



Search for high-mass neutral Higgs Bosons using the CMS detector

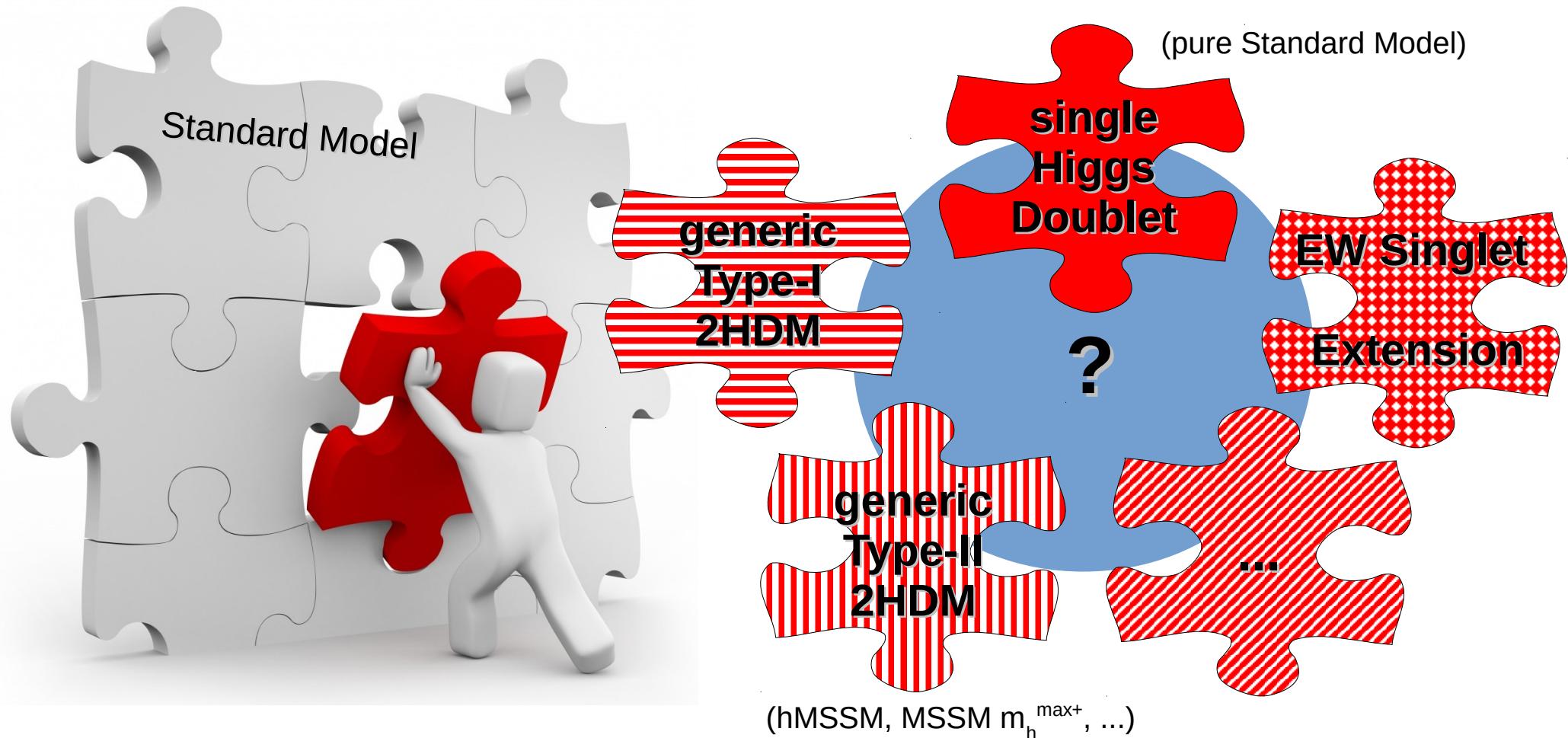
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Hamburg University
on behalf of the CMS collaboration



38th International Conference
on High Energy Physics
Chicago, 3.-10.08.2016

An Extended Higgs Sector?



- Higgs sector complements the Standard Model
- in most BSM scenarios: additional (heavier) **neutral scalar Higgs H**

possible couplings similar to SM Higgs:

- $H \rightarrow$ fermions
- $H \rightarrow$ vector bosons
- $H \rightarrow hh / A \rightarrow hZ$

searched for by

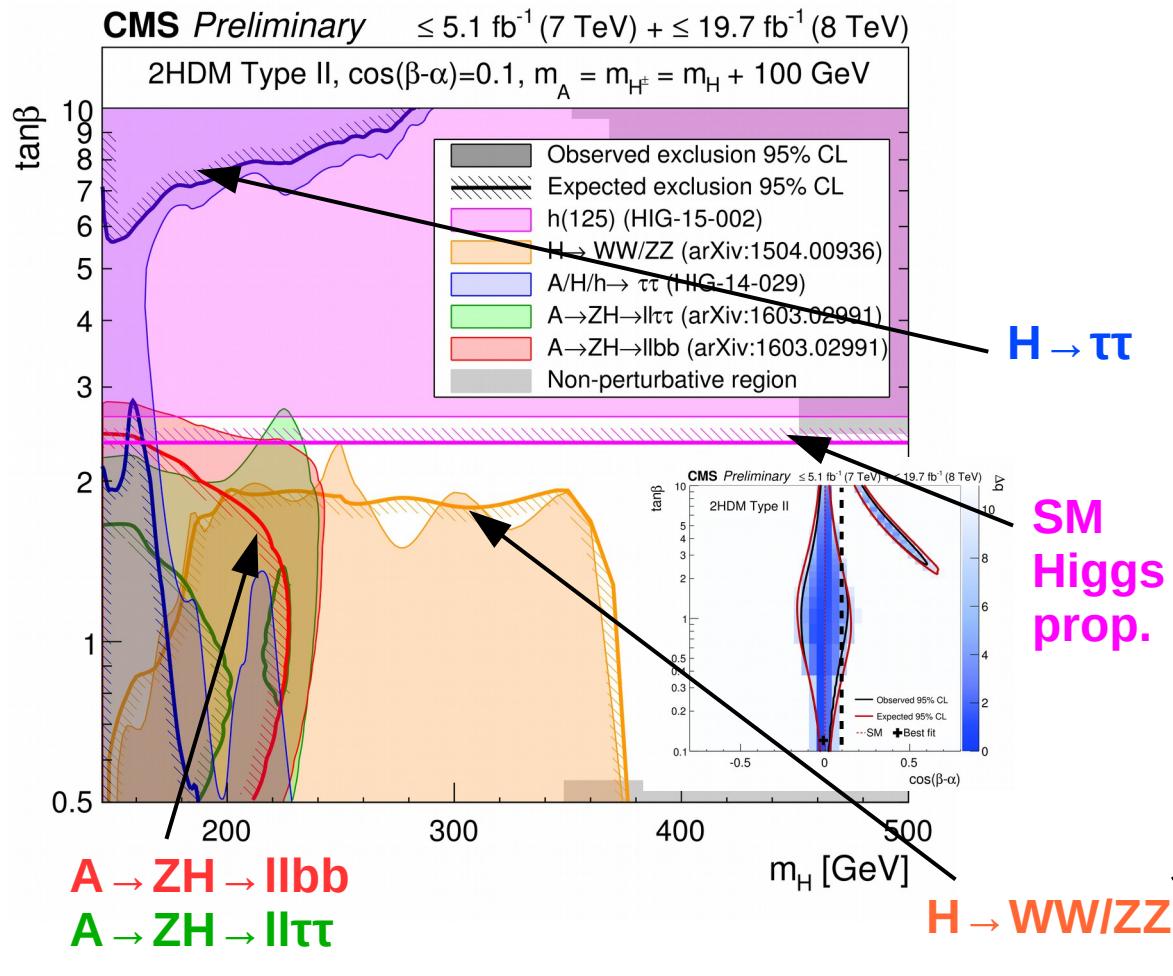


Where do we stand? 8TeV Summary

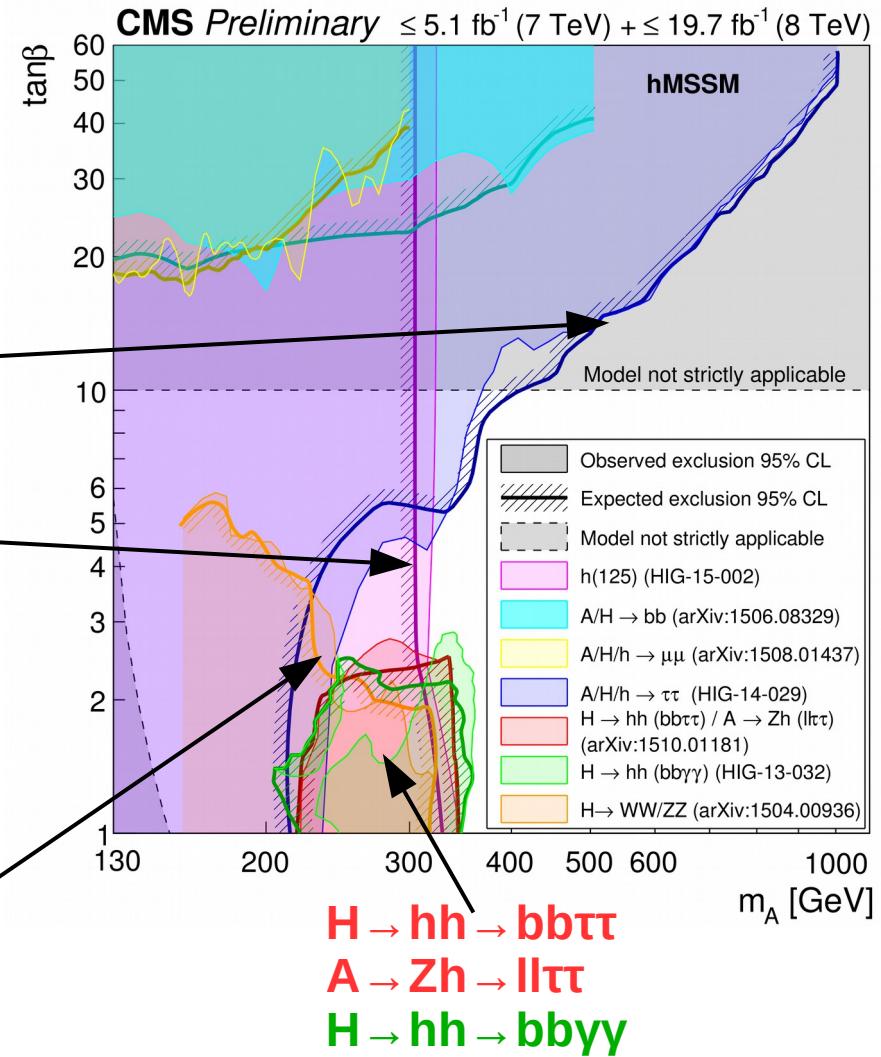
HIG-16-007

- combination of several neutral high-mass Higgs boson searches of Run-I ($\sqrt{s}=7+8\text{TeV}$)
- interpreted in generic 2HDMs as well as MSSM-inspired models

