CMS Searches for Exotic Decays of the H(125)

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Room for new physics

- At 95% CL, up to 34% allowed branching ratio to as-yet-unseen decays
- Direct searches for Higgs decays to exotics are a clear window onto new physics
    - Utilizes one important constraint: the Higgs exists!
    - Complementarity to Standard Model (SM) Higgs measurements
    - Many well motivated theories of new physics predict complex Higgs sectors

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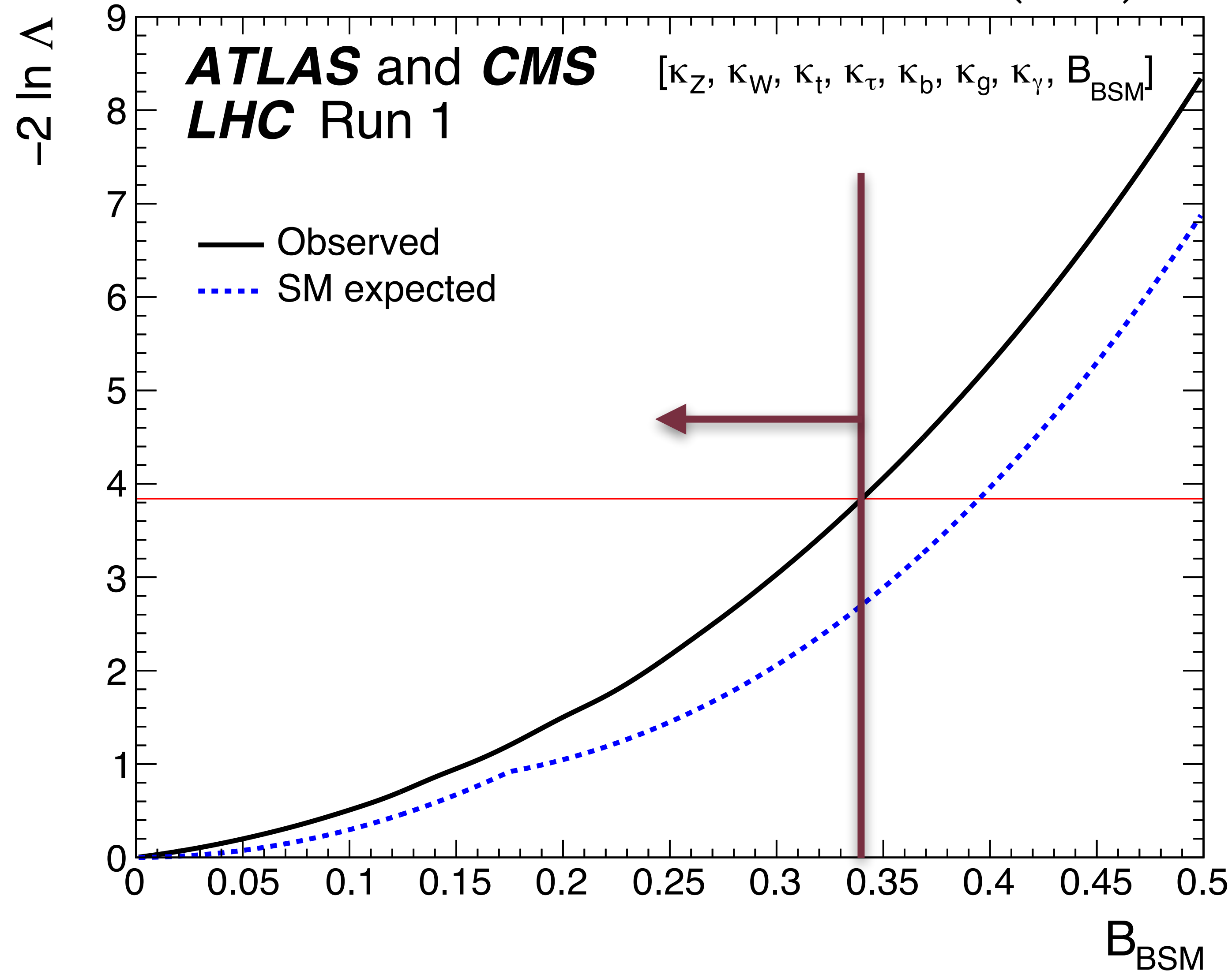
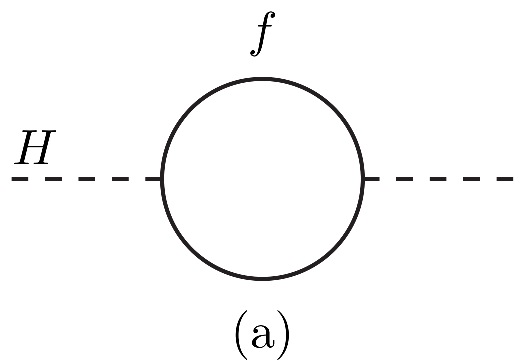


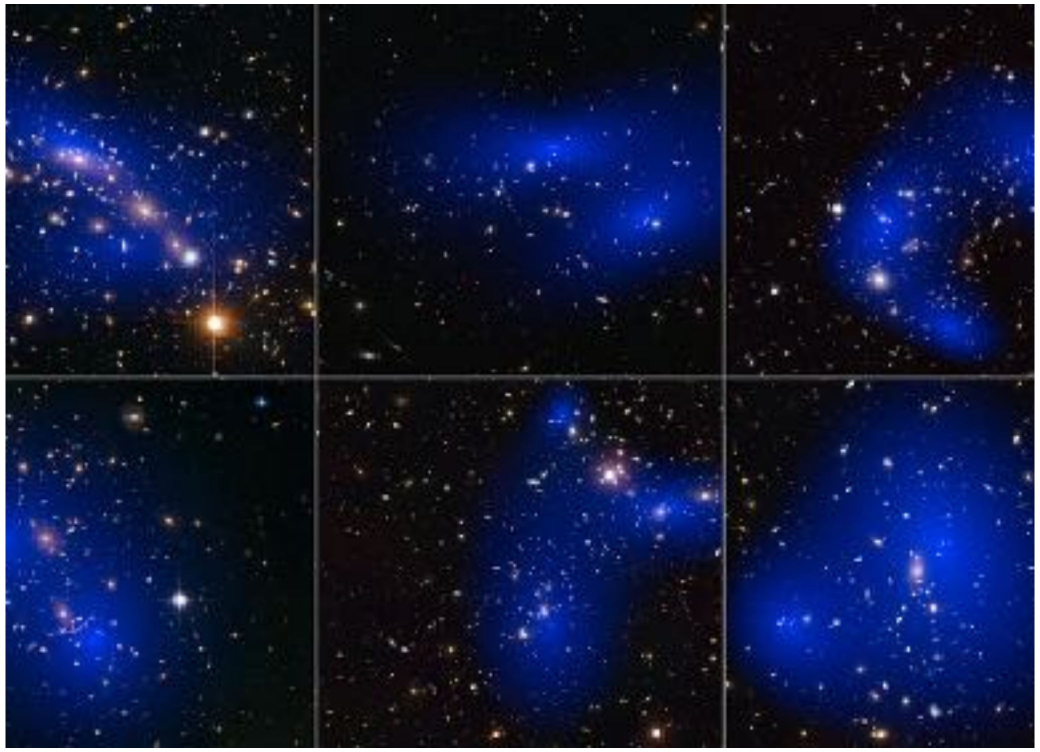
Motivation for new physics

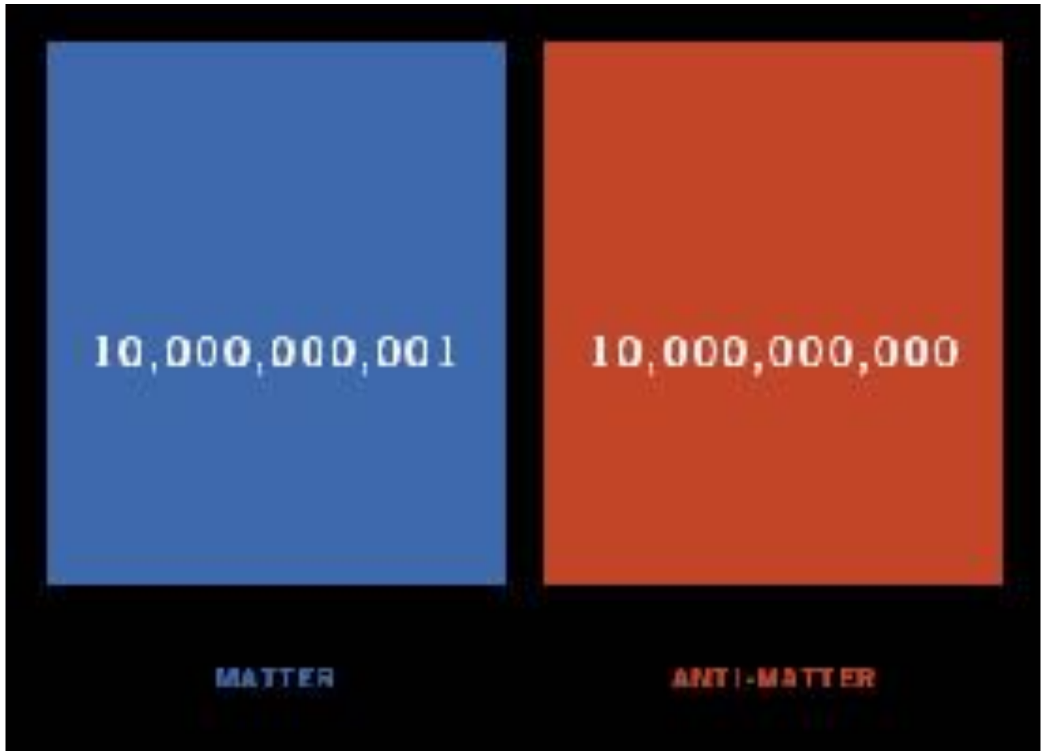
$m_H^2 \propto$



$$\Delta m_H^2 = \frac{1}{16\pi^2} \times -|\lambda_f|^2 \, \Lambda_{\mathrm{UV}}^2 + \ldots .$$

- Hierarchy problem
- Dark matter
- Baryon/anti-baryon asymmetry





Motivation for exotic Higgs decays

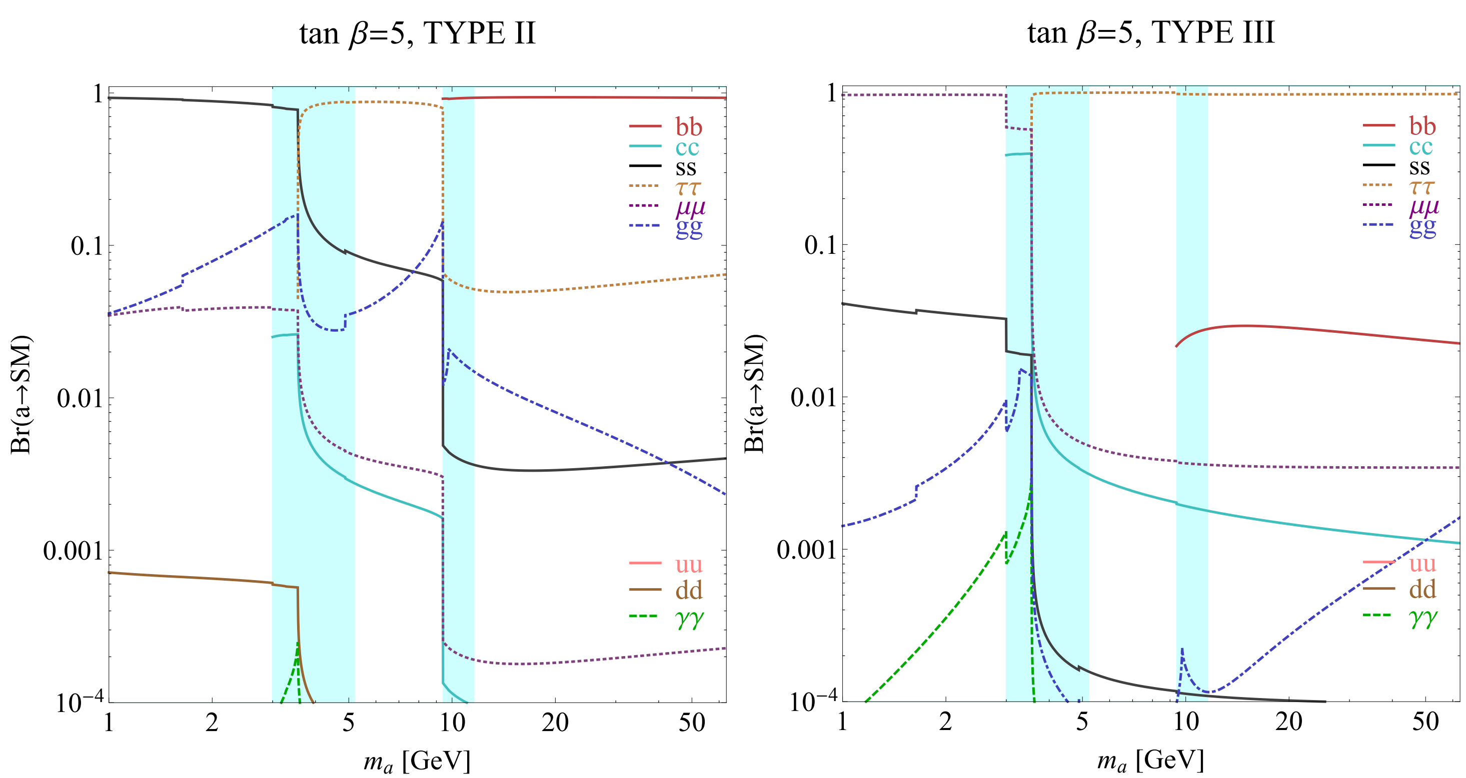
- Anything that adds a gauge singlet to the SM
  - Hidden valley
  - Higgs portal
  - Little Higgs
  - Next-to-minimal supersymmetric standard model (NMSSM)
- All address the tensions in the SM in some way
- All predict new light particles, potentially long-lived, that couple to the 125 GeV Higgs

Exotic decays take many forms

- $H \to \mu\tau$ (CMS Run 2, CMS Run 1); $H \to e\tau$, $H \to e\mu$ (CMS Run 1); $H \to e\tau$, $H \to \mu\tau$ (ATLAS Run 1)
- $H \to \Phi\gamma$ (ATLAS Run 2); $H \to J/\psi\gamma$, $H \to \Upsilon(nS)\gamma$ (ATLAS Run 1); $H \to J/\psi\gamma$ (CMS Run 1)
- $H \to ZZ_d$, $H \to Z_d Z_d$ (ATLAS Run 1)
- Related: direct production of light pseudoscalar (CMS Run 1) ($a \to \mu\mu$ + 2b, $a \to \tau\tau$ + 2b, SUSY cascade to $a \to b\bar{b}$)
- Today's focus
  - $H \to aa \to 4f$, predicted by the NMSSM
  - $H \to$ invisible, predicted by Higgs portal models

Two-Higgs-doublet models

Particle	Coupling	I	II (MSSM-like)	III (lepton specific)	IV (flipped)
A	g_{AVV}	0	0	0	0
	$g_{Au\bar{u}}$	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
	$g_{Ad\bar{d}}$	-$\cot\beta$	$\tan\beta$	-$\cot\beta$	$\tan\beta$
	$g_{A\ell\bar{\ell}}$	-$\cot\beta$	$\tan\beta$	$\tan\beta$	-$\cot\beta$



PRD 90 (2014) 075004

- General framework applicable to more detailed models of new physics with two Higgs doublets
  - Ex. minimal supersymmetric SM (MSSM)
  - Ex. NMSSM ~ 2HDM with extra gauge singlet

≥2 scalar Higgs, ≥1 pseudoscalar Higgs, ≥2 charged Higgs

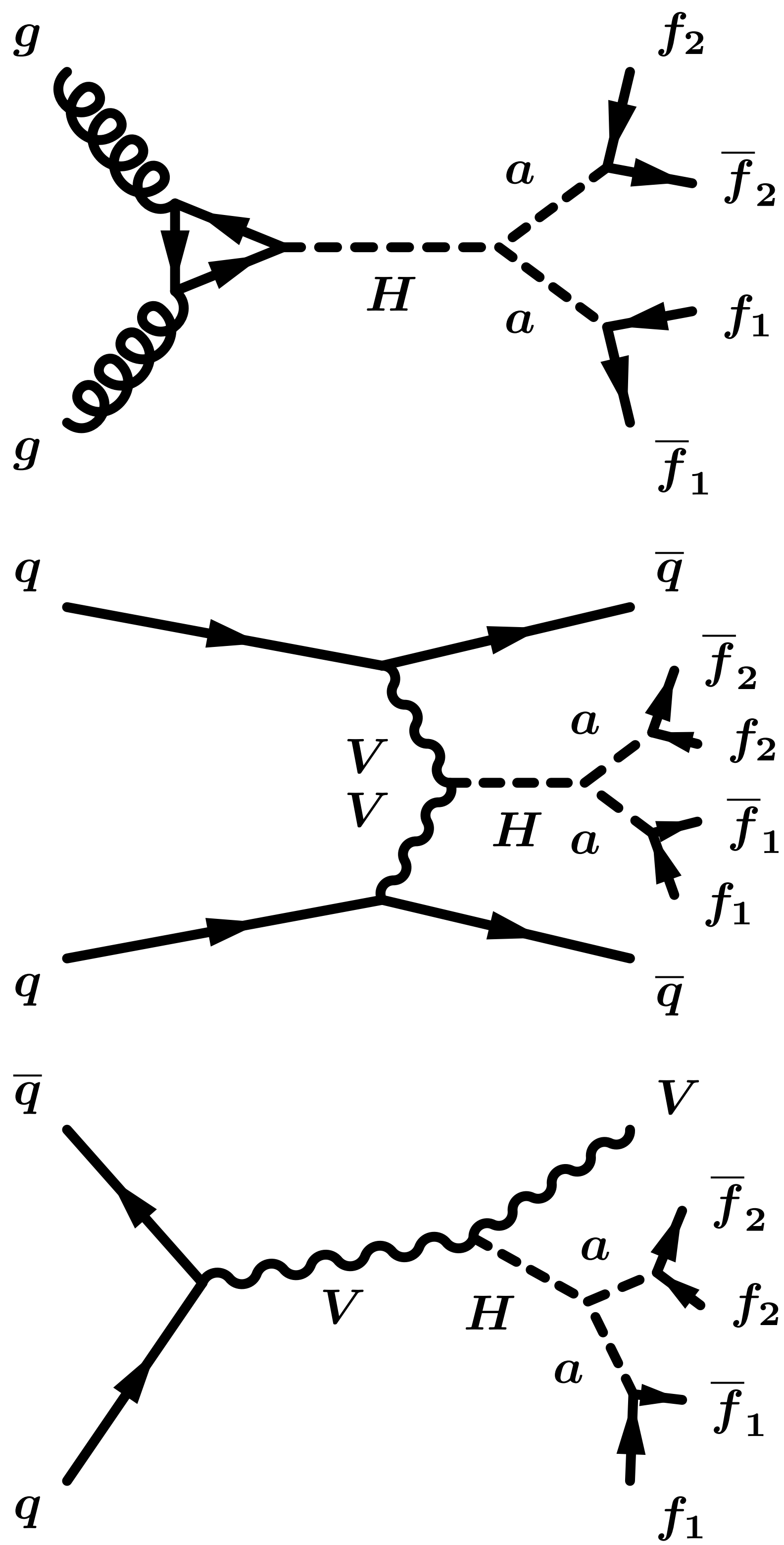
Two-Higgs-doublet models

- Searches can be interpreted in terms of the four types of models
- Simple relations exist among the branching ratios to muons, taus, and bottoms

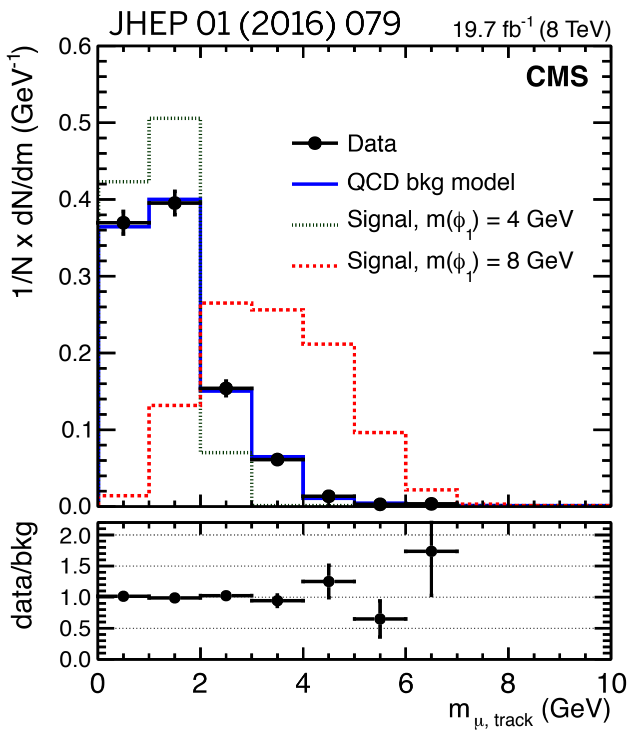
$$\frac{\Gamma(\mathrm{a}\to\mu^+\mu^-)}{\Gamma(\mathrm{a}\to\tau^+\tau^-)} = \frac{m_\mu^2\sqrt{1-(2m_\mu/m_\mathrm{a})^2}}{m_\tau^2\sqrt{1-(2m_\tau/m_\mathrm{a})^2}}$$

