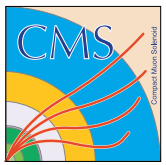
Searches for Neutral 2HDM, MSSM and NMSSM Higgs Bosons at the LHC

The Third Annual Large Hadron Collider Physics Conference
St. Petersburg

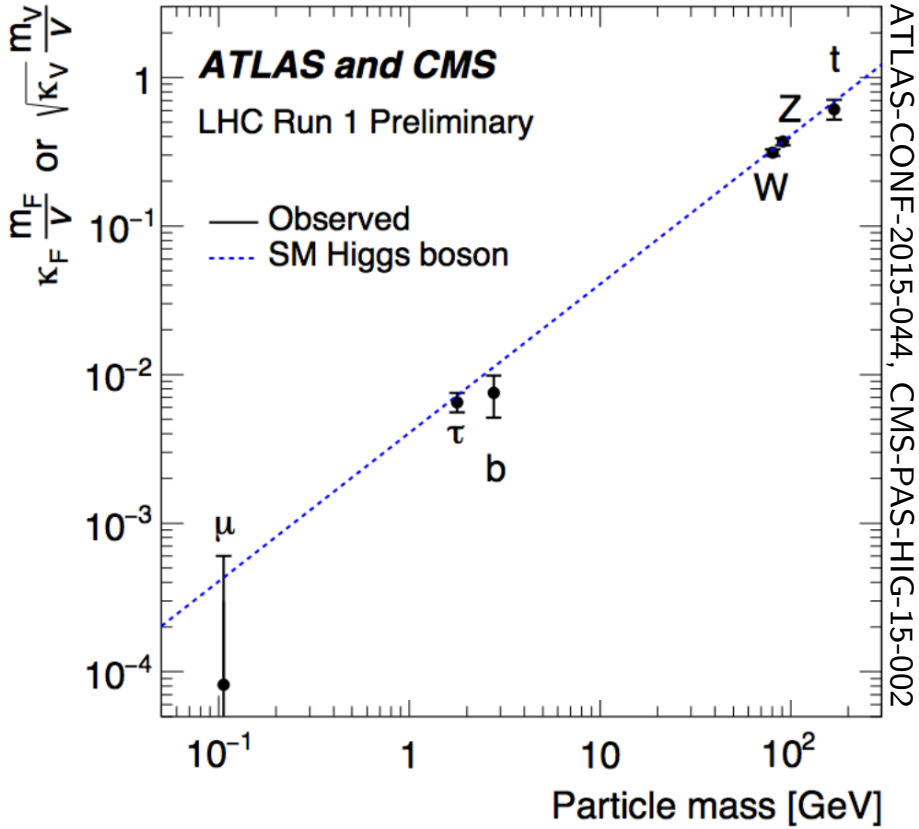
Matthias Schröder (KIT)
on behalf of the ATLAS and CMS Collaborations

September 4, 2015



First New Particle at the LHC: First Sign of New Physics?

1) What are the properties of the new boson?
   - Couplings compatible with SM expectation
   - But room for BSM behaviour
2) *Here:* Is it part of an extended Higgs sector?
   - Constraint: BSM models must contain a SM-like Higgs boson at 125 GeV



→ **Direct searches for additional Higgs bosons!**

Models with Extended Higgs Sectors

previous presentation
by Eduard Boos

Supersymmetry

- Minimal supersymmetric extension MSSM
  - 2 Higgs doublets $\rightarrow$ 5 physical bosons
    - ★ h, H, A $\equiv \Phi$ (neutral), H^+, H^- (charged)
  - 2 tree-level parameters m_A and $\tan\beta = \text{vev}_u/\text{vev}_d$
    - ★ Other SUSY parameters enter via radiative corrections, fixed in benchmark scenarios
  - Data: preference for h being the 125 GeV state

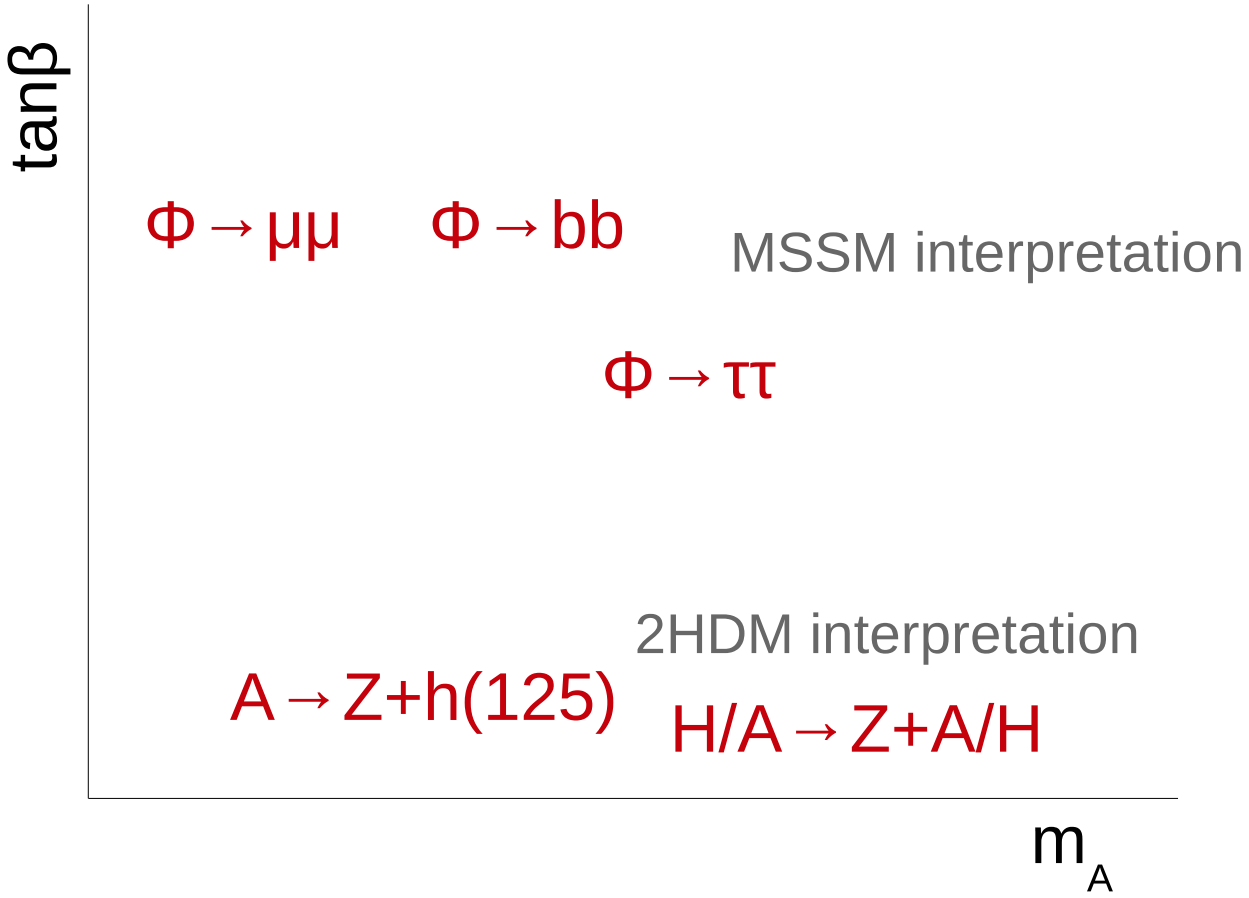
- Next-to-MSSM NMSSM
  - 1 additional Higgs singlet $\rightarrow$ 7 bosons

Generic 2-Higgs-Doublet Models 2HDM

- Effective extension of Standard Model adding a Higgs doublet
  - 5 parameters (no FCNC, $m_h = 125\,\text{GeV}$):
    m_A, m_H, $m_{H^\pm}$, $\tan\beta$, α = h-H mixing
- Different types depending on coupling structure
  - Type II: u- and d-type fermions couple to different doublets (MSSM)

Numerous Neutral-BSM-Higgs-Boson Searches at the LHC

Outline: will present **a few recent results**



NMSSM inspired $h(125) \to aa \to \mu\mu\tau\tau$ $h(125) \to aa \to 4\gamma$

Numerous Neutral-BSM-Higgs-Boson Searches at the LHC

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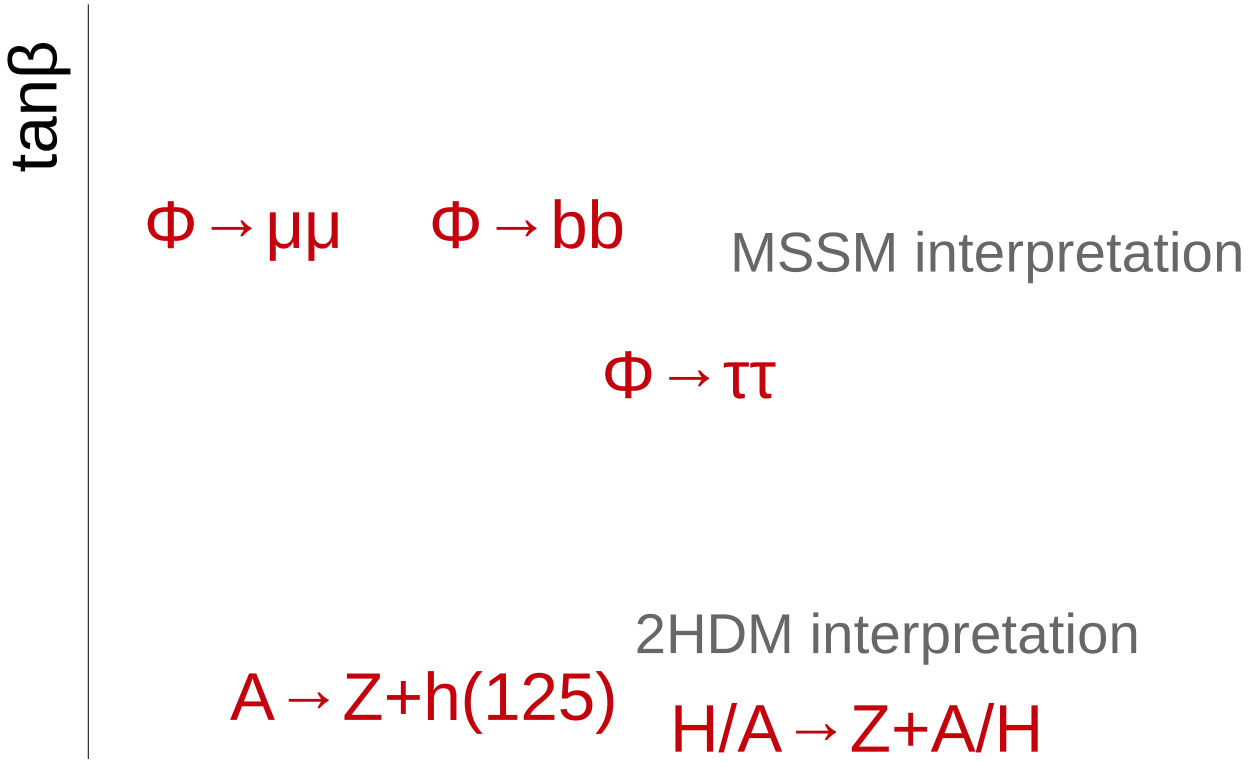
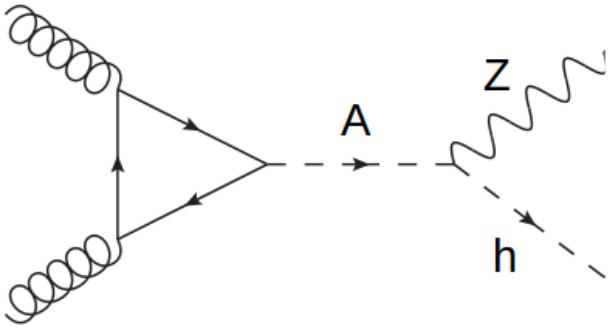


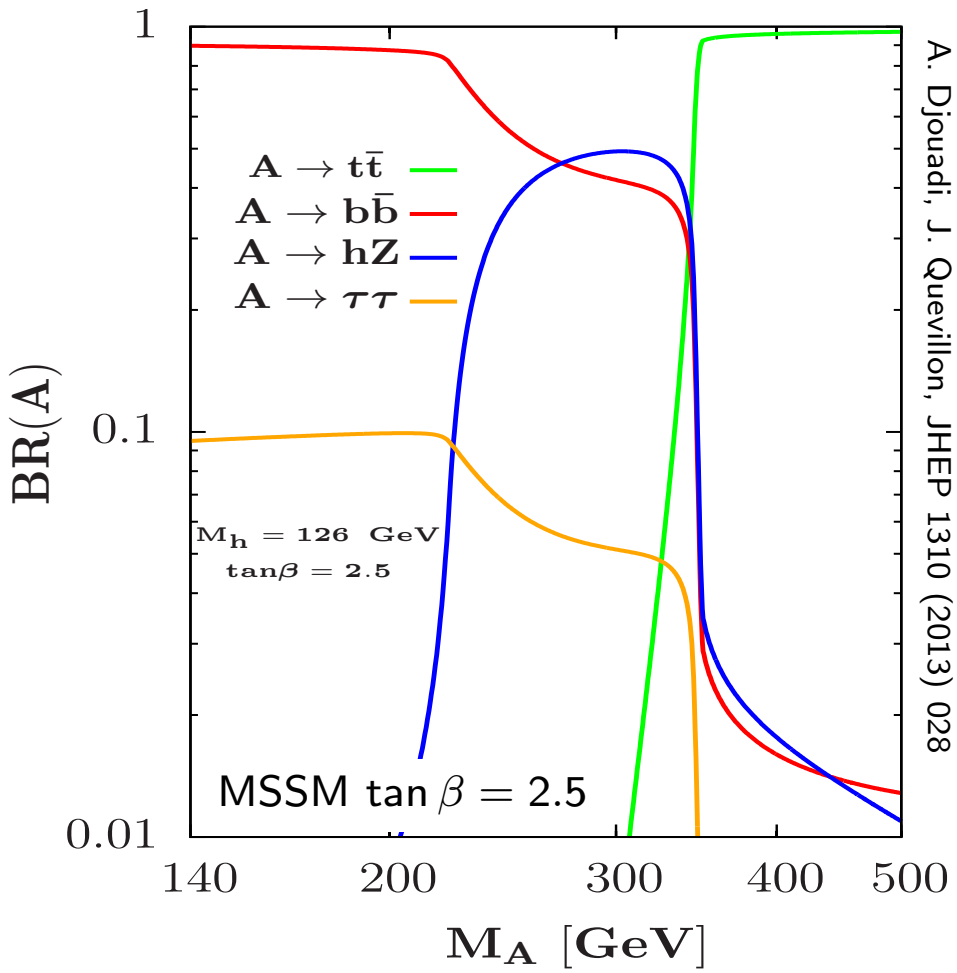
Further NEW results with 2HDM interpretation:

- Heavy H $\rightarrow$ ZZ search at ATLAS arXiv:1507.05930 (submitted to Eur. Phys. J.)
  see *High mass searches for SM like Higgs bosons at the LHC* by Song-Ming Wang
- H $\rightarrow$ hh $\rightarrow$ bb$\tau\tau$ search at CMS, CMS-HIG-14-034
  see *Searches for HH processes at LHC* by Andrea Rizzi

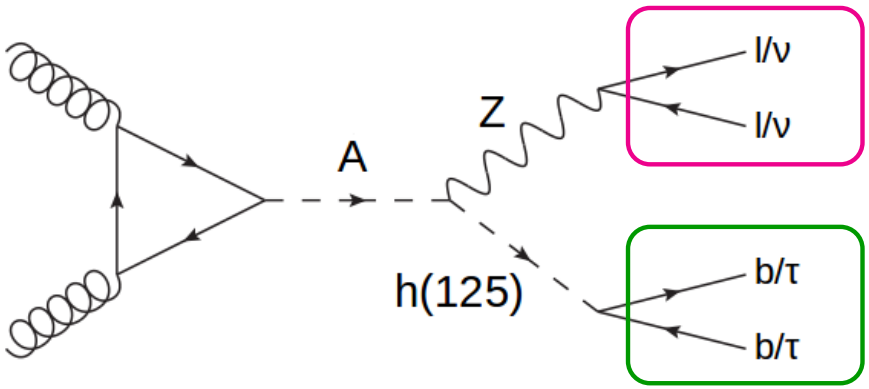
Pseudoscalar A → Z + h(125) Search at ATLAS & CMS



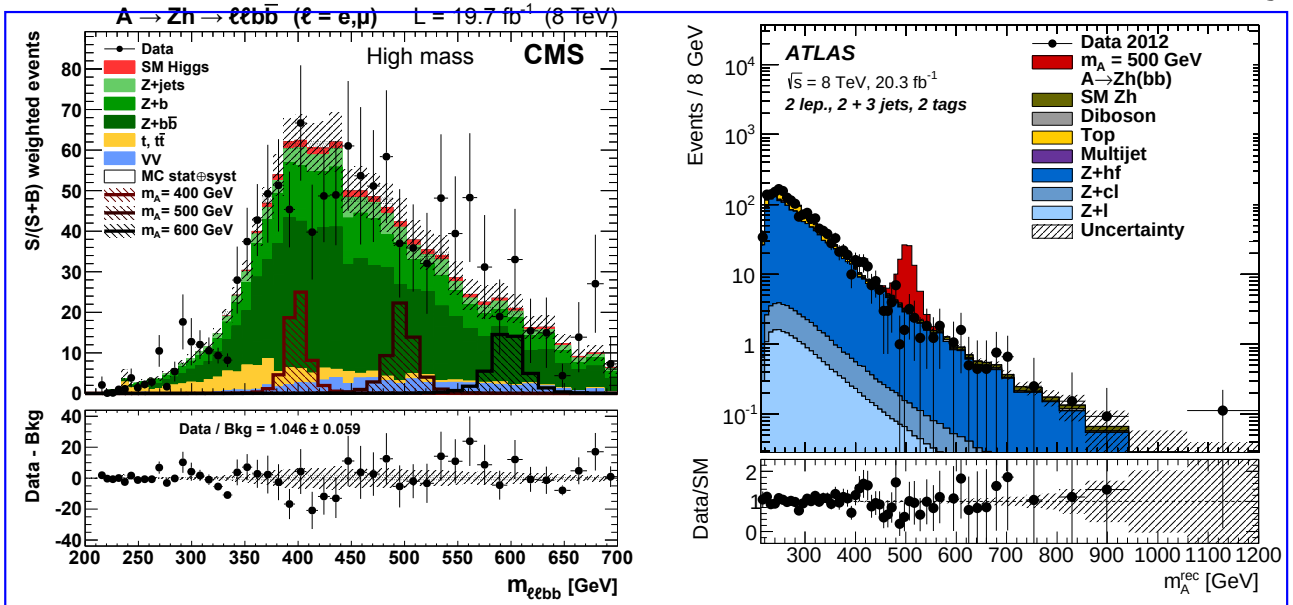
- Most 2HDMs: A predominantly produced by gluon-gluon fusion
- Often large $\mathcal{B}(A \to Z + h)$ for $m_h + m_Z \lesssim m_A \lesssim 2m_t$
  - MSSM: in low-tan β region
  - Can be important also above $2m_t$ in general 2HDMs

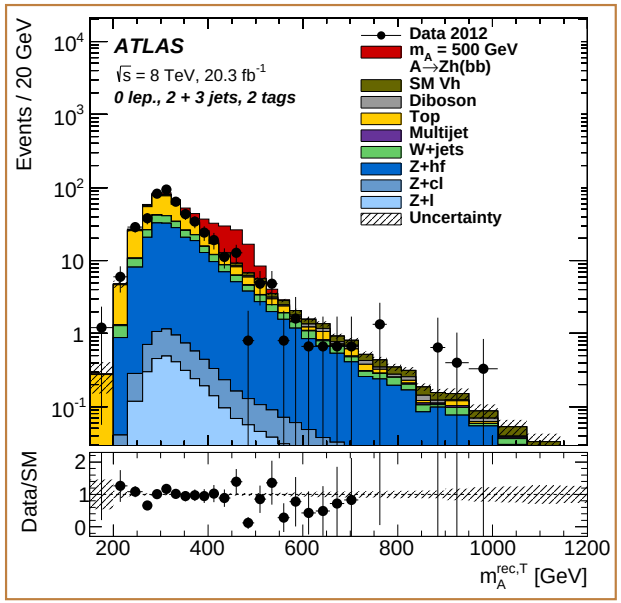


Pseudoscalar A → Z + h(125) Search at ATLAS & CMS



- $Z \to ll/\nu\nu$ clean signature
  - $\nu\nu$: ATLAS only
- $\mathcal{B}(h \to bb/\tau\tau)$ typically large
  - $\tau\tau$ CMS: CMS-HIG-14-034
- $m_h = 125\,\text{GeV}$ constraint deployed to improve resolution

