Light BSM Higgs boson searches

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in collaboration with
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Overview

- Look at searches for a light Higgs boson
  - CMS: 4τ
  - ATLAS: $2\mu 2\tau$
- Interpretation in the context of the NMSSM

NMSSM

- ***NMSSM***: ***N***ext-to-***M***inimal ***S***upersymmetric ***S***tandard ***M***odel
  - = MSSM + singlet/ino S + parameters λ, κ - parameter μ
- Keeps attractive features of MSSM
  - Solve Hierarchy problem, DM candidate…
- Fixes issues in MSSM
  - μ-problem → dynamically generate μ with ⟨S⟩, now scale independent
  - "little" fine-tuning problem → extra term ~ κ to ease fine-tuning
- More Higgses: $h_{1,2,3}$ (CP-even), $a_{1,2}$ (CP-odd), $h^{\pm}$ → $\mathbf{h_{125} = h_1}$ **or** $\mathbf{h_2}$

Motivation

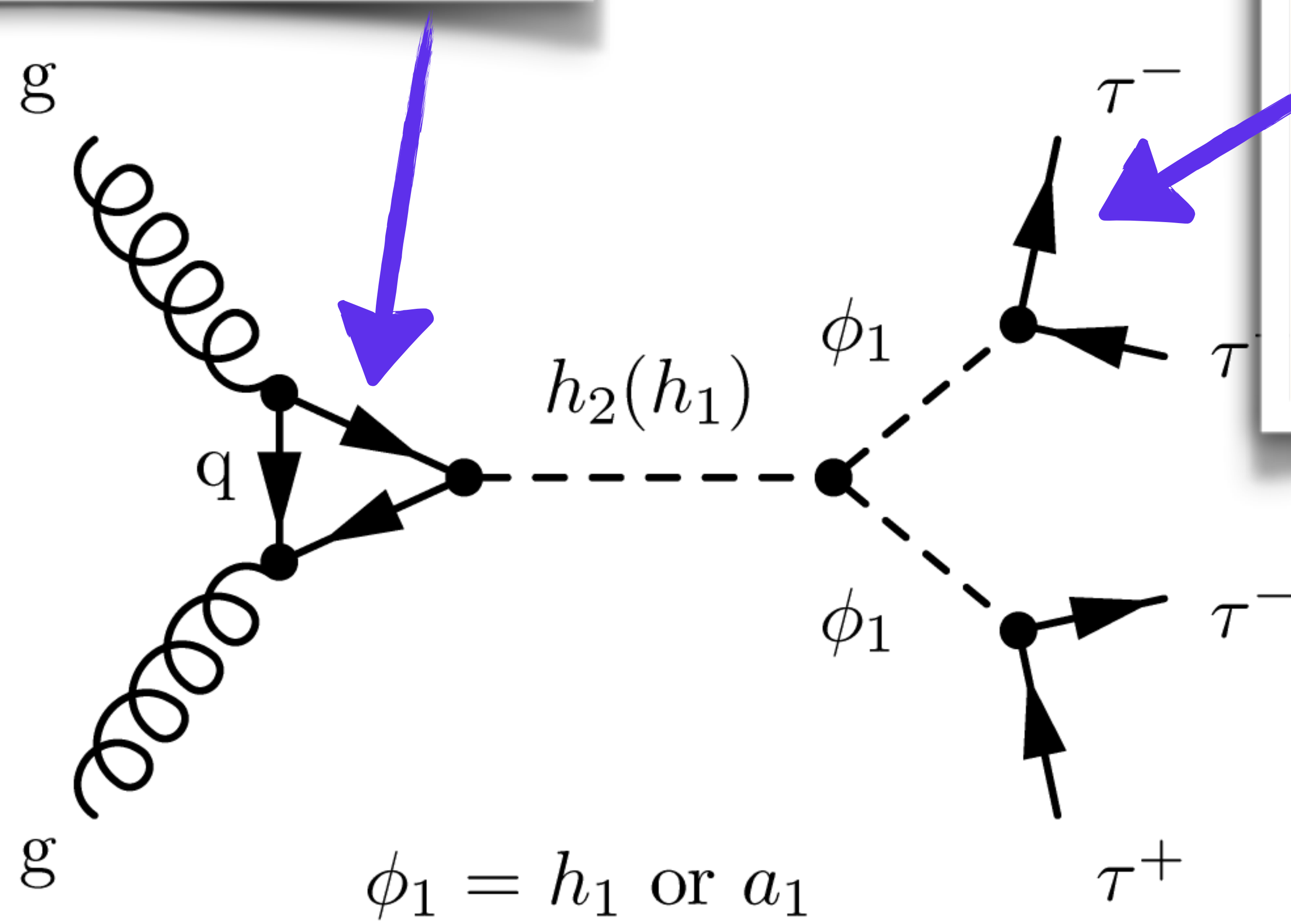
- Consider scenario where a_1 or h_1 ($\equiv \phi_1$) is light: $2m_\tau \rightarrow 2m_b$

h (125) = h_1 or h_2, produced via gluon-gluon fusion

BR ($\phi_1 \rightarrow \ell^- \ell^+$) ~ m_ℓ^2

Dominant decay:
$\phi_1 \rightarrow \tau\,\tau$

BR(μμ)/BR(ττ) ~ 0.004



- If $\phi_1 = h_1$: $h_2 \rightarrow 2h_1$
- If $\phi_1 = a_1$: $h_1 \rightarrow 2a_1$ or $h_2 \rightarrow 2a_1$

NMSSM landscape

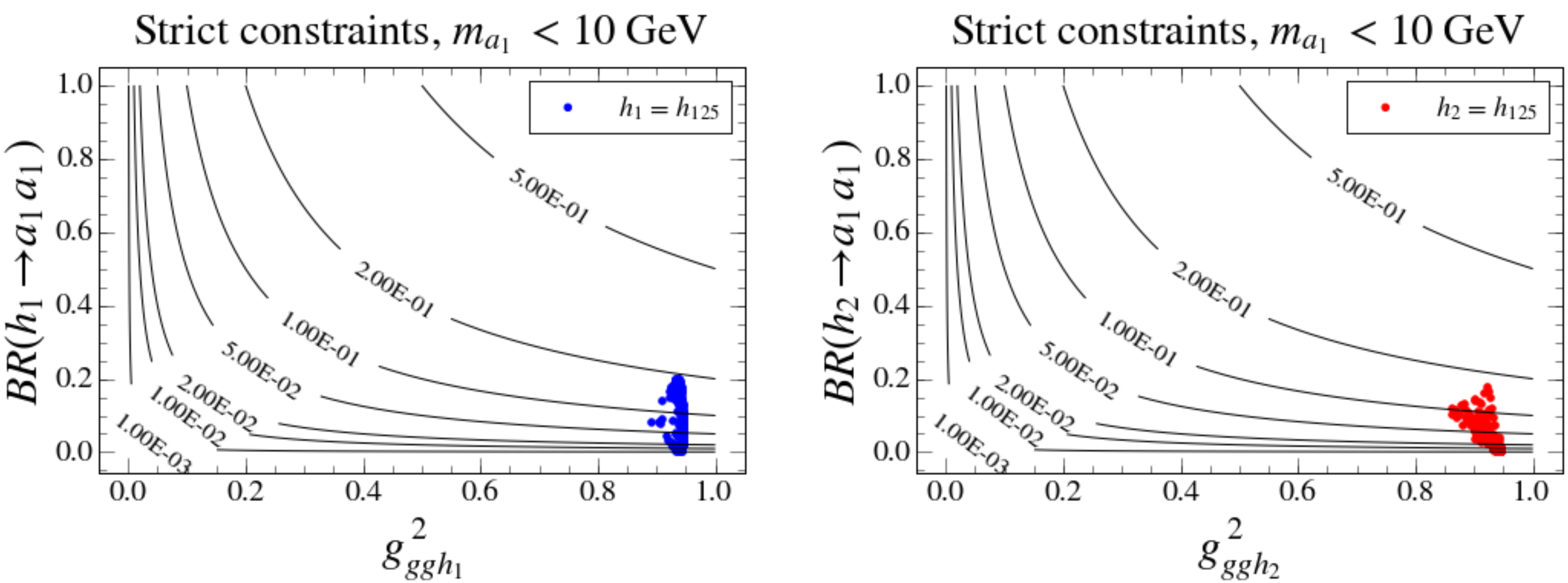
- What can we expect? Decompose the total cross-section × BR:

$$\sigma \times \mathrm{BR} \equiv \sigma^{\mathrm{ggh}}(\mathrm{SM}) \times \mathrm{ggh}^2 \times \mathrm{BR}(h \rightarrow \phi_1\phi_1) \times \mathrm{BR}(\phi_1 \rightarrow \tau\,\tau)^2$$

NMSSM landscape

- When $h_i = h_{125}$:

$$\sigma \times BR \equiv \sigma^{ggh}(SM) \times ggh^2 \times BR(h \to \phi_1\phi_1) \times BR(\phi_1 \to \tau\,\tau)^2$$



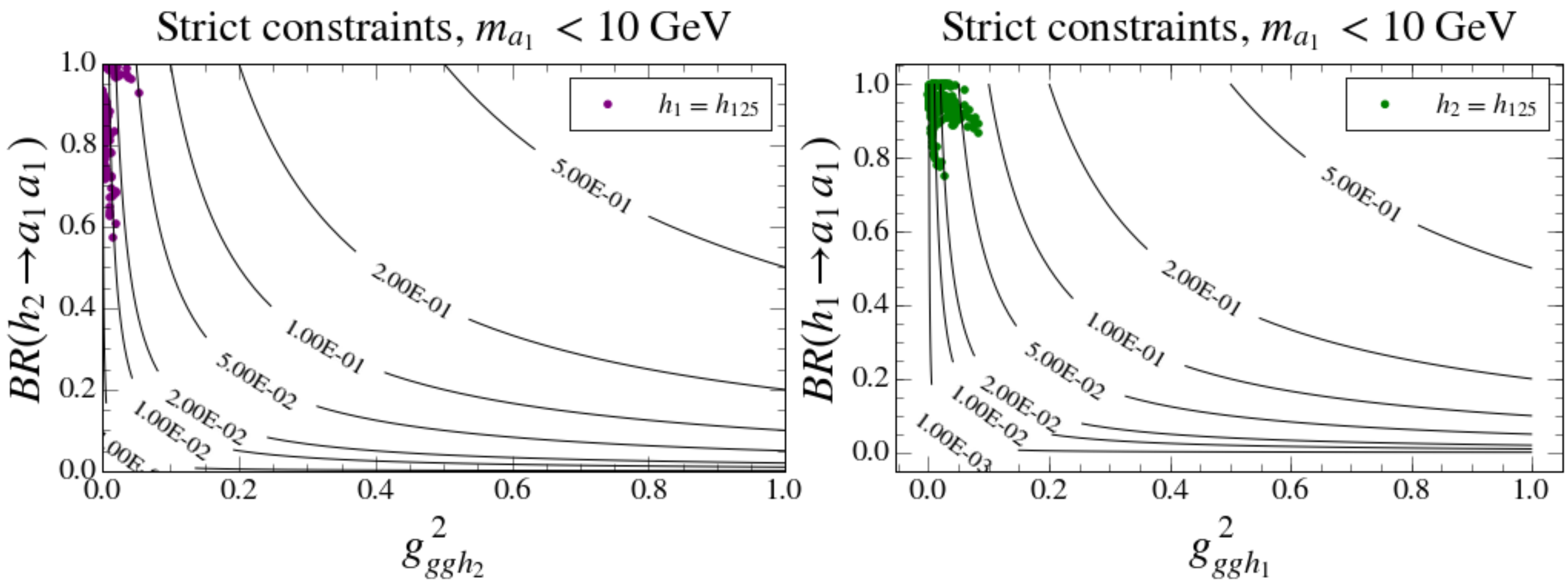
(wrt SM ggh^2 coupling)

Contours of constant ggh × BR
→ always ≲ 0.2
Limited by experimental constraints

NMSSM landscape

- When $h_i \neq h_{125}$:

$$\sigma \times BR \equiv \sigma^{ggh}(SM) \times ggh^2 \times BR(h \to \phi_1\phi_1) \times BR(\phi_1 \to \tau\,\tau)^2$$