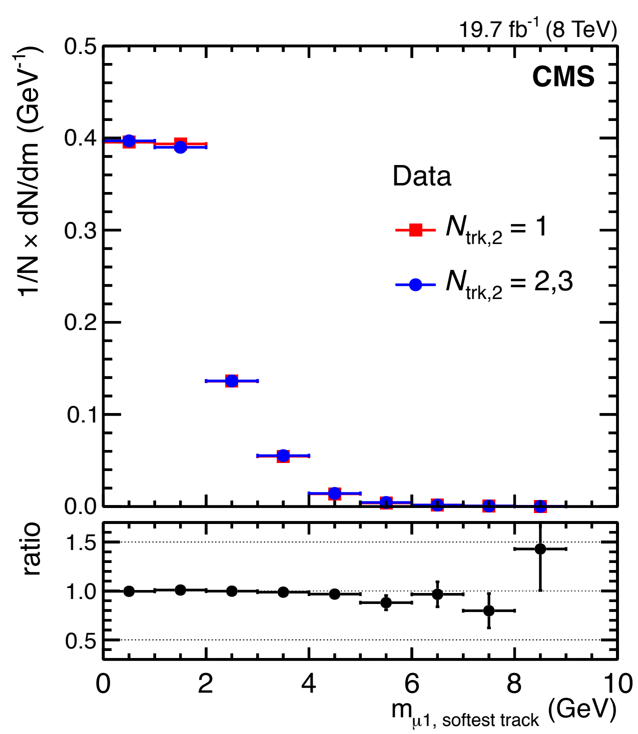
$$\frac{\Gamma(\mathrm{a}\to\mu^+\mu^-)}{\Gamma(\mathrm{a}\to\mathrm{b}\overline{\mathrm{b}})} = \frac{m_\mu^2\sqrt{1-(2m_\mu/m_\mathrm{a})^2}}{3m_\mathrm{b}^2\sqrt{1-(2m_\mathrm{b}/m_\mathrm{a})^2}\,(1+\text{QCD corrections})}$$

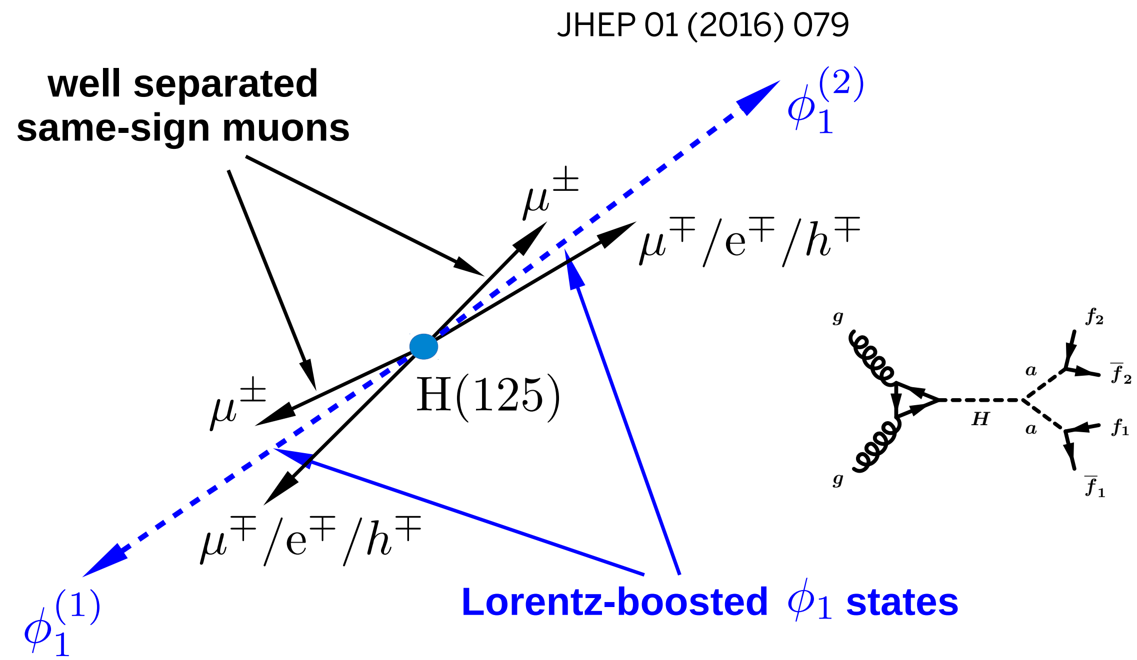
H→aa at the LHC



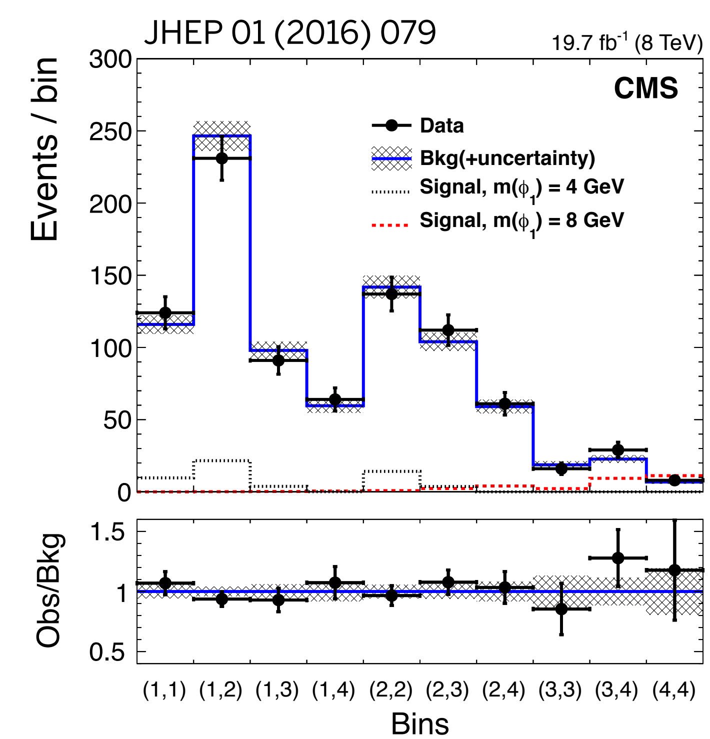
- Rich phenomenology
  - Boosted or resolved fermions depending on pseudoscalar mass
  - Pairs of muons, taus, or bottoms in the final state
  - Utilize 2- and 4-body mass reconstruction to discriminate against background
- Advantages over direct a production
  - H→aa provides a striking signature of new physics
  - a→b$\bar{\text{b}}$ and a→ττ reconstruction possible





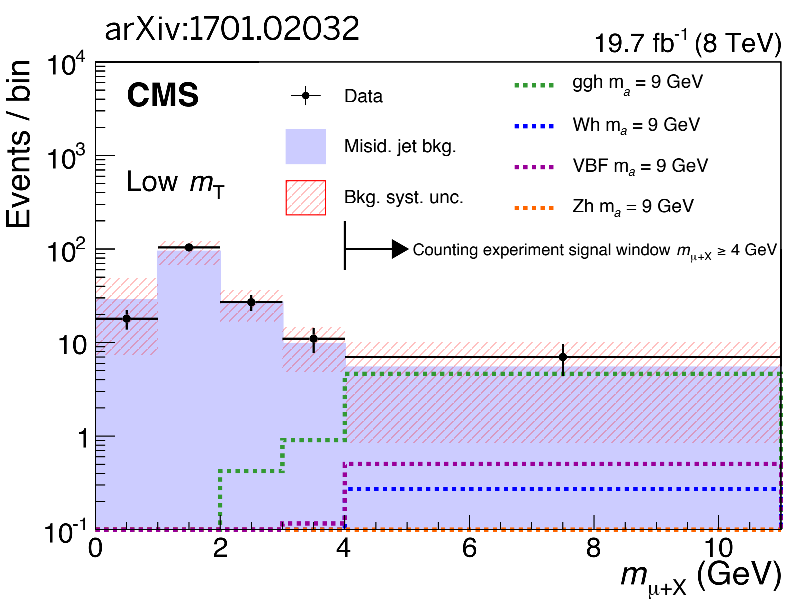


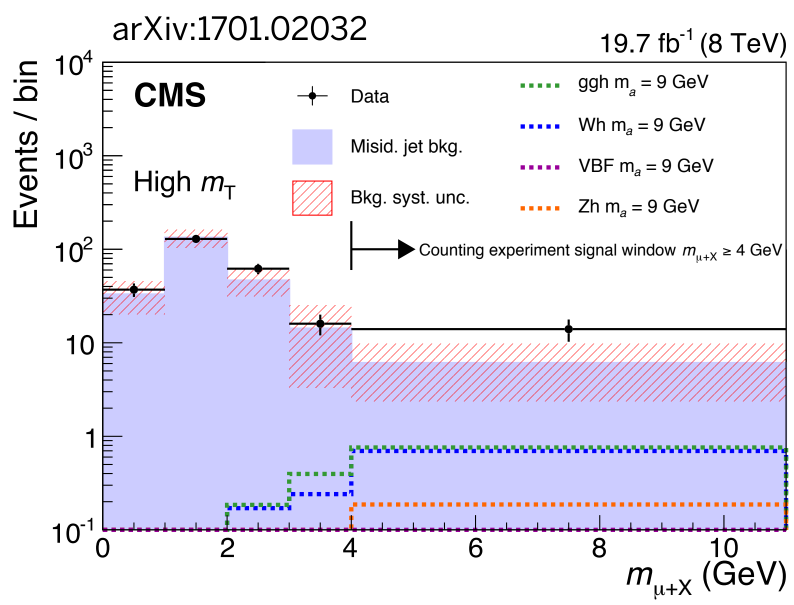
- Reconstruction of two well separated boosted a→$\tau_\mu\tau_{\text{1-prong}}$ decays
  - Leading muon p_T > 17 GeV, sub-leading muon p_T > 10 GeV
  - Same-sign muons to reject Drell-Yan
  - 1-prong track required to be prompt with p_T > 2.5 GeV
- Search for excess in the 2D di-tau visible mass distribution
- $b\bar{b}$ background modeled as a convolution of 1D distributions in events with one non-isolated di-tau pair

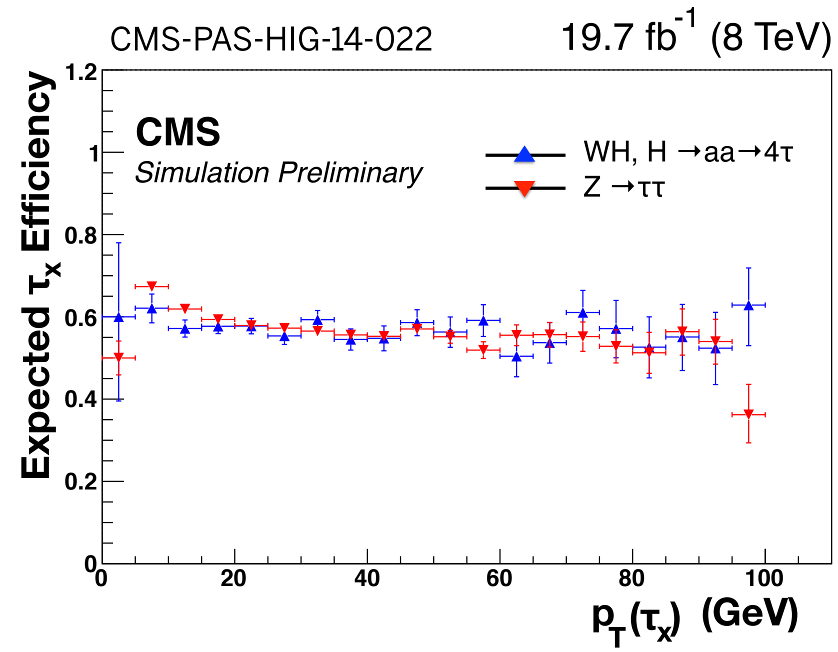


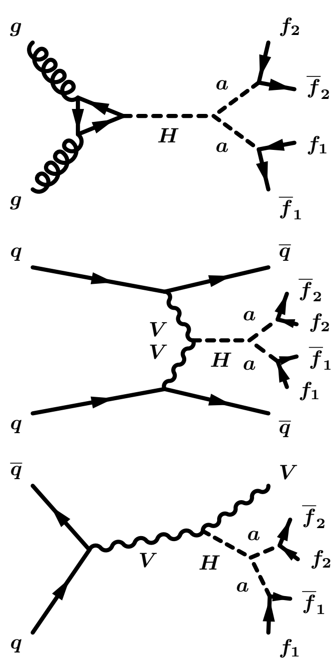
Run 1 8 TeV 19.7 fb⁻¹ | $\tau_\mu\tau_{\text{1-prong}}$

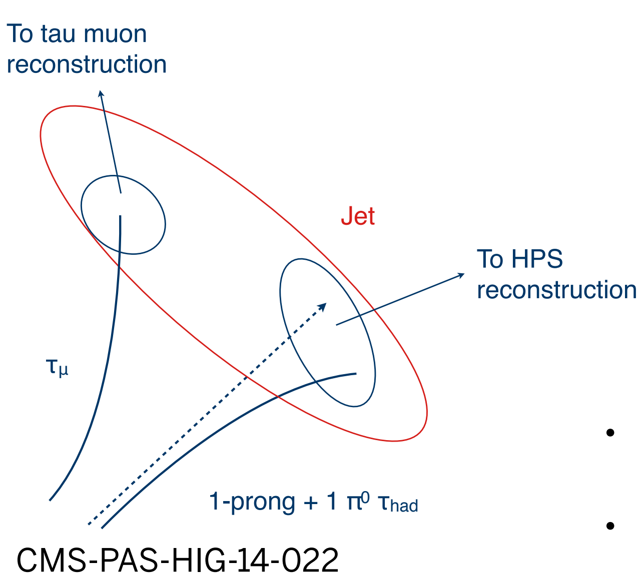
$H\rightarrow aa\rightarrow 4\tau$









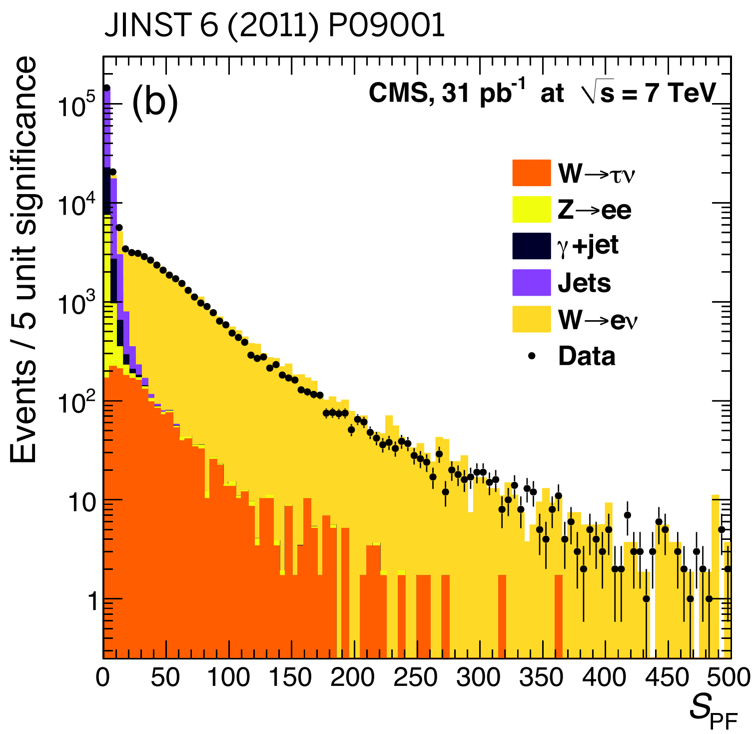


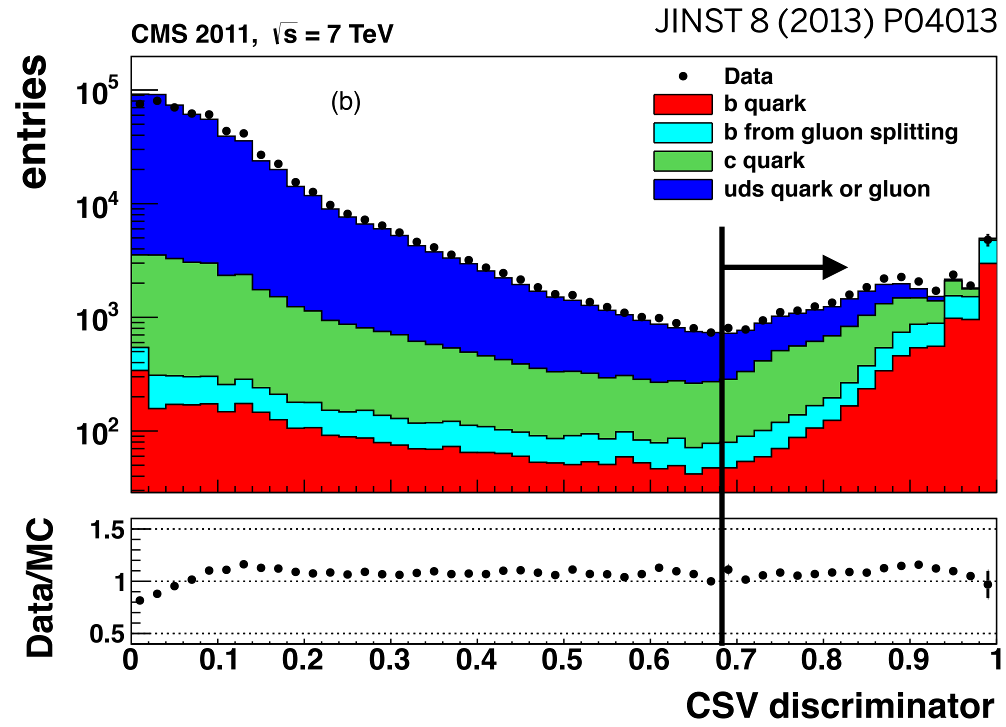
- Reconstruction of one boosted $a\rightarrow\tau_\mu\tau_X$ decay + one 25 GeV isolated muon
  - Isolated 24 GeV muon trigger gives sensitivity to VH and ggH/VBF with well separated pseudoscalar decay products
  - $p_T(\tau_\mu) > 5$ GeV, $p_T(\tau_X) > 20$ GeV
  - All tau decays reconstructed using CMS hadron + strips (HPS) algorithm after muon removal
- Search for excess in the 1D di-tau visible mass distribution
- Low- and high-m_T bins to isolate WH from ggH
- W and $t\bar{t}$ background modeled from muon + non-isolated di-tau sample

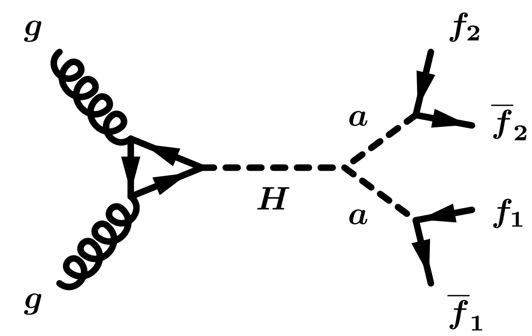
Run 1 8 TeV 19.7 fb^{-1} | $\tau_\mu\tau_X$

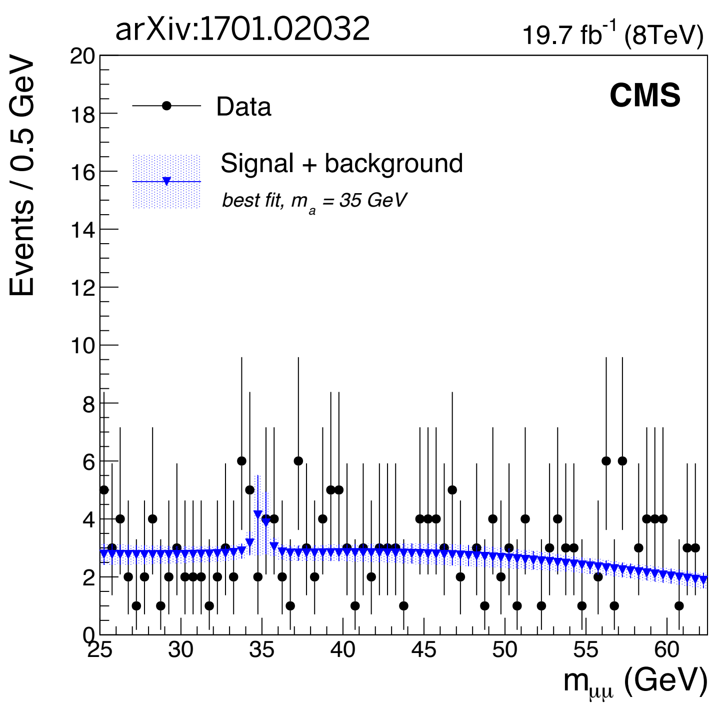
$$M_T = \sqrt{2p_T^{trg.\mu}\,\not{E}_T[1-\cos\Delta\Phi(trg.\mu,\not{E}_T)]}$$

H→aa→2μ2b







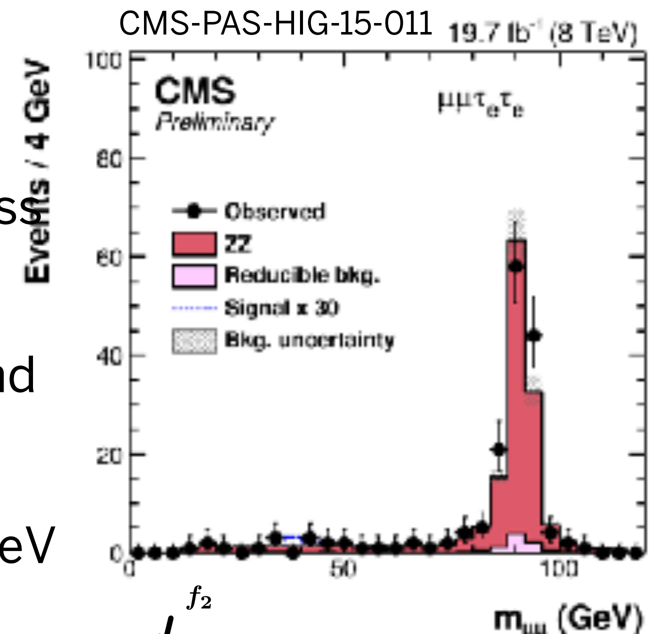


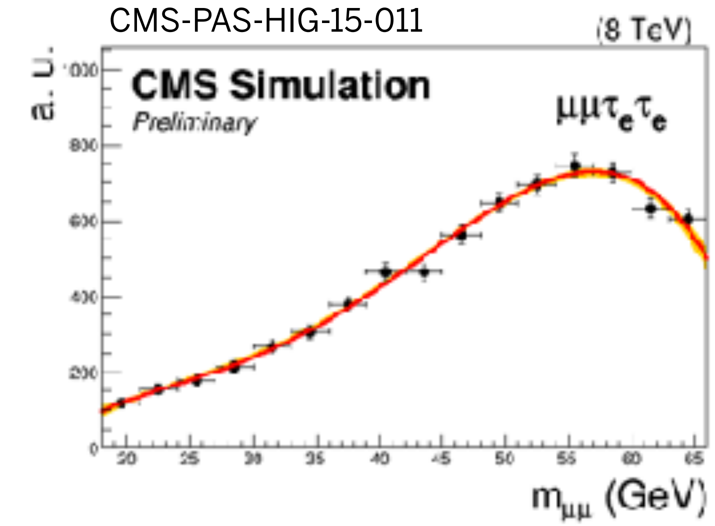
- Resolved pseudoscalar decay products
- Di-muon mass spectrum fit for a peaked signal to extract m_a
- Selection
  - Two opposite-charge muons with reconstructed $p_T > 24$ and 9 GeV (single- and di-muon triggers)
  - Two b jets with $p_T > 15$ GeV, distinguished from light quark jets by the presence of secondary vertices
  - Compatible with zero ME_T

