XI Latin American Symposium of High Energy Physics

(SILAFAE 2016)

CMS results on Higgs Physics

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EXCELENCIA MARÍA DE MAEZTU
2016-2019

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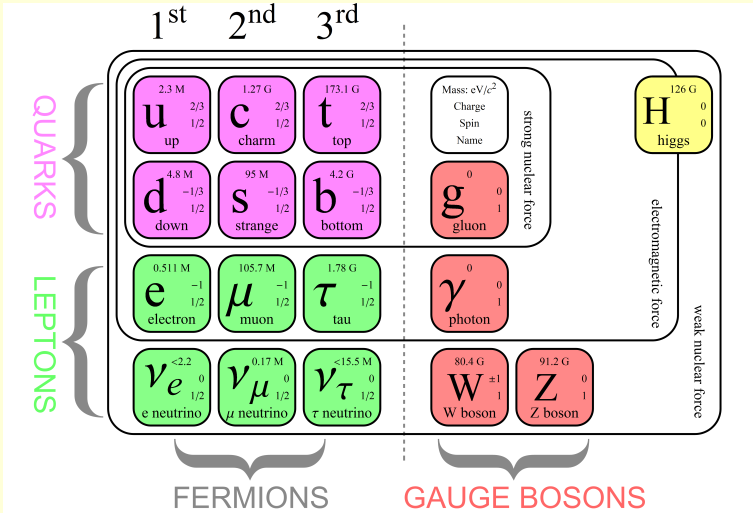
física de partículas

CMS
Compact Muon Solenoid

(Antigua Guatemala, 14-18/XI/2016)

The SM and the Higgs boson

The standard model of particles and their interactions (SM) is the best description of the fundamental pieces of Nature.



Based on symmetry group:

$$\mathbf{SU(3)_C \times SU(2)_L \times U(1)_Y}$$

- Include all the known interactions except Gravity.
- Describe most of the observations done about Nature and the Universe.

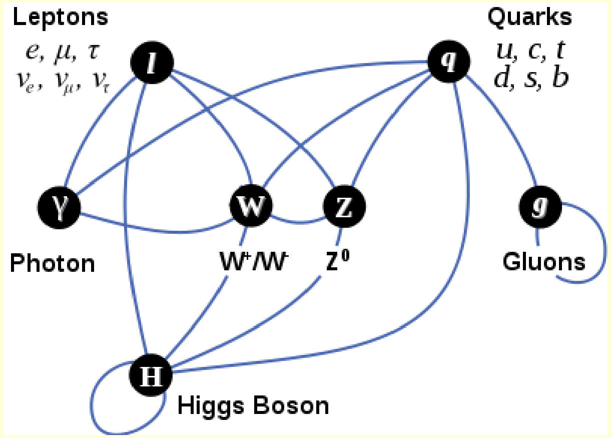
  Missing: Gravity-related observations, matter-antimatter asymmetry, neutrino masses,. . .

- The Higgs boson is the key piece of the model, making different pieces to match after requiring the breaking of the symmetry:

$$\mathbf{SU(2)_L \times U(1)_Y \Rightarrow U(1)_{em}}$$

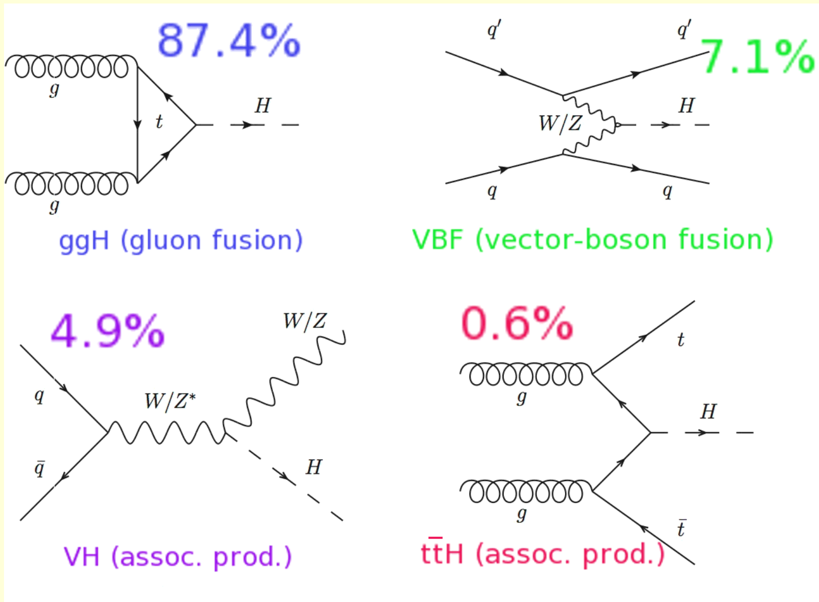
Studying the Higgs boson

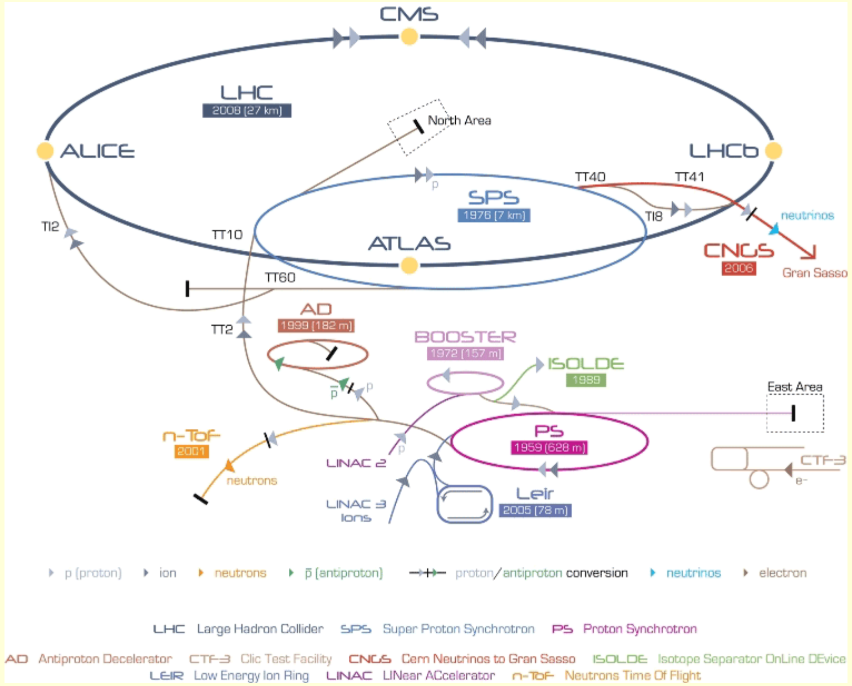
- Also the last one to be found: “debut” in society on July 4th 2012
- Now the main goal is studying its properties
- and understand whether and how it does its duty within the SM!



First, it needs to be produced!

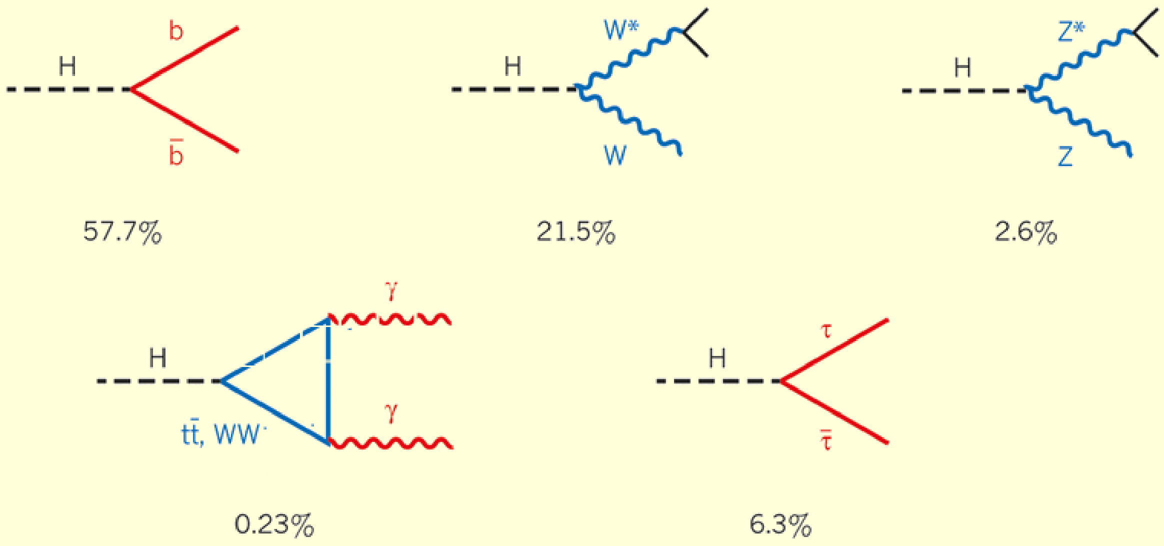
Use proton-proton collisions at the LHC. . . and several processes:

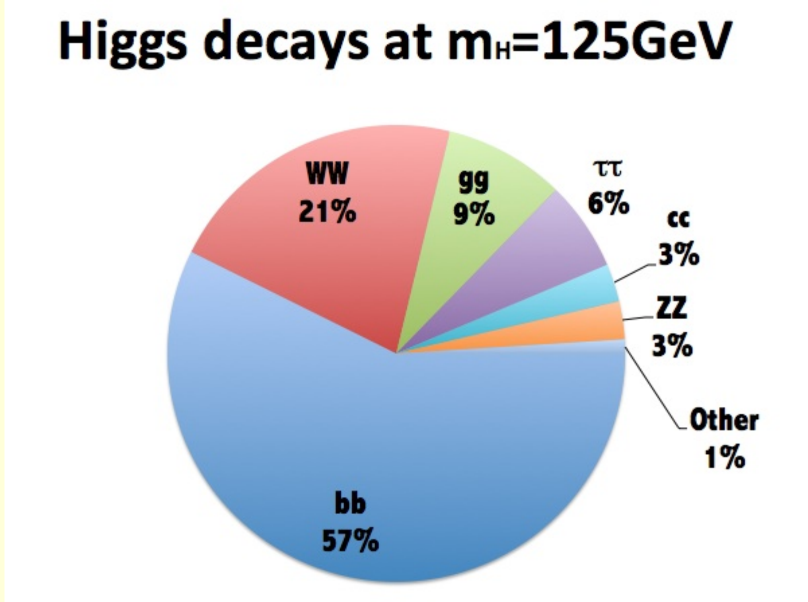




Studying the Higgs boson (II)

Once produced the Higgs boson decays into detectable objects.





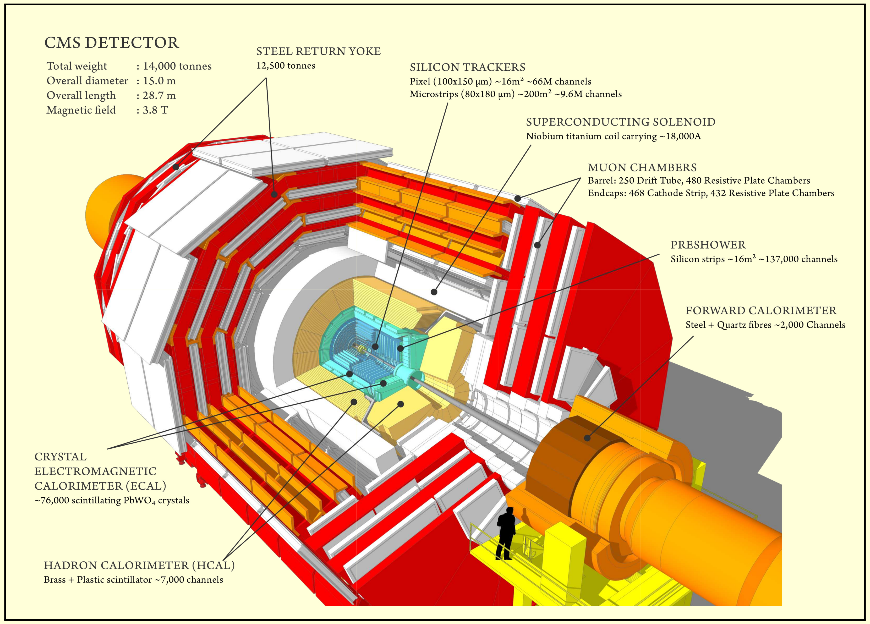
- ⇒ The Higgs has an amusing distribution of decay branching ratios: $b\bar{b}$, WW, gg, $\tau\tau$,...
- ⇒ This is due to the mass ($\sim$ Higgs coupling) spectra of the SM.
- ⇒ Need to reconstruct many types of objects in the final state.

We use the CMS detector to identify these final states

The CMS Experiment

Intended for studying all the possible physics topics by analysing the products of the LHC collisions.

- Very compact due to its strong magnetic field (solenoid).
- Strong point: tracking!
- Forward-backward and azimuthally symmetric, as the expected physics.



Electron/photon detection

$\Rightarrow$ Impressive energy resolution

$\Rightarrow$ Coverage up to $|\eta| < 2.5$

Muon detection

$\Rightarrow$ Redundant inner/outer tracking

$\Rightarrow$ Coverage up to $|\eta| < 2.4$

Hadronic Jets

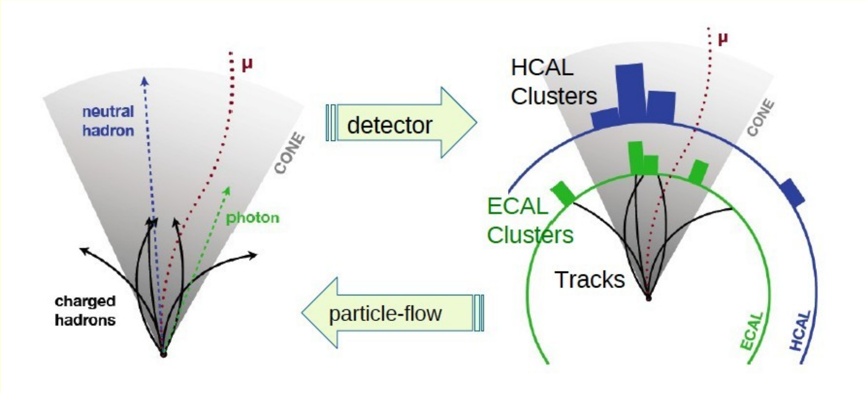
$\Rightarrow$ Coverage up to $|\eta| < 5$

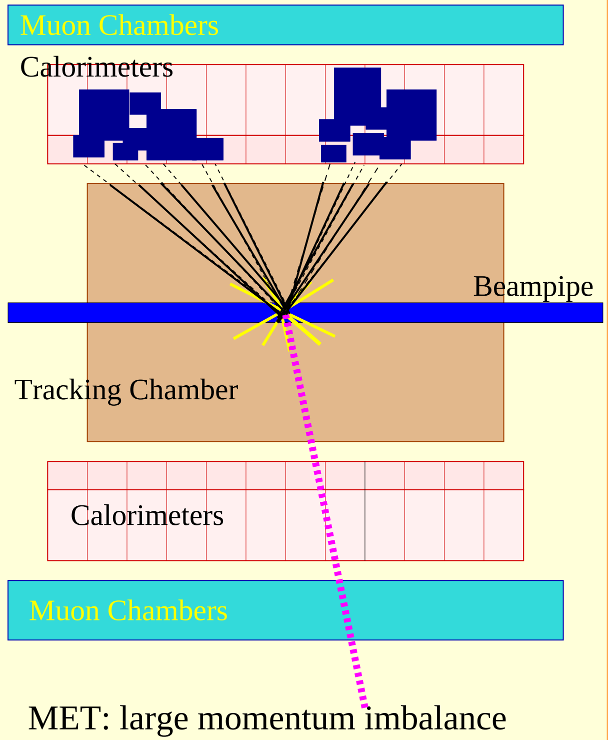
$\Rightarrow$ using particle-flow (next slide)

Event reconstruction at CMS

CMS reconstructs the event exploiting its great capabilities

An attractive approach is the identification of species of particles and use these “objects” instead of the raw quantities (tracks, calorimeter towers/cells).





Complex objects from this “Particle Flow”:

- Jets (Anti-KT run over PF objects)
- The MET, coming from the imbalance of detected momenta

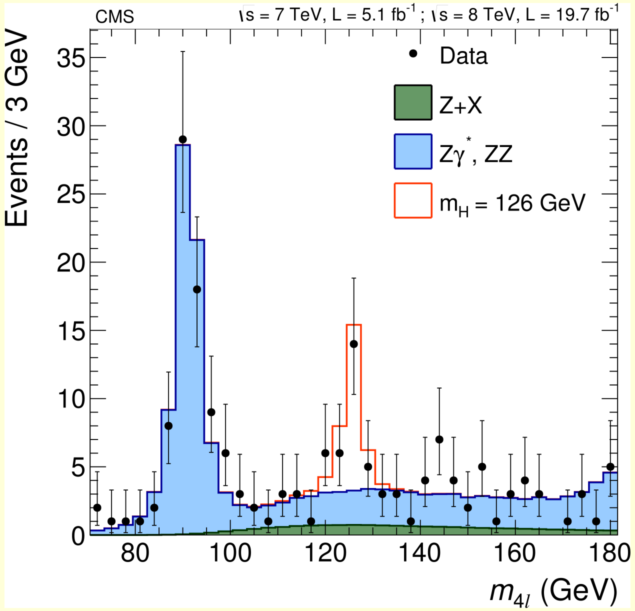
$$\text{MET} = \sqrt{[\Sigma\, p_x]^2 + [\Sigma\, p_y]^2}$$

This approach has turned out to be very useful to handle complicated final states and challenging problems (e.g. pile-up)

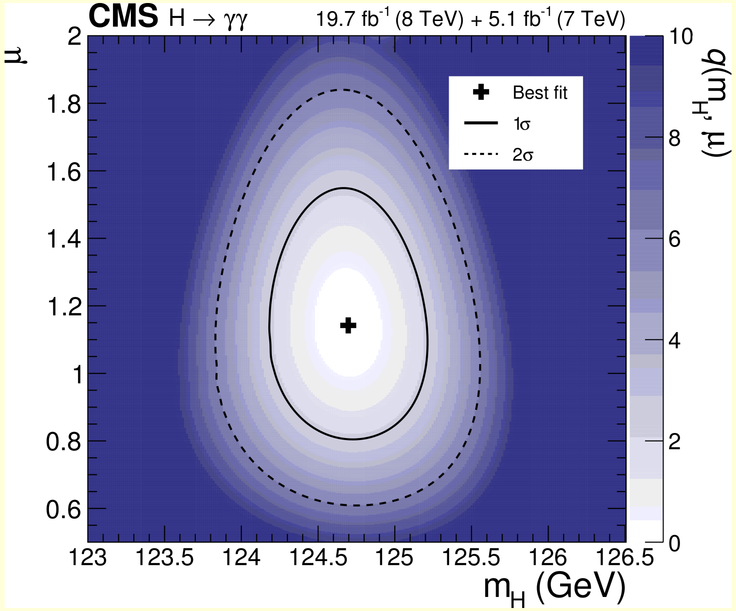
The Higgs Boson at CMS during Run I

- The Run I provided the data for the discovery of the Higgs and the first property measurements.
- The main channels were really enough to settle down the existence of "the 125 GeV Resonance" and related to the SM Higgs.

PRD 89 (2014) 092007



EPJC 74 (2014) 3076

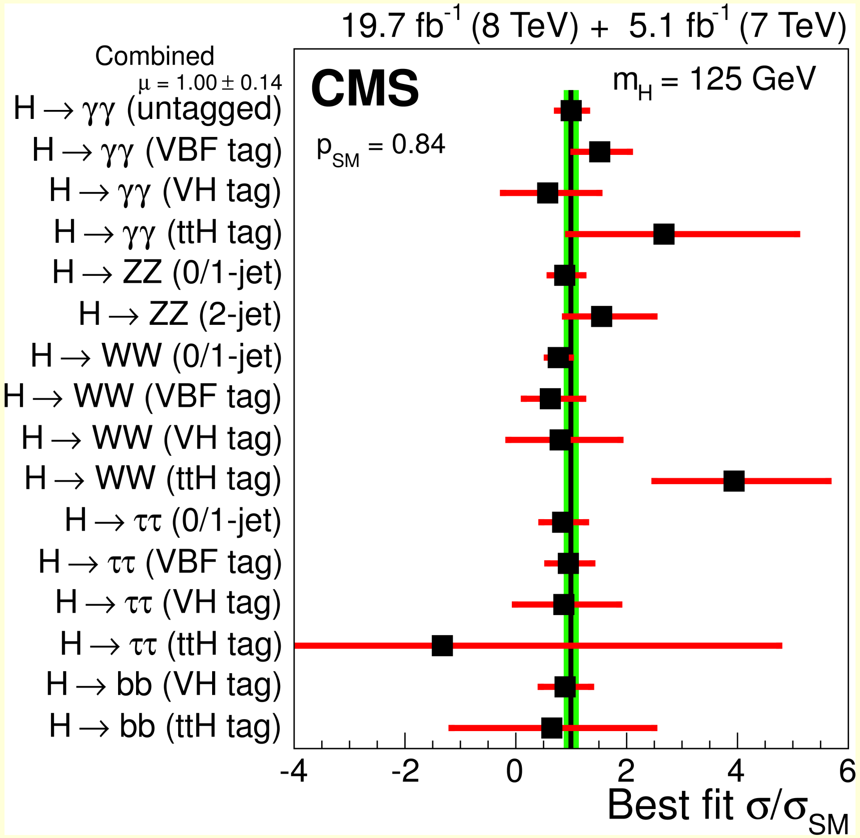


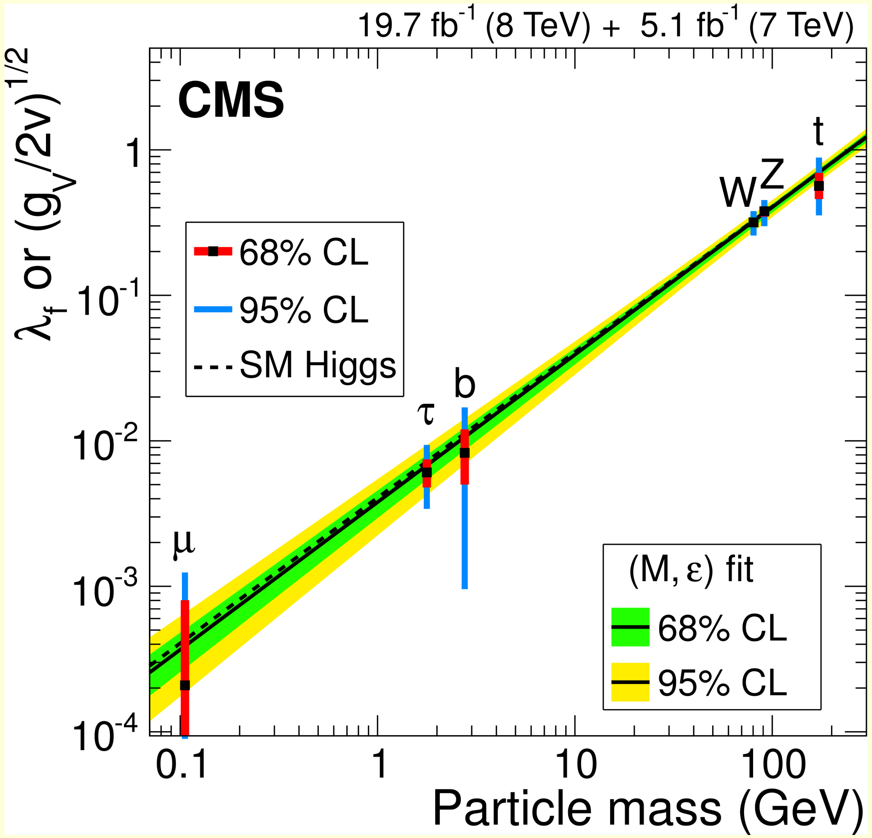
- And the other channels were helpful to confirm how close it is to be the actual SM Higgs.

