ICHEP2018 SEOUL
XXXIX INTERNATIONAL CONFERENCE ON high energy PHYSICS
JULY 4 - 11, 2018 COEX, SEOUL

Search for extended Higgs boson sectors at CMS

Chayanit Asawatangtrakuldee (DESY)
on behalf of the CMS Collaboration

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Extended Higgs sectors

★ Many BSM theories introduced to solve several phenomena not explained by the SM

- e.g. 2HDM → the simplest extension of the SM Higgs sector

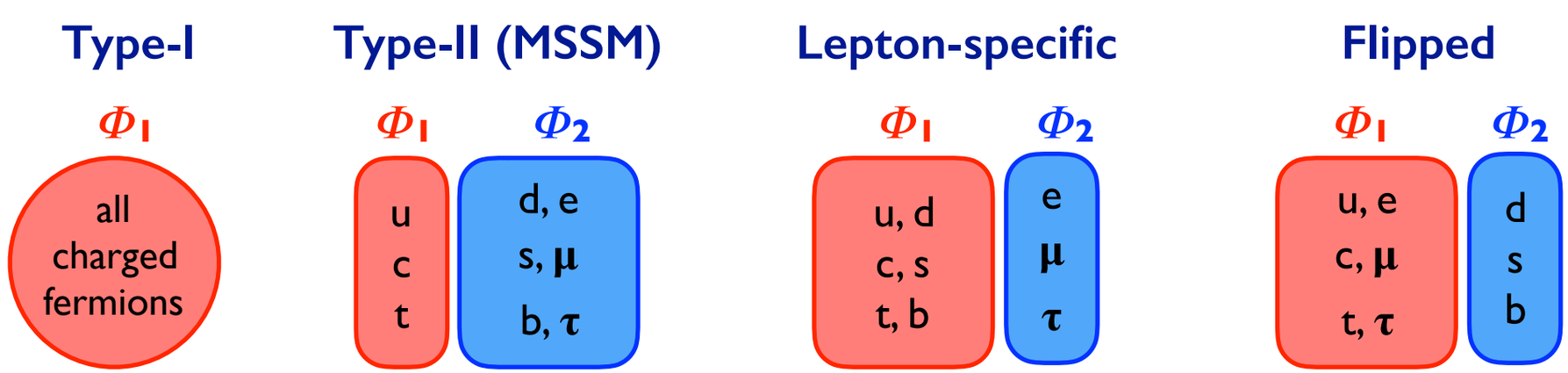
★ **Two Higgs Doublet Models (2HDM)** extend the SM with another scalar doublet

2 doublets	CP-even	CP-odd	Charged
Φ_1 Φ_2	H, h	A	$H^{\pm}$

- $\tan\beta$: the ratio of the vev of the two doublets
- α : the mixing angle of the two doublets

\+ other parameters

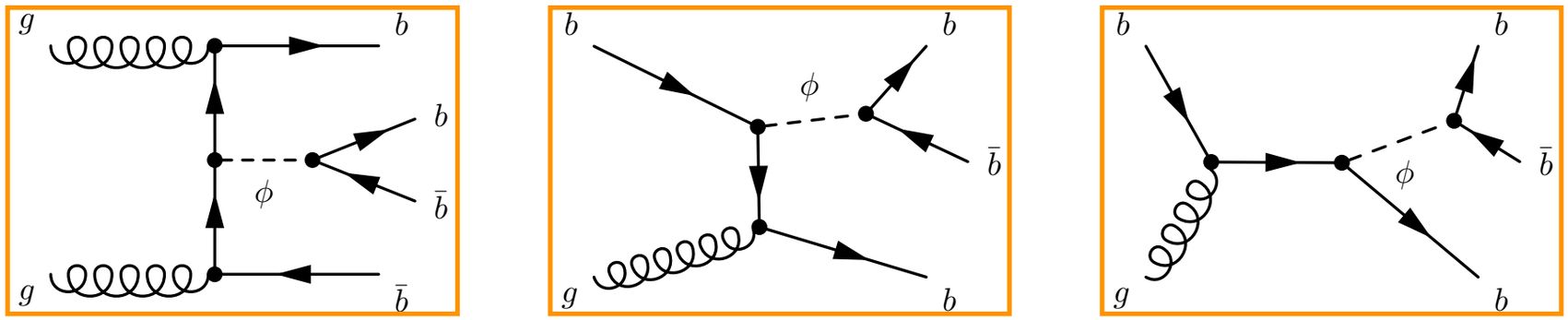
★ **4 types of 2HDM** with natural flavor and CP conservation, depending on how two Higgs doublets couple to the SM particles



arXiv:1805.12191

$A/H \rightarrow b\bar{b}$

- ★ Search for heavy A/H Higgs bosons in bb final state **with 35.7 fb^{-1} at 13TeV**
  - unique analysis at the LHC
  - dominant decay channel in large parameter space of MSSM and 2HDM

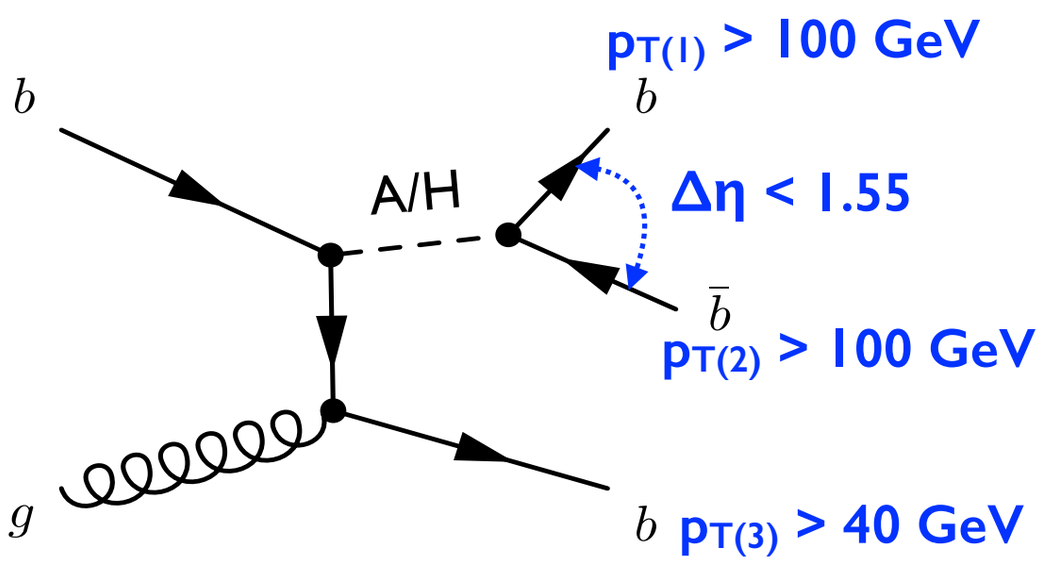


signal processes

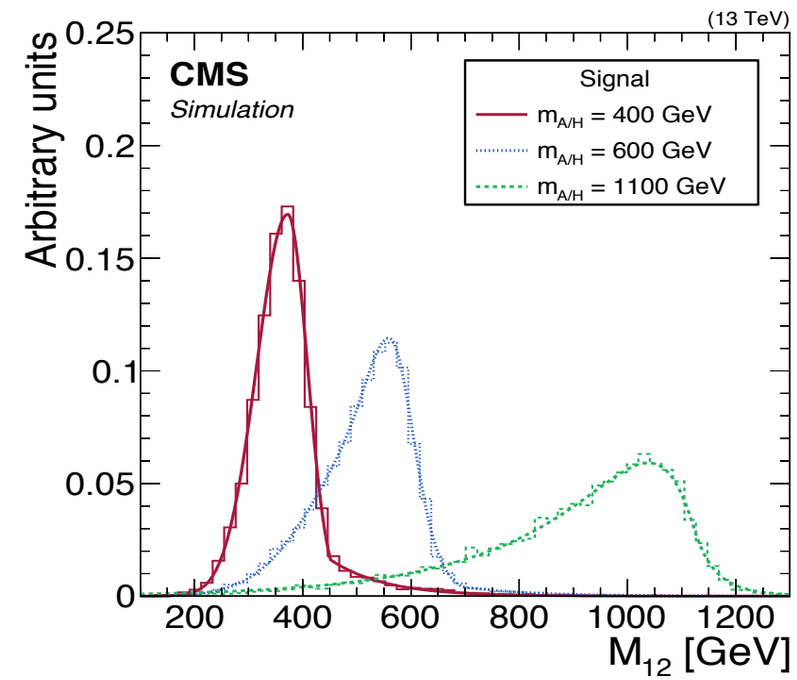
- ★ Sensitivity enhanced with **b-associated production**
  - cross-section up to ~2 $\tan^2\beta$
- ★ Dedicated triggers requiring **two online b-tagged jets**
- ★ Main challenge from **huge rate of QCD multijet background**
  - data-driven parametric approach developed in control region (CR)

A/H → $b\bar{b}$

★ Event offline selection requires at least **3 leading p_T jets to be b-tagged**

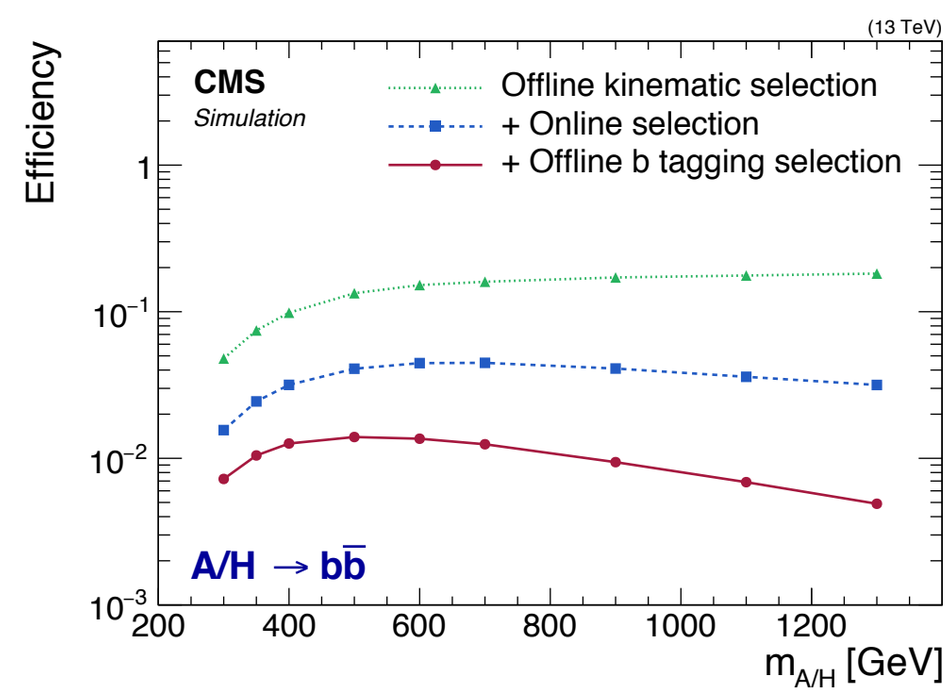


*CR: veto b-tag on the 3rd jet



★ Signal reconstructed from the **invariant mass of two leading b-jets (M_{12})**

