Search for h→aa→2μ2b/2τ2b with the CMS experiment

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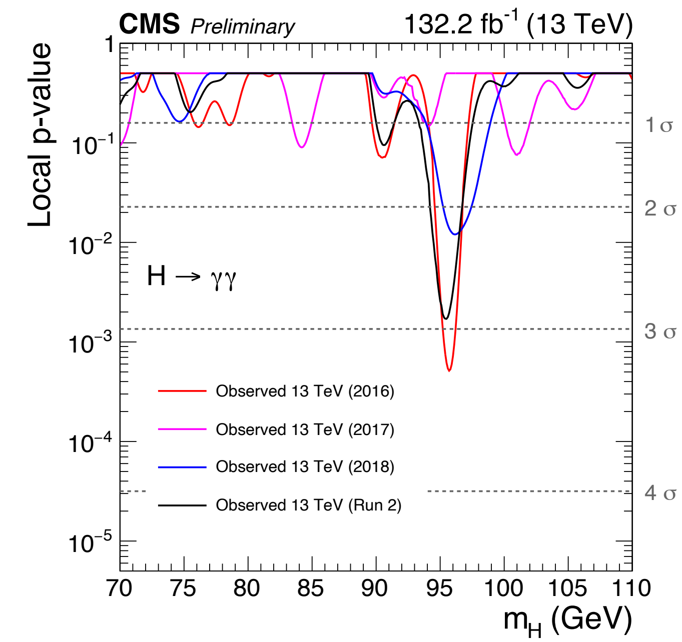
Introduction

The discovery of the Higgs boson 10 years ago established the theory of the SM

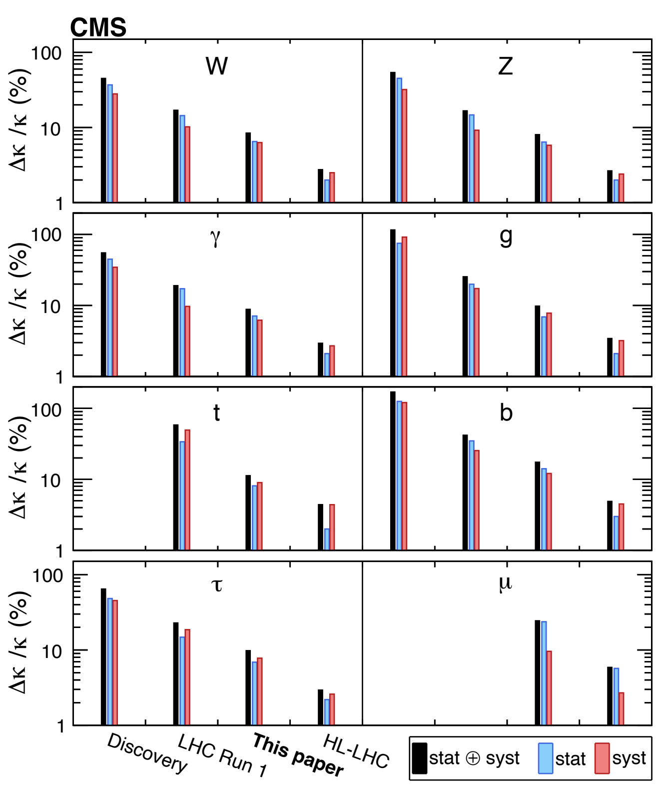
→ ***But many questions remain!***

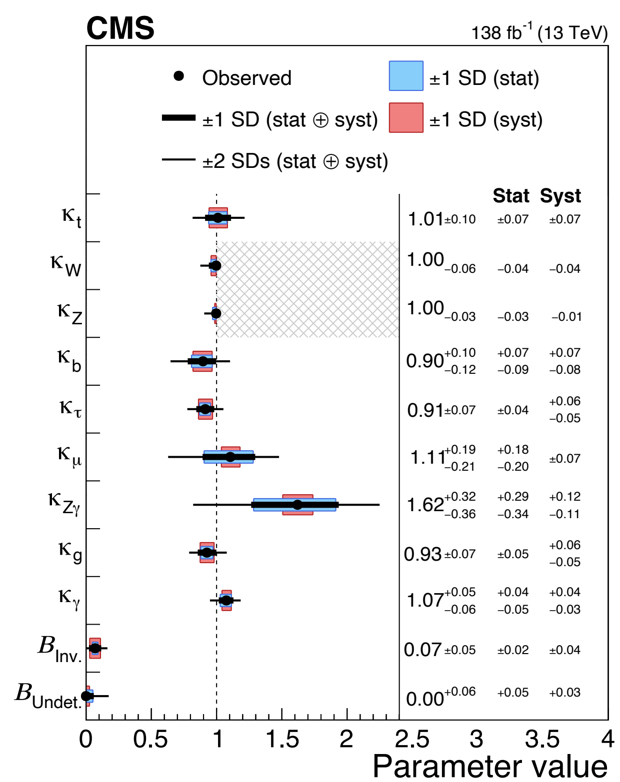
- Extended Higgs sector (MSSM, NMSSM etc.) theories can explain **Dark Matter** origin, **Hierarchy Problem**, etc. and also predict a **Higgs Resonance**
- Example: diphoton channel excess at 96 GeV can be accommodated in 2HDM, a minimal extension of SM with an extra Higgs doublet



CMS-PAS-HIG-20-002

Nature 607, 60–68 (2022)



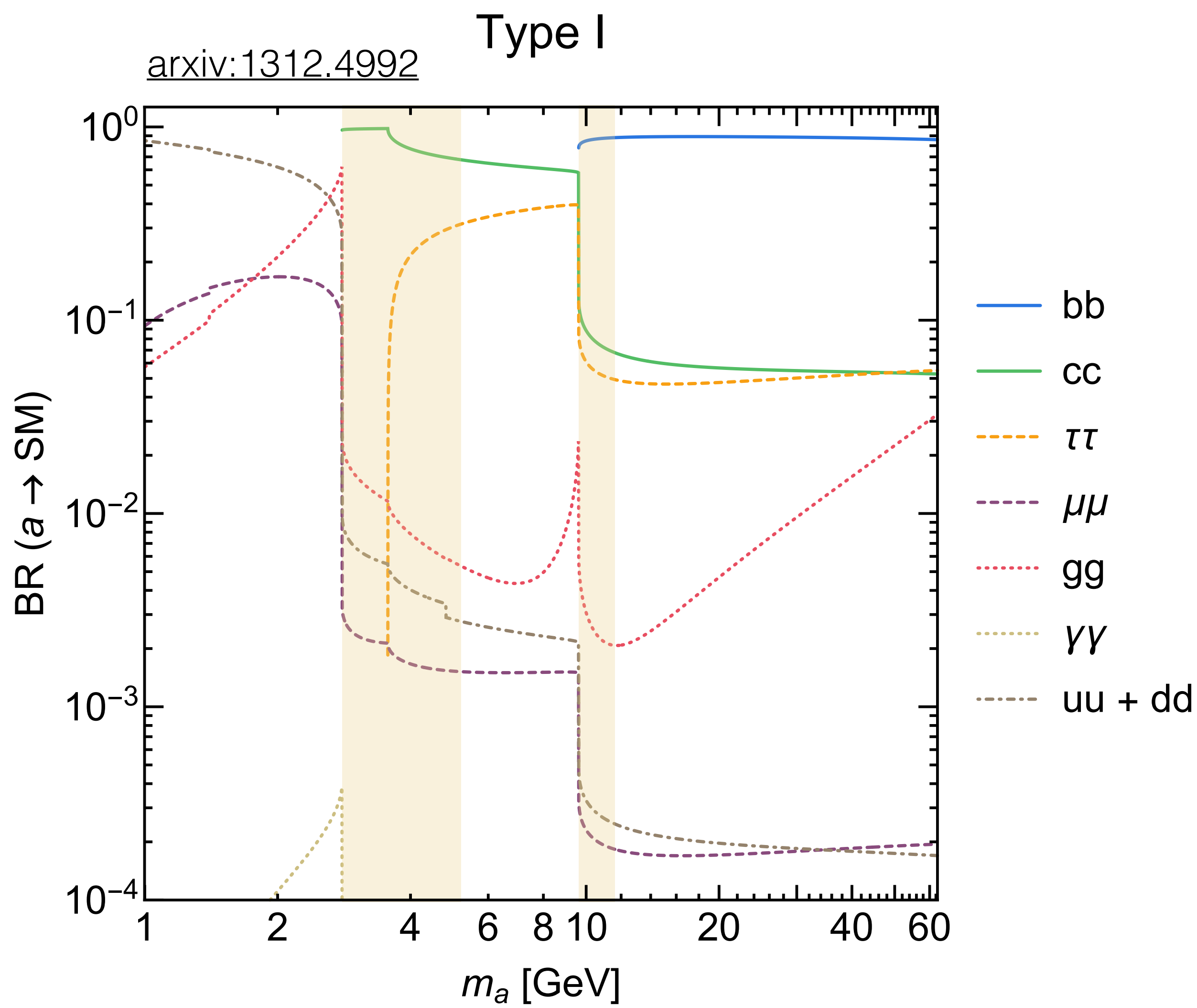


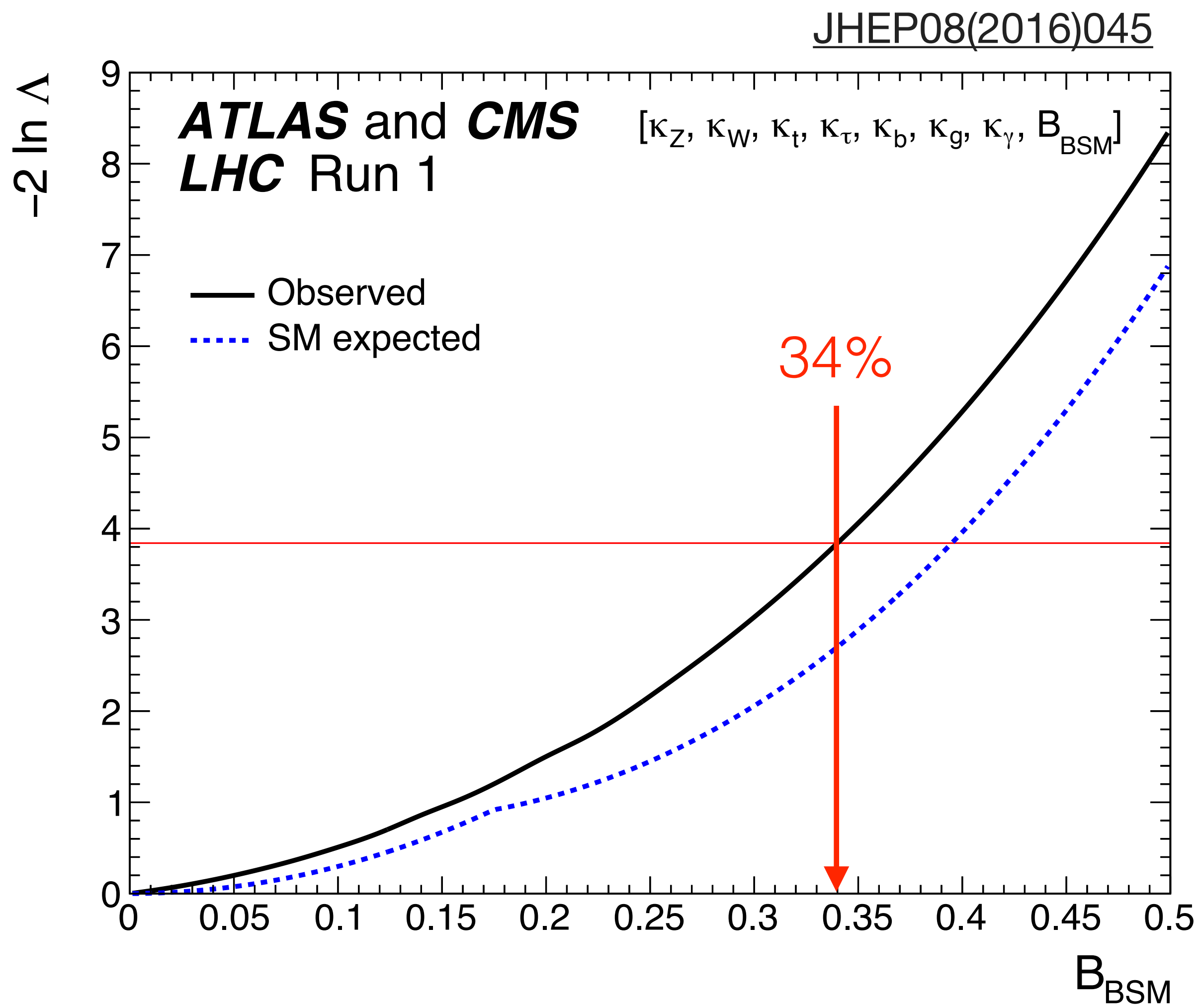
- Limited sensitivity to new physics interactions through SM Higgs coupling measurements
- Direct search for exotic particles able to probe several TeV energy scales