The Higgs Boson at CMS during Run I

Lots of measurements ⇒ lot of information/constraints

EPJC 75 (2015) 212



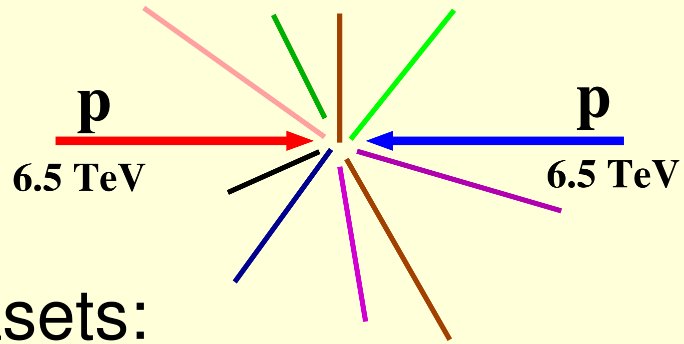


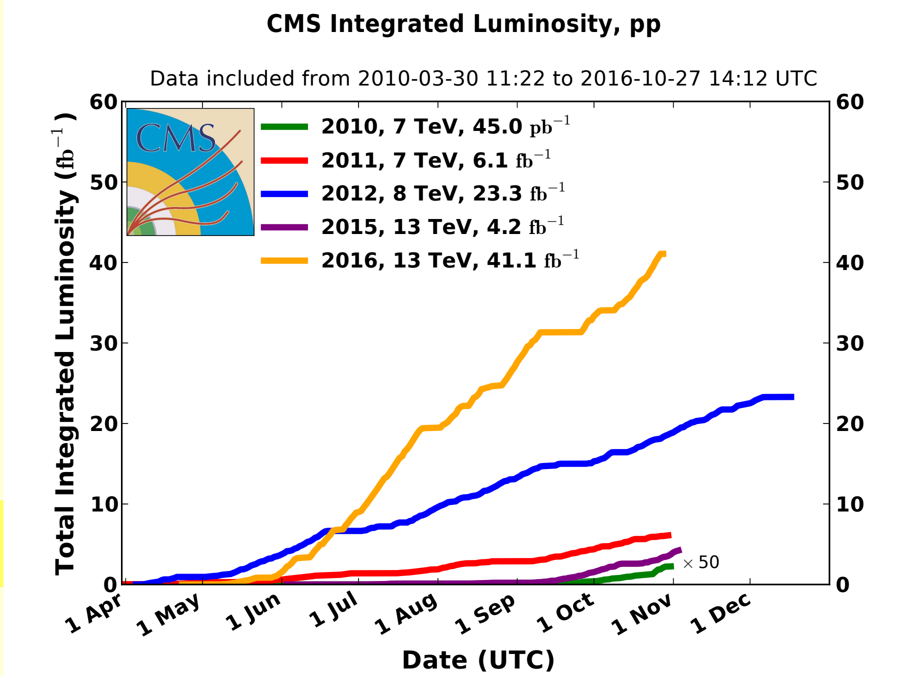
This resonance at 125-GeV does indeed look like the SM Higgs boson!

Some channels required further improvements in precision.

Studying the Higgs boson during Run II

- LHC Run II collisions at 13 TeV:





Two datasets:

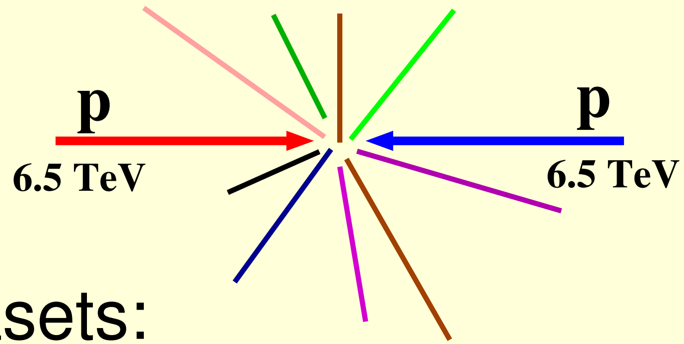
2015 set has 2.3-2.6 fb^{-1}

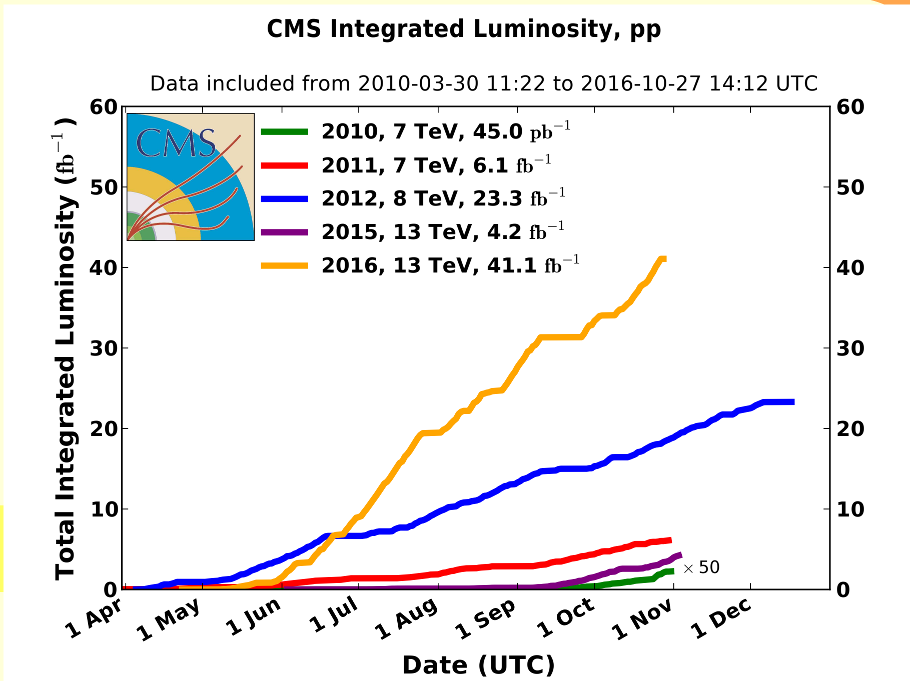
2016 ICHEP set: 12.9 fb^{-1}

- Analyses on-going to include the full 2016 data ($\sim$ 38 fb^{-1})

Studying the Higgs boson during Run II

- LHC Run II collisions at 13 TeV:



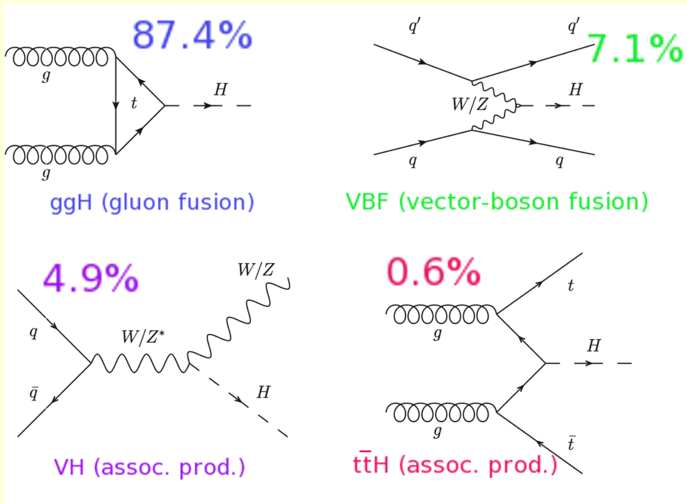


Two datasets:

2015 set has 2.3-2.6 fb^{-1}

2016 ICHEP set: 12.9 fb^{-1}

- This talk covers Higgs results about:



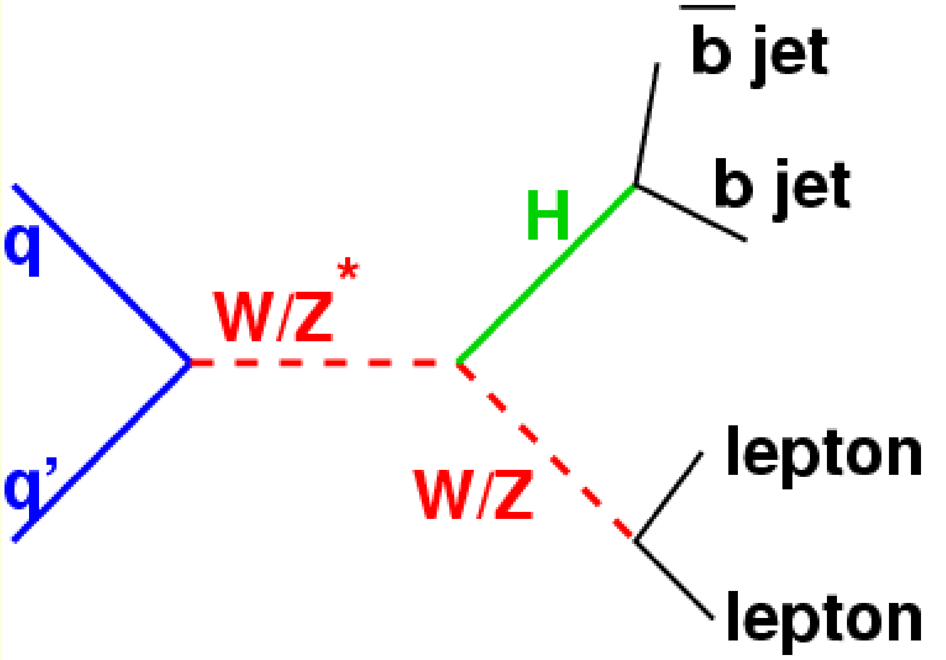
- Production (many decays)
- Properties (in SM)
- Looking for anomalies
- Search for other Higgs bosons

Studying the Higgs via

$$H \to b\bar{b}$$

Motivation and description of the channel

- Large branching ratio makes this the first channel to think about.
- Difficult final state due to hadronic jets.

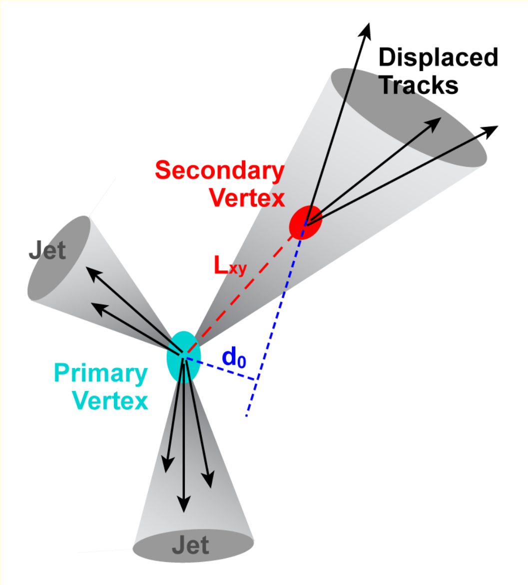


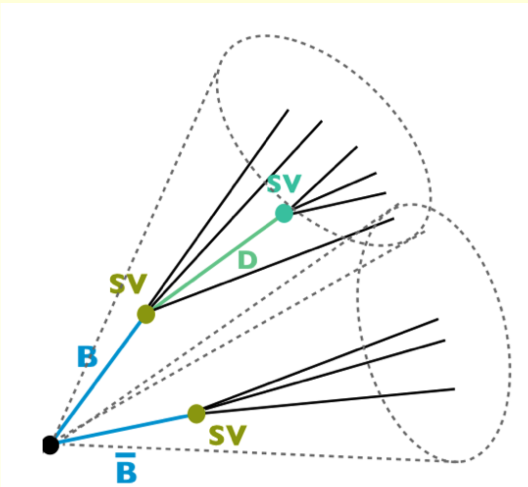
- Huge multijet background makes the inclusive production impossible to access
- Other possibilities (VBF and VH) are difficult but at reach.
- This final state extensively used in $t\bar{t}H$, BSM and diHiggs searches (later).

- Combination of channels needed to achieve higher precision
- Since it is a difficult channel with hard topologies (multijets, forward jets, MET) some analyses still focusing at the better understood 2015 dataset.

Identifying heavy-flavour jets at CMS

Nature of hadronic jets makes it impossible to identify flavour of the original partons.





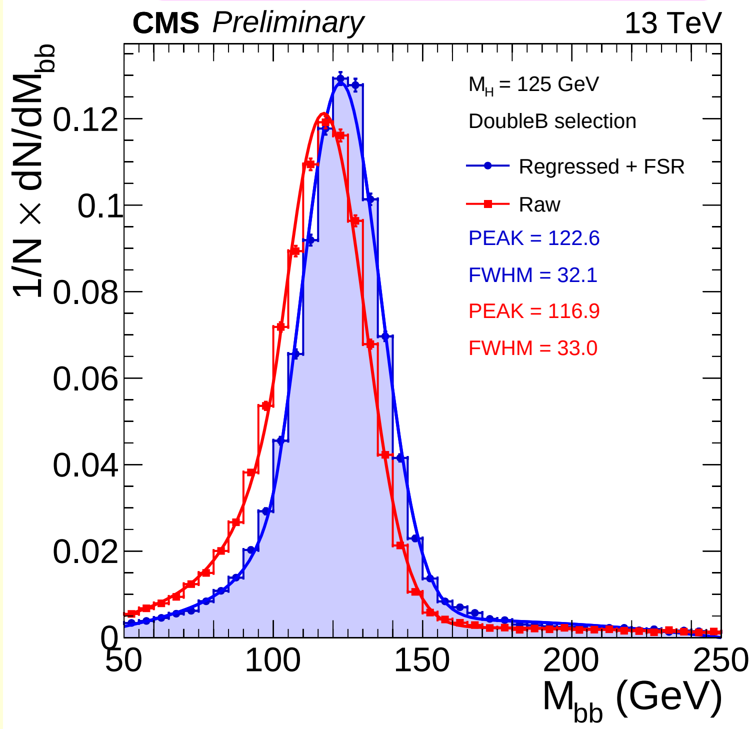
- However, heavy-flavour quarks (b and c) are hardly produced in hadronizacion and produce long-lived hadrons that are used to tag the presence of the quark.
- b-tagging (for b-tagged jets) relies on:
  - displaced decay tracks
  - displaced secondary vertices
  - semileptonic decays (p_T/displaced lepton)
- Special effort to identify heavy flavour in boosted-jet topologies (very challenging)

Recently charm-tagging is becoming important, but not used (yet) in Higgs analyses.

Search for VBF Higgs production

- 2015 dataset used to look the Higgs produced via VBF.
- Requires 1 or 2 b-tagged jets (2 jets from Higgs candidate).
- Two additional jets having large dijet mass and separation in η.
- Rejection of pile-up jets.
- Large effort to improve the mass with a regression technique using:
  - Jet kinematics
  - Sub-jet quantities (leading track p_T, fraction of energy from hadrons and photons)
  - Secondary vertex (if available)
  - Information on Pile-up
- Also additional gain by recovering FSR jet around Higgs candidate.

CMS-HIG-16-003



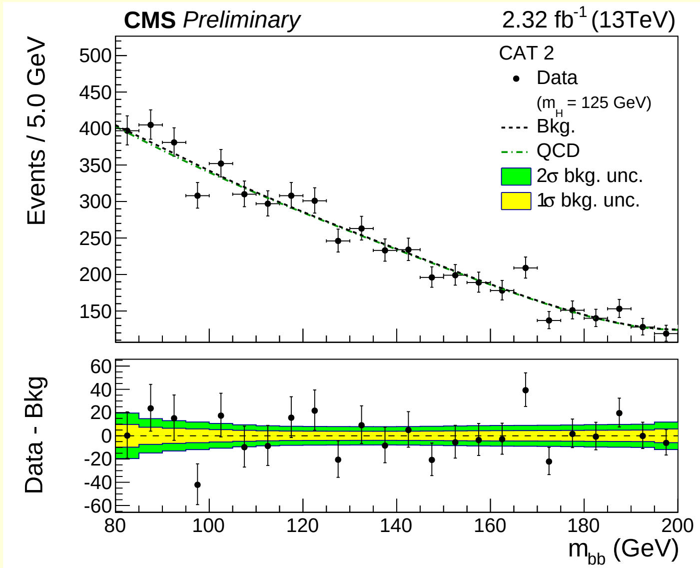
Optimization and results

- Final optimization using a BDT-based discriminant.
- Categories created from optimized bins in the BDT.

BDT boundary values	SingleB				DoubleB		
	Cat. 1	Cat. 2	Cat. 3	Cat. 4	Cat. 5	Cat. 6	Cat. 7
	0.28 – 0.72	0.72 – 0.87	0.87 – 0.93	0.93 – 1.0	0.36 – 0.76	0.76 – 0.89	0.89 – 1.0
Data	25298	5834	1281	302	69963	9831	1462
Z +jets	49$\pm$ 4	12.5$\pm$ 2.0	4.1$\pm$ 1.1	1.7$\pm$ 0.7	448$\pm$ 11	50$\pm$ 4	8.4$\pm$ 1.7
W +jets	25.8$\pm$ 3.5	1.6$\pm$ 0.9	0.1$\pm$ 0.1	$<$0.1	74$\pm$ 6	4.6$\pm$ 1.3	0.9$\pm$ 0.6
$t\bar{t}$	53$\pm$ 1	5.1$\pm$ 0.2	0.7$\pm$ 0.1	0.2$\pm$ 0.04	534$\pm$ 2	22.6$\pm$ 0.4	1.1$\pm$ 0.1
Single t	52$\pm$ 1	9.7$\pm$ 0.5	1.8$\pm$ 0.2	0.4$\pm$ 0.1	221$\pm$ 3	23.2$\pm$ 0.8	1.8$\pm$ 0.2
VBF $m_H(125)$	19.5$\pm$ 0.2	13.7$\pm$ 0.1	7.2$\pm$ 0.1	4.2$\pm$ 0.1	21.7$\pm$ 0.2	10.5$\pm$ 0.1	3.8$\pm$ 0.1
GF $m_H(125)$	5.5$\pm$ 0.2	1.8$\pm$ 0.1	0.6$\pm$ 0.07	0.2$\pm$ 0.04	18.7$\pm$ 0.4	3.1$\pm$ 0.1	0.6$\pm$ 0.07

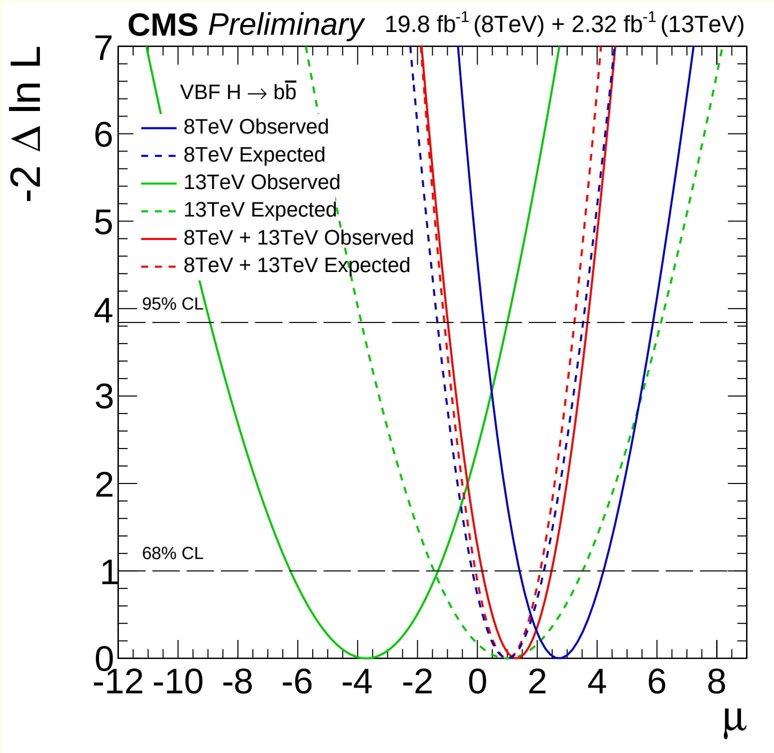
- Building the $m_{b\bar{b}}$ distribution for each category.
- Background model partly constrained from unused data (low-rank BDT)
- Excluding 3.0$\times$SM (from 5.0 expected)

Signal strength: $\mu = -3.7^{+2.4}_{-2.5}$



Combination with the Run I dataset

- Combining with the Run I result (at 8 TeV) that has higher sensitivity:



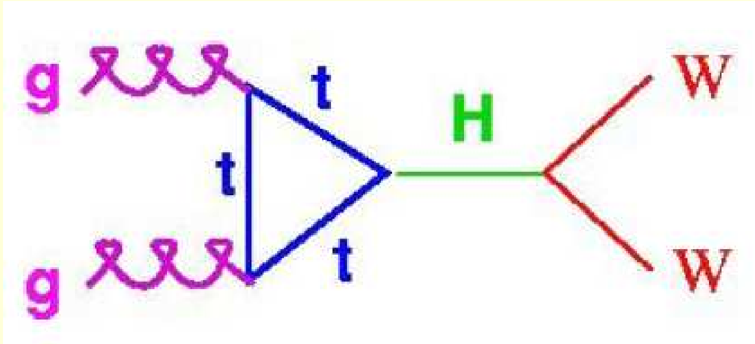
- Signal strength: $\mu = 1.3^{+1.2}_{-1.1}$
- More data needed to improve the result (2016 data set!)
- Additionally need to include other channels ($t\bar{t}H$ later).

Studying the Higgs via

$$H \to W^+W^-$$

Analysis strategy

- Second channel according to decay branching ratio.



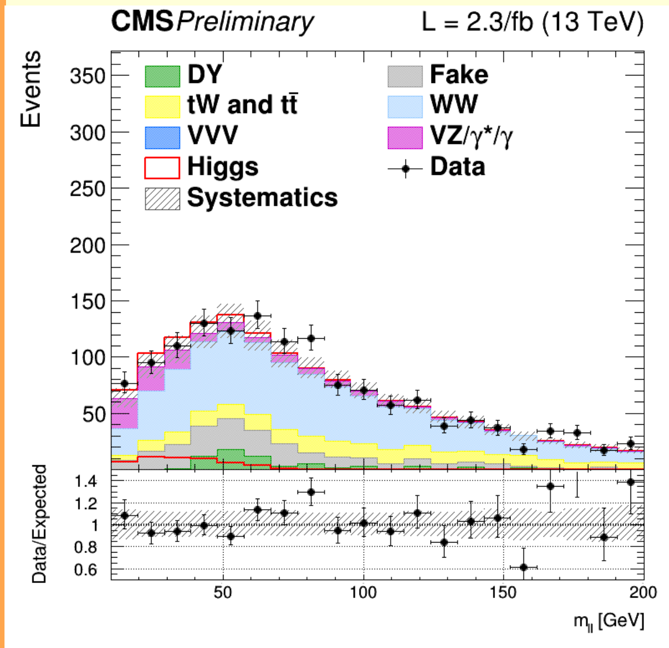
- Large brackgrounds and difficult to identify signal since mass cannot be fully reconstructed [due to neutrino(s)].
- Still at reach in all productions modes!
- Using the information on the transverse plane, a transverse mass allows to separate signal and backgrounds

$$m_T^{\ell\ell\text{MET}} = \sqrt{2p_T^{\ell\ell} \cdot \text{MET}\,(1 - \cos\Delta\phi_{\ell\ell,\text{MET}})}$$

- Similar to the variable used for the W boson, but here with the dilepton system.