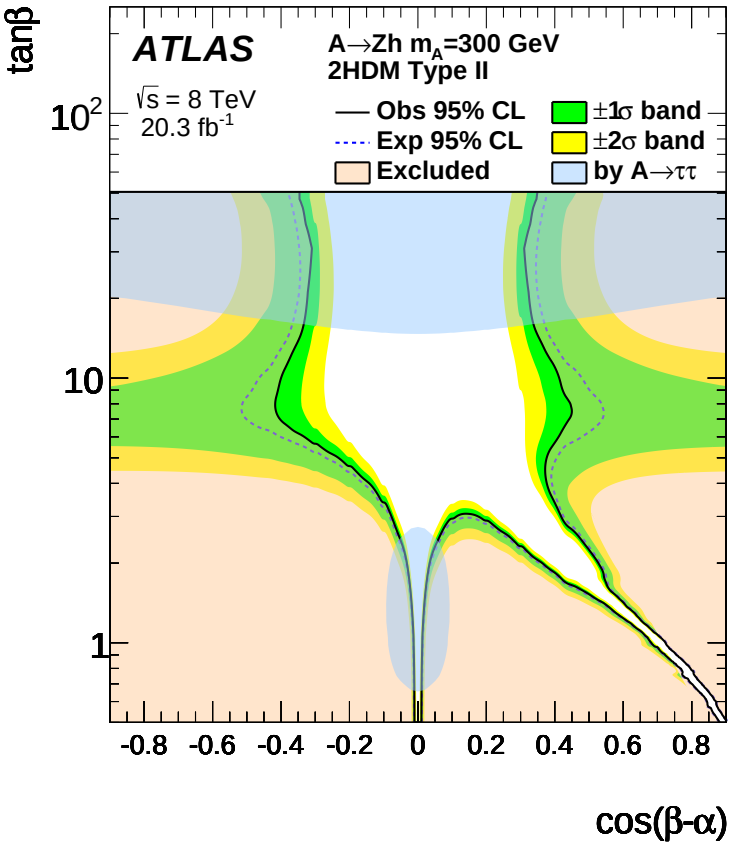


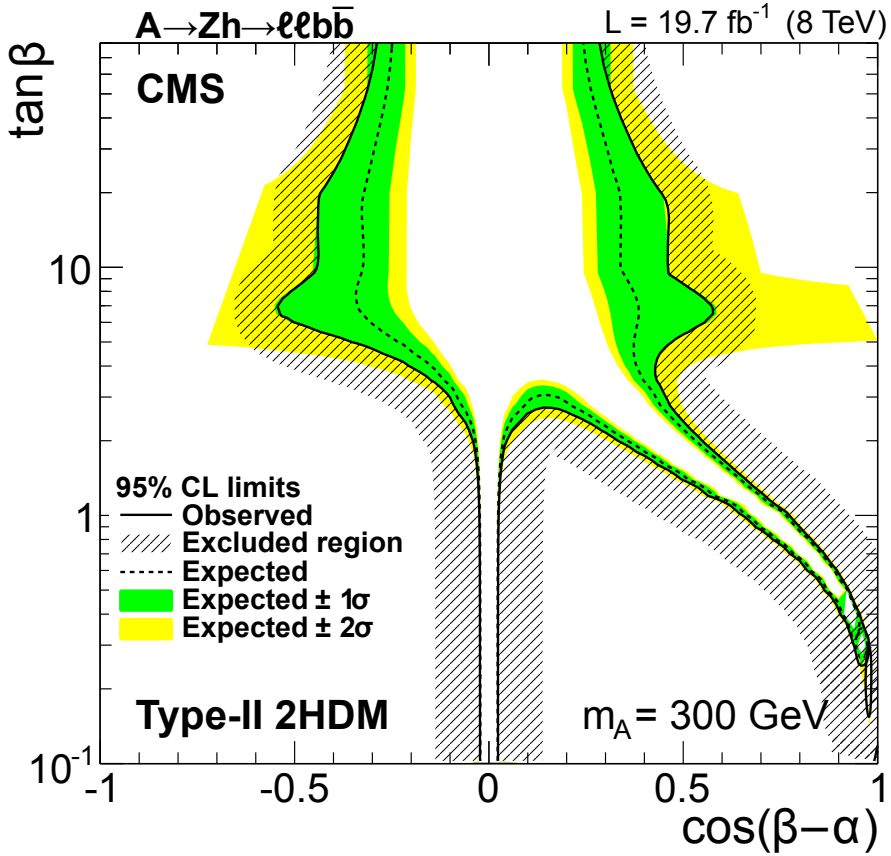


Peak search in invariant mass ($llbb/\tau\tau$) and transverse ($\nu\nu bb$) mass

2HDM Interpretation

Exclusion limits in type-II 2HDM, $m_A = m_H = m_{H^\pm} = 300\,\text{GeV}$

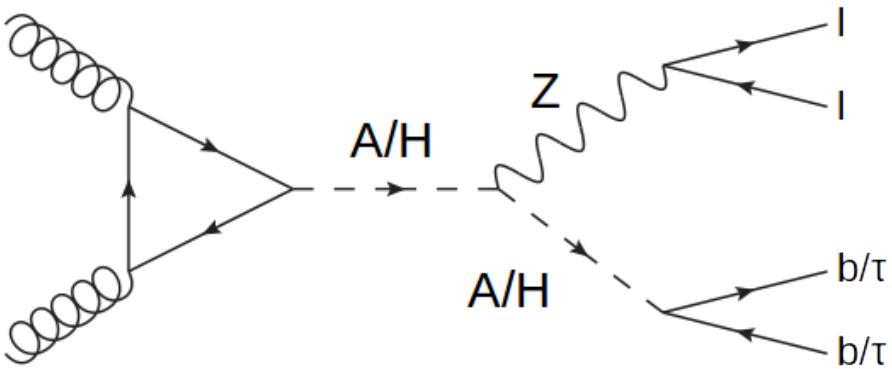


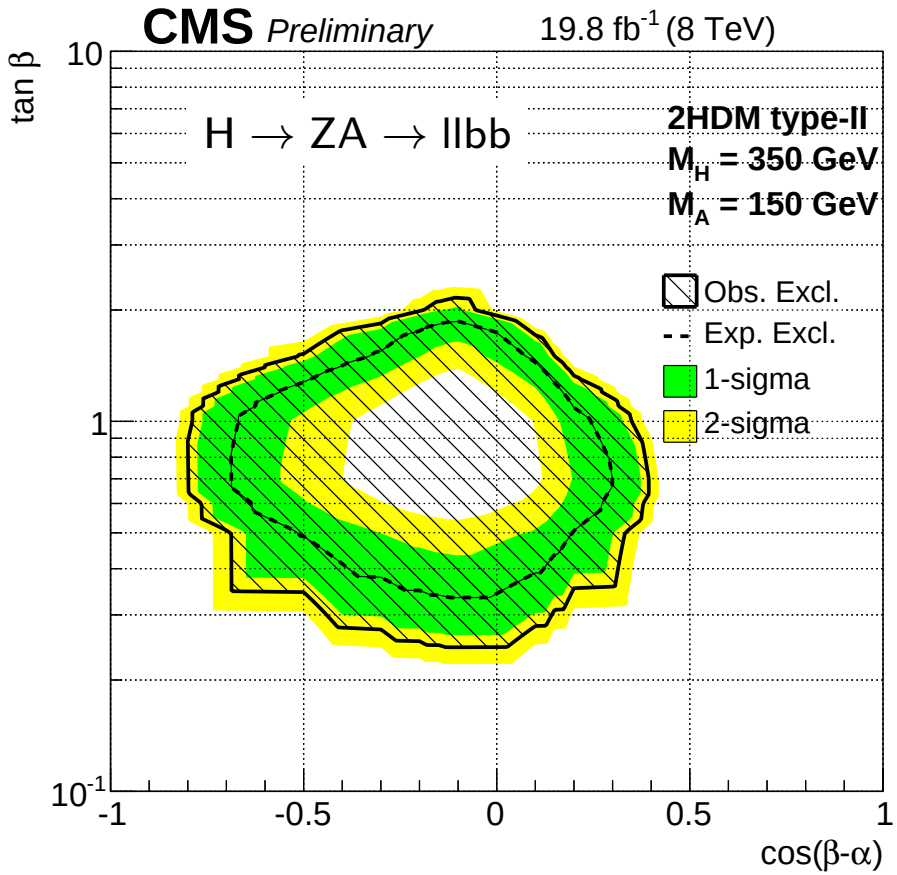


Large parts of type-II parameter-space excluded, also at high tan β

NEW H/A → Z(ll) + A/H(bb/ττ) at CMS

- More general approach: no specific h(125) requirement in final state



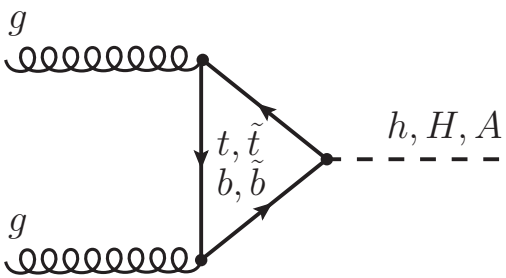


- Type-II 2HDM interpretation
- Either mass hierarchy
  $m_A > m_H$ or $m_H > m_A$
- Complementary information
  to A → Zh(125) searches

Access to 'alignment' region at $\cos(\beta - \alpha) \approx 0$

MSSM Neutral Higgs-Boson Searches

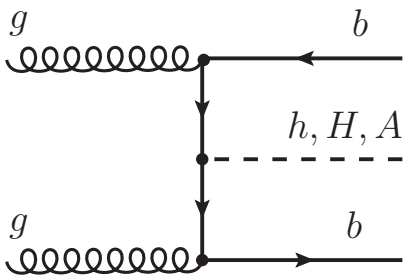
small $\tan\beta$



gg-fusion production

$\rightarrow$ no b-tagged jet

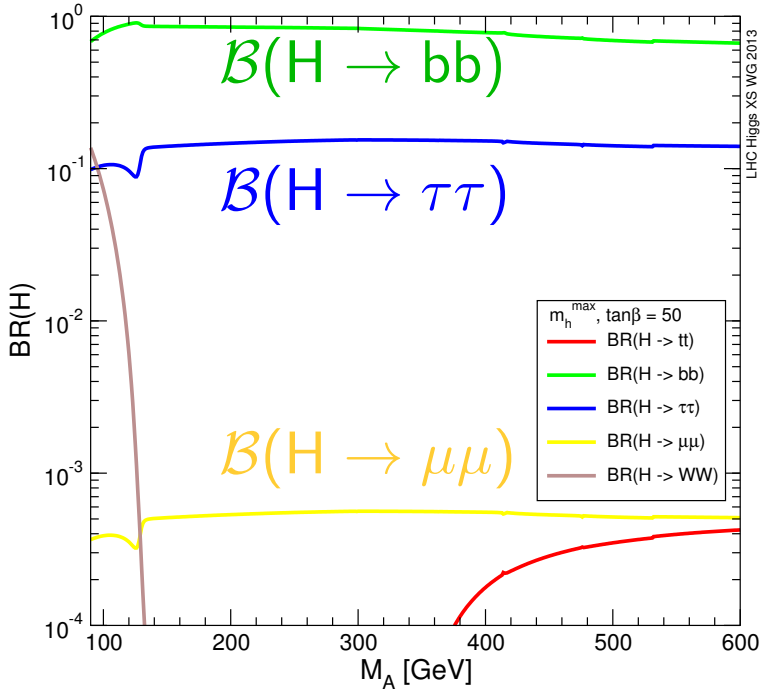
larger $\tan\beta$



b-assoc. production

$\rightarrow \geq 1$ b-tagged jets

$\tan\beta = 50$



$\Phi \rightarrow$ bb channel

- Very large $\mathcal{B}$
- Challenging bkg

$\Phi \rightarrow \tau\tau$ channel

- Relatively large $\mathcal{B}$
- Manageable bkg

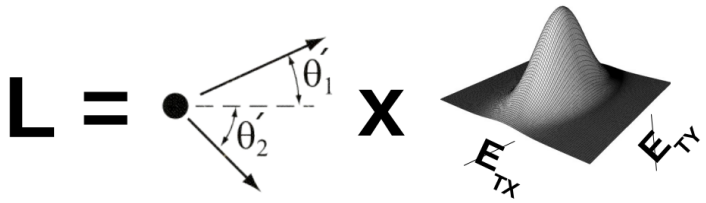
$\Phi \rightarrow \mu\mu$ channel

- Tiny $\mathcal{B}$
- Excellent mass resolution

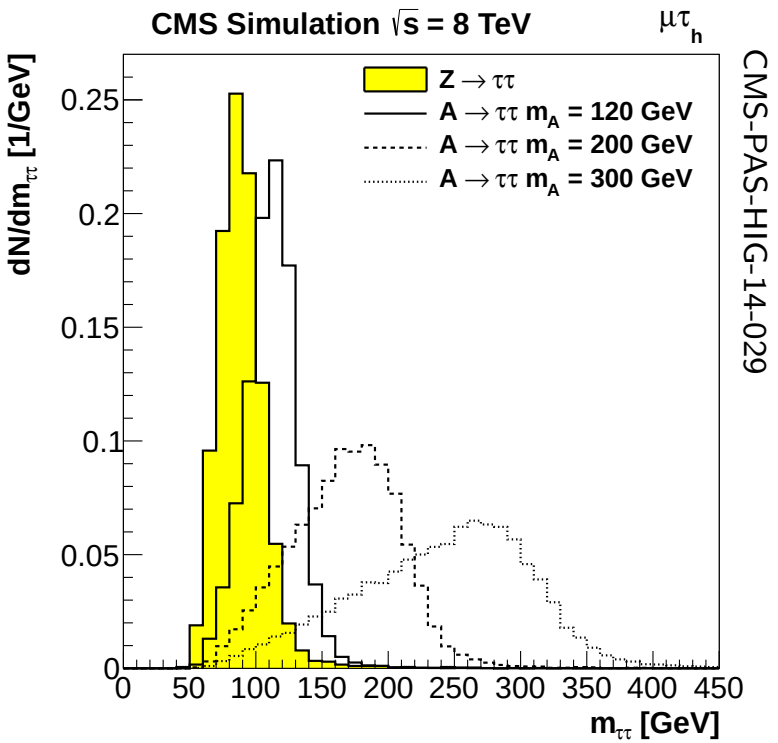
$\Phi \to \tau\tau$ Searches: $m_{\tau\tau}$ Reconstruction

Likelihood approach

CMS (ATLAS similar)



- Typical resolution of 20%

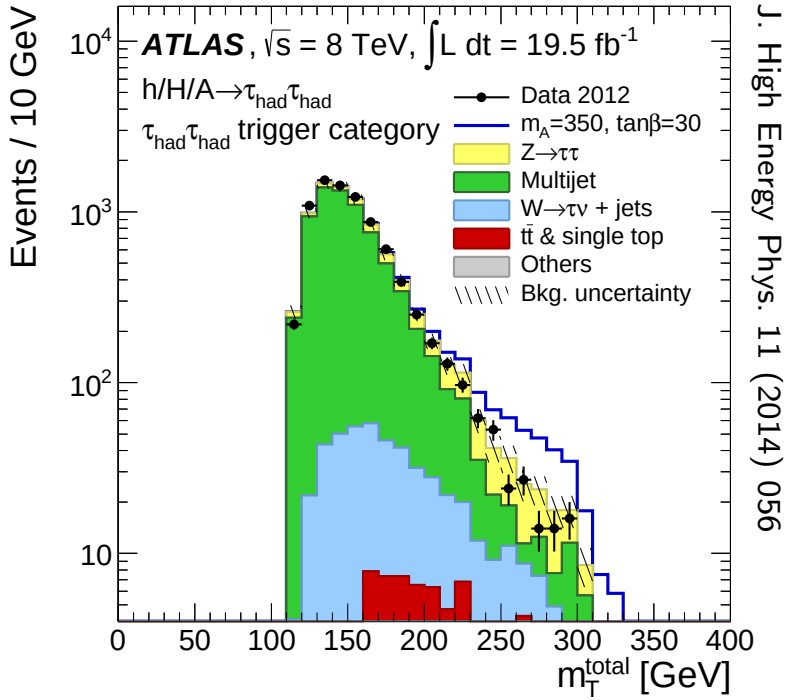


Total transverse mass

ATLAS in $\tau_h\tau_h$ channel

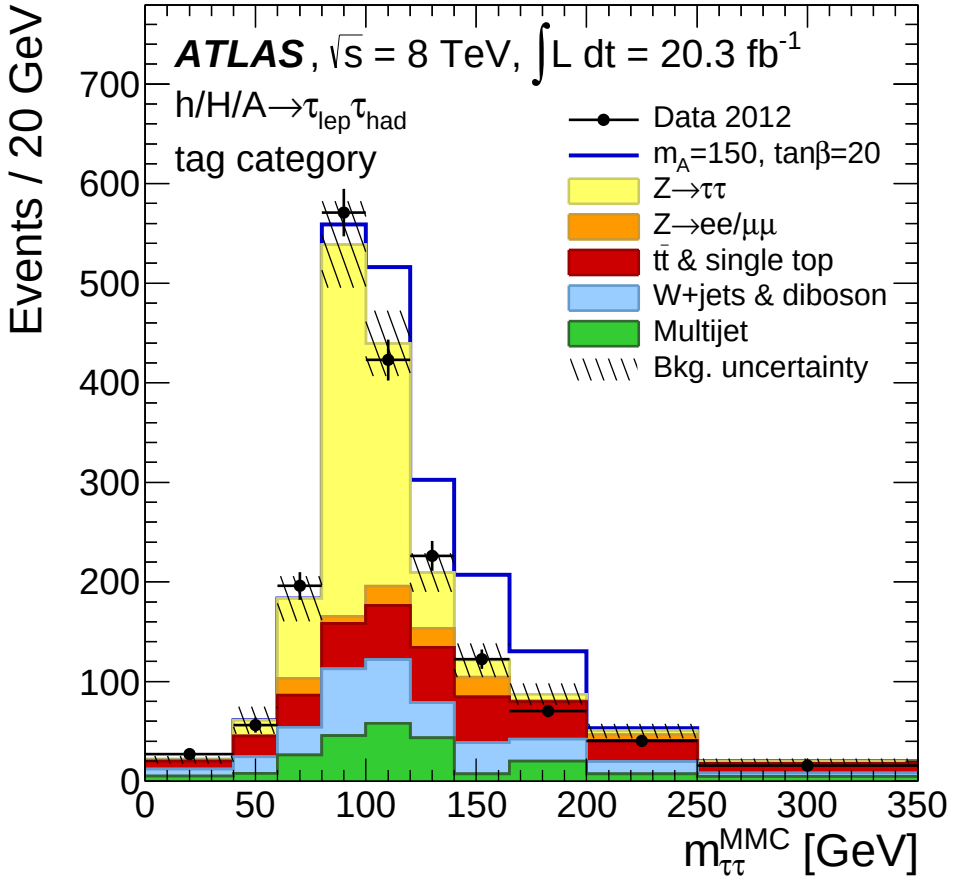
$$m_T(\tau_1, \tau_2) \oplus m_T(\tau_1, \not{E}_T) \oplus m_T(\tau_2, \not{E}_T)$$

- Improved separation of signal and QCD-multijet bkg



$\Phi \to \tau\tau$ Search at ATLAS

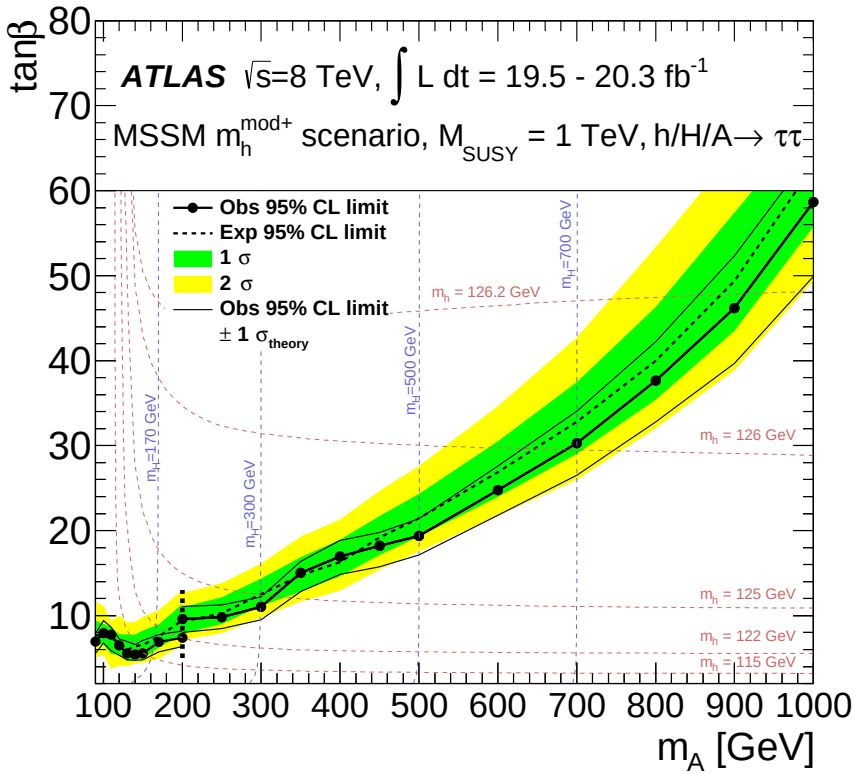
- Channels: $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- Event categories based on
  - Number of b-tagged jets
  - Low/high-mass specific selection
  - Used triggers
- Background composition depends on channel and category
- Major contributions measured from data
  - Similar techniques by ATLAS and CMS

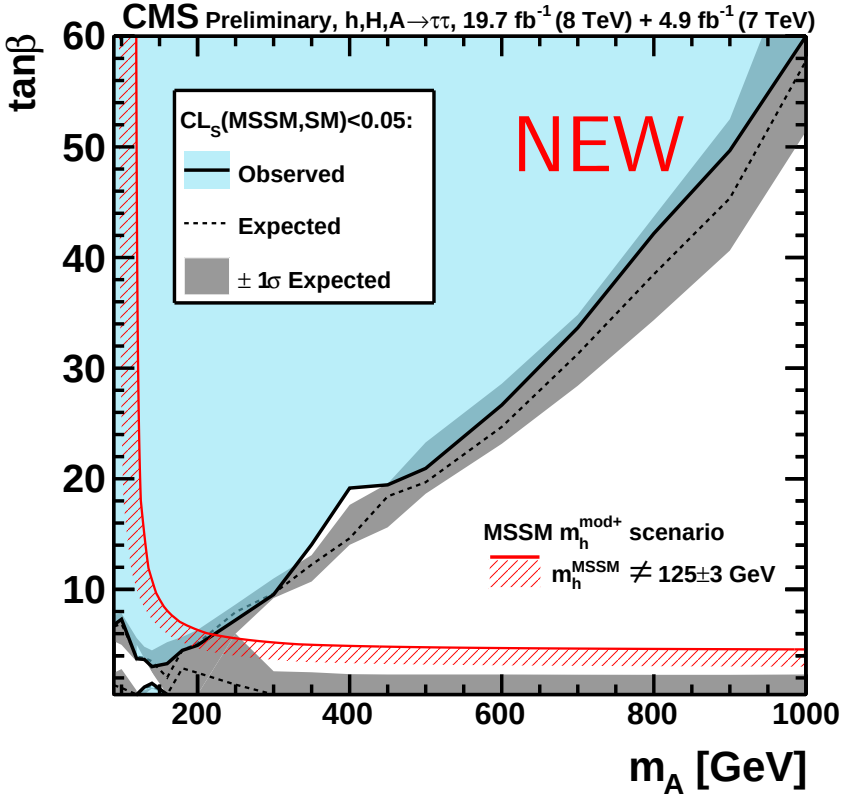


- $Z \to \tau\tau$: embedding method in $Z \to \mu\mu$ data
- QCD multijets: control sample with inverted τ_h-identification criteria