This talk: reviewing full Run-2 results of H→aa→2μ2b/2τ2b search from CMS-PAS-HIG-22-007

Higgs decays to pseudoscalars

- 2HDM+S theory provides wide range of possible exotic Higgs decays, while much of the parameter space of 2HDM is constrained by LHC experiments
- The additional singlet has no direct Yukawa coupling, only couples to the two Higgs fields
- Small mixing with Higgs field: H→aa→SM particles, where a is the pseudoscalar mass eigenstate mostly composed of the imaginary part of the singlet





SM compatibility: combining all Run-1 ATLAS and CMS measurements an upper limit of 34% is set on BSM Higgs decays→ loose constraint on BSM physics

2HDM+S couplings and BR

- Four types of 2HDM+S based on coupling structure of the two Higgs doublets and the SM fermions

	Type I	Type II	Type III	Type IV
Charged leptons	Φ_2	Φ_1	Φ_1	Φ_2
Up-type quarks	Φ_2	Φ_2	Φ_2	Φ_2
Down-type quarks	Φ_2	Φ_1	Φ_2	Φ_1

- Coupling of the pseudoscalar to the fermions depends on tanβ and the mixing angle between the S and Higgs doublets, θ
- Coupling ratio $\xi_f \propto \sin\theta$, thus BR(a→fermions) is independent of θ and has the following behaviour:
  - Type I: no tanβ dependence
  - Type II: decays to down quark and leptons suppressed (enhanced) for tanβ < 1 (tanβ > 1)
  - Type III: tanβ > 1 enhances all BR(a→leptons)
  - Type IV: decays to up quark and leptons suppressed (enhanced) for tanβ > 1 (tanβ < 1)

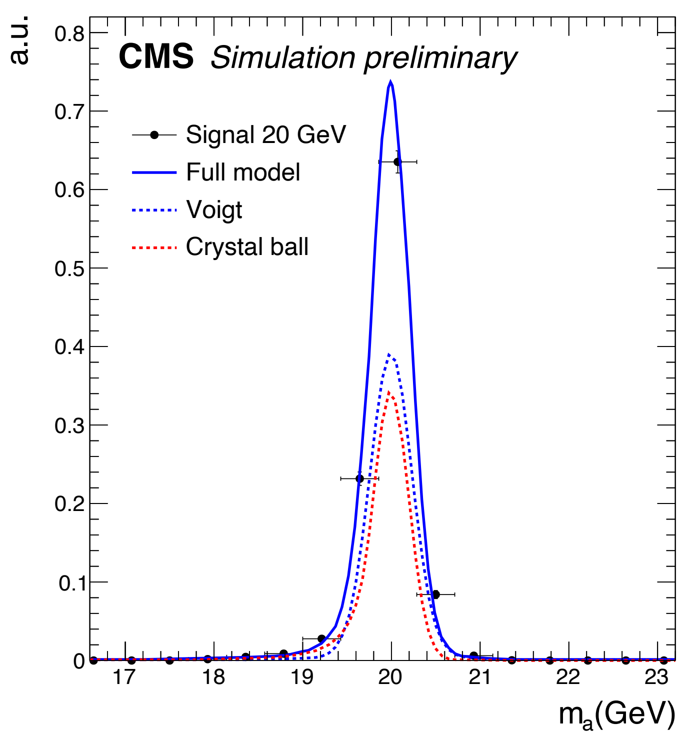
Highest production rate of H→aa→2μ2b/2τ2b is predicted by the Type III model

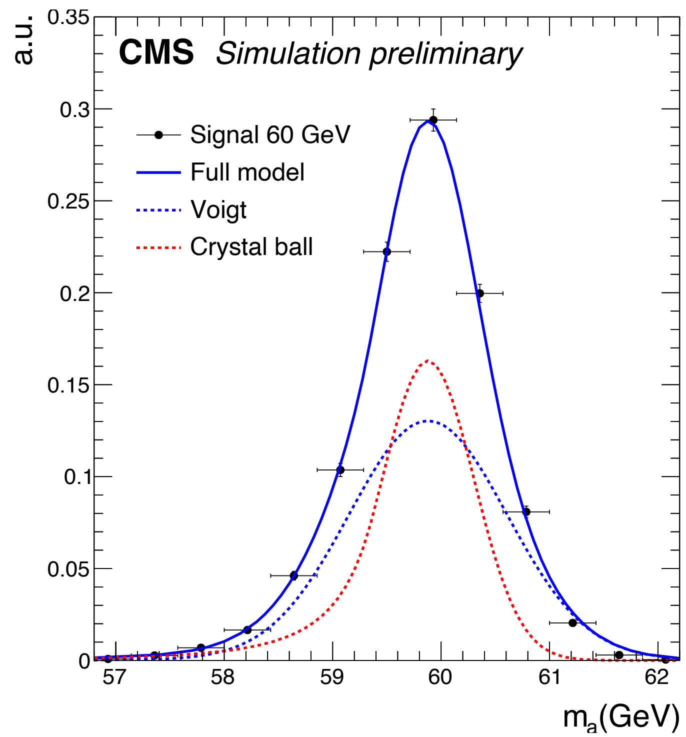
Clean signature with a precise mass resolution from $m_{\mu\mu}$ and large BR from bb

- Search for a masses within $15 < m_a < 62.5$ GeV
- Bump hunt analysis using the dimuon invariant mass $m_{\mu\mu}$

Most stringent observed upper limit till date in this final state, slightly better than ATLAS results

- Difference in analysis strategy with ATLAS: unbinned maximum likelihood fit, completely data-driven background
- Parameters of the signal model (Voight profile+Crystal Ball) are independent of m_a, only the resolution of the model varies linearly with m_a





2016-only result: BR($H \to aa \to 2\mu 2b$) values constrained at 95% CL between (1-7)x10^{-4} depending on m_a

2μ2b: event selection

- Signal events completely reconstructed from final state particles → not expected to produce any p_T^{miss}
  - Events should have at least two muons with opposite charge and at least two b-tagged jets
  - Both single and dimuon triggers are considered, p_T thresholds for muons are 17 and 15 GeV for the leading and subleading
  - Signal does not produce any genuine neutrino: $p_T^{miss} < 60$ GeV

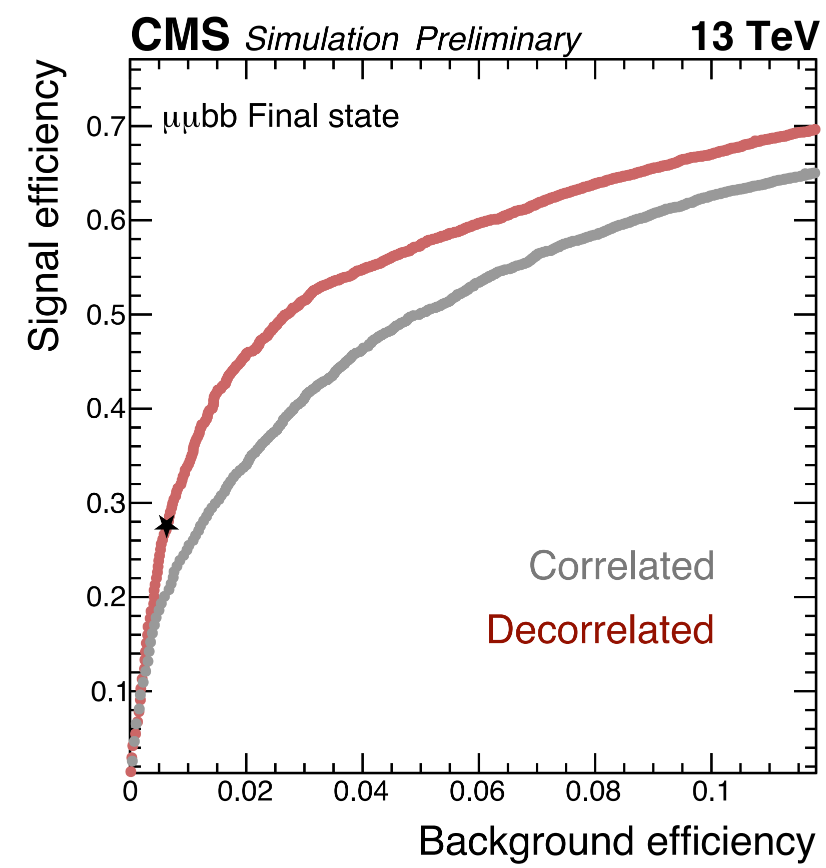
- Use of a single discriminating variable to suppress background:
  - Exploit the mass constraint: $m_{bb} \sim m_{\mu\mu} = m_a$ and $m_{bb\mu\mu} \sim m_H$

$$\chi^2_{\rm tot} \equiv \chi^2_{\rm bb} + \chi^2_{\rm H}$$

$$\chi_{\rm bb} \equiv \frac{(m_{\rm bb} - m_{\mu\mu})}{\sigma_{\rm bb}}$$

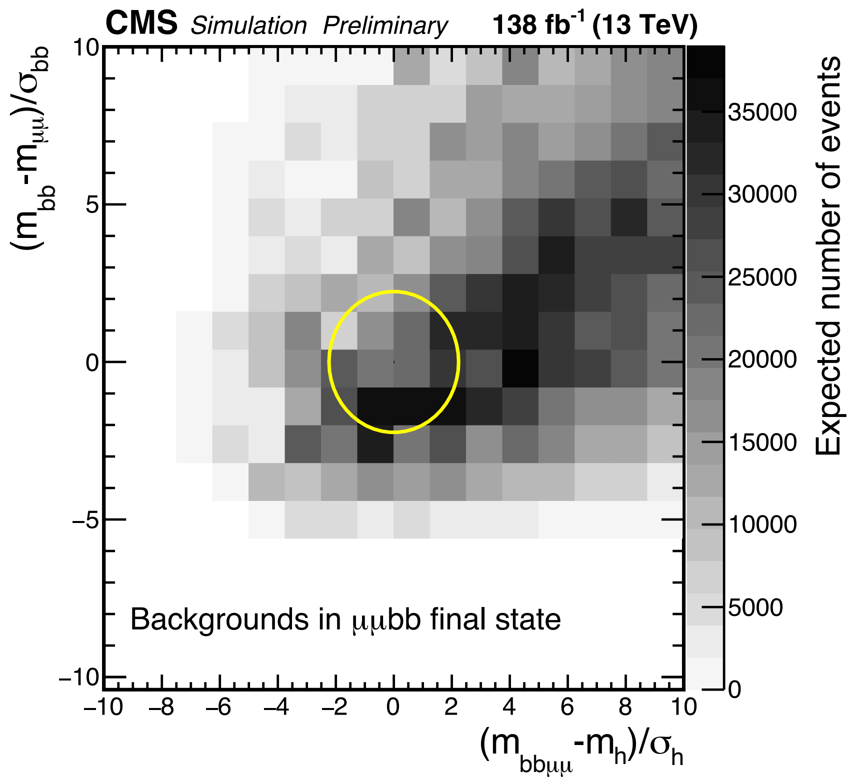
$$\chi_{\rm H} \equiv \frac{(m_{\mu\mu \rm bb} - 125)}{\sigma_{\rm H}}$$