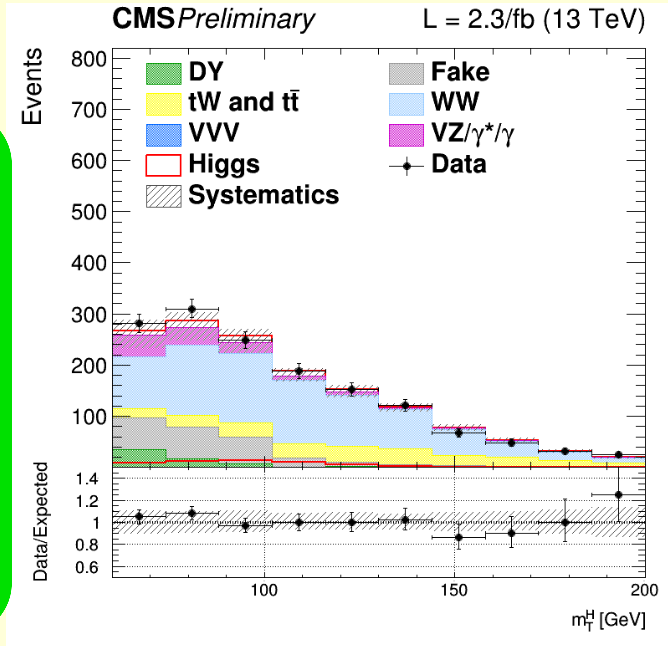
Selecting the events

- New analysis at 13 TeV (2015 dataset).
- Using only $e\mu$ events to suppress Drell-Yan production.
- Vetoing b-tagged jets to reduce top-pair production.



CMS-HIG-15-003

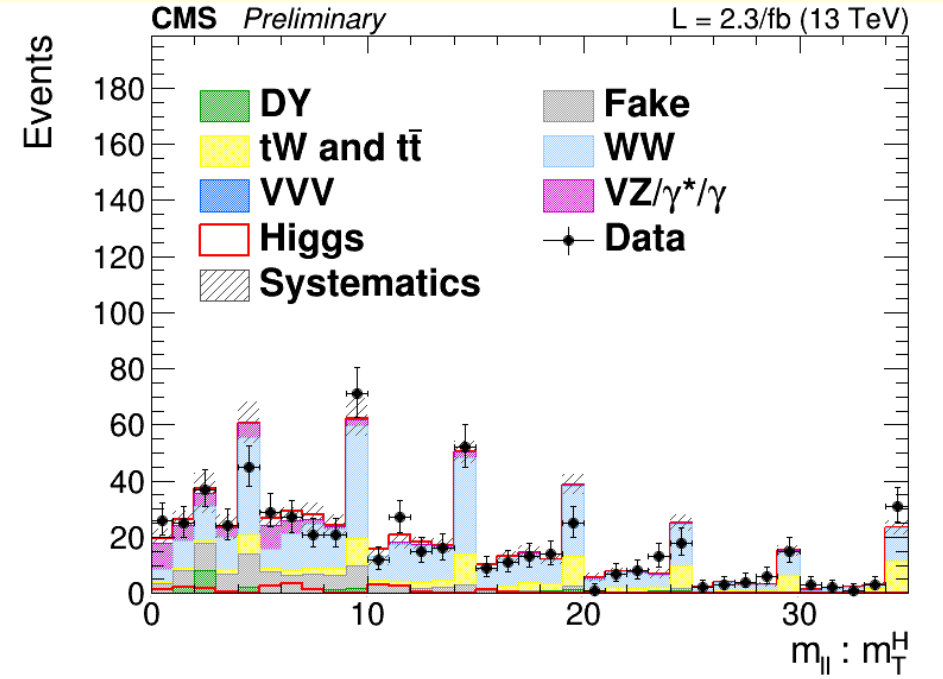
- Opposite-charged electron and muon
- For $e\mu$: $p_T^e > 20$ GeV and $p_T^\mu > 10$ GeV
- For μe: $p_T^\mu > 20$ GeV and $p_T^e > 13$ GeV
- MET> 20 GeV
- $m_T^{\ell\ell\text{MET}} > 60$ GeV
- Jets: $p_T > 30$ GeV

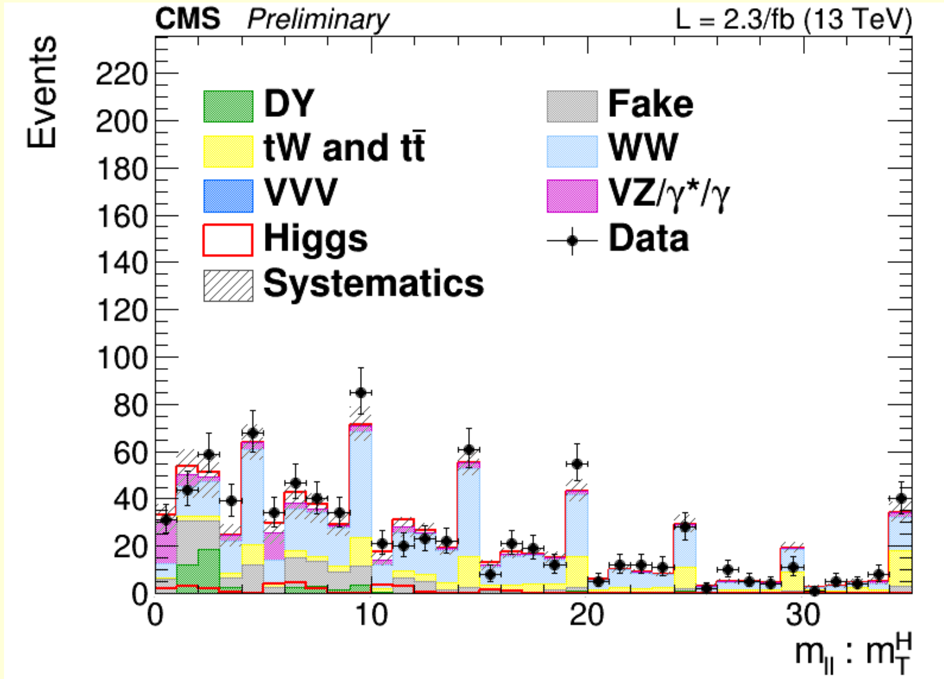


- To deal with the separation of signal and background, using a 2D template fit based on $m_{\ell\ell}$ (5 bins) and $m_T^{\ell\ell\text{MET}}$ (10 bins).

Results at 13 TeV

- Separating into categories:
  - 0 and 1 jet (different background contamination)
  - $e\mu$ and μe (different fake rate)





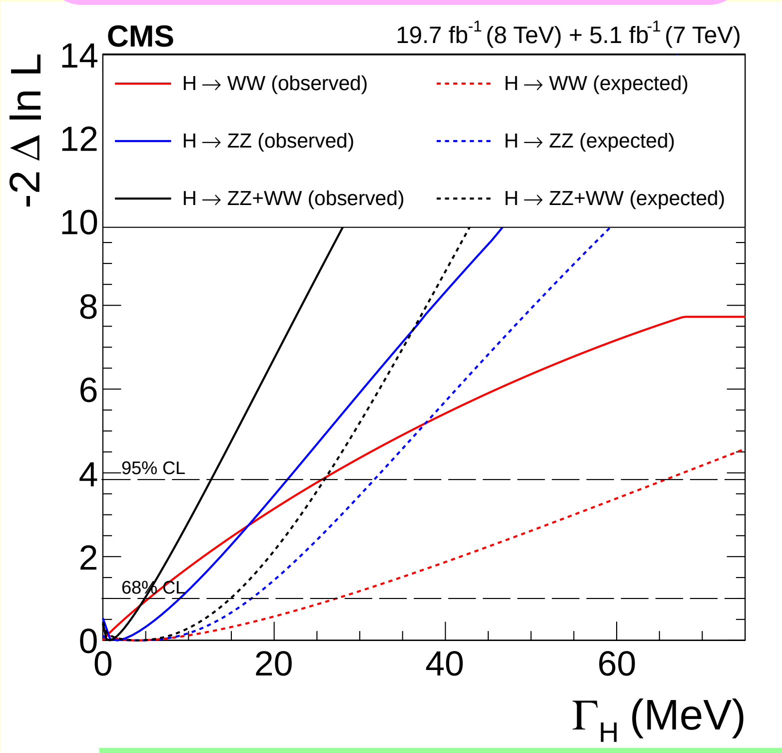
- Signal strength: $\mu = 0.3 \pm 0.5$ (0.7σ significance from 2.0σ expected)
- More data is needed to reduce uncertainty: 2016 data set!

Measurements using the Run I dataset

Still measurements using Run I data (well calibrated and understood)

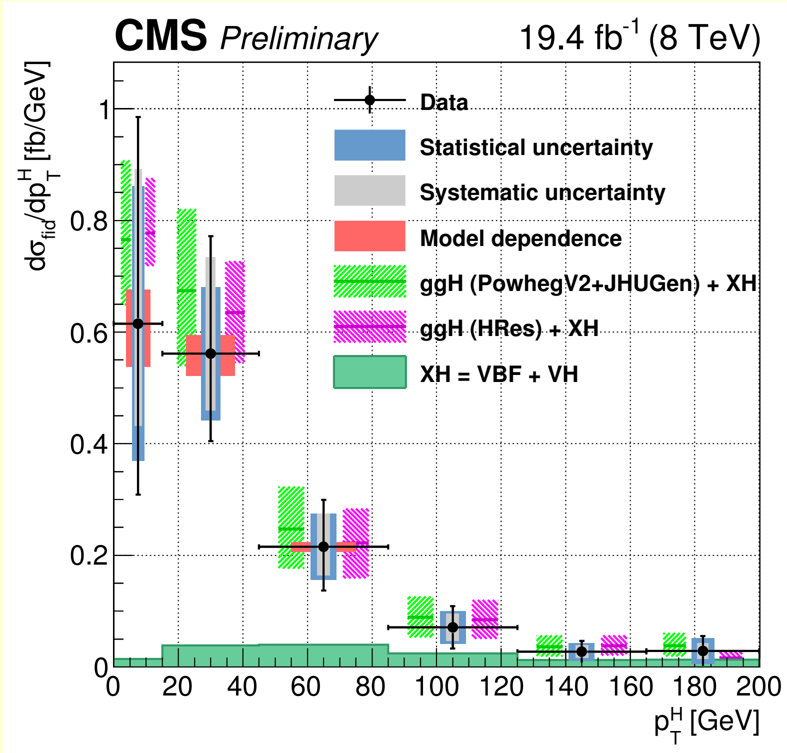
Measuring the Higgs width (using off-shell production) and the distribution as a function of p_T^H:

JHEP 09 (2016) 051



$\Gamma_H < 13$ MeV (combining WW and ZZ)

arXiv:1606.01522

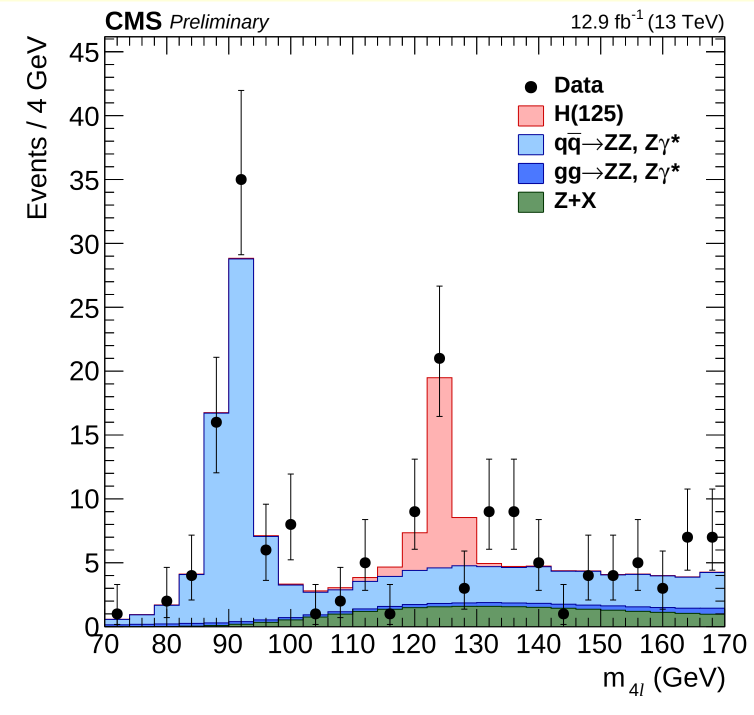


Studying the Higgs via

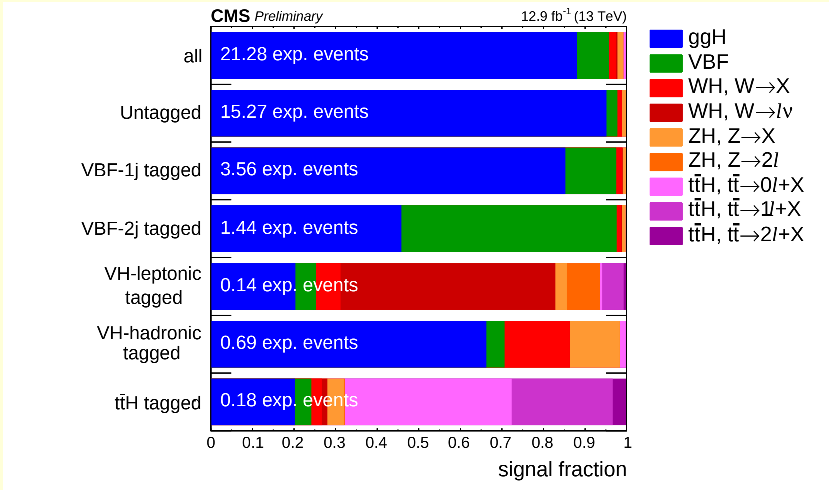
$$H \to ZZ$$

Using the 4ℓ decay to study the Higgs

- The cleanest channel by far. Since yield is small it benefits from using the data collected in 2016.
- The Higgs clearly observed where expected from Run I results.



CMS-HIG-16-033



6 categories

5 Production mechanisms

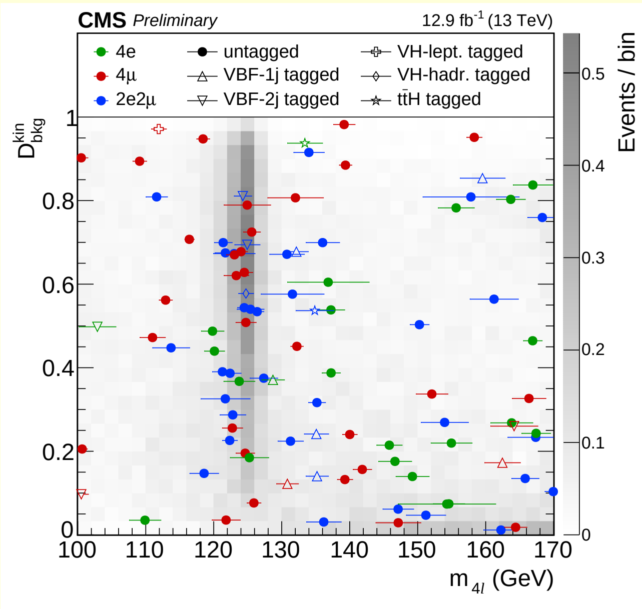
$4e$, 4μ and $2e2\mu$

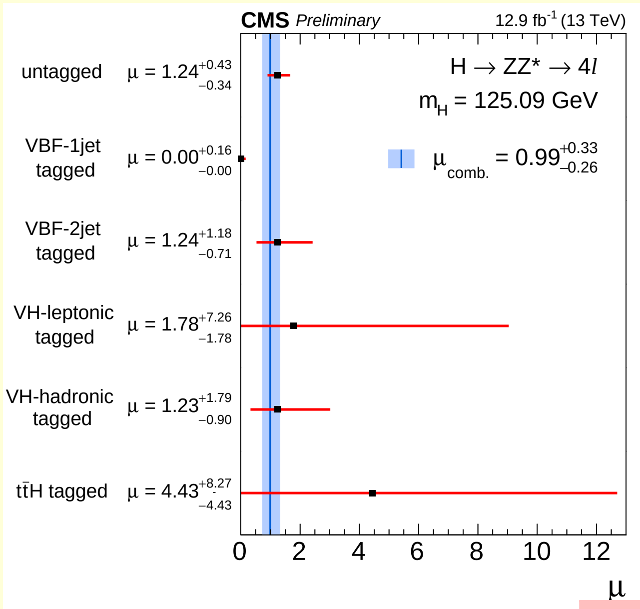
Using all 13 TeV data (at ICHEP)

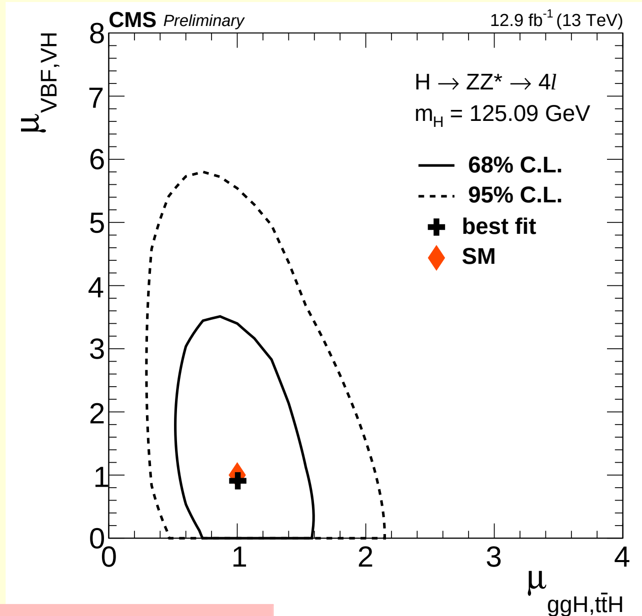
- Nice usage of the CMS capabilities to exploit the high purity.
- Great description of the $Z \to 4\ell$ reference.
- Now let's look at the properties!

Checking compatibility with SM

- The high purity allows to make precise measurements of properties in spite of the low statistics.
- Characterizing the event kinematics via a discriminant which takes into account the SM Higgs properties.
- Quantifying compatibility with SM via signal-strength:





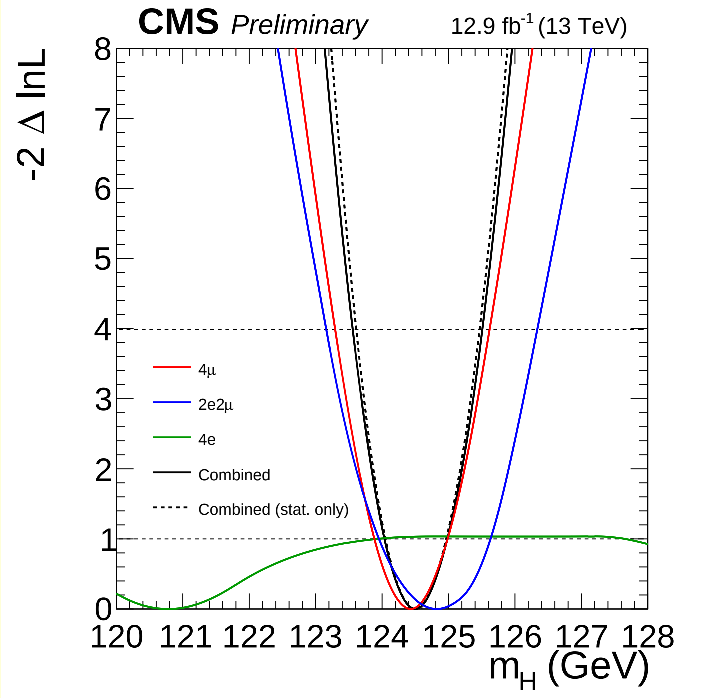


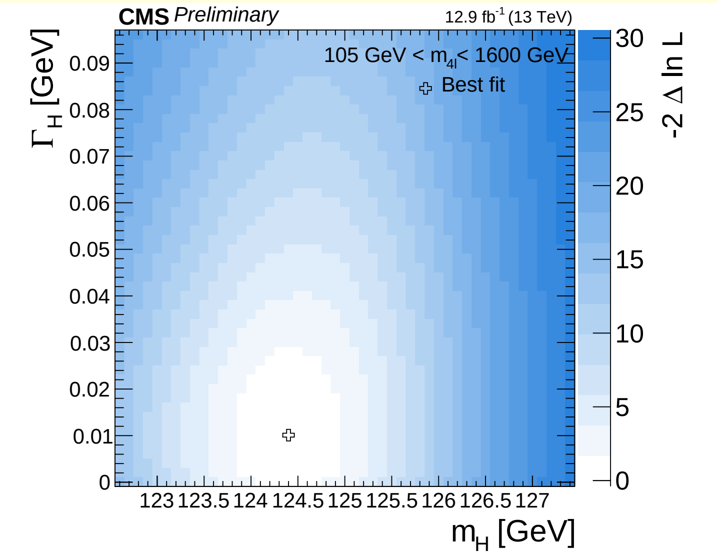
⇒ Compatible with the SM expectations: $\mu = 0.99^{+0.33}_{-0.26}$ (@125.09 GeV)

⇒ Results completely dominated by statistical uncertainties.

