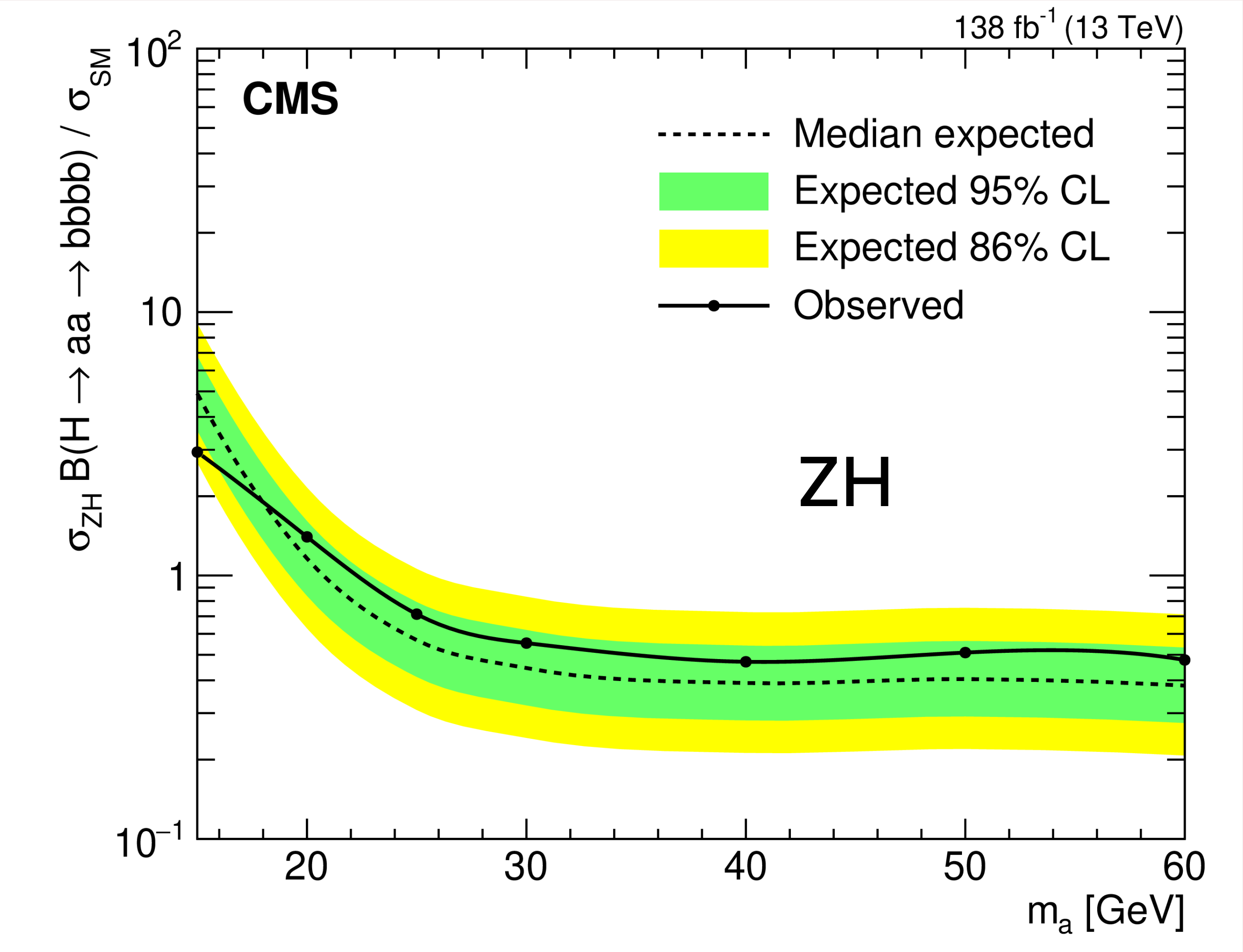


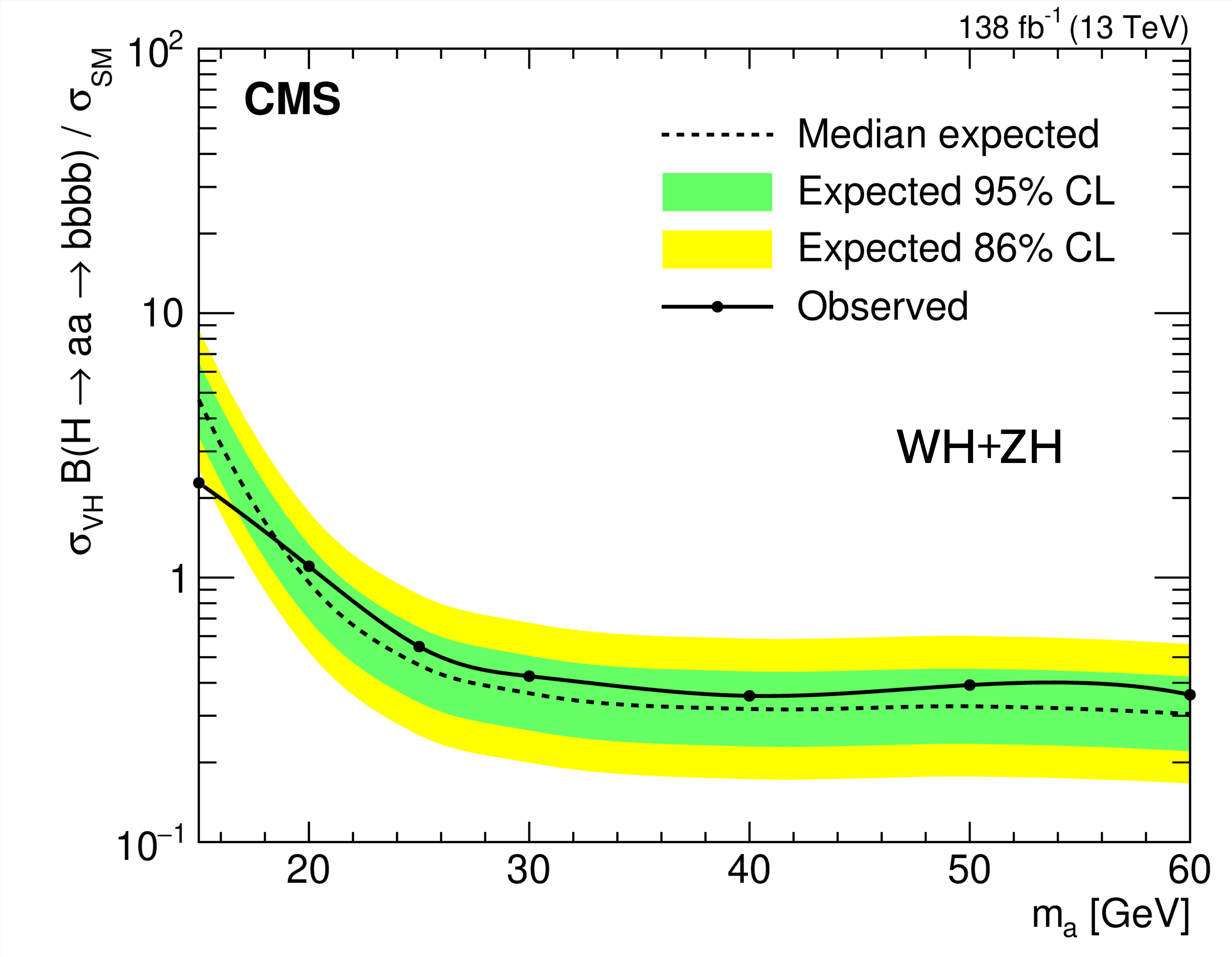
Label	(N_b, N_j)	Description
	WH channel	
SR (3b)	(3b, 3–4j)	3b signal region
SR (4b)	(4b, 4j)	4b signal region
CR (3b)	(2b, 3j)	W/tt̄+jets control region
CR (4b)	(2b, 4j)	tt̄+jets control region
	ZH channel	
SR (3b)	(3b, ≥3j)	3b signal region
SR (4b)	(4b, ≥4j)	4b signal region
CR (3b)	(2b, 3j)	DY control region
CR (4b)	(2b, 4j)	DY control region