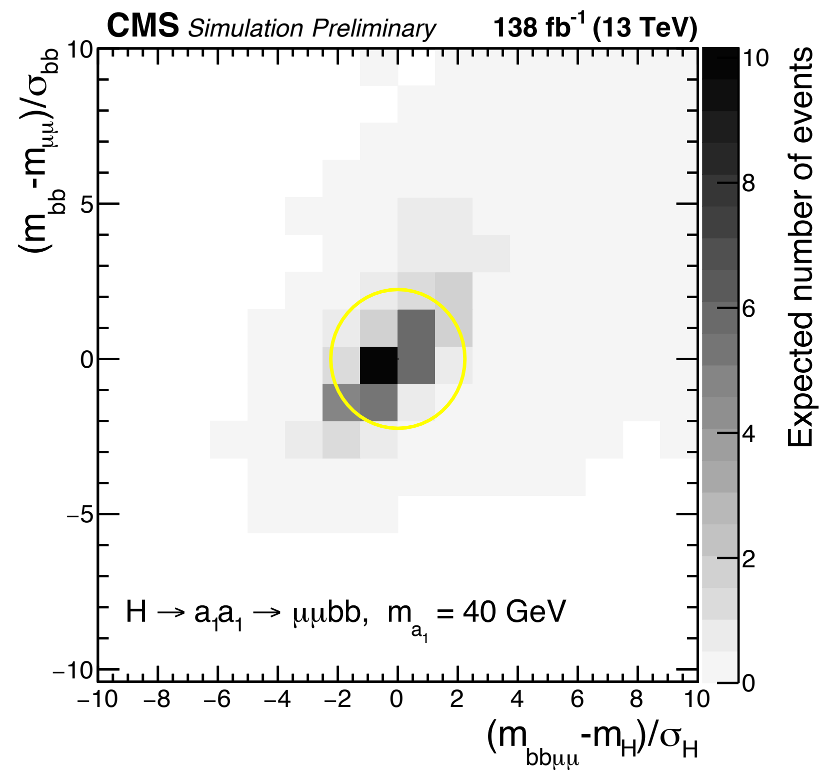
  - Single cut on $\chi_{\rm tot}$, but $\chi_{\rm H}$ and $\chi_{\rm bb}$ are correlated
  - Decorrelate using principal component analysis method



2μ2b: signal categorization

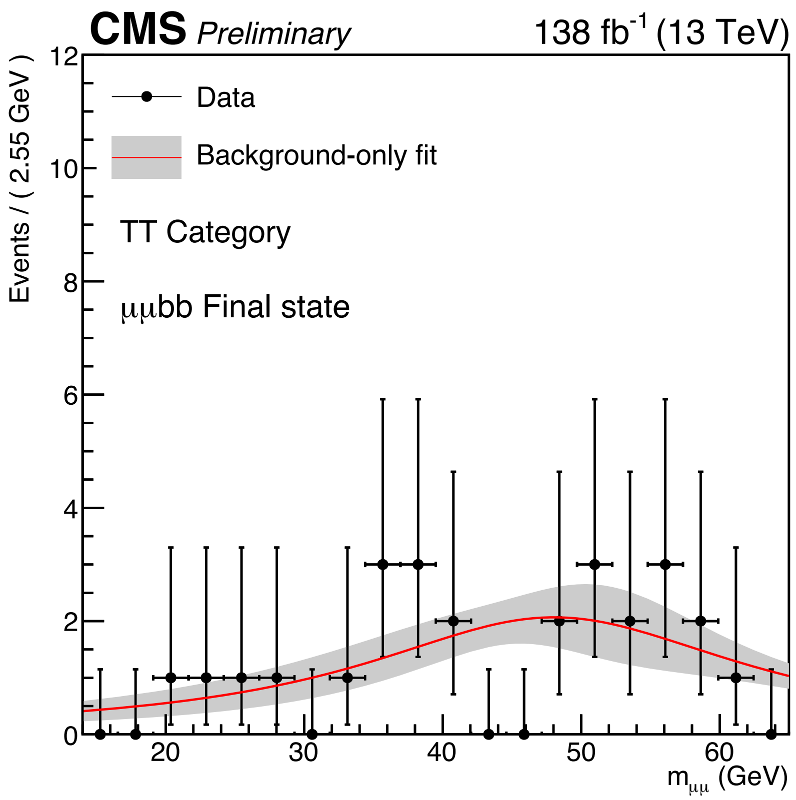
- Select $\chi^2_d < 1.5$ following optimisation studies using simulated events

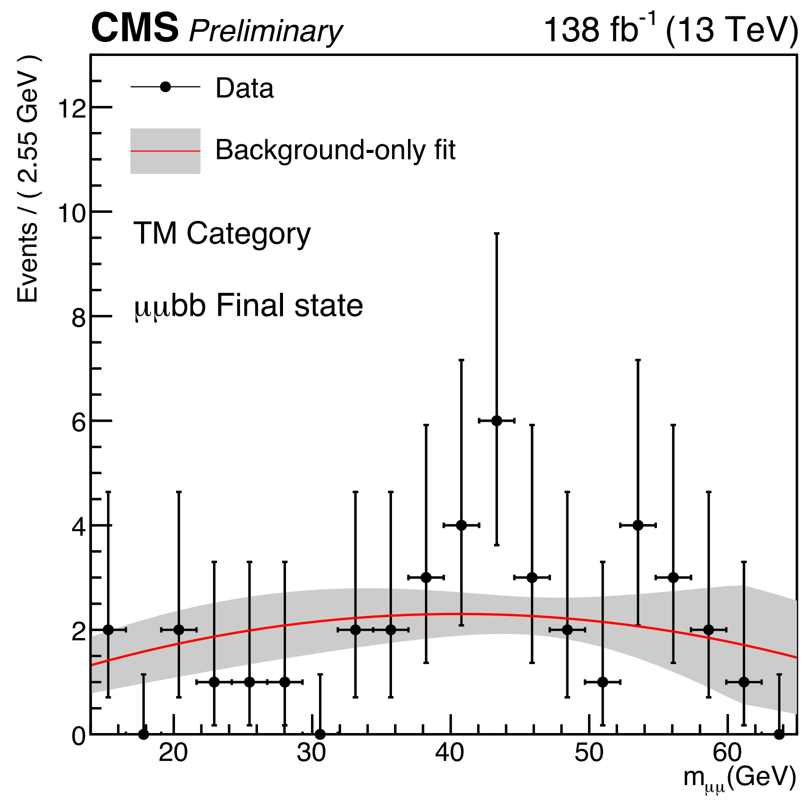


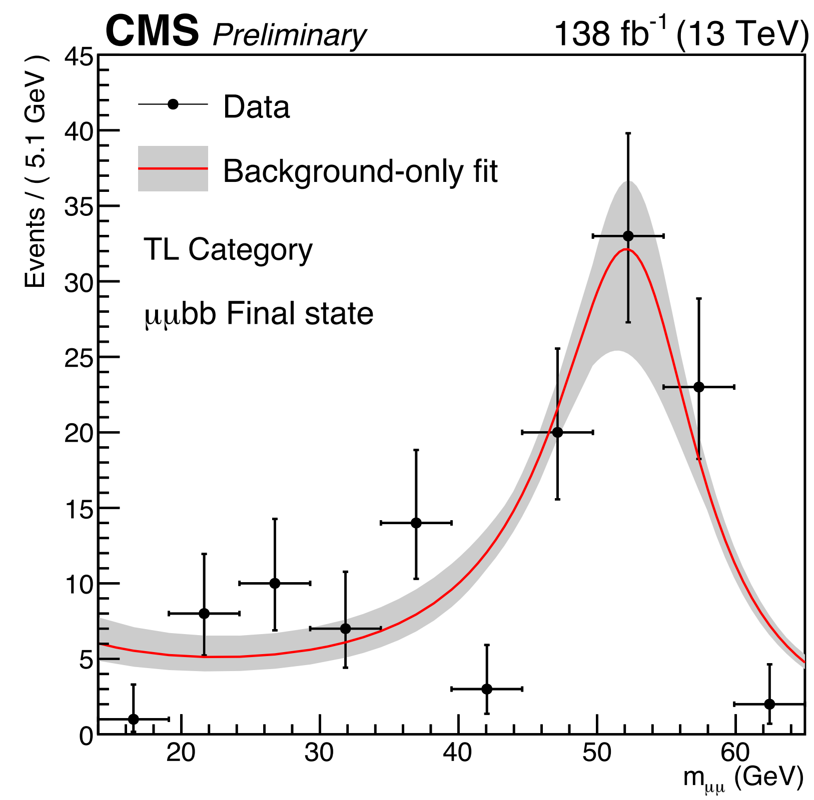


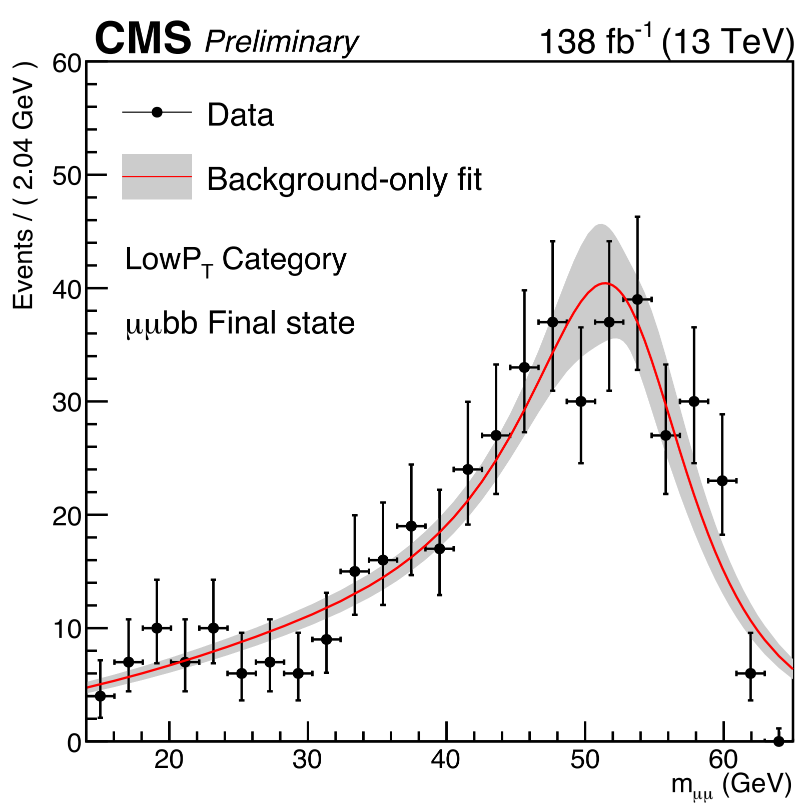
- Events are further categorised based on jet p_T and b-tag score
  - Low p_T: at least one b-jet with $p_T < 20$ GeV
  - VBF: two additional jets with $p_T > 30$ GeV, $|\eta| < 4.7$ and $m_{jj} > 250$ GeV
  - TL: looser b-jet passes L but fails M
  - TM: looser b-jet passes M but fails T
  - TT: looser b-jet passes T

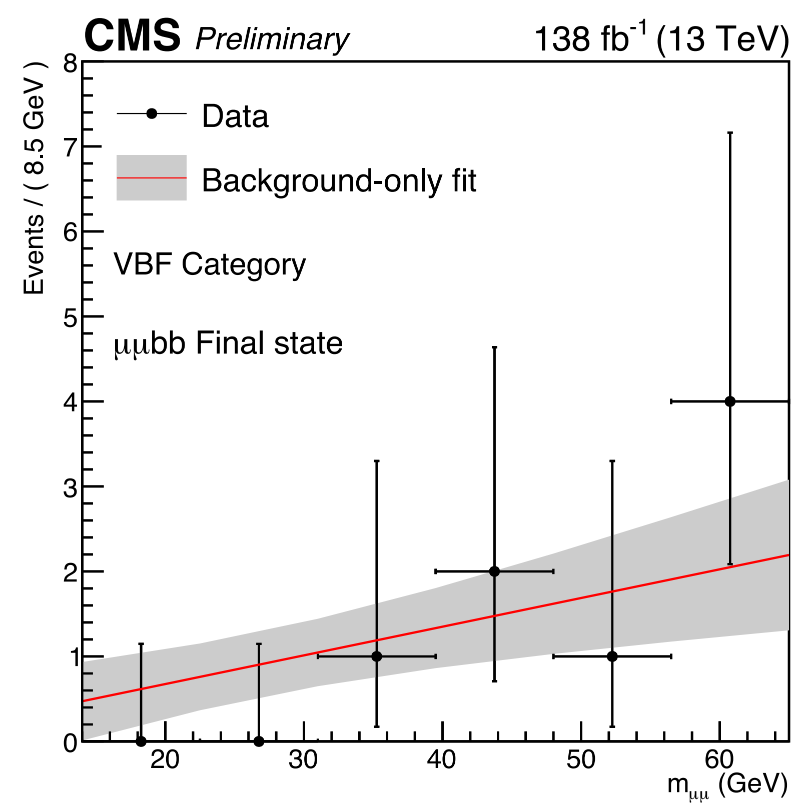
2μ2b: signal region $m_{\mu\mu}$ distributions











