Higgs properties and decays, searches for high mass Higgs bosons, and HH production

on behalf of the ATLAS and CMS Collaborations

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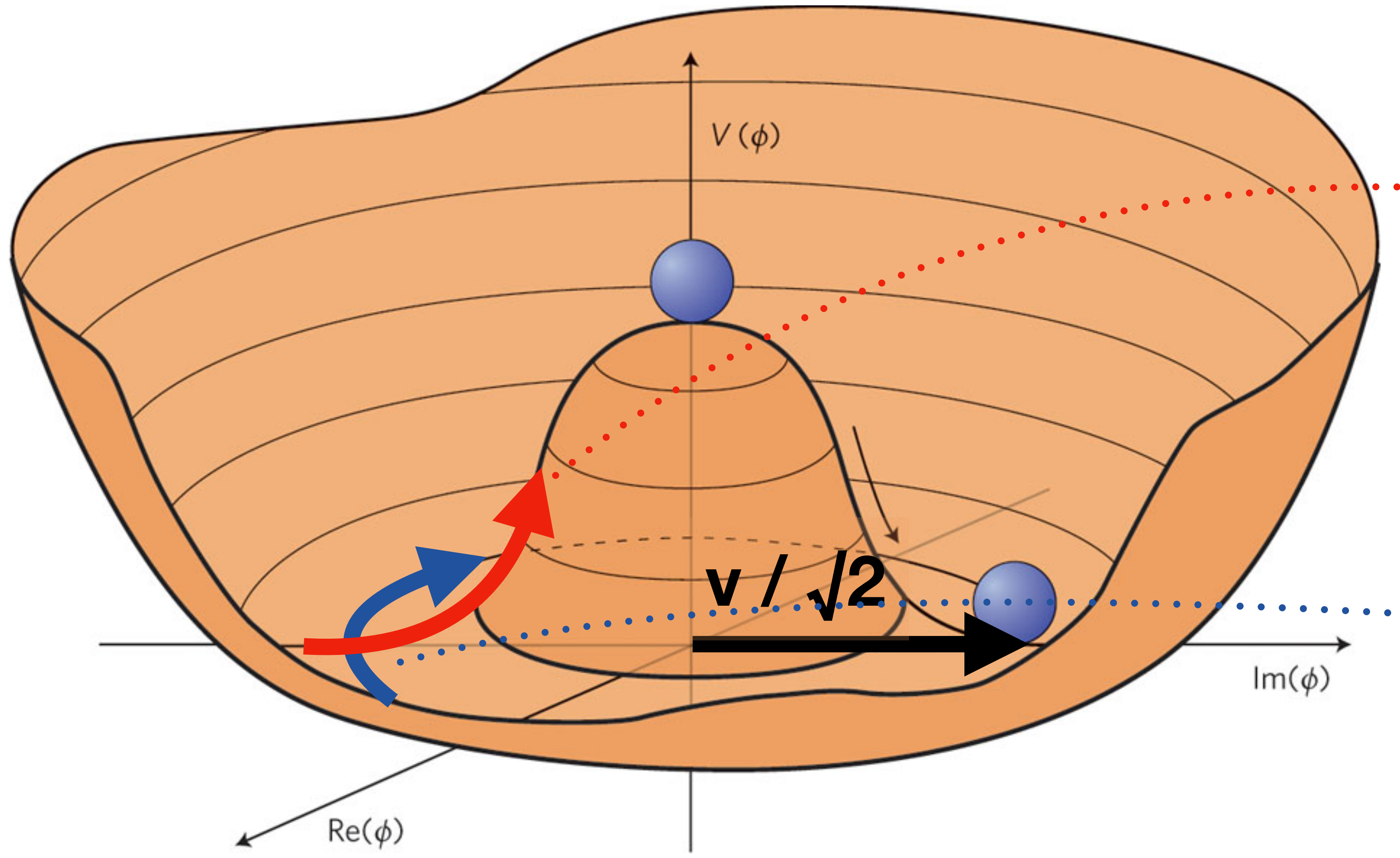
Rencontres de Physique de la Vallée d'Aoste
La Thuile, March 2nd, 2018

The scalar sector



Quantum of the field
$\Rightarrow$ **Higgs boson**

Additional d.o.f.
$\Rightarrow$ **W and Z polarisation**

Yukawa interaction
$\Rightarrow$ **fermion masses**

$$-\mathcal{L}_{\text{Yukawa}} = Y_{ij}\, \bar{\Psi}_{L_i}\, \Phi\, \psi_{R_j} + \cdots$$

The study of the scalar sector requires:

- A **precise characterisation** of the Higgs boson properties
- The search for **extensions** of the scalar sector itself
- The study of the **shape** of the scalar potential

Outline

Focus on latest 13 TeV results from 2016 dataset (~ 36 fb^{-1})

Higgs boson mass and width ($H\rightarrow\gamma\gamma$, $H\rightarrow ZZ^*\rightarrow 4\ell$)

Couplings to fermions and bosons discussed in Silvio's talk

- A **precise characterisation** of the Higgs boson properties

Production of new scalars $\boldsymbol{H}\rightarrow\tau\tau$, $\boldsymbol{H}\rightarrow ZZ$, $h'\rightarrow\gamma\gamma$
$H\rightarrow aa\rightarrow bb\tau\tau$, $H\rightarrow aa/Za\rightarrow\ell\ell\ell\ell$
$ZH\rightarrow\ell\ell$+invisible
Charged Higgs $H^{\pm}\rightarrow tb$

- The search for **extensions** of the scalar sector itself

Higgs boson pair production (HH), resonant and nonresonant production

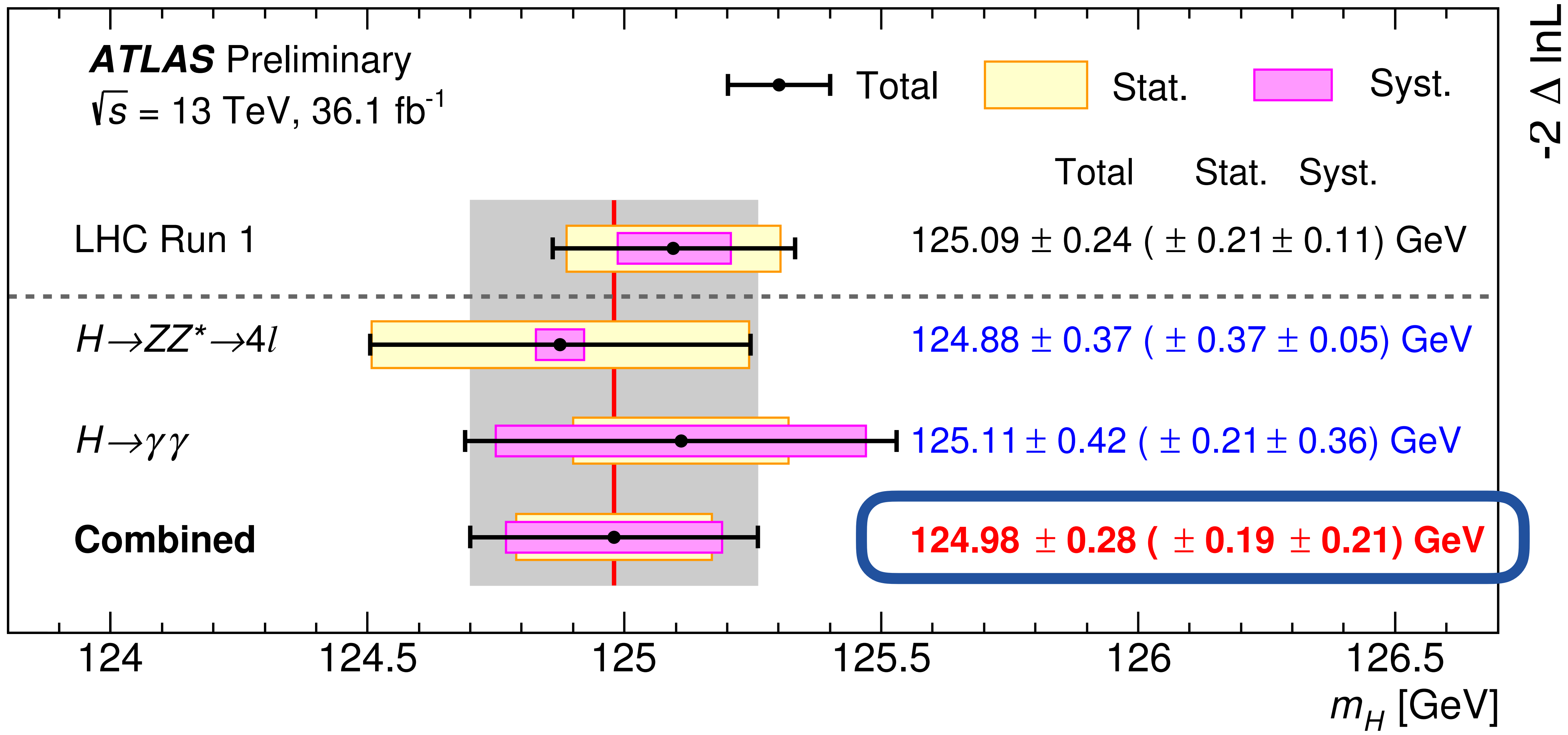
- The study of the **shape** of the scalar potential

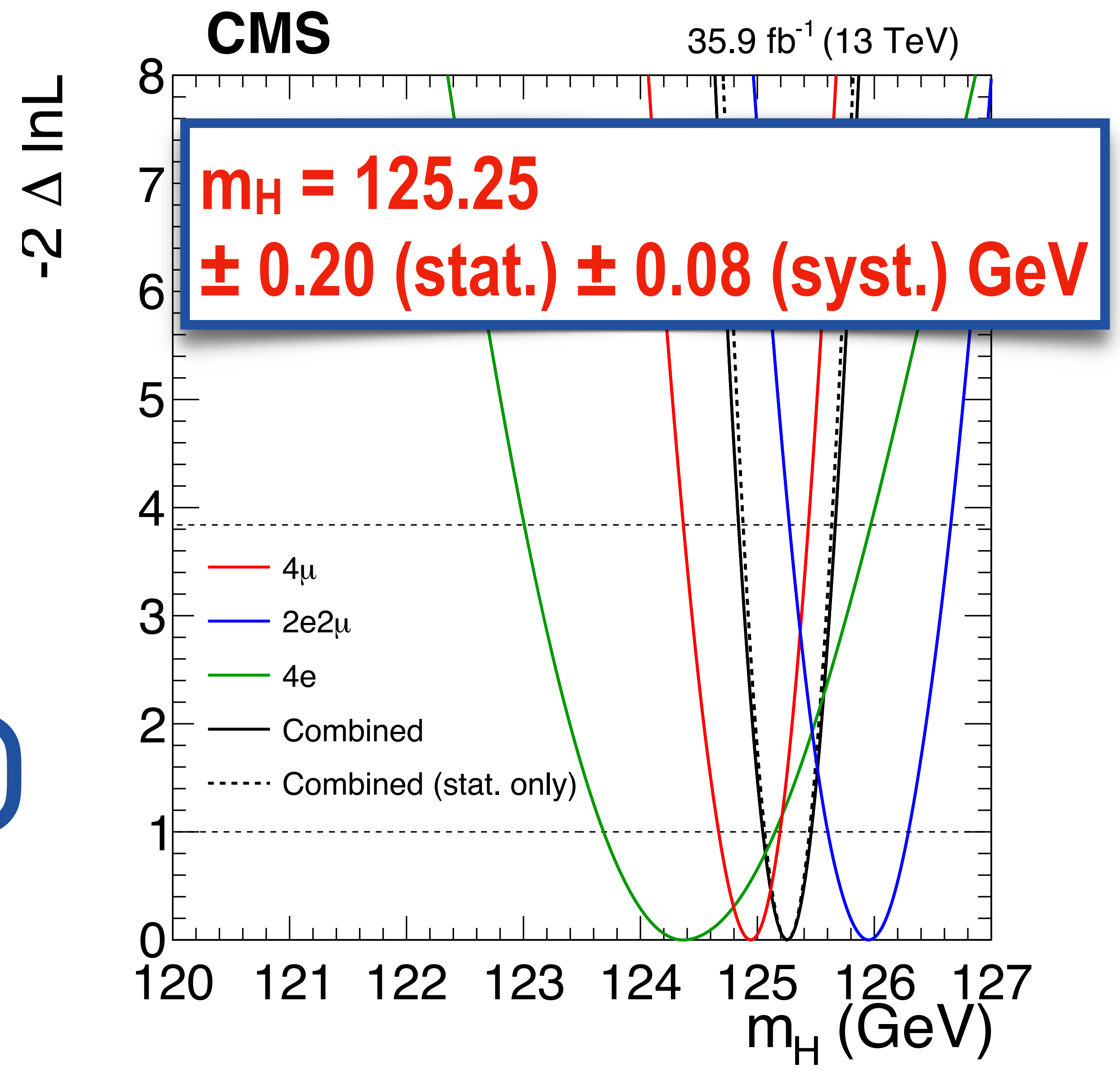
Properties: mass and width

Using the high resolution channels with 2016 data: **$H \rightarrow \gamma\gamma$** and **$H \rightarrow ZZ^* \rightarrow 4\ell$** (ATLAS), **$ZZ^* \rightarrow 4\ell$** only (CMS)

m_H

- $\sigma(m_H) / m_H = 0.18\%$: **precise measurement!**
  - excellent detector performance in lepton/photon energy scale determination
  - single experiments are better than ATLAS + CMS Run I combination
  - still dominated by statistical uncertainties

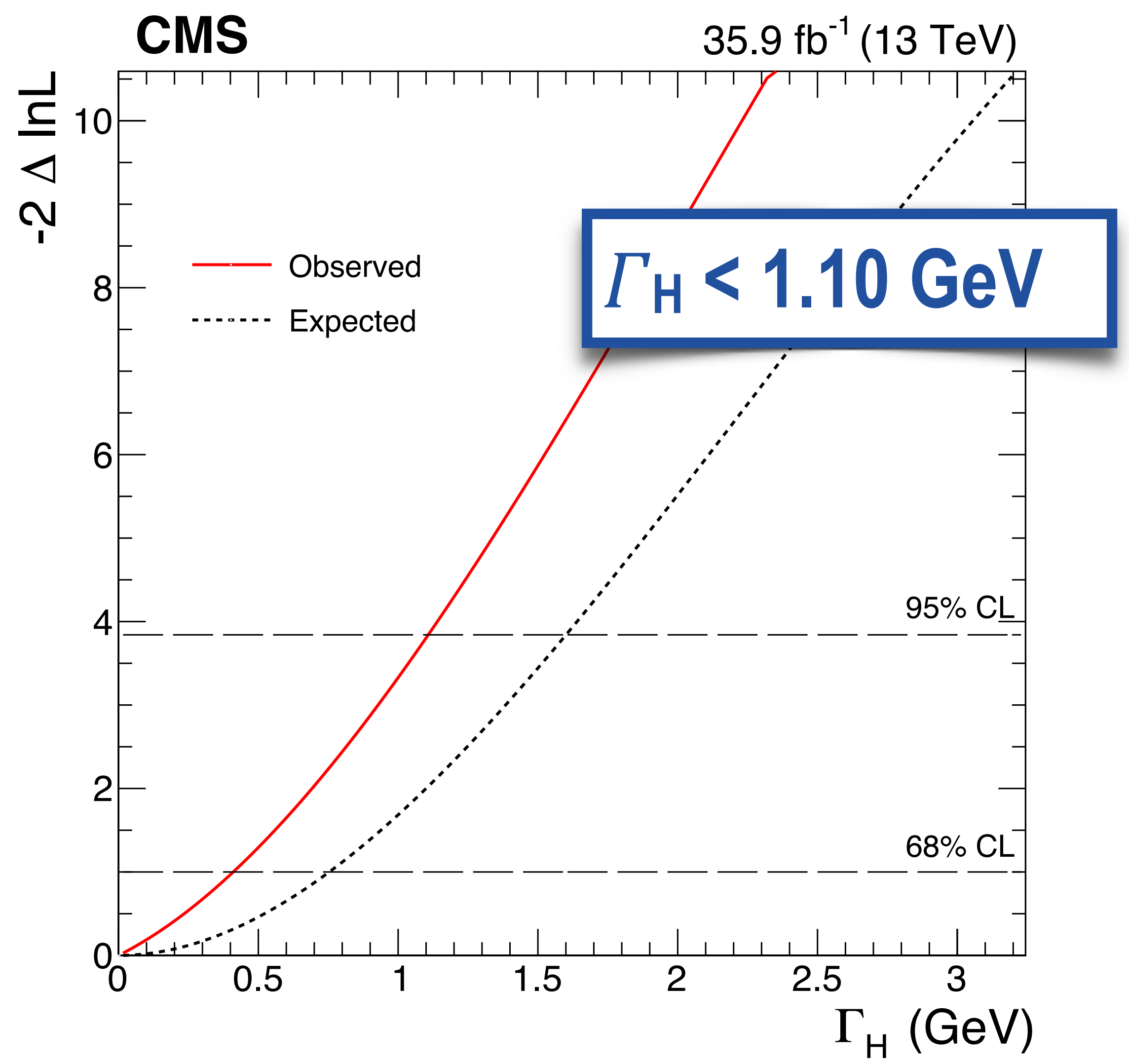




Γ_H

JHEP 09 (2016) 051

- **Γ_H < 13 MeV (3.2 × Γ_H^{SM})**
  - best limit from CMS Run I
  - from off-shell H→WW*/ZZ*
  - model dependent
- New result: direct limit from m_H lineshape



Extended scalar sectors

Why just one doublet?

- Extensions of the scalar sector can solve some known problems of the SM
- Two Higgs Doublet Model: **2HDM**
  - an extra doublet is added ⟹ **5 bosons!**
  - 7 free parameters: boson masses, tanβ (VEV ratio), cos(α-β) (α = mixing angle), m_{12} (soft Z_2-breaking mass)
  - Type I and II depending on the which fermion type the doublets couple to
- Minimal Supersymmetric Standard Model: **MSSM**
  - fixes the relations between bosons and α
    ⟹ two parameters: m_A, tanβ

Experimental signatures

H

h

A

H⁺/H⁻

$H \to VV$ (2HDM)
$H \to \tau\tau/bb$ (MSSM)
(ggf and bb associated production)
$H \to hh$

$A \to Zh$

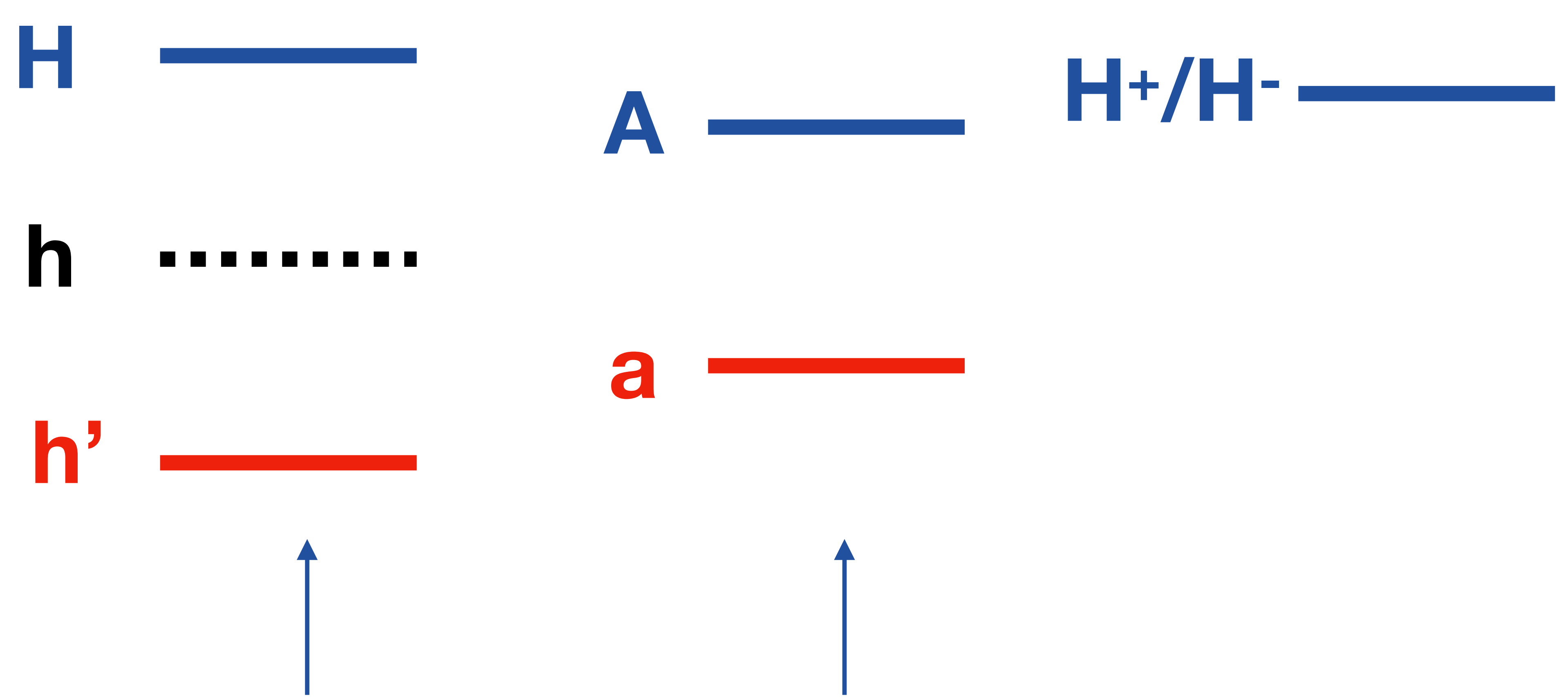
tb associated production
$H^{\pm} \to tb$ at high $m_{H\pm}$
$H^{\pm} \to \tau\nu_{\tau}$ at low $m_{H\pm}$

Extended scalar sectors

Why just one doublet?

- Extensions of the scalar sector can solve some known problems of the SM
- Two Higgs Doublet Model + Singlet: **2HDM + S**
  - extra doublet and singlet ⟹ **7 bosons!**
- Next-to-Minimal Supersymmetric Standard Model: **NMSSM**

Experimental signatures



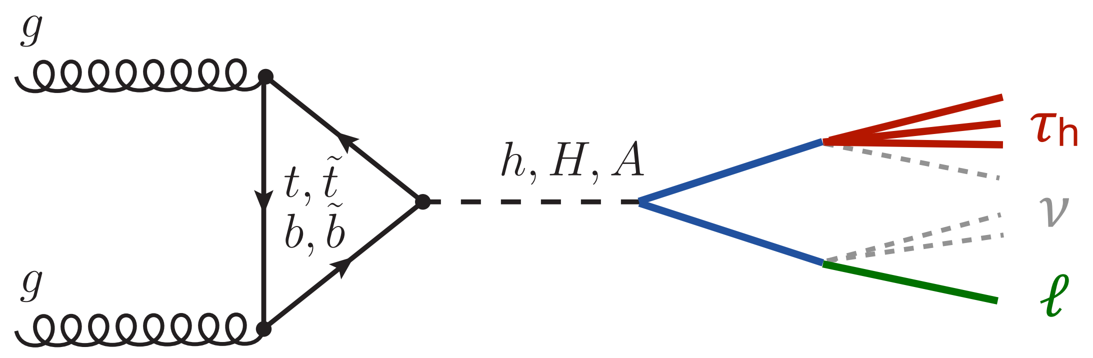
Higgs boson → light scalars decays
New light scalars → SM particles decays

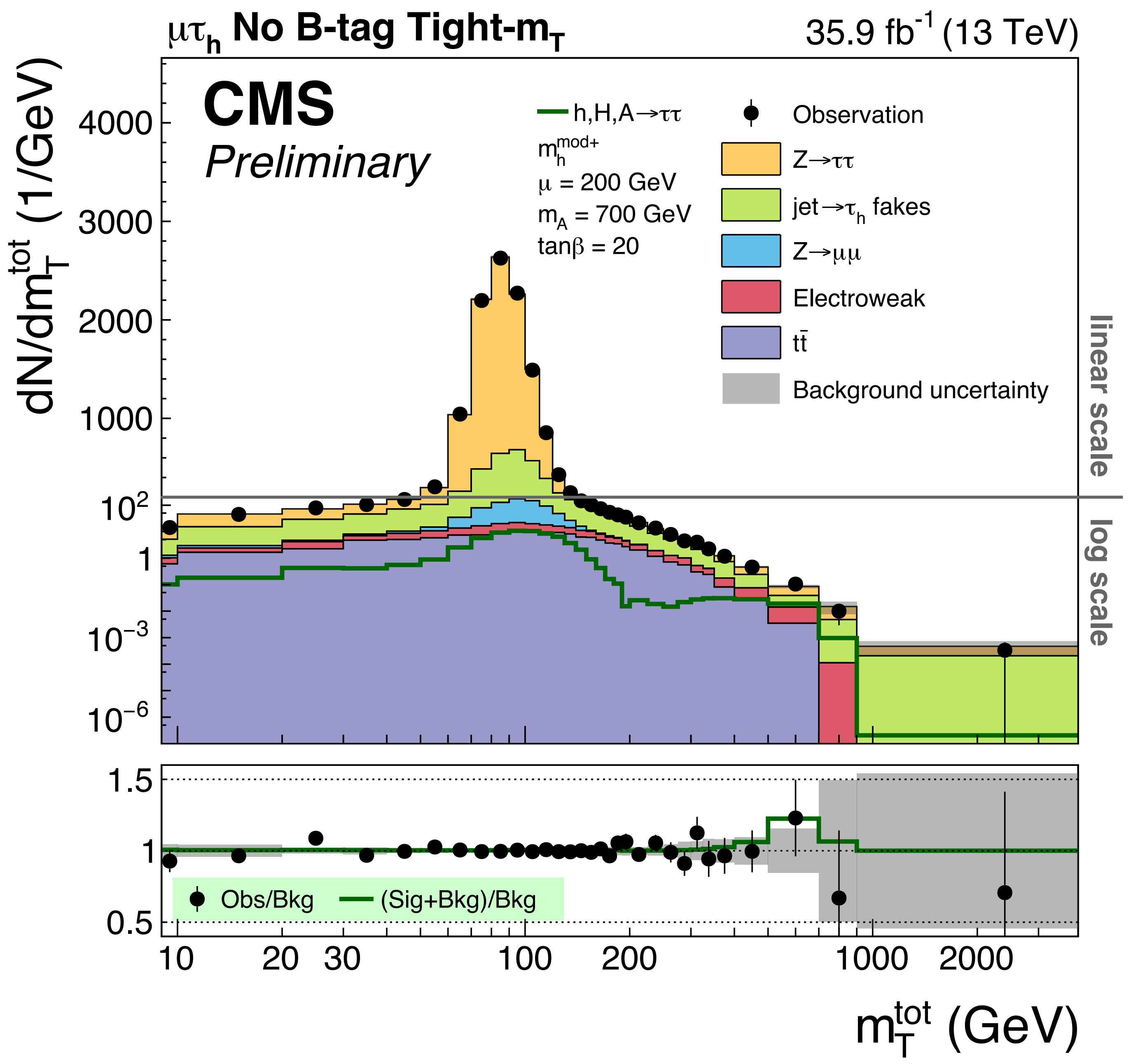
In general, scalar sector extensions and generic BSM scenarios predict new states and new Higgs boson decays

Heavy H→ττ

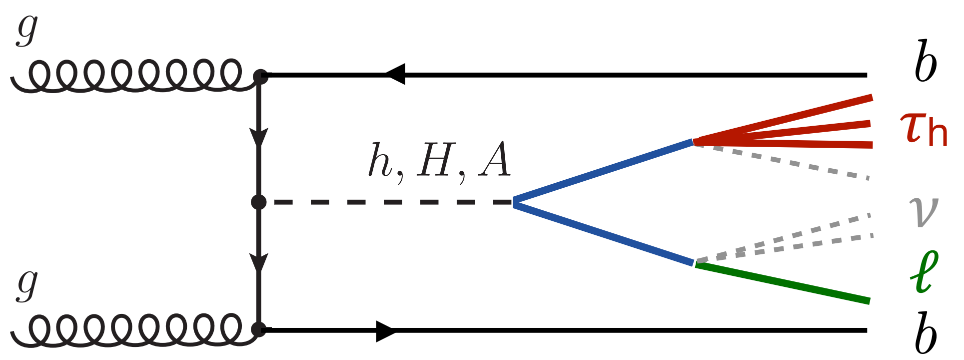
Production modes:

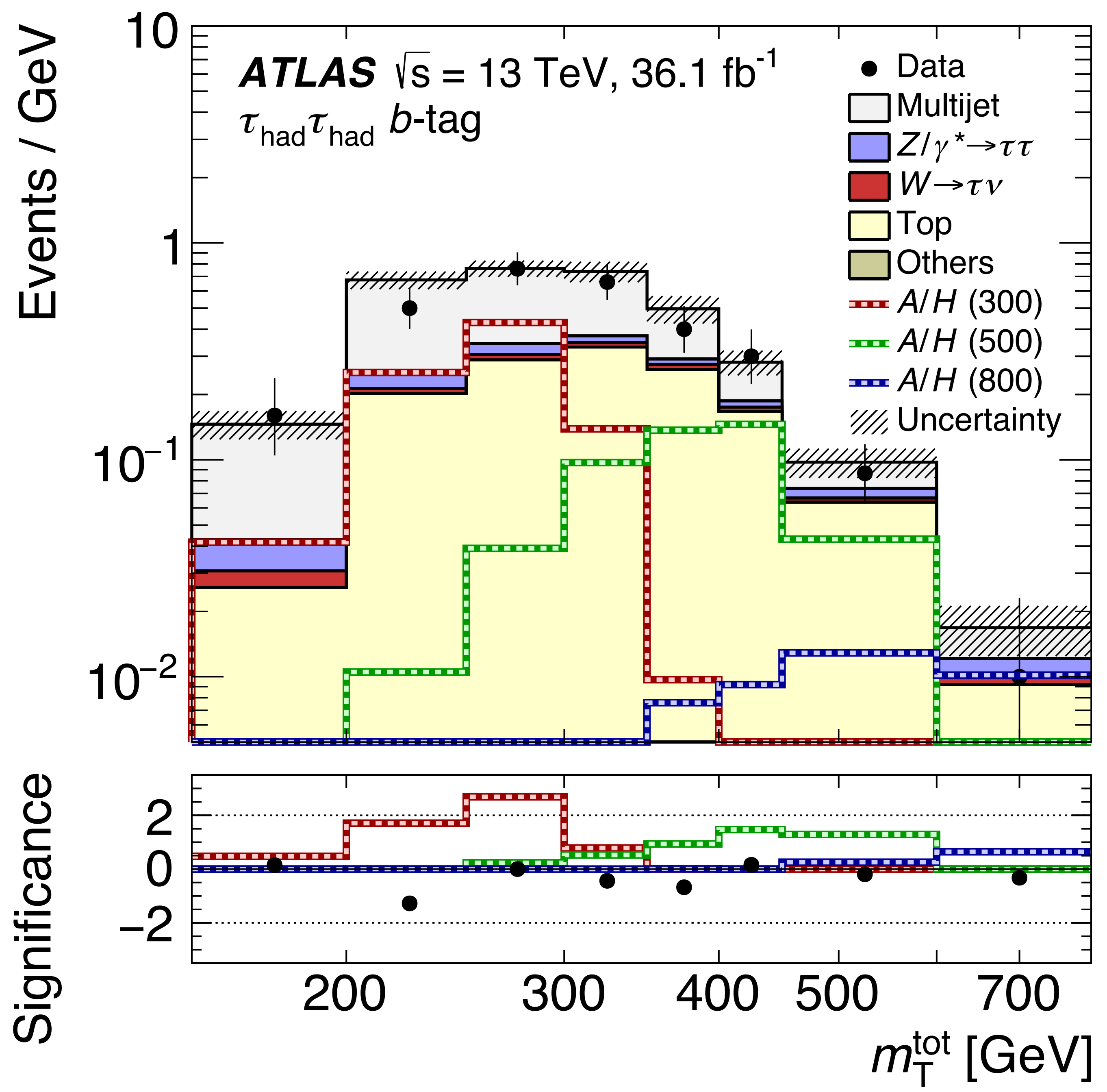
Gluon fusion





b associated production



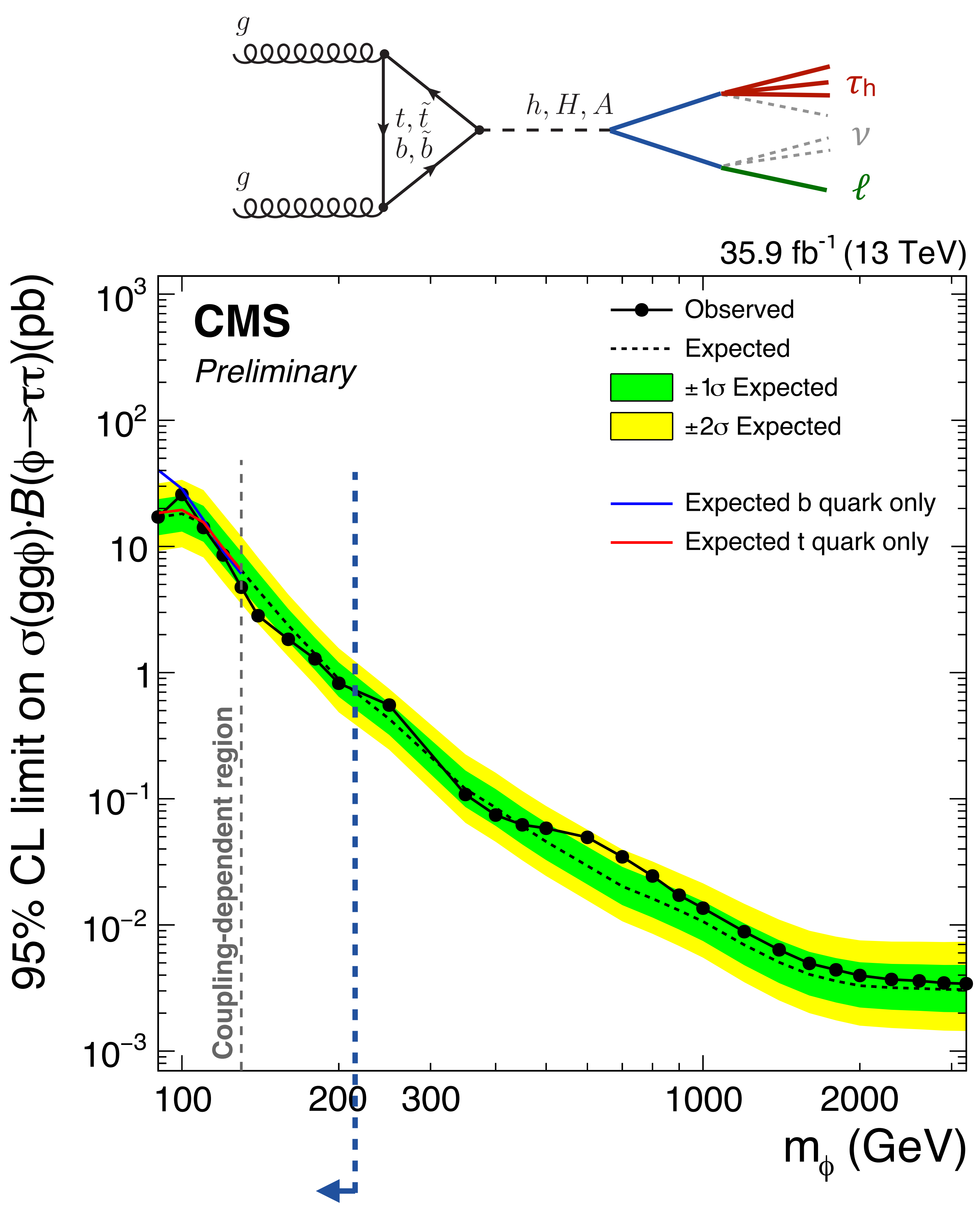


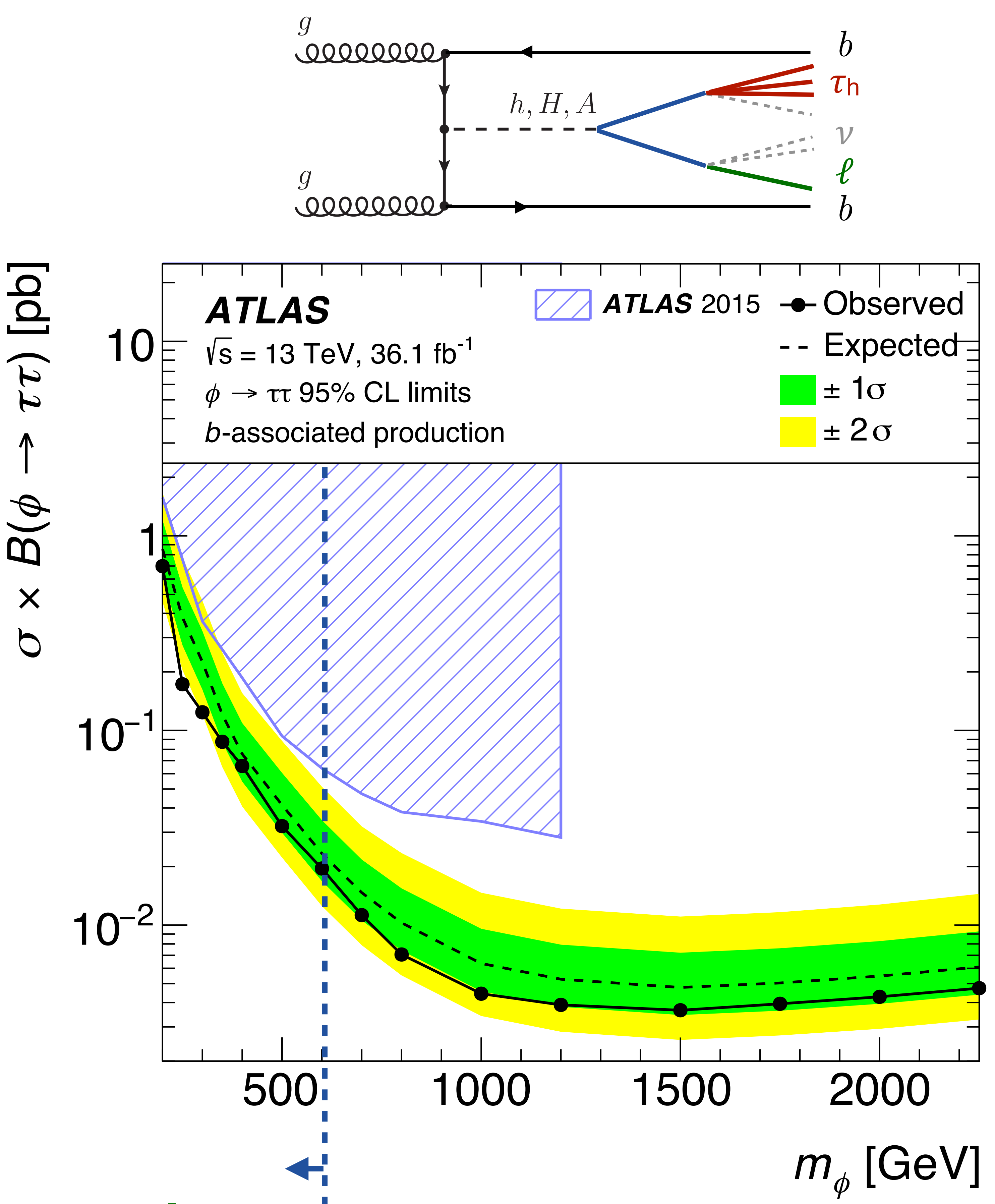
- $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$ final states (ATLAS) + μe (CMS)
  - $\ell\tau_h$: single lepton trigger
  - $\tau_h\tau_h$: single τ_h, $p_T > 80/125/160$ GeV (ATLAS) double τ_h, $p_T > 35$ GeV (CMS)
- Signal appears as an enhancement in the total transverse mass

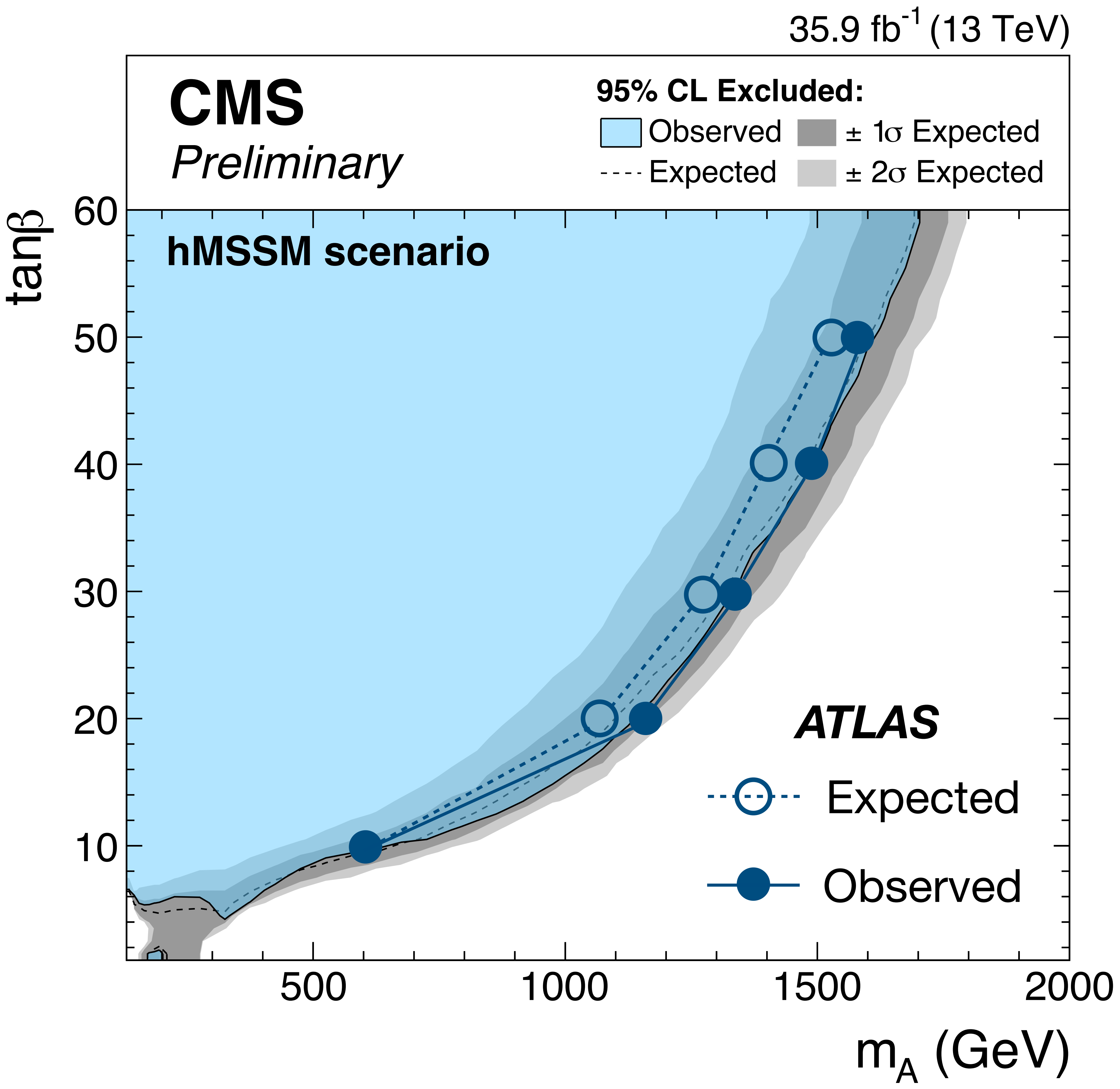
$$m_T^{tot} \equiv \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{miss})^2 - (\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2} + \mathbf{E}_T^{miss})^2}$$

- Main backgrounds
  - $Z\to\tau\tau$ (from simulation)
  - QCD multijet with mis-ID τ_h (data-driven) its precise estimation is crucial for the analysis sensitivity

Heavy H→ττ: results







reach lower m_ϕ thanks to lower trg. thresholds (on $\ell\tau_h$ and $\tau_h\tau_h$)

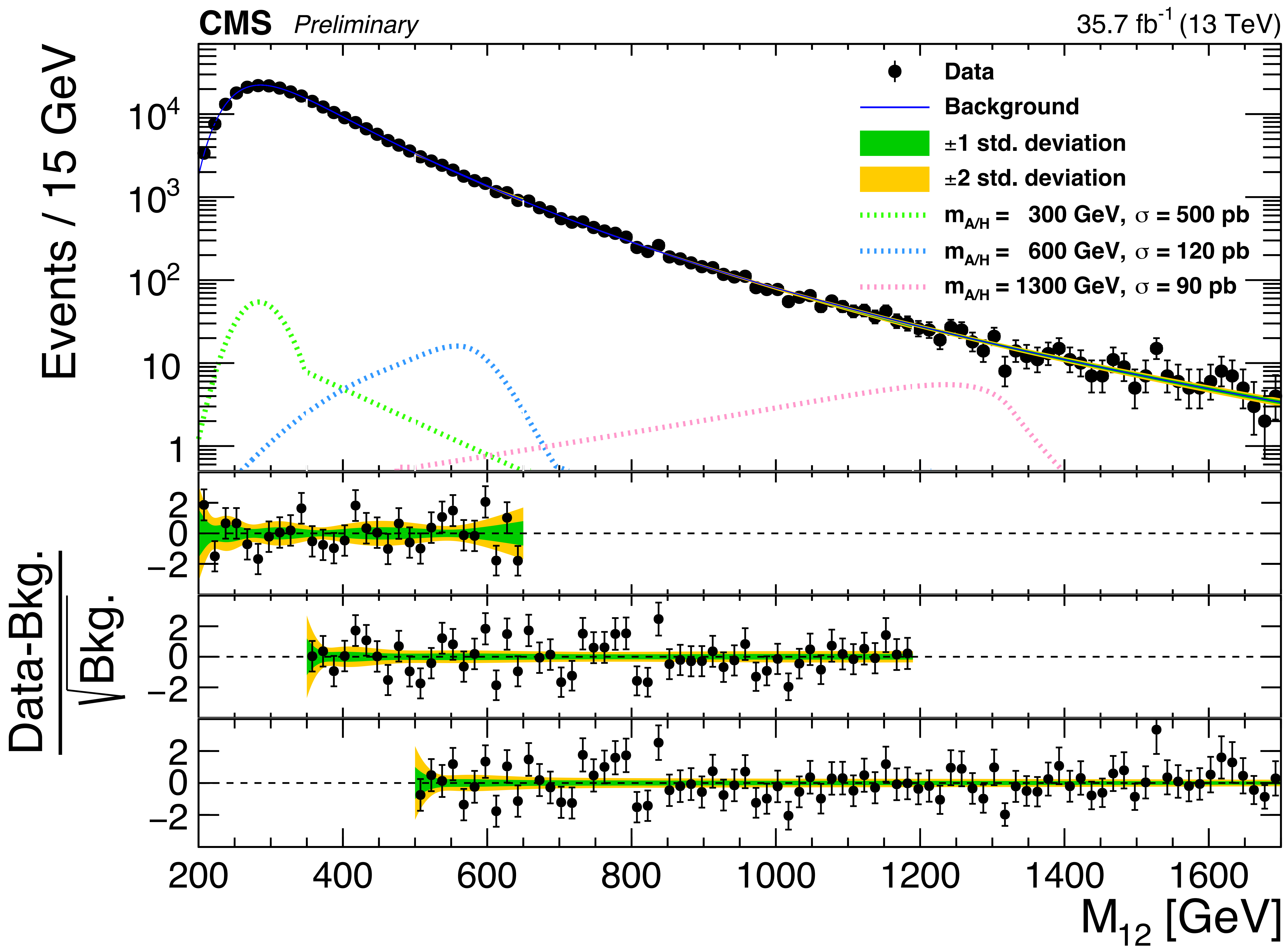
$\ell\tau_h$ best

$\tau_h\tau_h$ best

Results constrain the parameter space of MSSM models

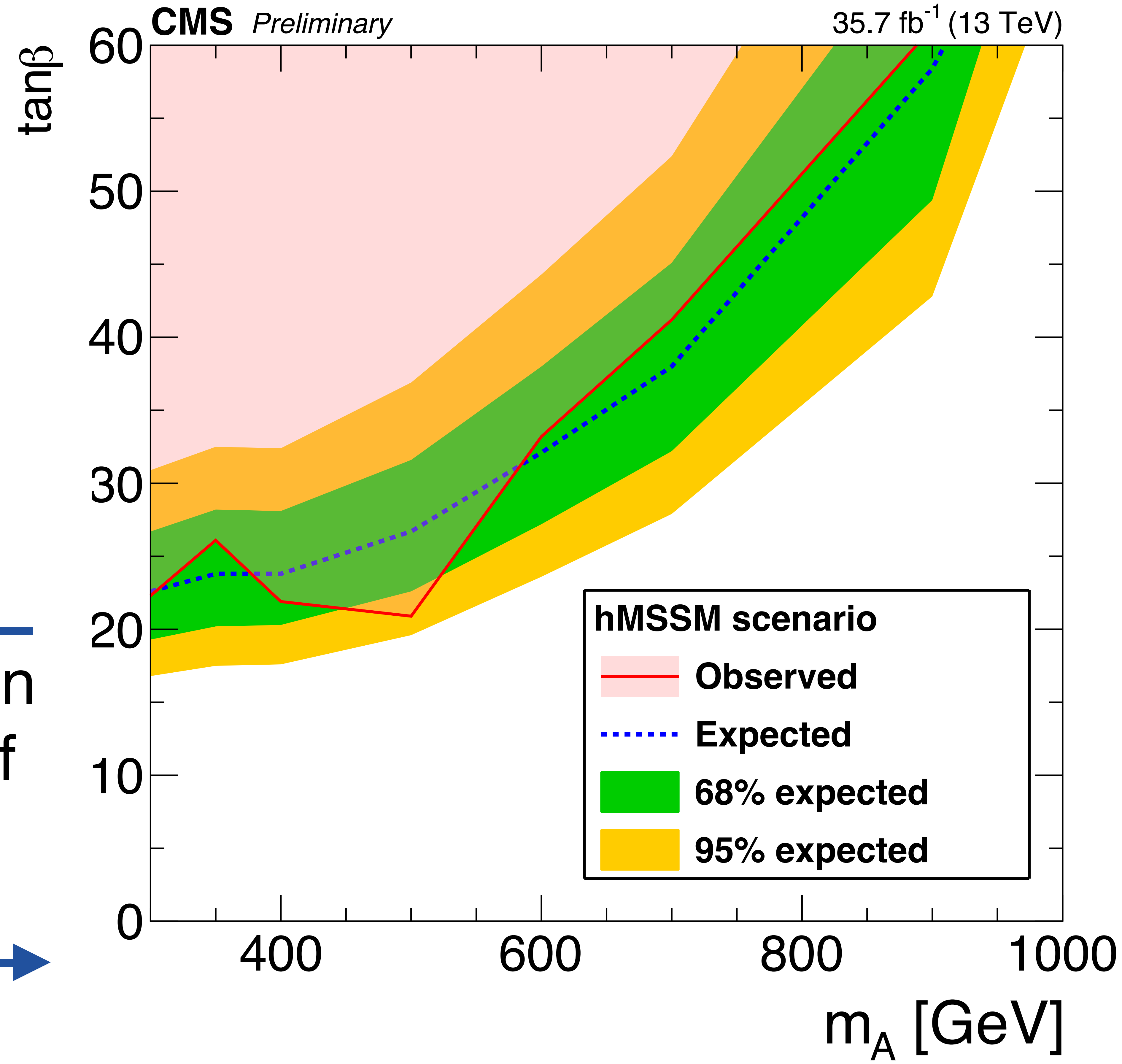
Heavy scalar bbH, H→bb

- H→bb in bb associated production to overcome the large multijet background : **4b final state**
- Efficient b-tagging (ε ~ 65%) is crucial for the sensitivity
  - use events with ≥ 3 b-tagged jet, recorded with b-tag triggers



Search for a signal in the leading jet pair invariant mass M_{12}

Constraints on parameters of extended scalar sector

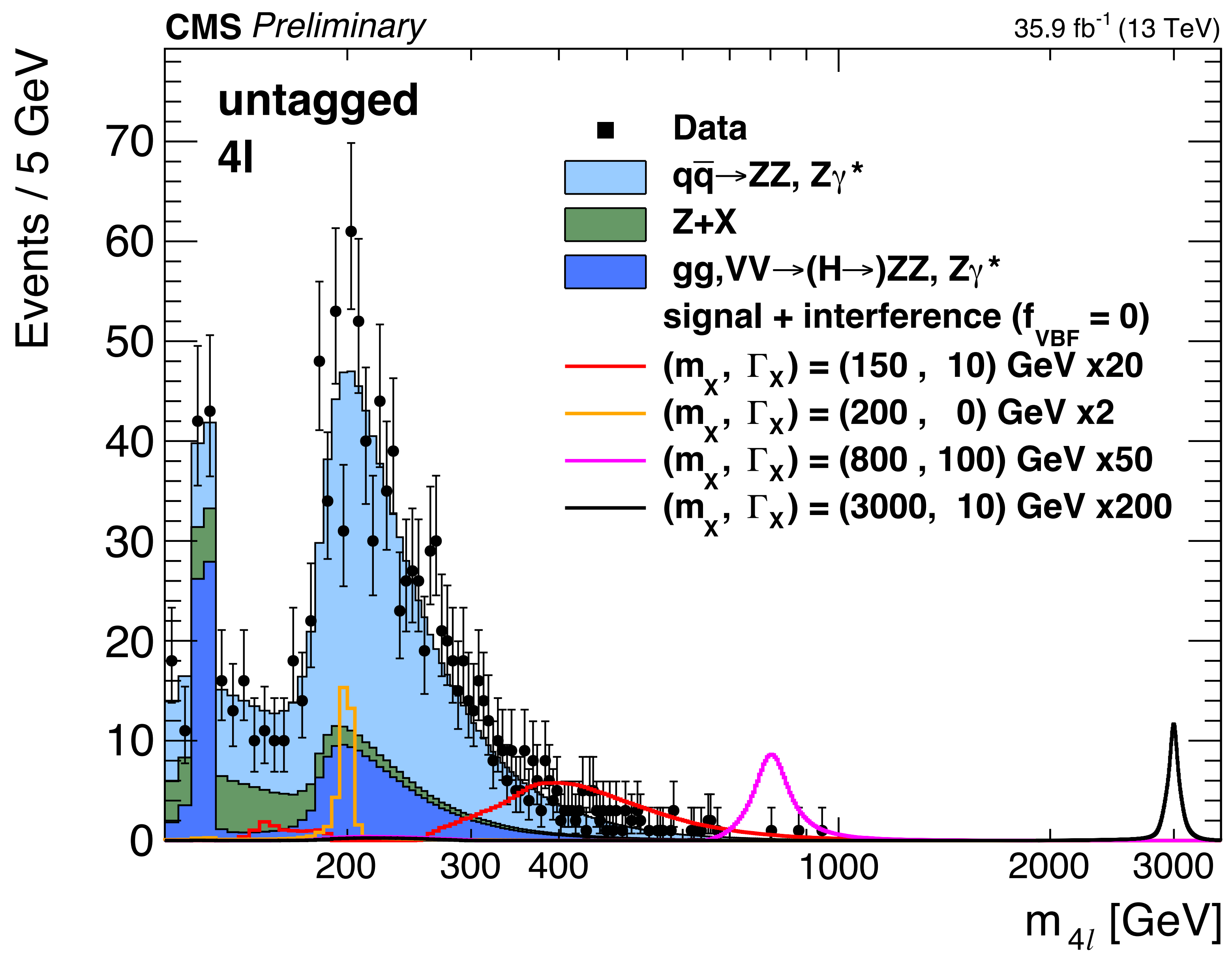


arXiv:1712.06386
Eur. Phys. J. C 78 (2018) 24
CMS PAS HIG-17-012

Heavy H→VV

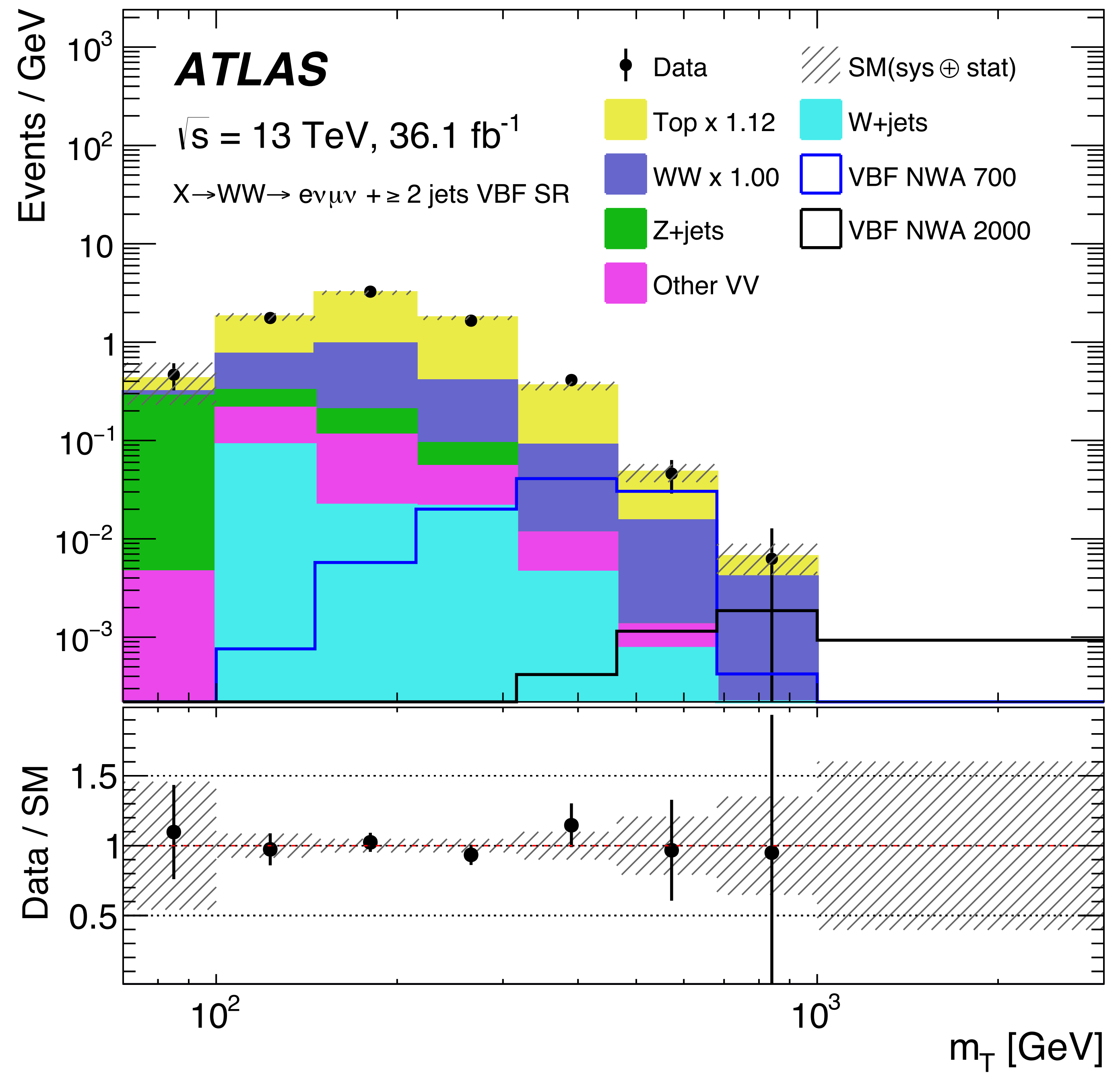
H→ZZ (ATLAS, CMS)