Measuring the mass and the width

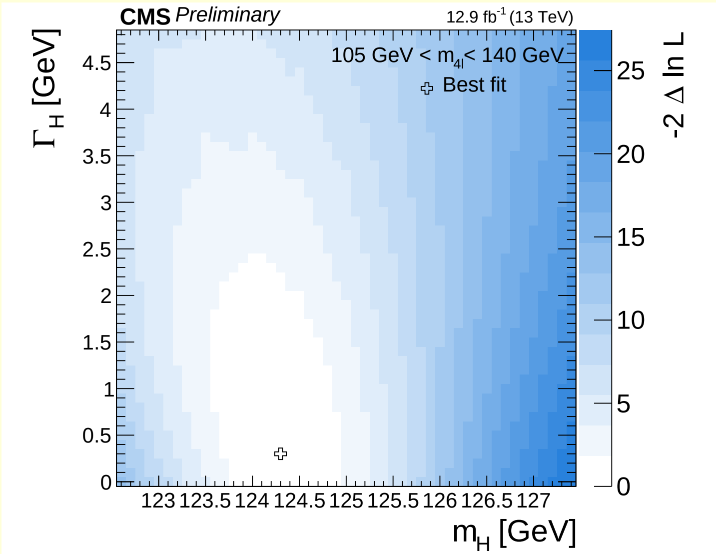
- Mass is measured performing a 1-D likelihood scan for mass hypothesis.
- Done for all the selections performed (using several discriminants)
- Also for different lepton classes
- Also measured the width:





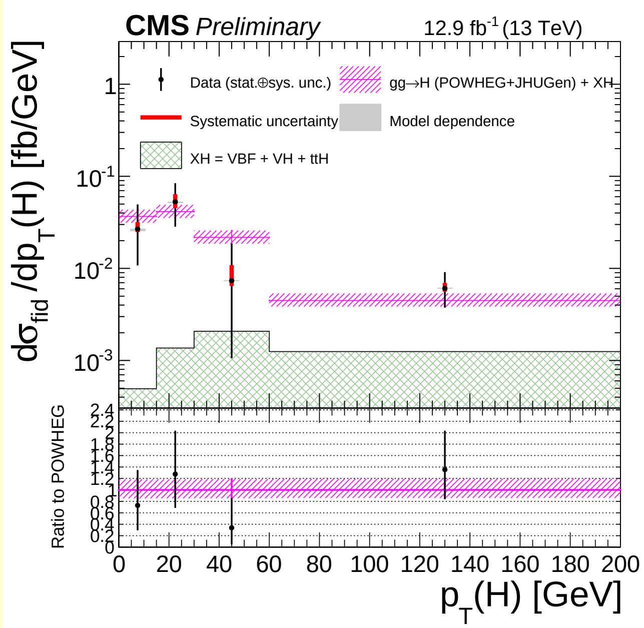
⇐ Off-shell production:
More sensitive to width

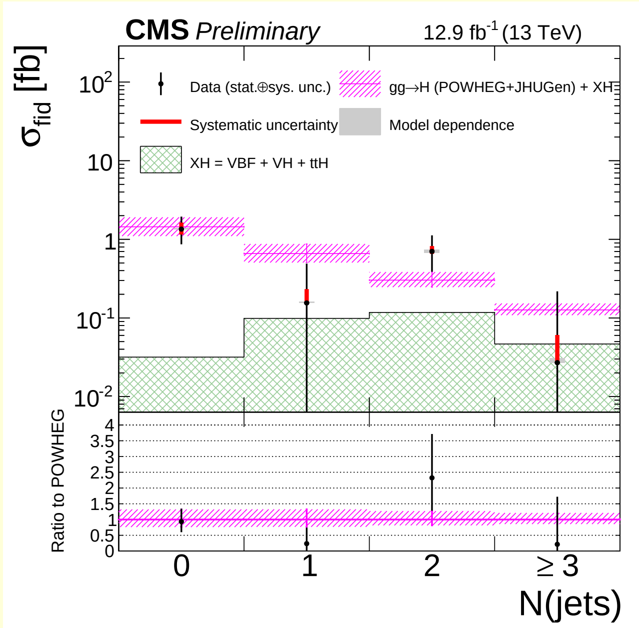
On-shell production: ⇒
Less model dependent
(lower BSM sensitivity)



Characterising the event topology

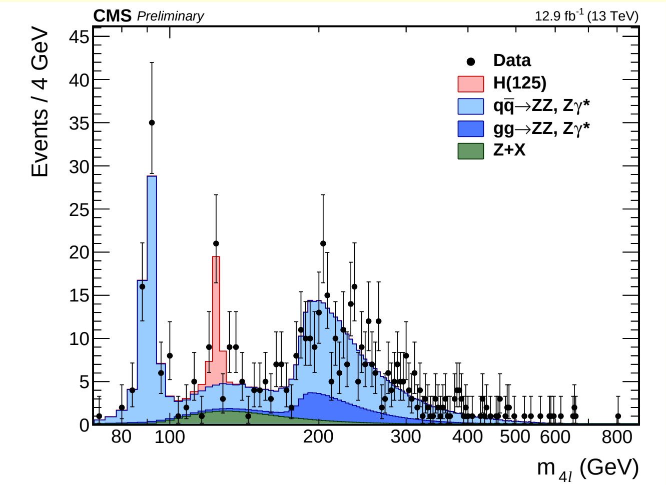
- Regardless of low statistics, the high purity also allows the study of the kinematics of the Higgs events.
- These are very important since they differ according to the production mode.
- Provide further test of the SM predictions.
- Good agreement observed in the measured distributions.
- More data to perform precise tests!
- Measurement of the fiducial cross section also performed in the analysis.

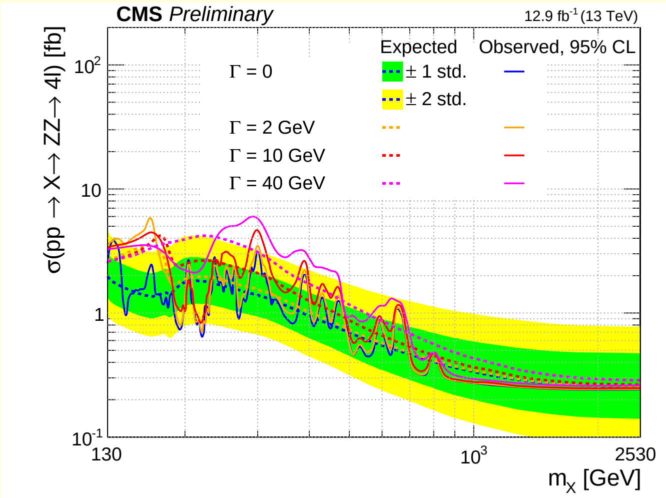


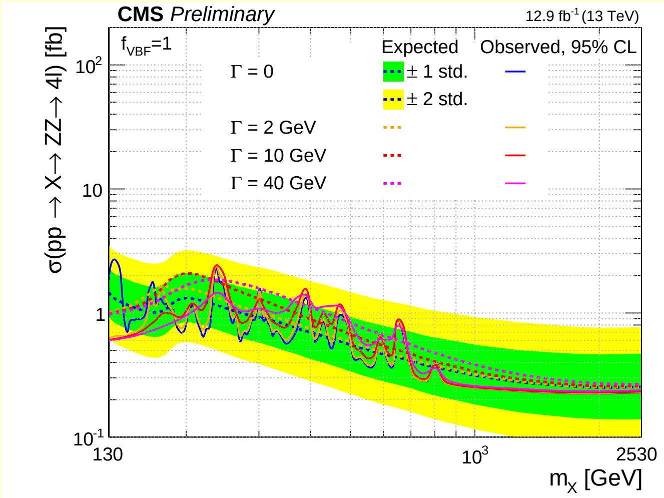


Searching for similar resonances in $ZZ(4\ell)$

- The same analysis was used to set limits on the production of other resonance decaying to ZZ.
- Width of the resonance allowed to have any value.
- An unbinned maximum likelihood fit of the $m_{4\ell}$ distribution







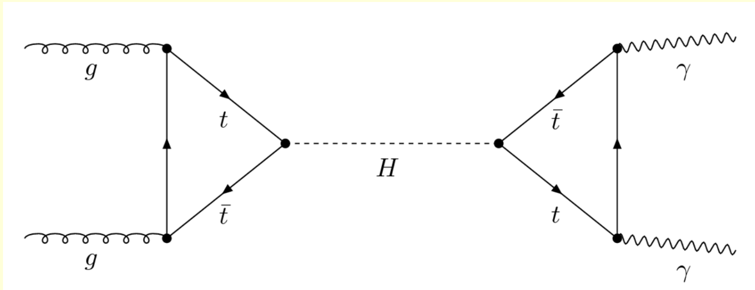
- Constraints tighter in the pure VBF approach due to lower backgrounds.
- No significant discrepancy observed in the data.

Studying the Higgs via

$$H \to \gamma\gamma$$

Analysis strategy

- Using already the 2016 dataset (the one available for ICHEP)
- Looking for two high-energy photons in the final state giving a excess at the resonance mass.
- Clean reconstruction compensates for the low production.



- Irreducible background is large. . . analysis is only feasible if events are smartly classified and selection is sensitive to a "bump":

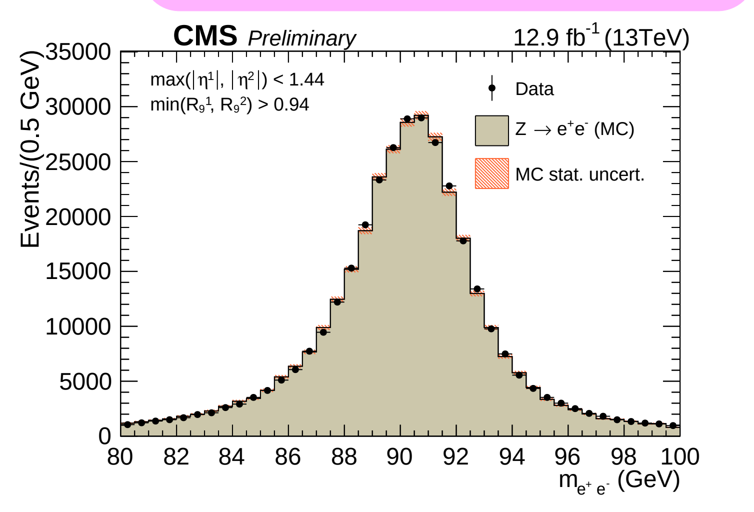
$$m_{\gamma\gamma} = \sqrt{2E_1E_2 \cdot (1 - \cos\theta_{\gamma\gamma})}$$

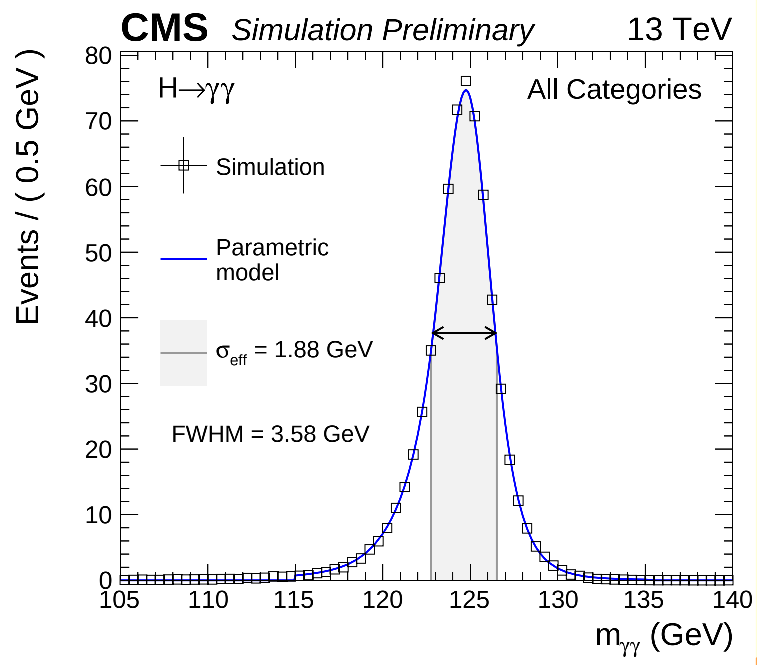
- Energy needs to be under control: energy scale for photons!
- Angle wrt Z axis is also key: correct vertex identification.

Energy scale for photons

CMS-HIG-16-020

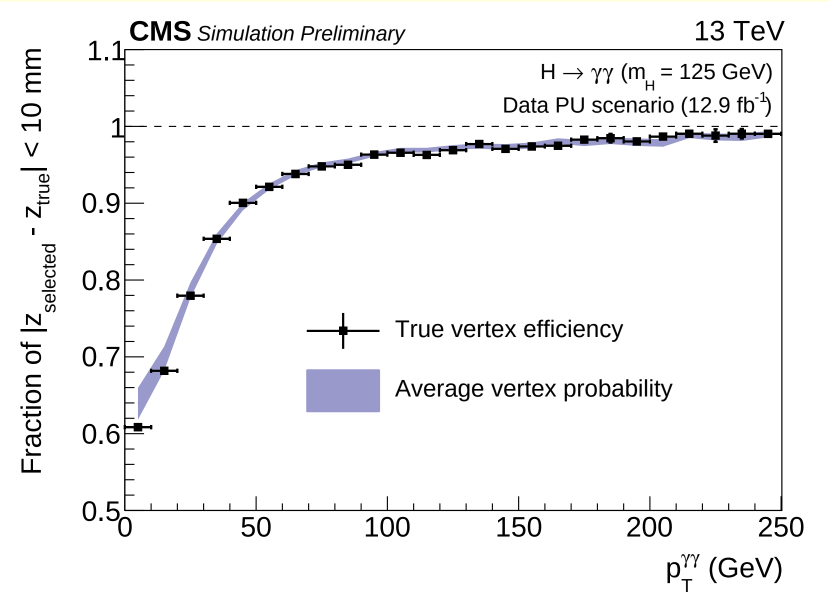
- The ECAL response needs to be calibrated:
  - change in time.
  - to be uniform in η/ϕ.
  - get the correct absolute scale.
- First we use $Z \to ee$ events reconstructed using photon IDs to set a preliminary reference point of the scale.
- Then a simulation-based correction is applied to account for slight differences between electrons and photons.
- Obtained a great resolution to boost sensitivity in all categories.

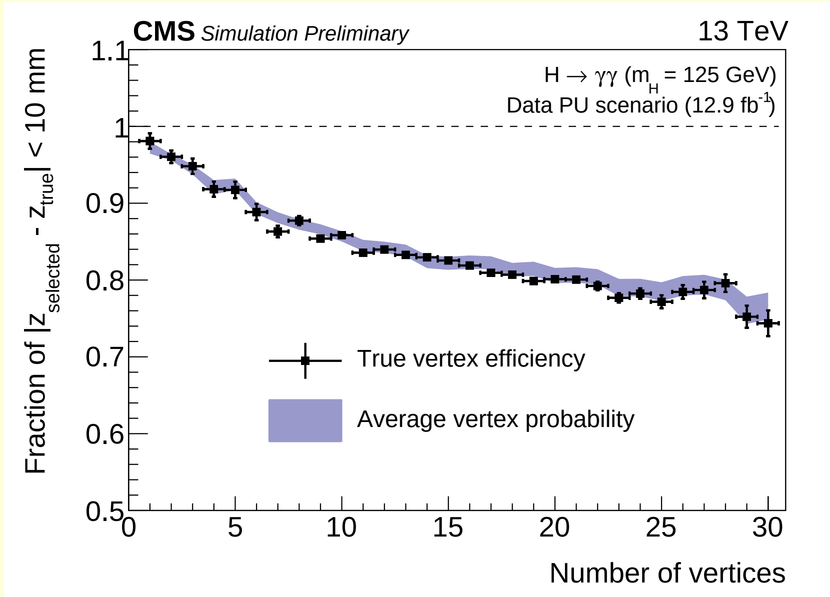




Identification of the primary vertex

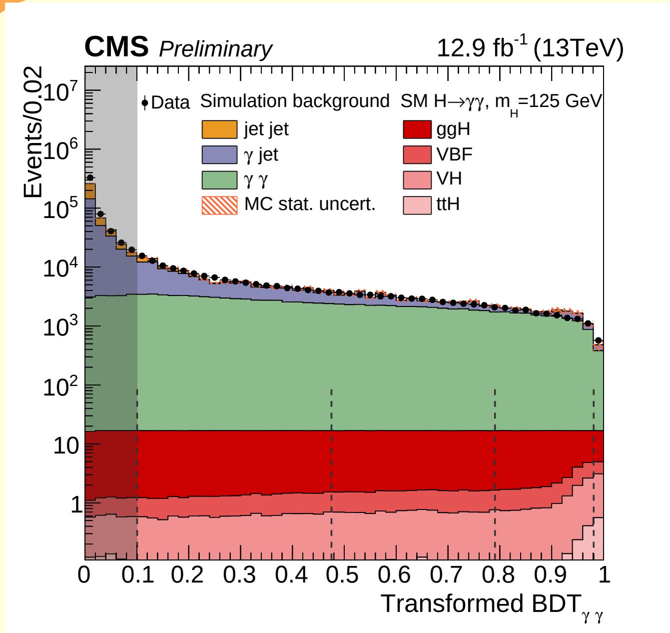
- Vertex Z correct within 1cm ⇒ no effect on mass resolution.
- Since (most) photons do not give hints on its original position, we need to use a multivariate approach to select vertex:
  - Exploit kinematic correlations and track imbalance.
  - Use conversion tracks when present.

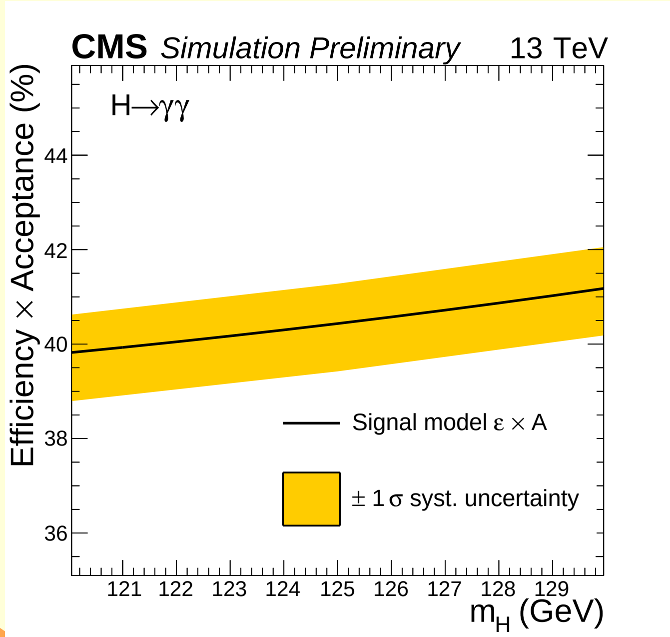




- Method was validated using $Z \to \mu\mu$, removing muon tracks.
- Using validation in γ+jet for converted photons.

Selecting and classifying the events

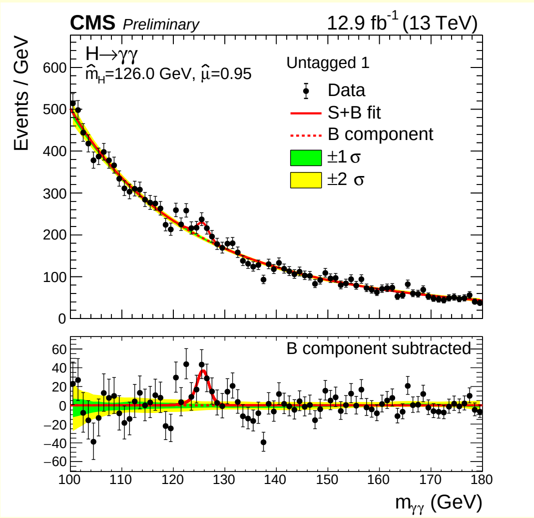


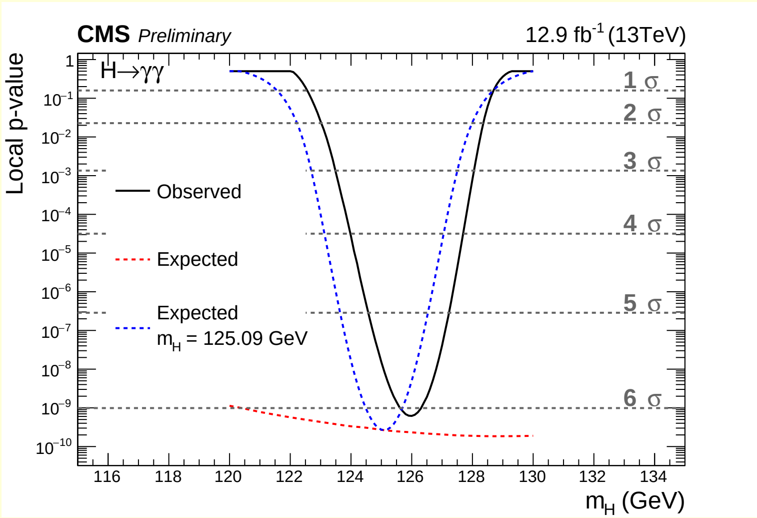


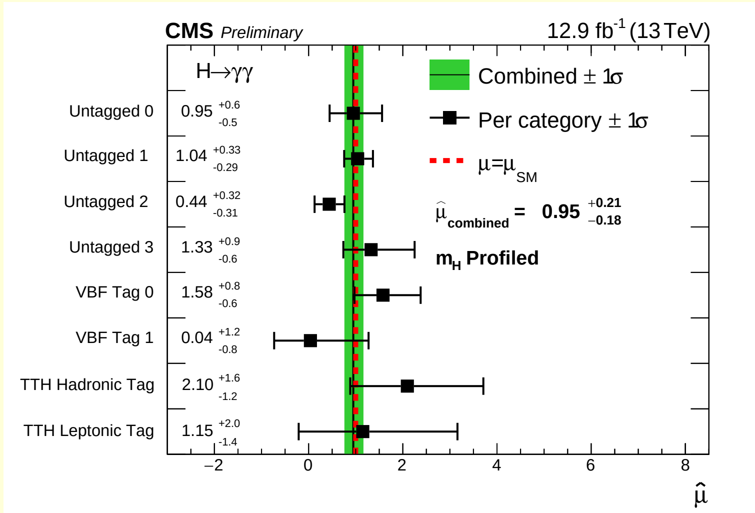
- A second MVA to estimate probability of correct vertex is used to classify the events.
- Tagging events:
  - $t\bar{t}H$ candidates (see later)
  - VBF candidates with forward jets (subclassified with BDT)
  - Rest is "untagged" (4 categories)
- Many categories to exploit all possible information about the candidates.
- and using as much yield as possible.
- High $\epsilon \times A$ in the area of interest!

Results: Signal strength

- Background is parameterized using the data: looking for a narrow peak over a smooth background.
- Functional form depends on category.







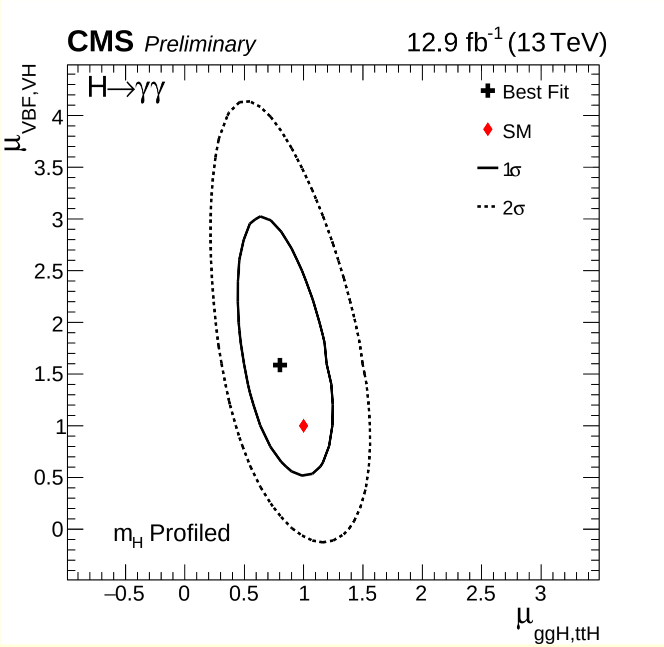
- The Higgs appears around 125 GeV with a high significance.