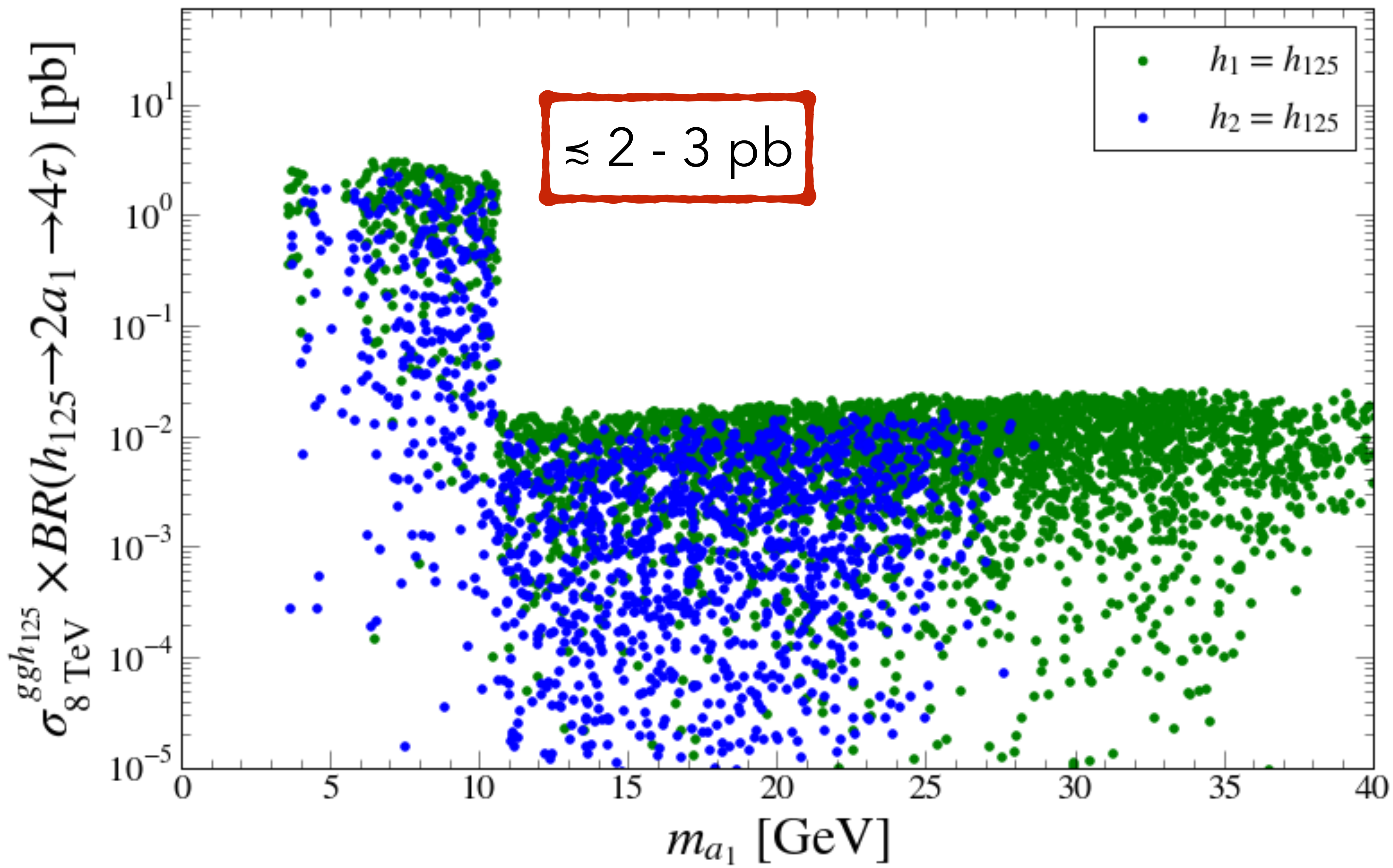


Contours of constant ggh × BR

→ always ≲ 0.07

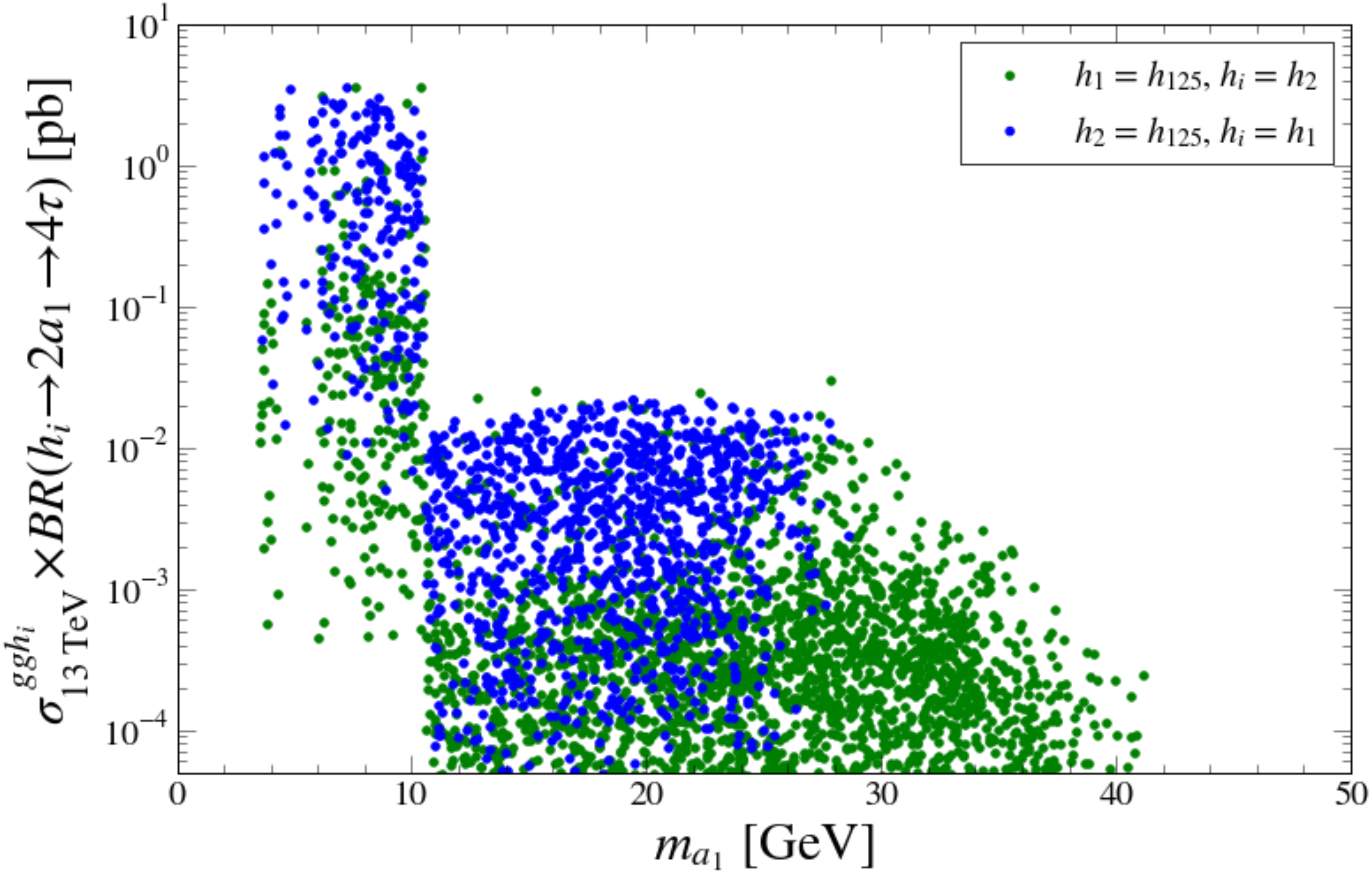
NMSSM landscape

- Total $\sigma \times$ BR ($h_i = h_{125}$):



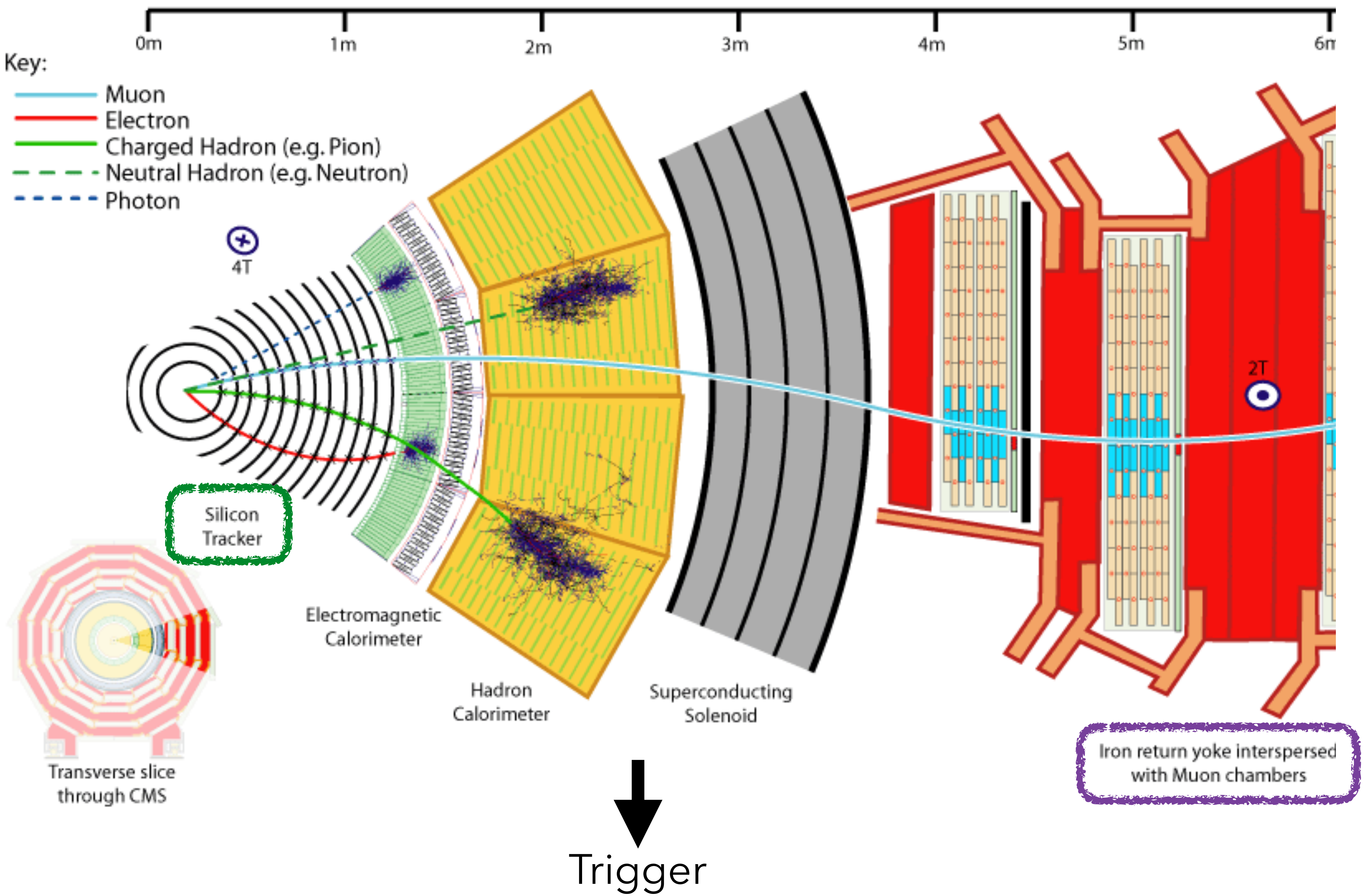
NMSSM landscape

- Total $\sigma \times$ BR ($h_i \neq h_{125}$):



Start searching!

Aside: how CMS detects objects

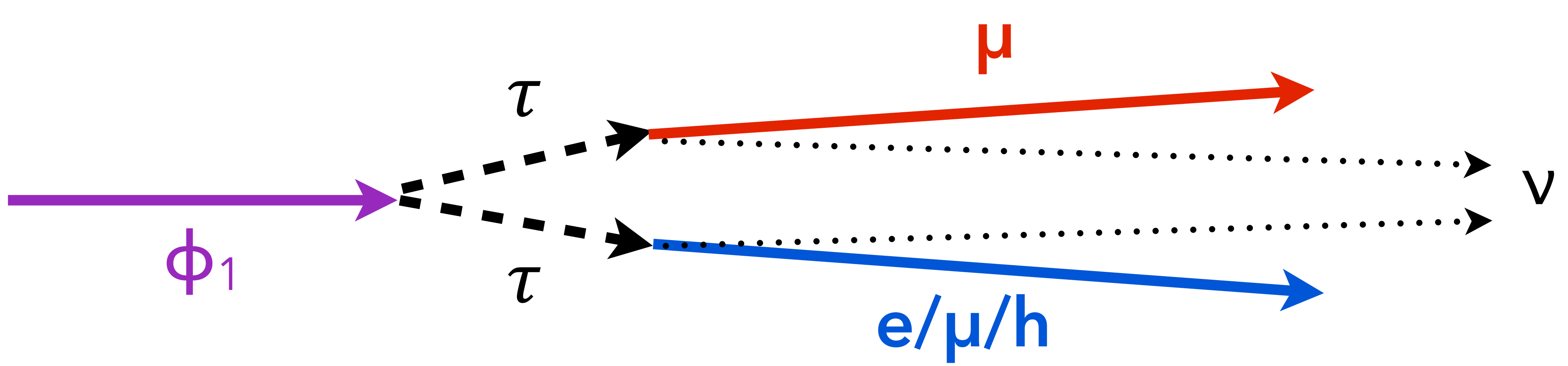


Signal Characteristics

- $m_h >> m_\phi \rightarrow \phi_1$ heavily boosted, tau pair collimated
  - Identifying 2 pairs of overlapping taus non-trivial
- Search strategies to cope with boosted taus:
  - Modify tau ID to remove overlapping particle (CMS HIG-14-022)
  - **Choose an alternative way of identifying taus (CMS HIG-14-019)**
  - Or choose a different decay channel (ATLAS HIGG-2014-02)
- ATLAS search for $2\mu2\tau$
  - Penalised by BR
  - Cleaner dimuon invariant mass spectrum to look for peak

Signal Characteristics

- Use simple objects instead to target 1-prong decays: 1 muon + 1 track
    - One tau in each pair decays to a muon
    - Other tau decays to 1 charged particle

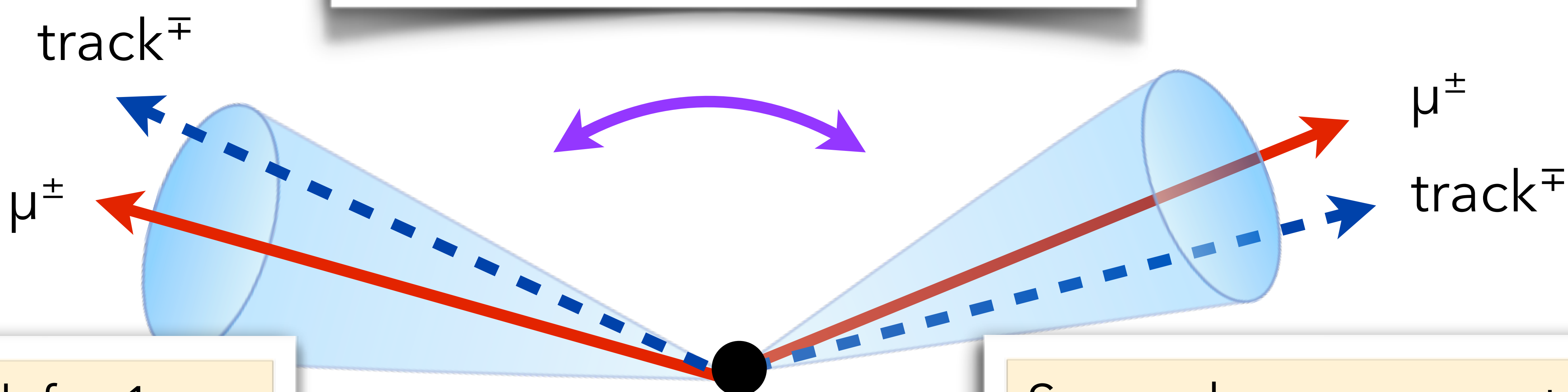


    - Can trigger on 2 muons

Signal Characteristics

Defines our
"signal region"

h (125) has low p_T → require large separation between muons



Look for 1 opposite-charge track close to μ

Same-charge muons to remove backgrounds

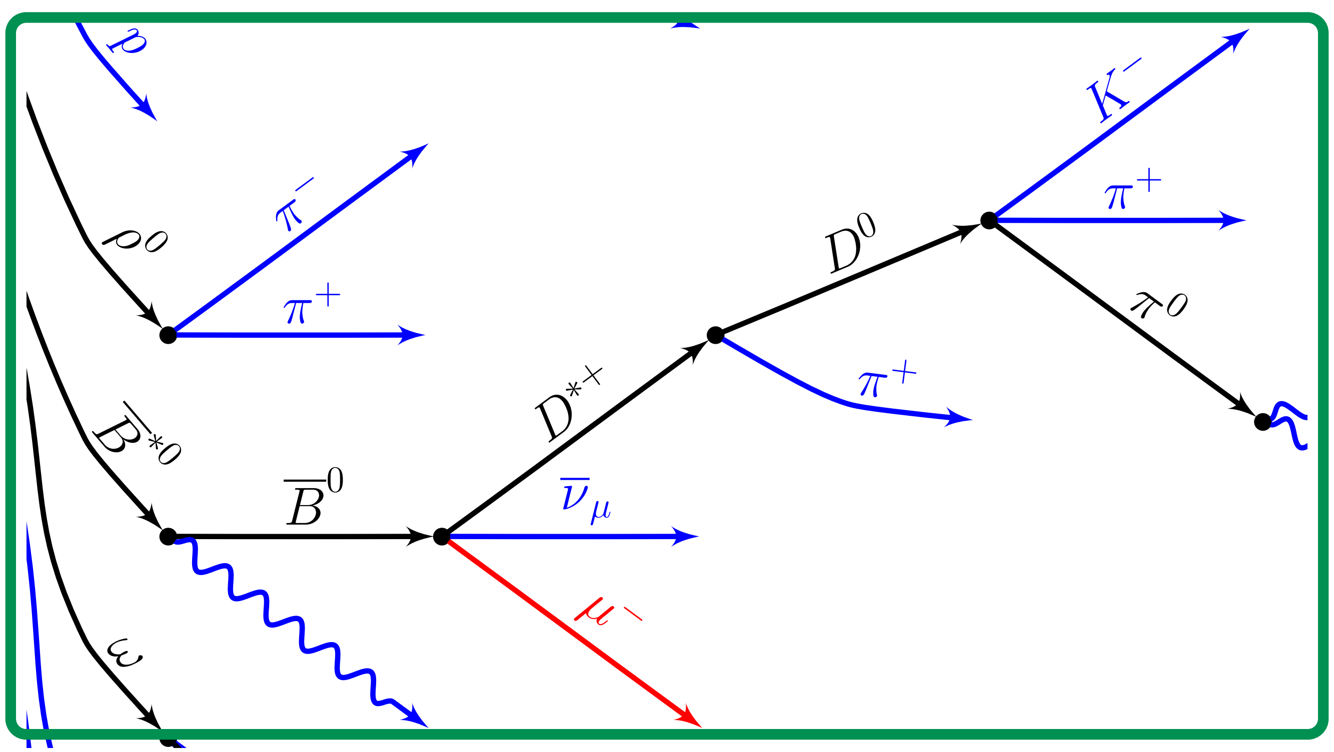
(ℓℓ, ttbar)

