13 TeV Non-BSM Higgs Results From CMS

John Stupak III
on behalf of the CMS Collaboration

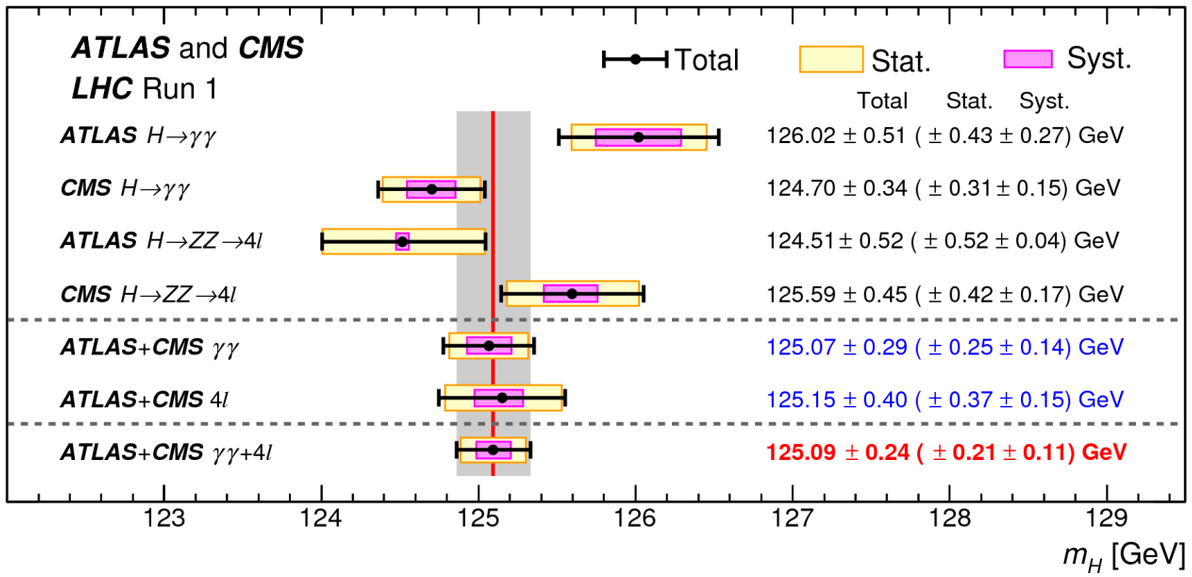
LHCP 2016

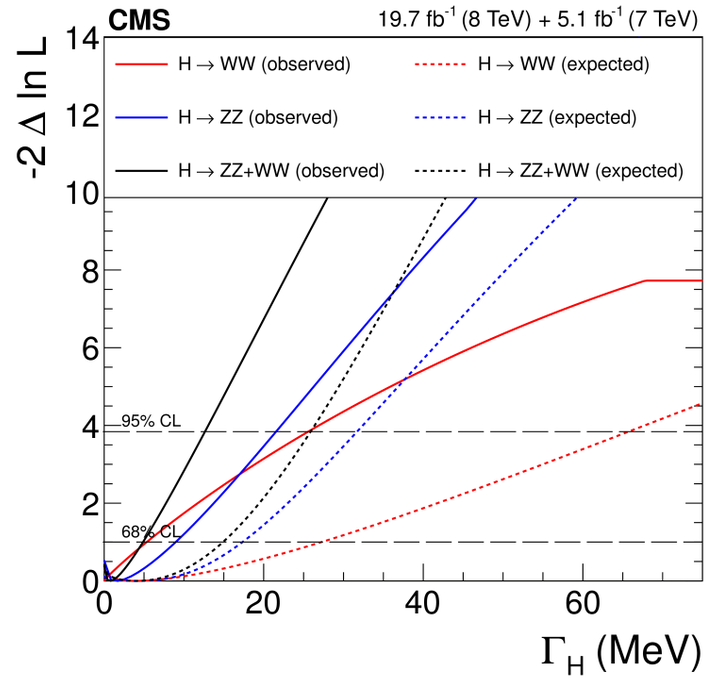
PURDUE UNIVERSITY CALUMET

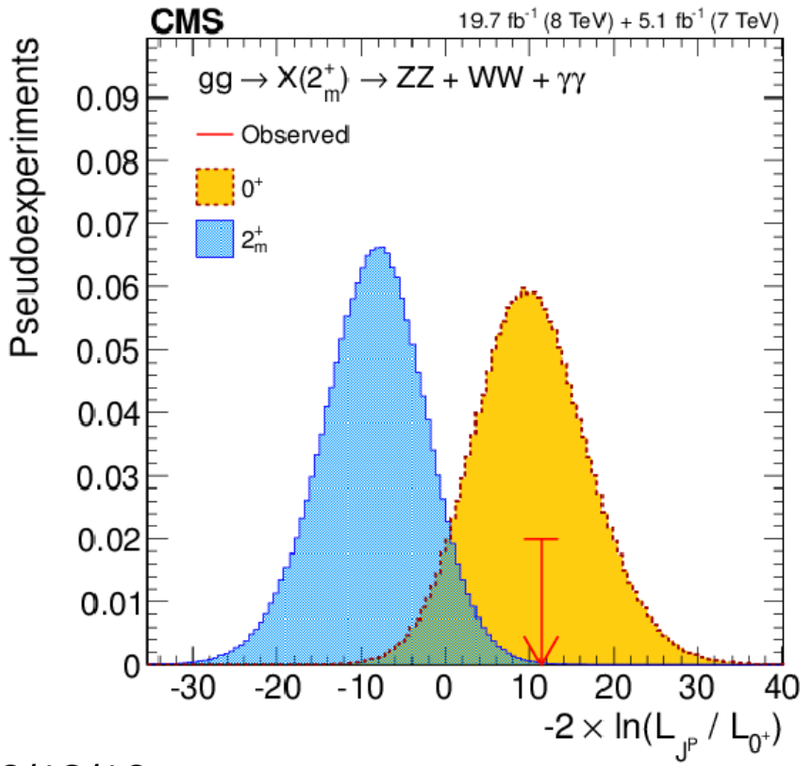
6/13/16

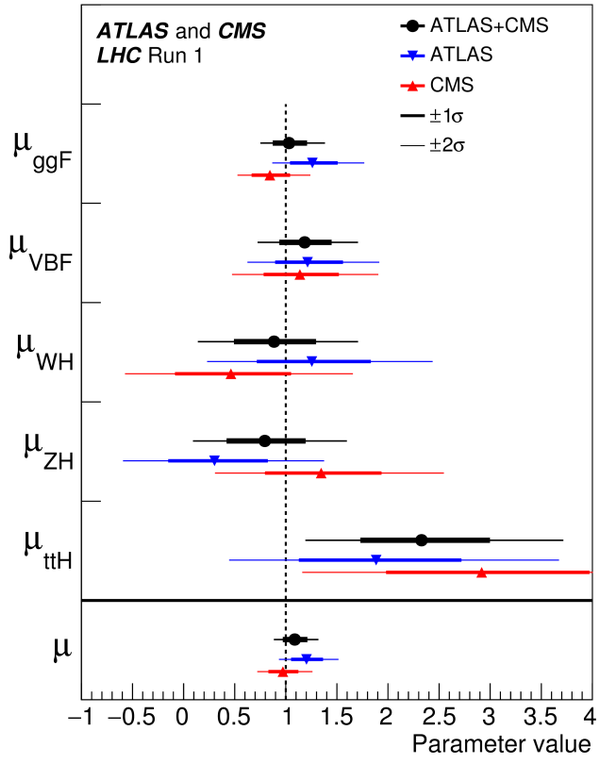
Run I Non-BSM Higgs Summary

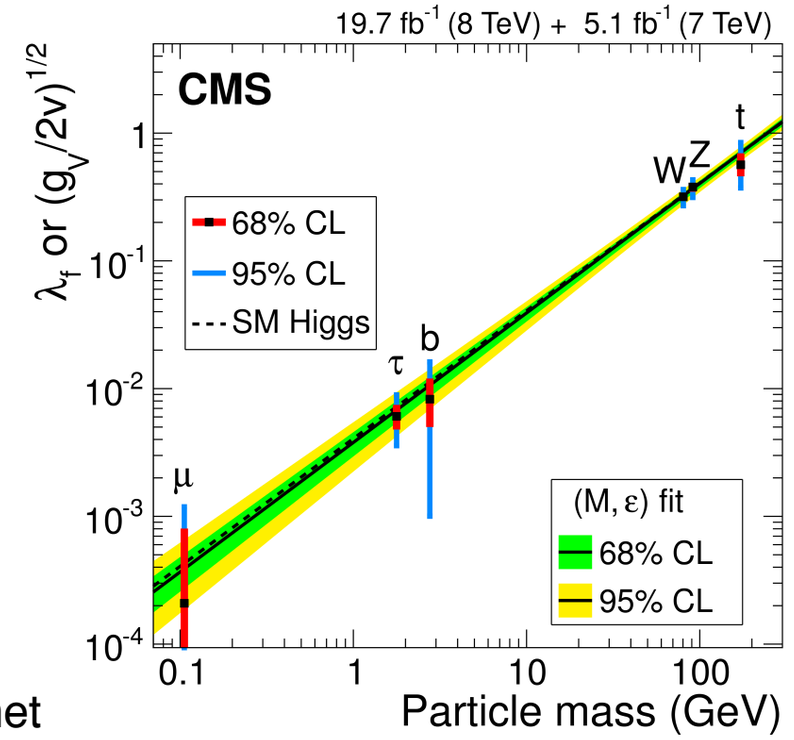
See talk by Silvio Donato for more detail





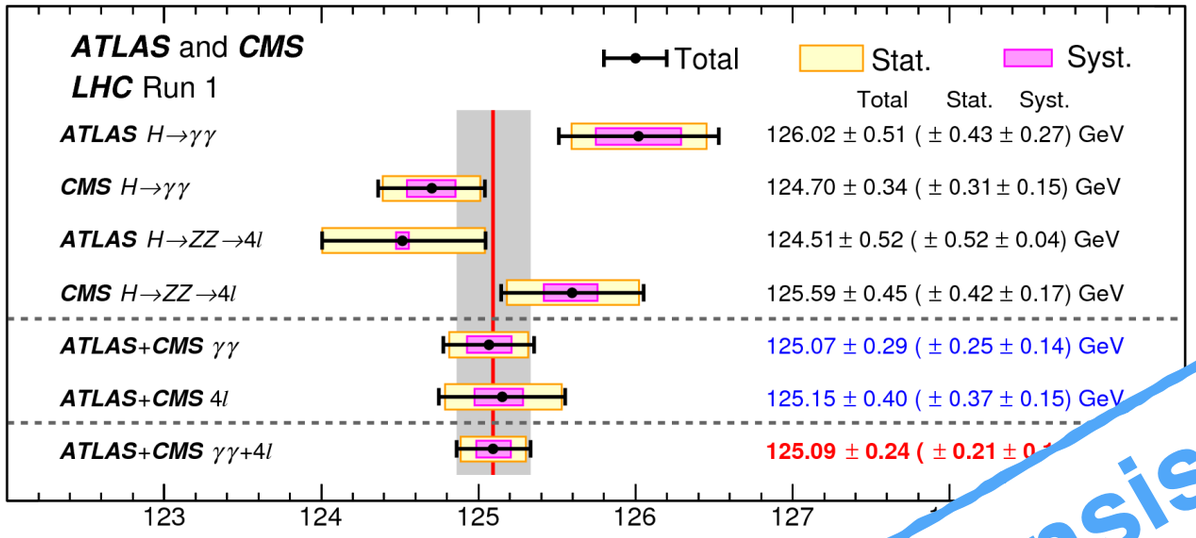


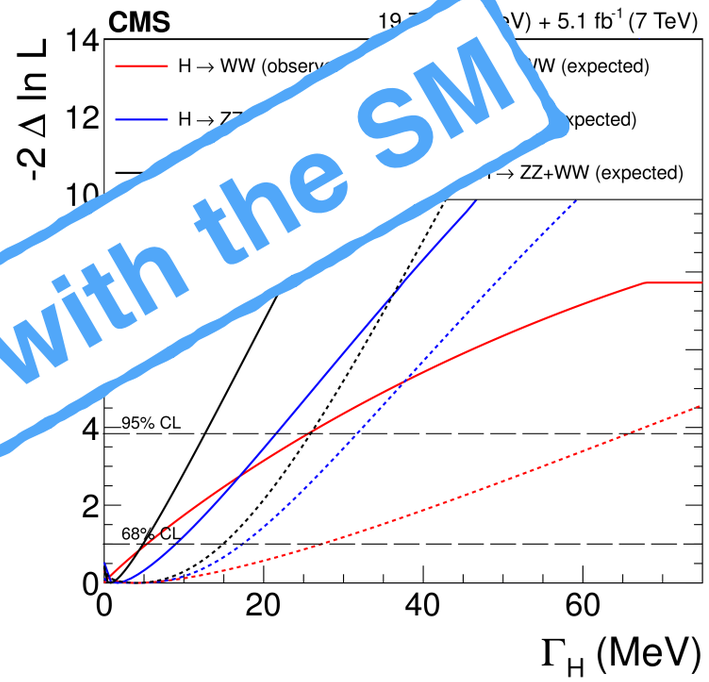




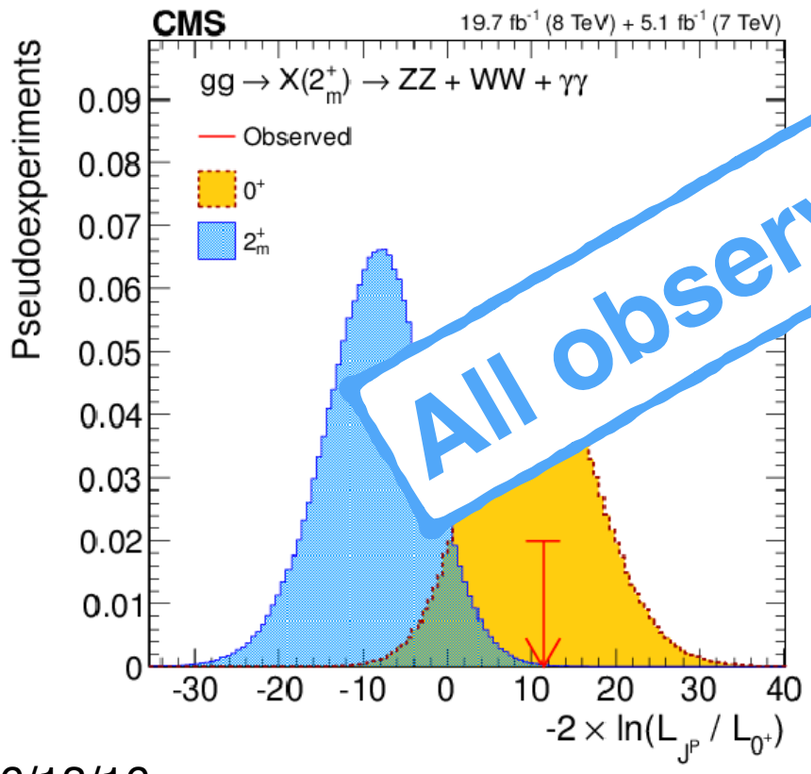
Run I Non-BSM Higgs Summary

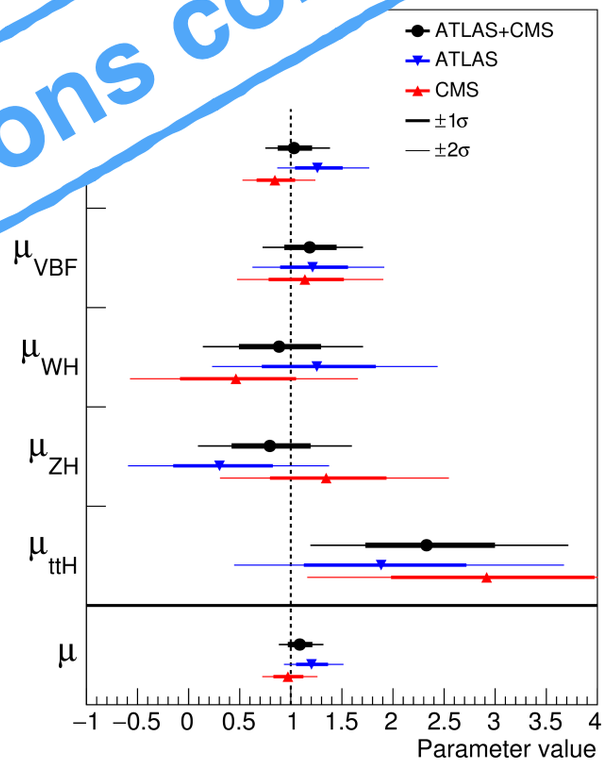
See talk by Silvio Donato for more detail