$H \to aa \to 2\tau 2b$

Relatively larger BR to bb and ττ, improved τ lepton reconstruction techniques

- Search for a masses within $12 < m_a < 60$ GeV
- Three final states explored: $e\mu$, $e\tau_h$, $\mu\tau_h$

Improved results compared to the previous analysis using partial Run-2 data (2016)

- Addition of > 1 b-jet category made possible due to increased statistics
- DNN categorisation vs. cut based event selection strategy
- SVfit algorithm to reconstruct di-tau invariant mass $m_{\tau\tau}$ including neutrino energies instead of only visible components of $m_{\tau\tau}$ distribution
- Better object reconstruction techniques based on DNN developed within CMS experiment in the recent years: DeepJet, DeepTau tagging
- More precise estimation of $Z \to \tau\tau$ using the embedding technique

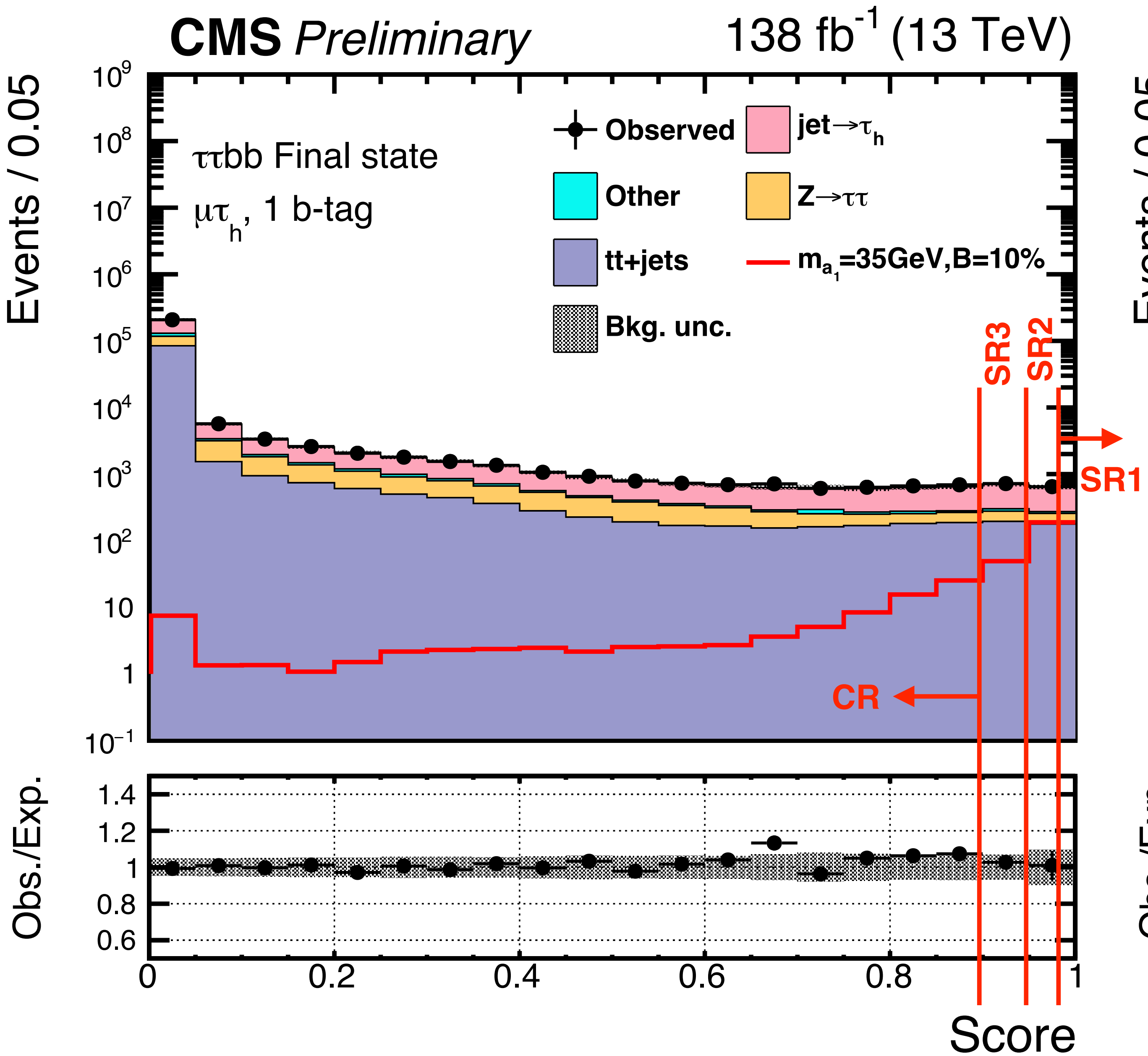
2016-only result: BR($H \to aa \to 2\tau 2b$) values constrained at 95% CL below (3-12)x10^{-2} depending on m_a

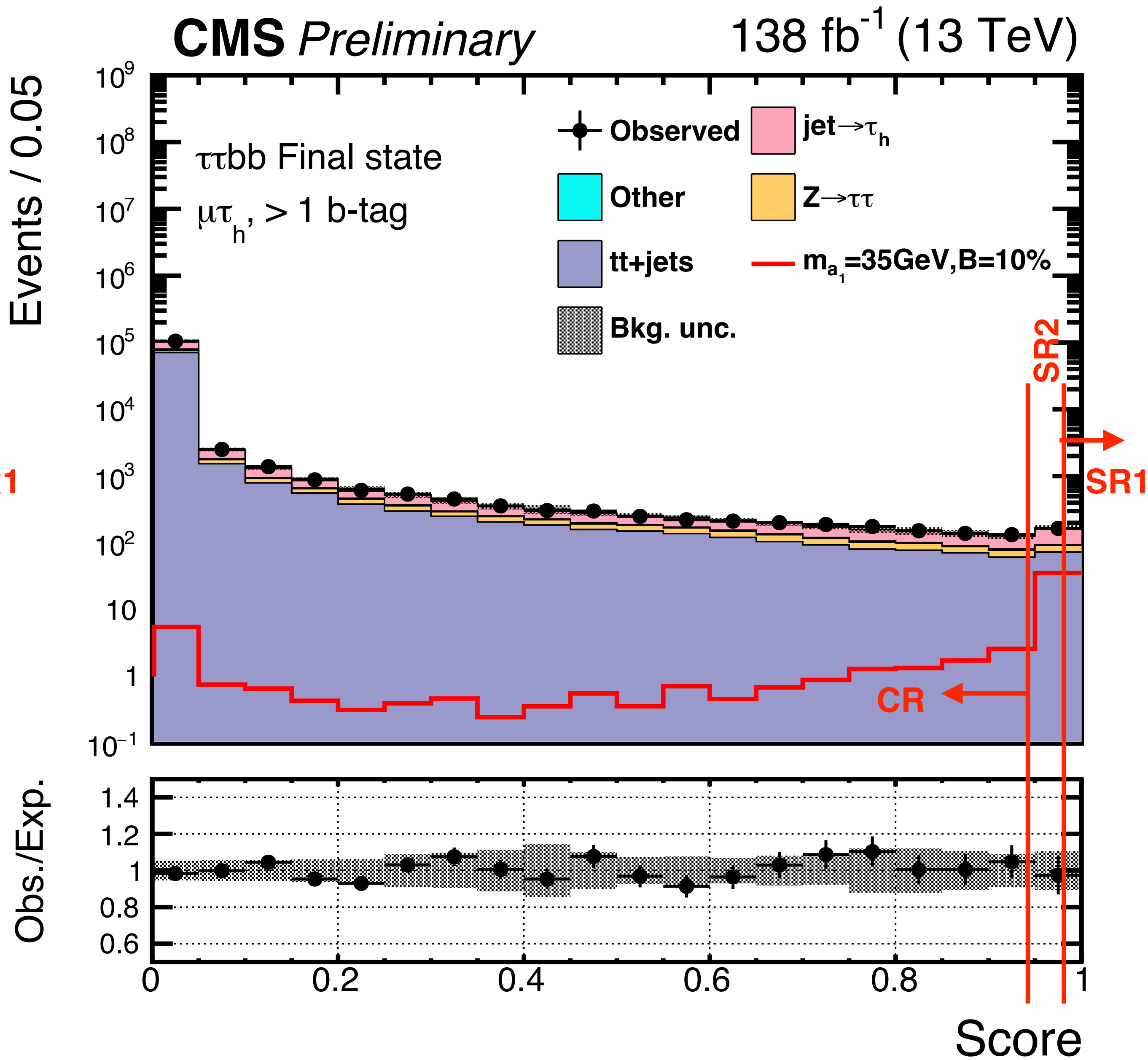
$2\tau 2b$: event selection

- Only three di-tau final states considered:
  - ee and $\mu\mu$ have low BR and large background from Drell-Yan process (DY+jets)
  - $\tau_h\tau_h$ has high trigger threshold
  - Extra lepton veto applied for each of the three final states to ensure mutually exclusive selection
  - Both single and cross-triggers used for each final state, with p_T thresholds being 1 GeV larger than the online threshold for e, μ; offline p_T threshold for τ_h is 35 GeV
- Events should have at least one loosely tagged b-jet with $p_T > 20$ GeV
  - Two broad categories based on b-jet multiplicity: = 1 and > 1 b-jet
- DNN categorisation:
  - Discriminate signal against a combination of major backgrounds ($t\bar{t}$+jets and DY+jets)
  - Train one DNN for each of the three channels and two b-jet categories: six in total
  - Training variables are based on kinematics of reconstructed final state particles
  - Split the selected events further into smaller categories based on the DNN scores: events with high DNN scores constitute signal regions (SR); background rich categories are taken as control regions (CR)