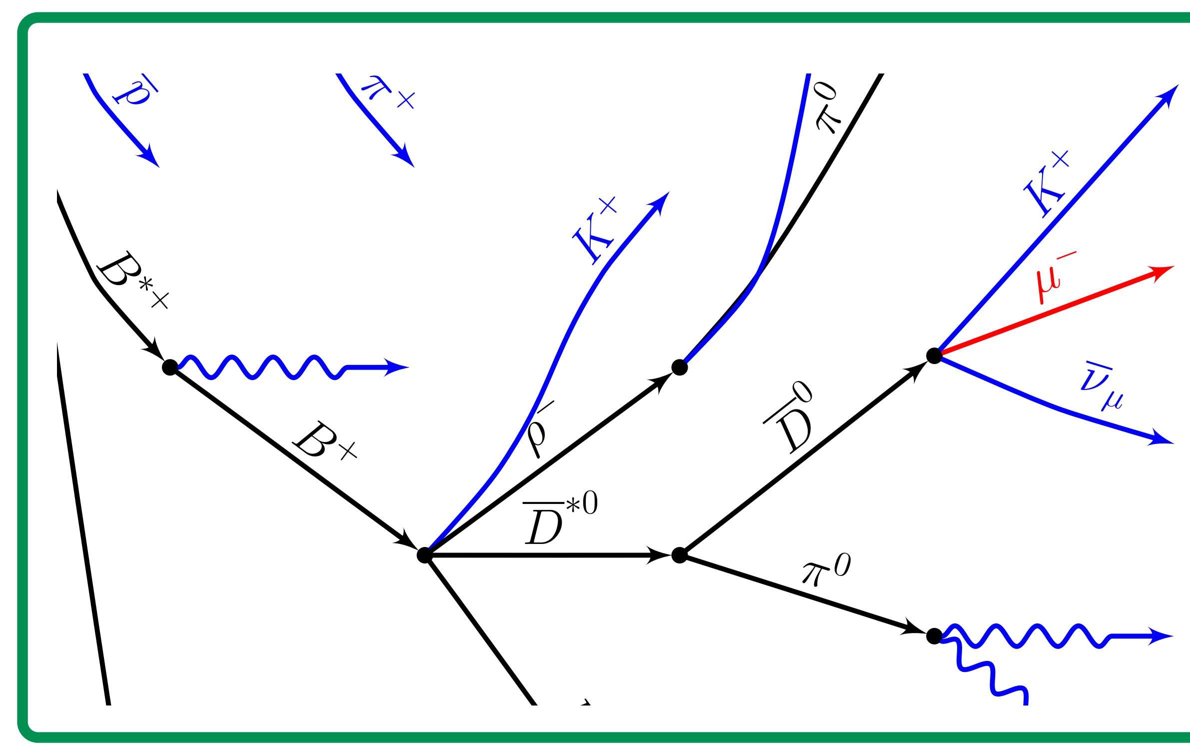
Muon-track "pair" or "system", randomly assign label "1" or "2"

Background

- Backgrounds dominated by QCD events
  - Typically semi-muonic b/c hadron decay from $b\bar{b}$ events
  - Same-charge muons result of: $b \rightarrow c + \mu^- \bar{\nu}_\mu$

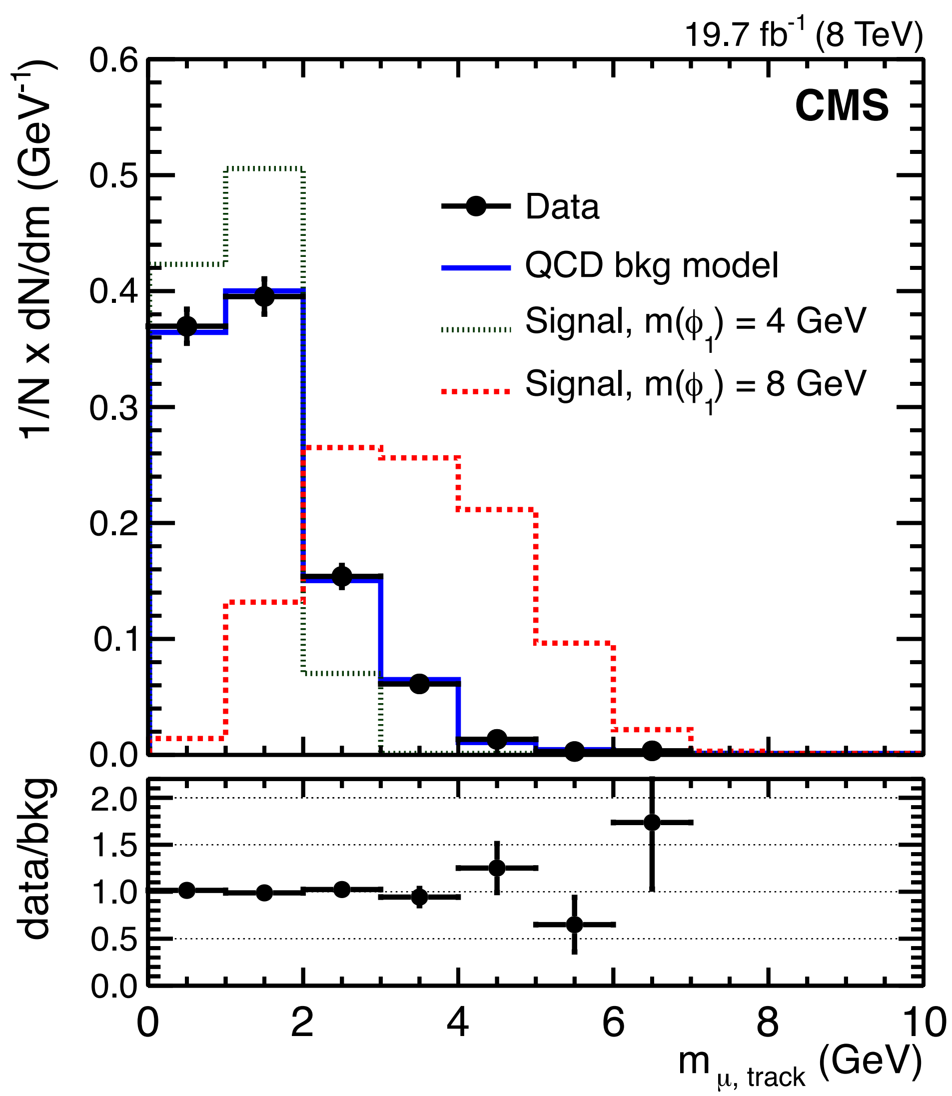
    $\bar{b} \rightarrow \bar{c} \rightarrow \bar{s} + \mu^- \bar{\nu}_\mu$
- Example from PYTHIA8:





Background Estimate

- Use data-driven estimate (lack of MC stats)
- Use **muon-track pair invariant mass (m_i)** as discriminating variable:
    - Use 2D distribution of m_1 vs m_2
    - Get distribution for background events from "sideband" region

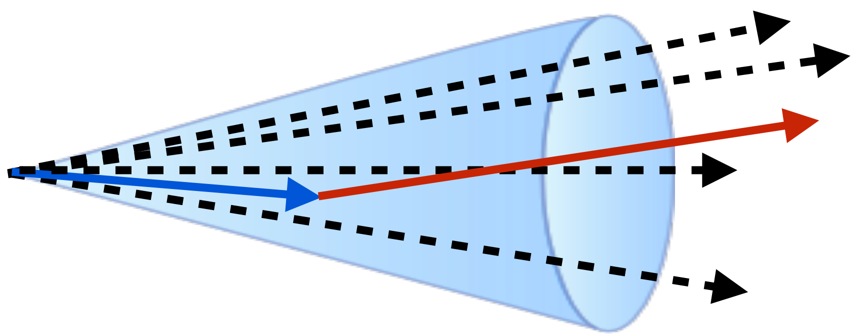


Stronger background rejection for $m_\phi = 8$, less powerful for $m_\phi = 4$

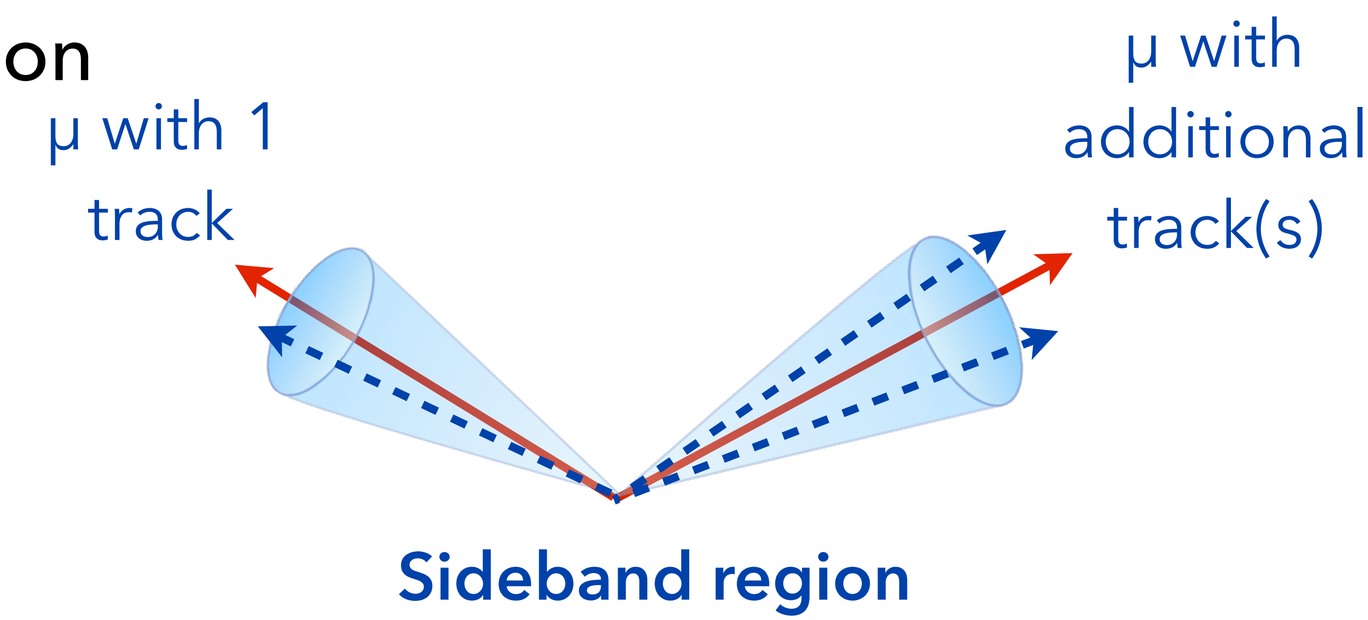
Background Estimate

- Want sideband region rich in QCD events, little signal contamination
  - with similar kinematics to signal region

- QCD events have muon amongst jet of other hadrons/leptons



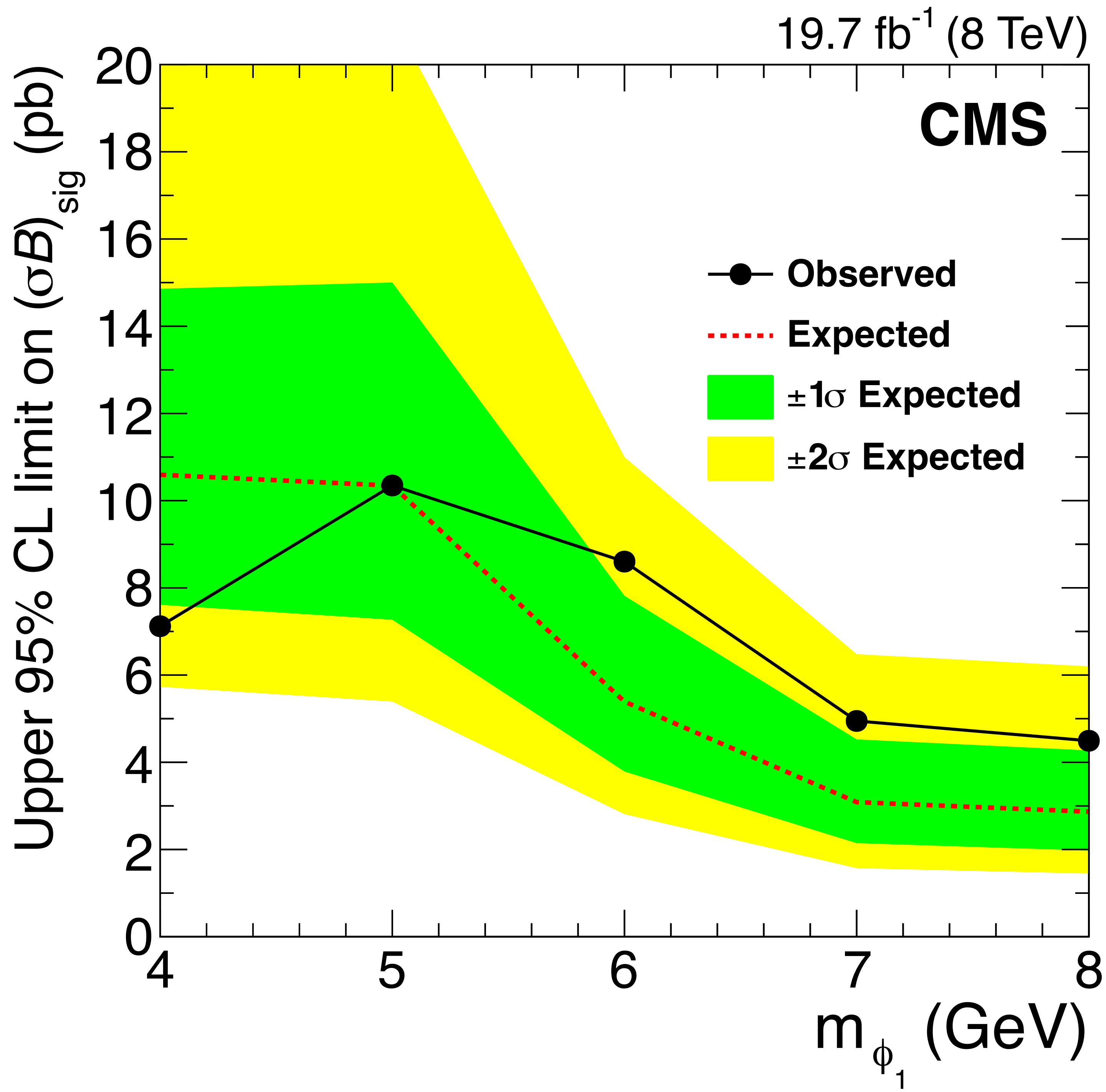
- **Sideband region** = signal selection but allowing 1 or 2 extra tracks around one muon



Limit

- See no significant excess in data → set upper limit on $\sigma \times$ BR

$$(\sigma\mathcal{B})_{\text{sig}} \equiv \sigma(\text{gg} \to \text{H}(125))\,\mathcal{B}(\text{H}(125) \to \phi_1\phi_1)\,\mathcal{B}^2(\phi_1 \to \tau\tau)$$