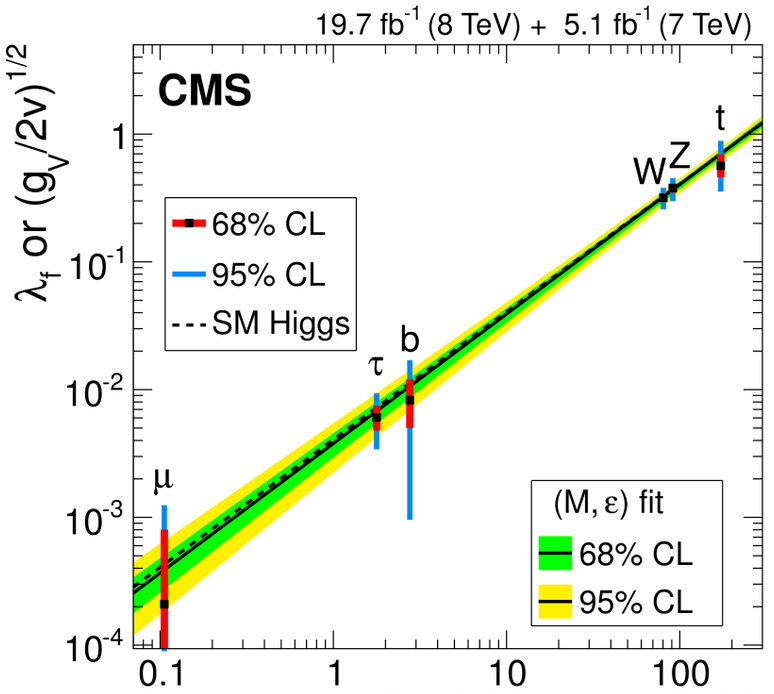




All observations consistent with the SM

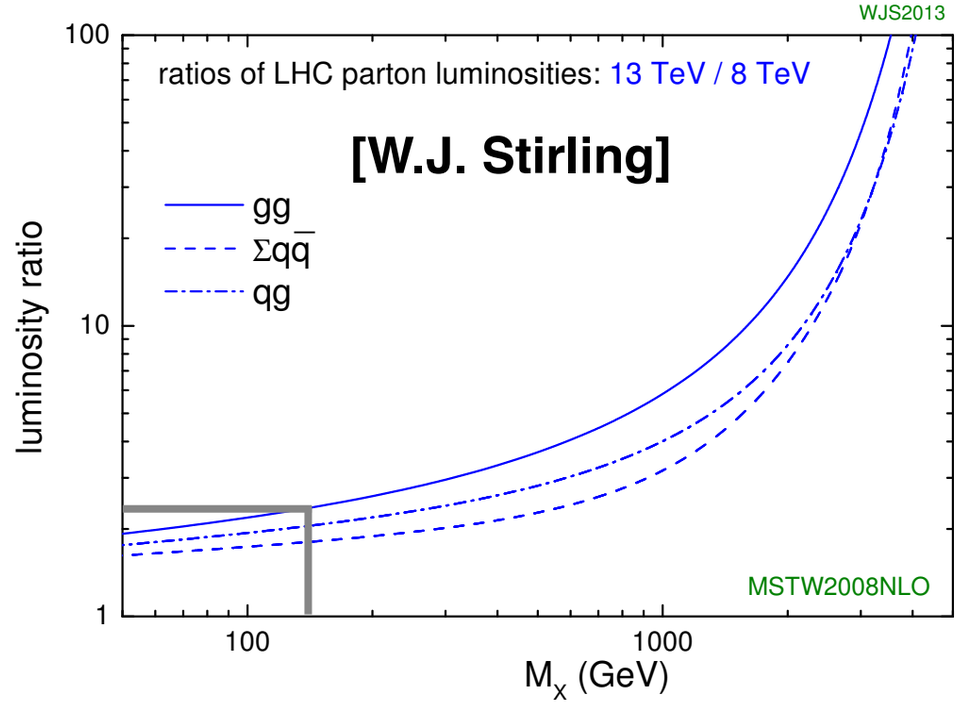






Run II Non-BSM Higgs Studies

- Rediscovering the Higgs at 13 TeV
  - H→ZZ*→4ℓ [CMS-PAS-HIG-15-004]
  - H→$\gamma\gamma$ [CMS-PAS-HIG-15-005]
- Searches for rare/challenging process
  - VBF H→bb [CMS-PAS-HIG-16-003]
  - HH→bb$\tau\tau$ [CMS-PAS-HIG-16-012]
  - ttH (See talk by Eleni Ntomari for details)
    - H→multileptons [CMS-PAS-HIG-15-008]
    - H→bb [CMS-PAS-HIG-16-004]



$\sigma_{13}(gg\rightarrow H) \approx 2.3 \times \sigma_8(gg\rightarrow H)$

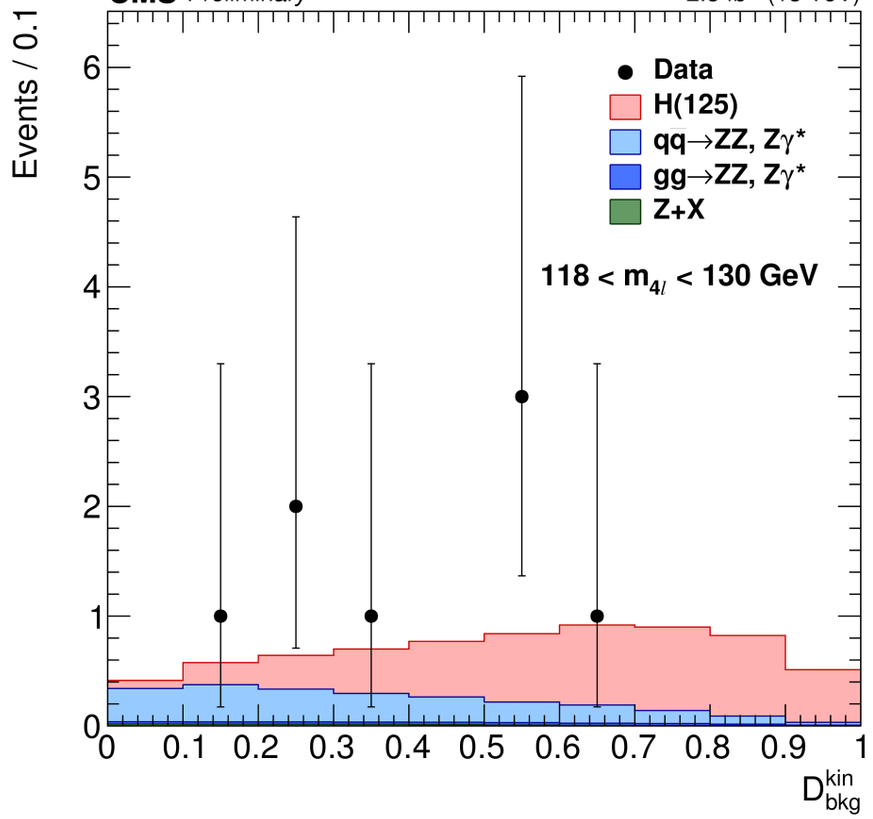
Brand New!

$H \rightarrow ZZ^* \rightarrow 4\ell$

CMS-PAS-HIG-15-004

- High-resolution, fully-reconstructible final state
- Similar strategy to Run I
  - Signal model taken from fits to POWHEG+JHUGen MC for various Higgs masses
  - Irreducible qq(gg)→ZZ modeled with POWHEG (MCFM) MC
    - k-factor(m_{ZZ}) takes MC to NNLO
  - Reducible backgrounds estimated by combining 2 data-driven methods
  - Exploit full kinematic information via MELA discriminant:

$$\mathcal{D}^{\text{kin}}_{\text{bkg}} = \frac{\mathcal{P}^{gg}_{\text{sig}}(\vec{\Omega}^{H\to 4\ell}|m_{4\ell})}{\mathcal{P}^{gg}_{\text{sig}}(\vec{\Omega}^{H\to 4\ell}|m_{4\ell}) + \mathcal{P}^{q\bar{q}}_{\text{bkg}}(\vec{\Omega}^{H\to 4\ell}|m_{4\ell})}$$

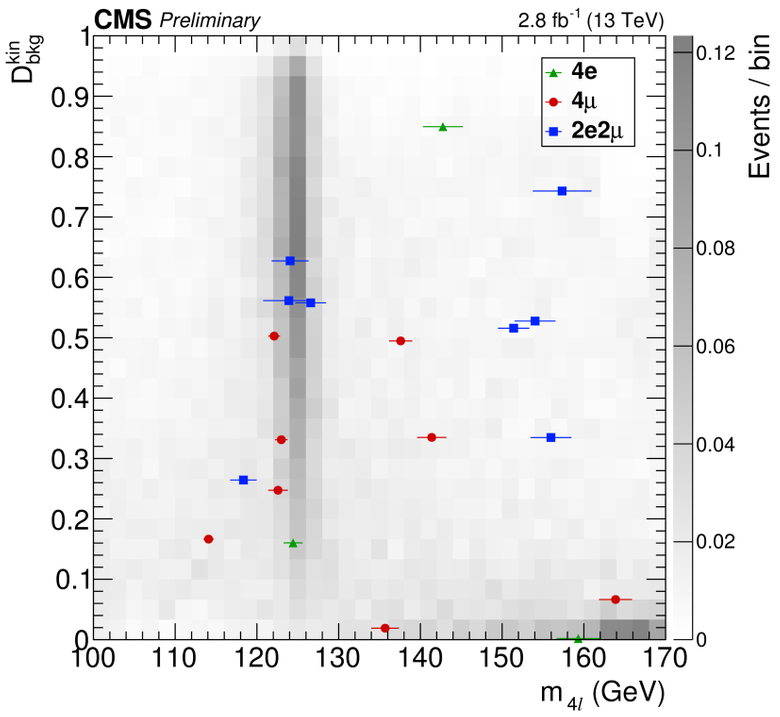


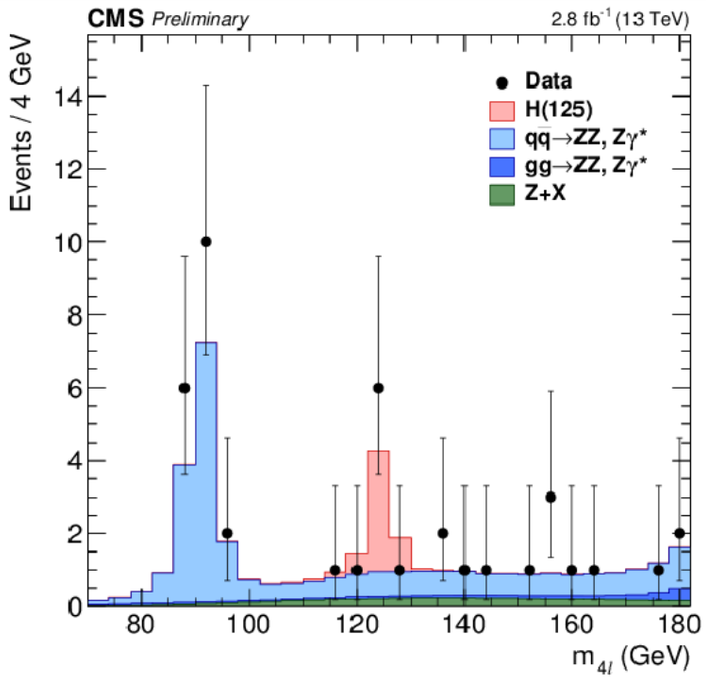
$\vec{\Omega}^{H\to 4\ell} = 8$ variables (3 masses + 5 angles) which fully characterize the matrix element

$H \to ZZ^* \to 4\ell$

CMS-PAS-HIG-15-004

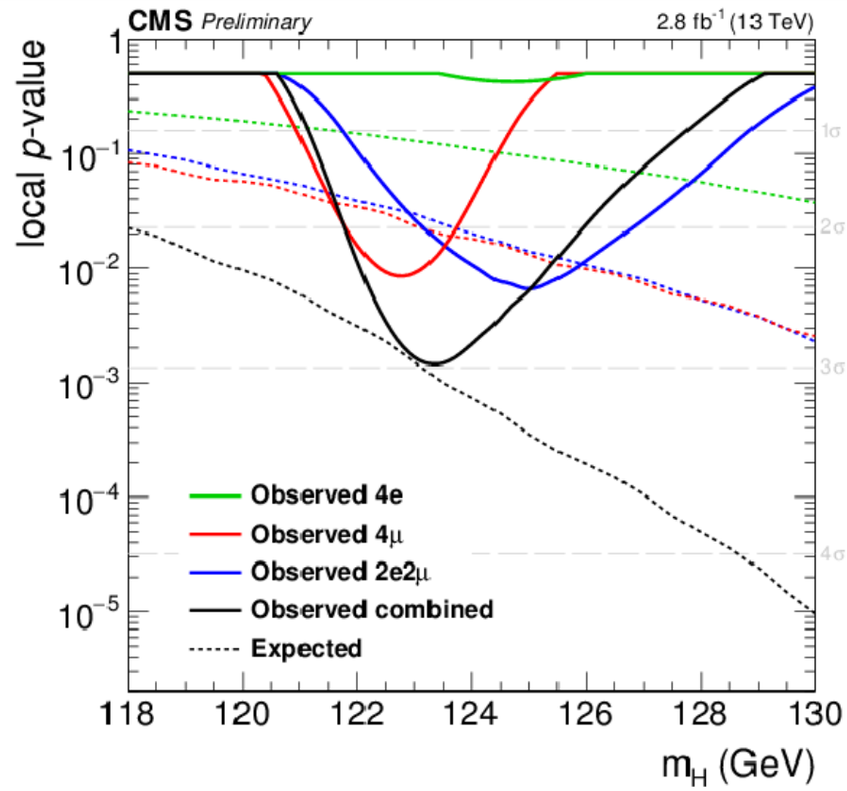
Signal extraction via 2D fit:

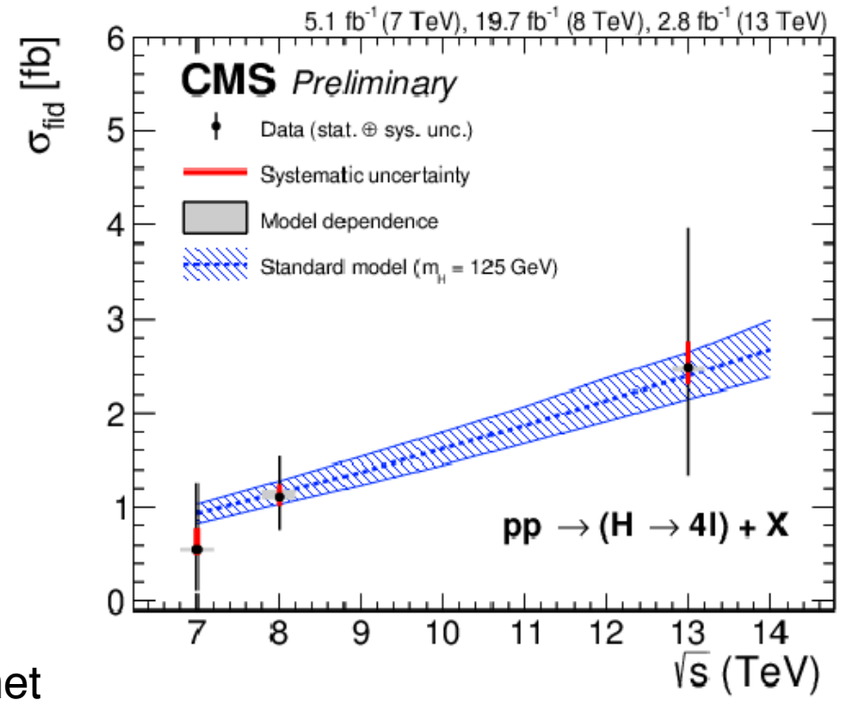




$m_H = 123.4^{+0.8}_{-0.7}$ GeV

Compatible with Run I measurement at 1.6σ





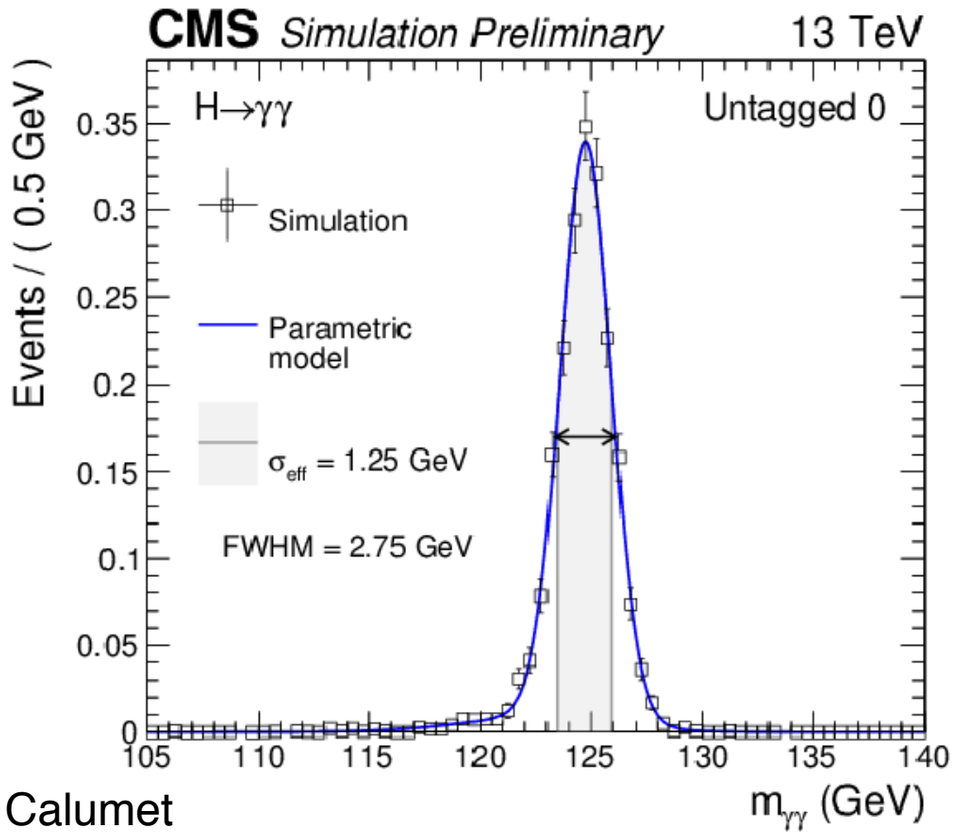
Best fit:
$\mu = 0.82^{+0.57}_{-0.43}$

Observed (expected) significance @ m_H = 125.09 GeV:
2.5σ (3.4σ)

$H \rightarrow \gamma\gamma$

CMS-PAS-HIG-15-005

- Another rare, yet high-resolution decay mode
- Sophisticated analysis required to extract signal
  - Similar to Run I analysis (categorize → bump hunt)
- Excellent photon energy resolution essential
  - Energy corrections
    - Crystal-by-crystal response
    - Shower containment, material effects (MVA)
      - Shower shape, position, pre-shower info, pileup observables
    - Residual corrections (Z→ee)



$H \rightarrow \gamma\gamma$

CMS-PAS-HIG-15-005

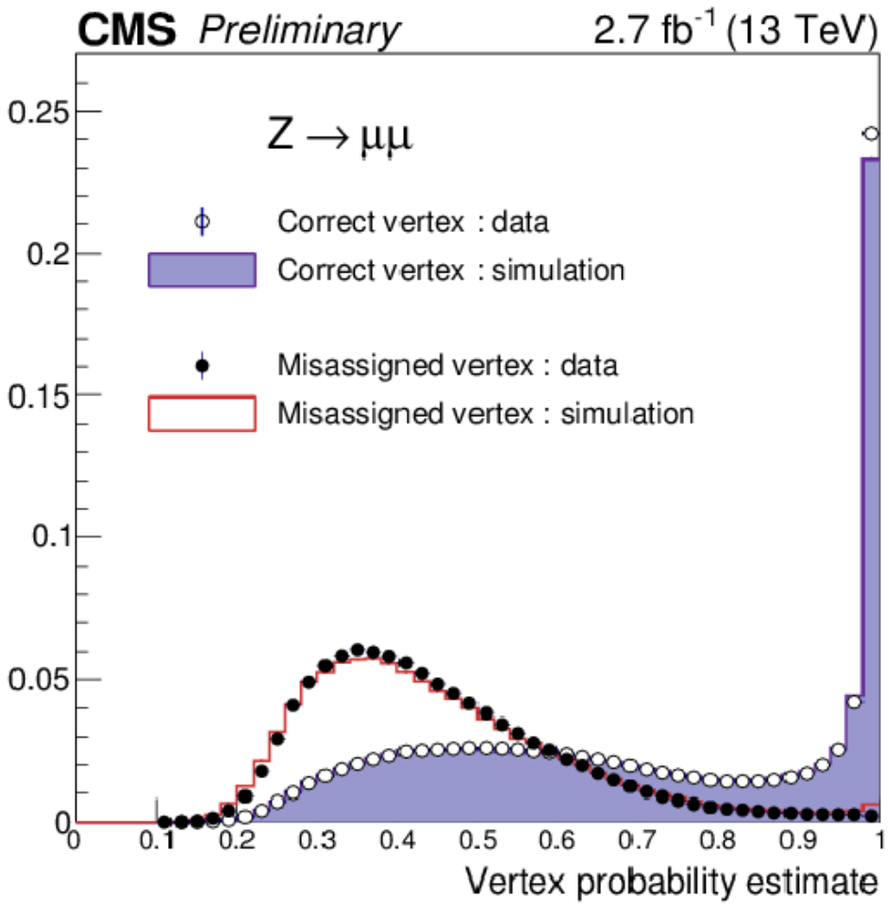
Primary Vertex (PV) ID

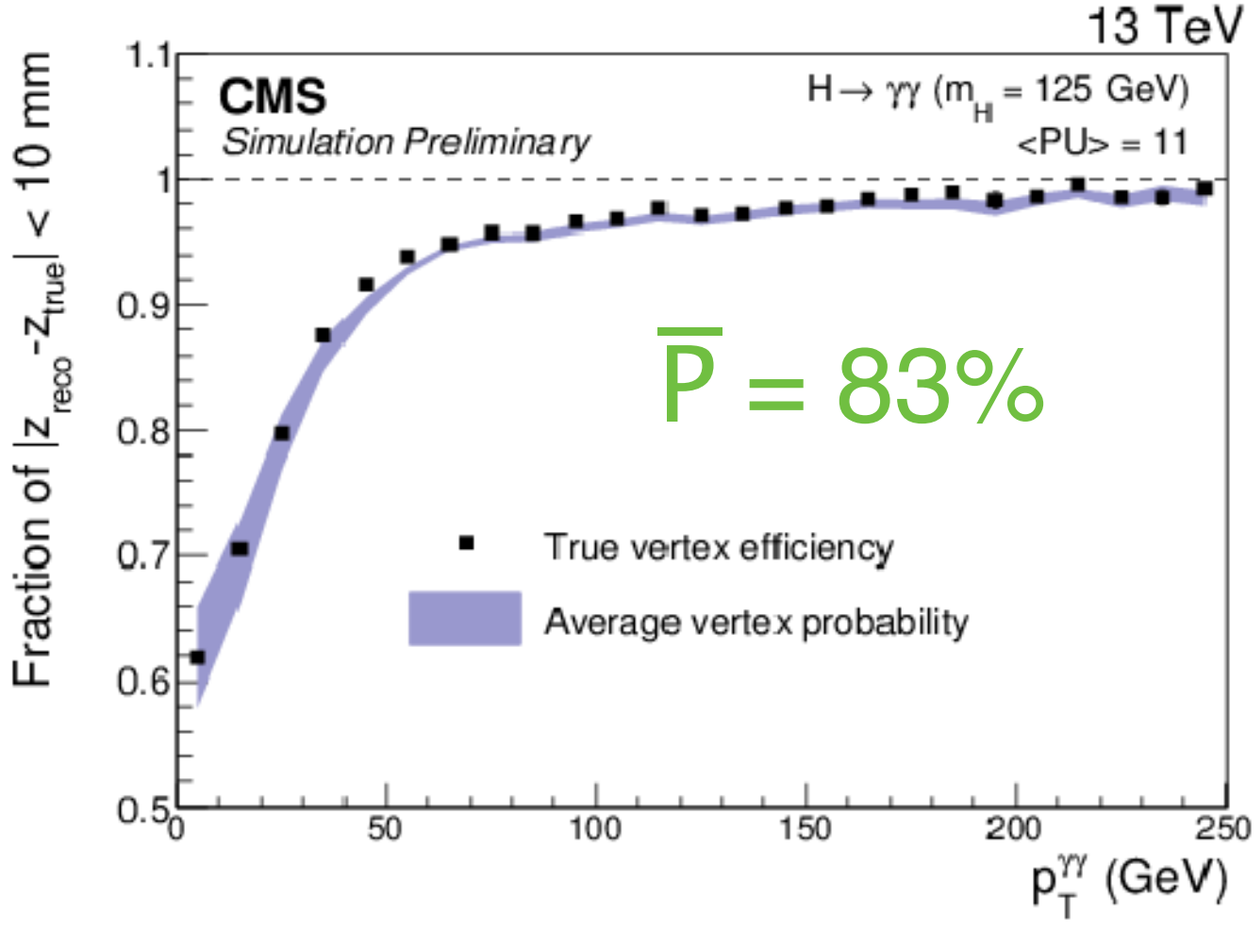
- Observables related to tracks roiling against the $\gamma\gamma$ system
- Tracks from conversions

v_1, v_2, v_3

Correct PV Probability

- Vertex multiplicity
- Conversion multiplicity
- $p_T(\gamma\gamma)$
- …





$H \rightarrow \gamma\gamma$

CMS-PAS-HIG-15-005

Primary Vertex (PV) ID
- Observables related to tracks roiling against the $\gamma\gamma$ system
- Tracks from conversions

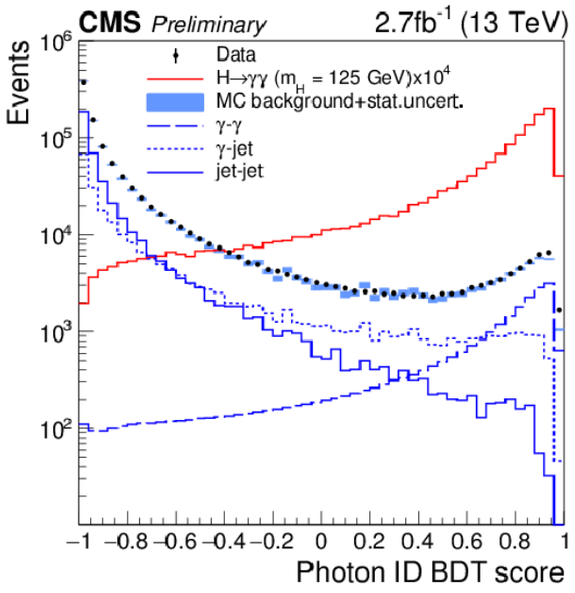
v_1, v_2, v_3

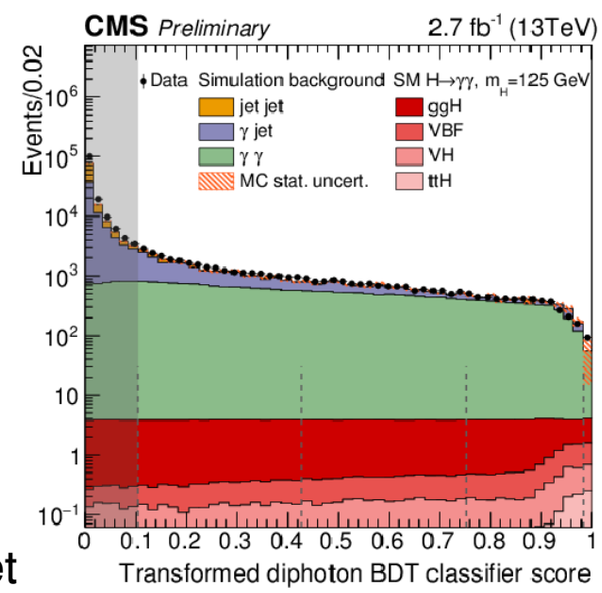
Correct PV Probability
- Vertex multiplicity
- Conversion multiplicity
- $p_T(\gamma\gamma)$
- …

Photon ID
- Shower shape observables
- Isolation
- Photon kinematics
- Median energy density of event

γ_1, γ_2

$H \rightarrow \gamma\gamma$ Classifier
- $\gamma\gamma$ kinematics (excluding mass)
- $m(\gamma\gamma)$ resolution (right PV choice)
- $m(\gamma\gamma)$ resolution (wrong PV choice)

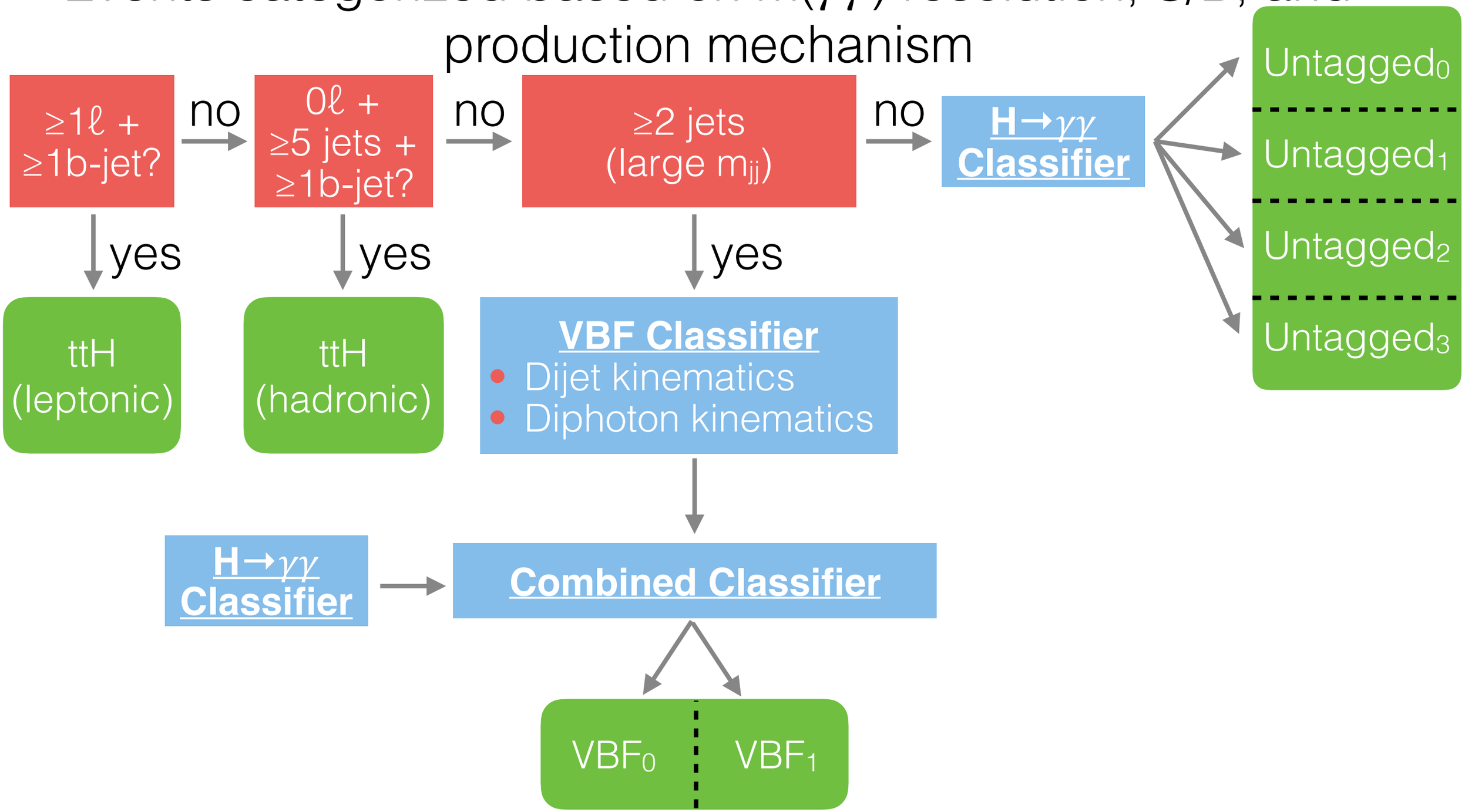




$H \rightarrow \gamma\gamma$

CMS-PAS-HIG-15-005

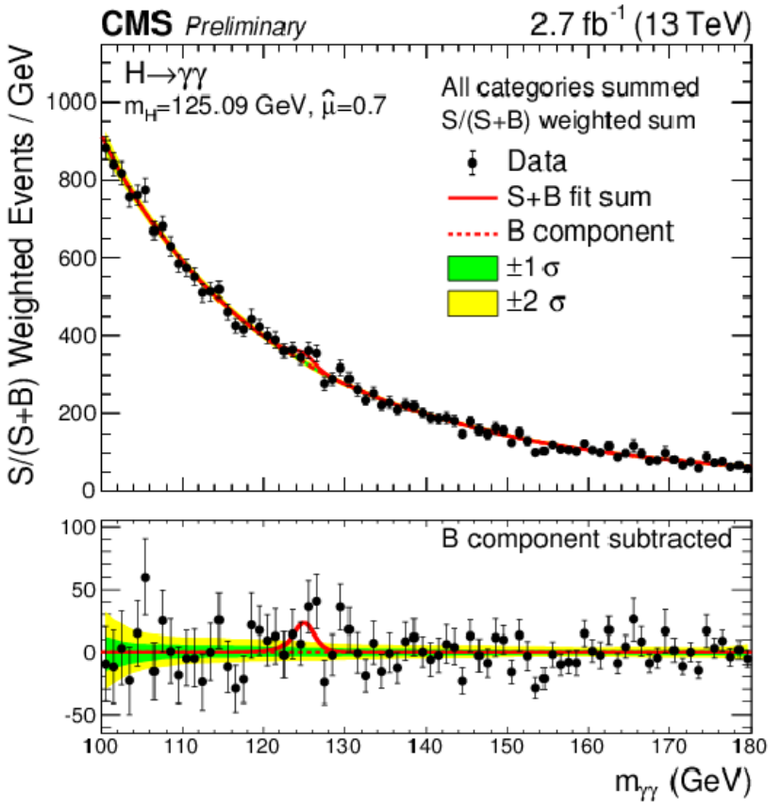
Events categorized based on m($\gamma\gamma$) resolution, S/B, and production mechanism



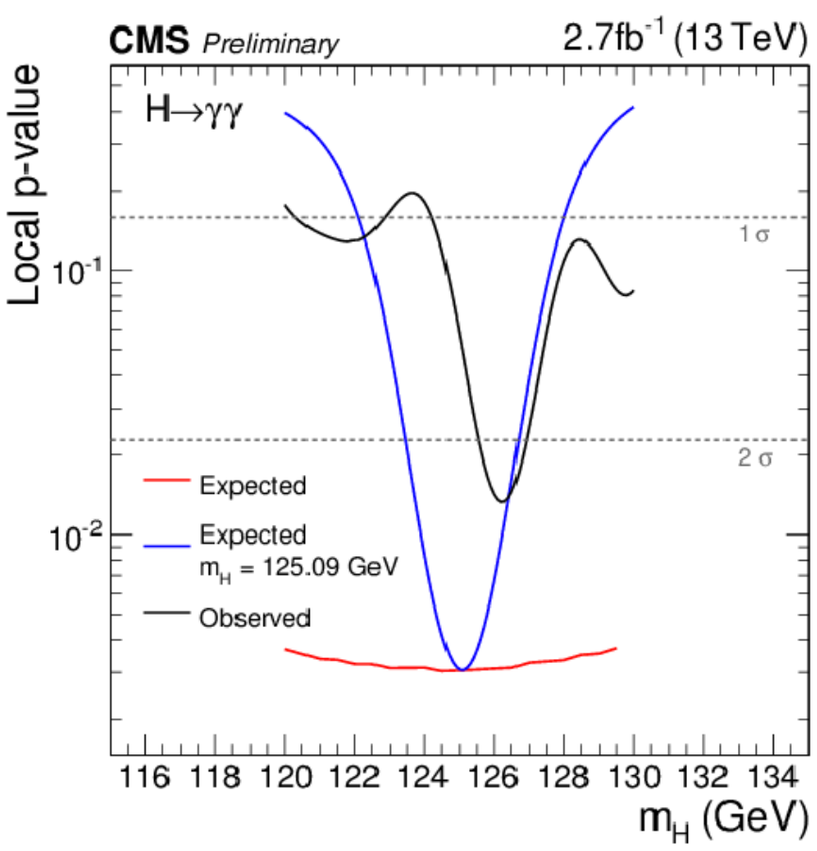
$H \rightarrow \gamma\gamma$

CMS-PAS-HIG-15-005

Simultaneous fit for signal on top of falling background in 8 categories

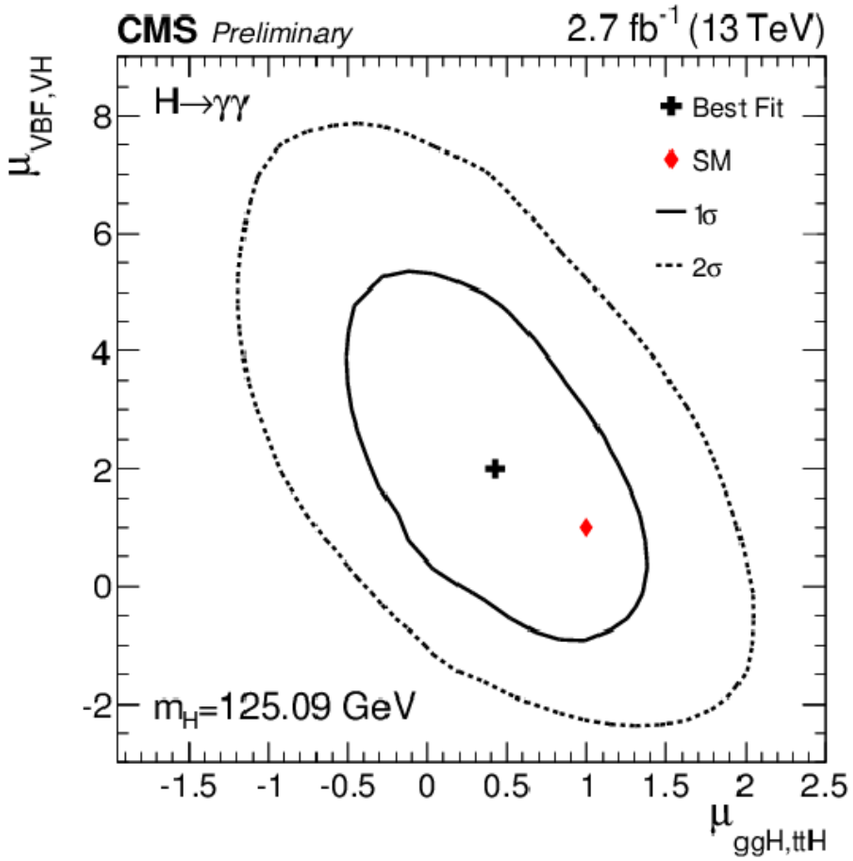


Events weighted according to S/(S+B)



Best fit:

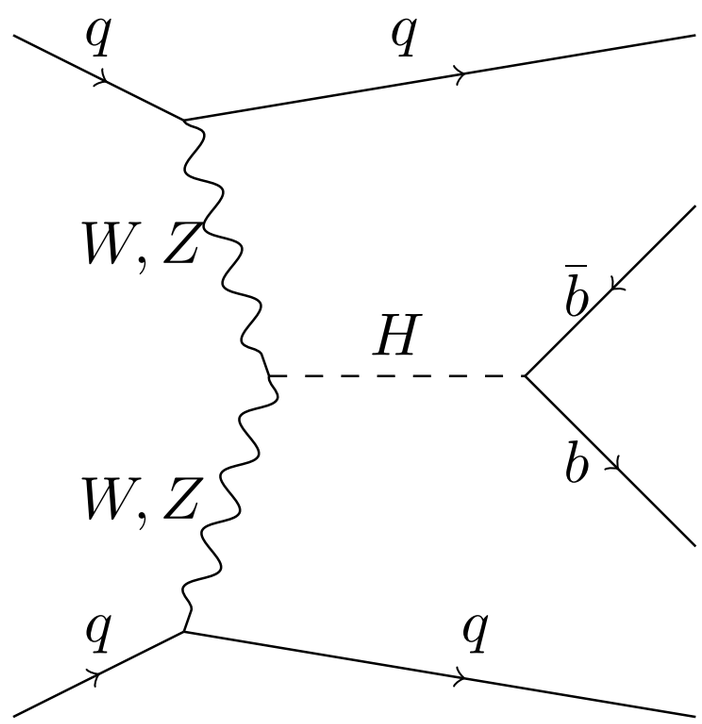
$\mu = 0.69^{+0.47}_{-0.42}$



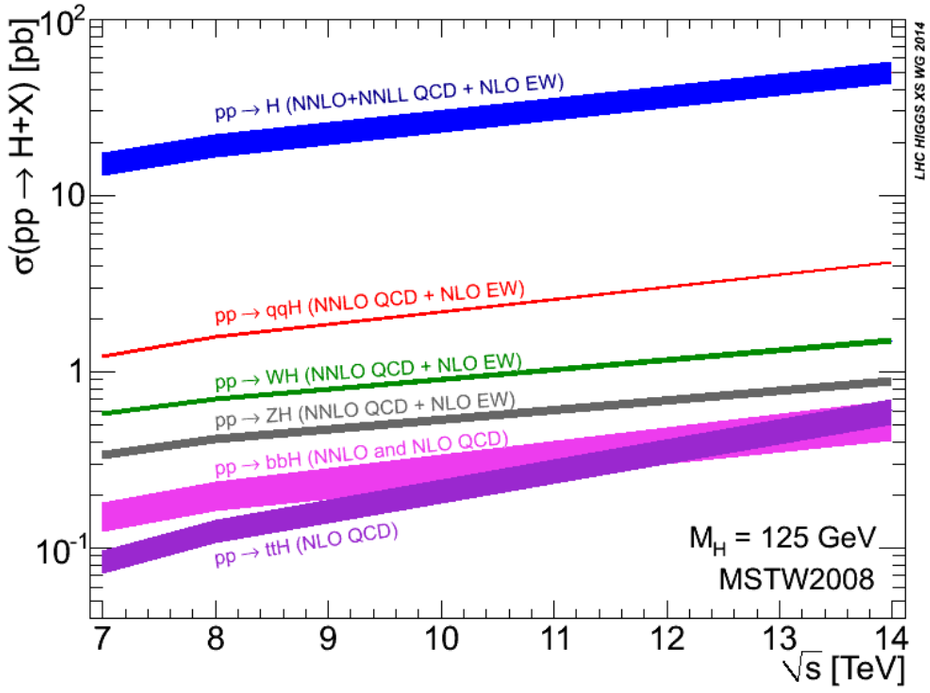
Observed (expected) significance @ m_H = 125.09 GeV: 1.7σ (2.7σ)

H→bb

- Important to establish coupling of Higgs to down-type quarks
- Hopeless to observe through gluon fusion at LHC
  - Focus instead on more distinctive production modes
- Run I results:



[1506.01010]	VBF	VBF+VH+ttH
μ	$2.8^{+1.6}_{-1.4}$	$1.03^{+0.44}_{-0.42}$
Significance observed (expected)	2.2σ (0.8σ)	2.6σ (2.7σ)

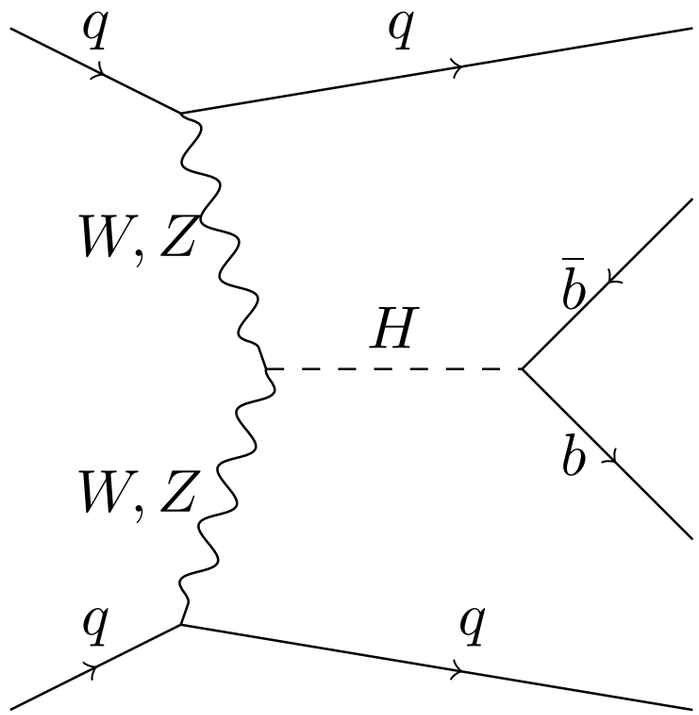


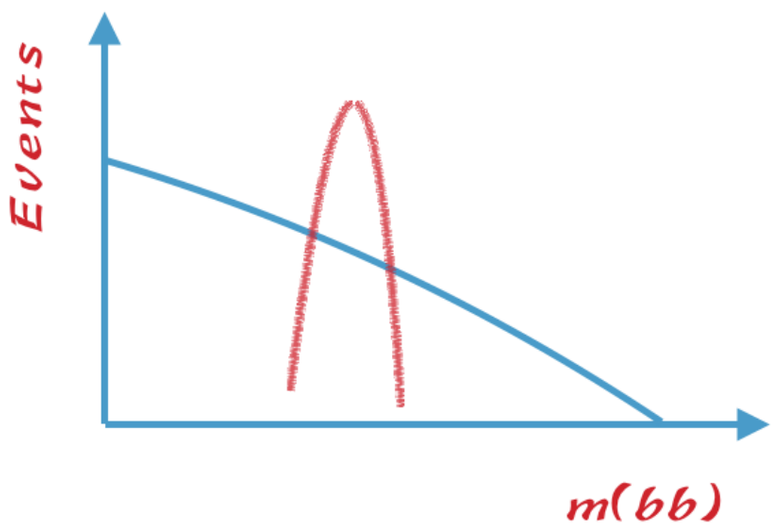
Brand New!

