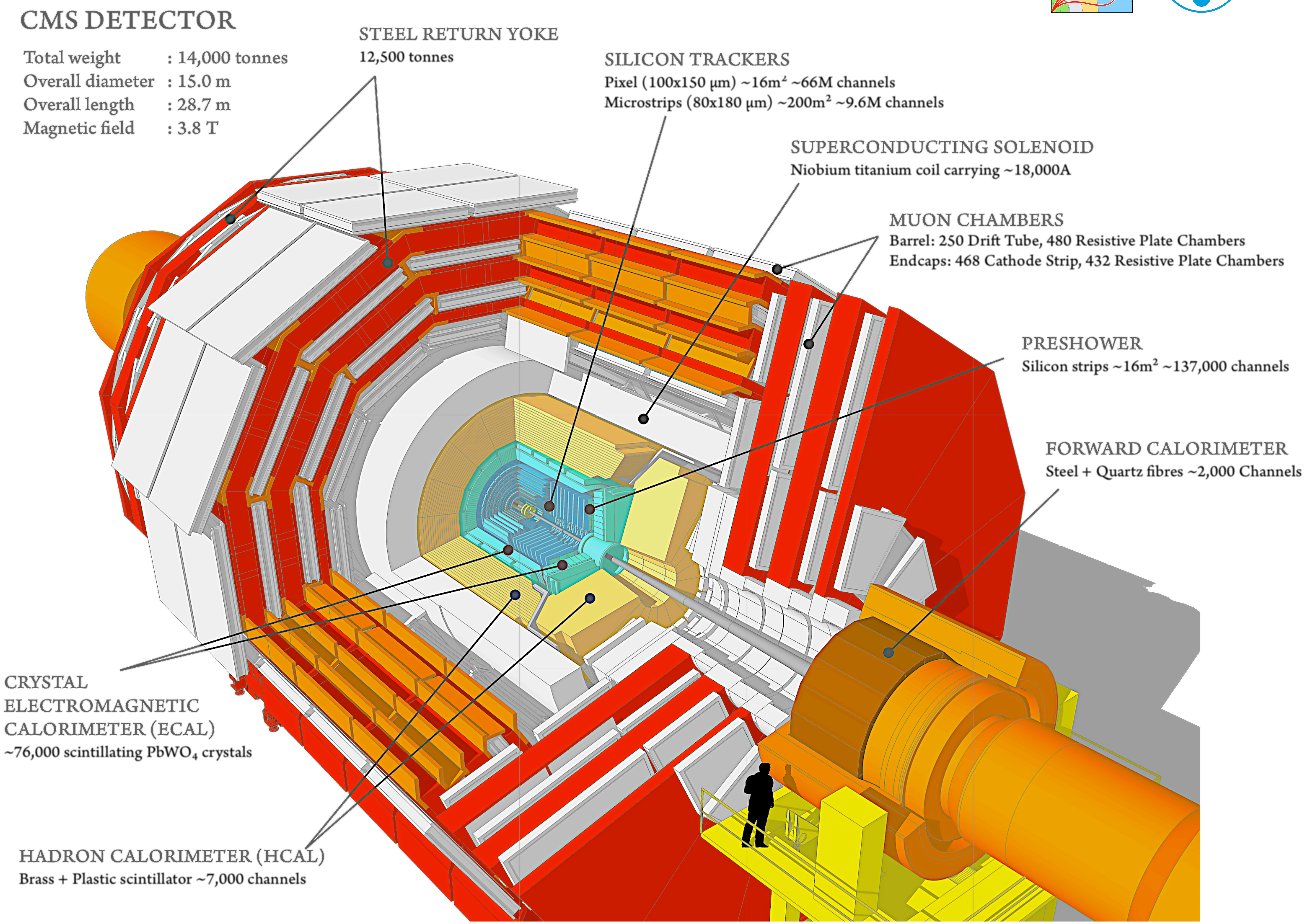
Search for beyond the standard model Higgs bosons decaying into a $b\bar{b}$ pair in pp collisions at 13 TeV

Roberval Walsh
DESY
(on behalf of the CMS Collaboration)

12th Annual Meeting of the Helmholtz Alliance "Physics at the Terascale"
27 November 2018

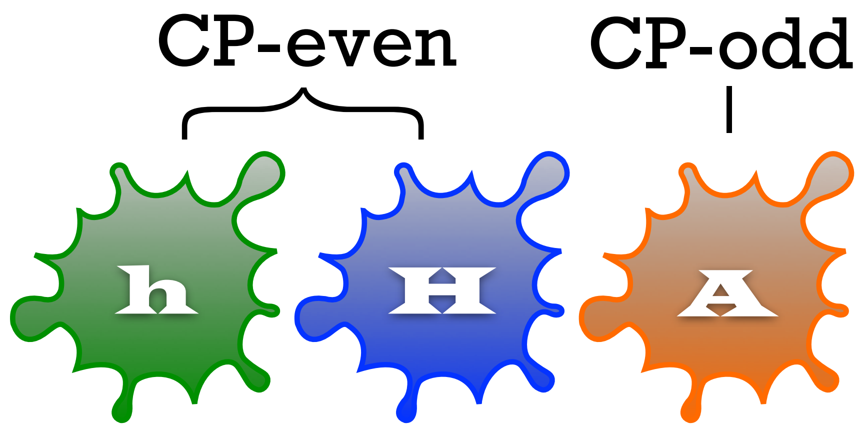
Outline

- Introduction
- Analysis strategy
- Results
- Summary



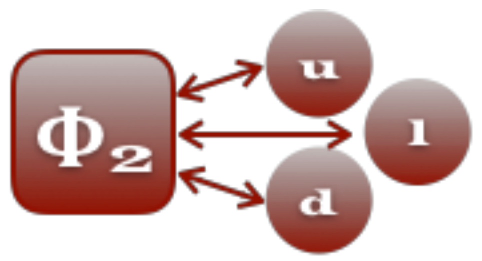
Two-Higgs-doublet and minimal supersymmetric models

› **2HDM: $SU(2)_L$ doublets Φ_1 Φ_2**



- 5 physical states: 3 neutral (ϕ) + 2 charged 

- Higgs sector free parameters @ tree level: tan β, m_A, α + 4 other parameters
- 4 types of models (CP-conserving, no tree-level FCNC)

Type I	Lepton-specific	Type II	Flipped
			

enhanced coupling to b-quarks for tan β > 1

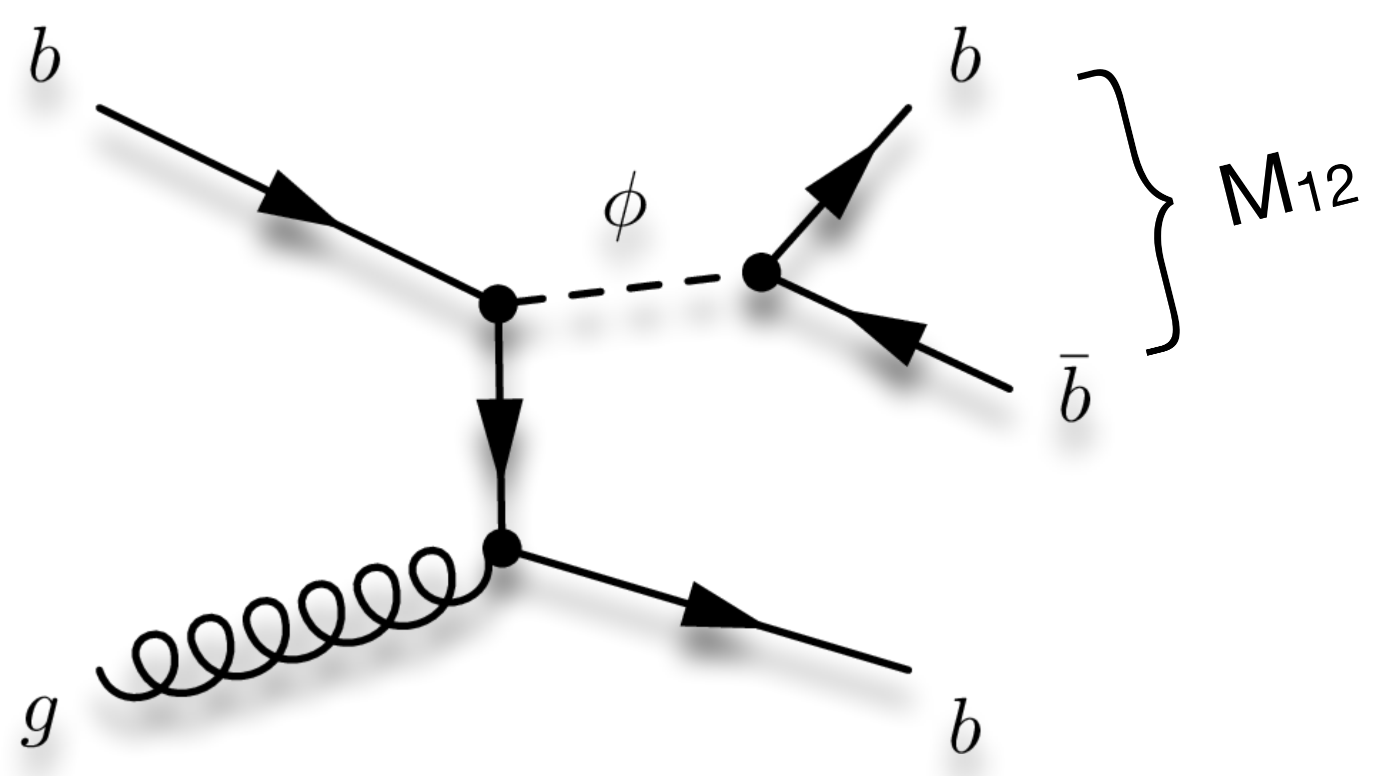
› **MSSM (~2HDM type II)**

- Same Higgs spectrum as 2HDM: (3 neutral + 2 charged) Higgs bosons
- Higgs sector free parameters @ tree level: tan β, m_A
- Several benchmark scenarios, e.g. m_h^{mod+}, hMSSM etc

u = (u,c,t) | d = (d,s,b) | l = (e,μ,τ)

Higgs → $b\bar{b}$ produced in association with b-quark(s)