Limit

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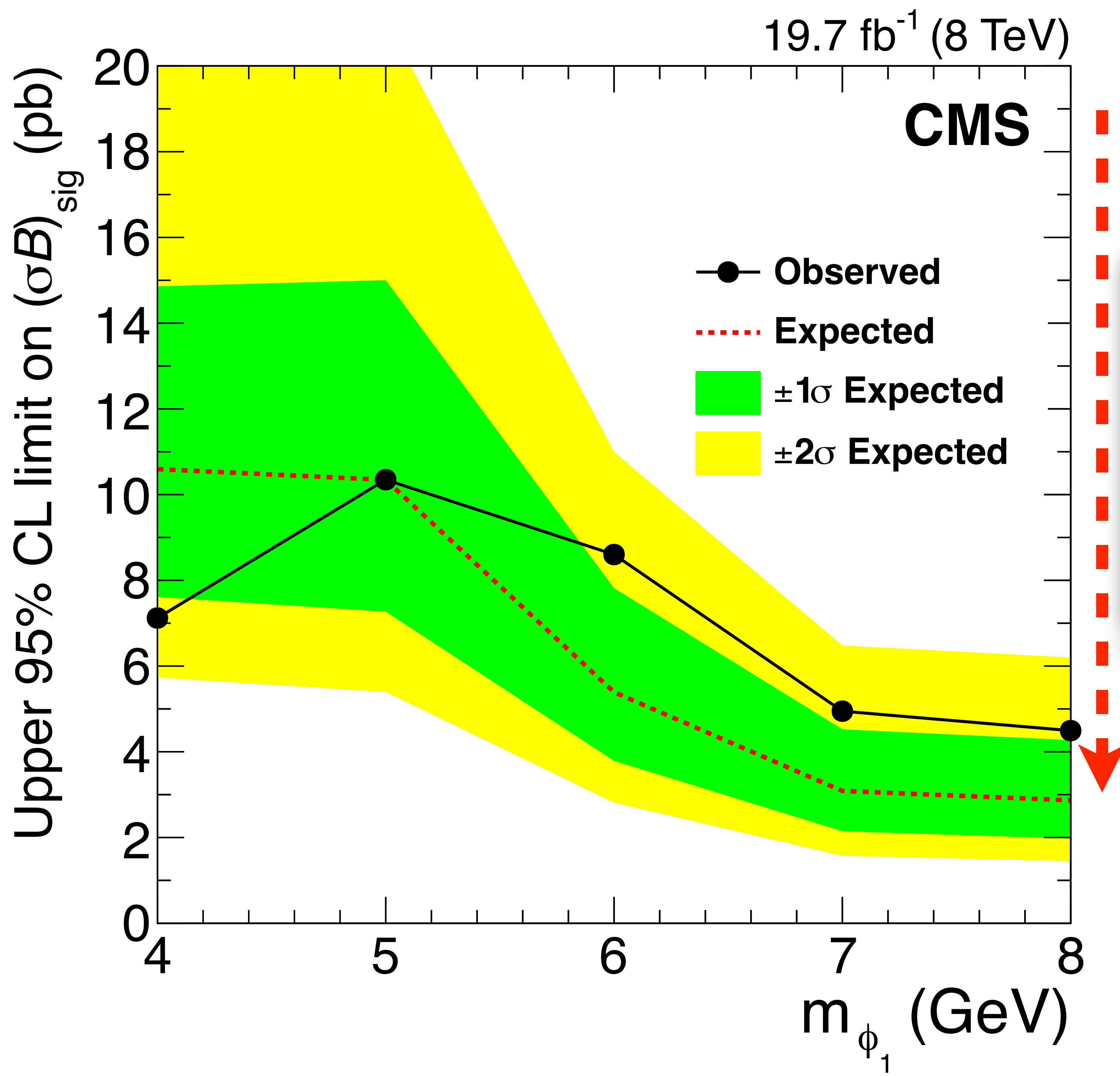
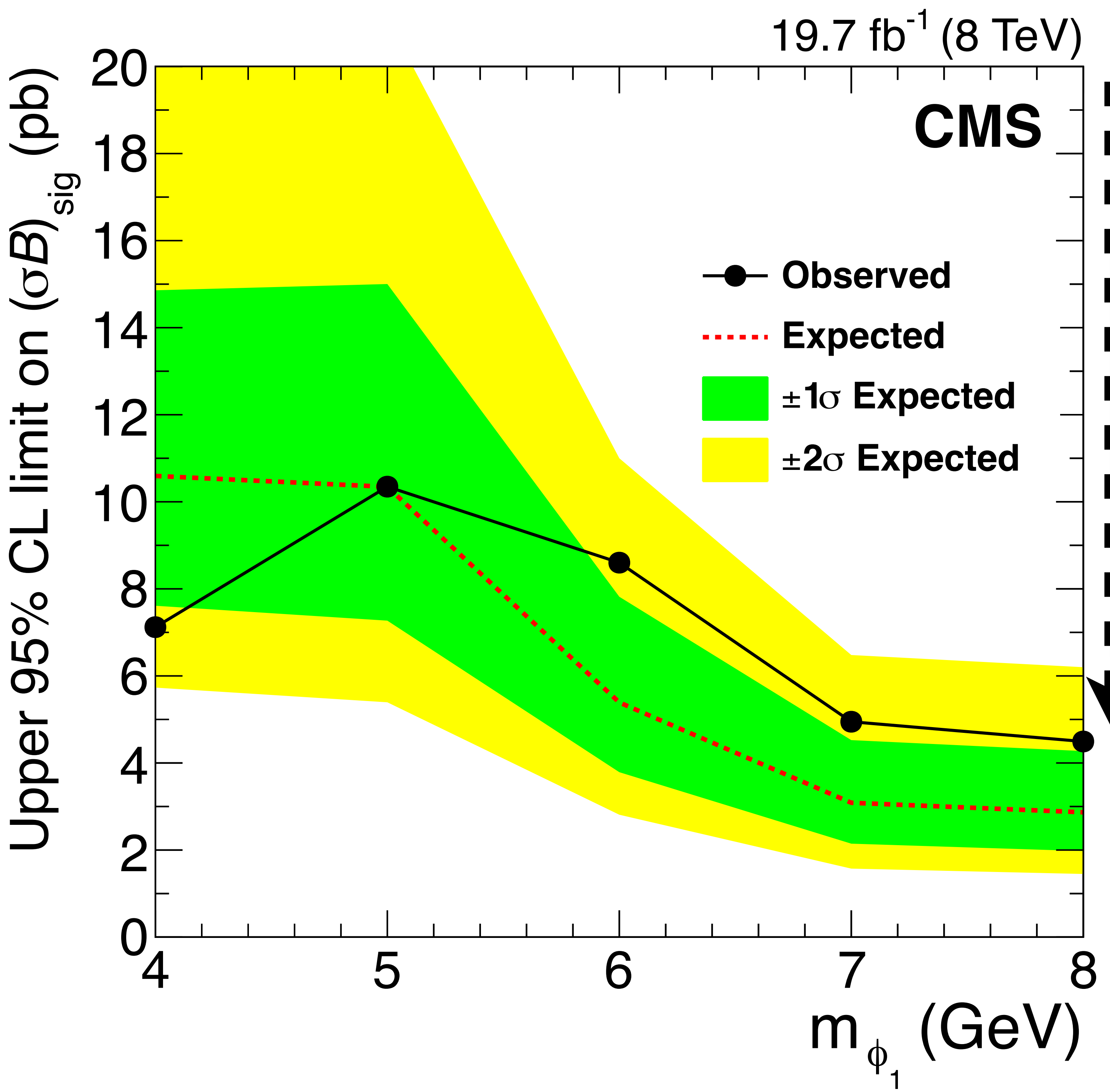


Expected quantifies sensitivity of search

Limit

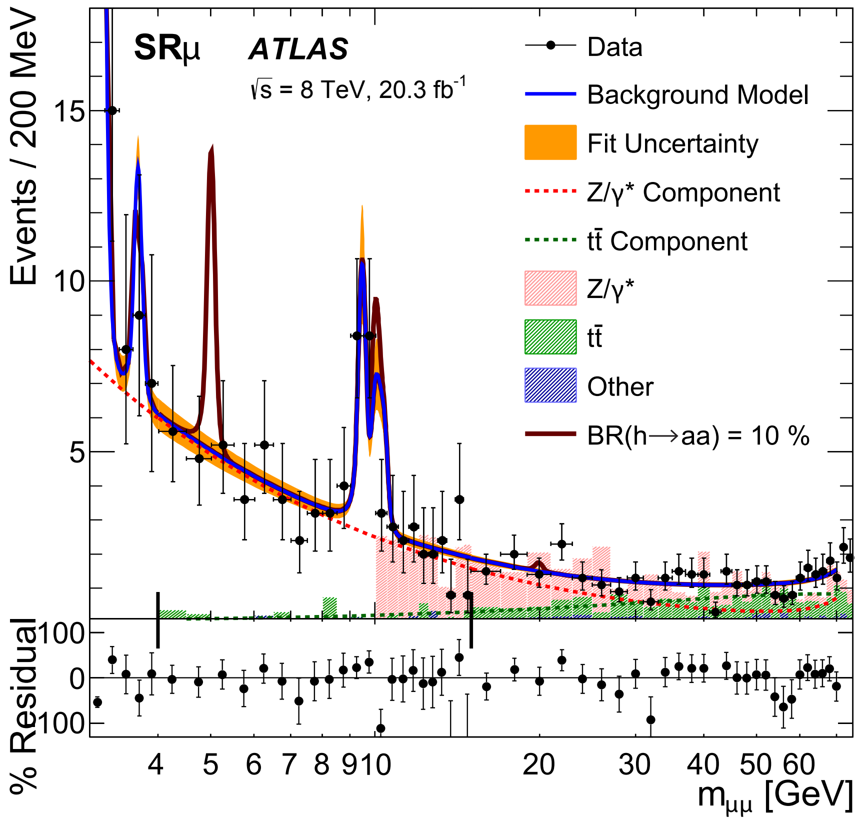
- See no significant excess in data → set upper limit on $\sigma \times$ BR