VBF H(bb)

CMS-PAS-HIG-16-003

- Challenging all-hadronic final state
  - Dominant background: QCD
  - Triggering is a challenge
- Strategy (similar to Run I)
  - Trigger on forward jets + central b-jet(s)
  - Categorize events based on MVA discriminant
  - Model QCD background as smoothly falling function
    - Search for bump in m_{bb}





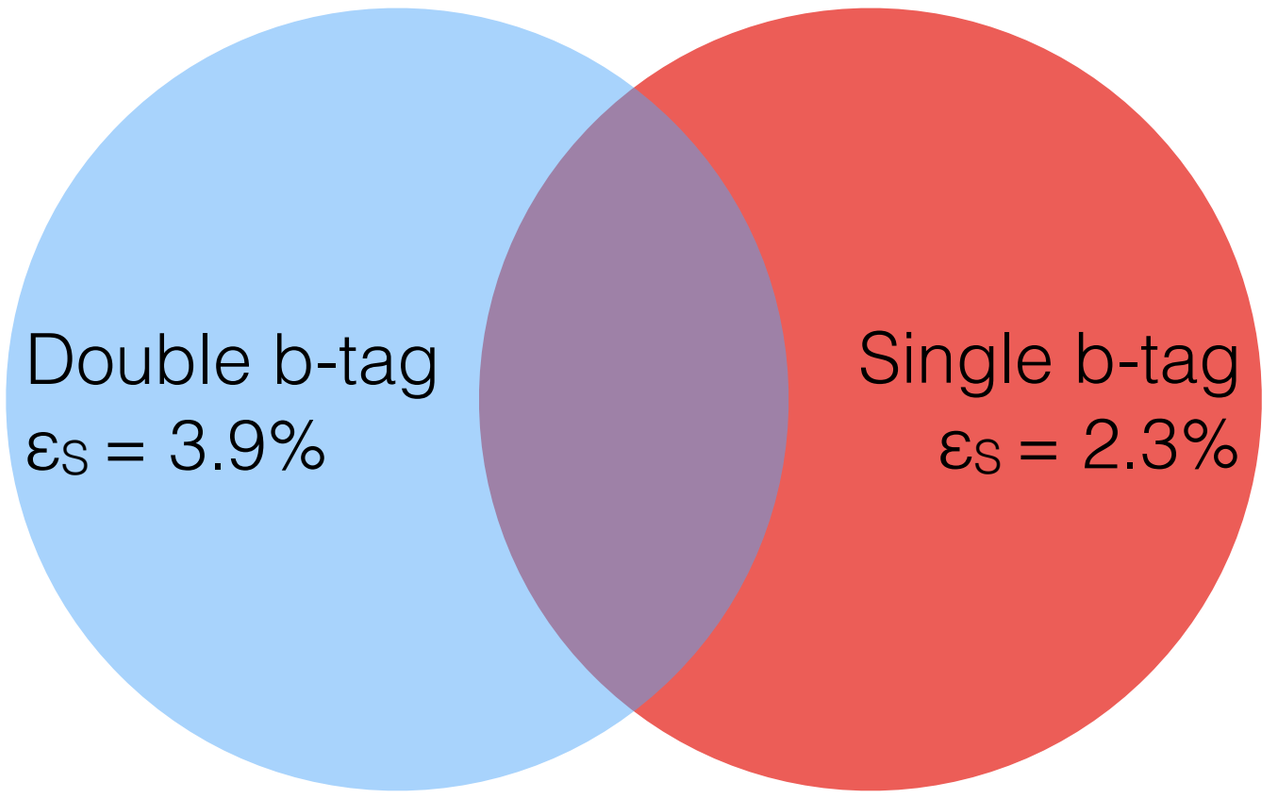
Brand New!

CMS-PAS-HIG-16-003

VBF H(bb)

- Trigger
  - 4 jets (p_T > 92/76/64/15 GeV)
    - 2 b-jets + $\Delta\Phi_{bb} < 3.2$ + $m_{qq} > 200$ GeV + $\Delta\eta_{qq} > 1.2$

      OR
    - 1 b-jet + $\Delta\Phi_{bb} < 1.6$ + $m_{qq} > 460$ GeV + $\Delta\eta_{qq} > 4.1$



Combined signal efficiency of 4.7%

Brand New!

CMS-PAS-HIG-16-003

VBF H(bb)

- Offline selection
  - Same kinematic cuts as trigger, except:
    - $p_T(j_4) > 30$ GeV
    - $\Delta\Phi_{bb} < 2.4$ (double tagged events)

	2 b-tag	1 b-tag
b-jets	2 jets with highest b-tag score	Chosen by BDT
q-jets	2 remaining highest p_T jets	2 remaining jets with largest $\Delta\eta$

Chosen by BDT →
- b-tag score
- b-tag ranking
- η
- p_T

~5% efficiency improvement

  - Pileup jet ID applied ($\varepsilon_S \approx 99\%$ / $\varepsilon_B \approx 10\%$)

Brand New!

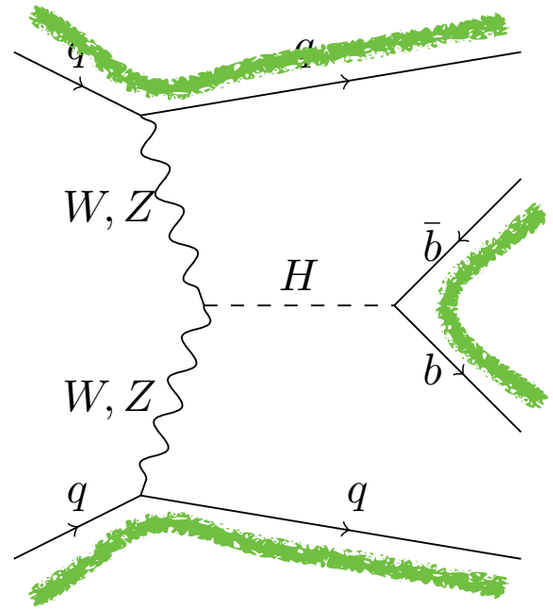
VBF H(bb)

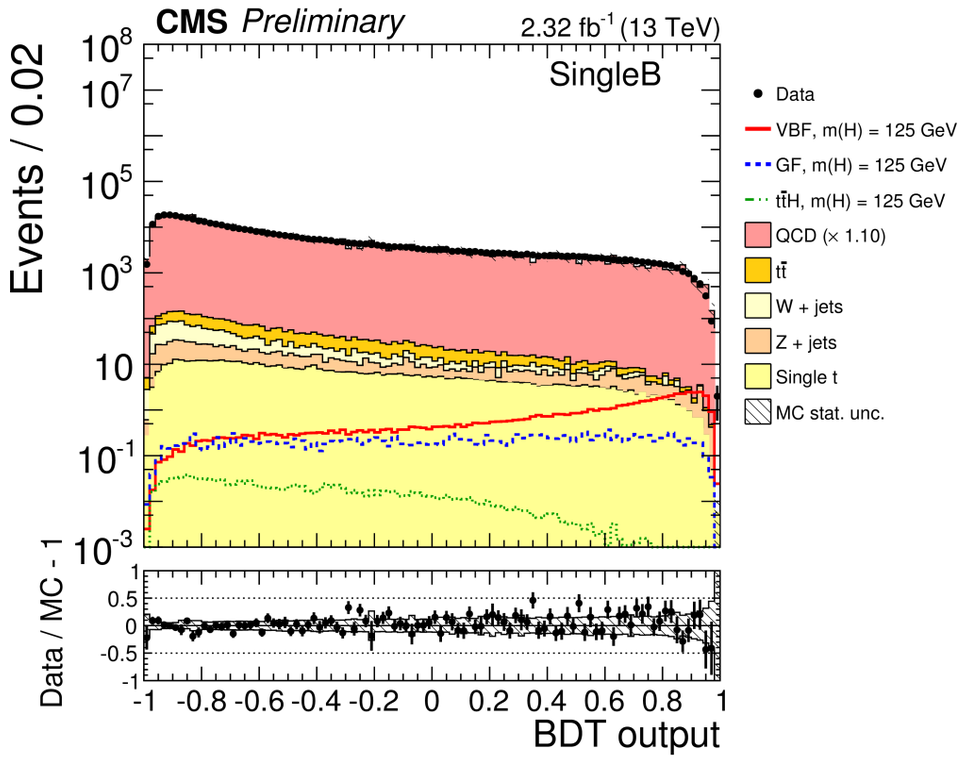
CMS-PAS-HIG-16-003

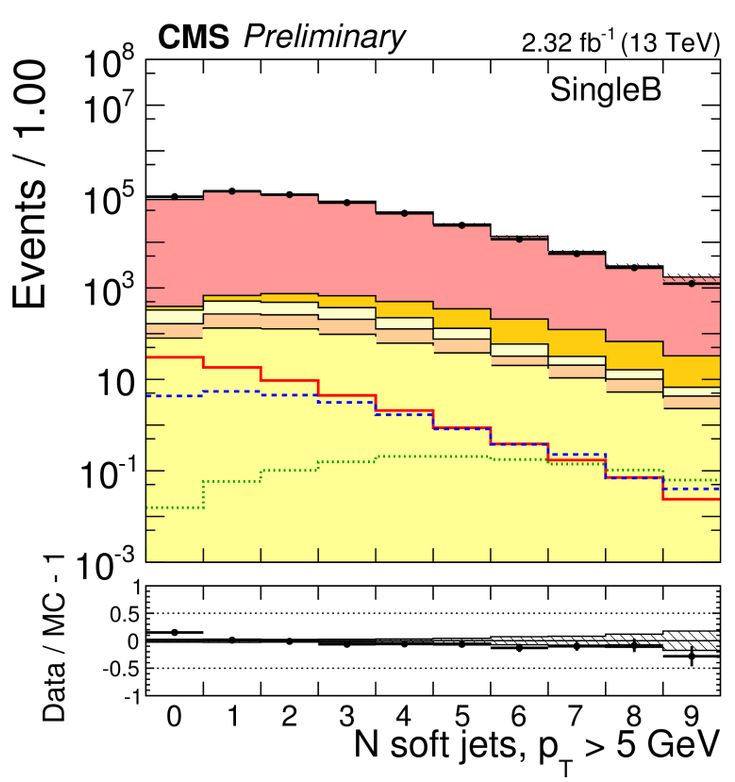
- Event categorization based on BDT **(with minimal correlation to m_{bb})**
  - Quark/gluon discrimination: jet minor-axis width σ_2 [CMS-PAS-JME-13-002]
  - Color flow: soft track-jet multiplicity outside of b jets
  - Plus:

$$m_{qq}$$
$$\Delta\eta_{qq}$$
$$\Delta\phi_{qq}$$
$$\Delta\eta^{f}_{qb} + \Delta\eta^{b}_{qb}$$
$$p_T(j_5)$$
$$p_T(qqbb)$$
$$p_z(qqbb)$$
$$\mathrm{CSV}_1$$
$$\mathrm{CSV}_2$$

color flow





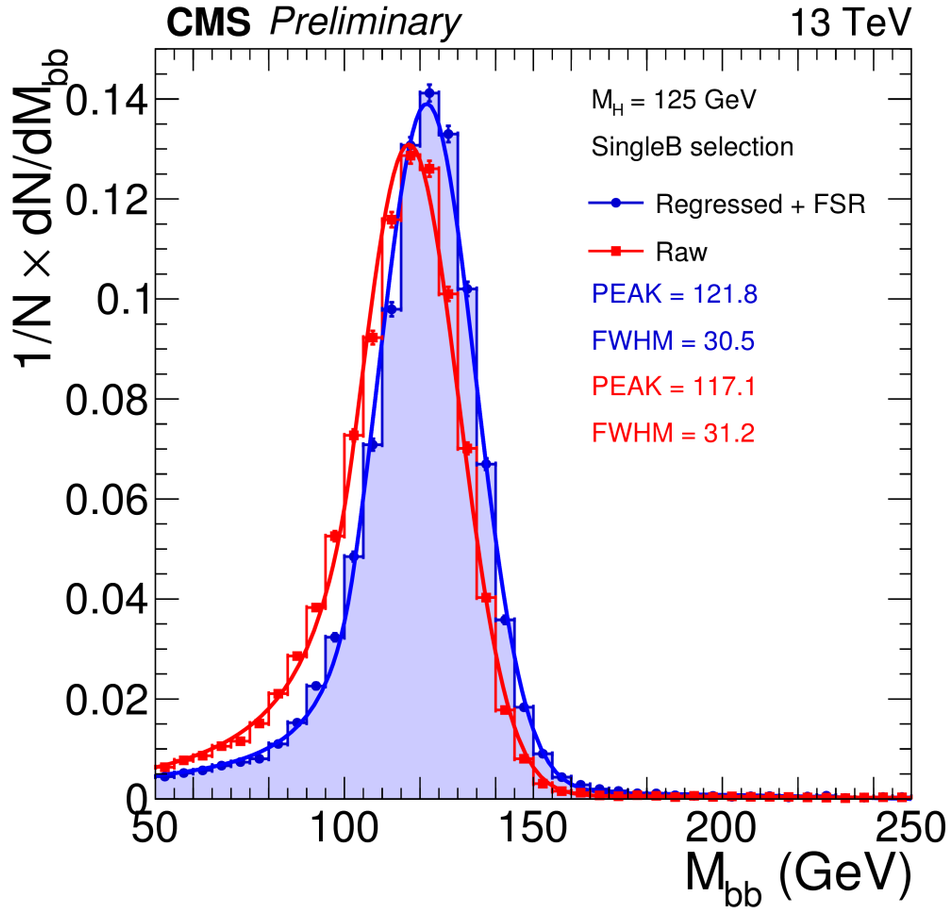


Brand New!