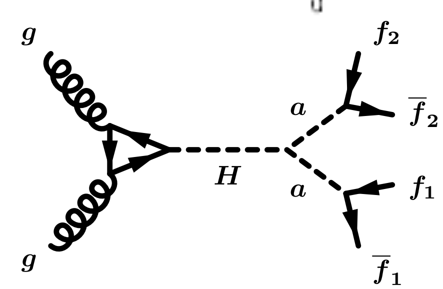
Run 1 8 TeV 19.7 fb^{-1}

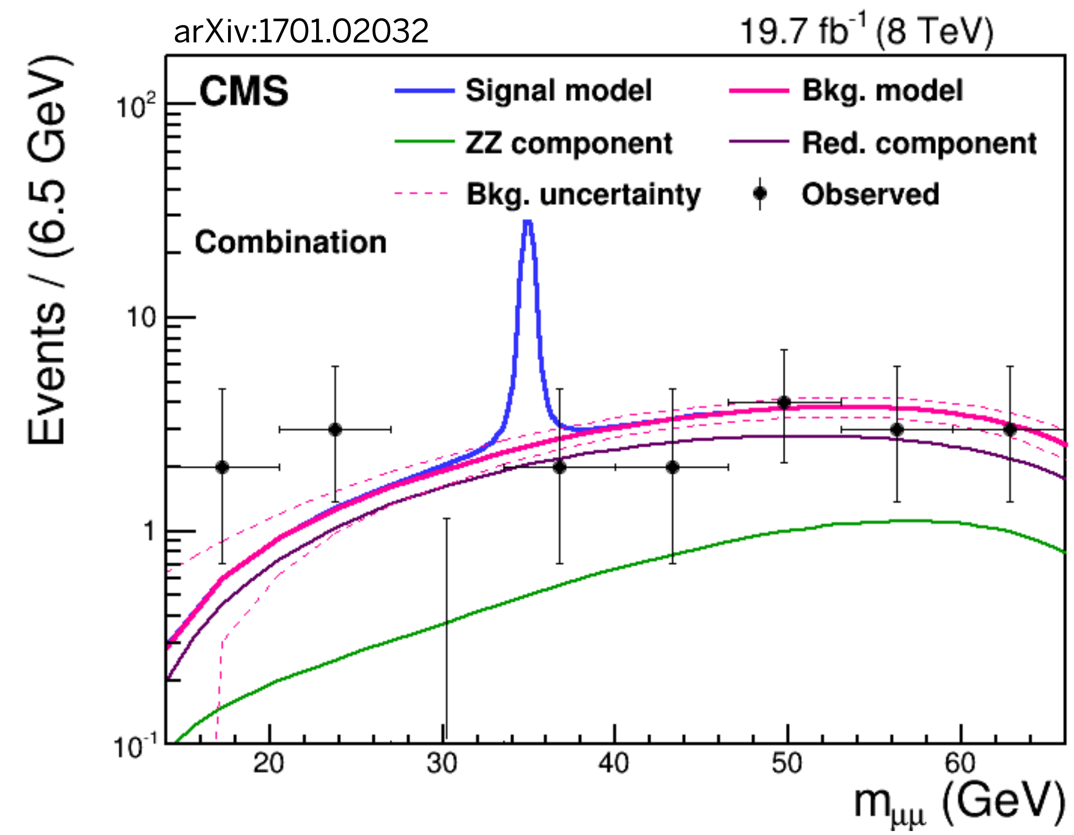
$H \to aa \to 2\mu 2\tau$

- Resolved pseudoscalar decay products
- Unbinned maximum likelihood fit to di-muon mass spectrum
- Final states $\mu\mu\tau_e\tau_e$, $\mu\mu\tau_e\tau_\mu$, $\mu\mu\tau_e\tau_{had}$, $\mu\mu\tau_\mu\tau_{had}$, and $\mu\mu\tau_{had}\tau_{had}$
- Two opposite charge muons with p_T > 18 and 9 GeV
- Veto b jets and additional leptons
- $|m_{\mu\mu} - m_{\tau\tau}|/m_{\mu\mu} < 0.8$
- $|m_{\mu\mu\tau\tau} - m_{H(125)}| < 25$ GeV, but $|m_{\mu\mu ee} - m_{H(125)}| > 30$ GeV in $\mu\mu\tau_e\tau_e$ final state
- Backgrounds
  - Reducible Z + jets determined from fake rates and parametrized with Bernstein polynomial fit
  - Irreducible eeμμ from NLO MC and parametrized with Bernstein polynomial fit



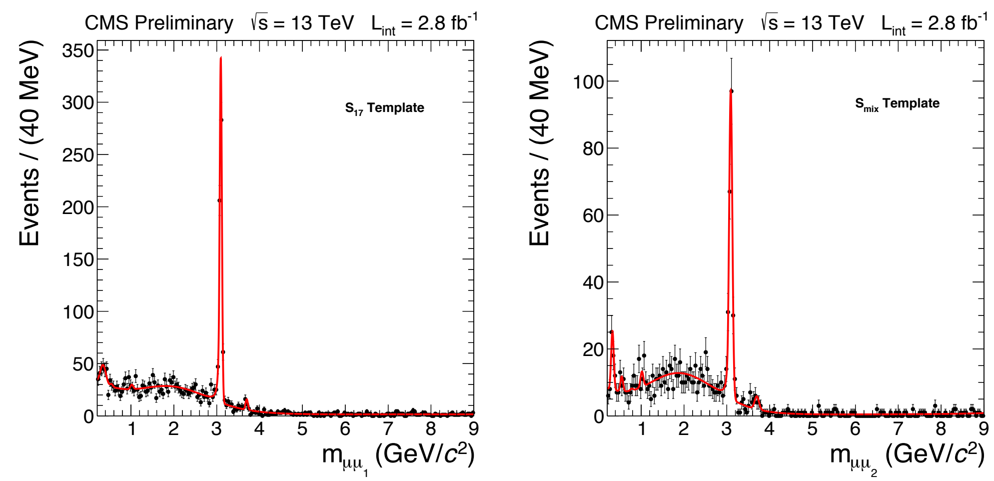


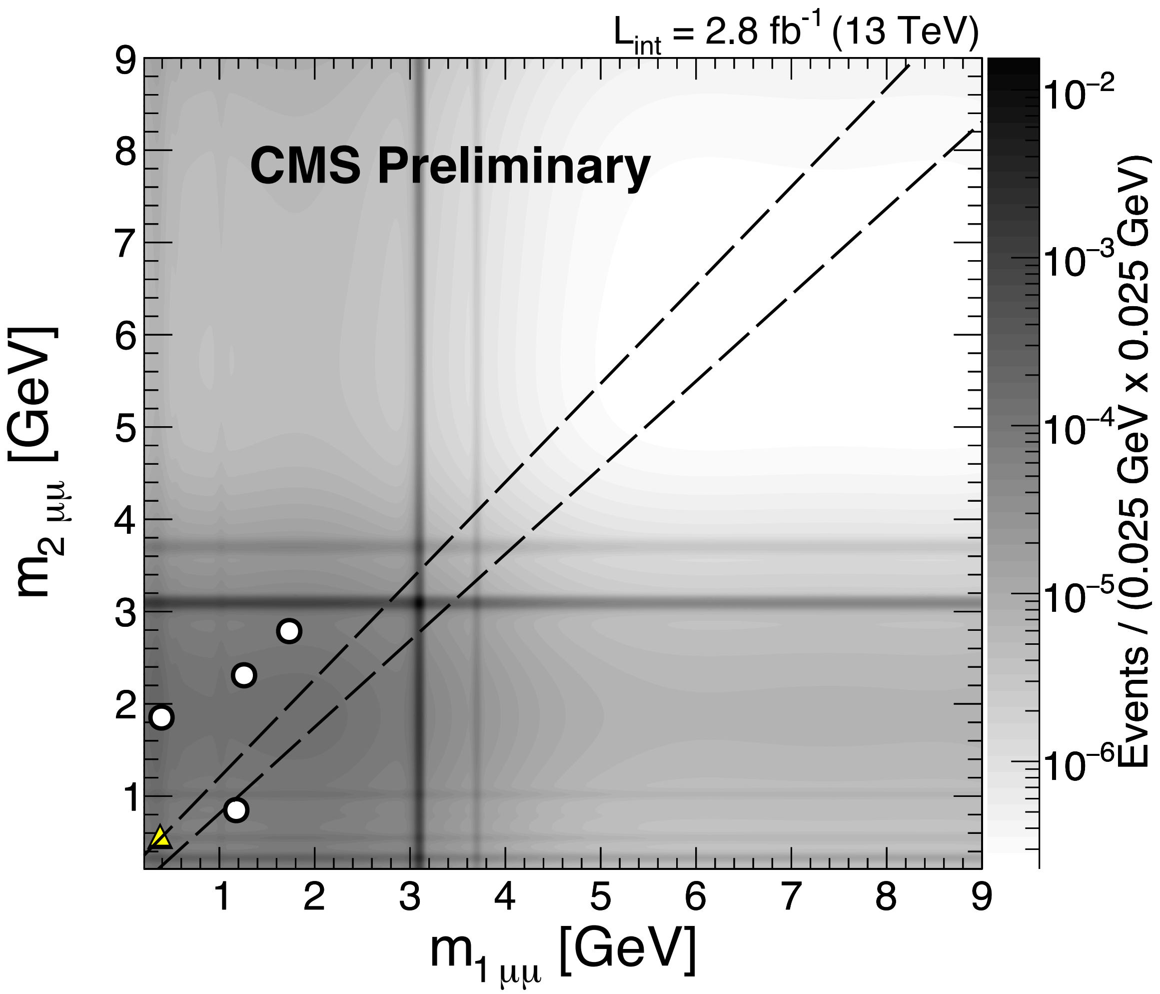




Run 1 8 TeV 19.7 fb⁻¹ resolved

- 17/8 GeV di-muon trigger
- Fit to 2D di-muon invariant mass spectrum
- Boosted isolated di-muon reconstruction
- $b\bar{b}$ background (mostly double semileptonic decays and resonances) estimated from 3-muon events
  - 2D background from 2 × 1-D convolution
  - Fit to analytic function
  - 2 shapes needed depending on which muons fire the trigger





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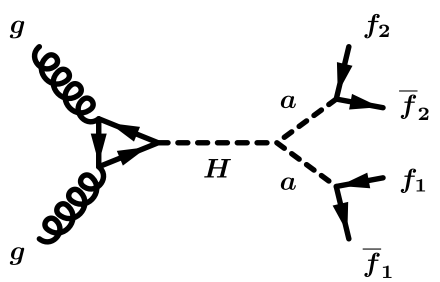
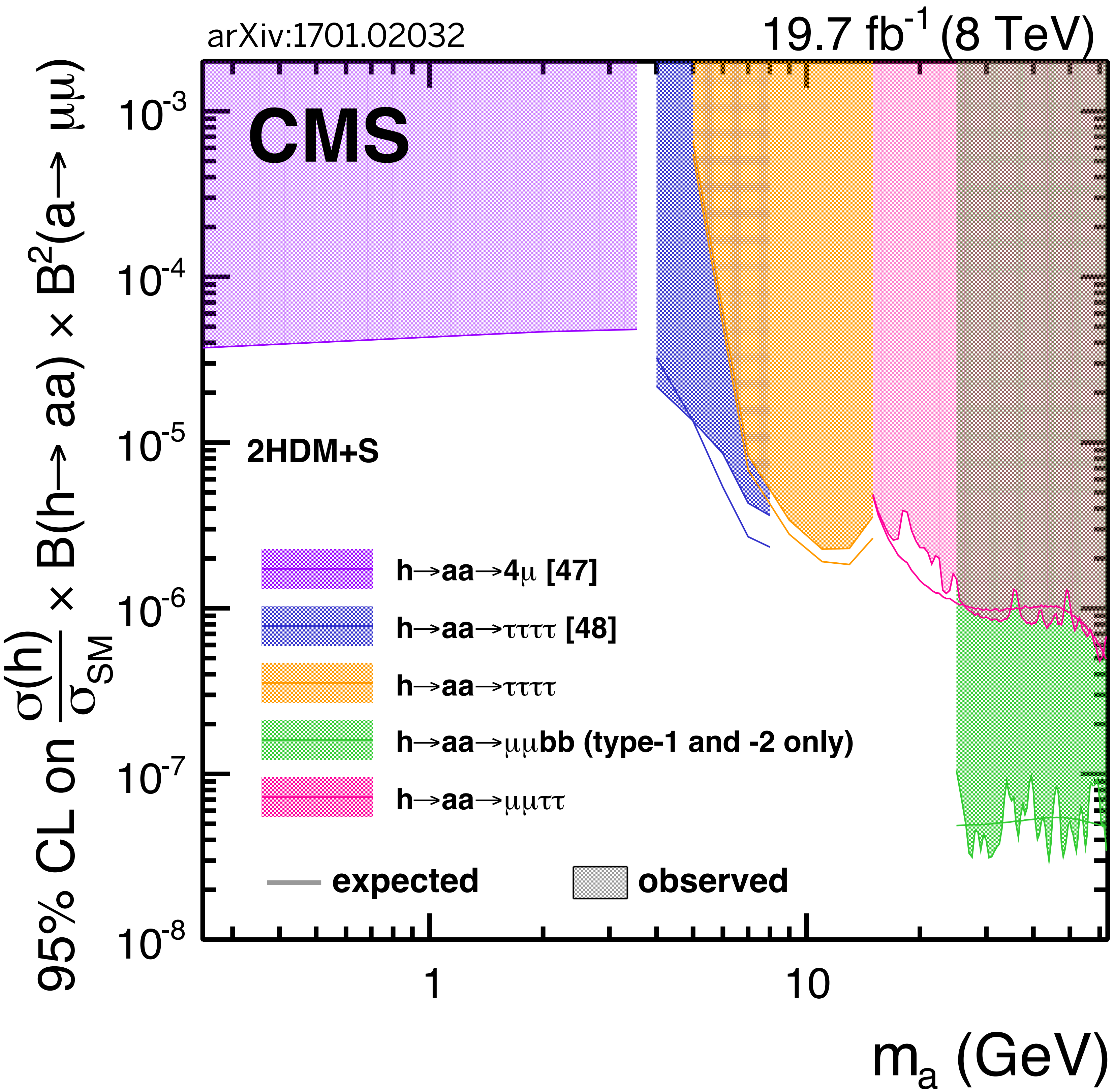
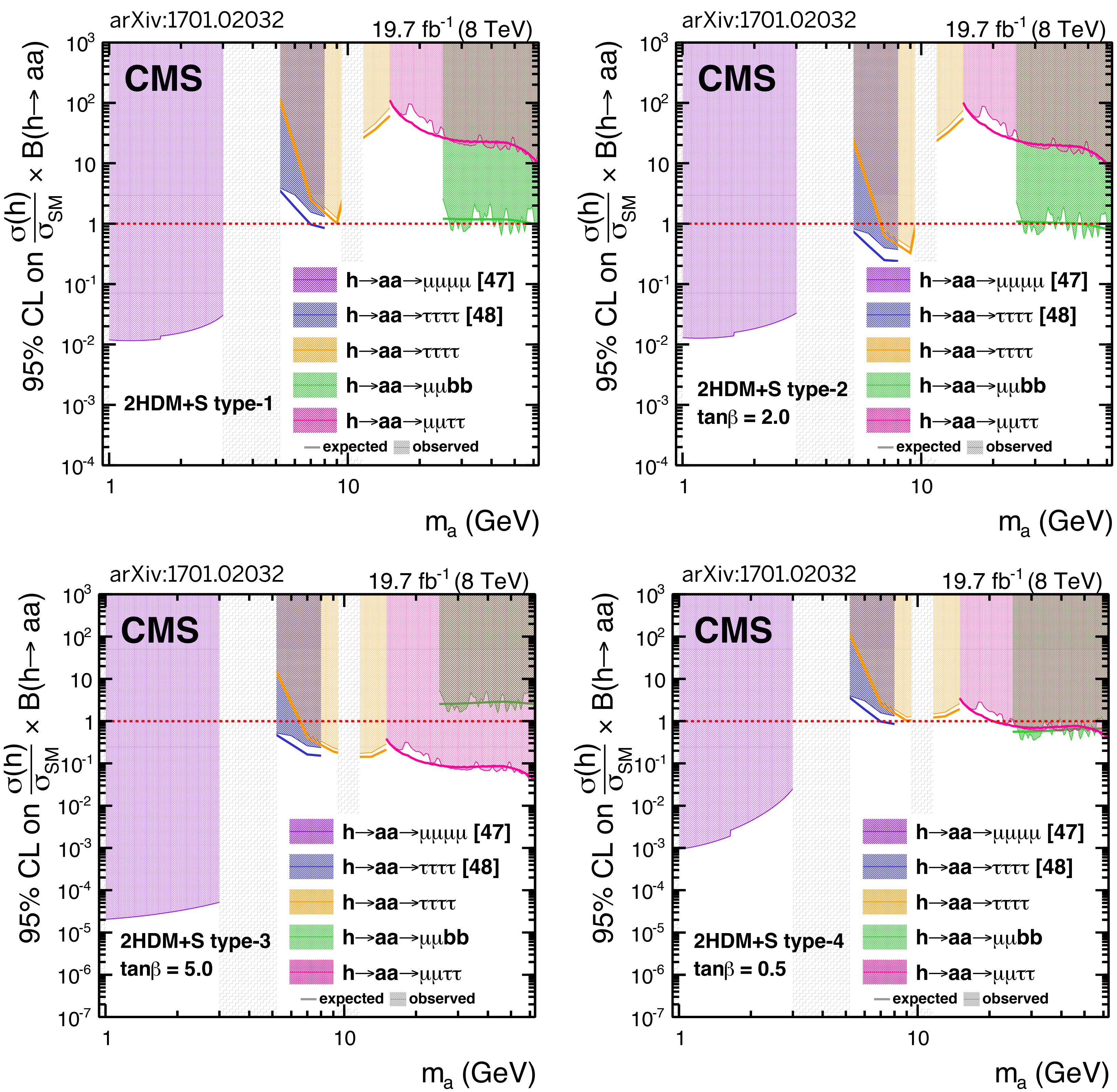
Run 2 13 TeV 2.8 fb^{-1}