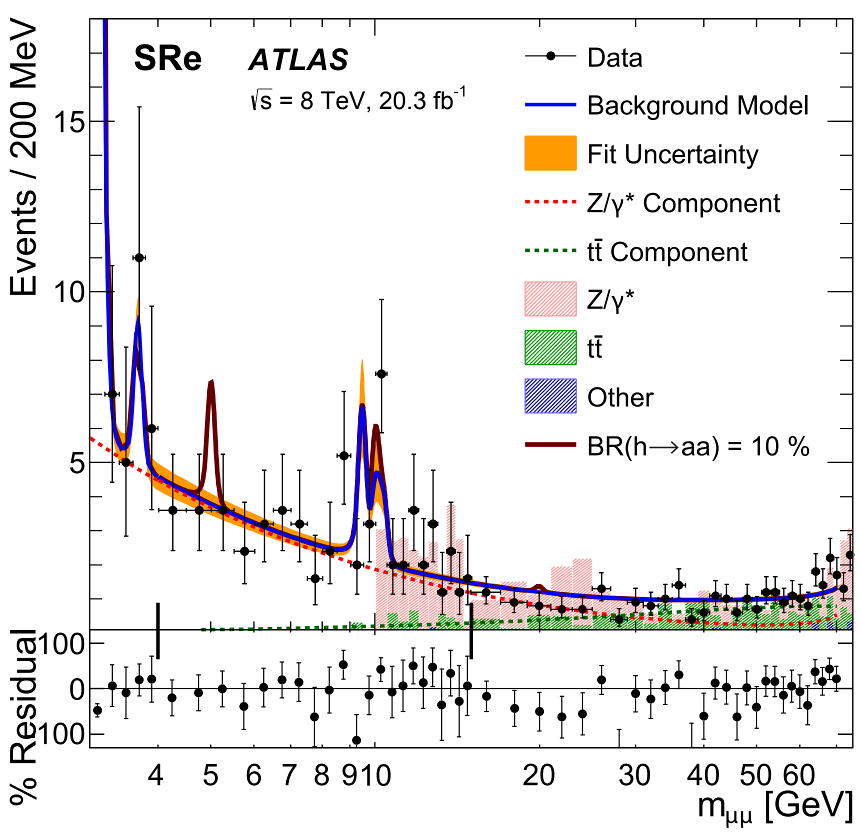


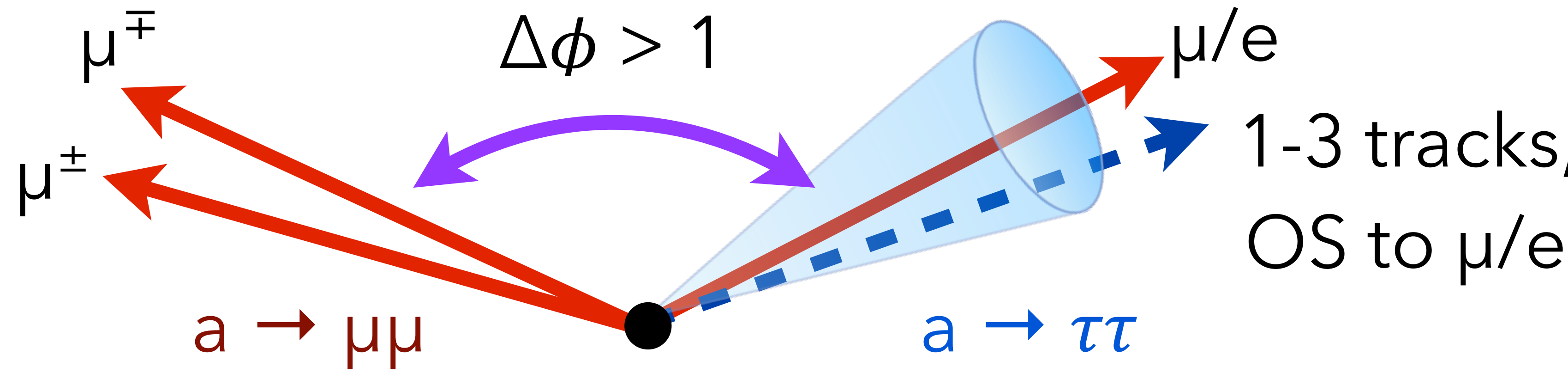
Observed

Exclude σ × BR at 95 % C.L. *above* the black line

ATLAS result

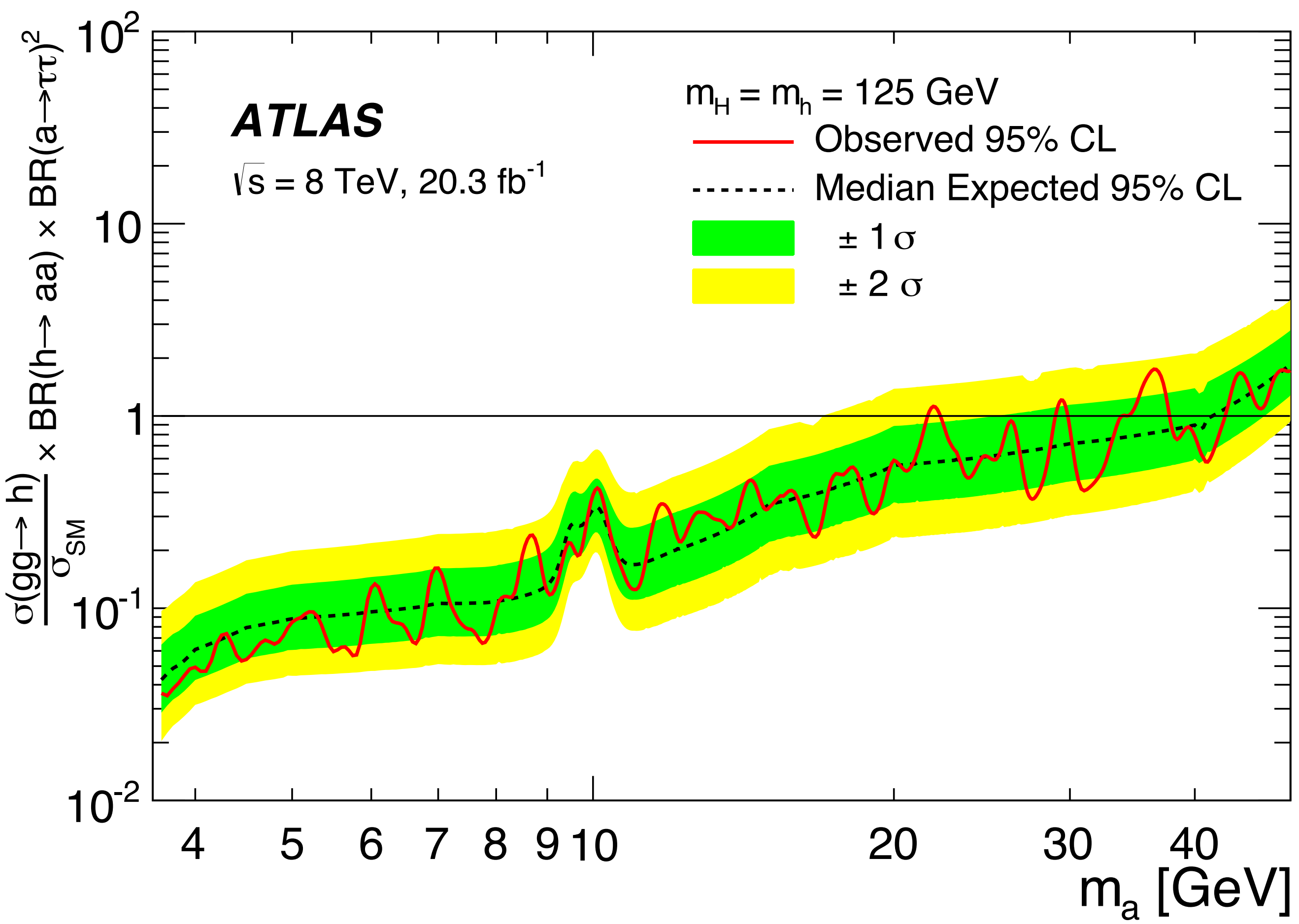


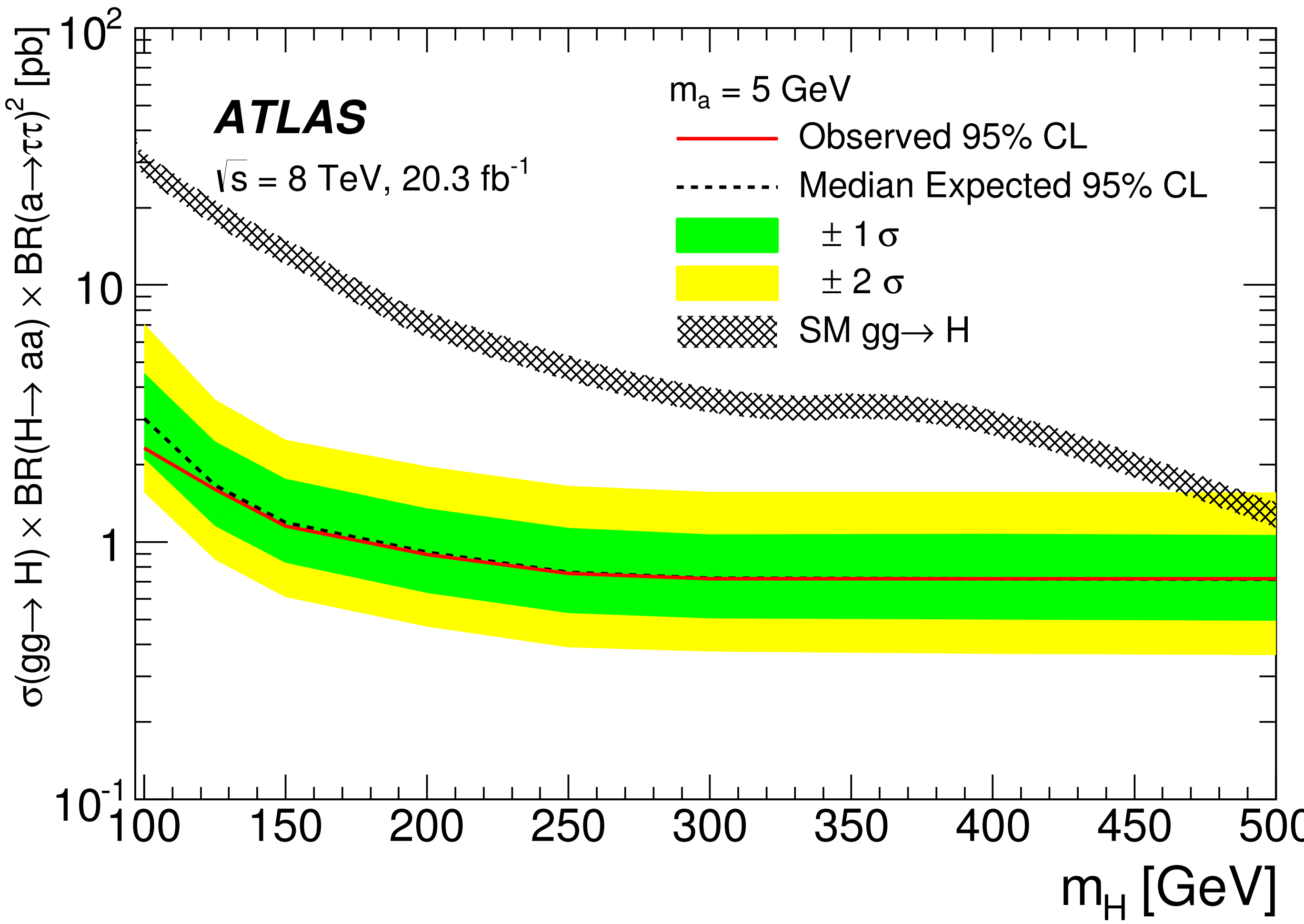




- Trigger on single μ (36 GeV) or di-μ (18 + 8)
- Optimised for $m_a \lesssim 10$ GeV
- Look in window $m_{\mu\mu} \in [2.8, 70]$ GeV
- Perform template fit on $m_{\mu\mu}$ data, including backgrounds from J/ψ, Υ, Drell-Yan (Z^*/γ), tt.

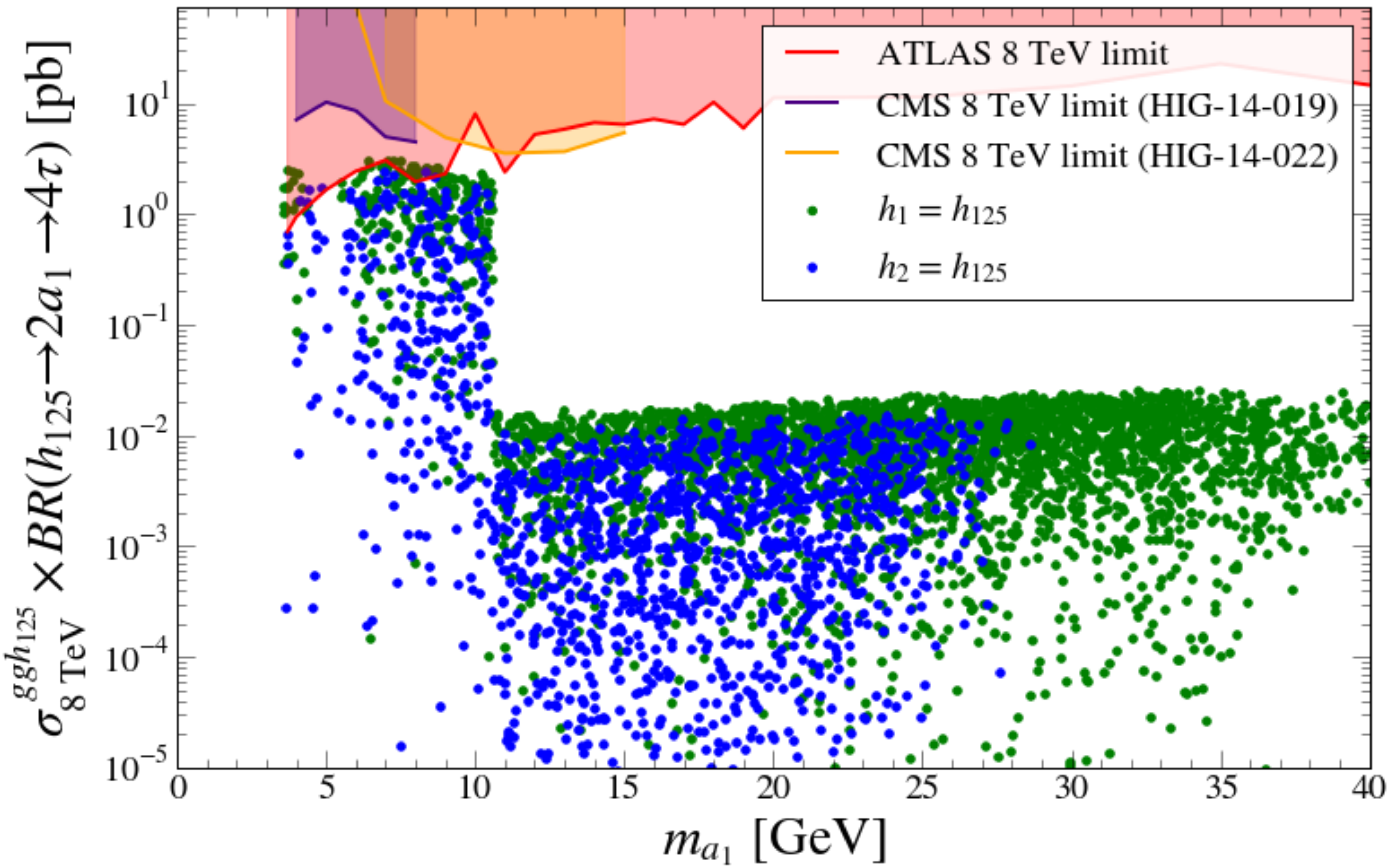
ATLAS result





Interpretation

- Compare to 8 TeV parameter space scans using ATLAS & CMS limits:



- For reference, $\sigma^{ggh}(m_h{=}125) = 19.3$pb at 8 TeV

Looking to Run 2

- Larger $\sqrt{s}$:
  - σ(ggh) increases by ~ × 2.7 ($\sigma^{ggh}_{SM} \approx$ 50pb)

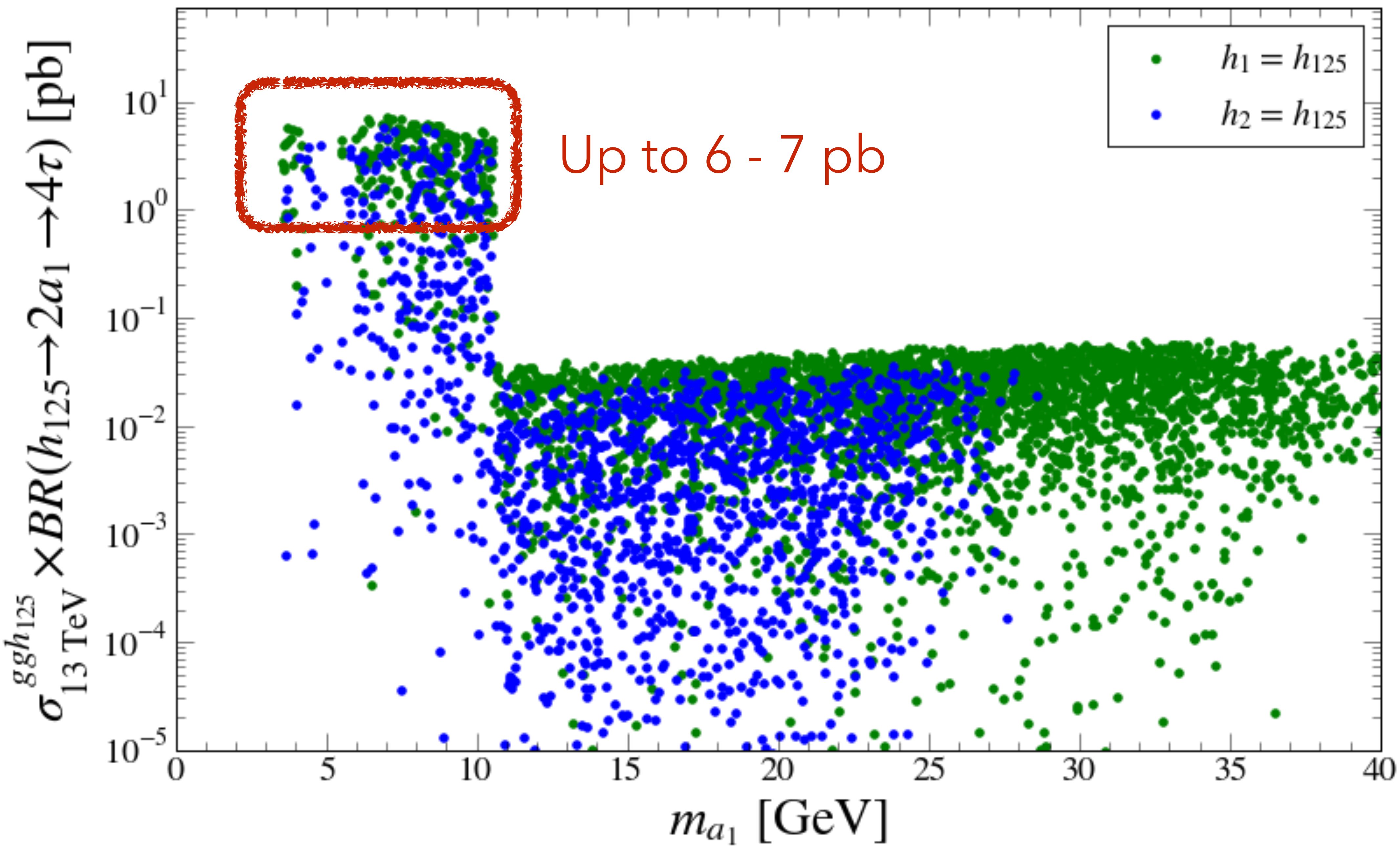
- QCD $b\bar{b}$ background increase: $\sigma \approx$ 200μb → 350μb (× ~1.5). Overall S:B increase by ~ × 1.8

- Potential for more sophisticated MVA-based techniques to conquer boosted di-taus

- Investigate region above $2m_b$

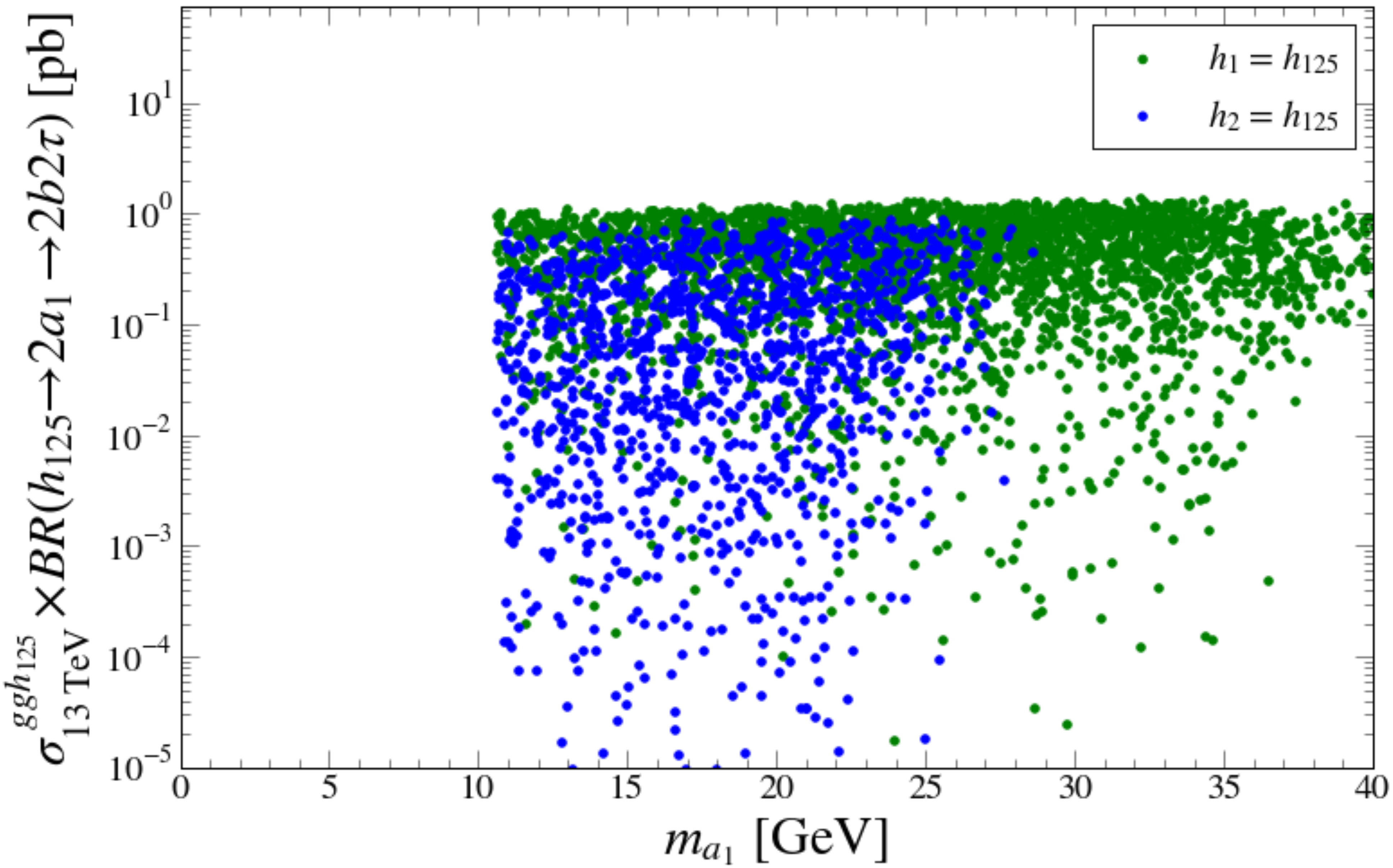
Looking to Run 2

- $\sigma \times$ BR landscape at 13 TeV:



$m_a > 2m_\tau$: $bb\tau\tau$

- Balance between:
  - BR(bb) >> BR($\tau\tau$) >> BR(μμ)
  - bb → lots of QCD background