VBF H(bb)

CMS-PAS-HIG-16-003

- Regression trained to correct jet p_T improves m_{bb} resolution by 7%
  - Targets semileptonic b decays that lead to mismeasurement due to undetected neutrino
  - Trained using tt events, validated with Z+jets
- Signal extracted from simultaneous fit to m_{bb} across 7 categories
  - Signal: Crystal ball + 3rd order polynomial
  - QCD: 5th (4th) order polynomial for single (double) tagged categories times a transfer function
    - Transfer function accounts for shape differences between categories (derived in m_{bb} sidebands)



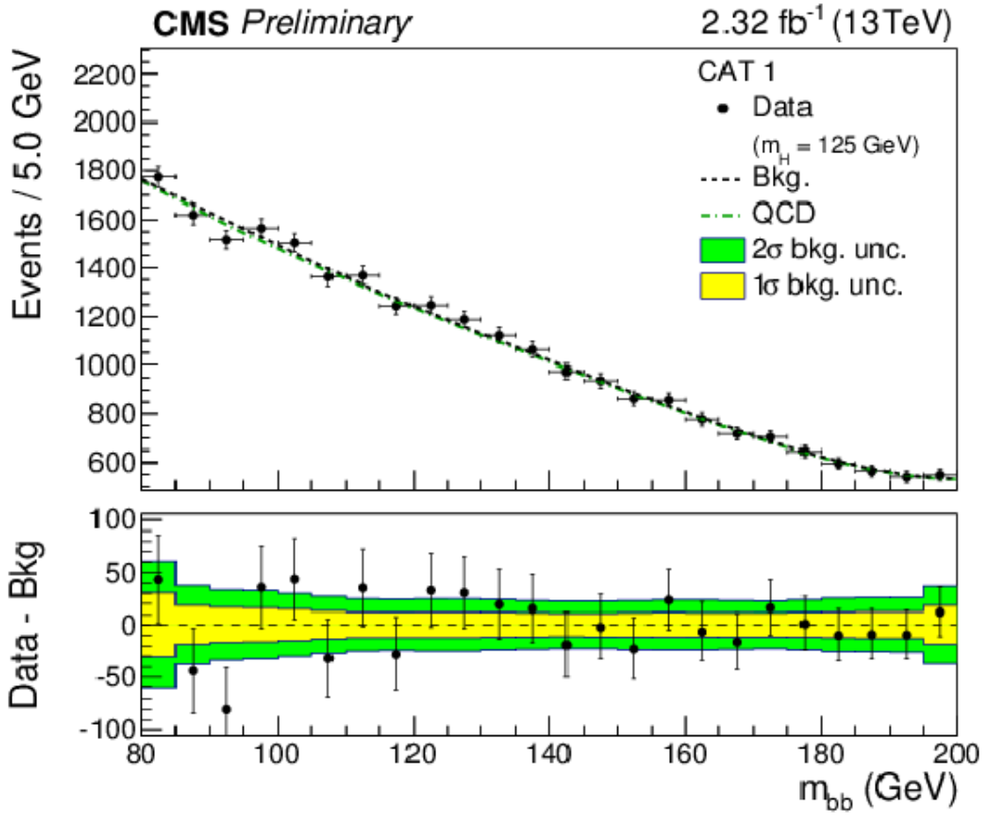
Brand New!

VBF H(bb)

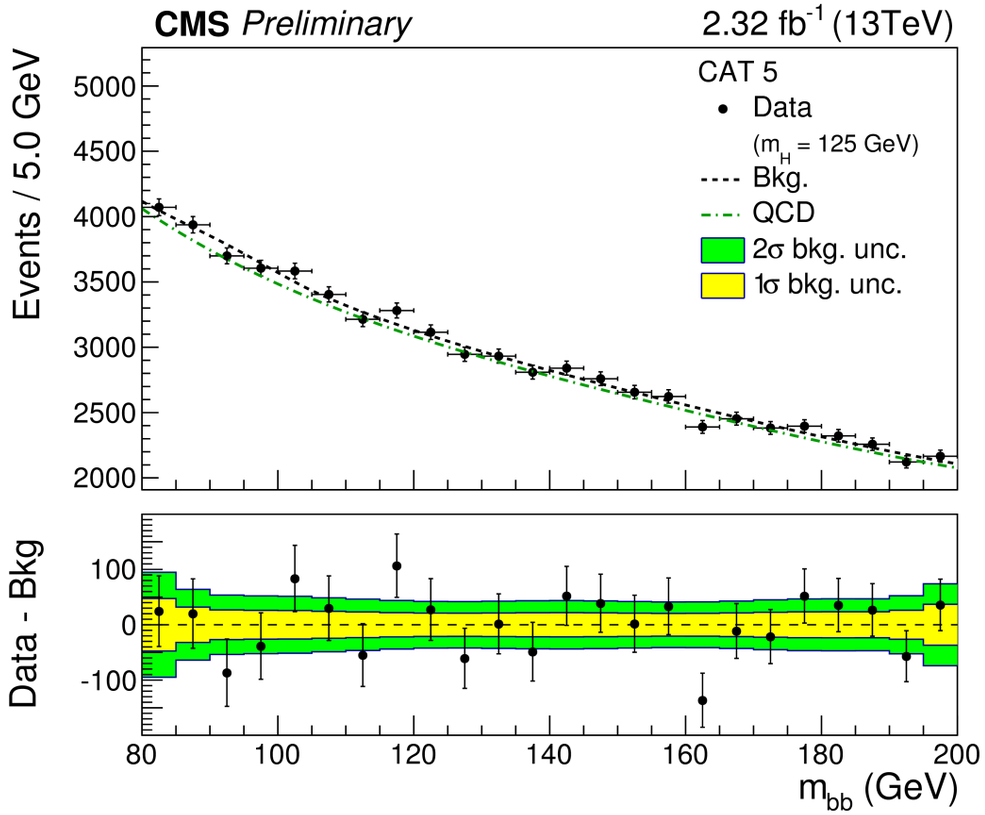
CMS-PAS-HIG-16-003

Simultaneous fit in 7 signal regions

1 b-tag



2 b-tag



Observed (expected)

95% CL exclusion:

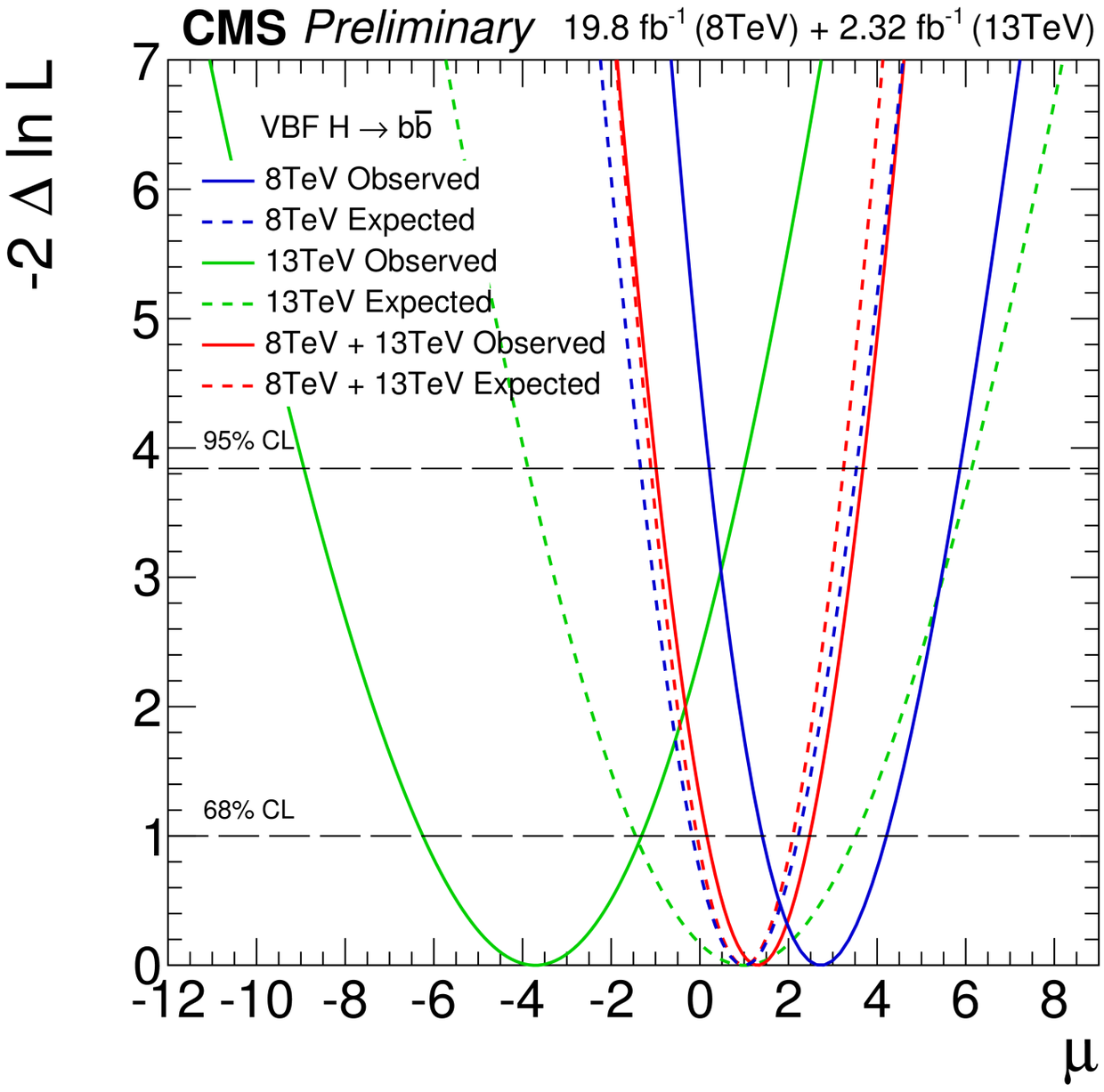
μ > 3.0 (5.0)

Brand New!

CMS-PAS-HIG-16-003

VBF H(bb)

Combination with Run I analysis



Observed (expected)
95% CL exclusion:
$\mu > 3.4\ (2.3)$

Run I + 2015 combined result:
$\mu = 1.3^{+1.2}_{-1.1}$

Observed (expected)
significance:
1.2σ (0.95σ)

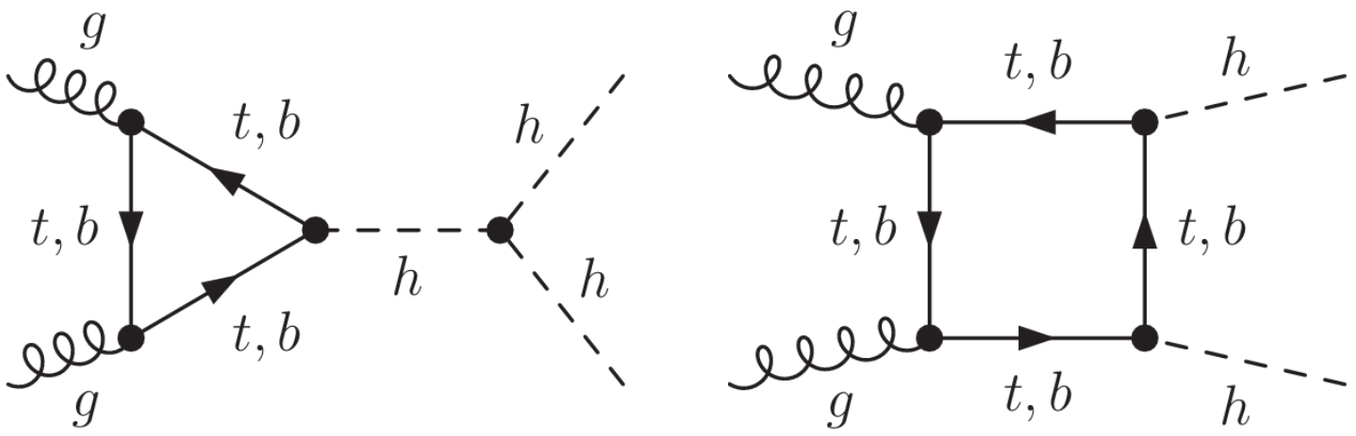
Non-resonant HH production

- Measurement of Higgs trilinear coupling provides important consistency check of SM Higgs Mechanism

$$V = \frac{1}{2}(2\lambda\nu^2)H^2 + \lambda\nu H^3 + \frac{\lambda}{4}H^4$$

m_H^2

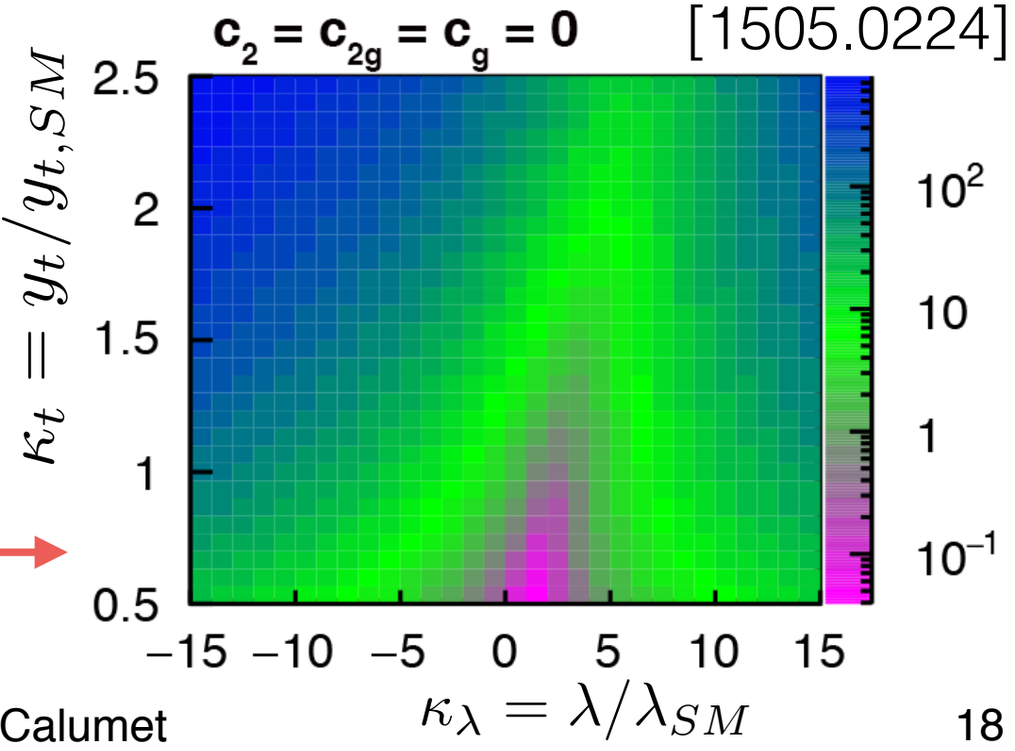
- Accessed through pair production: $\sigma_{SM} = 37.91$ fb