$\Phi \to \tau\tau$ Results

Exclusion limits on $\tan\beta$ in MSSM $m_h^{\text{mod+}}$ benchmark scenario

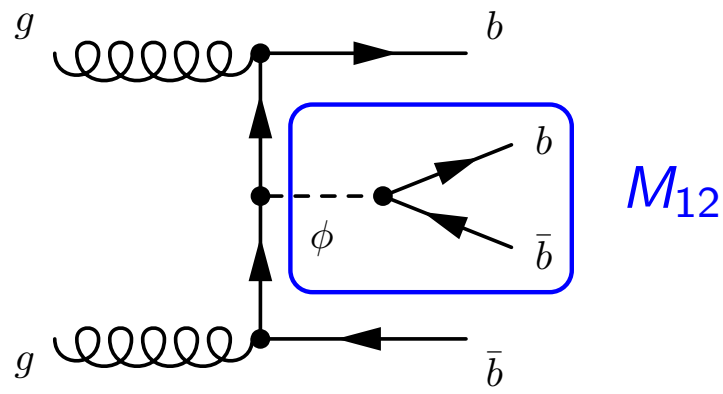




- Exclusion of $\tan\beta \gtrsim 5$ at low m_A, sensitivity up to 1 TeV
- Low $\tan\beta$ region incompatible with $m_h = 125\,\text{GeV}$

Exclusion of low-$m_A \lesssim 200\,\text{GeV}$ region in $m_h^{\text{mod+}}$ scenario

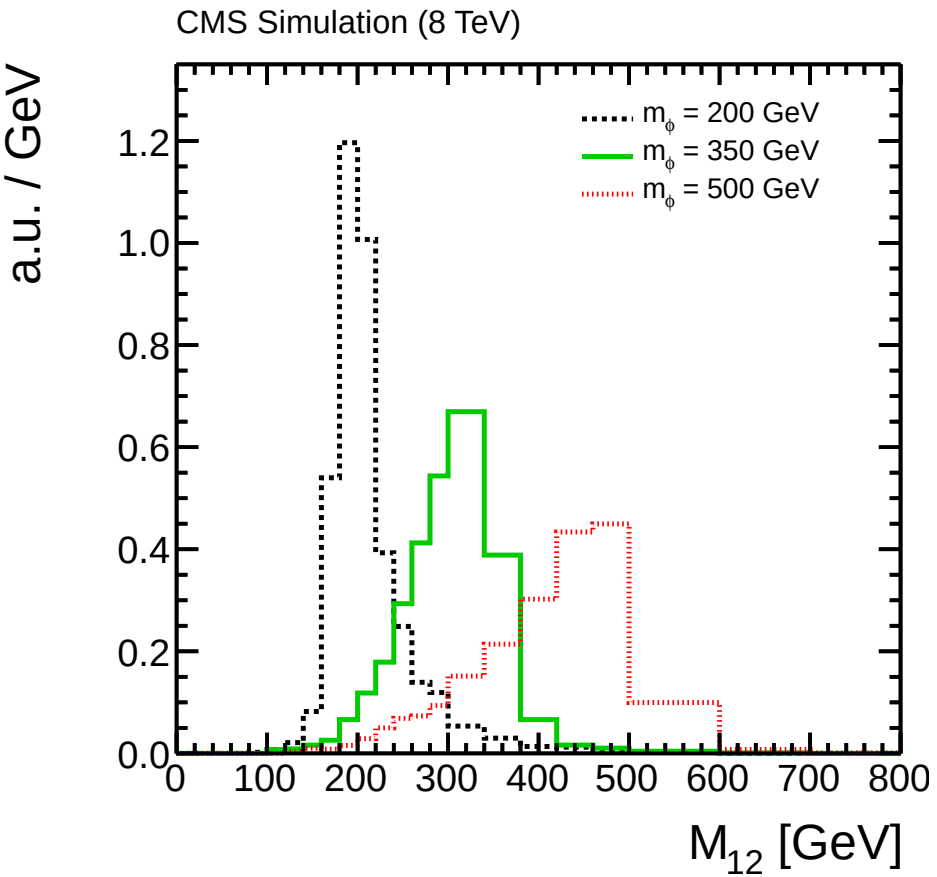
NEW $\Phi \to bb$ Search at CMS



- For not-too-small tan β
  - Dominant bbΦ production
  - Large $\mathcal{B}(\Phi \to b\bar{b}) \approx 90\%$
- Selection: $\geq$ **3 b-tagged jets**

Peak search in invariant mass distribution M_{12} of leading two jets

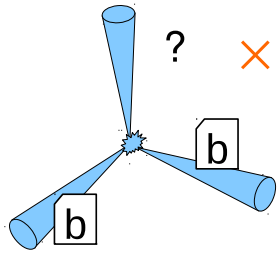
- Huge QCD-multijet background
  - Largely reduced by 3 b-tag requirement
- Requires dedicated triggers with **online b-tagging**



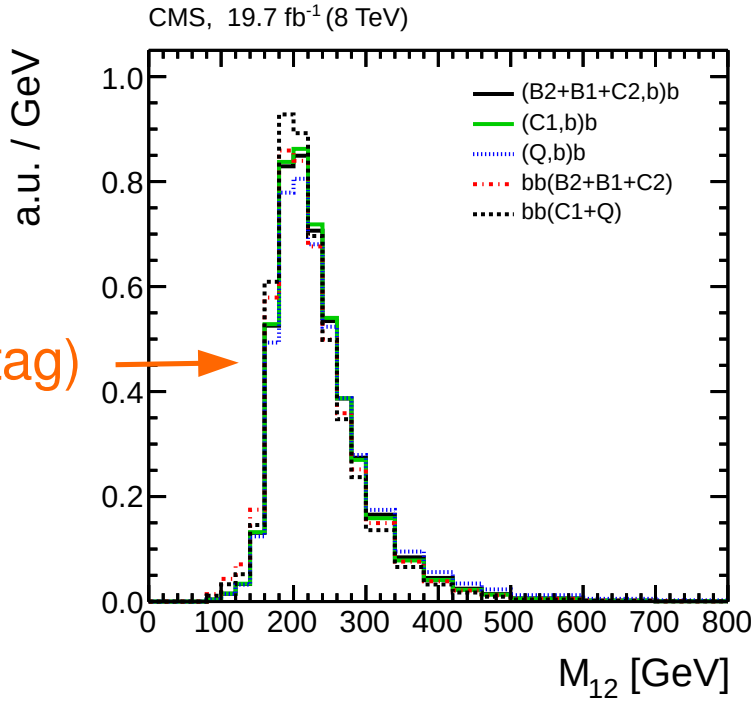
Data-Driven Background Model

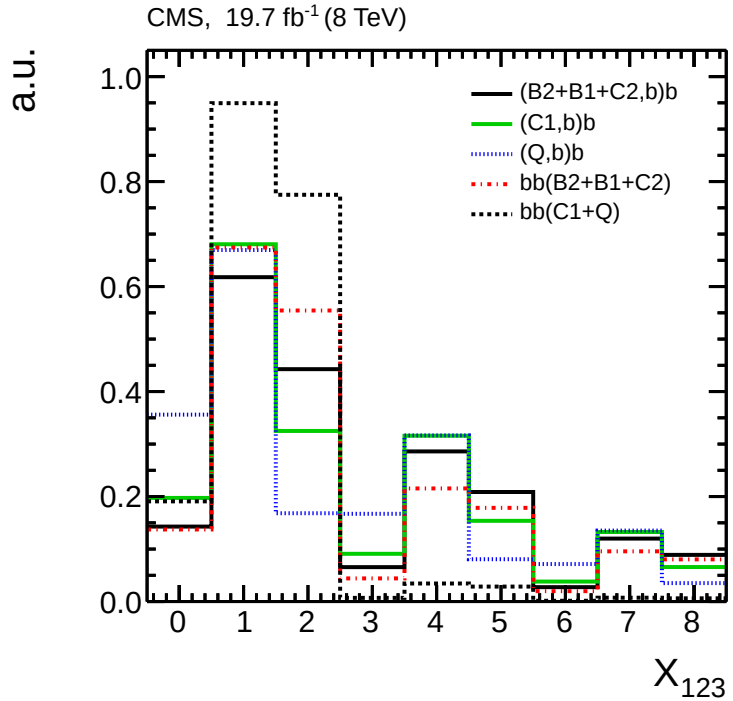
- **Template for each flavour combination** from 2 b-tag data
  - Weighted by b-tag probability of un-tagged jet
- Additional separation by condensed **event b-tag estimator** X_{123}
  - Based on secondary-vertex masses of 3 leading jets

double-b-tag data



$\times \varepsilon$(b-tag)

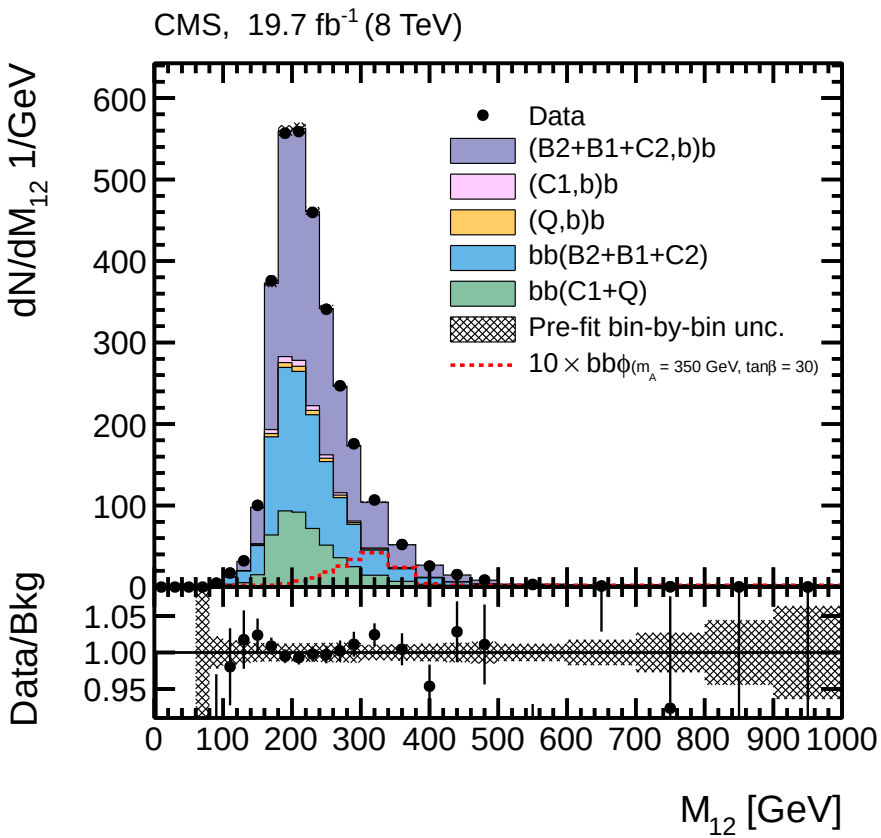


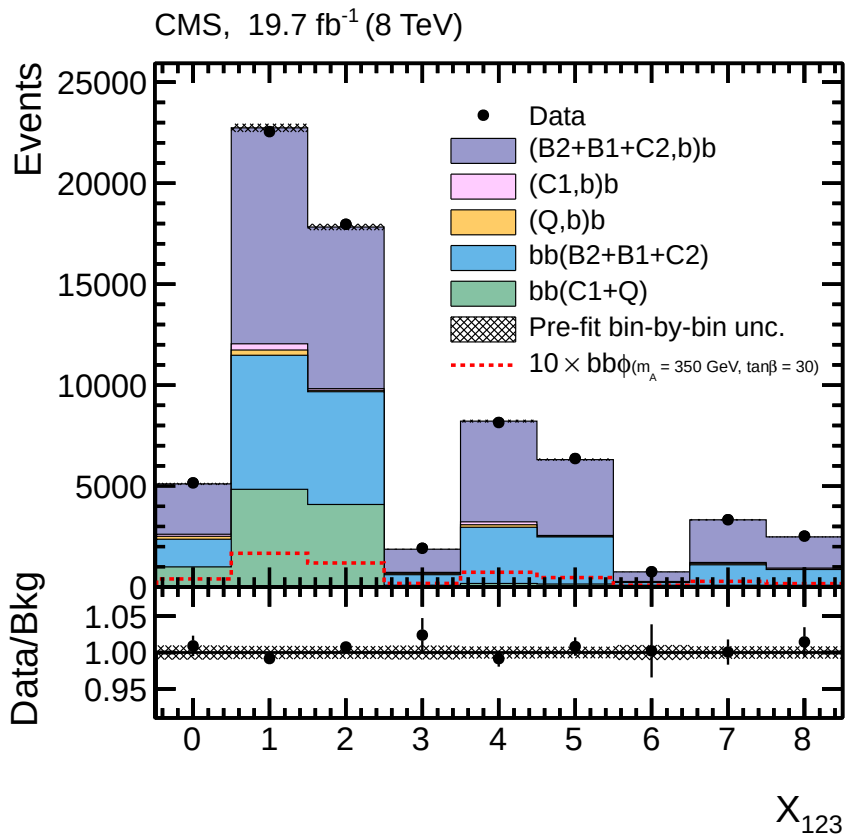


2D (M_{12}, X_{123}) background (+signal) templates fit to data

Background-Only Fit Results

Projection on M_{12} and X_{123}



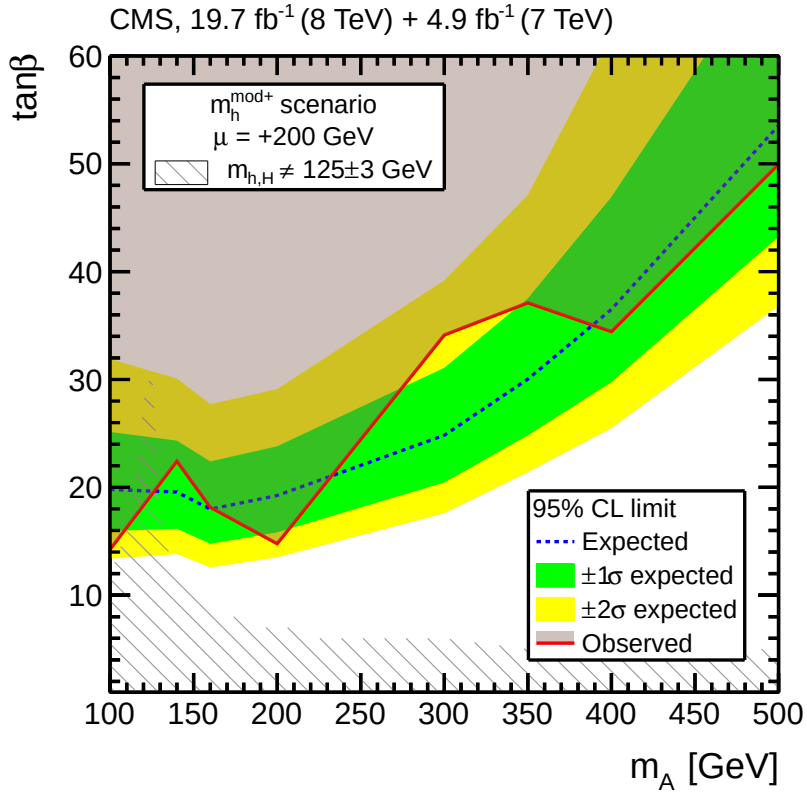


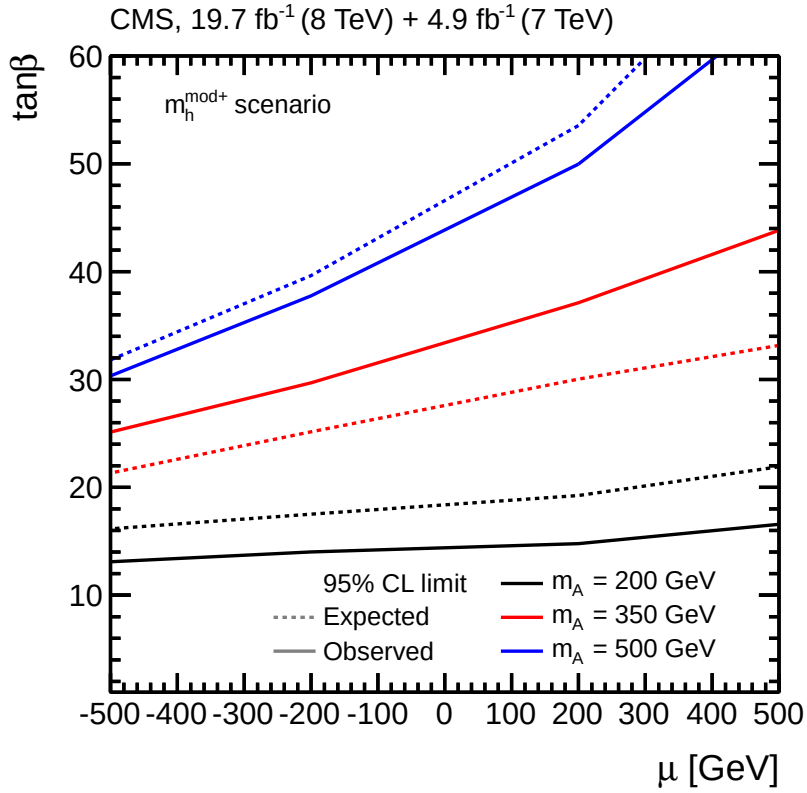
- Background dominated by processes with 3 b-jets (+ $\approx$ 80%)

Data well described by background-only hypothesis

MSSM Interpretation

Exclusion limits on $\tan\beta$ in MSSM $m_h^{\text{mod+}}$ benchmark scenario



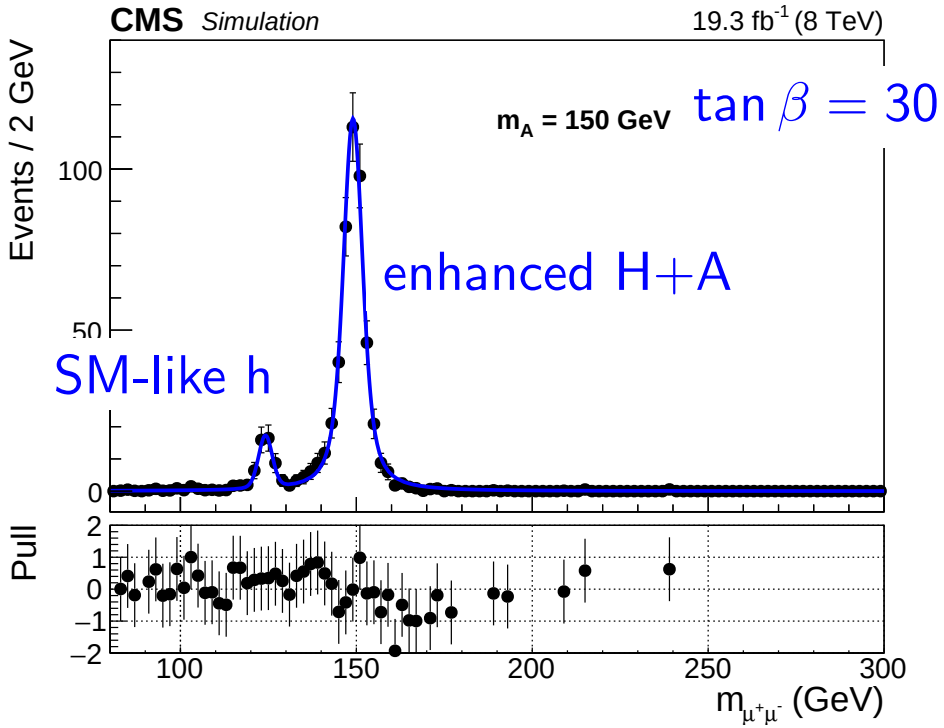


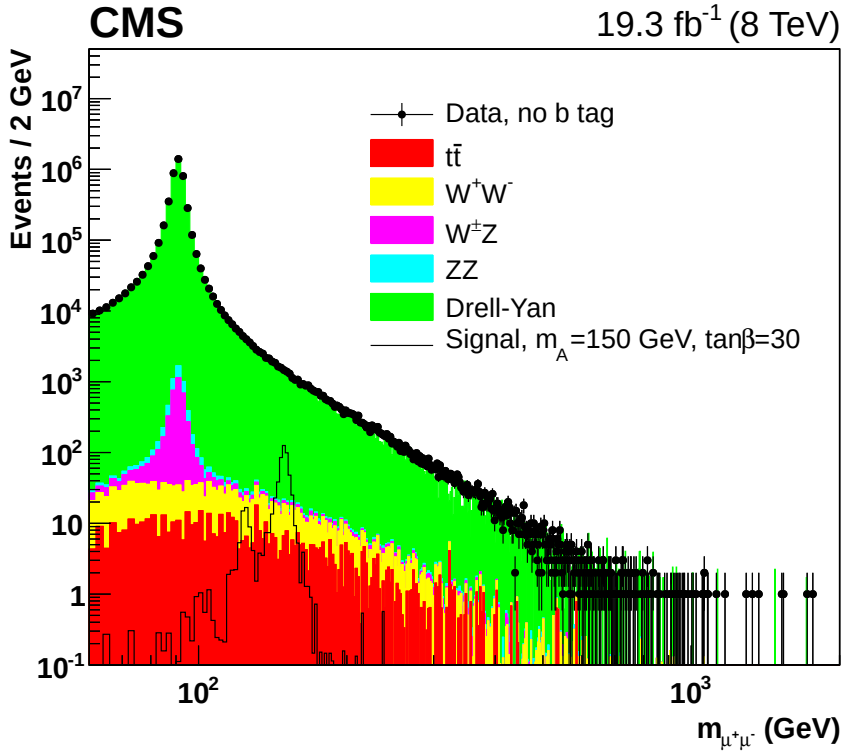
- Upper limits on $\tan\beta$ from 14–50
- Also dependence on Higgsino-mass parameter μ studied
  - Good sensitivity expected in this channel [Eur. Phys. J. C73 (2013) 2552]