$m_a > 2m_\tau$: $bb\tau\tau$

- Balance between:
  - BR(bb) >> BR($\tau\tau$) >> BR(μμ)
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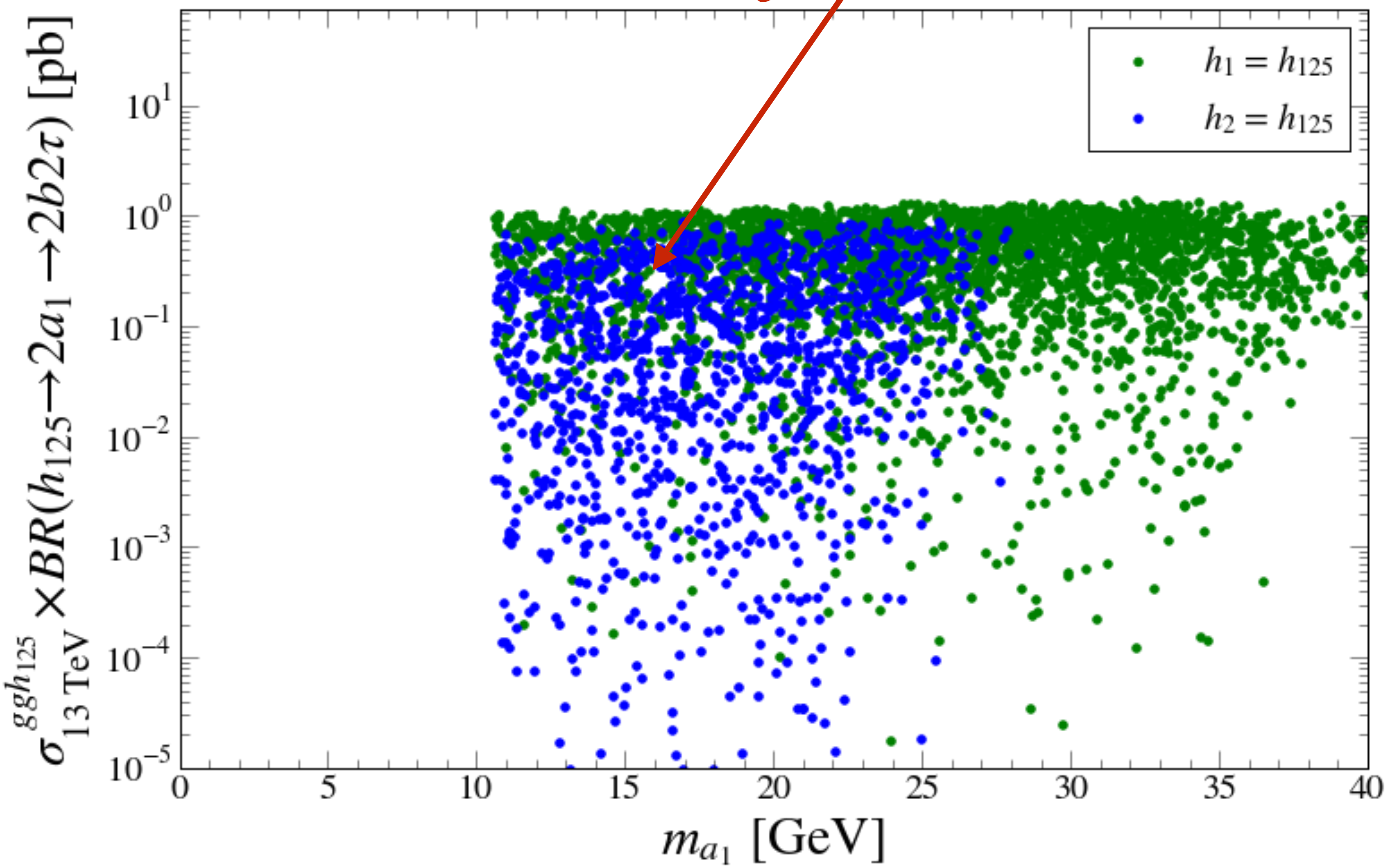
Interesting dynamics here - boosted B-jet pairs



Conclusion

- First LHC searches for production of a pair of light bosons decaying into pairs of taus performed

- Placed limits on $\sigma \times$ BR for ggh(125) $\rightarrow 2\phi \rightarrow 4\tau$
  - For m_{ϕ} = 8 GeV: CMS - 4.5 pb obs. (3pb exp.) , ATLAS - 1.97 pb obs. (2.06pb exp.)

- NMSSM still looking healthy

- Baseline for 13 TeV analysis

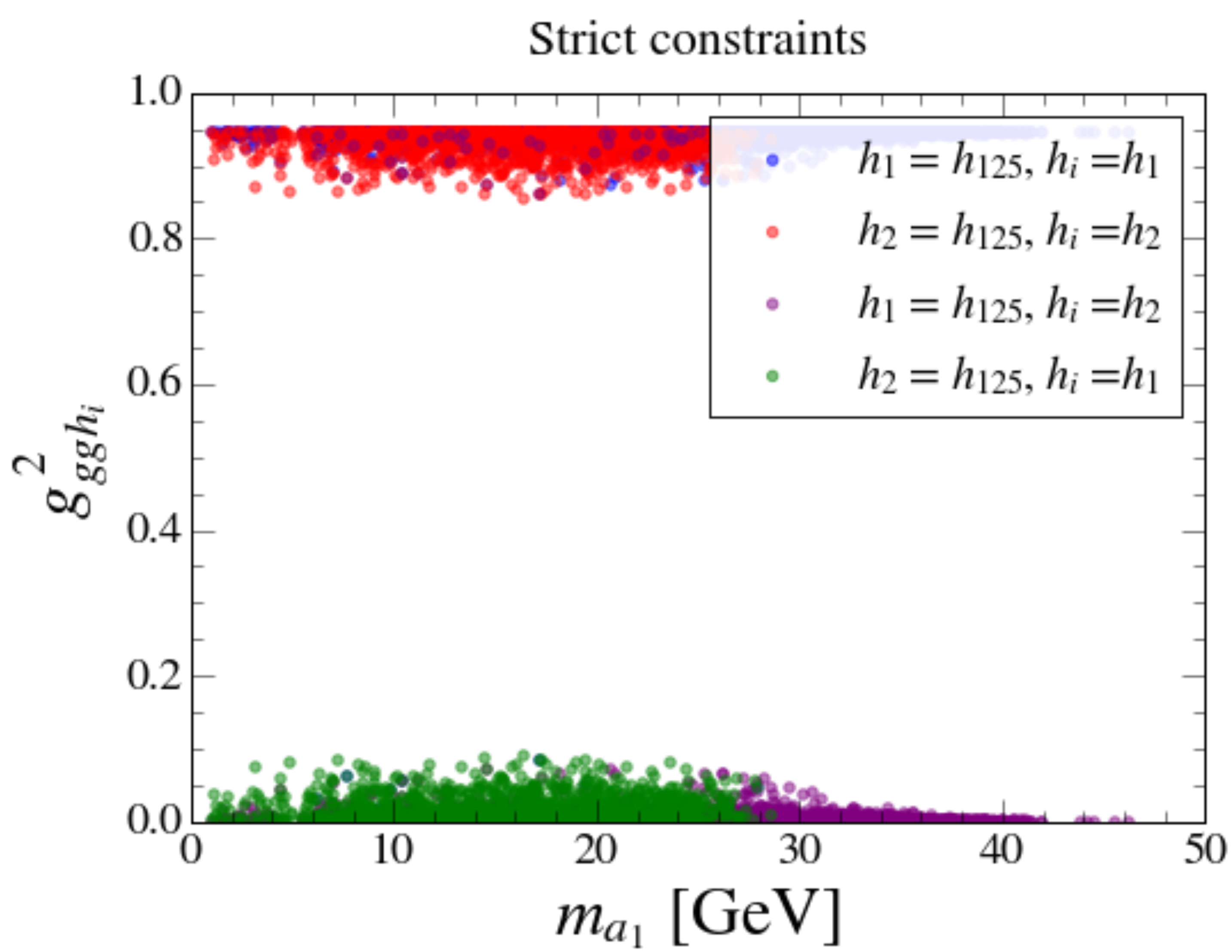
Backup

NMSSM landscape

- What can we expect? Decompose the total cross-section × BR:

$$\sigma \times BR \equiv \sigma^{ggh}(SM) \times ggh^2 \times BR(h \to \phi_1\phi_1) \times BR(\phi_1 \to \tau\,\tau)^2$$

(wrt SM ggh^2 coupling)



Parameter scans include latest updates to B-physics calculations & experimental values in NMSSMTools

NMSSM landscape

- What can we expect? Decompose the total cross-section × BR:

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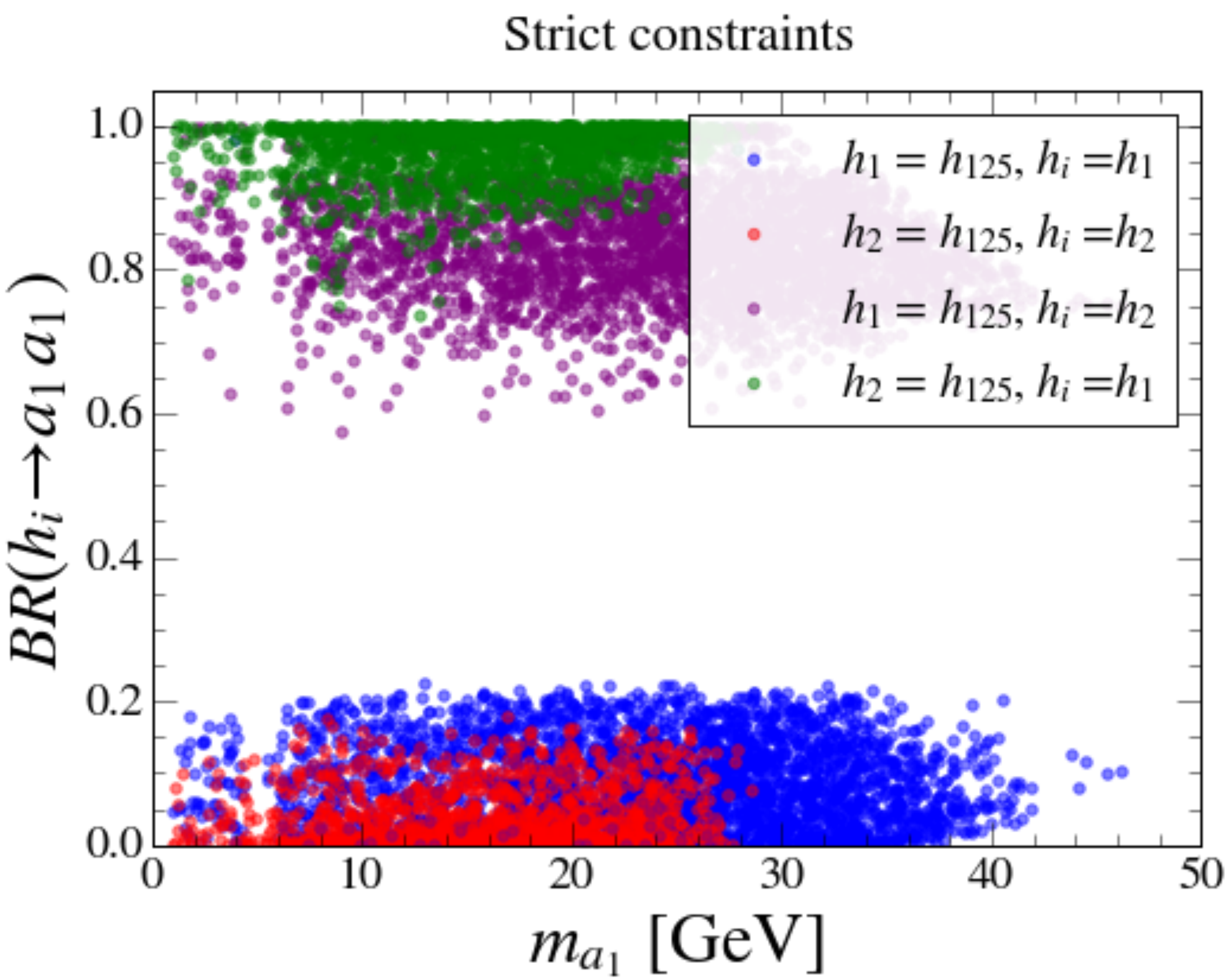

NMSSM landscape

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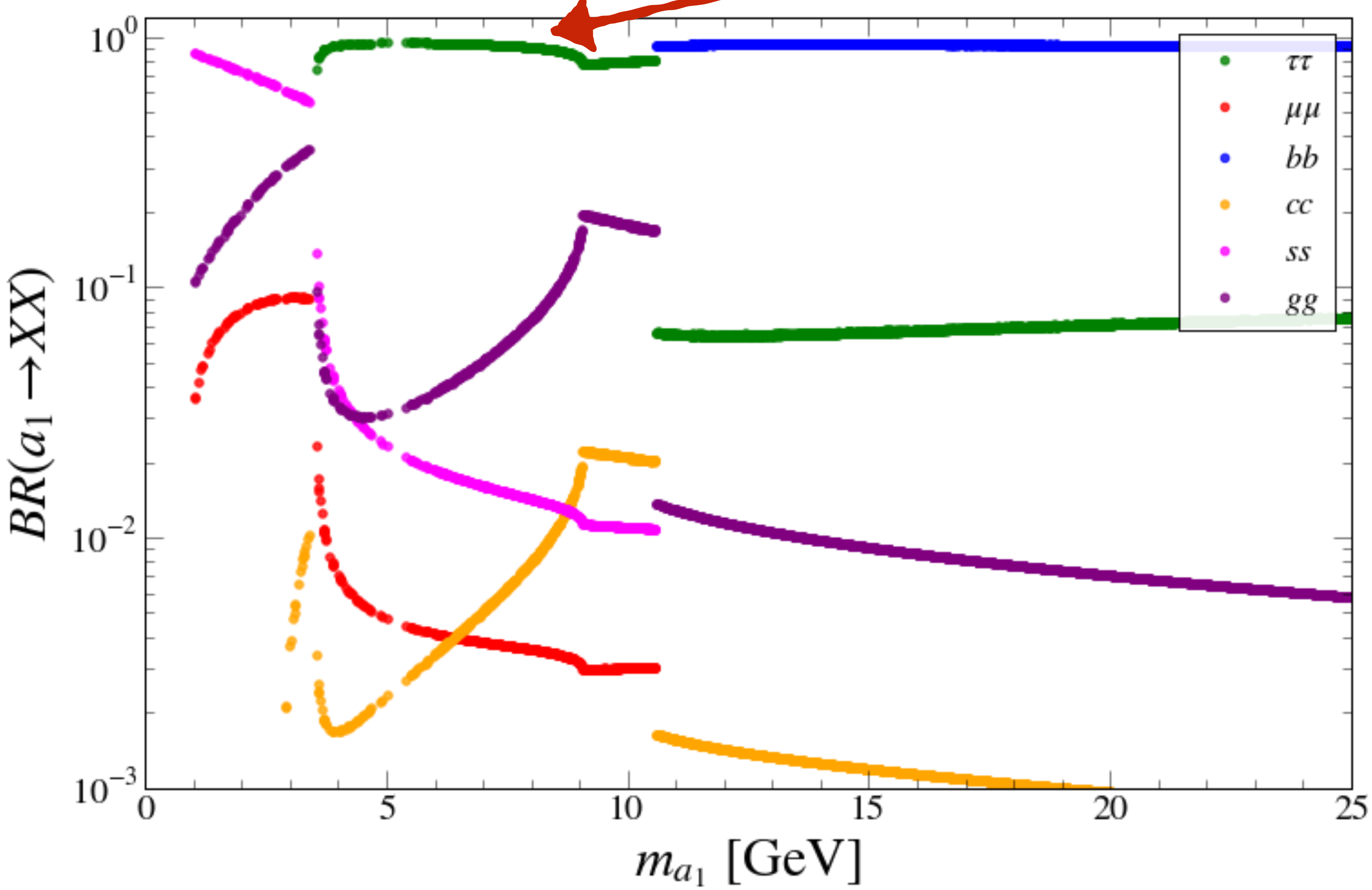

MC yields

Sample	Number of events
Data	873
Expected background events	
QCD multijet	820 ± 320
$t\bar{t}$	1.2 ± 0.2
Electroweak	5.0 ± 4.7
Signal acceptance $\mathcal{A}(gg \to H(125) \to \phi_1\phi_1 \to 4\tau)$	
$m_{\phi_1} = 4\,GeV$	$(5.38 \pm 0.23) \times 10^{-4}$
$m_{\phi_1} = 5\,GeV$	$(4.36 \pm 0.21) \times 10^{-4}$
$m_{\phi_1} = 6\,GeV$	$(4.00 \pm 0.23) \times 10^{-4}$
$m_{\phi_1} = 7\,GeV$	$(4.04 \pm 0.20) \times 10^{-4}$
$m_{\phi_1} = 8\,GeV$	$(3.13 \pm 0.18) \times 10^{-4}$
Expected signal events for $(\sigma\mathcal{B})_{sig} = 5\,pb$	
$m_{\phi_1} = 4\,GeV$	53.0 ± 2.3
$m_{\phi_1} = 5\,GeV$	43.0 ± 2.0
$m_{\phi_1} = 6\,GeV$	39.5 ± 2.0
$m_{\phi_1} = 7\,GeV$	39.9 ± 2.0
$m_{\phi_1} = 8\,GeV$	30.8 ± 1.8