Search for Vh, h → aa → 4b

- Good agreement with the SM expectation within the uncertainties
- The combined result for the associated WH and ZH Higgs boson production excludes branching fractions as low as 0.36 in the mass range 25 GeV-60 GeV
- Complementary to $\mu\mu\tau\tau$ and bbll searches







PUBLISHED

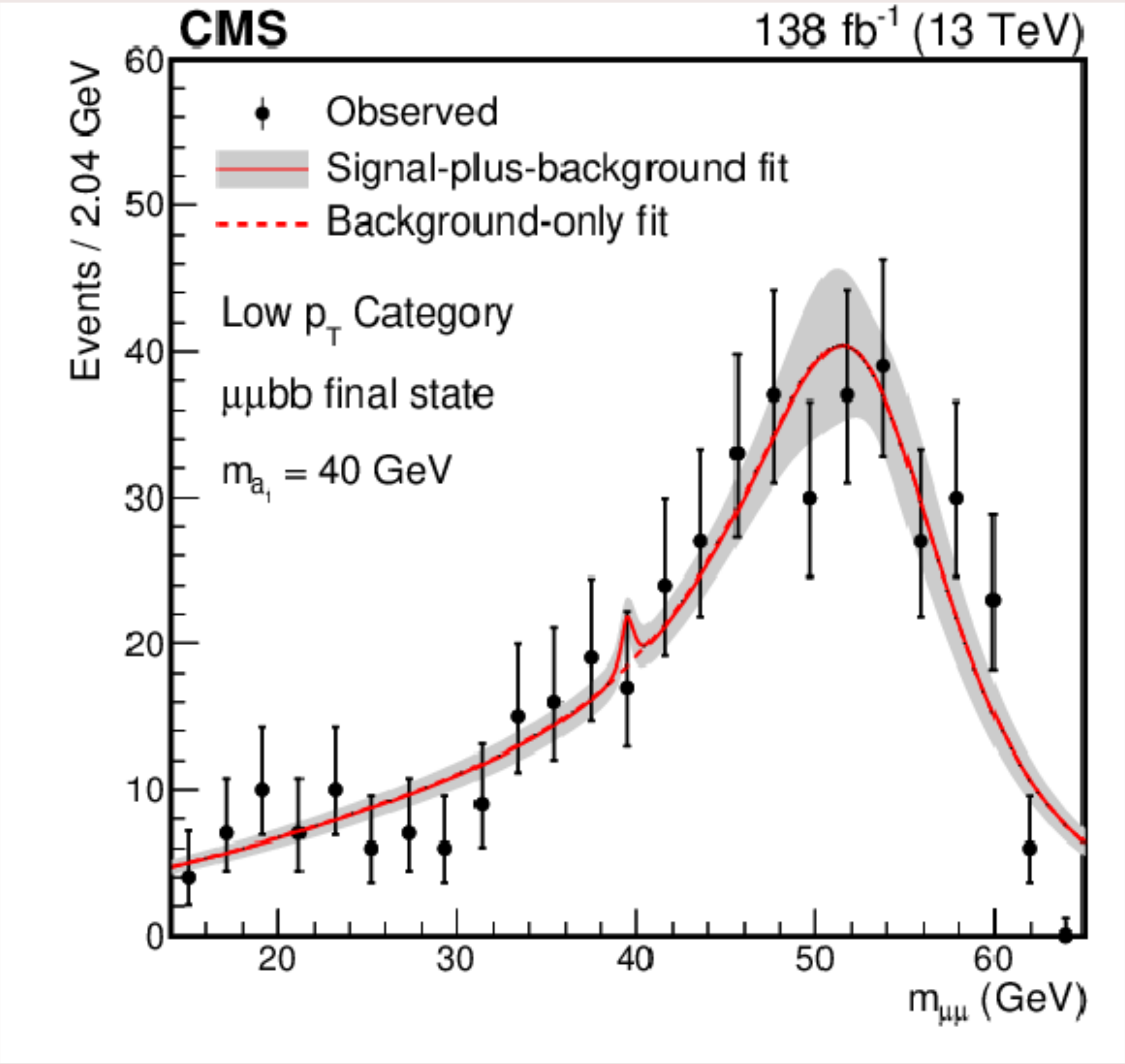
Search for h → aa → 2l2b

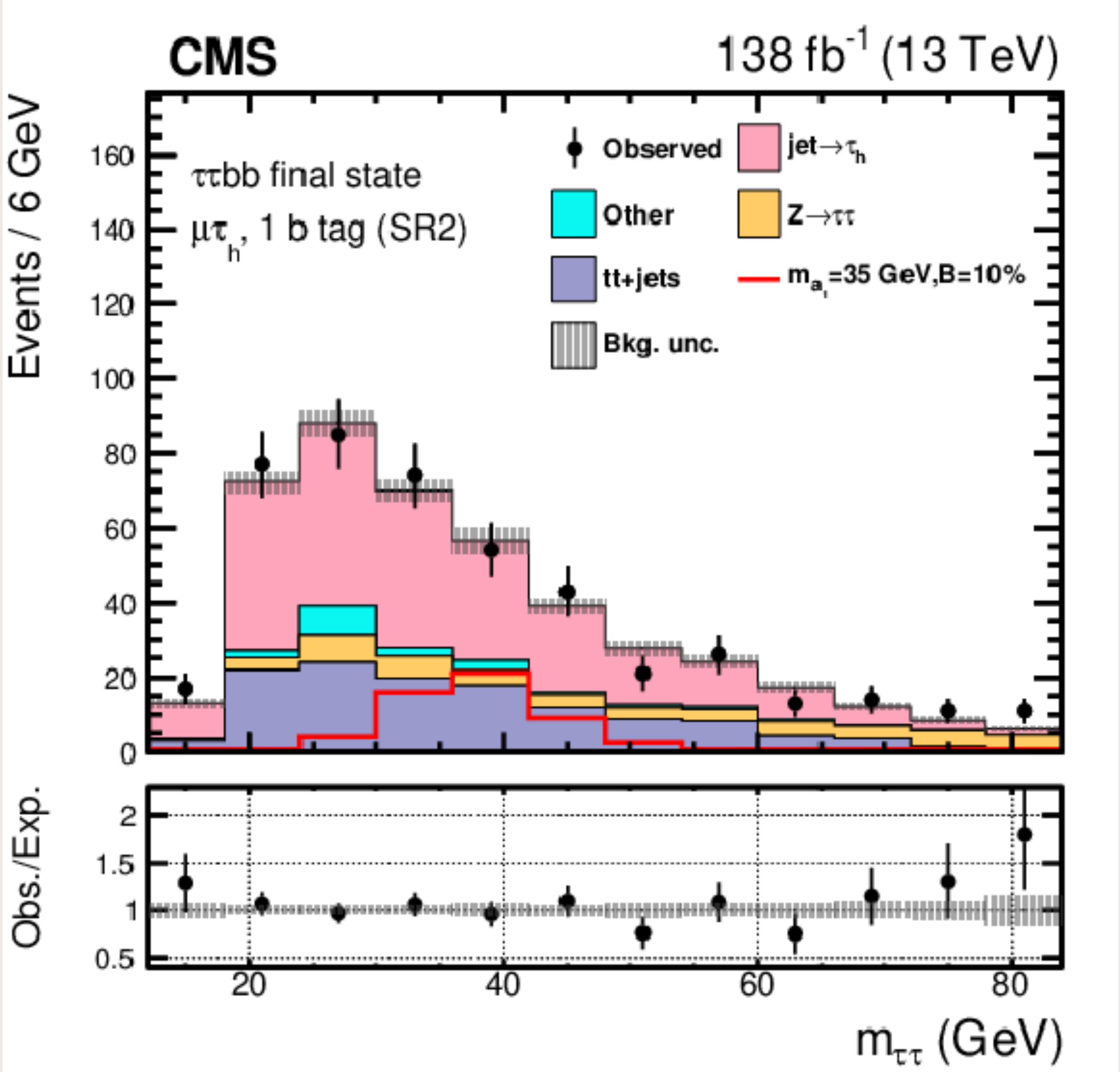
Mass range: 12-60 GeV

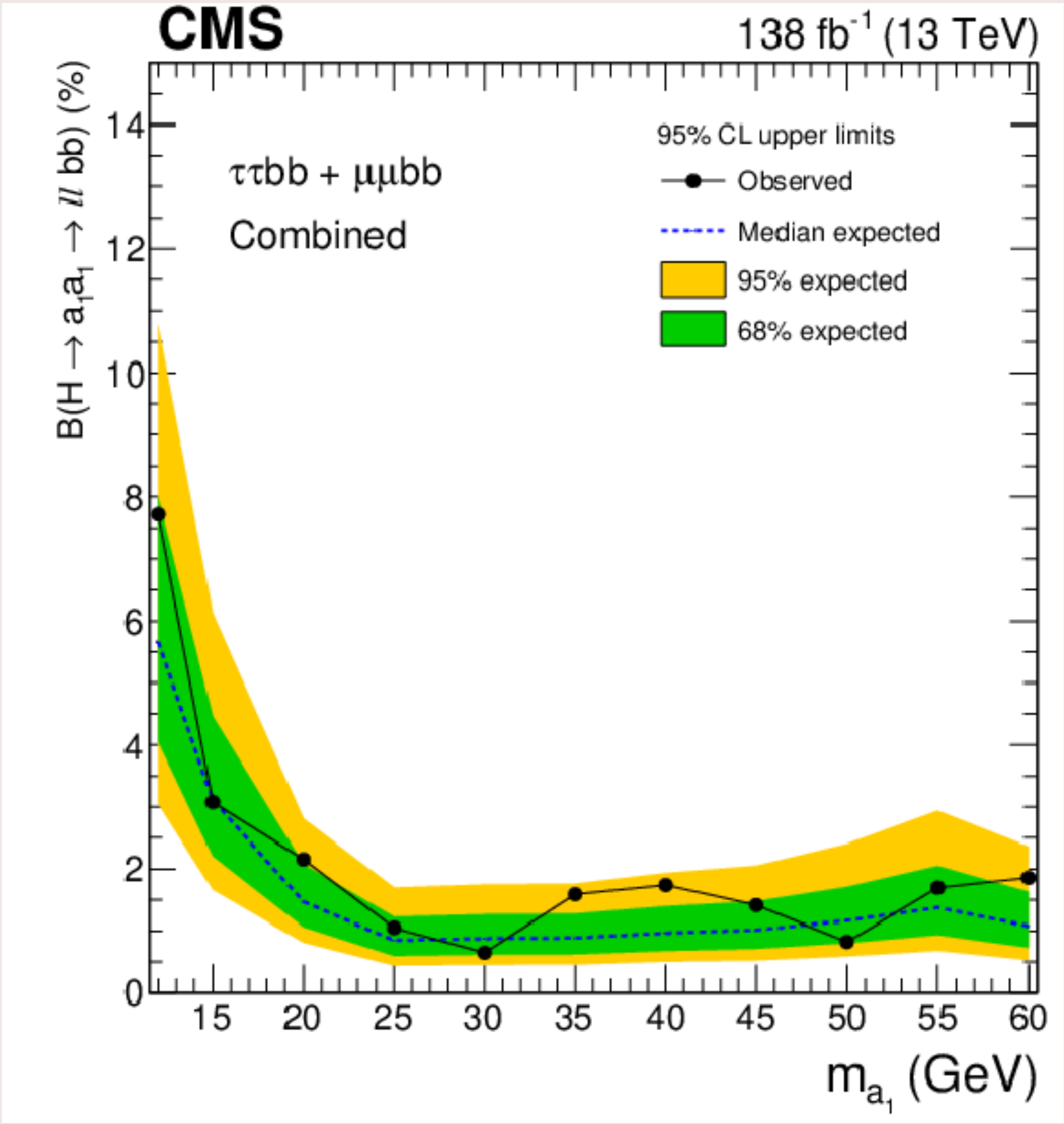
$\mu\mu$bb + $\tau\tau$bb

Eur. Phys. J. C 84 (2024) 493

- Model independent limit in terms of B(h—>aa—>llbb)
- Upper bounds on 2HDM+S B(H->aa). B(h->aa) values above 23% excluded at 95% CL for most of the parameter space between 15 GeV and G0 GeV.







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
- Phys. Rev. Lett. 131 (2023) 101801 : specific merged diphoton reconstruction —> VERY low mass probed