- 4ℓ / $2\ell2\nu$ (ATLAS) + $2\ell2q$ (CMS) final states
- 4ℓ
  - signal in $m_{4\ell}$
  - bkg: ZZ
- $2\ell2\nu$
  - signal in m_T
  - bkg: ZZ, WZ
- $2\ell2q$
  - signal in $m_{\ell\ell qq}$
  - bkg: Z+jets



H→WW (ATLAS)

- $e\nu\mu\nu$ final state
- Main backgrounds (single-t, tt) from simultaneous fit in control regions
- use m_T (e,μ,p_T^{miss}) to look for a signal

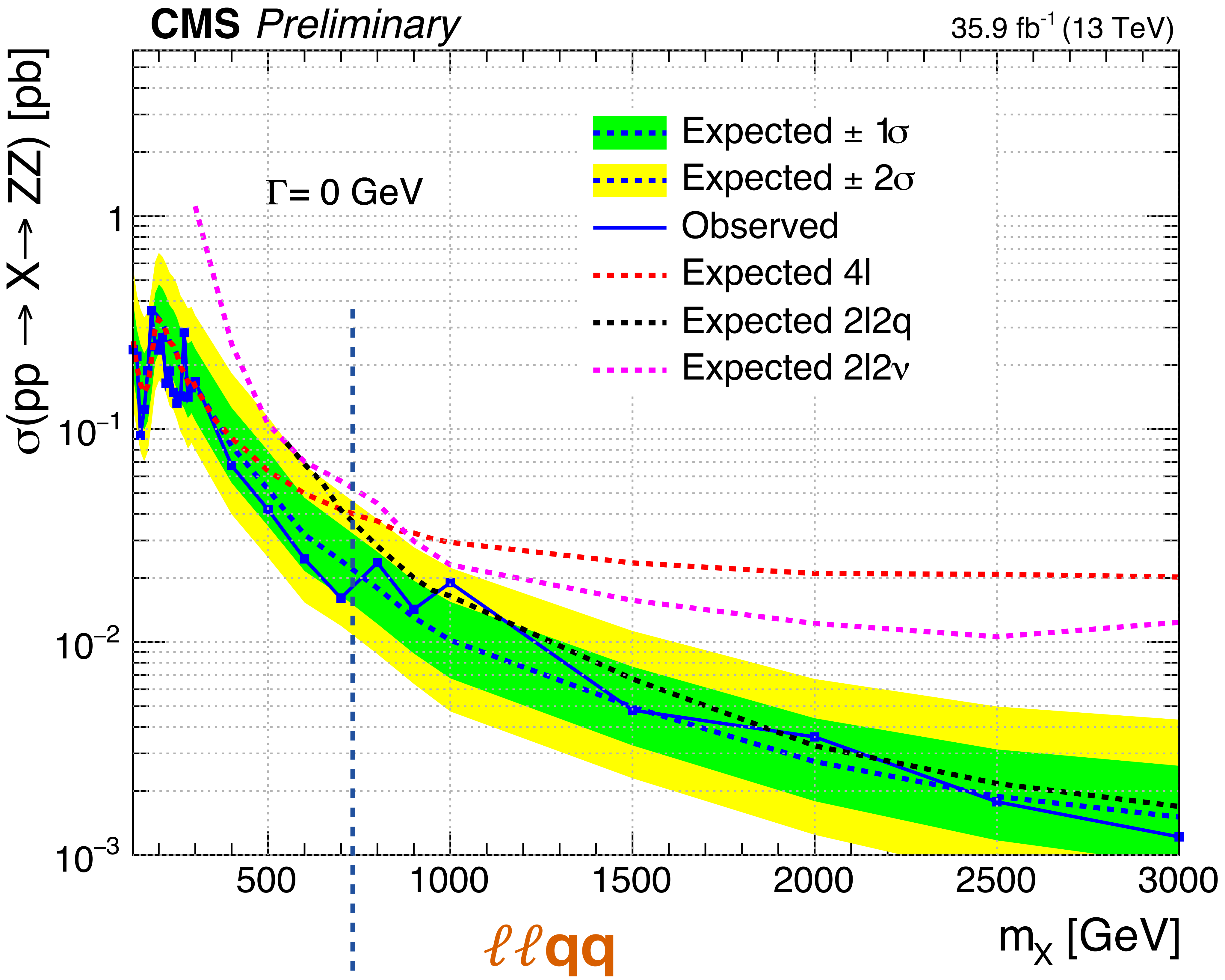


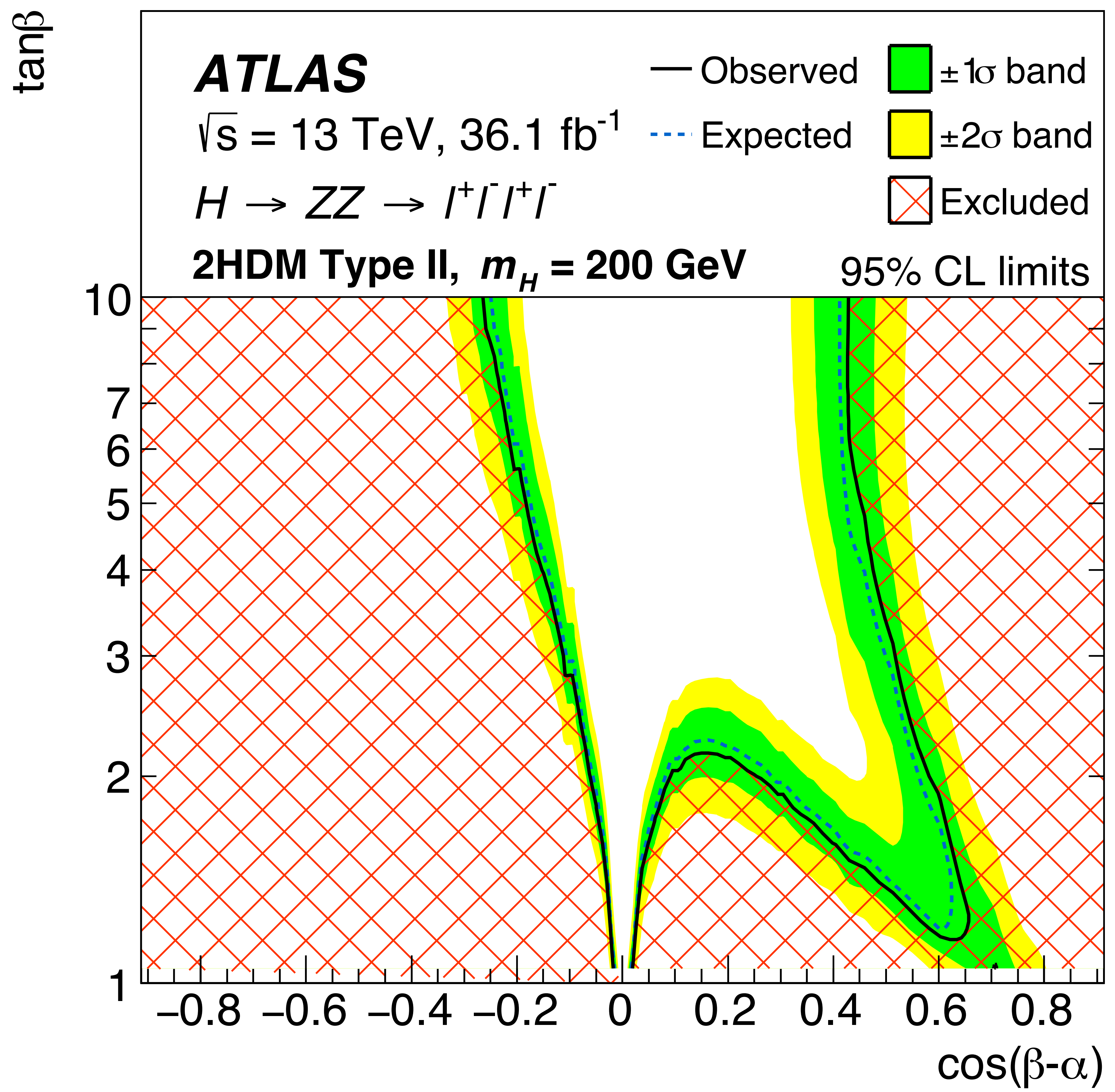
Search for both ggF and VBF production with dedicated categories
Explore different m_H in [100 GeV, 4 Tev] and Γ_H

More on searches for high-mass resonances in John's talk

arXiv:1712.06386
Eur. Phys. J. C 78 (2018) 24
CMS PAS HIG-17-012

Heavy H→VV: results





4ℓ most sensitive (best purity)

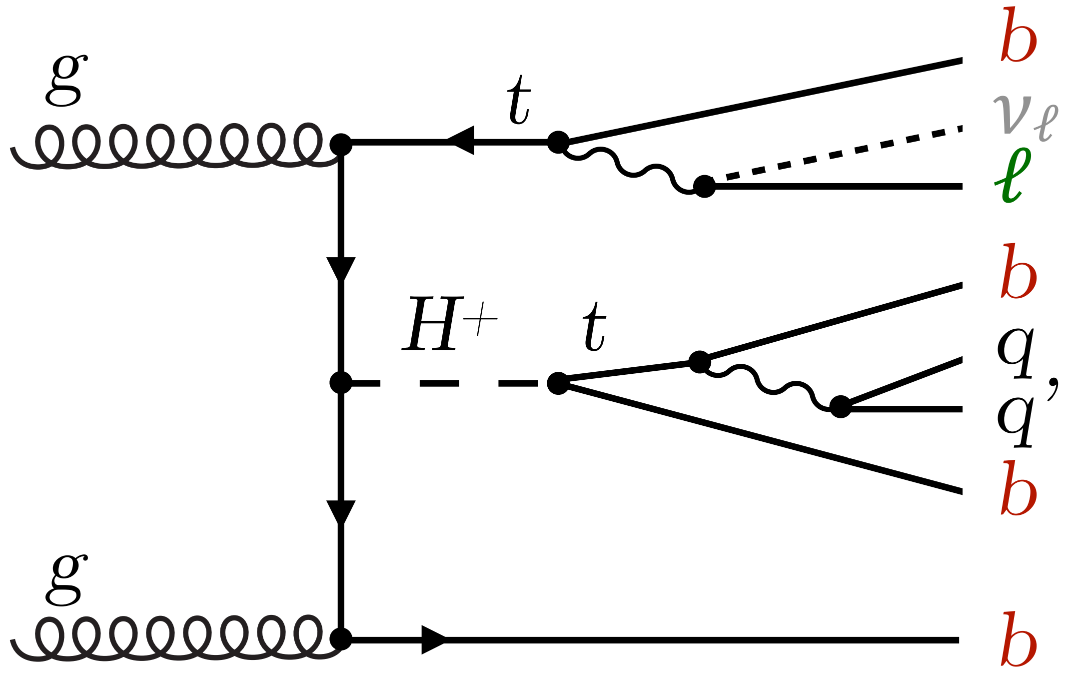
$\ell\ell qq$ most sensitive (highest BR)

Model independent limits on Heavy H production × branching fraction

Results constrain the 2HDM model parameter space

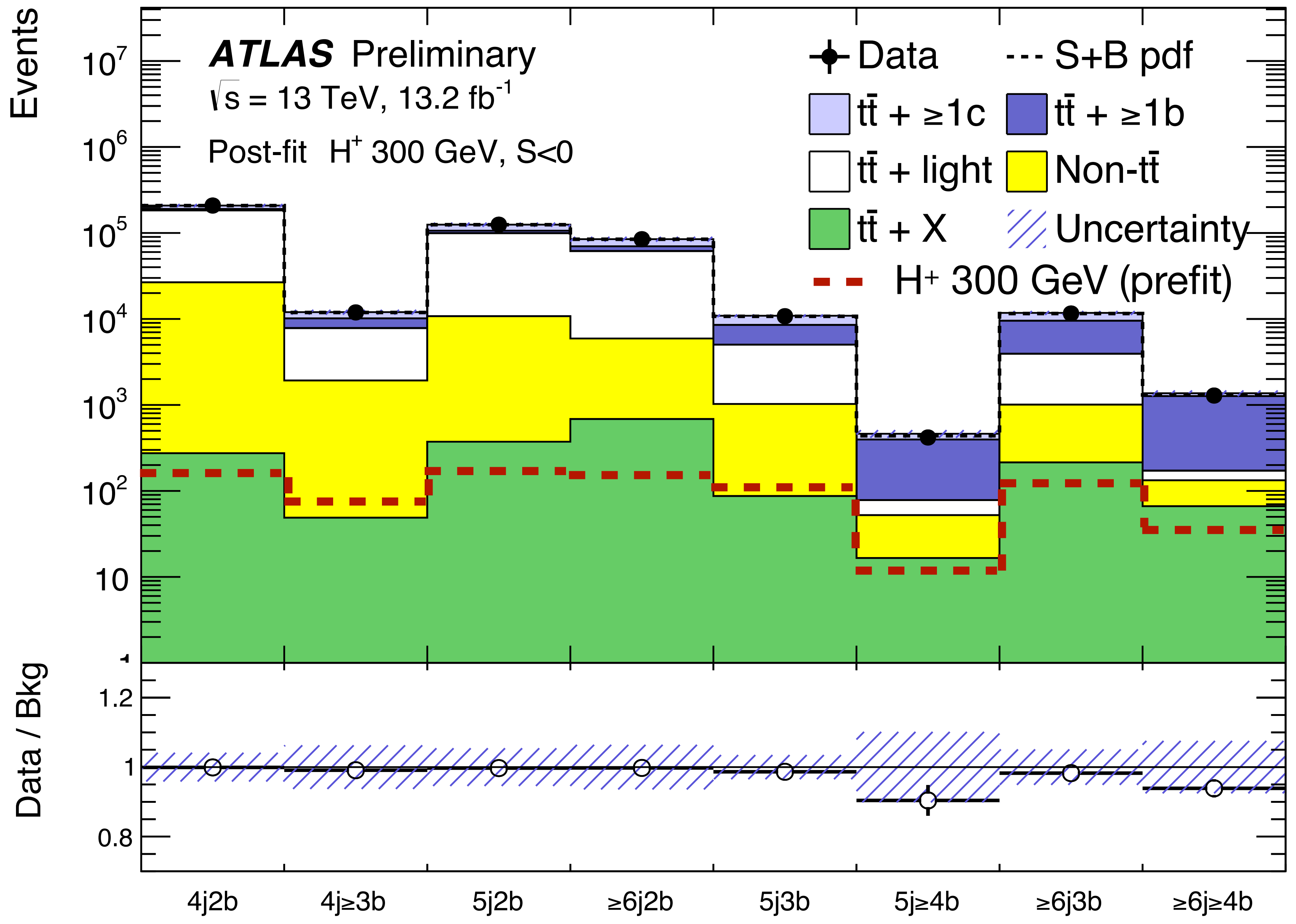
$H^{\pm} \longrightarrow tb$

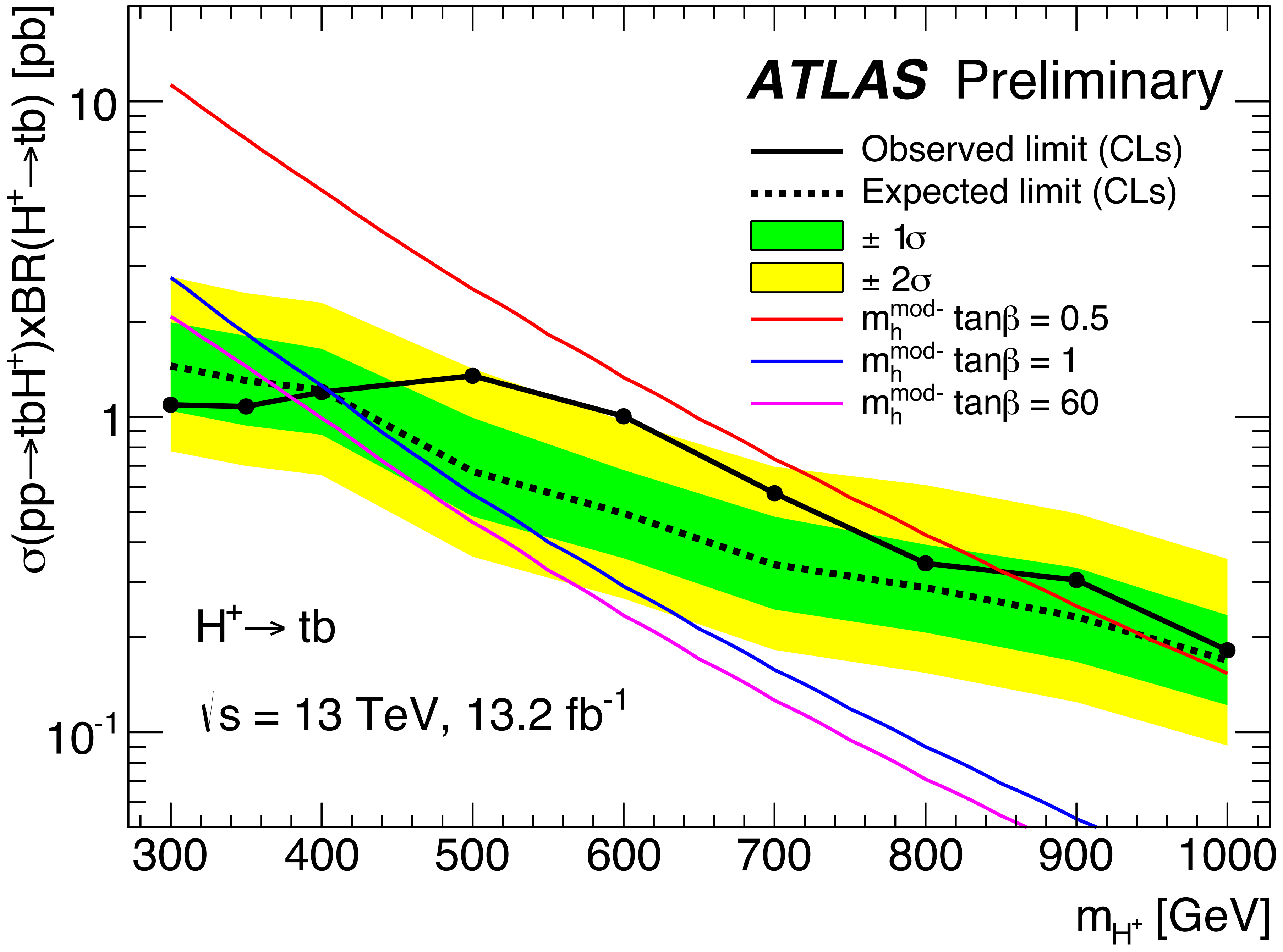
tb $H^{\pm}$, one leptonic W decay
$\Longrightarrow$ 4b + 1ℓ final state
Complex final state!



- Boosted decision tree to look for a signal
  - input: variables related to the kinematics of jets
  - dedicated training for each mass hypothesis

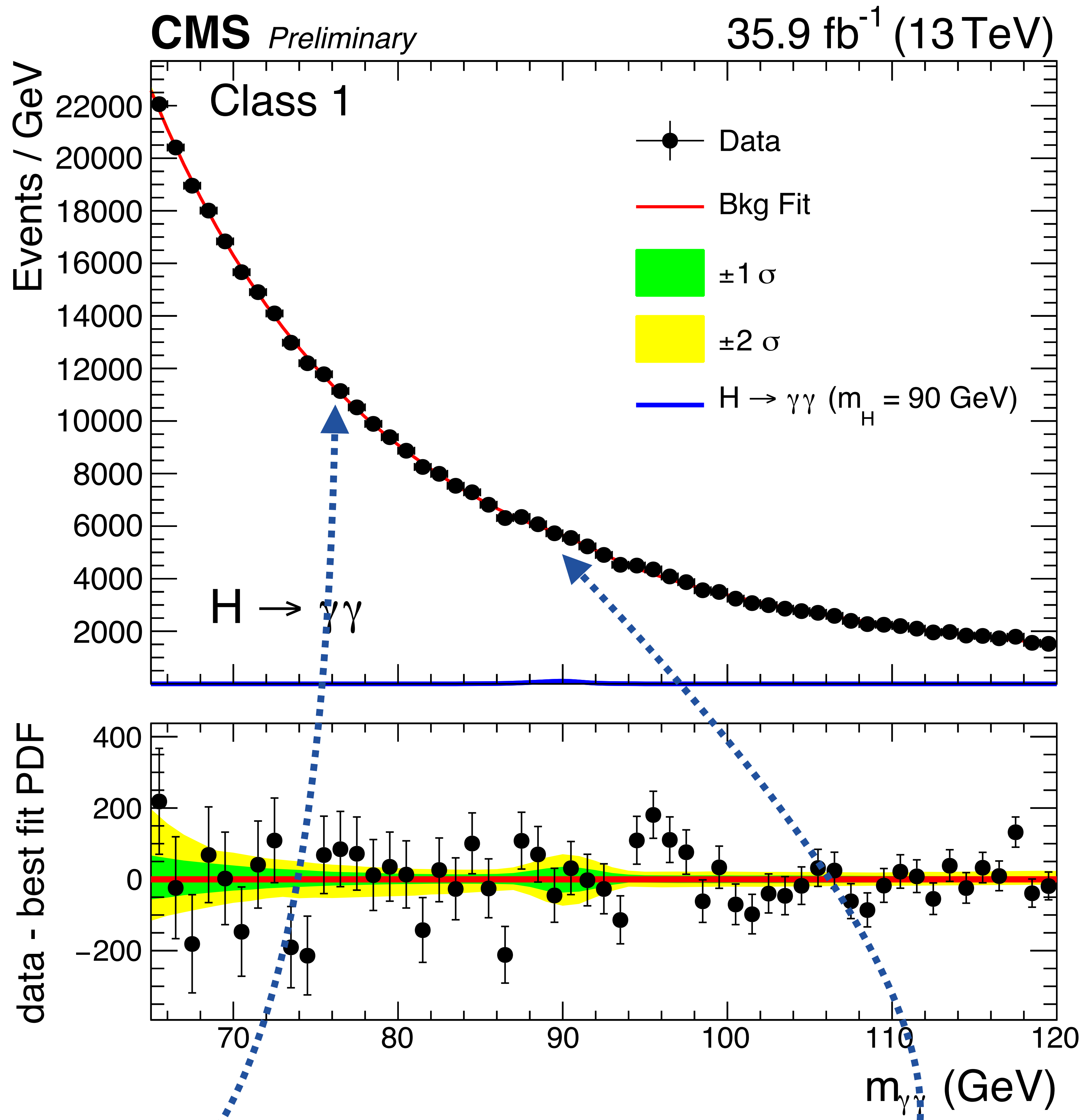
- Signal and control regions based on the number of b-tag and additional jets
  - simultaneous fit to constrain backgrounds and systematic uncertainties
- Sensitive to low m_{H^+}, low tanβ MSSM regions





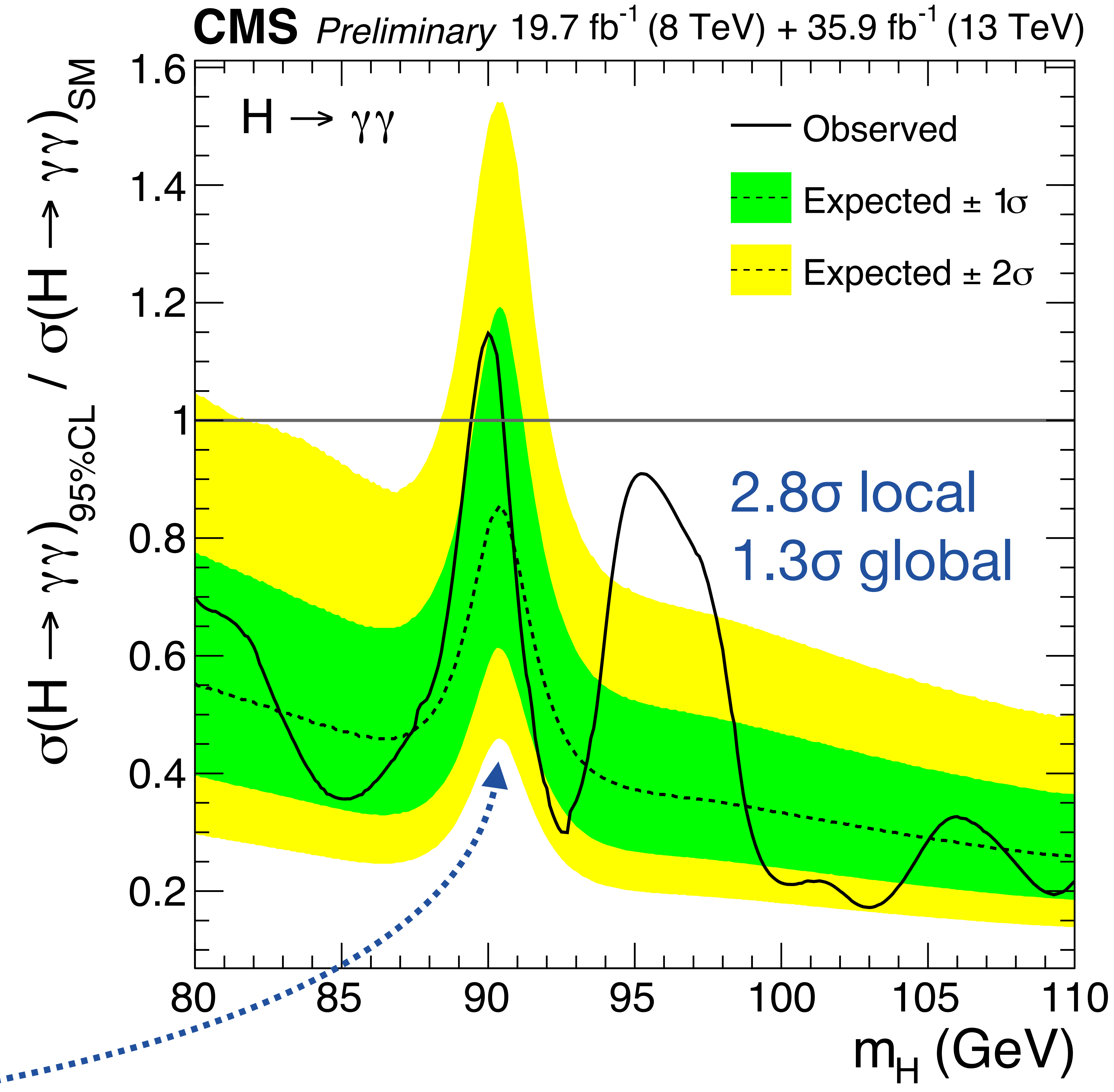
Light $h' \rightarrow \gamma\gamma$

- Low mass search
  - sensitivity crucially depends on dedicated low-mass $\gamma\gamma$ triggers
- Look for an excess in the $m_{\gamma\gamma}$ spectrum
- Analysis strategy similar to $H \rightarrow \gamma\gamma$
  - MVA method to identify $\gamma\gamma$ signal