NEW $\Phi \to \mu\mu$ Search at CMS

Similar search by ATLAS using 7 TeV data
J. High Energy Phys. 02 (2013) 095

- Very low expected $\mathcal{B}$
- But excellent mass resolution
  - $\Delta m = 1.2\,\text{GeV}$ at $125\,\text{GeV}$
- Analytic signal+bkg model



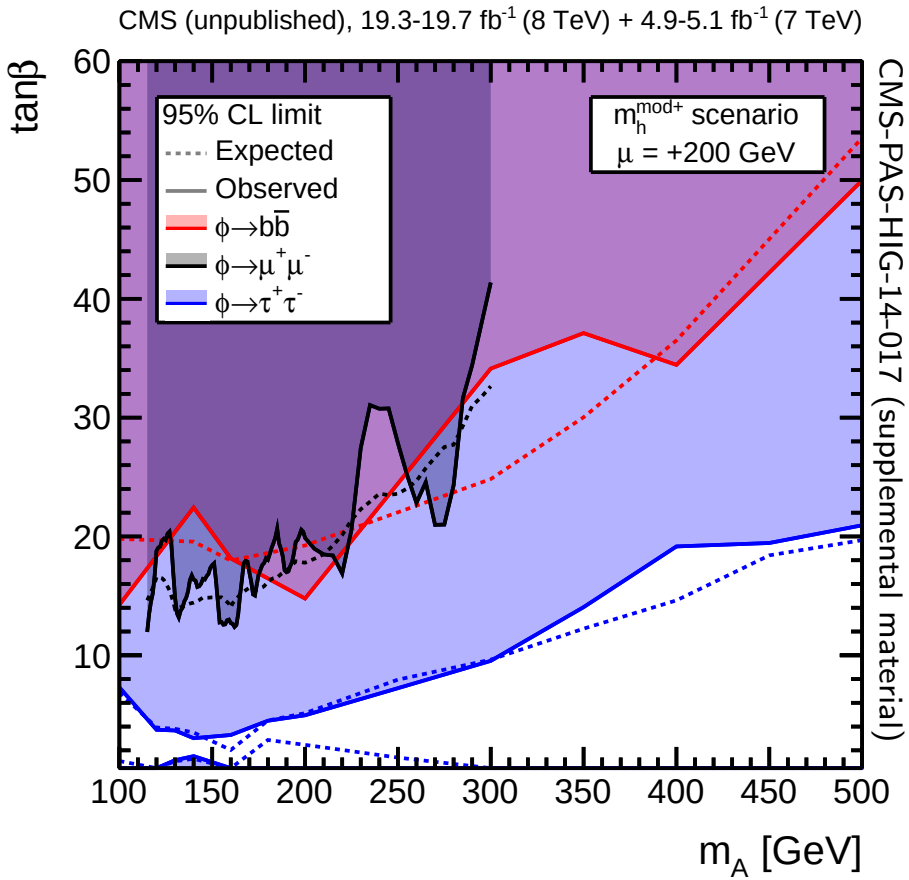


- Peak search in $m_{\mu\mu}$ distribution
  - Dominant bkg contribution from Drell-Yan production

Data well-described by background-only model

MSSM Interpretation

Exclusion limits on $\tan\beta$ in MSSM $m_h^{\text{mod}+}$ benchmark scenario



- Results from different channels complementing each other
  - Different mass resolution clearly visible (best for $\mu\mu$, worst for $\tau\tau$)
  - Most stringent limits from $\tau\tau$ channel, bb and $\mu\mu$ similar to each other

MSSM Interpretation

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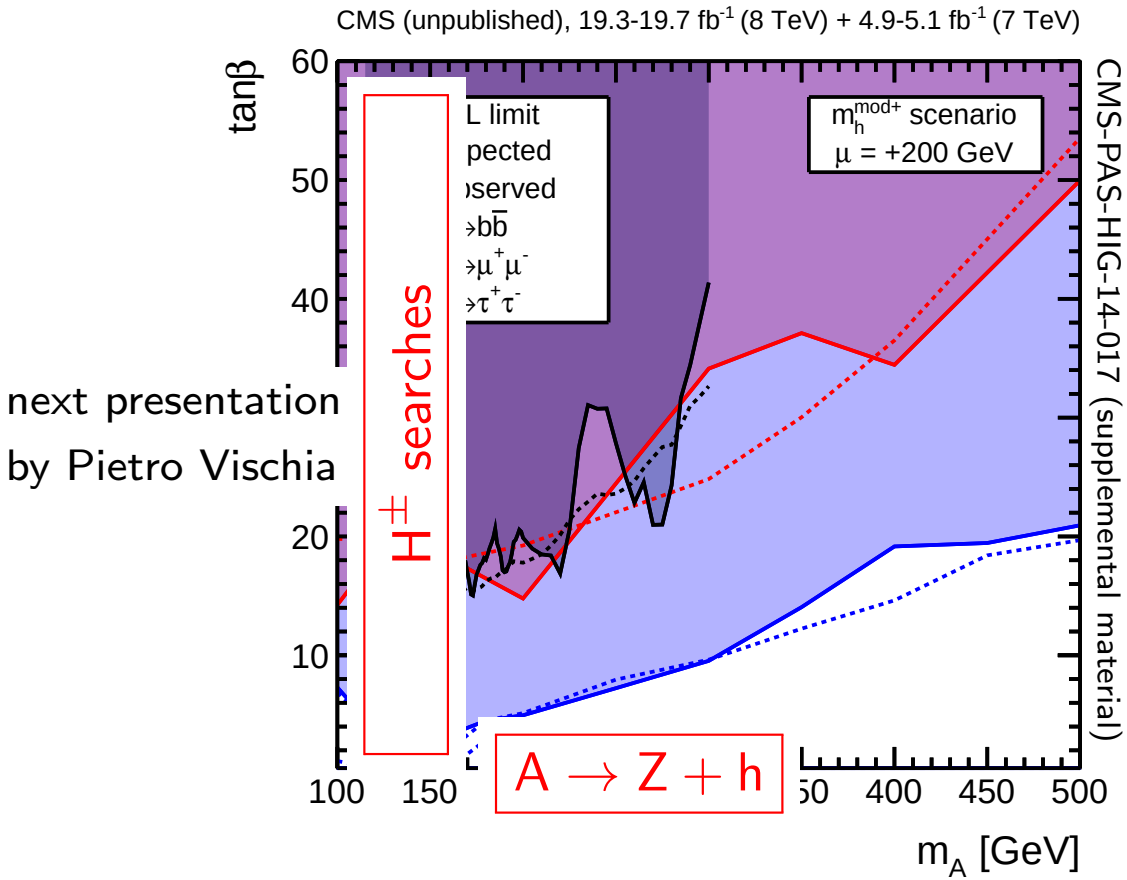

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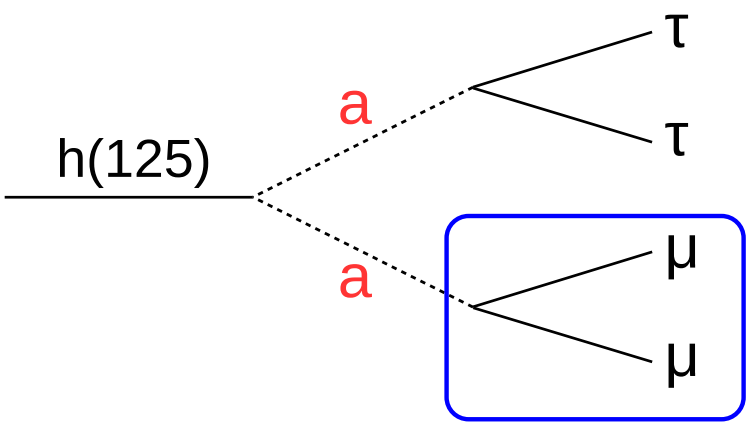
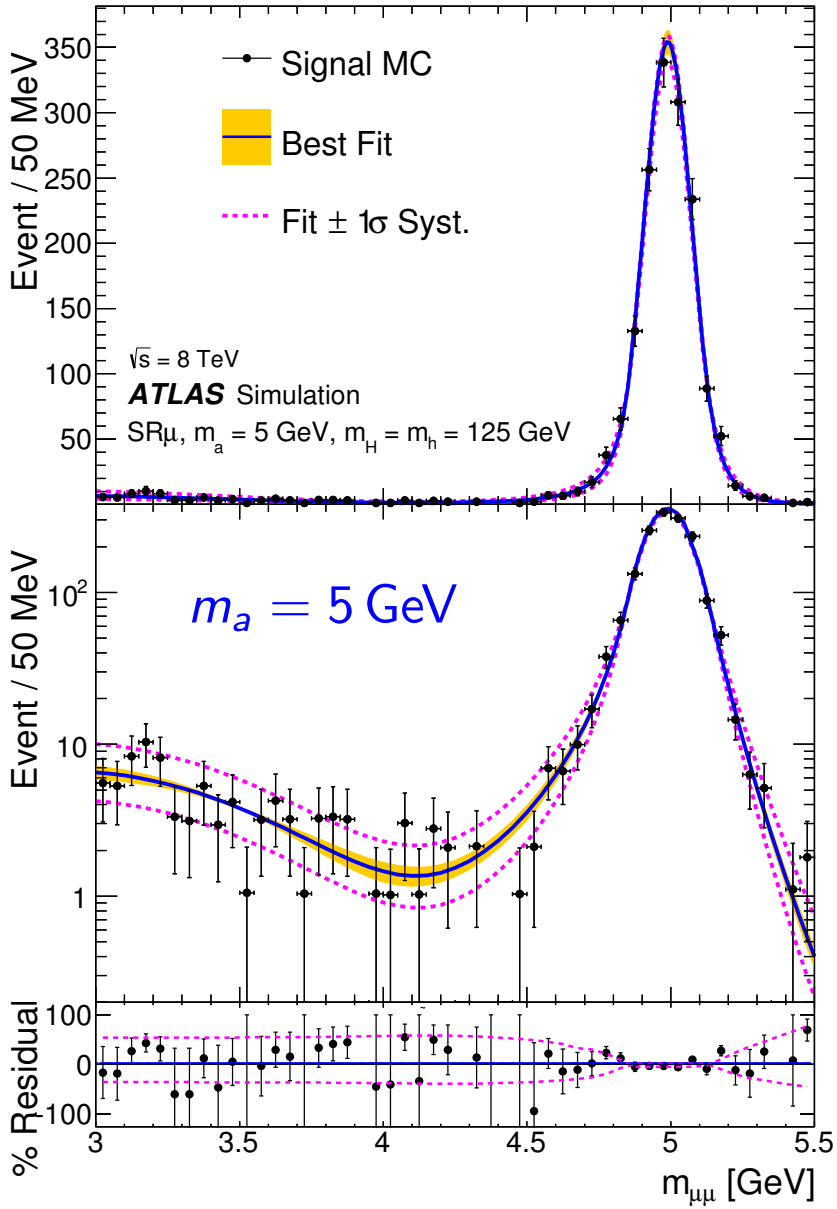
NEW NMSSM h(125) $\to aa \to \mu\mu\tau\tau$ Search at ATLAS

- Low expected $\mathcal{B}(a \to \mu\mu)$
- But high trigger efficiency and narrow di-μ resonance

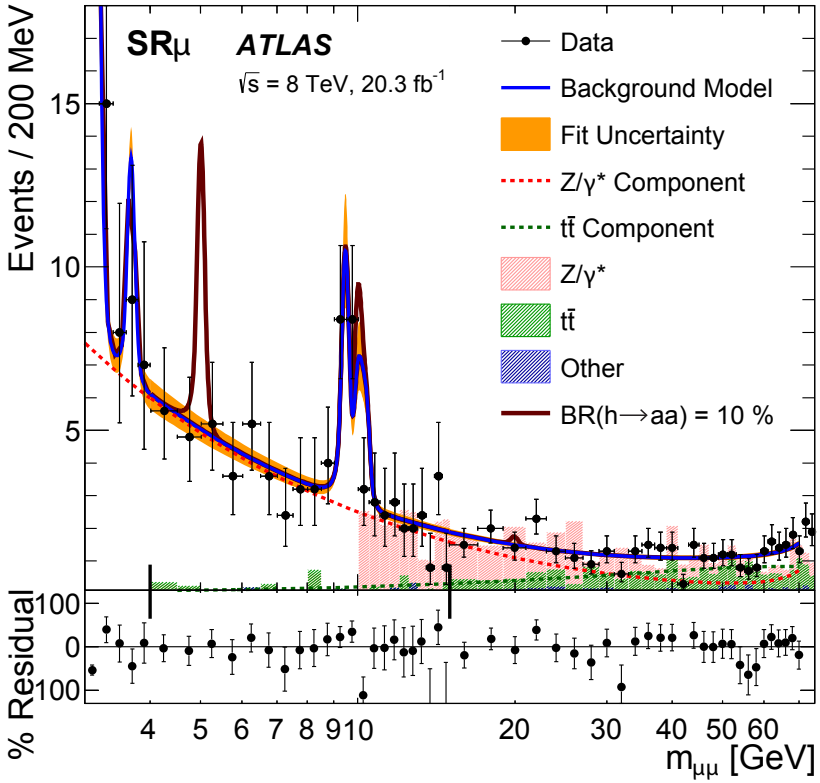


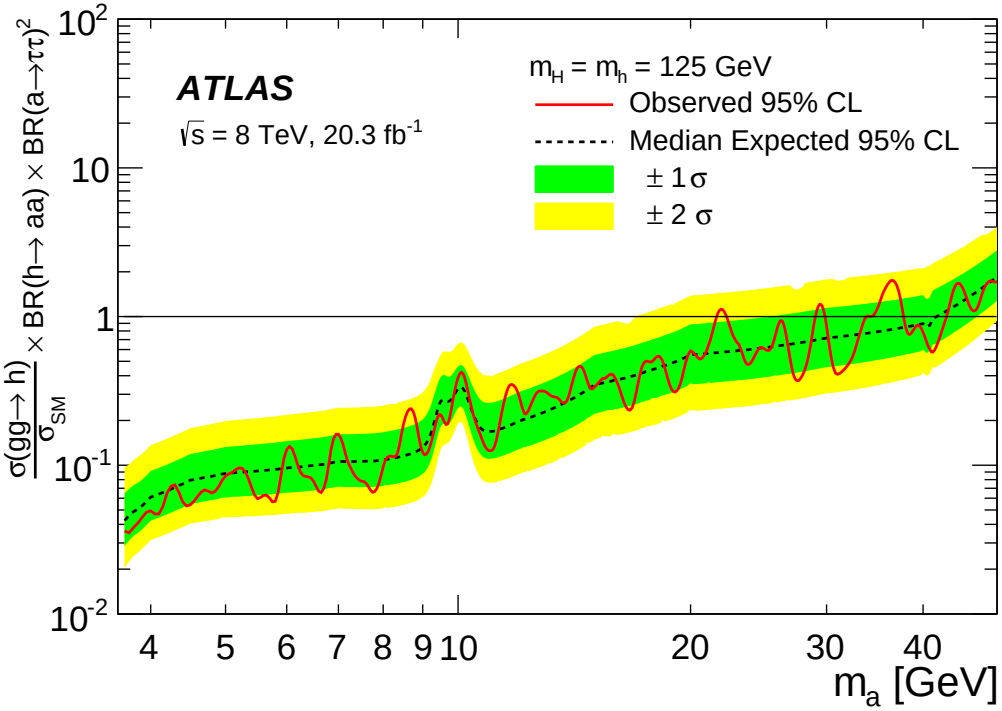
Peak search in $m_{\mu\mu}$ distribution from 3.7–50 GeV

- Analytic signal + bkg model
  - Assuming $\mathcal{B}(a \to \mu\mu) + \mathcal{B}(a \to \tau\tau) = 1$



Results

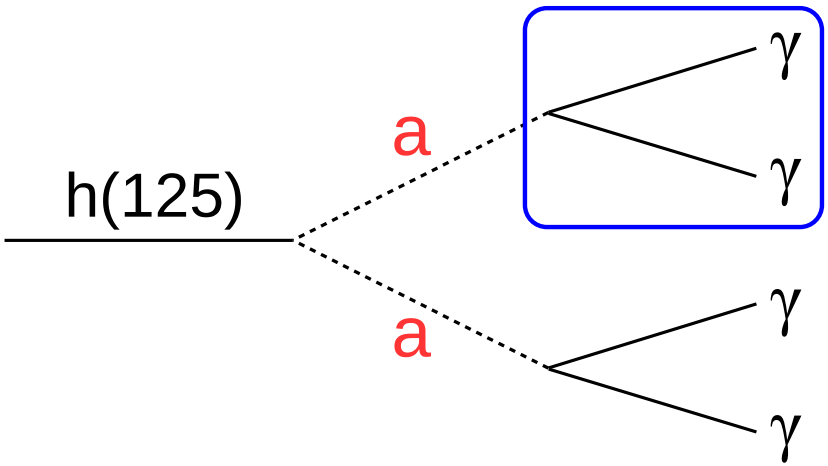


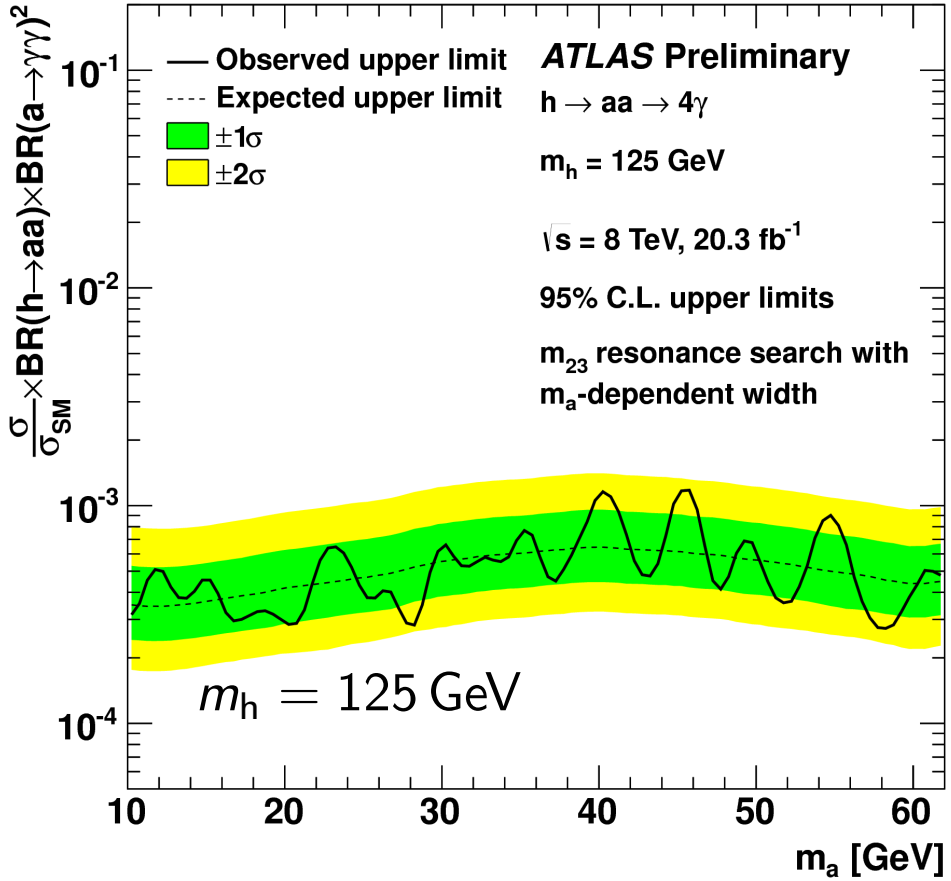


- Data well-described by background-only model
  - $J/\Psi, \Psi', \Upsilon_{1S}, \Upsilon_{2S}, \Upsilon_{3S}$, Z resonances + $t\bar{t}$ + Drell-Yan continuum
- Exclusion limit on $\sigma(gg \to h) \times \mathcal{B}(h \to aa)$
  - Relative to SM gluon-gluon-fusion Higgs-boson production

NEW NMSSM h(125) $\rightarrow$ $aa \rightarrow 4\gamma$ Search at ATLAS

- Events with ≥ 3 identified photons
- Peak search in $m_{\gamma 2\gamma 3}$ distribution





Exclusion limit on $\sigma/\sigma_{\mathrm{SM}}(gg \rightarrow h) \times \mathcal{B}(h \rightarrow aa) \times \mathcal{B}^2(a \rightarrow \gamma\gamma)$

- Additional H $\rightarrow$ *aa* interpretation

Are there any further Higgs bosons?

- Many complementary searches with LHC Run-I data
- Both model-independent limits and model-dependent interpretations
- Significantly improved constraints on 'BSM-Higgs parameter space', e. g.
  - closing low m_A-region in MSSM

$\longrightarrow$ We don't know yet...

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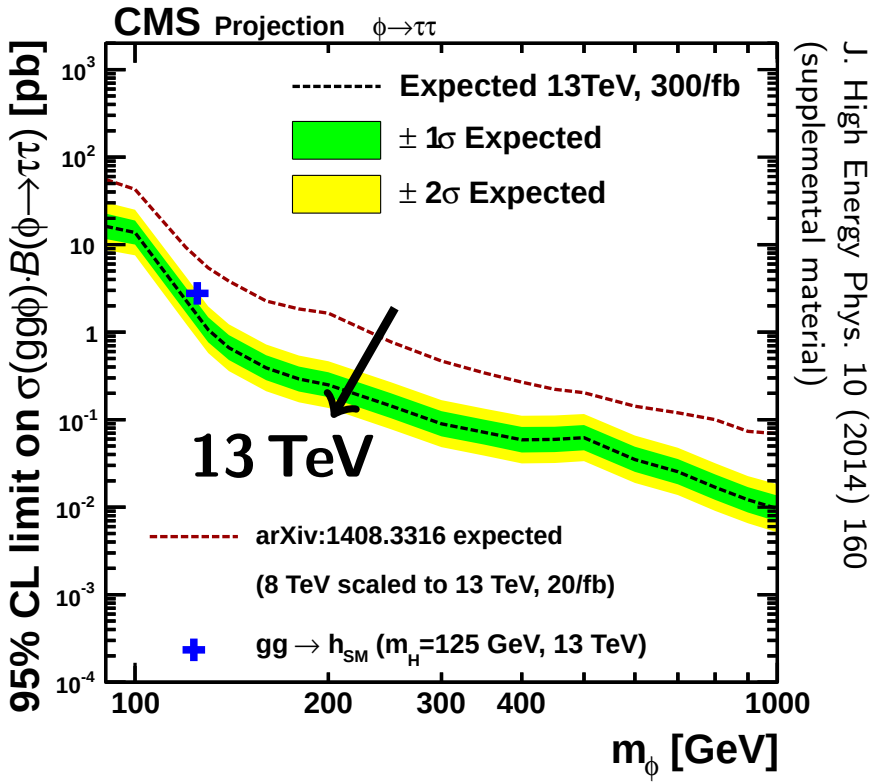
$\longrightarrow$ We don't know yet...