2HDM Type-II



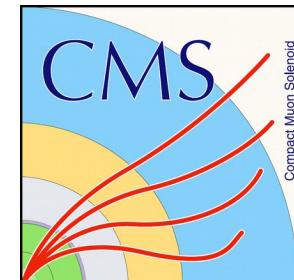
hMSSM



all searches very important to constrain different areas of parameter space

Heavy Higgs Searches at 13 TeV with CMS

Today's menu



Higgs to fermions

$H \rightarrow \tau\tau$	2.3fb-1	2015	CMS-HIG-16-006
$H \rightarrow bb$	2.7fb-1	2015	CMS-HIG-16-025

new

Higgs to vector bosons

$H \rightarrow ZZ \rightarrow 4l$	12.9fb-1	2016	CMS-HIG-16-033
$H \rightarrow ZZ \rightarrow 2l2v$	2.3fb-1	2015	CMS-HIG-16-001
$H \rightarrow WW \rightarrow l l' l' v'$	2.3fb-1	2015	CMS-HIG-16-023

new

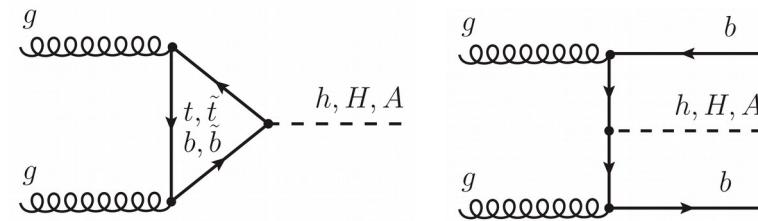
new

Higgs to Higgs

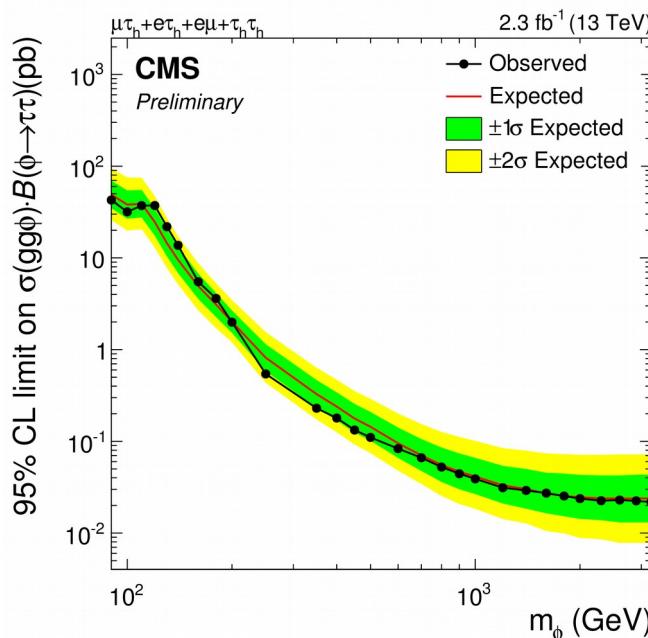
$H \rightarrow hh \rightarrow bb\tau\tau$	12.9fb-1	2016	CMS-HIG-16-029
$H \rightarrow hh \rightarrow bbbb$	2.3fb-1	2015	CMS-HIG-16-002
$H \rightarrow hh \rightarrow bbWW$	2.3fb-1	2015	CMS-HIG-16-011

new

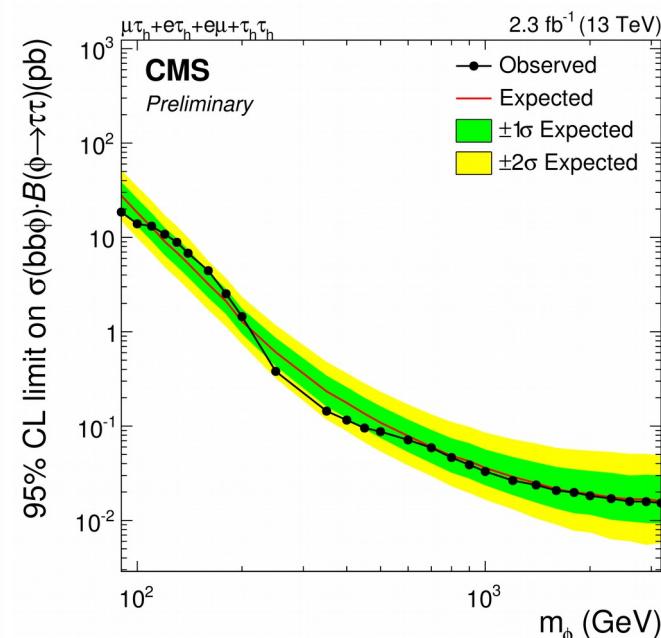
- in Type-II 2HDMs: large $\tan\beta \rightarrow$ coupling to down-type fermions enhanced \rightarrow perfect MSSM probe
- production involving b quarks and decay to τ leptons dominant



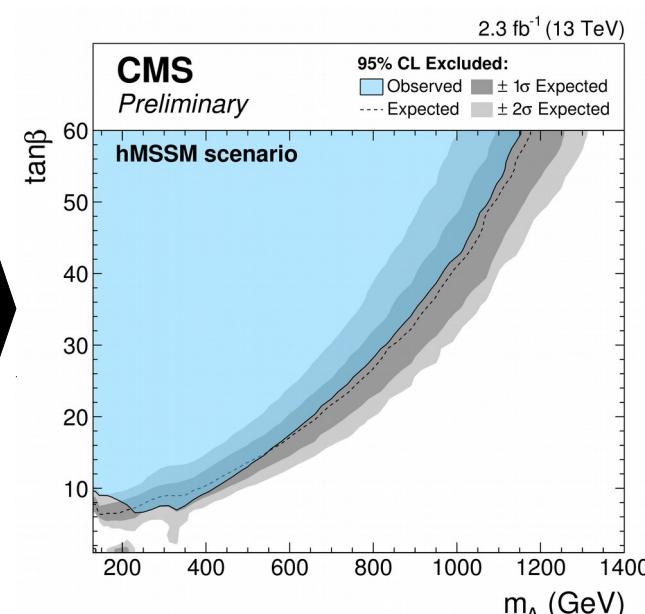
gluon fusion production



b-associated production



model interpretation



limit on one production mode – other profiled

**no excess observed in the mass range from 100GeV-3TeV
excluded parameter space significantly extended in hMSSM**

model

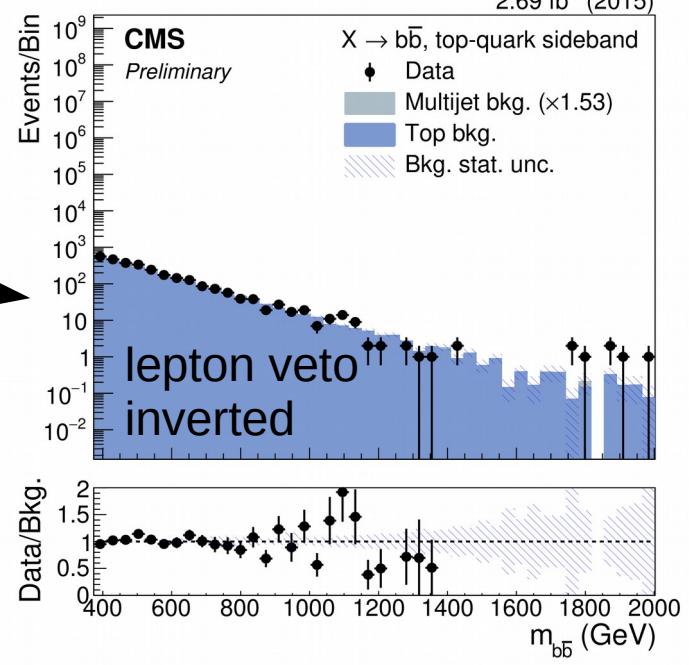
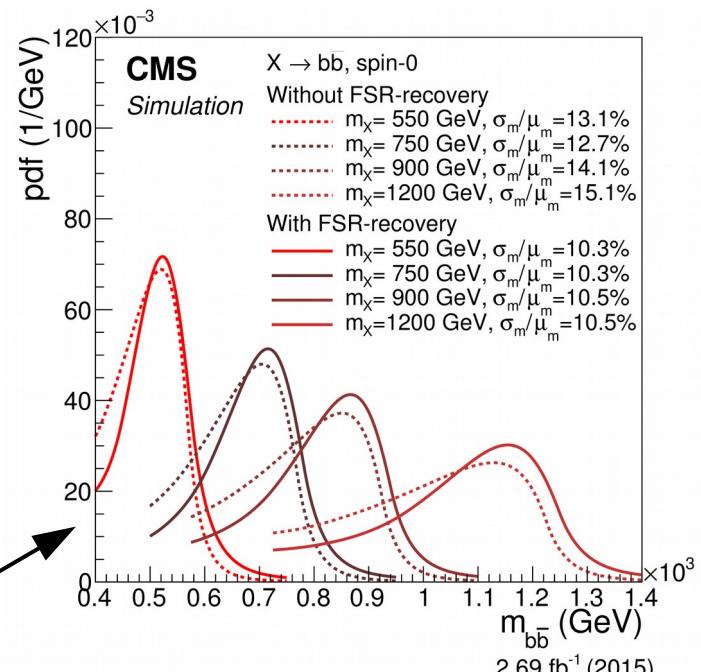
- generic search for spin-0/spin-2 resonance decaying into 2 b quarks
- spin-0: fixed $\Gamma/m=0.01$
- spin-2: RS eff. coupling = 0.1 $\rightarrow \Gamma/m=0.014$
- width negligible w.r.t. $\sigma(\text{dijet})=0.1$

event selection

- b tag** requirement already **on HLT level**
- ≥ 2 b tags, $p_T(\text{b-tagged jets}) > 100\text{GeV}$, lepton veto
- FSR recovery** in $m(bb)$: jets within $\Delta R < 0.8$, $p_T > 15\text{GeV}$ added to invariant mass
 → improves high-mass resolution by 6%
- top-quark sideband** (inverted lepton veto) for checking trigger emulation and object reconstruction

background

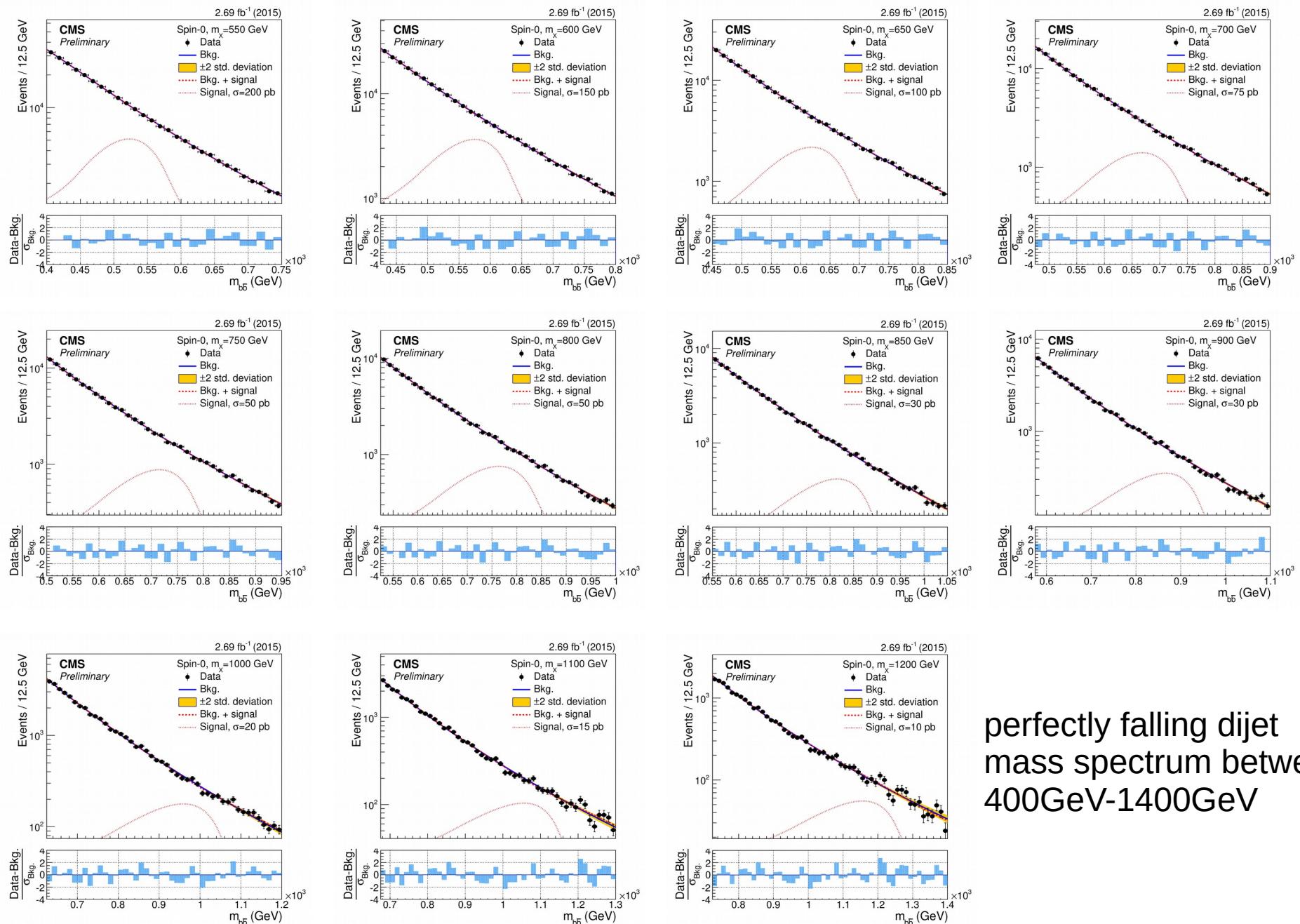
- falling dijet spectrum parametrized by function
- three different background PDFs studied
- comparison used to estimate systematic uncertainty