- signal mass range $m_{A/H}$ from 300 to 1300 GeV

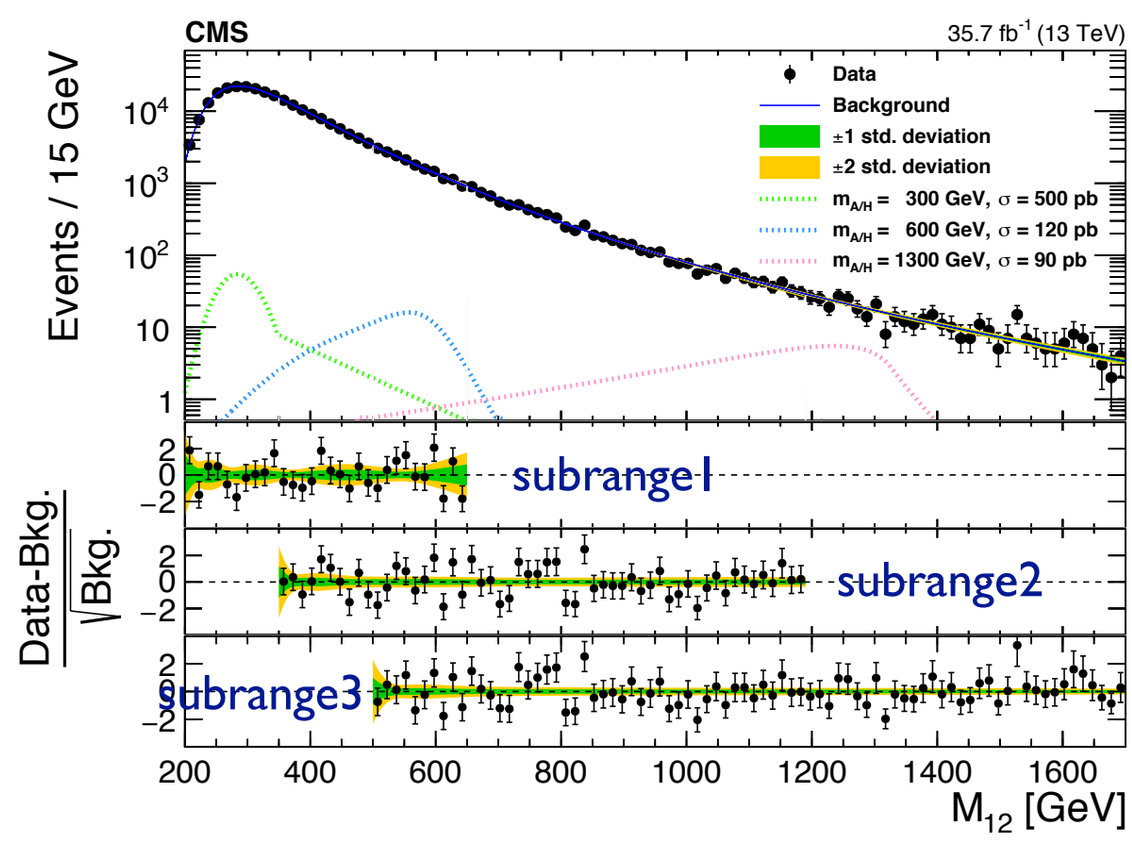


★ Signal efficiency ~ 0.5% up to **1.4% at 500 GeV**

arXiv:1805.12191

$A/H \rightarrow b\bar{b}$

- ★ Model **QCD multijet background** using **analytical function** developed in CR
  - well described by **Novosibirsk-style functions**
  - **subrange division** designed to reduce bias uncertainty
- ★ **Systematic uncertainties** dominated by trigger efficiency, b-tagging efficiency and background model bias
- ★ Perform a **maximum likelihood fit to M_{12}** distribution
- ★ Data is well fitted by background model
- ★ **No significant excess** is observed

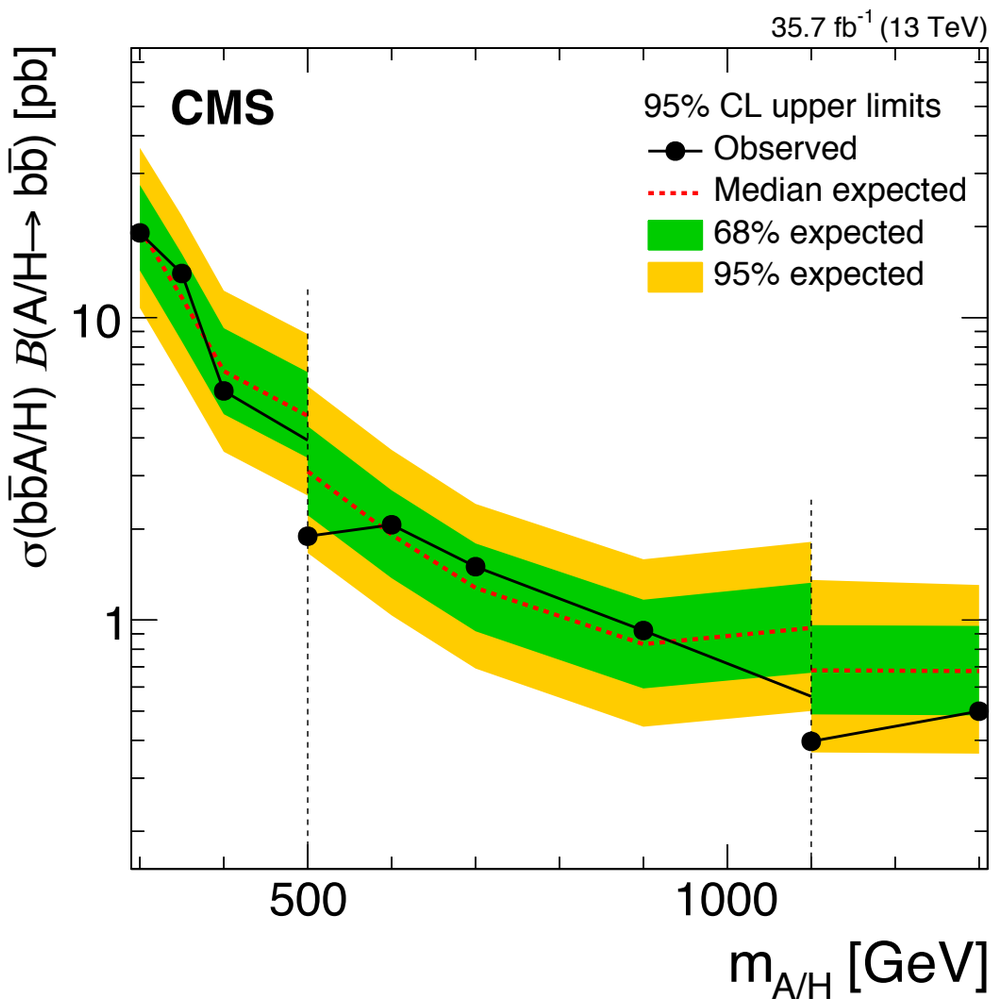


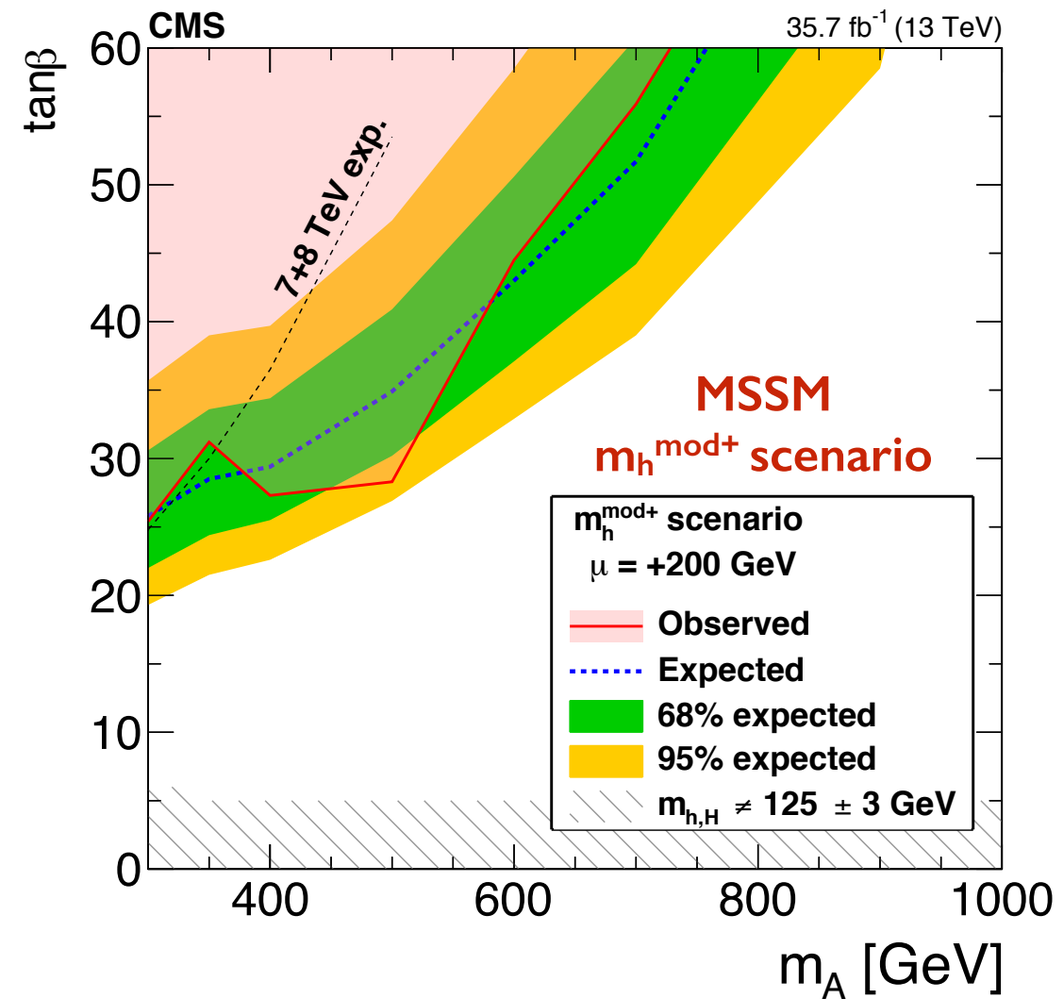
arXiv:1805.12191

$A/H \rightarrow b\bar{b}$

- ★ Upper limits at 95% CL on the **cross section times branching fraction**
  - 20 pb at $m_{A/H}$ = 300 GeV to 0.4 pb at $m_{A/H}$ = 1100 GeV
  - achieved **the best sensitivity** in this channel to date

- ★ Interpretation in various **MSSM scenarios** e.g. m_h^{mod+} scenario



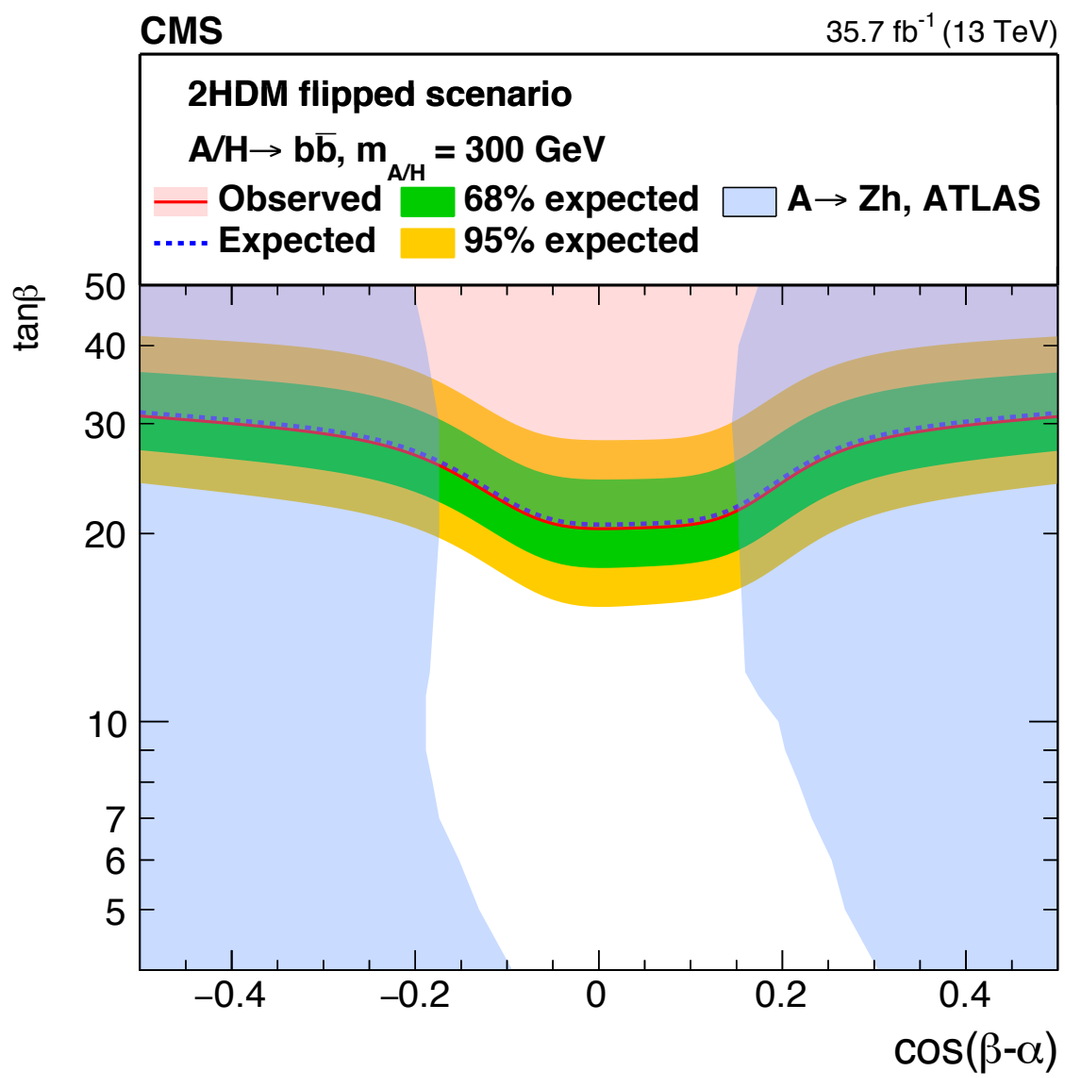


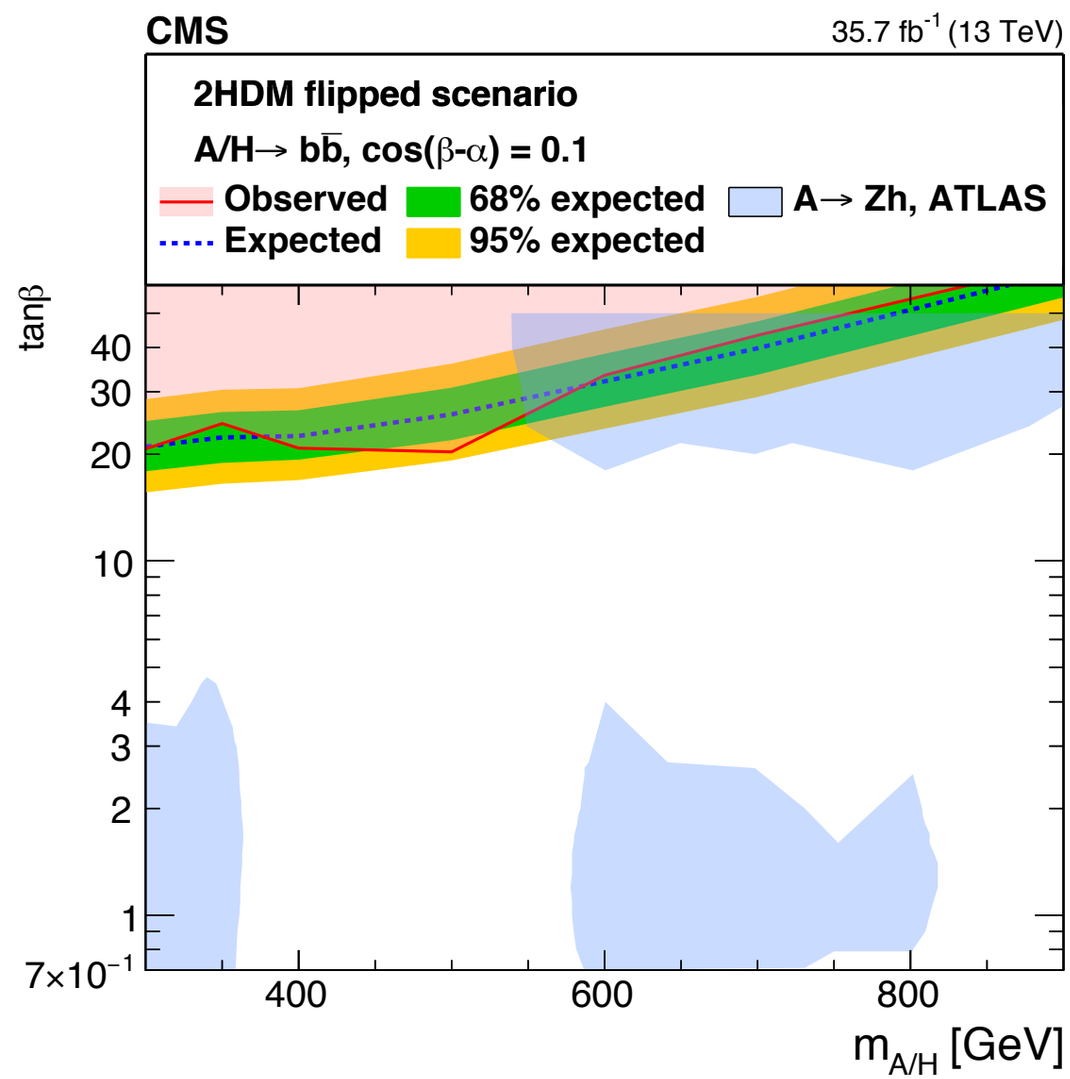
arXiv:1805.12191

A/H→$b\bar{b}$

★ Interpretation in 2HDM **Flipped model**

- **unique limits** for low cos(β-α) of the Flipped model
- complementary to A→Zh measurements**





* Type-II in backup slide ** JHEP 03 (2018) 174

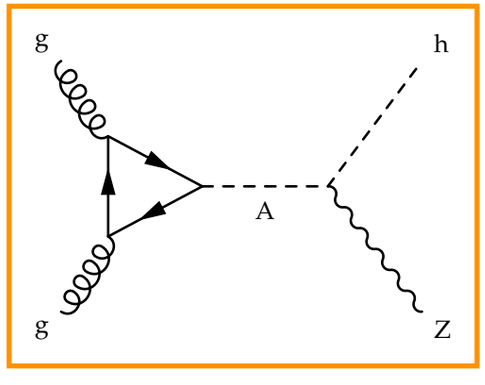
NEW

CMS PAS HIG-18-005

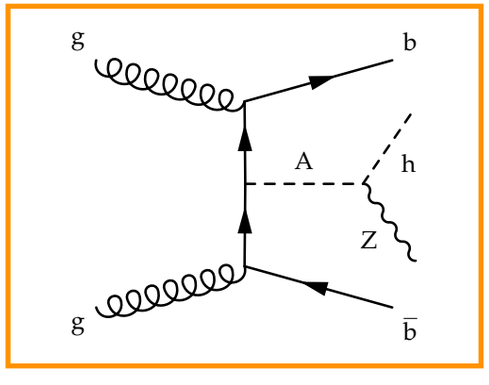
A→Z($\ell\ell$,$\nu\nu$)h($b\bar{b}$)

★ Search for A→Zh with 35.9 fb^{-1} at 13 TeV

- Z → ee, μμ : clean final states
- Z → νν : additional sensitivity (Br ~20%)
- h → bb : treated as the SM-like Higgs boson
  - largest branching fraction



gluon fusion



b-association

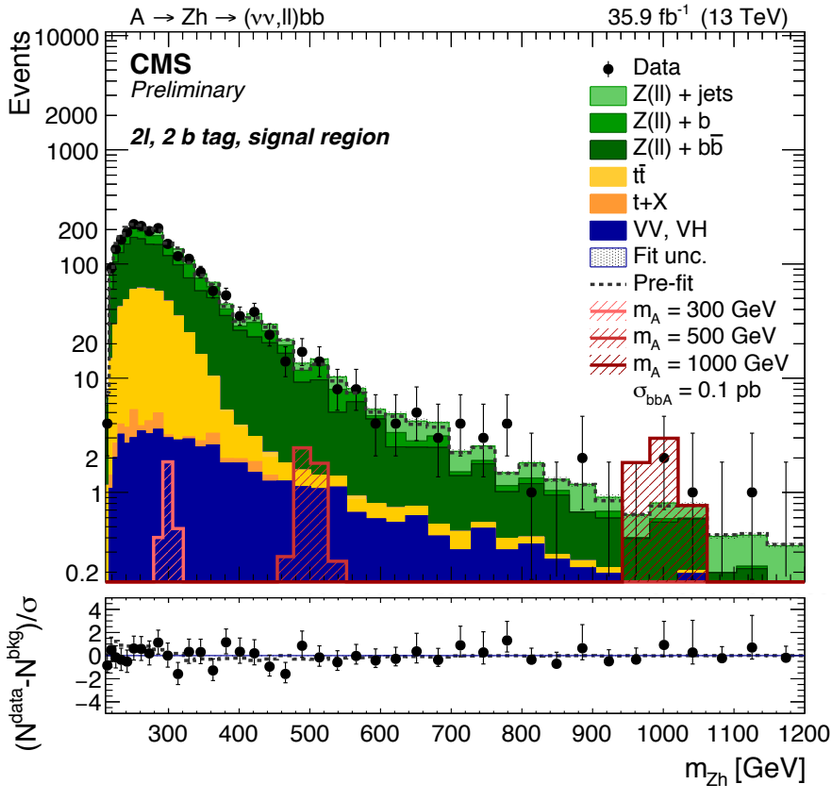
★ 2 production processes : gluon fusion and b-association

★ Event 6 categories : (0ℓ,2ℓ) x (1,2,3 b-tagged jets)

★ Maximize signal sensitivity with kinematic constraints, multivariate discriminators

★ Reconstruct A boson using the (transverse) invariant mass of Zh system

- signal mass range : m_A from 225 to 1000 GeV

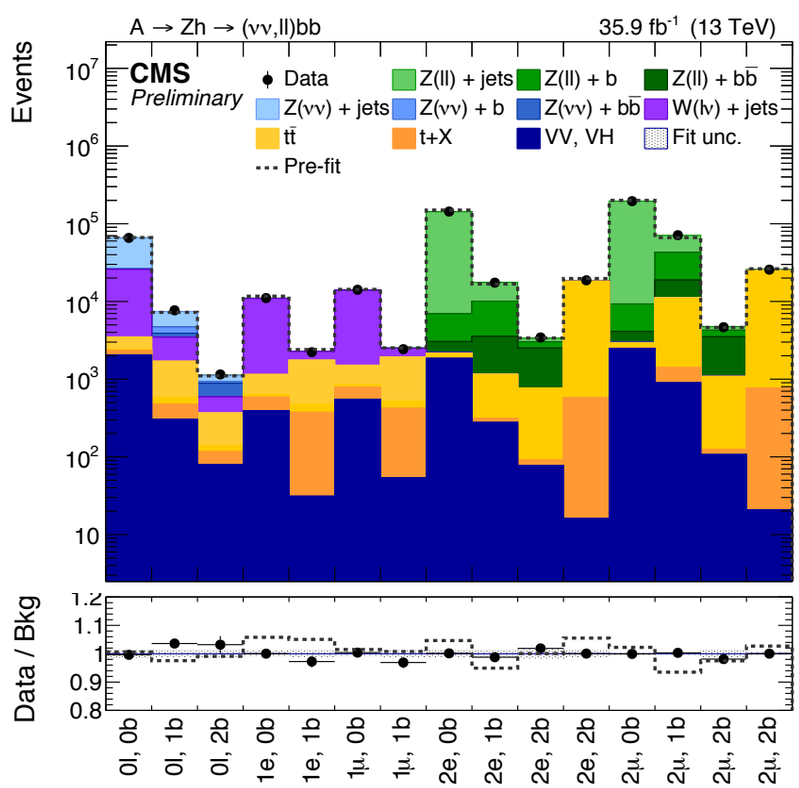


NEW

CMS PAS HIG-18-005

$A \rightarrow Z(\ell\ell,\nu\nu)h(b\bar{b})$

- ★ Overall **signal efficiency** after selection ~10–20%
- ★ **Background estimation** using data and MC
  - main backgrounds from Z+jets, W+jets and tt processes
  - introduce CRs to constrain main backgrounds normalization in the final fit
- ★ Perform **simultaneous fit of SR + CR** for the presence of signal



★ Data is well described by SM processes

Signal region	0ℓ, 1 b tag	0ℓ, 2 b tags	0ℓ, 3 b tags	2ℓ, 1 b tag	2ℓ, 2 b tags	2ℓ, 3 b tags
Data	2452 ± 50	398 ± 20	45 ± 7	10512 ± 103	2188 ± 47	129 ± 11
Z +jets	740 ± 12	48 ± 1	2.0 ± 0.2	4118 ± 15	175 ± 1	18 ± 1
Z +b	220 ± 6	13 ± 1	0.46 ± 0.06	4127 ± 18	365 ± 3	23 ± 1
Z +$b\bar{b}$	134 ± 3	86 ± 2	2.5 ± 0.3	1547 ± 11	1113 ± 7	51 ± 2
single top	74 ± 3	18 ± 1	3.0 ± 0.4	25 ± 0	10.0 ± 0.1	-
$t\bar{t}$	750 ± 12	143 ± 3	31 ± 3	592 ± 3	473 ± 3	26 ± 1
VV, Vh	76 ± 2	32 ± 1	0.93 ± 0.11	139 ± 1	53 ± 1	3.5 ± 0.1
W +jets	458 ± 13	65 ± 3	2.4 ± 0.3	3.7 ± 0.1	-	-
Total bkg.	2451 ± 26	405 ± 8	42 ± 5	10552 ± 35	2189 ± 12	121 ± 3
Pre-fit bkg.	2467 ± 26	427 ± 8	28 ± 5	10740 ± 35	2250 ± 12	100 ± 3
$m_A = 300$ GeV	-	-	-	3.1 ± 0.2	3.3 ± 0.2	0.10 ± 0.01
$m_A = 1000$ GeV	27.3 ± 5.2	28.6 ± 5.4	3.5 ± 0.7	5.4 ± 1.0	6.1 ± 1.2	1.2 ± 0.2

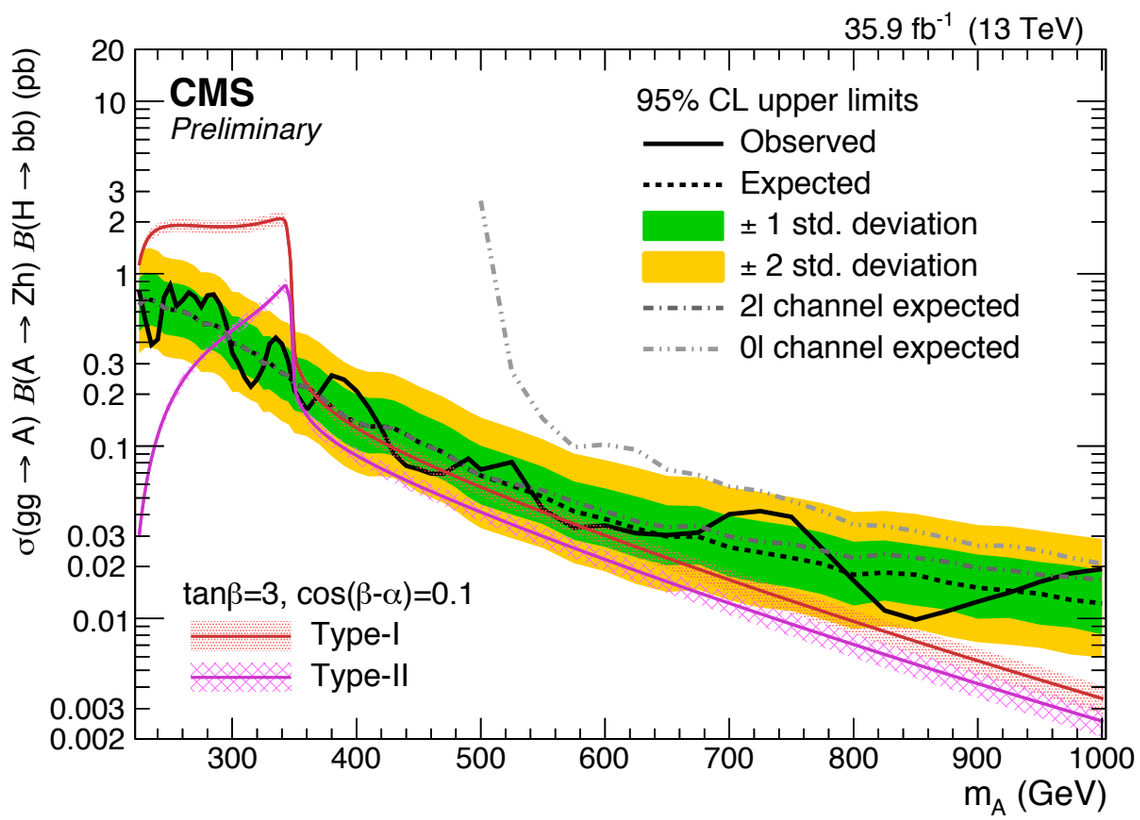
NEW

CMS PAS HIG-18-005

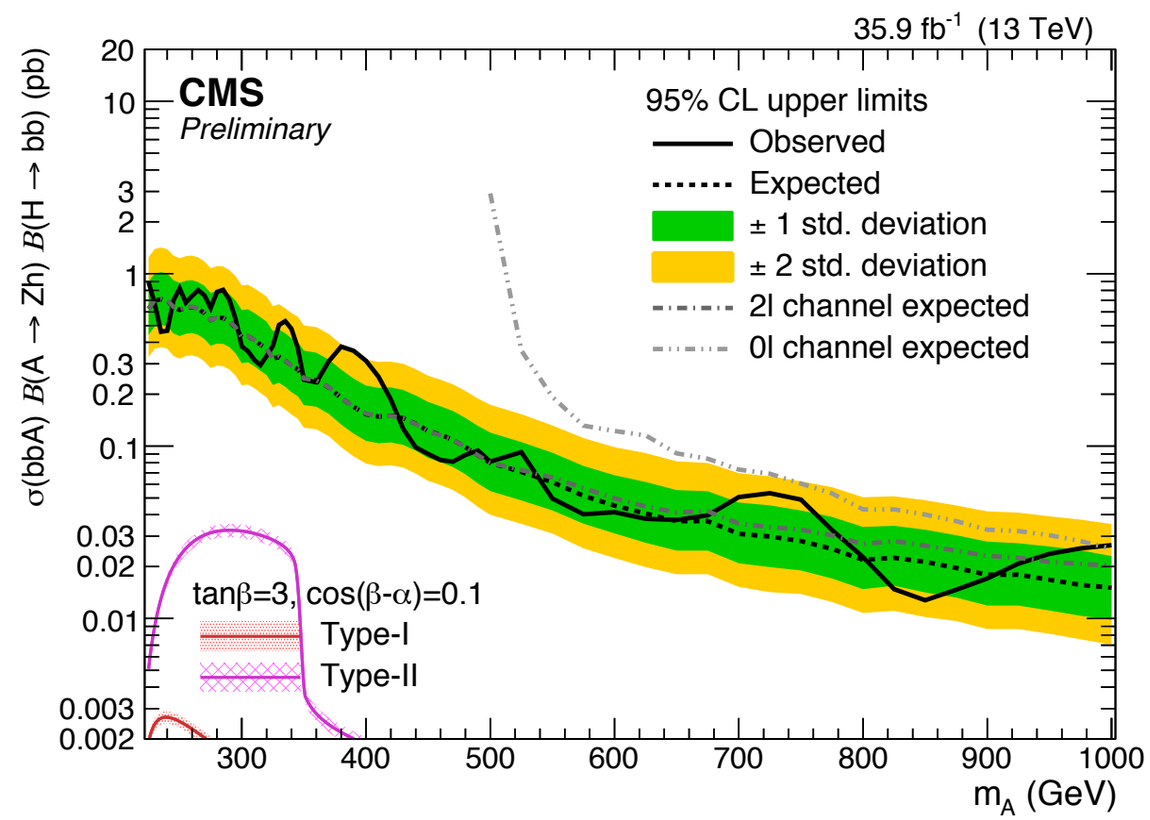
$A \rightarrow Z(\ell\ell, \nu\nu)h(b\bar{b})$

- ★ 95% CL upper limits on **cross-section times branching fraction**
  - **no excess is observed**
  - **stringent limits ranging from 1 to 0.01 pb** for 250 to 1000 GeV mass range

gluon fusion production



b-associated production



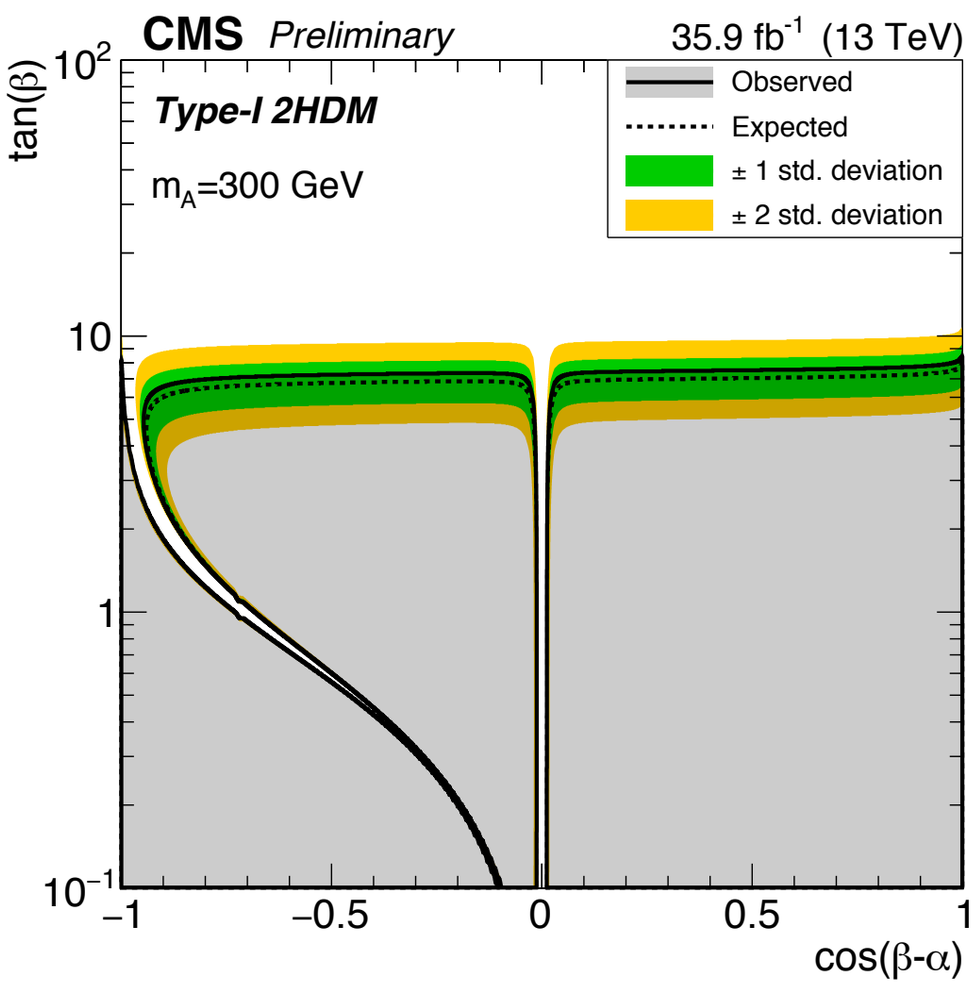
NEW

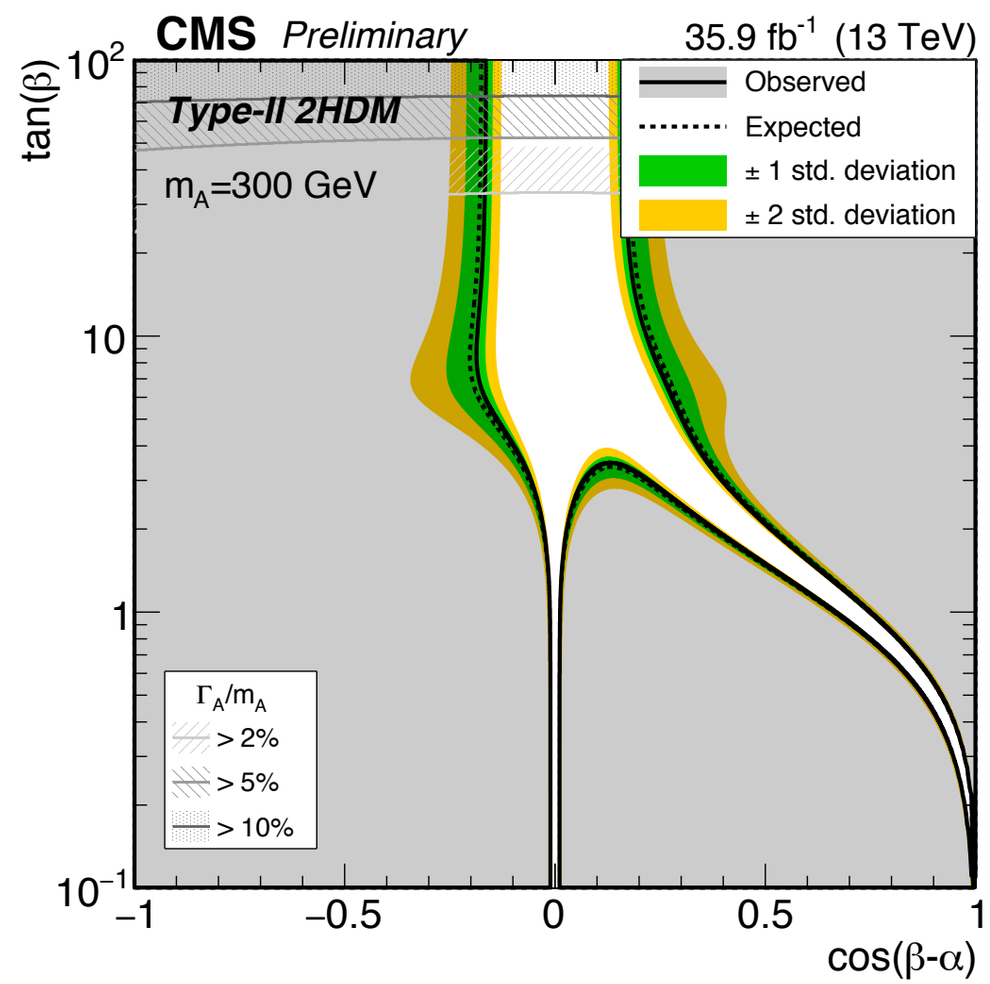
CMS PAS HIG-18-005

$A \rightarrow Z(\ell\ell,\nu\nu)h(b\bar{b})$

★ Interpretation in 2HDM Type-I and Type-II models*

- exclusion limits on tanβ vs cos(β-α) for m_A = 300 GeV
- comparable results with ATLAS** but no excess is observed in CMS data





* Lepton-specific and Flipped models in backup ** JHEP 03 (2018) 174

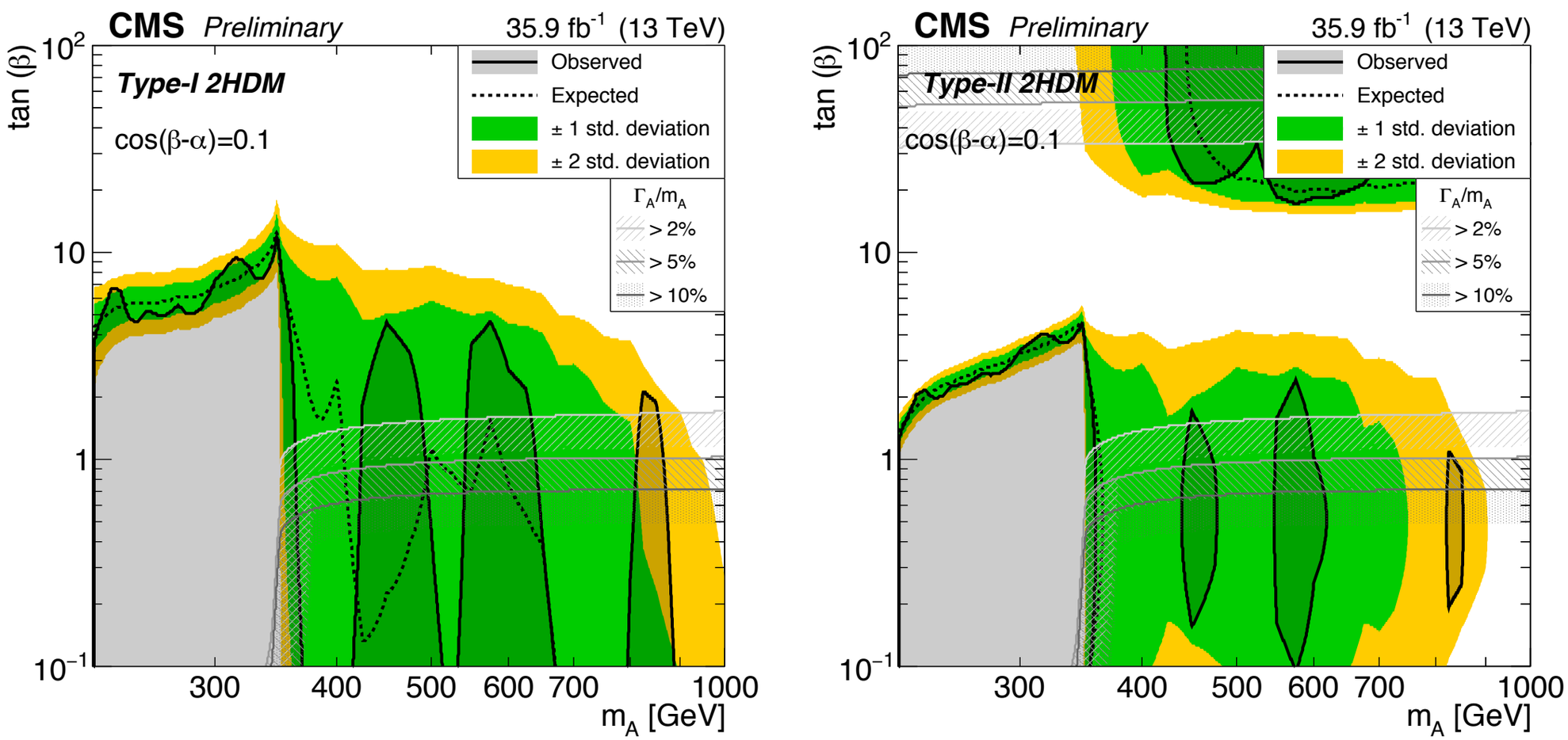
NEW

CMS PAS HIG-18-005

$A \rightarrow Z(\ell\ell,\nu\nu)h(b\bar{b})$

★ Interpretation in 2HDM Type-I and Type-II models*

- exclusion limits on tanβ vs m_A for cos(β-α) = 0.1
- the sensitivity extended up to 1 TeV compare to Run I analysis
- comparable results with ATLAS** but no excess is observed in CMS data



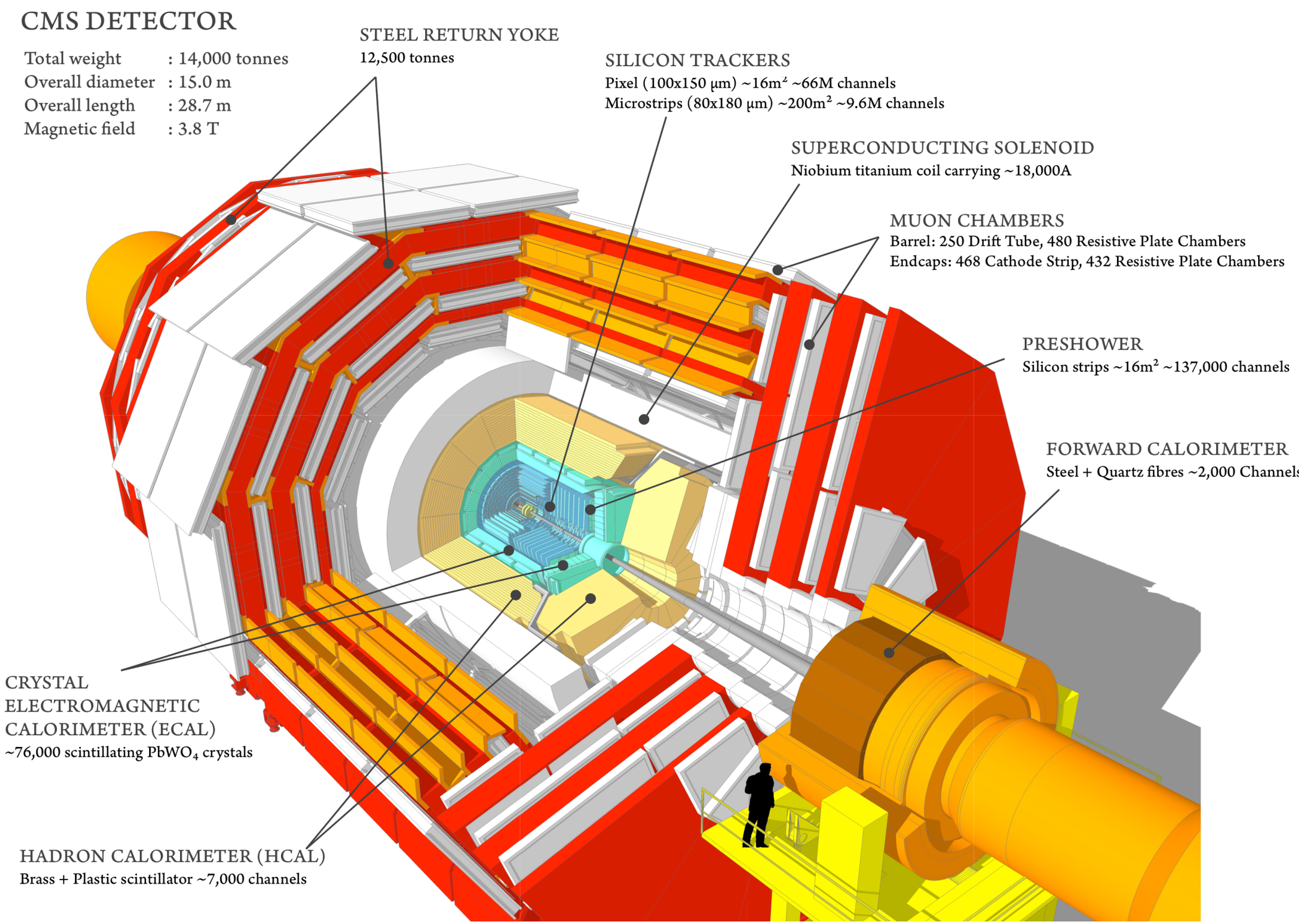
* Lepton-specific and Flipped models in backup ** JHEP 03 (2018) 174

Summary

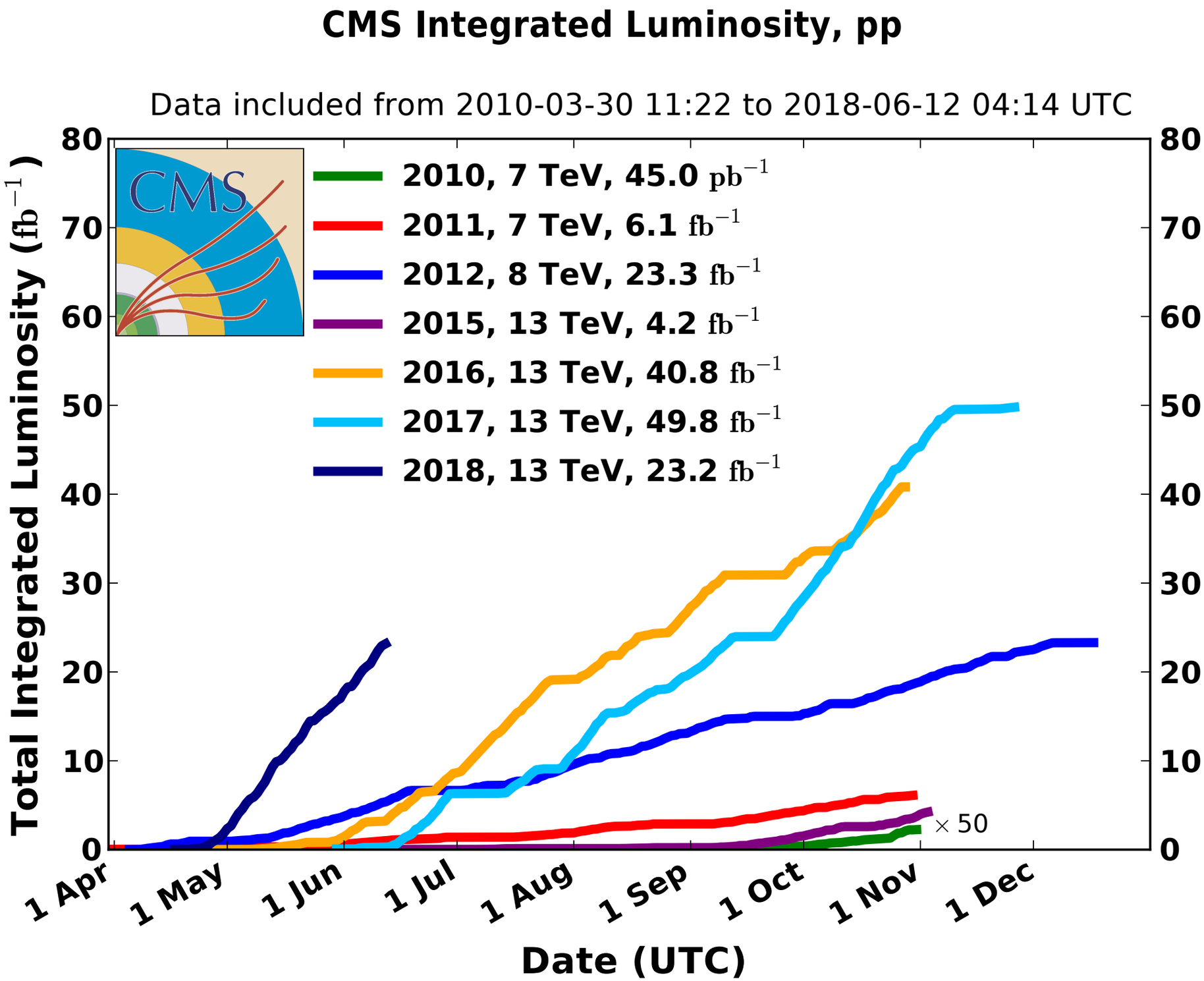
- ★ The latest results on search for extended Higgs sectors presented
- ★ No evidence for any BSM Higgs bosons is observed
  - sensitivity significantly increased after Run 1
- ★ Many improved results to come with full Run 2 data (>100 fb^{-1})
- ★ Follow the latest CMS results here
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Backup

Compact Muon Solenoid (CMS)



Luminosity 2011-2018



2HDM in the nutshell

- ★ Large number of free parameters: m_h, m_H, m_A, $m_{H(\pm)}$, m_{12}, β, α, $\lambda_{6,7}$

- ★ Recommendations from the Higgs Working Group:
  - ◉ $m_H = m_A = m_{H(\pm)}$: A searches not really dependent on m_H , $m_{H(\pm)}$ anyway
  - ◉ $m_{12}^2 = m_A(\tan\beta/1+\tan^2\beta)$: discrete Z_2 symmetry broken as in MSSM
  - ◉ $\lambda_{6,7} = 0$ to avoid CP-violation at tree level

- ★ Two parameters left other than mA:
  - ◉ α : mixing angle of the two doublets
  - ◉ $\tan\beta$: the ratio of the vev of the two doublets

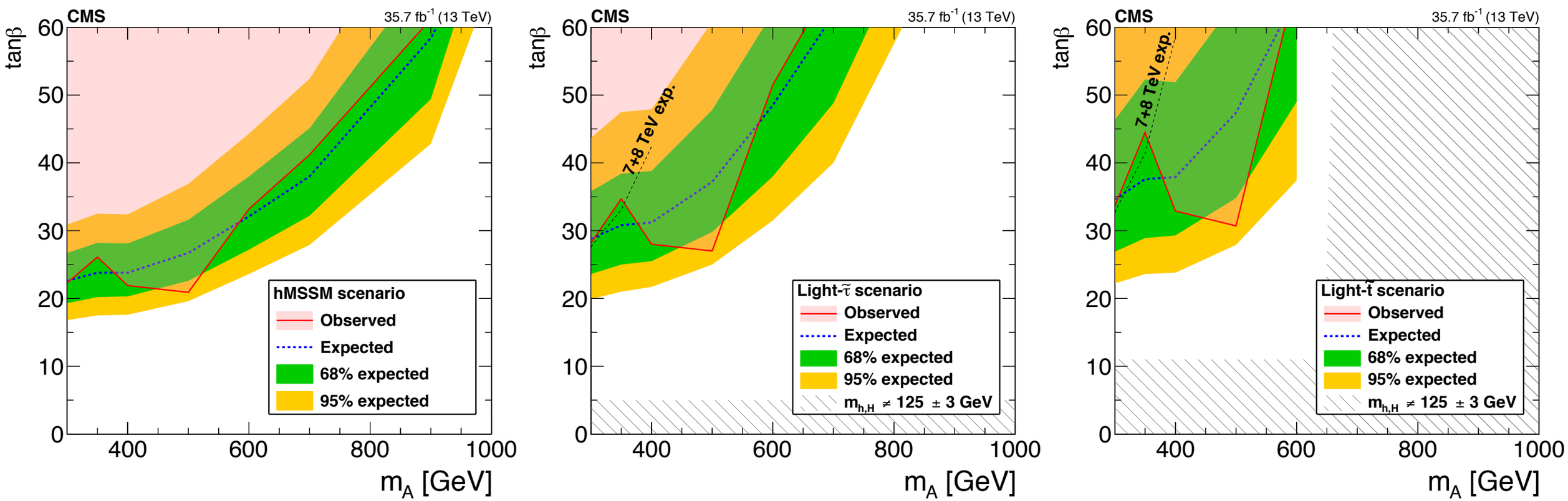
- ★ For each mass point, perform a scan in $\tan\beta$ and $\cos(\beta - \alpha)$
  - ◉ $0.1 < \tan\beta < 60$,
  - ◉ $-1 \leq \cos(\beta - \alpha) \leq 1$ $\qquad$ $0 \leq \beta - \alpha \leq \pi$

- ★ Cross sections and Br calculated at NNLO with SUSHI 1.6.1 and 2HDMC 1.7.0

arXiv:1805.12191

$A/H \rightarrow b\bar{b}$

- ★ Interpretation in MSSM **hMSSM, light stau and light stop scenarios**
  - first exclusion limits for hMSSM scenario in this channel
  - improve sensitivity for light stau and light stop with respect to Run 1

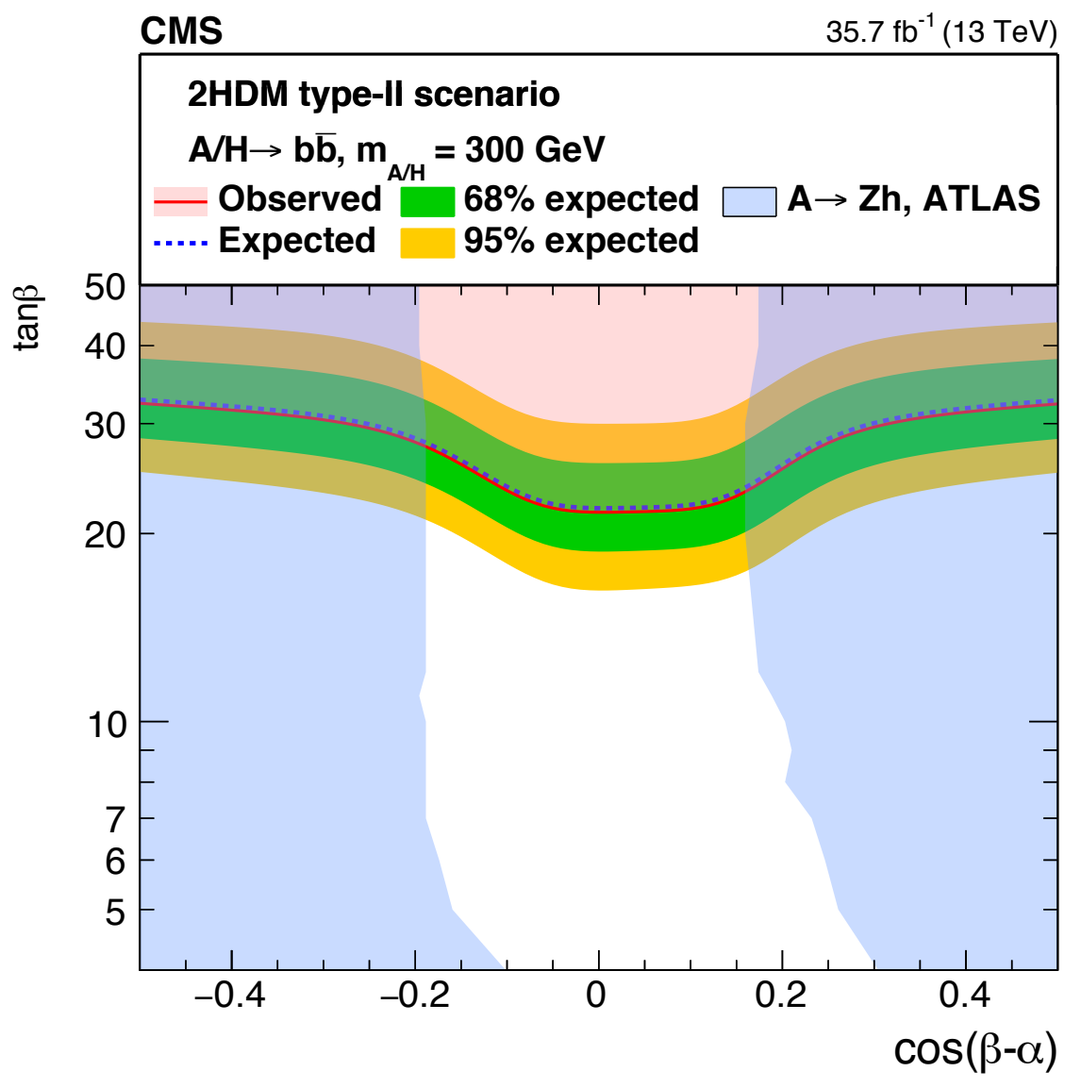


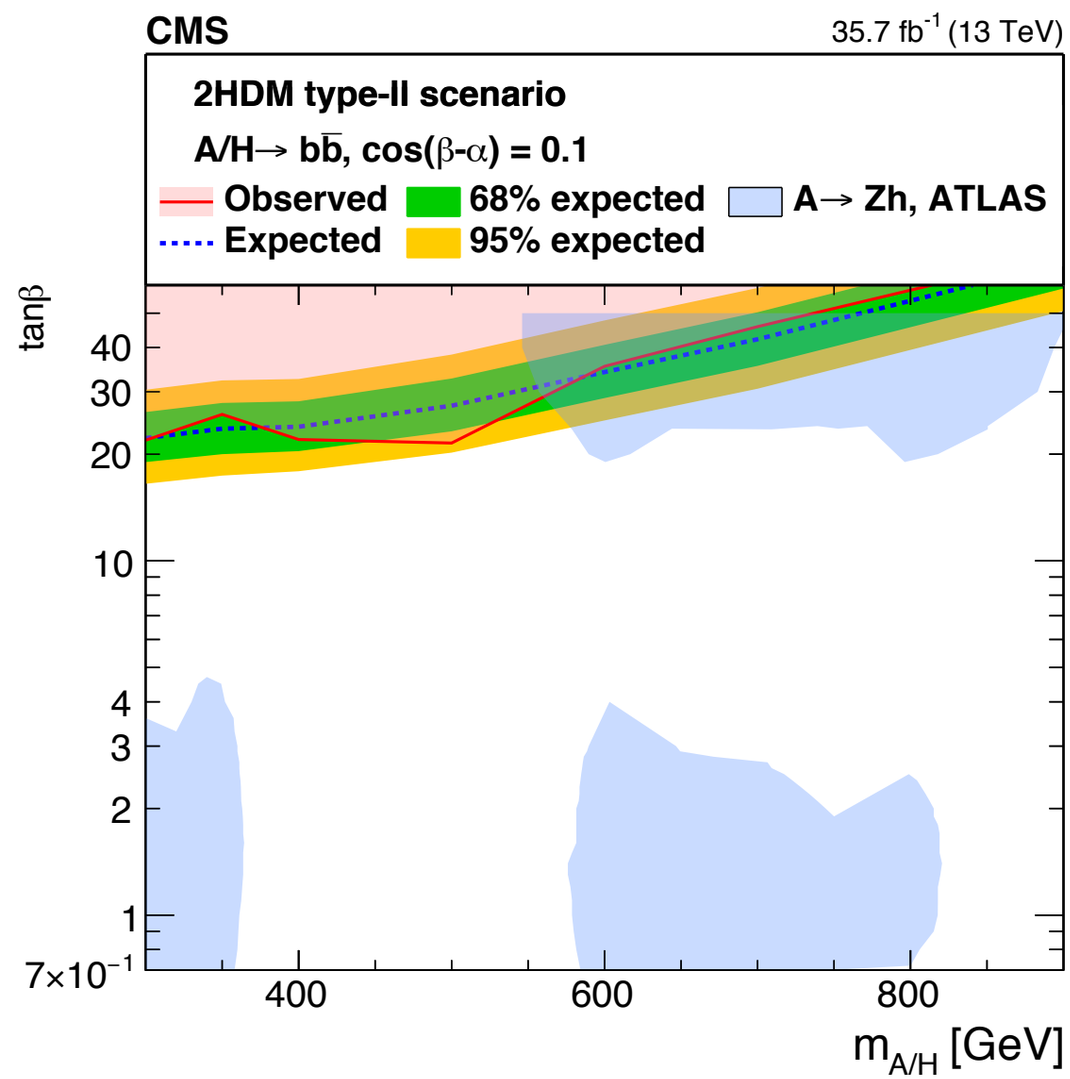
arXiv:1805.12191

A/H→$b\bar{b}$

★ Interpretation in 2HDM **Type-II model**

- complementary to A→Zh measurements*





* JHEP 03 (2018) 174

$A \rightarrow Z(\ell\ell,\nu\nu)h(b\bar{b})$

★ Systematic uncertainties

	Shape	Main backgrounds (Drell-Yan, $t\bar{t}$)	Other electroweak (single-top, VV, Vh)	Signal
Lepton and trigger efficiency	✓	-	2-3%	2-3%
Jet Energy Scale	✓	-	5%	2-6%
Jet Energy Resolution	✓	-	2%	1-2%
b-tagging	✓	-	4%	4-12%
Unclustered p_T^{miss}	✓	-	1%	1%
Pile-up	✓	-	1%	1%
PDF	✓	-	3-5%	4-8%
top quark p_T	✓ (only $t\bar{t}$)	8–15%	-	-
Factorization and renormalization scale	✓	2-6%		6-14%
Monte Carlo modeling	✓	1-15 %		-
Monte Carlo statistics	✓	1–20%		-
Interpolation to SR		2–10%		-
Extrapolation to 3 b-tag SR		20–46% (3 b-tag only)		-
Cross section		-	2-10%	-
Luminosity		-	2.5%	2.5%

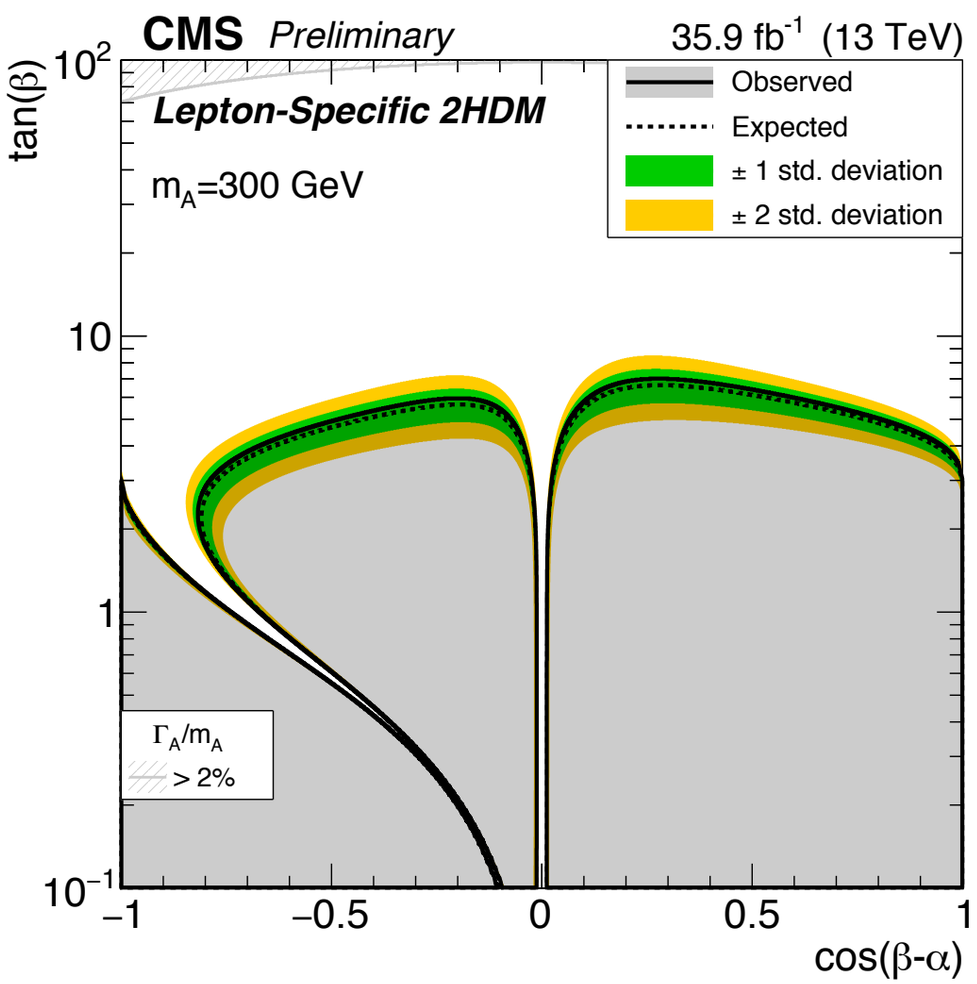
NEW

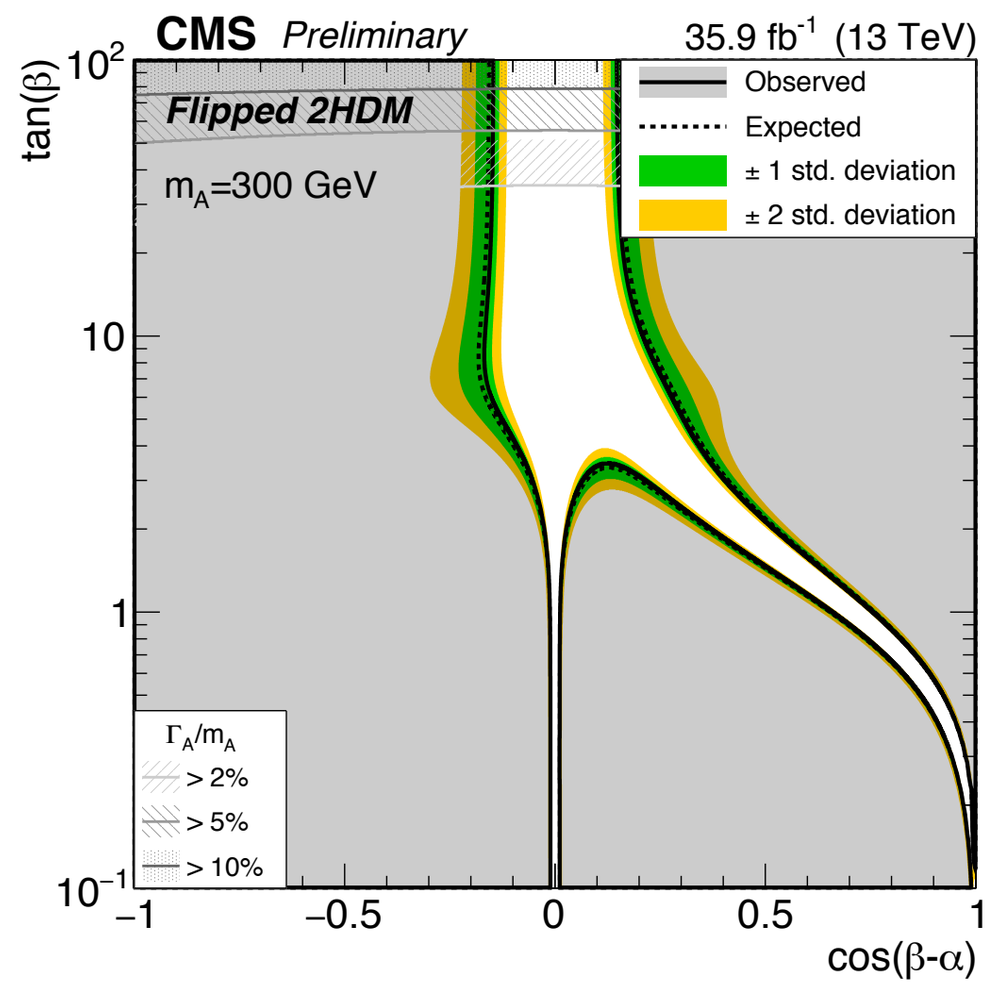
CMS PAS HIG-18-005

$A \rightarrow Z(\ell\ell,\nu\nu)h(b\bar{b})$

★ Interpretation in 2HDM Lepton-specific and Flipped models

- exclusion limits on tanβ vs cos(β-α) for m_A = 300 GeV
- comparable results with ATLAS* but no excess is observed in CMS data





* JHEP 03 (2018) 174

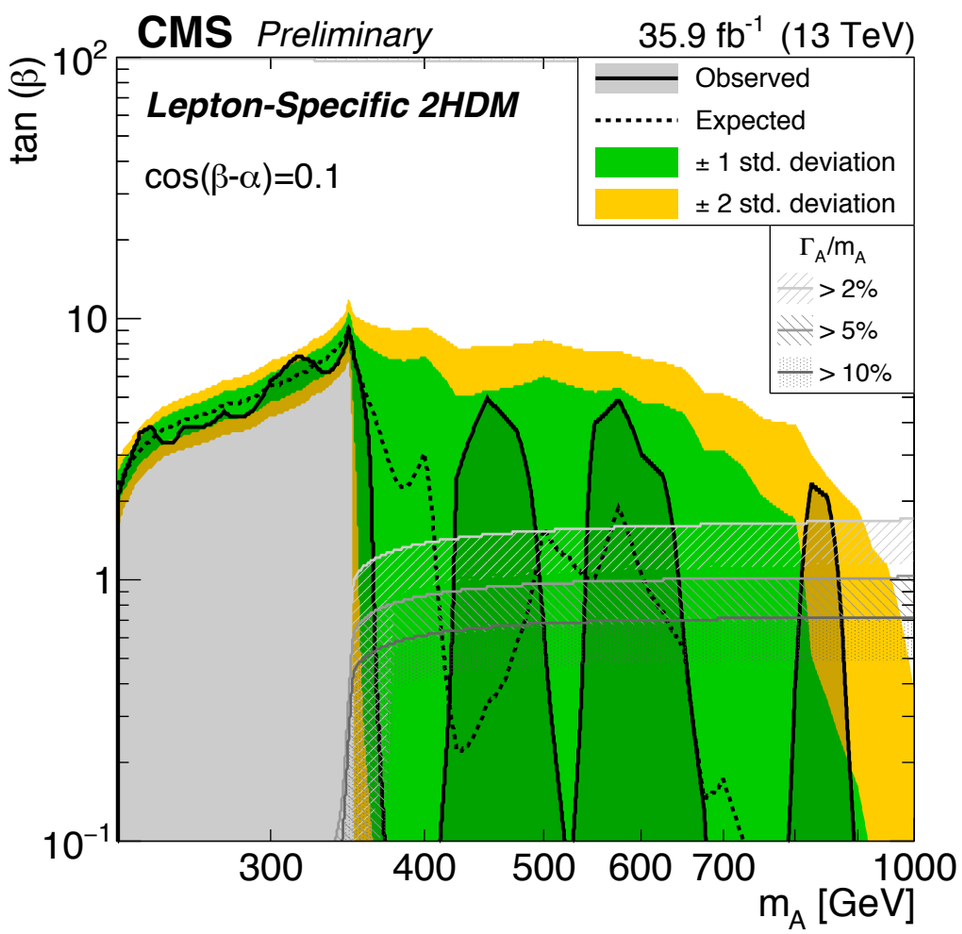
NEW

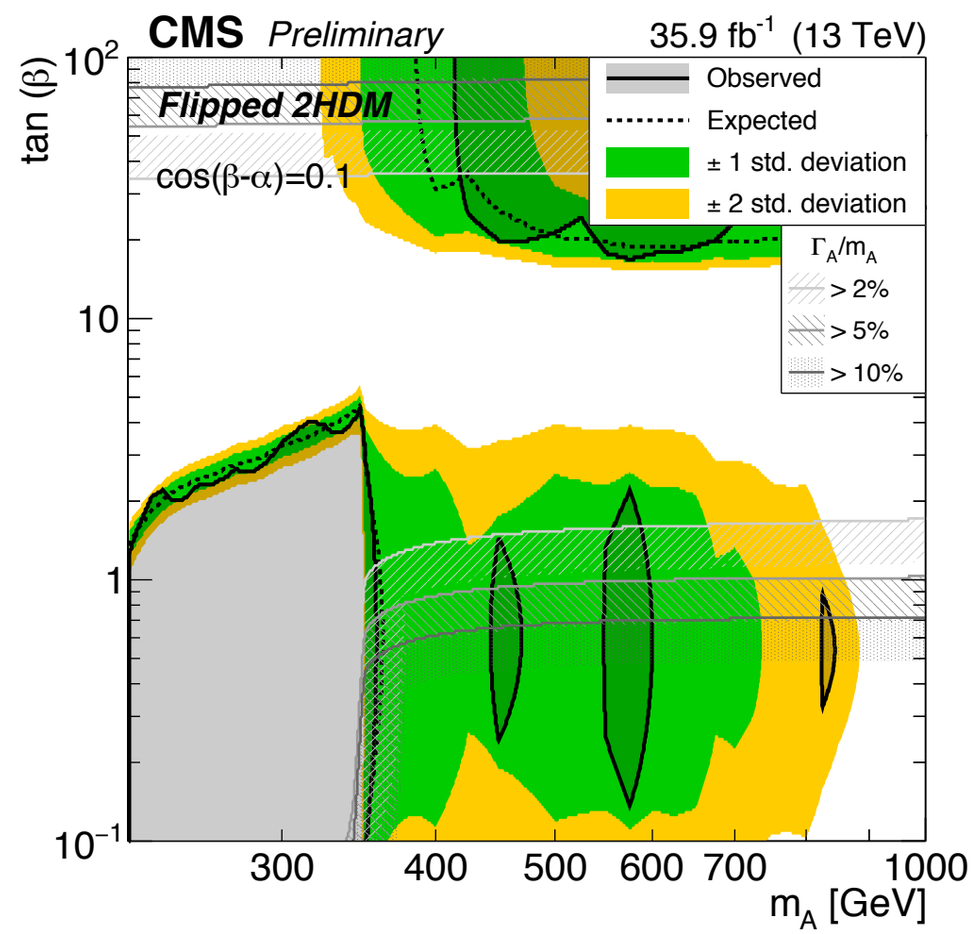
CMS PAS HIG-18-005

$A \rightarrow Z(\ell\ell,\nu\nu)h(b\bar{b})$

★ Interpretation in 2HDM Lepton-specific and Flipped models

- exclusion limits on tanβ vs m_A for cos(β-α) = 0.1
- the sensitivity extended up to 1 TeV compare to Run I analysis
- comparable results with ATLAS** but no excess is observed in CMS data





* JHEP 03 (2018) 174