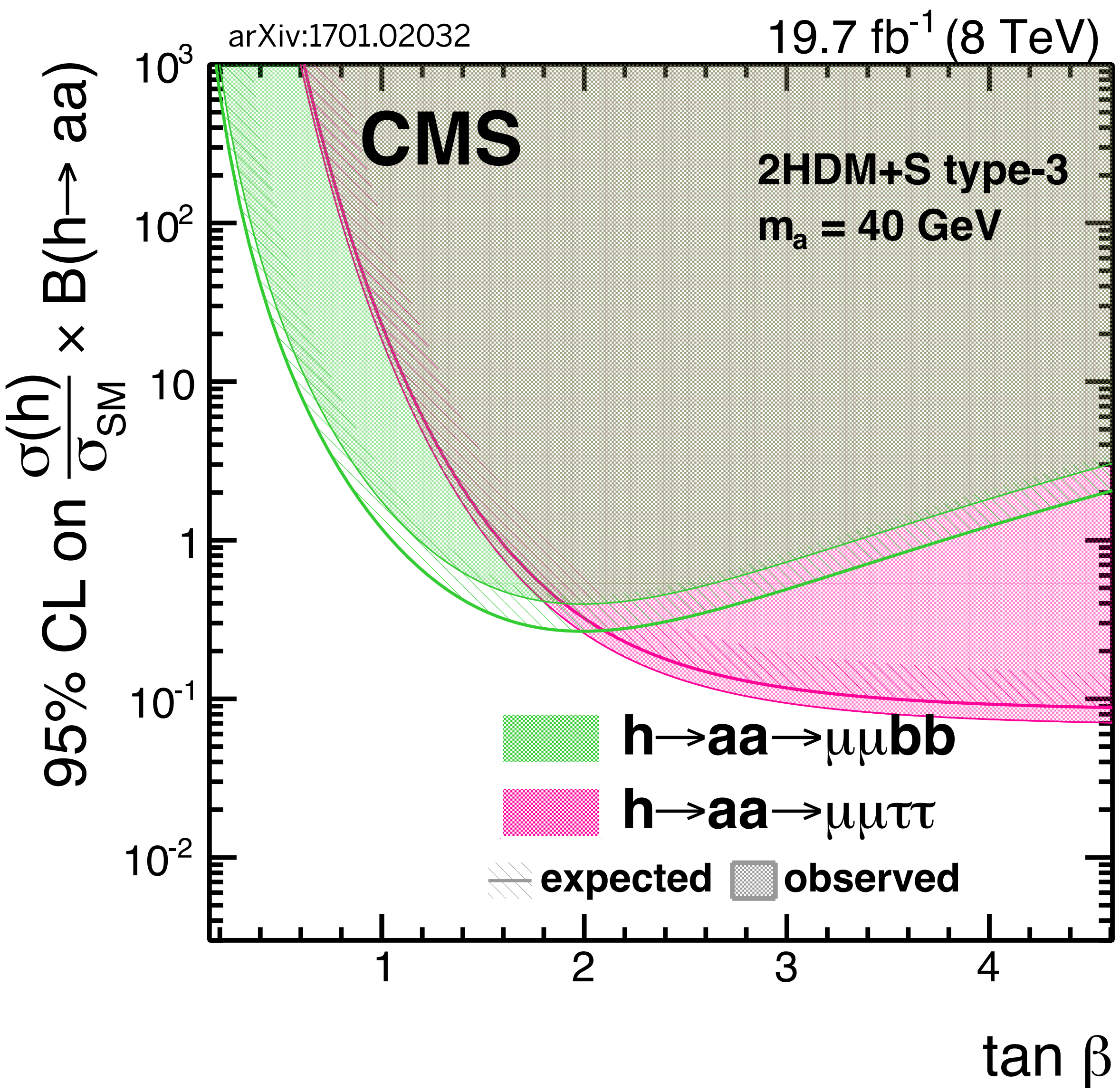
2HDM+S interpretation

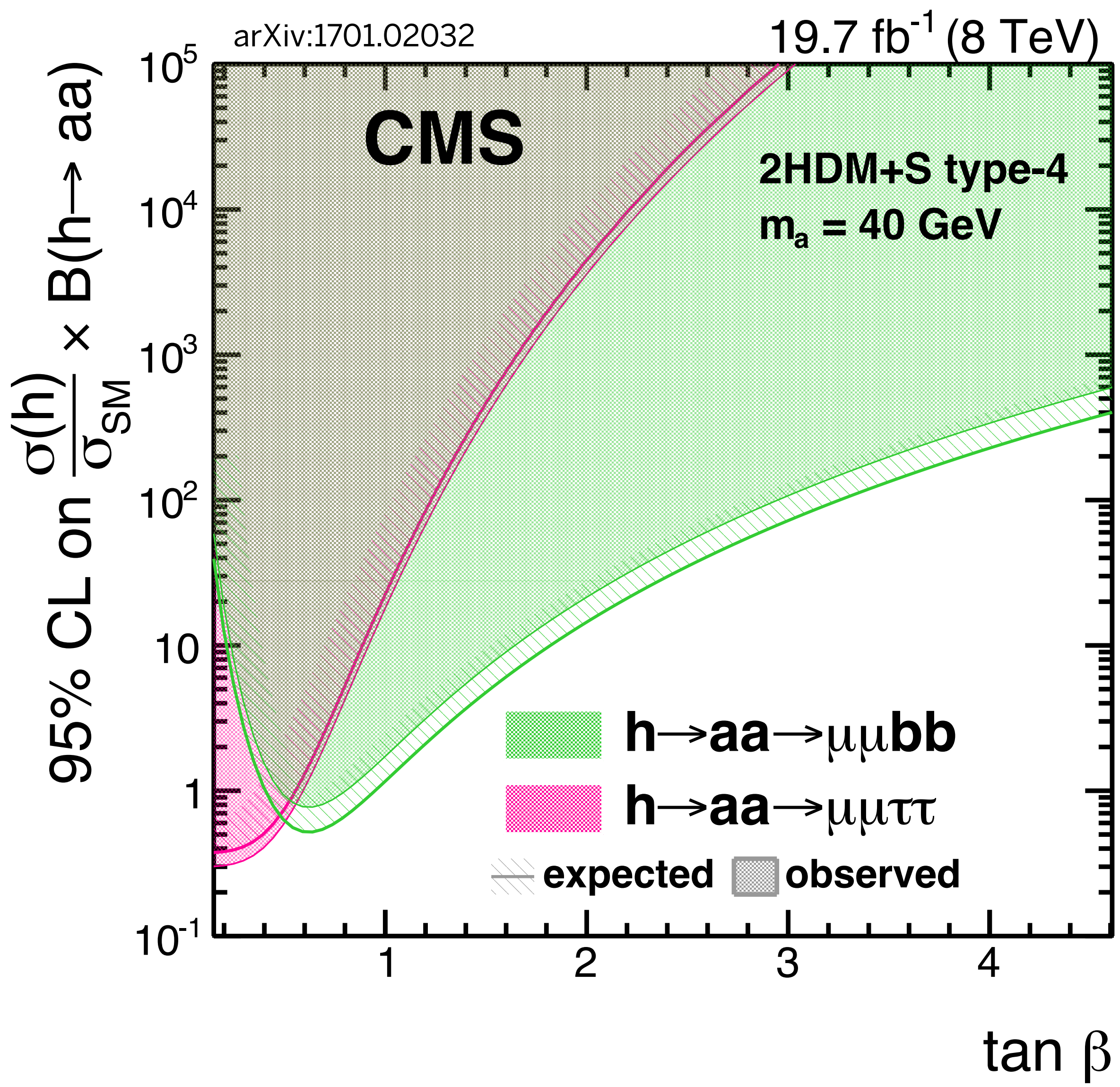


2HDM+S interpretation



2HDM+S interpretation





H→invisible at the LHC

Analysis	Final state	Int. $\mathcal{L}$ (fb^{-1})			Expected signal composition (%)	
		7 TeV	8 TeV	13 TeV	7 or 8 TeV	13 TeV
qqH-tagged	VBF jets	—	19.2 [16]	2.3	7.8 (ggH), 92.2 (qqH)	9.1 (ggH), 90.9 (qqH)
VH-tagged	$Z(\ell^+\ell^-)$	4.9 [16]	19.7 [16]	2.3	100 (ZH)	
	$Z(b\bar{b})$	—	18.9 [16]	—	100 (ZH)	
	V(jj)	—	19.7 [60]	2.3	25.1 (ggH), 5.1 (qqH), 23.0 (ZH), 46.8 (WH)	38.7 (ggH), 7.1 (qqH), 21.3 (ZH), 32.9 (WH)
ggH-tagged	Monojet	—	19.7 [60]	2.3	70.4 (ggH), 20.4 (qqH), 3.5 (ZH), 5.7 (WH)	69.3 (ggH), 21.9 (qqH), 4.2 (ZH), 4.6 (WH)

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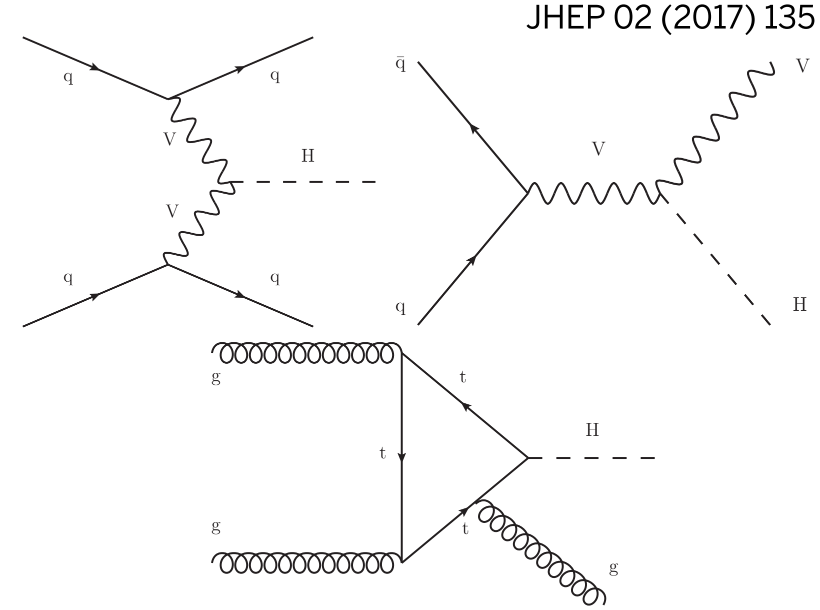
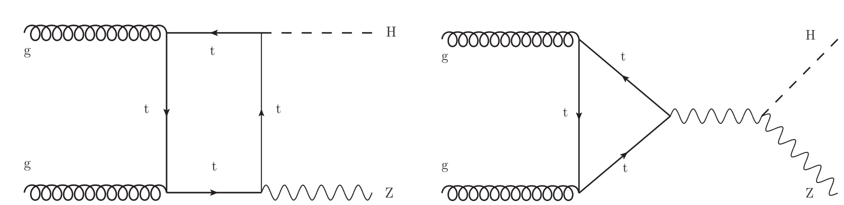
- VBF and ZH modes provide good S/B discrimination
- Additional sensitivity from large cross section ggH mode when accompanied by a jet
- Characteristic signature of large ME_T recoiling against jets or leptons



Targeted production modes



Additional ZH modes

Run 1 7 TeV 5.1 fb^{-1}
Run 1 8 TeV 19.7 fb^{-1}
Run 2 13 TeV 2.3 fb^{-1}

VBF H→invisible

- Forward jet + ME_T trigger
- Tighter offline requirements + lepton veto
- Main Z→νν, W→lν (lost lepton), and QCD backgrounds estimated from data
  - Simultaneous fit of Z→μμ, W→lν, and low min ΔΦ(ME_T, j) control regions to extract W + Z and QCD scale factors to signal region
  - Ratio of W→lν to Z→νν taken from LO simulation

Run 2 13 TeV 2.3 fb-1

<table>
<tr><th>JHEP 02 (2017) 135</th><th>8 TeV</th><th>13 TeV</th></tr>
<tr><td>p_T^{j1}</td><td>>50 GeV</td><td>>80 GeV</td></tr>
<tr><td>p_T^{j2}</td><td>>45 GeV</td><td>>70 GeV</td></tr>
<tr><td>m_{jj}</td><td>>1200 GeV</td><td>>1100 GeV</td></tr>
<tr><td>E_T^{miss}</td><td>>90 GeV</td><td>>200 GeV</td></tr>
<tr><td>$S(E_T^{miss})$</td><td>$>4\sqrt{\mathrm{GeV}}$</td><td>—</td></tr>
<tr><td>$\min\Delta\phi(\vec{p}_T^{miss}, j)$</td><td colspan="2">$>2.3$</td></tr>
<tr><td>$\Delta\eta(j_1, j_2)$</td><td colspan="2">>3.6</td></tr>
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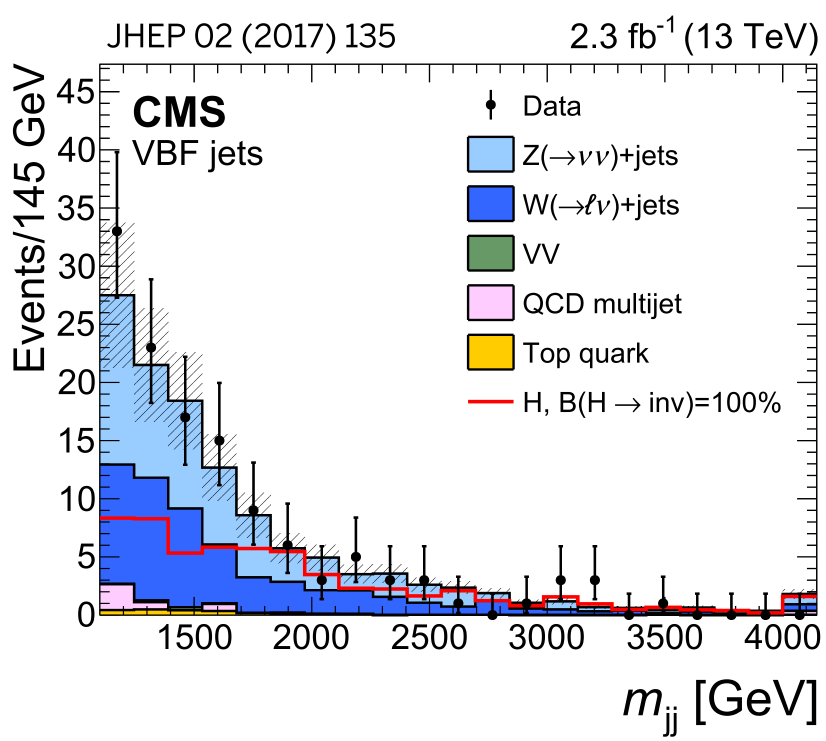
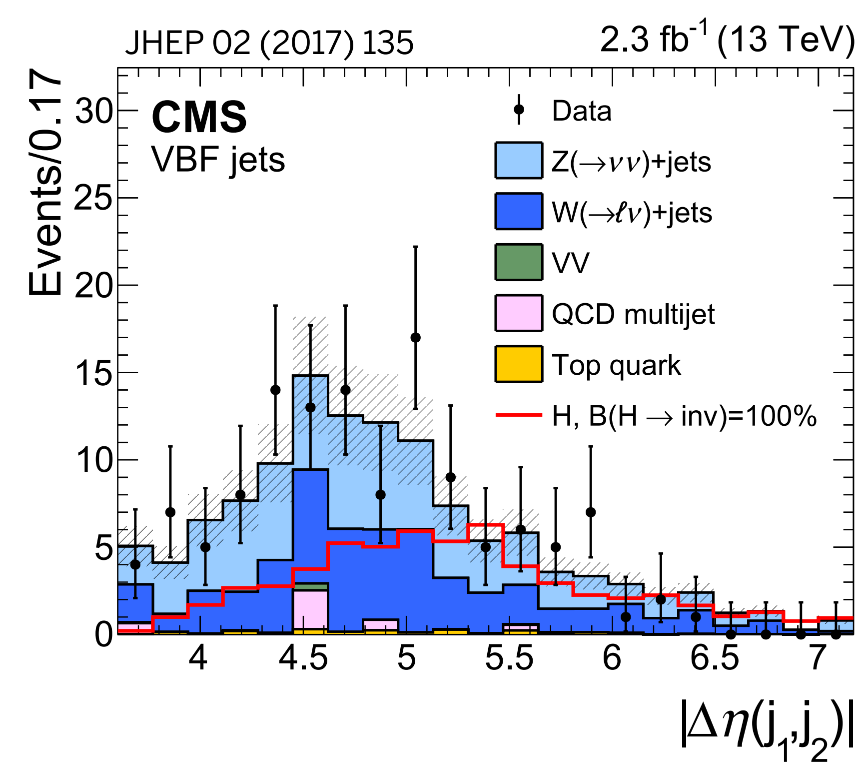
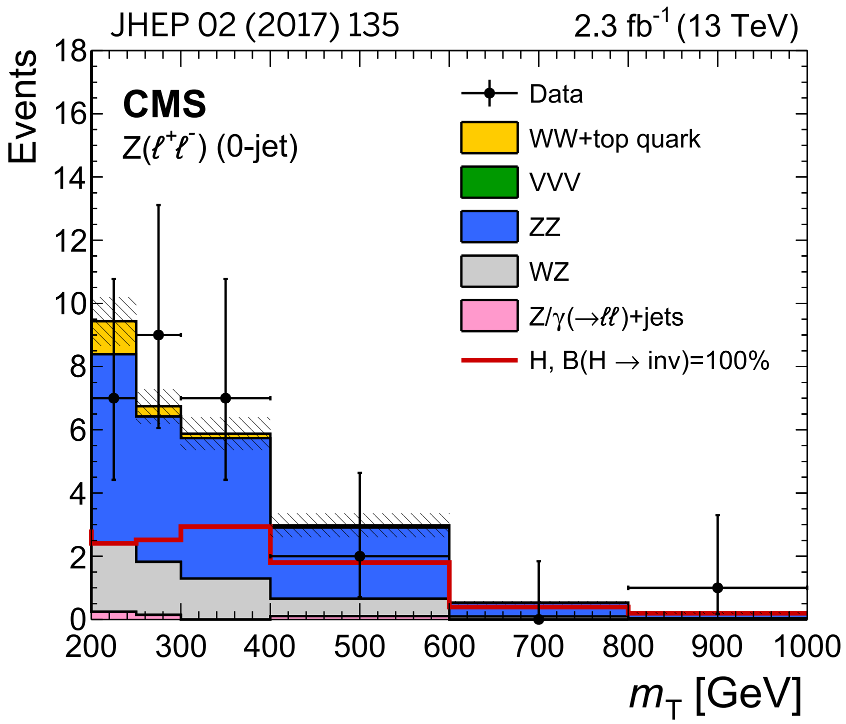
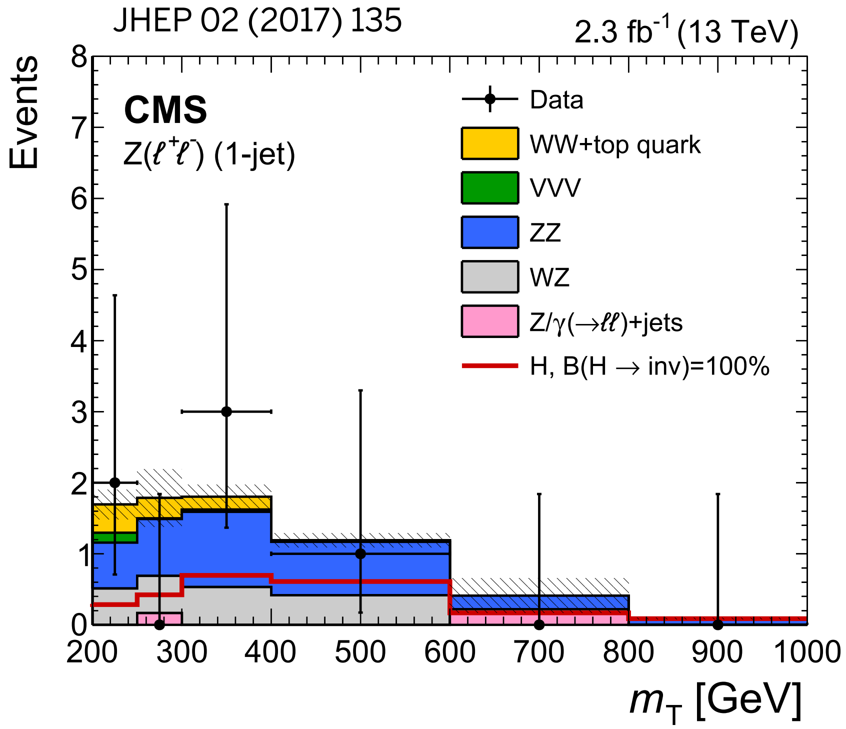




Z(→ll)H→invisible





Run 2 13 TeV 2.3 fb-1

JHEP 02 (2017) 135	7 and 8 TeV	13 TeV
$p_T^{e,\mu}$	>20 GeV	
$m_{\ell\ell}$	76–106 GeV	
$\Delta\phi(\ell,\ell)$	—	$<\pi/2$
E_T^{miss}	>120 GeV	>100 GeV
$\Delta\phi(\ell\ell,\vec{p}_T^{miss})$	>2.7	>2.8
$\Delta\phi(\vec{p}_T^{miss},j)$	—	>0.5
$\lvert E_T^{miss} - p_T^{\ell\ell}\rvert / p_T^{\ell\ell}$	<0.25	<0.4
m_T	>200 GeV	

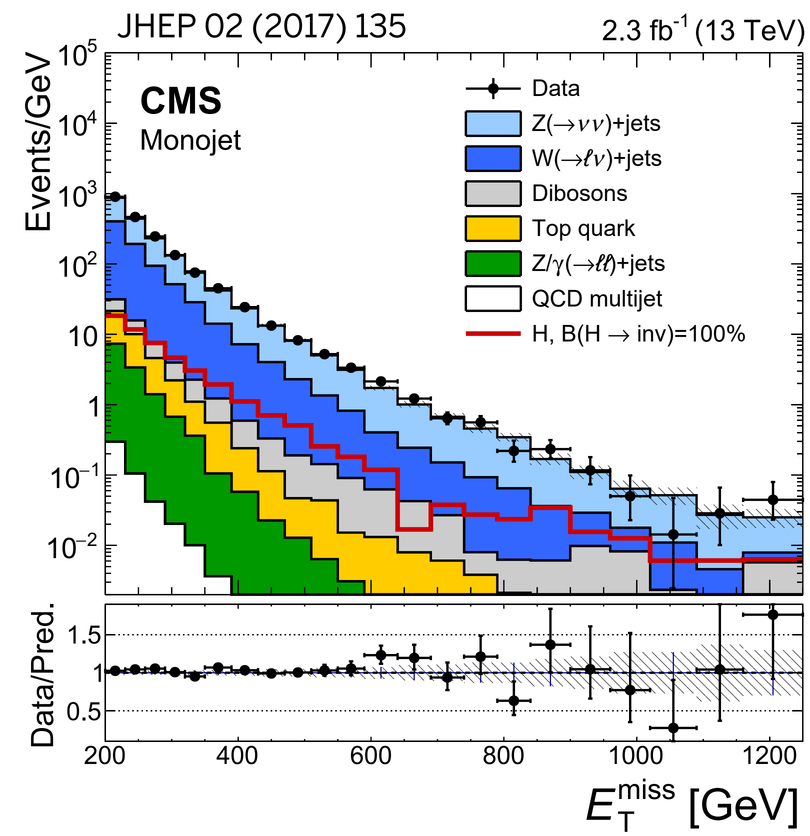
- Di-muon (17 and 8 GeV) and di-electron (17 and 12 GeV) triggers
- m_T(di-lepton system, ME_T) exploited to reduce Z + jets background
- $\Delta\Phi(l,l) < \pi/2$ to reduce SM Z production
- Veto on >1 jet with p_T > 30 GeV
- ZZ and WZ backgrounds from MC, Z + jets from γ + jets in data, non-resonant backgrounds from opposite-flavor pairs

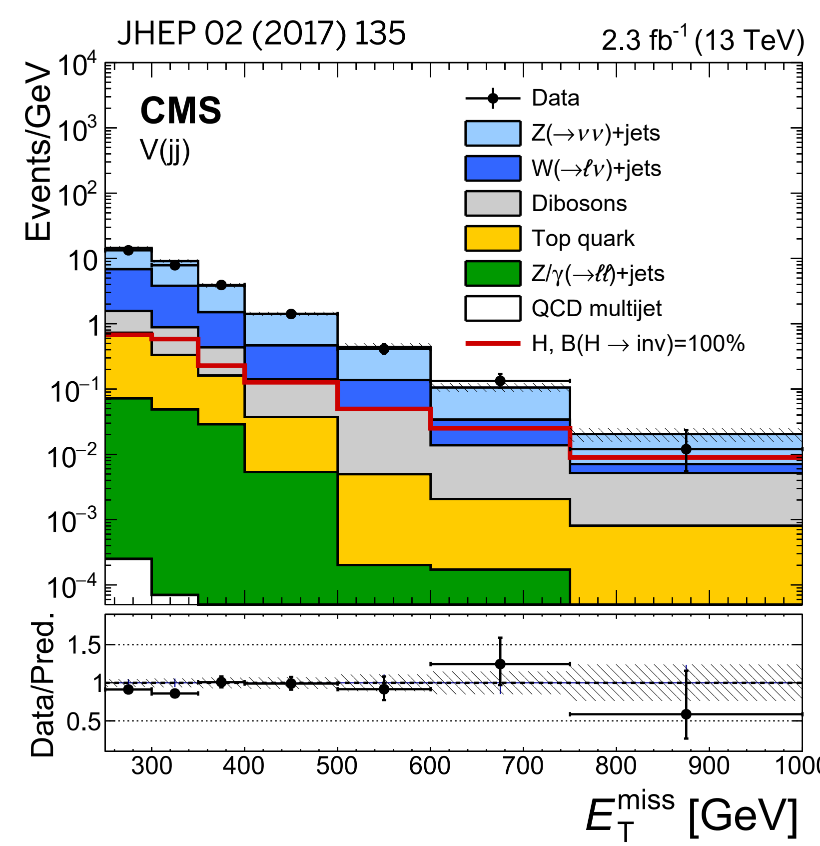
V(→jj)H→invisible and monojet

- ME_T and H_T triggers
- Lepton, photon, and b veto
- Fat jet reconstruction of V→jj
- Z→νν and W→lν estimated from di-lepton, single lepton, and γ + jet data control regions, similar to the VBF analysis
- Other backgrounds from simulation