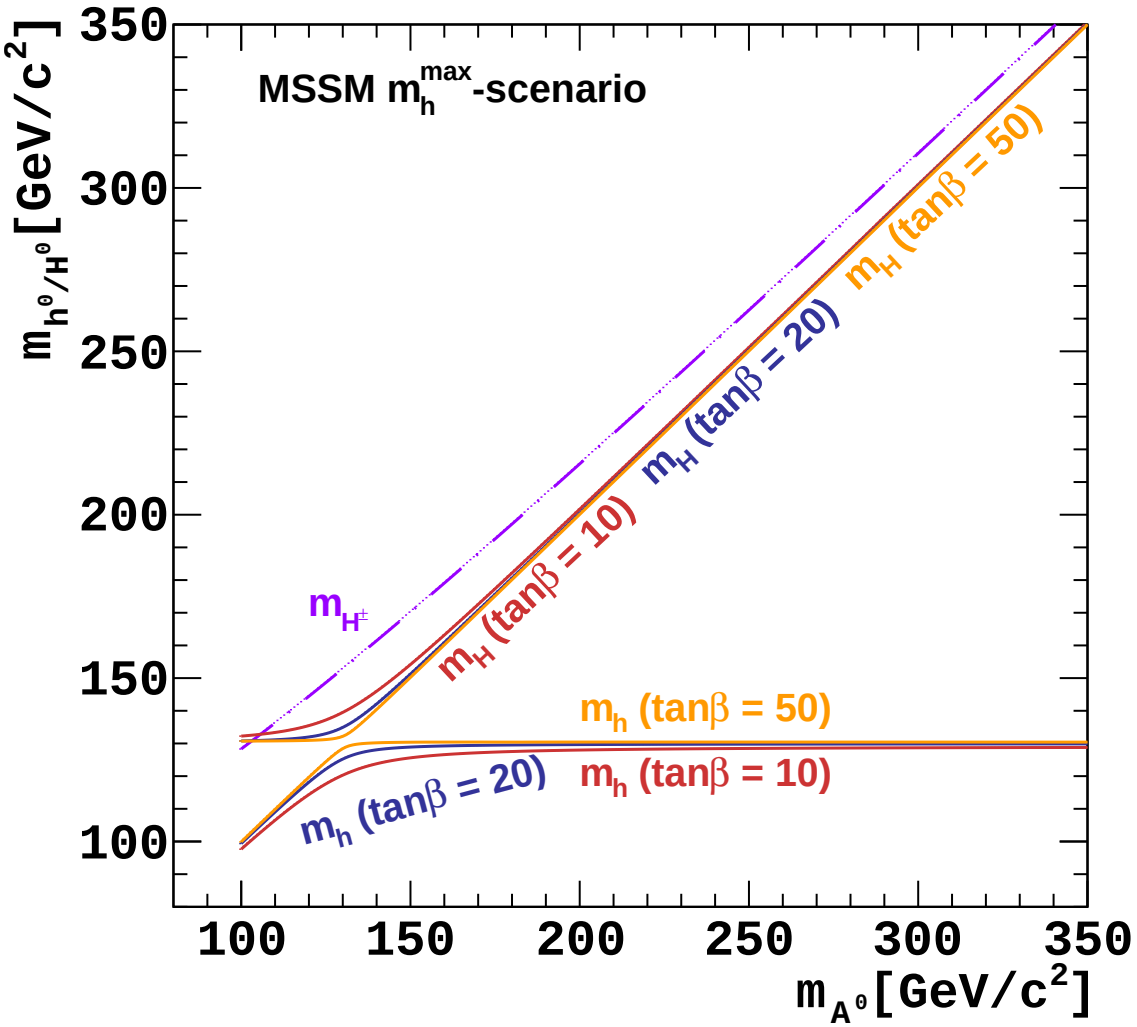
...but 13 TeV data ahead
We might know soon!



Additional Material

Neutral MSSM Higgs-Boson Masses in m_h^{max} Scenario

CMS-PAS-HIG-12-011



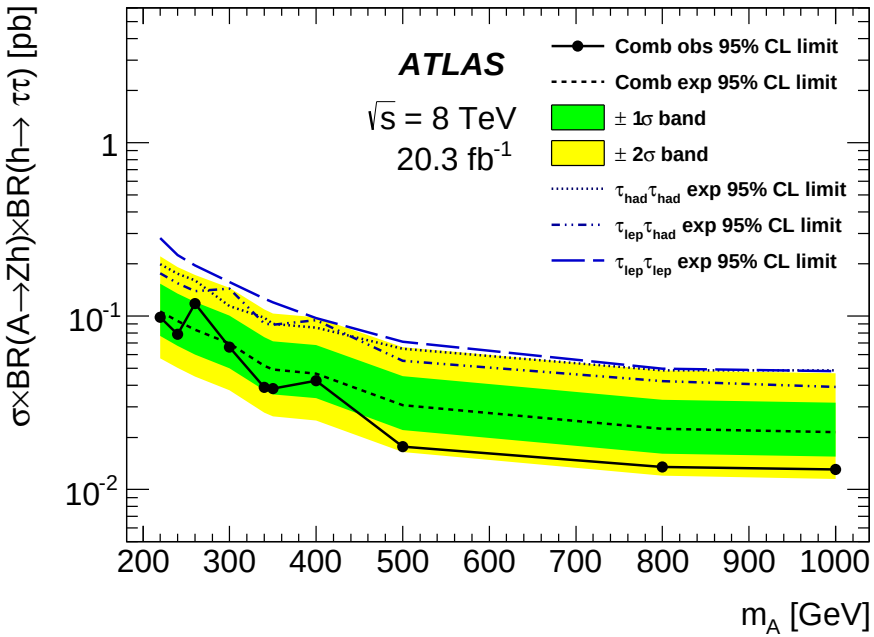
Types of 2HDM

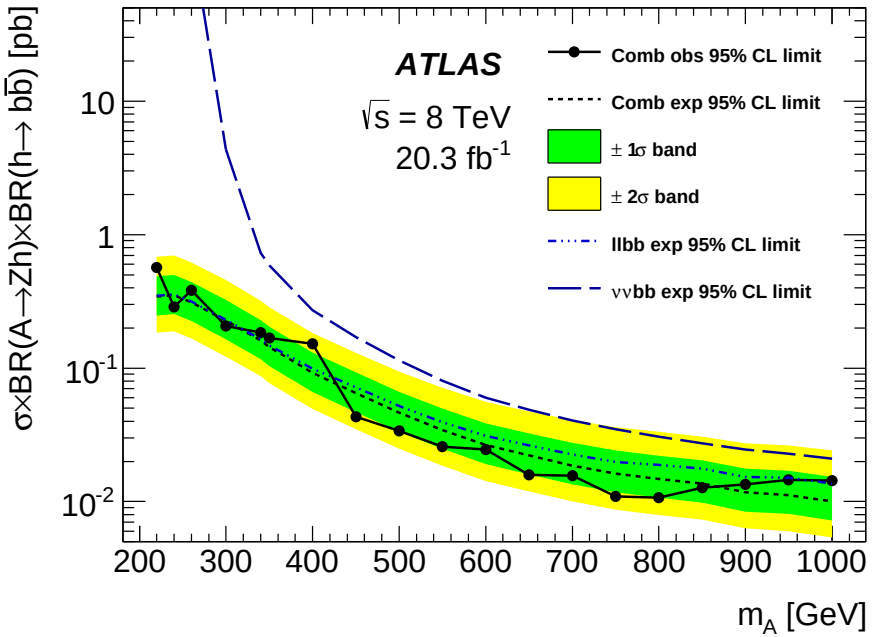
Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

Branco et al. *Theory and phenomenology of two-Higgs-doublet models*, Physics Reports 516 (2012) 1-102