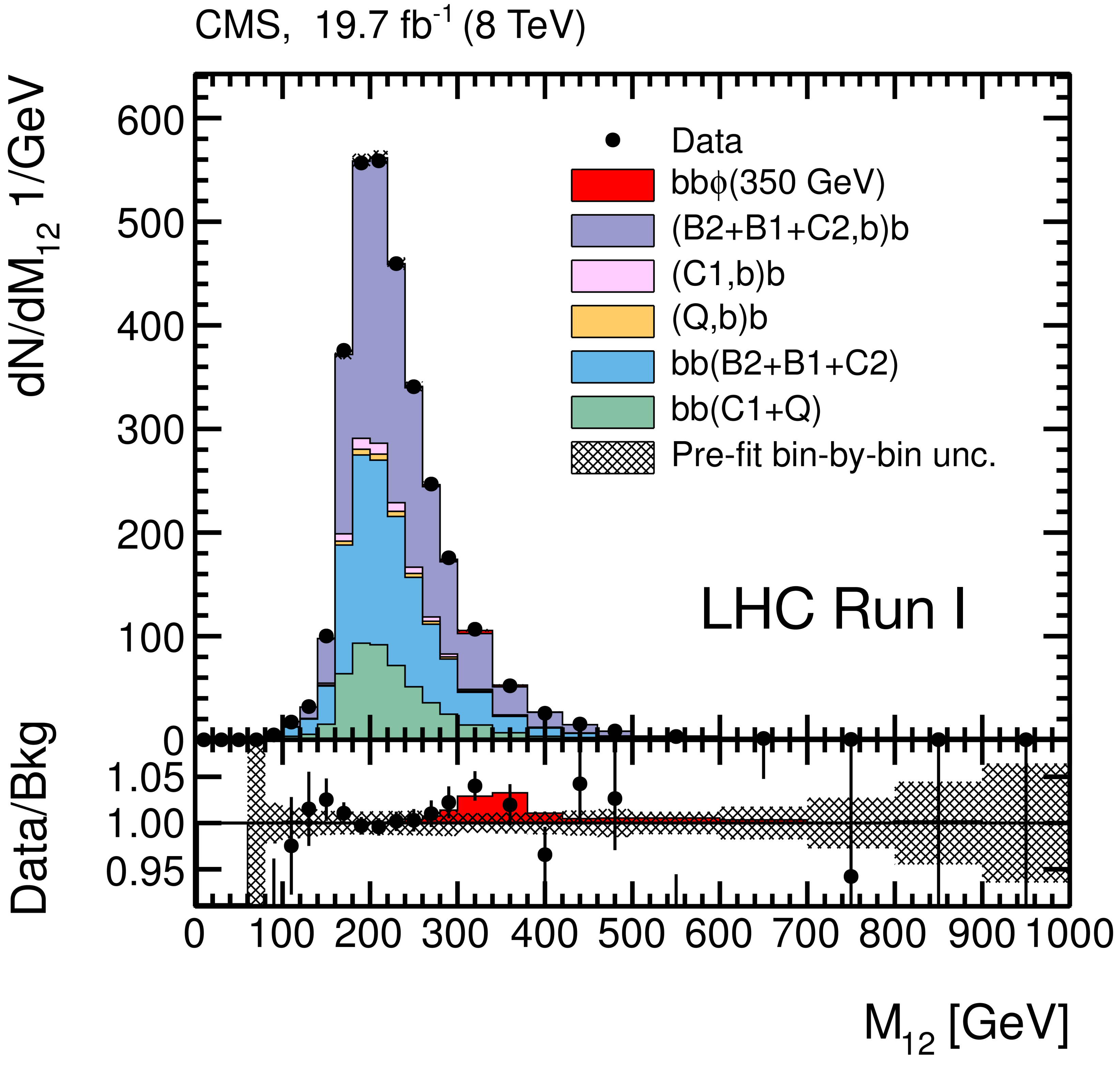
- b-quark-associated production
  - Cross section ∝ $\tan^2 \beta$
  - Suppression of the large multi jet background, dominated by QCD

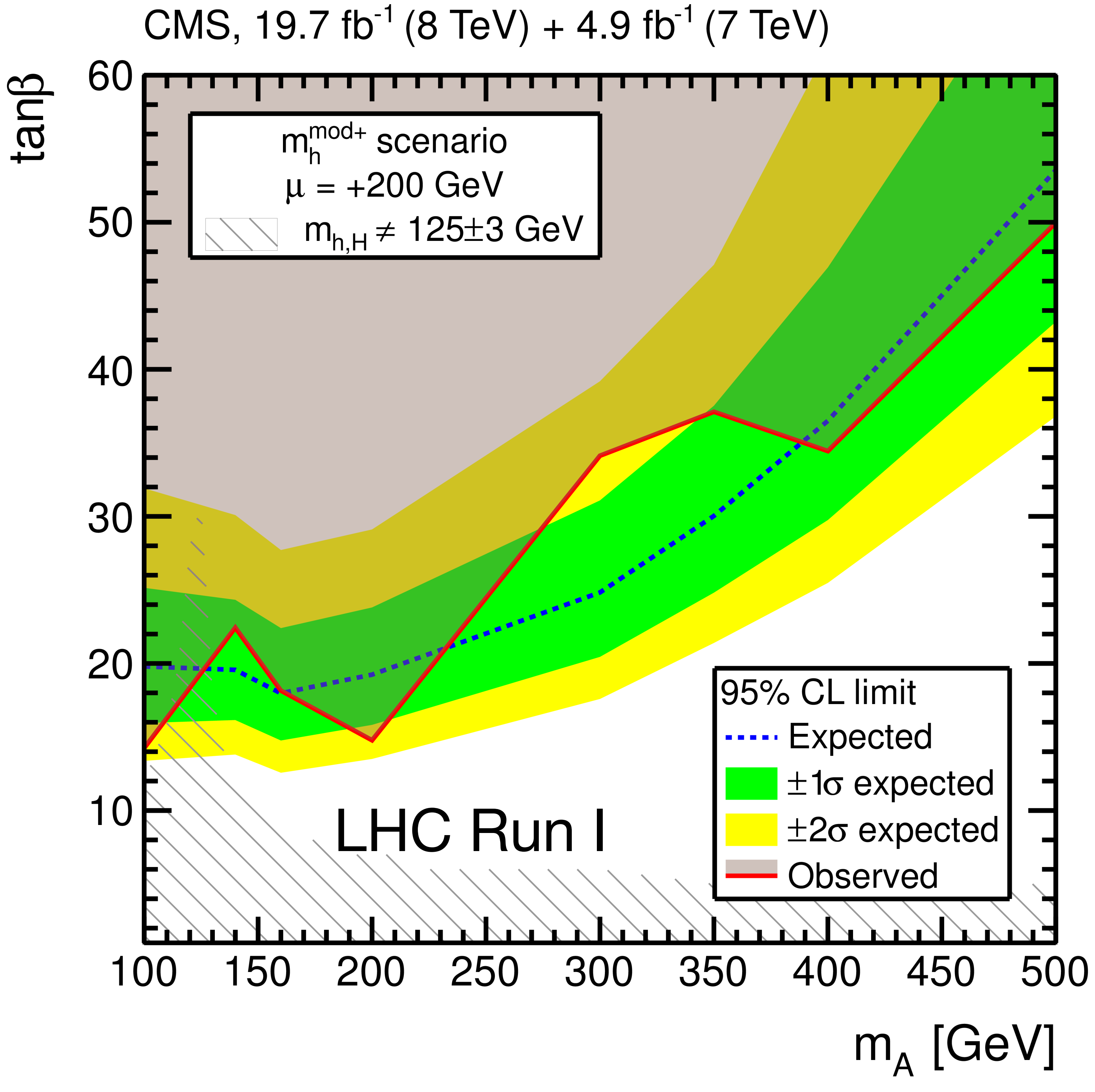


- Signal arises as an excess on the di-jet mass (M_{12}) distribution of the two p_T-leading b-tagged jets

- Run I analyses:
  - 7 TeV: PLB 722 (2013) 207
  - 8 TeV: JHEP 11 (2015) 071

- **[New]** Run II analysis @ 13 TeV with 2016 data, L = 35.7 fb^{-1}, presented today
  - Recently published JHEP 08 (2018) 113