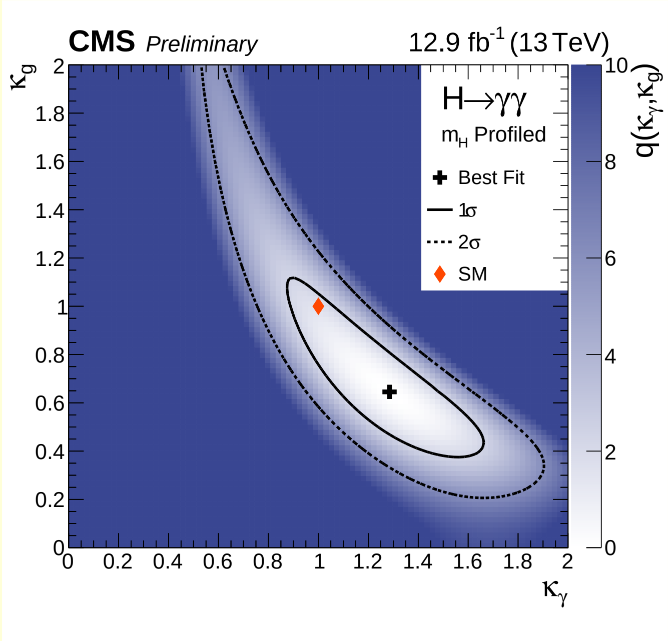
Signal strength: $\mu = 0.95 \pm 0.17(\mathrm{stat})^{+0.10}_{-0.07}(\mathrm{syst})^{+0.08}_{-0.05}(\mathrm{th})$

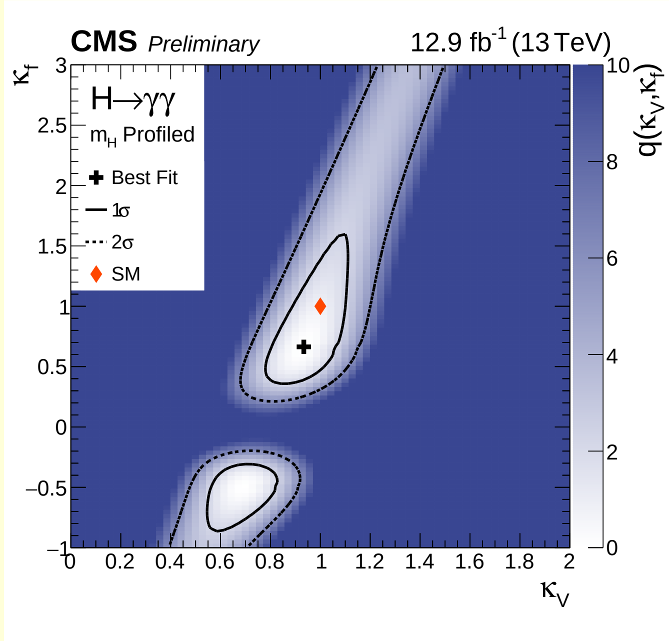
- All categories in good sync, with differences in precision.
- More data to improve this!

Measuring properties: couplings

- Measured signal strength in bosonic and fermionic and perform statistical analysis.
- Also interpreted in terms of “coupling modifiers” of the Higgs to vector bosons, fermions, gluons and photons.





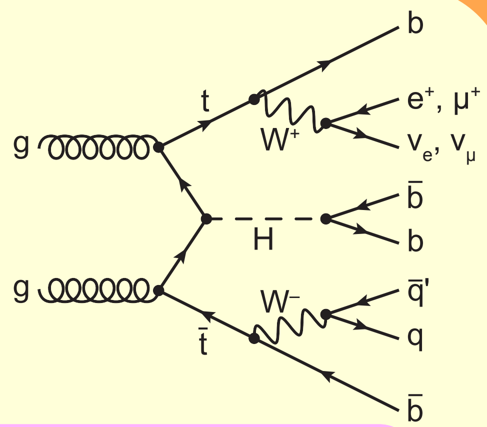


Although the Higgs has been (re-)observed a precise measurement on the mass in this channel require further refinement to reduce systematics.

Studying the Higgs via

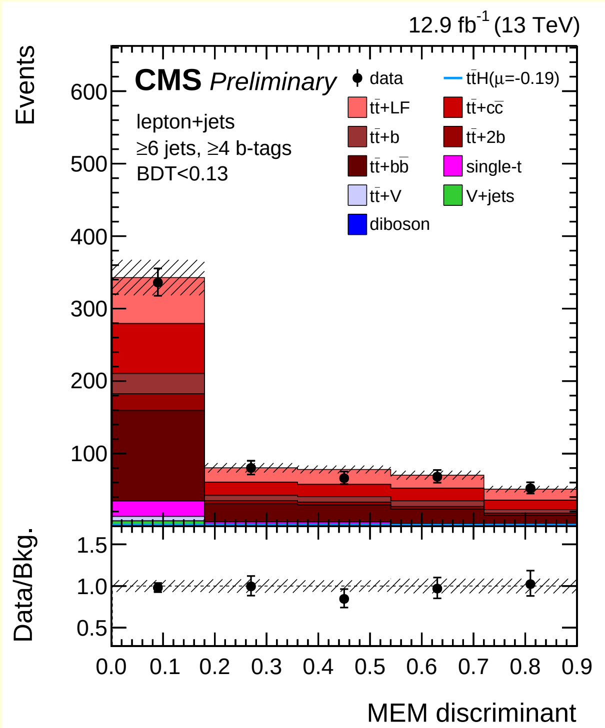
H coupling to top quark

Searching for $t\bar{t}H$ in $H \to b\bar{b}$



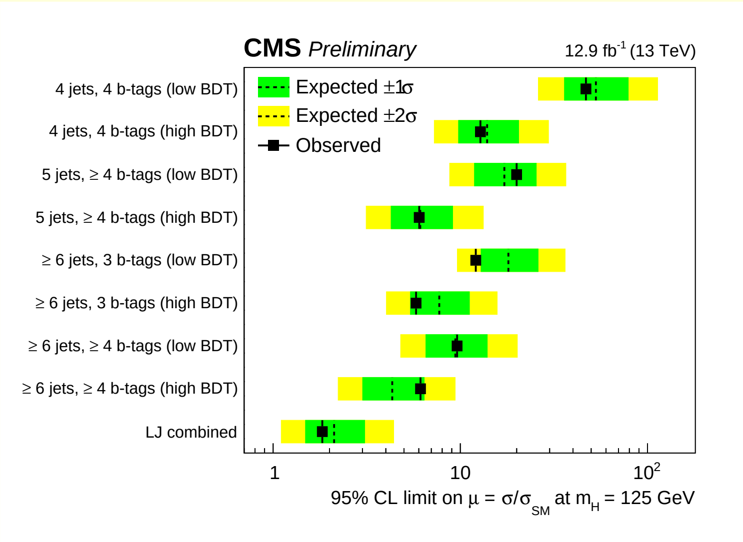
- Important process to check the coupling of top and Higgs.
- We really need to understand this coupling!
- Using $H(b\bar{b})$ to gain acceptance
- Dileptonic+"Lepton+Jets" channels used.
- 13 categories:
  - ⇒ Number of jets
  - ⇒ Number of b-tagged jets
  - ⇒ Even a boosted-jet category in ℓ+jets
- BDT-based discriminants used in each category.
- Input from Matrix-Element (MEM).

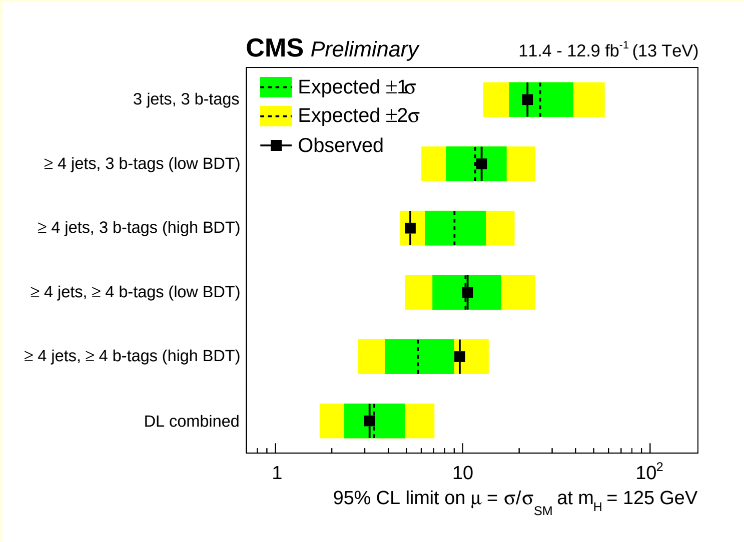
CMS-HIG-16-038

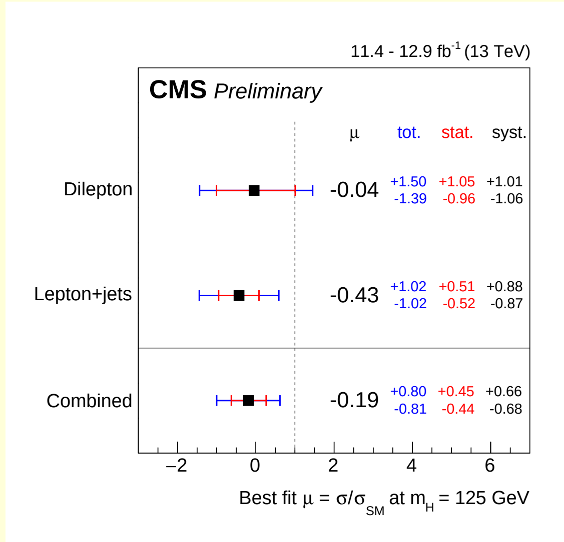


Results and Limits

- BDT shape fit is performed to extract signal.
- In the most sensitive ℓ+jets category: 2D analysis (BDT vs MEM).







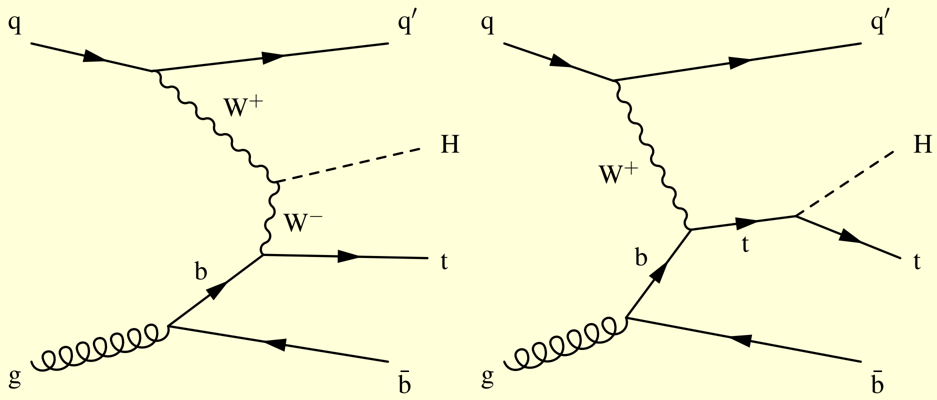
- No presence of the expected signal obtaining:

$$\mu = -0.19^{+0.45}_{-0.44}(\mathrm{stat})^{+0.66}_{-0.68}(\mathrm{syst})$$

- Excluding $\mu < 1.5$ (from 1.7 expected).
- Analysis will benefit from the larger sample in 2016.

Probing the tH coupling

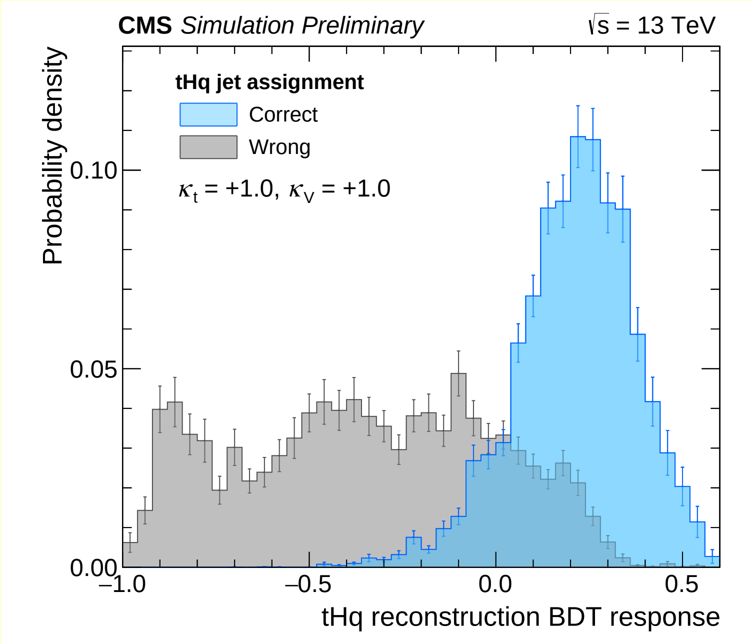
- Process with a single top on the final state highly sensitive to the nature of the tH coupling.



These diagrams interfere destructively in SM, so final-state very sensitive to anomalies in the coupling!

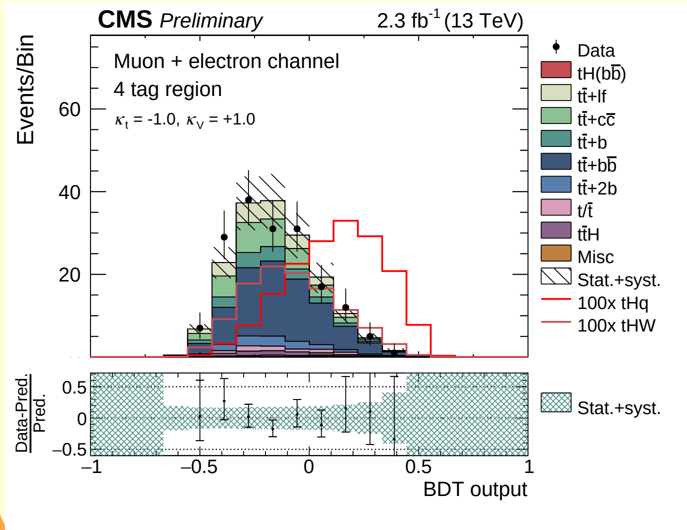
CMS-HIG-16-019

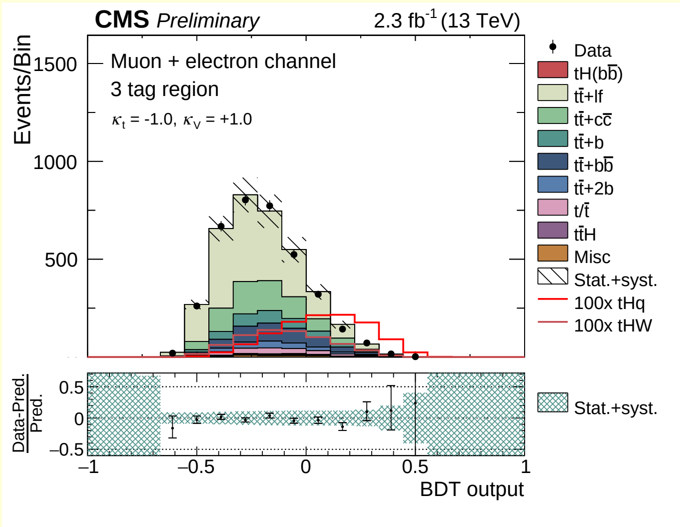
- Other diagrams present but their contribution is neglected (they contribute to incresase the signal).
- Using ℓ+jets topology
- Multijet final state require BDT-based tool to decide jet association to top, Higgs and the extra quark

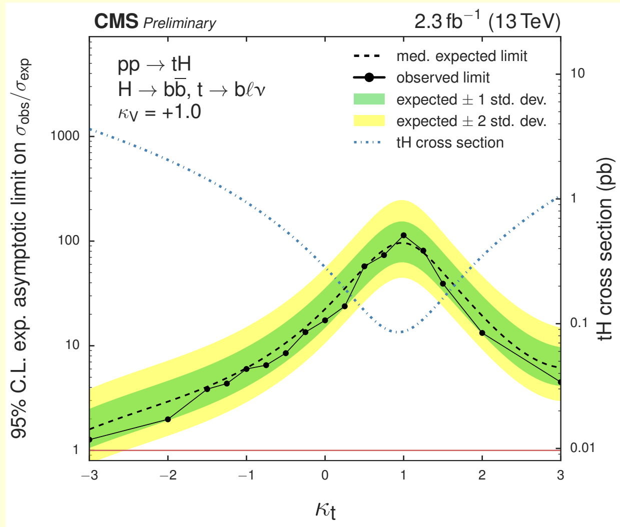


Results and limits

- Other BDT classifier used for assigment under $t\bar{t}$ hypothesis.
- Variables from different assignments (and additional ones) used for final discrimination).
- Shape analysis of the discriminant, whose training depends on the signal parameter hypothesis
- Good agreement with the SM expectation observed, in the context of inverted top coupling







$t\bar{t}H$ using $H \to \gamma\gamma$

CMS-HIG-16-020

- From categories of the global analysis
- Two kind of "event tags" used:

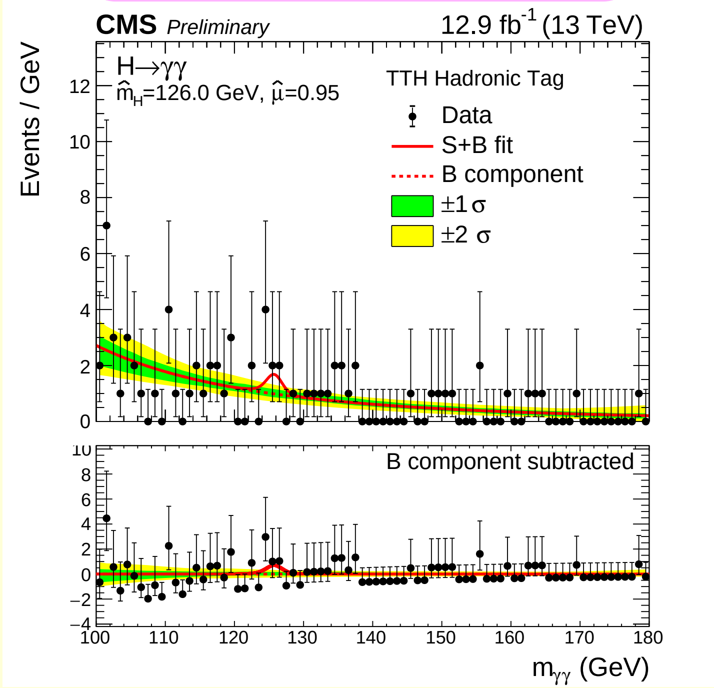
  (1) Leptonic-tag
  - At least one e or μ with p_T>20 GeV
  - all leptons have $\Delta R(\ell, \gamma) > 0.4$
  - At least 2 jets ($p_T > 25$ GeV)

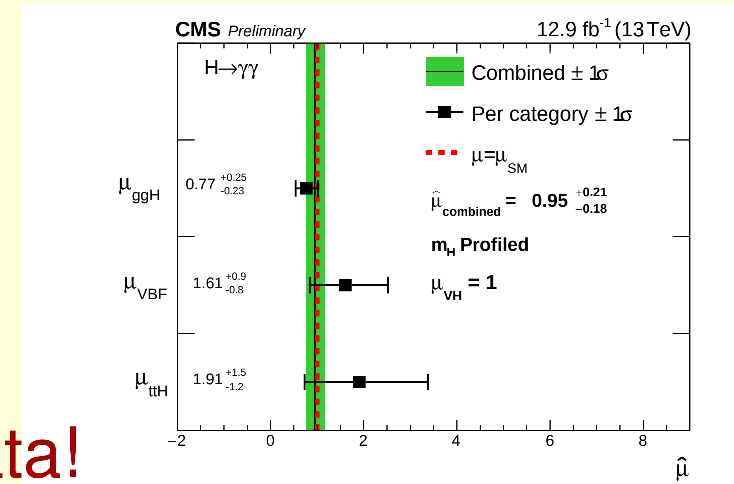
  (2) Hadronic-tag
  - No e nor μ (as above)
  - At least 5 jets ($p_T > 25$ GeV)

- In both cases, at least a b-tagged jet

These to get: $\mu = 1.9^{+1.5}_{-1.2}$

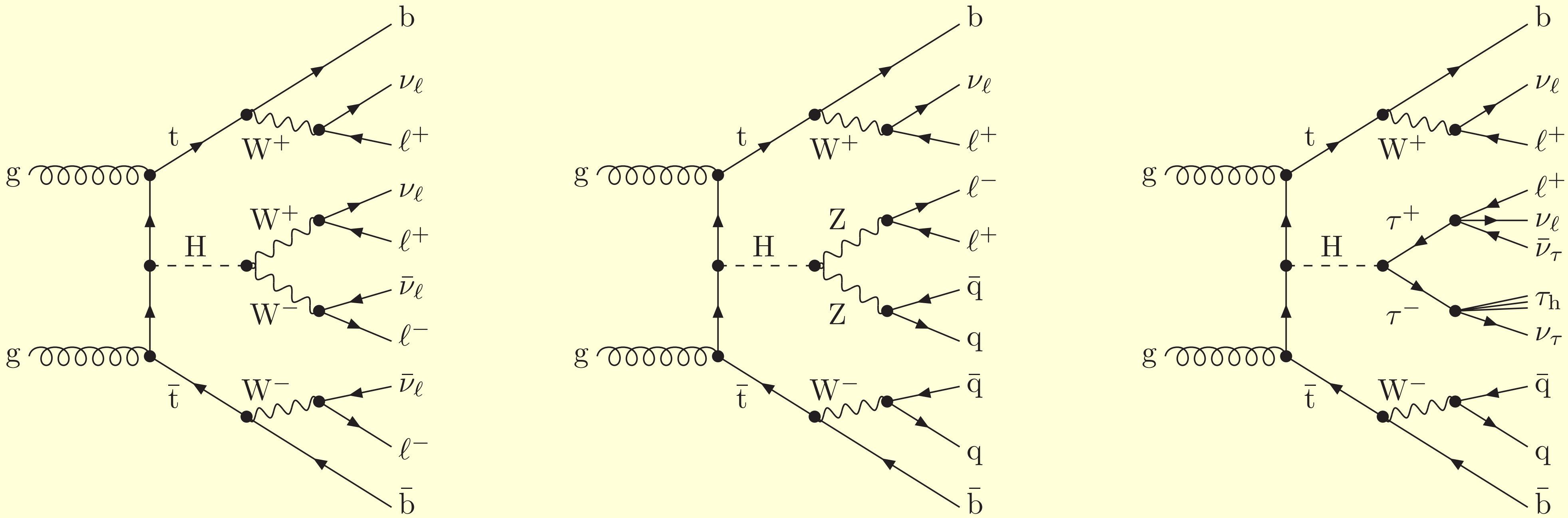
- Sensitivity reduced due to yield: more data!





$t\bar{t}H$ in multileptonic final states

Looking at the following final states for $t\bar{t}H$:



they can be identified taking advantage of the many leptons in the final state.

⇒ Low backgrounds having two same-charge dileptons.

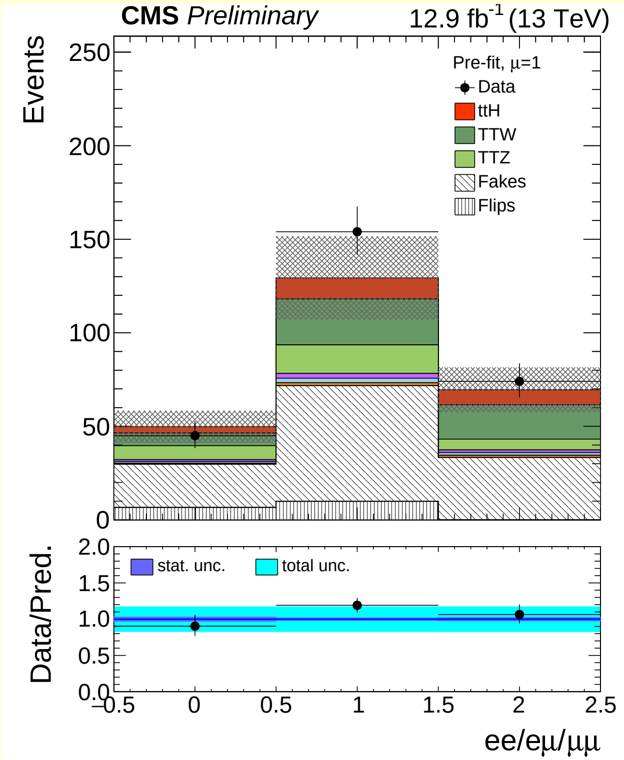
⇒ Low backgrounds with 3 or more leptons.