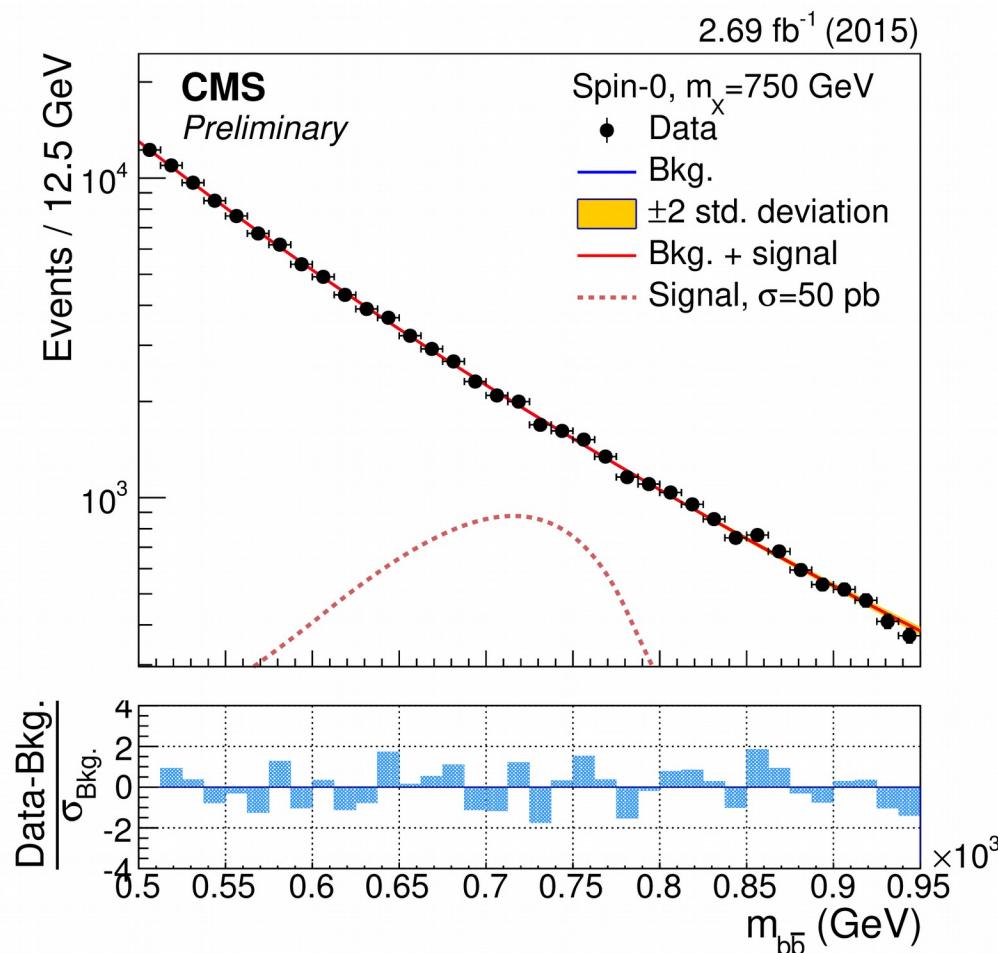
H \rightarrow bb: Results

new run 2 – 2015
2.7 fb $^{-1}$

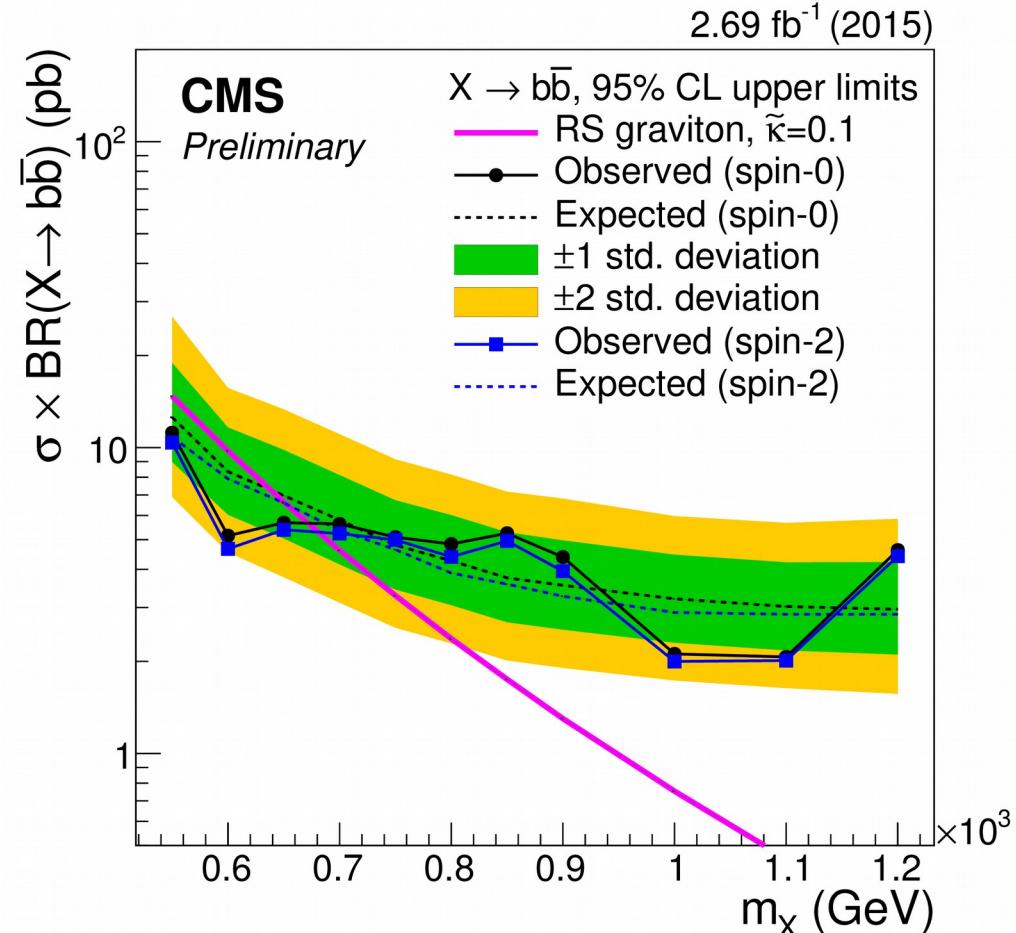
HIG-16-025



perfectly falling dijet
mass spectrum between
400GeV-1400GeV



fit of background and signal PDF
to data to extract limit



no excess observed in the mass range from 500GeV-1.2TeV

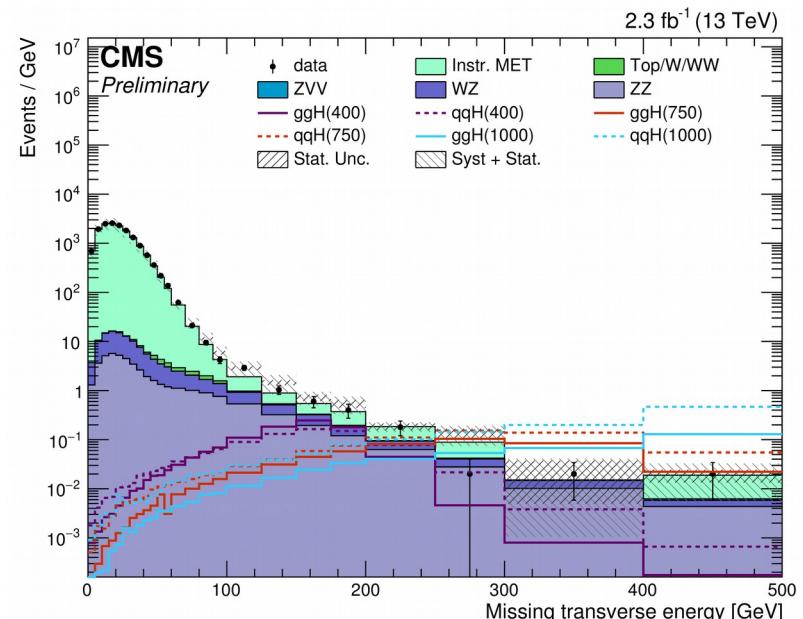
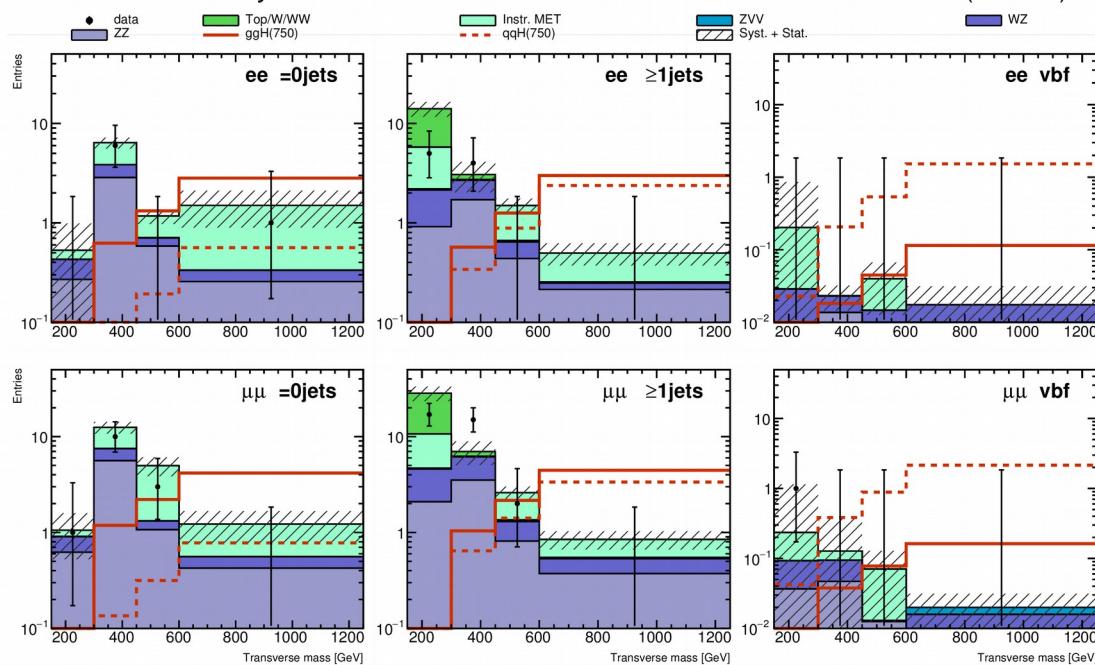
event selection

- selection of di-lepton pair (ee , $\mu\mu$) with inv. mass close to Z-boson mass ($\Delta m=30\text{GeV}$)
- large missing $E_T > 125\text{GeV}$
- 3 event categories: **VBF** (2 back-to-back forward jets), **≥ 1 jet, no jet**

signal extraction

$$M_T^2 = \left(\sqrt{p_T(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{E_T^{\text{miss}}{}^2 + M_Z^2} \right)^2 - (\vec{p}_T(\ell\ell) + \vec{E}_T^{\text{miss}})^2$$