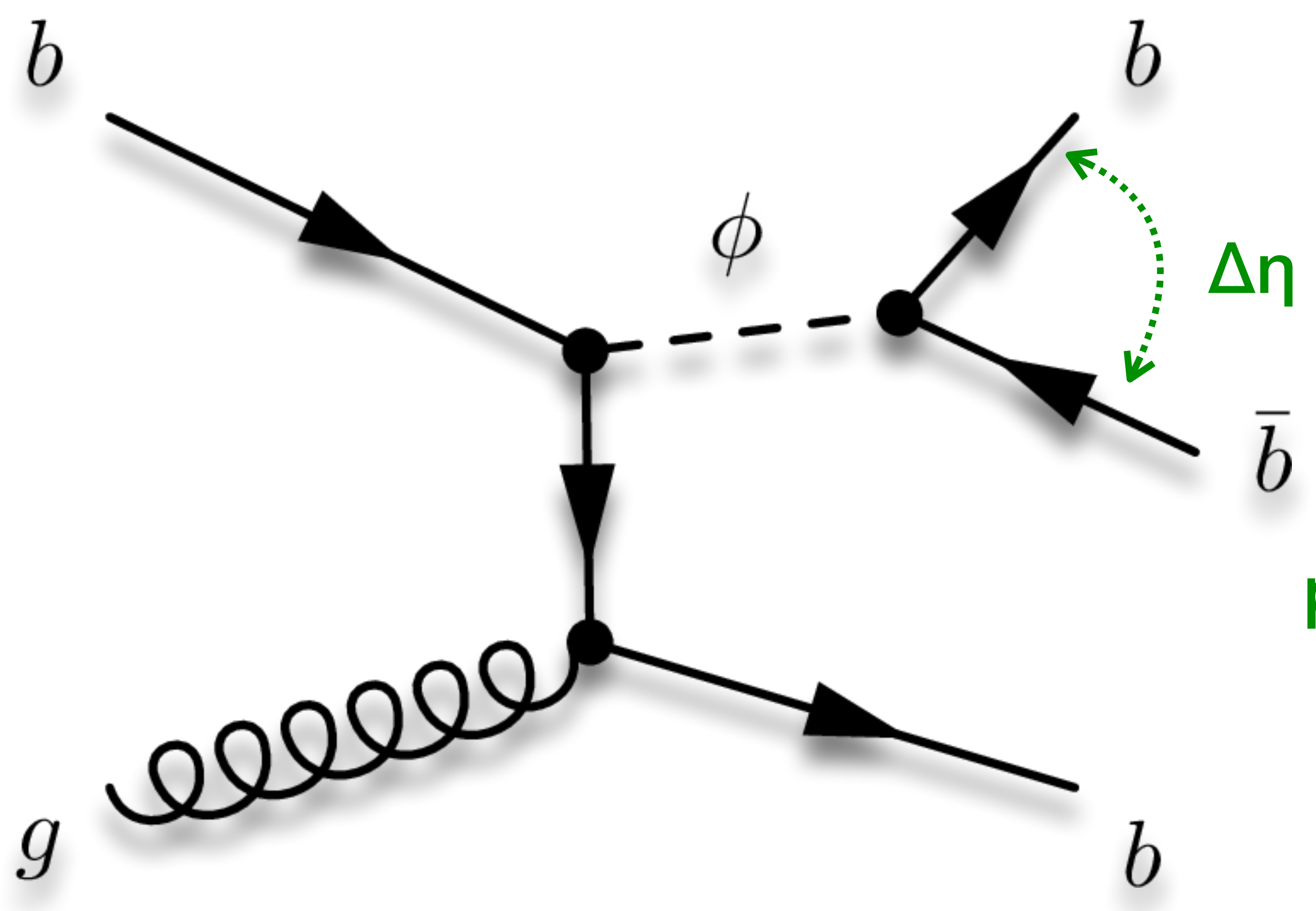


Analysis strategy – trigger

› **Level 1 Trigger**

- At least two jets with pT ≥ 100 GeV
  - Increased threshold with respect to Run I → loss of sensitive at low masses ($M_{\Phi} \geq 300$ GeV)

› **High-Level Trigger**



$p_{T(1)} > 100$ GeV

$\Delta\eta < 1.6$

$p_{T(2)} > 100$ GeV

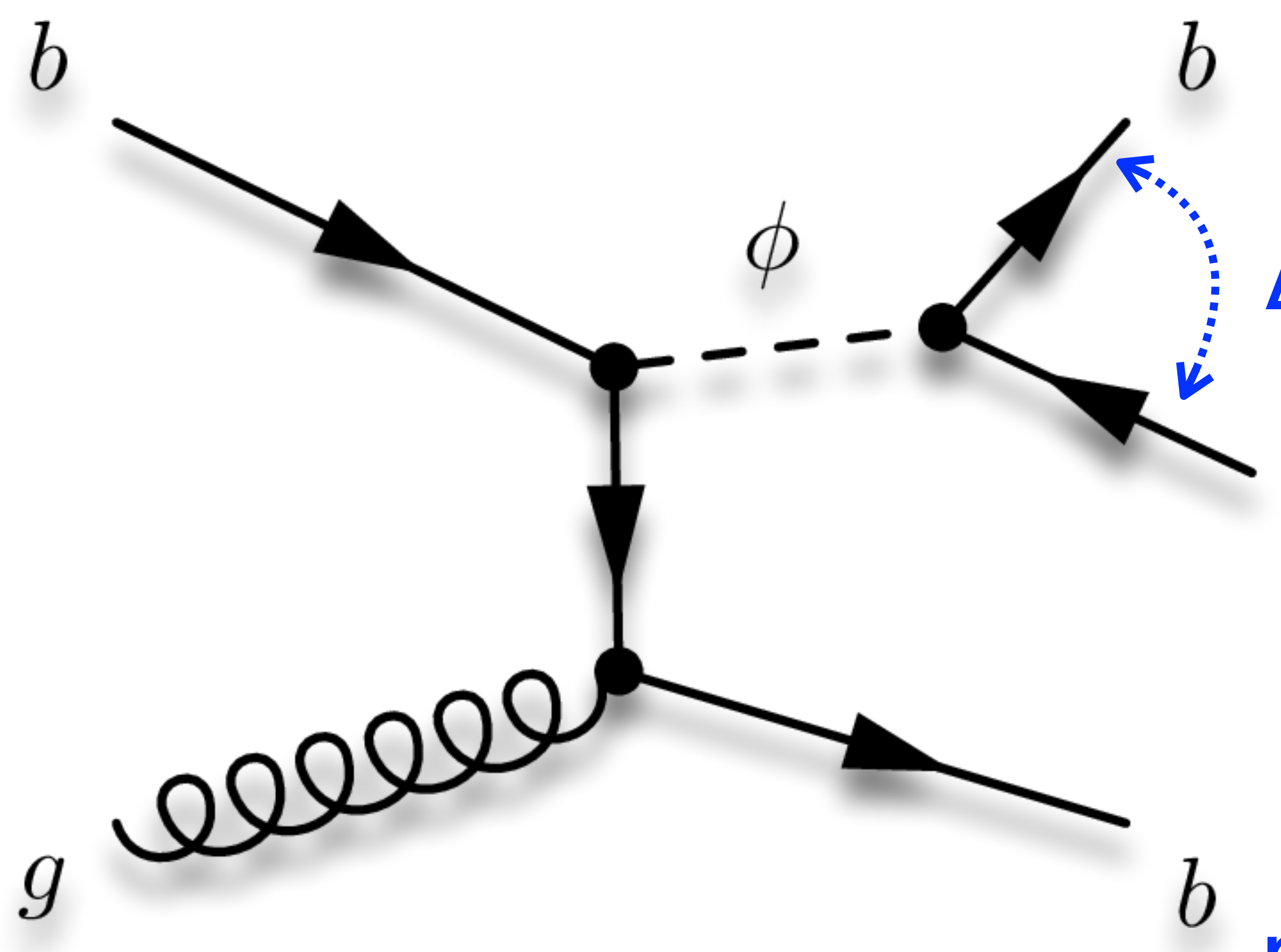
- Online b-tagged jets ≥ 2
  - Online CSVv2 btag > 0.84 (1.4% light flavour)
  - Up to 6 jets with $p_T > 80$ GeV

Analysis strategy – offline event selection

› Signal region – Triple b-tag (bbb)

- PFJets ≥ 3

$p_{T(1)} > 100$ GeV



$\Delta\eta < 1.55$

$p_{T(2)} > 100$ GeV

$p_{T(3)} > 40$ GeV

- $\Delta R(\text{jet}_i, \text{jet}_j) > 1$, i, j = 1,2,3, i≠j
- CSVv2 b-tag (jet_i) > 0.8484, i = 1,2,3 (1% light flavour rate)

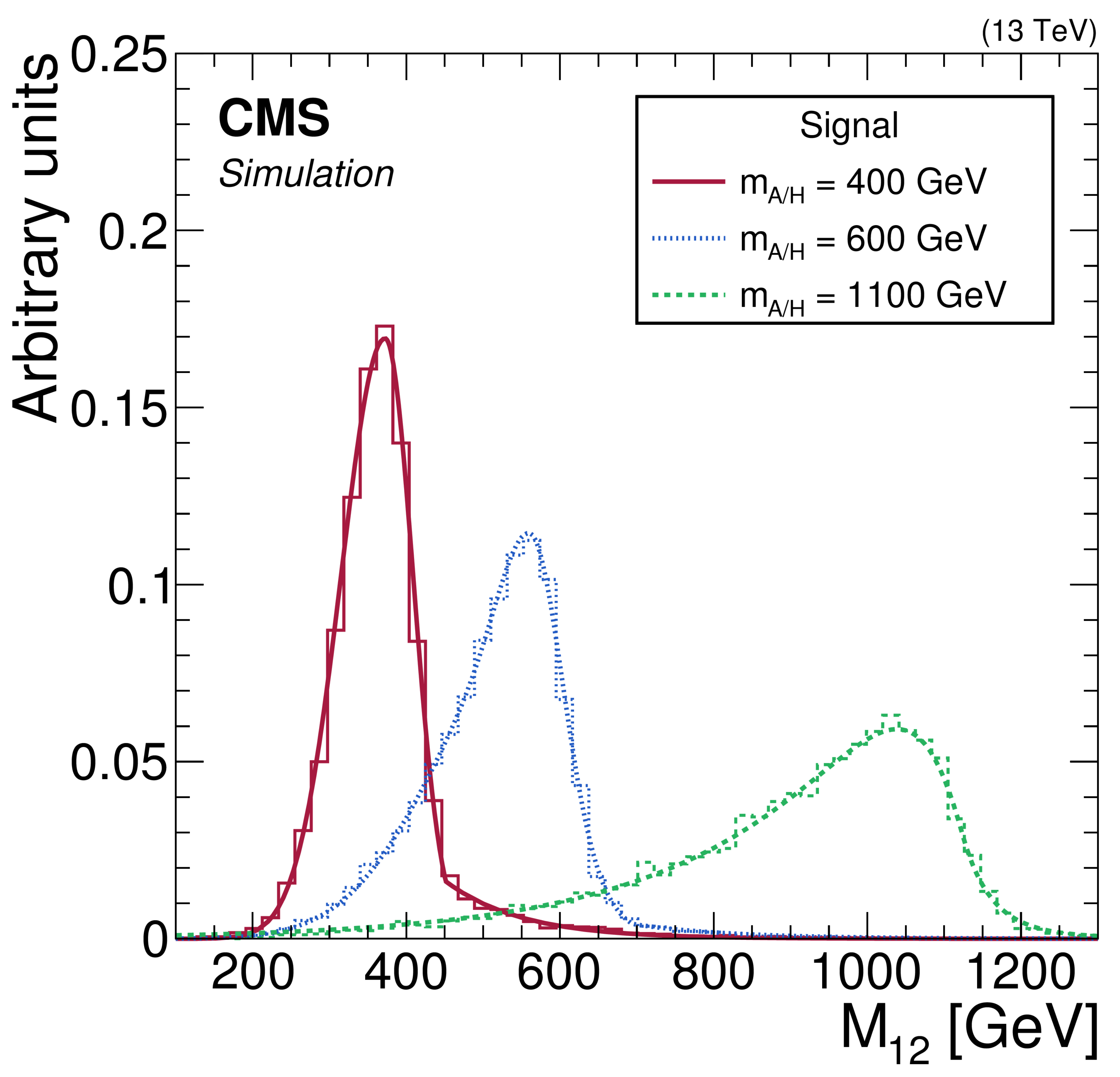
› Control region – Reverse b-tag (bbnb)