MC yields

Better acceptance for lighter m_a due to larger τ boost

Sample	Number of events
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Expected background events	
QCD multijet	820 ± 320
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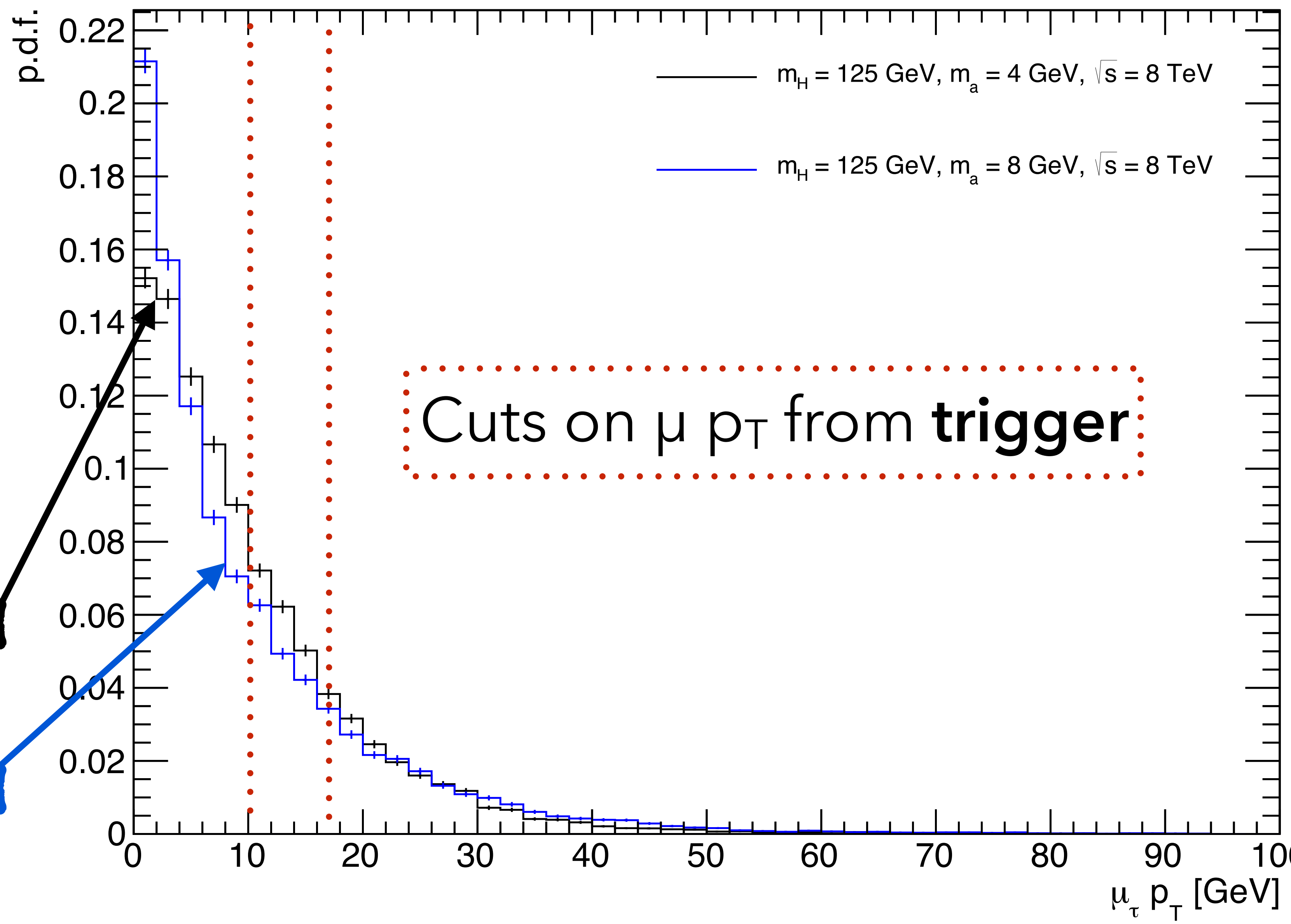
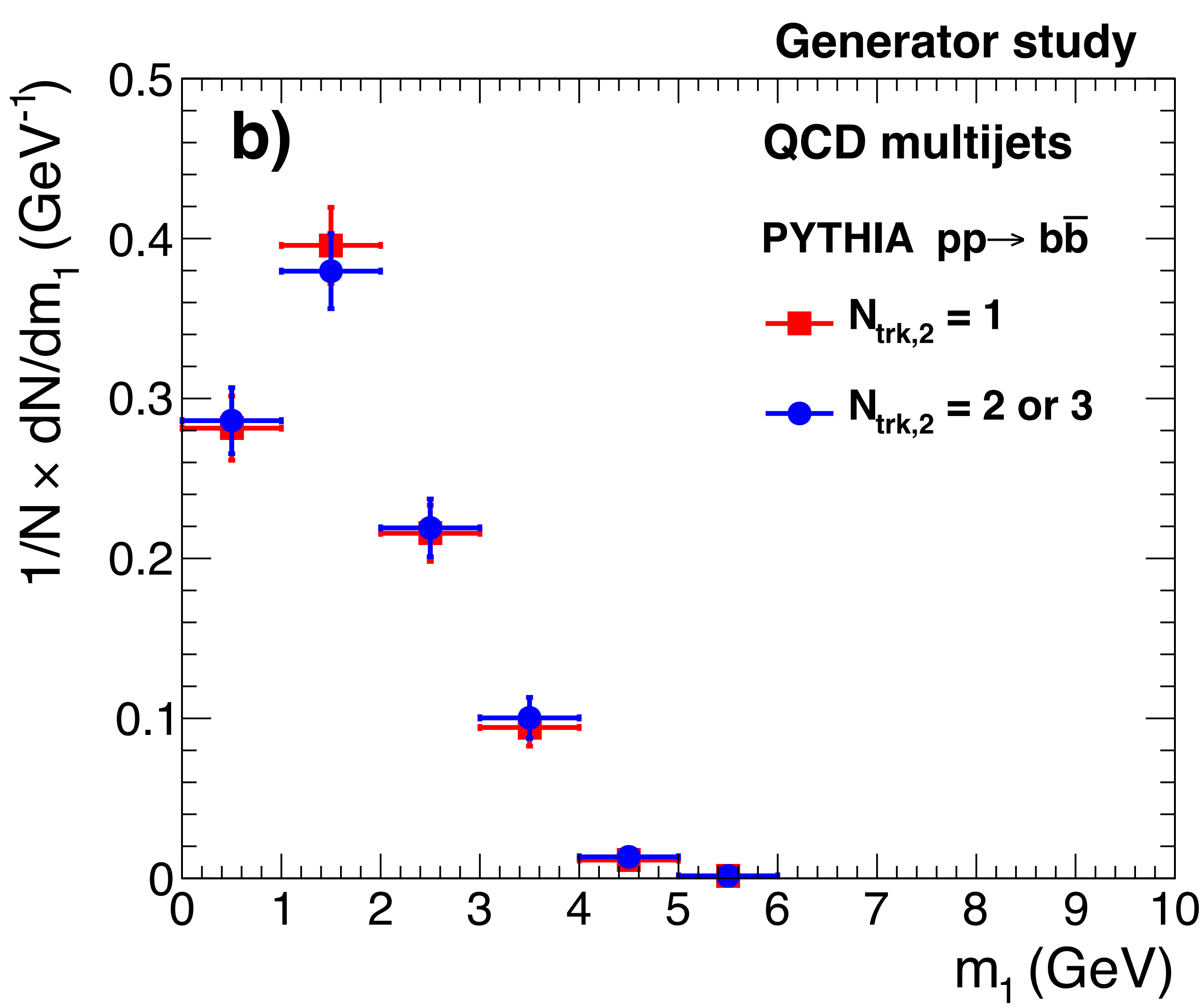
ggH → 2a → 4τ (Gen. level), require ≥ 2 SS μ



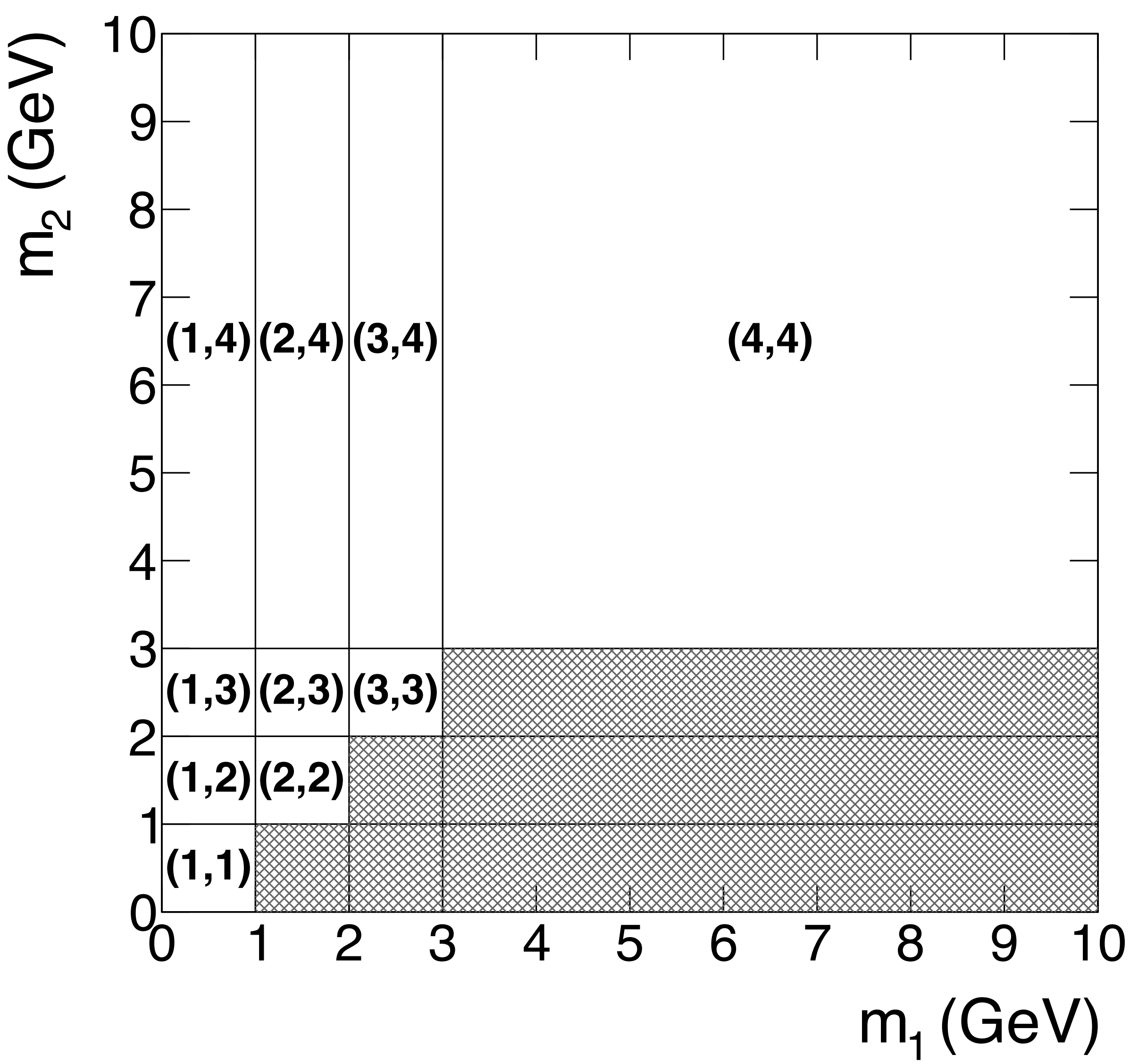
Background Estimate

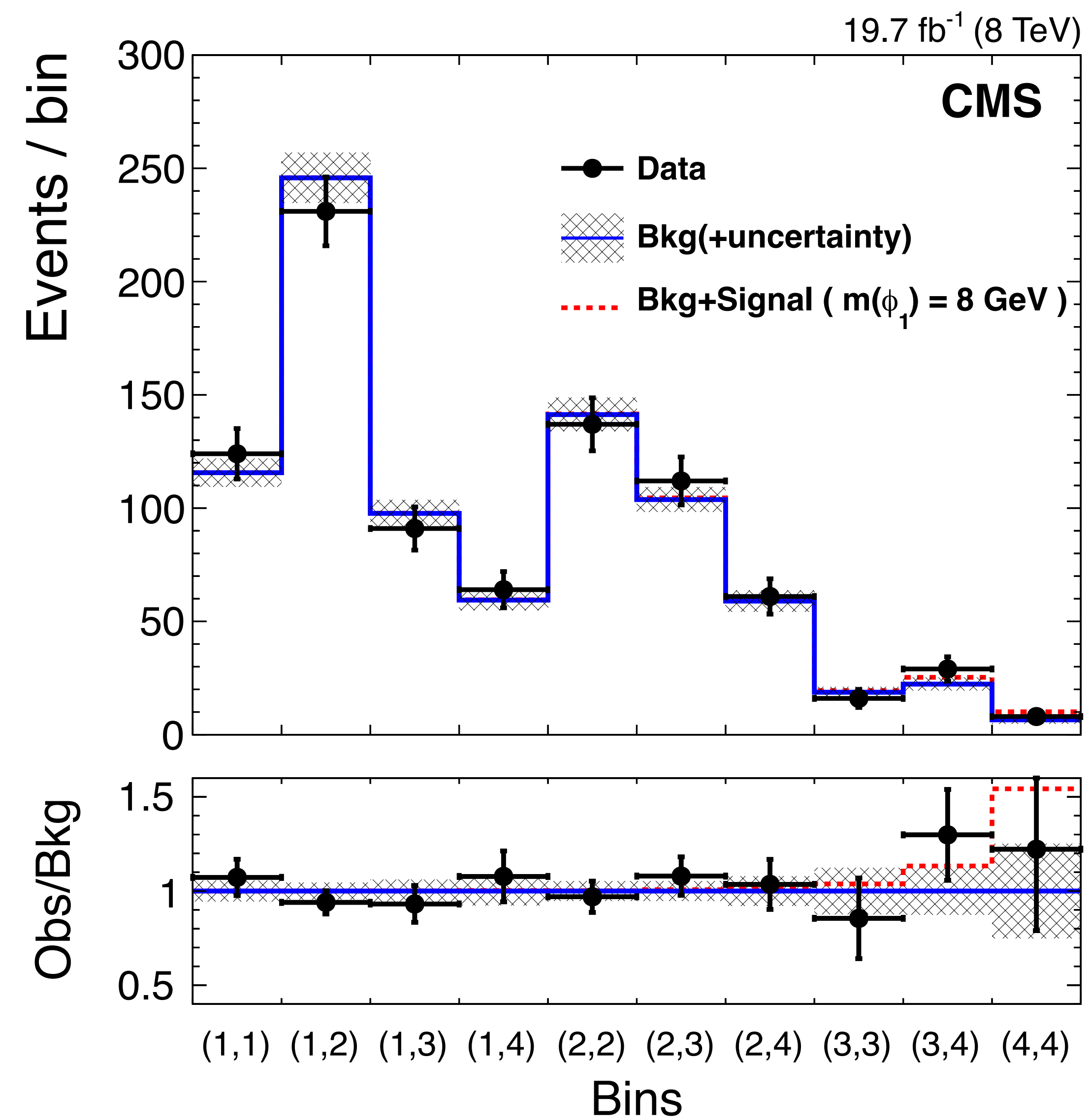
- Relies on same shape for background events in both signal & sideband regions
  - distribution shape ***uncorrelated*** with track multiplicity around a muon
  - tested using dedicated MC made with PYTHIA8, no detector effects



Signal Extraction

- Use 2D plot of m_1 vs m_2 to fit signal + background to data
    - Normalisations of signal & background templates not fixed





Limit

Table 4: The observed upper limit on $(\sigma\mathcal{B})_{\text{sig}}$ at 95% CL, together with the expected limit obtained in the background-only hypothesis, as a function of m_{ϕ_1}. Also shown are $\pm1\sigma$ and $\pm2\sigma$ probability intervals around the expected limit.