Continuum background

Z→ee, with mis-ID electrons

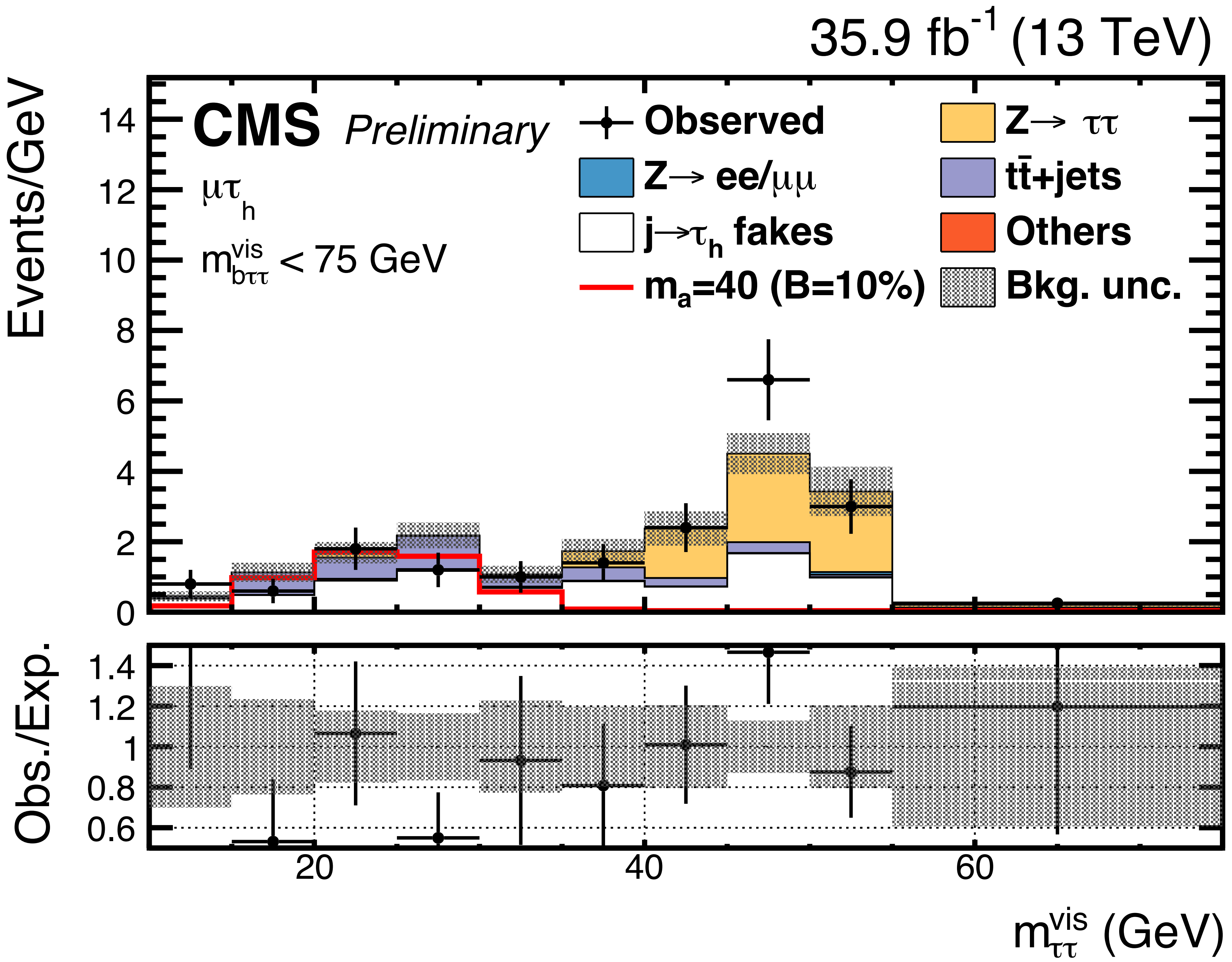


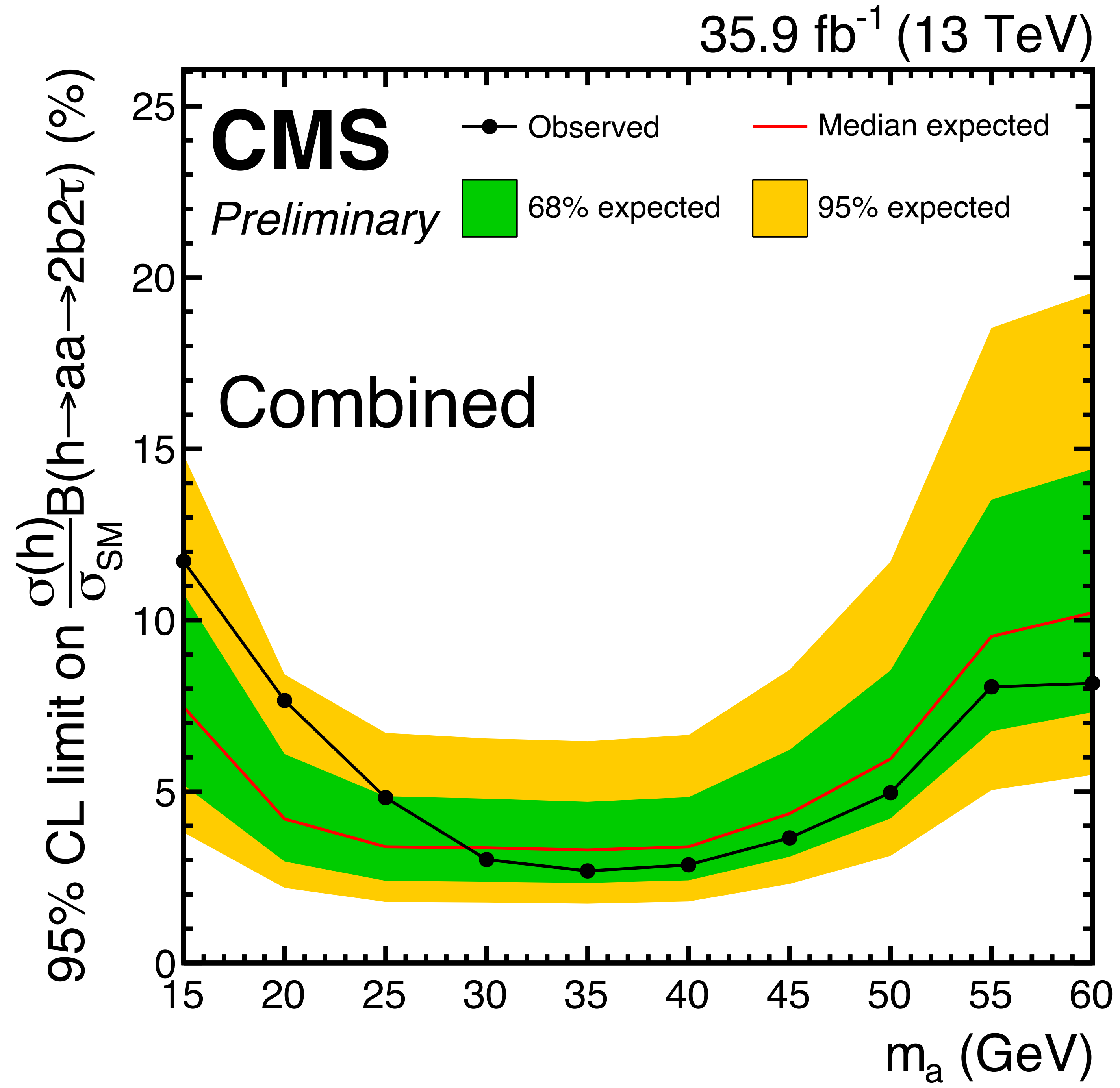
Run I + Run II combination

$H \to aa \to bb\,\tau\tau$ **NEW !**

Low mass search (15-60 GeV) in a decay channel never explored so far

- Three $\tau\tau$ final states: $e\tau_h$, $\mu\tau_h$, $e\mu$ + ≥ 1 b-tagged jet
  - rely on the lepton signature at trigger
  - jets too soft to reconstruct both of them
- Four categories in $m^{vis}_{b\tau\tau}$ to separate signal and background
- Main backgrounds
  - tt (simulation)
  - $Z \to \tau\tau$ (simulation + corr. in $Z \to \mu\mu$)
  - mis-ID jets as τ_h (from data)
- Look for a signal using visible $\tau\tau$ mass

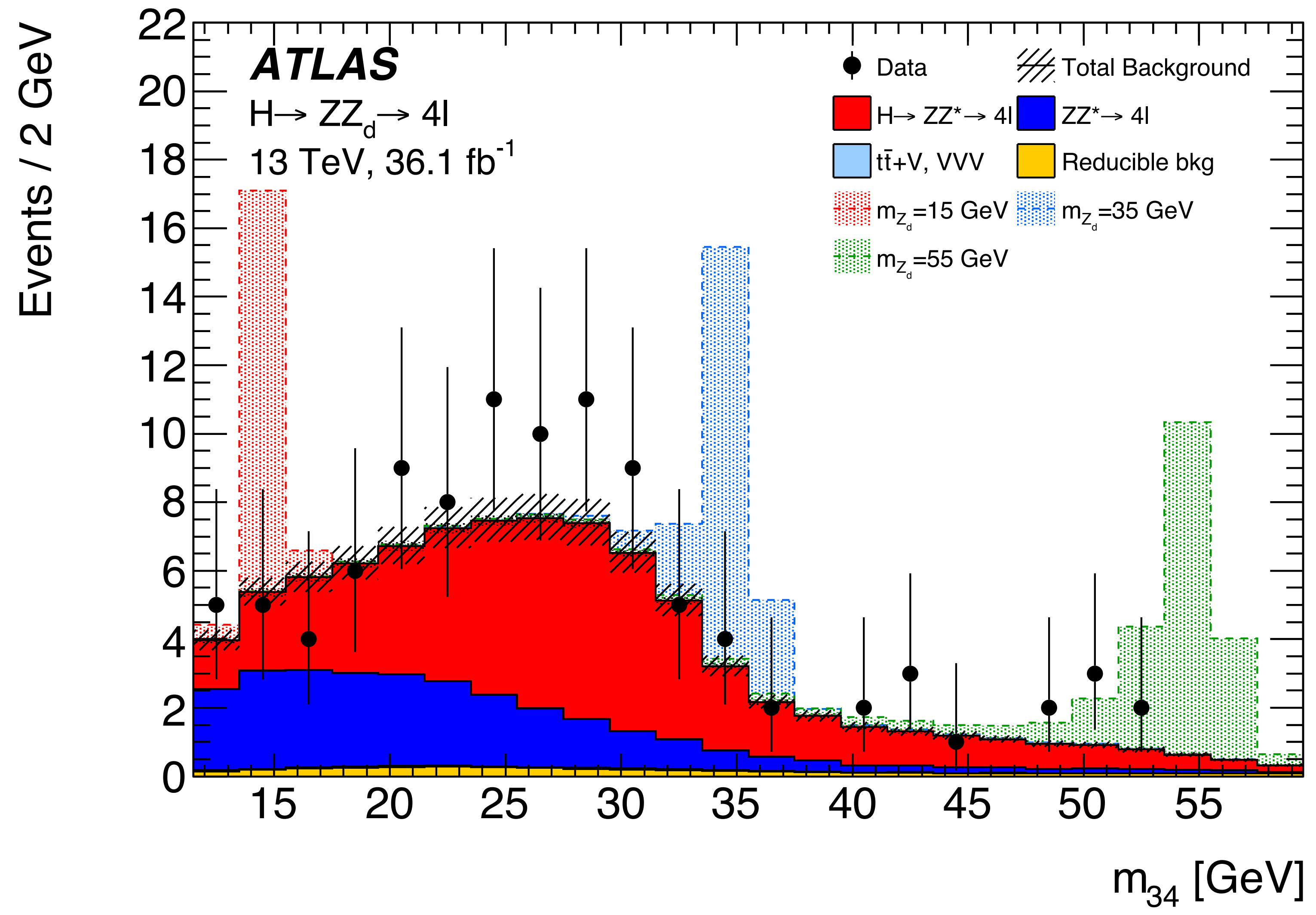


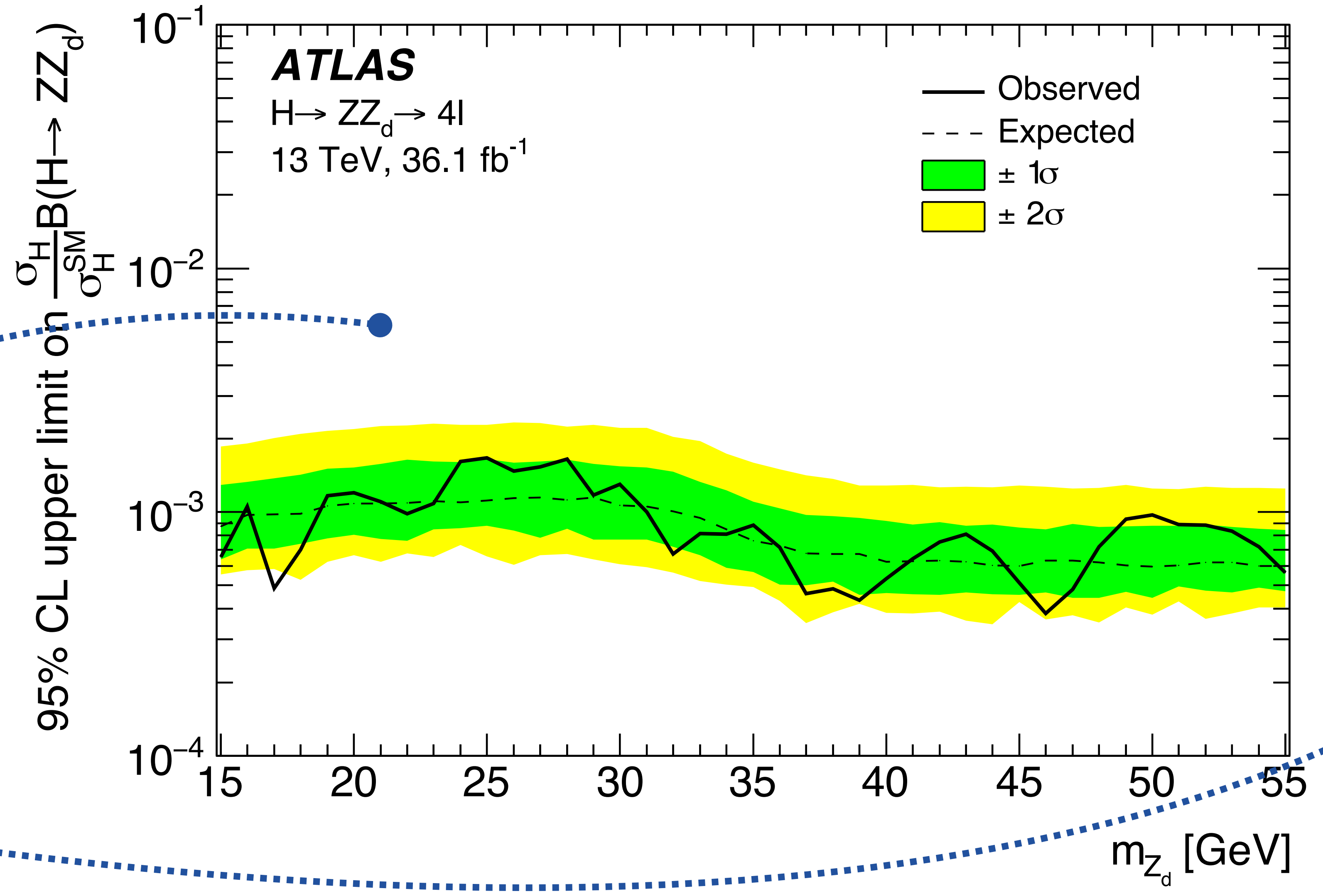


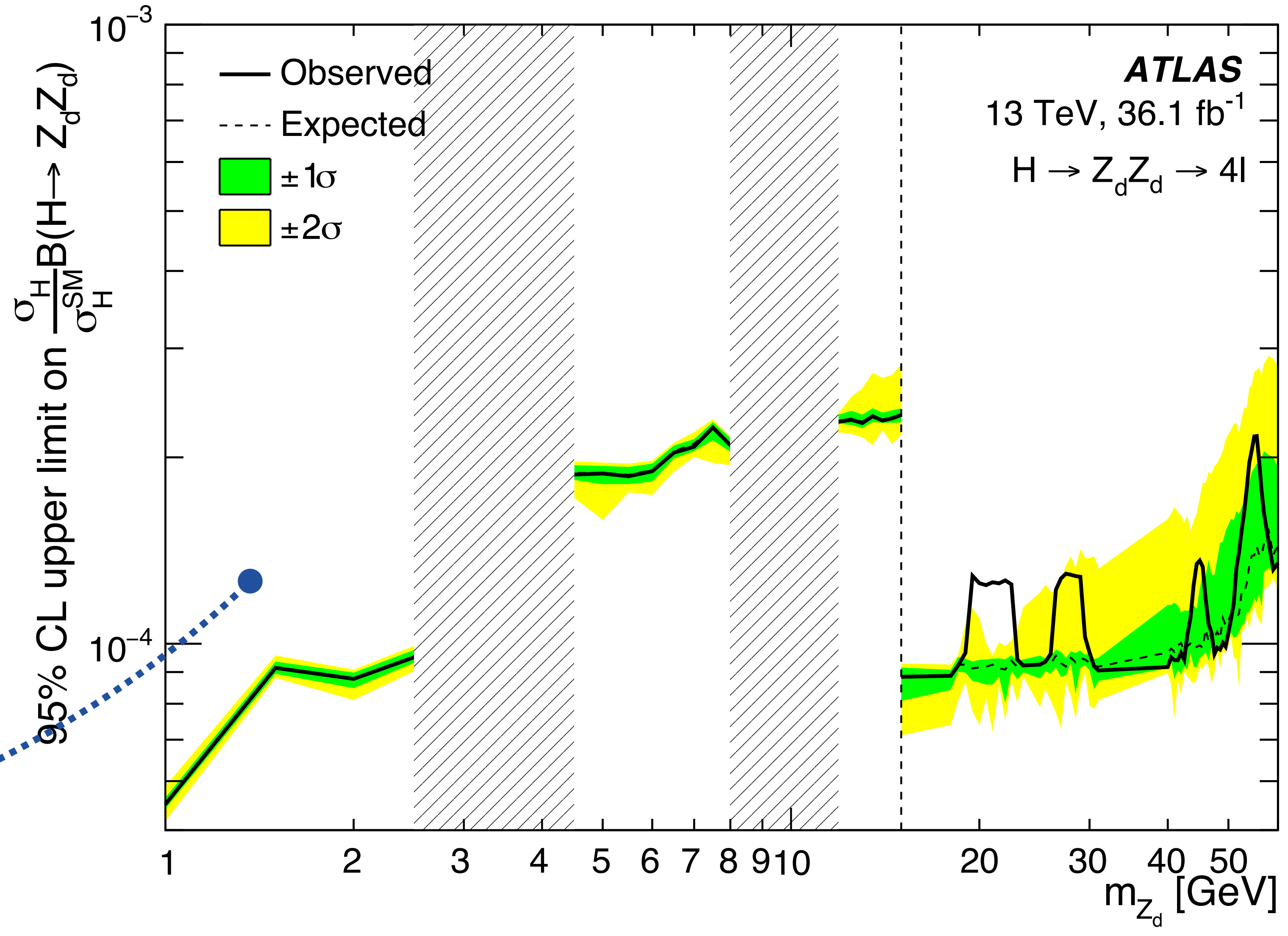
Best sensitivity for m_a > 15 GeV

H→Zx / xx→4ℓ

- **x** : light pseudoscalar or vector boson
- Dominant background
  - SM H→ZZ*→4ℓ
  - triboson (MC) and heavy flavours (data-driven) at very low mass
- Exploit x→ℓℓ resonant signature
  - Zx: search for the m_x peak over background distribution
  - xx: search for a peak over average ℓℓ mass $\langle m_{\ell\ell}\rangle$
- Low mass search!
  - **Zx:** m_x in [15, 55] GeV
  - **xx:** m_x in [15, 60] GeV and [1, 15] (4μ only)

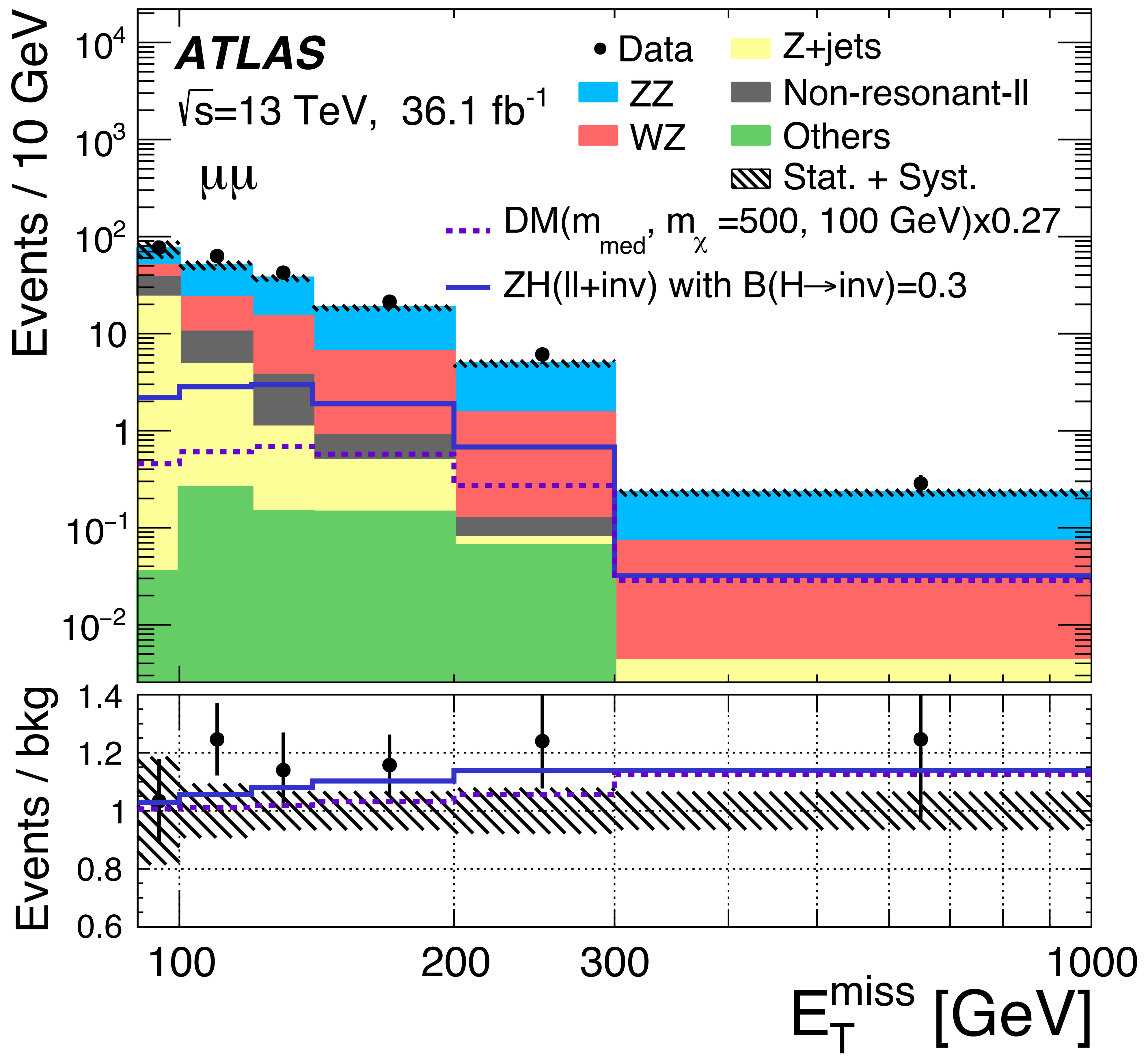






H(125)→invisible decays

- Searches performed using ggF, VBF, and VH production
  - current best limit on **$\mathcal{B}$(H→inv.) = 24%** from CMS Run I + 2015 combination (JHEP 02 (2017) 135)
  - searches under update with the full 2016 dataset
- Search for a signal as an enhancement in the E_T^{miss} distribution
- New ATLAS search with full 2016 dataset using ZH, $Z\to\ell\ell$
- Main backgrounds
  - VV, from simulation with data-driven correction
  - Z+jets, data-driven
- Sensitivity improved by 40% w.r.t. Run I results in the same channel

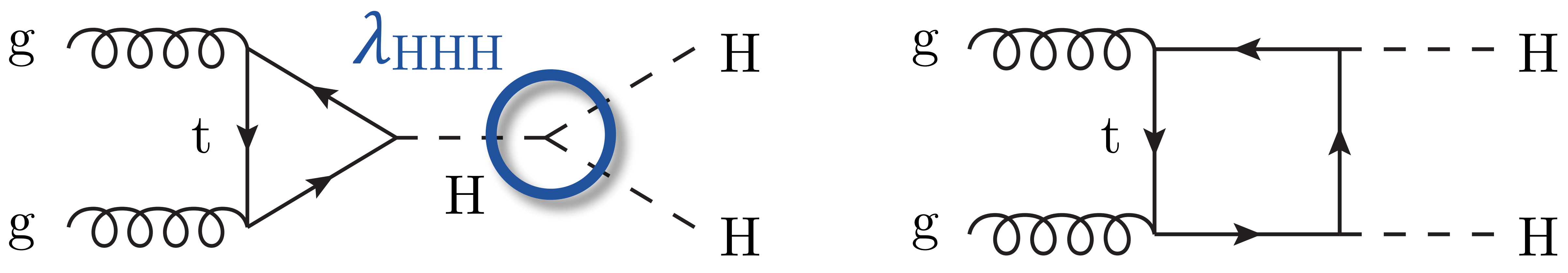


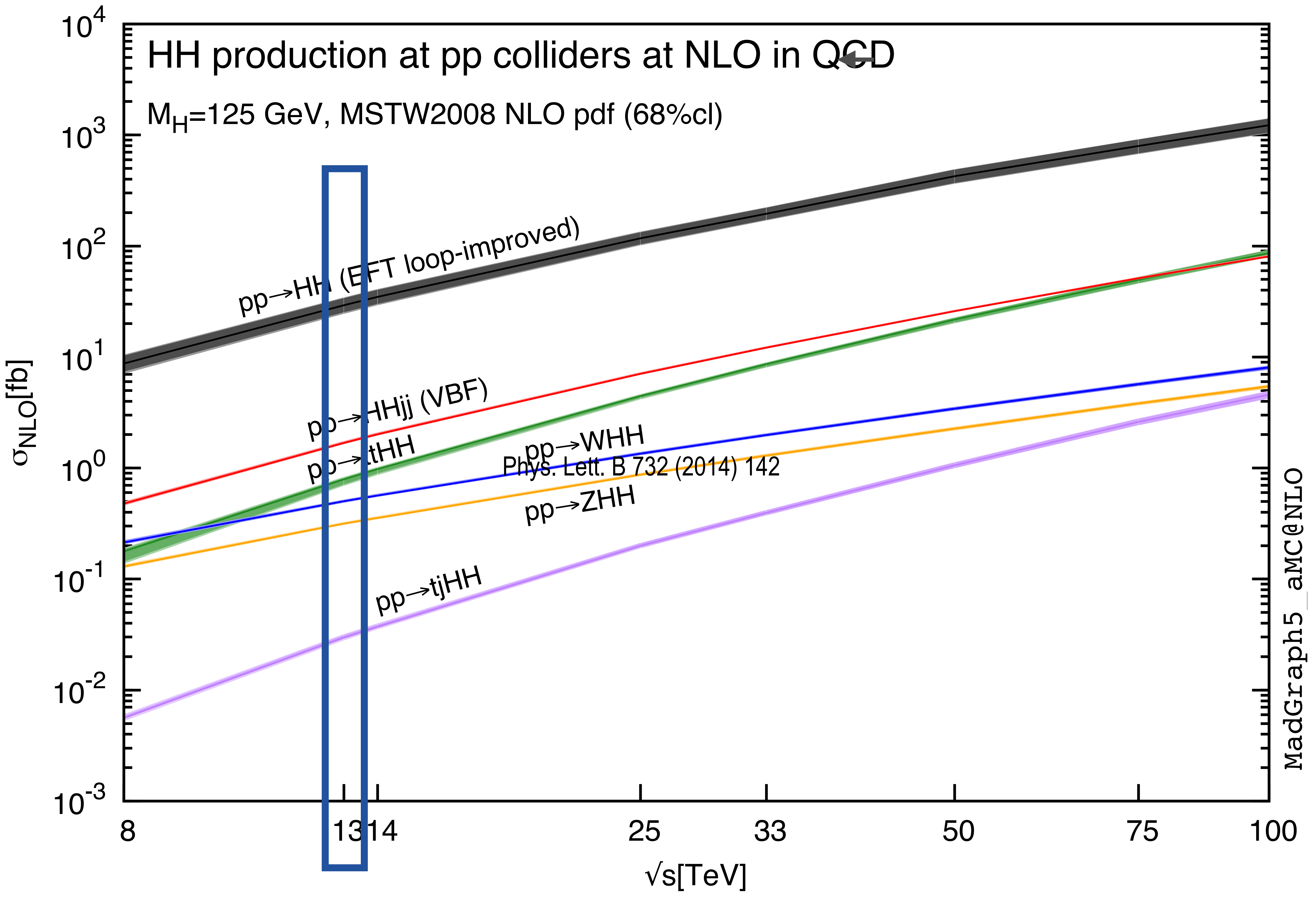
Obs. (exp.) : $\mathcal{B}$ (H→inv.) < 67% (39%)