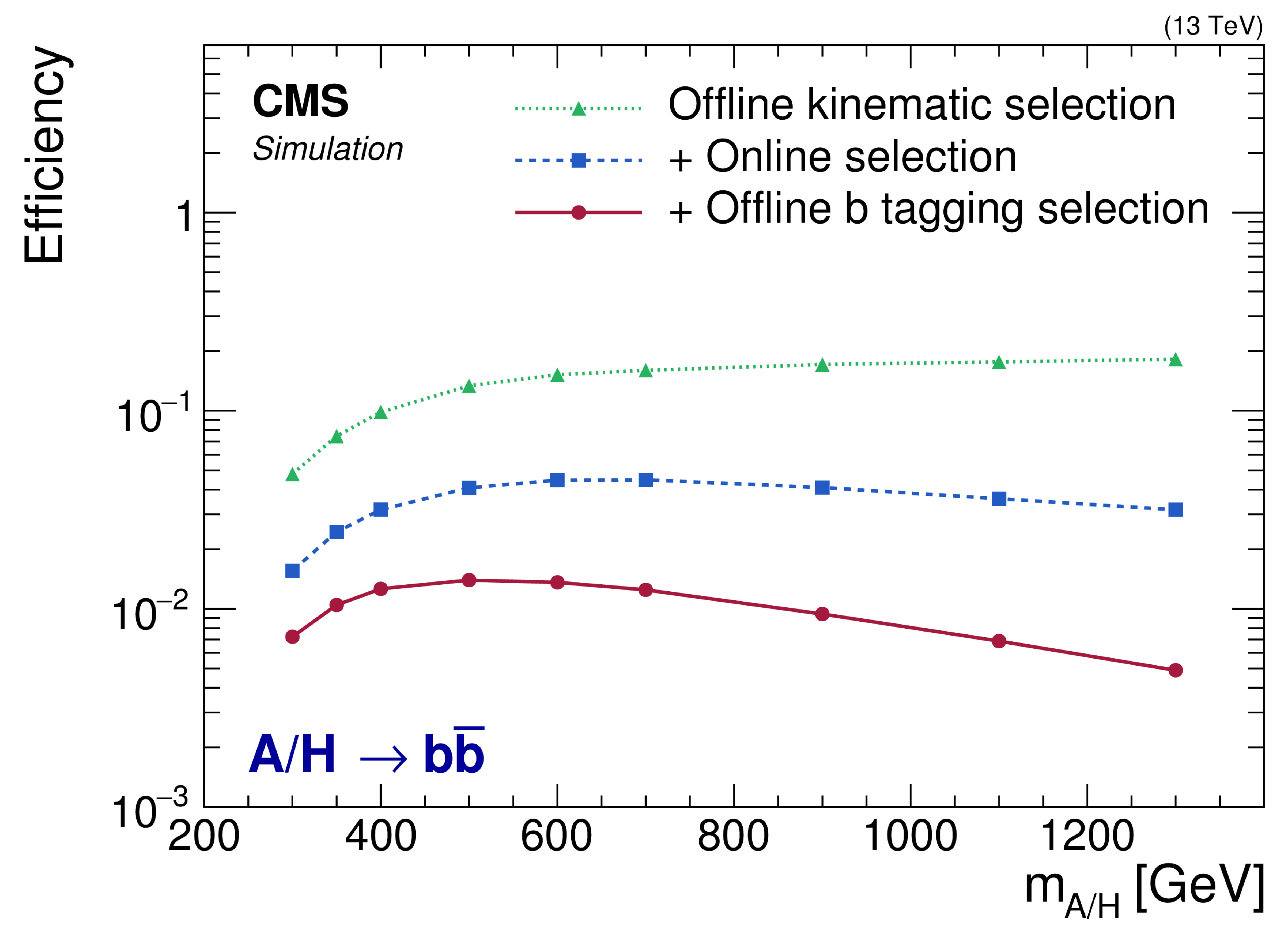
- Data-driven background modelling
- Reverse b-tag (3rd jet)
  - CSVv2 b-tag (jet_3) < 0.5426
  - Signal depleted sample
  - Simulation show no significant bias of M_{12} distribution

Analysis strategy – signal model

› pp → $b\bar{b}$A + X, with A → $b\bar{b}$ (leading order 4-flavour scheme Pythia8)

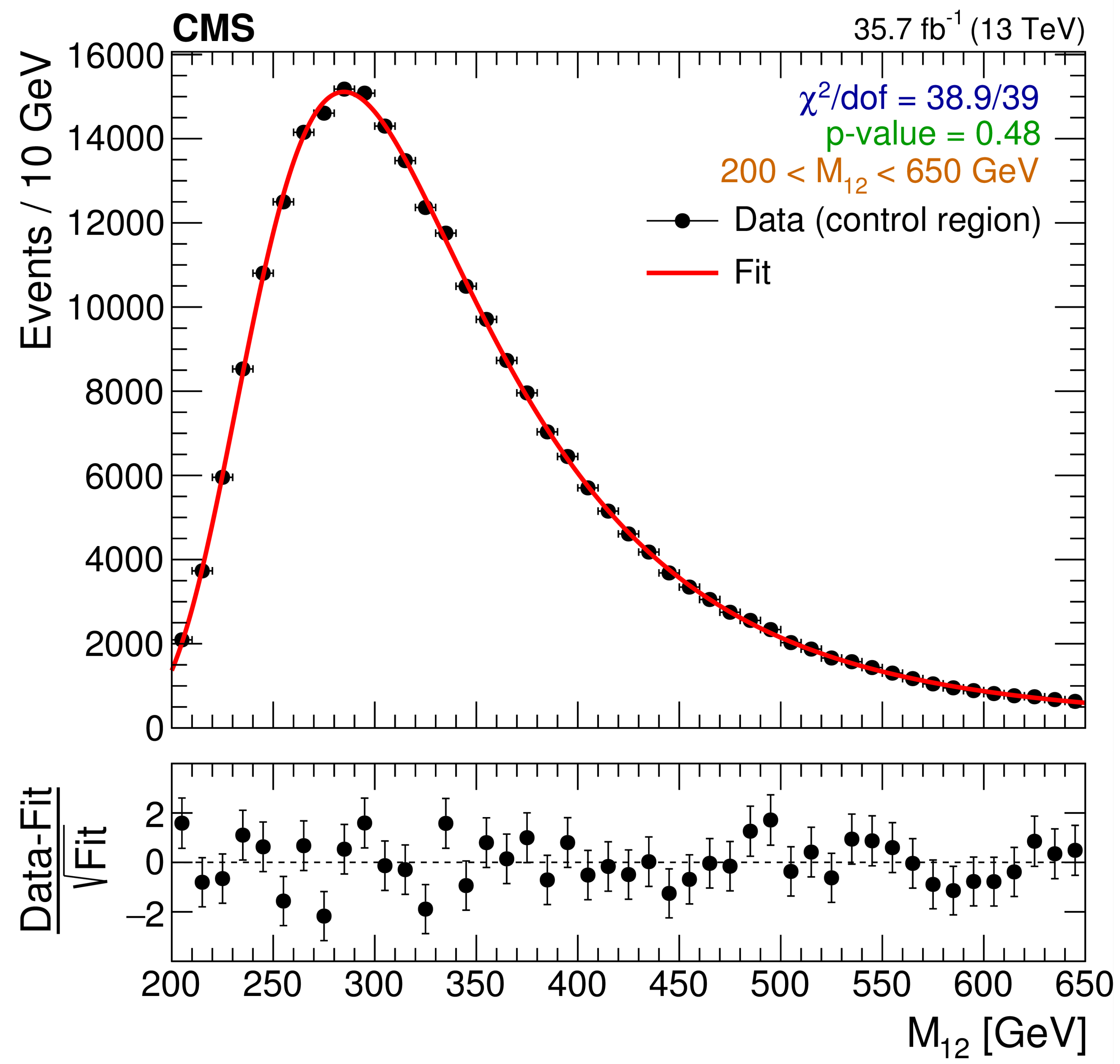
- Samples $m_{A/H}$ from 300 GeV to 1300 GeV
- Signal M_{12} shape well described by parametrisations