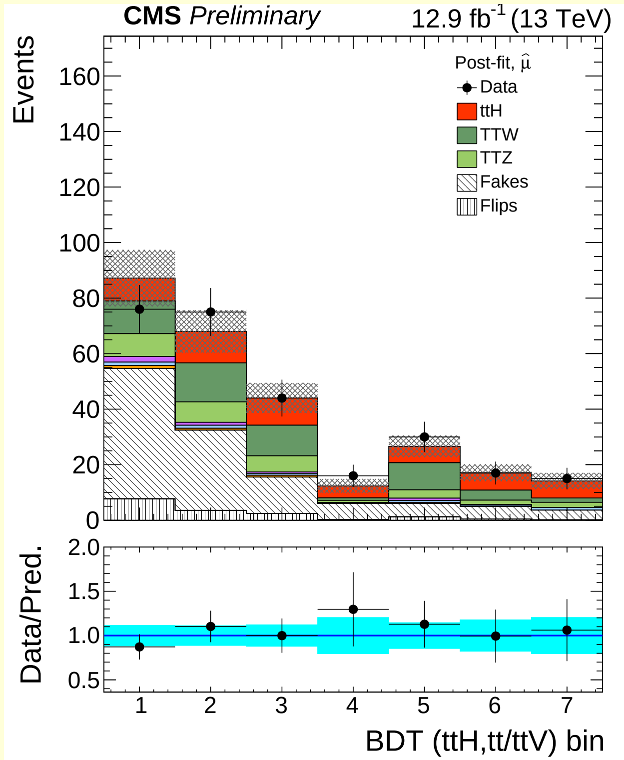
Some loss in acceptance, but increase in sensitivity!

$t\bar{t}H$ in same-sign dilepton events

- Requiring two same-sign leptons (e or μ) and 4 jets.
- We require some b-tagged jets (two loose or 1 medium) to enhance the presence of top-quark processes.

CMS-HIG-16-022



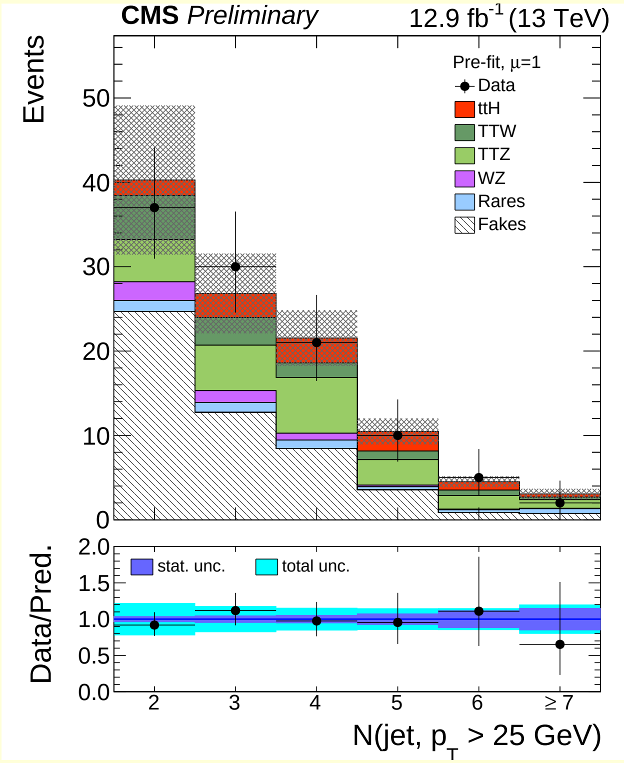


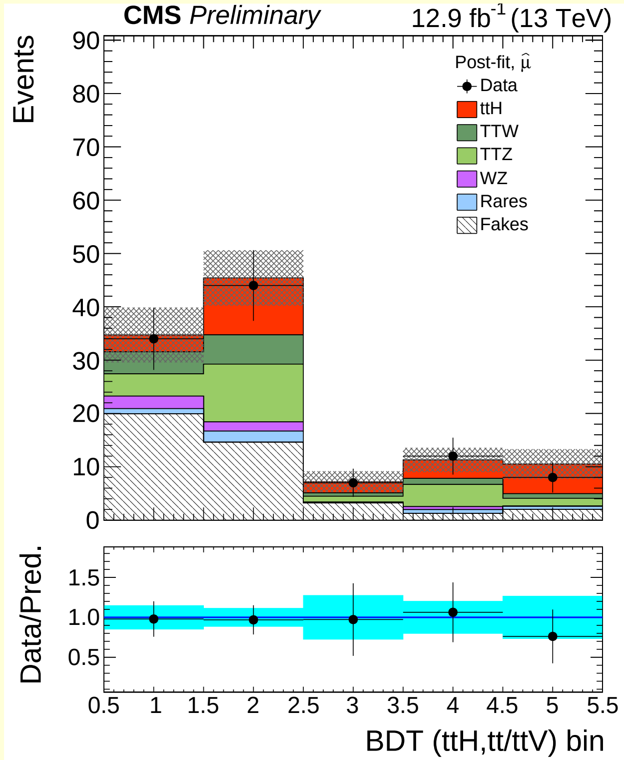
- Enhancing sensitivity with a BDT-based categorization.

$t\bar{t}H$ in trilepton events

- Similar as before, but now for 3 leptons.
- New in 3ℓ: using matrix-element weights for $t\bar{t}H$ and $t\bar{t}V$ hypothesis to help discrimination.

CMS-HIG-16-022





- Presence of signal: a 2D fit to the discriminators.

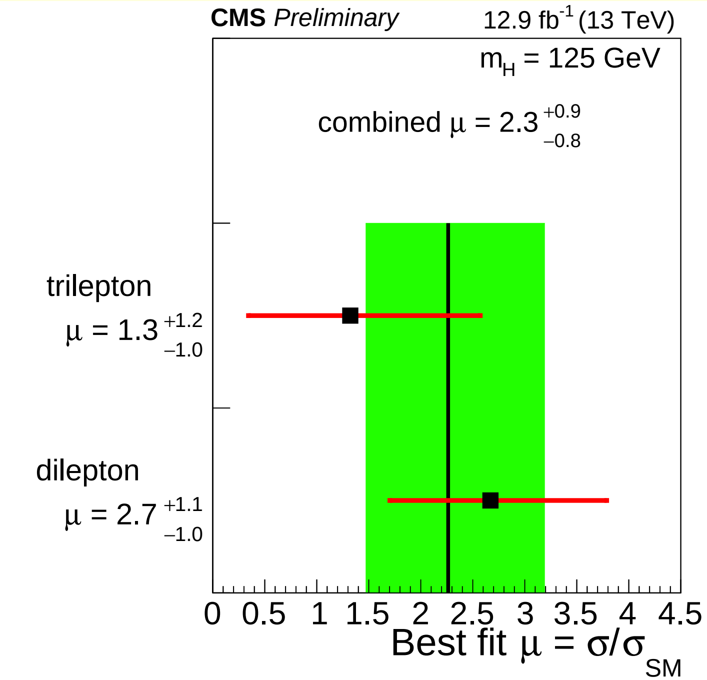
Results

- Obtained yields and results show high sensitivity regardless hard-to-deal detector-induced events:

  $\Rightarrow$ something misidentified (lepton charge, particle nature)

  $\Rightarrow$ hadronic-origin leptons taken as coming from weak bosons

	$\mu\mu$	ee	eμ	3ℓ
$t\bar{t}W$	18.3 ± 0.9	6.8 ± 0.6	24.5 ± 1.1	12.2 ± 0.7
$t\bar{t}Z/\gamma^*$	5.8 ± 0.6	7.4 ± 0.6	15.3 ± 1.3	22.6 ± 1.0
Di-boson	1.4 ± 0.2	1.1 ± 0.2	2.6 ± 0.3	5.7 ± 0.4
tttt	0.8 ± 0.2	0.4 ± 0.1	1.5 ± 0.2	1.2 ± 0.1
tqZ	0.2 ± 0.3	0.4 ± 0.4	0.6 ± 0.6	2.7 ± 0.8
Rare SM bkg.	1.6 ± 0.3	0.5 ± 0.1	1.8 ± 0.1	0.3 ± 0.1
Charge mis-meas.		6.7 ± 0.1	10.0 ± 0.1	
Non-prompt leptons	33.4 ± 1.2	23.1 ± 1.1	61.9 ± 1.7	51.0 ± 1.8
All backgrounds	61.5 ± 1.7	46.4 ± 1.5	118.0 ± 2.5	95.7 ± 2.3
$t\bar{t}H$ ($H \to WW^*$)	6.3 ± 0.2	2.6 ± 0.1	8.5 ± 0.2	8.0 ± 0.2
$t\bar{t}H$ ($H \to \tau\tau$)	1.6 ± 0.1	0.7 ± 0.1	2.5 ± 0.1	2.1 ± 0.1
$t\bar{t}H$ ($H \to ZZ^*$)	0.2 ± 0.0	0.1 ± 0.0	0.3 ± 0.0	0.5 ± 0.0
Data	74	45	154	105



Combining with 2015 result: $\mu = 2.0^{+0.8}_{-0.7}$

The Higgs sector
beyond its basic properties

(anomalies, self-coupling, partners & Co.)

Is *this* Higgs really what the SM expects?

- No doubt something like the expected Higgs is there, and most of their properties are reasonably known by now.

Do we care about something else to confirm it is *the* SM Higgs?

- Yes, it may show small deviations from SM expectations.
- Yes, it may have unexpected decays! (Pseudoscalars, invisible, . . .)
- Yes, we need to test the self-coupling properties.

Should we care about something else?

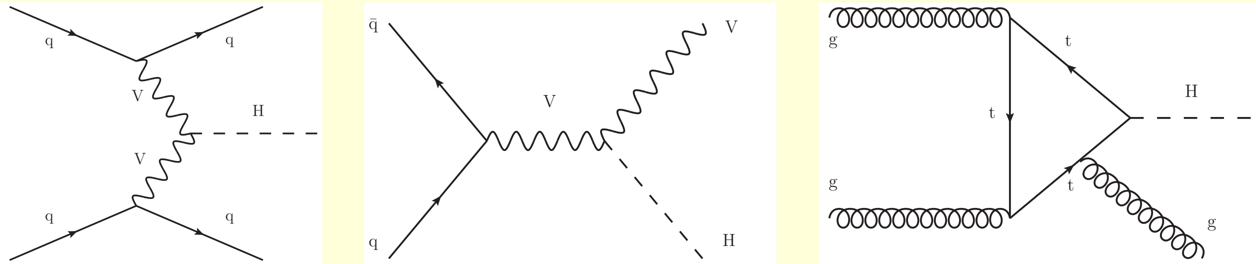
- Yes, the Higgs sector is interesting by itself: are there more Higgs bosons? Is the Higgs a door to find new particles?
- The Higgs sector could be the way to "New Physics".

- The Higgs looks too important to make the SM to work. . .

Hard to believe it is just "the last piece"

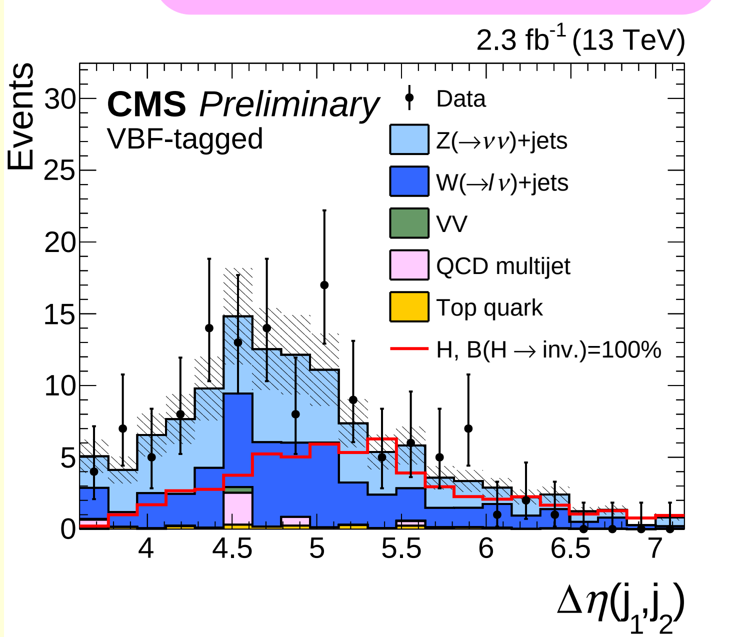
Invisible Higgs decays

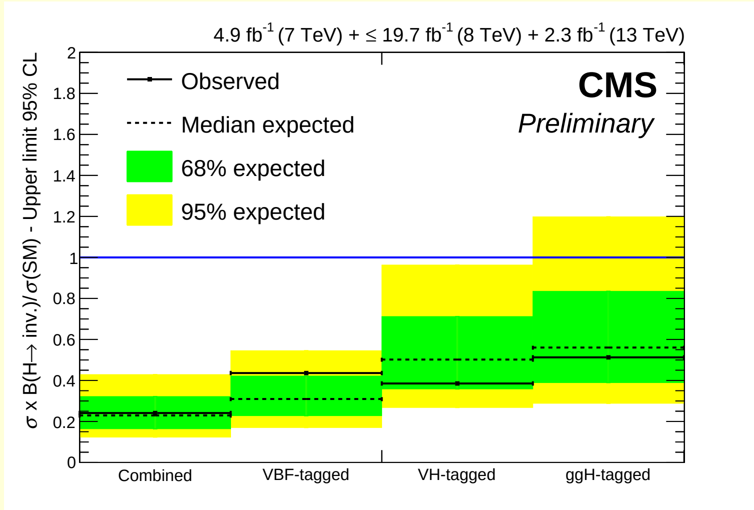
- The Higgs may be coupling to undetectable particles and decaying into them.
- The Higgs is coupled to a Dark-sector (or neutrinos)?
- Constrained by the width measurements.
- To "observe" this decay, we need to tag events with additional objects:



- Need to identify VBF topology (forward jets)
- Or identify the associated objet.
- No deviation observed: limits set by channel (and all combined)

arXiv:1610.09218

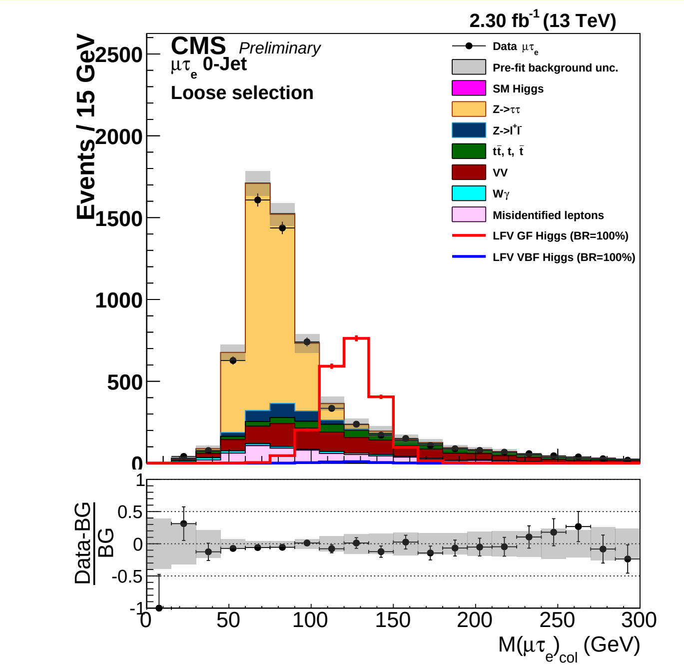


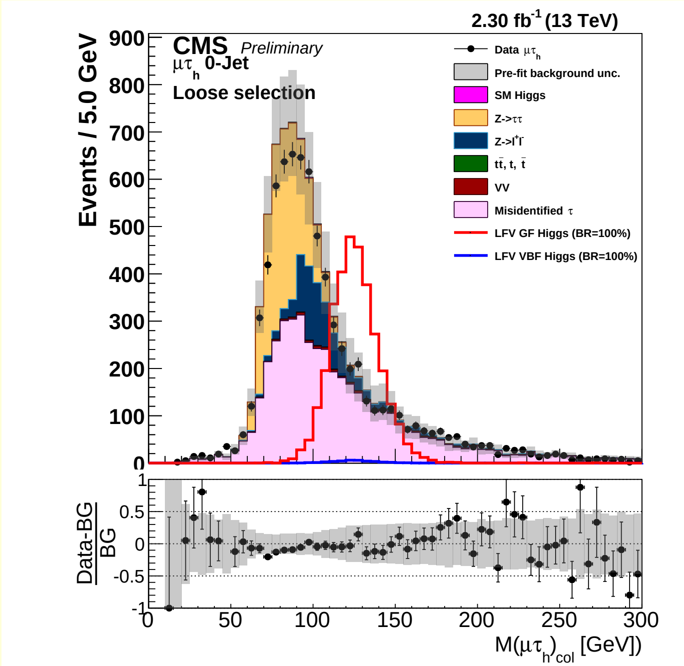


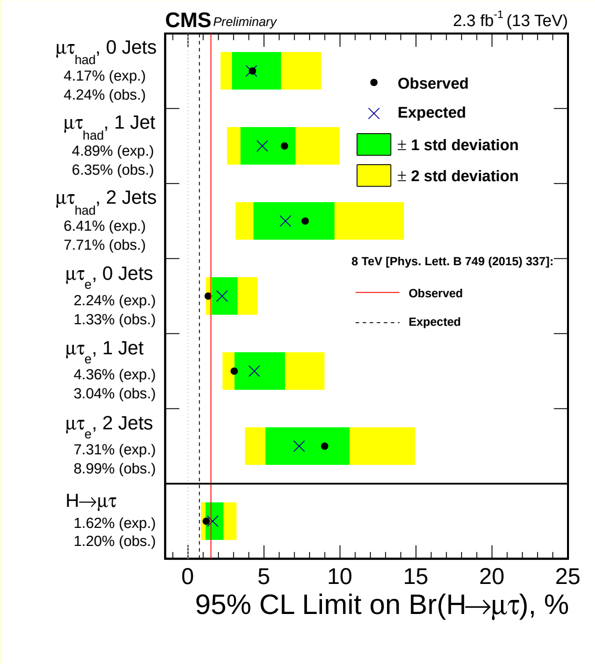
Search for LFV $H \to \mu\tau$

- Its detection would imply physics beyond the SM!
- Excess ($\sim 2.4\sigma$) observed in the Run I data
- Challenging channel: good knowledge of detector/objects.

CMS-HIG-16-005





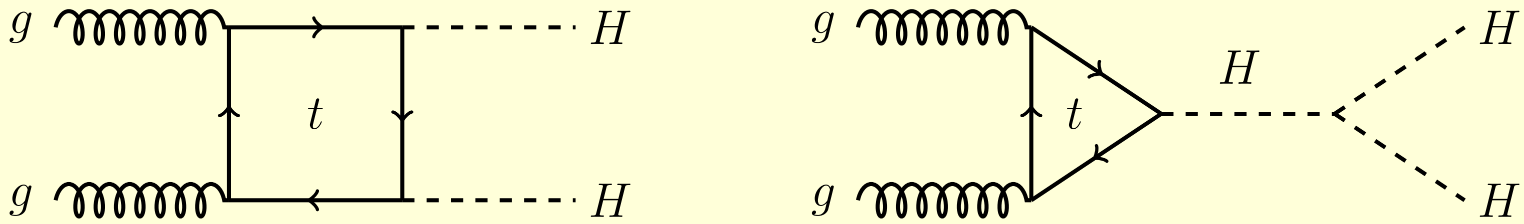


$B(H \to \mu\tau) <$ 1.20 (1.62 expected)

- No excitement, but not yet excluding the excess in Run I.

Double Higgs production

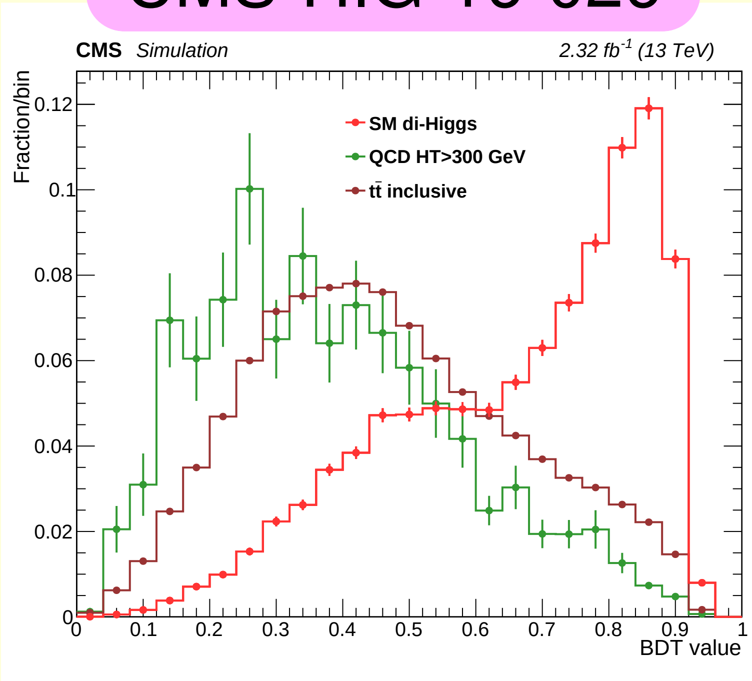
- Production of two Higgs boson is sensitive to Higgs self-coupling:



- Important test of the SM Higgs sector and Higgs potential.