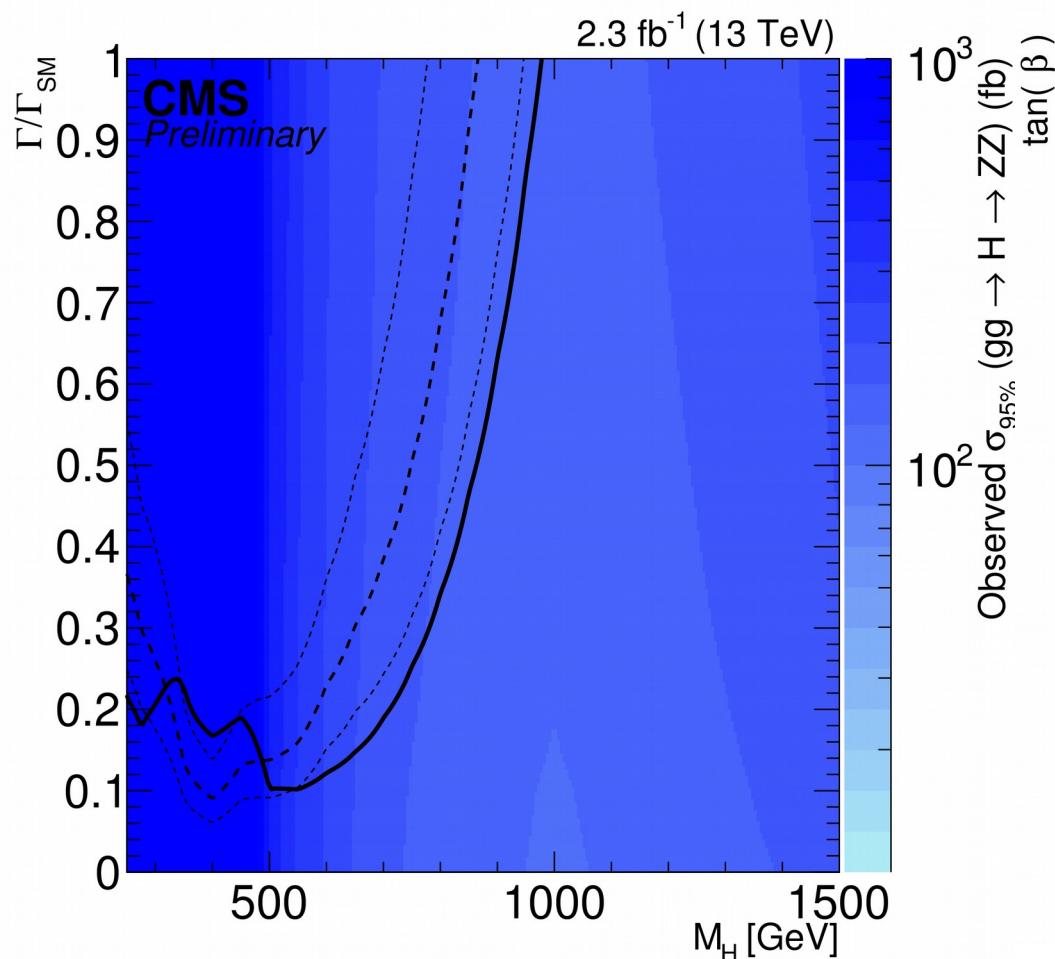
CMS Preliminary



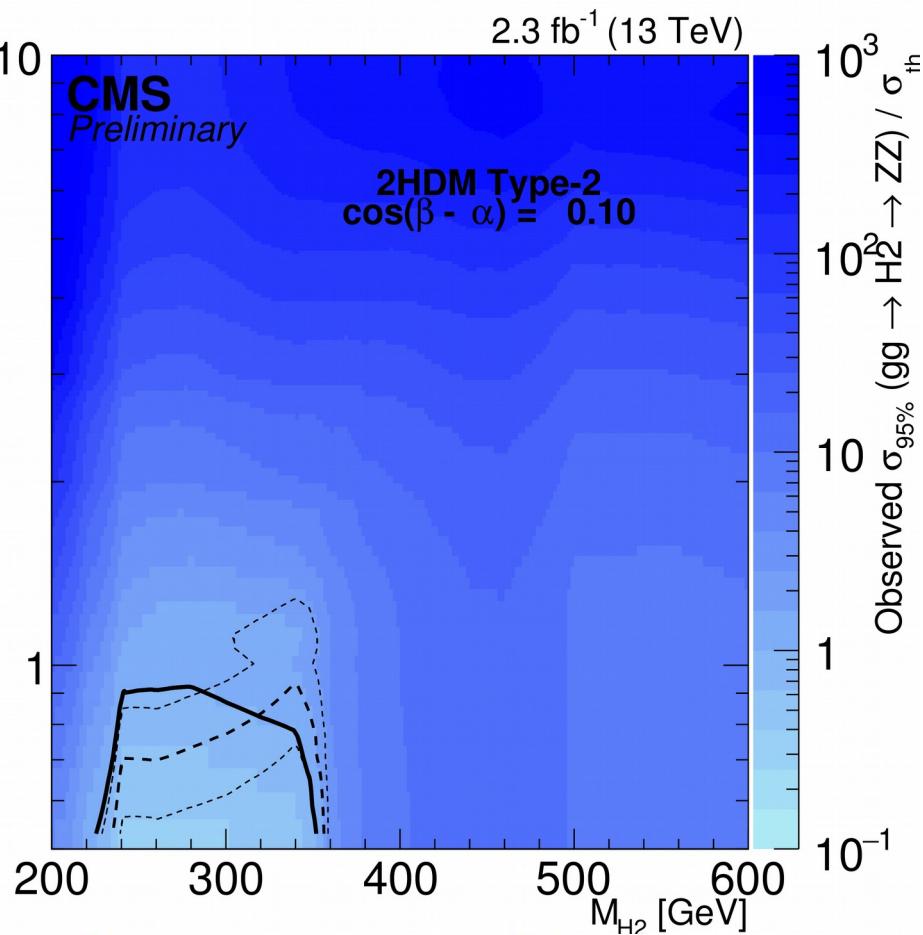
backgrounds

- ZZ/WZ (from MC, NNLO/NLO norm.)
- Z+jets (from y+jets selection)
- non-resonant BG (from opposite flavor control sample)

model independent ggF limit



2HDM Type-II



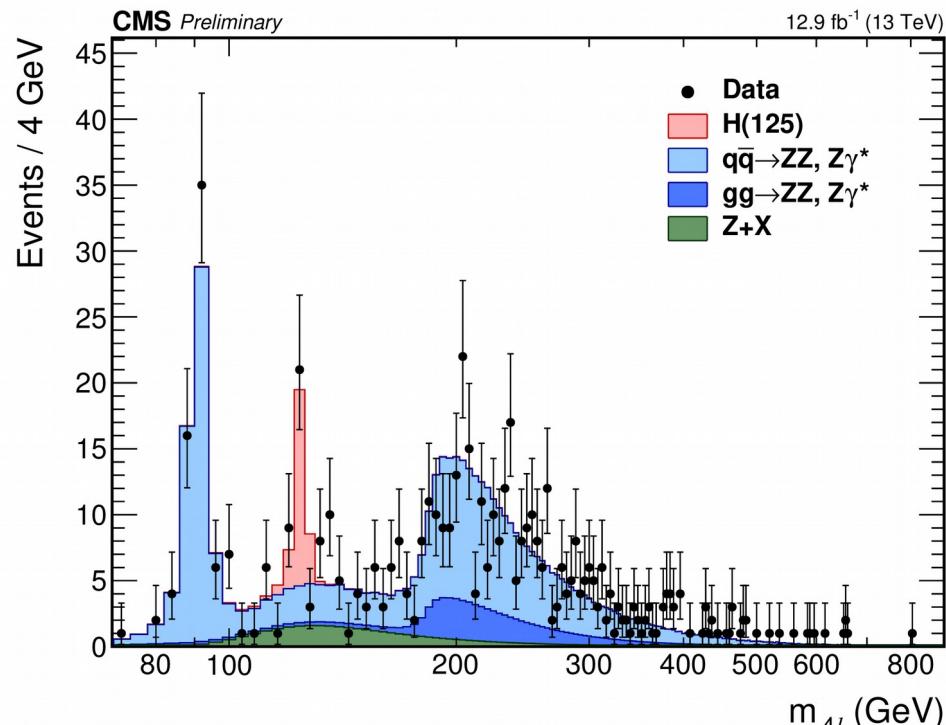
Parameter	Value
m_h	125.09 GeV
m_A	$m_H + 100$ GeV
m_{H^+}	$m_H + 100$ GeV
$\cos(\beta - \alpha)$	0.1
m_{12}^2	$\max(1 - \tan \beta^{-2}, 0) \cdot \frac{1}{2} \sin(2\beta) (m_A^2 + \lambda_5 v^2)$
m_H	scanned
$\tan \beta$	scanned

channels and categories

- extension of the SM h \rightarrow ZZ analysis to the high mass region
- three mutual sub-channels: **4e, 4 μ , 2e2 μ**
- reduced number of categories: **VBF, untagged**

backgrounds

- irreducible: ZZ production from q \bar{q} annihilation (estimated from MC)
- reducible: Z+jets (estimated from two independent data driven methods)



matrix element method

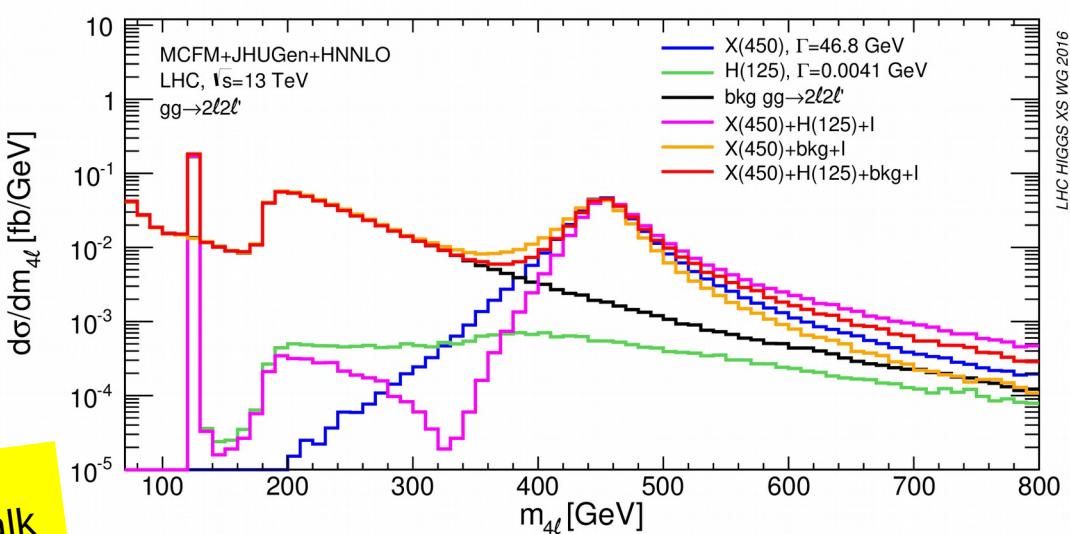
general parameterization of $P(m_{4l} | m_x, \Gamma_x, \sigma_x)$ for