A → Z + h: Model-Independent Interpretation

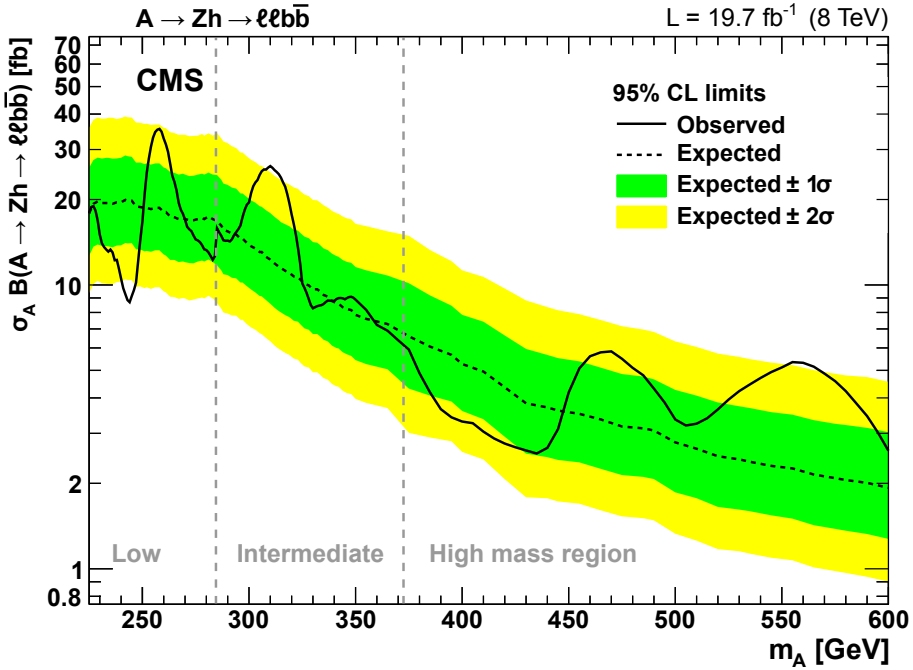
Phys. Lett. B 744 (2015) 163-183

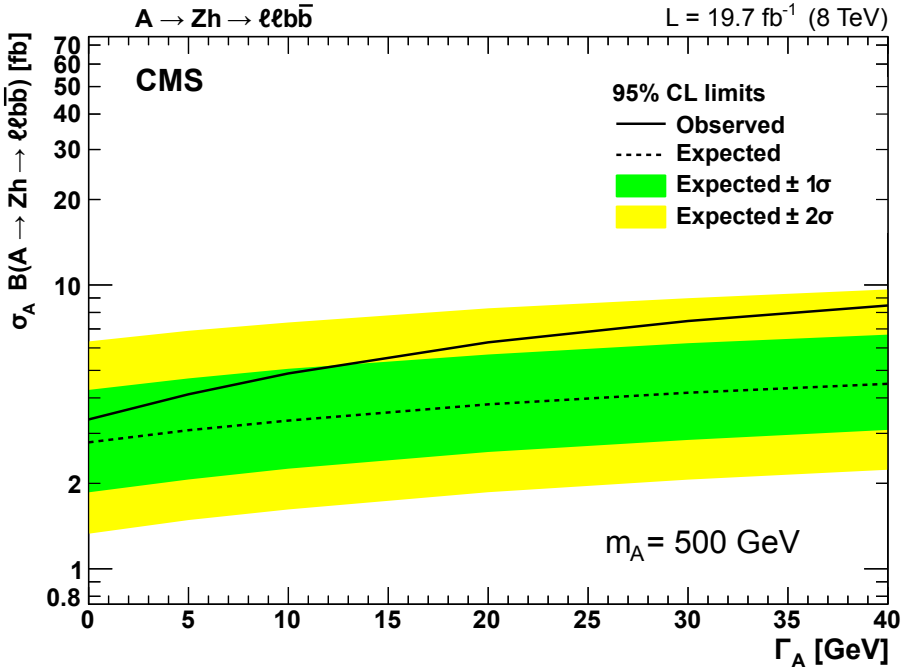




A → Z + h: Model-Independent Interpretation

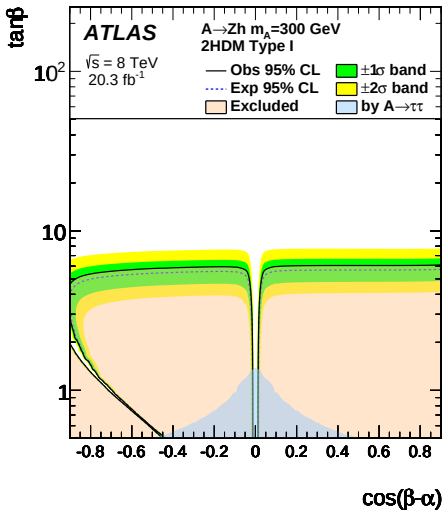
Phys. Lett. B 748 (2015) 221

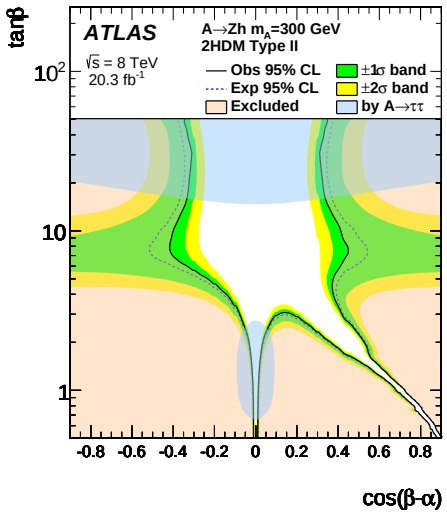


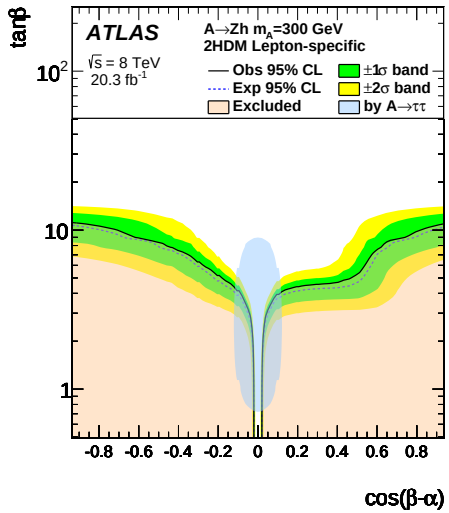


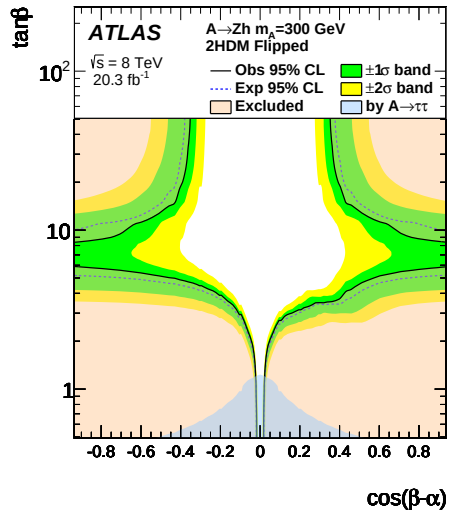
A → Z + h: 2HDM Interpretation

Phys. Lett. B 744 (2015) 163-183



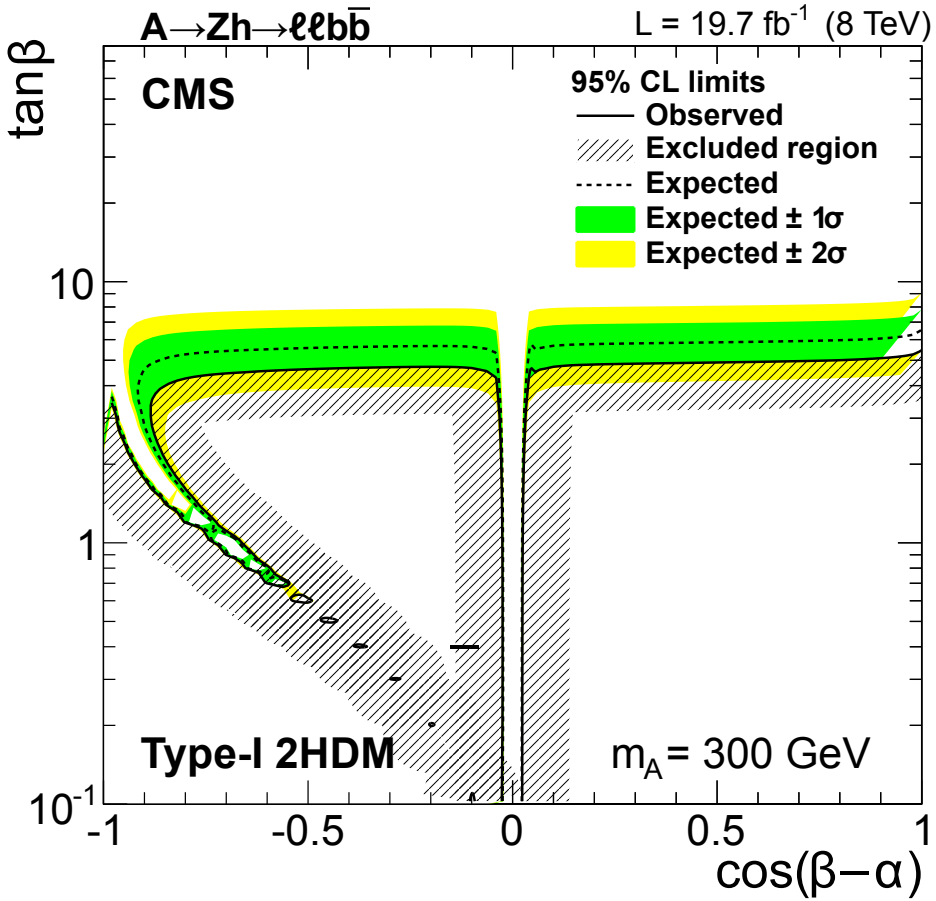


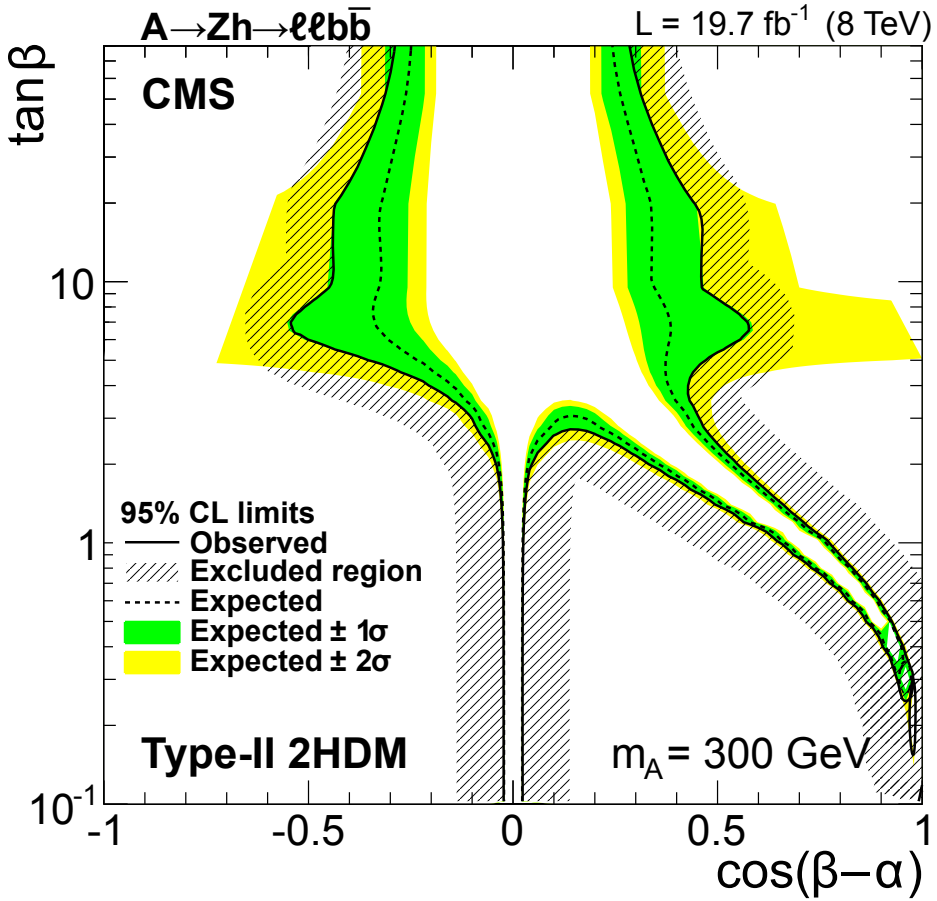




A → Z + h: 2HDM Interpretation

Phys. Lett. B 748 (2015) 221

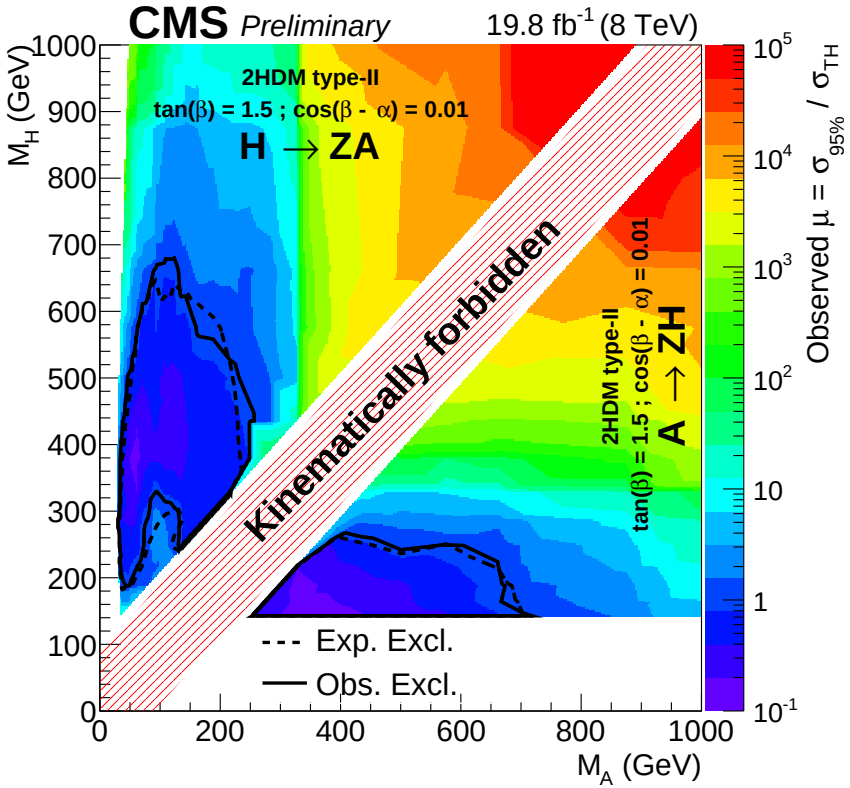




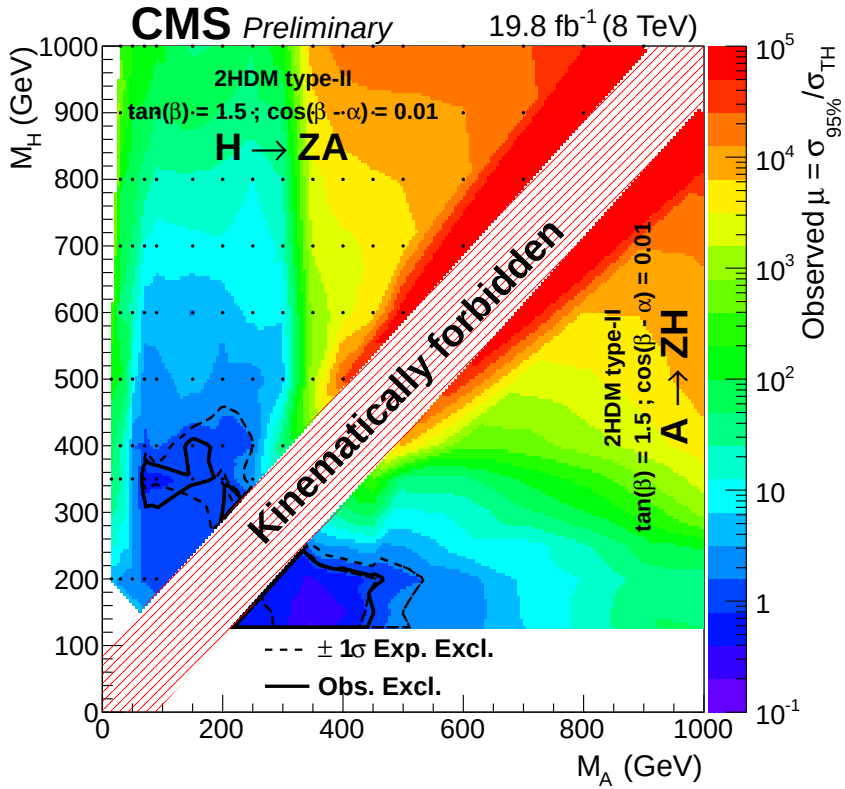
H/A → Z + A/H: 2HDM Interpretation

CMS-PAS-HIG-15-001

Z → bb channel



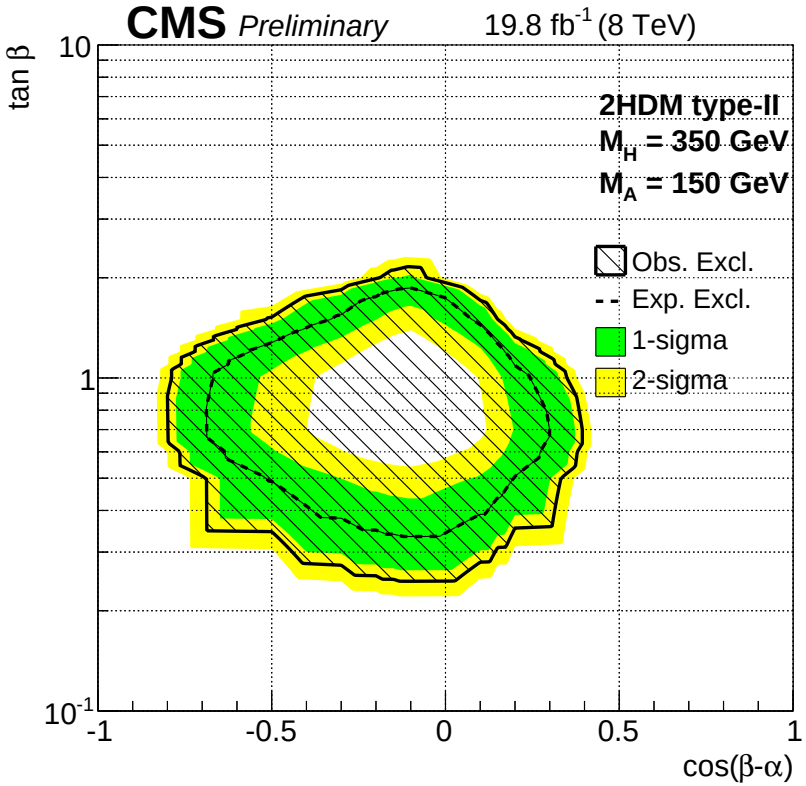
Z → ττ channel (shape analysis)



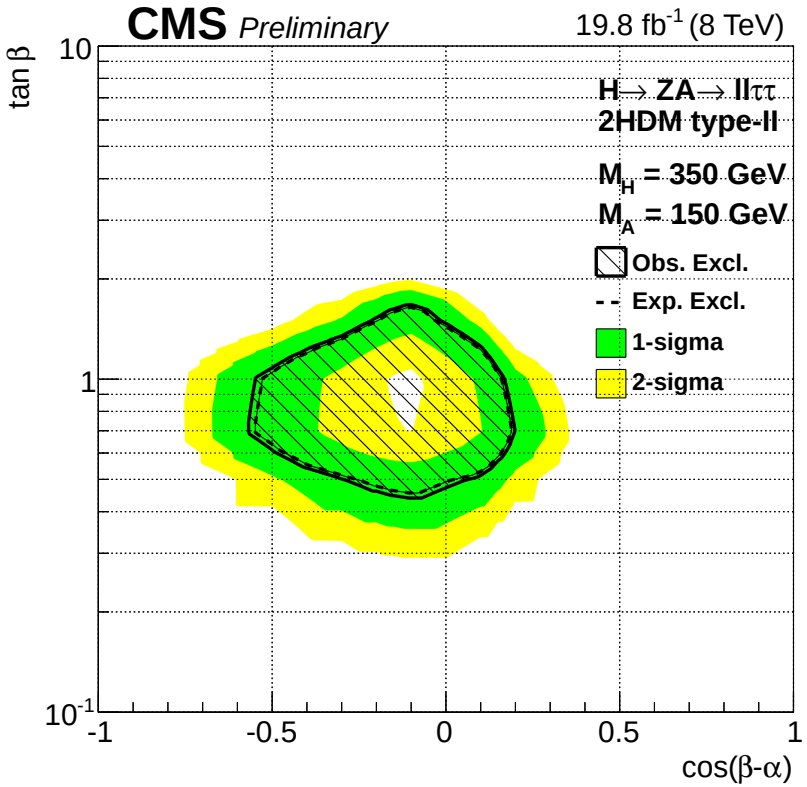
H/A → Z + A/H: 2HDM Interpretation

CMS-PAS-HIG-15-001

Z → bb channel



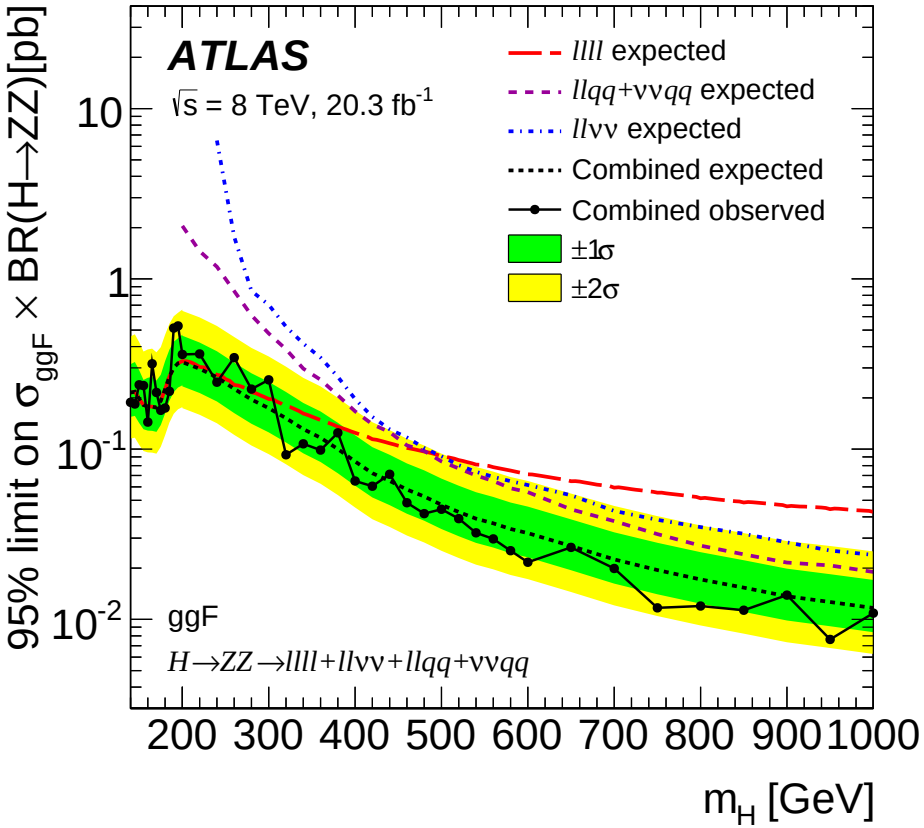
Z → ττ channel (shape analysis)

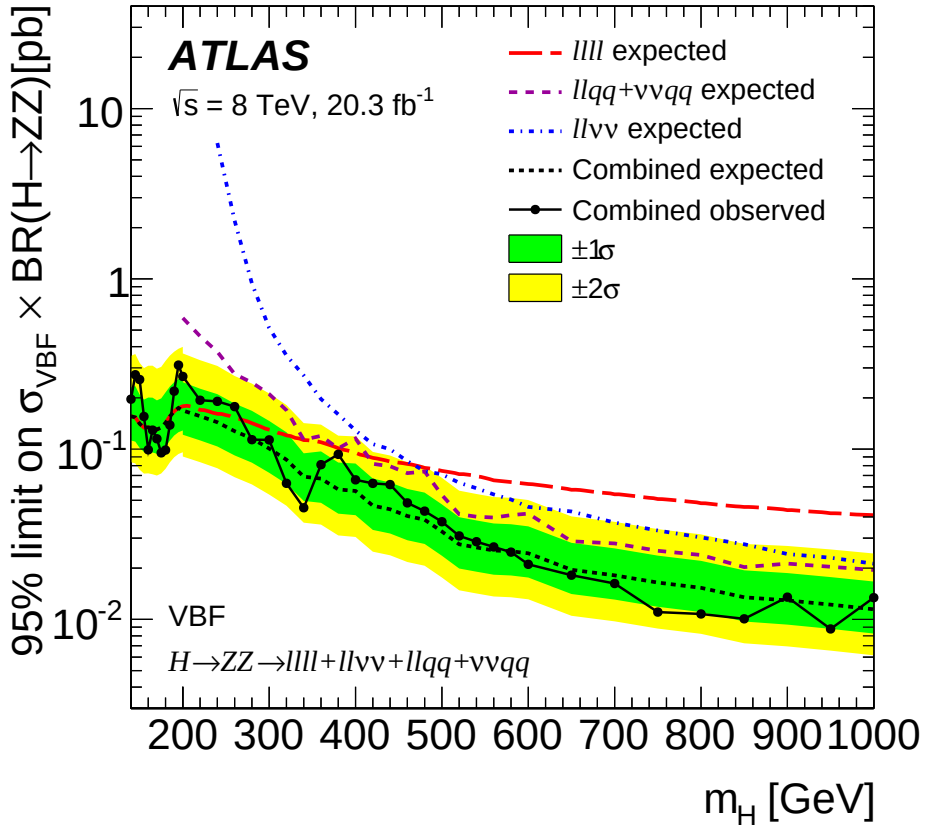


Search for Heavy H → ZZ at ATLAS

arXiv:1507.05930 (submitted to Eur. Phys. J.)

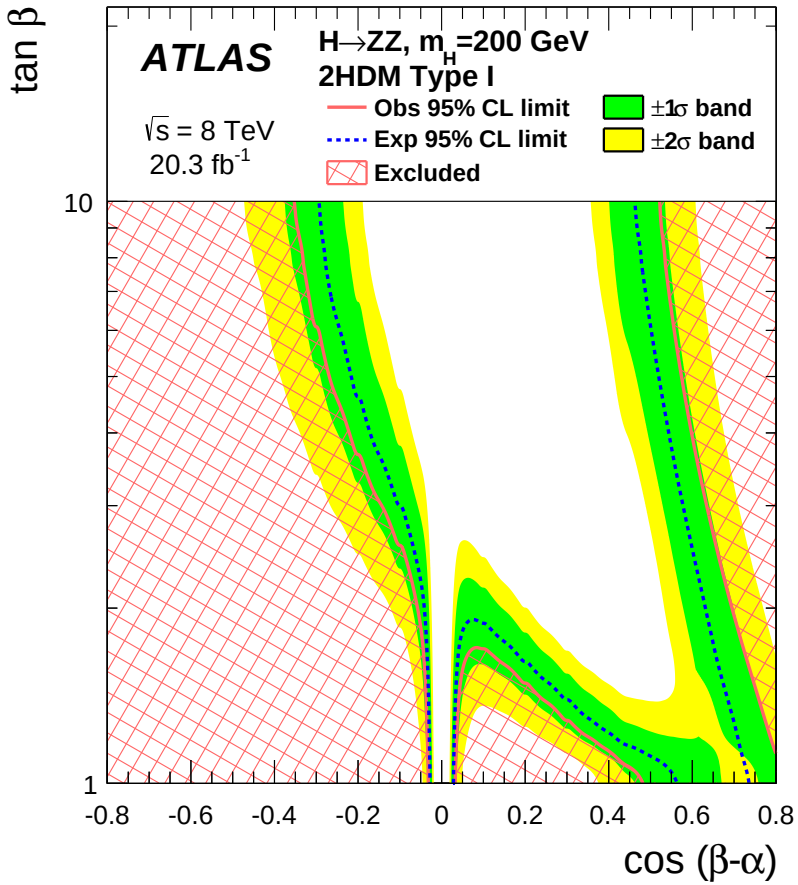
- 4 channels: llll, ll$\nu\nu$, llqq, qq$\nu\nu$

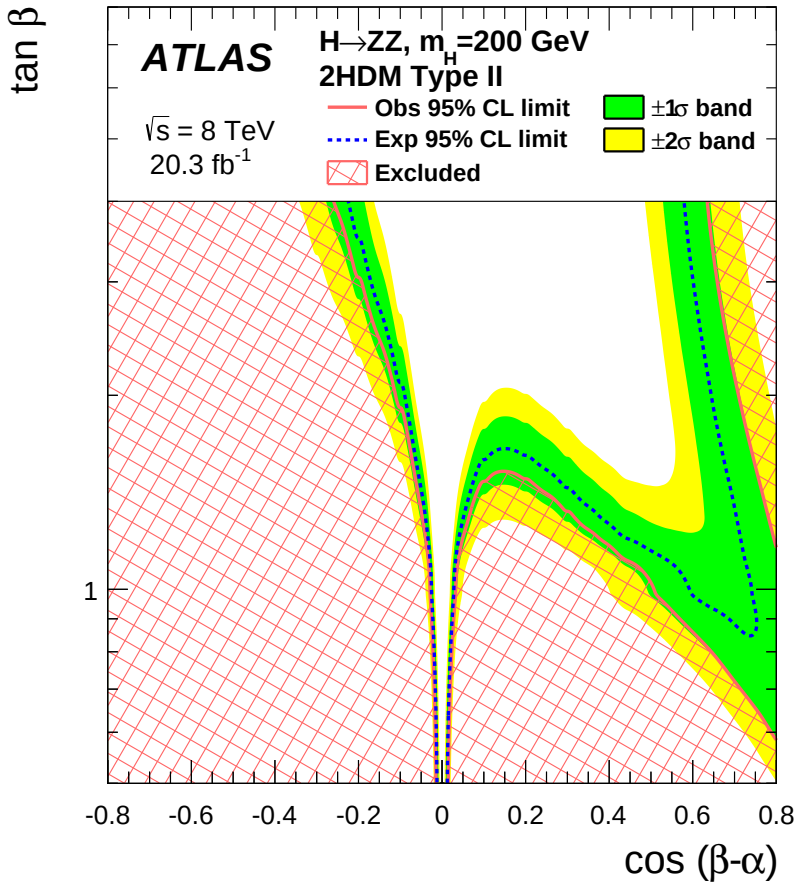




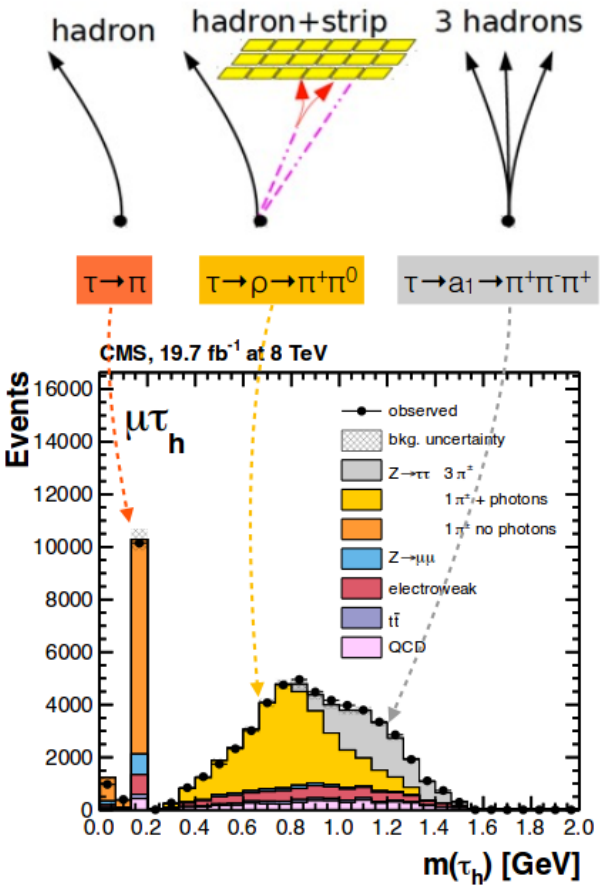
Search for Heavy H → ZZ: 2HDM Interpretation

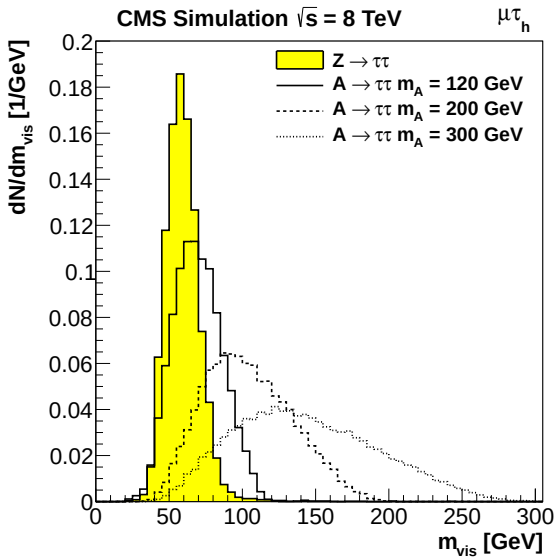
arXiv:1507.05930 (submitted to Eur. Phys. J.)