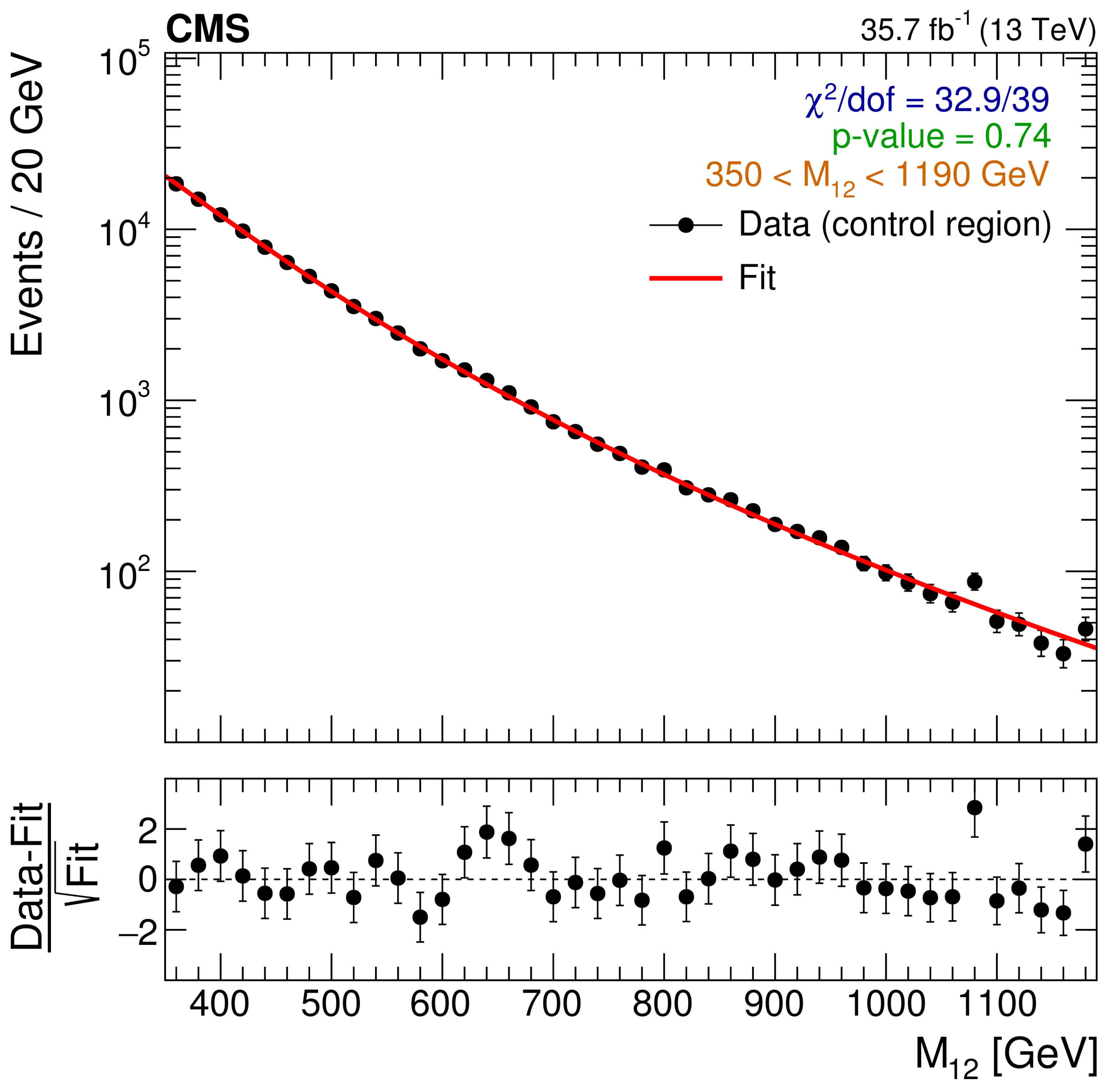


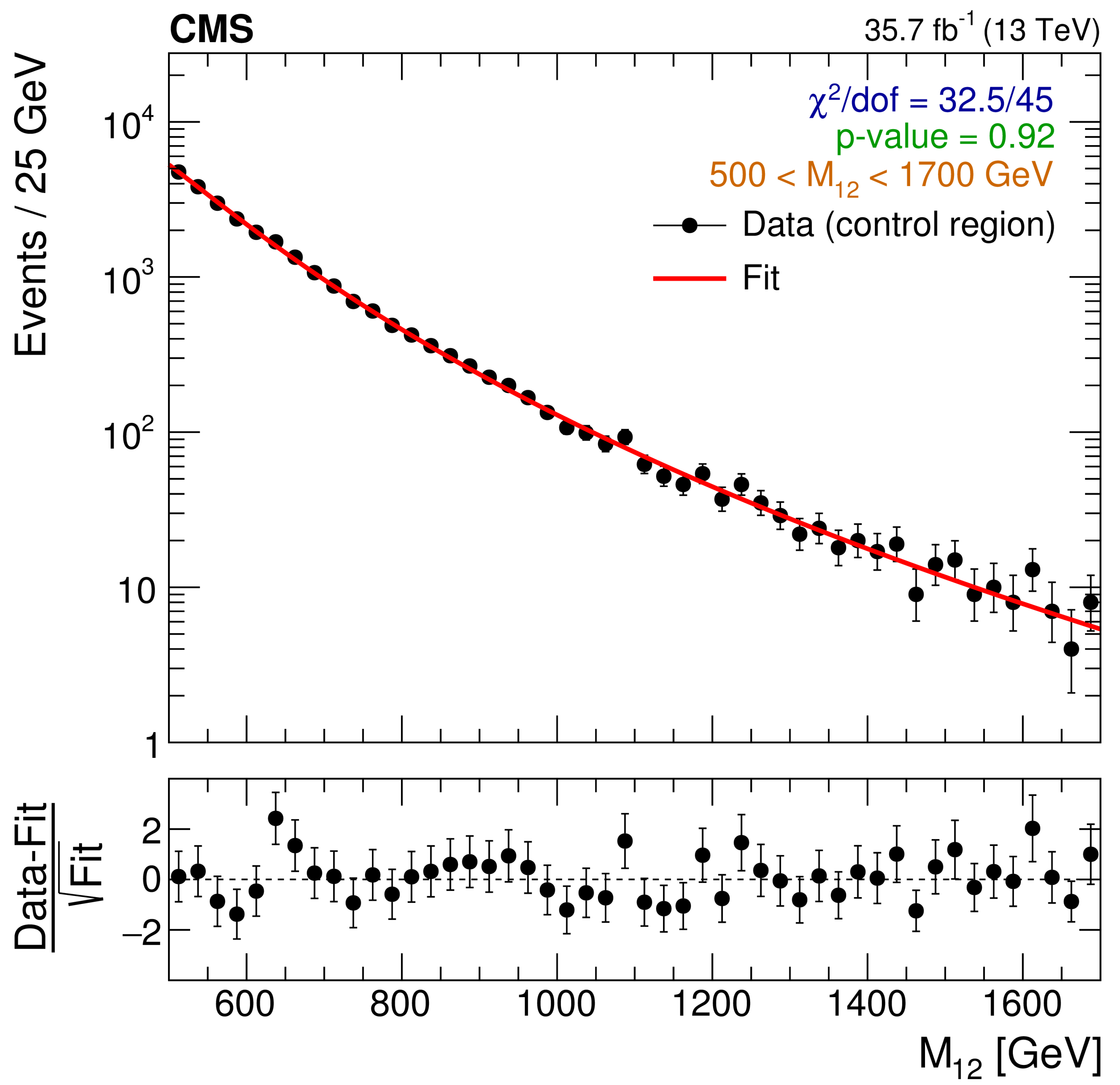


Analysis strategy – background model

- Analytical functions used to describe the M_{12} distribution in the reverse b-tag control region
  - M_{12} distribution divided into three subranges
    - improve background description
    - reduce potential bias