VBF/gg \rightarrow bkg+H(125)+X(m_x) \rightarrow 4l

based on the MELA framework

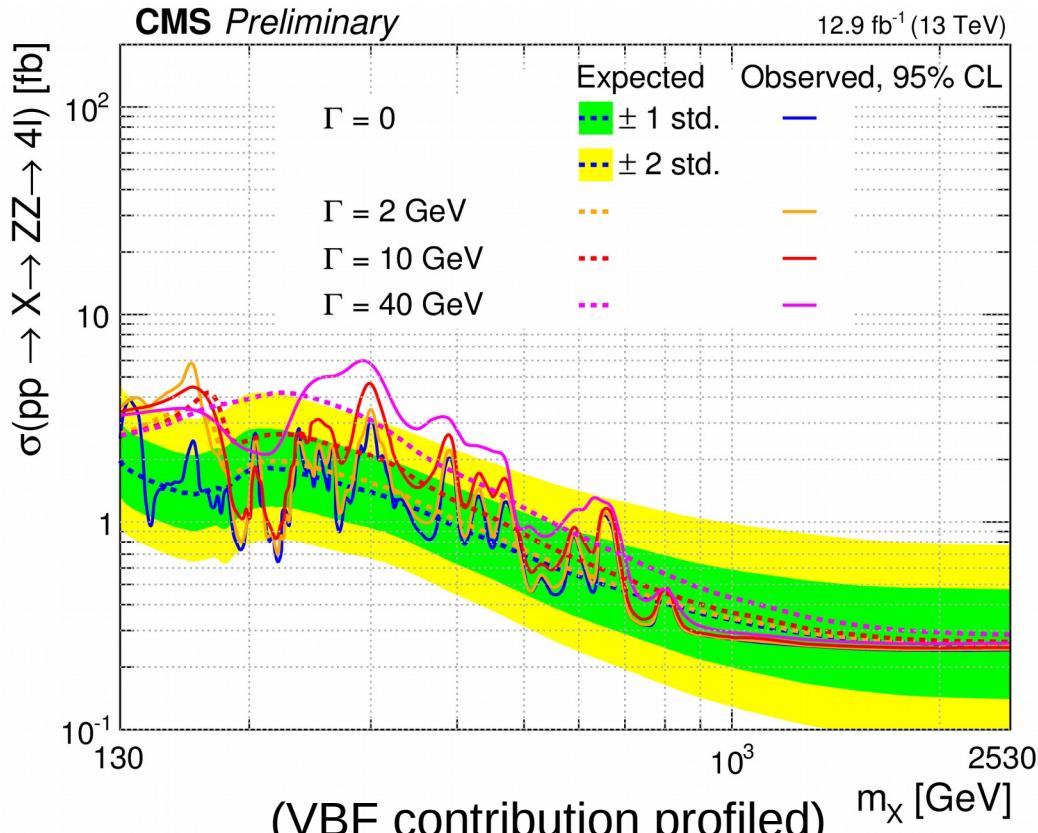
→ proper modelling of **interference effects**
(bkg+off-shell Higgs 125+heavy Higgs)

for more details:
see Meng Xiao's talk



- decay width Γ_x free parameter in the limit (only assumption: $\Gamma_x < m_x$)
- 4 arbitrary values depicted

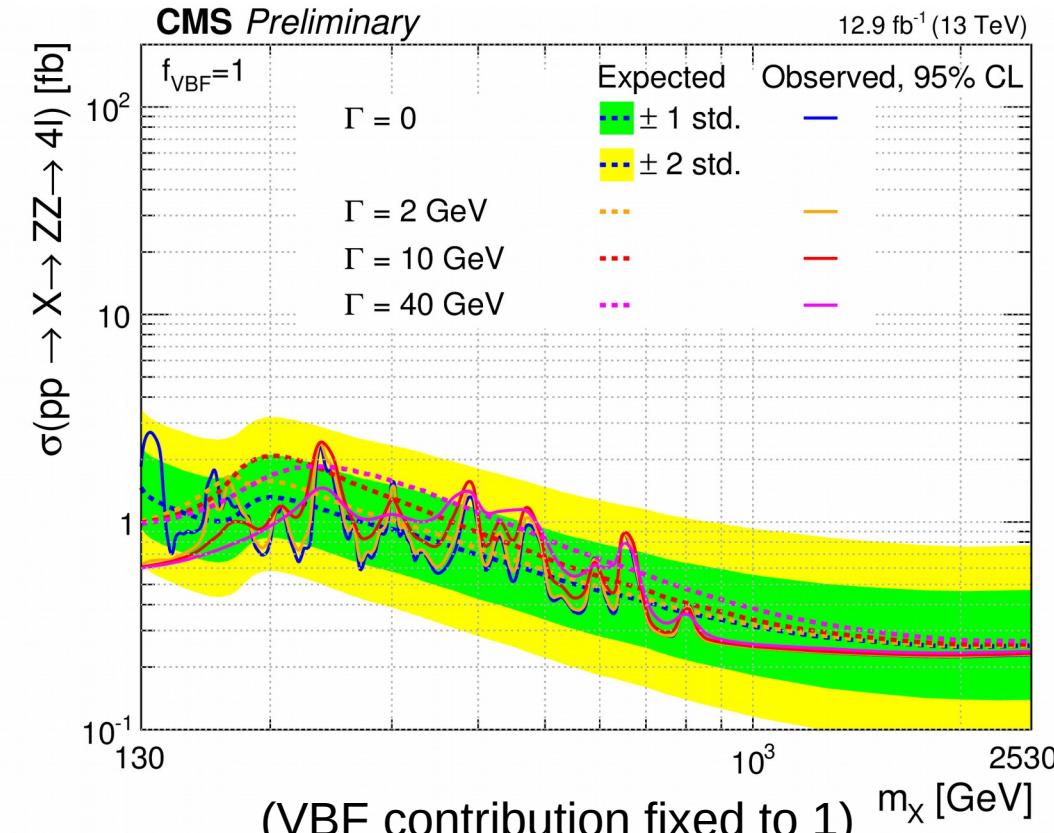
general limit



$$\sigma_{ggH} = \sigma_x \cdot (1 - f_{VBF})$$

$$\sigma_{VBF/VH} = \sigma_x \cdot f_{VBF}$$

pure EW production



$$\sigma_{ggH} = 0$$

$$\sigma_{VBF/VH} = \sigma_x$$

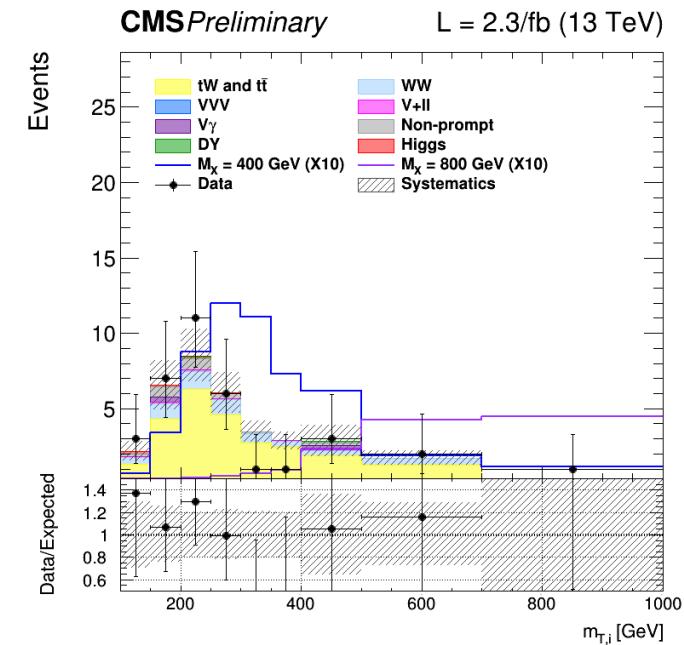
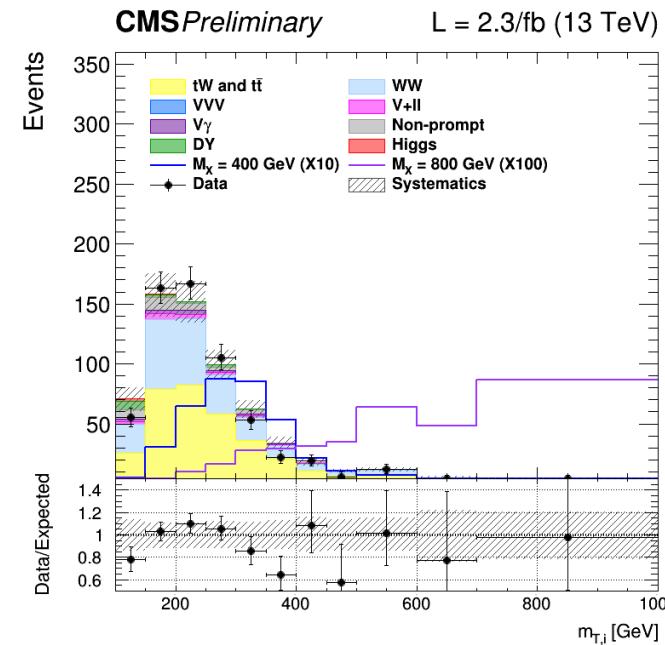
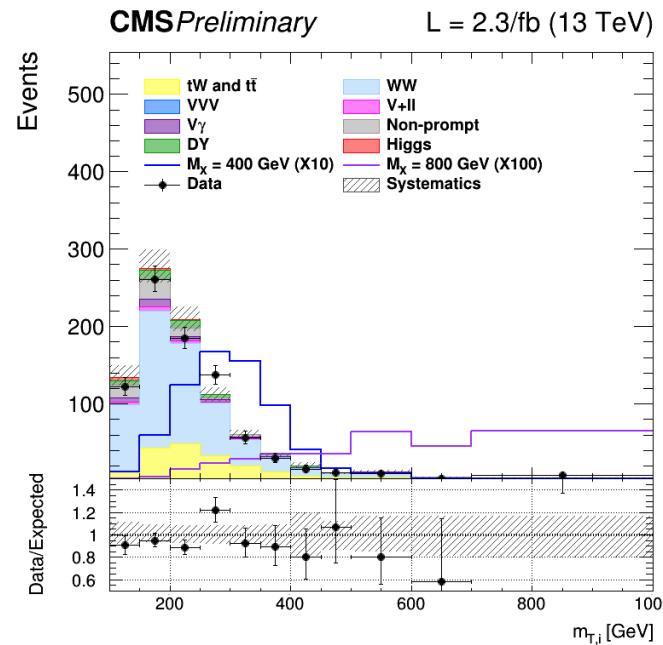
no excess observed in a mass range from 130 GeV-2.5 TeV

channels and categories

- only mixed leptonic channel: **ep**
- same flavor excluded due to Drell-Yan
- 3 categories: **0 jet, 1-jet, VBF**

event selection

- additional lepton veto
- missing $E_T > 20\text{ GeV}$
- b-tag veto



main backgrounds

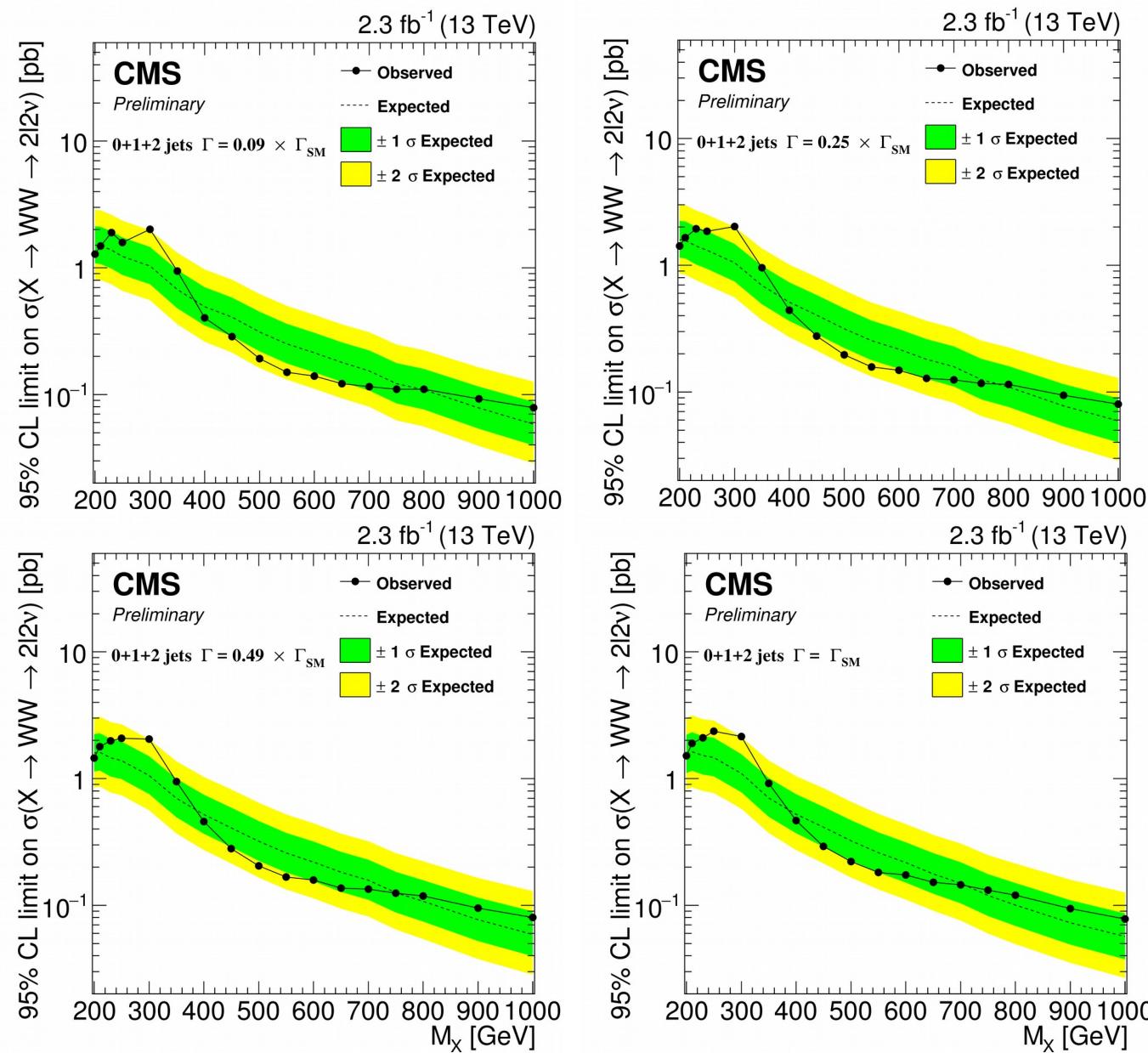
- non-resonant WW (part of the signal model)
- tt, tW (shape from MC, normalization from data)