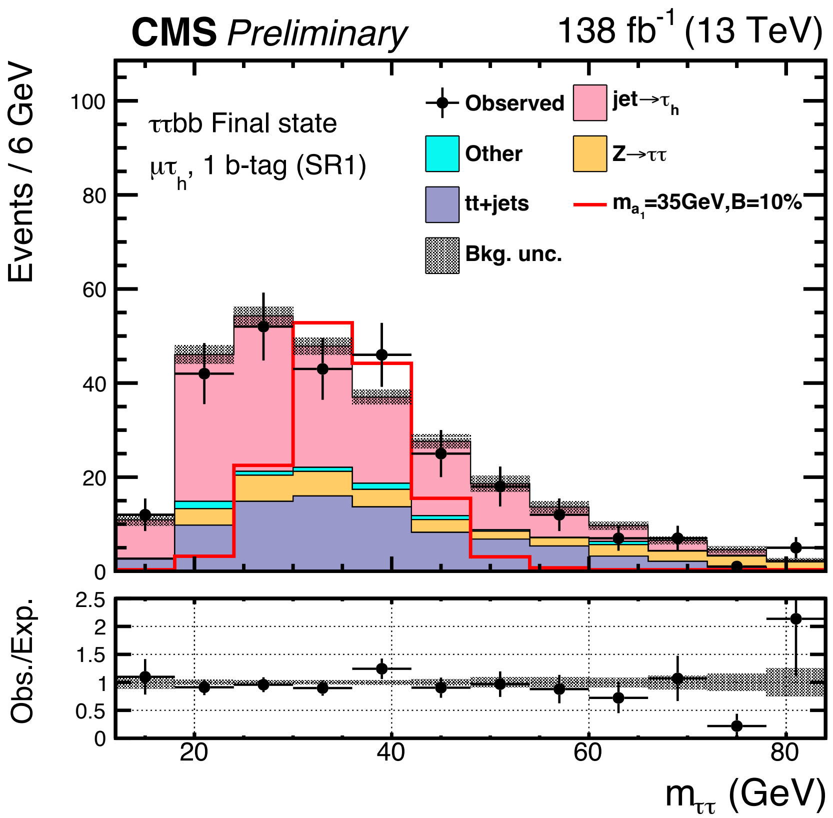
2τ2b: signal categorization

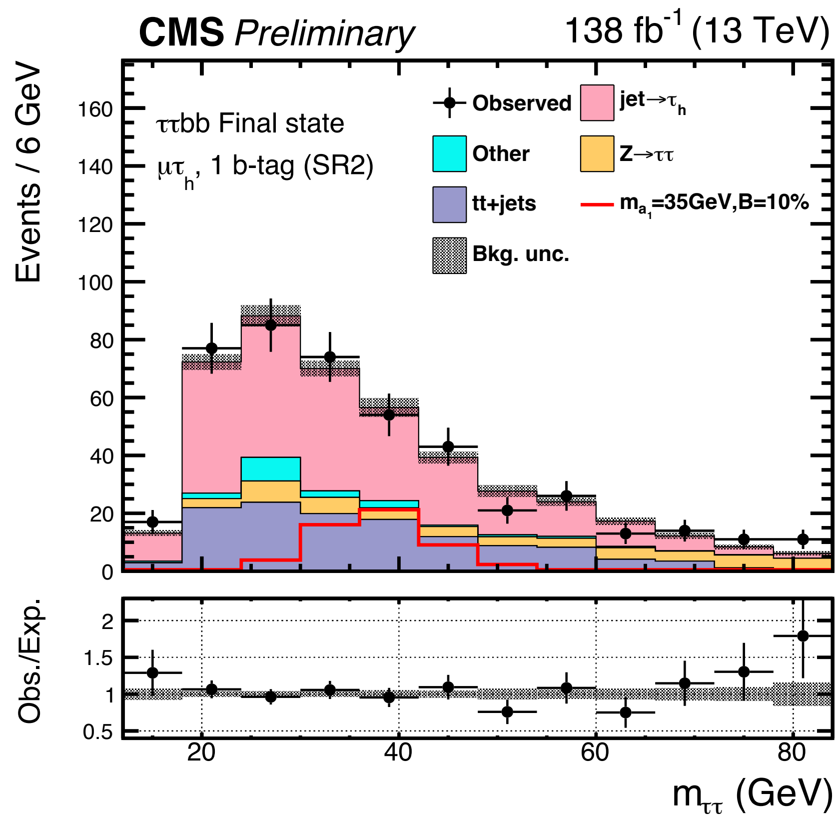
- Discriminating observables include invariant mass of visible decay products, transverse mass between an object and p_T^{miss}, m_{bb}-$m_{\tau\tau}$ etc.
- Final observable used in maximum likelihood fit: $m_{\tau\tau}$, not used as an input to DNN

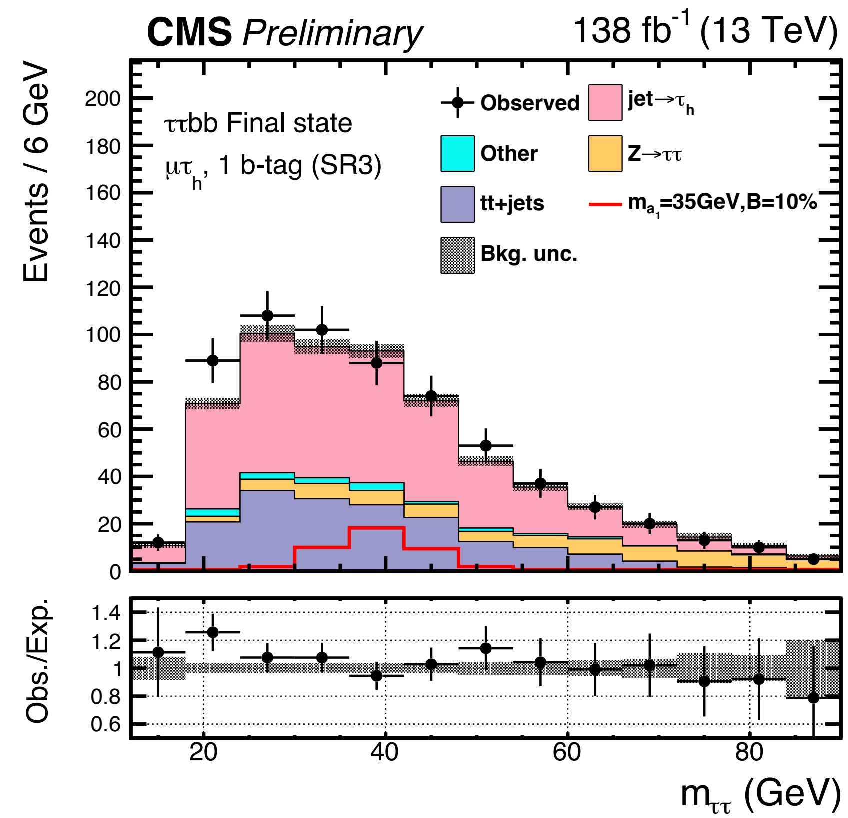


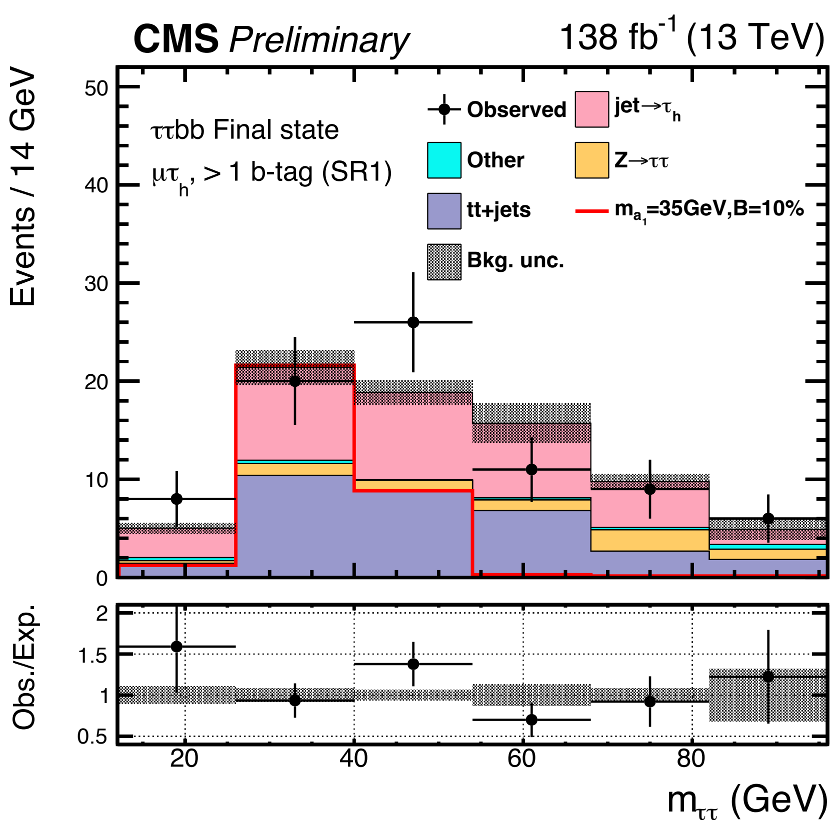


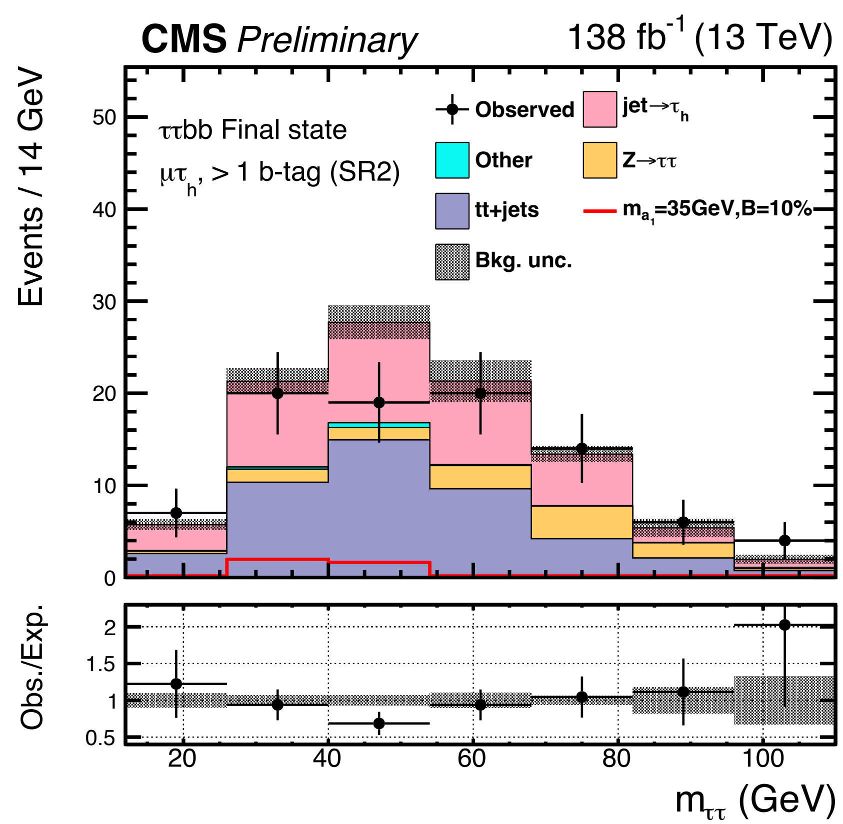
2τ2b: signal region $m_{\tau\tau}$ distributions











most sensitive channel: $\mu\tau_h$

Background estimation methods

For the $H \to aa \to 2\mu 2b$ analysis background evaluated through the ML fit, without any reference to simulation

- Discrete profiling method is used choose best-fit from a pool of background models

In the $H \to aa \to 2\tau 2b$ analysis:

- Irreducible physics backgrounds: genuine particles forming the $\tau\tau$ final state from other physics processes
  - $t\bar{t}$+jets
  - Diboson, single top, SM Higgs$\to\tau\tau$/WW
  - $Z\to\tau\tau$: the limitations in reconstructing taus is overcome by selecting well reconstructed $Z\to\mu\mu$ events from data and replacing the muon candidates with simulated taus
- Reducible backgrounds: mis-identified or *fake* particles forming the final state are estimated from data
  - Jets faking τ_h: W+jets and QCD processes have large jet multiplicity, leading to fake τ_h
  - QCD process in $e\mu$ channel: jets can also be mis-identified as e/μ and are most significant in QCD process

Systematic uncertainties

- Two broad categories: experimental and theoretical, most of which are common to both analyses

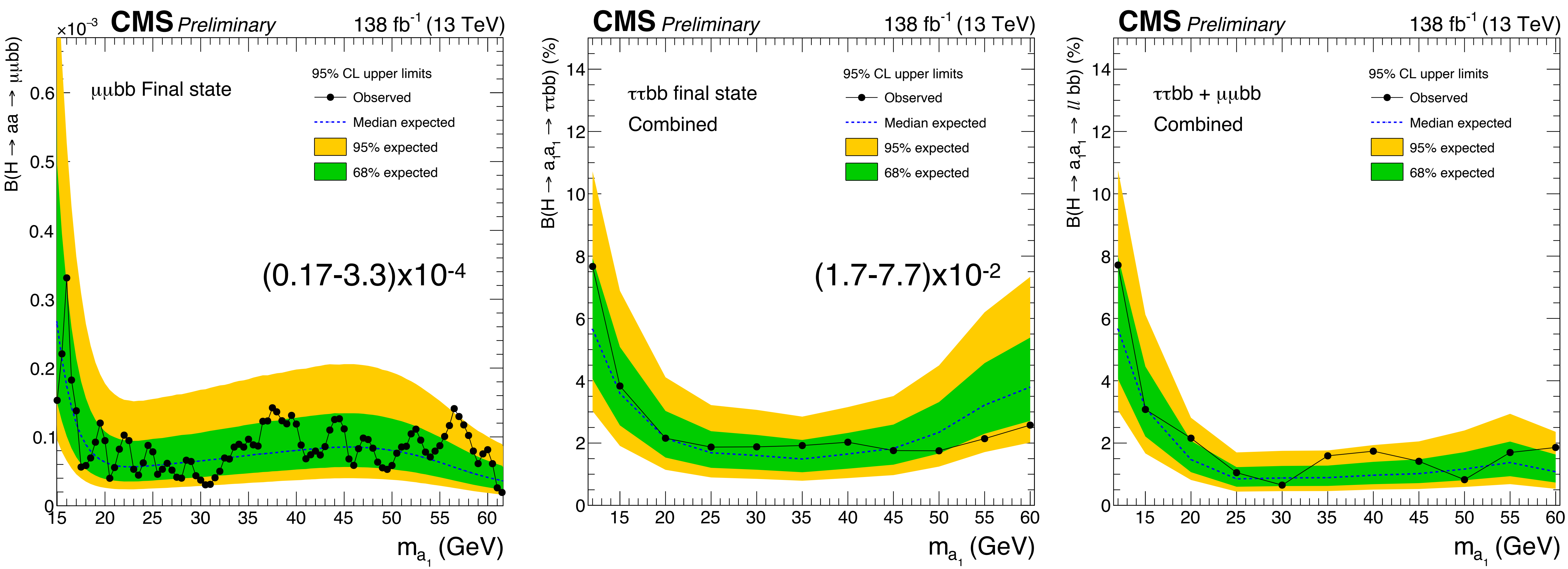
- Experimental:
  - Luminosity measurement
  - Uncertainty in measuring efficiency scale factors for e/μ/τ_h selection and trigger
  - Jet energy correction and b-tagging efficiencies
  - ECAL timing shift due to misalignment
  - Background estimations:
    - Normalisation of various SM process
    - Uncertainty in measuring different fake rates/scale factors for data-driven backgrounds
    - Uncertainty in estimating the embedded background
    - Uncertainty for imprecise background modelling from discrete profile method

2τ2b
2μ2b

- Theoretical:
  - Uncertainty in the ggF and VBF production cross sections of the Higgs boson
  - Scale variations in $t\bar{t}$+jets, single top and diboson simulations
  - Parton-shower uncertainties in $t\bar{t}$+jets

Upper limits on exotic Higgs BR

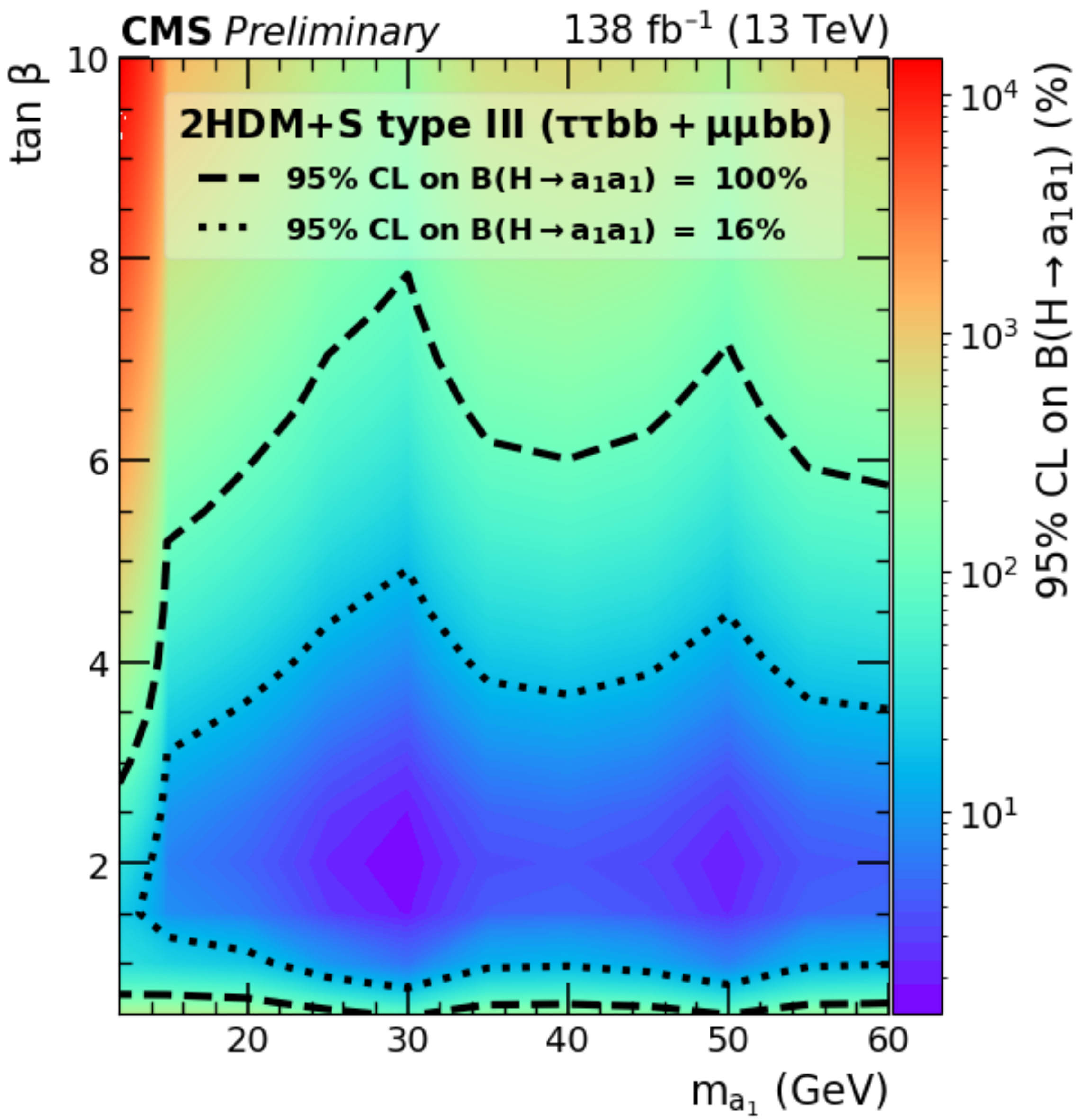
- Straightforward statistical combination: analyses utilise orthogonal data samples
- Some common uncertainties are treated as correlated, such as luminosity measurement, jet energy scale, variations in signal cross section etc
- Type-independent upper limits on BR(H→aa→llbb) in the context of 2HDM+S are derived as a function of m_a where l is a μ or τ

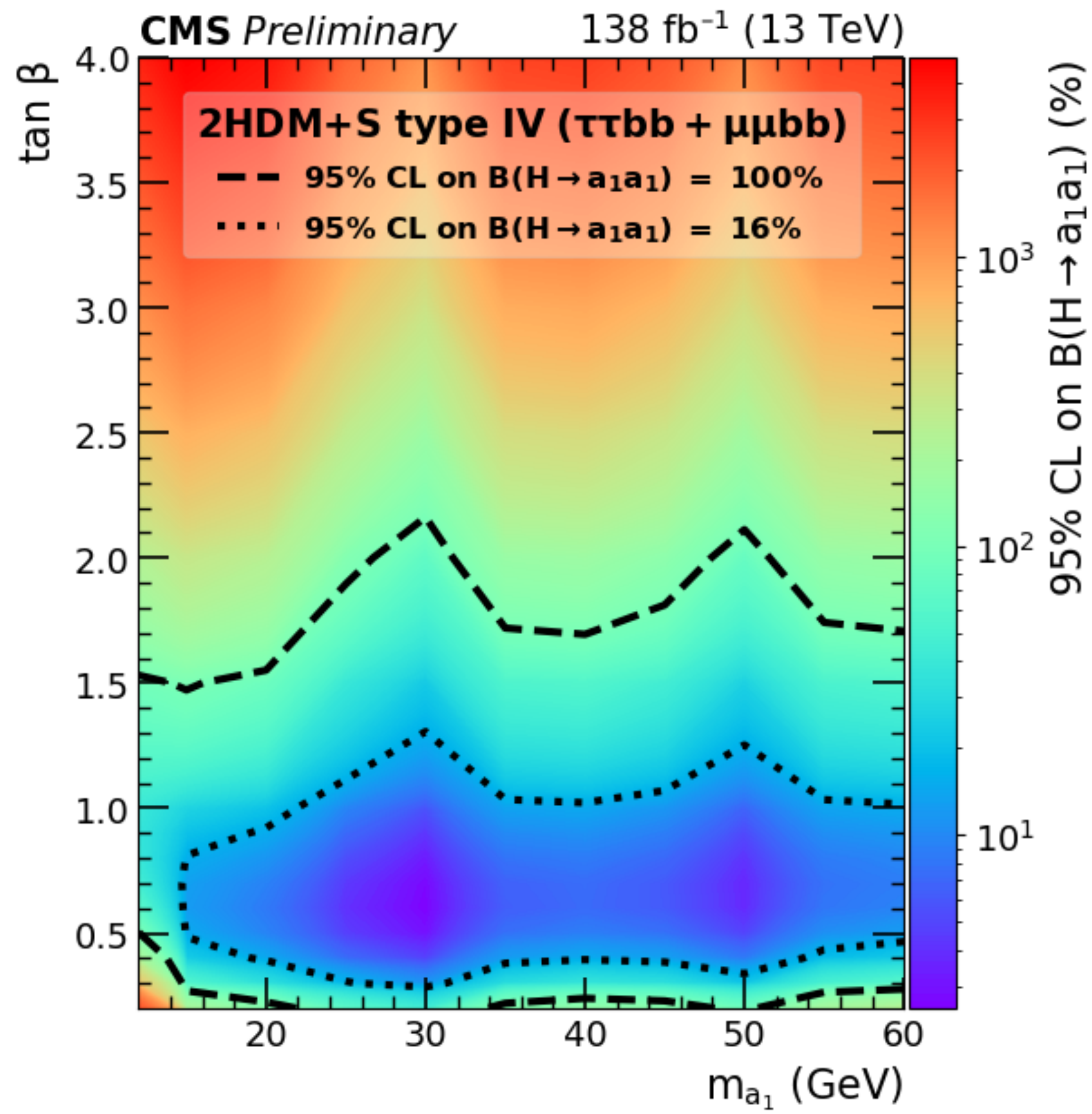


Interpreting in terms of different 2HDM+S: BR(H→aa) values excluded above 23% (Type II tanβ > 1), 7% (Type III tanβ = 2.0) and 15% (Type IV tanβ = 0.5)

Implications for different models

Stringent upper limits are set for most Type III and Type IV 2HDM+S scenarios





16% contour corresponds to combined upper limit on Higgs to invisible decays obtained from previous Run 2 results