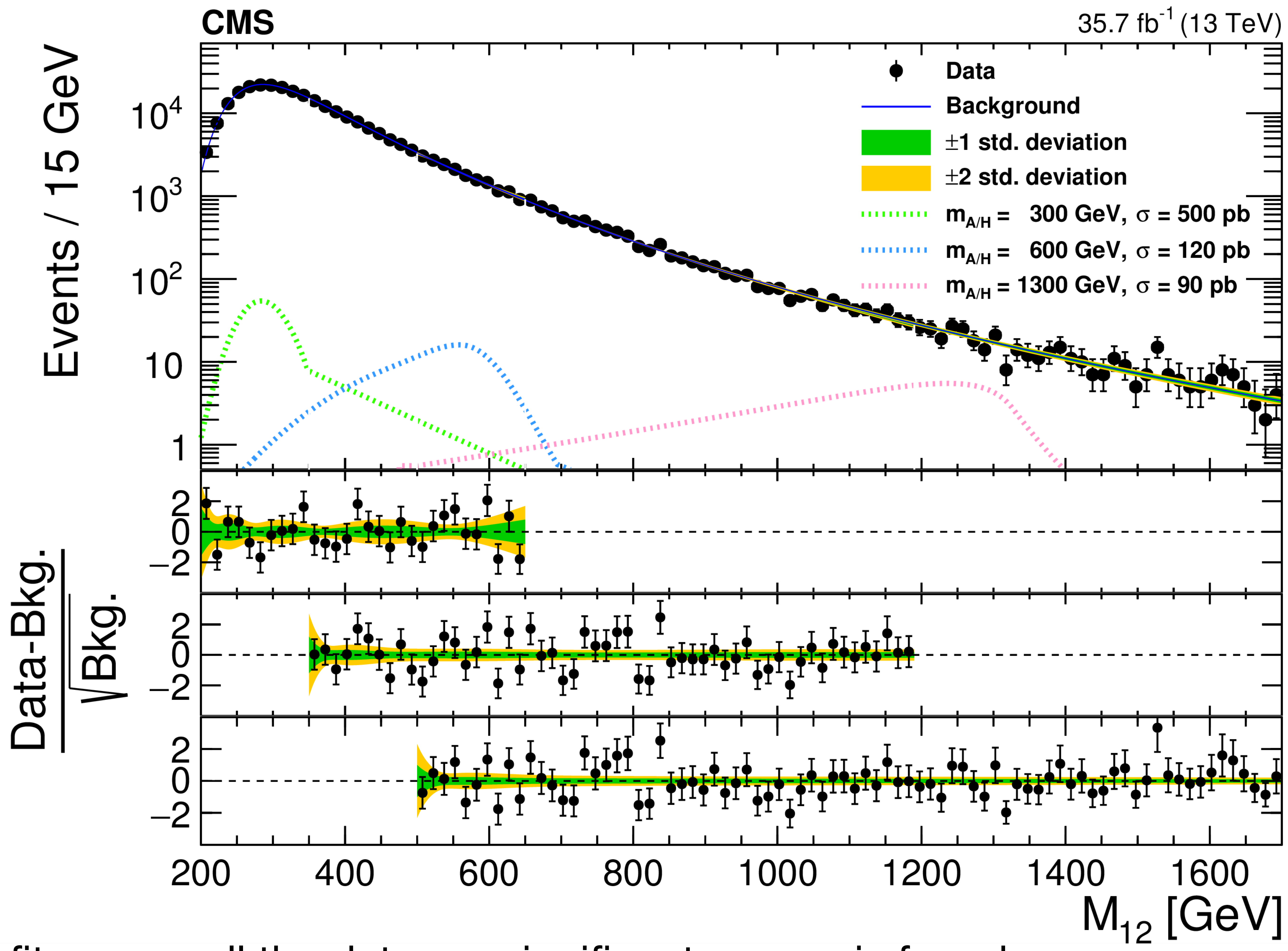






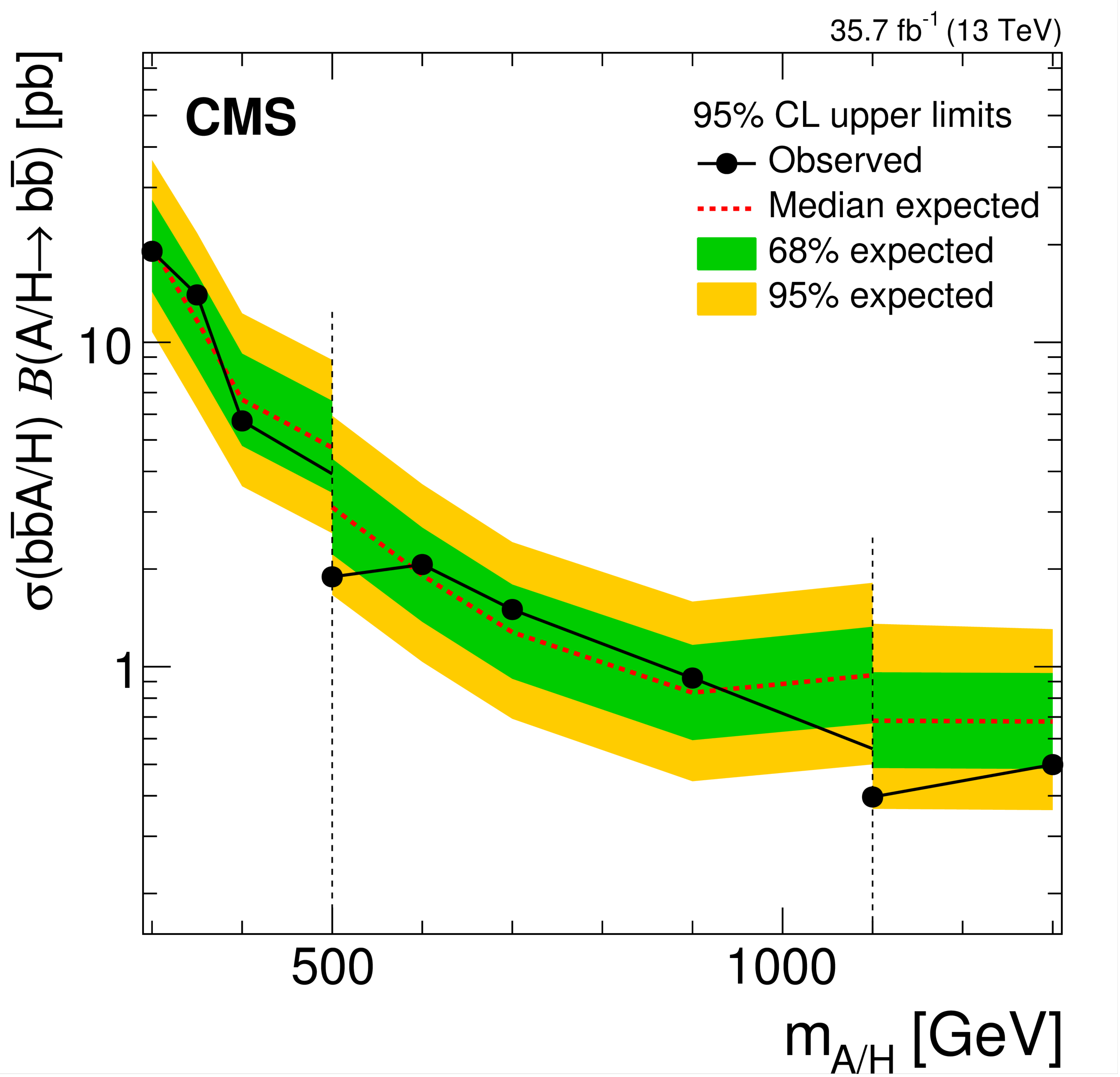
Results – fit to the data

› Background-only fit to data in the triple b-tag signal region



• Background model fits very well the data, no significant excess is found

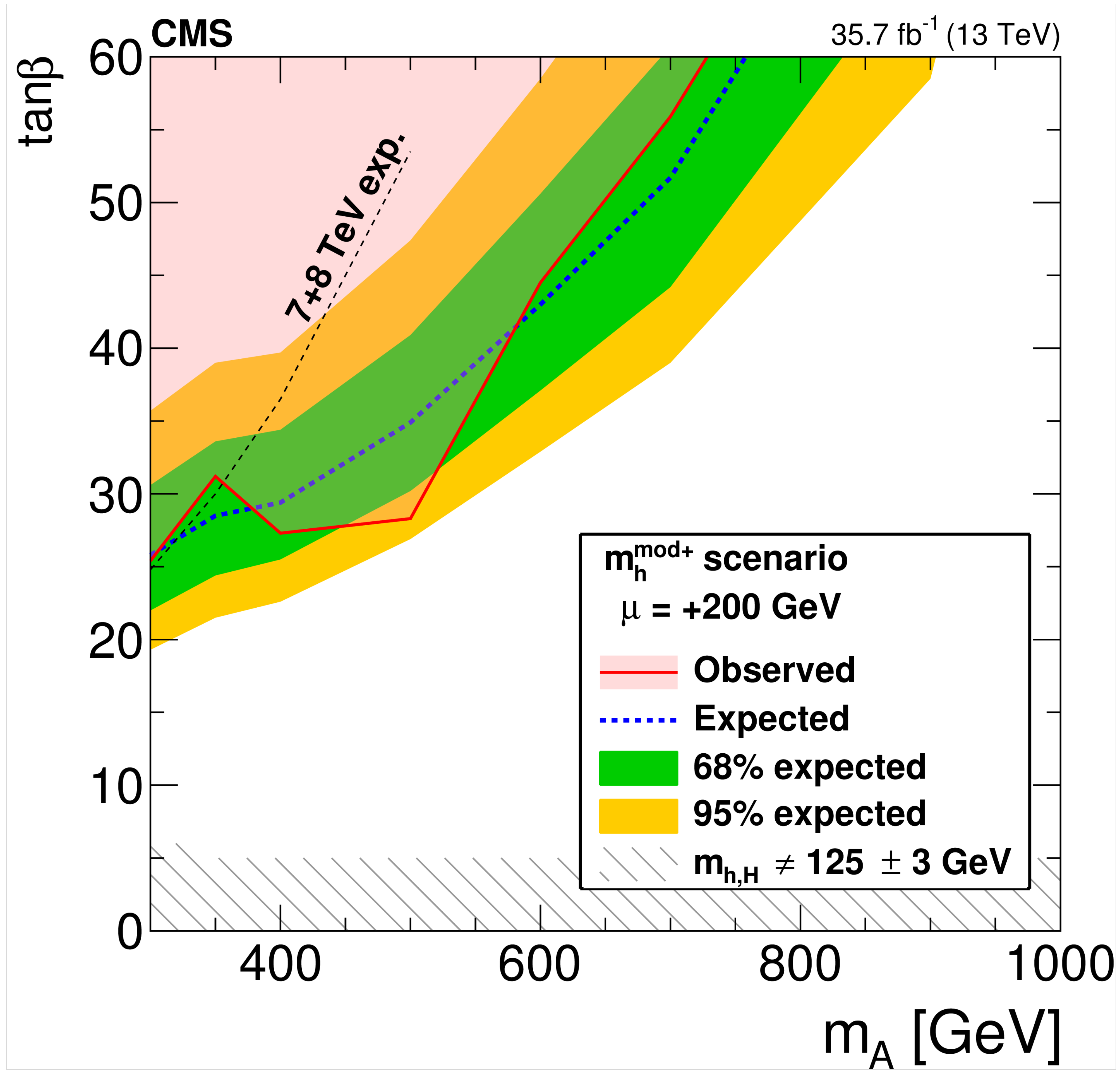
Results – model independent limits

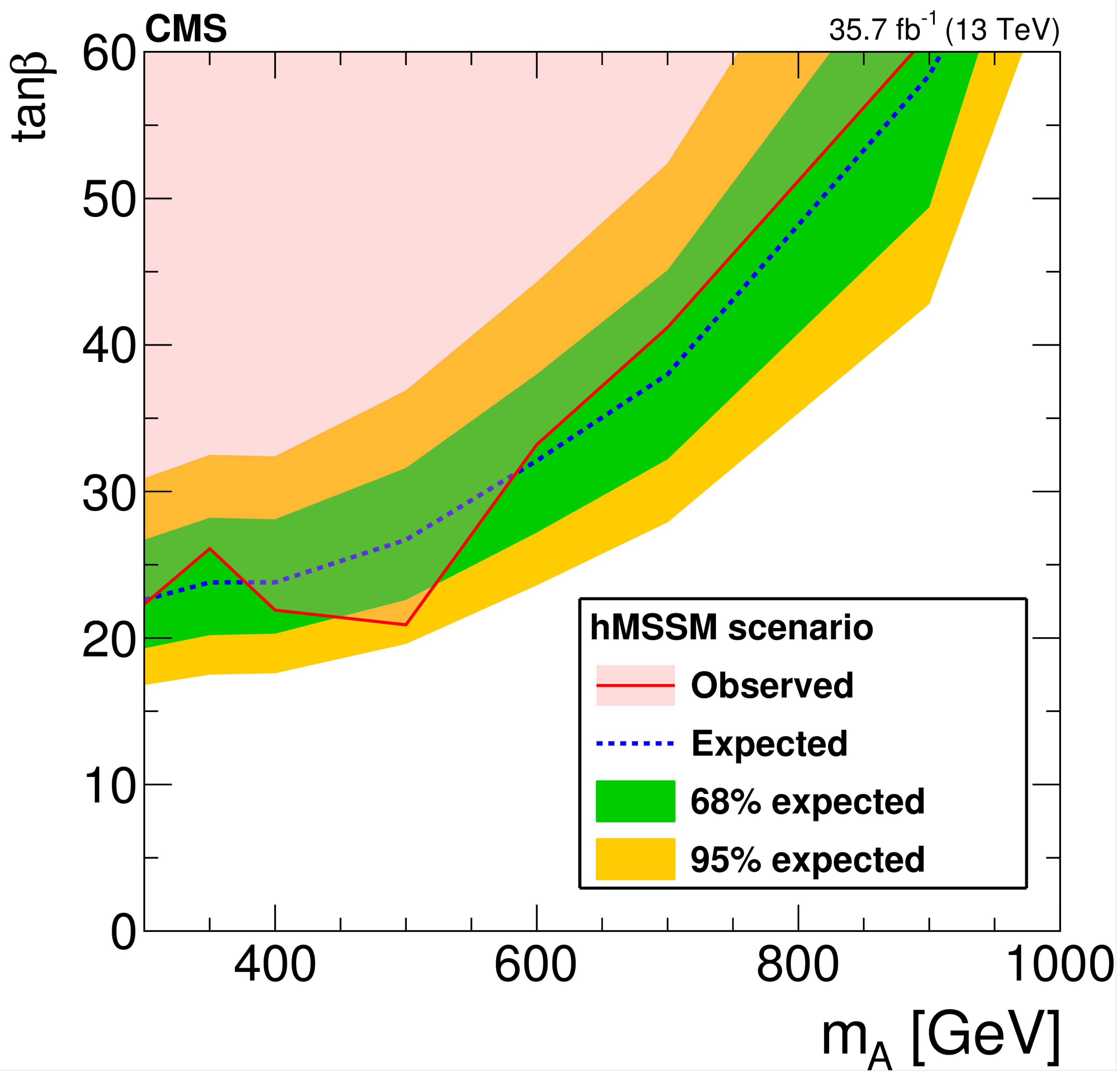


- 95% CL upper limits on σ(bb̄A/H)×B(A/H→bb̄)
  - Subrange optimisation clearly improves the sensitivity