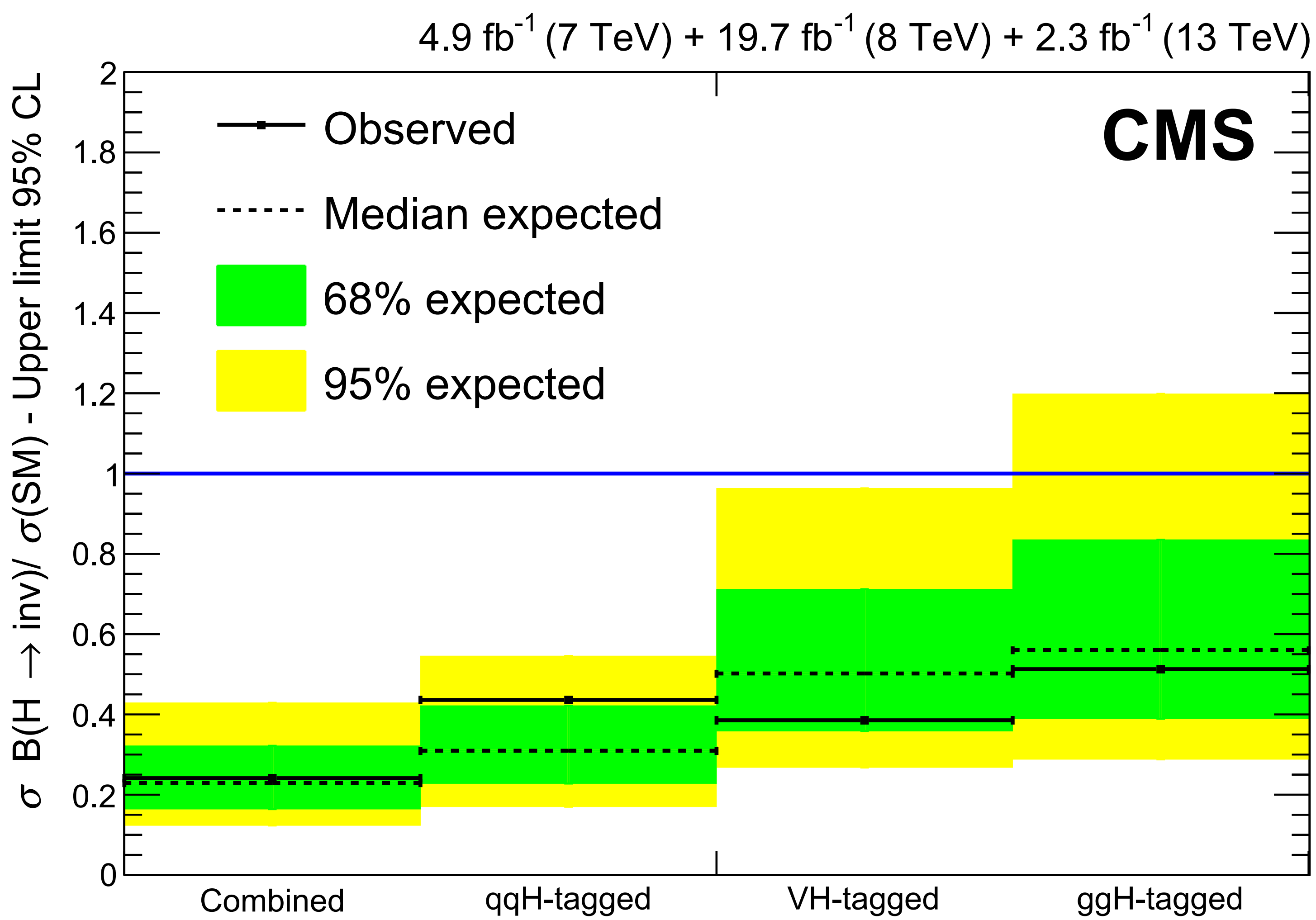
JHEP 02 (2017) 135	8 TeV		13 TeV	
	V(jj)	Monojet	V(jj)	Monojet
p_T^j	>200 GeV	>150 GeV	>250 GeV	>100 GeV
$\|\eta\|^j$	<2		<2.4	<2.5
E_T^{miss}	>250 GeV	>200 GeV	>250 GeV	>200 GeV
τ_2/τ_1	<0.5	—	<0.6	—
m_{prune}	60–110 GeV	—	65–105 GeV	—
$\min \Delta\phi(\vec{p}_T^{miss}, j)$	>2 rad		>0.5 rad	
N_j	=1		—	

Run 2 13 TeV 2.3 fb⁻¹





SM interpretation



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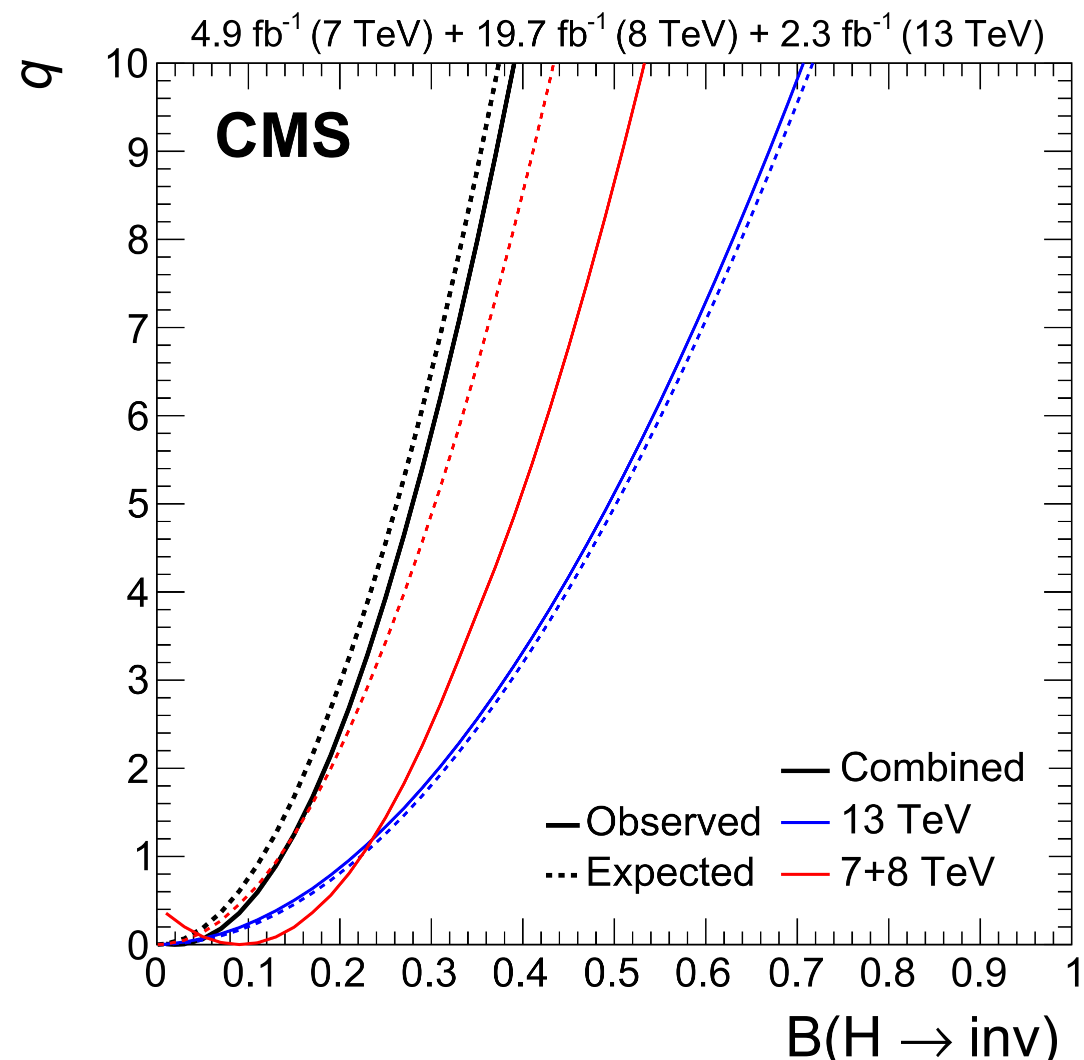

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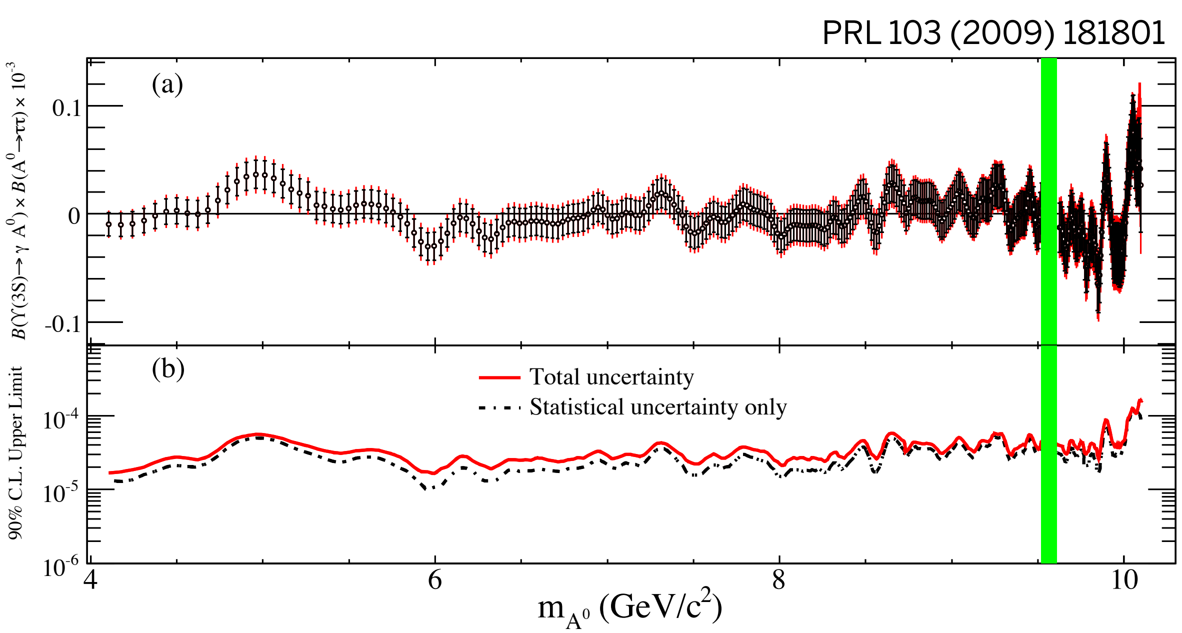
Conclusions

- Robust program of searches for nonstandard Higgs decays at CMS
- Complementarity between coupling measurements and searches
- Detector and reconstruction improvements during Run 2 and the HL-LHC will improve reach
- Many paths to elucidating the nature of the Higgs

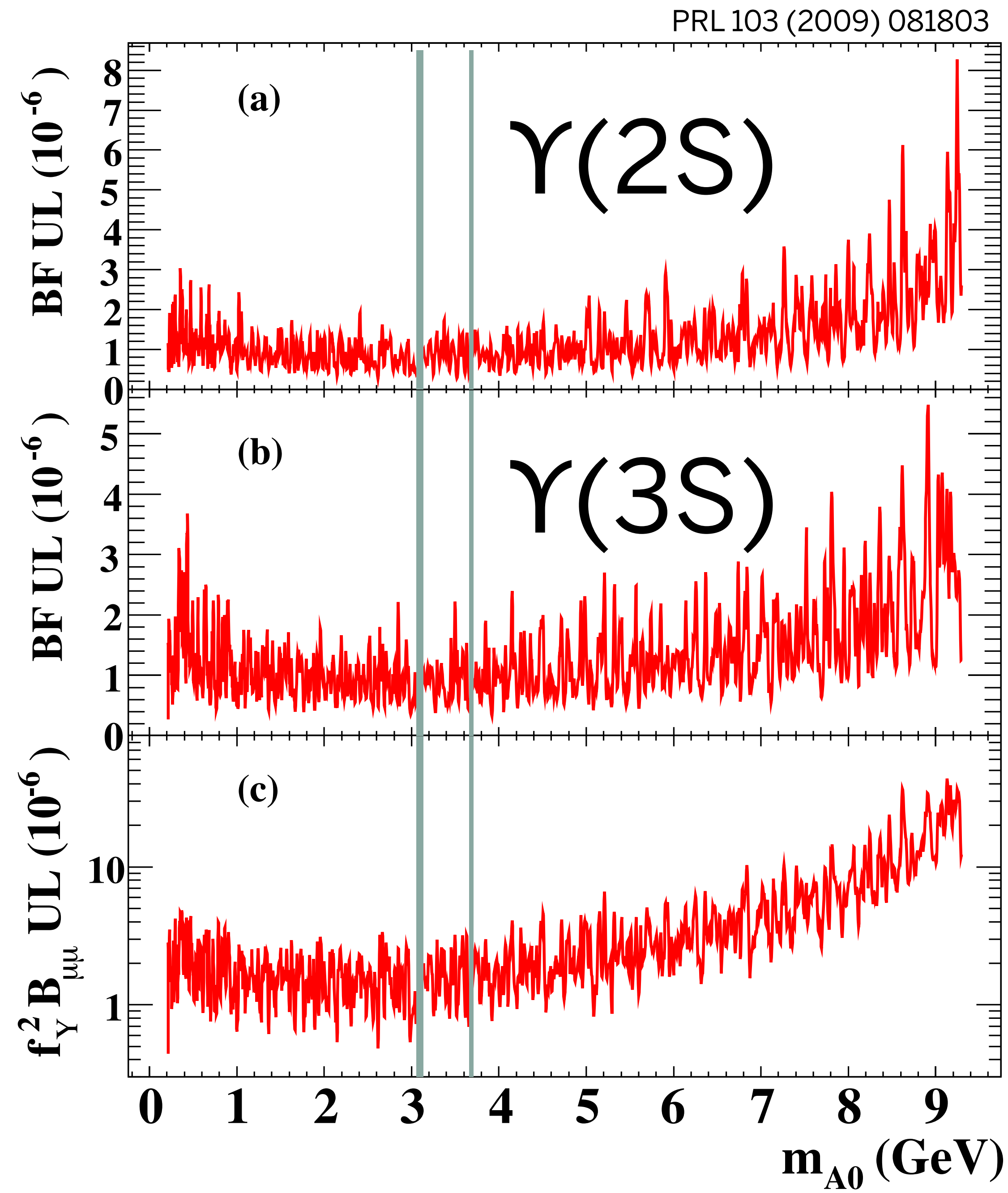
Backup

Direct pseudoscalar production

- BaBar: $\Upsilon(2S,3S)\to\gamma a$, $a\to\mu\mu$ or $a\to\tau_{e/\mu}\tau_{e/\mu}$



$a\to\tau_{e/\mu}\tau_{e/\mu}$

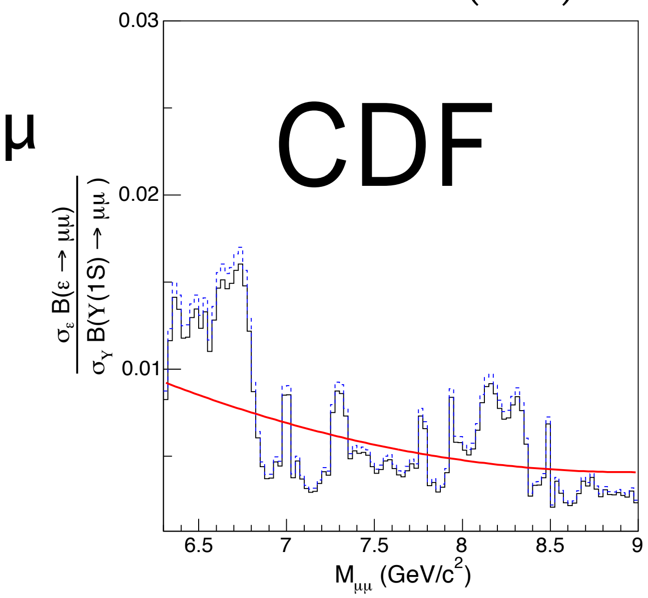


$a\to\mu\mu$

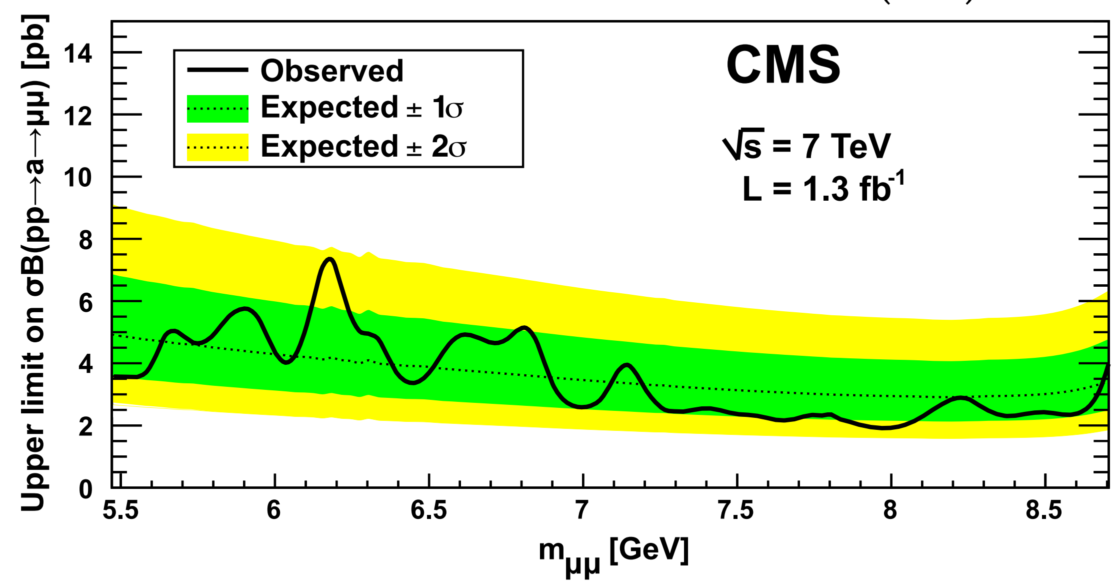
Direct pseudoscalar production

- CDF and CMS: gg→a, a→μμ
- $\theta_A \equiv$ mixing angle between MSSM doublet pseudoscalar and NMSSM singlet pseudoscalar

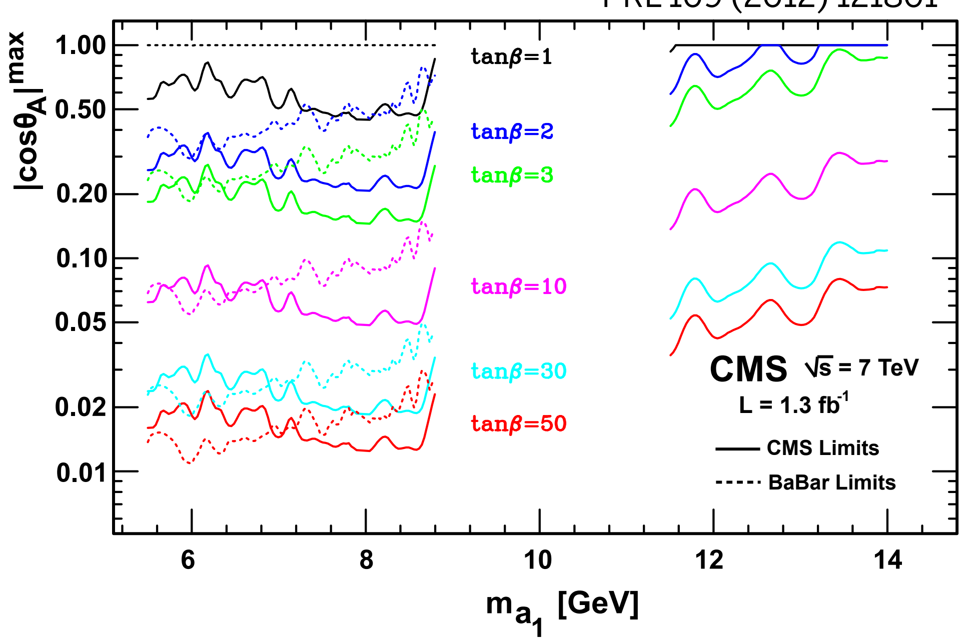
EPJC 62 (2009) 319

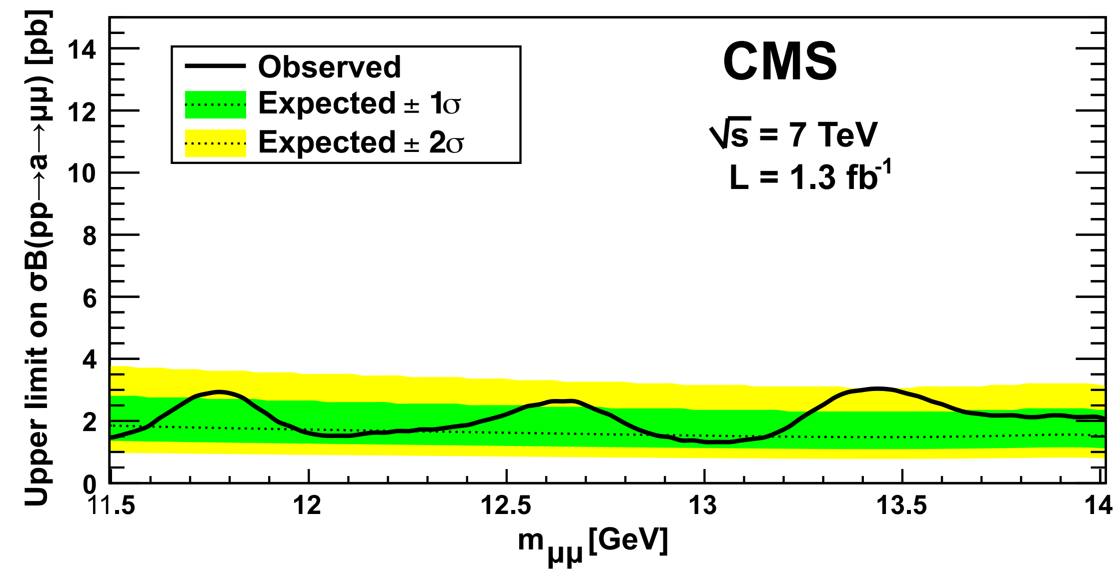


PRL 109 (2012) 121801



PRL 109 (2012) 121801

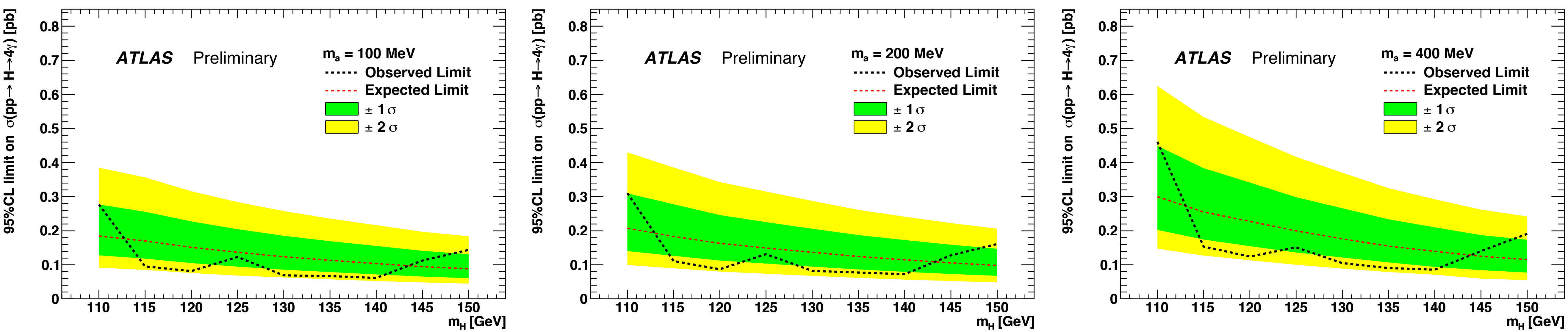




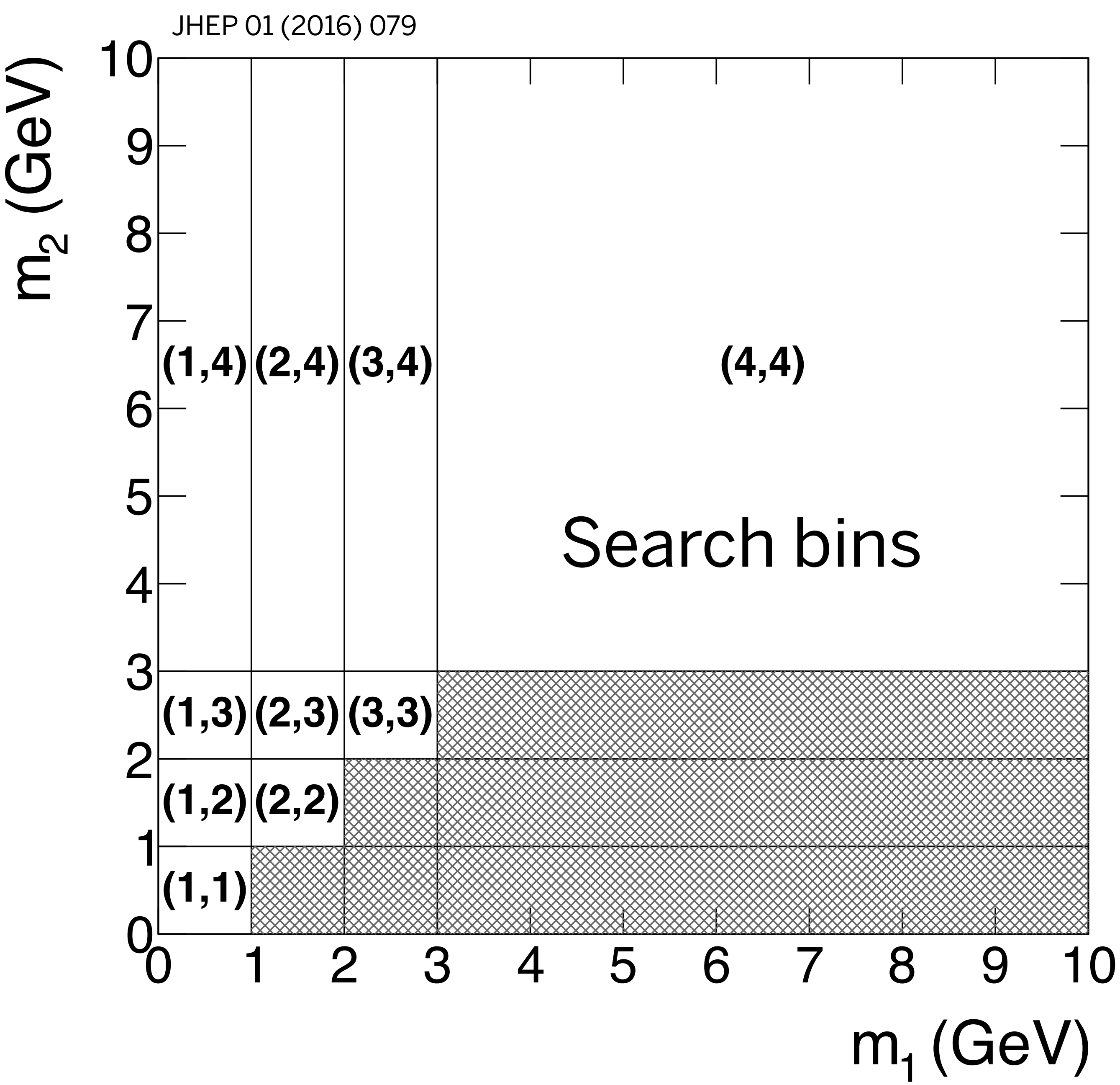
H(125) decay to pseudoscalars

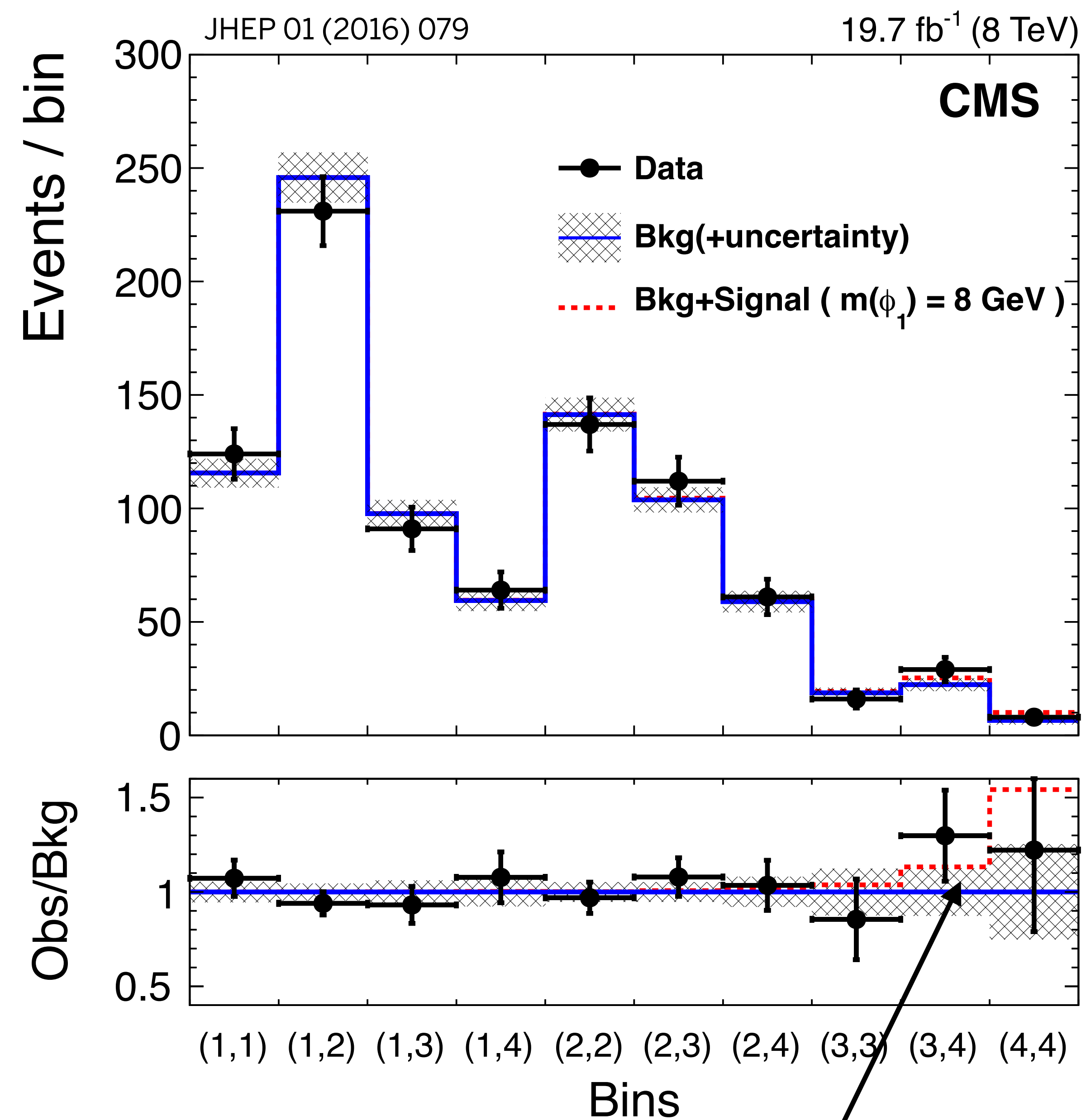
H→aa→4γ

ATLAS-CONF-2012-079



$H \to aa \to 4\tau$



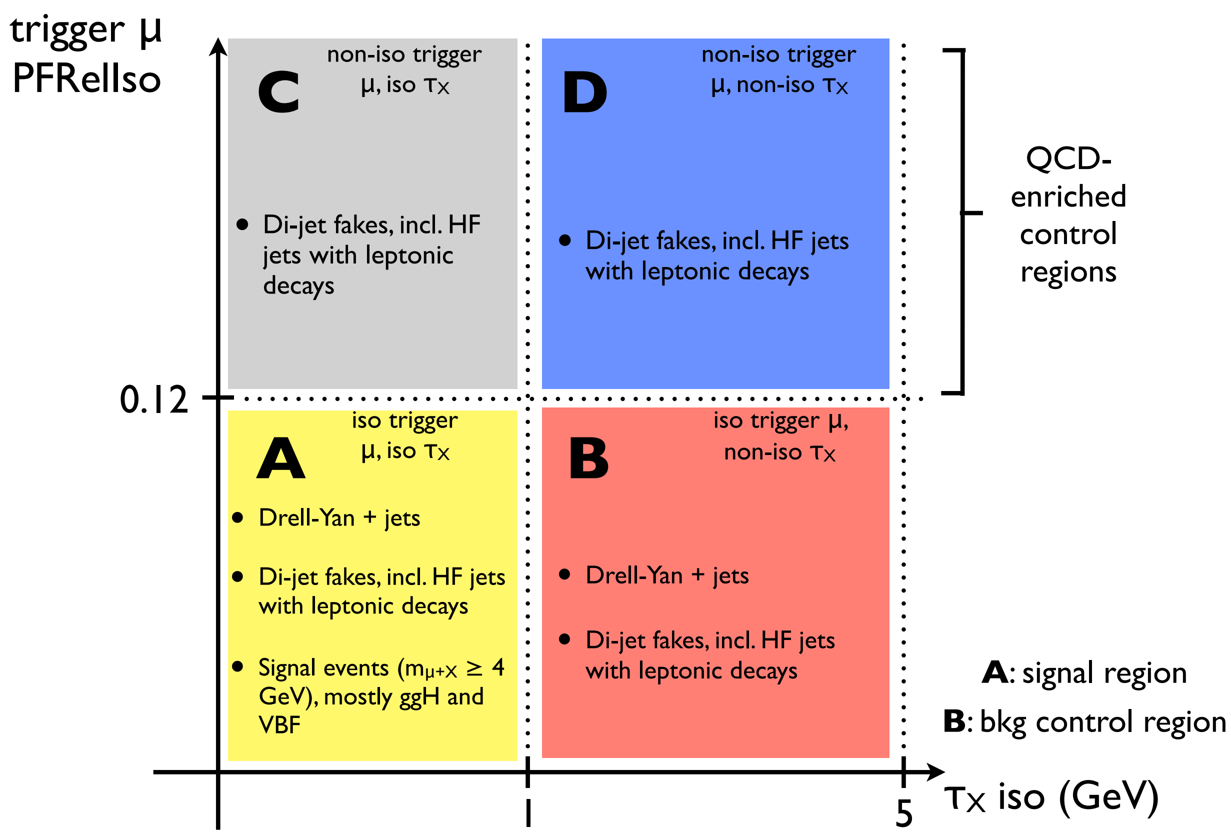


Red dashed line is signal + background hypothesis

Run 1 8 TeV 19.7 fb^{-1} | $\tau_\mu \tau_{1\text{-prong}}$

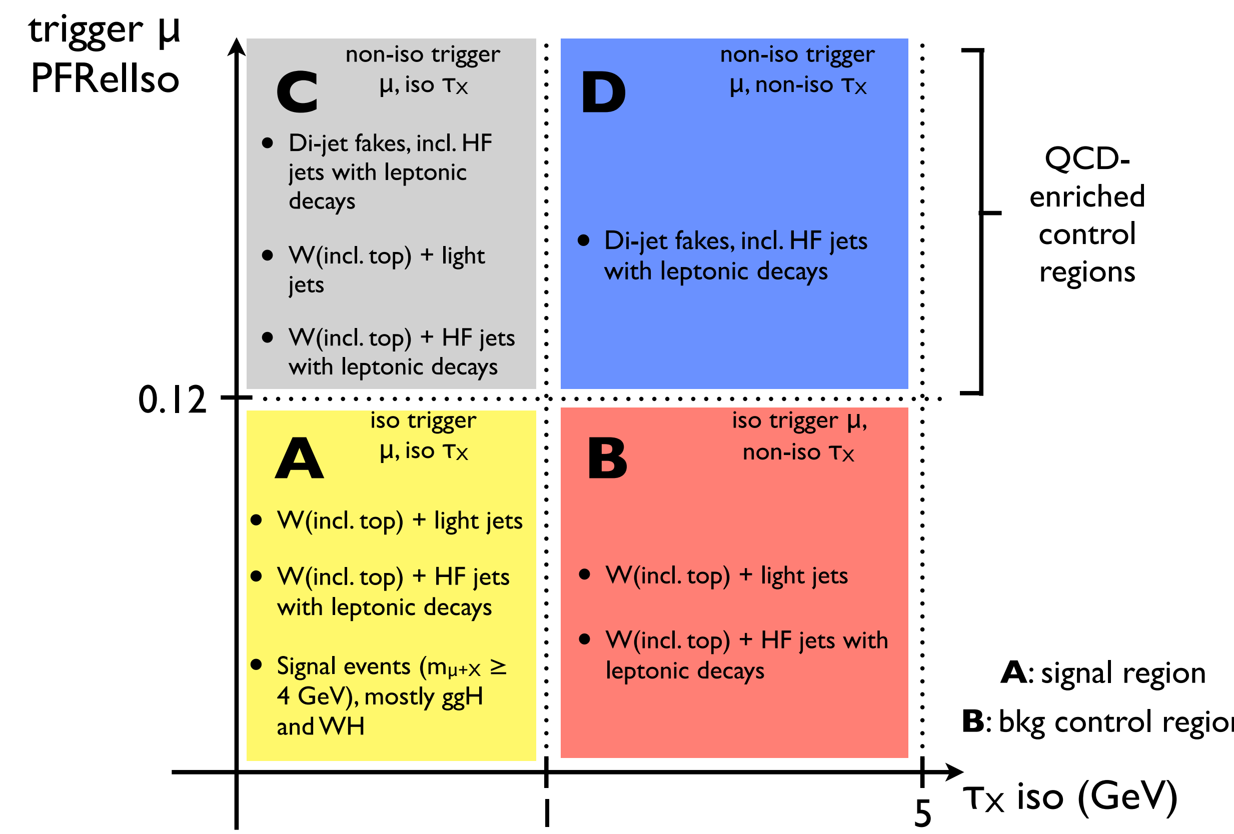
$H \to aa \to 4\tau$

Low m_T



CMS-PAS-HIG-14-022

High m_T



CMS-PAS-HIG-14-022

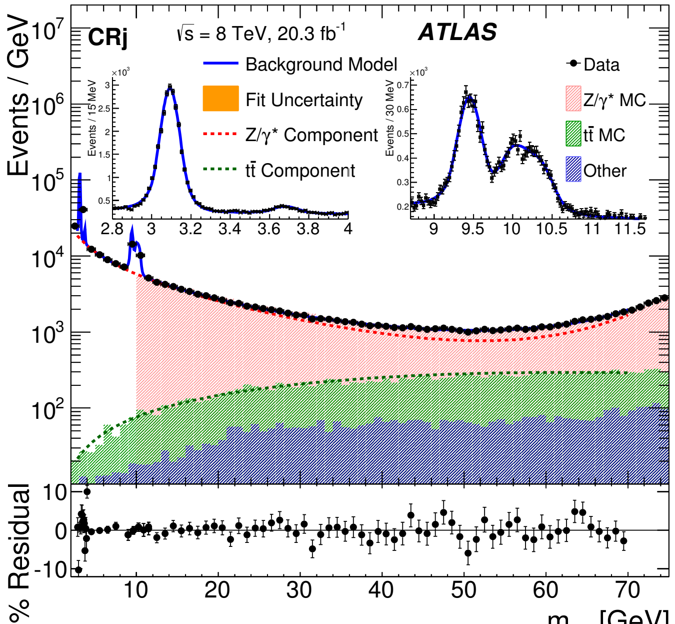
Run 1 8 TeV 19.7 fb^{-1} | $\tau_\mu \tau_X$

- Signal parametrization derived from MC
  - Voigt + Crystal Ball
  - Voigt = Gaussian ⊗ Lorentz (to model theoretical signal)
  - Crystal Ball = Gaussian ⊗ power-law tail (to model energy not reconstructed)
- Background fit modeled with different analytical functions using the discrete profiling method
  - Polynomials and $1/P_n(x)$ functions up to the degree for which the p-value for compatibility of the function with the data drops below 5%
  - p-value calculation accounts for the number of degrees of freedom in the fit and the parameter uncertainty
  - Functional form is a discrete nuisance parameter and enters the likelihood calculation like all other continuous nuisance parameters
  - Likelihood minimization chooses the best-fit background model

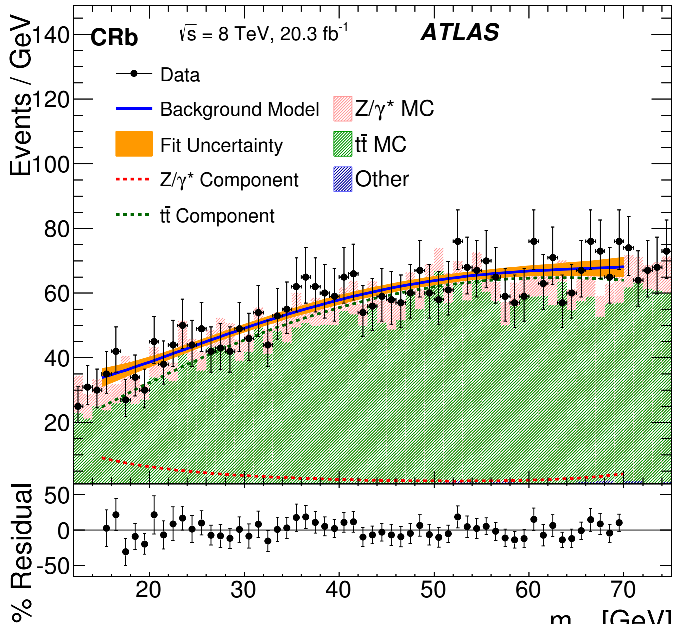
Run 1 8 TeV 19.7 fb^{-1}

H→aa→2μ2τ

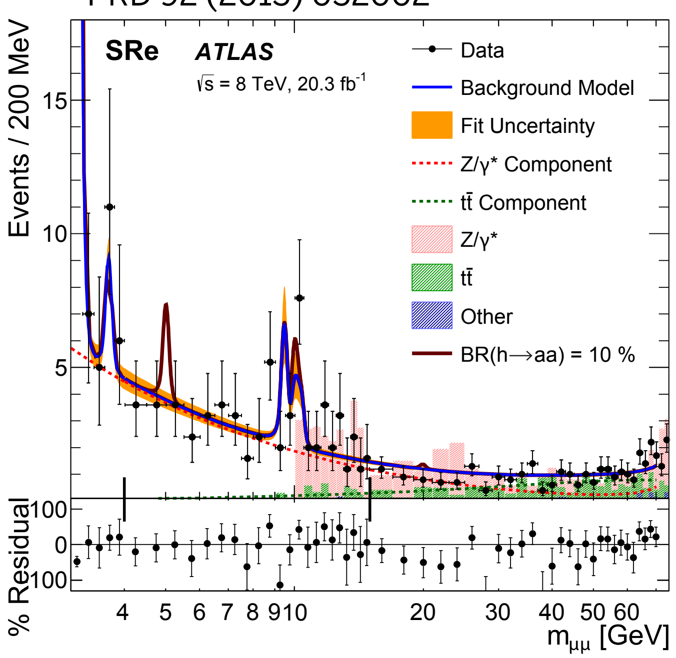
PRD 92 (2015) 052002



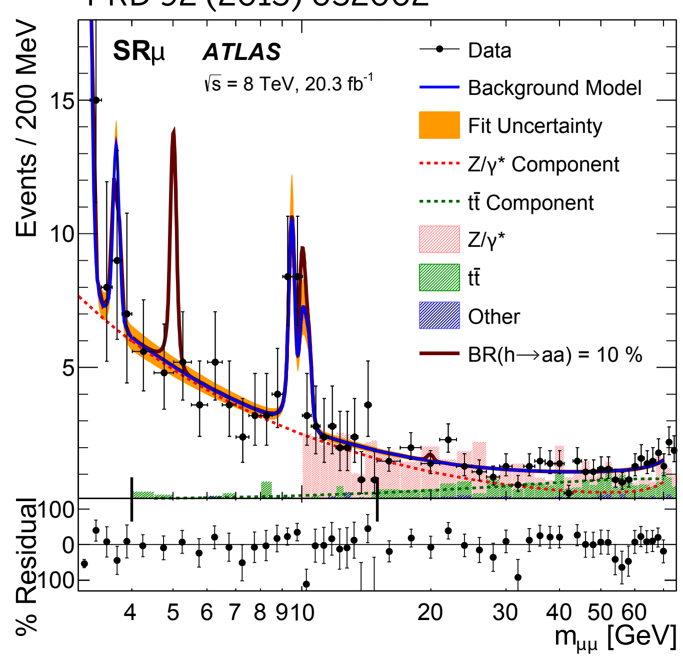
PRD 92 (2015) 052002



PRD 92 (2015) 052002

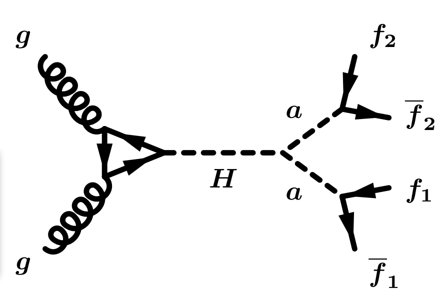


PRD 92 (2015) 052002

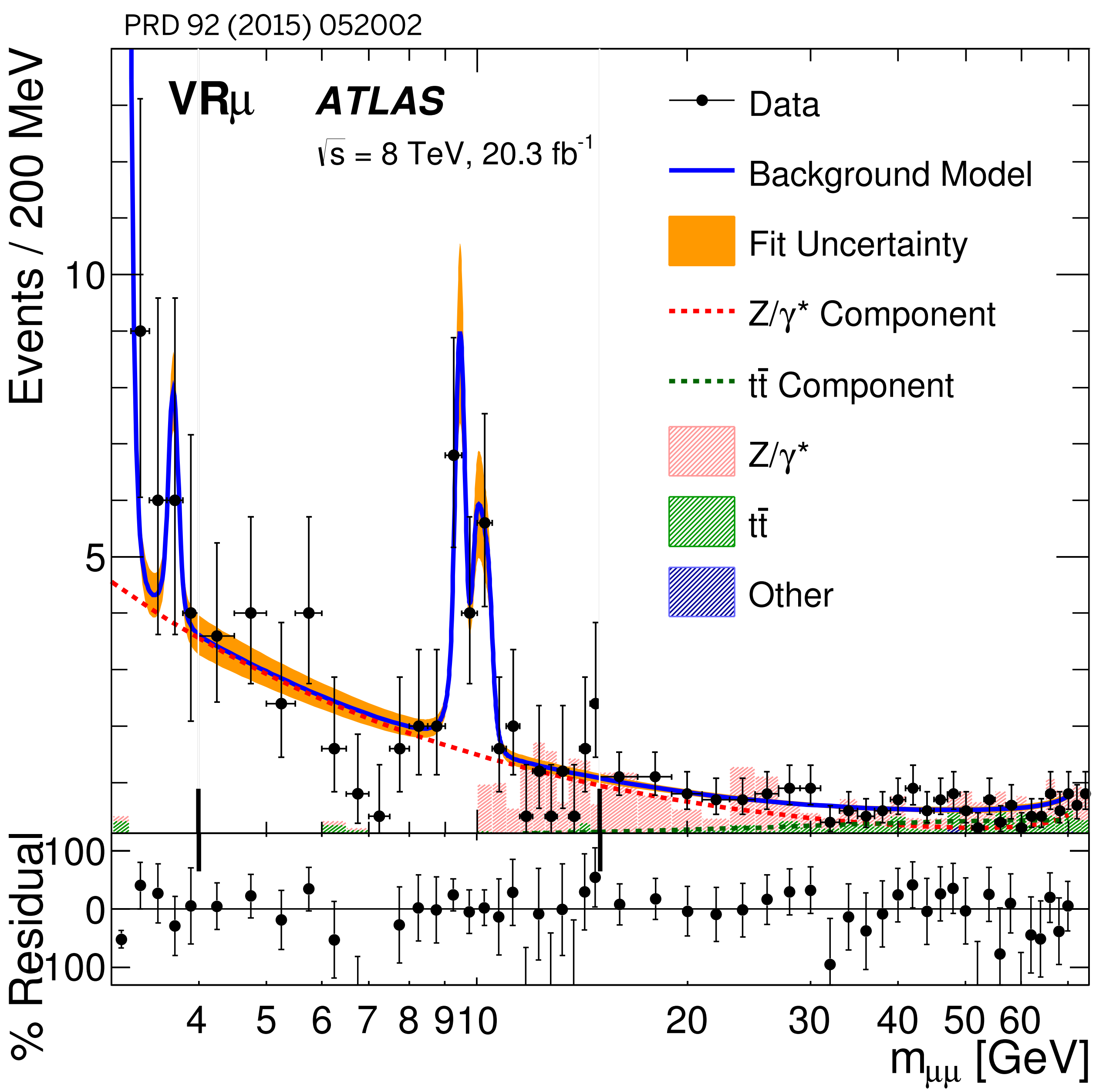


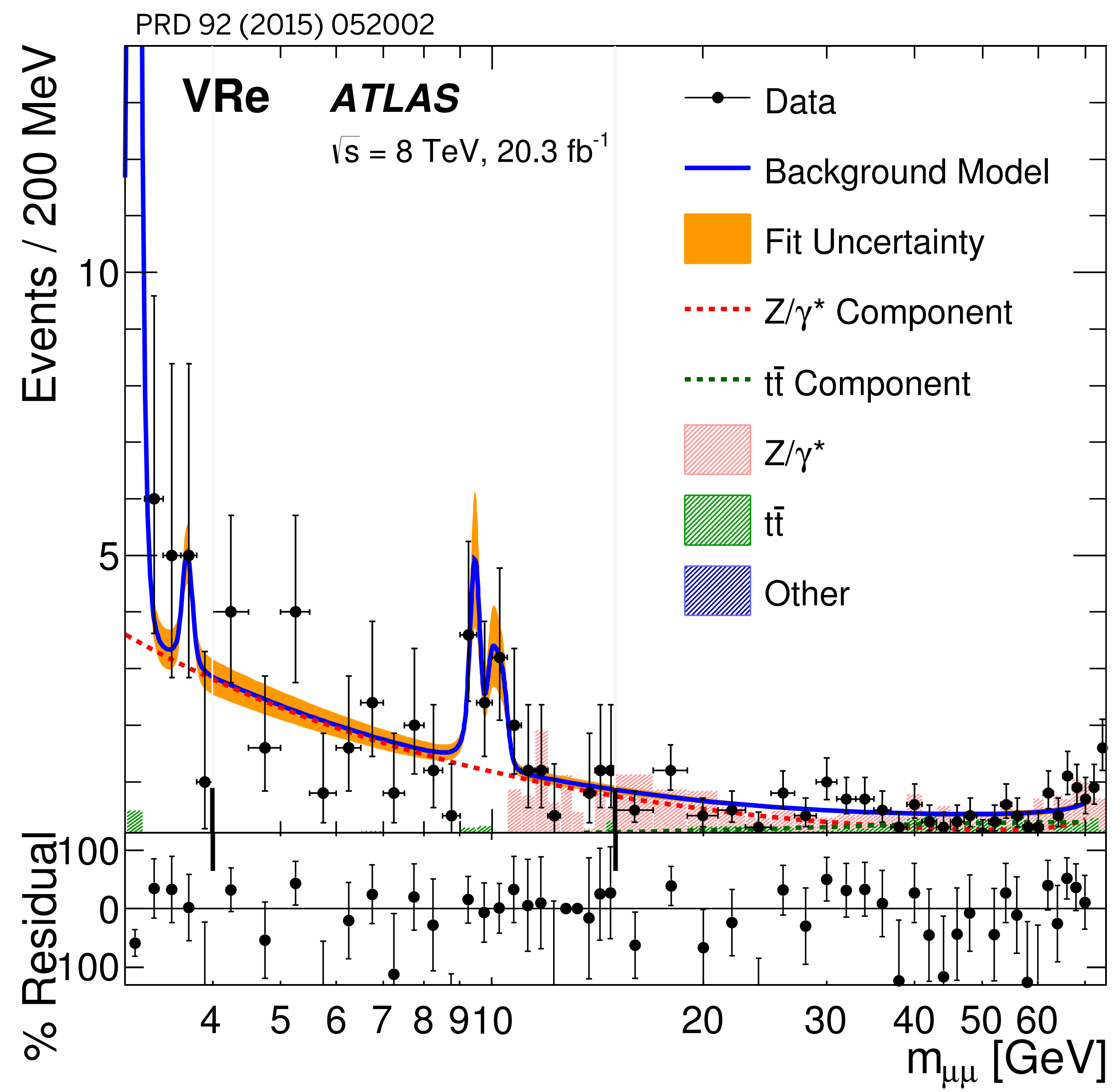
- $3.7 < m_a < 50$ GeV
- 36 GeV single- and 18/8 GeV di-muon triggers
- Di-muon pair with $p_T > 40$ GeV formed from resolved muons
- Boosted di-tau reconstruction
  - Third soft lepton (7 GeV τ_e or τ_μ) with 1, 2, or 3 1-GeV tracks within a $\Delta R = 0.4$ cone
  - Isolated di-tau well separated from di-muon
- SM resonances, $t\bar{t}$, and Drell-Yan backgrounds modeled by analytic functions and constrained by fits in control regions

Run 1 8 TeV 20.3 fb⁻¹ | boosted



$H \to aa \to 2\mu 2\tau$



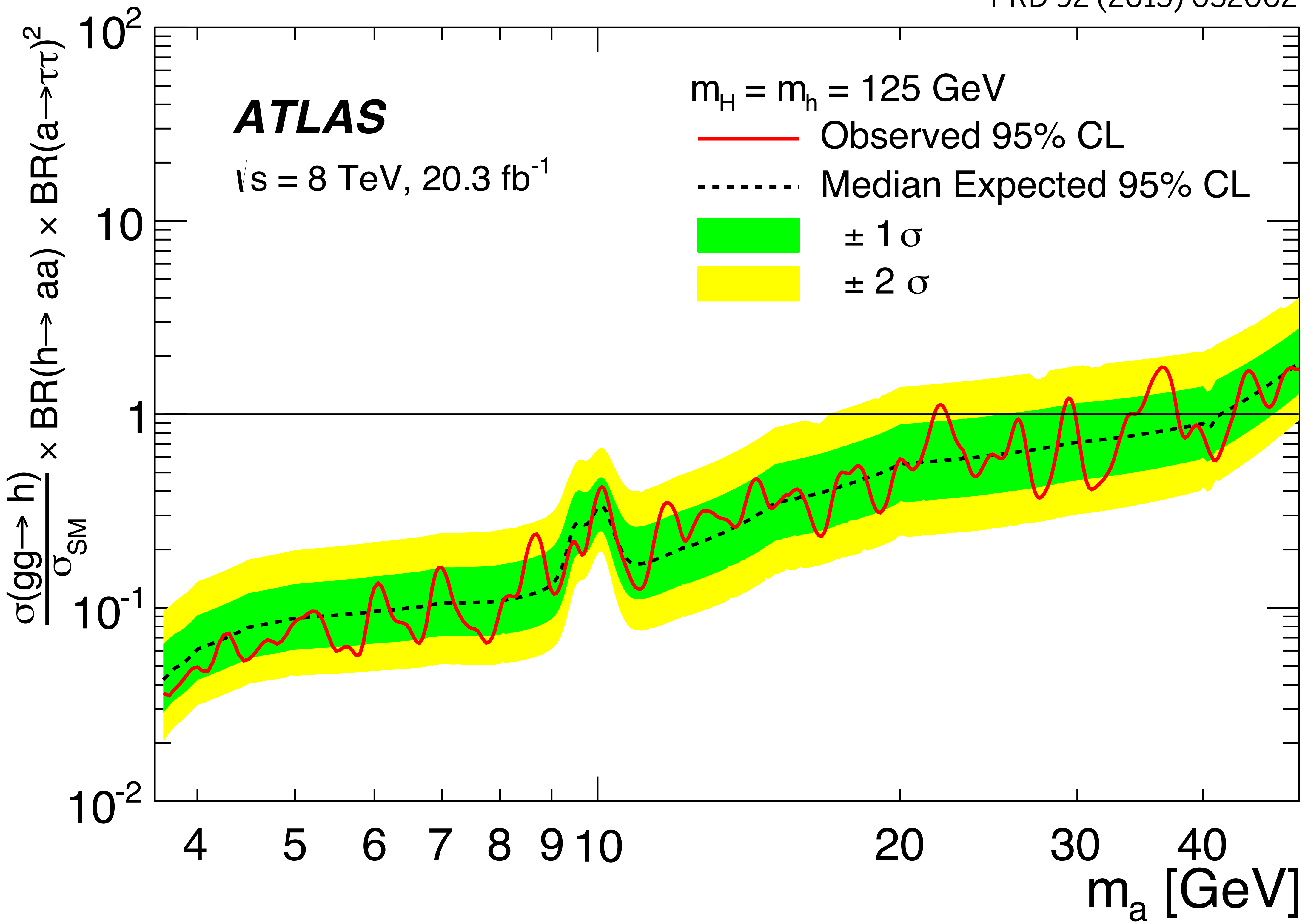


Validation of background modeling

Run 1 8 TeV 20.3 fb^{-1} | boosted

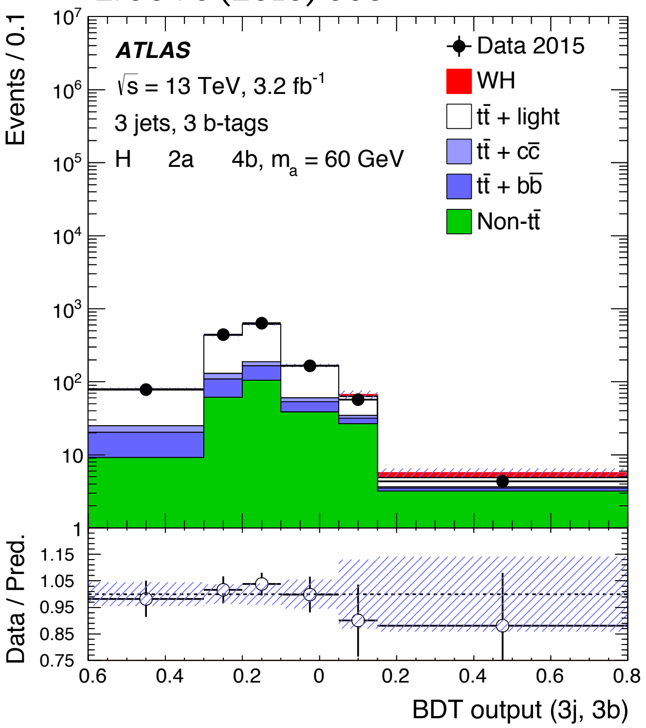
2HDM+S interpretation

PRD 92 (2015) 052002

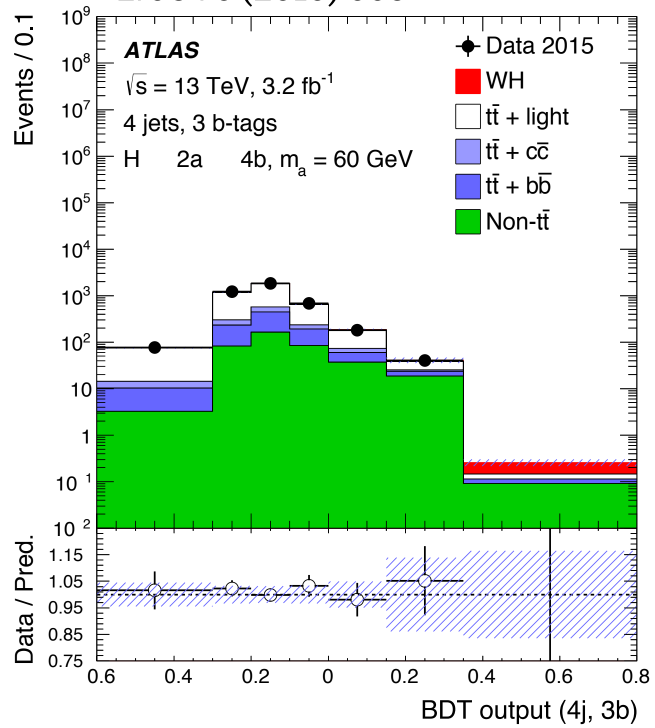


H→aa→4b

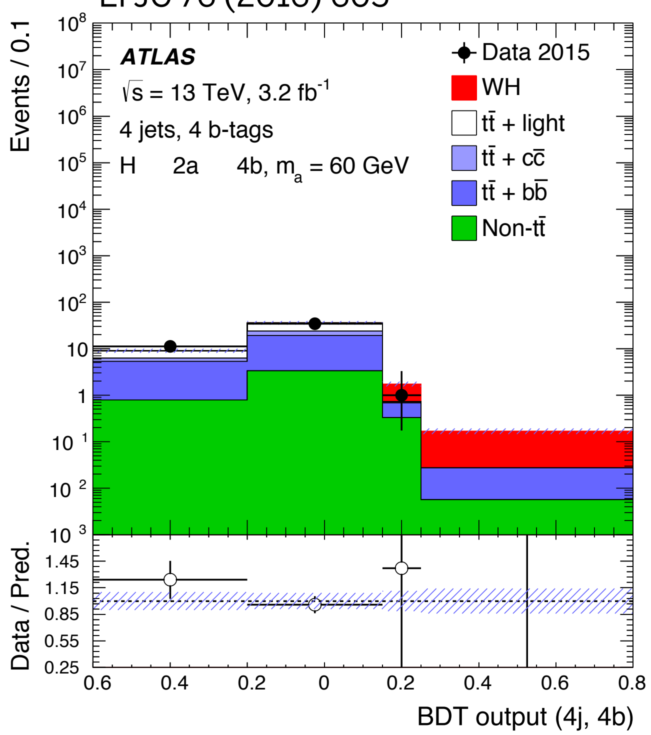
EPJC 76 (2016) 605

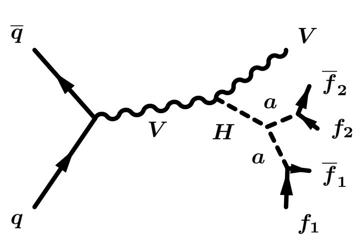


EPJC 76 (2016) 605



EPJC 76 (2016) 605





- W reconstruction with 20 < m_a < 60 GeV
  - Trigger on isolated 25 GeV electron or muon
  - m_T > 50 GeV
- Events classified according to number of jets and b tags identified
- BDT discriminator trained on 60 GeV pseudoscalar signal and tt background
- $t\bar{t}$ backgrounds taken from simulation, with BDT(H_T) discriminant distributions fit to data in the search(control) bins
- Small QCD background from jets faking isolated leptons estimated from data using fake rates

ATLAS EXPERIMENT *Run 2 13 TeV 3.2 fb-1*

Region		m_{bbb}	m_{bbbb}	$\Delta m^{bb}_{\rm min}$	$H_{\rm T}$	$p^{W}_{\rm T}$	$\Delta R^{bb}_{\rm av}$	$\Delta R^{\ell b}_{\rm min}$	m_{bbj}	$m_{\rm T2}$
Signal	(3j, 3b)	✓			✓	✓	✓	✓		
	(4j, 3b)	✓			✓	✓	✓		✓	
	(4j, 4b)		✓	✓	✓		✓			✓
Control					✓					

EPJC 76 (2016) 605

Systematic uncertainty [%]	$WH,\ H \to 2a \to 4b$	$t\bar{t}$ + light	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$
Luminosity	4	4	4	4
Lepton efficiencies	1	1	1	1
Jet efficiencies	6	4	4	4
Jet energy resolution	5	1	3	1
Jet energy scale	4	2	4	3
b-tagging efficiency	17	5	5	9
c-tagging efficiency	1	6	12	4
Light-jet-tagging efficiency	2	29	5	3
Theoretical cross sections	–	5	5	5
$t\bar{t}$: modelling	–	6	45	26
$t\bar{t}$+HF: normalisation	–	–	35	18
$t\bar{t}$+HF: modelling	–	–	–	5
Signal modelling	7	–	–	–
Total	21	31	54	21

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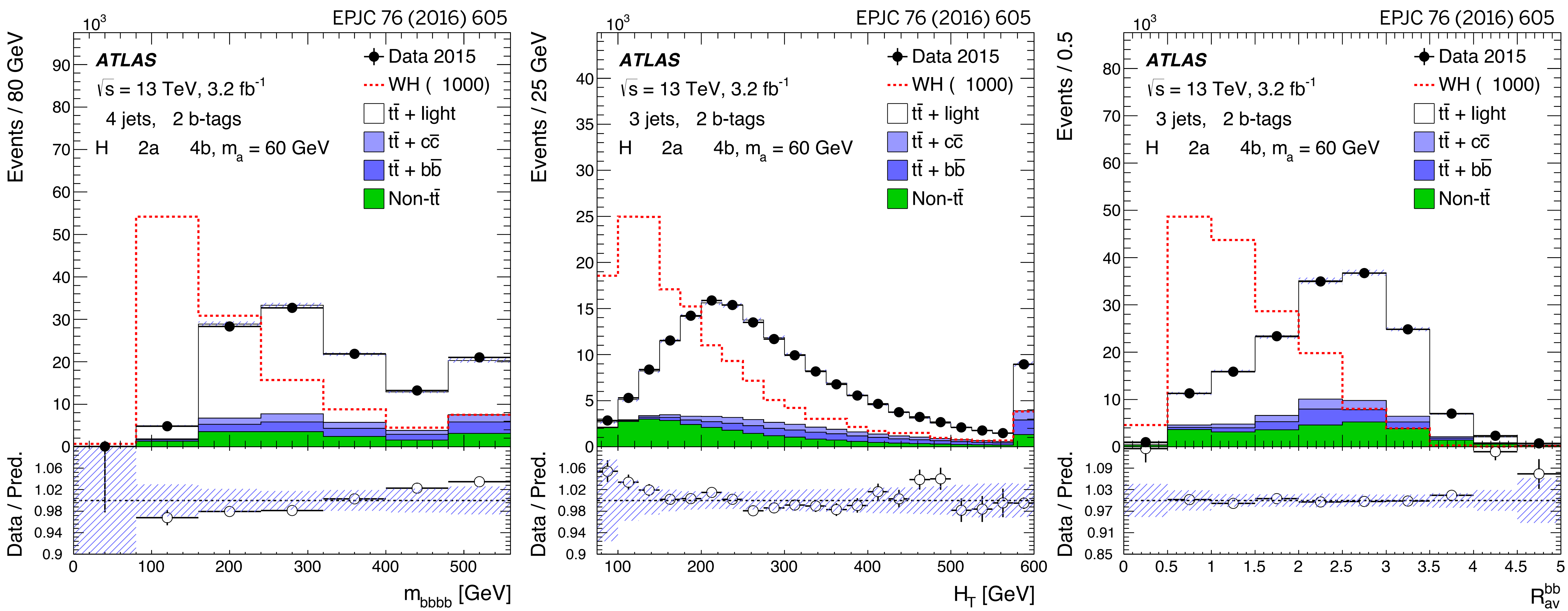
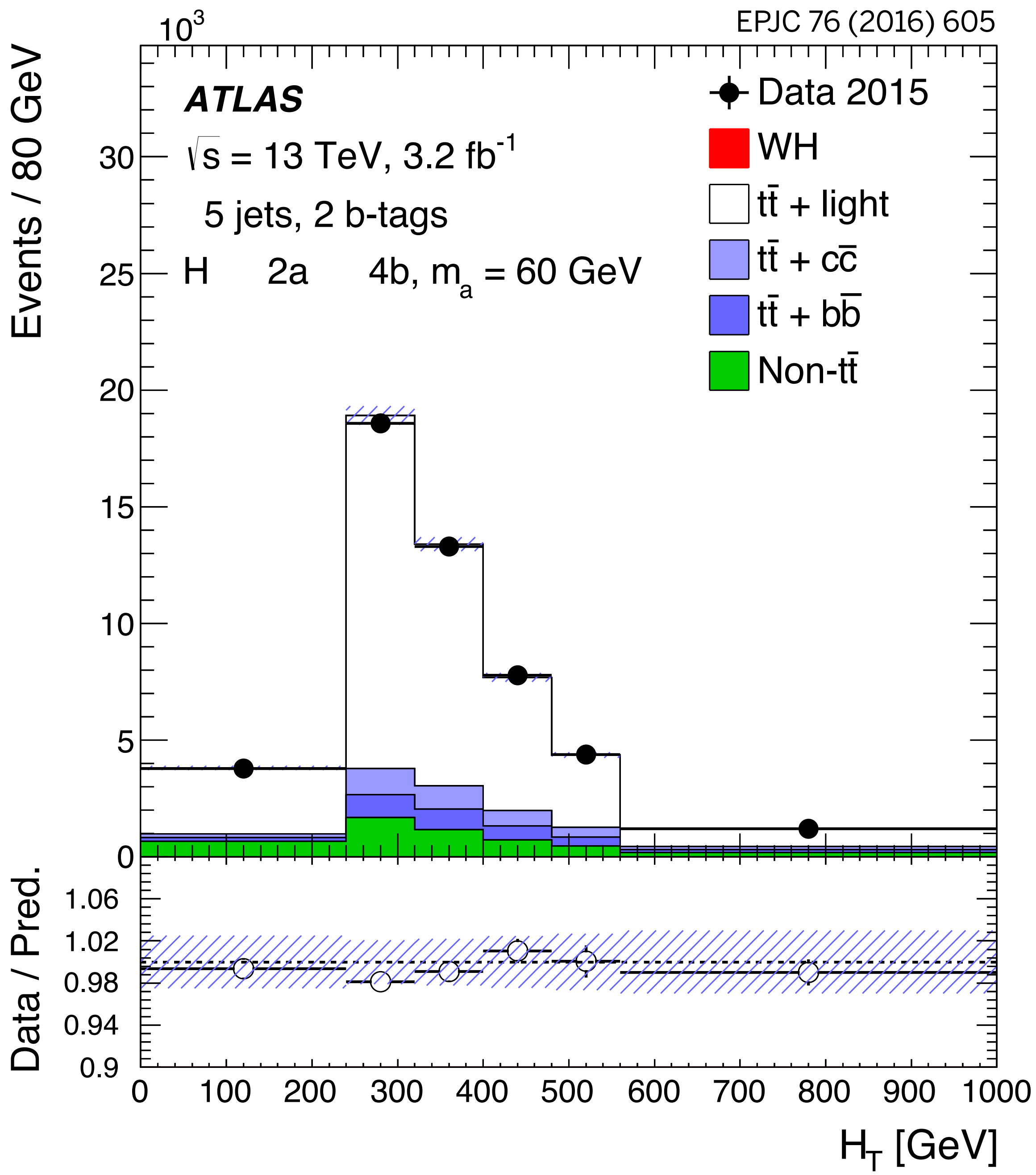
Run 2 13 TeV 3.2 fb^{-1}

H→aa→4b



Some BDT variables

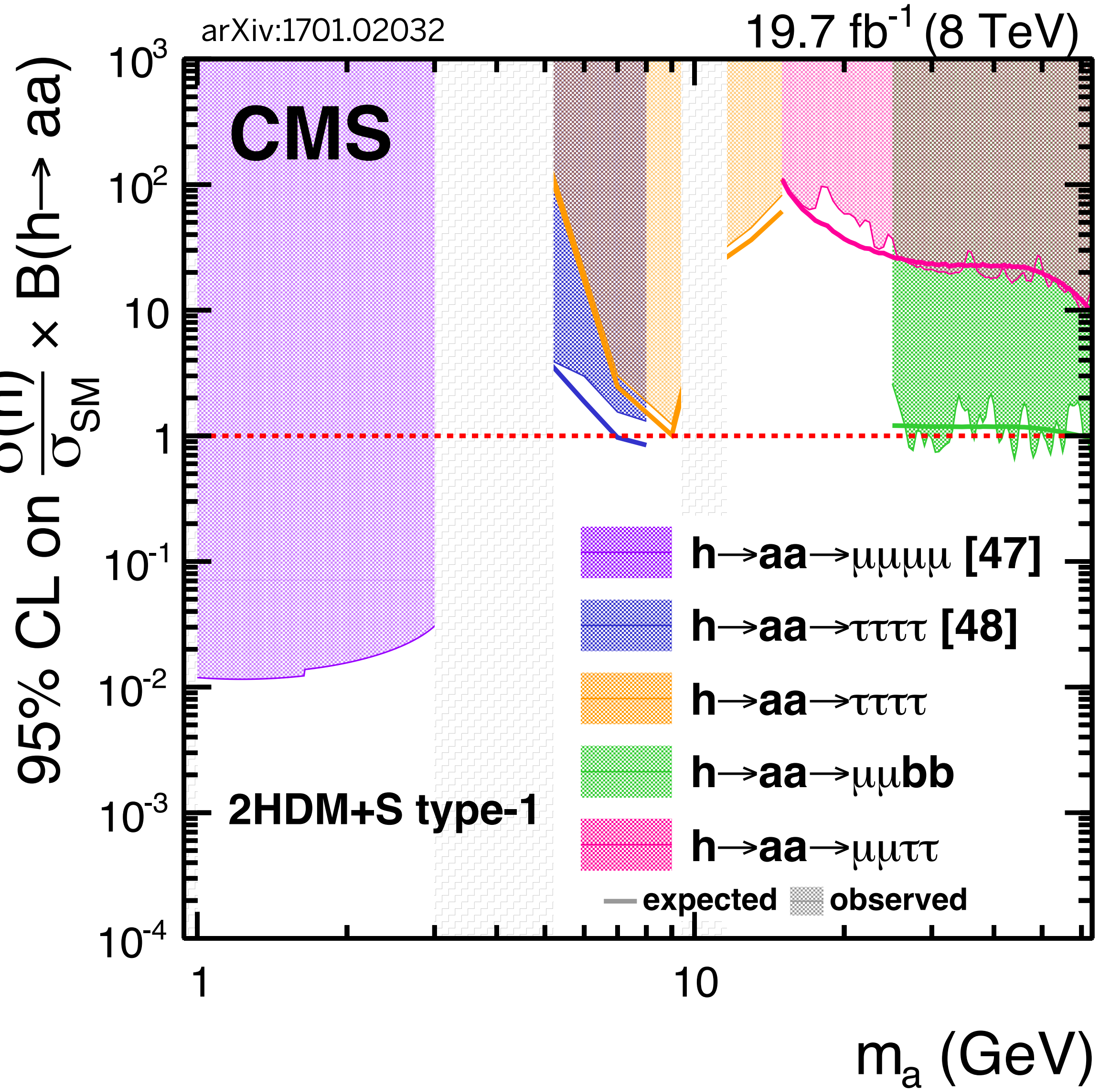
Run 2 13 TeV 3.2 fb^{-1}

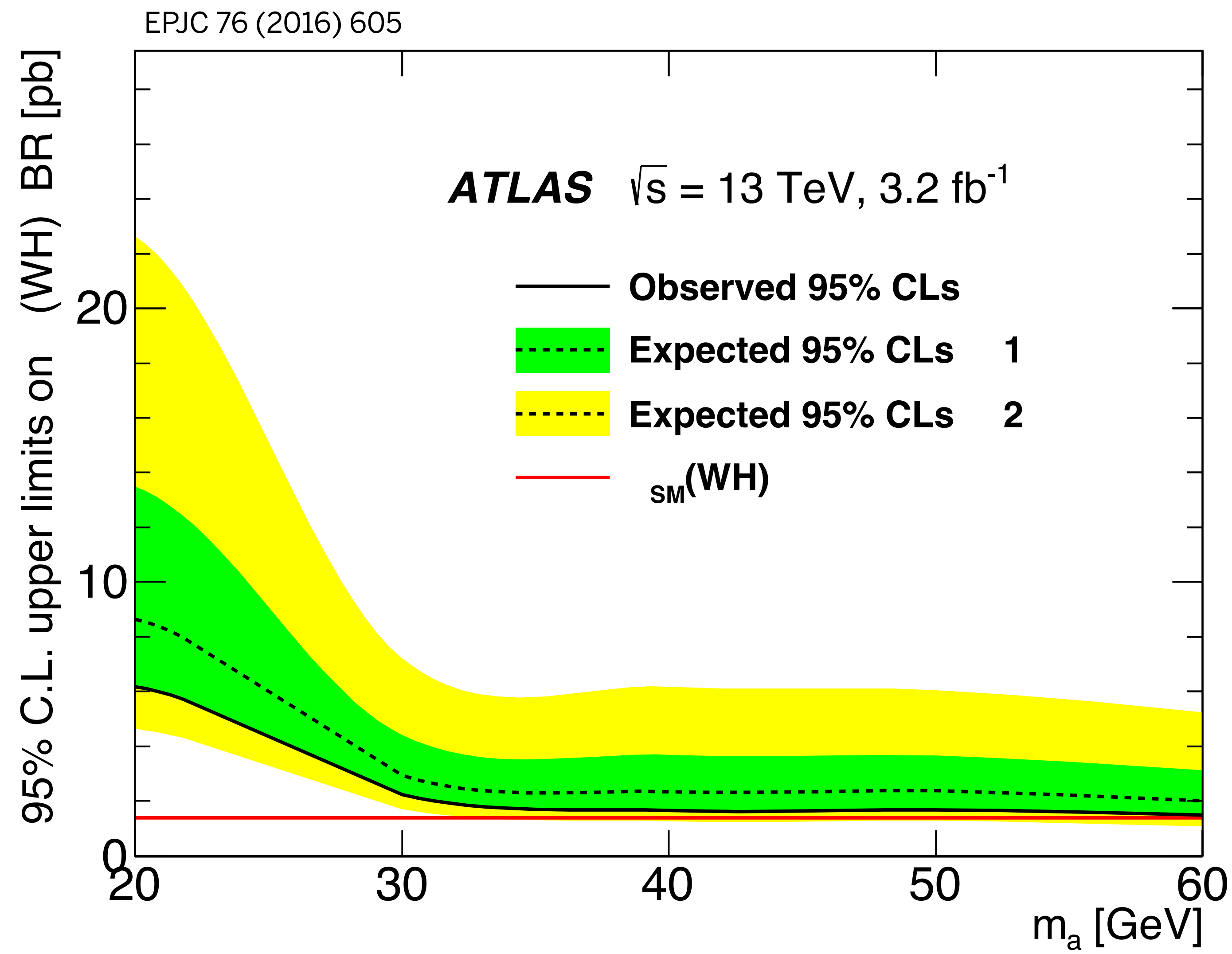


Validation of background modeling

Run 2 13 TeV 3.2 fb^{-1}

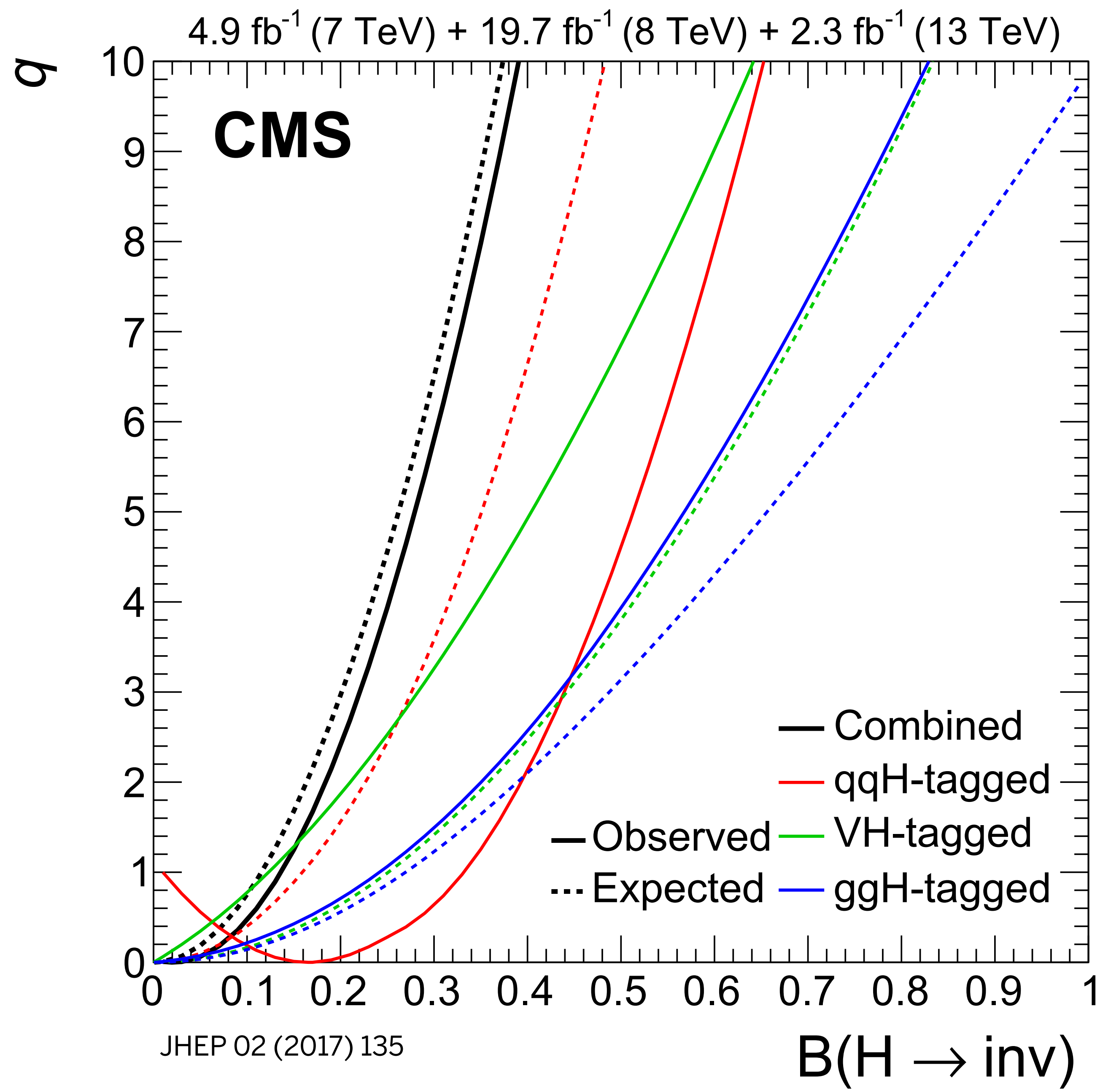
2HDM+S interpretation



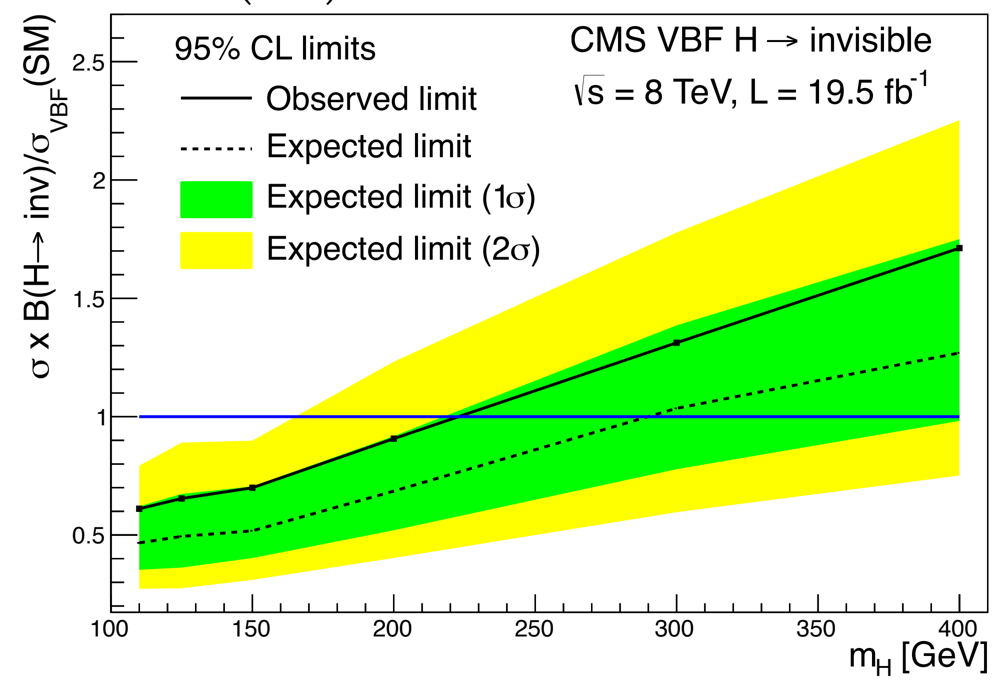


Systematic uncertainty JHEP 02 (2017) 135	Impact
Common	
Muon efficiency	24%
Electron efficiency	22%
Lepton veto efficiency	16%
b jet tag efficiency	3.2%
$W(\ell\nu)$+jets/$Z(\nu\nu)$+jets ratio, theory	16%
γ+jets/$Z(\nu\nu)$+jets ratio, theory	5.8%
Jet energy scale and resolution	10%
E_T^{miss} scale	1.8%
Integrated luminosity	3.0%
Diboson background normalisation	2.7%
Top quark background normalisation	$<$1%
Signal specific	
ggH p_T-spectrum	15%
Renorm. and fact. scales and PDF (ggH)	5.8%
Total systematic	$^{+57}_{-50}$%
Total statistical only	$^{+25}_{-22}$%
Total uncertainty	$^{+62}_{-55}$%

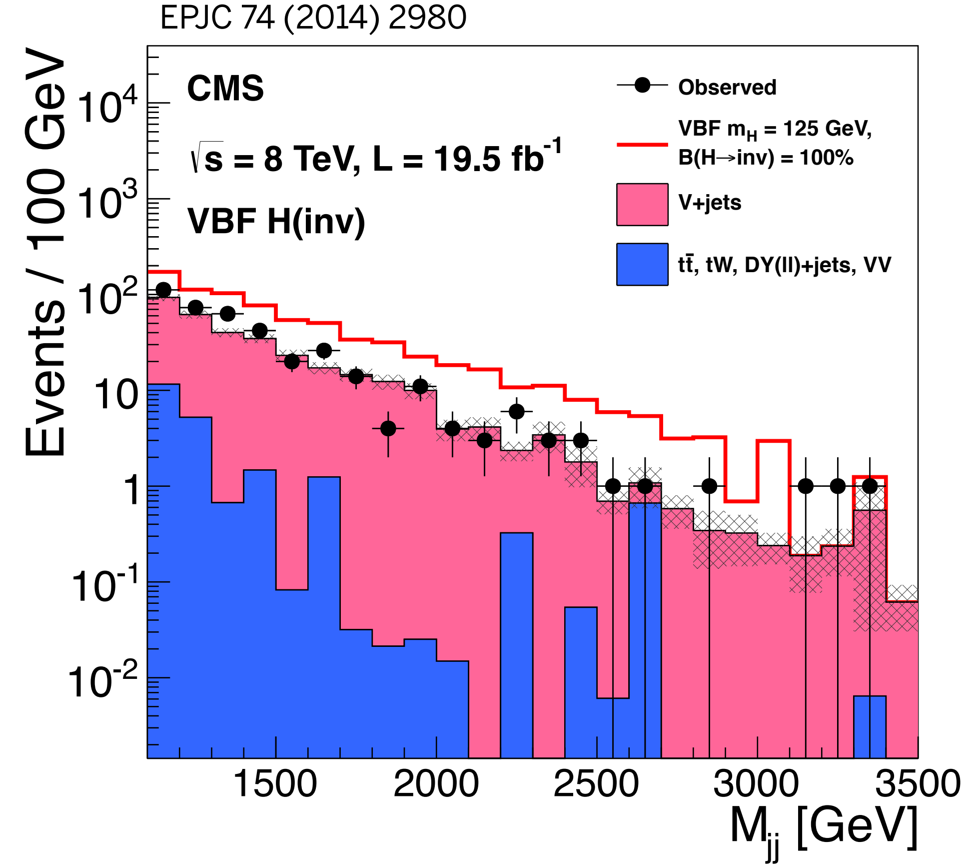
SM interpretation



EPJC 74 (2014) 2980



EPJC 74 (2014) 2980



EPJC 74 (2014) 2980