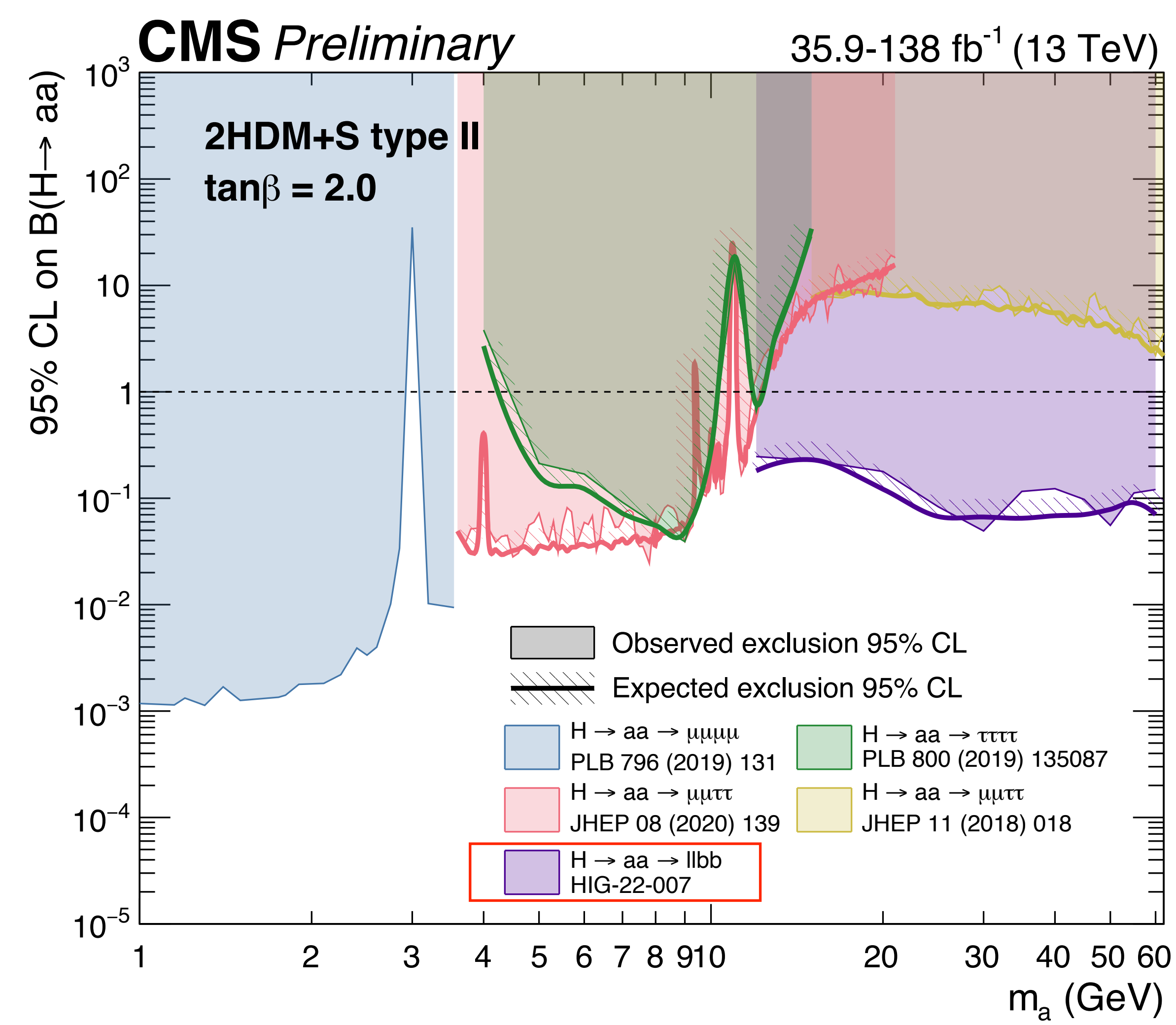
Summary

Higgs portal to hidden BSM sector being explored by CMS analyses in different final states

→ **Many full Run-2 results are public, some are work in progress**

- Improved sensitivity compared to previous searches due to changes in analysis strategy rather than the increase in data statistics alone
- No significant excess over SM prediction *just yet*, many other possibilities remain to be explored
  - Asymmetric pseudoscalar masses
  - Signals with low pseudoscalar mass to be analysed using boosted reconstruction techniques

Direct searches benefit the most with increase in luminosity: look forward to Run-3!



Thank You

Backup

$2\tau 2b$: triggers and objects

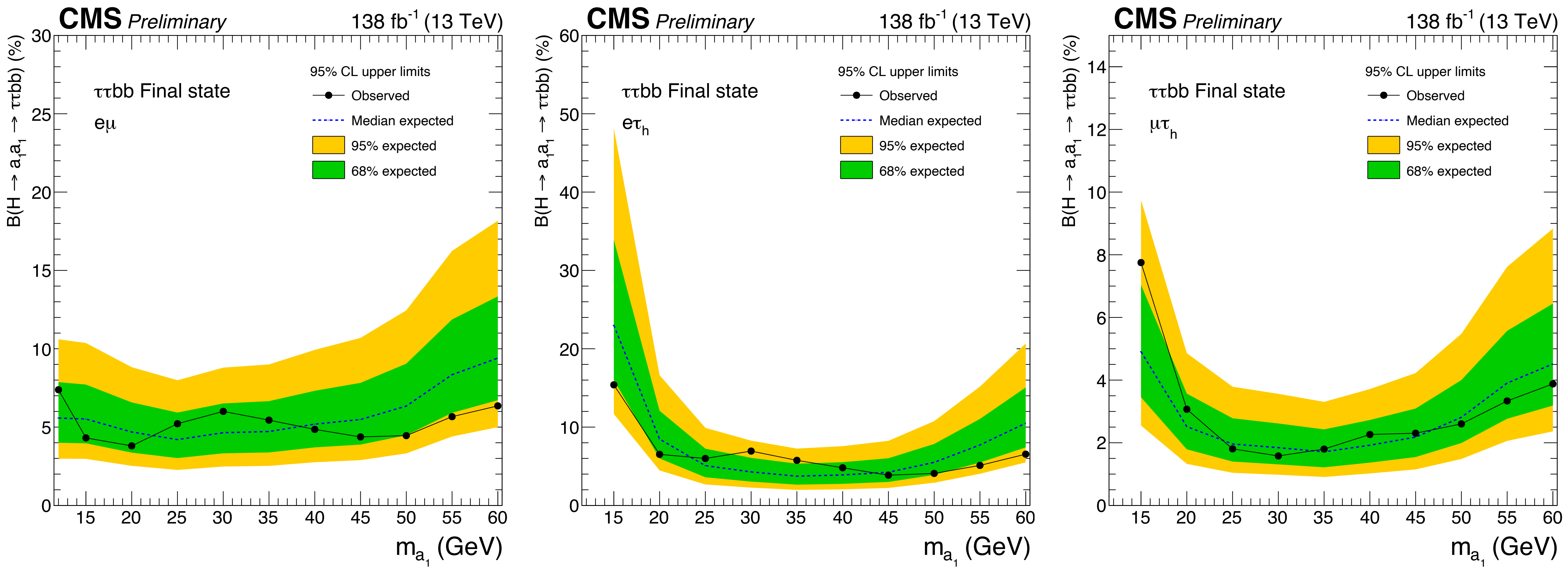
	Type	$e\mu$		$e\tau_h$		$\mu\tau_h$	
		e	μ	e	τ_h	μ	τ_h
2016	single	-	-	25	-	22	-
	leading	23	23	-	-	-	20
	sub-leading	12	8	-	-	19	-
2017	single	-	-	27, 32	-	24, 27	-
	leading	23	23	-	30	-	27
	sub-leading	12	8	24	-	20	-
2018	single	-	-	32, 35	-	24, 27	-
	leading	23	23	-	30	-	27
	sub-leading	12	8	24	-	20	-

- Electrons and muons are reconstructed within $|\eta| < 2.4$ and τ_h within $|\eta| < 2.1$
- Offline e, μ and τ_h are matched to the trigger objects, with p_T thresholds being 1 GeV larger than the online threshold for e, μ; offline p_T threshold for τ_h is 35 GeV
- In case both single and cross-triggers are present in the event, use lowest threshold
- Additional identification/isolation requirements on e/μ/τ_h
- Anti-k_T jets are reconstructed within $|\eta| < 2.4$ using a cone size of 0.4

Upper limits on exotic Higgs BR

Limit is set on SM like Higgs→aa→2τ2b:

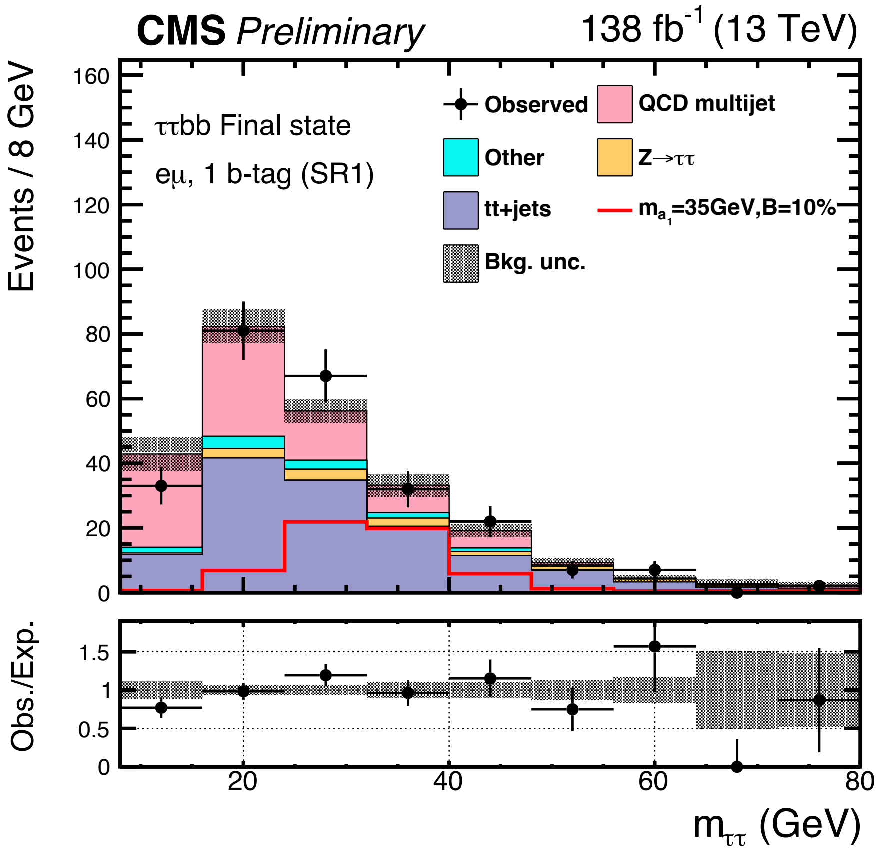
- Most sensitive channel: $\mu\tau_h$, dominant background is Z→ττ and τ_h fakes from QCD multijet
- Dominant systematic uncertainty from fake τ_h background estimation
- Analysis is still statistically limited