Searching in the $H(b\bar{b})H(b\bar{b})$ channel

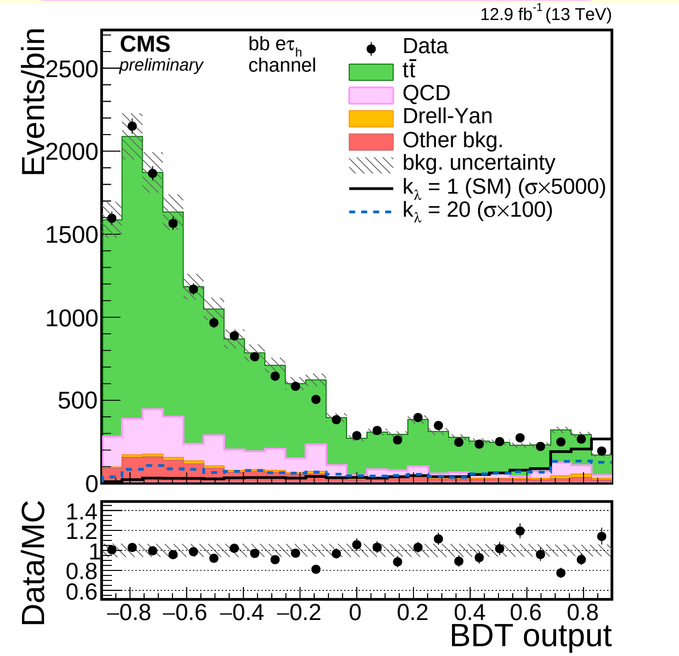
CMS-HIG-16-026

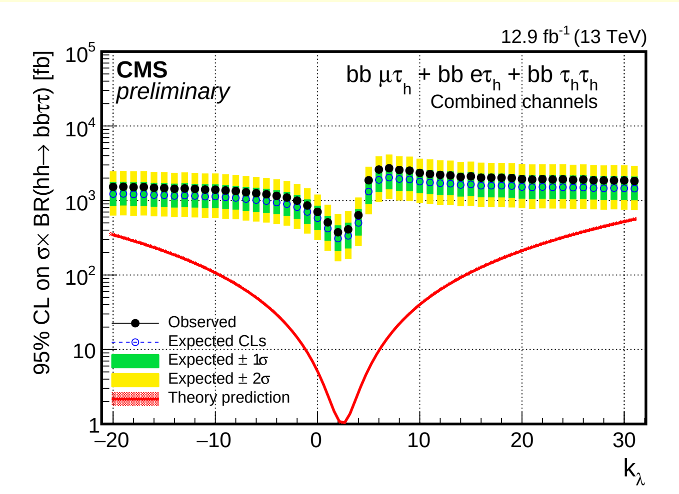


- Large Branching Ratio
- Needs to deal with high background:
  - $\Rightarrow$ 4 b-tagged jets
  - $\Rightarrow$ BDT-classifier (dijet properties)
- No presence of signal detected
- Limit set: $\sigma \cdot B(H \to b\bar{b})^2 <$3880 fb

Double Higgs production: $b\bar{b}\tau^+\tau^-$ channel

CMS-HIG-16-028

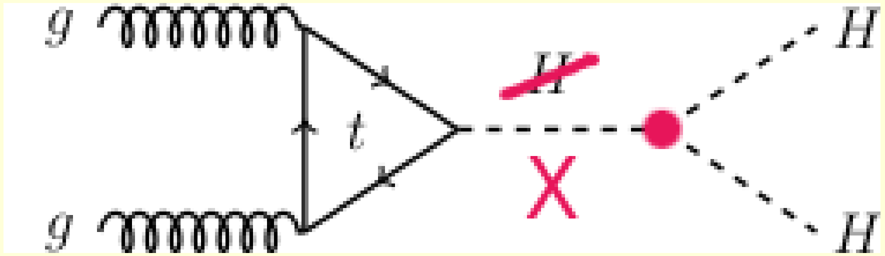




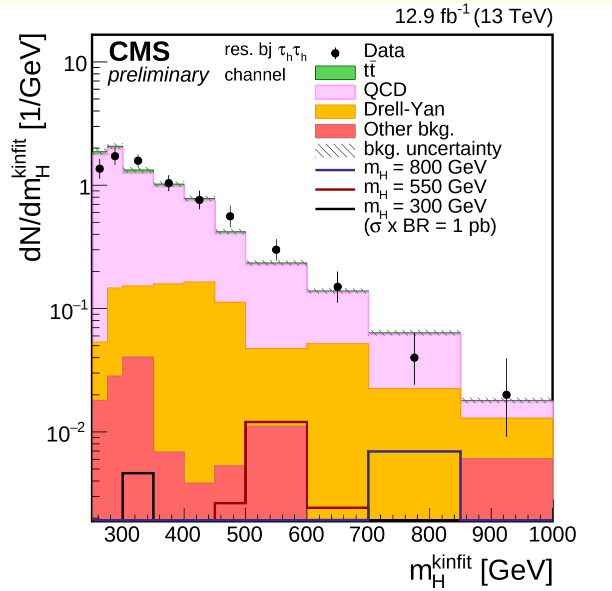
- Lower BR, more handable backgrounds.
- 3 tau-modes: $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$
- Cut on masses of $b\bar{b}$ y $\tau\tau$ (compatibility with the Higgs).
- Large $t\bar{t}$ background is dealt with using a BDT discriminant.
- Based on angular variables only.
- The visible mass is used as final discriminant.
- No excess observed, limit at 200×SM.
- Studied as a function of an anomalous trilinear coupling ($k_\lambda = \lambda_{hhh}/\lambda_{SM}$).

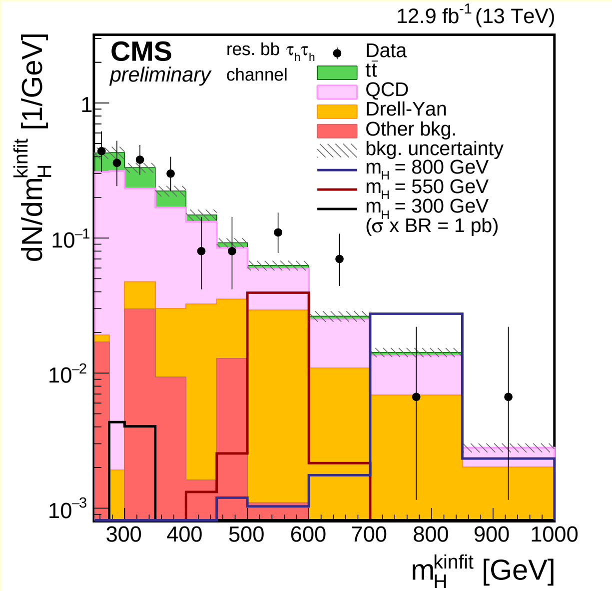
Double Higgs: resonant production?

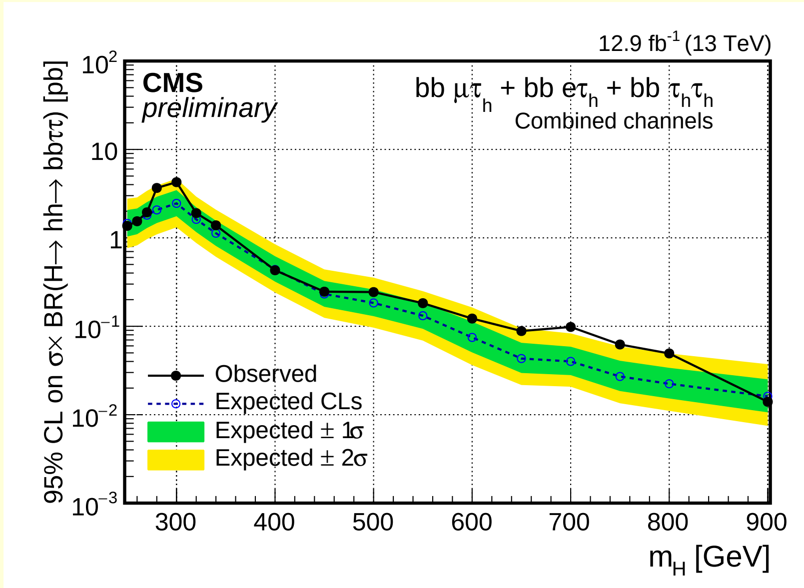
- Double Higgs production may be also enhanced by an intermediate resonance.
- Similar analysis using 4-body mass (with a kinematic fit)



CMS-HIG-16-029







- Three categories: 2 b-jets, 1 b-jet and boosted b-jets
- No significant excess: setting limit on $\sigma \cdot B$

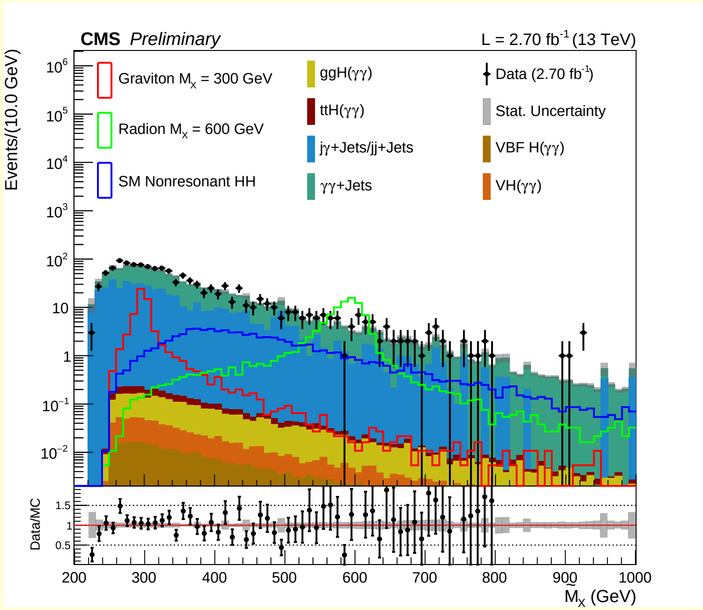
Double Higgs Production: $b\bar{b}\gamma\gamma$ channel

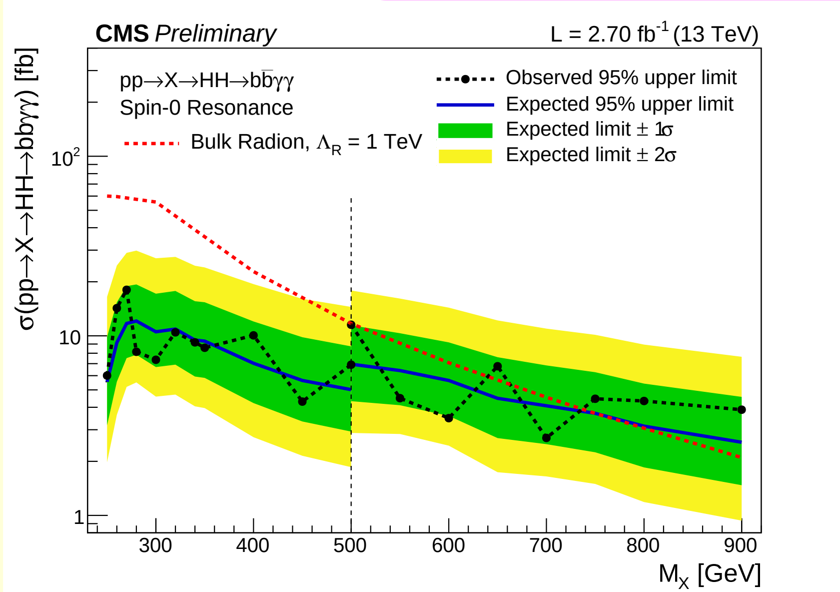
- The branching ratio is expected to be so small that a resonant analysis is more motivated.
- To improve the sensitivity, the following "adjusted" mass is obtained from the final-state objects:

$$\tilde{M}_X = M(jj\gamma\gamma) - M(jj) + 125\ \mathrm{GeV}$$

- Main variable of the analysis.

CMS-HIG-16-032



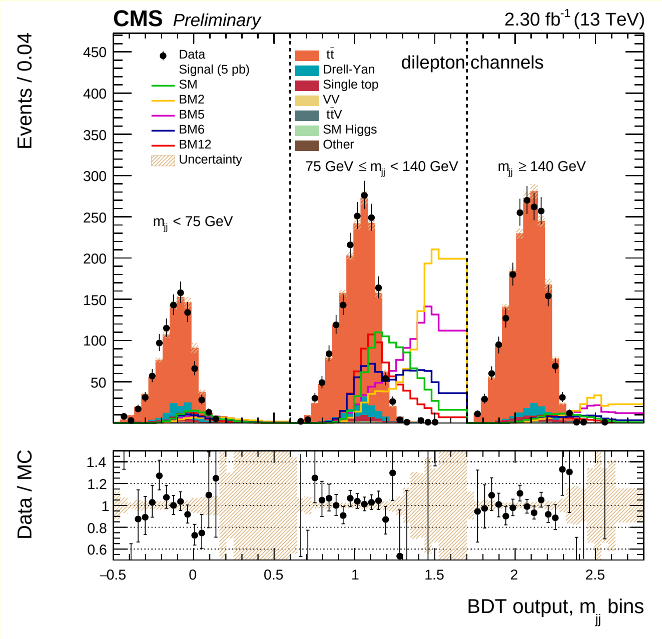


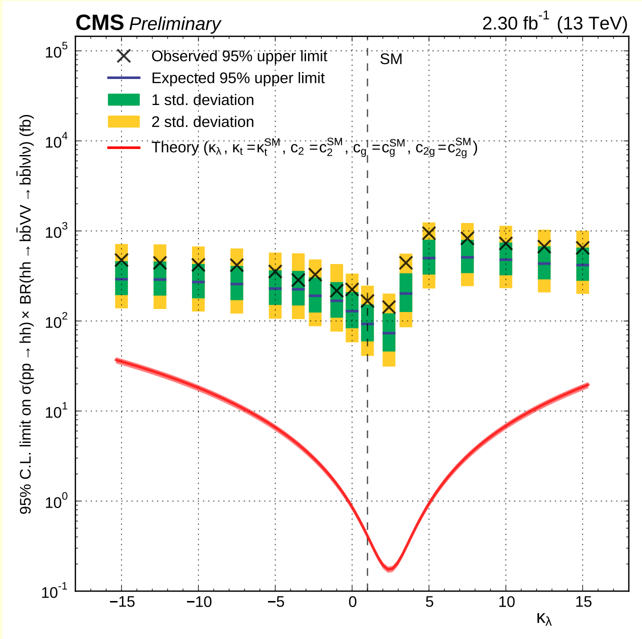
Limits on spin-0 (Radion), spin-2 (Graviton) and non-resonant production.

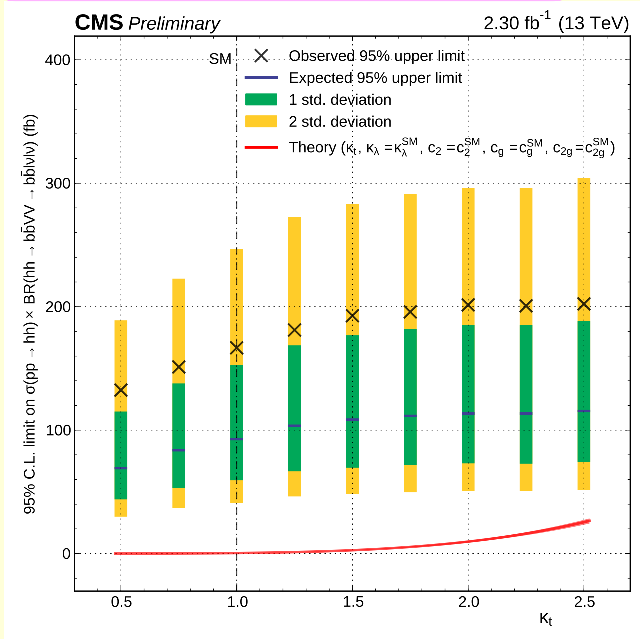
Double Higgs Production: $b\bar{b}\ell\nu\ell\nu$ channel

- Search for $H(WW)H(b\bar{b})$ in the dilepton channel.
- BDT-based discriminant to enhance sensitivity and use 2D fit on the discriminant and $b\bar{b}$ mass.

CMS-HIG-16-024







- Good description from backgrounds.
- Non-resonant analysis sensitive to $\mathscr{O}(400\times\text{SM})$.
- Similar analysis (2 BDTs) for resonant interpretation.

Completing the Higgs sector

Searches of other Higgses predicted in models extending the SM.

The Higgs sector is still unknown: needs exploration!

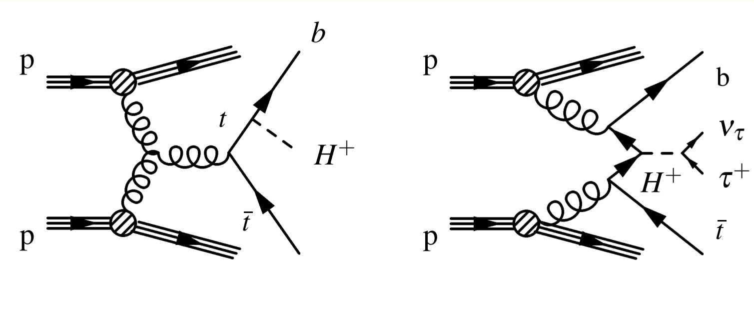
Here some of the latest efforts:

CMS-HIG-16-031	Search for charged Higgs bosons with the $H^{\pm} \to \tau^{\pm}\nu$ decay channel in the fully hadronic final state
CMS-HIG-16-027	Search for charged Higgs bosons in WZ decays at 13 TeV
CMS-HIG-16-030	Search for $H^{+} \to c\bar{b}$ in lepton+jets channel using top quark pair events
CMS-HIG-16-025	Search for a narrow heavy resonance decaying to bottom quark-antiquark pairs
CMS-HIG-16-023	Search for high mass Higgs to WW with fully leptonic decays using 2015 data
CMS-HIG-16-037	Search for a neutral MSSM Higgs boson decaying into $\tau\tau$

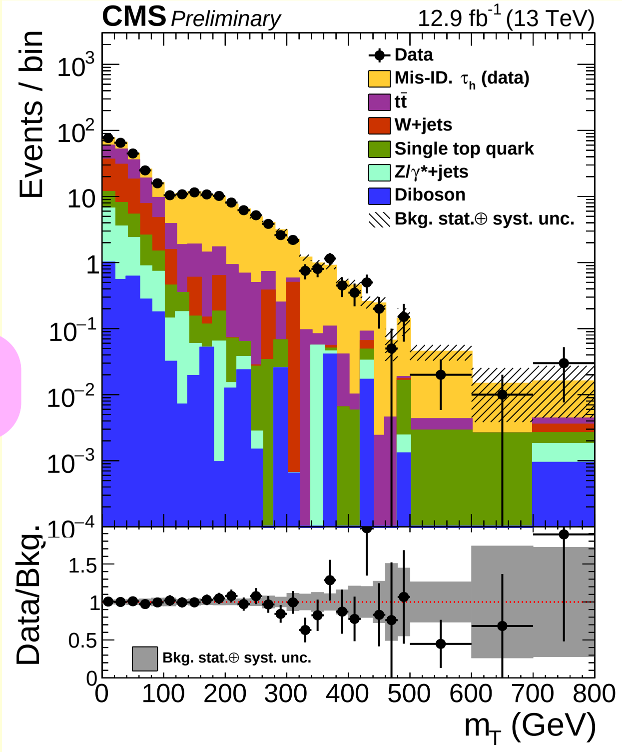
that come to join the many others done previously!

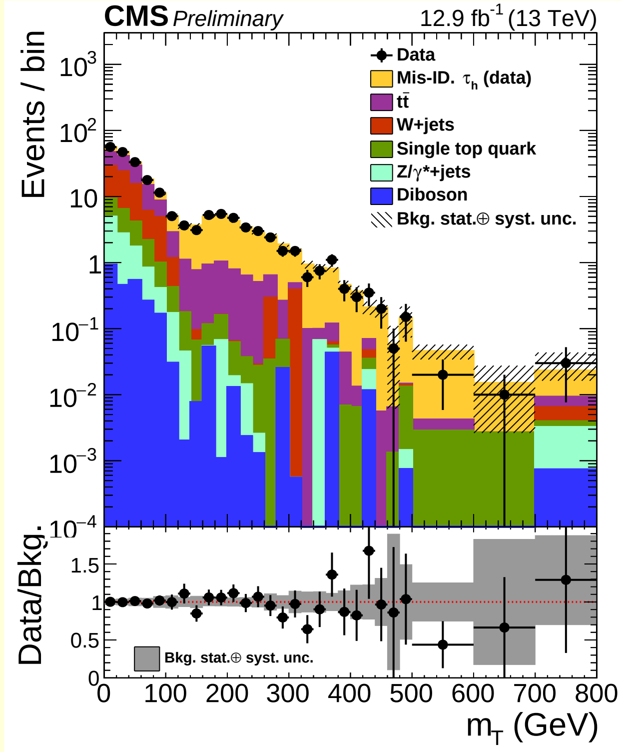
Charged Higgs bosons with $H^{\pm} \to \tau^{\pm}\nu_{\tau}$

- Both approaches: with mass larger than the top quark in the $pp \to H^{\pm}tb$ production process, and lighter than the top quark in the $pp \to t\bar{t} \to H^{\pm}W^{\mp}b\bar{b}$ channel.
- The Higgs decay preferentially in $\tau\nu_{\tau}$ (large $\tan\beta$).



CMS-HIG-16-031



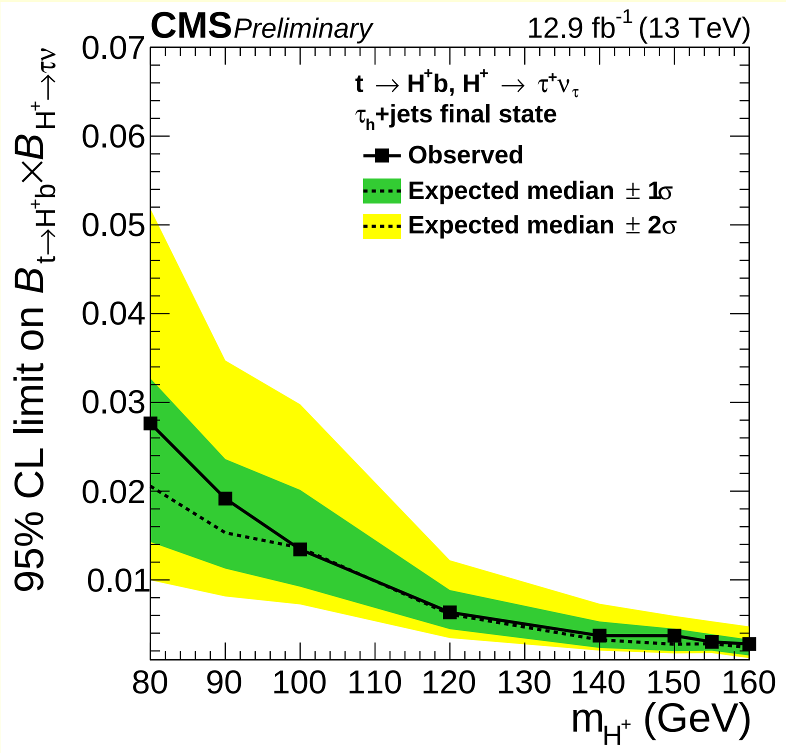


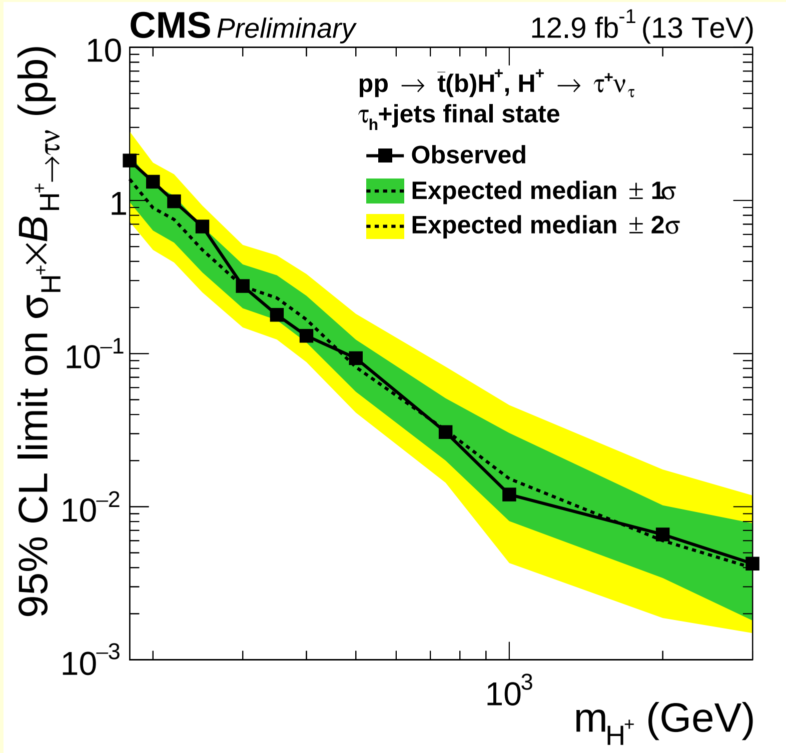
- Looking for excess on the trasnverse mass (τ and MET).
- Good agreement with the SM expectations.

Charged Higgs bosons with $H^{\pm} \to \tau^{\pm}\nu_{\tau}$ (II)

- No hint of a resonance decaying into $\tau\nu$ has been observed.
- Model-independent limits were obtained.