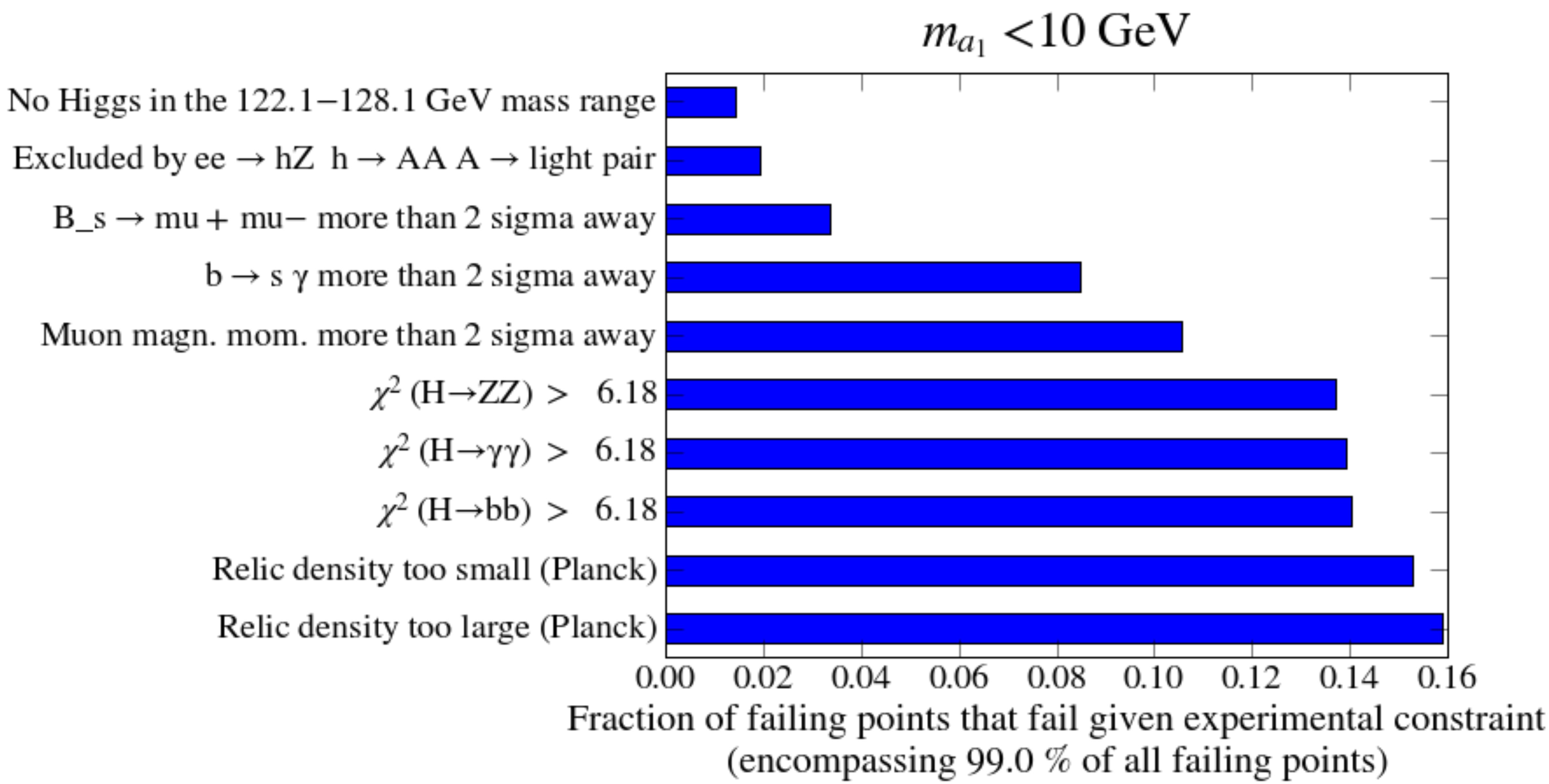
Upper limits on $(\sigma\mathcal{B})_{\text{sig}}$ [pb] at 95% CL						
m_{ϕ_1} [GeV]	observed	-2σ	-1σ	expected	$+1\sigma$	$+2\sigma$
4	7.1	5.7	7.6	10.6	14.9	20.2
5	10.3	5.4	7.3	10.3	15.0	21.2
6	8.6	2.8	3.8	5.4	7.8	11.0
7	5.0	1.6	2.2	3.1	4.5	6.5
8	4.5	1.5	2.0	2.9	4.3	6.2

Yields

Table 3: The number of observed data events, the predicted background yields, and the expected signal yields, for different masses of the ϕ_1 boson in individual bins of the (m_1, m_2) distribution. The background yields and uncertainties are obtained from the maximum-likelihood fit under the background-only hypothesis. The signal yields are obtained from simulation and normalized to a signal cross section times branching fraction of 5 pb. The uncertainties in the signal yields include systematic and MC statistical uncertainties. The bin notation follows the definition presented in Fig. 2.

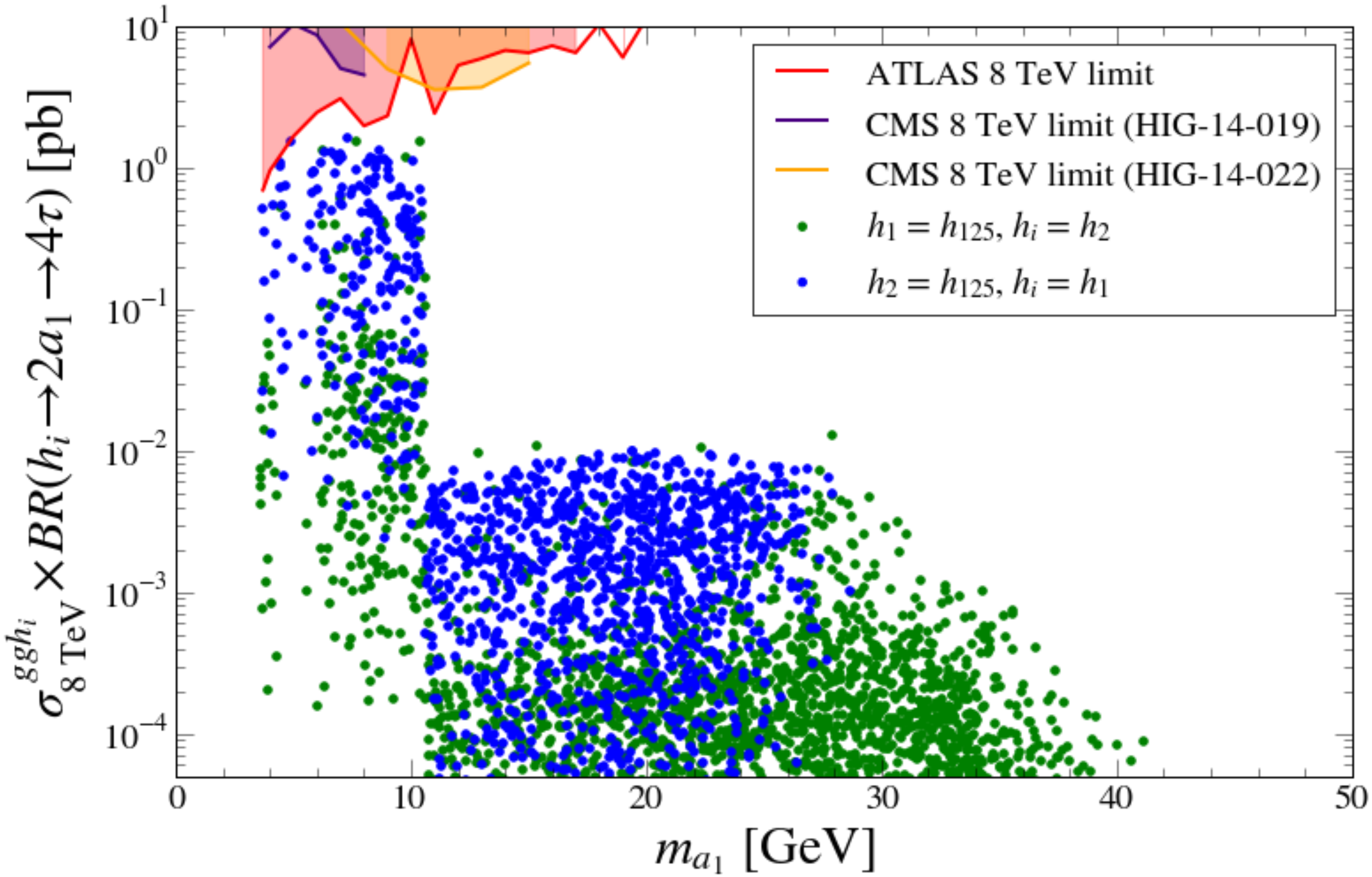
Bin	Data	Bkg.	Expected signal for $(\sigma\mathcal{B})_{sig}$ = 5 pb, m_{ϕ_1} [GeV] = 4	5	6	7	8
(1,1)	124	116 ± 7	9.7 ± 1.5	1.9 ± 0.5	< 0.1	0.1 ± 0.1	< 0.1
(1,2)	231	247 ± 10	21.6 ± 2.9	6.8 ± 1.1	1.9 ± 0.5	0.3 ± 0.2	0.1 ± 0.1
(1,3)	91	98 ± 6	3.8 ± 0.8	4.9 ± 0.9	2.4 ± 0.6	0.9 ± 0.3	0.2 ± 0.2
(1,4)	64	60 ± 5	0.1 ± 0.1	1.5 ± 0.4	1.8 ± 0.5	0.8 ± 0.3	0.5 ± 0.2
(2,2)	137	142 ± 8	14.2 ± 2.0	8.2 ± 1.3	2.8 ± 0.6	1.5 ± 0.4	0.8 ± 0.3
(2,3)	112	104 ± 6	3.7 ± 0.7	10.4 ± 1.6	9.2 ± 1.4	4.4 ± 0.8	2.3 ± 0.6
(2,4)	61	59 ± 5	< 0.1	2.6 ± 0.6	5.6 ± 1.0	8.1 ± 1.3	4.0 ± 0.8
(3,3)	16	19 ± 2	< 0.1	4.8 ± 0.9	4.8 ± 0.9	3.7 ± 0.7	2.2 ± 0.5
(3,4)	29	23 ± 3	< 0.1	1.9 ± 0.5	8.0 ± 0.9	11.1 ± 1.5	9.4 ± 1.4
(4,4)	8	7 ± 1	< 0.1	< 0.1	3.1 ± 0.6	9.1 ± 1.4	11.2 ± 1.7

Experimental constraints



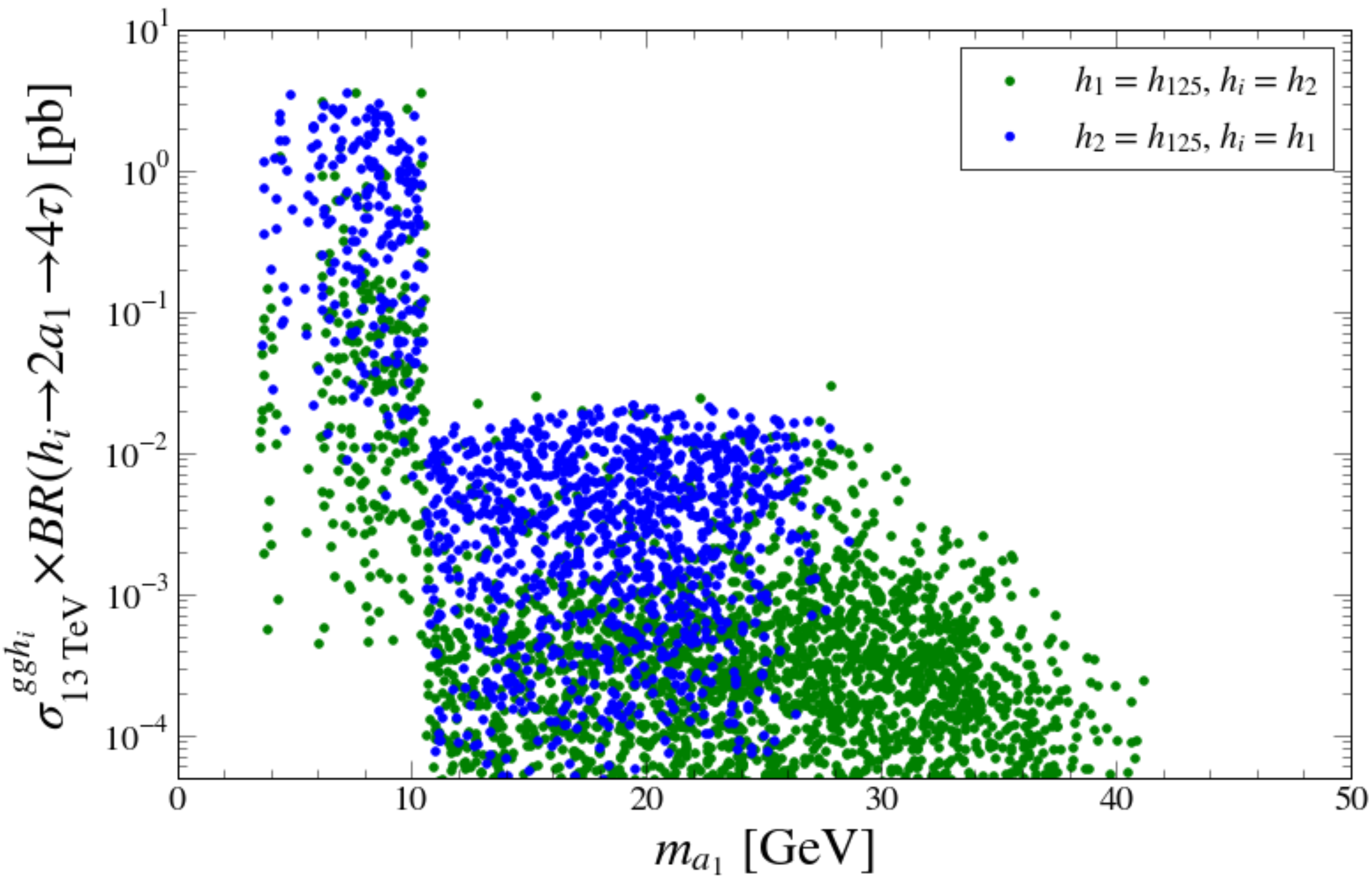
Interpretation

- Analysis doesn't constrain $m_{\tau\tau\tau\tau}$ - can have contributions from $h \neq h_{SM}$
  - Similar $\sigma \times$ BR



Looking to Run 2

- $\sigma \times$ BR landscape at 13 TeV:



ATLAS

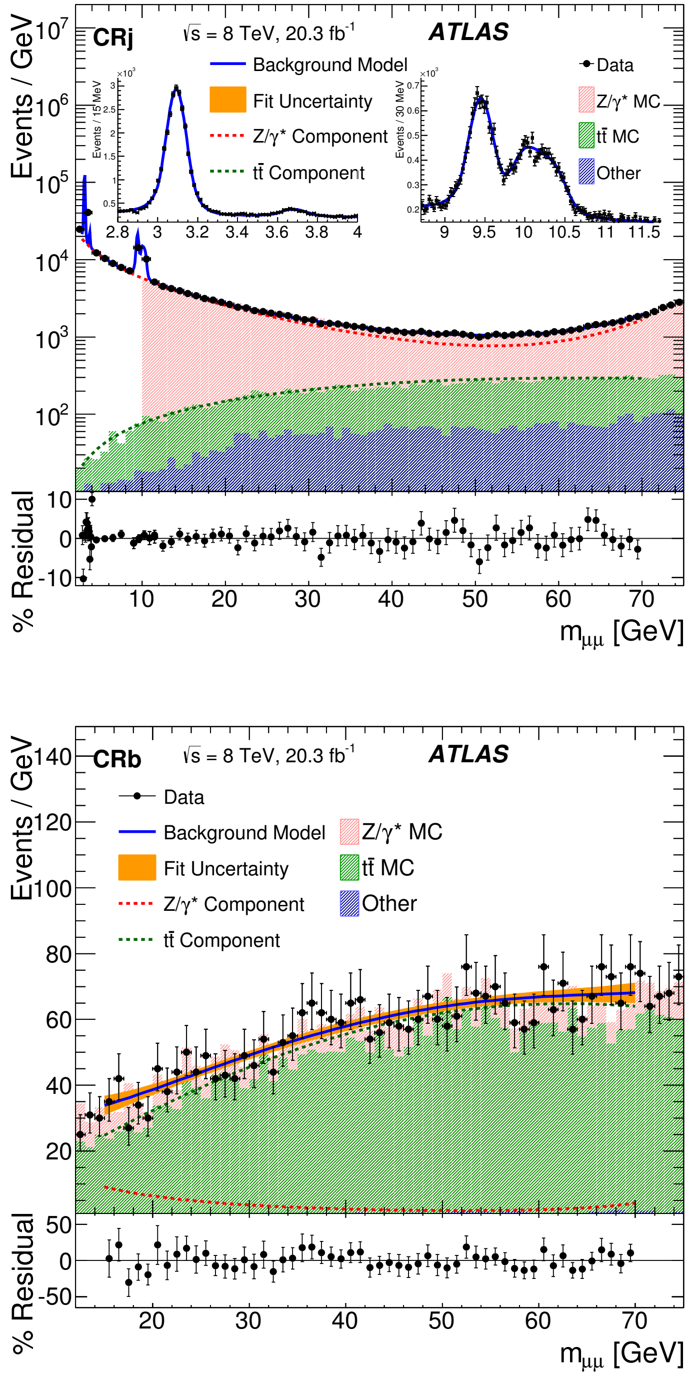


Figure 2: Observed $m_{\mu\mu}$ distribution in CRj (top) and CRb (bottom) and the SM background model after a simultaneous fit. The Z/γ^* component of the fit is the combination of the Z boson resonance and the γ^* continuum models. The % residual of the fit is shown below each plot. Simulated SM backgrounds are shown in the stack, with the Z/γ^* sample only valid above $m_{\mu\mu}$ >10 GeV. The two insets show magnified versions of the J/ψ and Υ resonances.