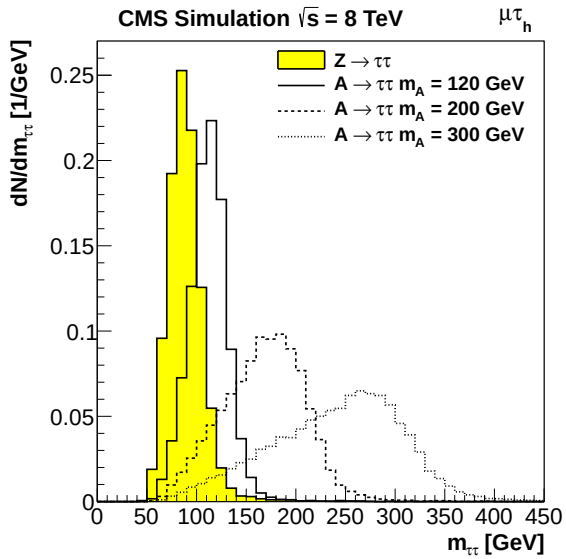




$m_{\tau\tau}$ Reconstruction at CMS





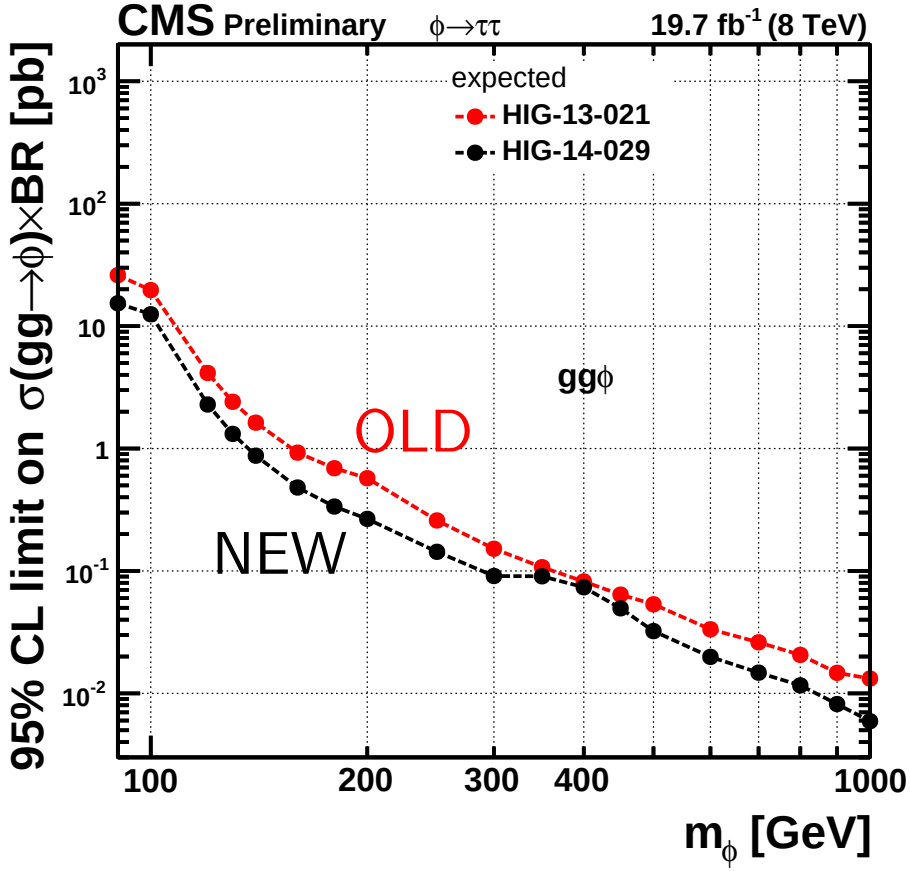


Updated $\Phi \to \tau\tau$ Search at CMS

CMS-PAS-HIG-14-029

- Channels: $\mu\mu$, $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- Refinements over earlier results

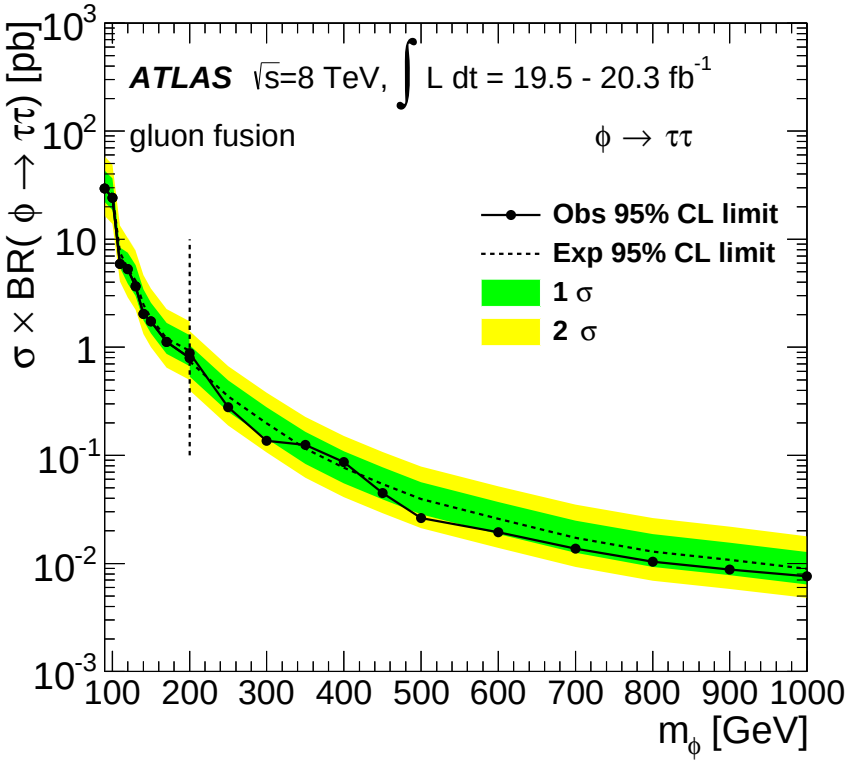
1) MVA-based identification of boosted τ_h
   - Combines isolation and lifetime information
   - 40–50% reduction of fake rate
2) Further event categorization
   - Depends on $p_T(\tau_h)$

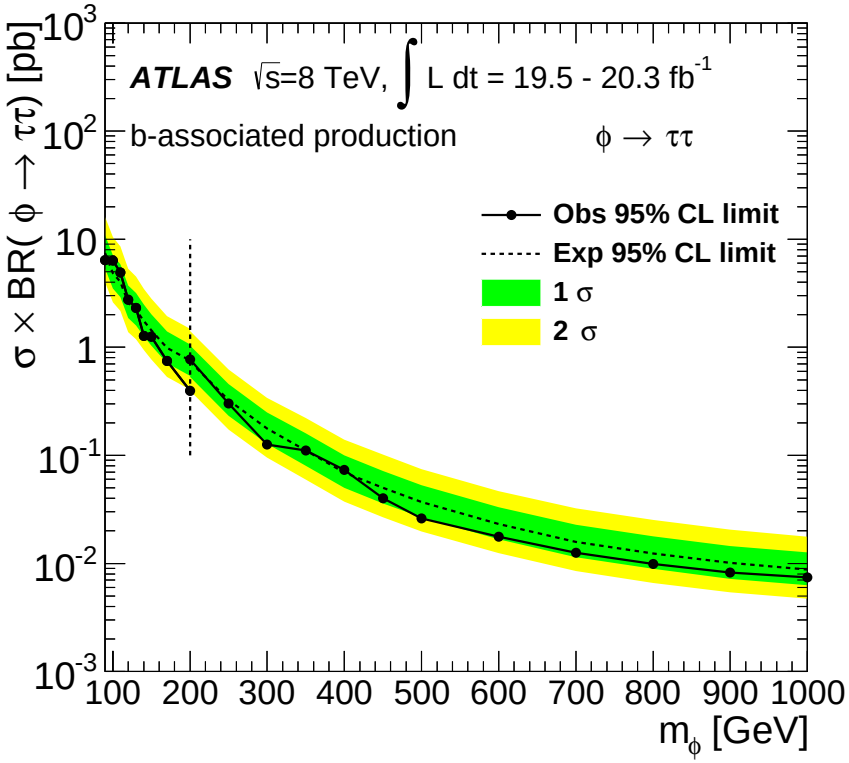


20–50% improvement in expected sensitivity for most mass points

$\Phi \to \tau\tau$: Model-Independent Results

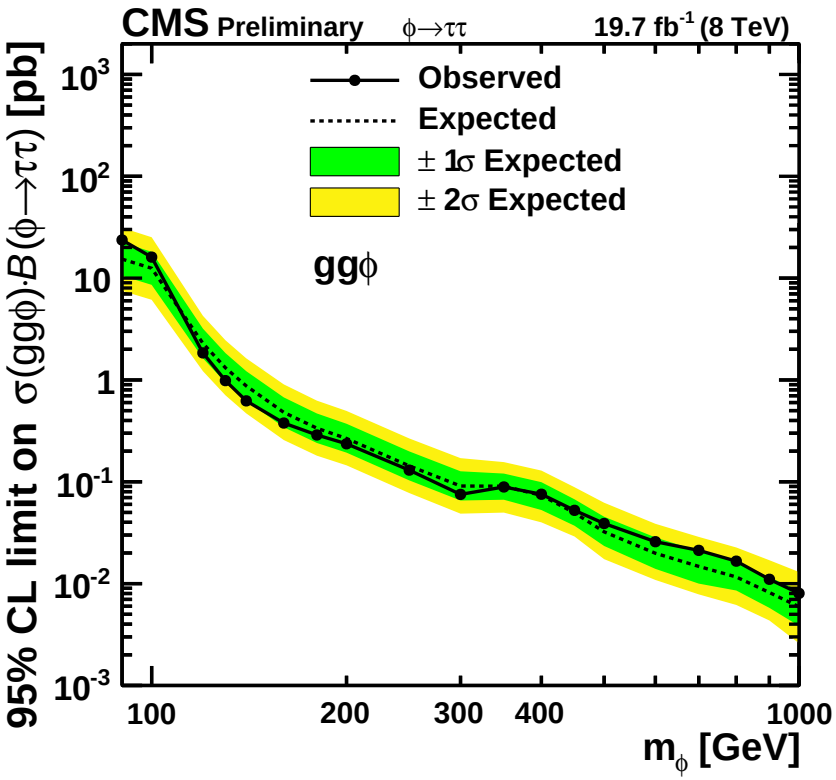
J. High Energy Phys. 11 (2014) 056

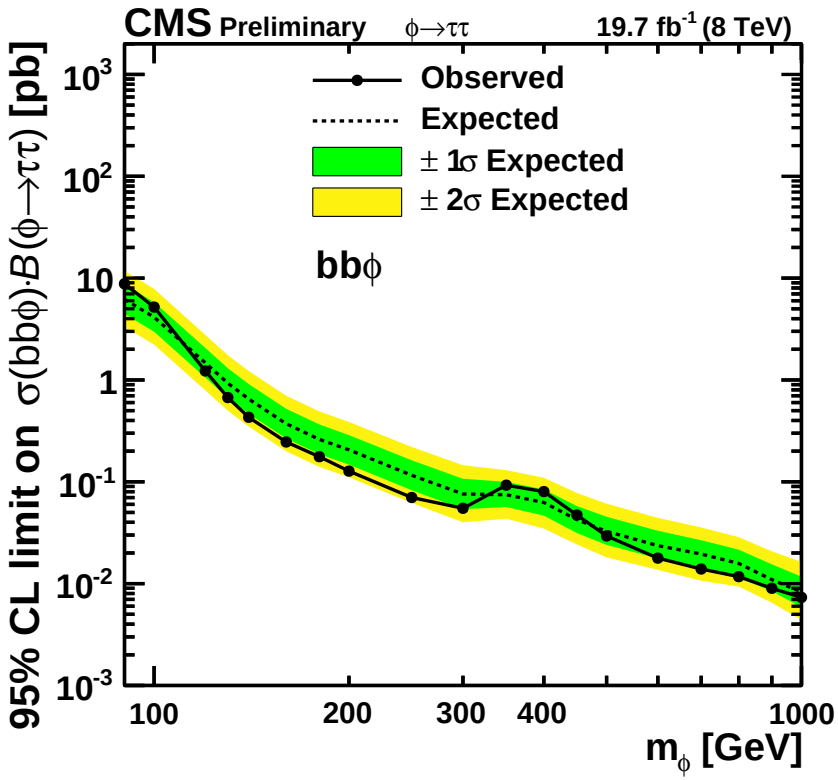




$\Phi \to \tau\tau$: Model-Independent Results

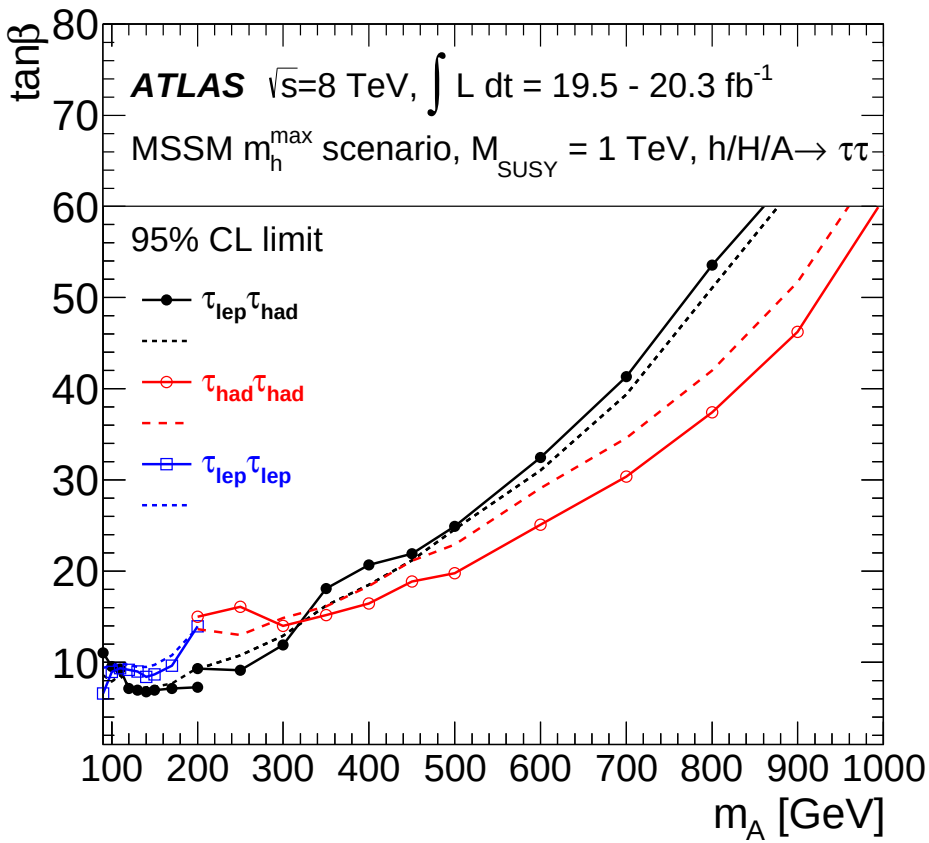
CMS-PAS-HIG-14-029





$\Phi \to \tau\tau$: Sensitivity of Different Channels

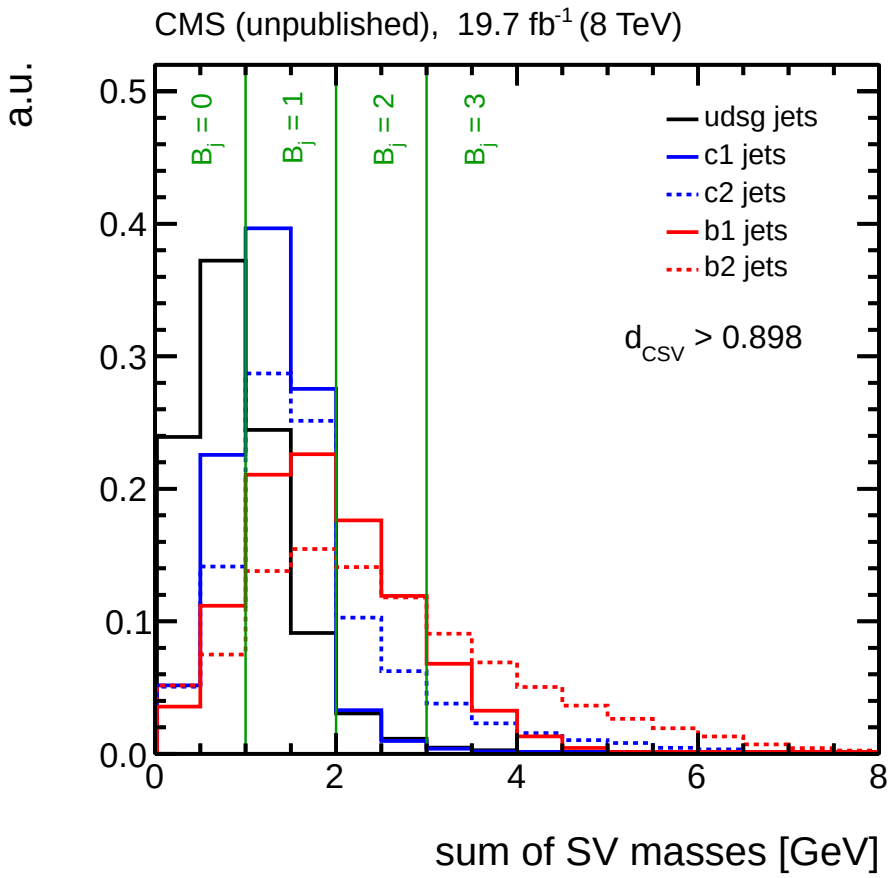
J. High Energy Phys. 11 (2014) 056



$\Phi \to bb$: Event-B-Tag Definition

CMS-PAS-HIG-14-017 (submitted to J. High Energy Phys.)

- M_{12} templates similar for different flavour combinations
- Additional separation by SV-mass information as 2nd dimension



- $\sum$ SV-masses (SVMS) per jet
- Combined into event-b-tag X_{123}

$$X_{123} = T_{12} + T_3$$

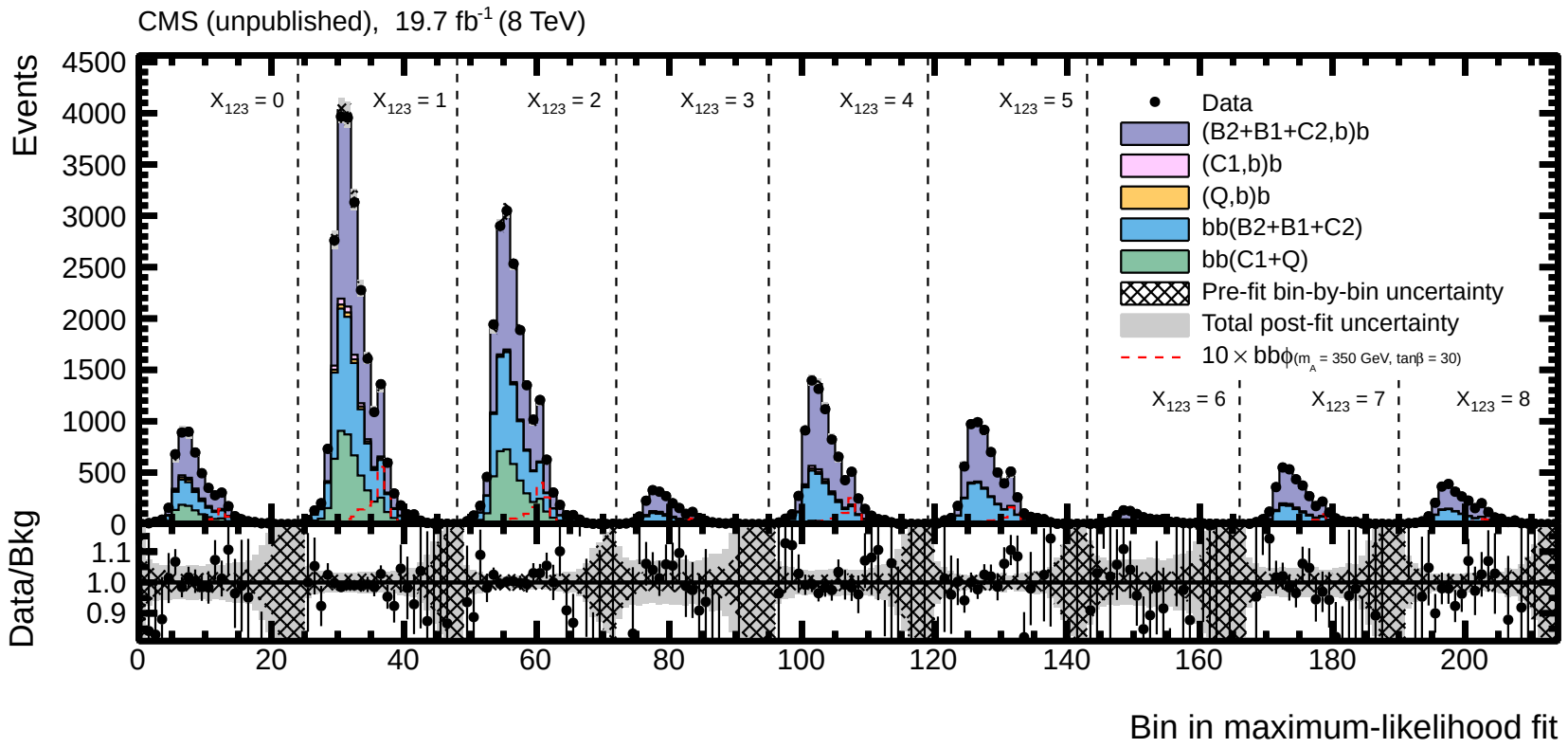
$T_{12} = 0$ if $B_1 + B_2 \leq 1$
$T_{12} = 1$ if $2 \leq B_1 + B_2 \leq 3$
$T_{12} = 2$ if $B_1 + B_2 \geq 4$

$T_3 = 0$ if $B_3 \leq 1$
$T_3 = 3$ if $B_3 = 2$
$T_3 = 6$ if $B_3 = 3$

$\to$ 9 different values by construction

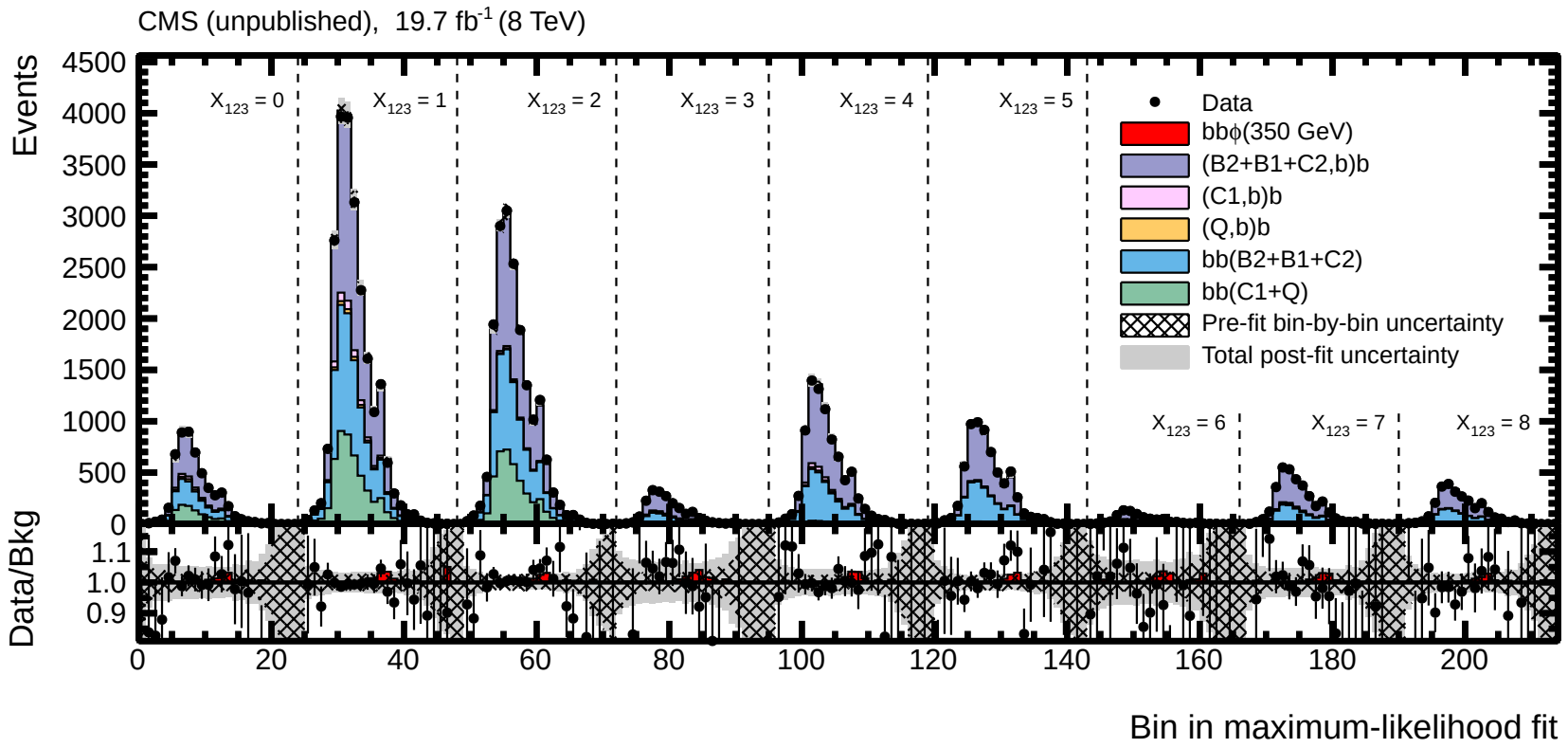
$\Phi \to bb$: Background-Only Fit (Unrolled Bins)

CMS-PAS-HIG-14-017 (submitted to J. High Energy Phys.)