destructive interference

- HH cross section particularly sensitive to new physics

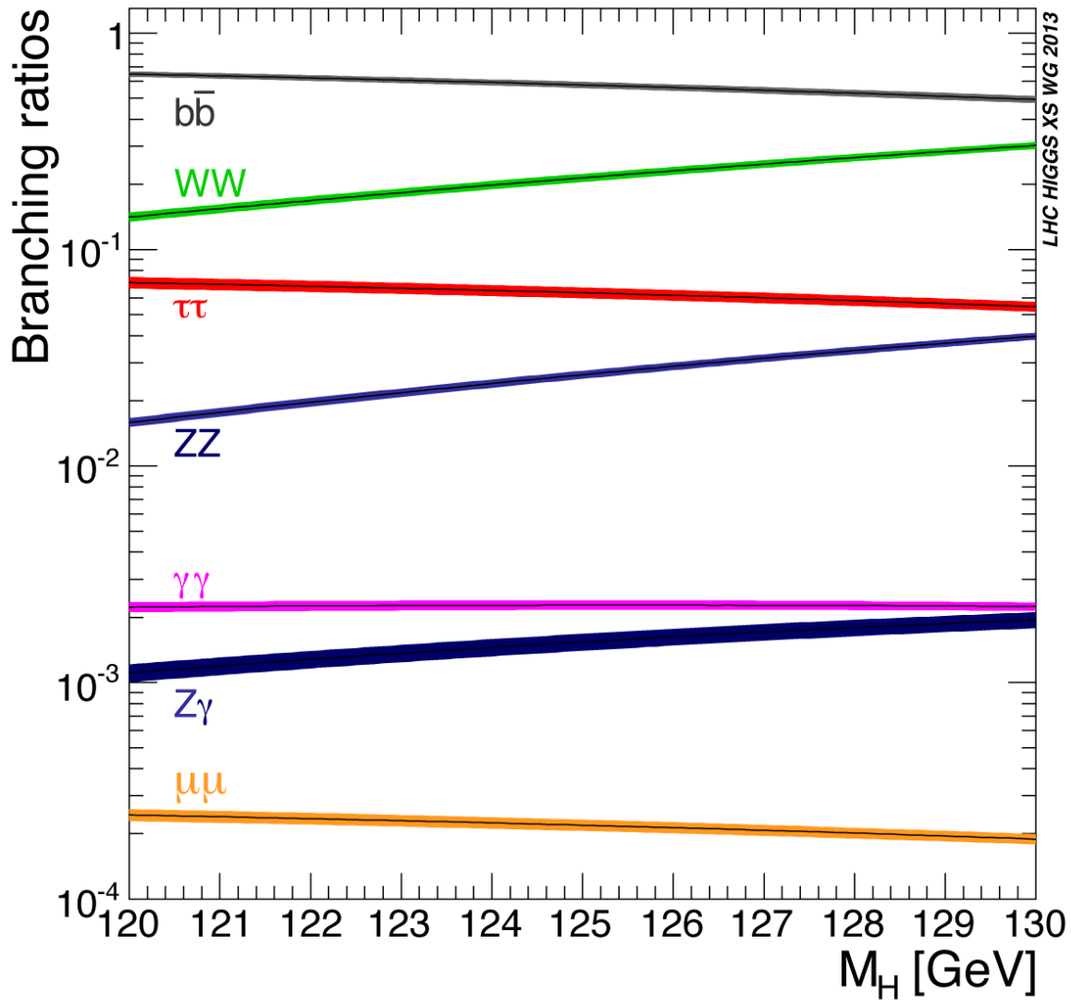
σ/σ_{SM}



CMS-PAS-HIG-16-012

H(bb)H($\tau\tau$)

- Due to small cross section, must focus on decays with large BR
  - Triggering is difficult in a 4b final state
  - bb$\tau\tau$ mode permits triggering and has relatively large cross section
- Consider 3 most sensitive final states: bb+$\tau_h\tau_h$/eτ_h/$\mu\tau_h$
  - Triggers
    - $\tau_h\tau_h$ channel: 2 τ_h
    - $\ell\tau_h$ channels: 1 ℓ
  - Dominant background: top pair-production



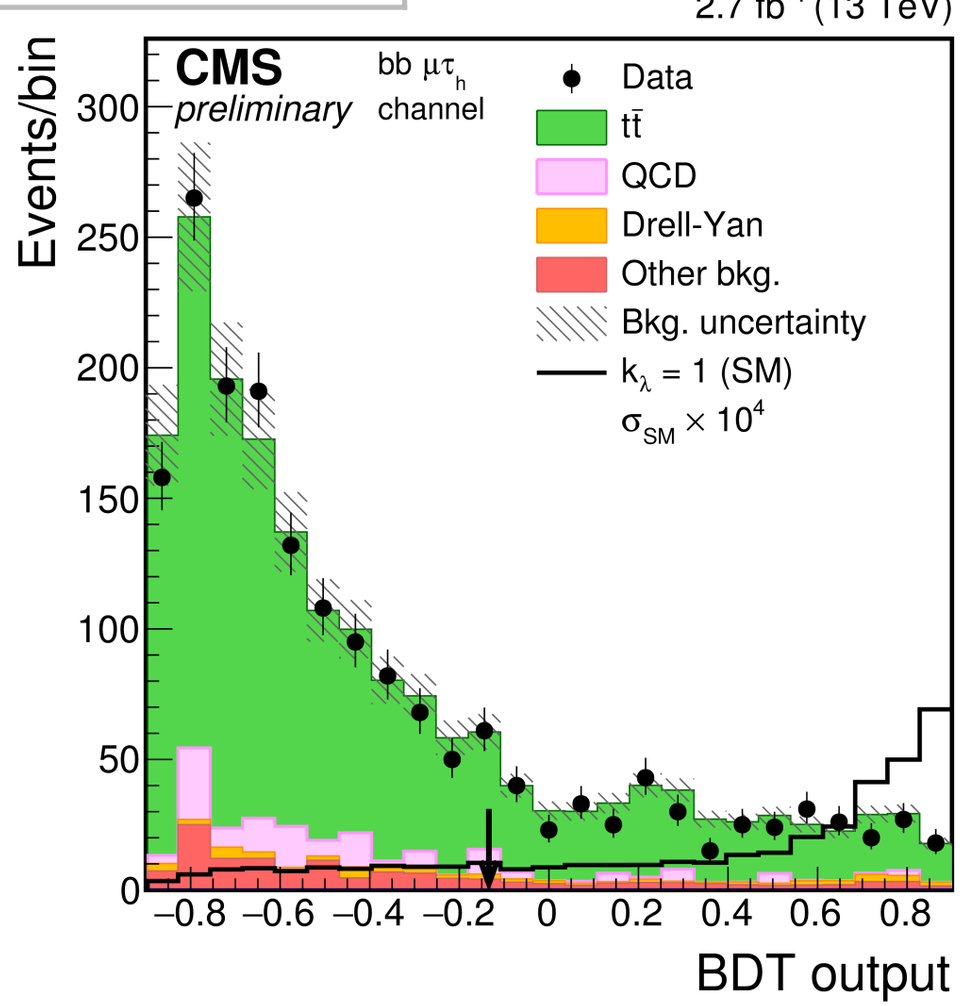
CMS-PAS-HIG-16-012

H(bb)H($\tau\tau$)

- Offline selection:

2 OS leptons
2 “loose” b-jets ($\varepsilon_b \approx 85\%$ / $\varepsilon_q \approx 8\%$)
80 GeV < $m_{\tau\tau}(m_{bb})$ < 160 GeV

- Additional requirement on MVA discriminant (BDT) in leptonic channels
  - Trained to reject top pair-production based on angular observables
    - $\Delta\phi(h_{bb},h_{\tau\tau})$, $\Delta\phi(h_{\tau\tau},\text{MET})$, $\Delta\phi(h_{bb},\text{MET})$, $\Delta R(b,b)$, $\Delta R(\ell, \tau_h)$
  - $\varepsilon_S \approx 80\%$ / $\varepsilon_B \approx 15\%$



H(bb)H($\tau\tau$)

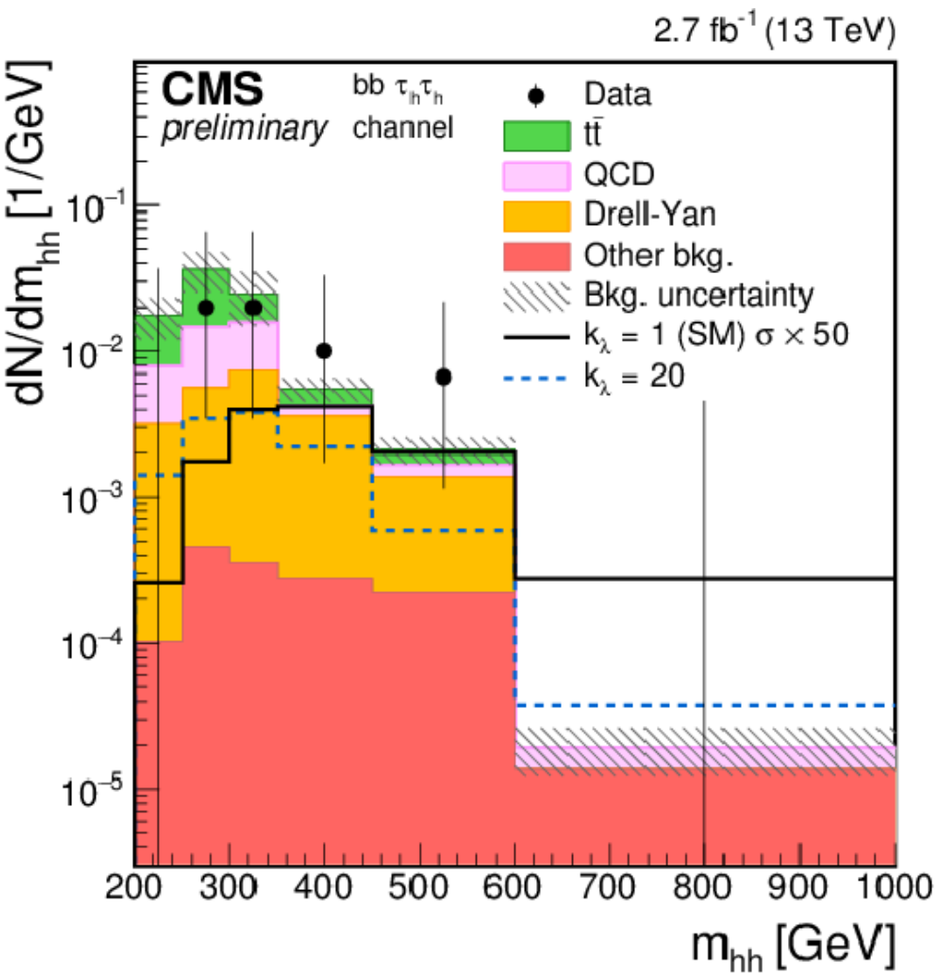
CMS-PAS-HIG-16-012

- Background estimation
  - QCD
    - Yield: Taken from SS CR scaled by ratio of OS/SS yields in CR with relaxed isolation
    - Shape: Taken from SS CR with relaxed isolation
  - Top pair-production
    - MC with shape corrections to top p_T
  - Z+jets
    - MC with flavor-dependent SFs derived in CRs with 0,1,2$^+$ b-jets (simultaneously fit with SR)

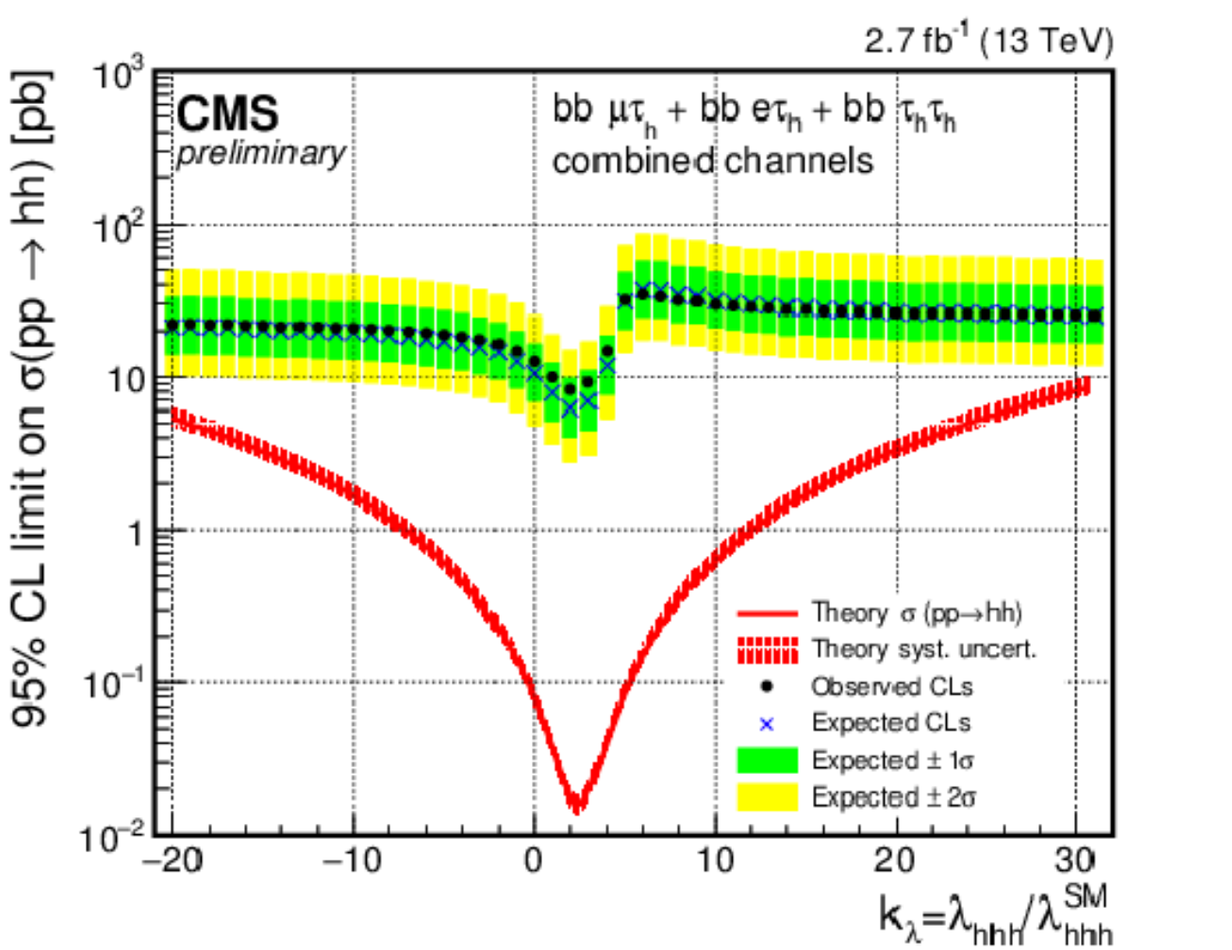
CMS-PAS-HIG-16-012

H(bb)H($\tau\tau$)