Results – MSSM interpretations

- 95% CL upper limits on tan β versus m_A for m_h^{mod+} (1) and hMSSM(2) scenarios
  - Improved sensitivity with respect to Run I

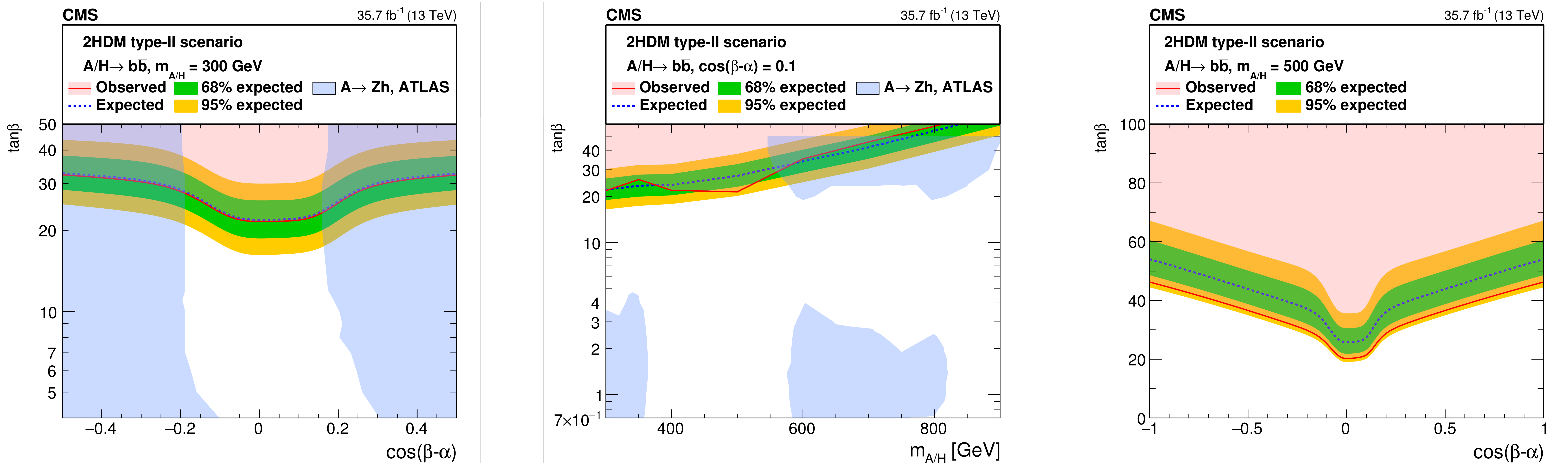




(1) M. Carena et al, Eur.Phys.J. C73 (2013) 2552
N.B.: New MSSM benchmark scenarios for Run 2 recently published (H. Ball et al, arXiv:1808.07542) were not used.
(2) D. Djouadi et al, Eur. Phys. J. C 73 (2013) 2650

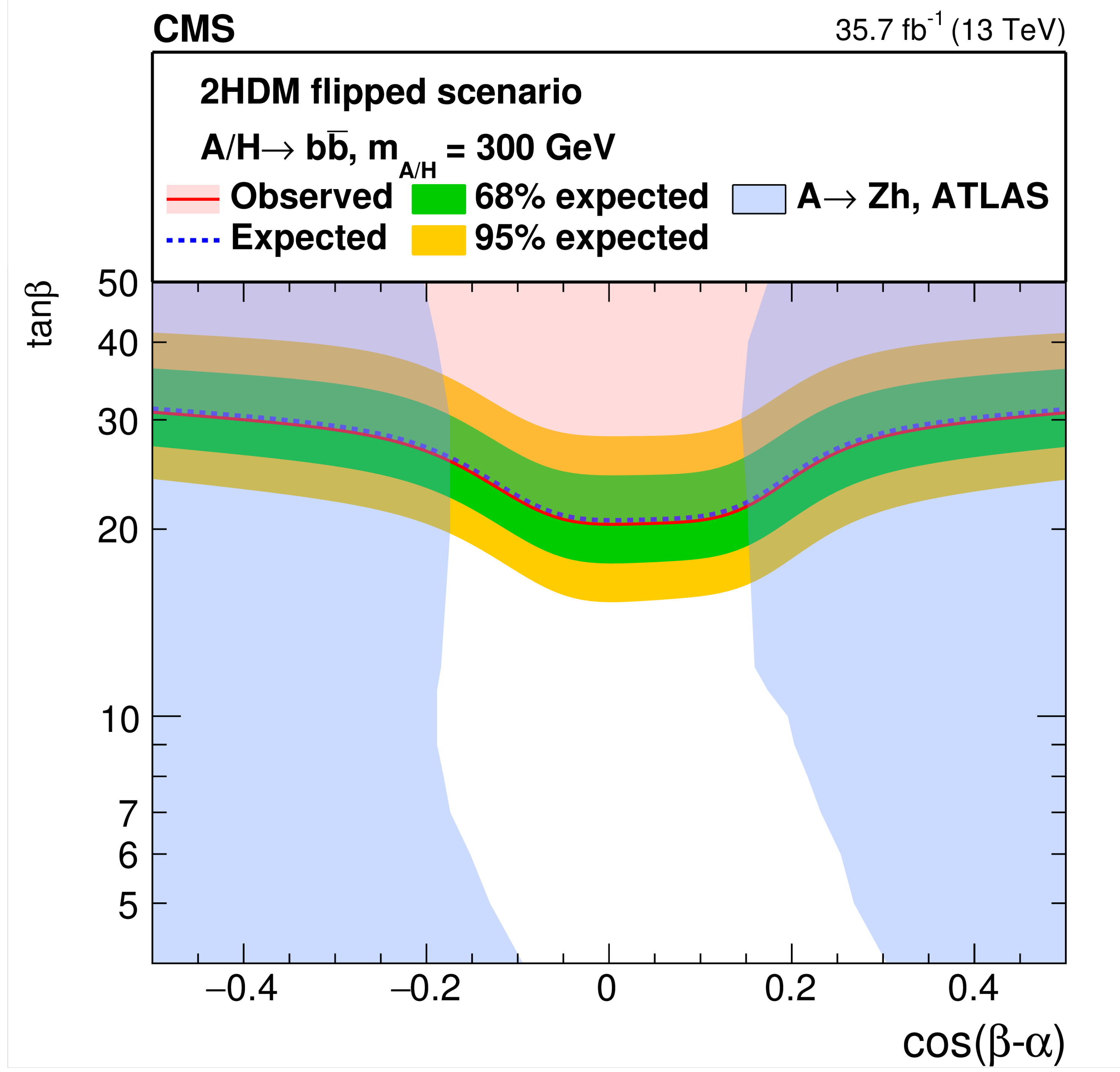
Results – 2HDM type II model

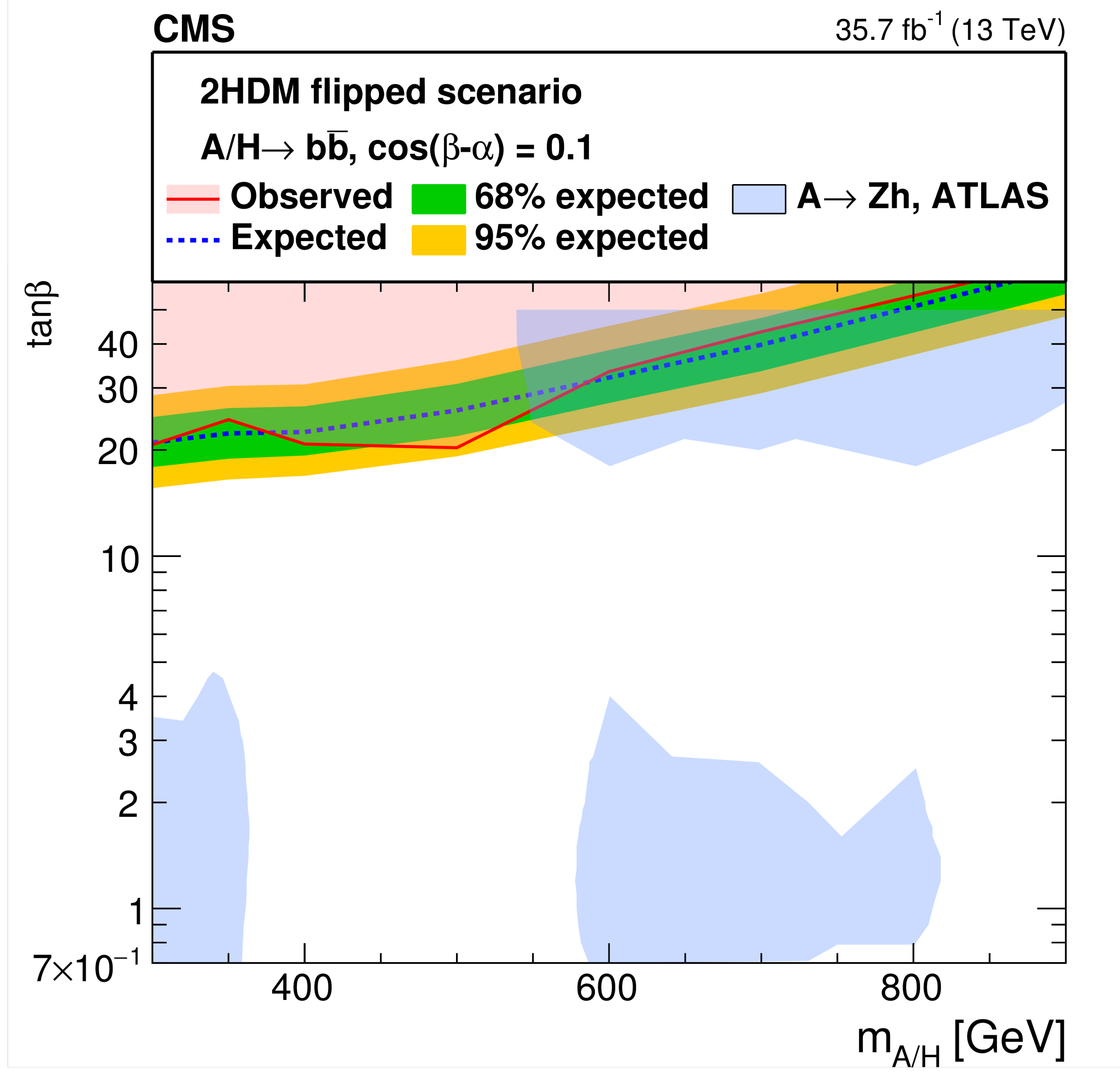
- Upper limits for the parameter tan β at 95% CL
  - 2HDM parameters "Scenario G"(1)
    - Additional assumptions: $m_A = m_H = m_{H\pm}$; $m_{12}^2 = 0.5\, m_A^2 \sin(2\beta)$
  - Strong constraints on tan β
  - Complementary A→Zh results from ATLAS(2) also shown

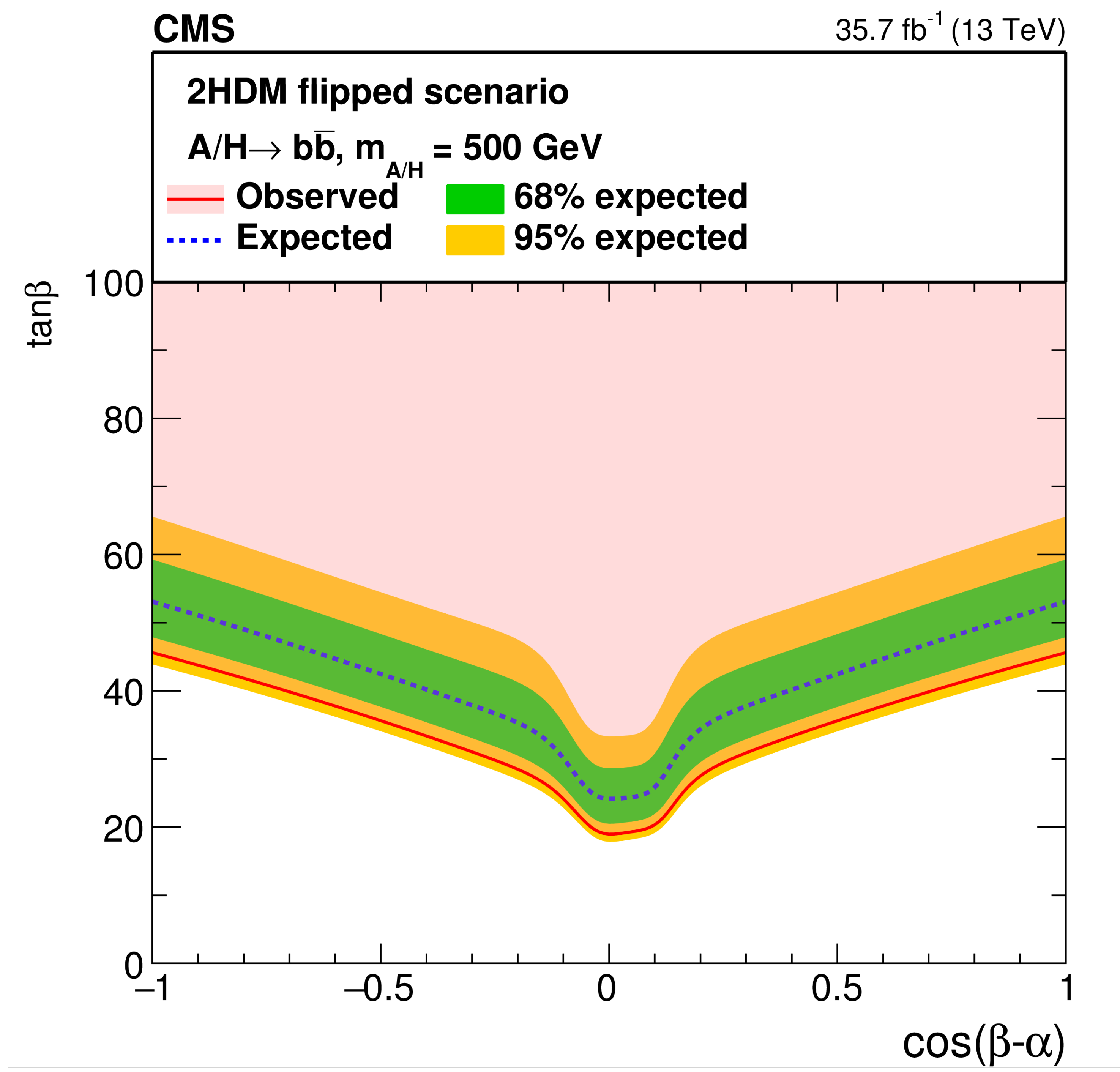


(1) H. E. Haber, O. Stål, Eur. Phys. J. C 75 (2015) 491
(2) ATLAS, JHEP 03 (2018) 174   N.B. CMS HIG-18-005 not published by the time of our paper

Results – 2HDM flipped model







- Upper limits for the parameter tan β at 95% CL
  - 2HDM parameters "Scenario G”(1)
    - Additional assumptions: $m_A = m_H = m_{H\pm}$; $m_{12}^2 = 0.5\, m_A^2 \sin(2\beta)$
  - Strong unique constraints on tan β
  - Complementary A→Zh results from ATLAS(2) also shown

(1) H. E. Haber, O. Stål, Eur. Phys. J. C 75 (2015) 491
(2) ATLAS, JHEP 03 (2018) 174   N.B. CMS HIG-18-005 not published by the time of our paper

Summary

- A search for BSM Higgs → $b\bar{b}$ produced in association with b-quark(s) in pp collision at 13 TeV was presented

- Unique analysis at the LHC!

- No significant excess was found in the data collected by CMS in 2016
  - 95% CL upper limits in the σ x BR(A/H→$b\bar{b}$) and in the tan β – m_A parameter space for several scenarios in 2HDM and MSSM
  - Improved sensitivity and extended mass reach with respect to Run I analyses
  - Strong unique limits on 2HDM flipped model

Thank you for your attention!

backup

Signal model

- *$pp \to b\bar{b}A + X$, with $A \to b\bar{b}$*
  - Leading order 4-flavour scheme with Pythia 8.212
  - Masses from 300 GeV to 1300 GeV
  - Signal M_{12} shape well described by parametrisations
    - double gaussian + exponential for $m_{A/H}$ = 300 GeV – 500 GeV
    - double gaussian on each side of the peak + exponential for $m_{A/H}$ = 600 GeV
    - Bukin function for $m_{A/H}$ = 700 GeV – 1300 GeV (see right)
  - Mass-dependent next-to-leading-order corrections to signal efficiency applied
    - (MadGraph5_aMC@NLO 2.3.0)

$$f(M_{12}) = A_p \exp\left[-\ln 2 \frac{\ln^2\left(1+\sqrt{2}\xi\sqrt{\xi^2+1}\frac{(M_{12}-x_p)}{\sqrt{\ln 2}\sigma_p}\right)}{\ln^2\left(1+2\xi(\xi-\sqrt{\xi^2+1})\right)}\right],$$

$$\text{if } x_1 < M_{12} < x_2, \quad (5)$$

$$f(M_{12}) = A_p \exp\left[\pm\frac{\xi\sqrt{\xi^2+1}(M_{12}-x_i)\sqrt{2\ln 2}}{\sigma_p \ln(\sqrt{\xi^2+1}+\xi)\left(\sqrt{\xi^2+1}\mp\xi\right)^2} + \rho_i\left(\frac{M_{12}-x_i}{x_p-x_i}\right)^2 - \ln 2\right],$$

$$\text{if } M_{12} \le x_1 \text{ or } M_{12} \ge x_2, \quad (6)$$

where $\rho_i = \rho_1$ and $x_i = x_1$ for $M_{12} \le x_1$, $\rho_i = \rho_2$ and $x_i = x_2$ when $M_{12} \ge x_2$, and:

$$x_{1,2} = x_p + \sigma_p\sqrt{2\ln 2}\left(\frac{\xi}{\sqrt{\xi+1}} \mp 1\right). \quad (7)$$

The parameters x_p and σ_p are the peak position and width, respectively, and ξ is an asymmetry parameter.

Background model - parametrisations

- Subrange 1:
  - Product of a Gaussian error function $f(M_{12}) = 0.5\left[\mathrm{erf}(\mathrm{p_0}[\mathrm{M_{12}} - \mathrm{p_1}]) + 1\right]$, where $\mathrm{erf(x)} = \frac{2}{\sqrt{\pi}}\int_0^{\mathrm{x}} \mathrm{e^{-t^2}dt}$, to describe the turn-on, and an extended Novosibirsk (below) to describe the falling part of the spectrum

$$g(M_{12}) = p_2 \exp\left(-\frac{1}{2\sigma_0^2}\ln^2[1 - \frac{M_{12}-p_3}{p_4}p_5 - \frac{(M_{12}-p_3)^2}{p_4}p_5p_6] - \frac{\sigma_0^2}{2}\right)$$

$\sigma_0 = \frac{2}{\xi}\sinh^{-1}(p_5\xi/2)$, where $\xi = 2\sqrt{\ln 4}$.

- Subranges 2 and 3:
  - The non-extended Novosibirsk was chosen, i.e., $p_6 = 0$, without turn on factor

- Bias studies, alternative functions
  - Bernstein polynomials
  - Dijet function