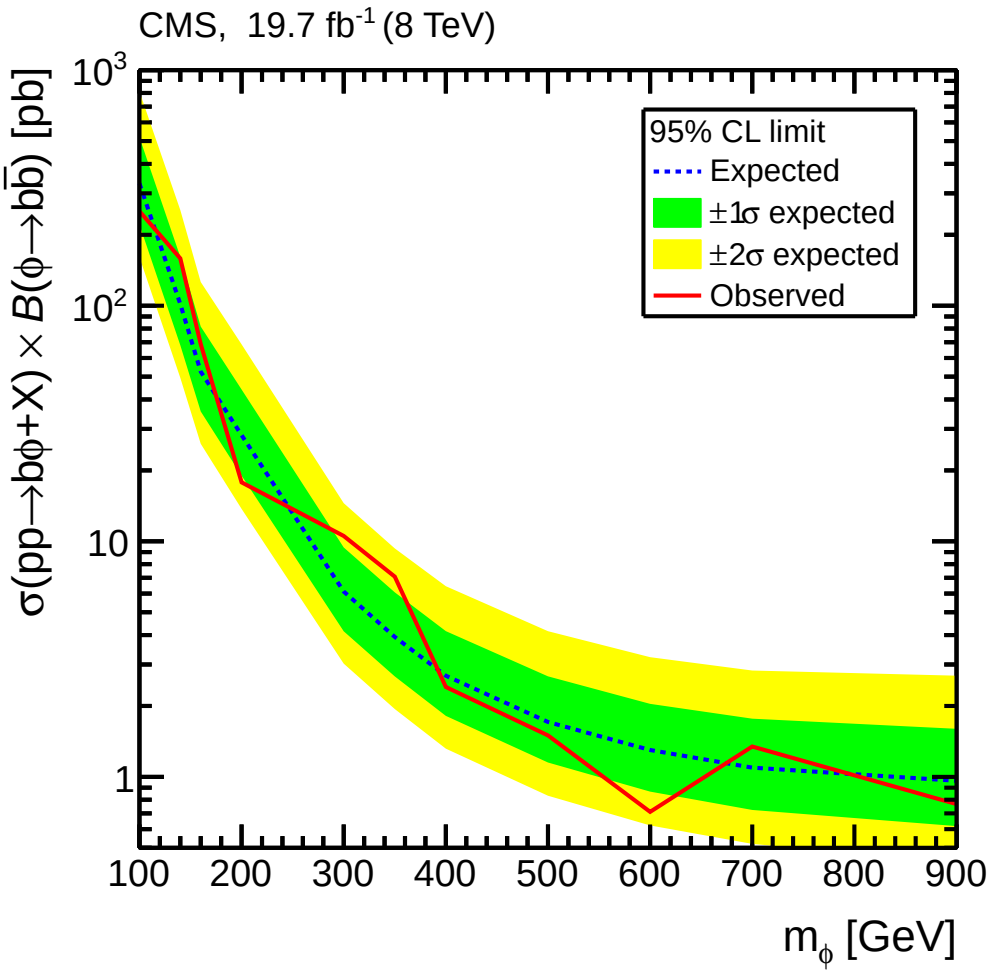
Φ → bb: Signal+Background Fit (Unrolled Bins)

CMS-PAS-HIG-14-017 (submitted to J. High Energy Phys.)



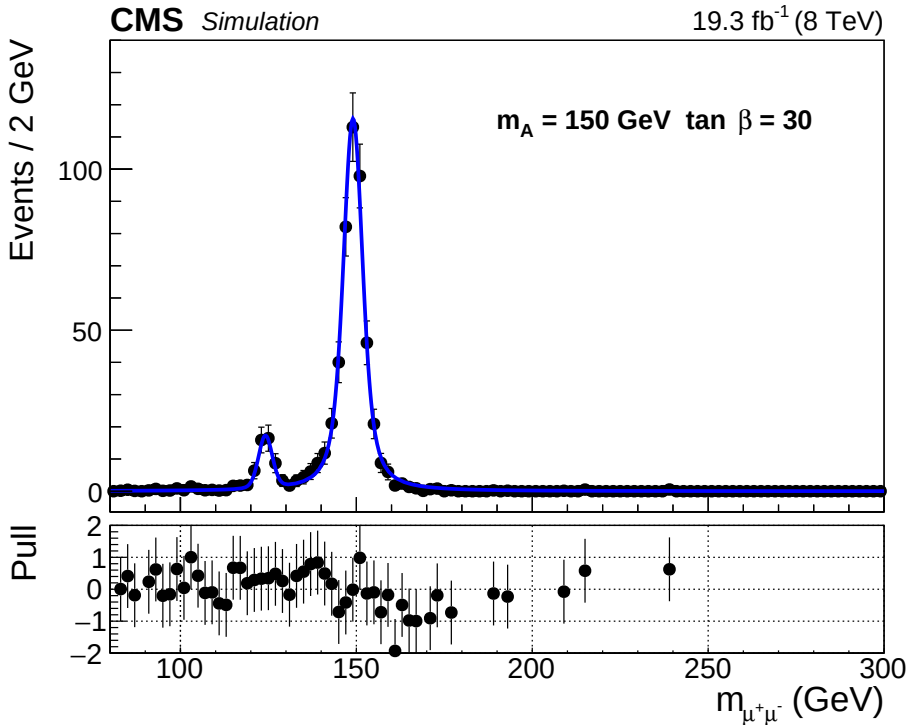
$\Phi \to bb$: Model-Independent Interpretation

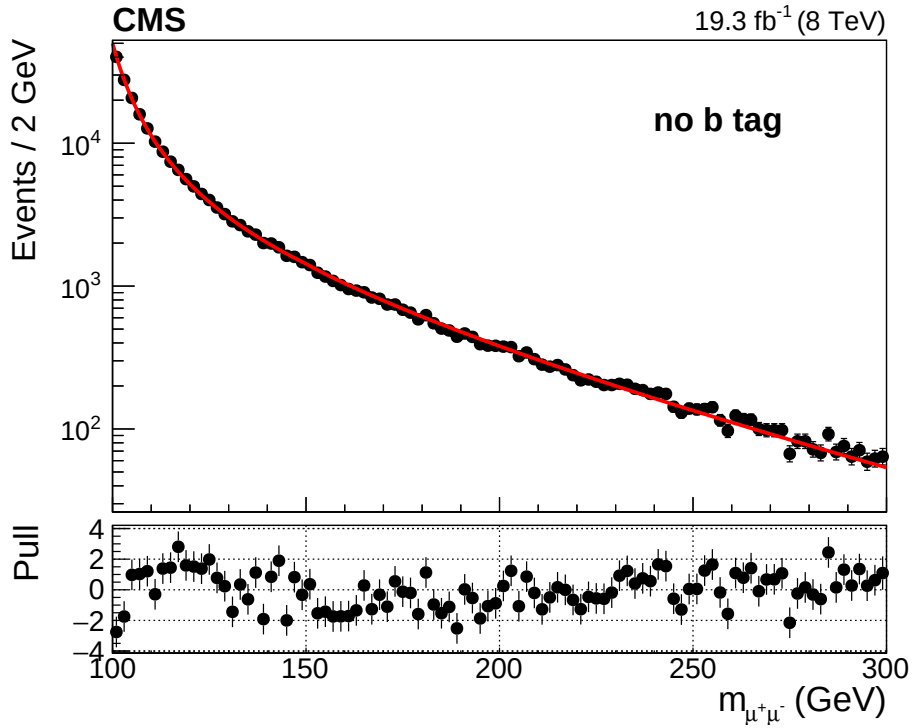
CMS-PAS-HIG-14-017 (submitted to J. High Energy Phys.)



$\Phi \to \mu\mu$: Signal & Background Models

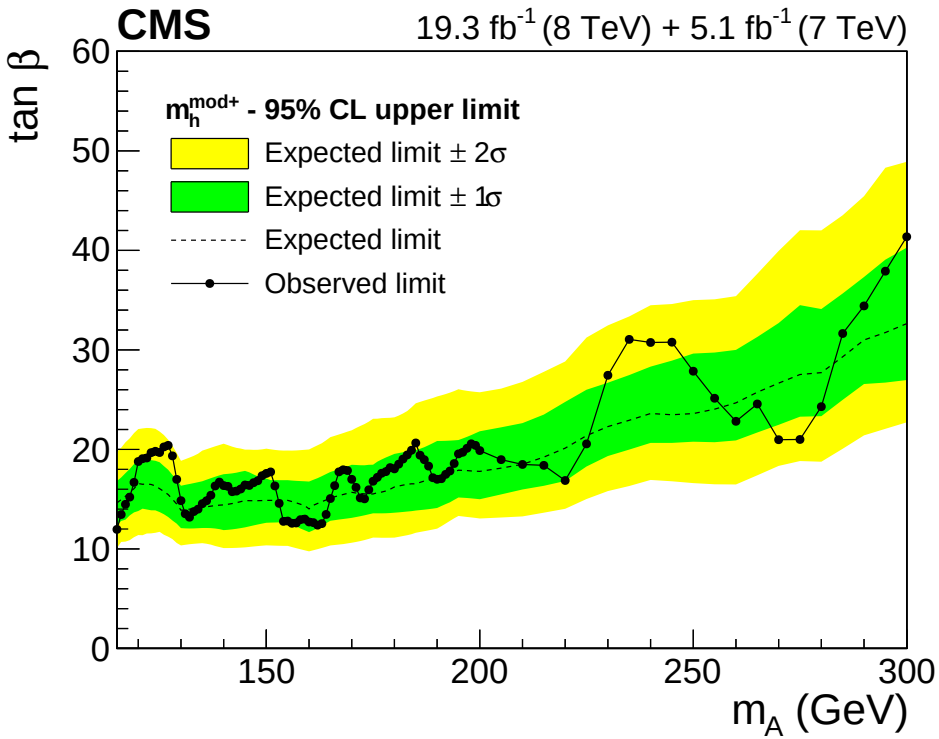
CMS-PAS-HIG-13-024 (submitted to Phys. Lett. B)

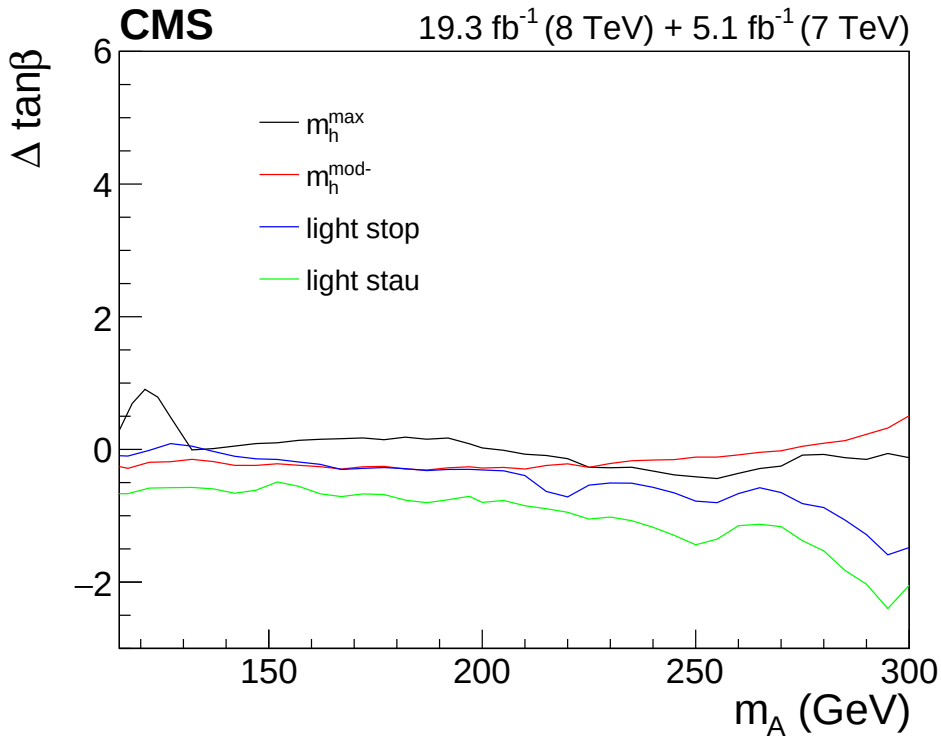




$\Phi \to \mu\mu$: MSSM Interpretation

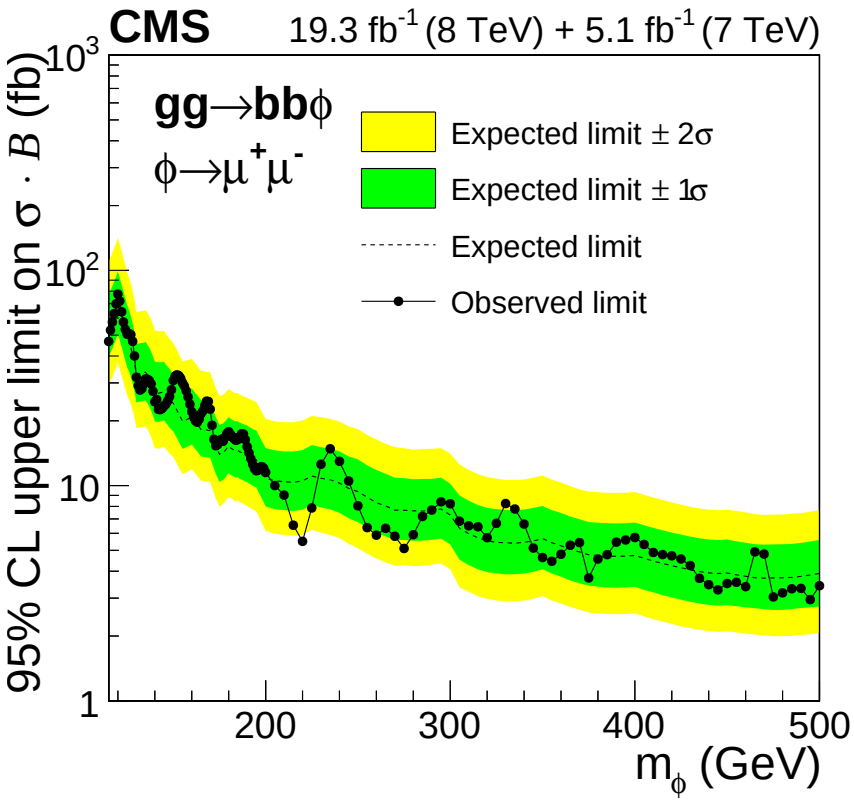
CMS-PAS-HIG-13-024 (submitted to Phys. Lett. B)

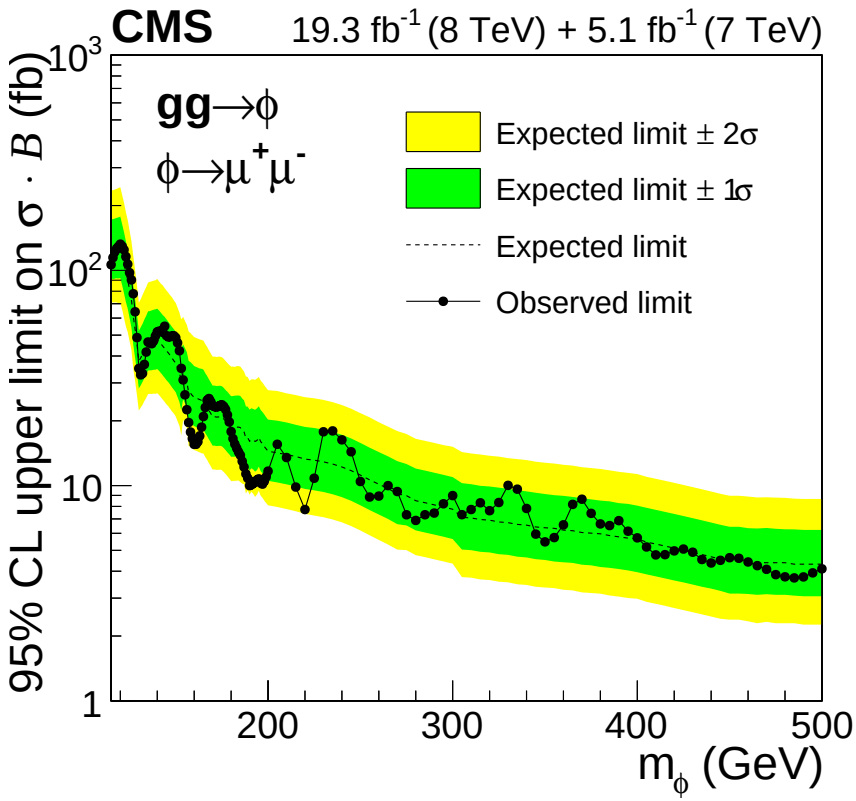




$\Phi \to \mu\mu$: Model-Independent Results

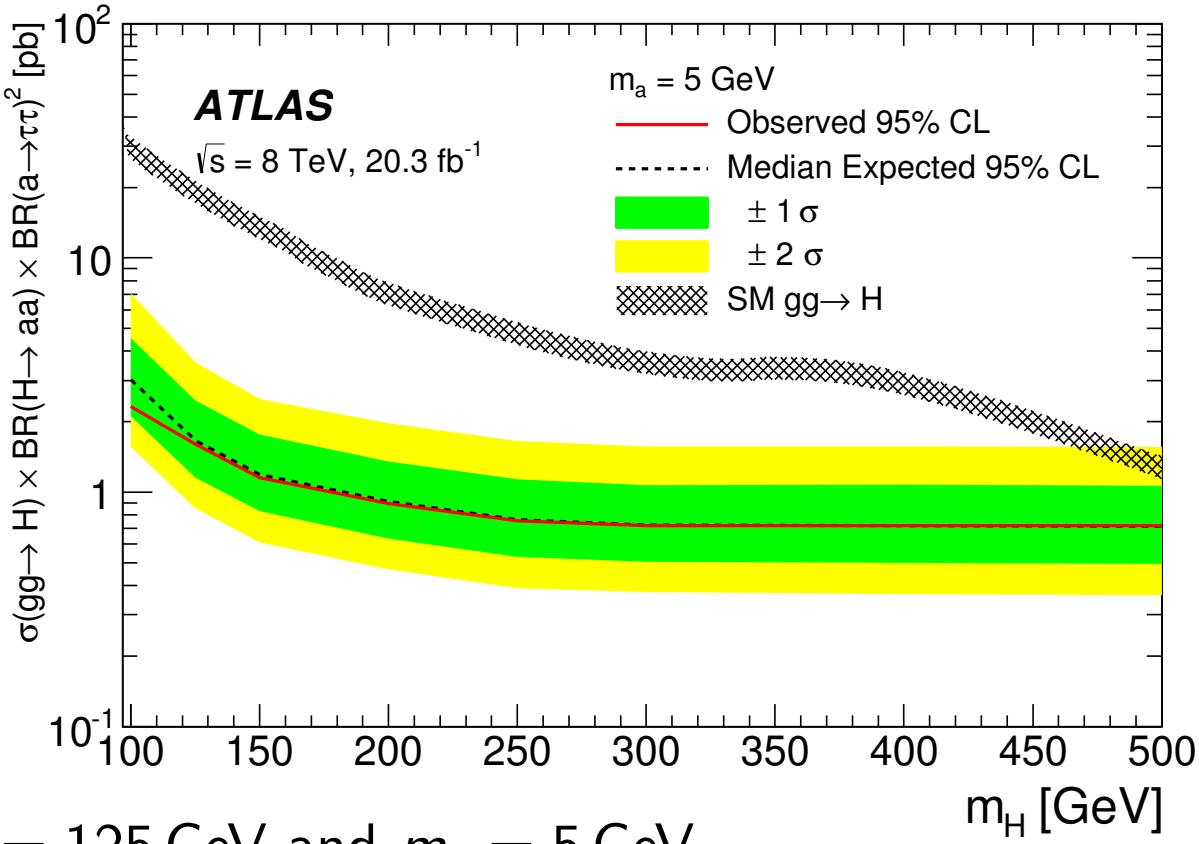
CMS-PAS-HIG-13-024 (submitted to Phys. Lett. B)





H → a(5)a(5) → μμττ Interpretation

arXiv:1505.01609 (submitted to Phys. Rev. D)



Assuming $m_h = 125\,\text{GeV}$ and $m_a = 5\,\text{GeV}$