signal extraction

- improved transverse mass:

$$m_{T,i} = \sqrt{(p_{ll} + E_T^{\text{miss}})^2 - (\vec{p}_{ll} + \vec{p}_T^{\text{miss}})^2}.$$

- template shape analysis considering interference effects



no excess observed in a mass range from 200GeV-1TeV

channels and categories

- 3 search channels:

$$hh \rightarrow bb\tau\tau \rightarrow bb(e\tau_h | \mu\tau_h | \tau_h\tau_h)$$

- 3 categories:

1 b-tagged ak4 jet | 2 b-tagged ak4 jets
1 b-tagged ak8 jet

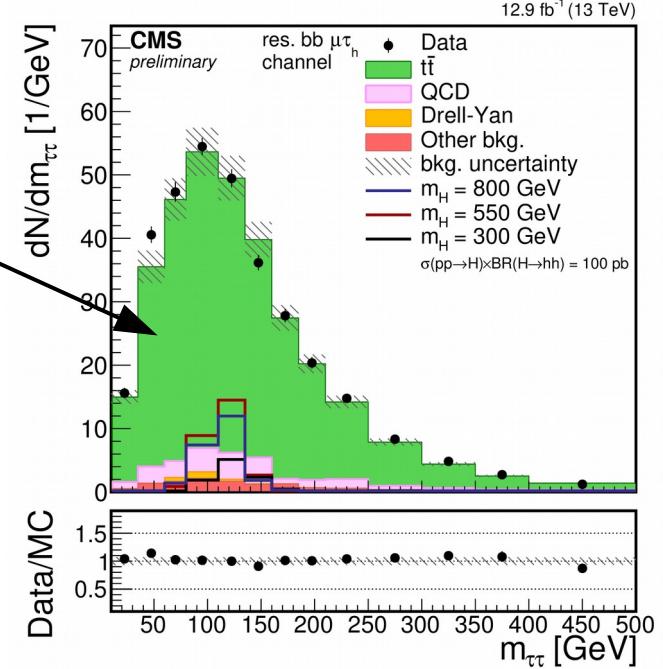
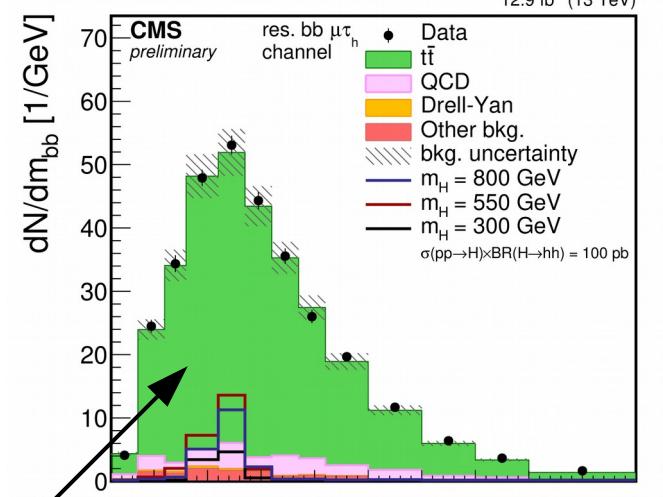
“resolved”
“boosted”

event selection

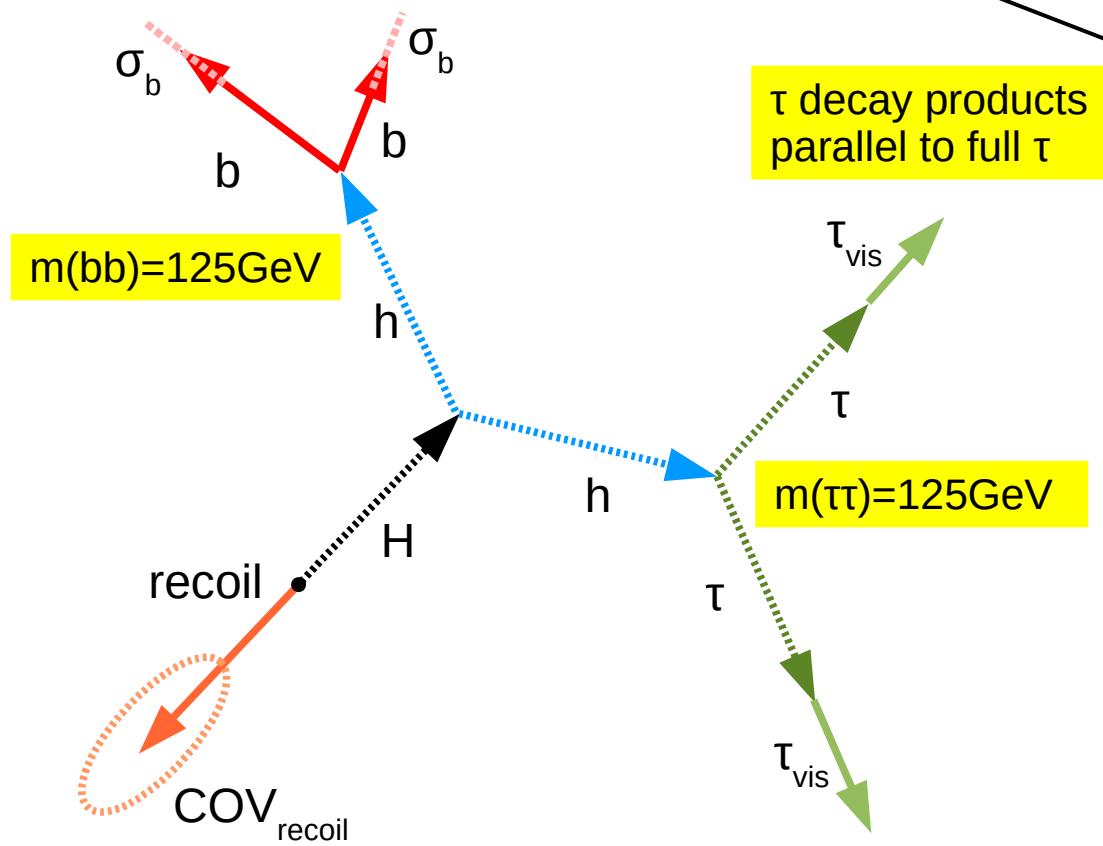
- 2 ak4 jets with at least 1 b tag **or** 1 b-tagged ak8 jet
- 2 oppositely charged leptons
- inv. mass of di-jet pair close to SM Higgs boson mass
(80GeV<math>m_{bb}<160GeV**or** 90GeV<math>m_{ak8}<160GeV)
- inv. mass of di-tau system estimated with likelihood based estimator close to SM Higgs boson mass
(80GeV<math>m_{\tau\tau}<160GeV)

backgrounds

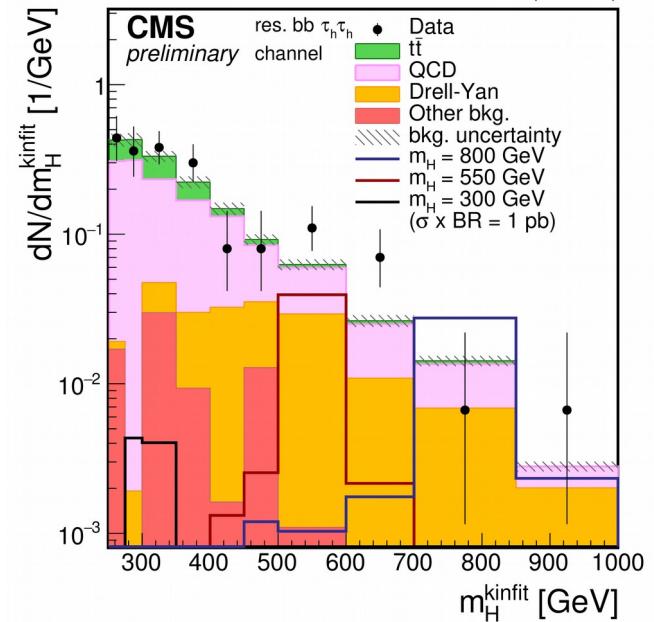
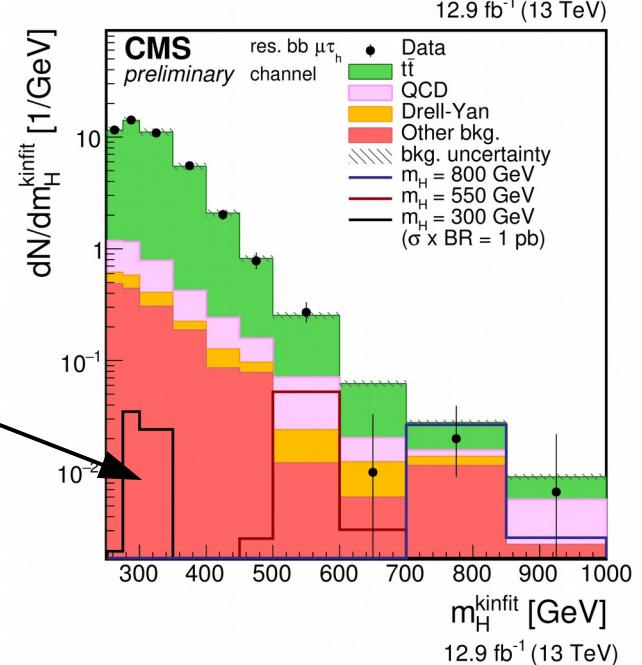
- QCD (yield and shape from data)
- tt (shape from MC, normalized to NNLO prediction)
- Z+jets (shape from MC, normalized to NNLO prediction)
- W+jet, single top, di-boson subdominant (solely MC)