HH in the SM

$$\sigma^{\rm SM}_{\rm HH} = 33.49^{+7.3\%}_{-8.4\%}\ \text{fb}\,(\text{scale} \oplus \text{PDF} \oplus \alpha_S \oplus m_t)$$

NNLO + NNLL with top quark mass effects at NLO





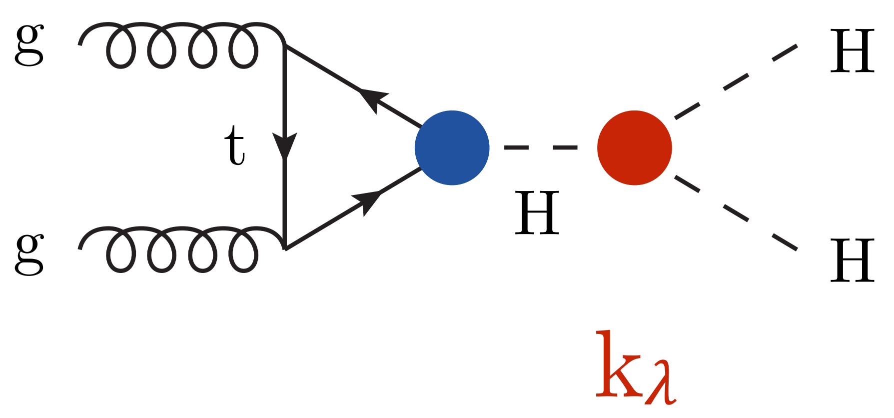
HH production ⟹ direct determination of Higgs trilinear coupling λ_{HHH}

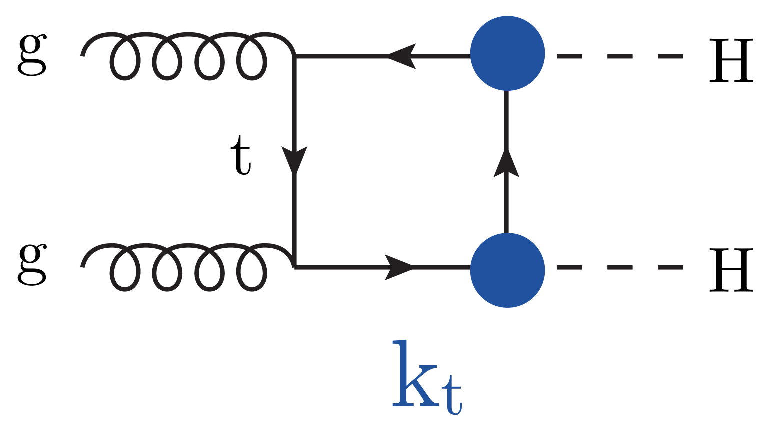
- **Gluon fusion**: dominant production mode
- Large destructive interference ⟹ tiny cross section
  - not sensitive to SM prediction with current data

HH beyond the SM

Two production mechanisms:

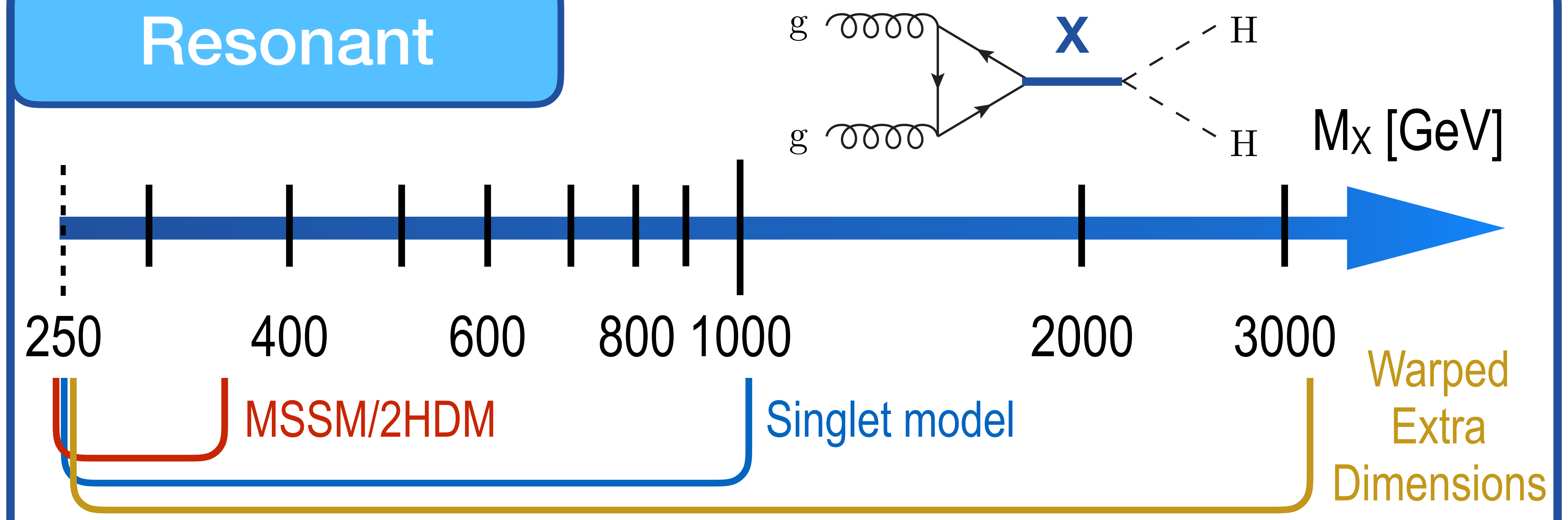
Nonresonant





- Anomalous Higgs boson couplings
  - strong effects on cross-section and shapes
  - described with EFT approach

Resonant



- Several BSM models accessible with the same signature
  - model-independent searches + interpretation
- Need to cover a broad m_X range
  - complementarity of several channels

HH is an ideal place to look for BSM physics
Sensitive with current LHC data

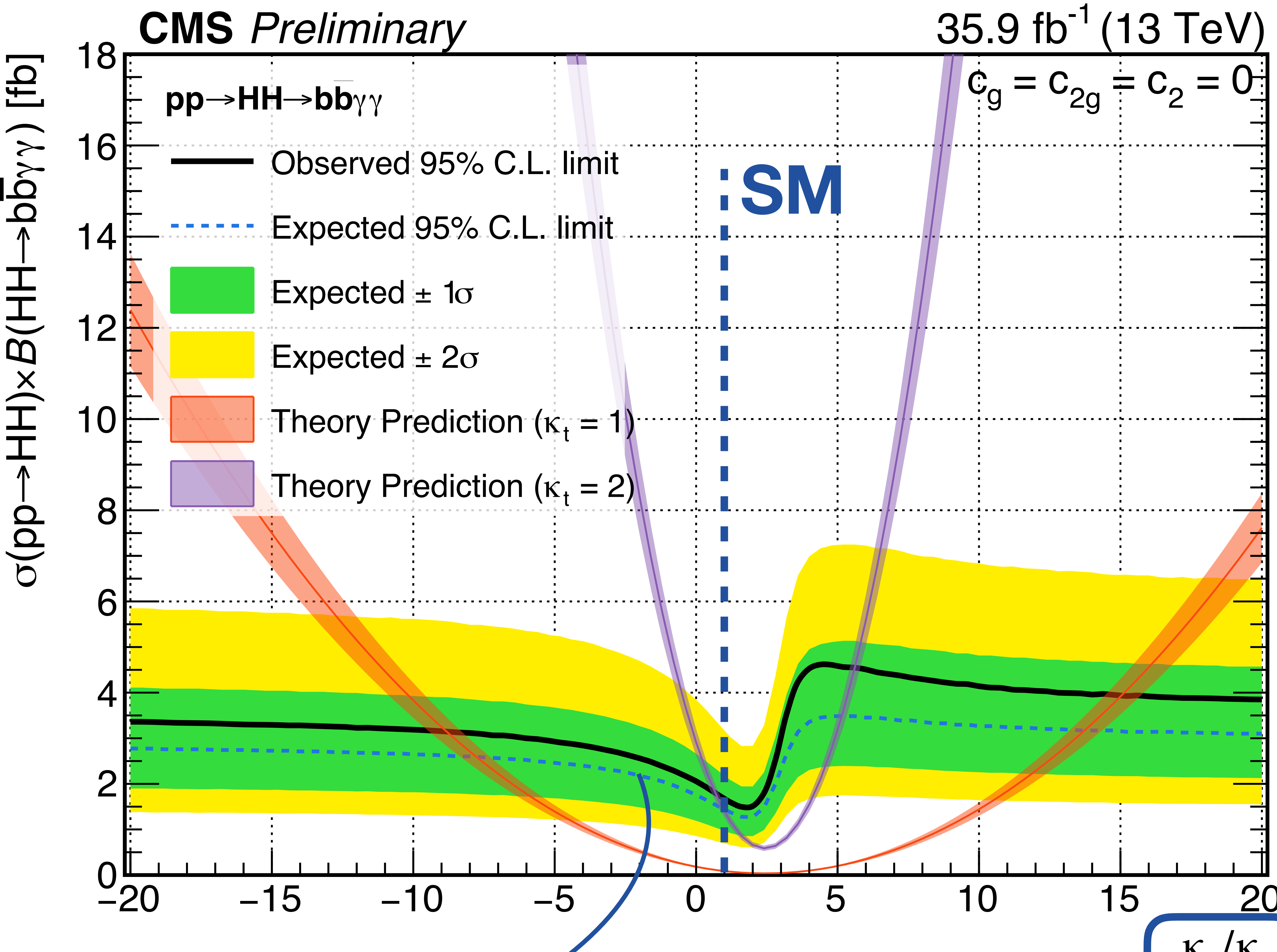
An example: HH→bb$\gamma\gamma$

Nonresonant

- Focus on the CMS result (full 2016 dataset)
  - search also performed by ATLAS with 2015 dataset
- Rare but clean final state
  - main background from continuum jj$\gamma\gamma$ estimated from data
- Use excellent $m_{\gamma\gamma}$ resolution + m_{bb} signature to look for a signal
  - categories based on m_{HH} and the number of b-tagged jets to increase the sensitivity
  - regression of m_{bb} with multivariate method
  - fit in the ($m_{\gamma\gamma}$, m_{bb}) 2D plane

Obs (exp) : 18 (17) × σ_{HH}^{SM}

Constrains anomalous couplings



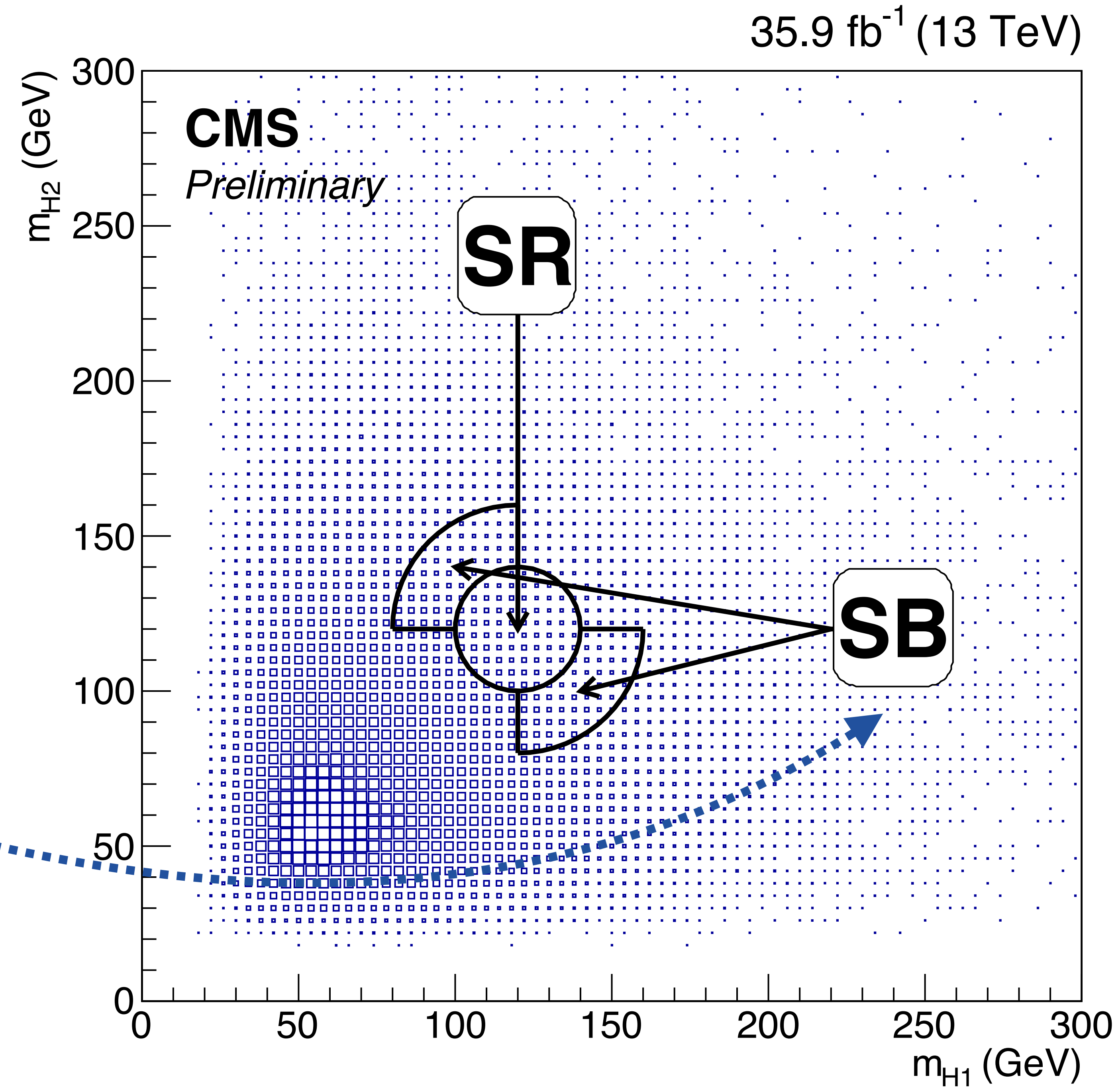
Changes in the signal kinematics (from interference) affect the upper limit

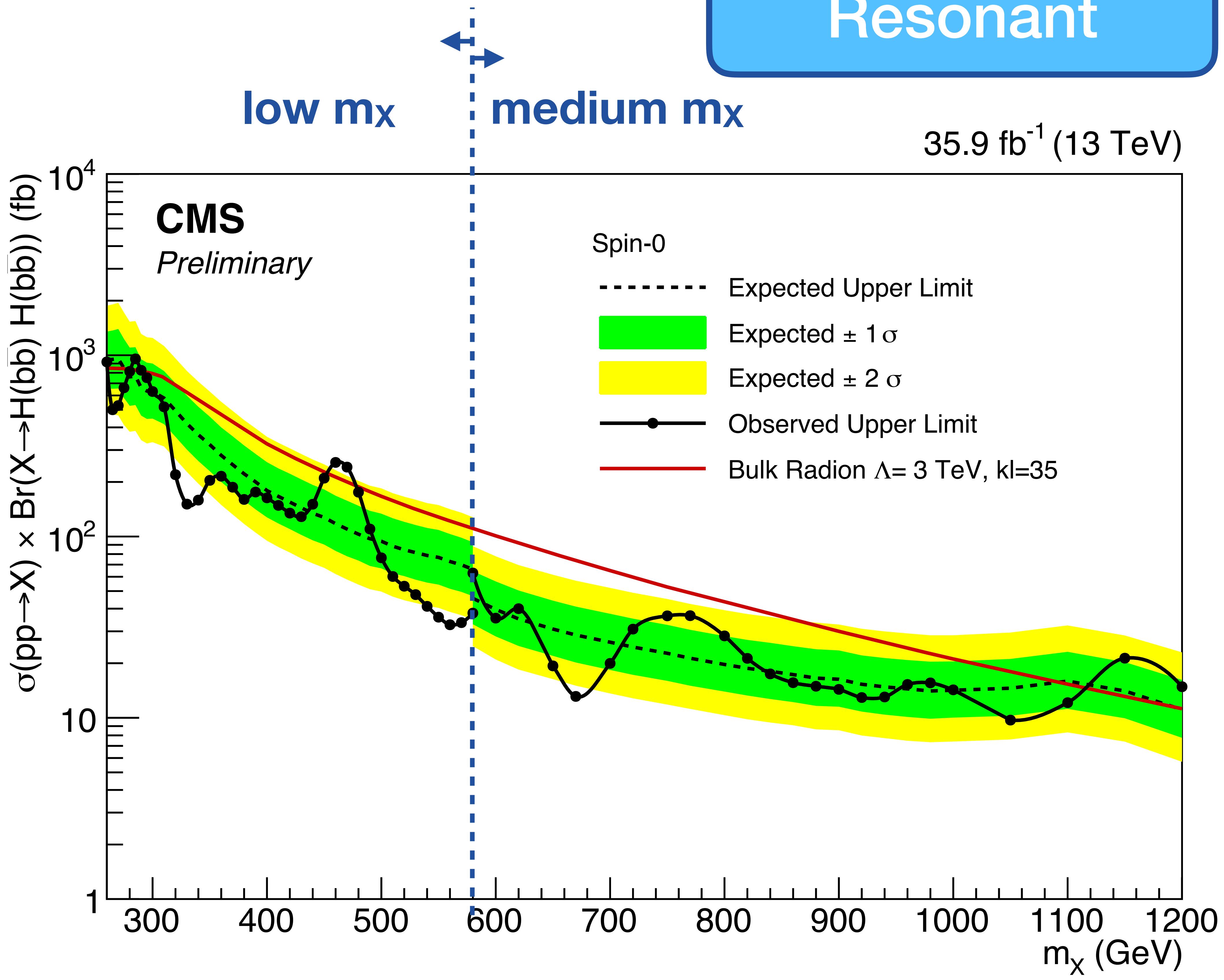
Anomalous λ_{HHH} and y_t couplings

An example: HH→bbbb

Resonant

- Focus on the CMS result (full 2016 dataset)
  - search also performed by ATLAS with first half of 2016 dataset
- High BR, but large background from QCD mutlijet
  - data-driven estimation
- Use m_{bb} to define the signal region, and m_{bbbb} to look for a signal
  - kinematic fit to improve the resolution





Boosted jet topologies also used in a separate analysis to extend the search to m_X ~ 3 TeV

Results summary

ATLAS EXPERIMENT CMS

Nonresonant

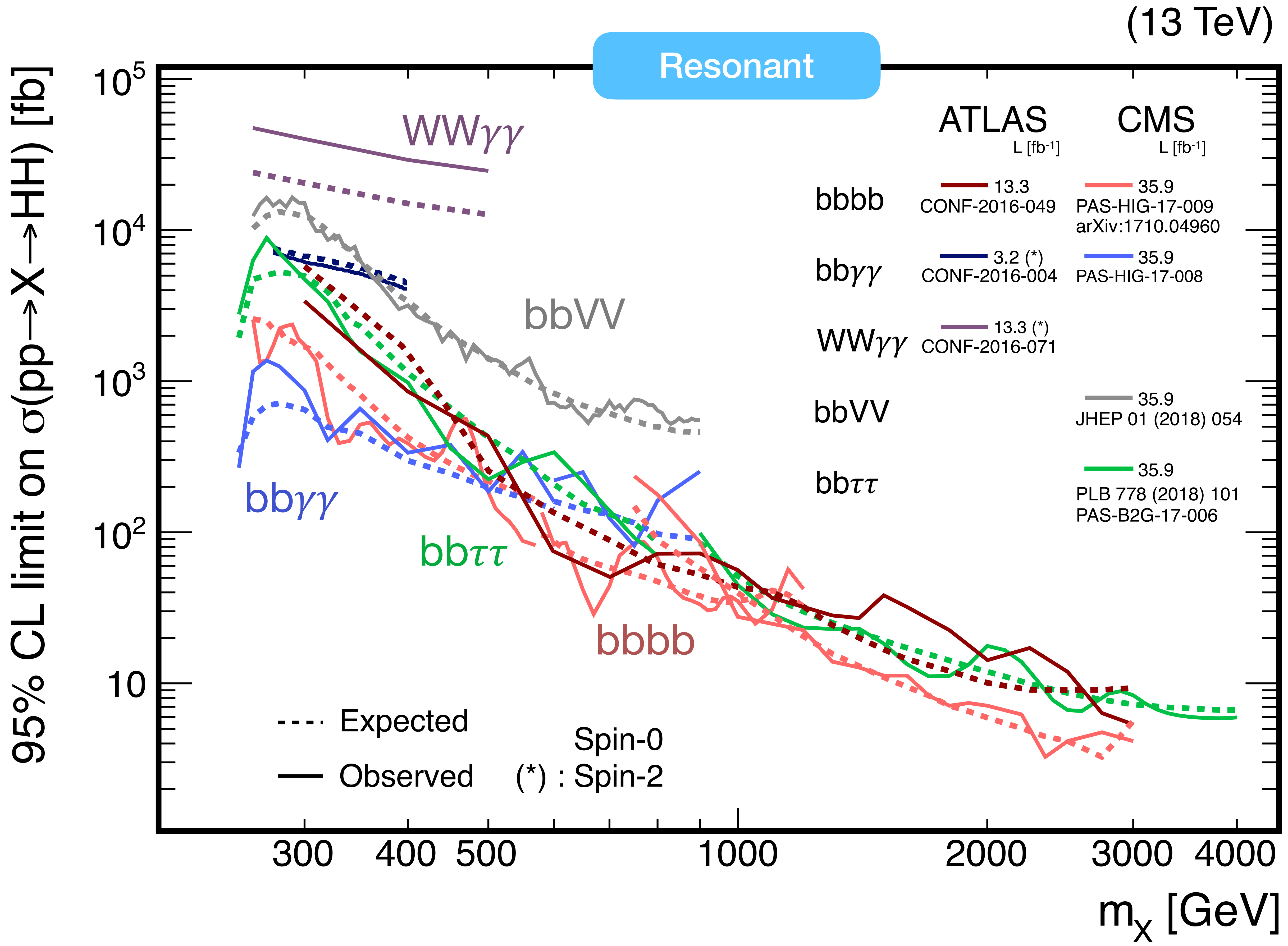
Chan.	Obs. (exp.) 95% C.L. limit on σ/σ_{SM} ATLAS	CMS
bbbb	29 (38)	342 (308)
bbVV	-	79 (89) ⊡
$bb\tau\tau$	-	31 (25) ⊡
$bb\gamma\gamma$	117 (161)	18 (17) ⊡
$WW\gamma\gamma$	747 (386)	-

2.3-3.2 fb^{-1}

13.3 fb^{-1}

35.9 fb^{-1}

⊡ : Test of anomalous HH couplings



- Five channels currently explored
  - common techniques and channel-specific challenges
  - complementarity ⟹ benefit of a **combination**!

Conclusions

An intensive programme of exploration of the scalar sector is ongoing at the LHC

1) Precise characterisation of the Higgs boson properties
   - m_H known at 0.18% precision
2) Search for extensions of the scalar sector itself
   - heavy and light scalars, BSM H decays, $H^{\pm}$
3) Search for HH production
   - resonant and nonresonant

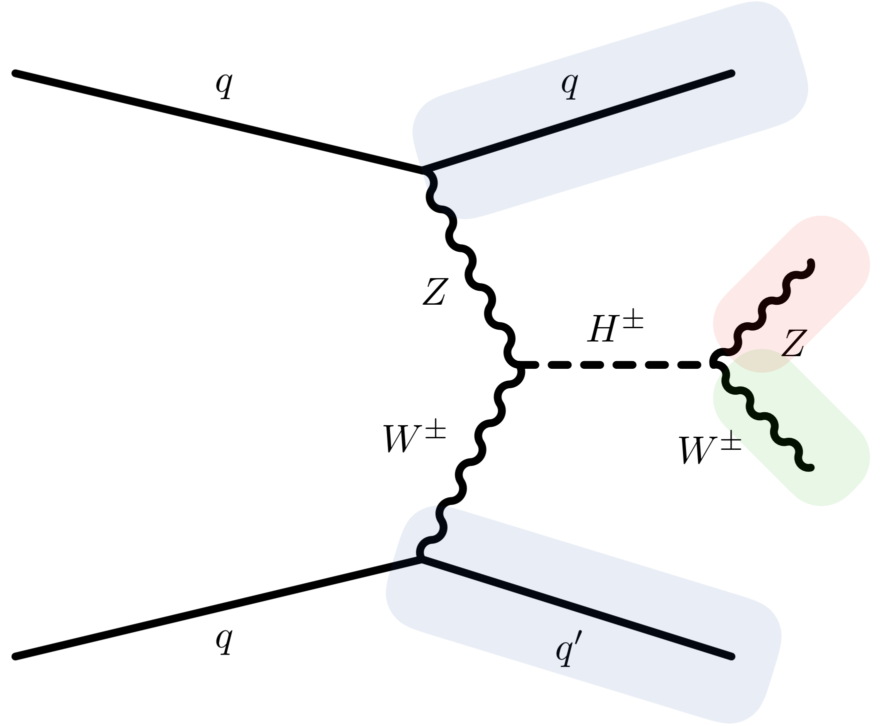
- Challenging experimental measurements giving rewarding physics results
  - many different signatures investigated
  - possible only thanks to the excellent performance of the ATLAS and CMS detectors
- This exciting exploration is continuing as more data are collected and analysed

Additional material

VBF $H^{\pm} \rightarrow WZ$

$H^{\pm}$ couplings to vector bosons in scalar sector extended with SU(2) triplets

$\Longrightarrow$ VBF production and decay to $W^{\pm}Z$

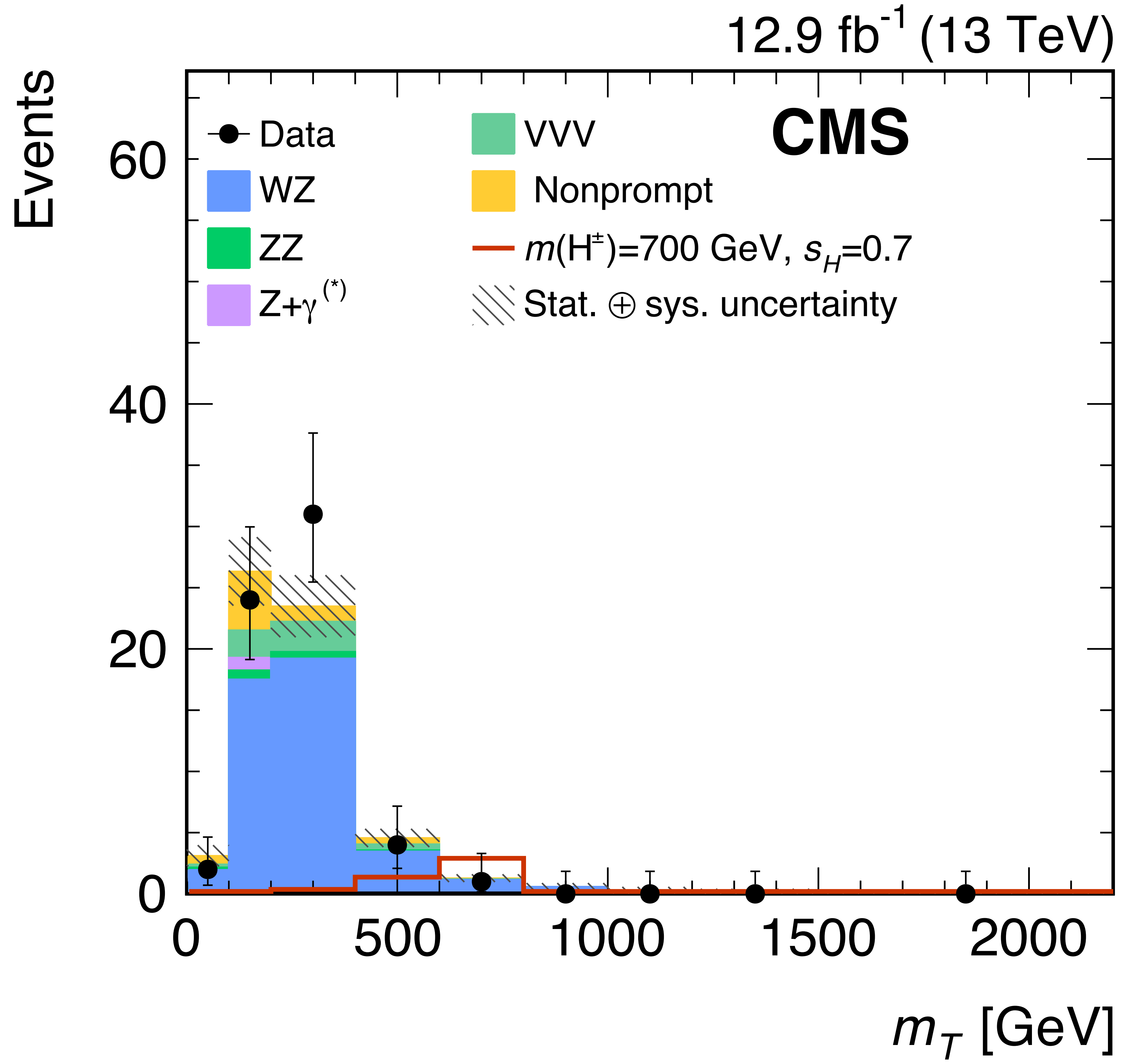


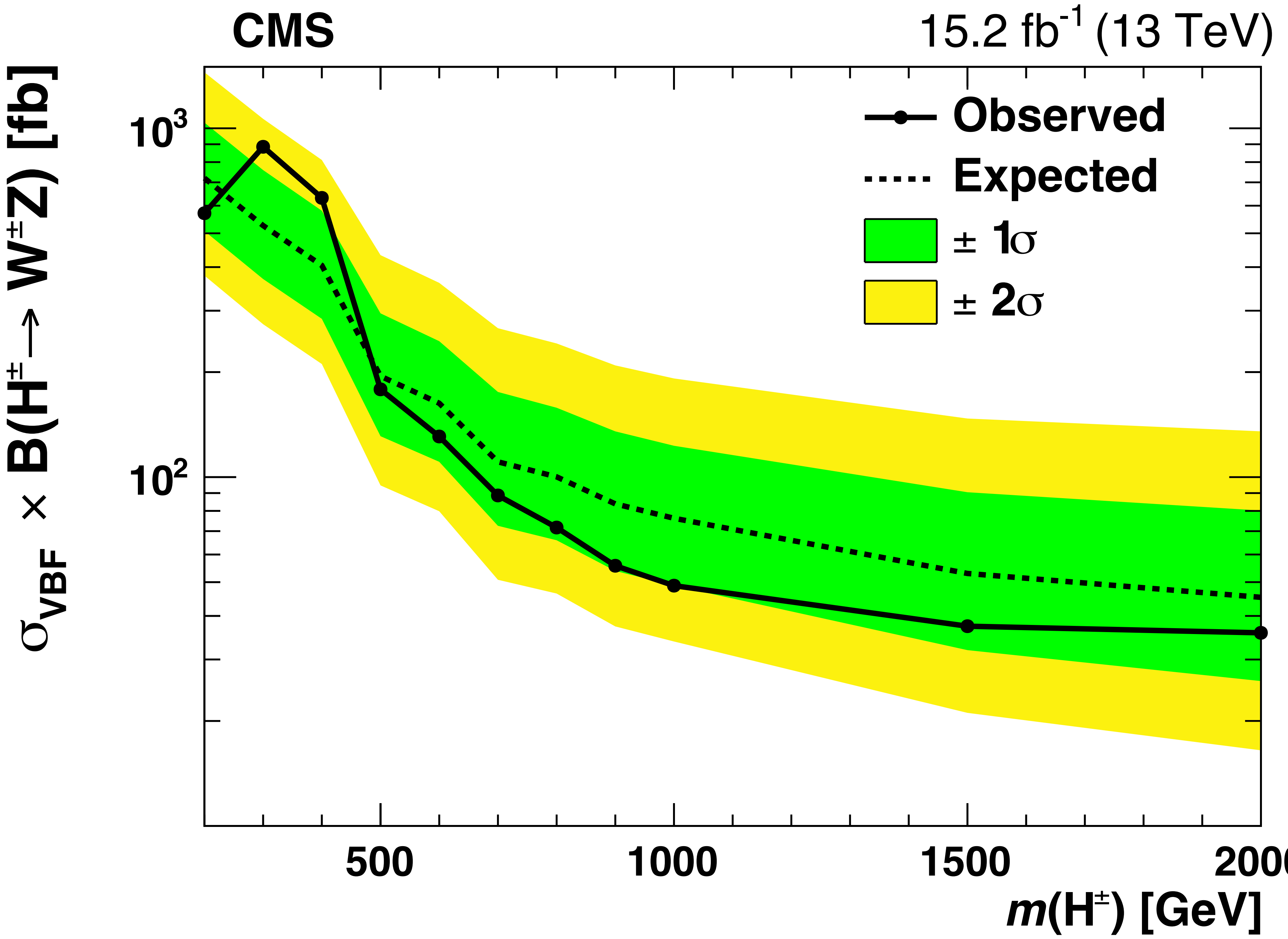
high m_{jj} and Δη jet pair

$\ell\ell$ pair at m_Z

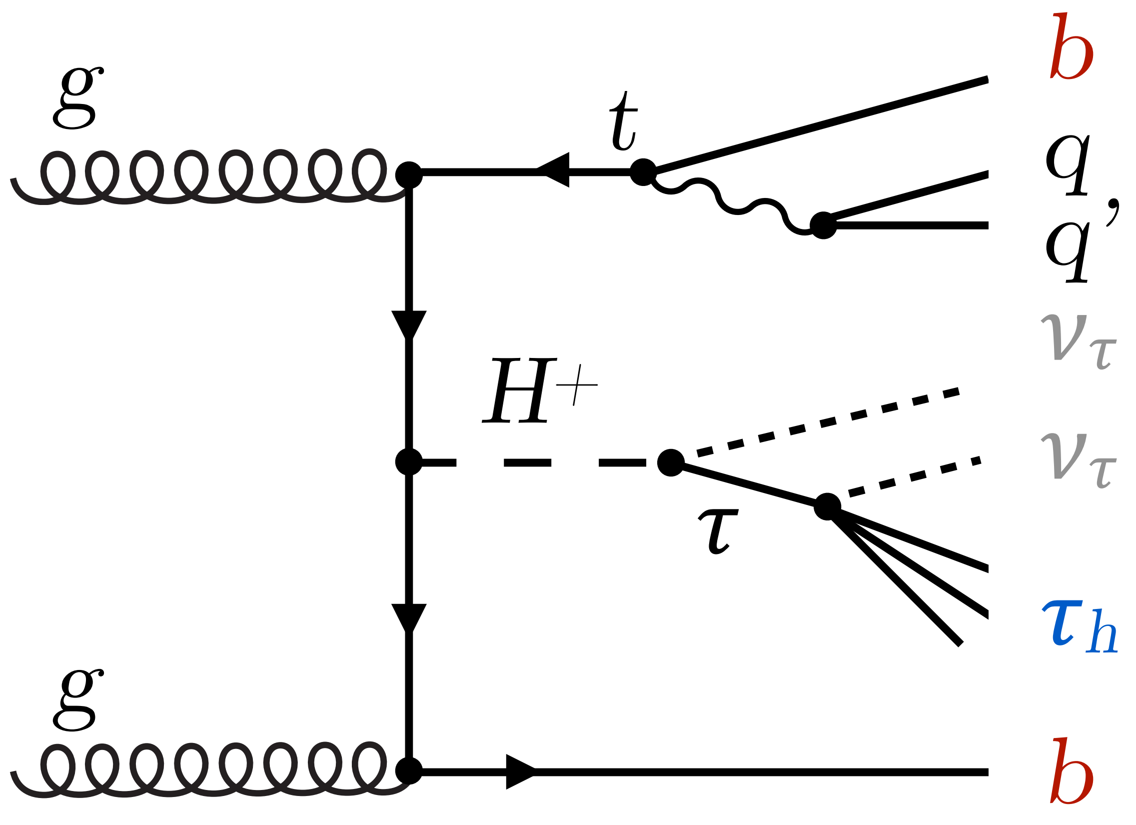
extra ℓ + p_T^{miss}

- Clean final state!
  - mostly WZ+jets background
  - normalised to data sideband
- Look for a signal in m_T(WZ)

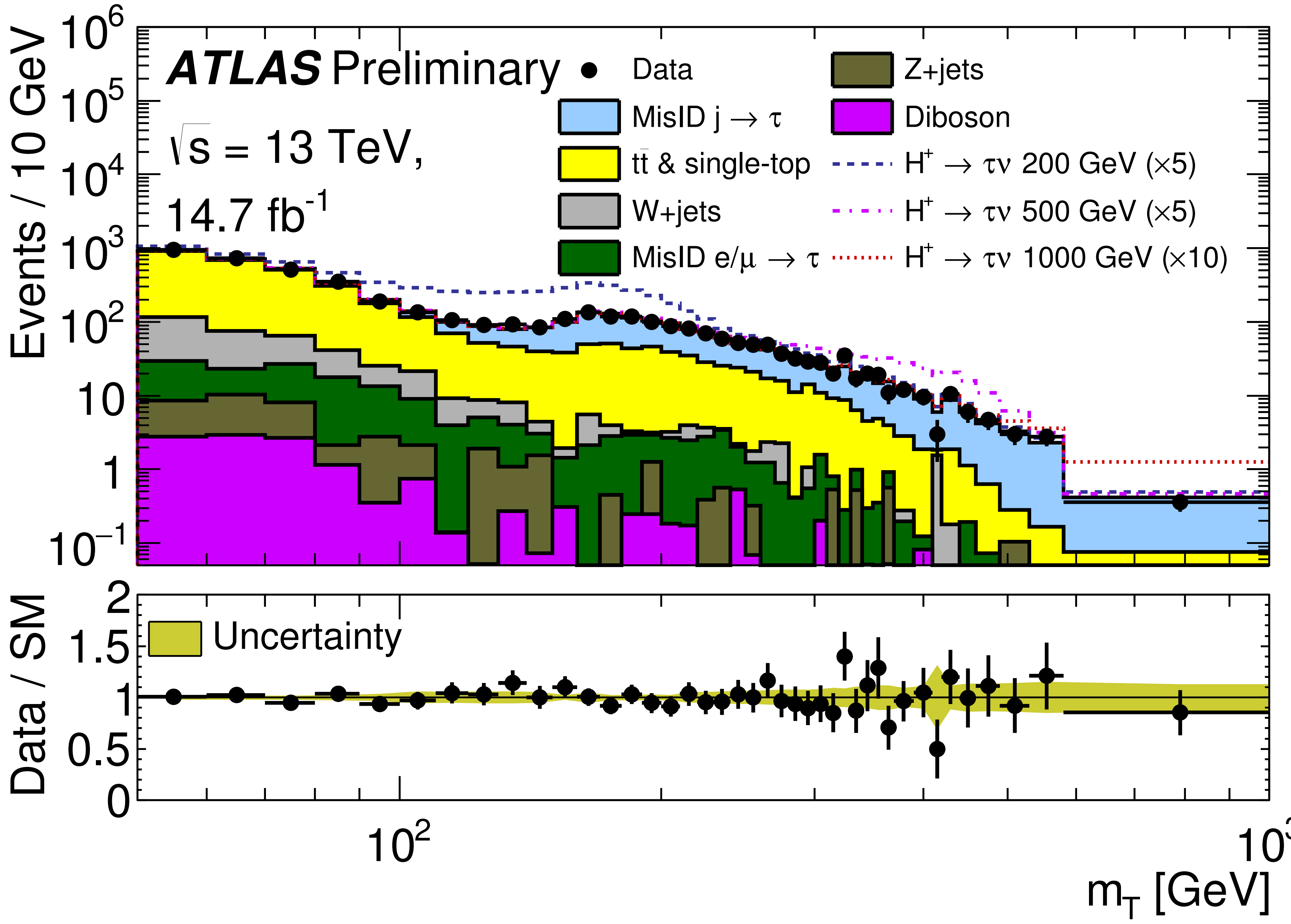


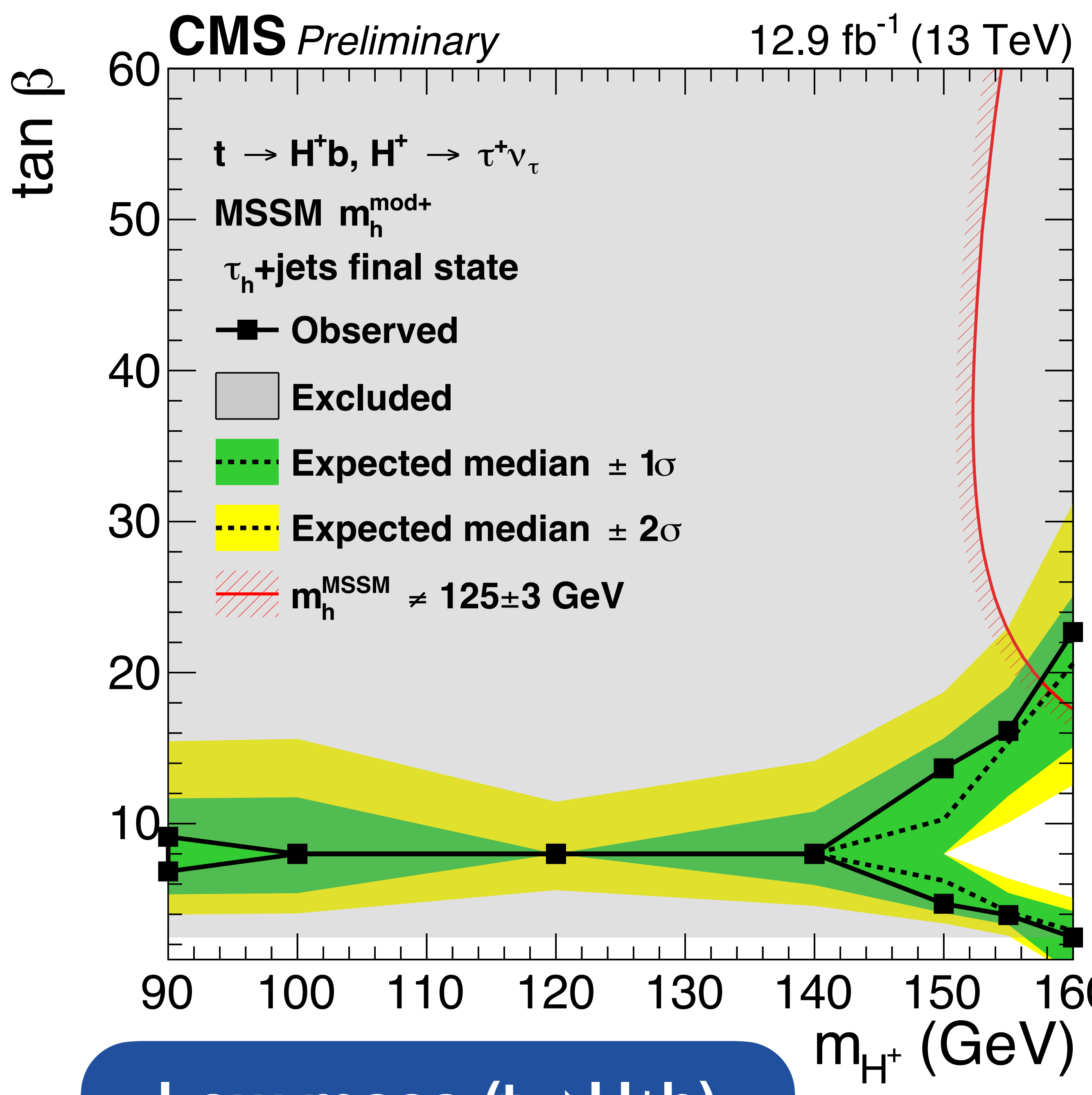


$H^{\pm} \rightarrow \tau\nu$

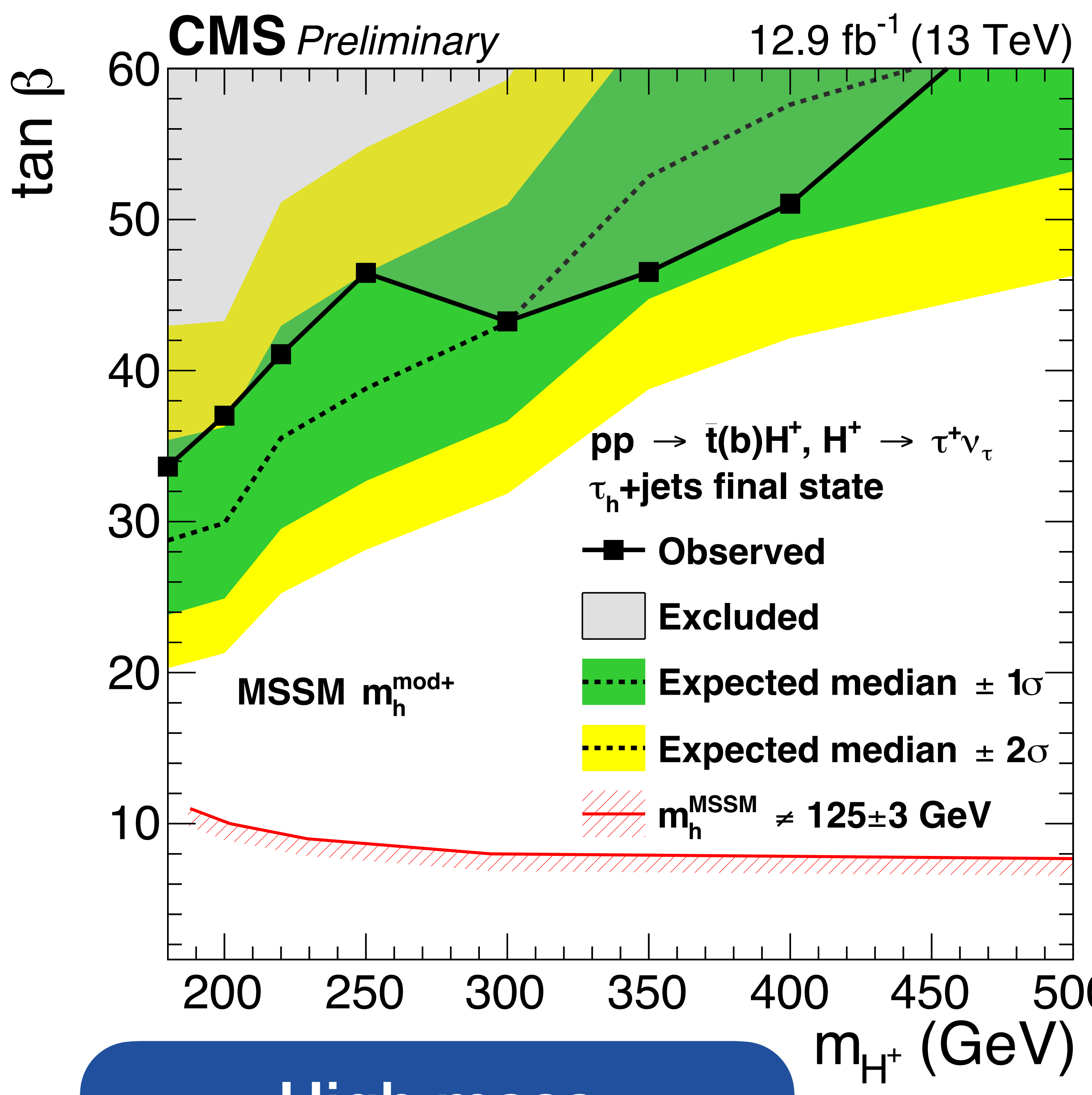


- Fully hadronic final state (2b, 2j, $1\tau_h$)
- main background: mulitjet with mis-ID τ_h (data-driven)
- Trigger: E_T^{miss} (ATLAS), single $\tau_h + E_T^{miss}$ (CMS)
- Use $m_T(\tau_h)$ to look for the presence of a signal





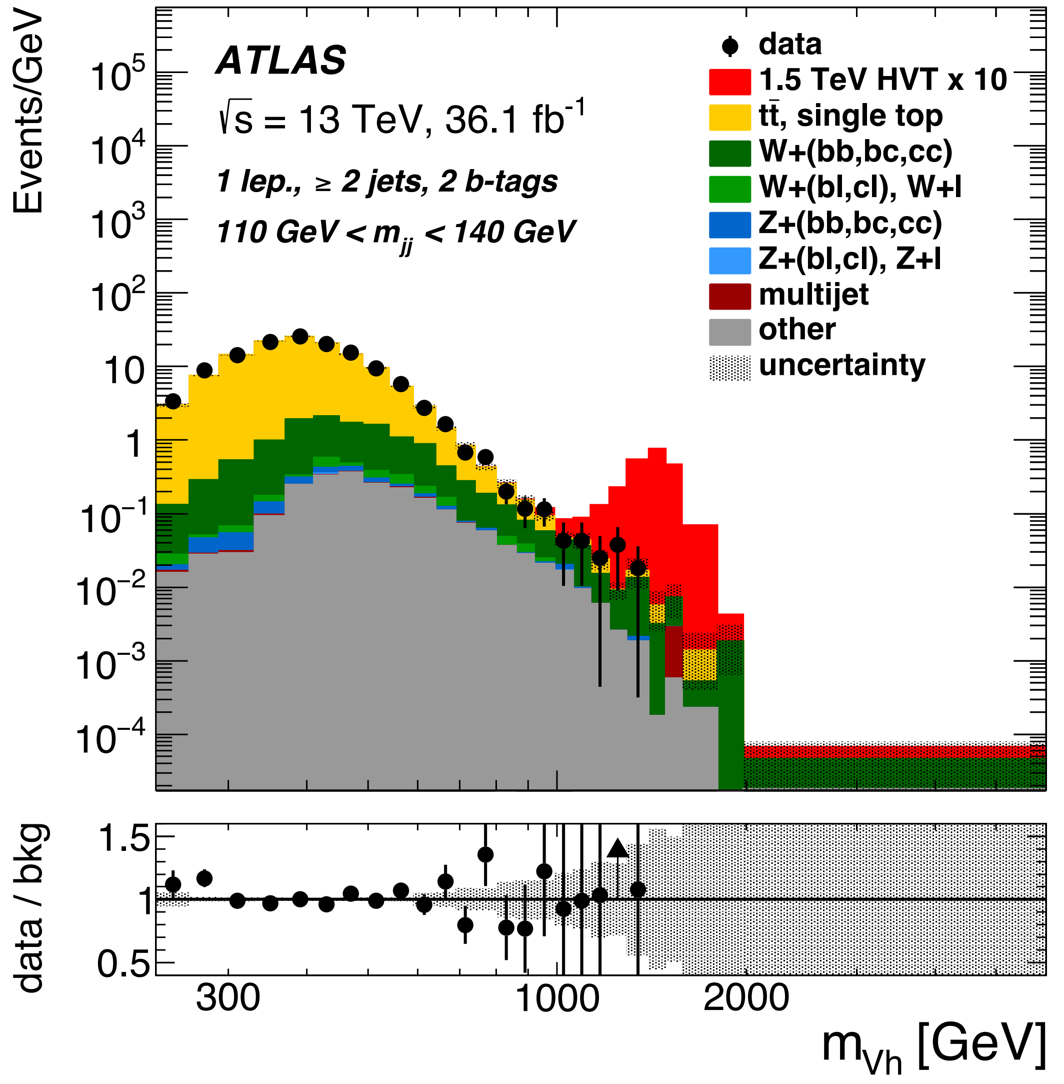
Low mass (t→H+b)

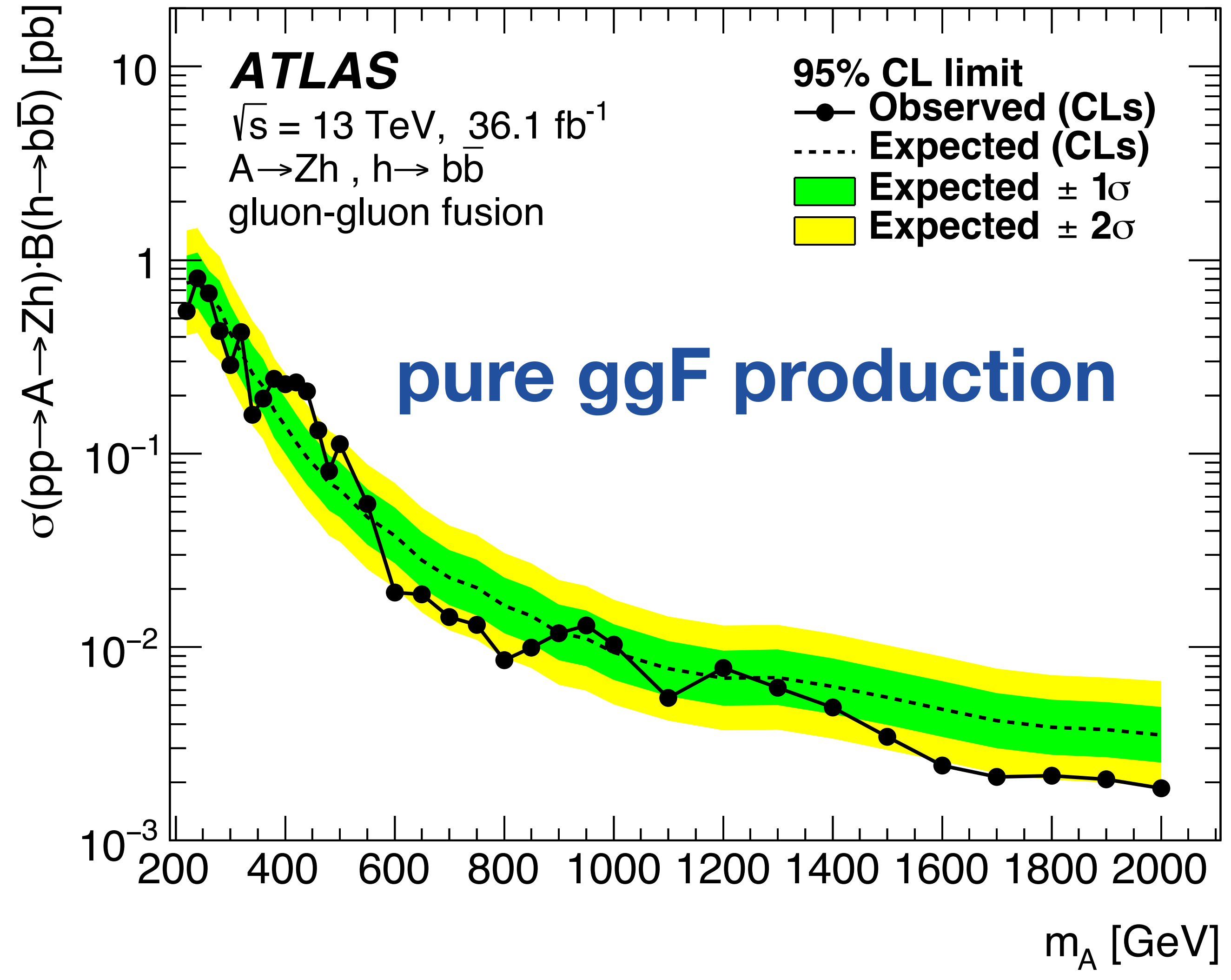


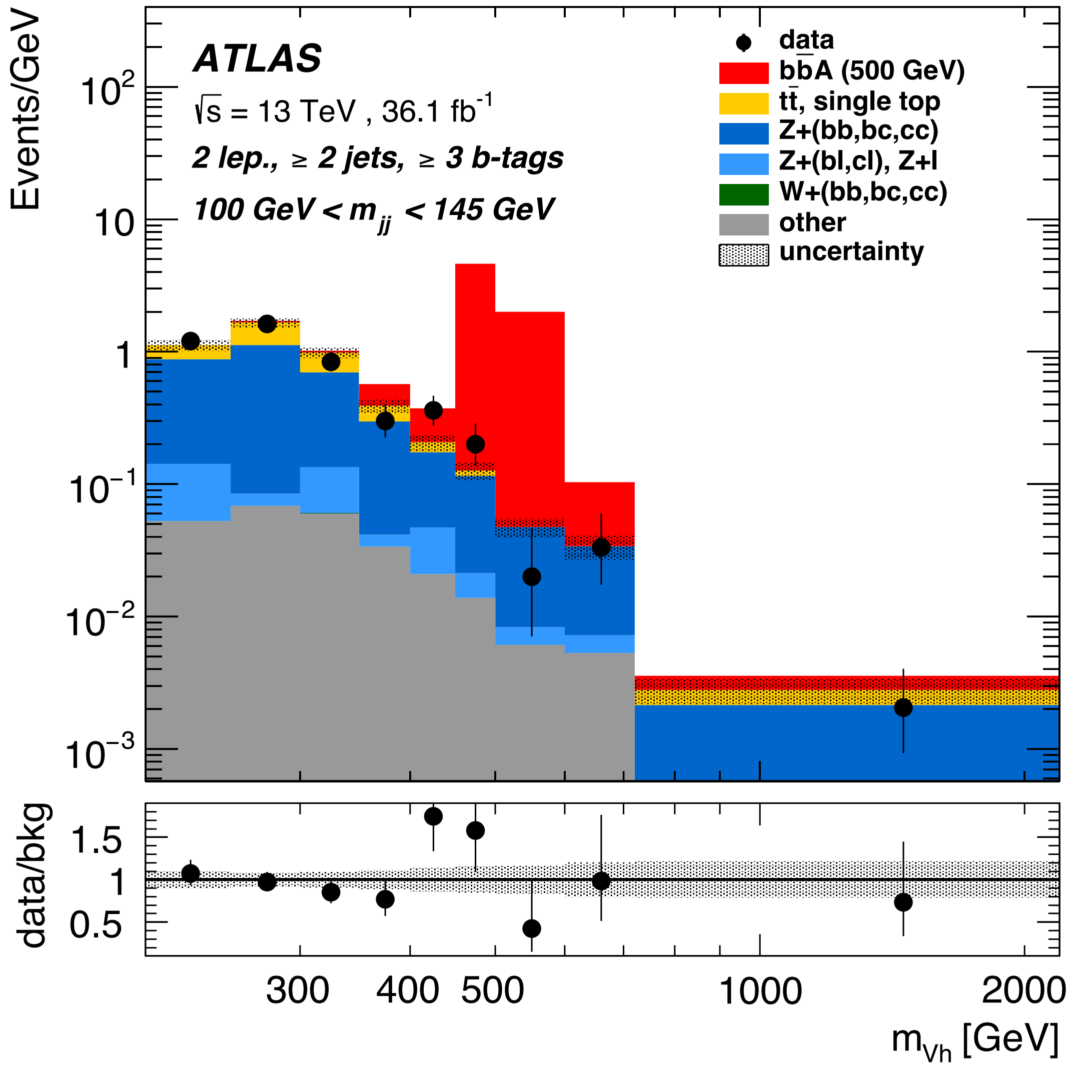
High mass

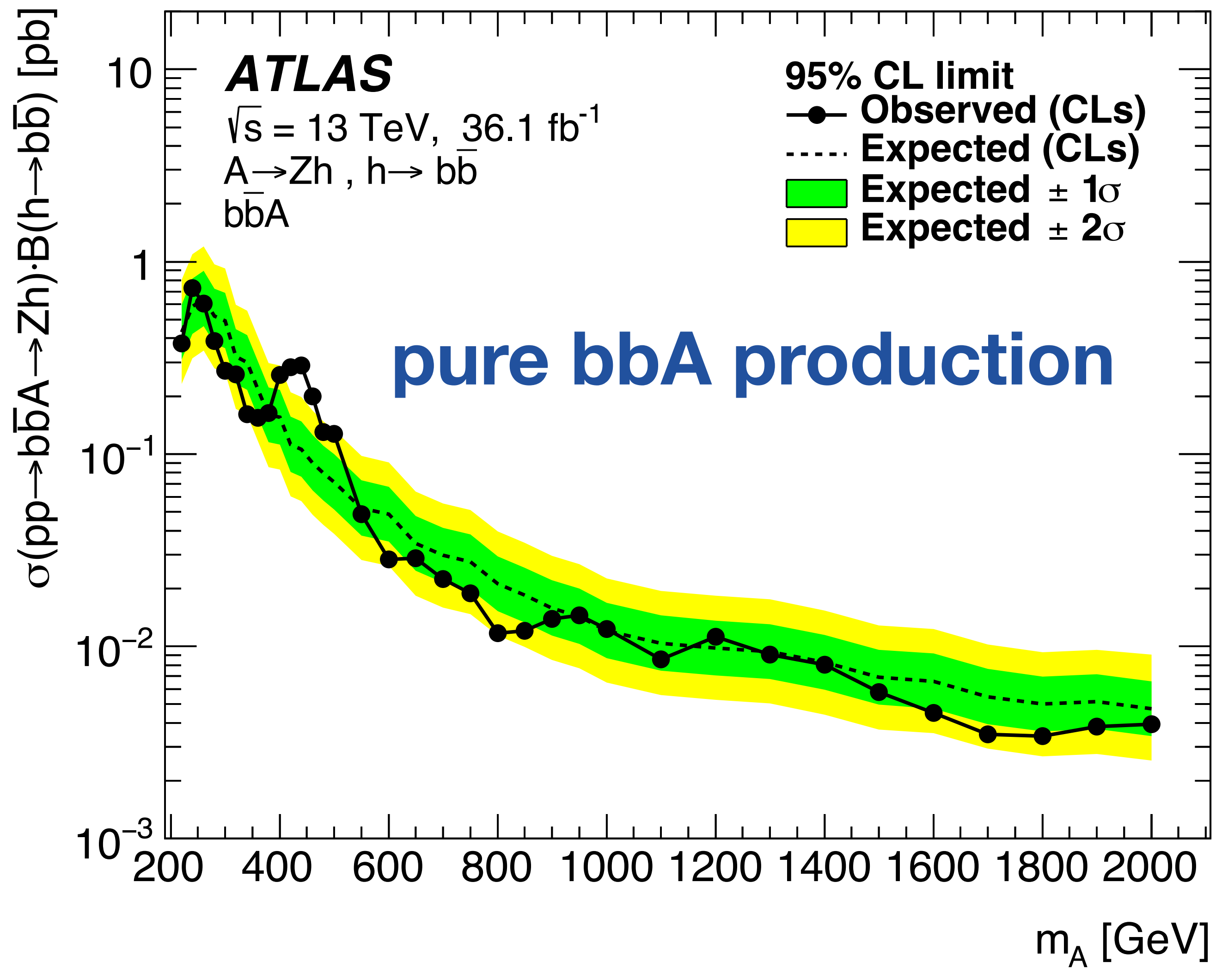
A→VH

- Search using the full 2015+2016 dataset
- H→bb, giving the final states $\ell\ell$ bb, $\nu\nu$ bb, $\ell\nu$ bb
- Target both ggF and bb associated production modes
- m_A from 220 GeV to 5 TeV
  - both resolved and boosted topologies depending on p_T(H)
- Categorisation on the number of tagged jets
  - 1, 2, ≥3 tagged jets
- Look for localised excesses over the background distribution
  - m_T (VH) for $\nu\nu$ bb
  - m_A for $\ell\ell$ bb, $\ell\nu$ bb (with W mass constraint)
- Results also interpreted in 2HDM models



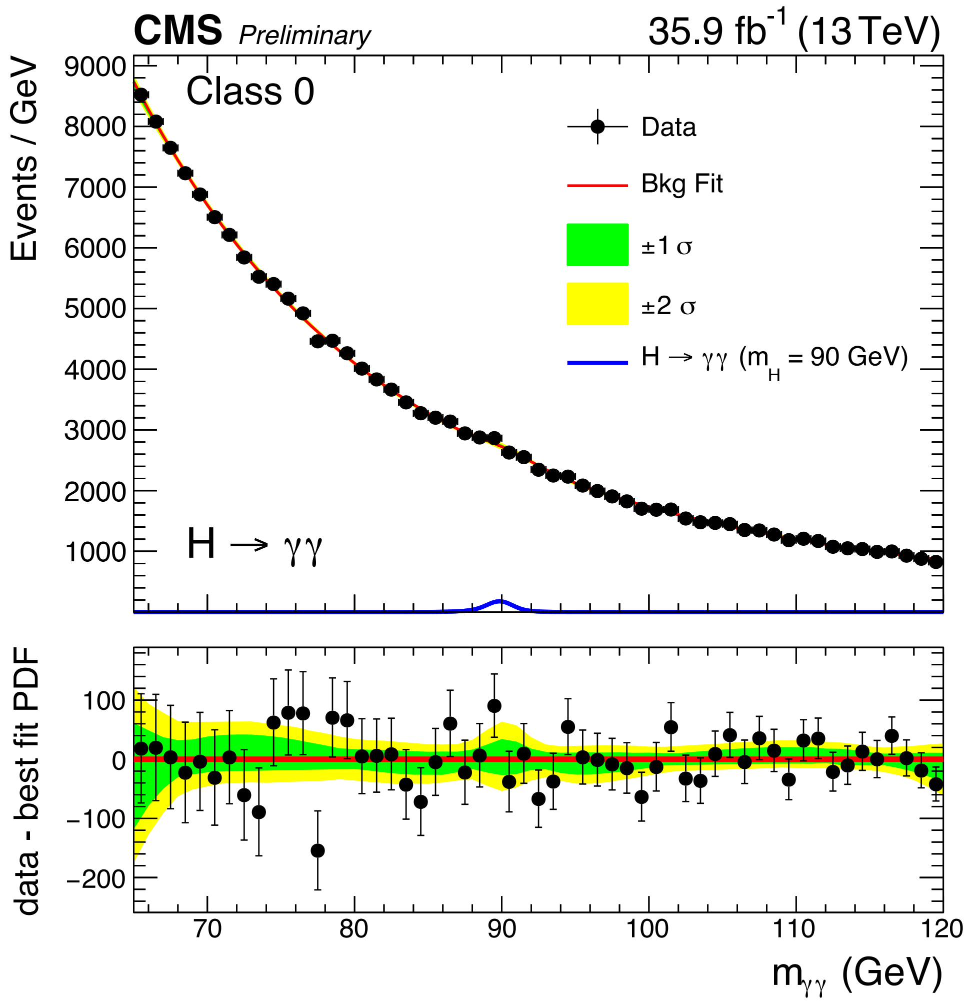


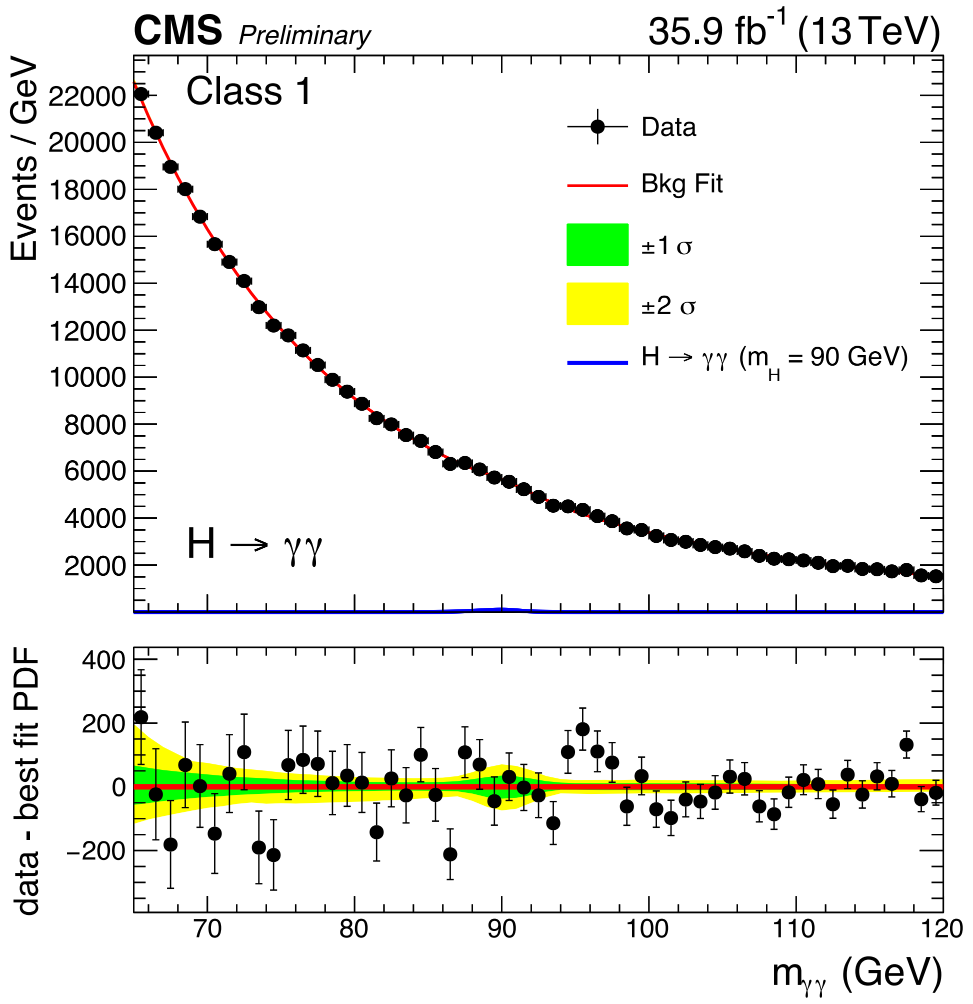


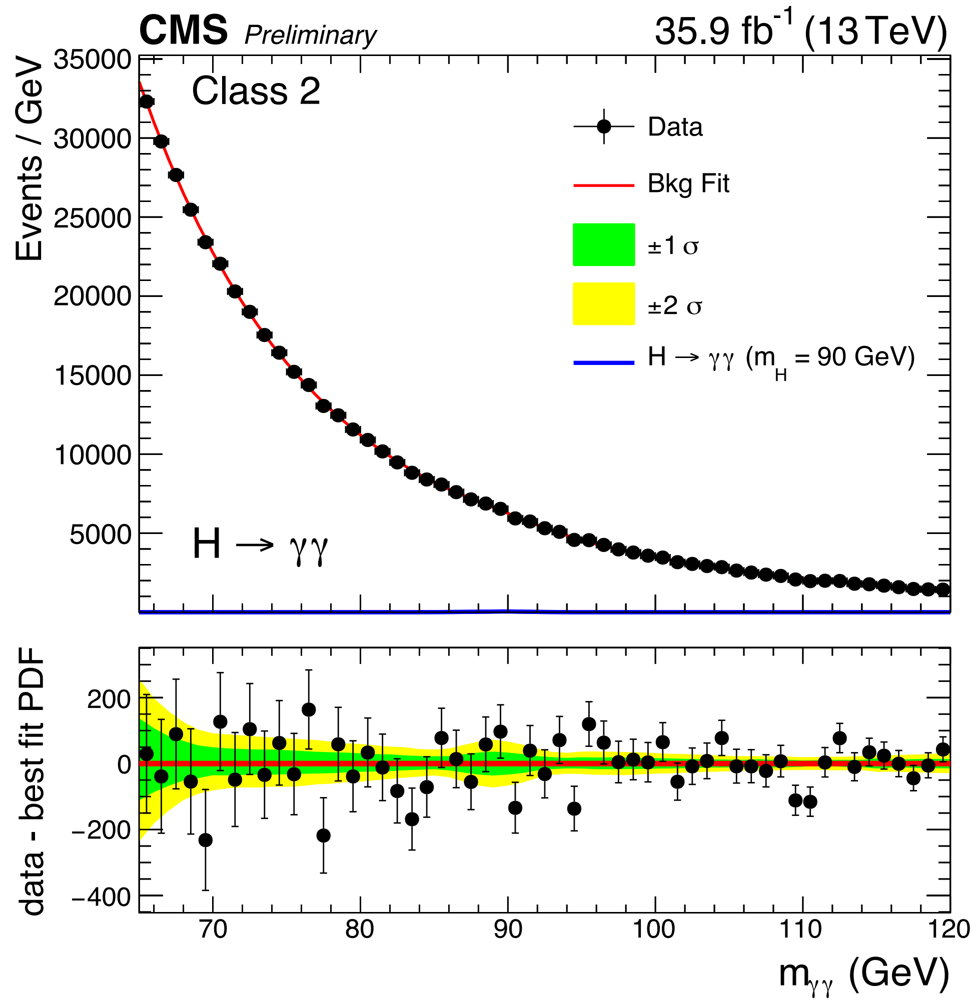


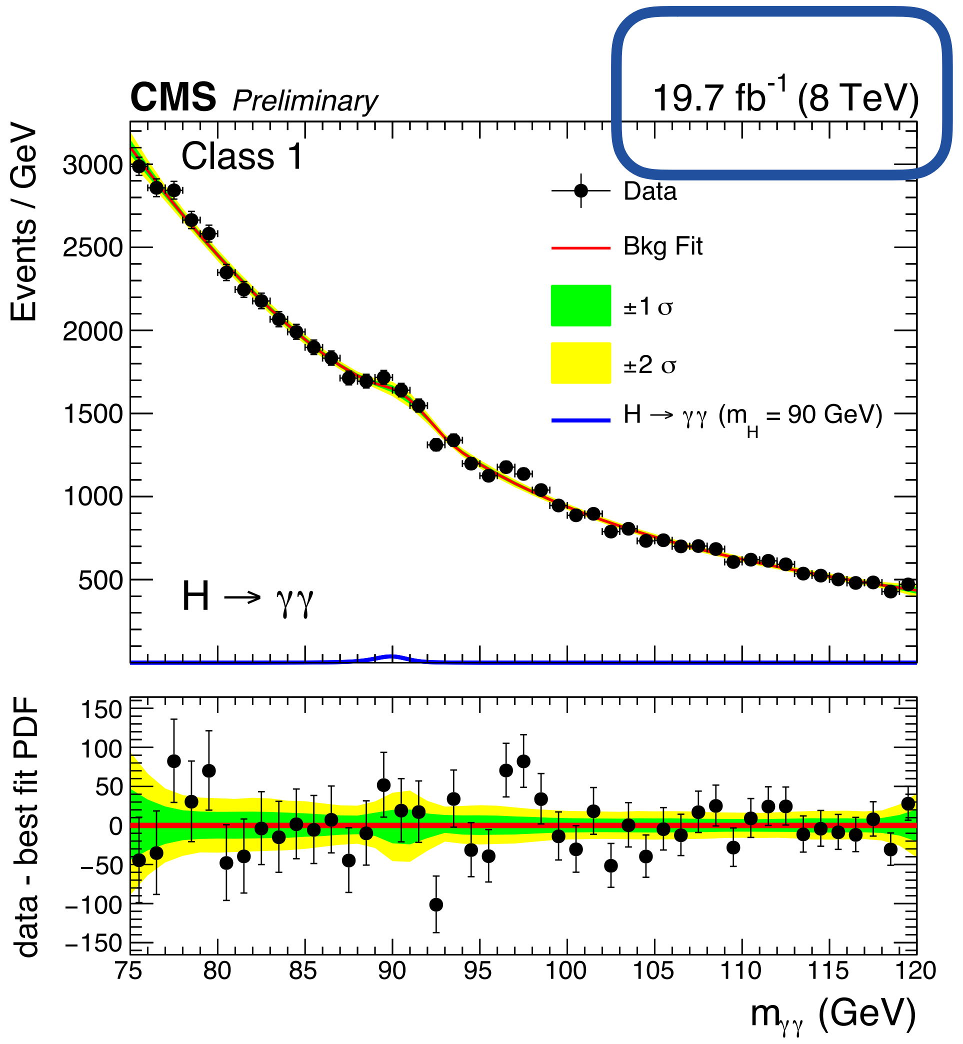
Light h′→γγ

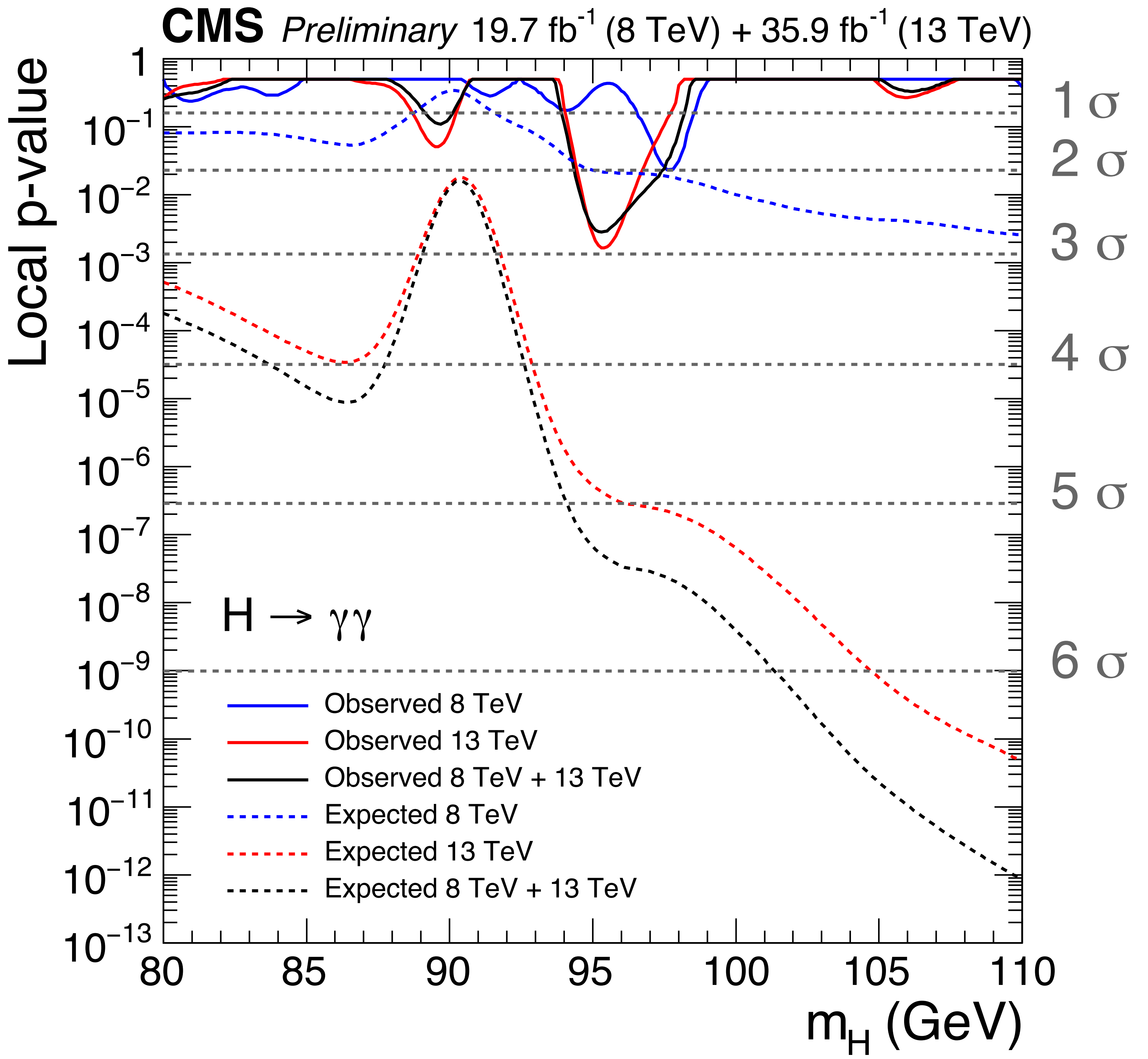
- Events are divided in 3 classes (4 for Run I data) of signal purities
  - P(0) > P(1) > P(2) > P(3)