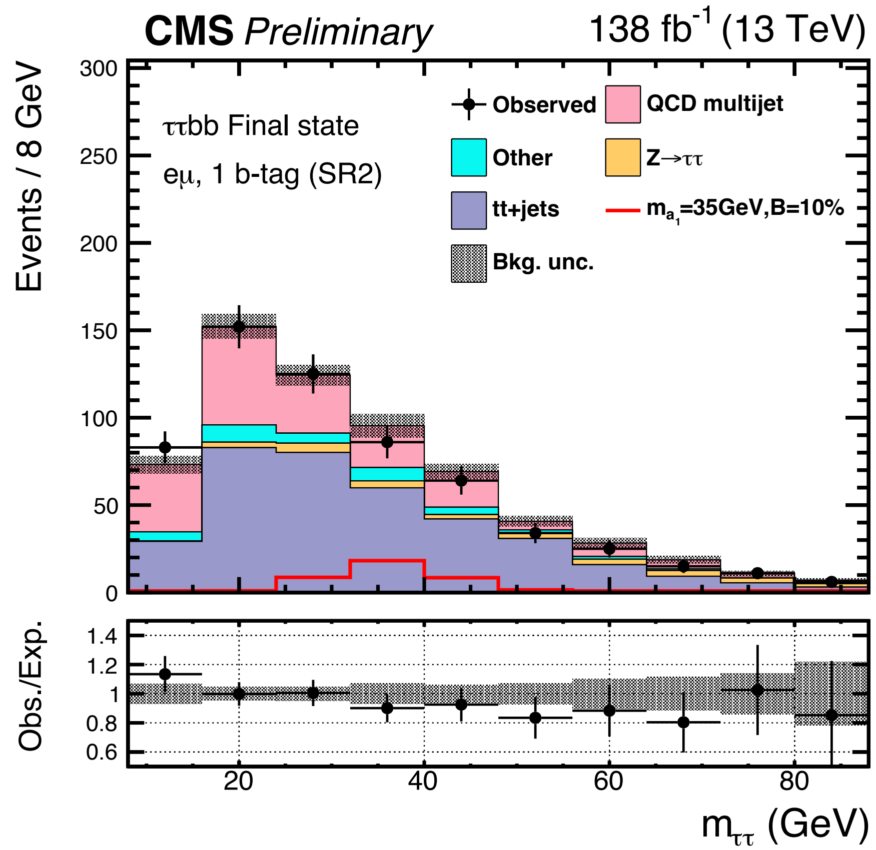


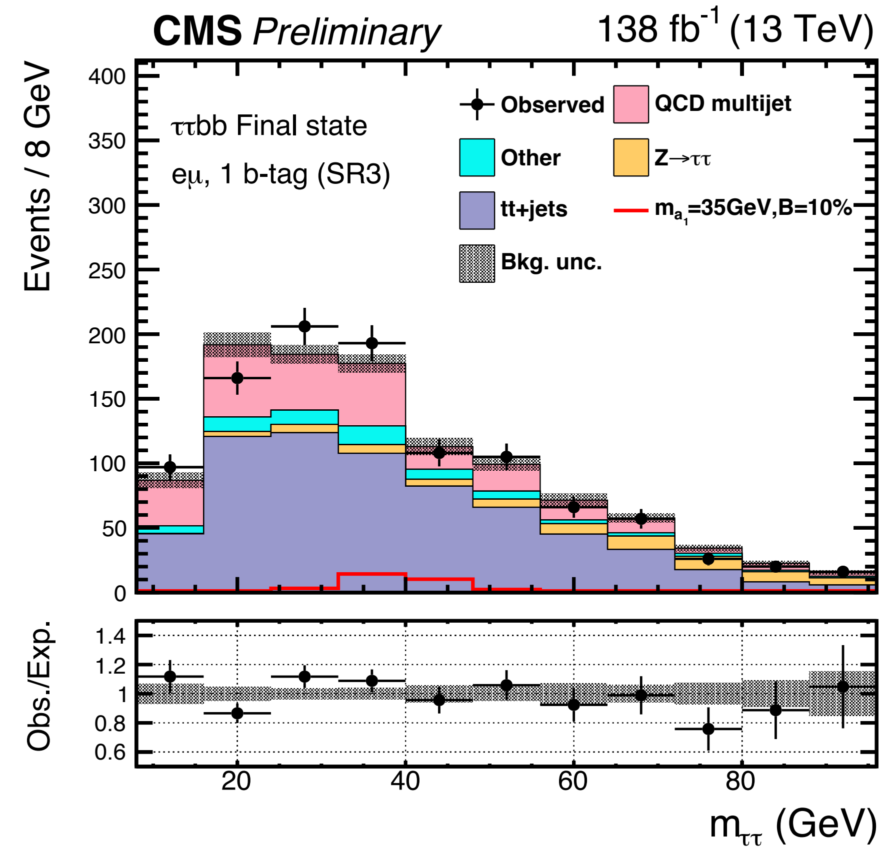
Only the $e\mu$ channel is sensitive to the 12 GeV mass point

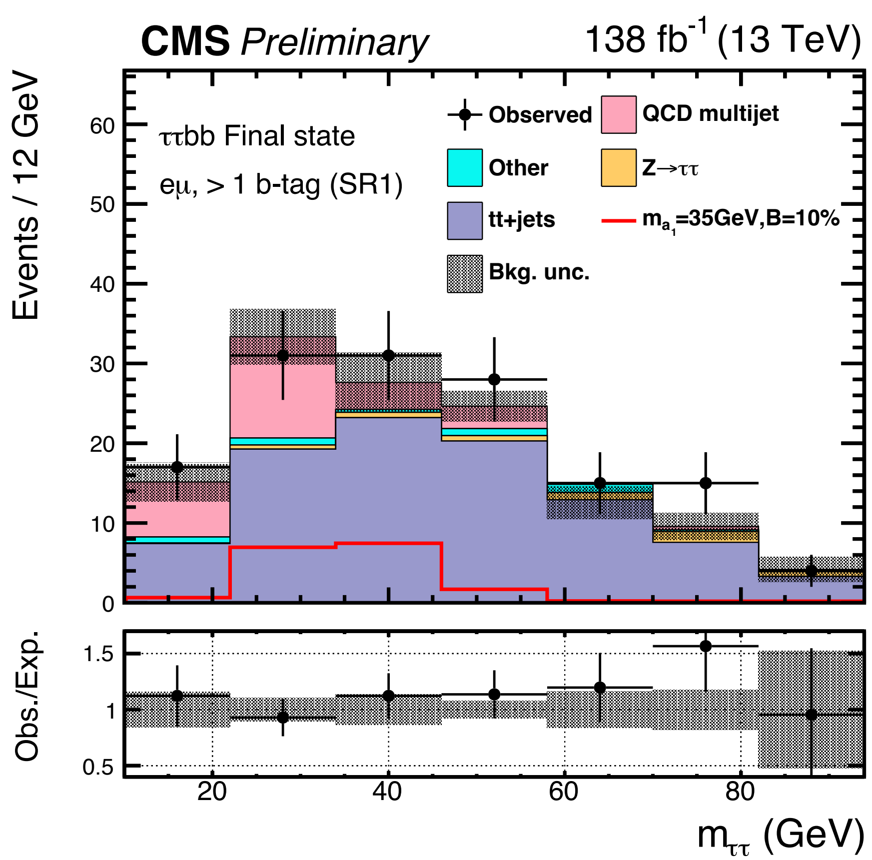
- For low m_a the decay products are boosted, need dedicated reconstruction
- In this analysis, a ΔR requirement is applied between the final state particles, which has a lower threshold in $e\mu$ channel

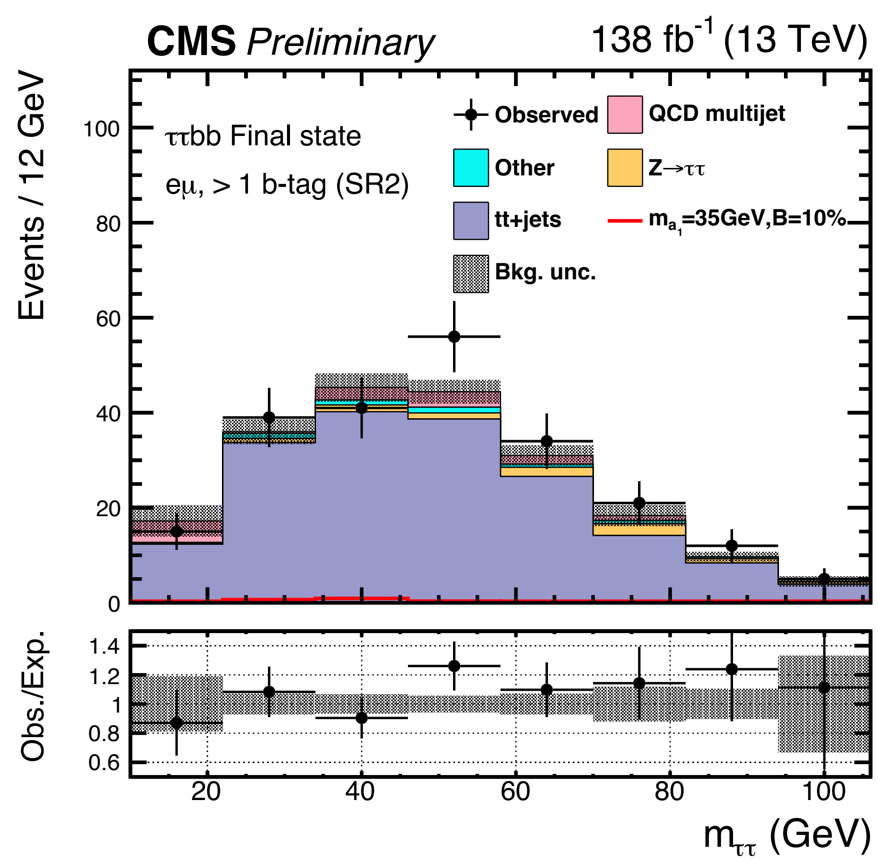
Single region distributions: eμ

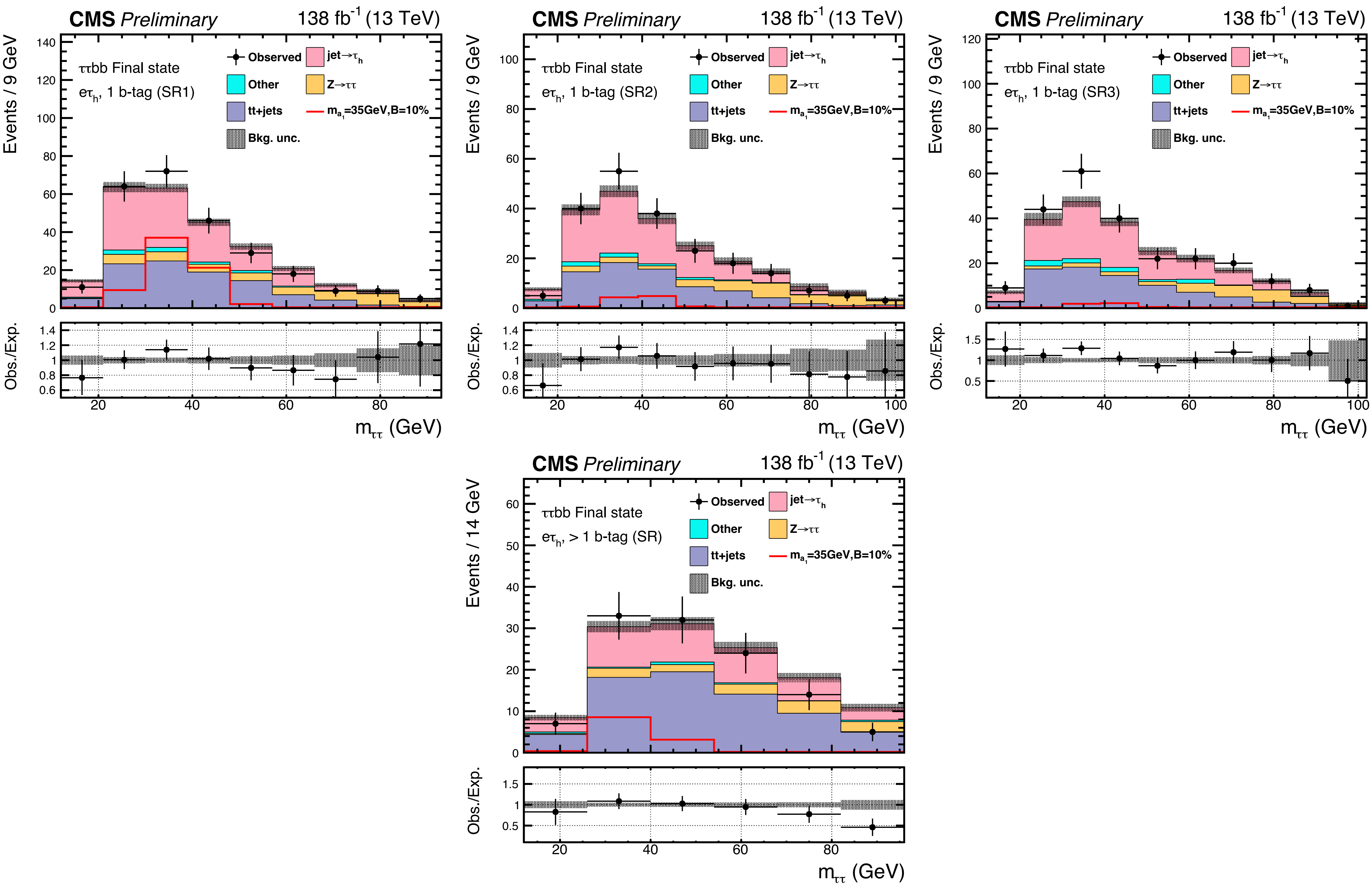











CMS Preliminary
138 fb-1 (13 TeV)
ττbb Final state
eτh, 1 b-tag (SR1)
eτh, 1 b-tag (SR2)
eτh, 1 b-tag (SR3)
eτh, > 1 b-tag (SR)
Observed
jet→τh
Other
Z→ττ
tt+jets
ma1=35GeV,B=10%
Bkg. unc.
Events / 9 GeV
Events / 14 GeV
Obs./Exp.
mττ (GeV)

Single region distributions: μτh