Test for signal in m_{hh}



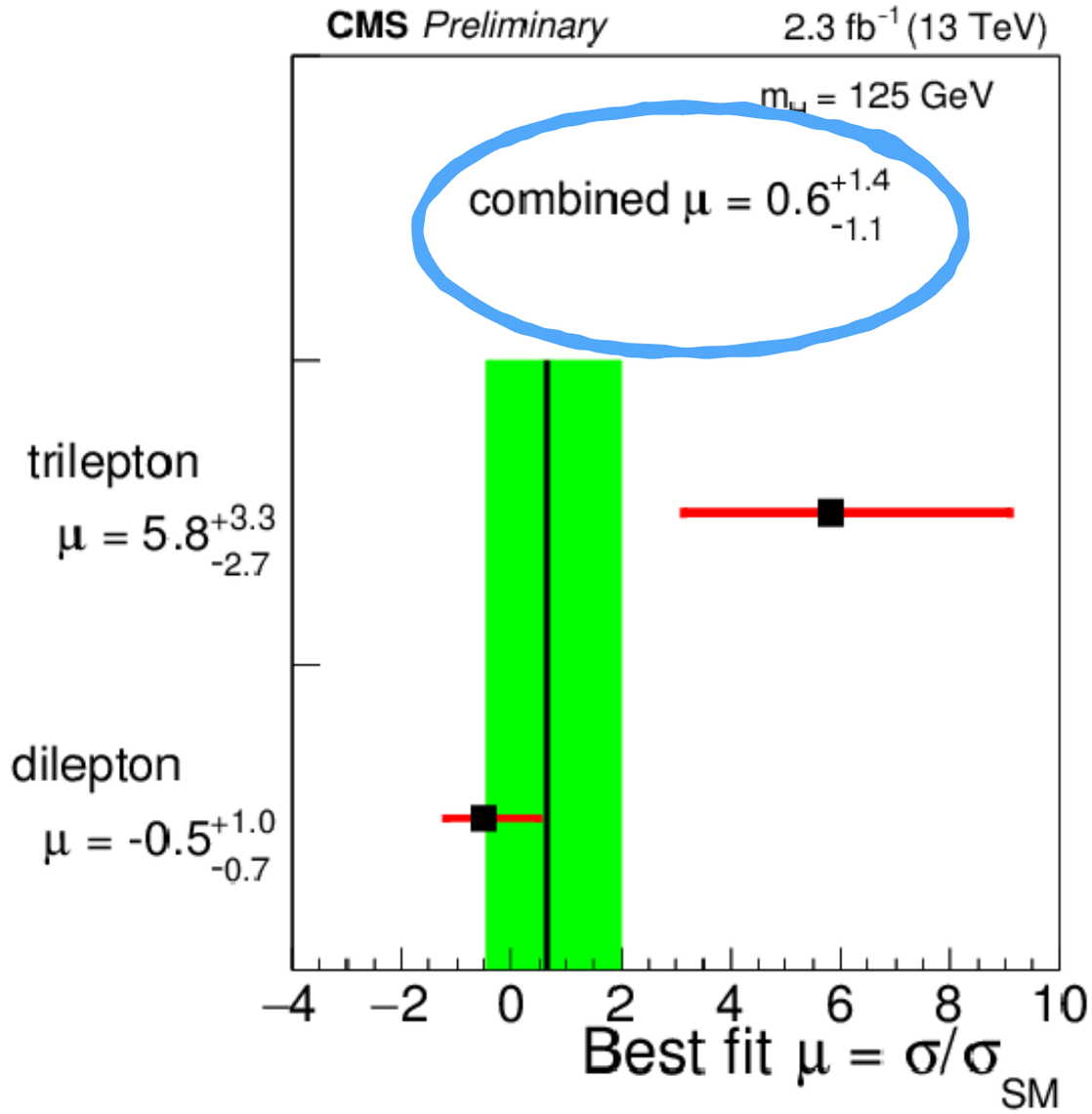
Process	bb$\mu\tau_h$	bb$e\tau_h$	bb$\tau_h\tau_h$
$t\bar{t}$	45.5 ± 5.7	25.0 ± 3.2	2.2 ± 0.3
QCD	1.2 ± 1.0	5.2 ± 2.3	1.2 ± 1.0
Z+jets	5.2 ± 1.7	2.1 ± 0.7	1.3 ± 0.4
W+jets	0.9 ± 0.2	1.1 ± 0.2	-
single top	2.0 ± 0.2	1.1 ± 0.1	-
di-boson	0.4 ± 0.1	0.08 ± 0.02	0.11 ± 0.02
Total expected background	55.2 ± 6.0	34.6 ± 4.0	4.8 ± 1.2
$k_\lambda = 1$	$(3.2 \pm 0.3) \cdot 10^{-2}$	$(1.7 \pm 0.2) \cdot 10^{-2}$	$(2.1 \pm 0.2) \cdot 10^{-2}$
$k_\lambda = 20$	1.0	0.55	0.76
DATA	59	30	4

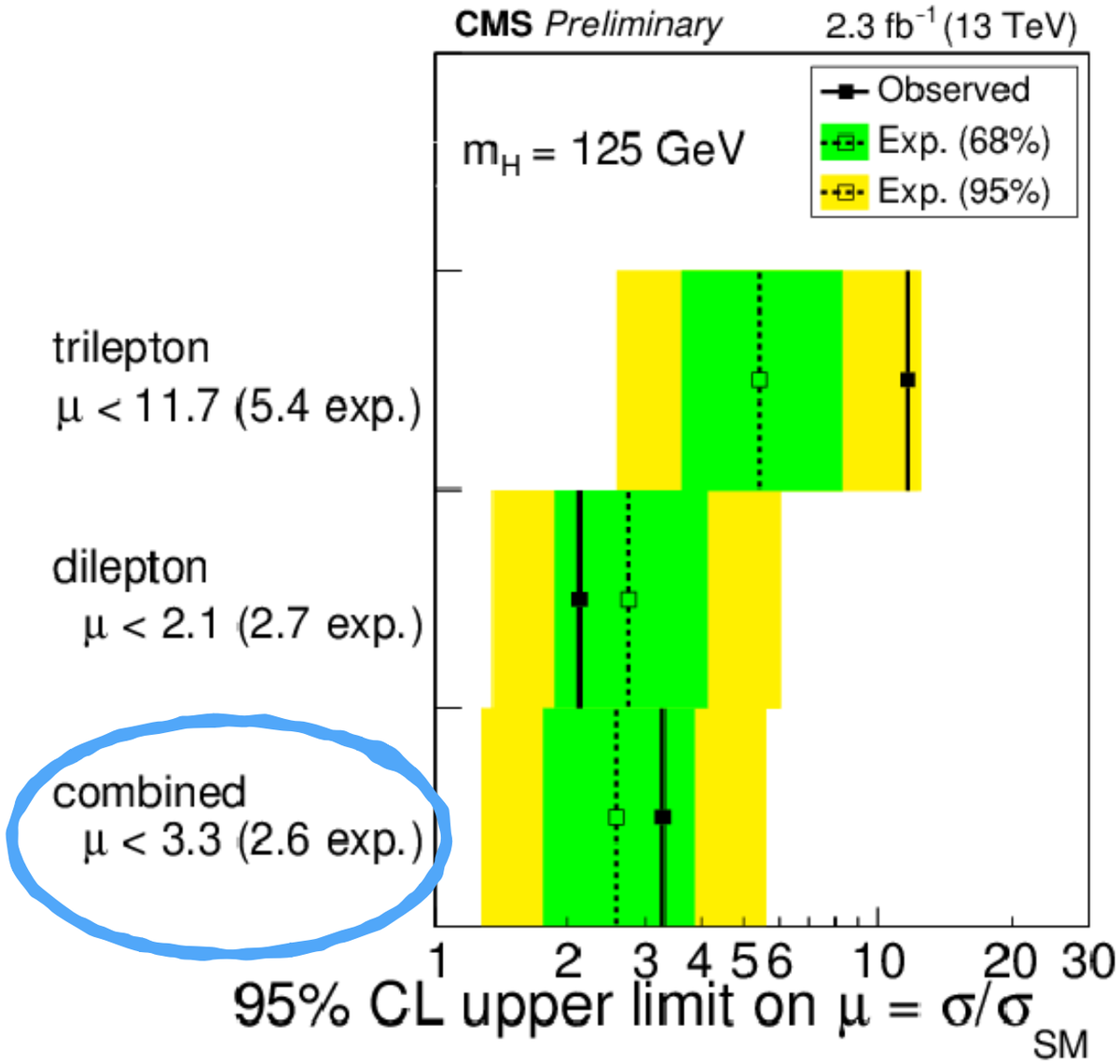


CMS-PAS-HIG-15-008

ttH(multileptons)

See talk by Eleni Ntomari for details

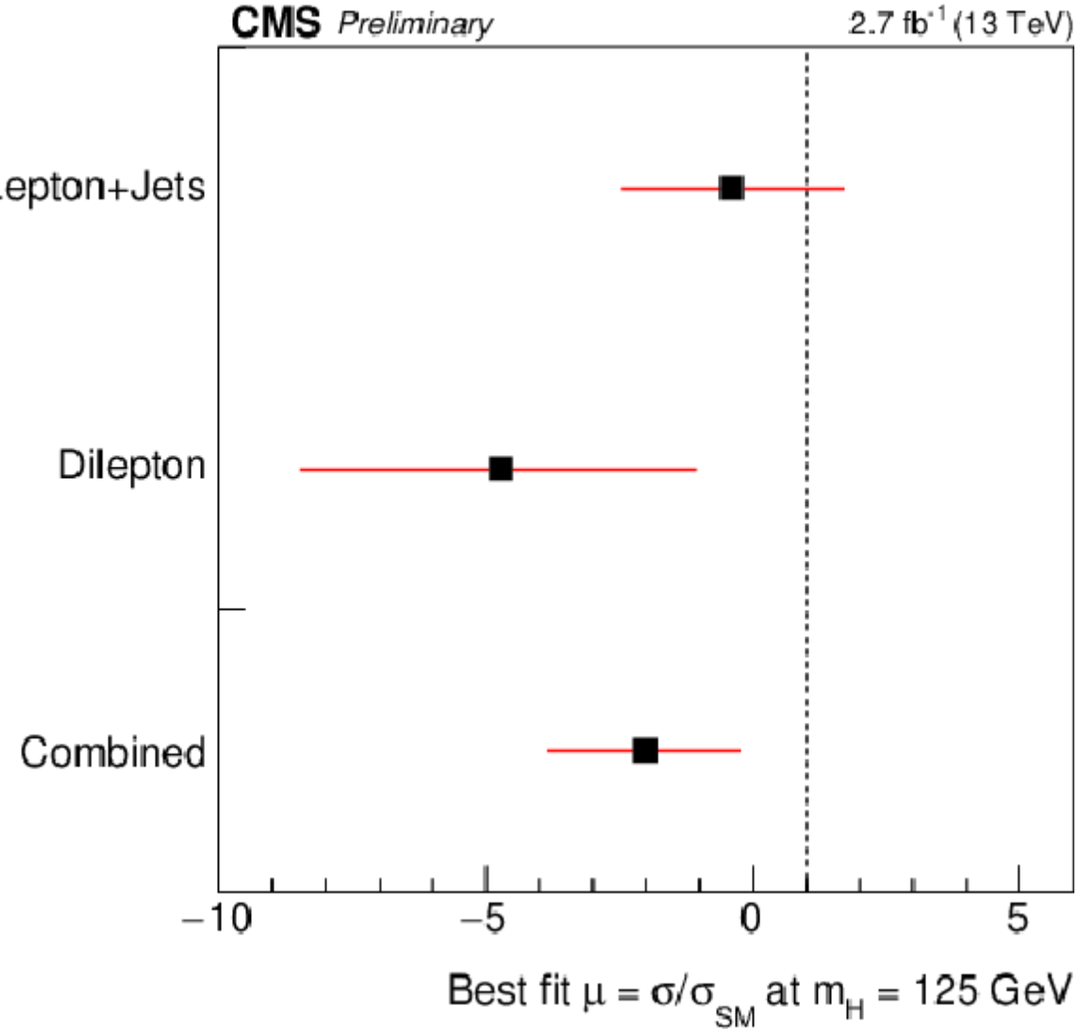


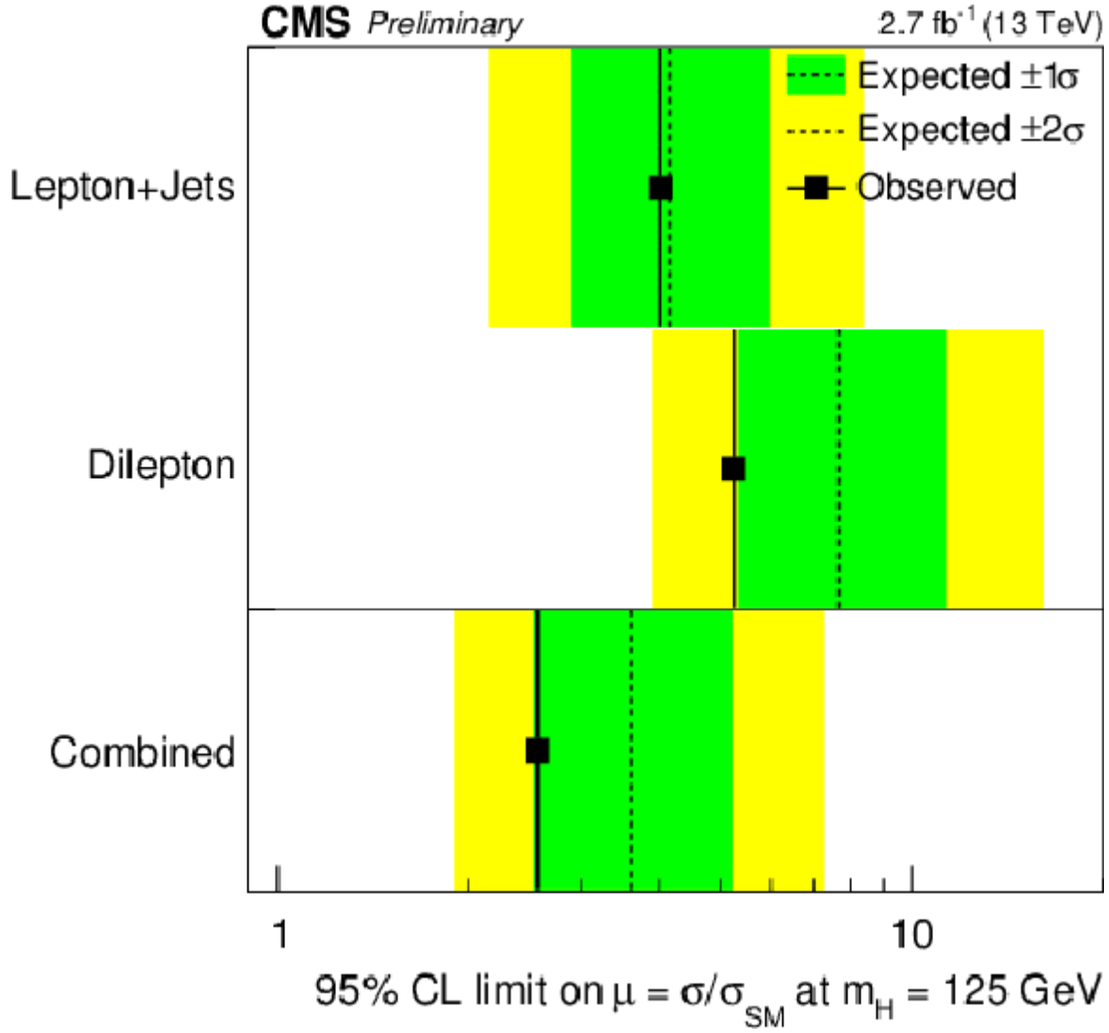


ttH(bb)

CMS-PAS-HIG-16-004

See talk by Eleni Ntomari for details





Best fit:

$\mu = -2.0^{+1.8}_{-1.8}$

Compatible with μ=1 at 1.7σ

Observed (expected) 95% CL exclusion:

μ > 2.6 (3.6)

Summary

- On the way to rediscovery of the Higgs at 13 TeV
- As with Run I, so far all results consistent with the SM
- Generally, more data is needed to compete with Run I analyses
  - New results with 2016 data coming soon!