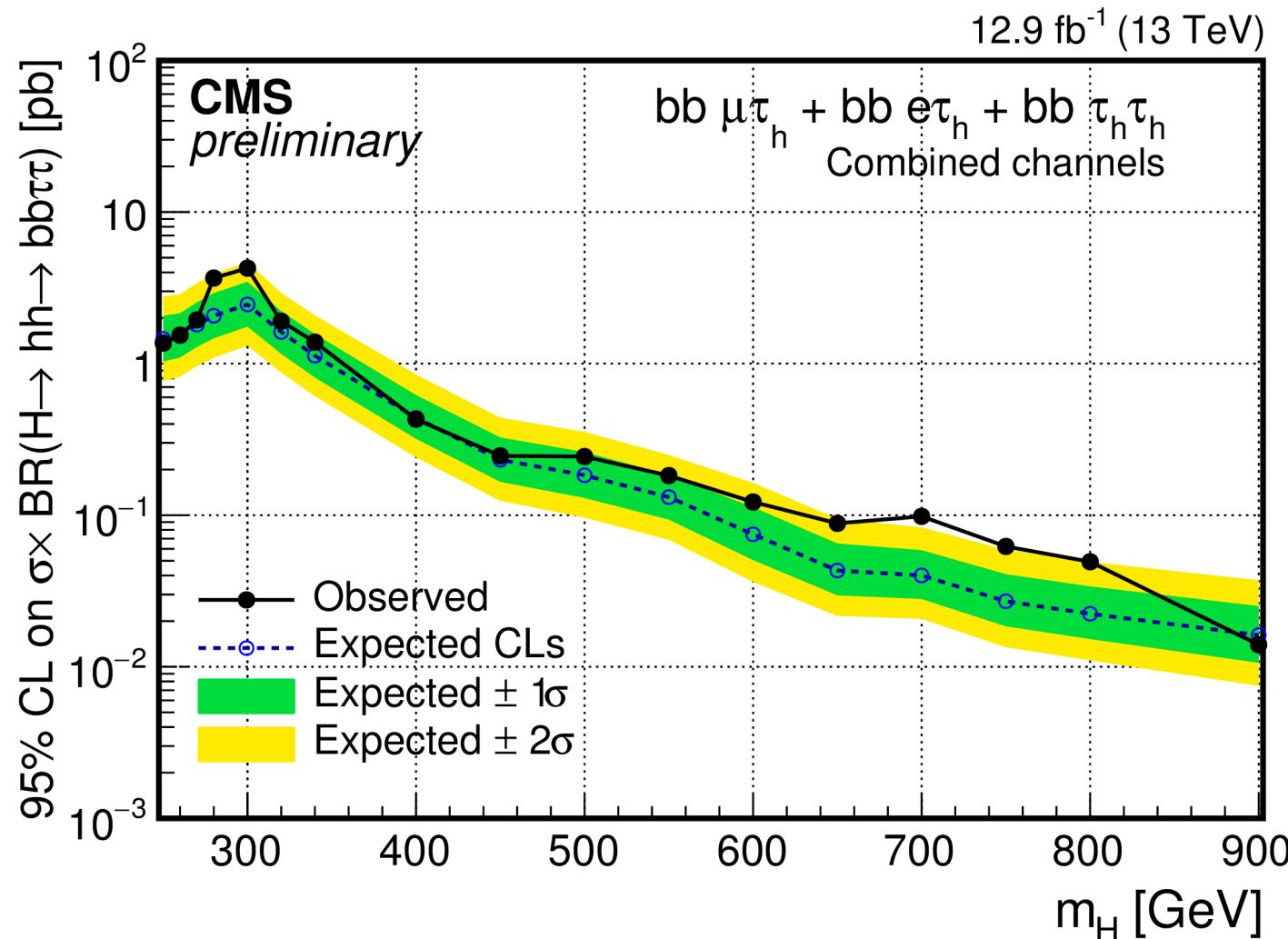
- event kinematically highly constrained
- kinematic fit:
 - get a good full τ 4-vector reconstruction
 - get heavy higgs mass reconstruction ($\sim 10\%$)



fitted heavy Higgs mass significantly improved compared to simple 4-body mass



combination of all channels and categories



no excess observed in a mass range from 250-900 GeV

Conclusions

- very rich search program for high-mass neutral Higgs bosons ongoing at CMS
- significant expansion of the tested mass ranges for 13 TeV/2016 data

Higgs to fermions			
$H \rightarrow \tau\tau$	2.3fb-1	2015	100GeV-3TeV
$H \rightarrow b\bar{b}$	2.7fb-1	2015	500GeV-1.2TeV
Higgs to vector bosons			
$H \rightarrow ZZ \rightarrow 4l$	12.9fb-1	2016	130GeV-2.5TeV
$H \rightarrow ZZ \rightarrow 2l2\nu$	2.3fb-1	2015	200GeV-1.5TeV
$H \rightarrow WW \rightarrow l\nu l'\nu'$	2.3fb-1	2015	200GeV-1TeV
Higgs to Higgs			
$H \rightarrow hh \rightarrow b\bar{b}\tau\tau$	12.9fb-1	2016	250GeV-900GeV

new 

new 

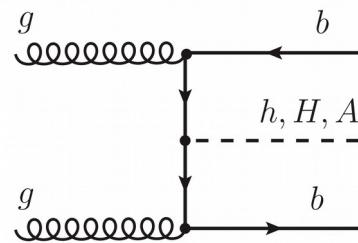
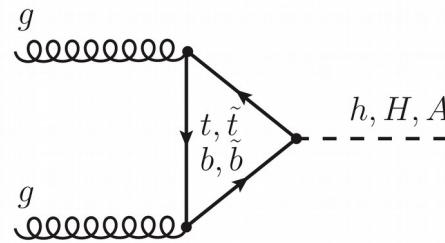
new 

new 

- no significant excess observed ... so far! Still a long time till YETS!

Backup

- in Type-II 2HDMs: large $\tan\beta \rightarrow$ coupling to down-type fermions enhanced
- production involving b quarks and decay to τ leptons dominant



channels and categories

- four final states of τ pairs considered: $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- two categories: no b-tag and at least one b-tag

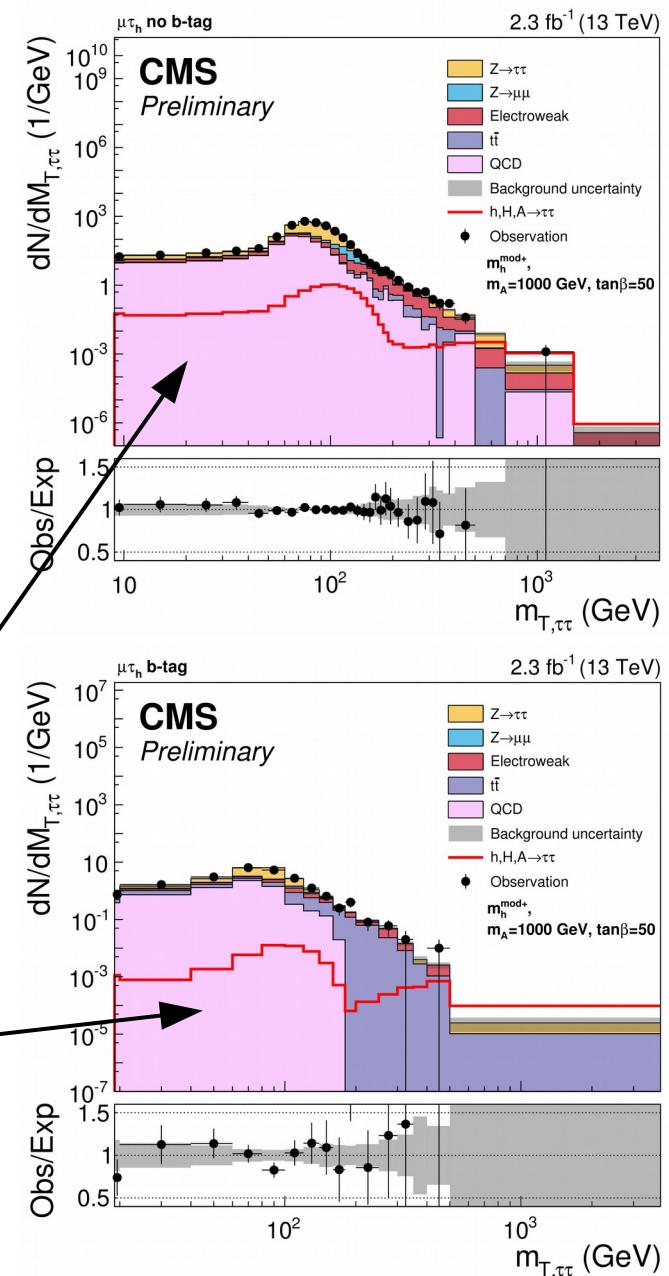
backgrounds

- Drell-Yan $Z/\gamma^* \rightarrow \tau\tau$ (reweighted MC)
- fake τ , QCD (data driven)
- ttbar (MC)

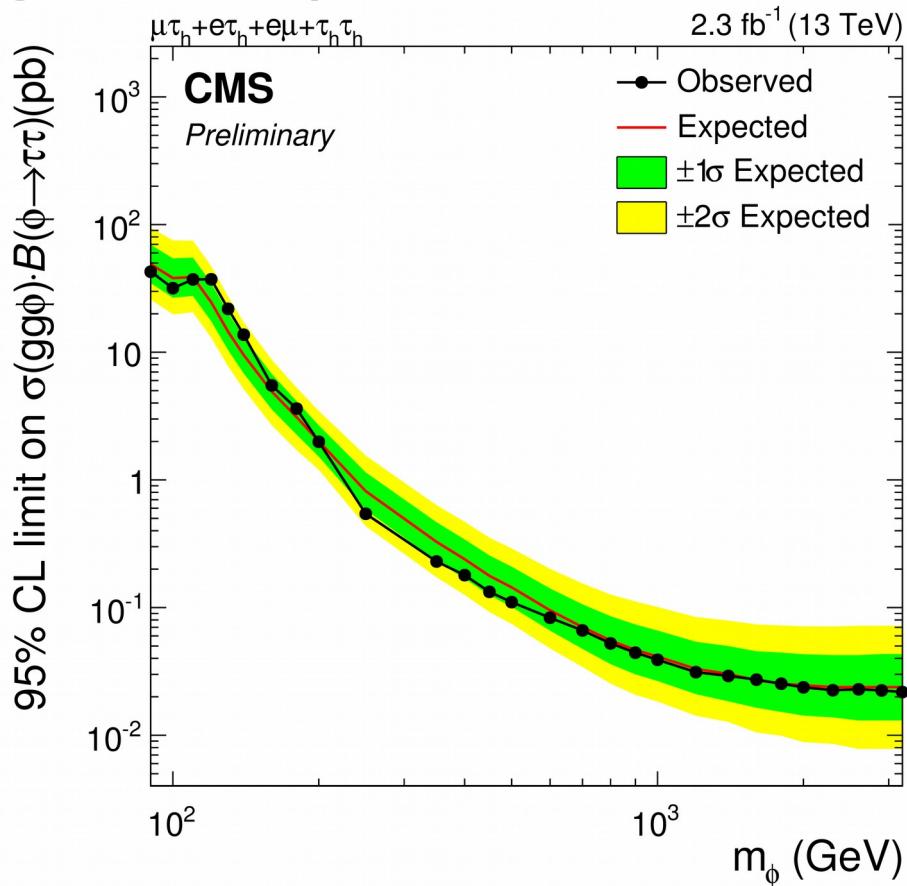
signal extraction

transverse invariant mass of di-tau candidate using a maximum likelihood based estimator:

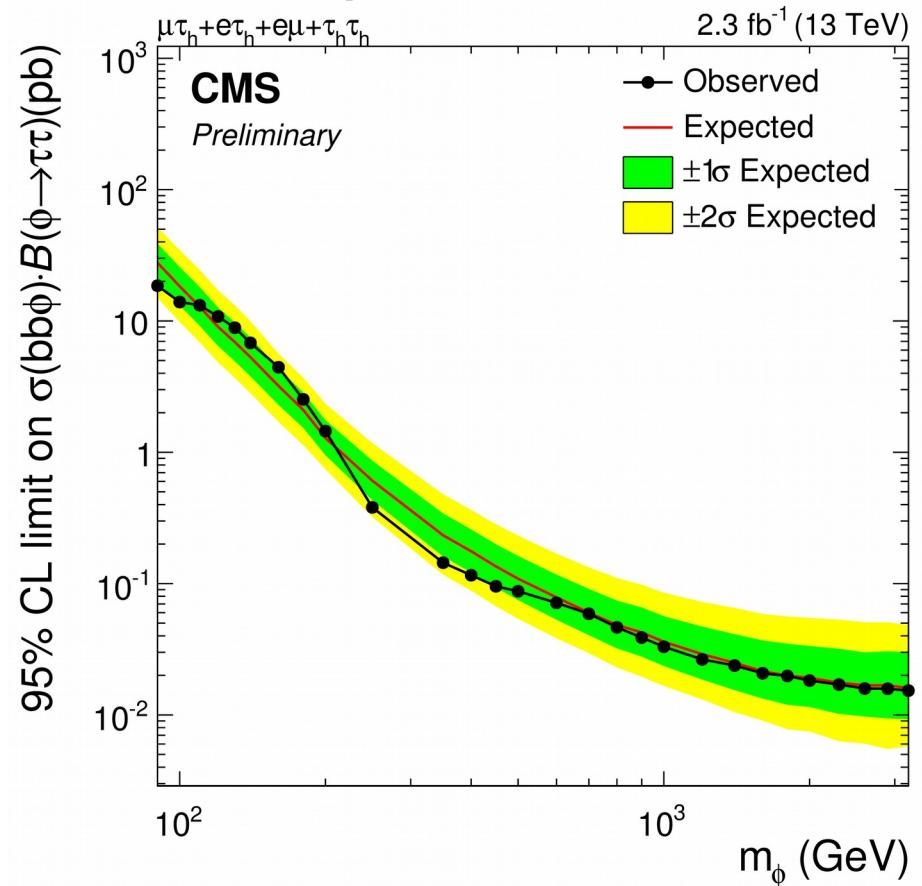
- missing $E_T +$ uncertainty
- visible decay products of di- τ system



gluon fusion production



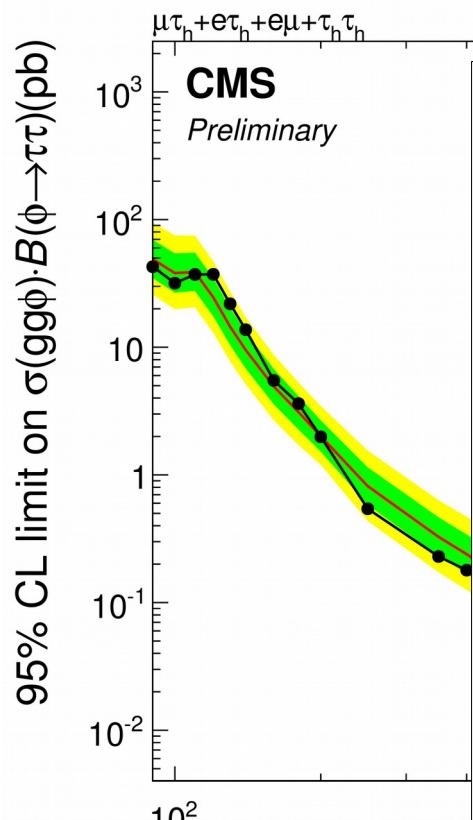
b-associated production



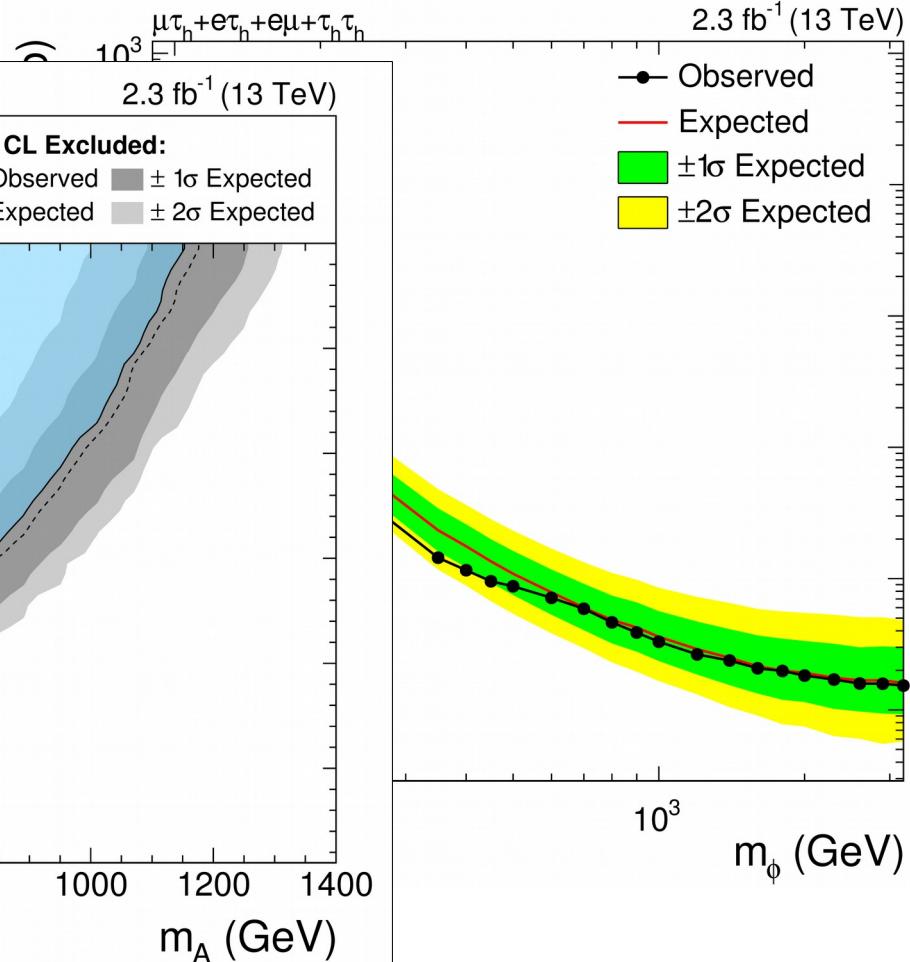
limit on one production mode – other profiled (floating freely)

no excess observed in the mass range from 100GeV-3TeV

gluon fusion production



b-associated production



excluded parameter space significantly extended in hMSSM

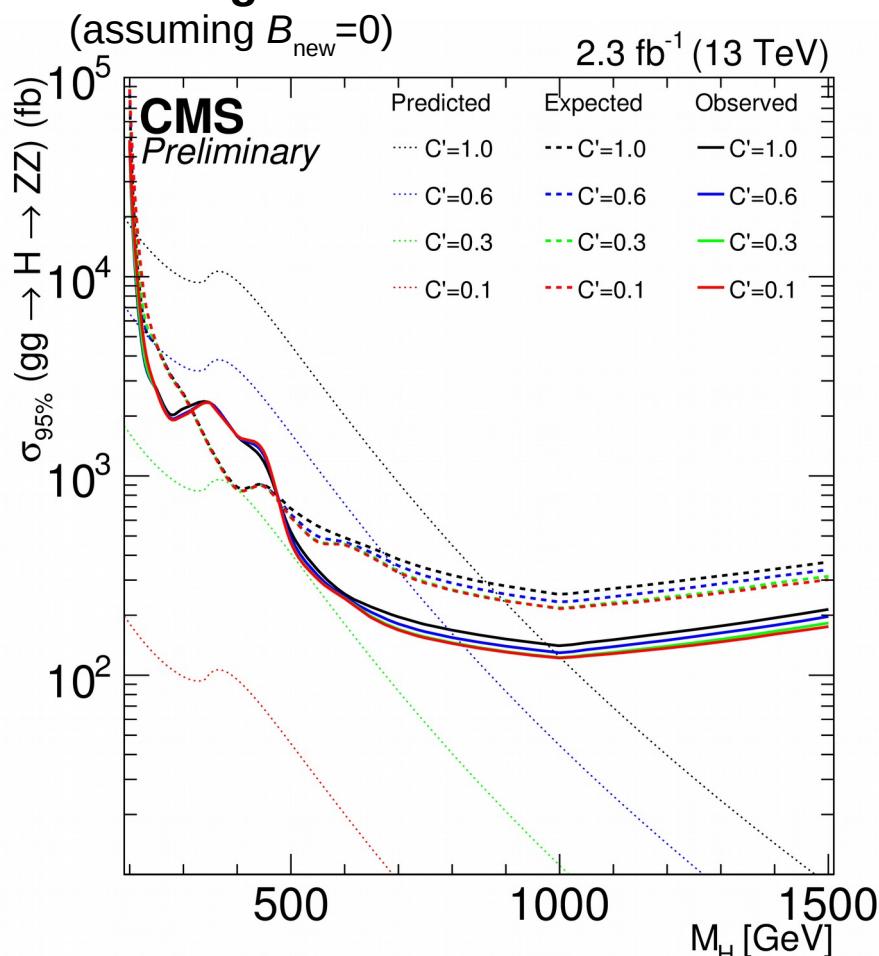
for more details:
see Pooja Saxena's talk

H \rightarrow ZZ \rightarrow llvv: Results

run 2 – 2015
2.3 fb $^{-1}$

HIG-16-001

EW singlet extension

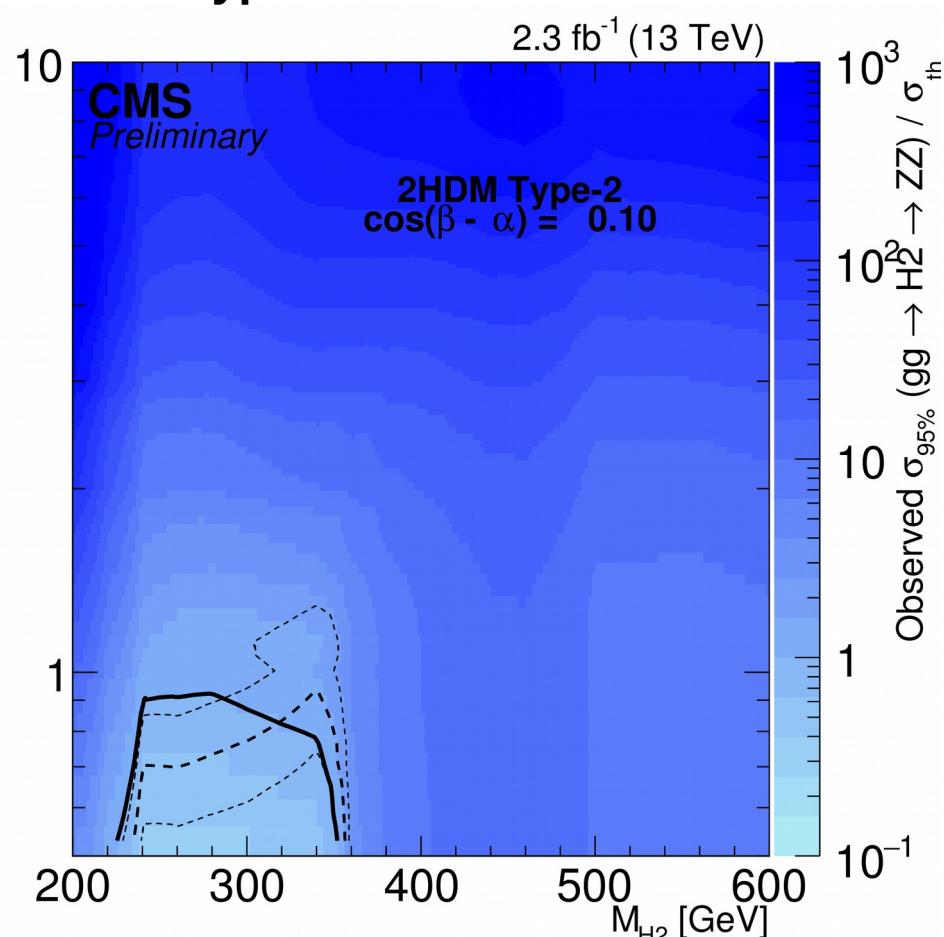


$$\mu' = C'^2 (1 - \mathcal{B}_{\text{new}})$$

$$\Gamma' = \Gamma_{\text{SM}} \frac{C'^2}{1 - \mathcal{B}_{\text{new}}}$$

C': scale factor of heavy Higgs boson couplings w.r.t. SM Higgs couplings

2HDM Type-II



Parameter	Value
m_h	125.09 GeV
m_A	$m_H + 100$ GeV
m_{H^+}	$m_H + 100$ GeV
$\cos(\beta - \alpha)$	0.1
m_{12}^2	$\max(1 - \tan \beta^{-2}, 0) \cdot \frac{1}{2} \sin(2\beta) (m_A^2 + \lambda_5 v^2)$
m_H	scanned
$\tan \beta$	scanned

