[1]*University of California San Diego (UCSD)*

Experimental results and progress: CMS

Speaker : Raffaele Gerosa[1]

On behalf of the CMS Collaboration

WG3 working meeting 20th September 2018 (CERN)

General overview

- **General Goal:** give a short summary of the most recent results obtained with 2016 data in the context of

Additional Neutral Scalars

- MSSM H($\tau\tau$) HIG-17-020
- bbH, H(bb) HIG-16-018
- A(Zh) HIG-18-005
- H(ZZ) HIG-17-012

Charged Higgs

Several new charged Higgs results under internal CMS review

No analysis presented in this talk

Exotic Higgs decays

- h → aa(2b2τ) HIG-17-024
- h → aa(2μ2τ) HIG-17-029
- h → aa(4μ) HIG-18-003
- h → invisible HIG-17-023

X → hh

- hh(2b2γ) HIG-17-008
- hh(4b) HIG-17-009
- hh(2b2τ) HIG-17-002
- hh(2l2v2b) HIG-17-006

Constraints from h_{125}

- HIG-17-031

Main focus of this talk

Describe tools and recipes used for the signal modelling

Describe the explored experimental signatures and possible extensions

Current and missing interpretations of the already published searches

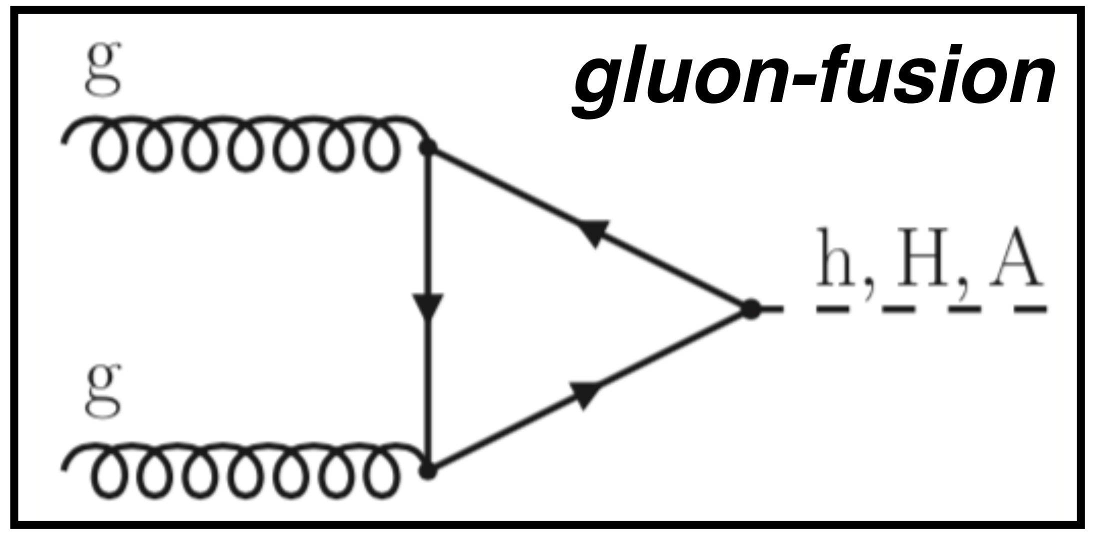
BSM scalar/pseudo-scalar resonances

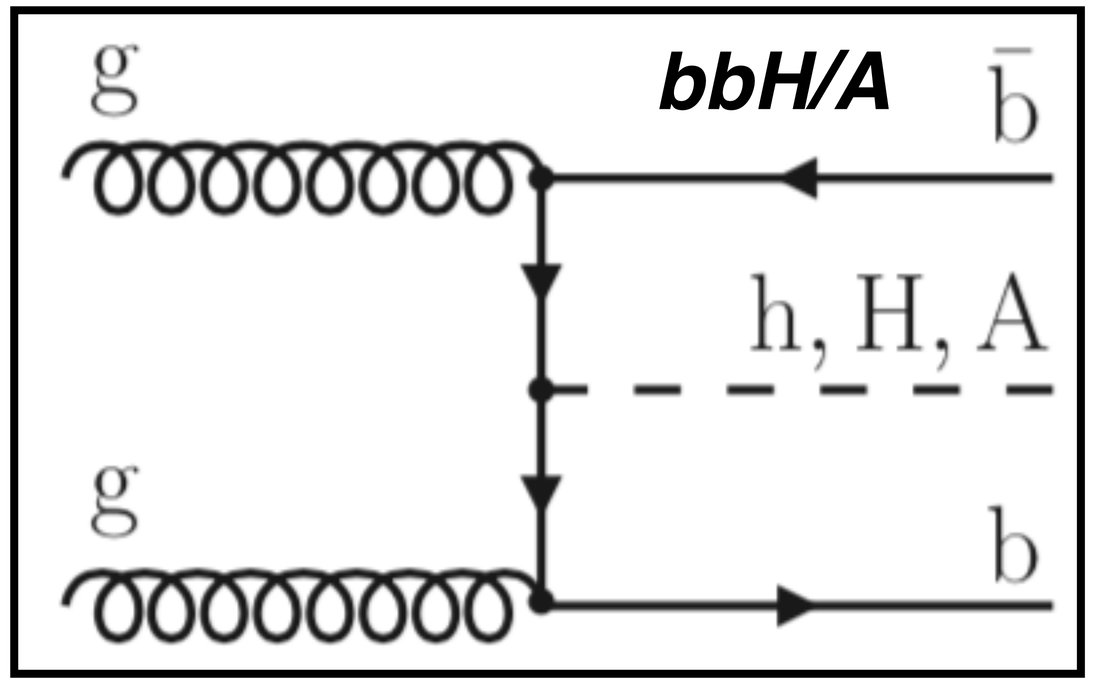
MSSM H → $\tau\tau$: overview

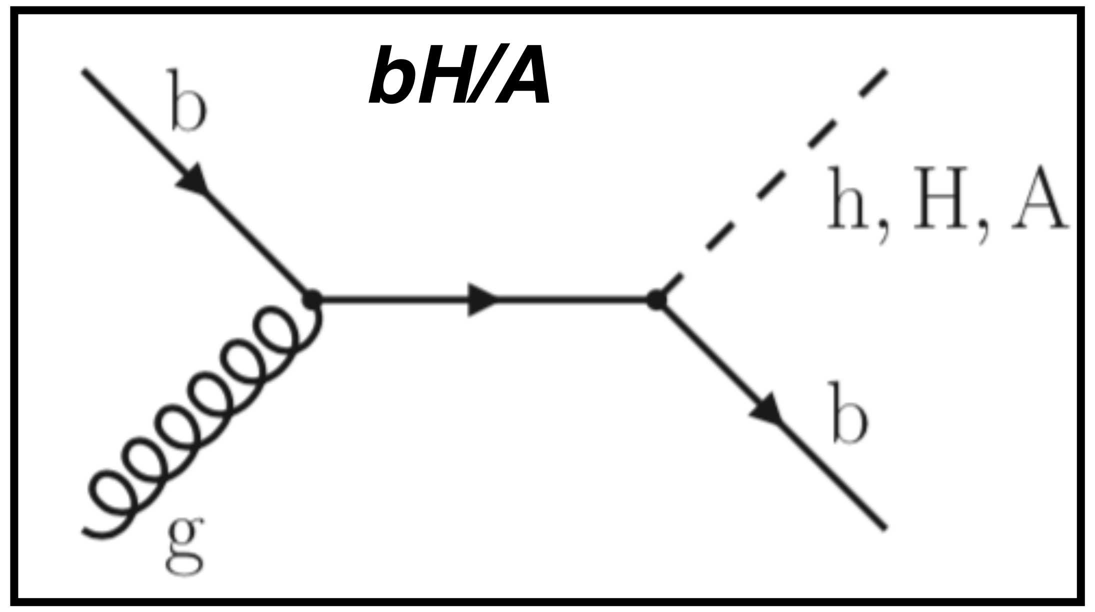
HIG-17-020

- **MSSM free parameters: m_A** and **tan(β) = v_u/v_d**

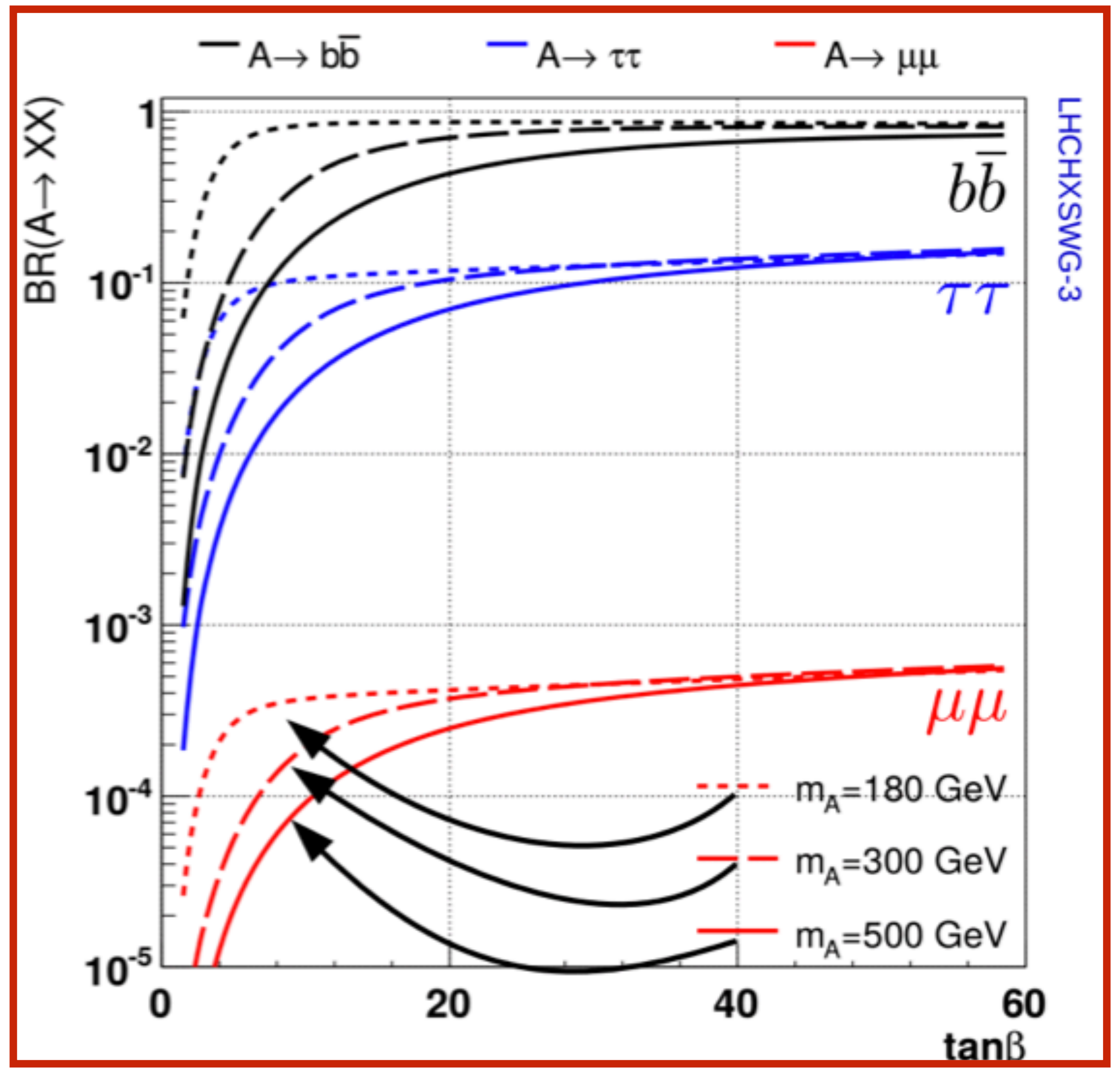
Production modes: in MSSM scenario coupling to b-quarks enhanced by tan(β)







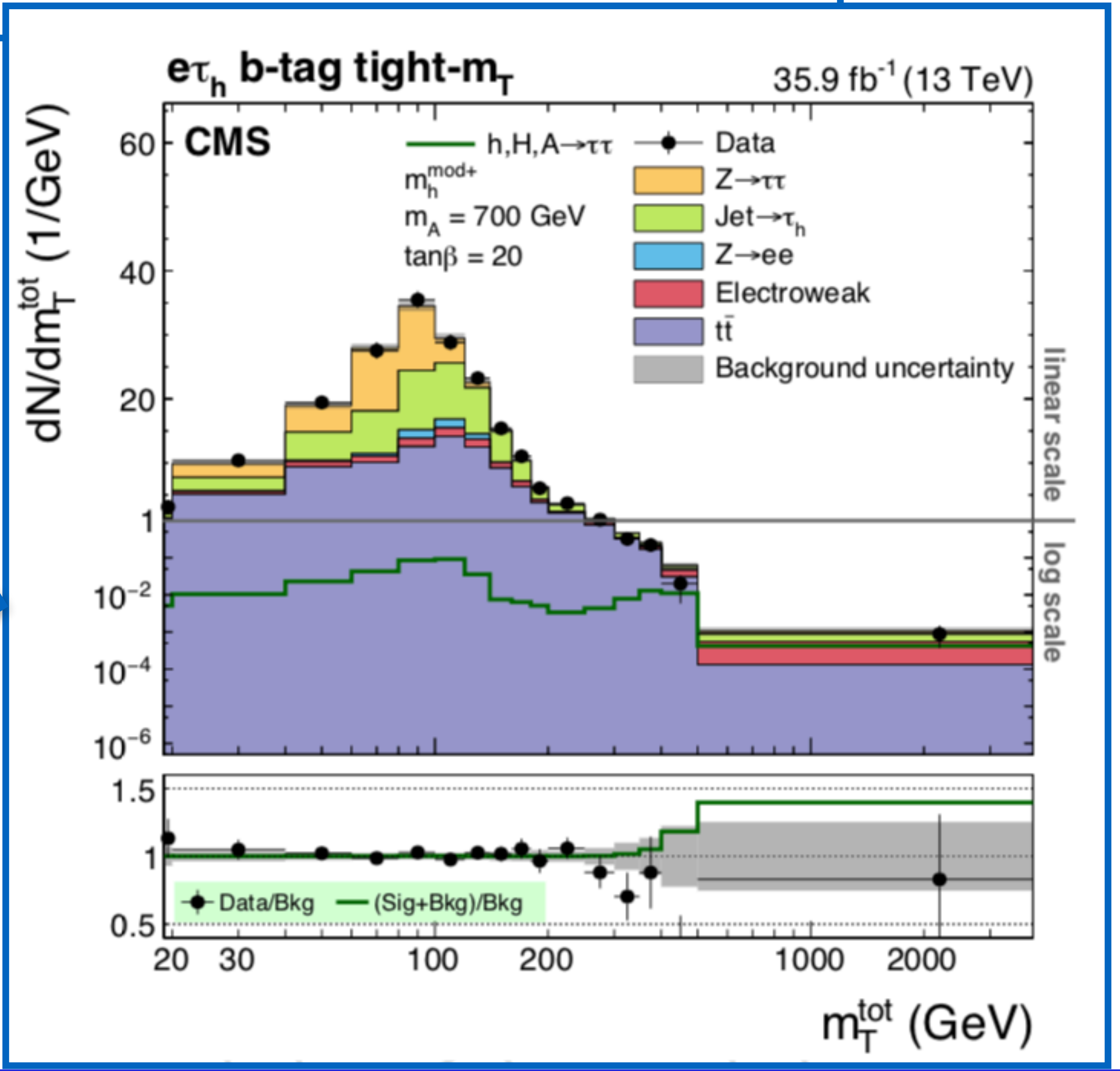
Decay modes: enhanced BR for 3rd generation at high value of tan(β)



Search in a nutshell

- $H\tau\tau$ is the **golden channel** to constrain the high tan(β) parameter space
- **τ-decay modes**: $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, eμ
- **b-quark jet tagging** used to define a bbA/bbH enriched sample
- m_T is used to separate prompt from fake τ_h backgrounds

Signal extracted by fitting the m_T^{tot}. The region with the largest S/B roughly corresponds to the $m_T > m_A/2$



MSSM H → $\tau\tau$: results

HIG-17-020

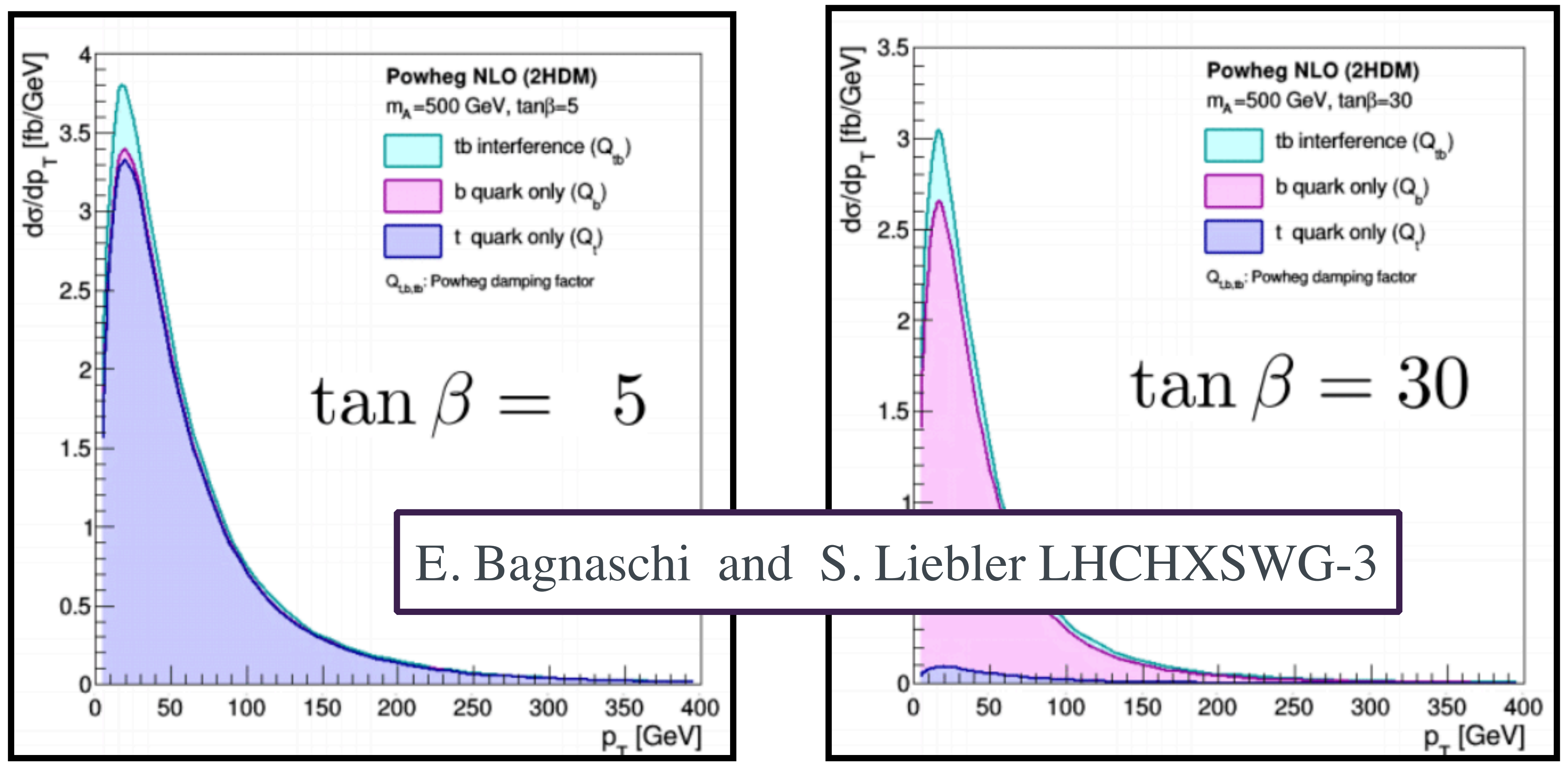
Gluon fusion signal

- **Gluon-fusion** events generated via PYTHIA LO
- **p_T^H distribution** re-weighted to NLO via POWHEG

For the MSSM interpretation,
assuming only top and b-quark in loop

$$\frac{d\sigma}{dp_T^H} = \sigma^t_{MSSM}(Q_t) + \sigma^b_{MSSM}(Q_b) + I(Q_{tb})$$

$$\propto Y_t^2 \qquad \propto Y_b^2 \qquad \propto Y_t Y_b$$



E. Bagnaschi and S. Liebler LHCHXSWG-3

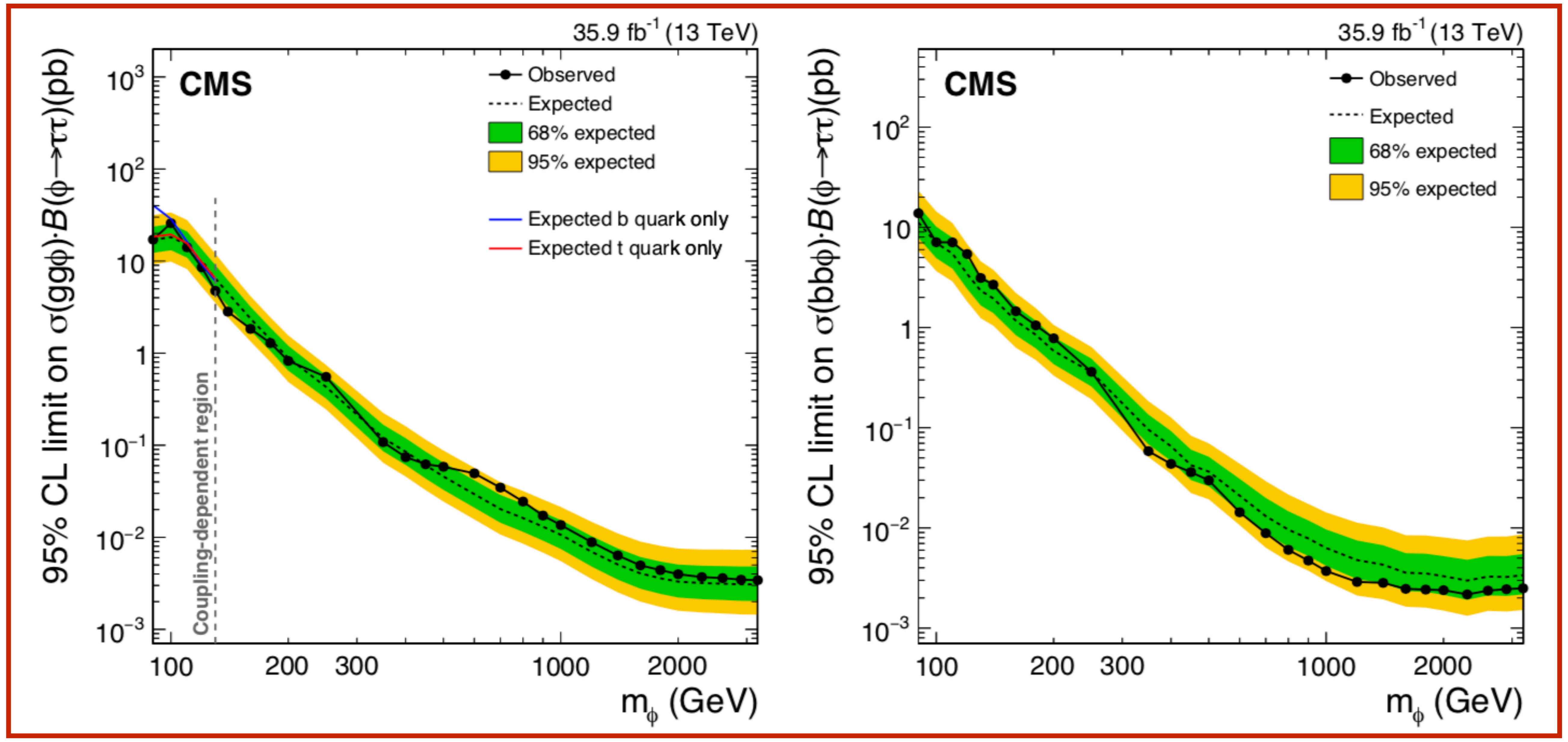
top-dominated → b-dominated

B-associated production (bbH)

- Generated with NLO precision via aMC@NLO

Limits in narrow width approximation

- When ggϕ limits are set, bbϕ contribution allowed to float freely and viceversa



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HIG-17-020

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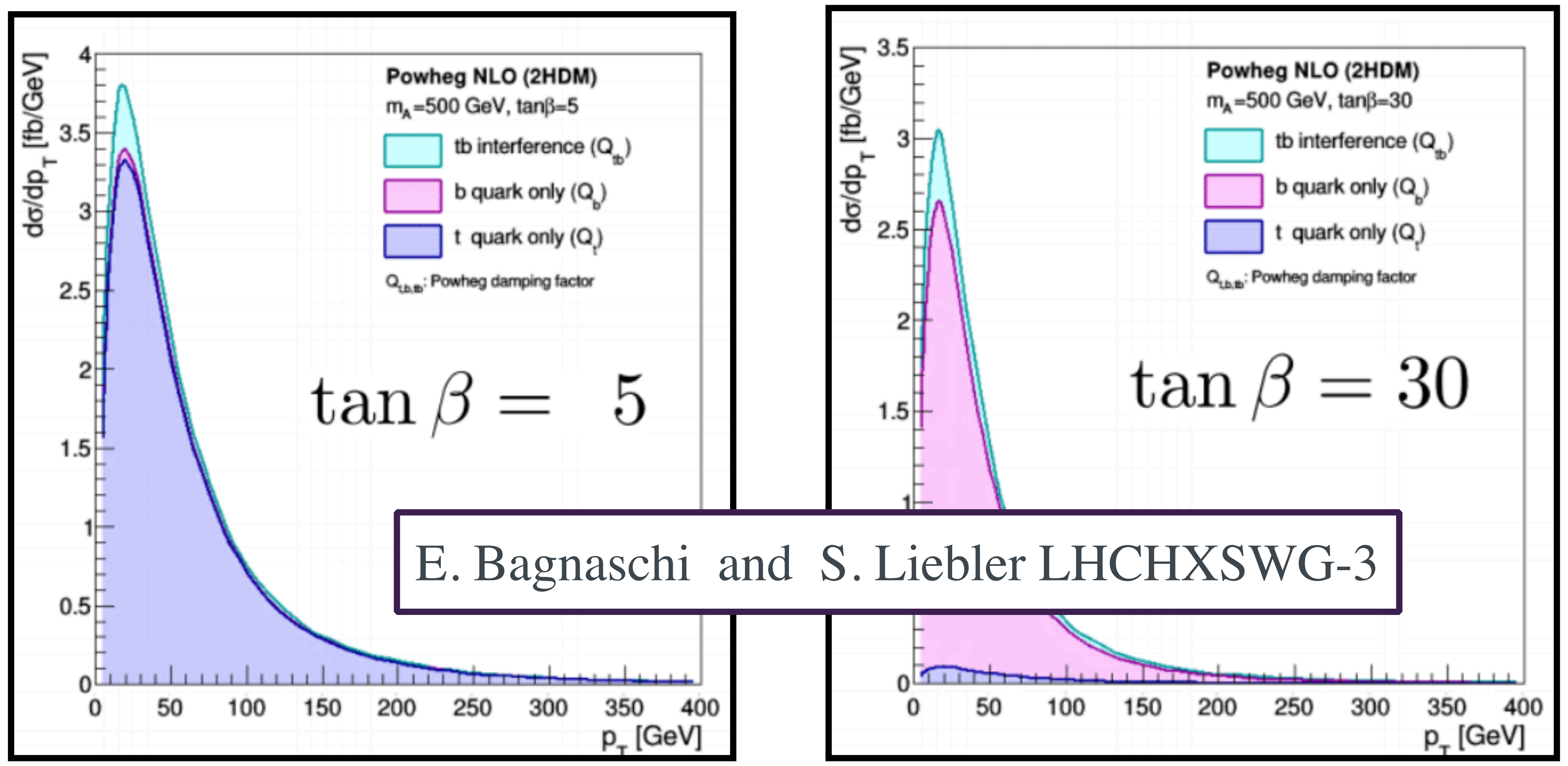
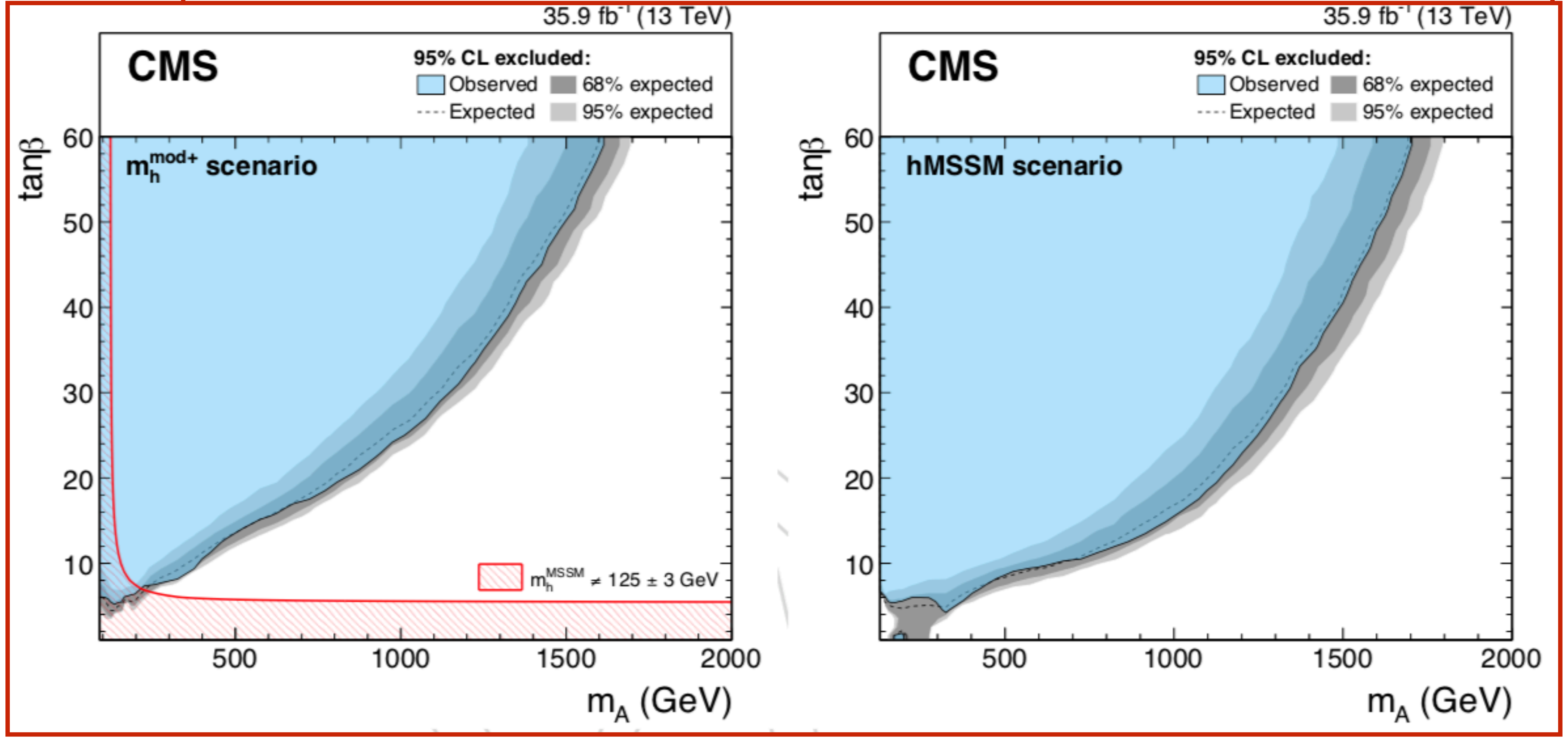


top-dominated → b-dominated

MSSM constraints

- Two representative benchmarks: hMSSM and m_h^{mod+}
- *ggH cross section*: SusHi NLO-QCD for MSSM + NNLO-QCD for top-quark contribution
- *bbH cross section*: NLO-QCD from SusHi and bbH@NLO combined via Santander matching
- *branching fraction:* FeynHiggs (m_h^{mod+}) and HDECAY (hMSSM)

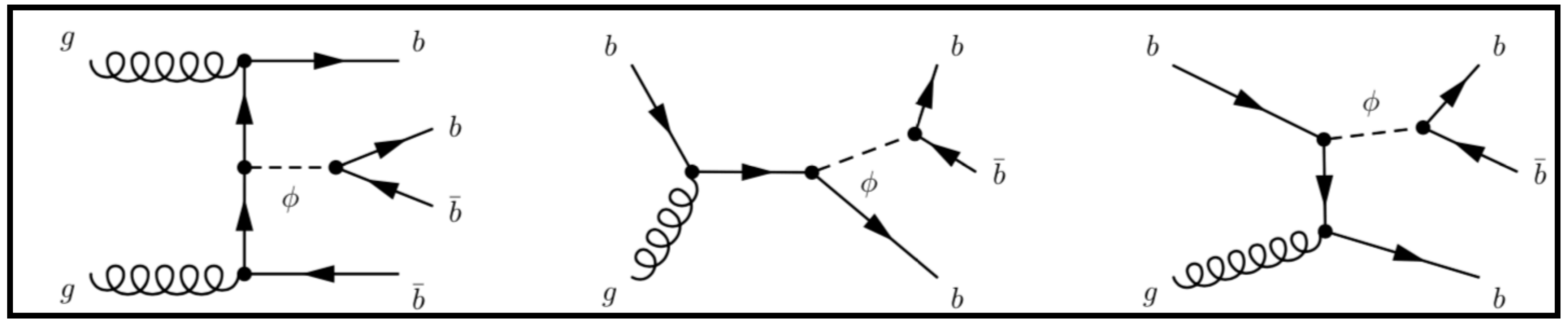


bbH, H→bb : overview

HIG-16-018

- **Signal benchmark:** analysis designed to target 2HDM type-II and flipped scenarios
- **A/H→bb** promising channel in these 2HDM scenarios where d-type quarks are exclusively coupled to one doublet
- **Limitations**: huge background from QCD multijet production at the LHC compared to A/H→ $\tau\tau$ search

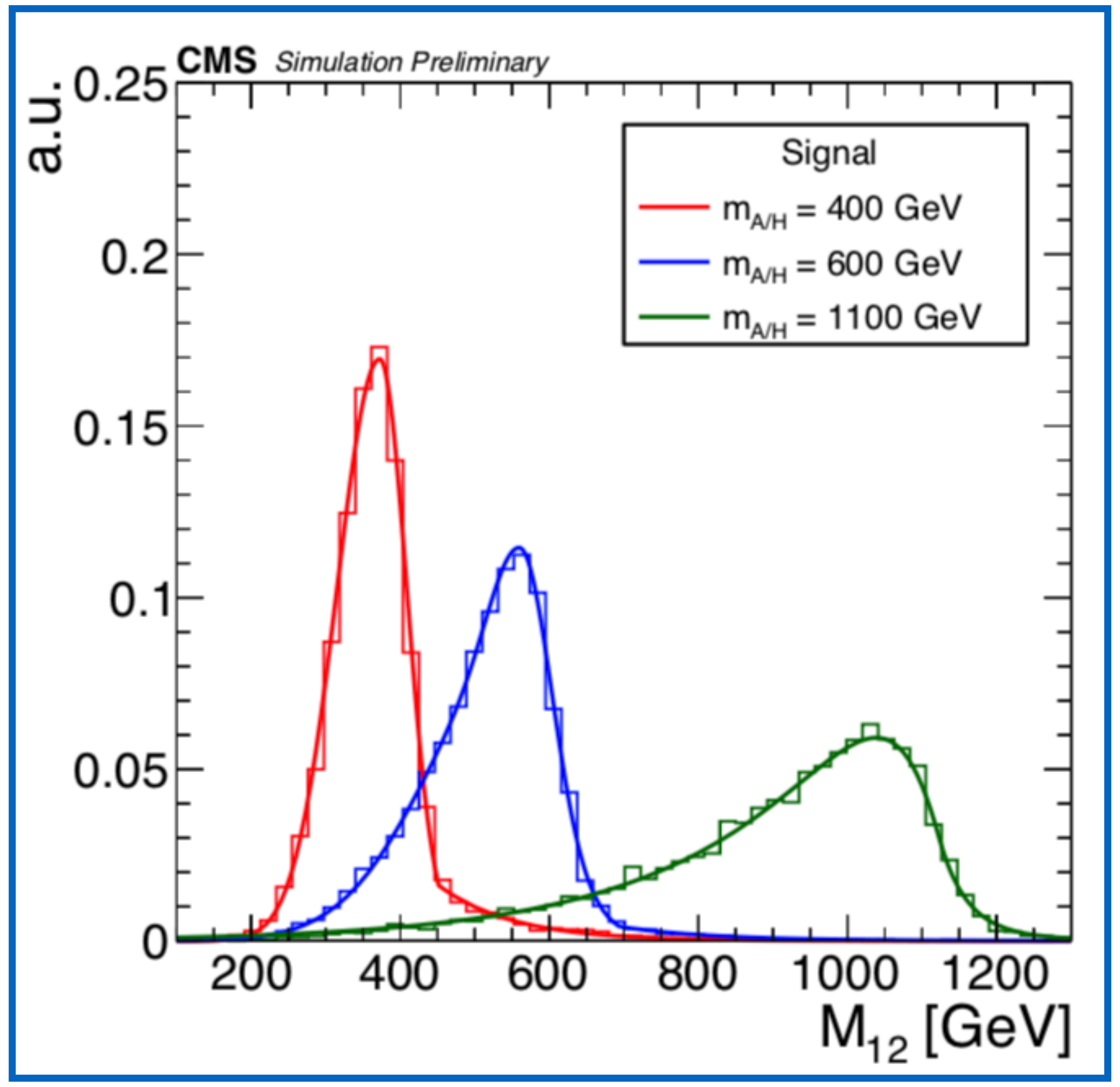
bbA/H and bA/H modes



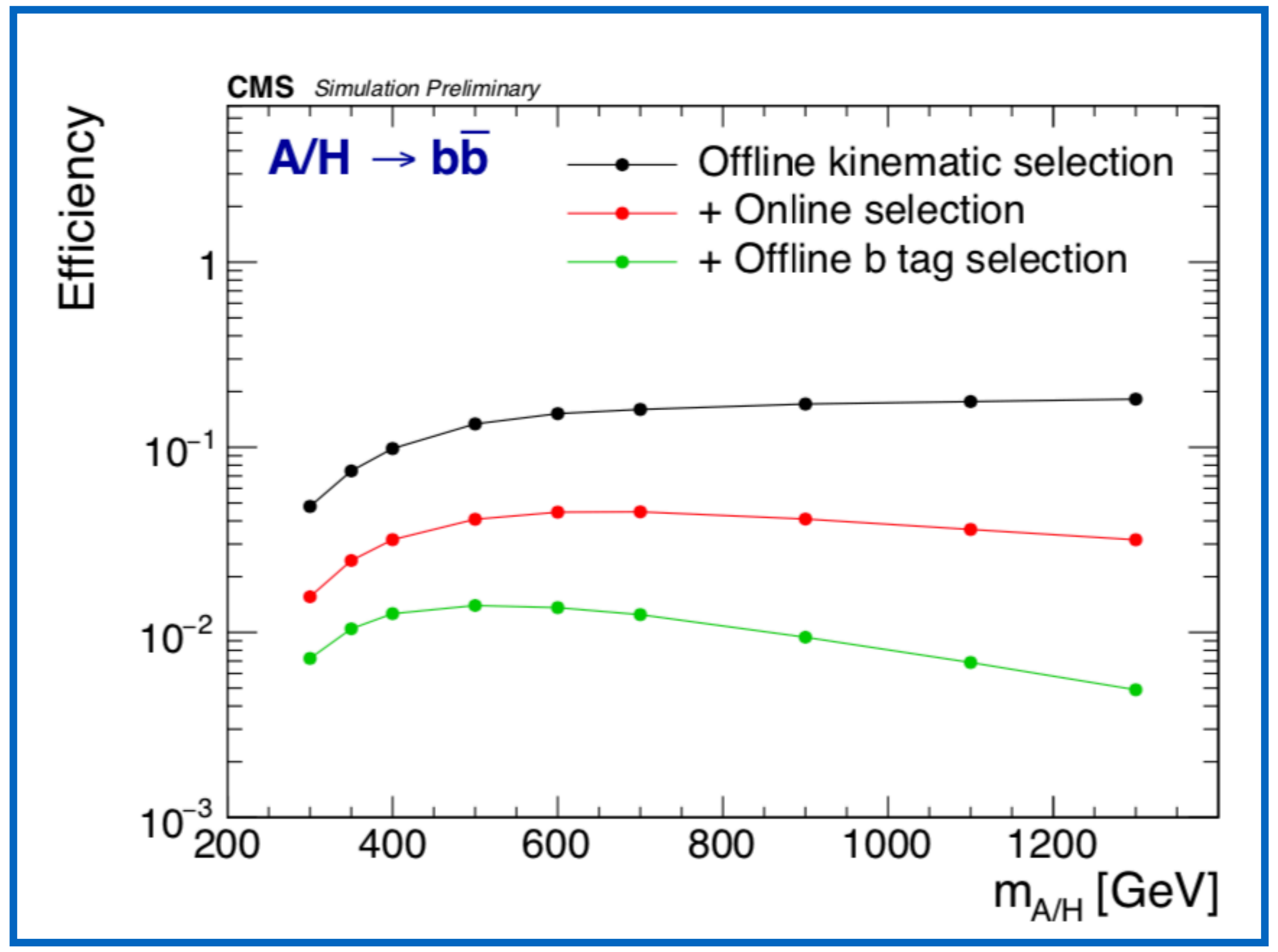
- Natural signal width is negligible compared to the experimental resolution

Analysis overview

- Because of trigger limitations: two high p_T central jets and $\Delta\eta_{jj} < 1.6$
- At least 3 b-tagged jets
- Presence of h_{125} not considered because not relevant for m(H/A) > 300 GeV
- Signal extracted by fitting the invariant mass distribution of the two leading jets



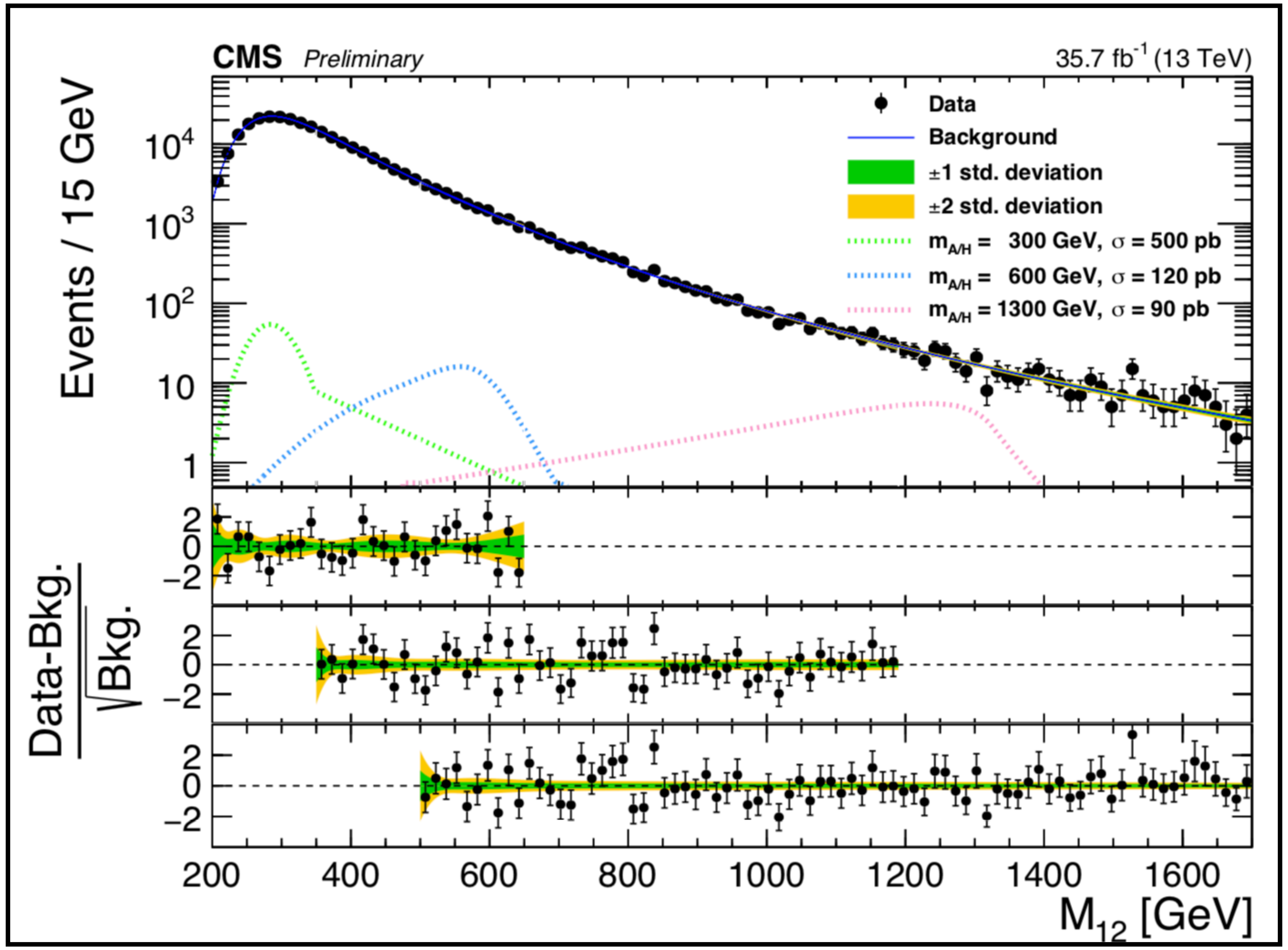
Small signal acceptance < 1%



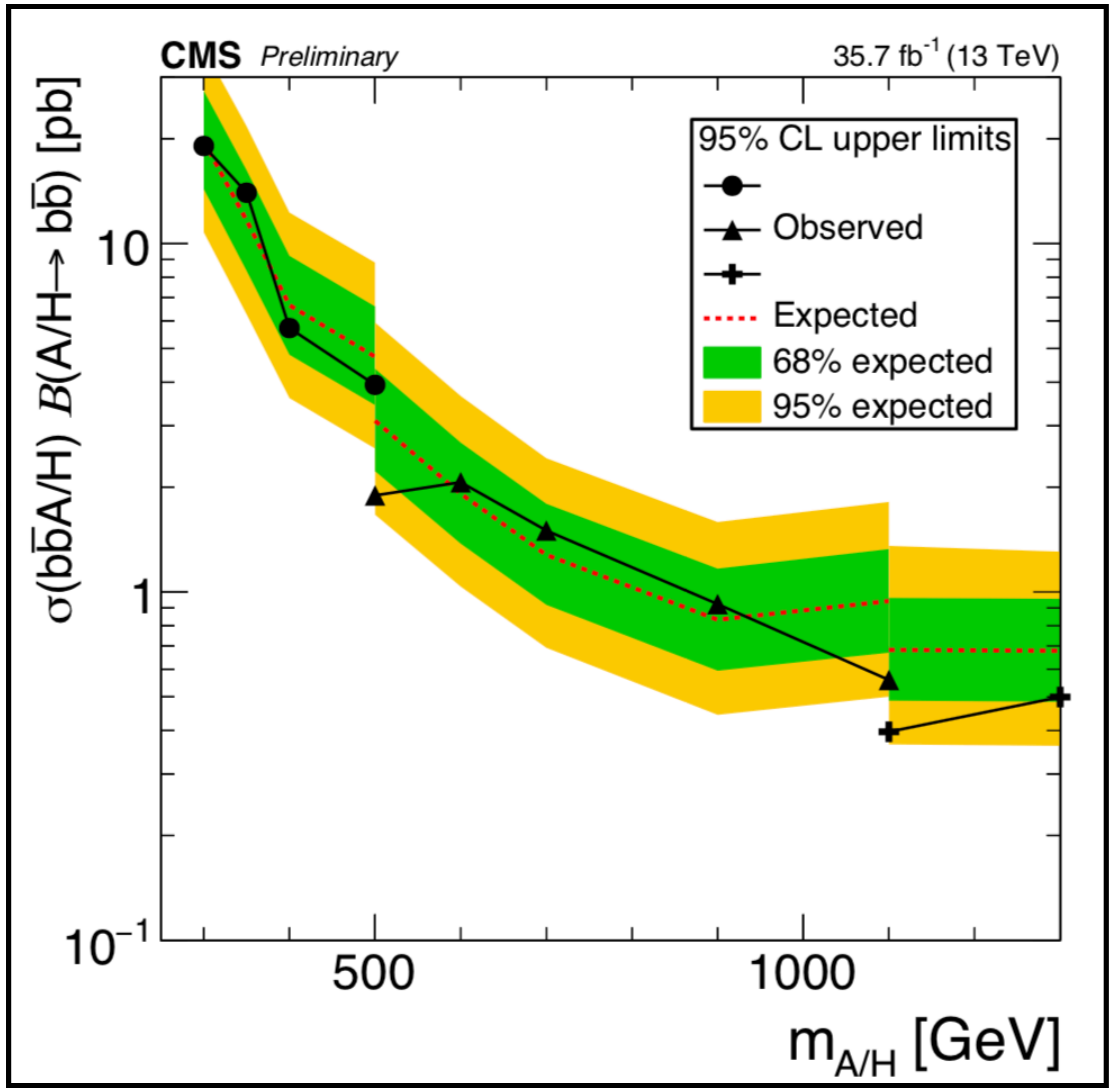
bbH, H→bb : results

HIG-16-018

- Analytical model of the background tested in a control region where only 2 bjets are required
- Analytical model chosen independently for three overlapping sub-ranges
- Bias on the fitted signal strength studied on toy experiments comparing the nominal fit model vs alternative truth functions

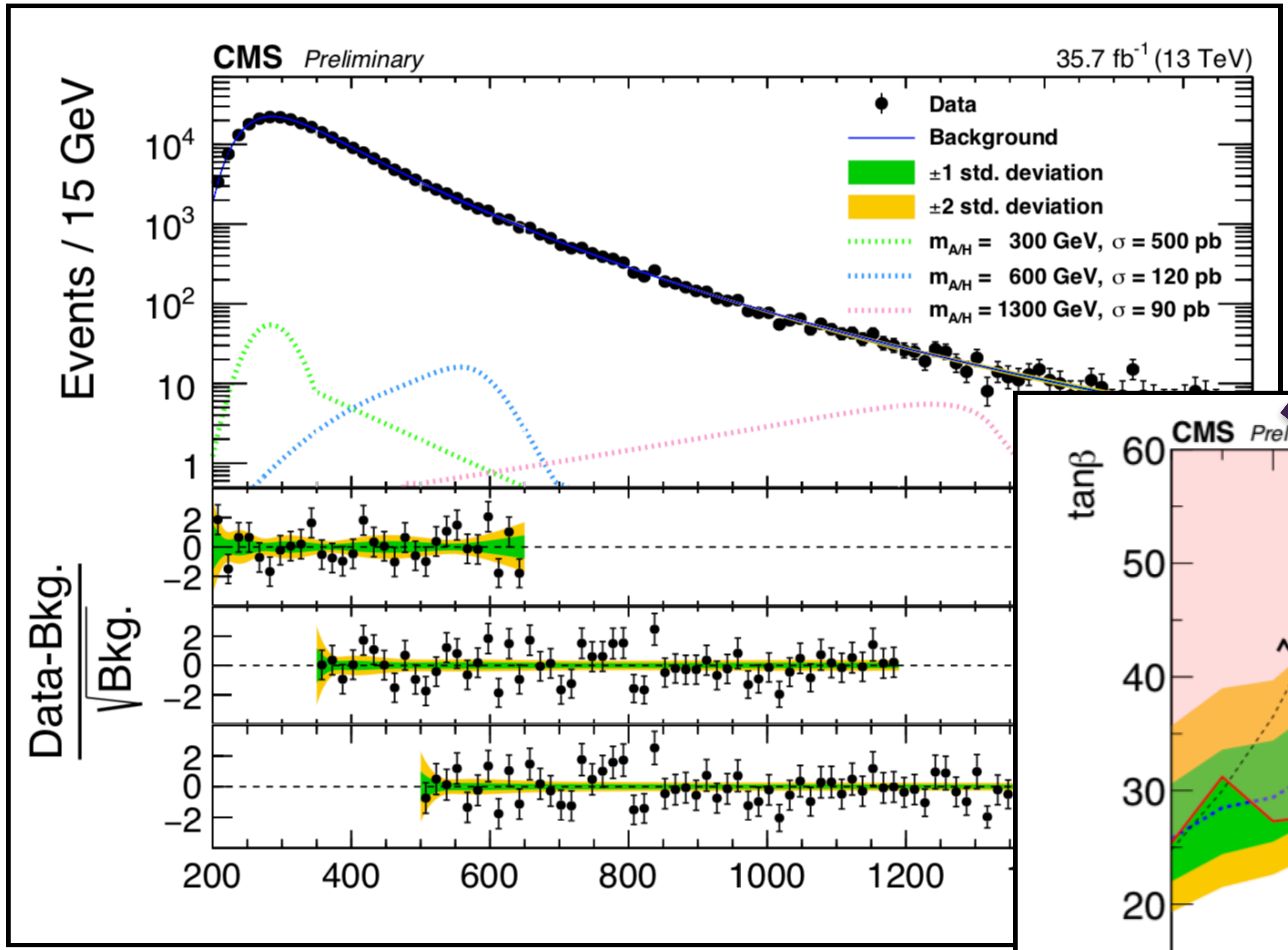


model independent limit



bbH, H→bb : results

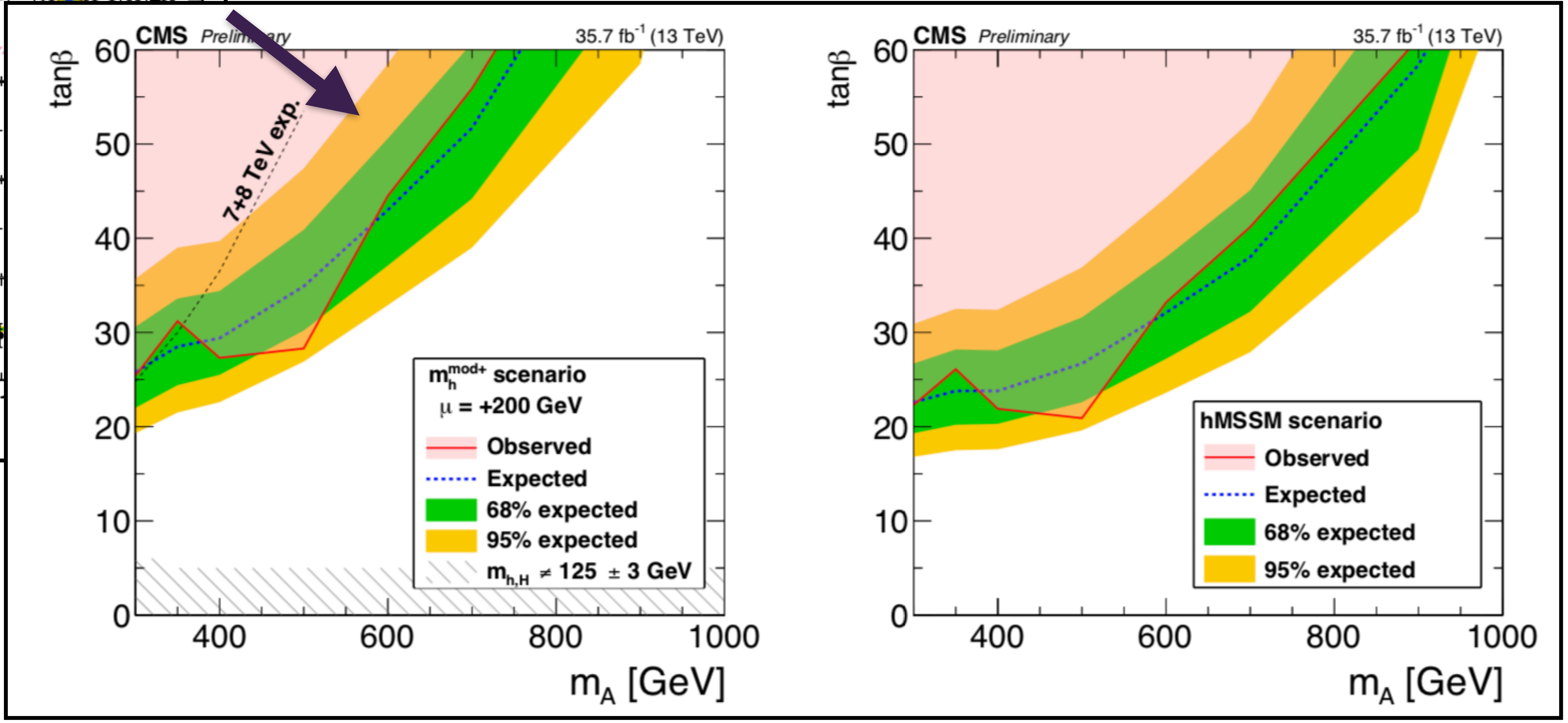
HIG-16-018



MSSM interpretation

- ***bbH cross section***: NLO-QCD from SusHi and bbH@NLO combined via Santander matching
- ***branching fraction:*** FeynHiggs (m_h^{mod+}) and HDECAY (hMSSM)

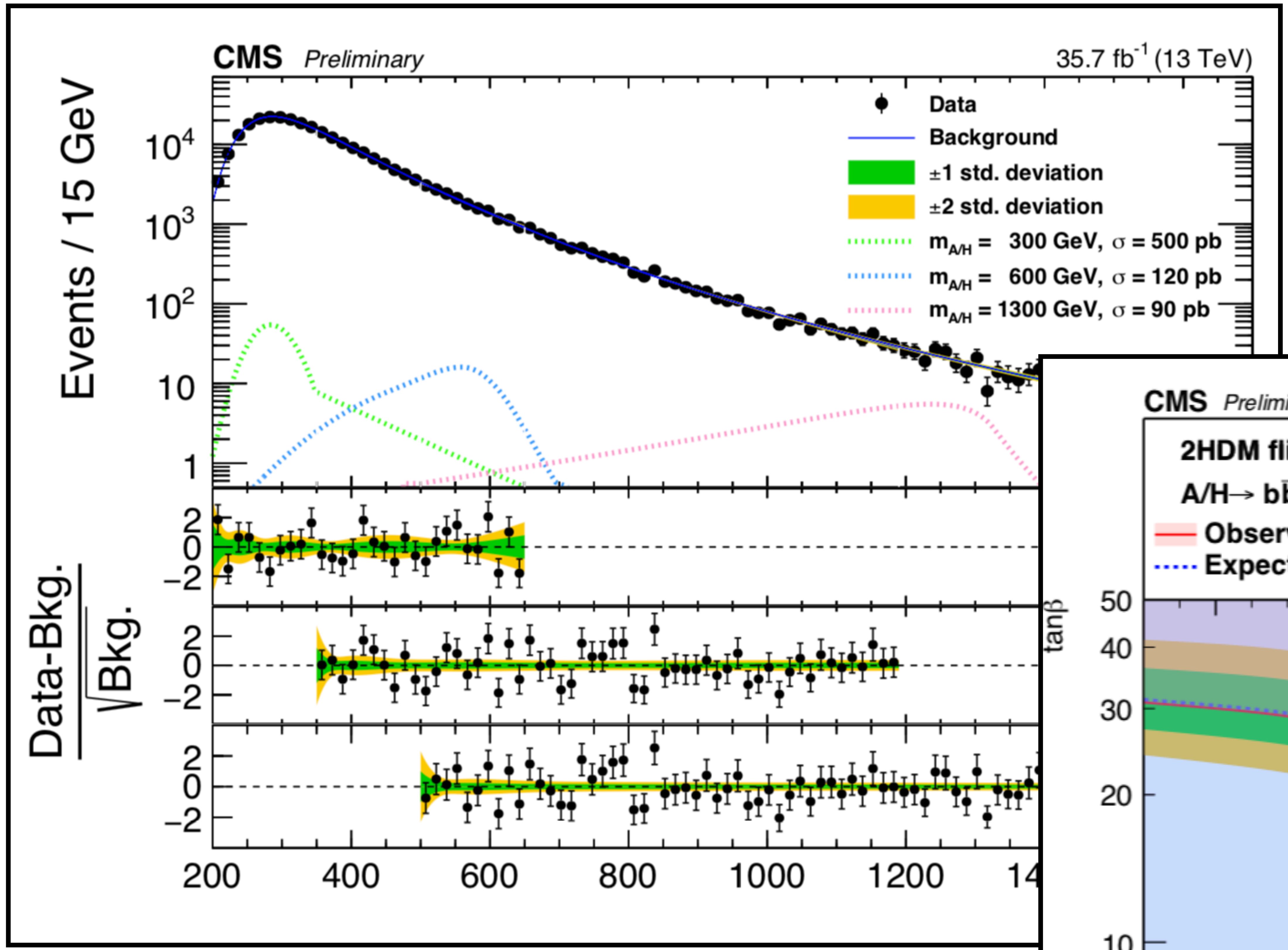
same recipe of H(ττ)



Weaker constraints compared to MSSM H(ττ)

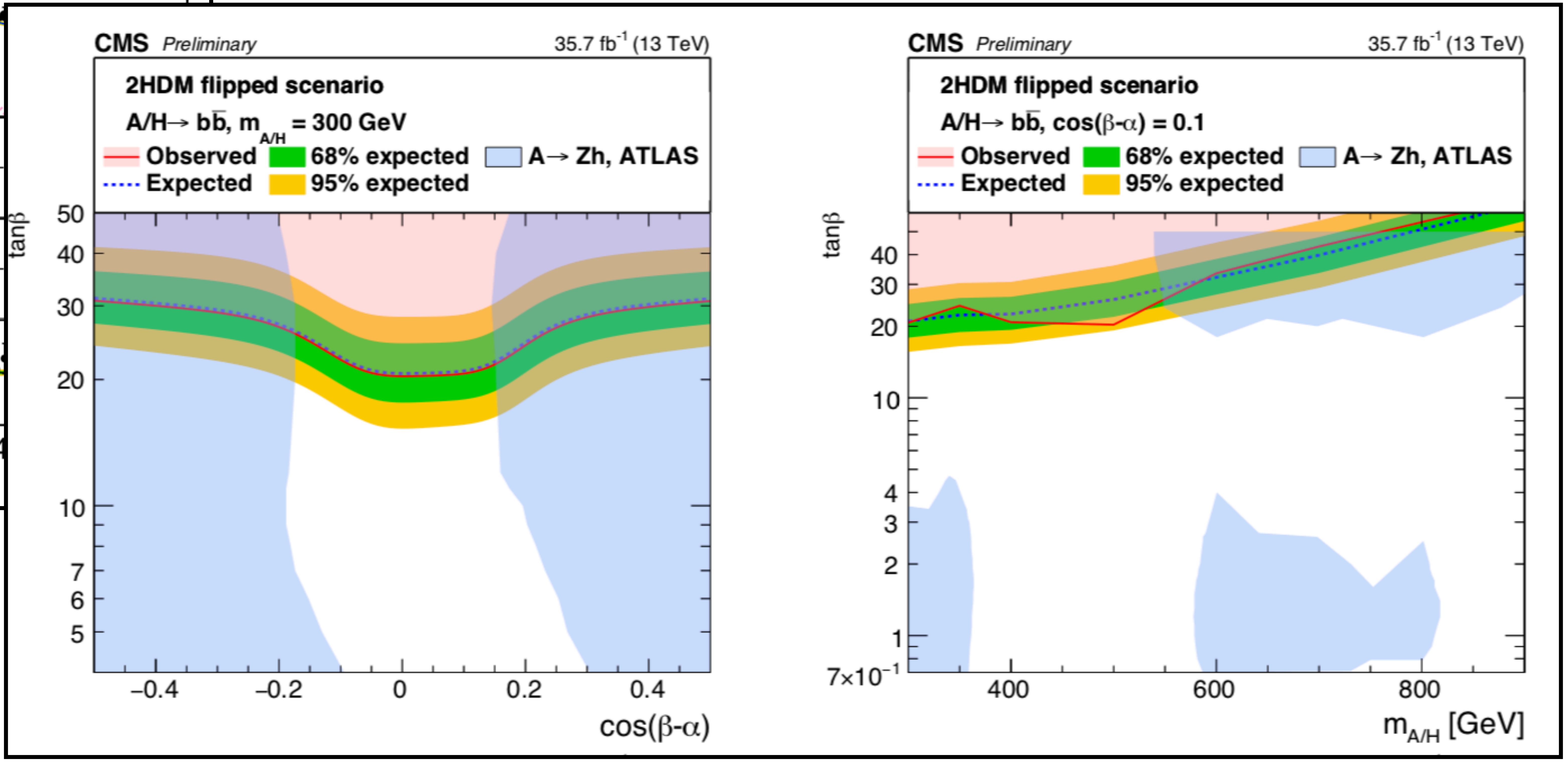
bbH, H→bb : results

HIG-16-018



2HDM interpretation

- Parameters set according to LHCXSWG recommendation: $m_A = m_H = m_{H\pm}$ and $m_{12}^2 = 1/2\, m_A^2 \sin(2\beta)$
- bbH and bbA cross section and branching fractions computed at NNLO via SusHi, 2HDMC and LHAPDF

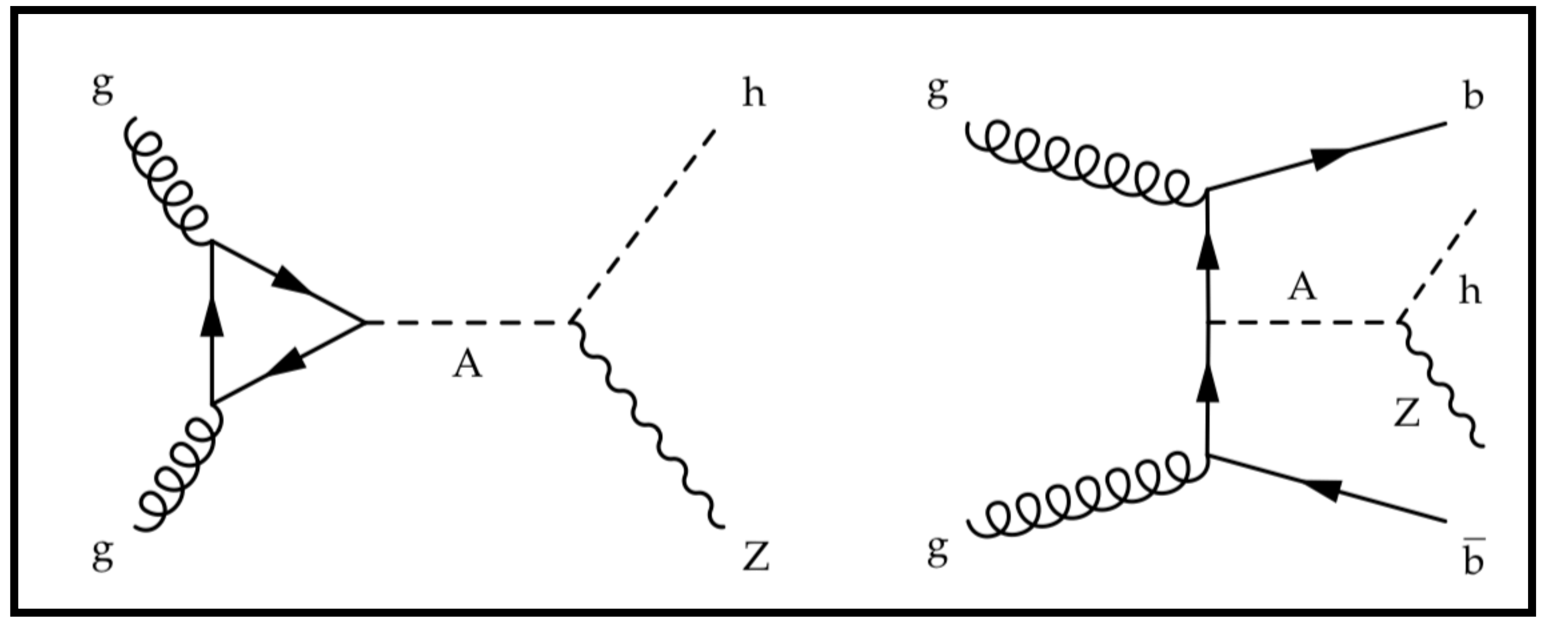


Complementarity with A→Zh searches for high tan(β) and small cos(β-α)

$A \rightarrow Zh \rightarrow Z(\nu\nu,\ell\ell)h(bb)$: overview

HIG-18-005

- In addition to fermionic decay modes $A \rightarrow (\tau\tau, bb)$, it may decay with a large BR to a Z-boson and a Higgs boson when kinematically allowed $m_A > m_Z + m_h$
- **Region of interested:** m_A [200,350] GeV and small tan(β) complementarity with fermionic final states
- **Production modes:** ggA or bbA



Best compromise between decay branching fraction and background contamination is represented by final states where ***h → bb*** and ***Z → leptons or neutrinos***

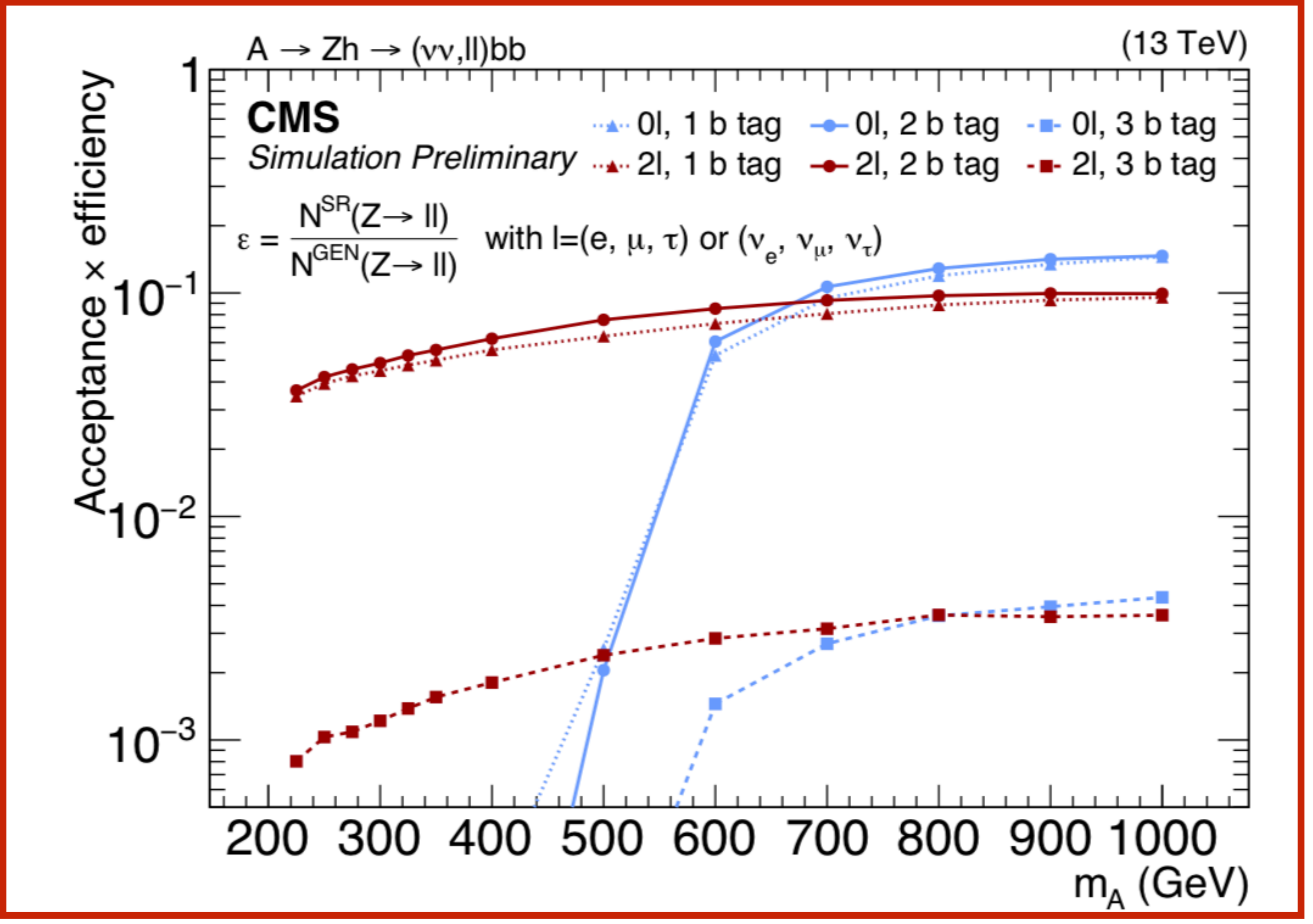
Analysis strategy

2-muons or electrons
$E_T^{miss} < 100$ GeV

- m_A can be reconstructed
- Z-boson mass constraint imposed to suppress SM backgrounds
- Events split in 1, 2 and 3 b-tag categories
- Kinematic fit imposing m(bb) = 125 GeV to improve the resolution of the reconstructed m_A peak

0-leptons
$E_T^{miss} > 200$ GeV

- m_A cannot be reconstructed → m_T used for the signal extraction
- At least one b-tagged jet
- $m_T > 500$ GeV
- Only used to probe high m_A values



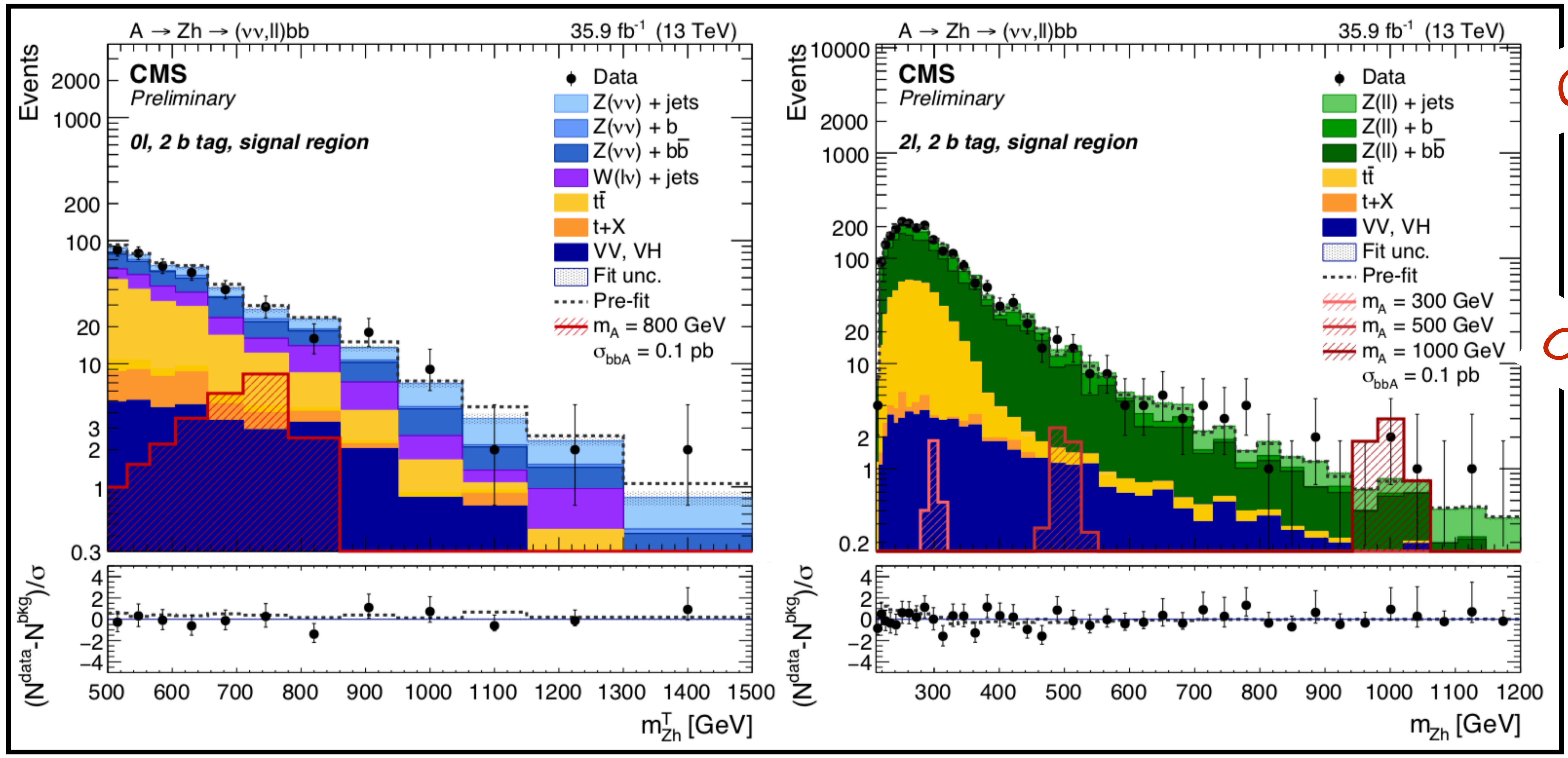
A → Zh → Z(νν,ℓℓ)h(bb) : results

HIG-18-005

- **Main backgrounds:** estimated from dedicated control regions

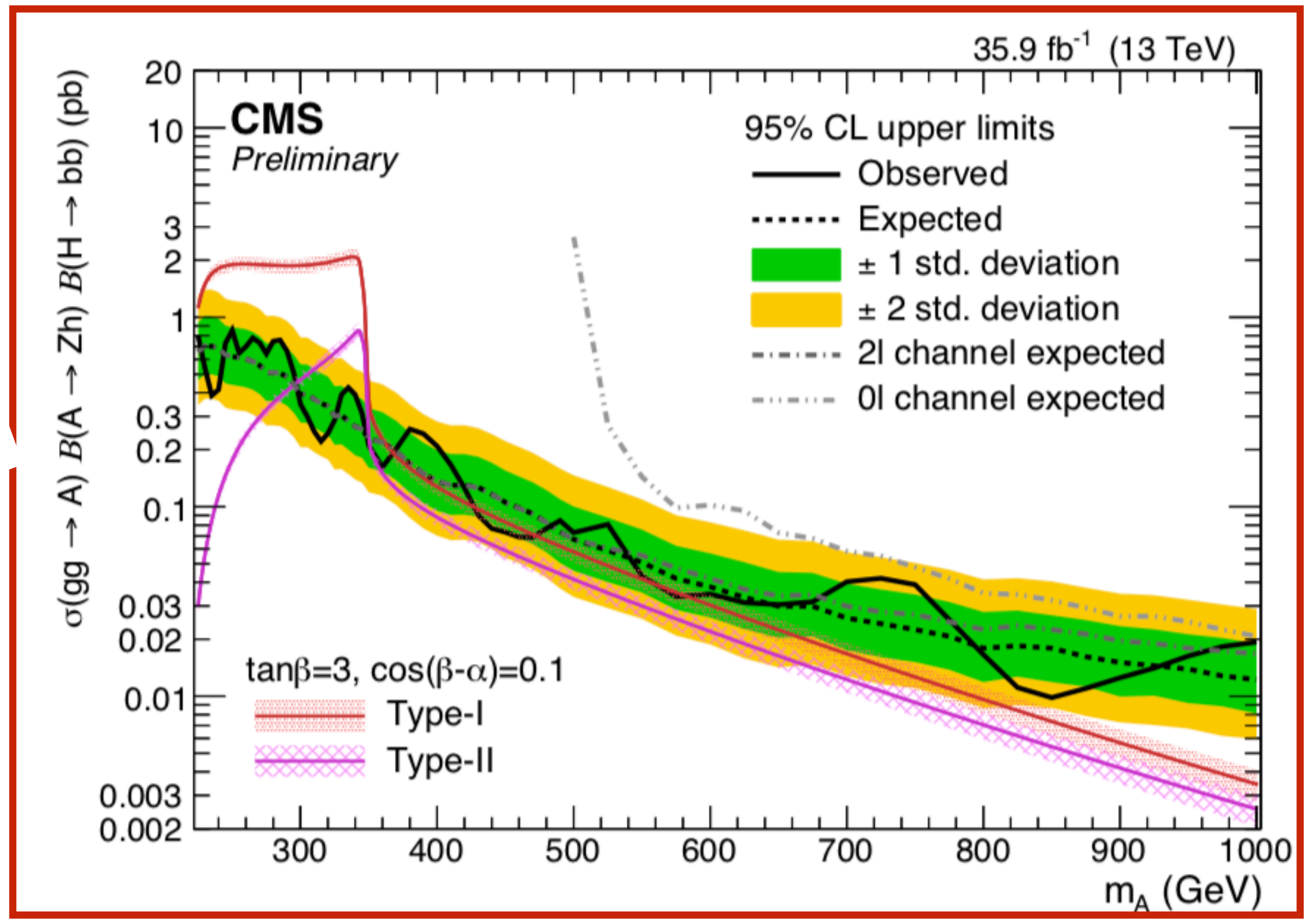
Z+jets → via mass sidebands   W+jets → 1-lepton CR   ttbar → Z-mass sidebands

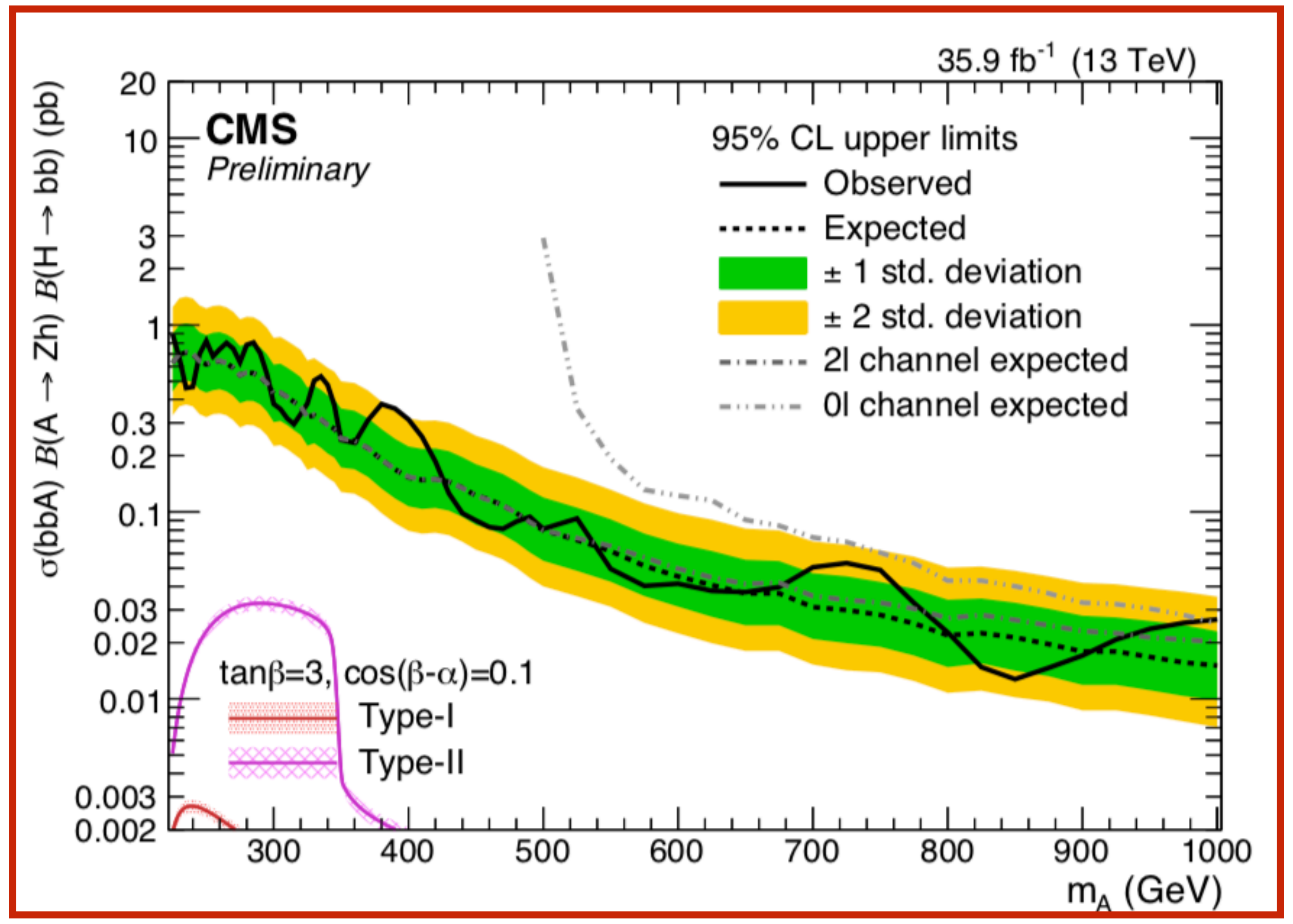
- **2-lepton categories**: MVA using the Zh kinematic properties, e.g. the five helicity dependent angles



Considering ggA only

Considering bbA only

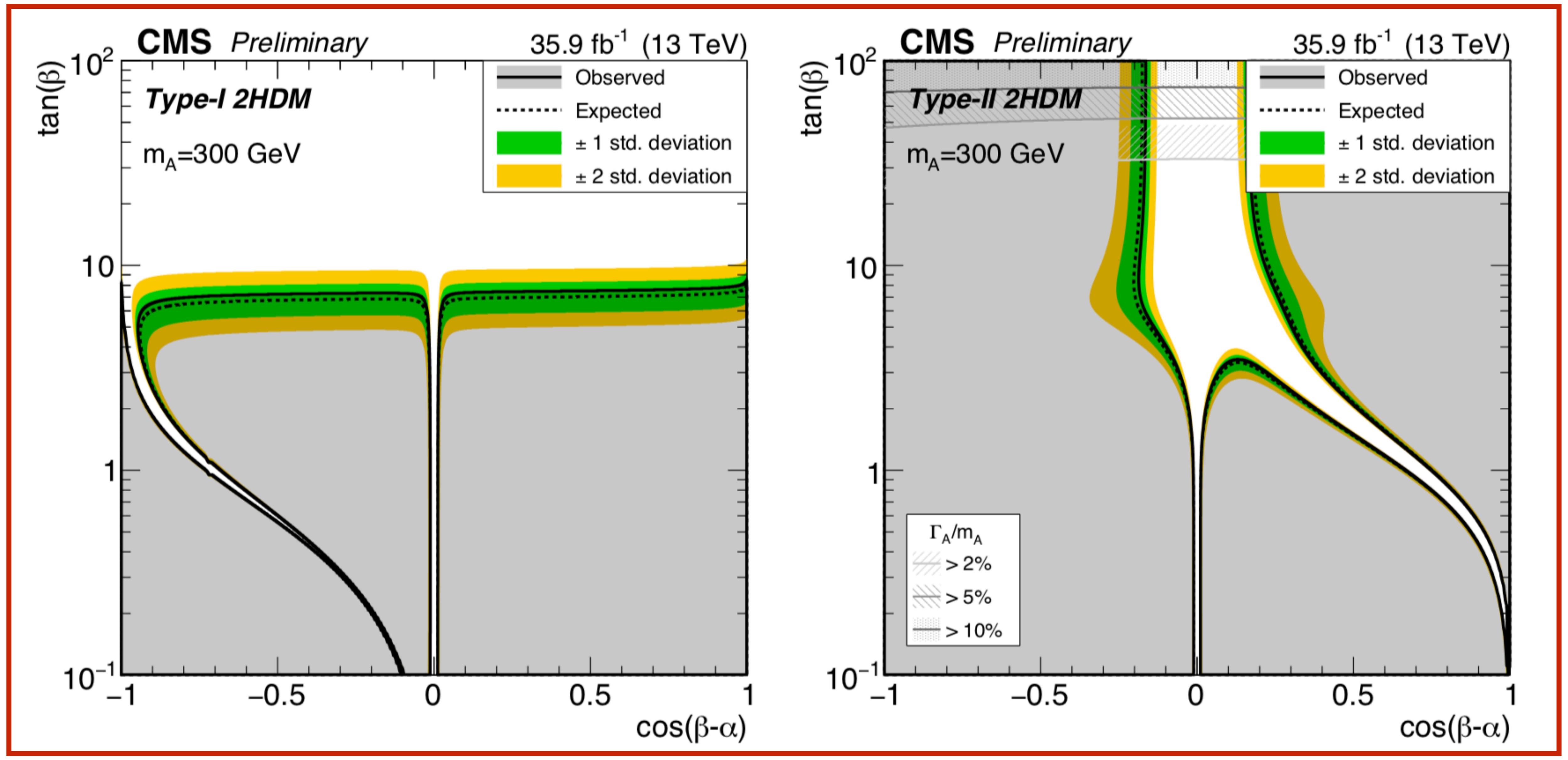


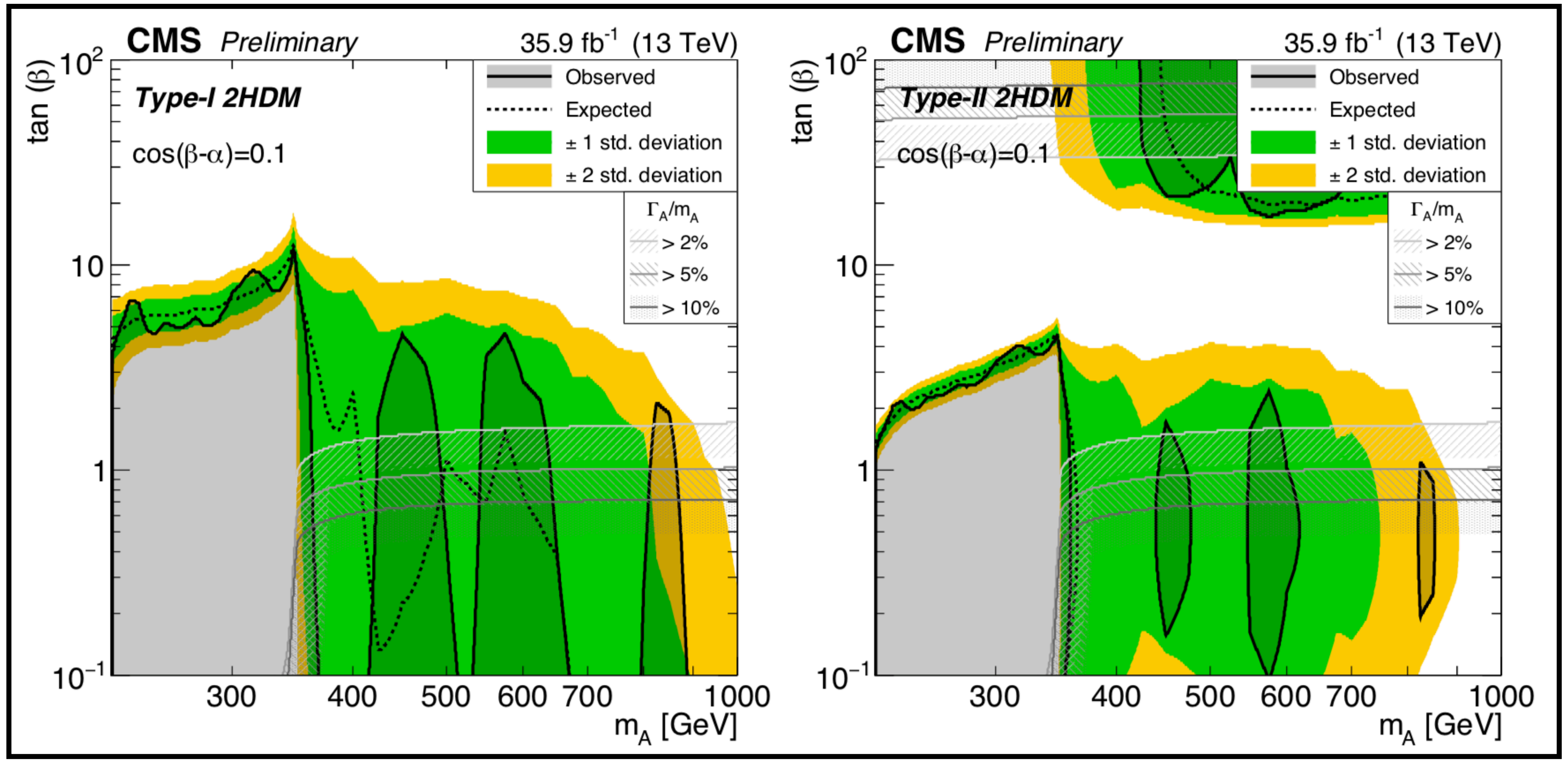


$A \to Zh \to Z(\nu\nu,\ell\ell)h(bb)$: 2HDM

HIG-18-005

- Cross sections and branching fractions computed via 2HDMC and SusHi
- **Parameters:** $m_H = m_{H\pm} = m_A$ and $m_{12}^2 = m_A^2 \tan(\beta) / (1+\tan(\beta)^2)$, $\lambda_{6,7} = 0$ to ensure CP-conservation
- $B(h \to bb)$ goes to zero in the regions where $\alpha \to 0$ ($\pm\pi/2$) in the Type-II (Type-I) scenarios





Excluded regions in 2HDM Type-I: for mA < 350 GeV: tan(β) < 7 and cos(β-α) > 0.01

Excluded regions in 2HDM Type-II: for mA < 350 GeV: all tan(β) for |cos(β-α)| > 0.5

High mass X → ZZ resonances

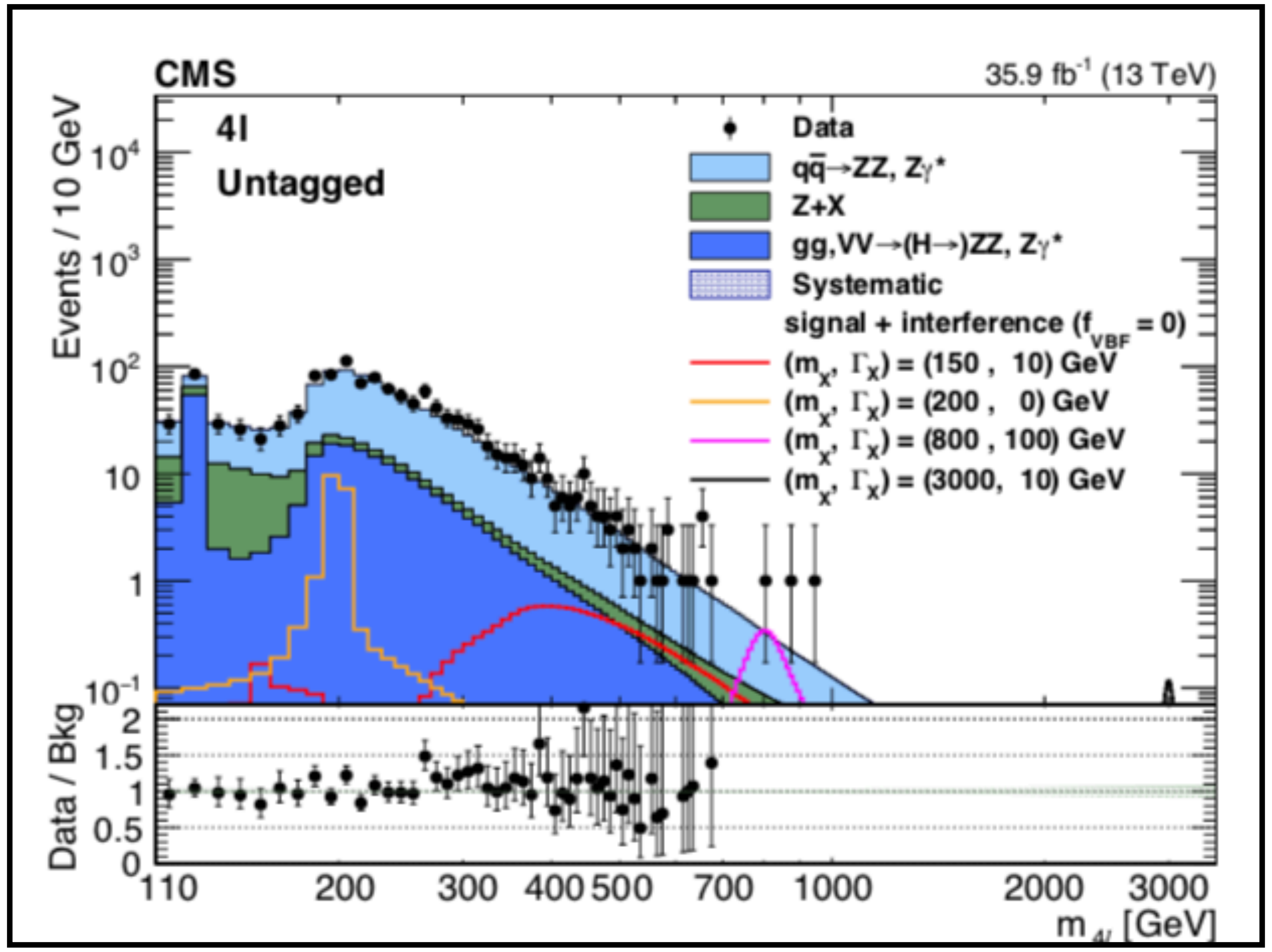
HIG-17-012

Basic assumptions of this search

- Search for an heavy scalar partner (X) of the Higgs boson
- Branching fractions are assumed to be SM-like → dominant in ZZ when $m_X > 2*m_Z$
- Mass unknown: searches are covering m_X = [0.2,3] TeV
- **Model independent approach:** for a given m_X, Γ_X and production mechanisms are assumed to be unknown
- **Production modes:** ggX, qqX (VBF), qqVX or ggZX are minor
- **Interference:** when Γ_X is not small there is a sizeable interference with ggZZ or qqZZ production
- ***Signal events simulated via JHUGen at NLO-QCD***
- ***MELA package*** interfaced to JHUGen and MCFM used to model the interference contribution

Four lepton channel

- ***X → ZZ → 4μ,4e,2μ2e*** where events further split in VBF and ggH categories
- The separation between signal and background is maximised via the m_{4l} and a kinematic discriminant built using the kinematic information of the fully reconstructed ZZ decay system



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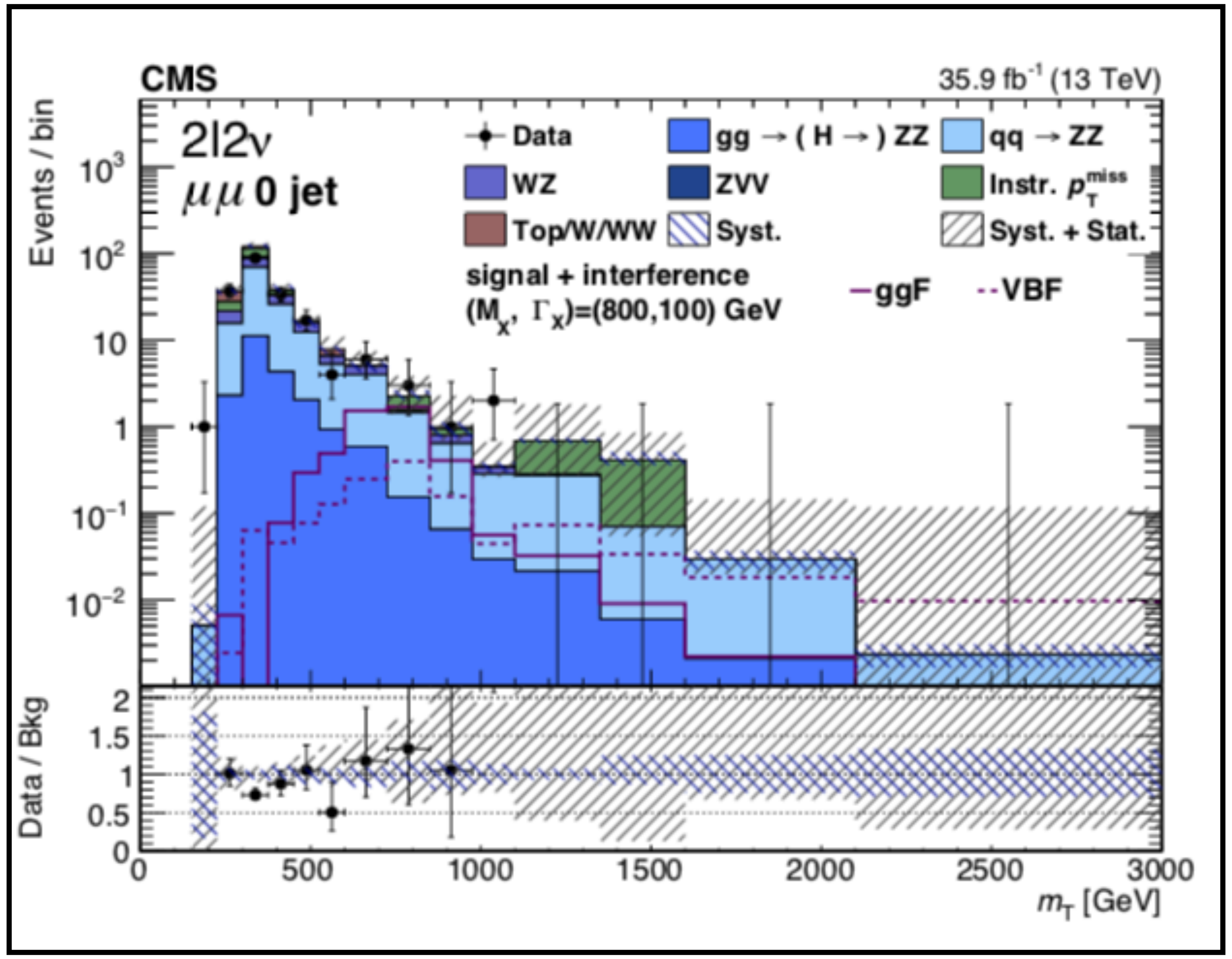
2-lepton + 2-neutrino channel

- ***X → ZZ → 2μ2ν,2e2ν*** where events need to contain a Z-candidate with $p_T > 55$ GeV and $p_T^{miss} > 125$ GeV
- Signal extracted by fitting the m_T distribution
- **Categories:** VBF-tag, 1-jet and 0-jet events



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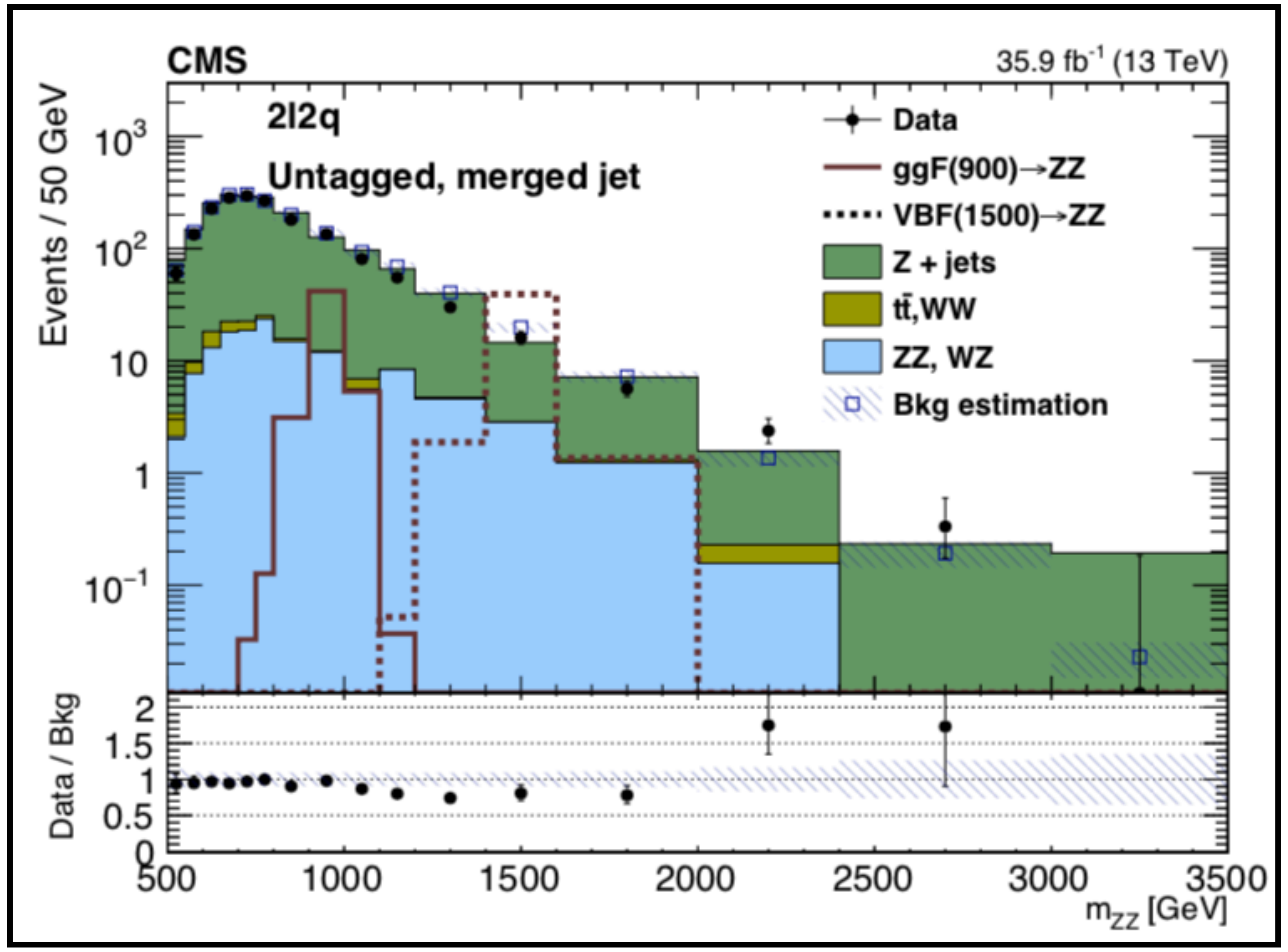
2-lepton + 2-jets channel

- ***X → ZZ → 2μ2q,2e2q*** where events need to contain a Z-candidate with $p_T > 100$ GeV
- Events are split into a ***resolved*** and a ***merged*** category depending on the p_T of the hadronic Z-candidate.
- $m_{ZZ} > 500$ GeV therefore no access to low mass resonances
- Events further split in: VBF, b-tagged and ggH categories



High mass X→ ZZ : signal model

HIG-17-012

$$\mathcal{P}^{i,k}_{vv}(\vec{x}_j; m_X, \Gamma_X) = \mu_i \mathcal{P}^{i,k}_{vv\to X\to 4f}(\vec{x}_j; m_X, \Gamma_X) + \sqrt{\mu_i}\mathcal{P}^{i,k}_{\text{int}}(\vec{x}_j; m_X, \Gamma_X) + \mathcal{P}^{i,k}_{vv\to 4f}(\vec{x}_j),$$

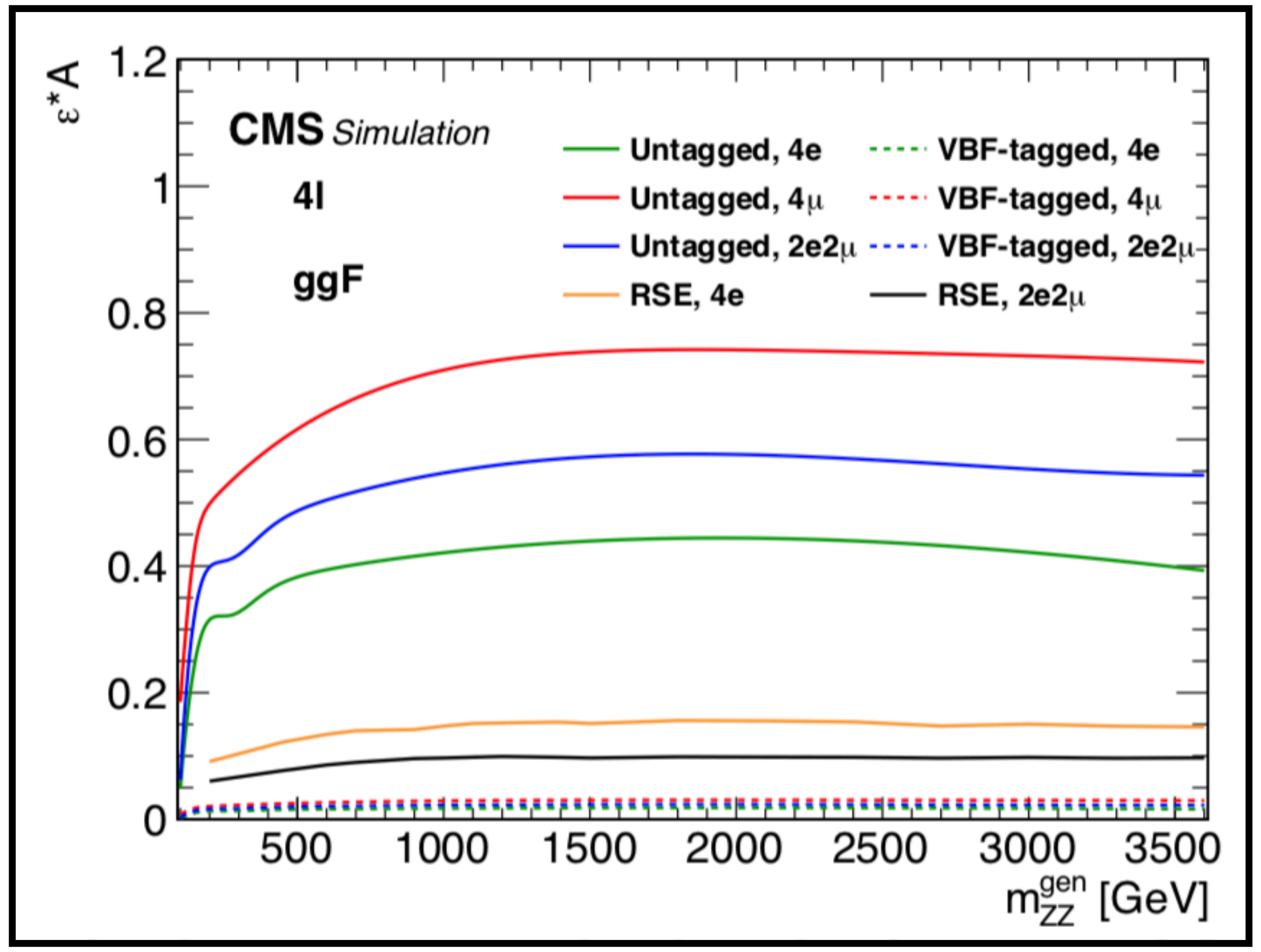
S+B cross section for a production mode i in the category k

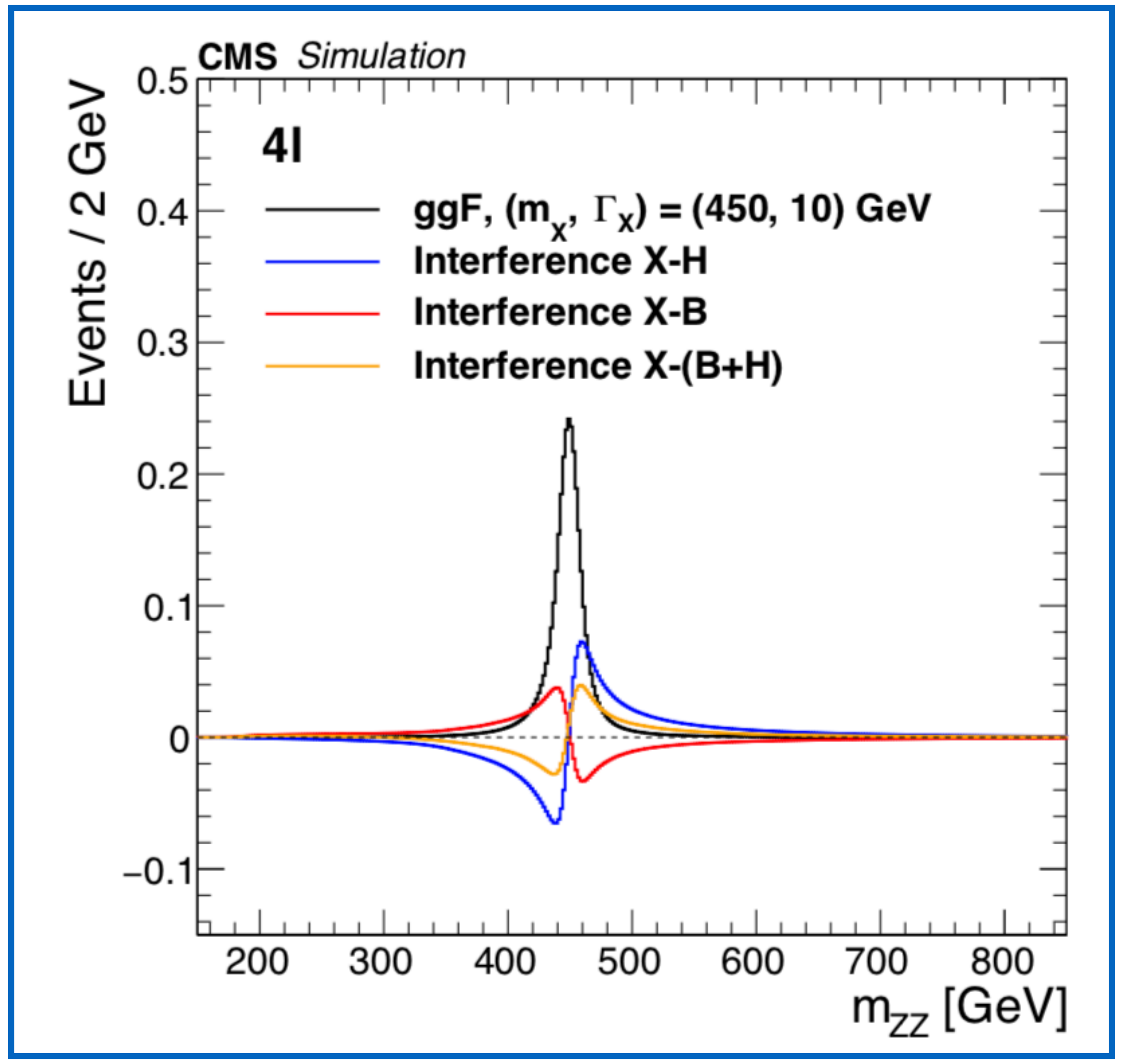
Signal-only contribution

interference

background-only term

Parametrize acceptance x efficiency using a set of generated resonances





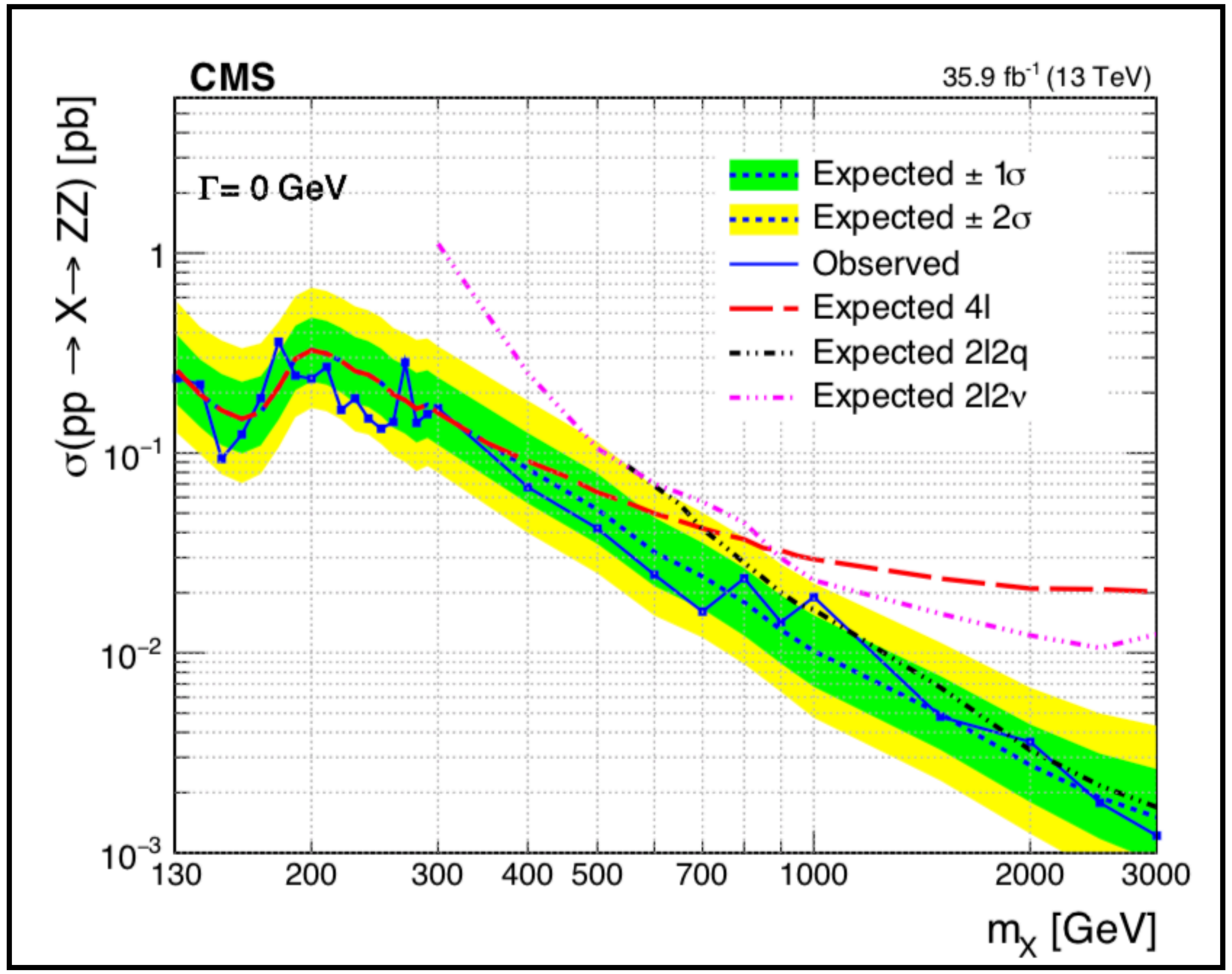
High mass X→ ZZ : results

HIG-17-012

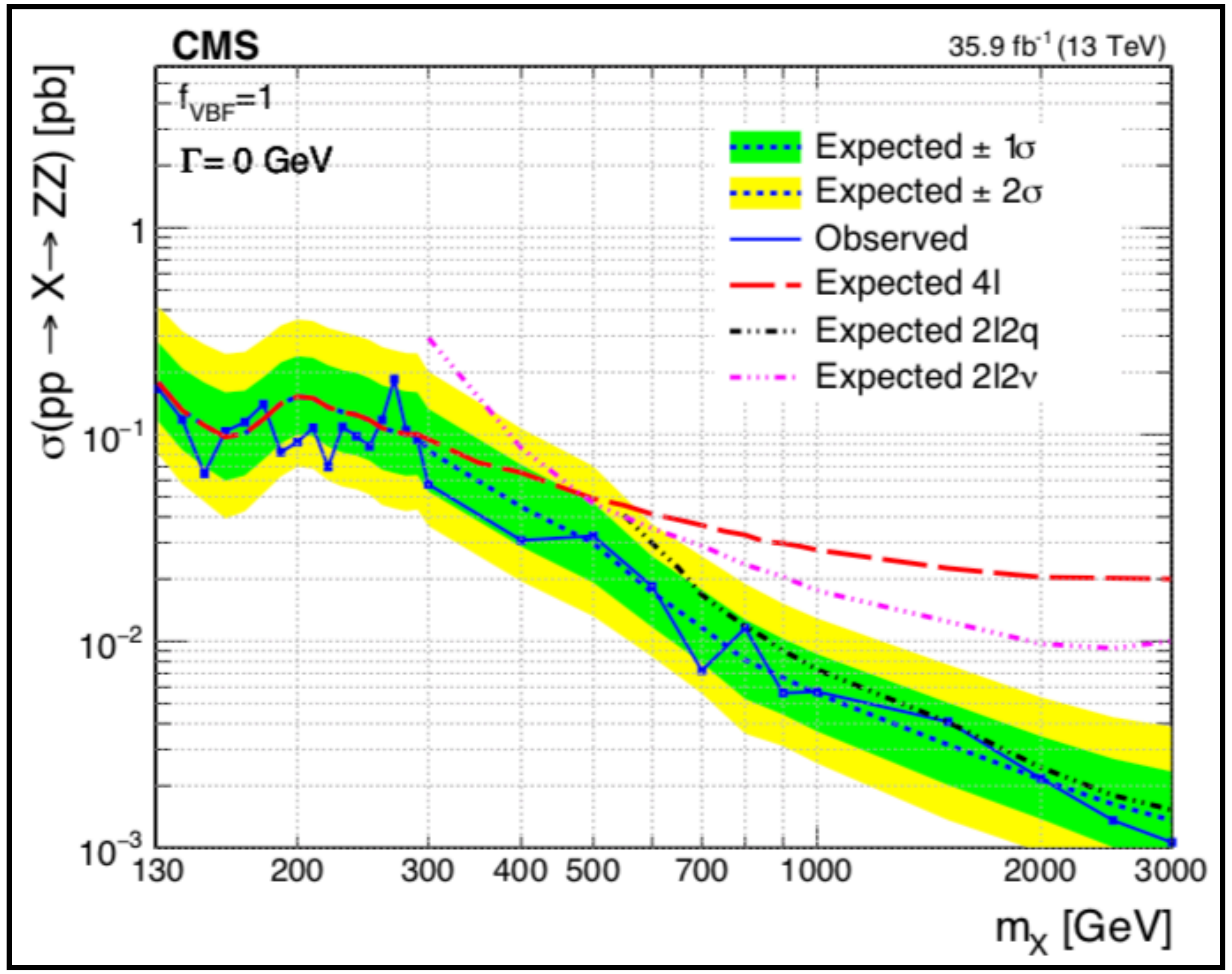
Sensitivity

- In the range m_X in [130,500] GeV, the most sensitive is the X → ZZ → 4l
- In the range m_X [500,700] GeV, the X → ZZ → 2l2ν channel dominates
- For m_X > 700 GeV, the X → ZZ → 2l2q channel dominates

Both ggX and VBF production considered



Only VBF production allowed



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HIG-17-012

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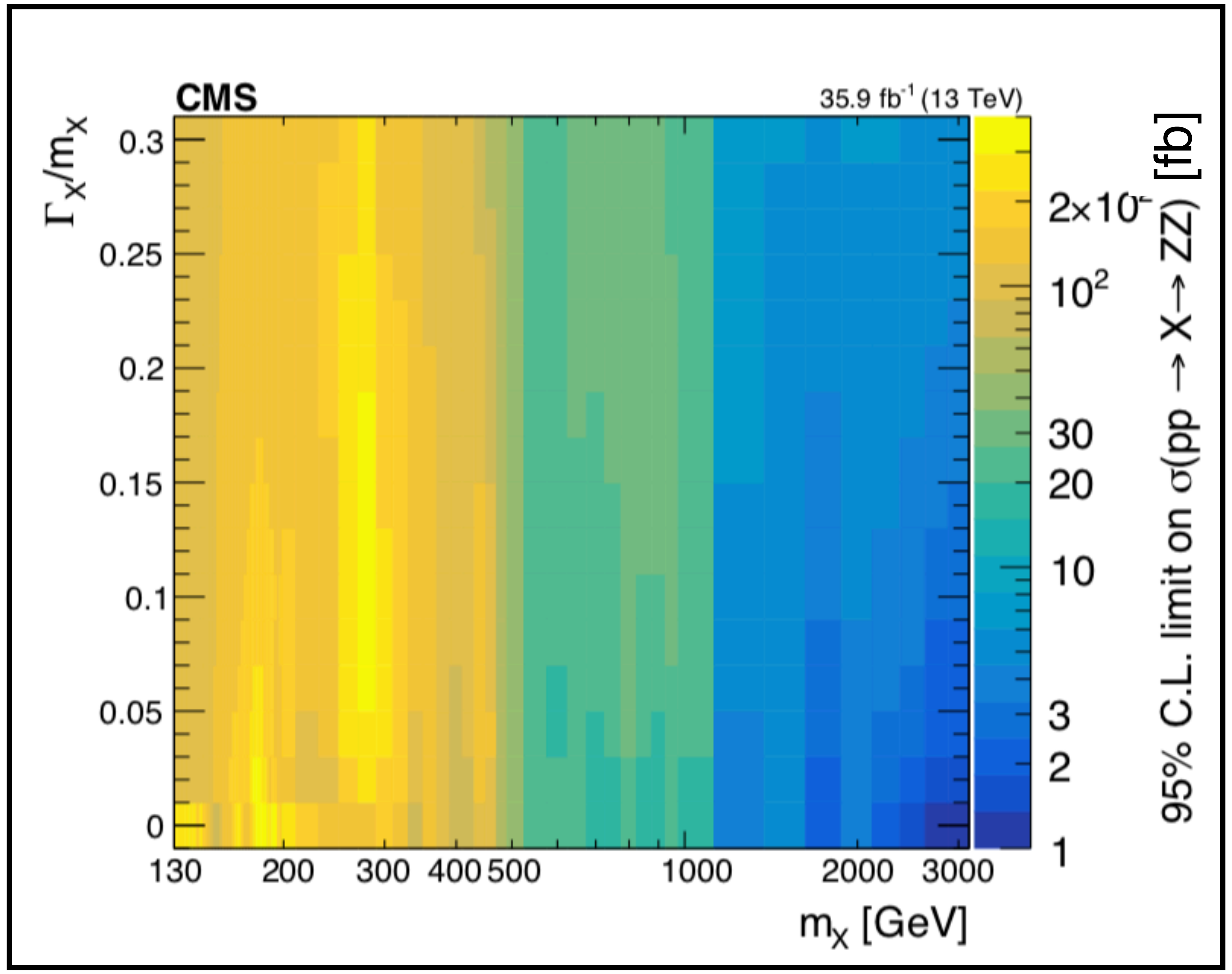

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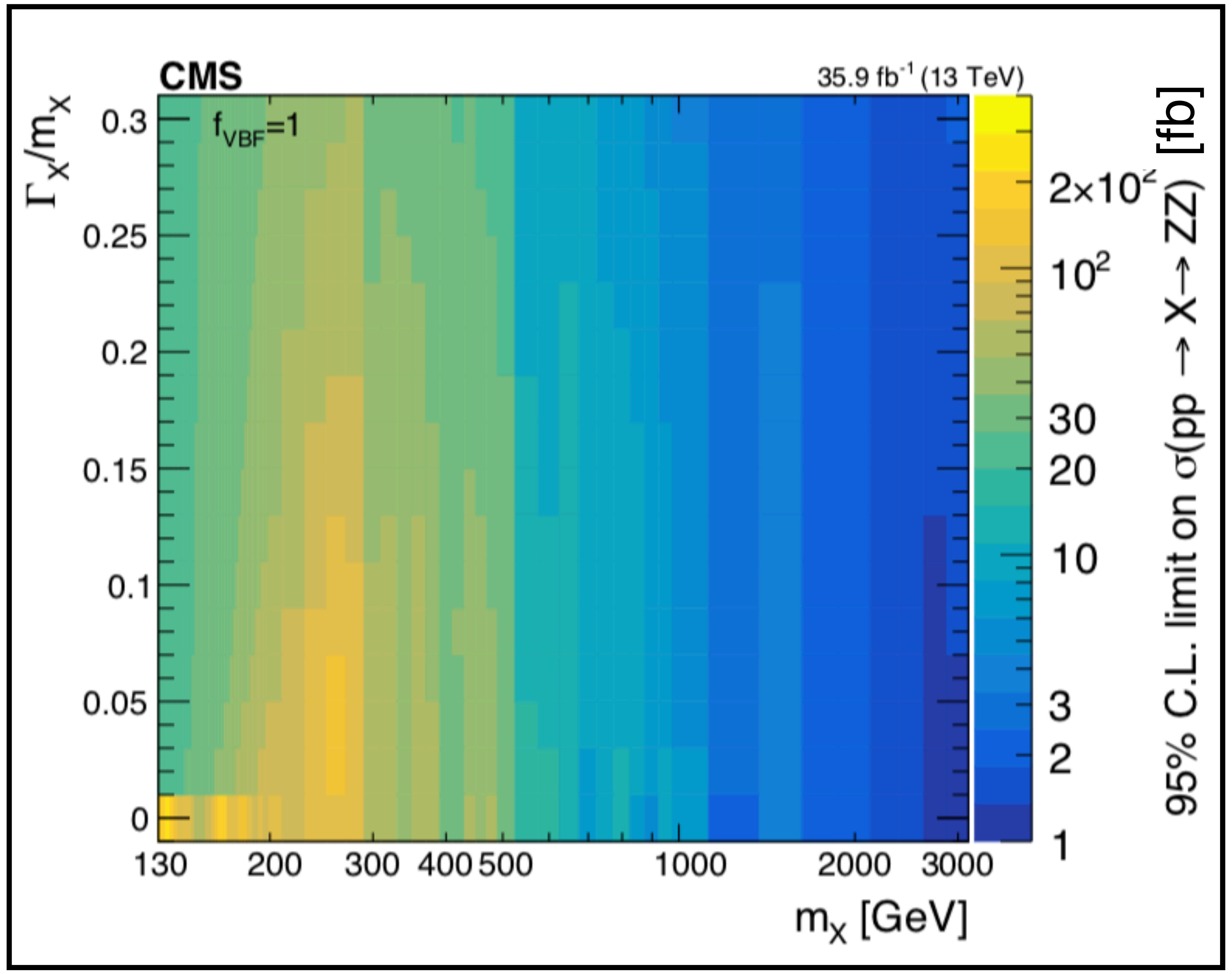

Summary on neutral resonances

- **General Goal:** give a short summary of the most recent results obtained with 2016 data in the context of

Additional Neutral Scalars

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Constraints from h_{125}

- HIG-17-031

Are the current searches fully covering the interesting phase space?

Are there missing signatures which might be particularly interesting ?

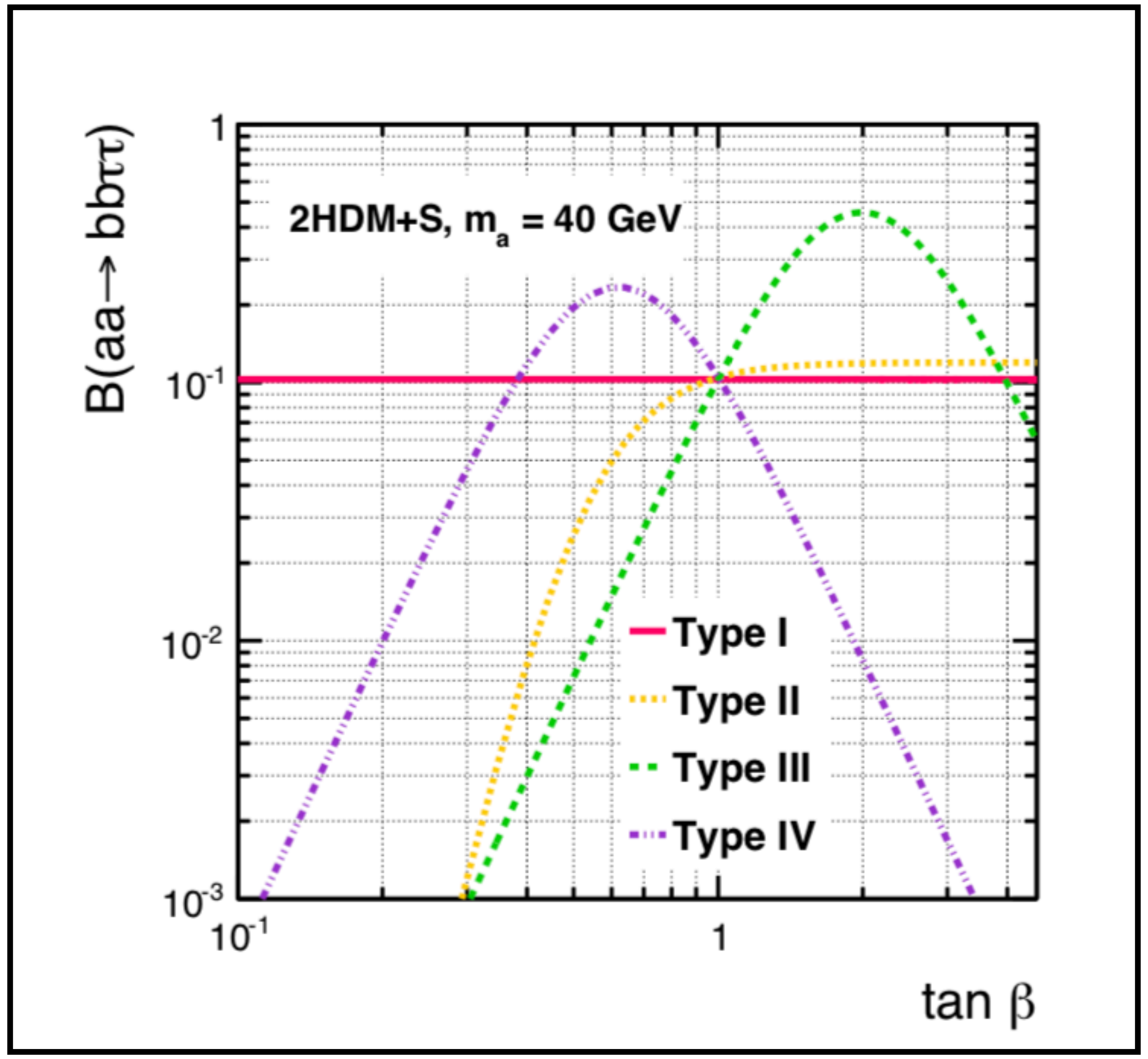
Are we doing proper interpretations of our results ?

Exotic decays of h_{125}

h → aa → 2b2τ search

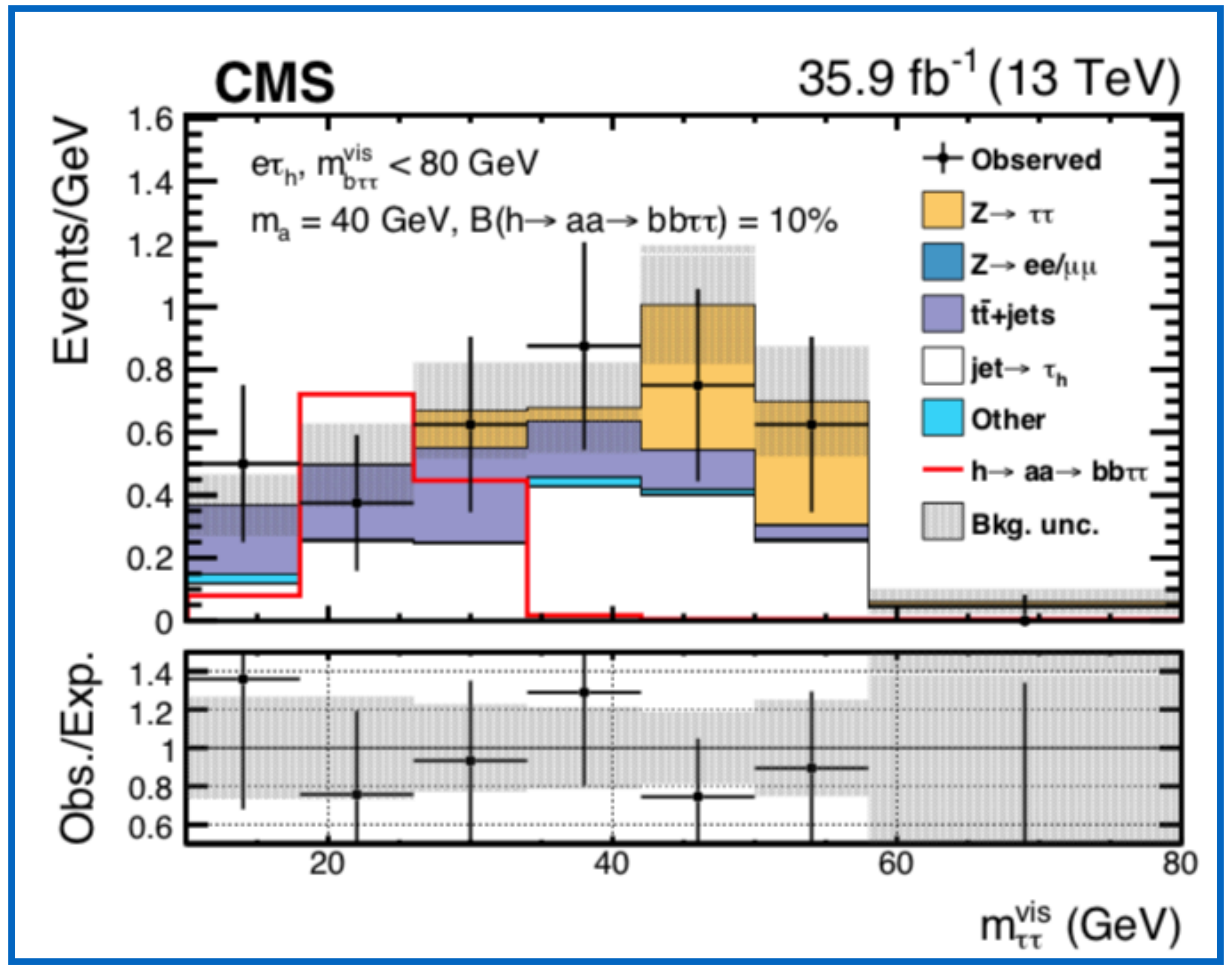
Exotic decays of h_{125} interesting for many reasons

- Higgs width is narrow and not well known experimentally
- Small deviation can be justified/induce relatively large BR to non SM particles
- ***In 2HDM+S models, h → aa decays are allowed***



Search in a nutshell

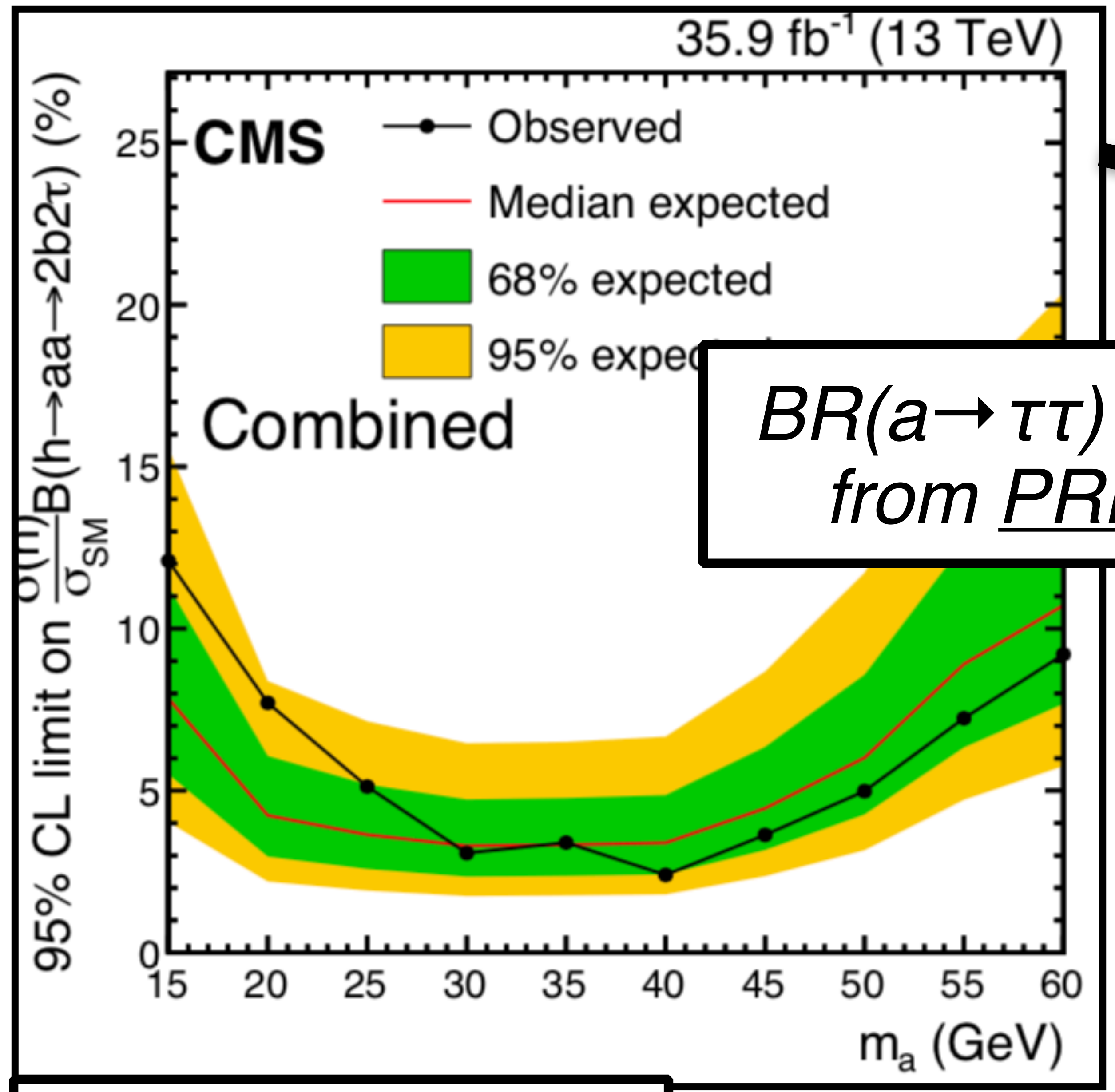
- All Higgs production modes are considered: ggH, VBF, VH
- **Categories:** μe, $e\tau_h$ and $\mu\tau_h$ + at least one b-tagged jet
- **Backgrounds:** Z(ττ) and ttbar processes
- **Challenging:** particles produced in the decay are typically very soft
- Events in each category are further divided by exploiting the discrimination power of: m_T, $m(\tau\tau b)$



Search for signal in the visible m(ττ)

$h \to aa \to 2b2\tau$ results

HIG-17-024



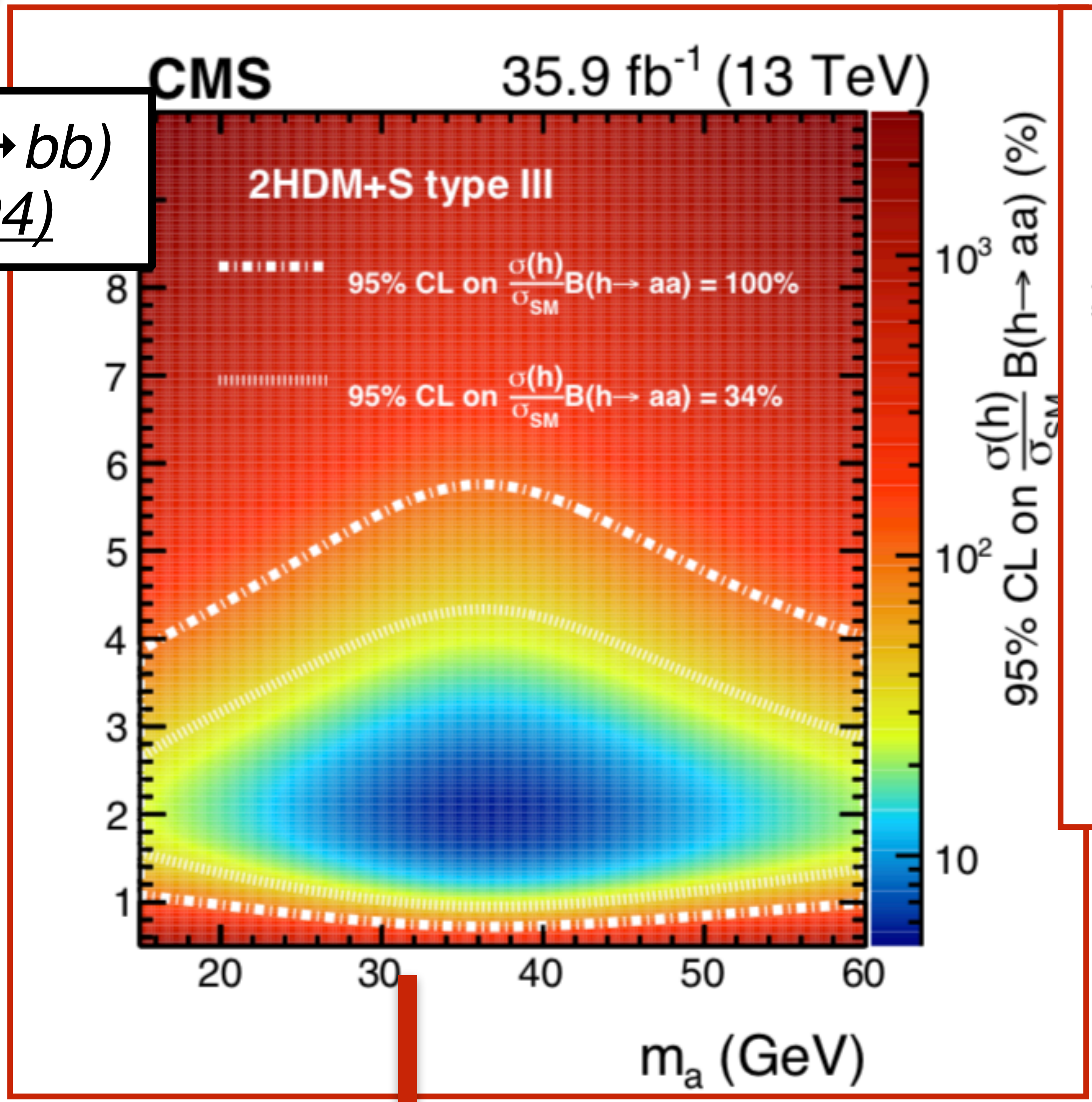
BR(a→ττ) and B(a→bb) from PRD(9075004)

σ from YR4

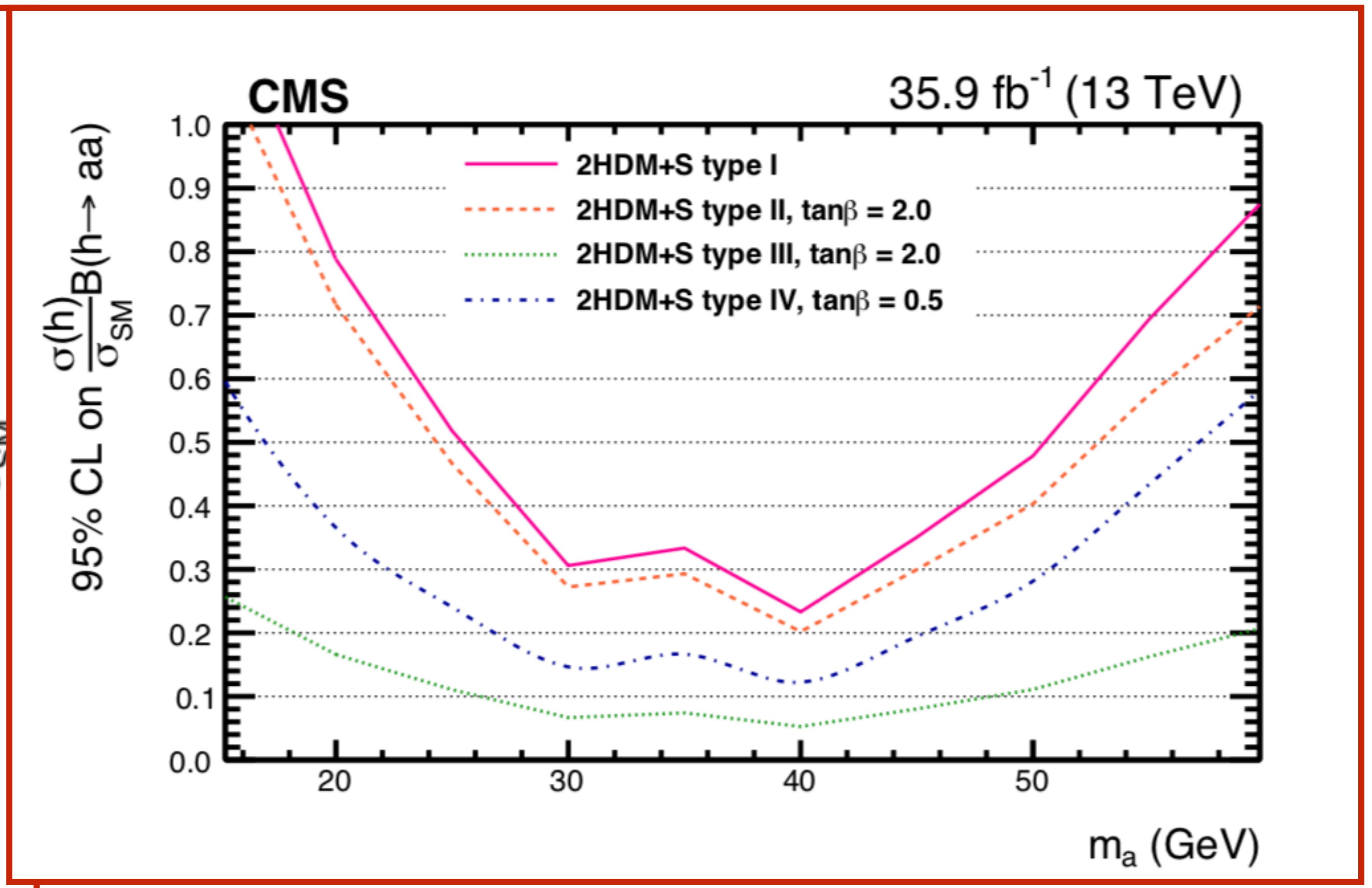
Branching ratio upper limit

- For small m_a → leptons are close-by so lower identification efficiency
- For large m_a → more background-like, so decrease in S/B

Interpretation in 2HDM + S scenario: B(a→ττ) and B(a→bb) are analytically expressed asaf m_a and tan(β)



Allowed region according to direct measurement of the Higgs couplings



Search sensitive to 2HDM type-III and type-IV which are maximising the interesting branching ratios

h → aa → $2\tau 2\mu$ search

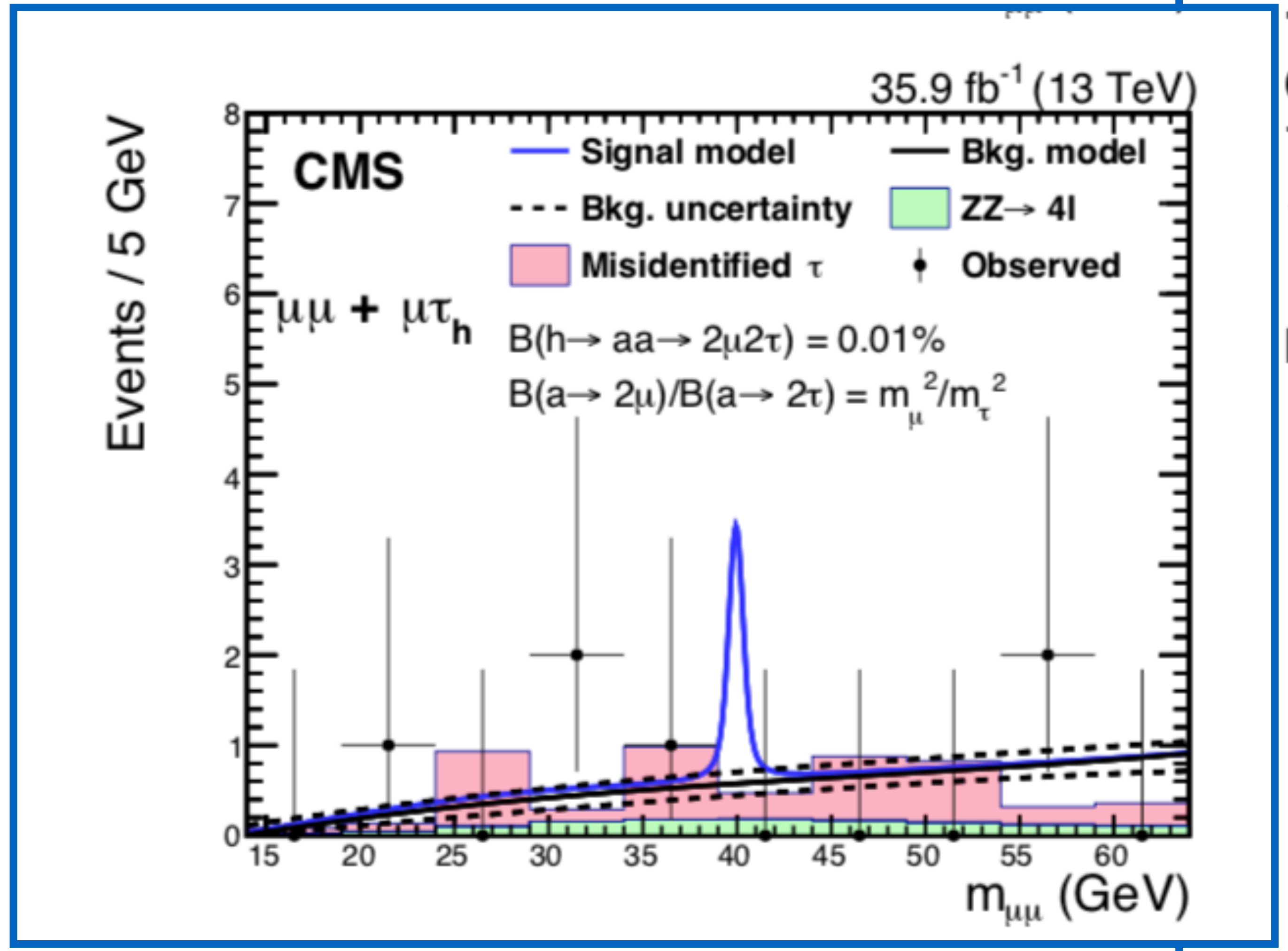
HIG-17-029

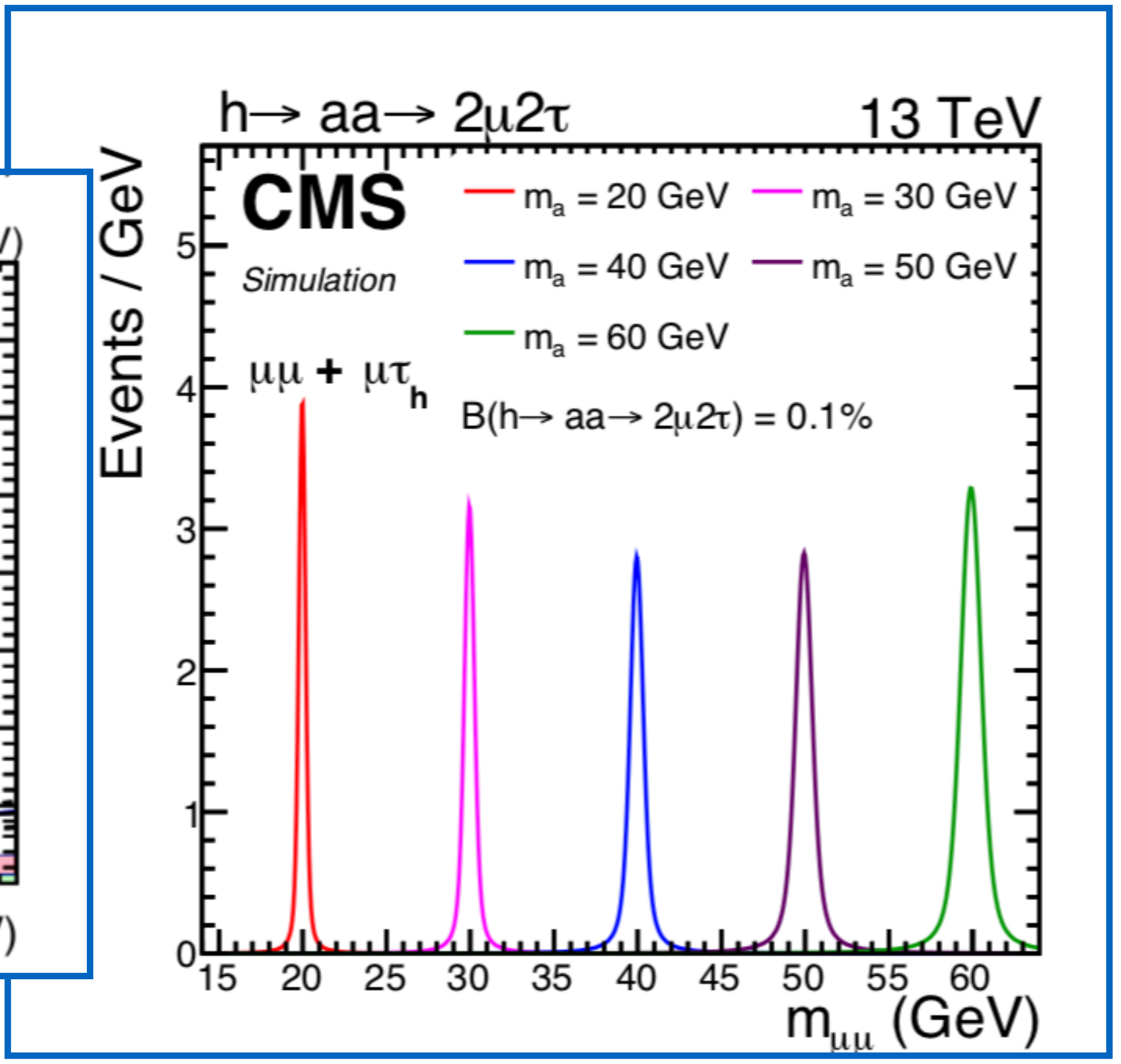
Why looking at this final state signature ??

- Branching ratio of B(a→xx) ~ m_x^2
- This implies B(a→μμ) to be 10^3 times smaller than B(a→bb)
- ***This channel provides complementary results in the high tan(β) region***
- The background contamination is expected to be much smaller than the one in the $2\tau 2b$ final state

Search in a nutshell

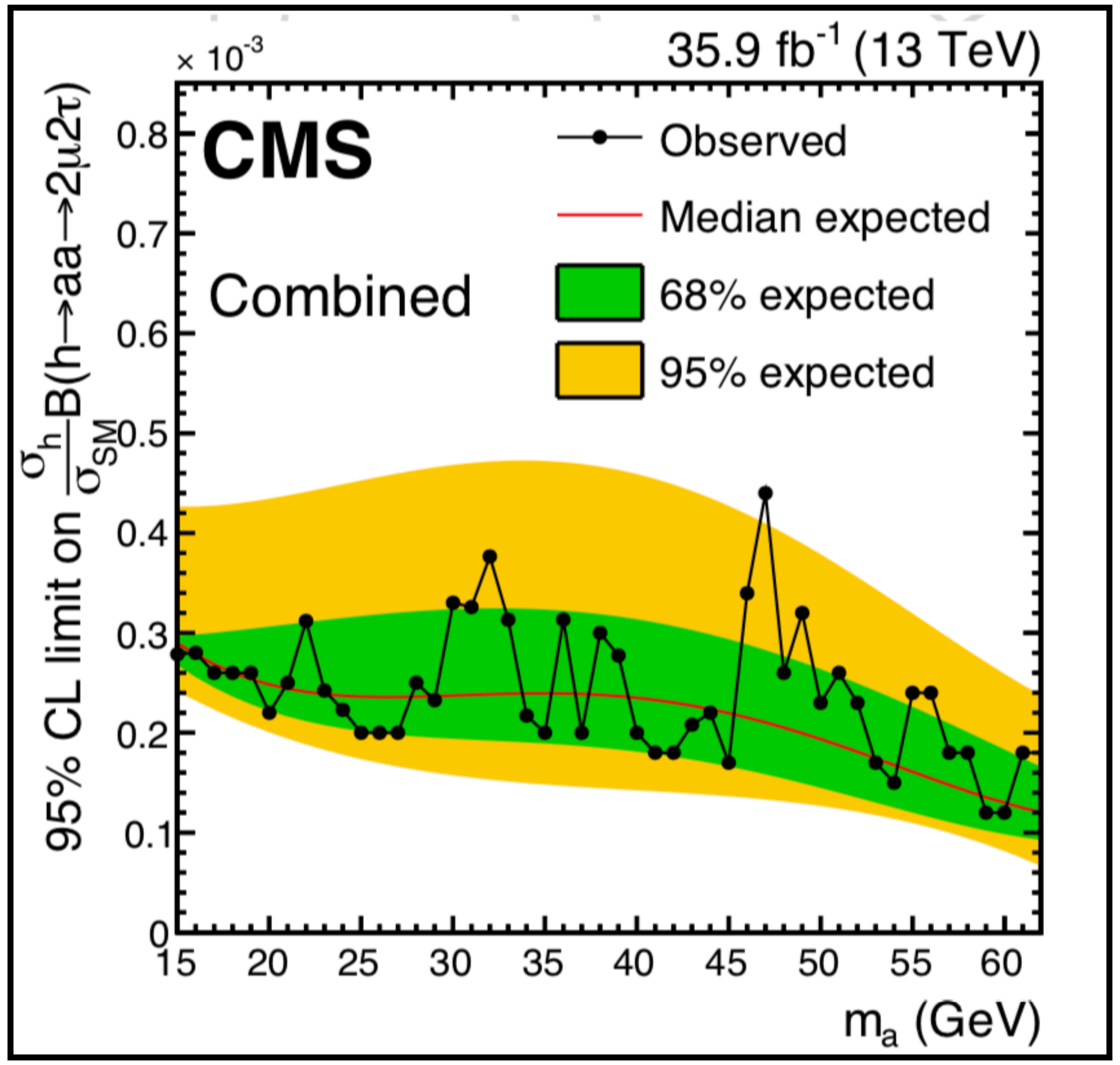
- Presence of many leptons allows to use low p_T triggers
- **Categories:** μμμe, $\mu\mu e\tau_h$ and $\mu\mu\mu\tau_h$ and $\mu\mu\tau_h\tau_h$
- In three lepton final states, the softest muon typically comes from a τ-decay
- **Background suppression:** visible invariant mass smaller than 110-120 GeV
- Relevant contamination from h → aa → 4τ which has much higher branching fraction. It needs to be taken into account but does not exhibit a peaking $m_{\mu\mu}$ spectrum
- **Signal extracted by fitting the $m_{\mu\mu}$ spectrum**



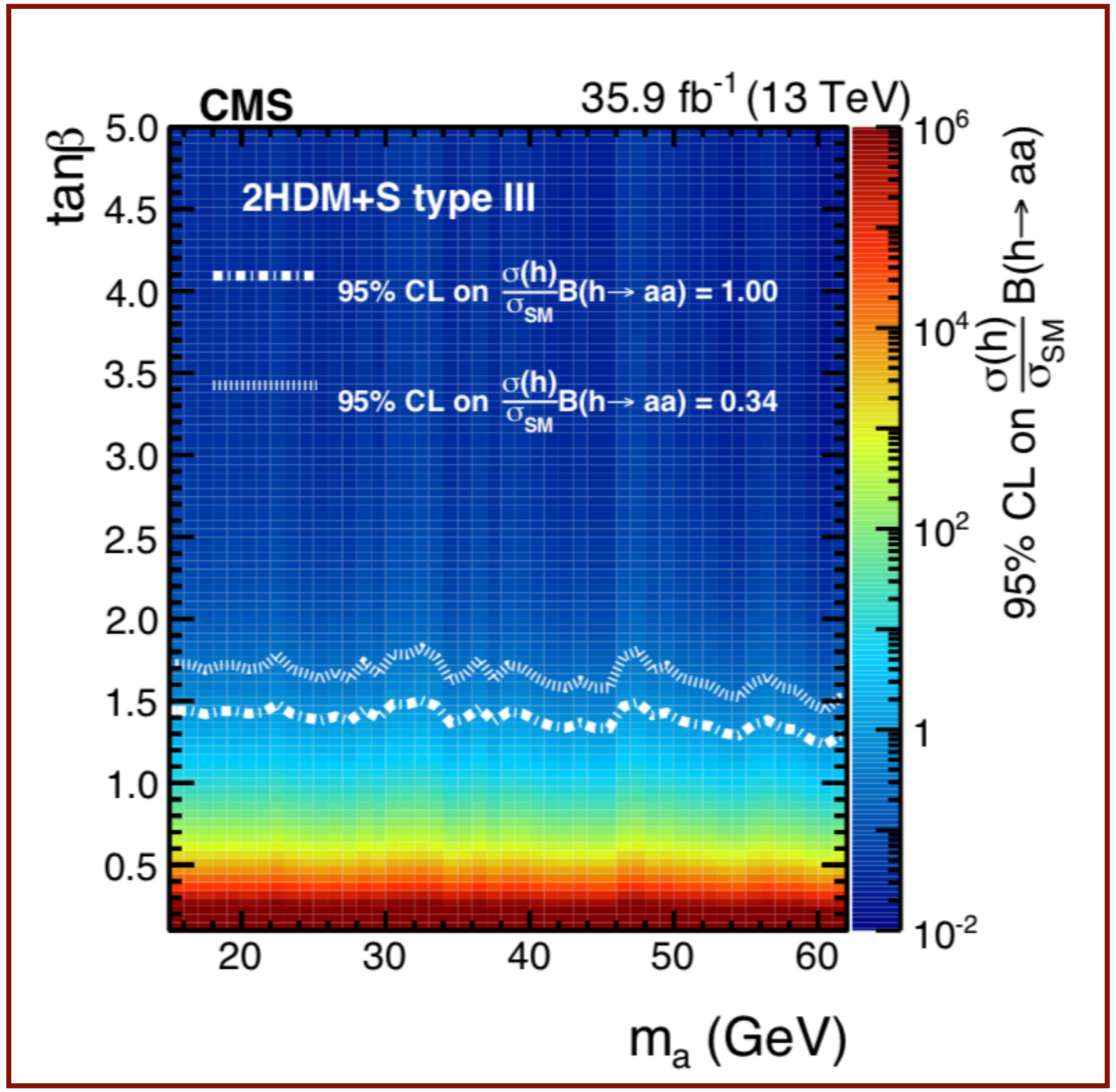


$h \rightarrow aa \rightarrow 2\tau2\mu$ results

HIG-17-029



BR(a→ττ) and B(a→μμ) from PRD(9075004)



Branching ratio upper limit

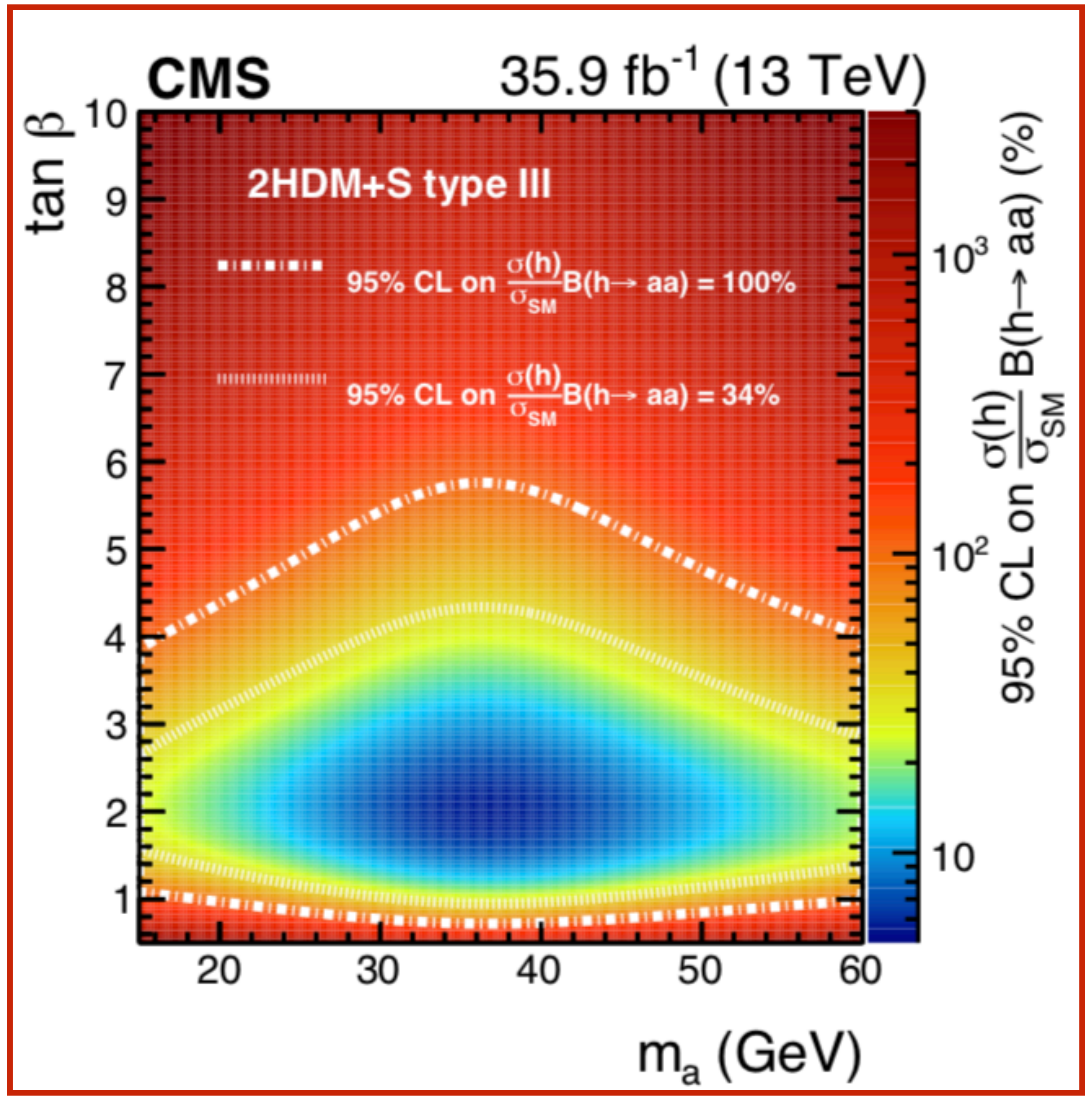
- Upper limit on $B(h\rightarrow 2\mu2\tau) < 0.3\%$ for all m_a tested [15,62.5] GeV
- CLs bands largely asymmetric due to very limited statistics in the SR

Most sensitive region, for which BR < 3%, is tan(β) > 3

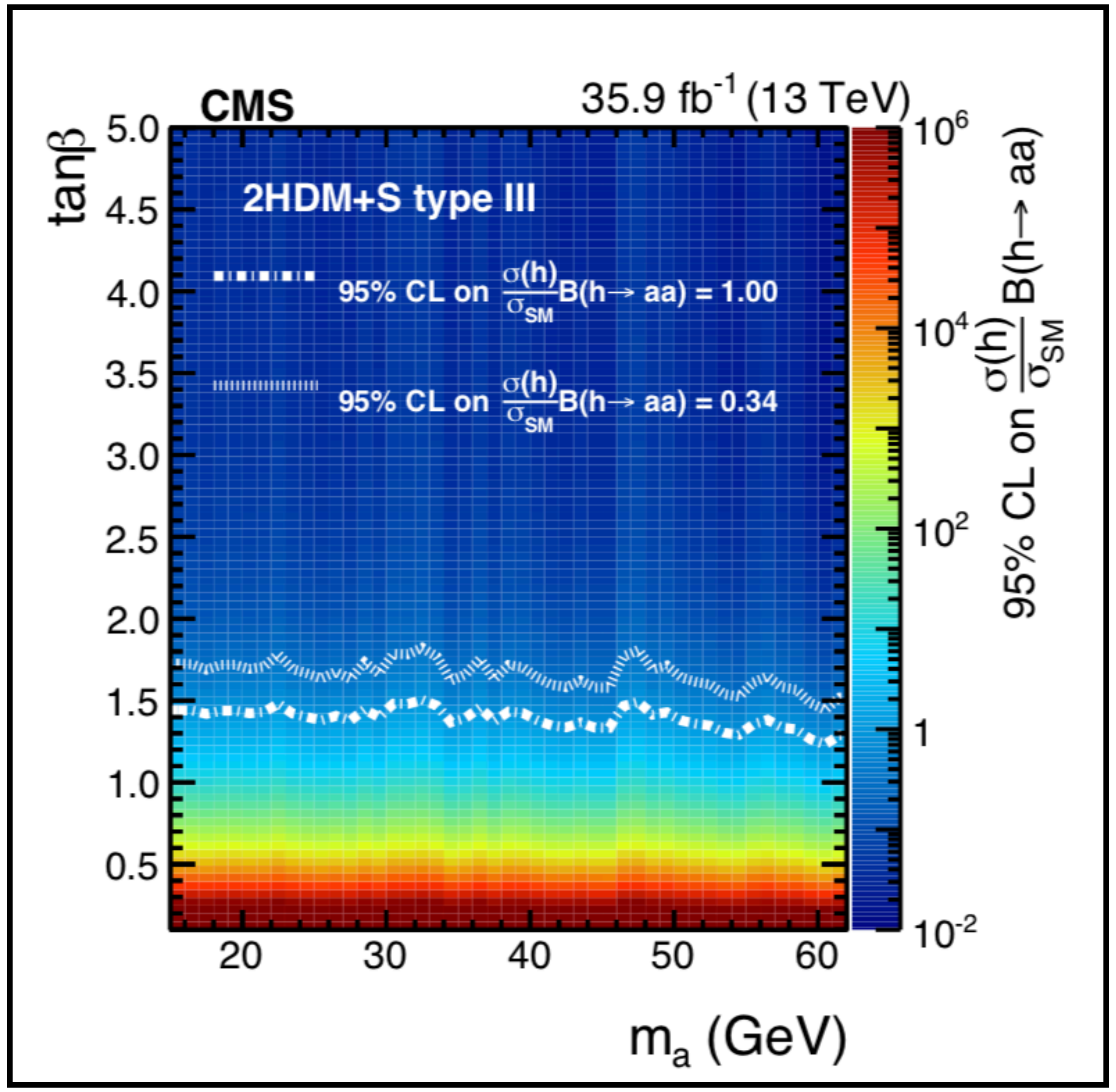
$2\tau 2b$ vs $2\tau 2\mu$

HIG-17-029

$h \rightarrow aa \rightarrow 2\tau 2b$



$h \rightarrow aa \rightarrow 2\tau 2\mu$



Comparing the sensitivity of the two searches, in view of a possible combination, the $2\beta 2\tau$ channel can help in improving the result for tan(β) [1.0,1.5]

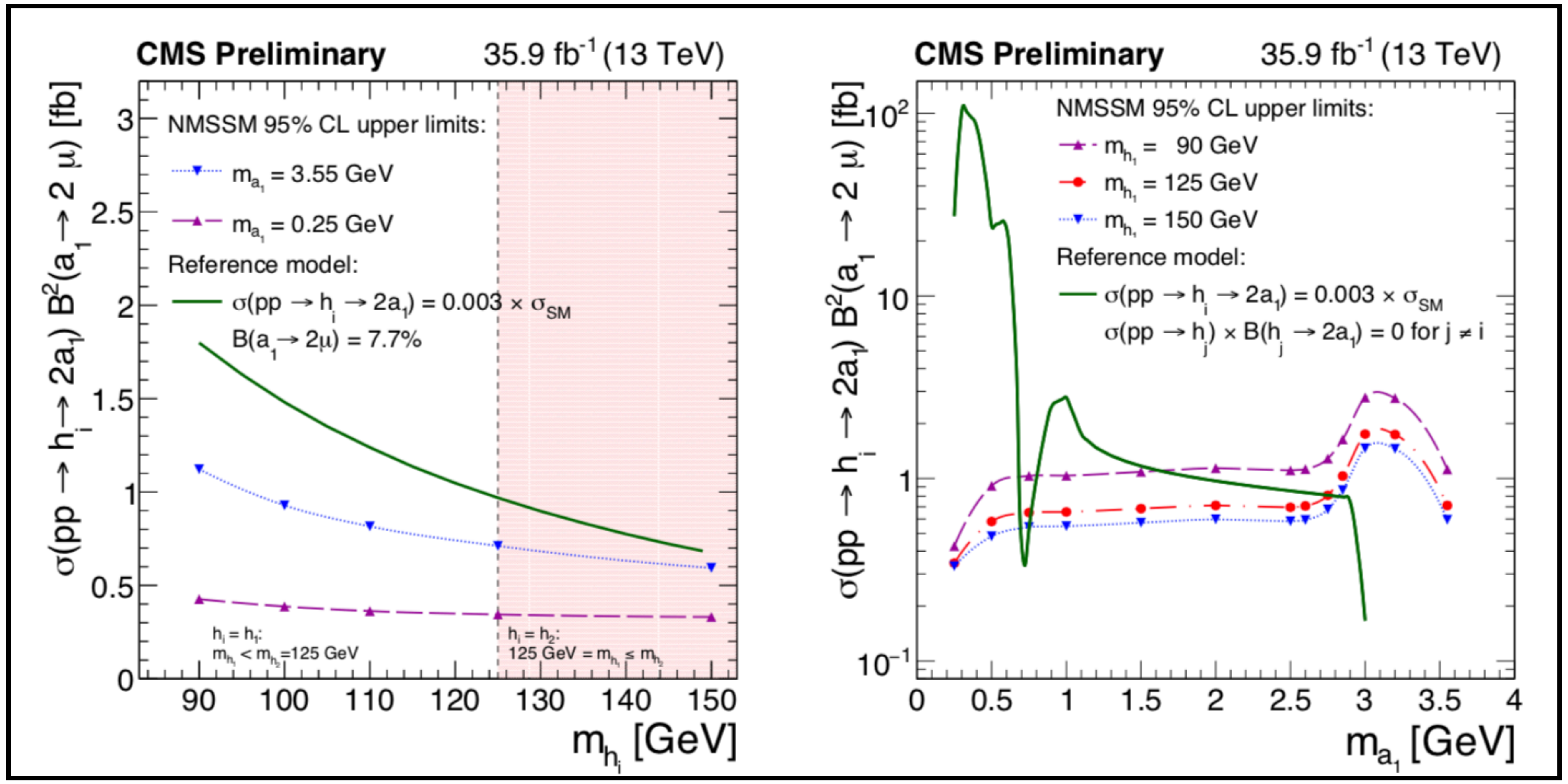
$h \to aa \to 4\mu$ search

HIG-18-003

- **Signal benchmark:** analysis designed to search for light pseudo scalar decays of a Higgs boson in NMSSM or dark-SUSY.

NMSSM scenario

- **Signal generation:** via PYTHIA at LO, only gluon-fusion production
- $h_2 \to 2a_1$, $m(h_2)$ [90,150] GeV taking into account LEP and relic-density constraints
- **Light pseudo-scalar:** assumed to have mass between 2μ and 2τ



Analysis strategy

Analysis designed to reconstruct two low mass dimuon resonances with simple selections such that the difference between the event selection efficiency and the generator acceptance does not depend on the benchmark model

Upper limits on the cross section x branching-ration in the NMSSM derived for a set of discrete points in the m_{a1}-m_{h1} plane

Reference model: $\tan(\beta) = 20$, $\sigma(pp \to h_1 \to 2a_1) = 0.003 \times \sigma_{SM}$

h → aa → 4μ search

HIG-18-003

- **Signal benchmark:** analysis designed to search for light pseudo scalar decays of a Higgs boson in NMSSM or dark-SUSY.

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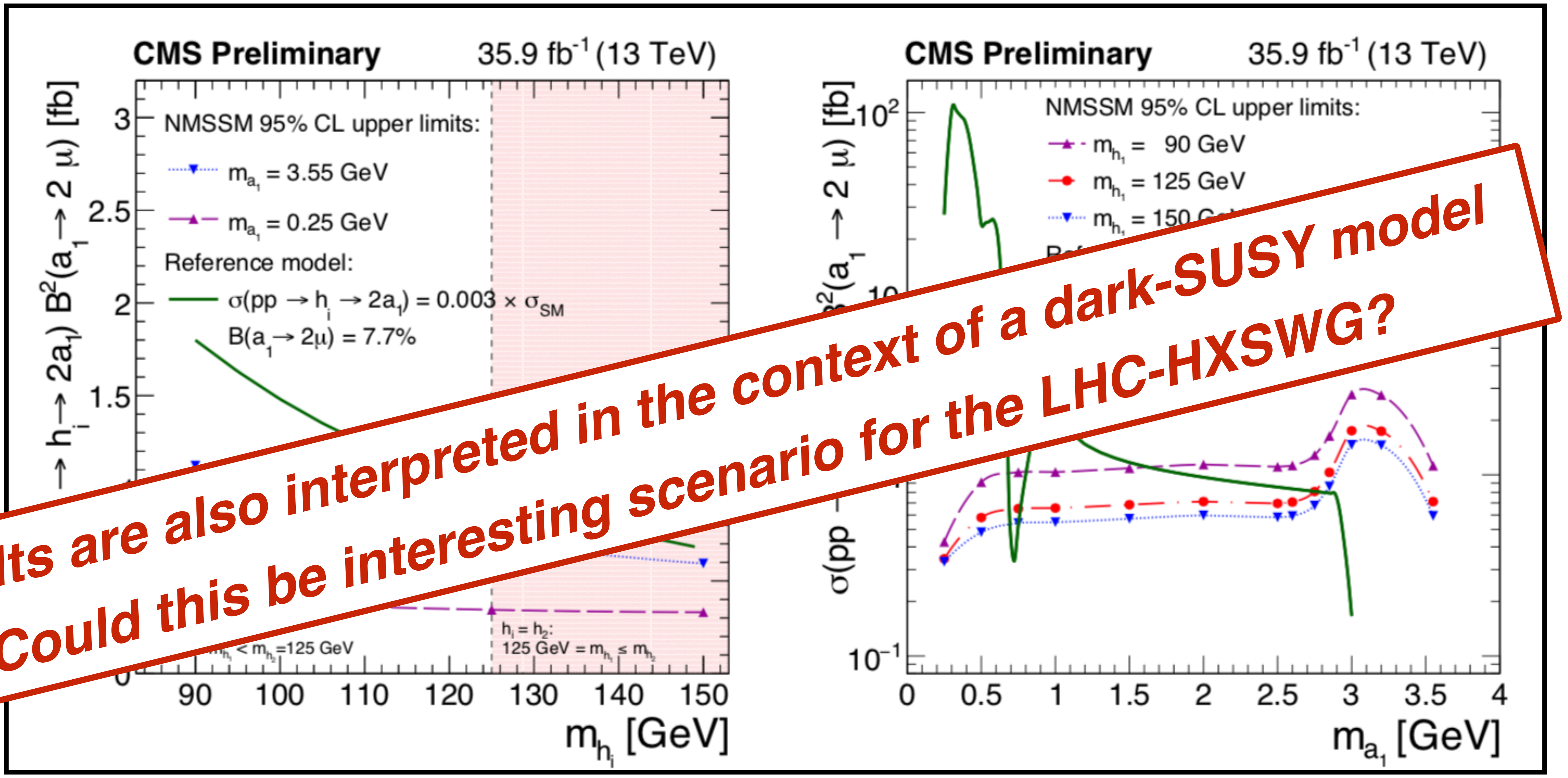

Results are also interpreted in the context of a dark-SUSY model

Could this be interesting scenario for the LHC-HXSWG?

Analysis strategy

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Upper limits on the cross section x branching-ration in the NMSSM derived for a set of discrete points in the m_{a1}-m_{h1} plane

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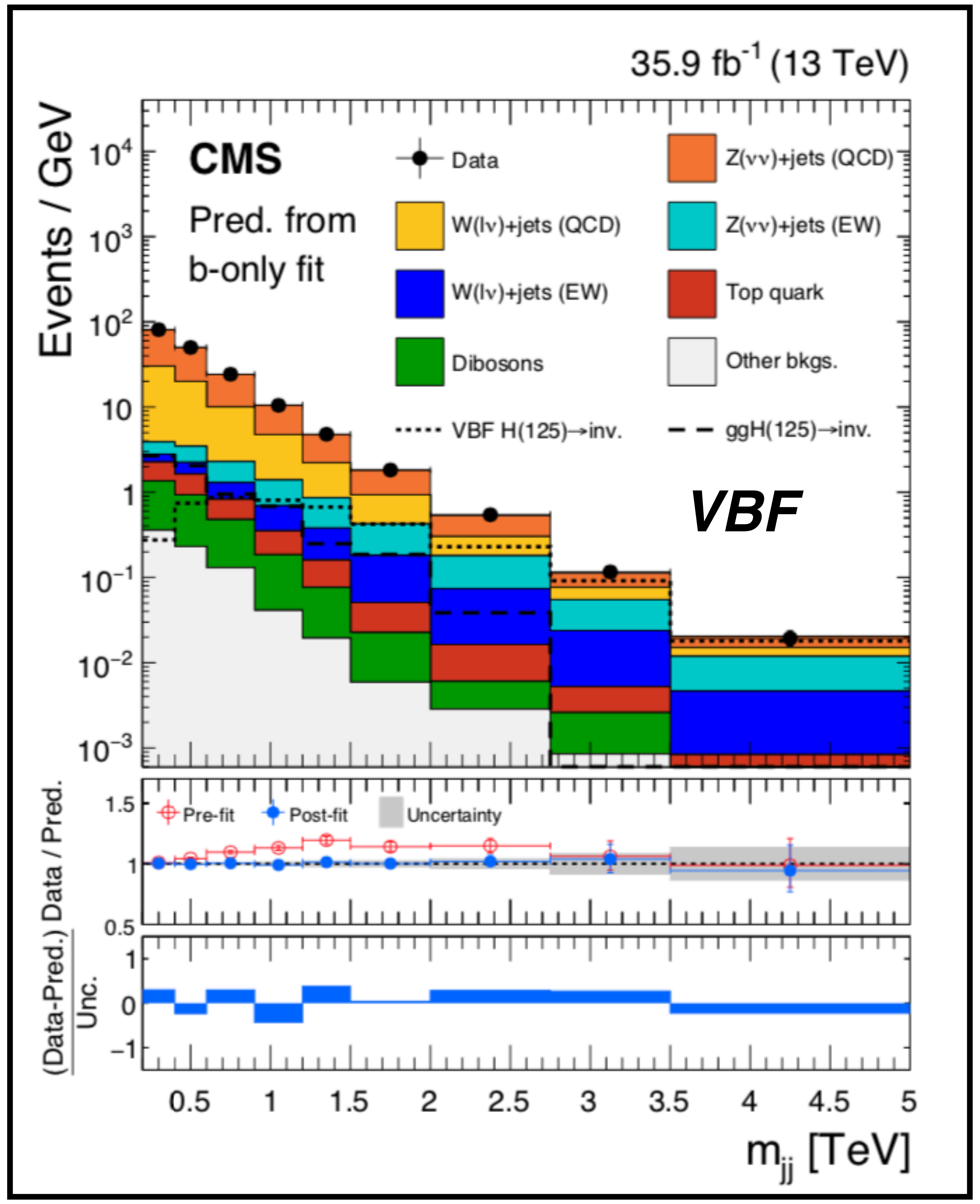
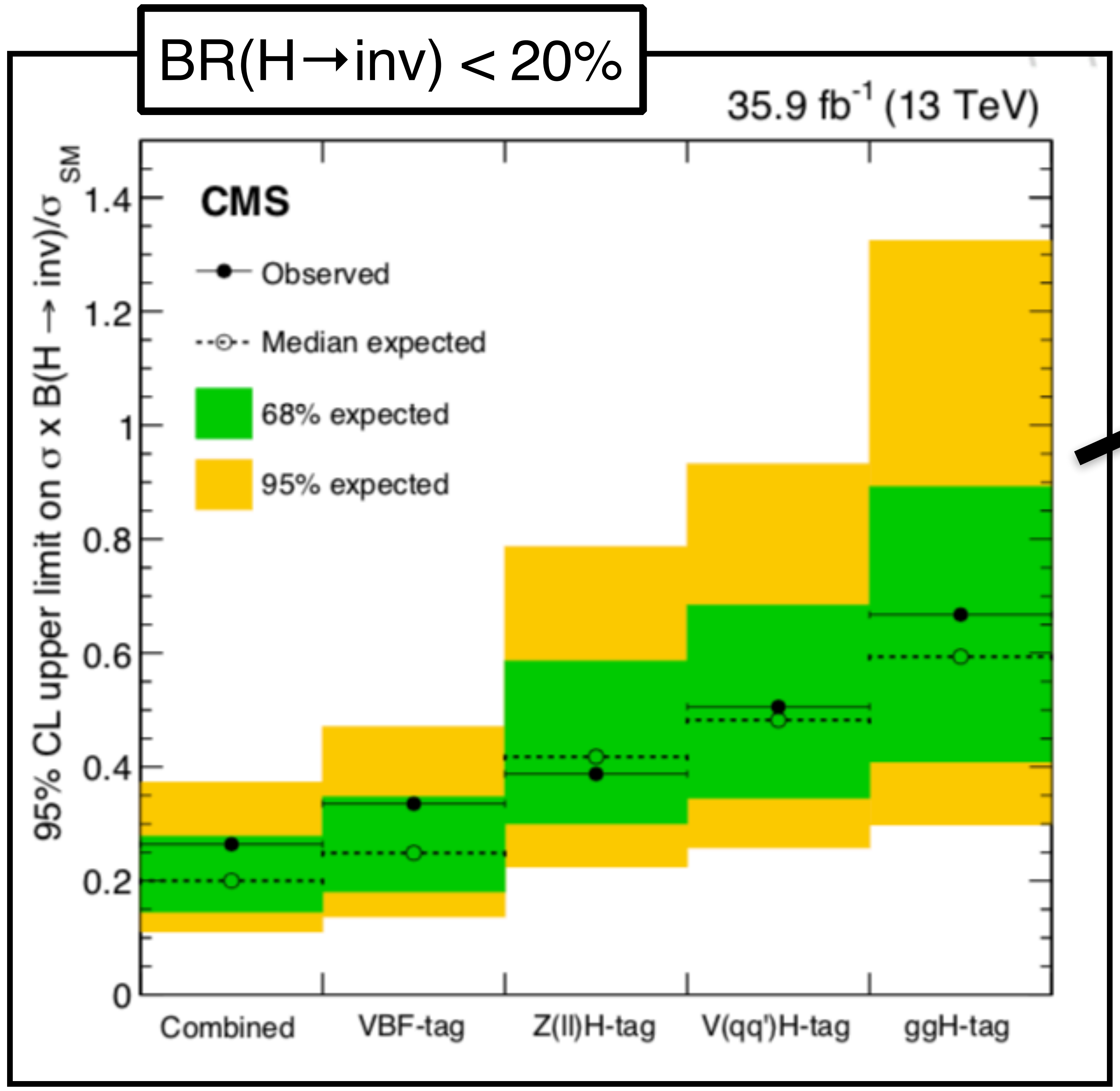
h → invisible

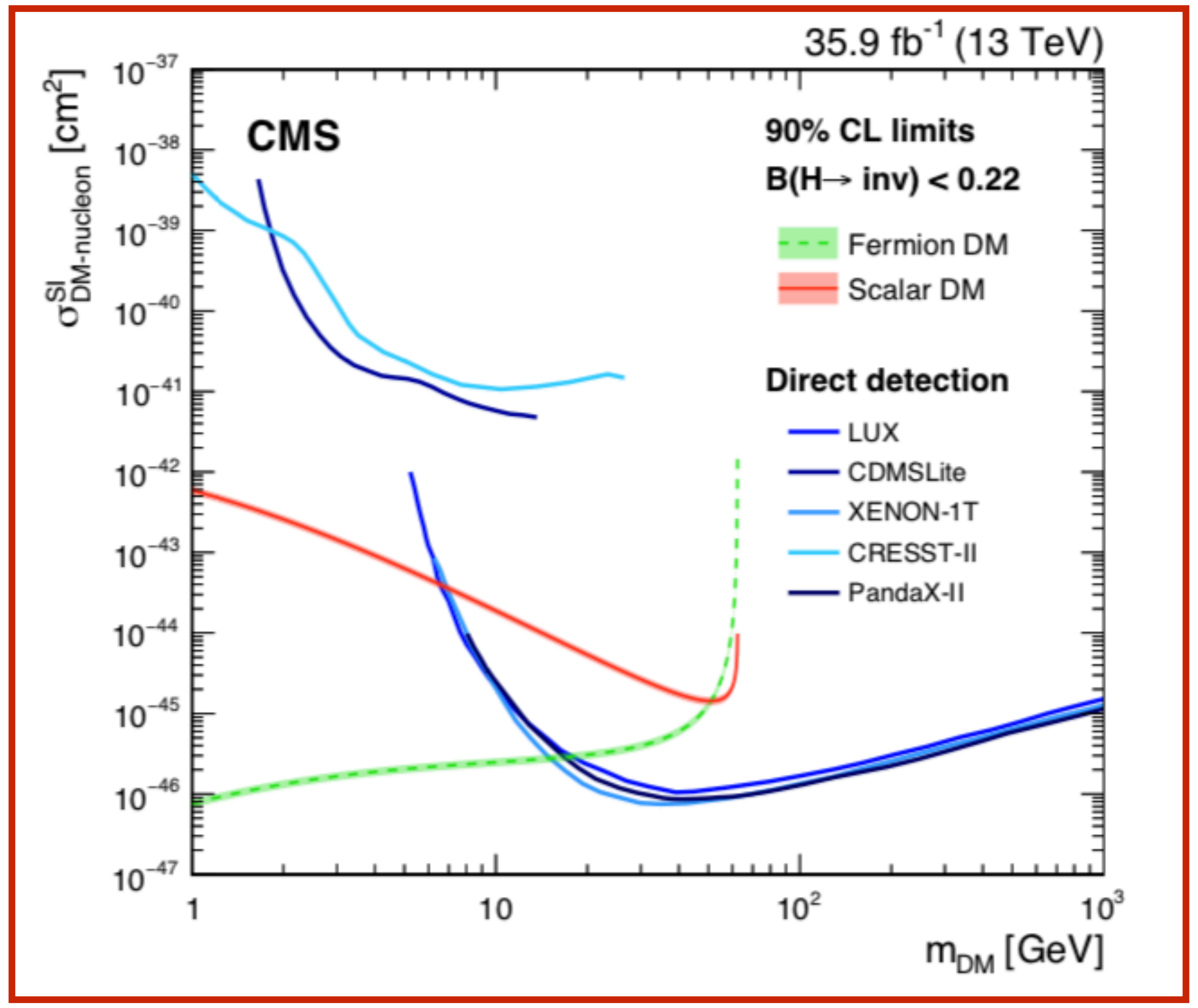
HIG-17-023

Submitted to PLB

- Searches for decays of the SM Higgs boson to BSM particles that cannot be stopped/measured inside detectors
- In the SM, Higgs boson decays invisibly via h → ZZ → 4**ν** with BR < 0.1% → ***not accessible at the LHC***
- ***Interesting final state → Higgs can be portal to a dark-sector***
- Specific analysis targeting production modes: → ***VBF and Z(ll)H most sensitive channels***







BR(limit) recasted in Higgs-portal models of DM interaction

h → invisible

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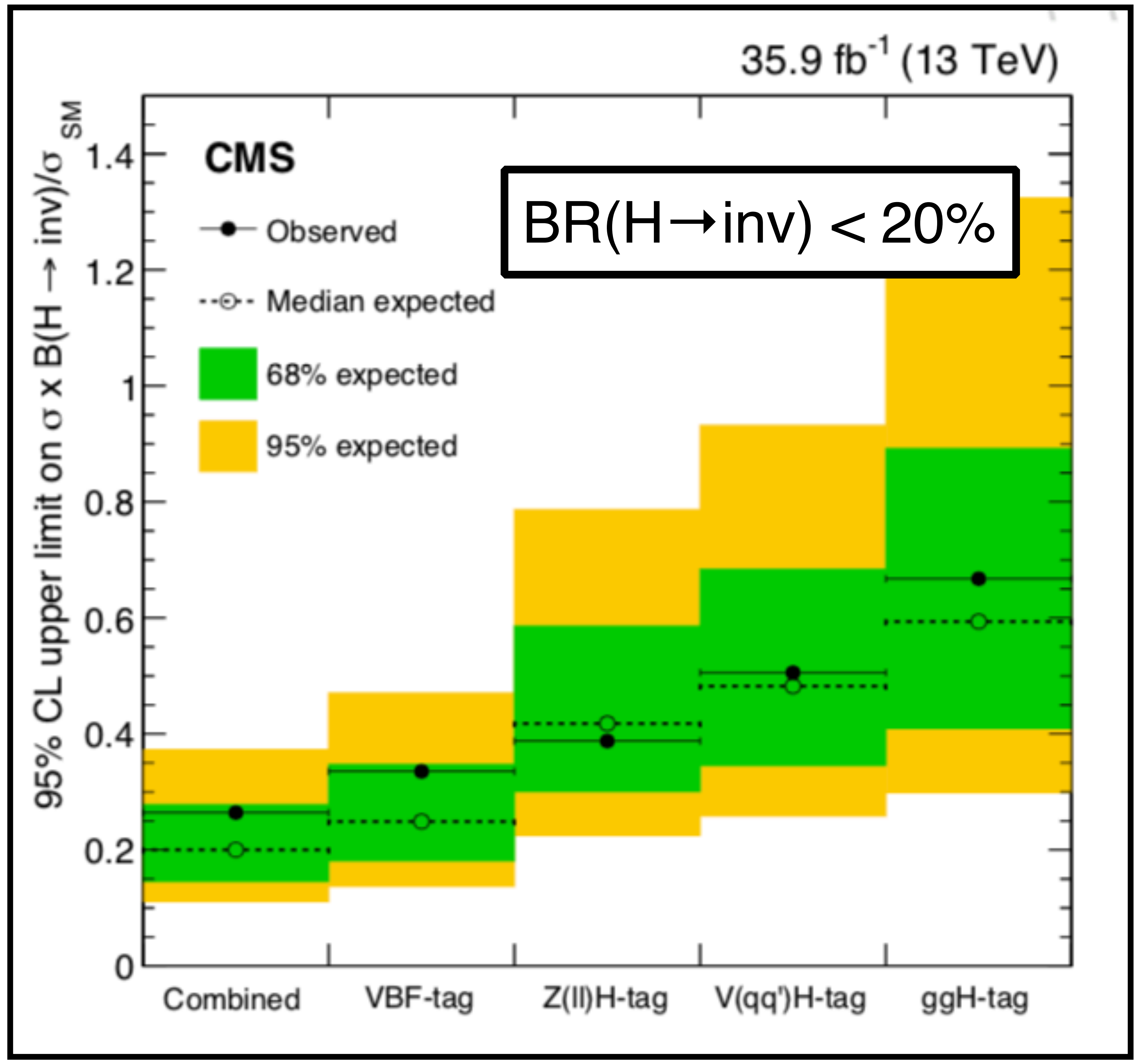
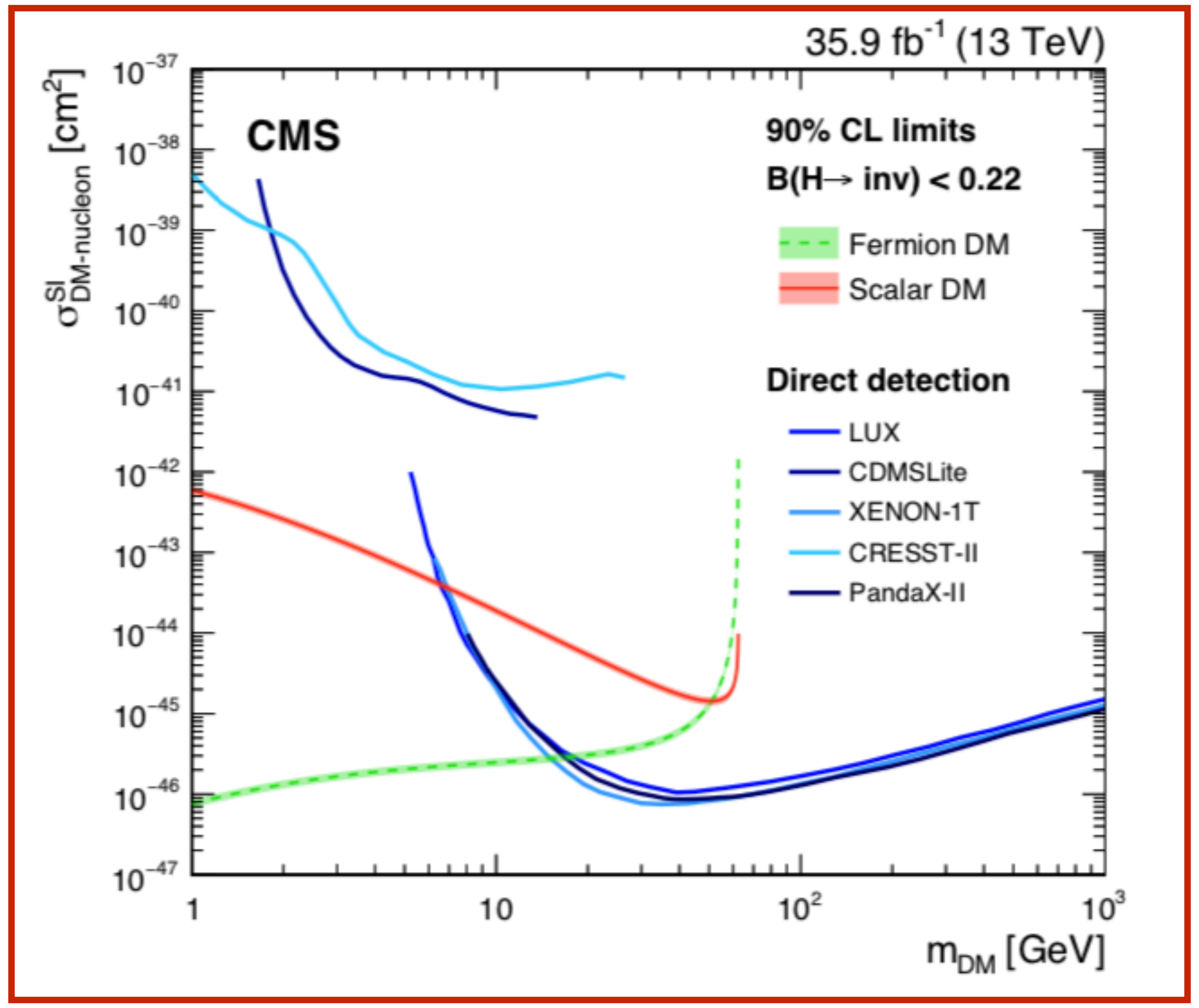




- Results from the less sensitive channels, i.e. ggH and ggZH can also be re-interpreted in the context of simplified DM models
- ***Not easy to re-interpret VBF and ZH results in the context of theories/models predicting a DM particle***

we need coupling with vector-bosons without spoiling EWK symmetry breaking

↓

Are there possible models (i2HDM ..etc) that can predict these signatures with a dark-matter candidate ?

Summary on exotic Higgs decays

- **General Goal:** give a short summary of the most recent results obtained with 2016 data in the context of

Additional Neutral Scalars
- MSSM $H(\tau\tau)$ HIG-17-020
- bbH, H(bb) HIG-16-018
- A(Zh) HIG-18-005
- H(ZZ) HIG-17-012

Charged Higgs

Several new charged Higgs results under internal CMS review

No analysis presented in this talk

Exotic Higgs decays
- $h \rightarrow aa(2b2\tau)$ HIG-17-024
- $h \rightarrow aa(2\mu2\tau)$ HIG-17-029
- $h \rightarrow aa(4\mu)$ HIG-18-003
- $h \rightarrow$ invisible HIG-17-023

$X \rightarrow hh$
- $hh(2b2\gamma)$ HIG-17-008
- hh(4b) HIG-17-009
- $hh(2b2\tau)$ HIG-17-002

Constraints from h_{125}
- HIG-17-031

Would be interesting to combine $h \rightarrow aa$ searches under a specific model ?
Are dark-SUSY scenarios potentially interesting?

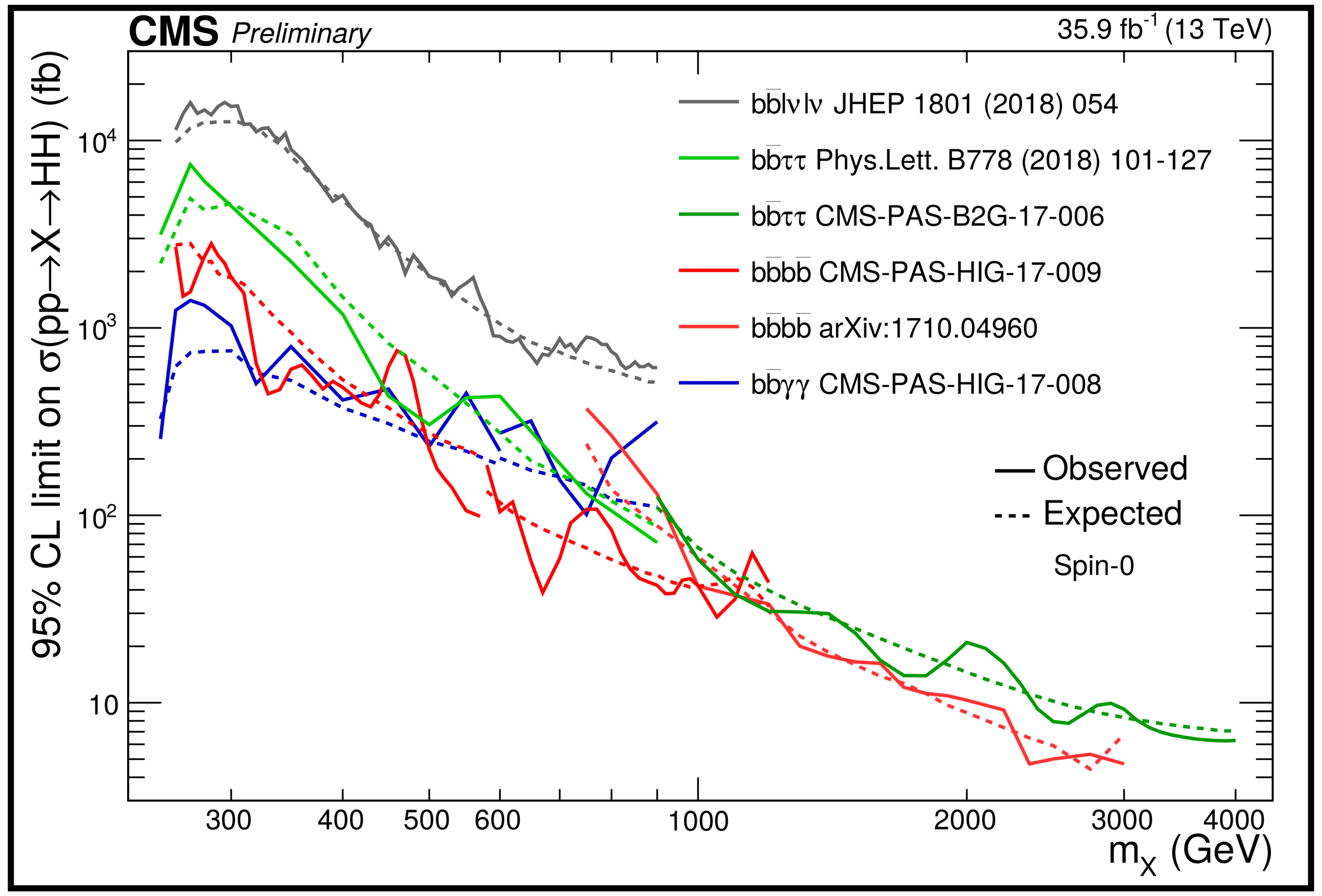
For H_{inv} searches what else more than a Higgs-portal interpretation ?
Are there interesting 2HDM scenarios providing DM candidates ?
What about having a discussion with LHC DMWG which is working on a 2HDM+a model ?

Di-Higgs searches

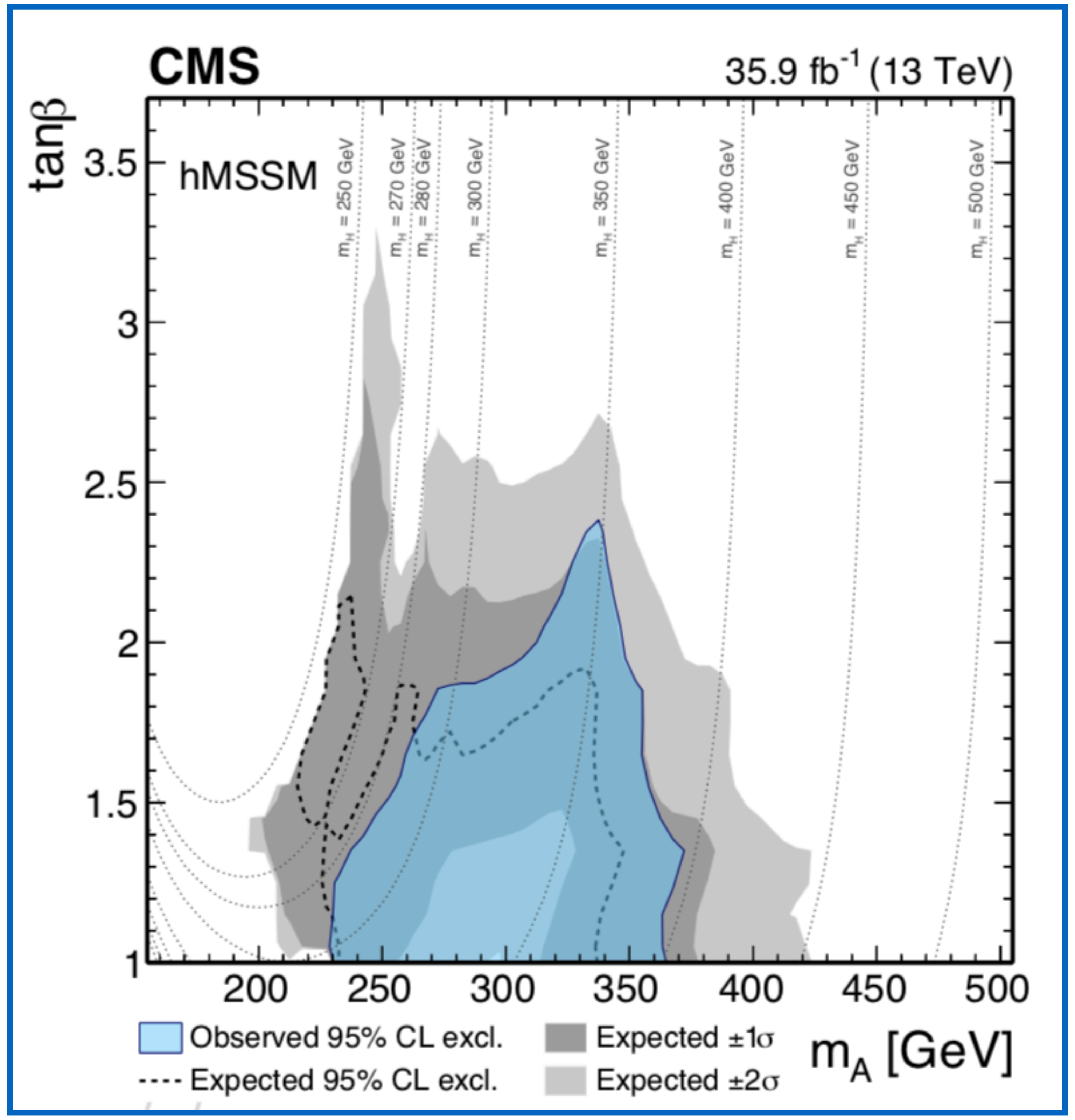
HIG-17-002 HIG-17-006 HIG-17-008 HIG-17-009

- Fixing a given final state, two independent searches: ***BSM resonances*** or dedicated to ***di-higgs non resonant production***

Typically CMS results interpreted in WED models predicting a spin-0 / spin-2 resonance



Most sensitive channels for the **interesting MSSM/2HDM parameter space** are **$2\gamma 2b$** and **$2\tau 2b$**



hMSSM interpretation provided only in HH(2b2τ) analysis

- Signal samples from ggH produced at LO with PYTHIA
- Inclusive cross section from SusHI NLO as provided by LHCXSWG

Sensitivity

- $m_A > 2 * m_h$ is the kinematically allowed region
- $m_A < 2 * m_{top}$: small branching fraction in hh above tt pole
- Small tan(β) value. Above BR in bb or $\tau\tau$ dominates

Summary on di-higgs resonances

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- MSSM H($\tau\tau$) HIG-17-020
- bbH, H(bb) HIG-16-018
- A(Zh) HIG-18-005
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- h → aa(2μ2τ) HIG-17-029
- h → aa(4μ) HIG-18-003
- h → invisible HIG-17-023

X → hh

- hh(2b2γ) HIG-17-008
- hh(4b) HIG-17-009
- hh(2b2τ) HIG-17-002
- hh(2l2v2b) HIG-17-006

Constraints from h_{125}

- HIG-17-031

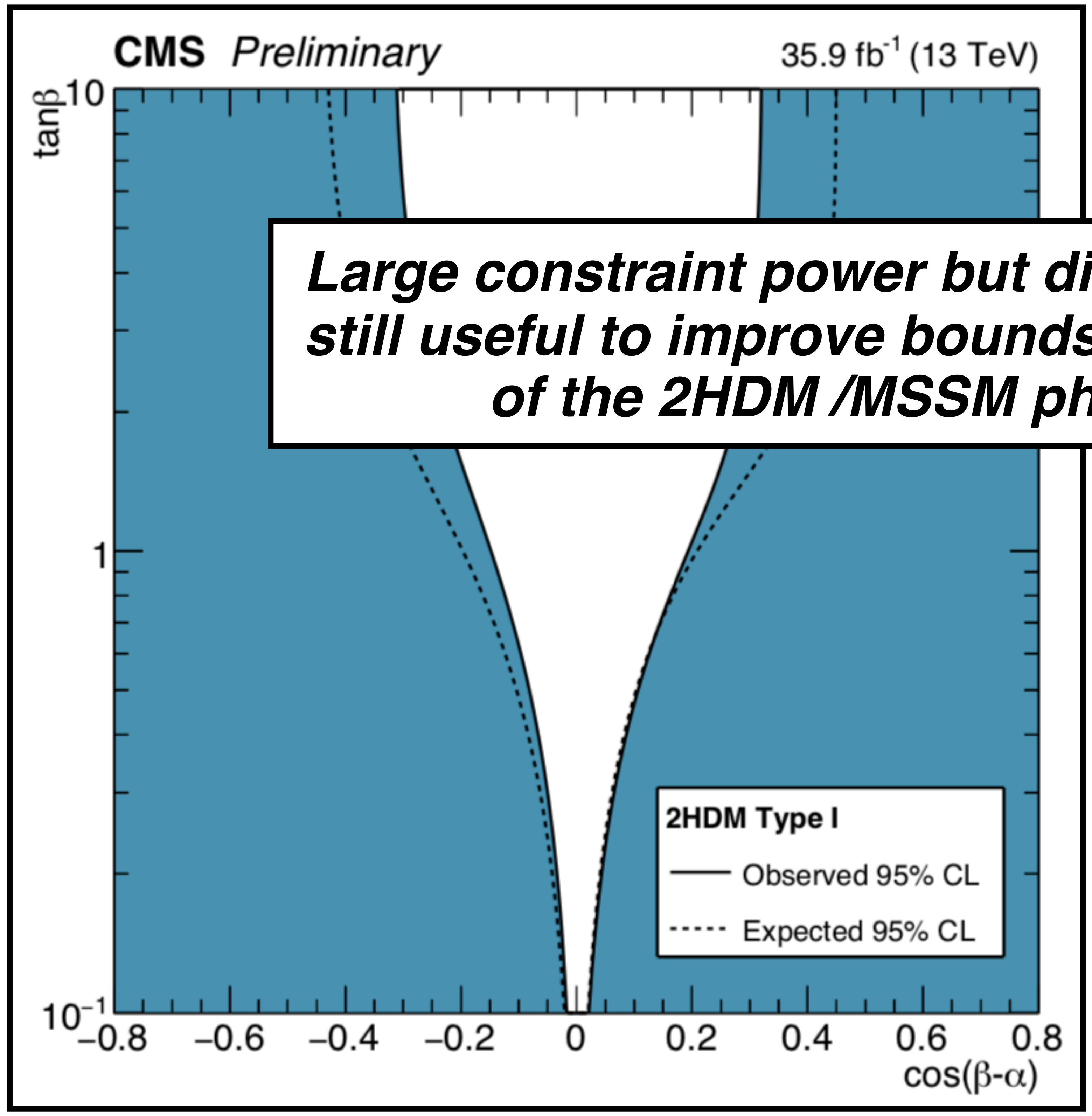
Can these searches constrain part of the 2HDM parameter space?

Would be interesting to have such interpretations ?

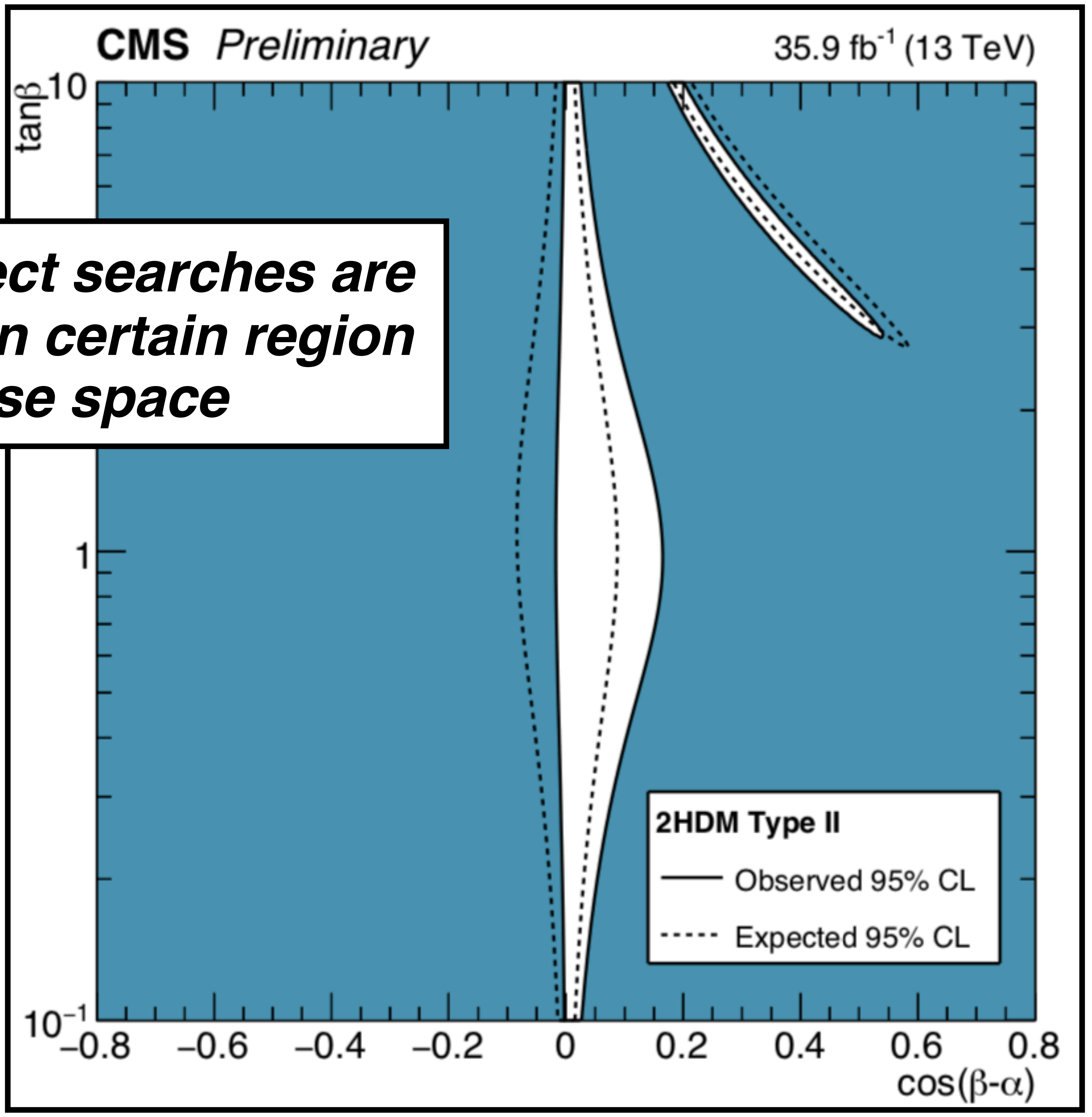
Direct constraints from h_{125}

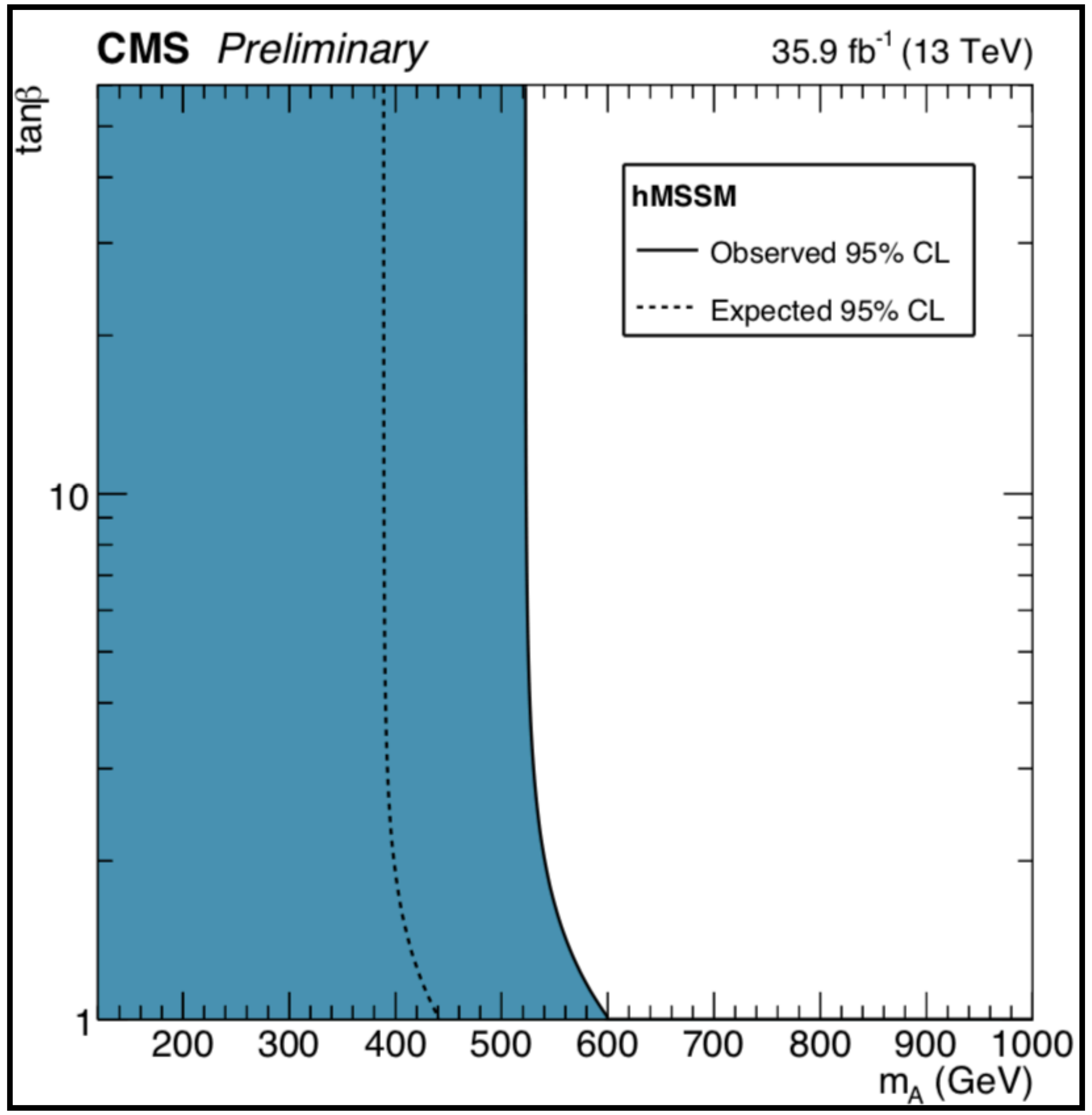
- Measurement of Higgs couplings used to constrain 2HDM models with: CP-conservation and Z_2 symmetry (no FCNC)
- Higgs boson is assumed to be the lightest CP-even state of the extended Higgs sector

	2HDM				hMSSM
	type I	type II	Type III	Type IV	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$s_d\sqrt{1+\tan^2\beta}$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_d\sqrt{1+\tan^2\beta}$



Large constraint power but direct searches are still useful to improve bounds in certain region of the 2HDM /MSSM phase space





Direct constraints from h_{125}

HIG-17-031

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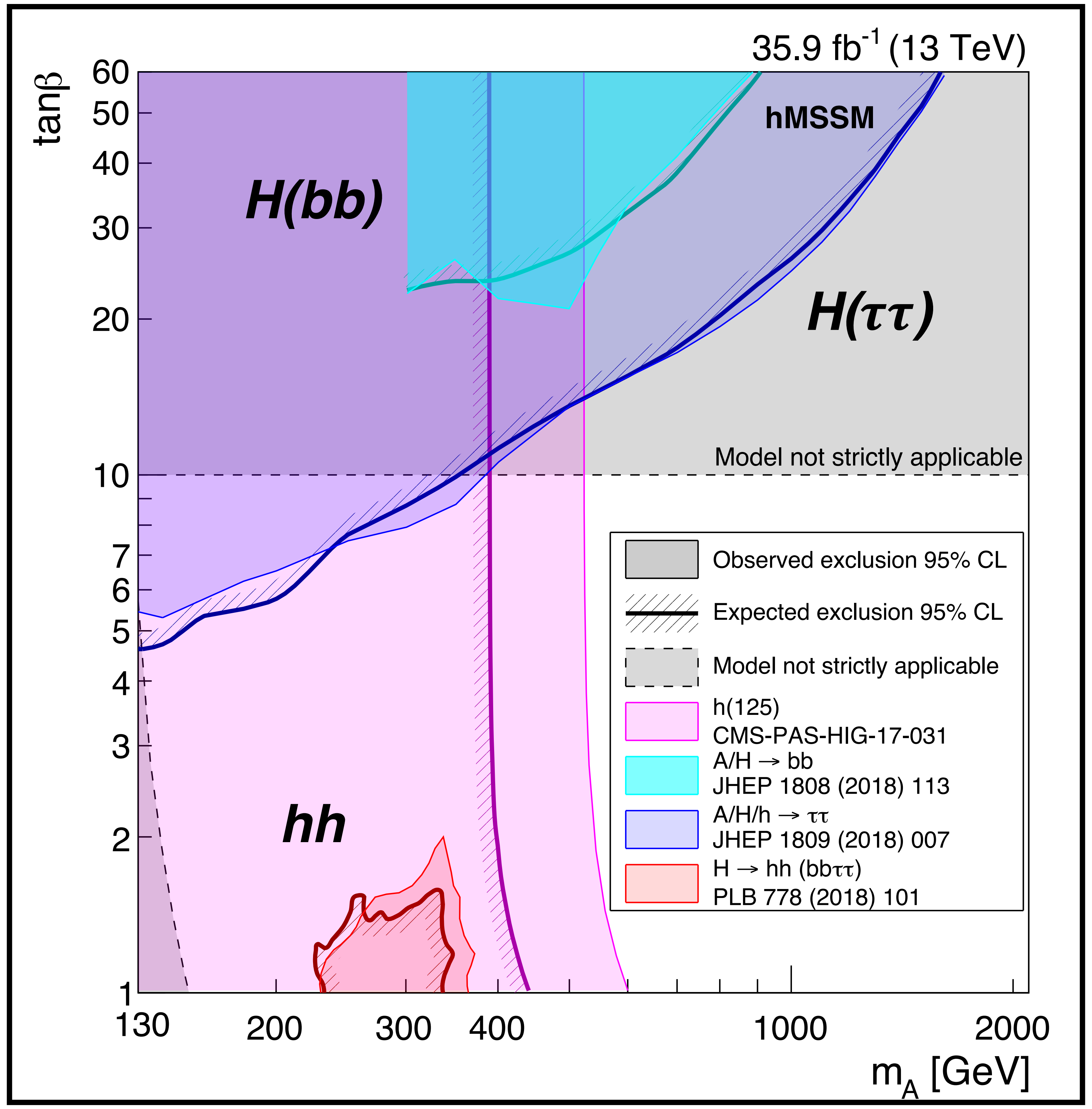

Summary on h_{125} coupling constraints

Additional Neutral Scalars

- MSSM $H(\tau\tau)$ HIG-17-020
- bbH, H(bb) HIG-16-018
- A(Zh) HIG-18-005
- H(ZZ) HIG-17-012

Charged Higgs

- $H^{\pm} \to cb$ HIG-16-030

Exotic Higgs decays

- $h \to aa(2b2\tau)$ HIG-17-024
- $h \to aa(2\mu2\tau)$ HIG-17-029
- $h \to aa(4\mu)$ HIG-18-003
- $h \to$ invisible HIG-17-023

$X \to hh$

- $hh(2b2\gamma)$ HIG-17-008
- hh(4b) HIG-17-009
- $hh(2b2\tau)$ HIG-17-002
- hh(2l2v2b) HIG-17-006

Constraints from h_{125}

- HIG-17-031

Could we use direct measurements of h_{125} to constrain more BSM models ?

if so, analytical expressions for the coupling modifiers are needed so that the relevant parameters can be extracted from the h(125) coupling fit ….