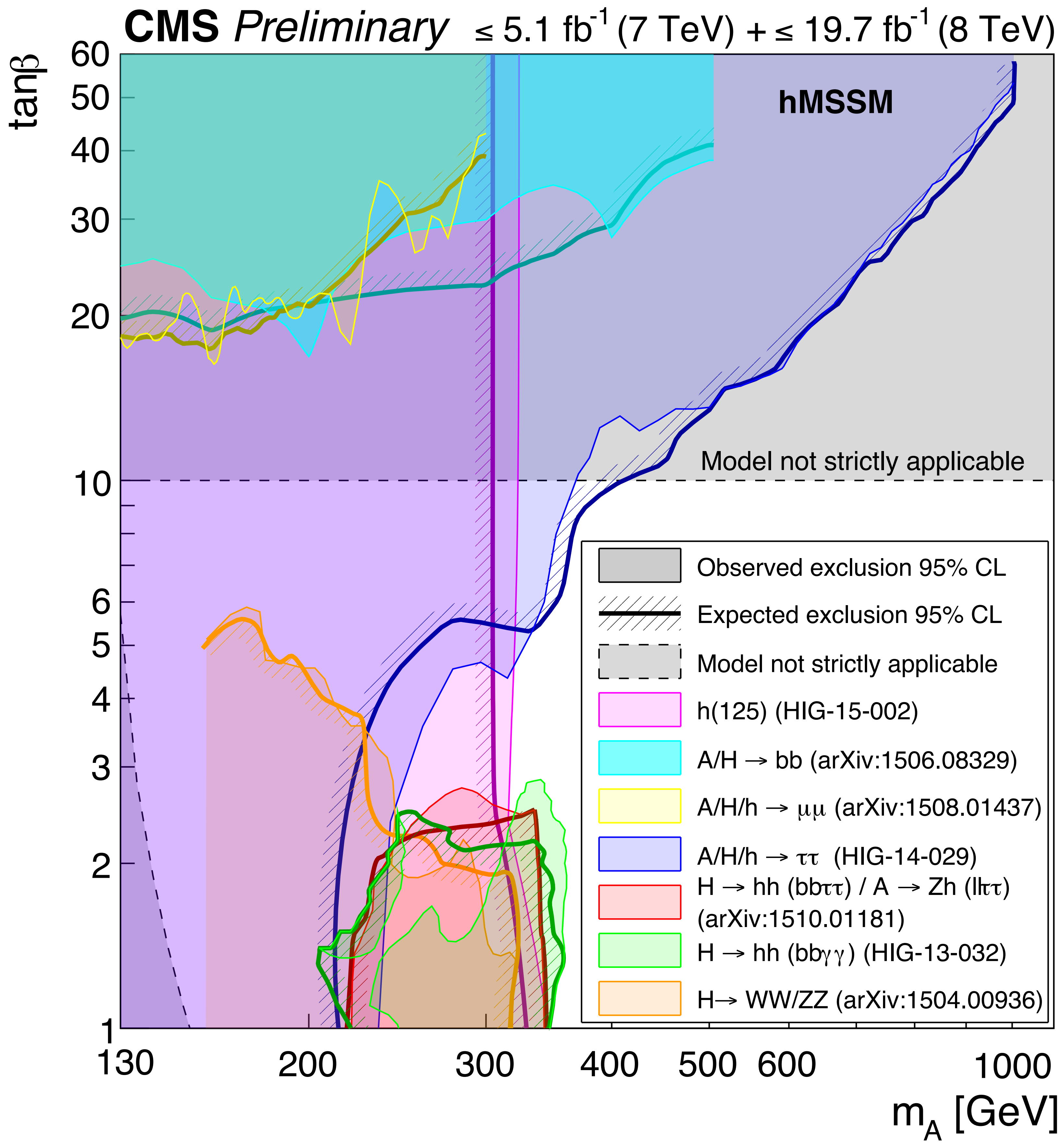


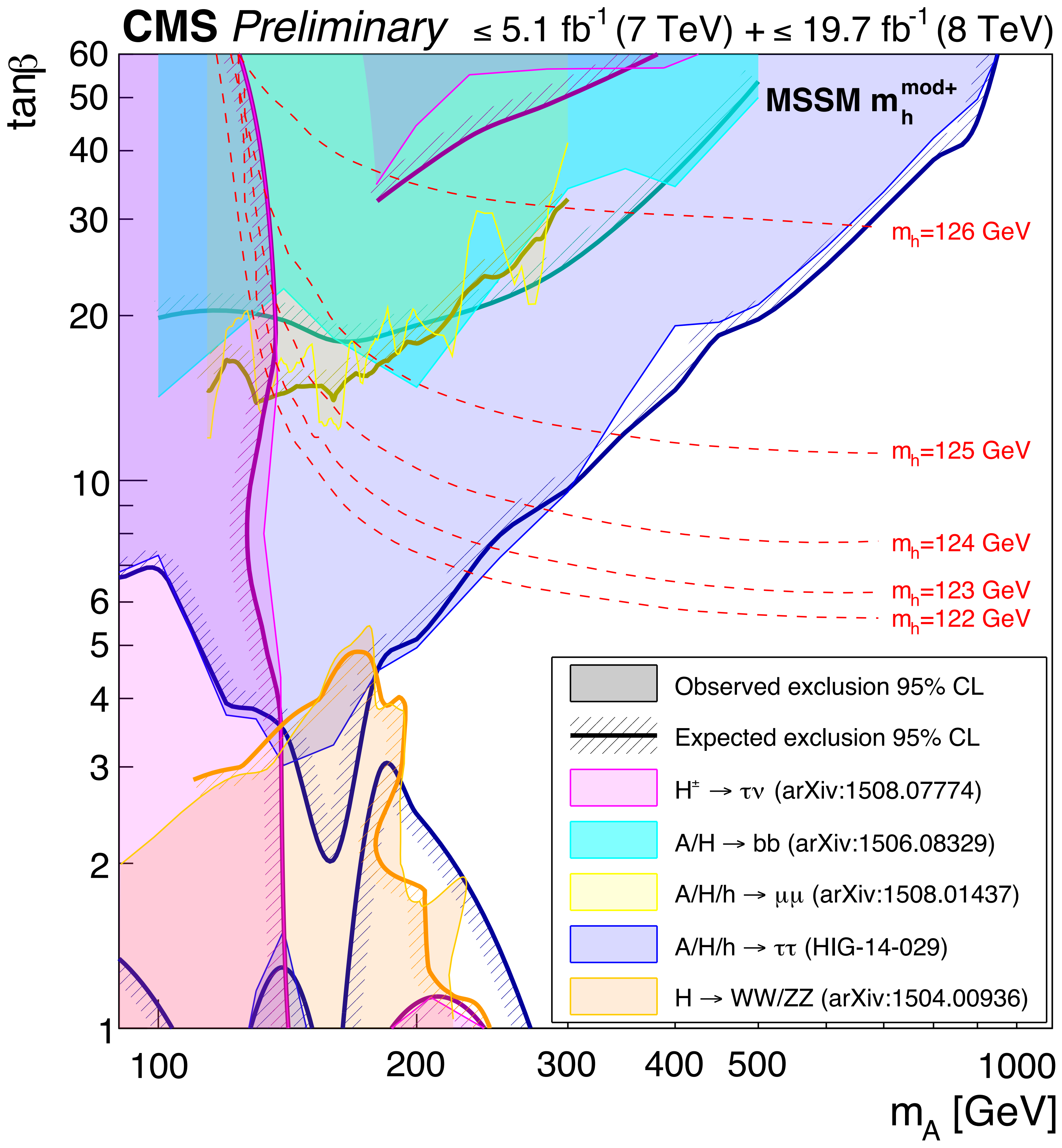






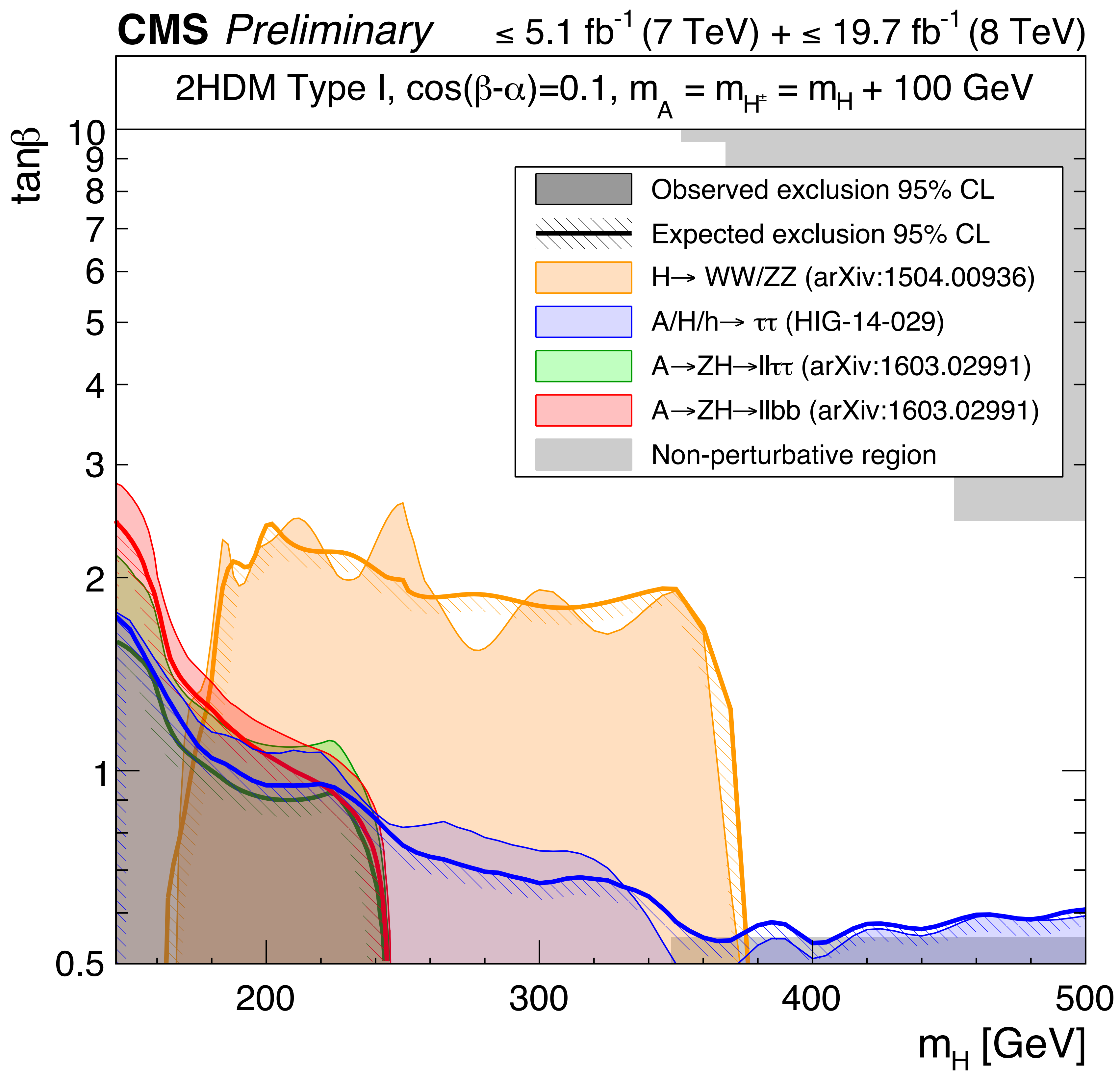
MSSM constraints - Run I

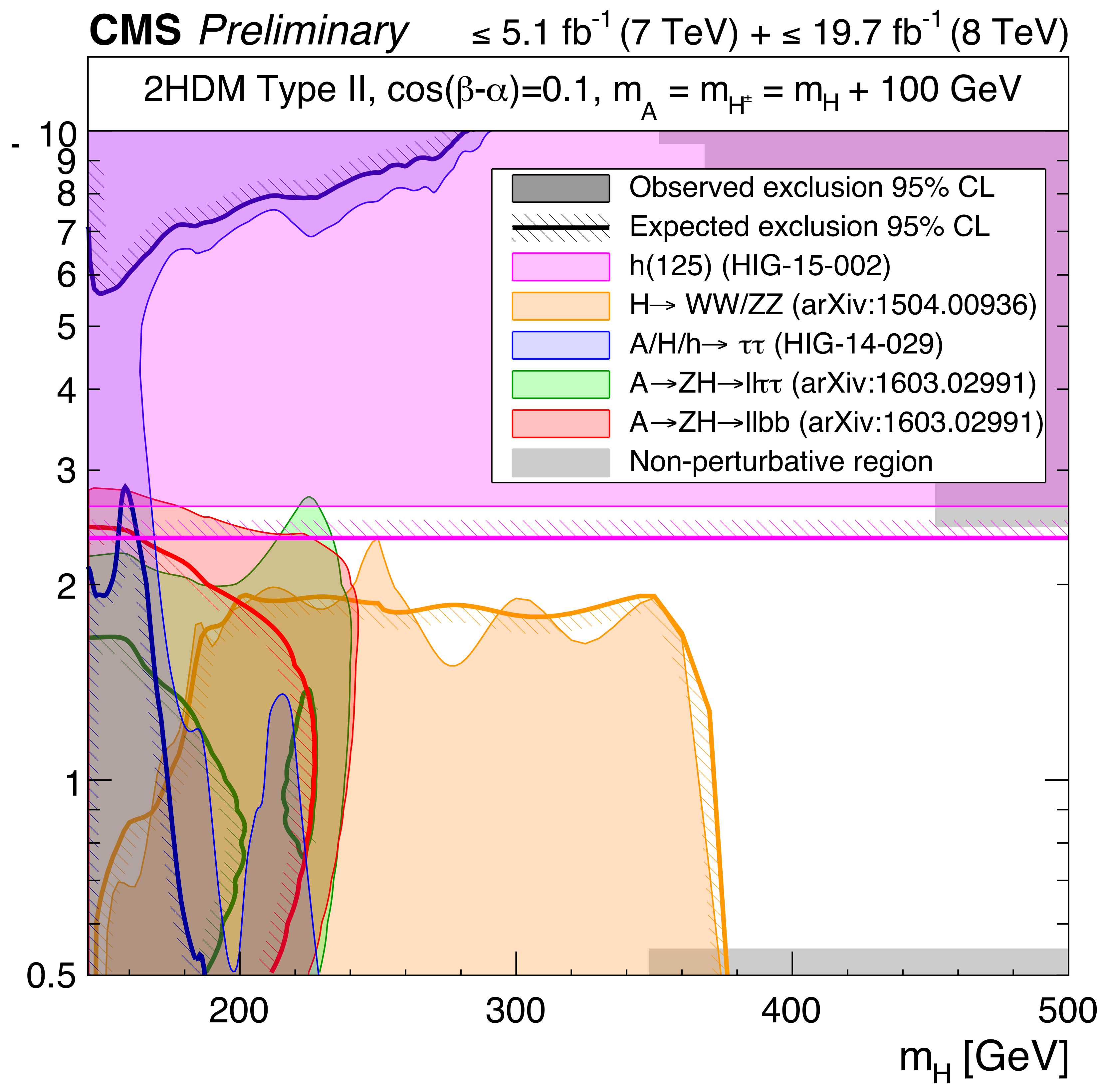




- Channels are complementary in covering different models and parameters

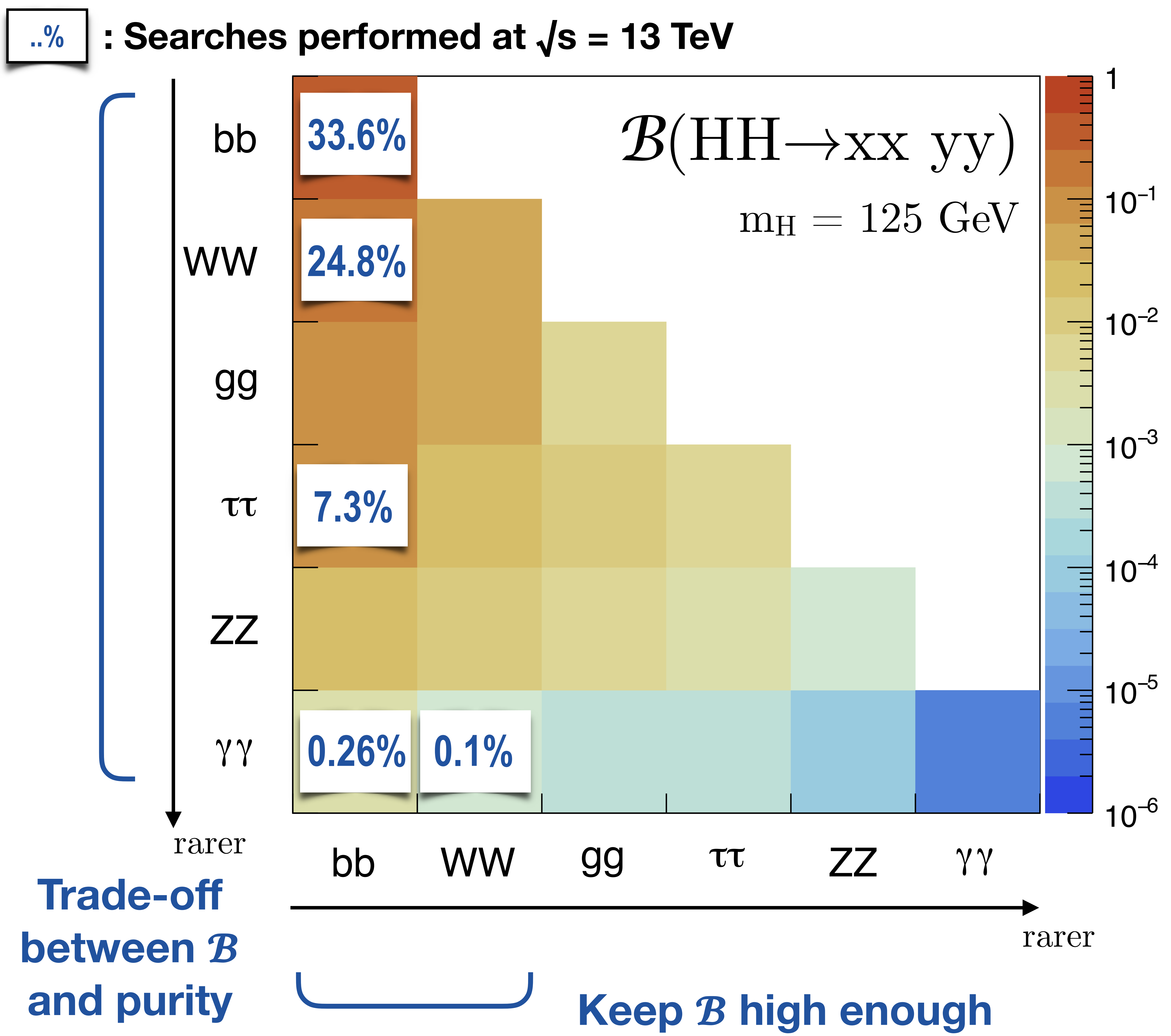
2HDM constraints - Run I





- Channels are complementary in covering different models and parameters

HH decay channels

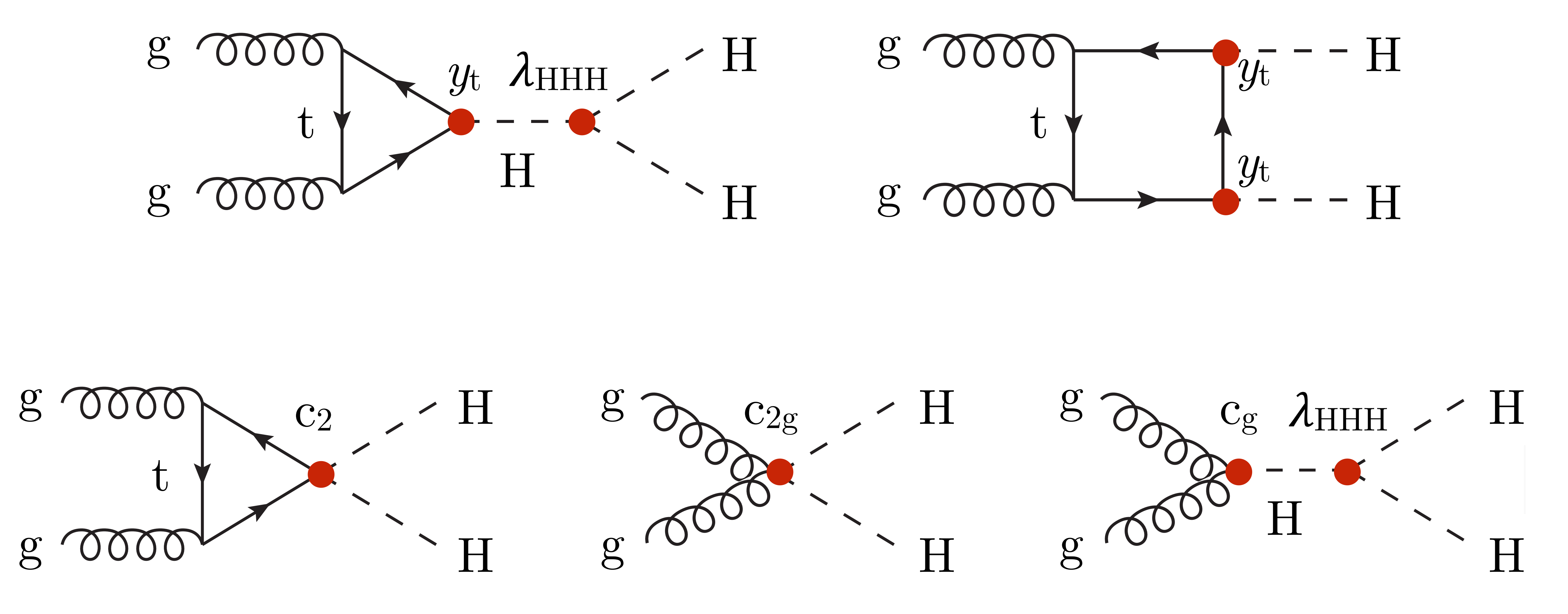


- Phenomenologically rich set of decay channels
- Good **complementarity**
  - essential to cover many decay channels to fully study different SM+BSM signal hypotheses
- **Common techniques…**
  - identification of b-jets
  - m_{HH} reconstruction
- **…** and **channel specific challenges**
  - partially reconstructed final states (bbWW, bb$\tau\tau$)
  - large multijet background (bbbb)
  - small branching fractions (bb$\gamma\gamma$, WW$\gamma\gamma$)

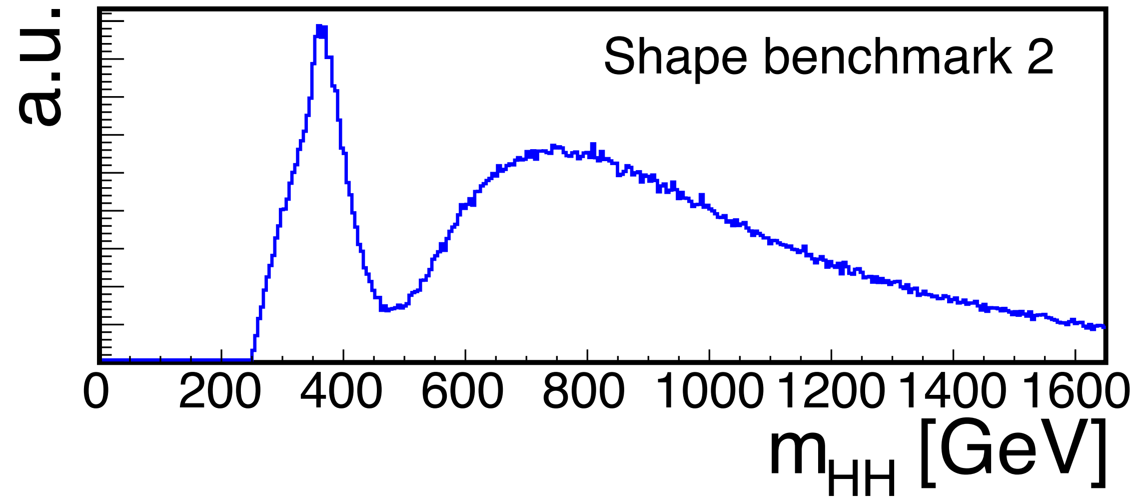
HH in a EFT approach

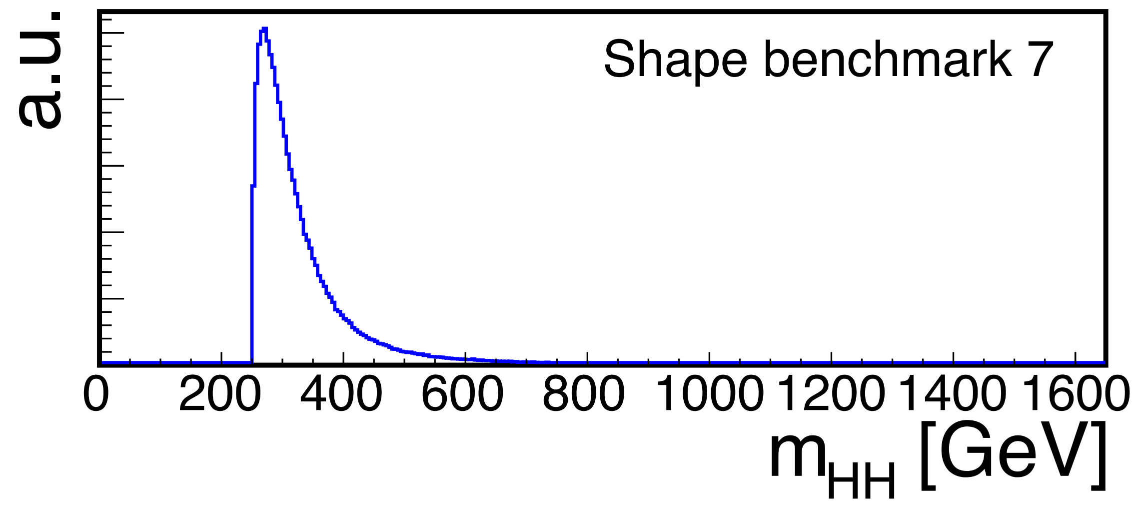
- Extensions of the SM Lagrangian with dim-6 operators
- Anomalous y_t and λ_{HHH} couplings and three contact interactions (c_2, c_g, c_{2g})

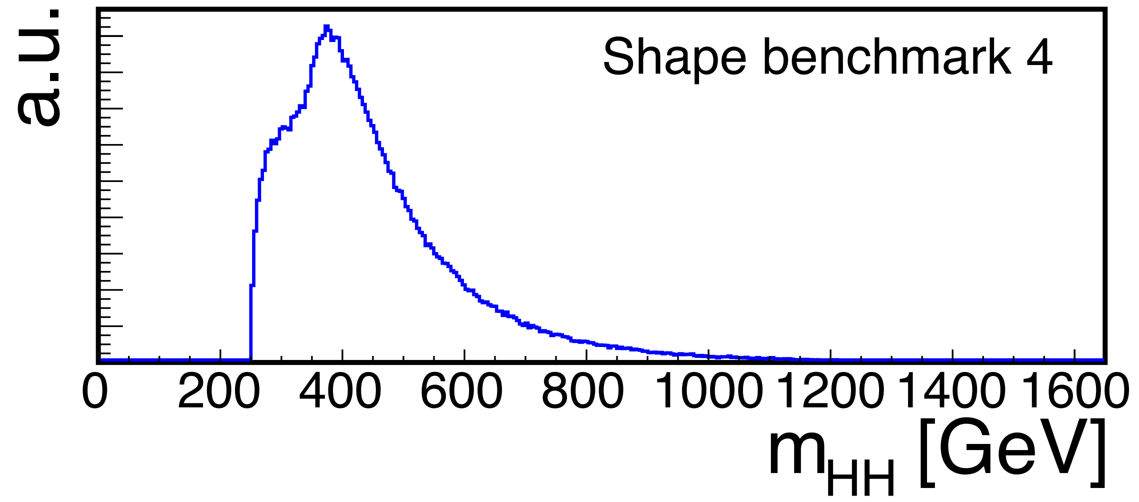
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^6 + \cdots$$



- Five-dimensional parameter space to be explored
  - 12 points defined as benchmarks of representative shapes

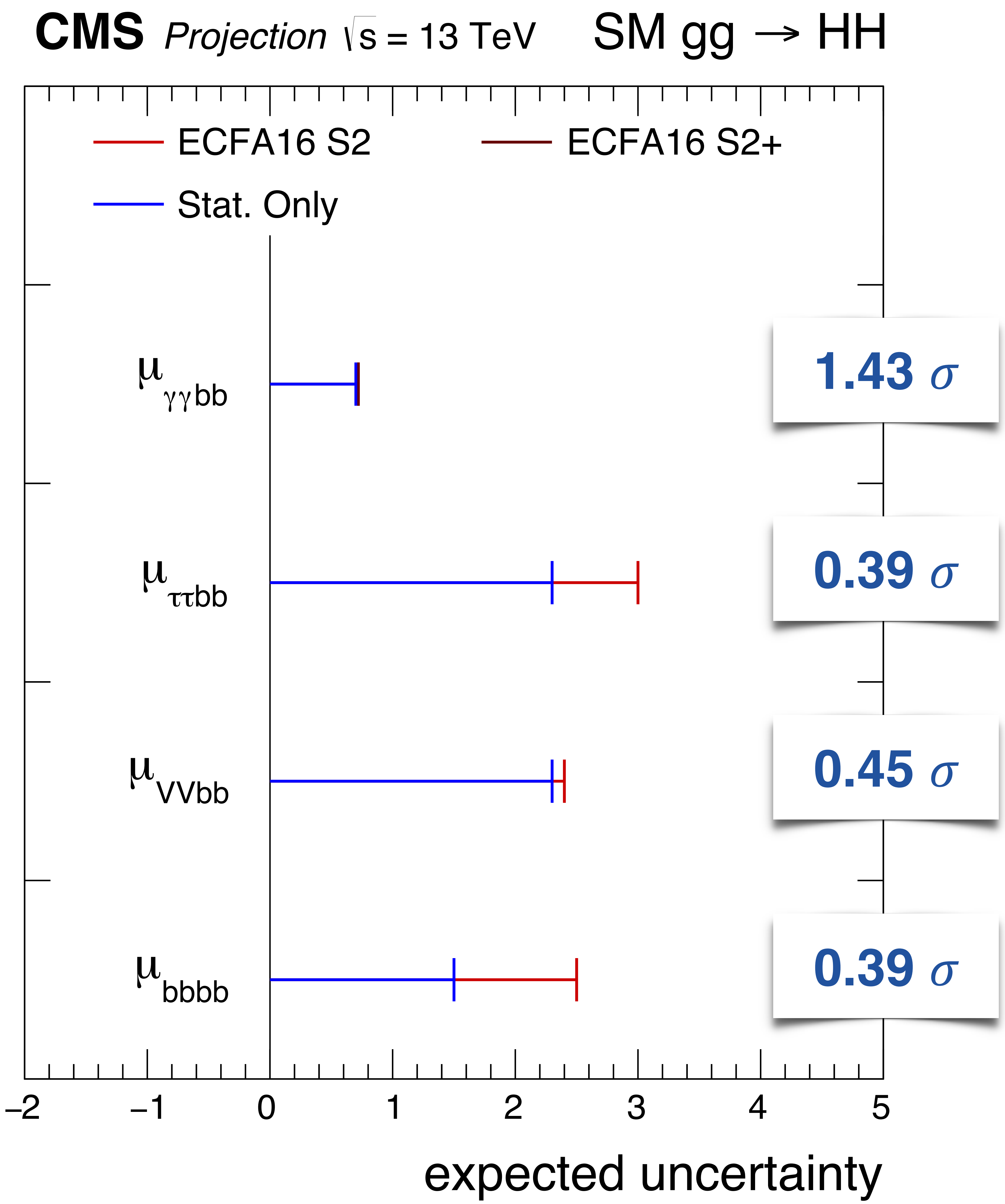






(few representative examples, 12 benchmarks in total)

Prospects for HH measurements

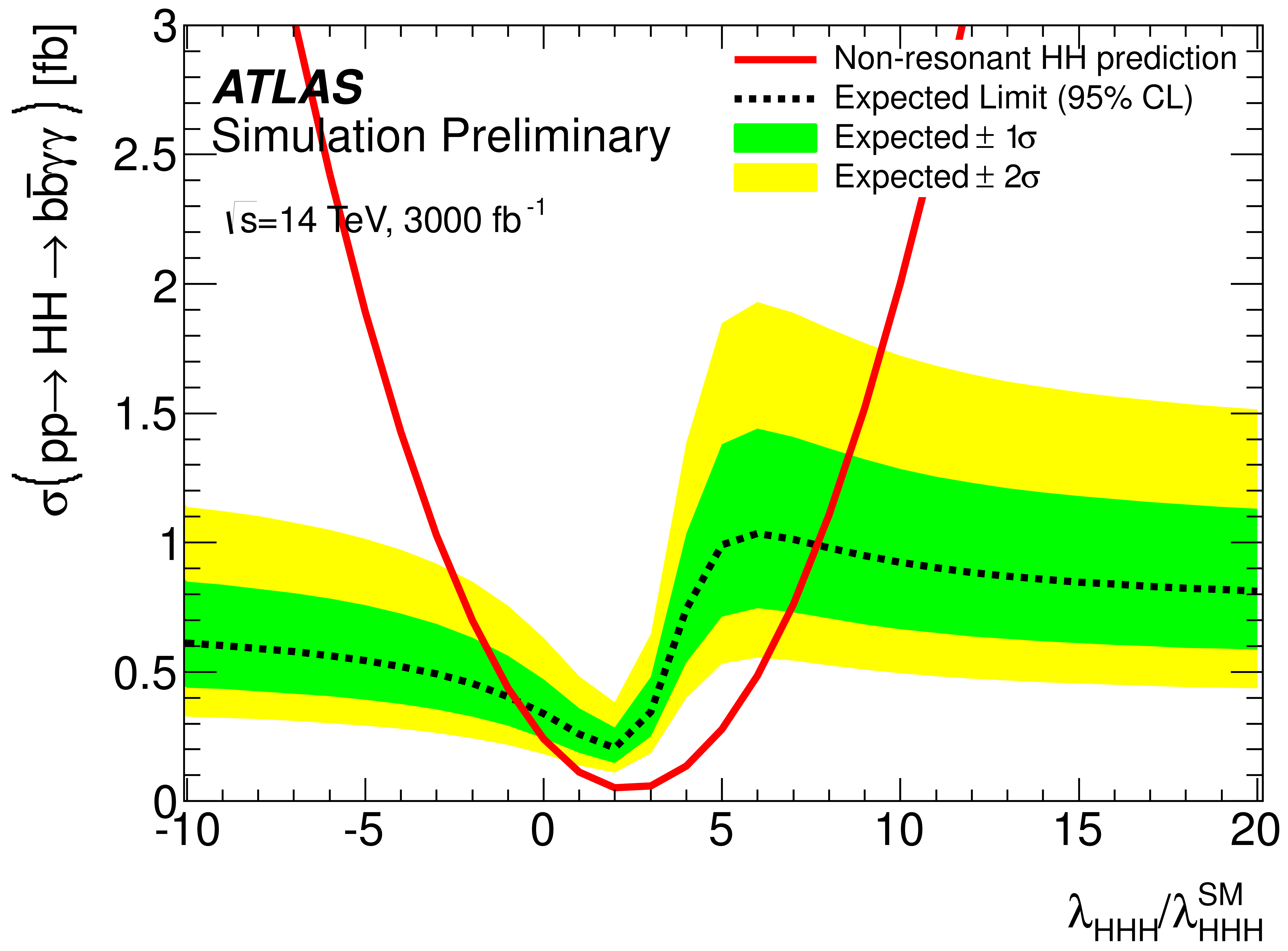


Channel	Median expected limits on $\mu = \sigma_{HH}/\sigma_{HH}^{SM}$		Significance (Z-value)		Uncertainty as a fraction of μ	
	ECFA16 S2	Stat. only	ECFA16 S2	Stat. only	ECFA16 S2	Stat. only
$HH \to bb\gamma\gamma$(S2+)	1.44	1.37	1.43	1.47	0.72	0.71
$HH \to bb\tau\tau$	5.2	3.9	0.39	0.53	2.6	1.9
$HH \to bbVV$	4.8	4.6	0.45	0.47	2.4	2.3
$HH \to bbbb$	7.0	2.9	0.39	0.67	2.5	1.5

- Projections of early Run II results (2.3/2.7 fb^{-1}) to 3000 fb^{-1}
  - conservative: improvements already achieved in full 2016 dataset analyses

Decay channel combination is essential for an evidence of HH production

Prospects for HH measurements



- $bb\gamma\gamma$, $bb\tau\tau$ and bbbb studied
- parametric simulation of the detector upgraded response
- full analysis on parametric simulation, assuming 3000 fb^{-1} of data collected
- best significance is 1.05σ from $bb\gamma\gamma$
  - maintaining the resolution on $m_{\gamma\gamma}$ is crucial to increase the sensitivity