	Yields ($m_{H^{\pm}} < mt - mb$)	Yields ($m_{H^{\pm}} > mt - mb$)
EW	1454.3	1151.7
Top	1792.9	1318.4
Fake-τ^h	2564.4	1197.8
Tot	5811.6	3667.9
Data	6276	4179

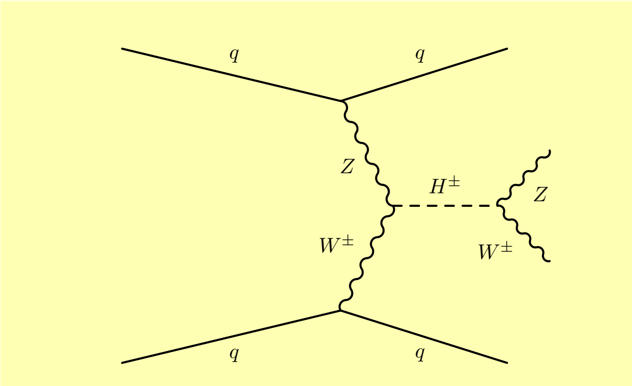




- Also explicitly interpreted in the context of the MSSM m_h^{mod+} benchmark scenario.

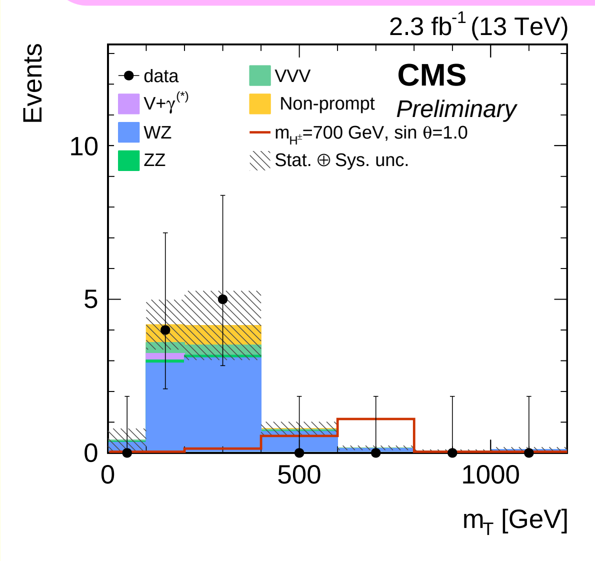
$H^\pm \to W^\pm Z$ via VBF production

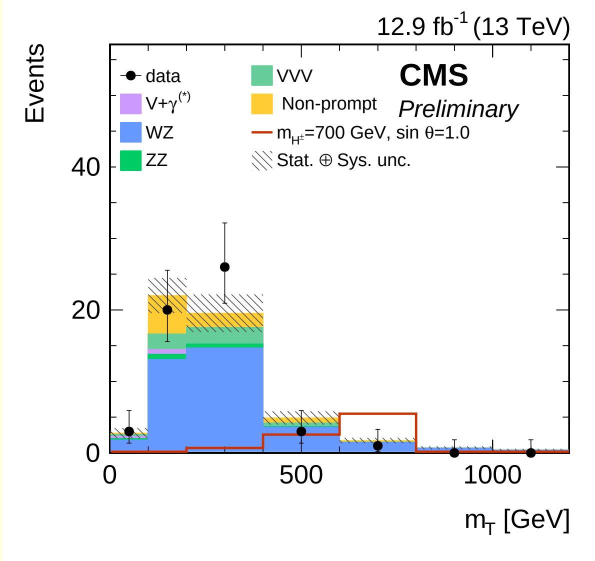
- Looking in the trilepton(e, μ)+MET signature.

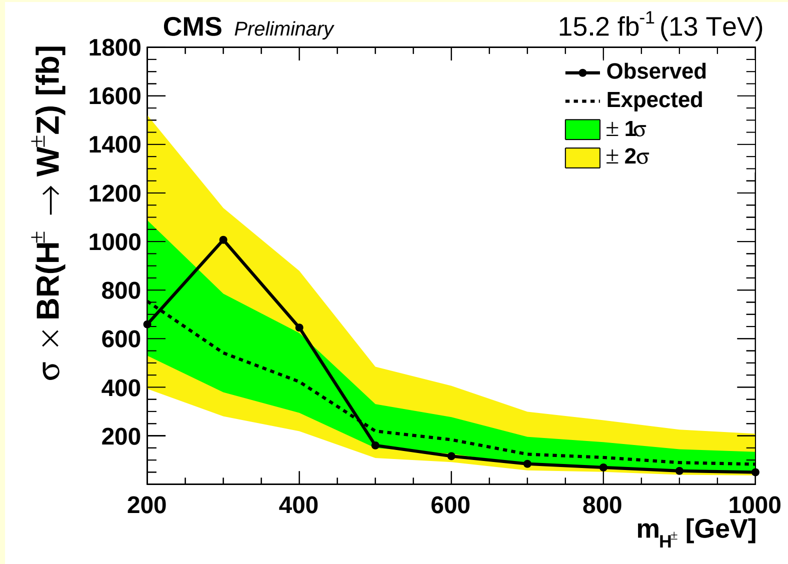


- Two of same flavour, opposite charge and having $|m_{\ell\ell} - m_Z| < 15$ GeV
- MET>30 GeV
- VBF: 2 jets with $p_T > 30$ GeV and $|\eta| < 5$
  $m_{jj} > 500$ GeV and $\Delta\eta_{jj} > 2.5$

CMS-HIG-16-027





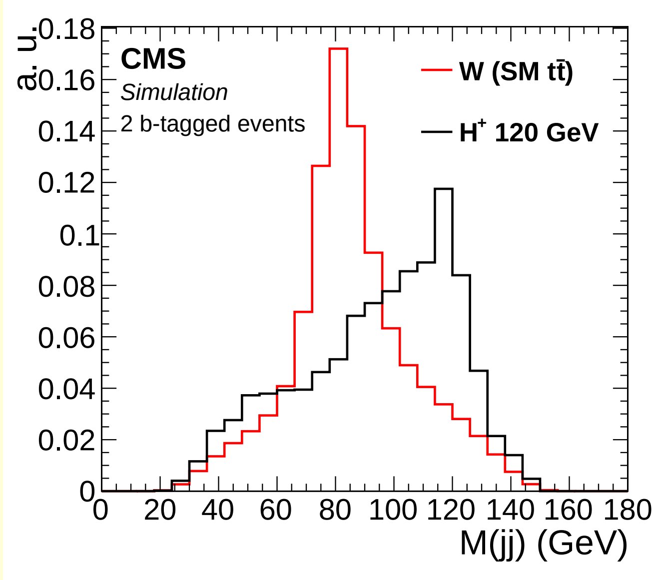


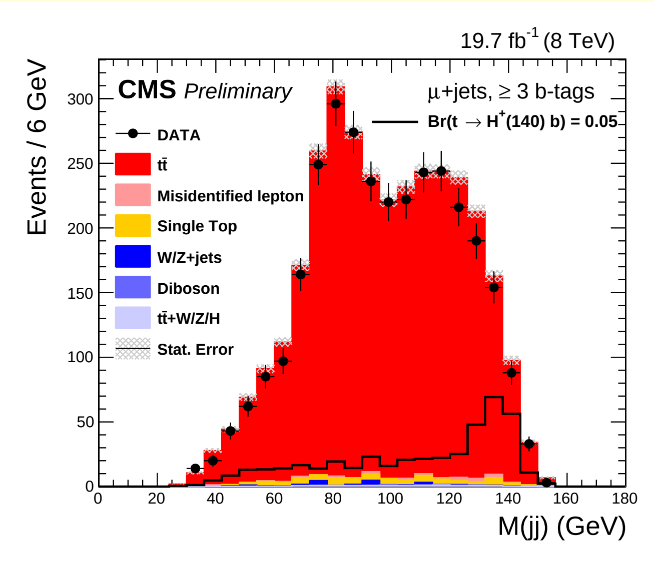
- Good description by SM: limits are set on $\sigma \cdot B$

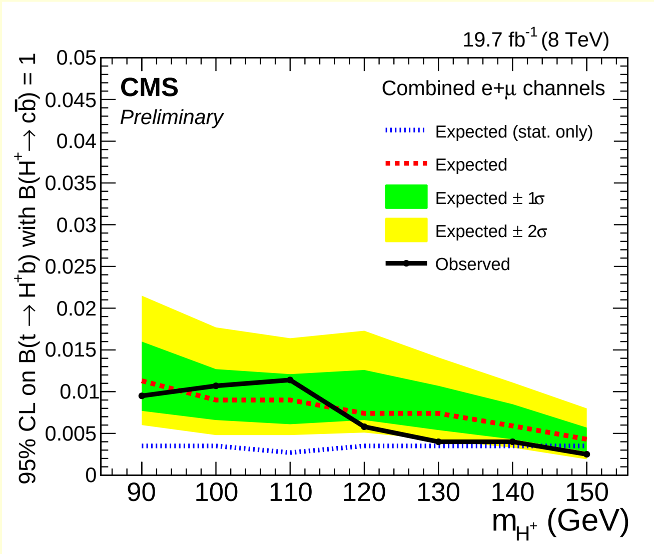
Search for $H^{\pm} \to cb$ from top-quark decays

CMS-HIG-16-030

- Result using the 8 TeV data set using the ℓ+jets sample.
- Discriminant: $M(jj)$ from W (or H).
- Using a kinematic fitter to reconstruct the final state.
- Two categories: 2 and $\geqslant$3 b-tagged jets.
- No significant excess observed.



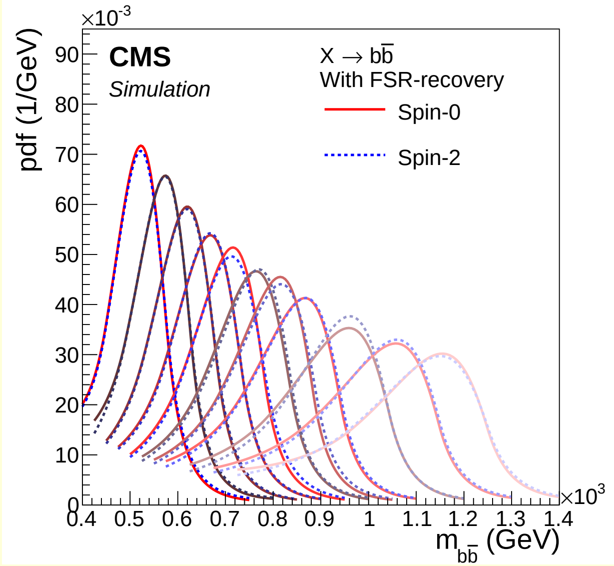


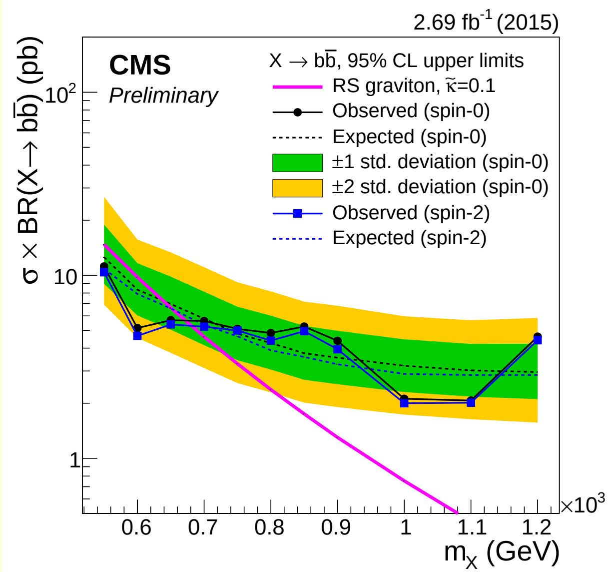


Narrow resonance decaying to $b\bar{b}$

- Searching for a generic resonance having spin 0 or spin 2.
- Requiring at least two b-tagged jets with $p_T > 100$ GeV (already online at the "trigger").
- Using FSR recovery to improve dijet mass resolution:
  - $\Rightarrow$ jets within $\Delta R < 0.8$ and $p_T > 15$ GeV
  - $\Rightarrow$ improvement $\sim 6\%$ at high masses
- Looking for a "bump" above the smooth background.
- Parameterizing data by function.
- No excess seen: limits set on both models.

CMS-HIG-16-025





Search for high mass Higgs to WW

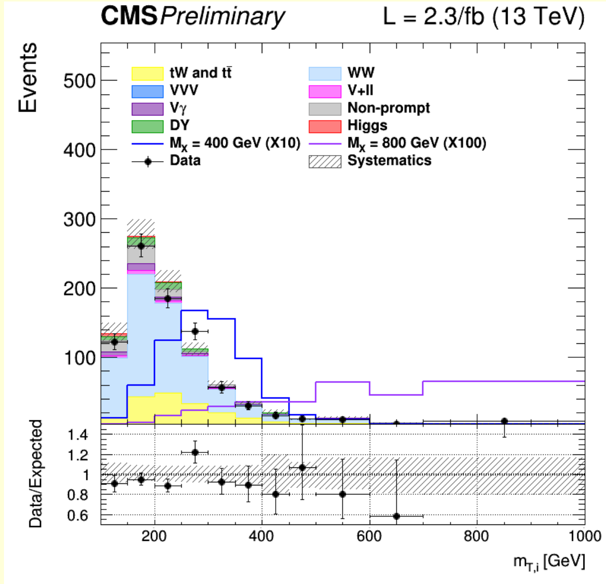
CMS-HIG-16-023

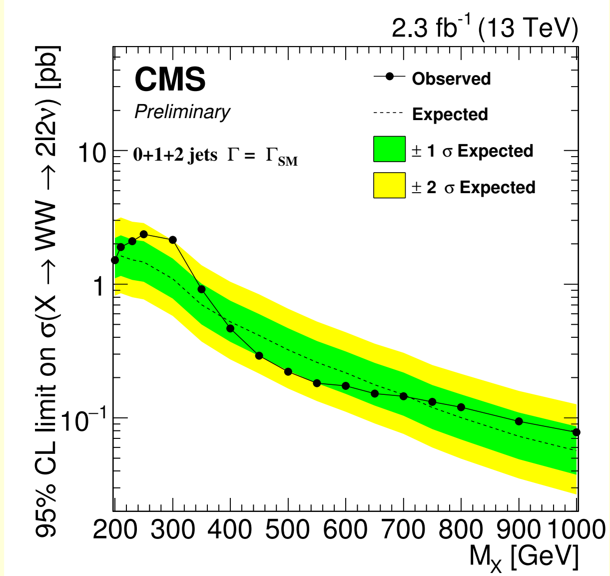
- Only $e\mu$ channel: mass not fully reconstructed!
- Strategy similar to the H(125) analysis.
- 3 categories: 0-jet, 1-jet and VBF.
- Using the "improved" invariant mass for the dilepton object:

$$m_{T,\mathrm{i}} = \sqrt{(p_{\ell\ell} + MET)^2 - (\vec{p}_{\ell\ell} + \overrightarrow{MET})^2}$$

which allows a better discrimination between signal and background.

- Perform a template shape analysis which accounts for interfence effects.
- No excess observed for several width hypothesis considered.

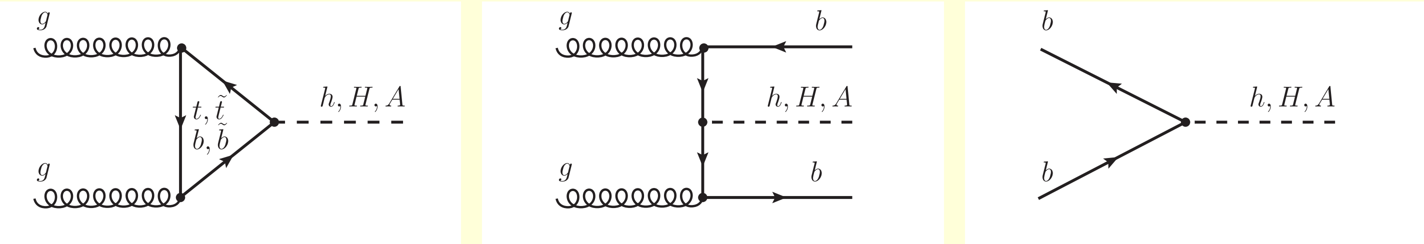




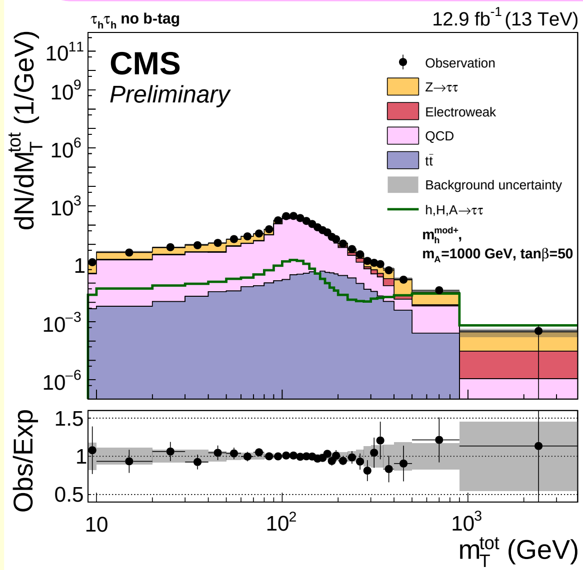
A neutral MSSM Higgs boson in $\tau\tau$

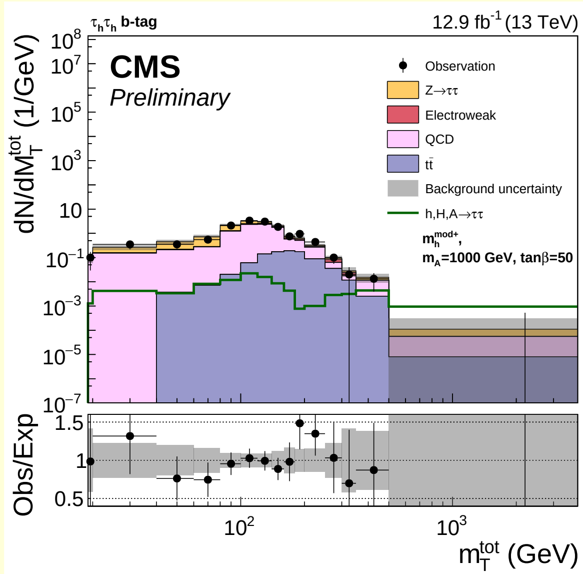
CMS-HIG-16-037

- Higgs production and decay to down-type fermion may be enhanced at large $\tan\beta$.



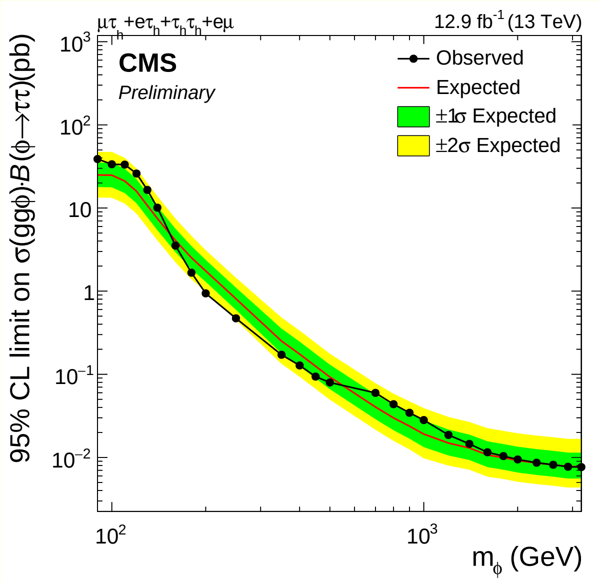
- Hard analysis, using $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$ and $e\mu$.
- Several categories used according to the presence of b-tagged jets.
- Backgrounds estimated from simulation and data-based methods.
- Transverse mass of the ditau system used as final discriminant.
- No significant discrepancy observed.

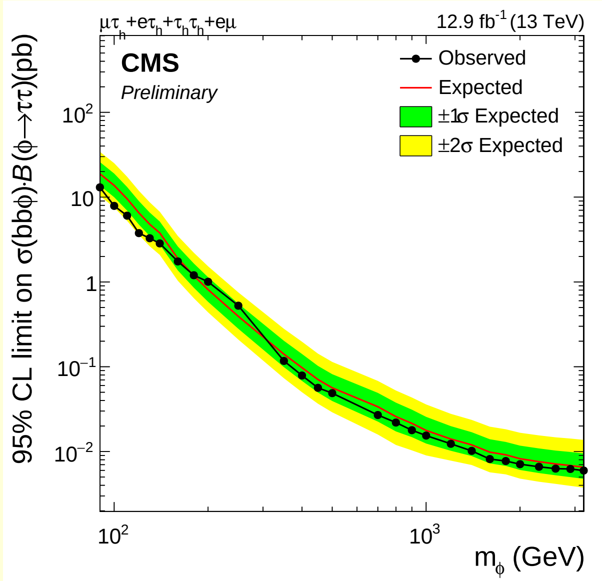


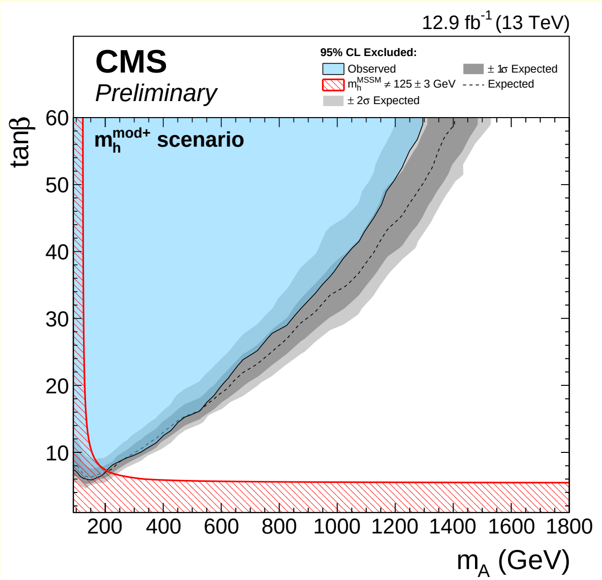


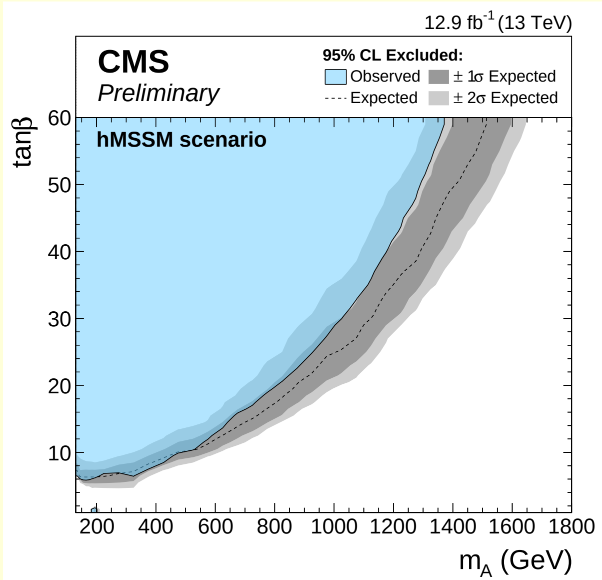
A neutral MSSM Higgs boson in $\tau\tau$ (II)

- Limits are set on cross-section and on MSSM parameters.









Outlook and Conclusions

- Impressive effort by CMS to understand the Higgs sector!
- The Higgs boson rediscovered at Run II:
  - Studying its properties at 13 TeV.
  - No significant anomaly (or unexpected partner) observed.
  - Larger dataset to improve measurements (for Moriond!)
- As soon as single measurements are under control: Combination!

  As proven in Run I: Combining several results improves precision (and knowledge).
- The Run II will provide very useful and accurate information about the Higgs and similar objects.
- All the (Higgs-related) CMS public results can be found at:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG