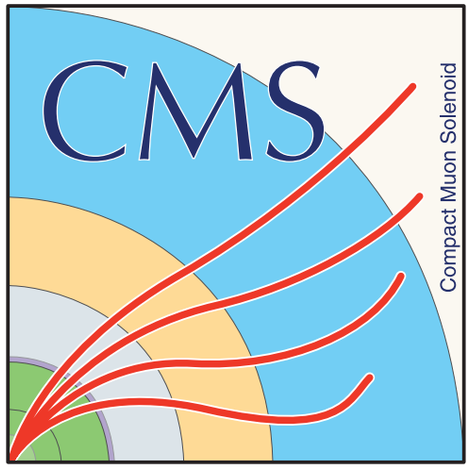


New Higgs results from CMS

Meng Xiao (Johns Hopkins University)
on behalf of the CMS collaboration

Rencontres de Moriond QCD and High Energy Interactions
LA THUILE, MARCH 25 - APRIL 1, 2017

Introduction

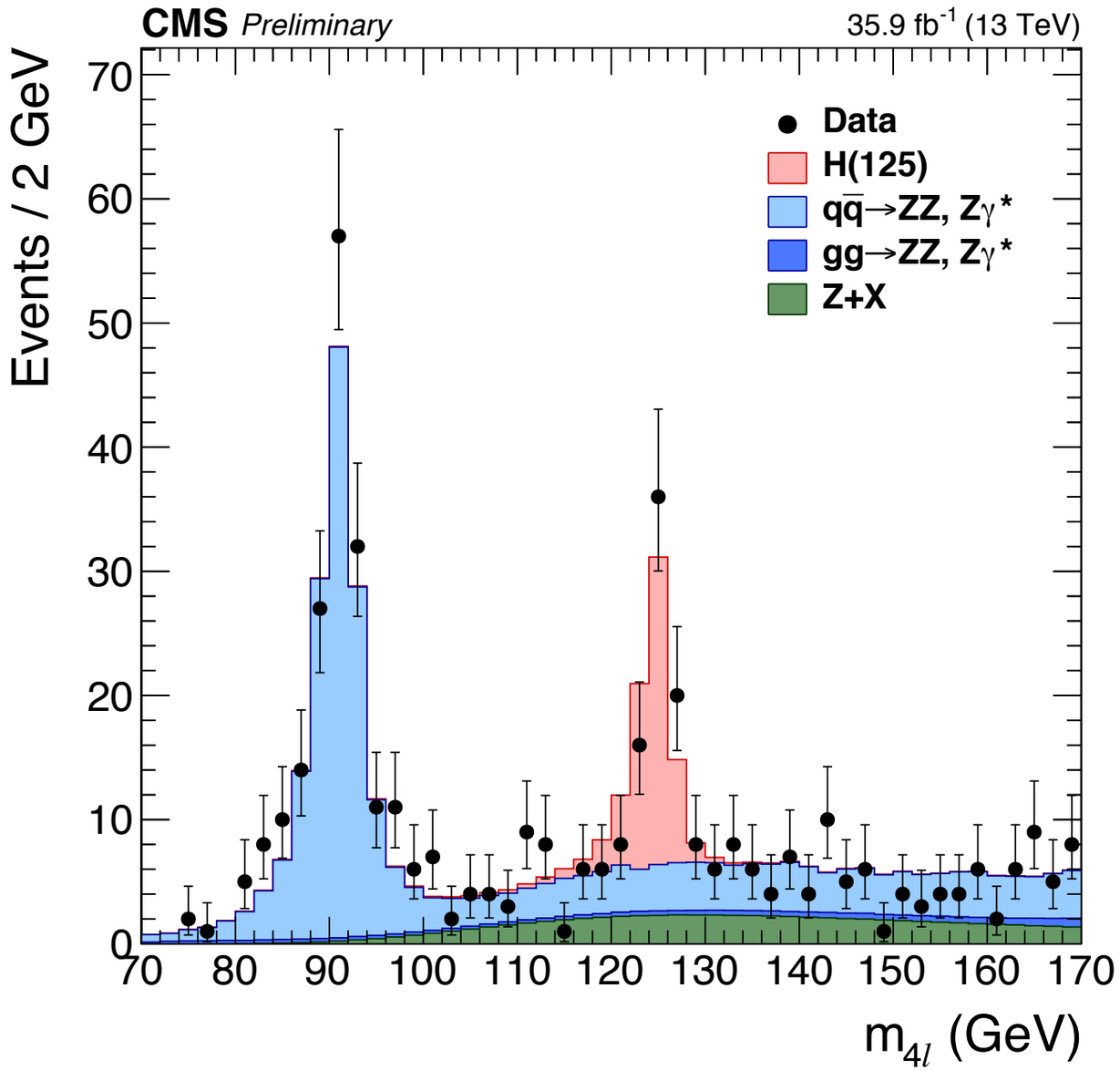
- The talk will focus on new results based on full 2016 data
  - H→ ZZ→ 4ℓ, CMS-PAS-HIG-16-041
  - H→ 4ℓ anomalous coupling, CMS-PAS-HIG-17-011
  - H→ $\gamma\gamma$, differential fiducial cross-section, CMS-PAS-HIG-17-015 NEW!
  - HH→ bb$\tau\tau$, CMS-PAS-HIG-17-002
  - HH→ bbℓvℓv, CMS-PAS-HIG-17-006 NEW!
- New results from ttH, see Nicolas Chanon's talk

NEW! for Moriond QCD

HIG-16-041

H→ ZZ→ 4ℓ

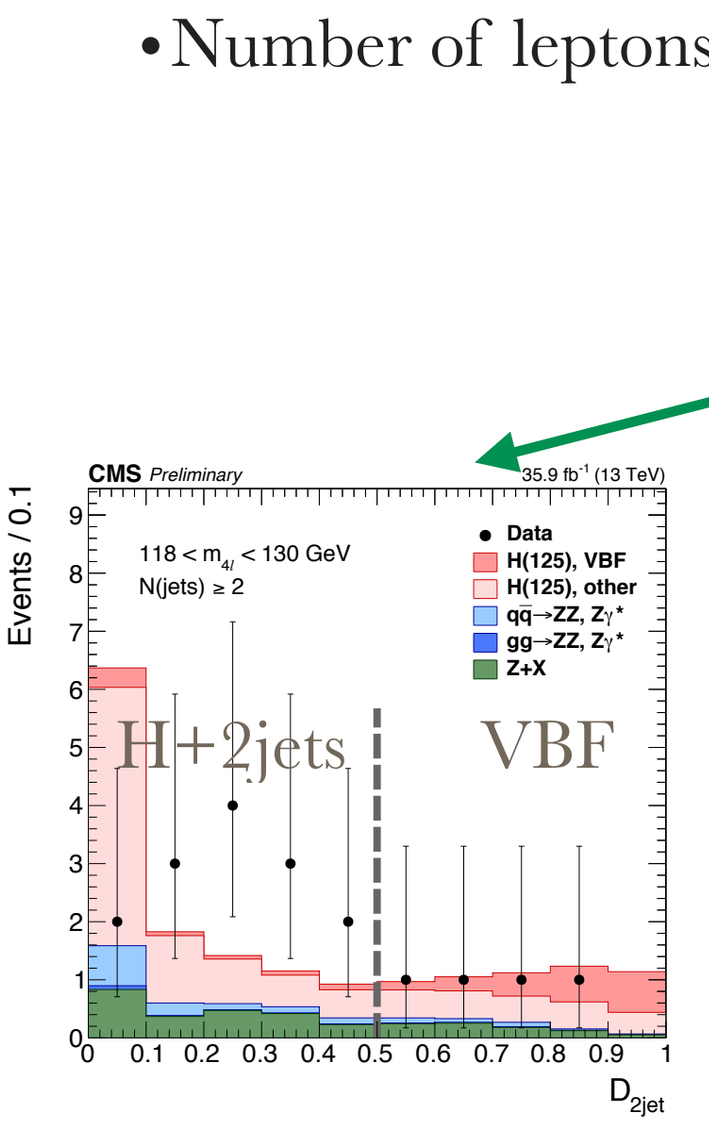
Nice Higgs peak, what can we learn from it?

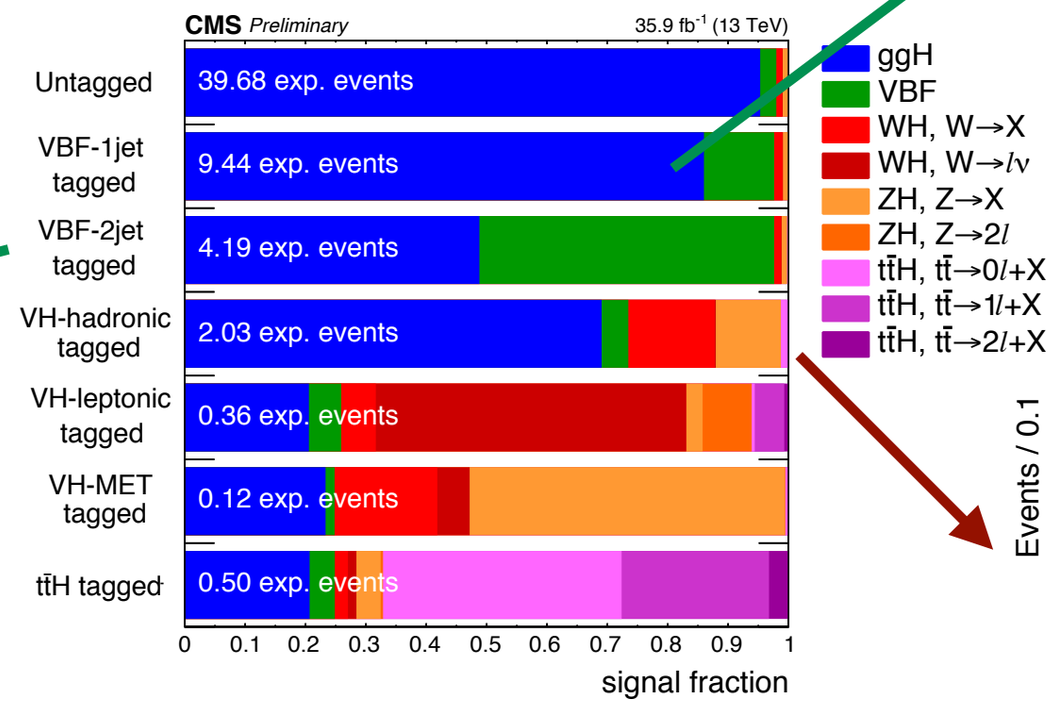


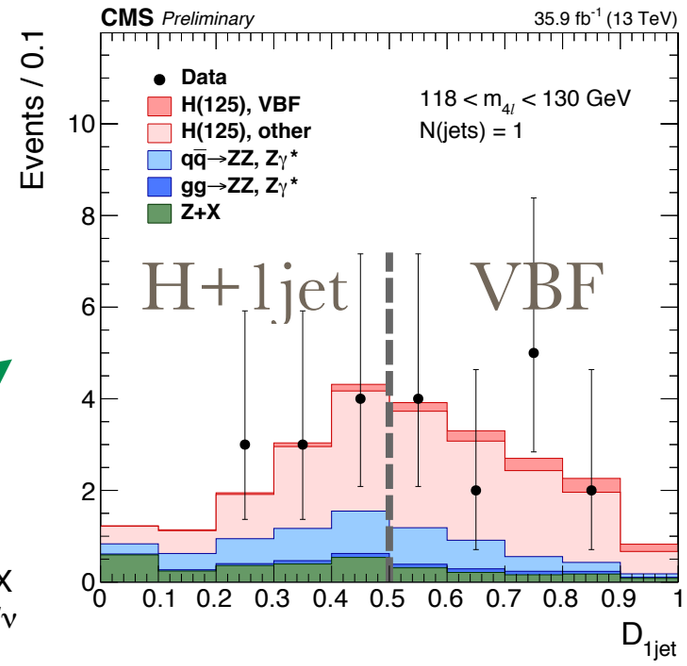
HIG-16-041

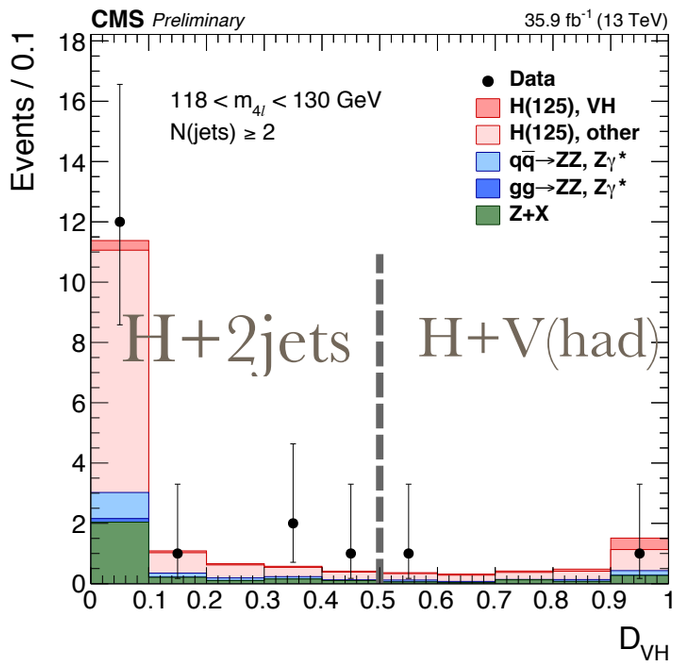
H→ ZZ→ 4ℓ: production mode

- Production information
  - ME based discriminants from MELA (full information)
  - Number of leptons, b-jets, MET



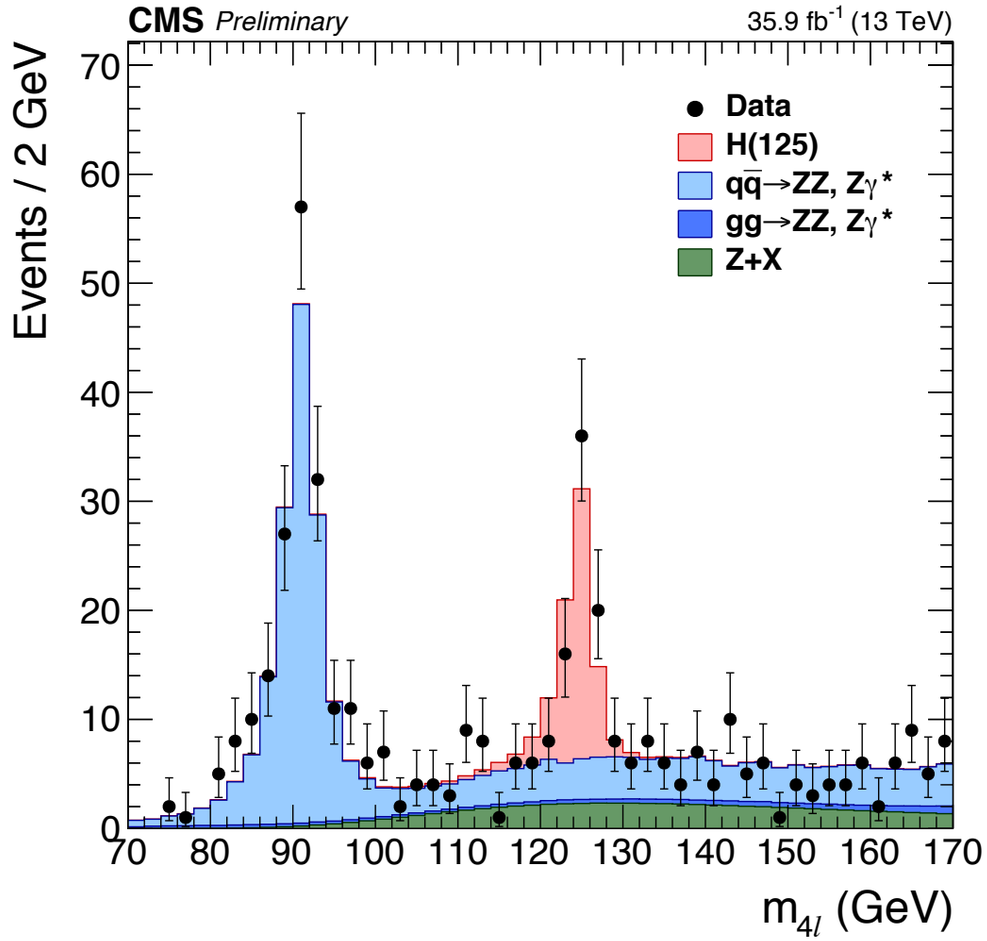






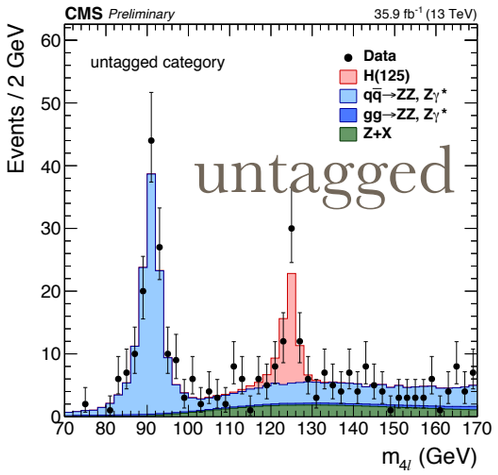
HIG-16-041

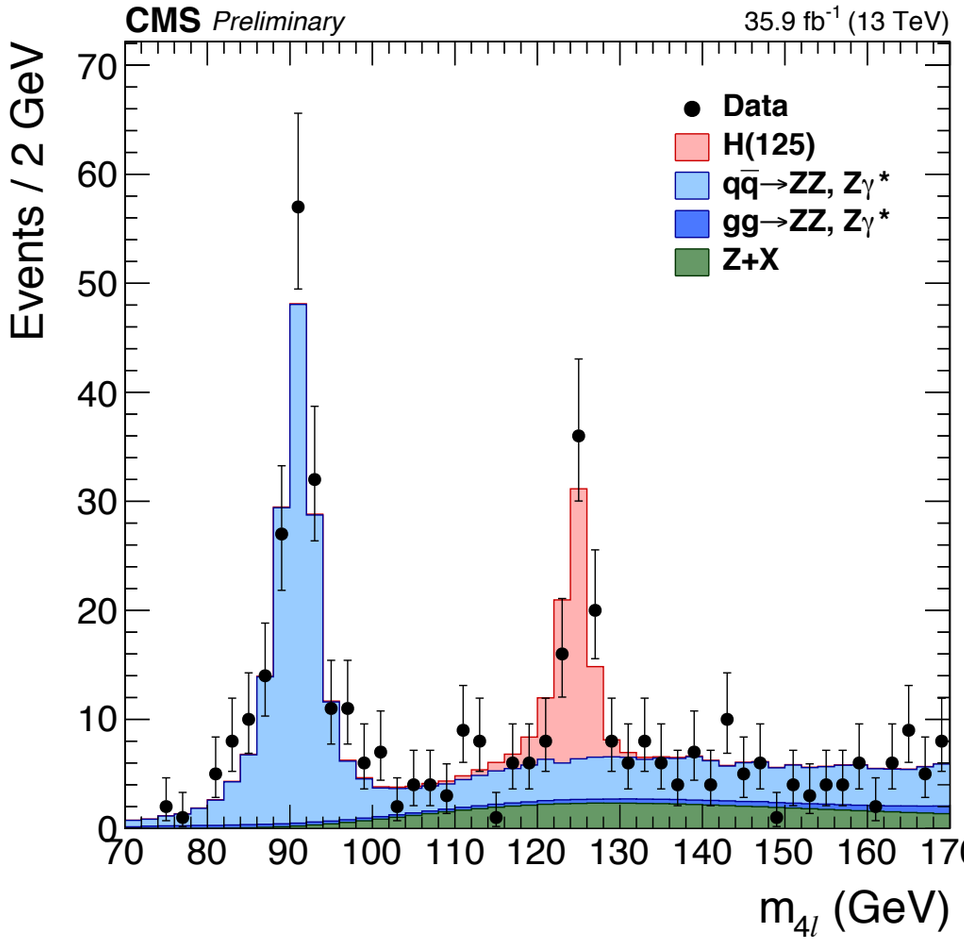
H→ ZZ→ 4ℓ: production mode

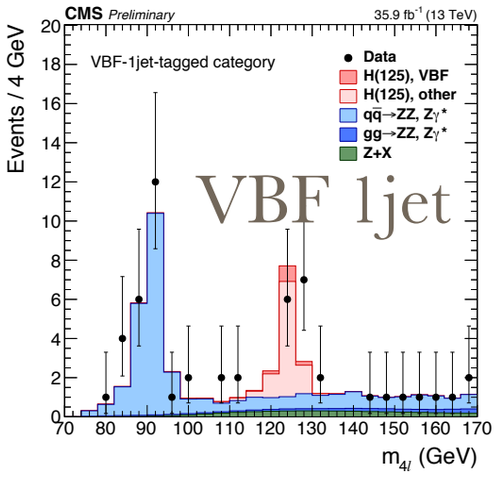


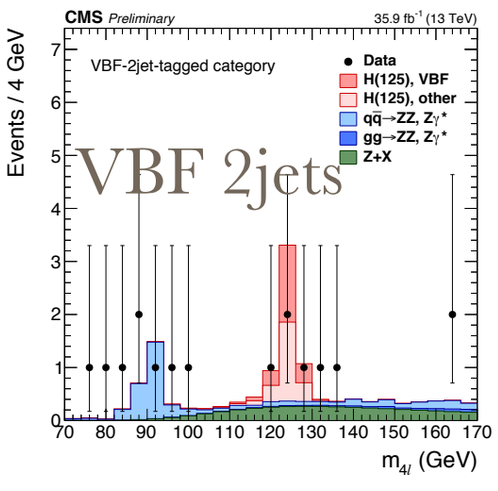
HIG-16-041

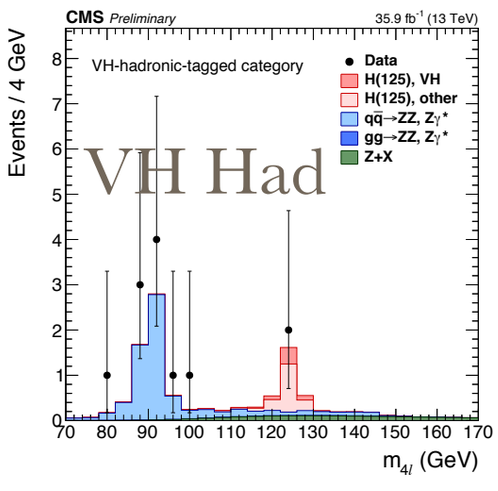
H→ ZZ→ 4ℓ : production mode

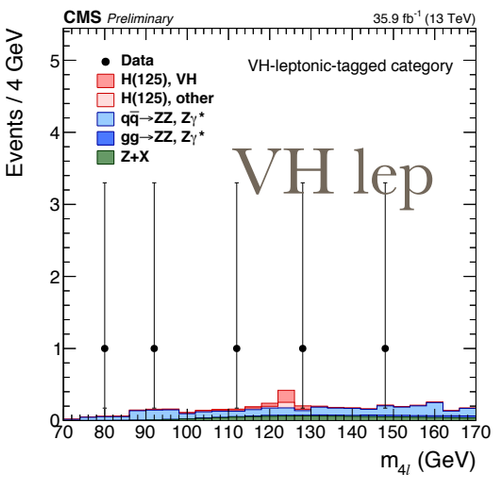


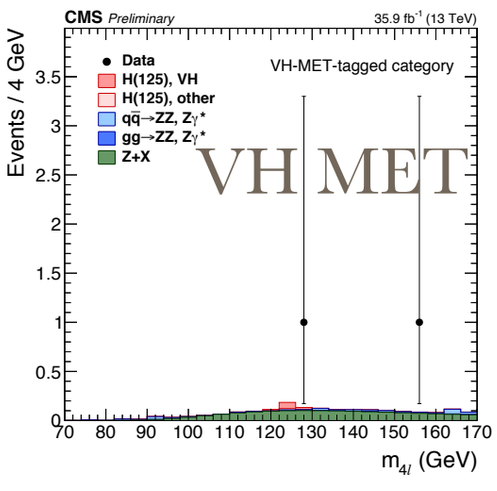


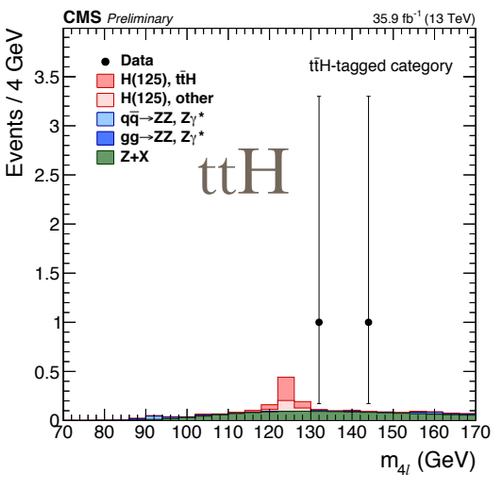






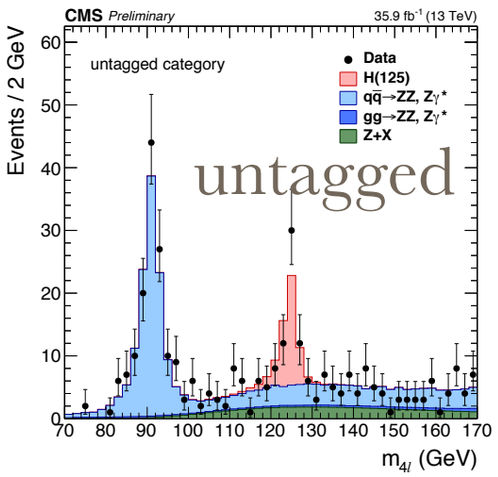


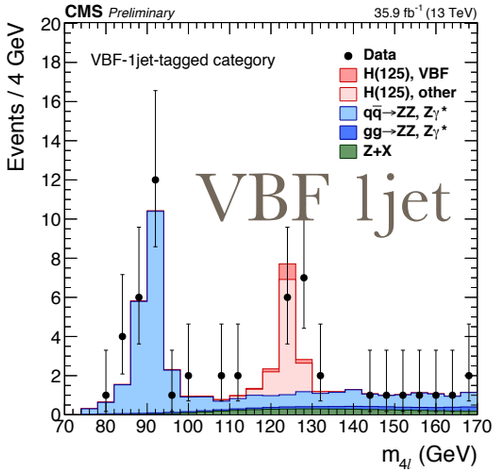


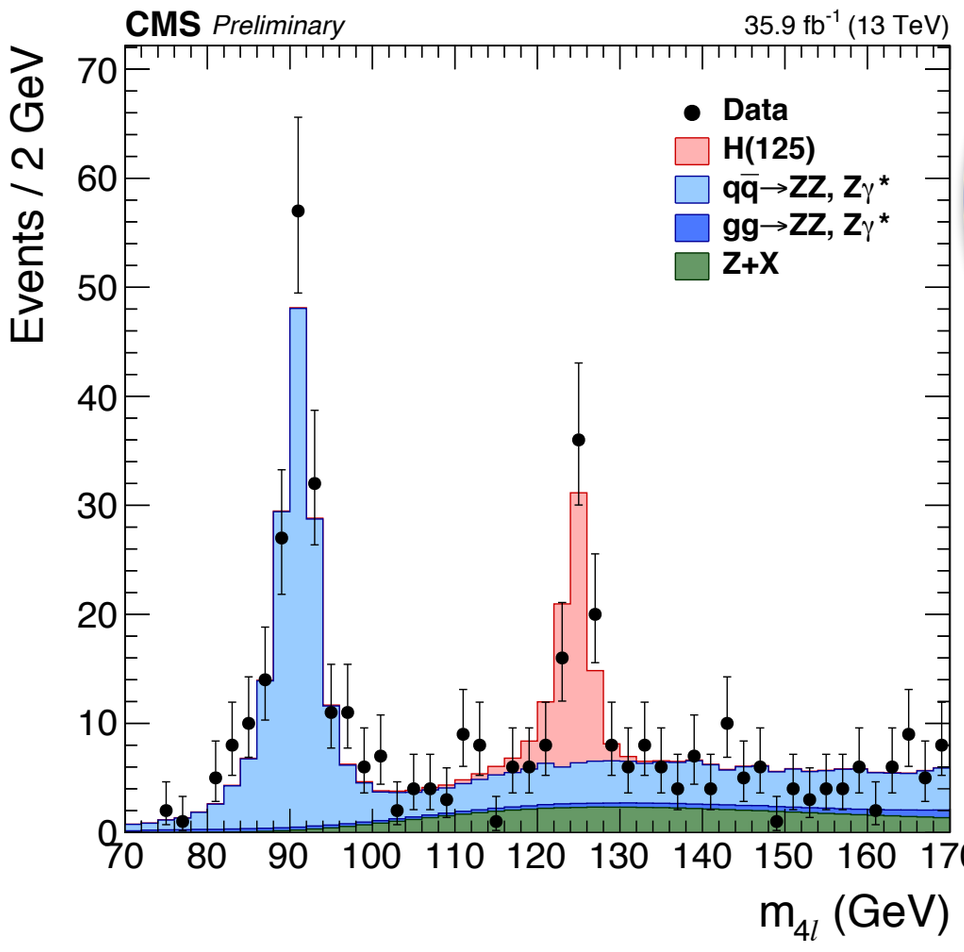


HIG-16-041

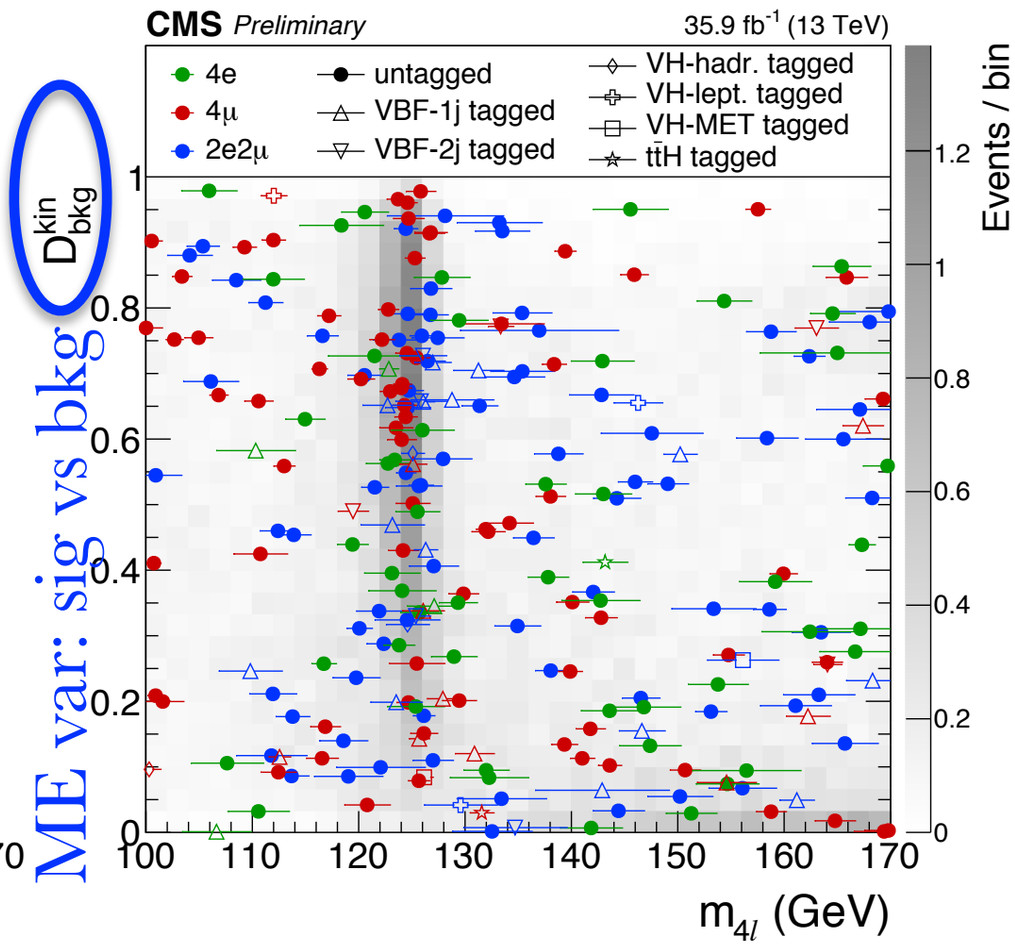
H→ ZZ→ 4ℓ: production mode

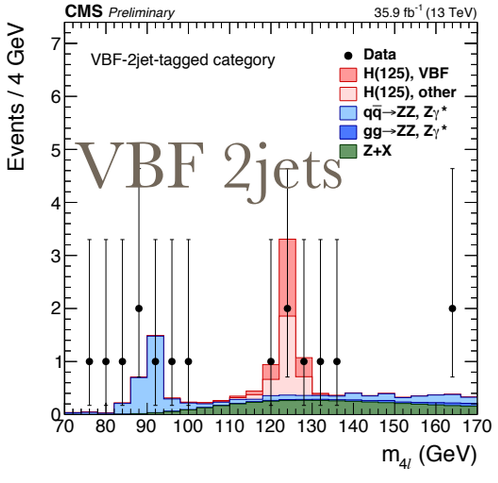


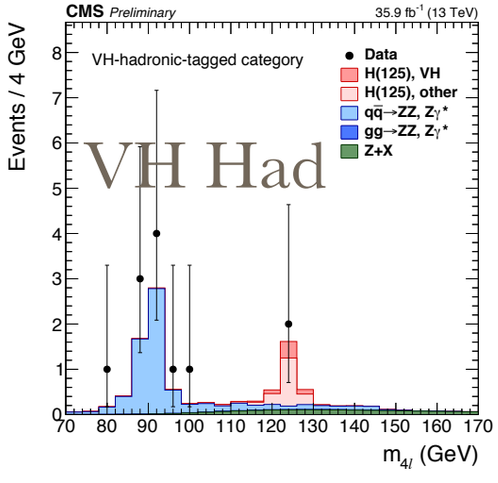


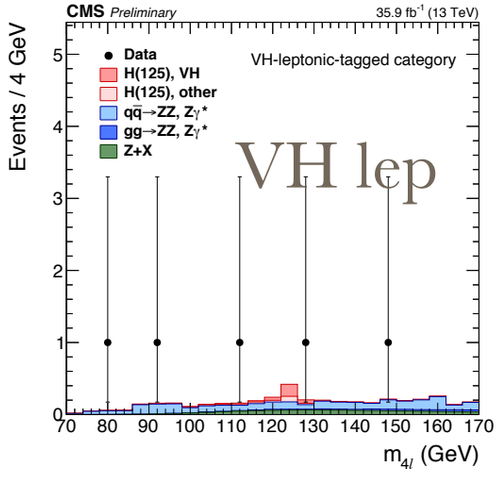


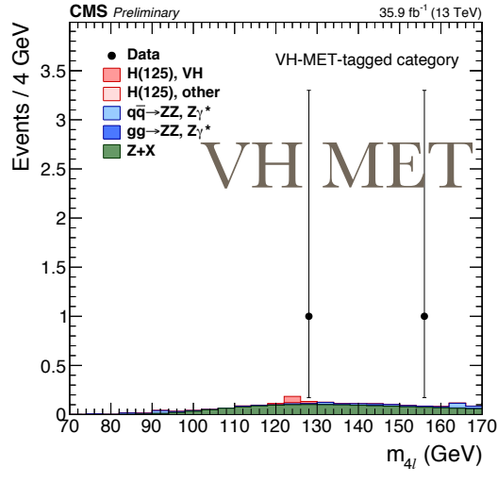
2D analysis: m_{4l} vs D_{bkg}^{kin}

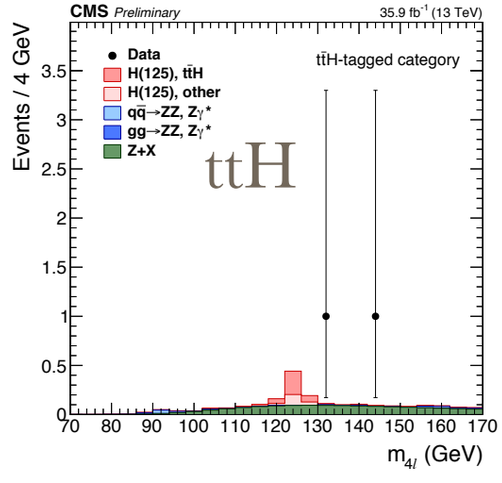








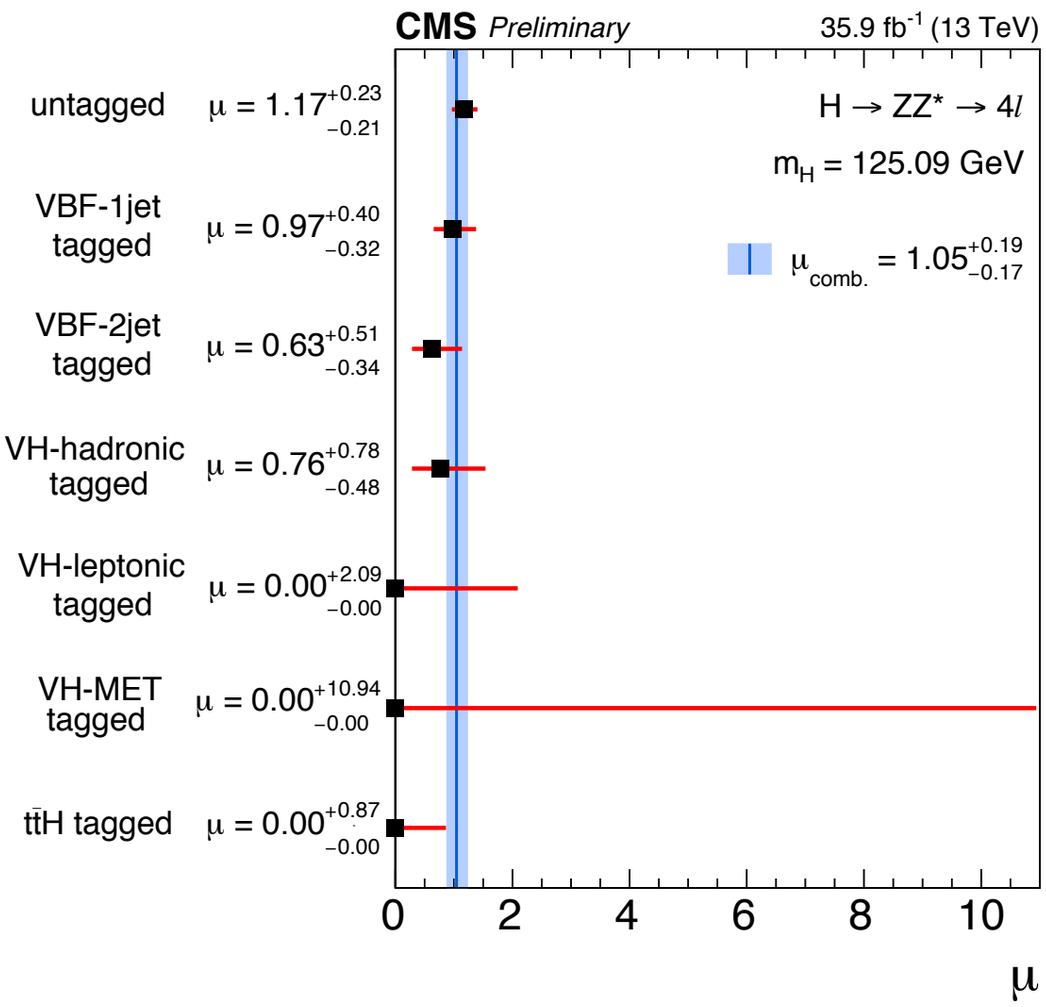




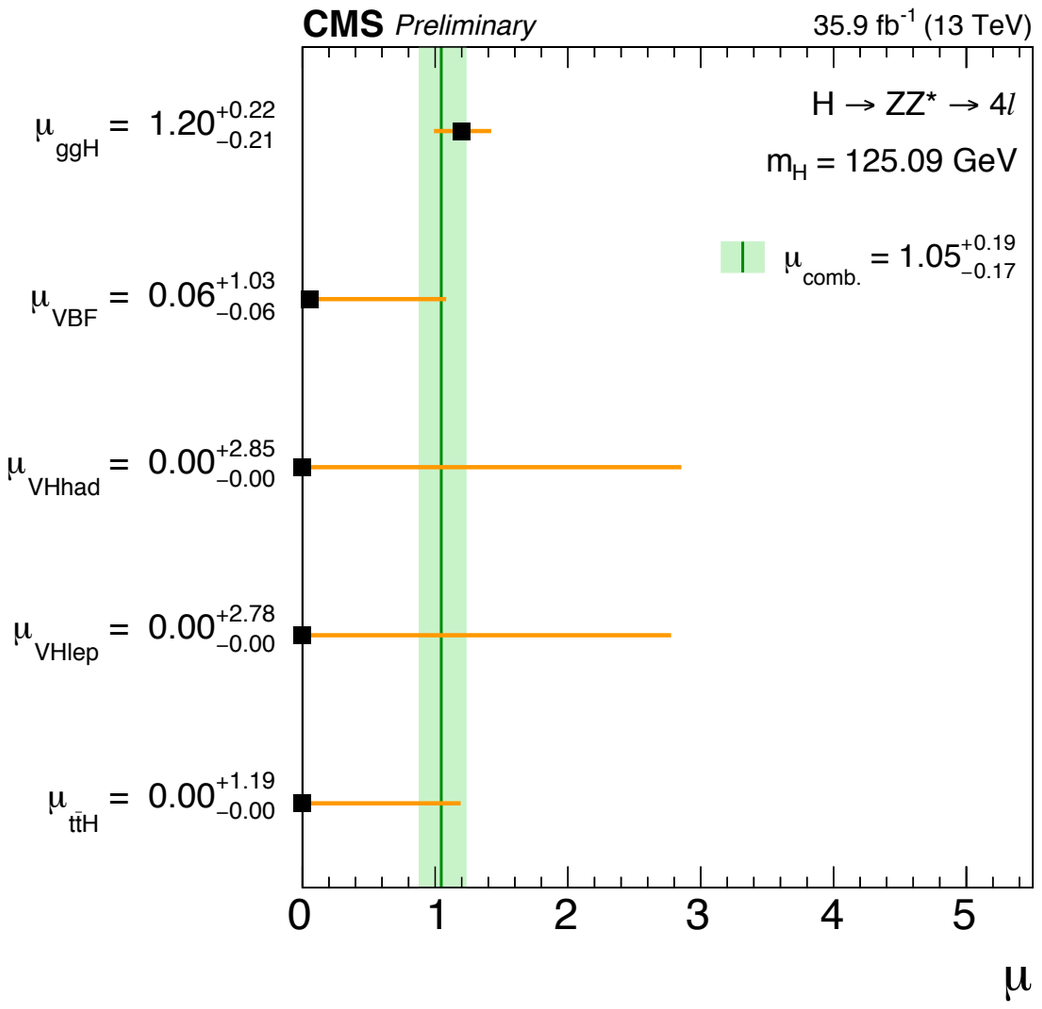
H→ ZZ→ 4ℓ: production mode

2D analysis: m_{4l} vs D_{bkg}^{kin}

μ per category



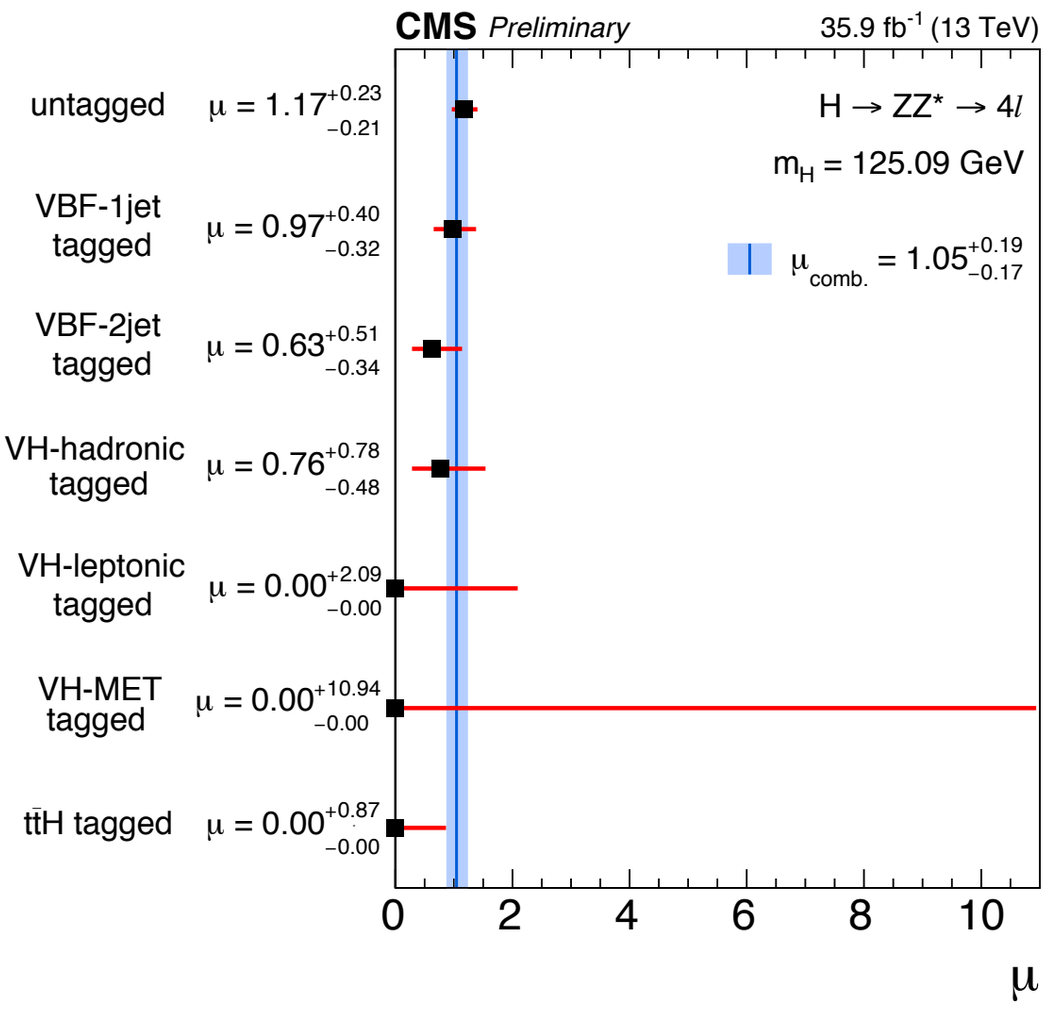
μ per production



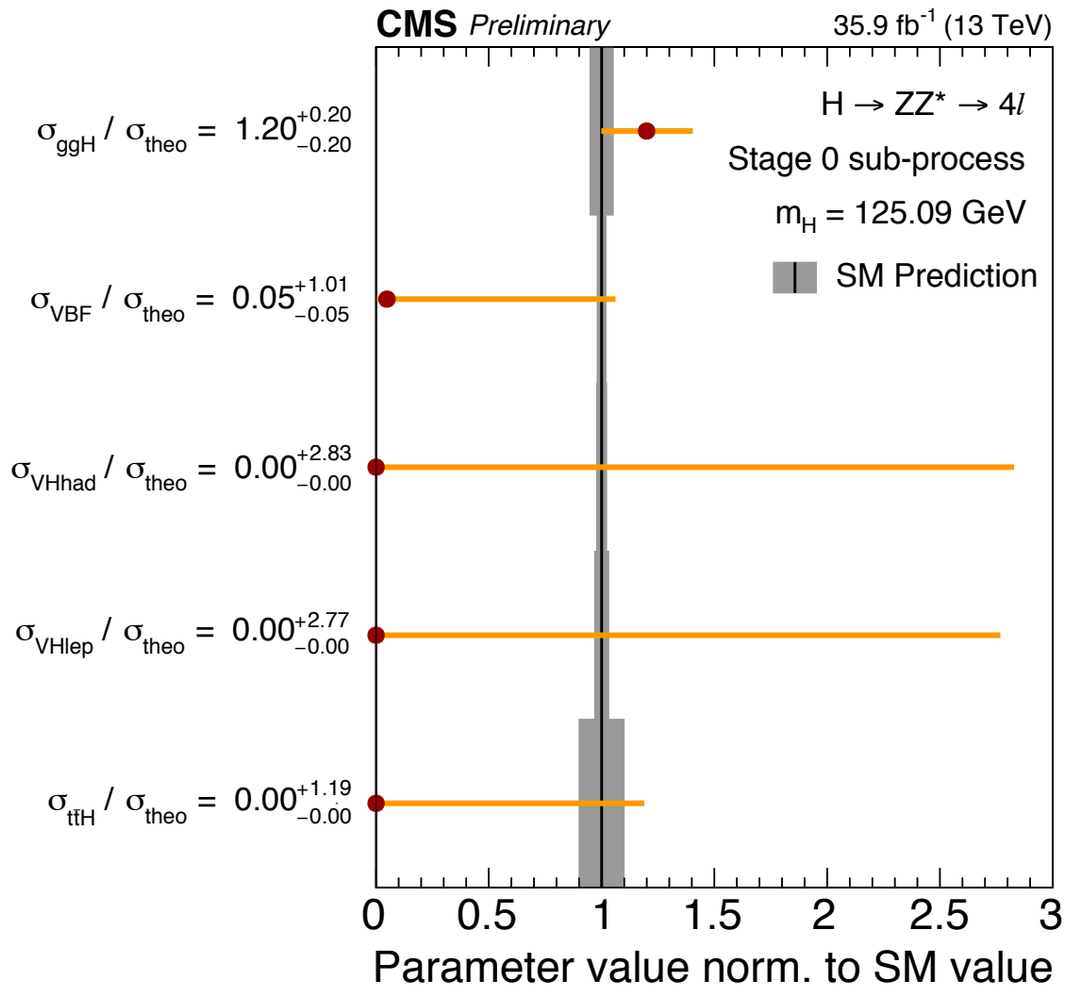
H→ ZZ→ 4ℓ: production mode

2D analysis: m_{4l} vs D_{bkg}^{kin}

μ per category



σ per production

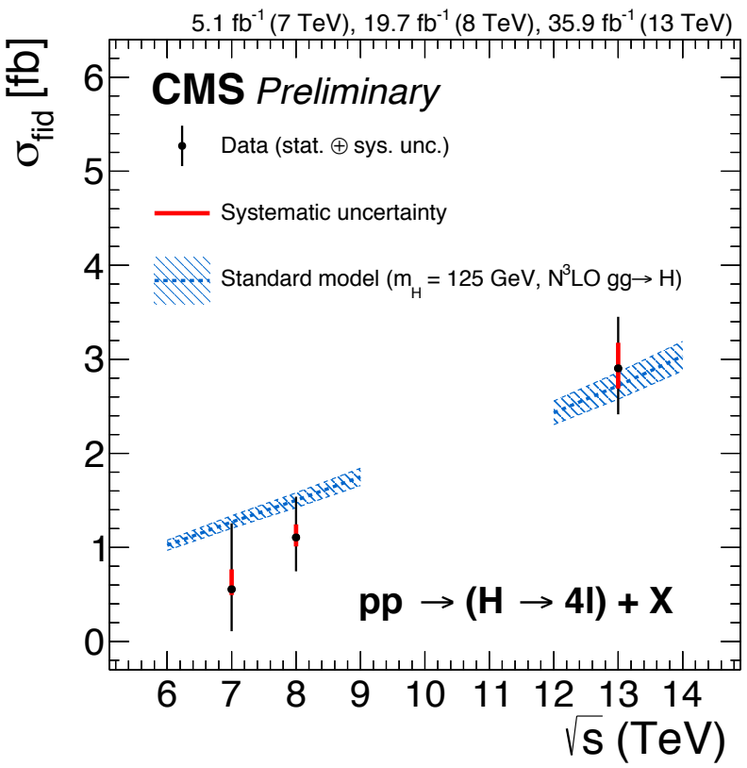


Fiducial volume $|y_H|<2.5$

No theoretical uncertainty on overall xsec

HIG-16-041

H→ ZZ→ 4ℓ: fiducial cross section



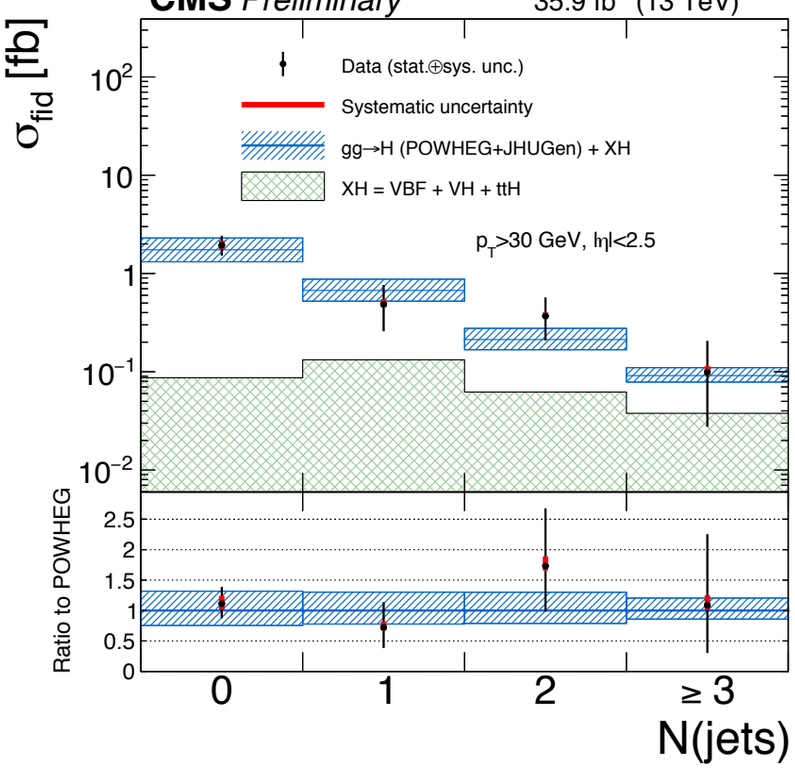
Model independant:

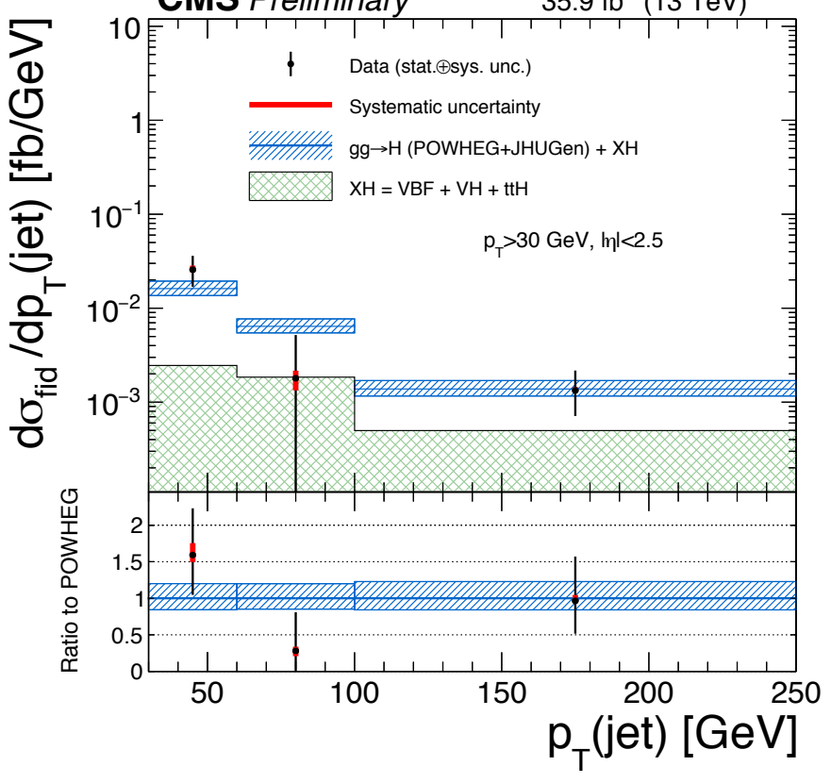
- No categorization
- 1D analysis: m_{4l}

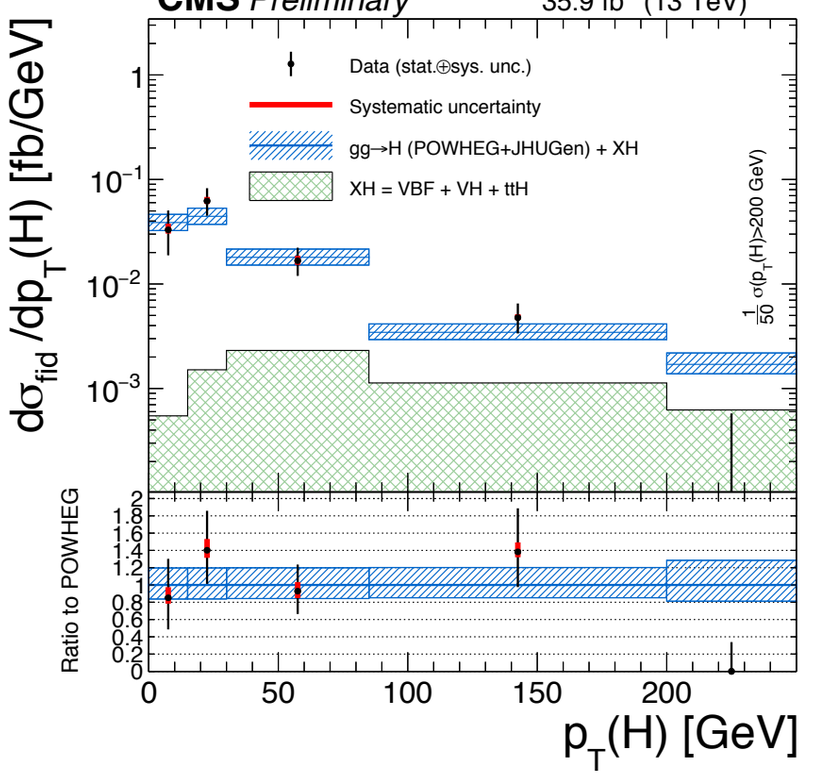
Fiducial phase space close to reconstruction

$$\sigma_{\text{fid}} = 2.90^{+0.48}_{-0.44}(\text{stat.})^{+0.27}_{-0.22}(\text{sys.})\text{fb}$$

σ_{SM}= 2.72 ± 0.14 fb







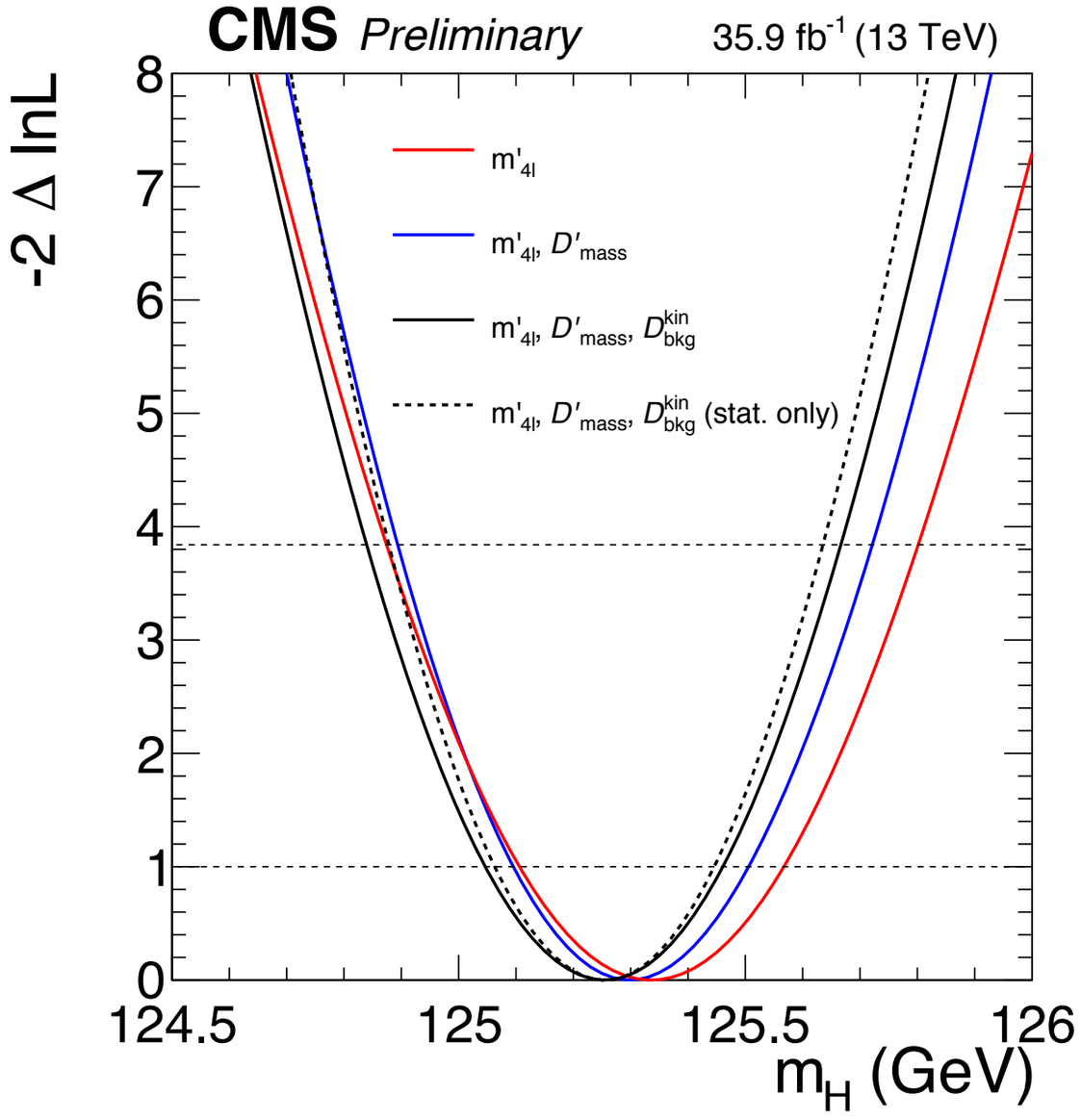
H→ ZZ→ 4ℓ: mass

- 3D analysis: m'_{4l}, D_{bkg}^{kin}, m_{4l} error
  - Kinematic fit to constrain m_Z, $m_{4l} \rightarrow m'_{4l}$
  - 8% gain $m_{4l} \rightarrow m_{4l}$, in 3D
  - 21% gain w.r.t 1D m_{4l}

$m_H = 125.26 \pm 0.20(stat.) \pm 0.08(sys.)$ GeV

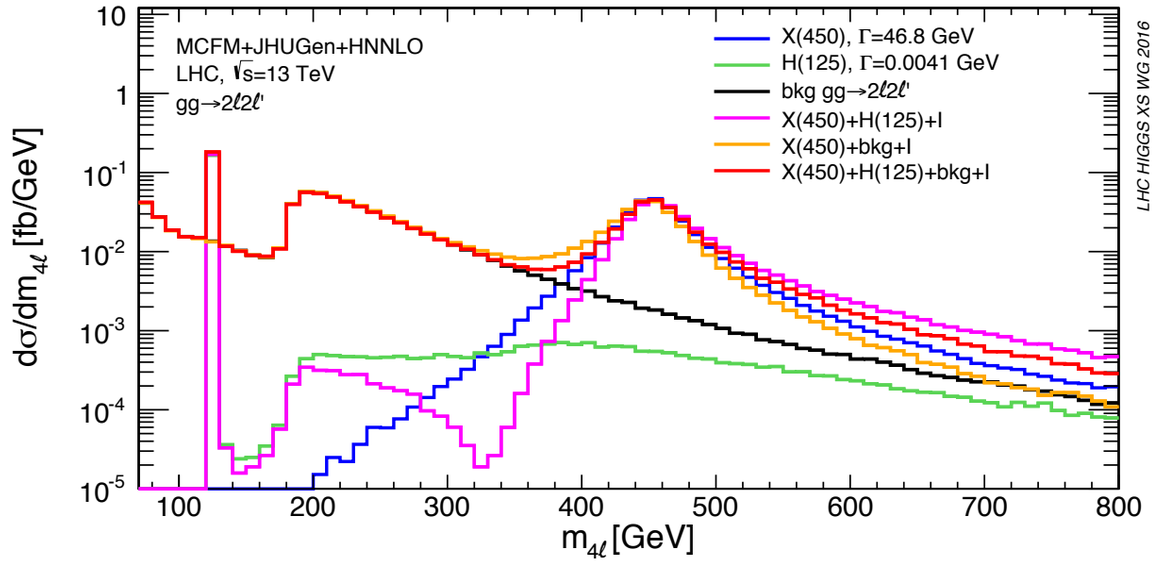
Compared to

$m_H = 125.09 \pm 0.21(stat.) \pm 0.11(sys.)$ GeV from Run1 ATLAS+CMS (4l+ γγ) combination

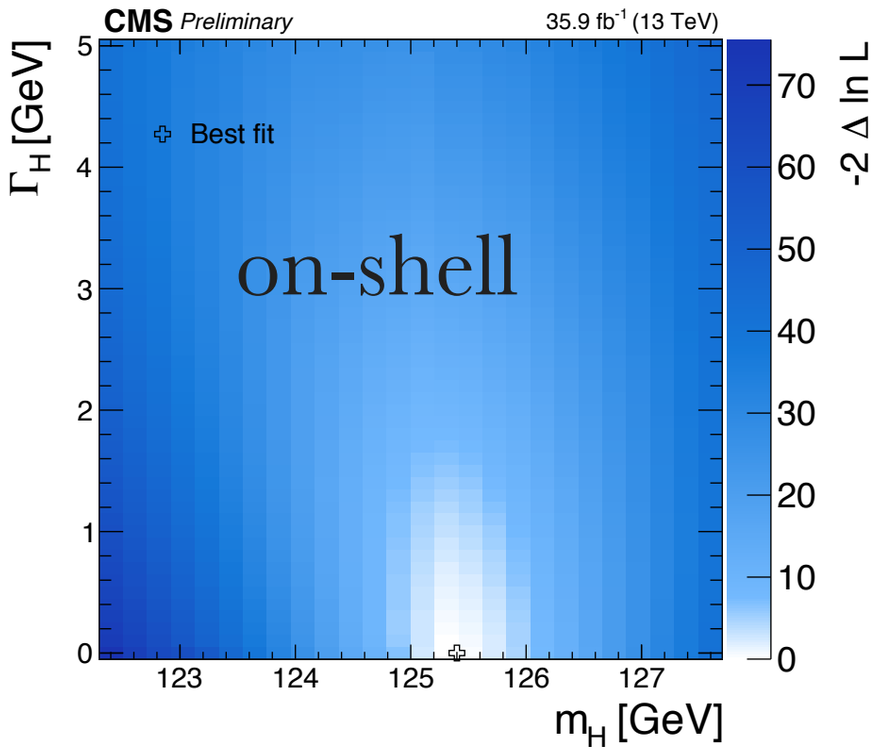


HIG-16-041

H→ ZZ→ 4ℓ: width



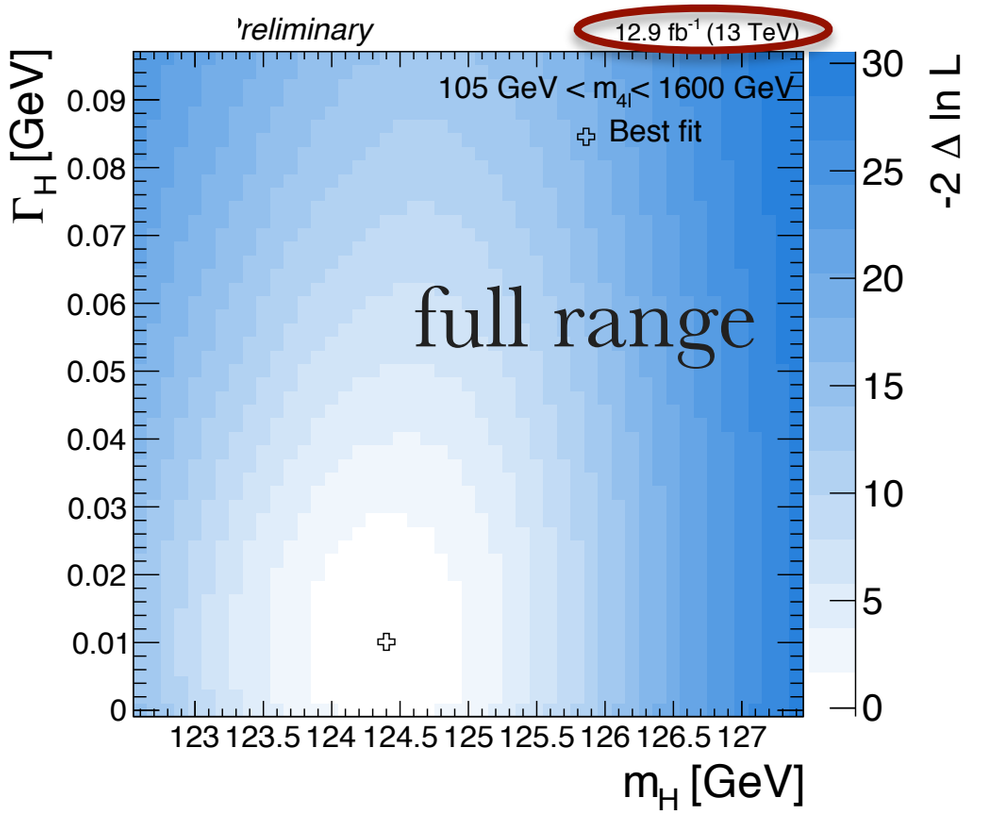
ICHEP



$\Gamma_H < 1.1$ GeV 95% CL
$(0^{+0.41}$ GeV)

1D analysis: m_{4l}

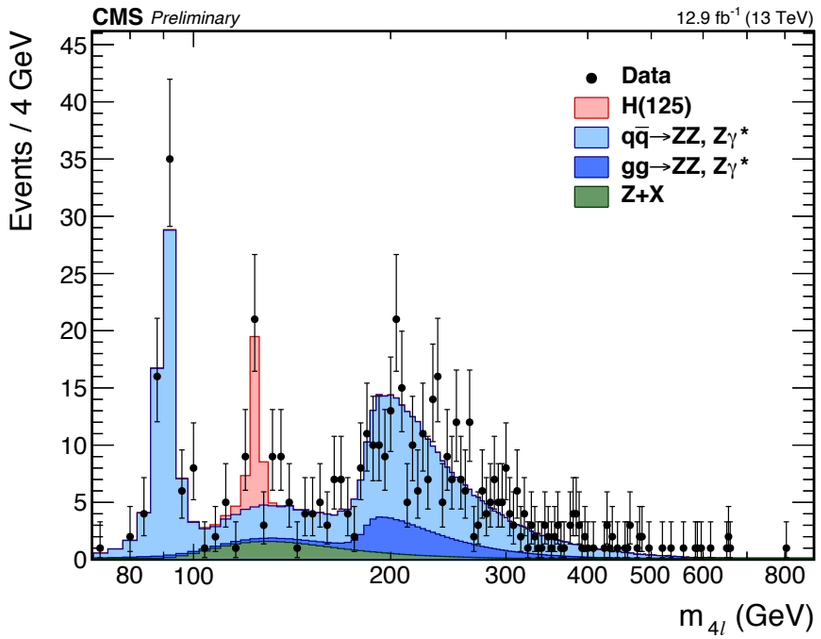
Interference: H and background

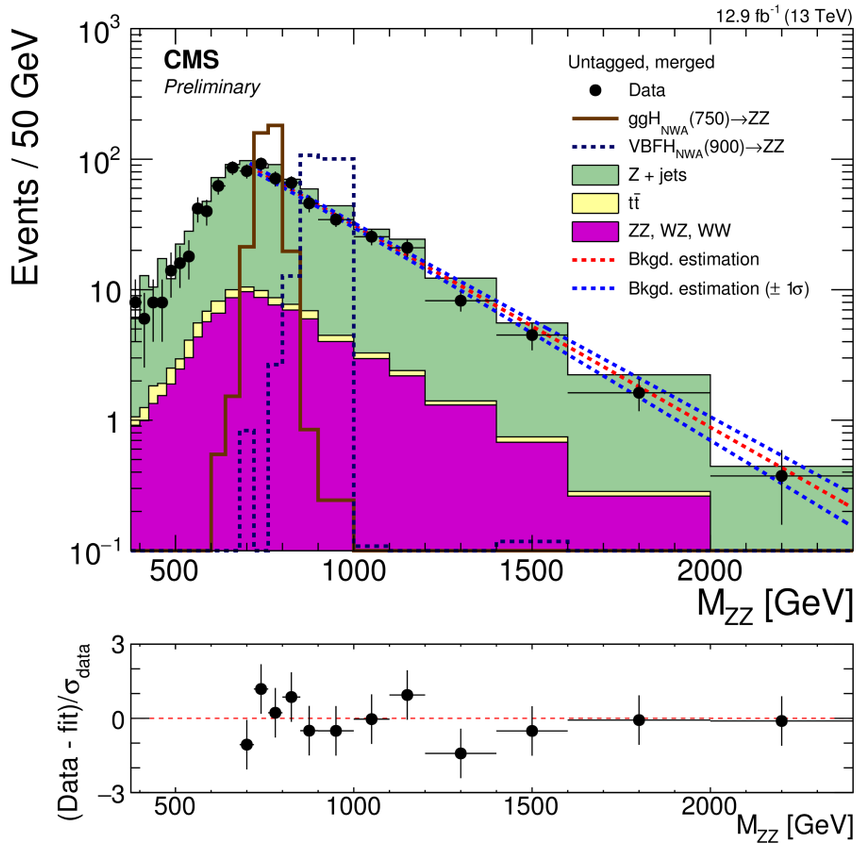


$\Gamma_H < 0.041$ GeV 95% CL
$(0.010^{+0.014}_{-0.010}$ GeV)

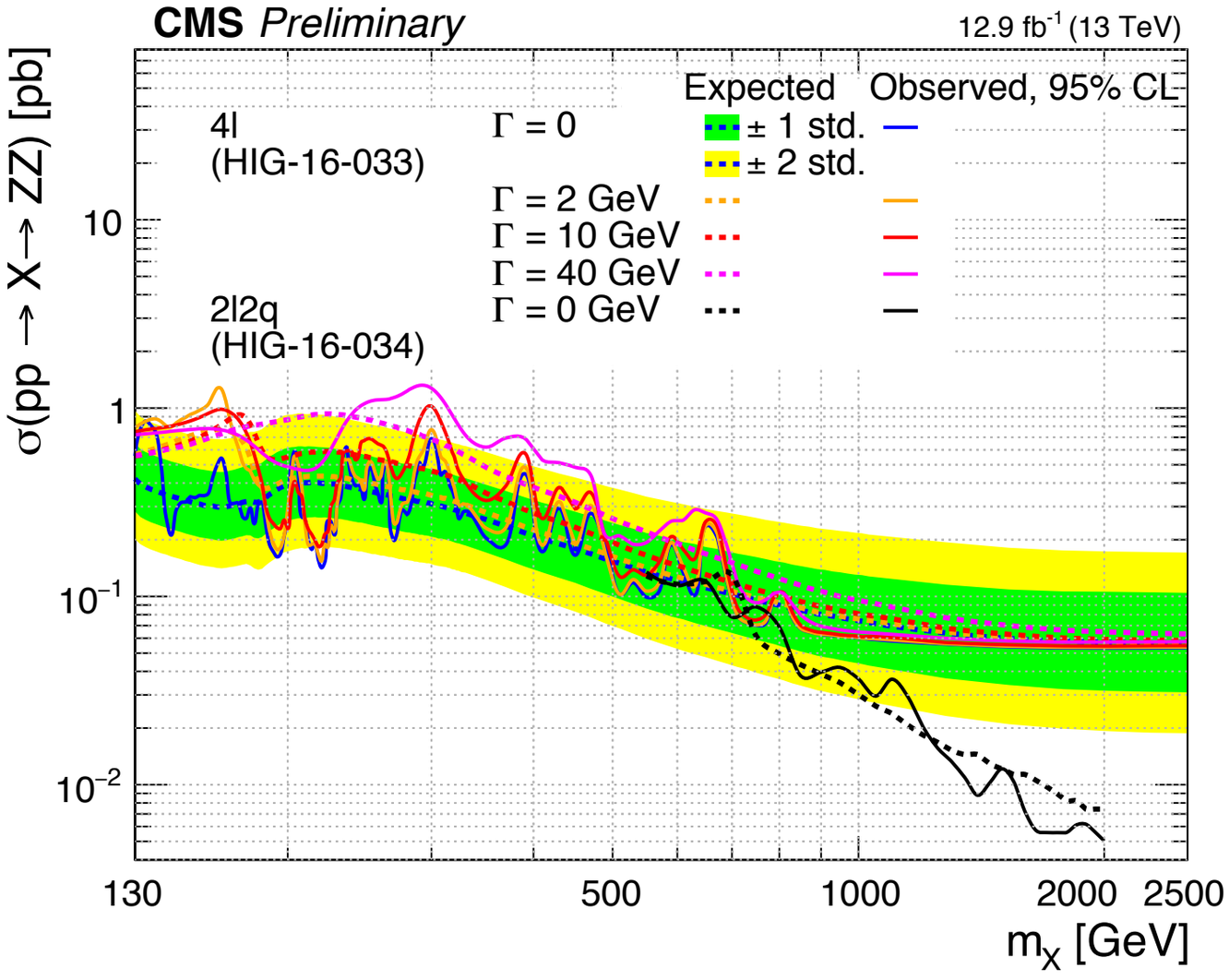
HIG-16-033
HIG-16-034

H→ ZZ→ 4ℓ and 2ℓ2q: resonance search





- Search for spin-0 resonance with any different width
- Interference among X, H, and background



H→ 4ℓ: anomalous couplings

Test the H-VV anomalous couplings via H->4l final state

$$A = \frac{1}{v}\left[\underbrace{a_1^{\mathrm{VV}}}_{\textbf{SM}} + \underbrace{\frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}}(q_1+q_2)^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}}_{\textbf{leading momentum expansion}}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \underbrace{a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}}_{\textbf{higher order cp-even}} + \underbrace{a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}_{\textbf{cp-odd}}$$

Same selection, similar categories: VBF, VH, untagged

3D analysis: ME discriminants (prod+decay)

- to suppress background

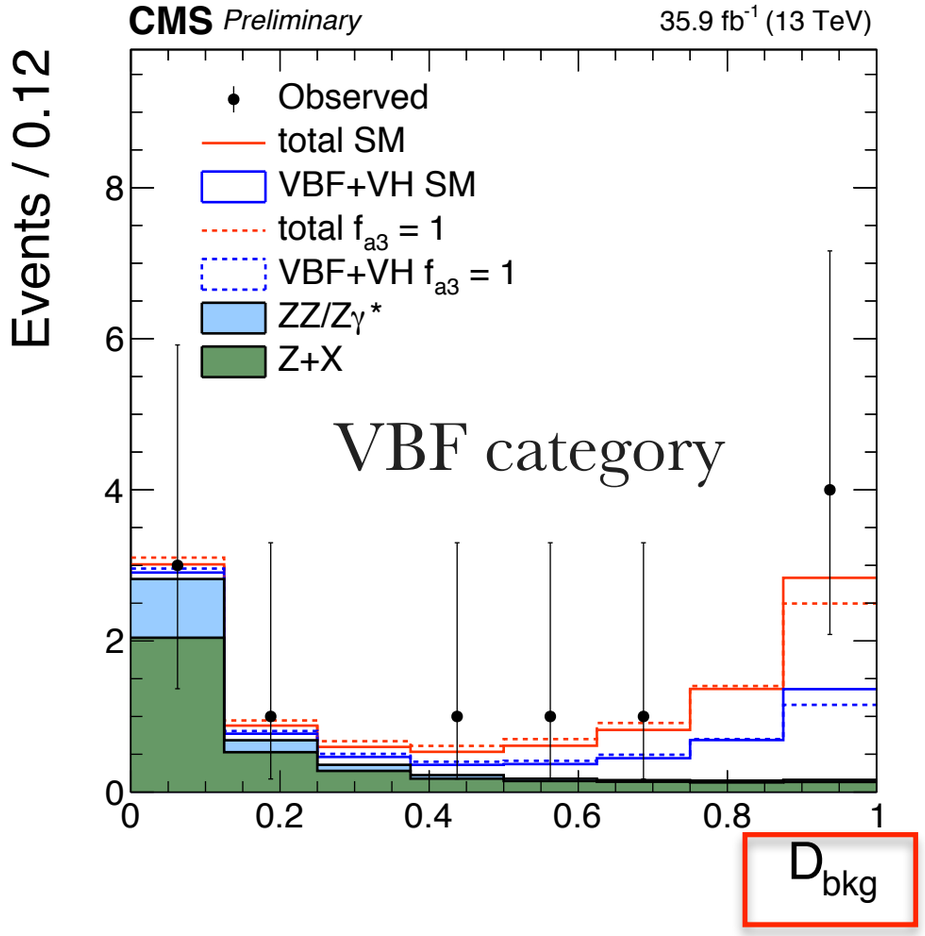
$$\mathcal{D}_{\mathrm{bkg}} = \frac{\mathcal{P}_{\mathrm{SM}}}{\mathcal{P}_{\mathrm{SM}} + c \times \mathcal{P}_{\mathrm{q\bar{q}ZZ}}}$$

- to separate BSM vs SM

$$\mathcal{D}_{J^P}^{\mathrm{kin}} = \frac{\mathcal{P}_{\mathrm{SM}}^{\mathrm{kin}}}{\mathcal{P}_{\mathrm{SM}}^{\mathrm{kin}} + \mathcal{P}_{J^P}^{\mathrm{kin}}}$$

- to isolate interference of BSM and SM

$$\mathcal{D}_{\mathrm{int}} = \frac{\mathcal{P}_{J^P}^{\mathrm{int}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\mathrm{SM}}^{\mathrm{kin}} + \mathcal{P}_{J^P}^{\mathrm{kin}}}$$



H→ 4ℓ: anomalous couplings

Test the H-VV anomalous couplings via H->4l final state

$$A = \frac{1}{v}\left[\textbf{SM}\ a_1^{VV} + \textbf{leading momentum expansion}\ \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \textbf{higher order cp-even}\ a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \textbf{cp-odd}\ a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Same selection, similar categories: VBF, VH, untagged

3D analysis: ME discriminants (prod+decay)

- to suppress background

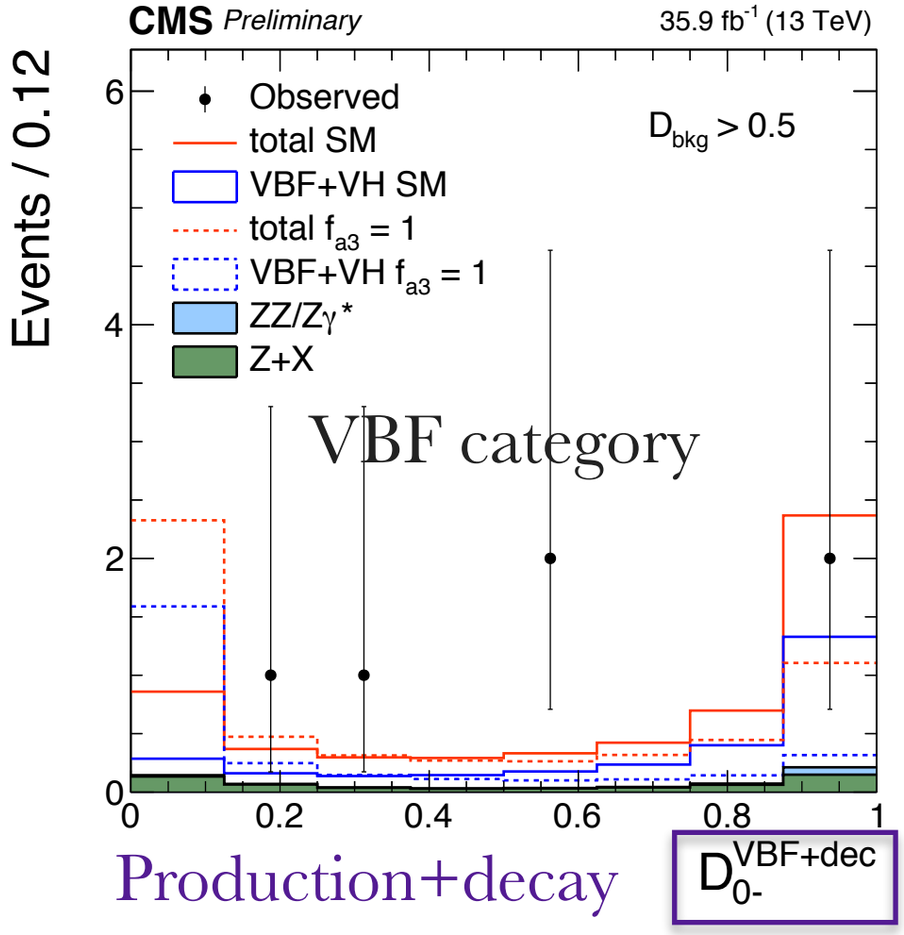
$$\mathcal{D}_{\rm bkg} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + c \times \mathcal{P}_{\rm q\bar{q}ZZ}}$$

- to separate BSM vs SM

$$\mathcal{D}_{J^P}^{\rm kin} = \frac{\mathcal{P}_{\rm SM}^{\rm kin}}{\mathcal{P}_{\rm SM}^{\rm kin} + \mathcal{P}_{J^P}^{\rm kin}}$$

- to isolate interference of BSM and SM

$$\mathcal{D}_{\rm int} = \frac{\mathcal{P}_{J^P}^{\rm int}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm SM}^{\rm kin} + \mathcal{P}_{J^P}^{\rm kin}}$$



H→ 4ℓ: anomalous couplings

Test the H-VV anomalous couplings via H->4l final state

$$A = \frac{1}{v}\left[\underbrace{a_1^{\mathrm{VV}}}_{\textbf{SM}} + \underbrace{\frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}}(q_1+q_2)^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}}_{\textbf{leading momentum expansion}}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \underbrace{a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}}_{\textbf{higher order cp-even}} + \underbrace{a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}_{\textbf{cp-odd}}$$

Same selection, similar categories: VBF, VH, untagged

3D analysis: ME discriminants (prod+decay)

- to suppress background

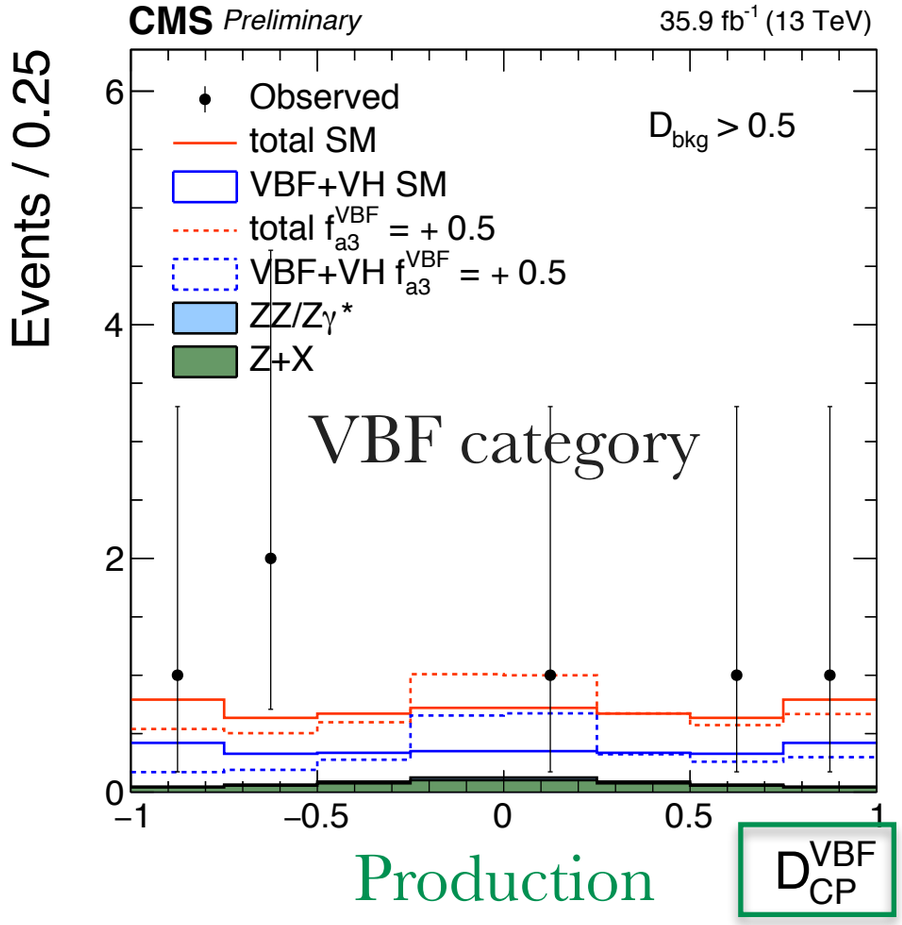
$$\mathcal{D}_{\mathrm{bkg}} = \frac{\mathcal{P}_{\mathrm{SM}}}{\mathcal{P}_{\mathrm{SM}} + c \times \mathcal{P}_{\mathrm{q\bar{q}ZZ}}}$$

- to separate BSM vs SM

$$\mathcal{D}_{J^P}^{\mathrm{kin}} = \frac{\mathcal{P}_{\mathrm{SM}}^{\mathrm{kin}}}{\mathcal{P}_{\mathrm{SM}}^{\mathrm{kin}} + \mathcal{P}_{J^P}^{\mathrm{kin}}}$$

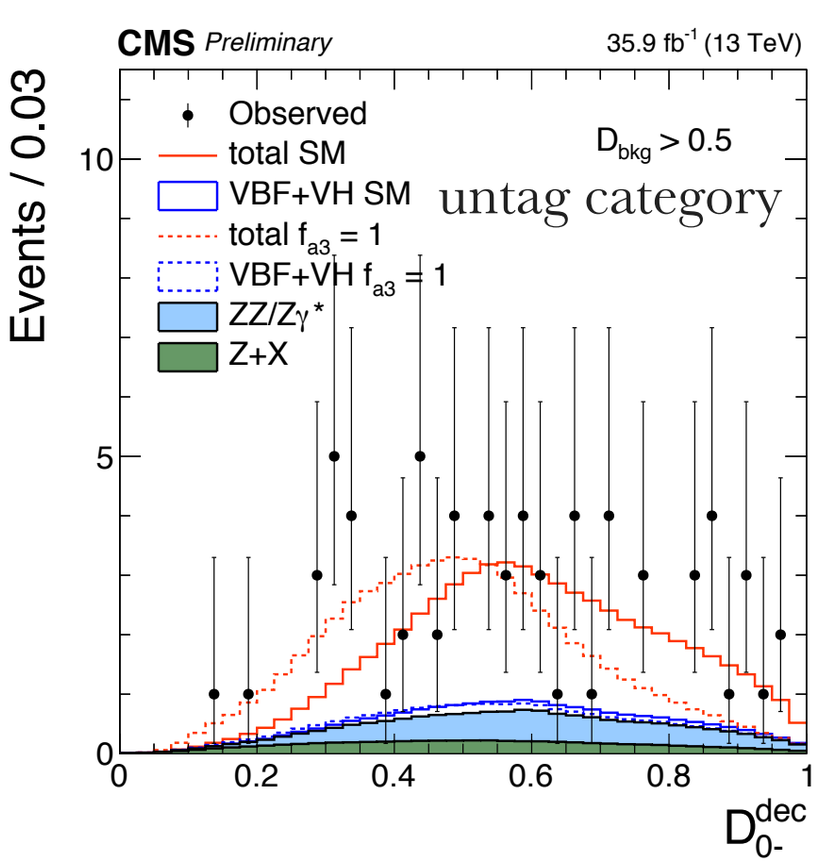
- to isolate interference of BSM and SM

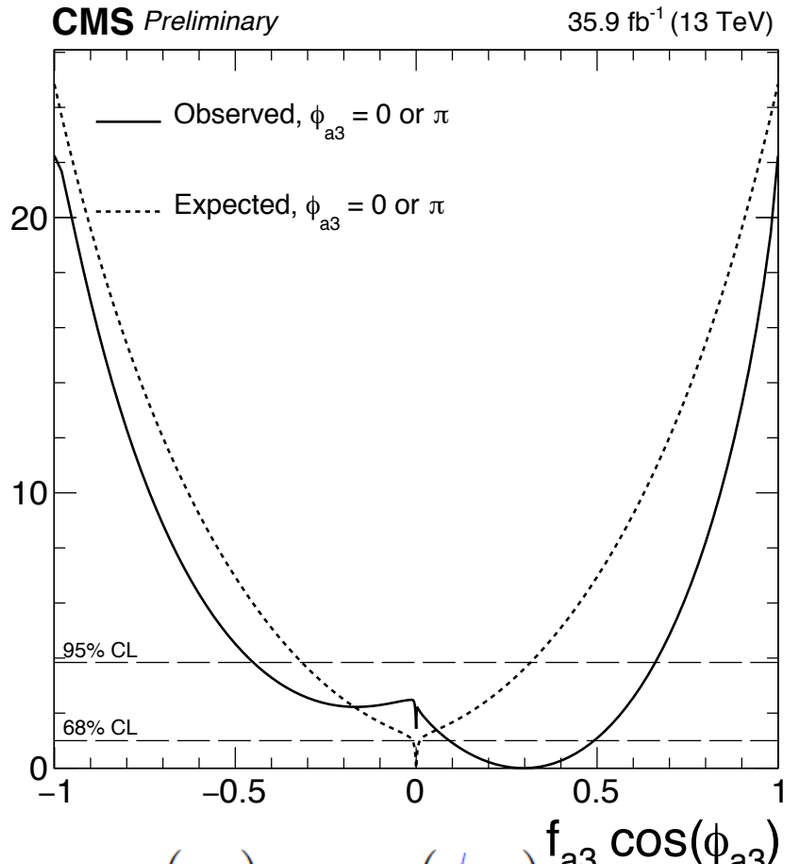
$$\mathcal{D}_{\mathrm{int}} = \frac{\mathcal{P}_{J^P}^{\mathrm{int}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\mathrm{SM}}^{\mathrm{kin}} + \mathcal{P}_{J^P}^{\mathrm{kin}}}$$

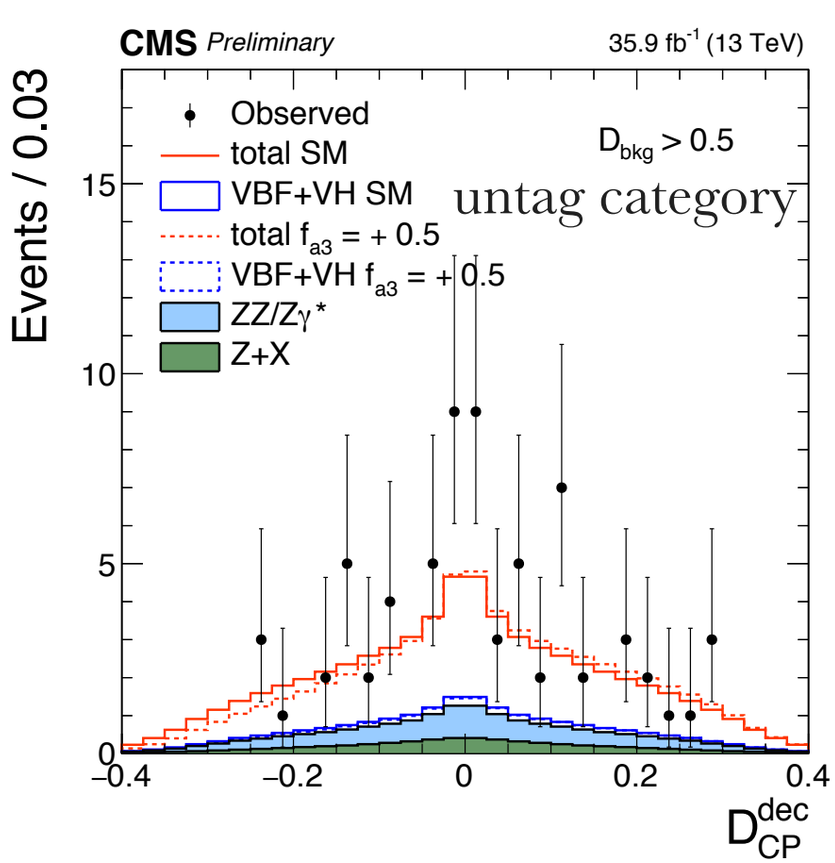


HIG-17-011

H→ 4ℓ: anomalous couplings







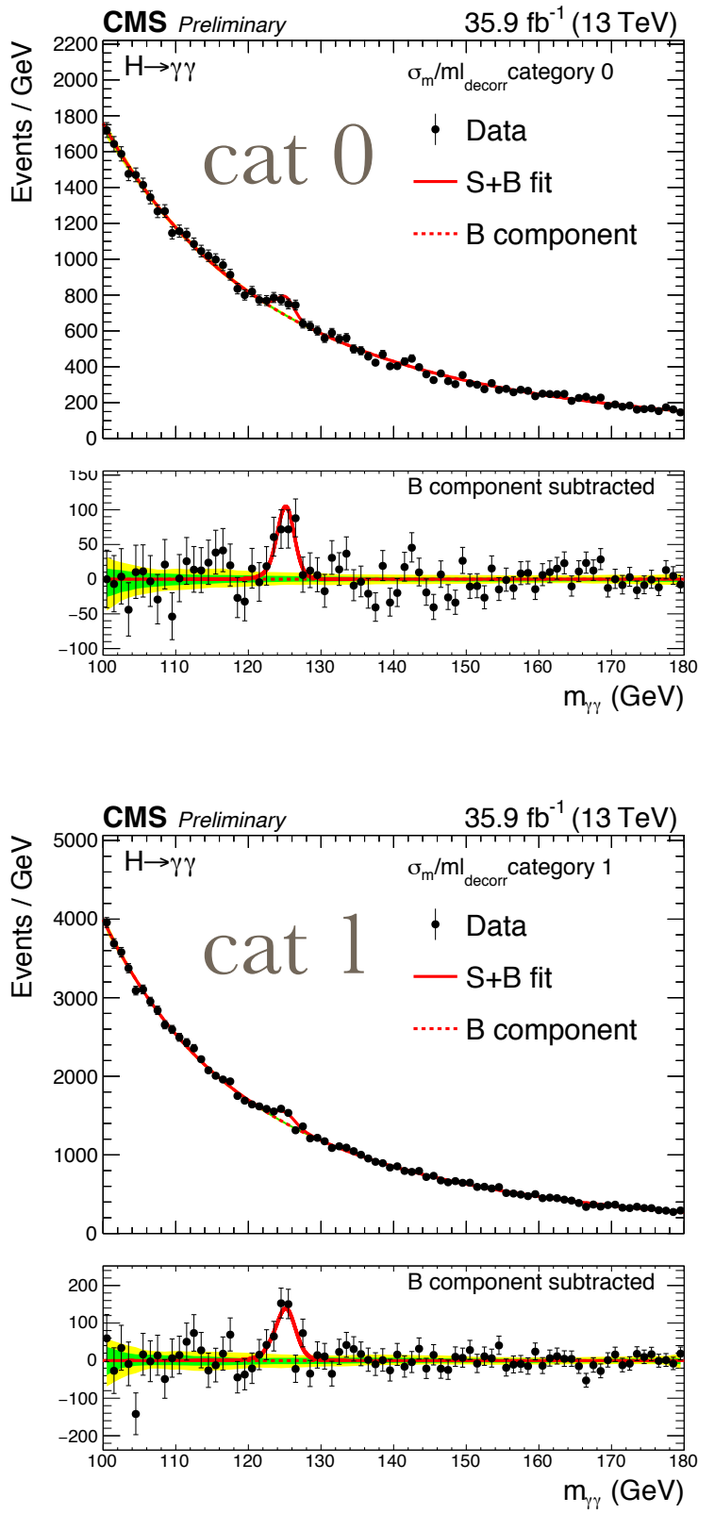
$$f_{a3} \Rightarrow \frac{\sigma(a_3) \times \cos(\phi_{a3})}{\sigma(a_1) + \sigma(a_3)}$$

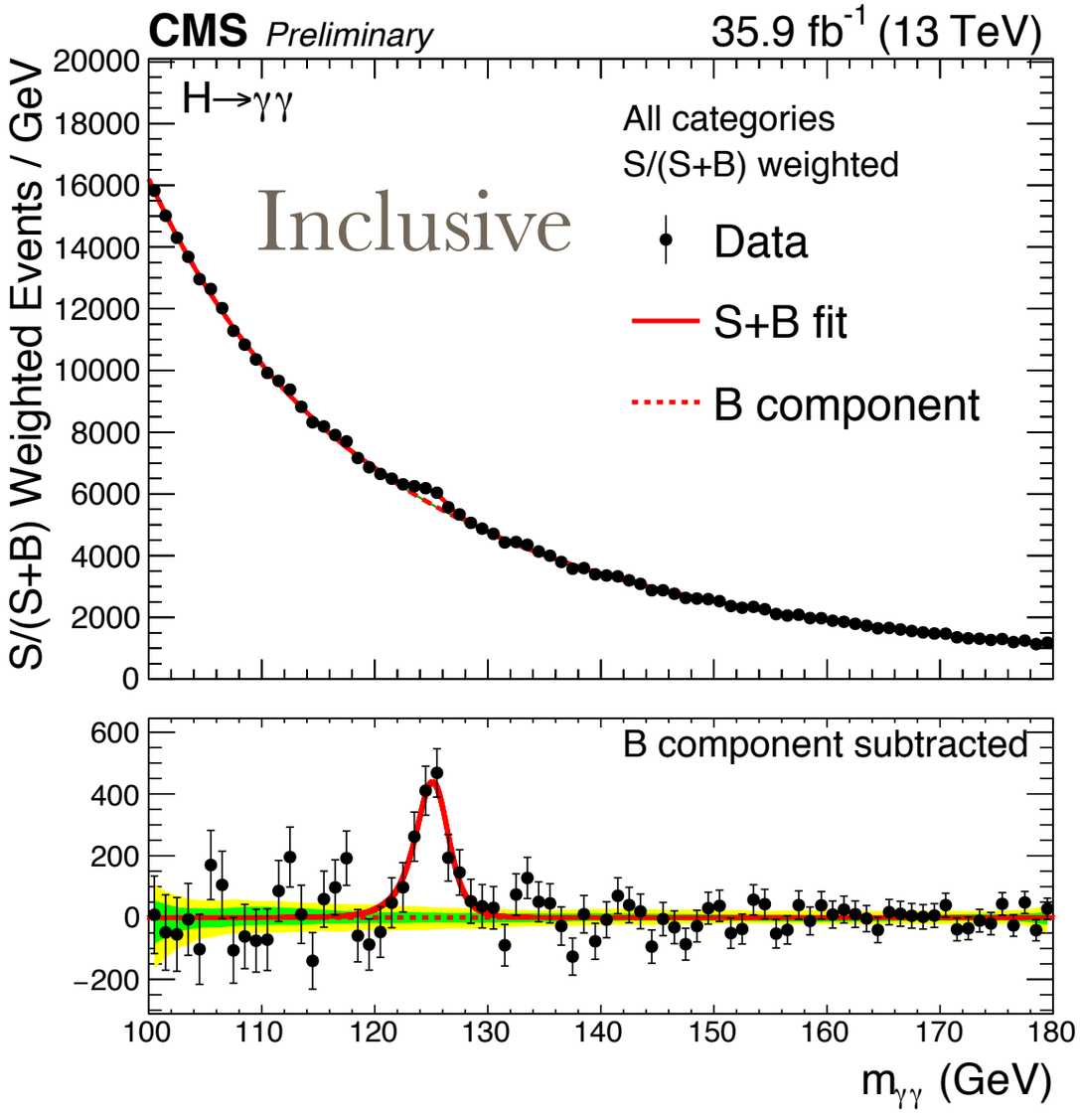
Parameter	Observed	Expected	Run1 (HZZ+HWW)
$f_{a3}\cos(\phi_{a3})$	$0.30^{+0.19}_{-0.21}$ $[-0.45, 0.66]$	$0.000^{+0.017}_{-0.017}$ $[-0.32, 0.32]$	$0^{+0.23}_{-0.23}$
$f_{a2}\cos(\phi_{a2})$	$0.04^{+0.19}_{-0.04}$ $[-0.69, -0.64] \cup [-0.04, 0.64]$	$0.000^{+0.015}_{-0.014}$ $[-0.08, 0.29]$	$0^{+0.08}_{-0.03}$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.00^{+0.06}_{-0.33}$ $[-0.92, 0.15]$	$0.000^{+0.014}_{-0.014}$ $[-0.79, 0.15]$	$0^{+0.15}_{-0.08}$
$f^{Z\gamma}_{\Lambda 1}\cos(\phi^{Z\gamma}_{\Lambda 1})$	$0.16^{+0.36}_{-0.25}$ $[-0.43, 0.80]$	$0.000^{+0.020}_{-0.024}$ $[-0.49, 0.80]$	

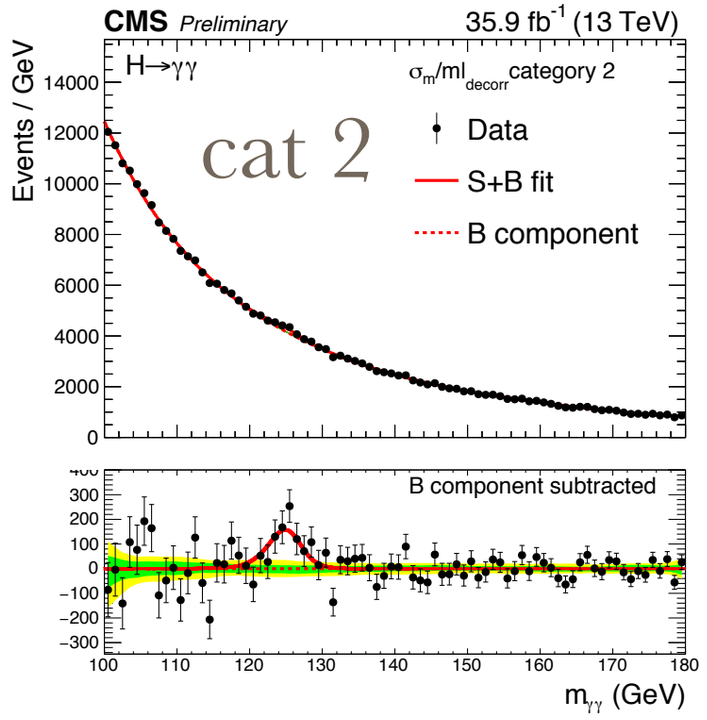
H→ γγ: fiducial cross section

3 categories to optimize signal significance

based on mass resolution







H→ γγ: fiducial cross section

Fiducial volume:

$p_{T1}/m_{\gamma\gamma} < 1/3$, $p_{T2}/m_{\gamma\gamma} < 1/4$

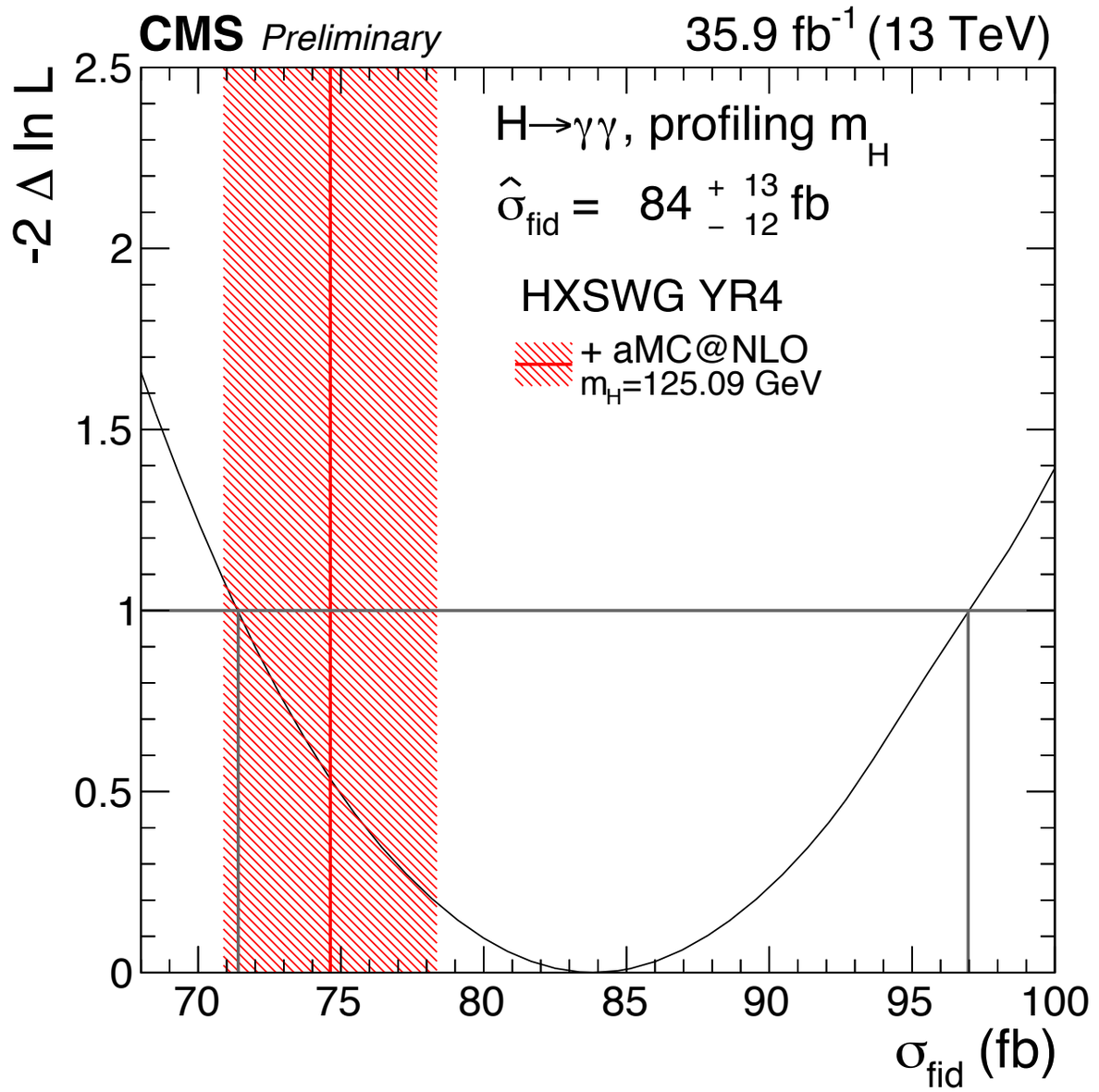
$|\eta_{1,2}| < 2.5$

$Iso_{gen1,2} < 10$ GeV ($\Delta R=0.3$)

1D analysis: $m_{\gamma\gamma}$

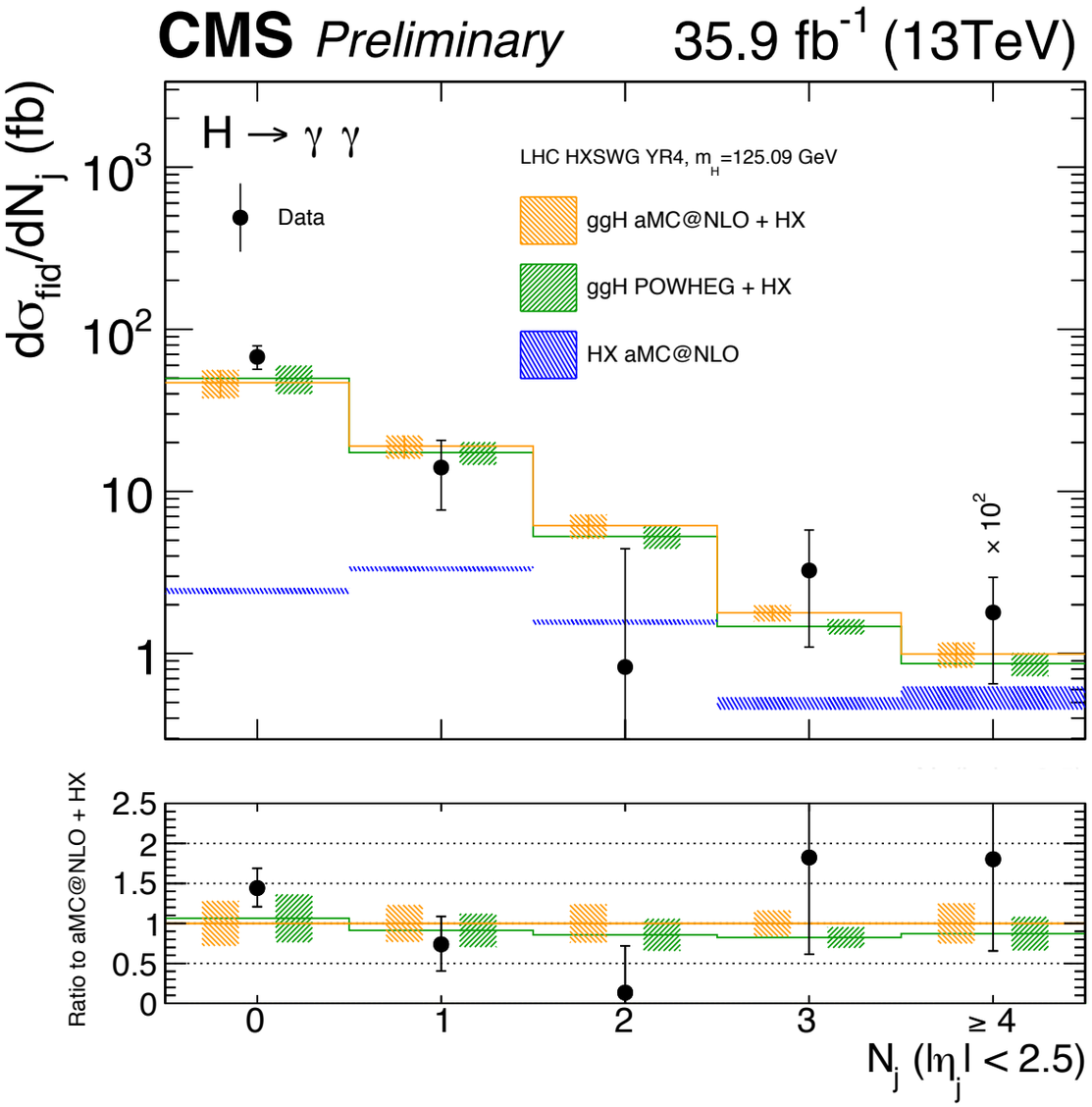
$\sigma_{fid}= 84 \pm 11$ (stat.) ± 7 (sys.) fb

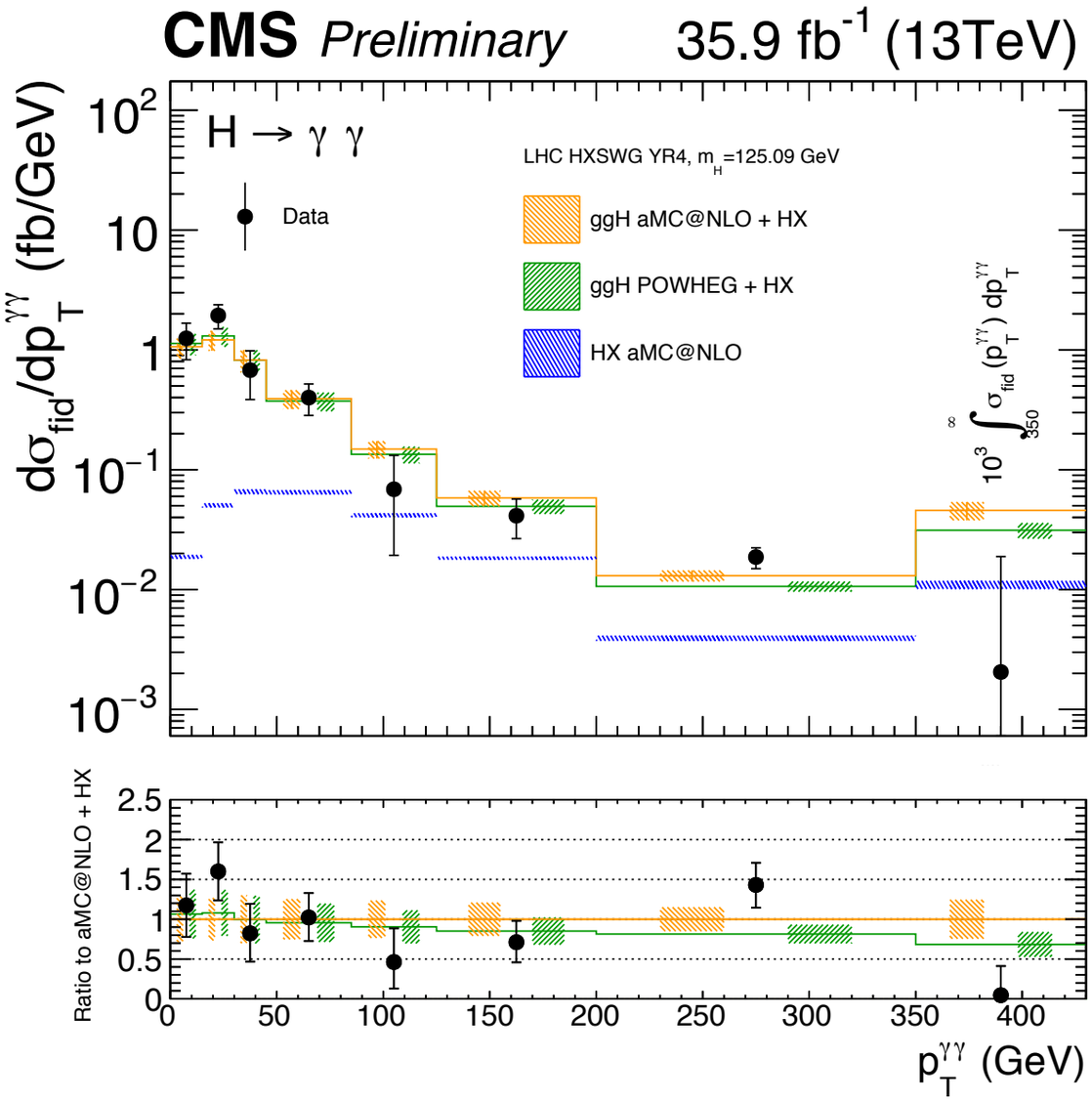
$\sigma_{SM}= 75 \pm 4$ fb



Most precise fiducial xsec so far

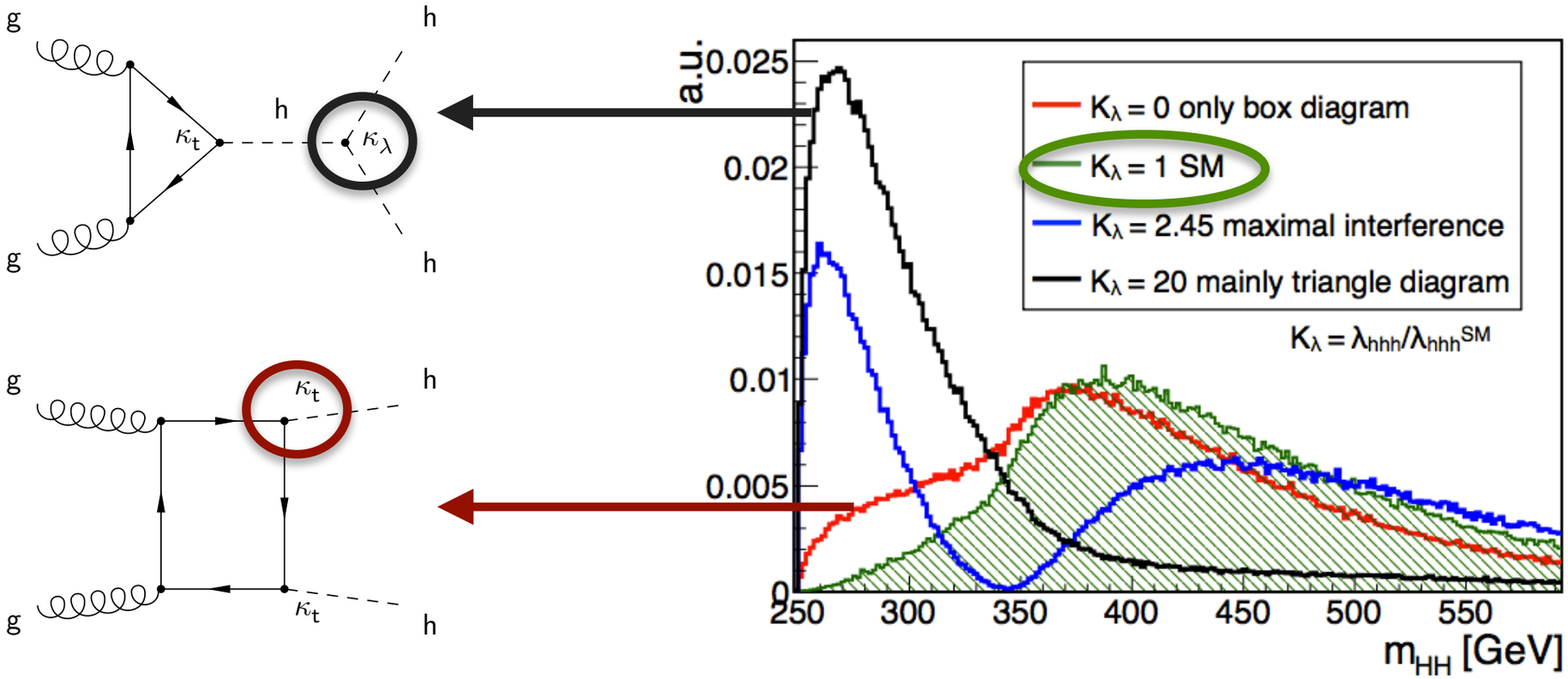
H→ γγ: differential fiducial cross section





Most precise fiducial xsec so far

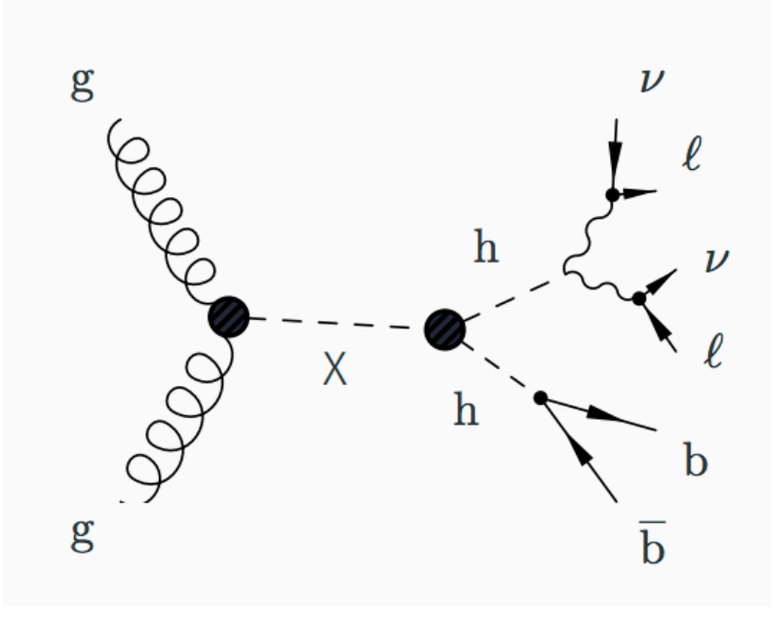
HH production

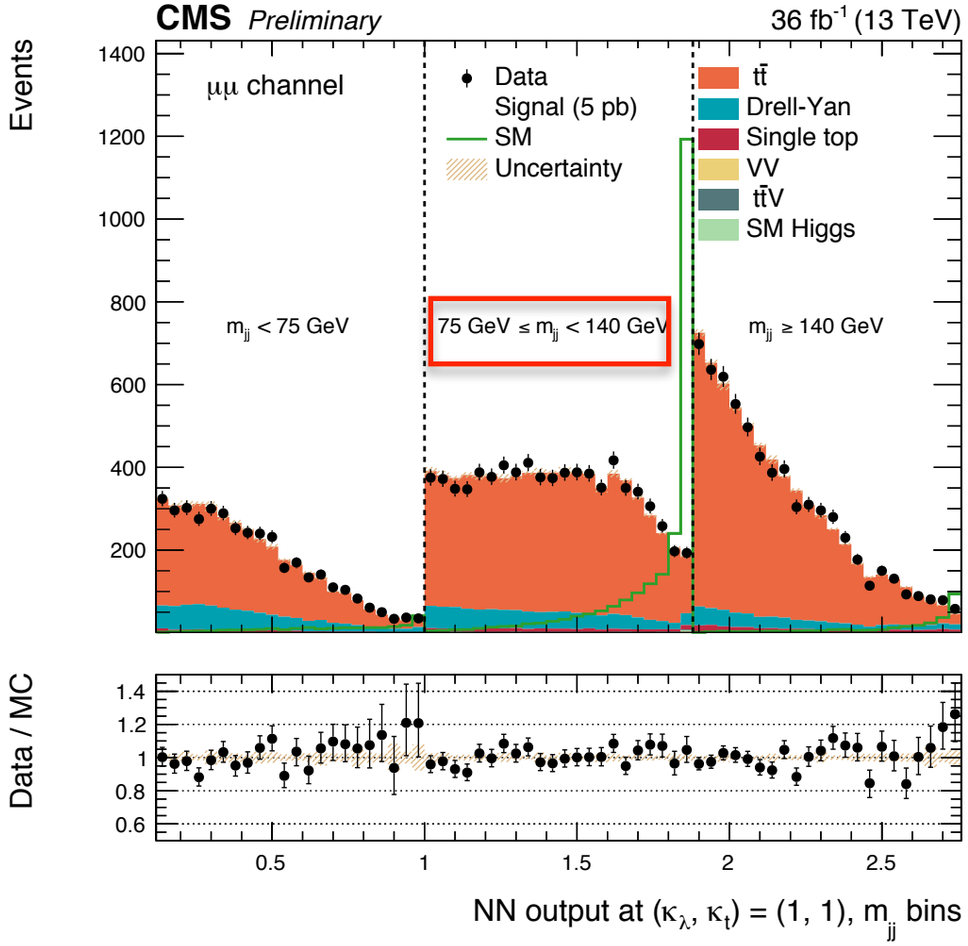


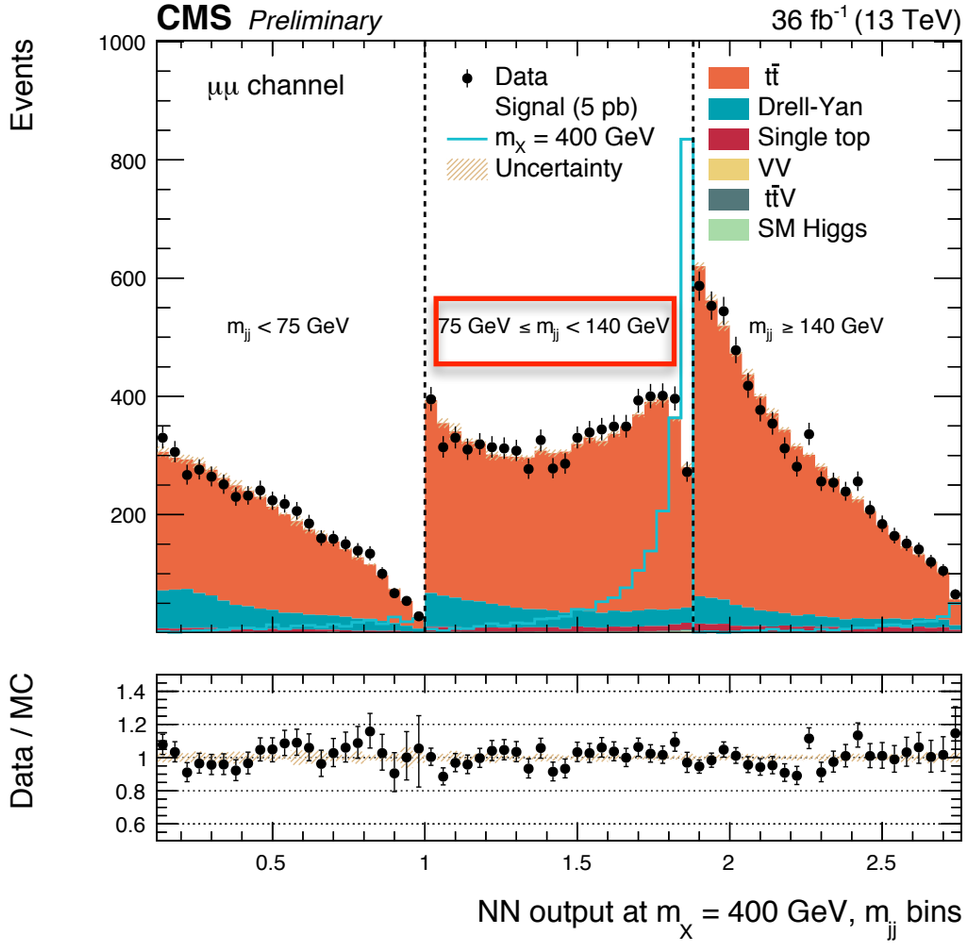
- SM: κ_t and κ_λ induced diagrams interfere destructively, σ_{SM} small (~33.5 fb)
  - sensitive to the anomalous couplings κ_t , κ_λ , c_2, c_{2g}, c_g ➪ non-resonant spectrum testing anomalous couplings
- Predicted by many theories: X->HH ➪ resonant search

HH production: bbVV(lνlν)

- 3 $\ell\ell$ flavors: e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$
- 3 m_{bb} regions: [0,75], [75 ,140], >140 GeV
- 1D analysis: parameterized deep neural network output
  - a single training provides smooth interpolation





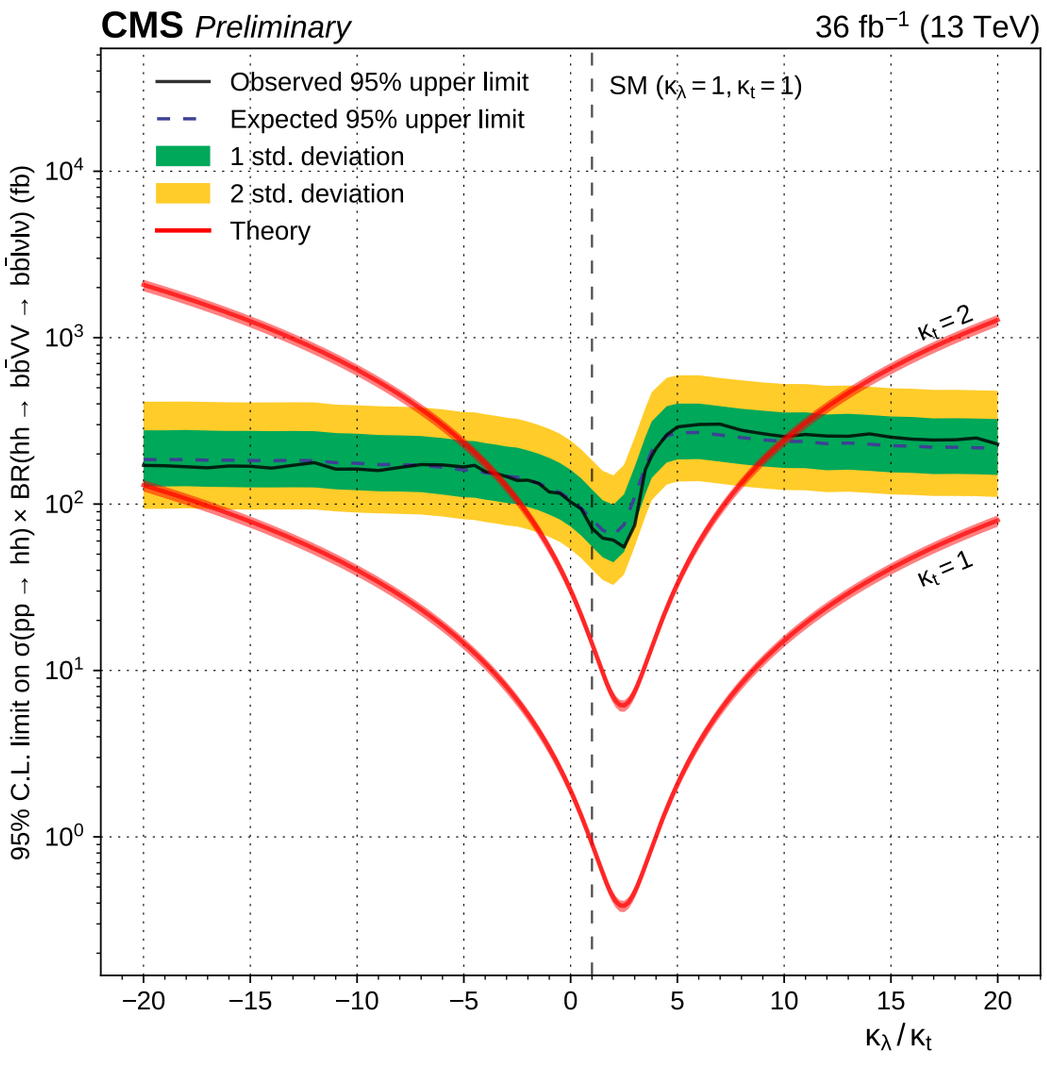


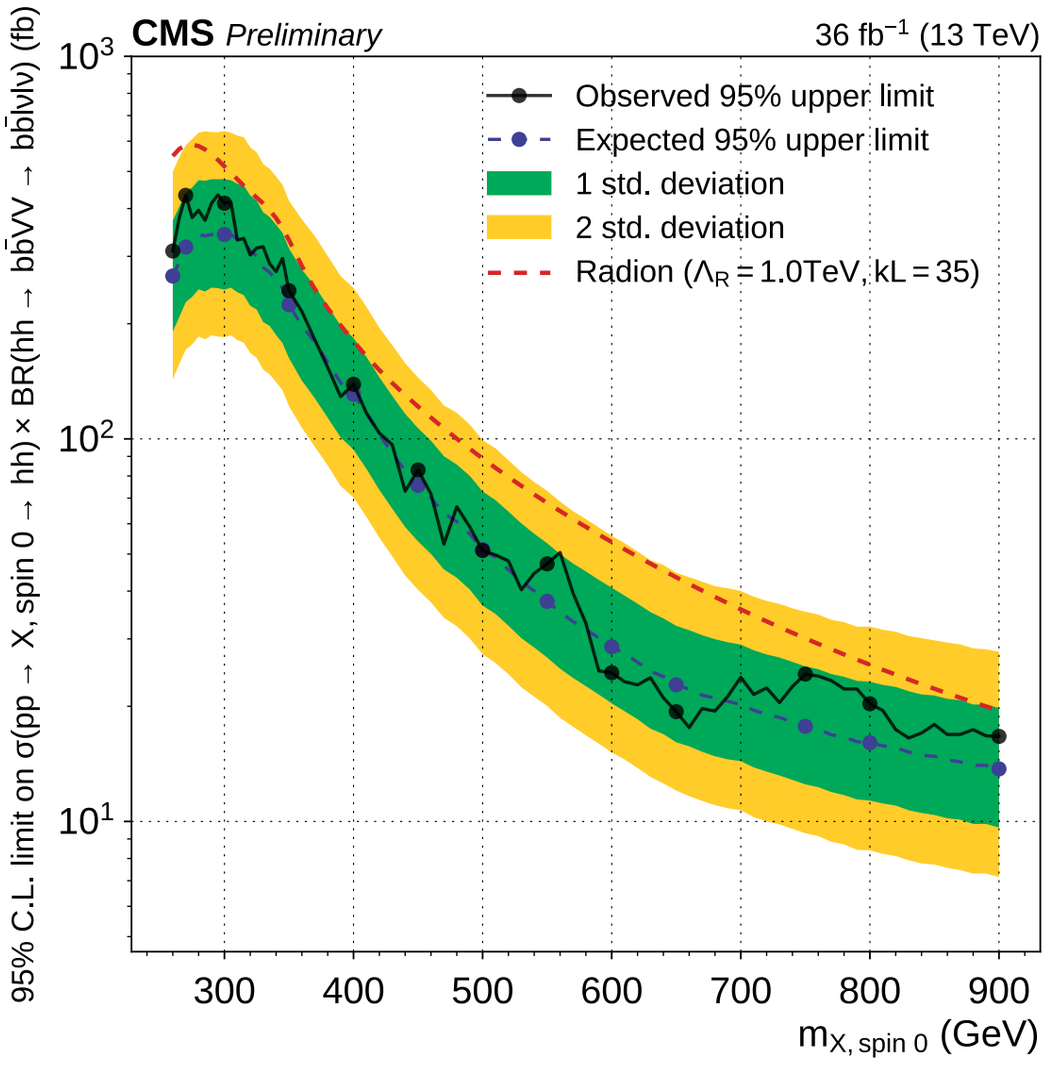
HIG-17-006

HH production: bbVV

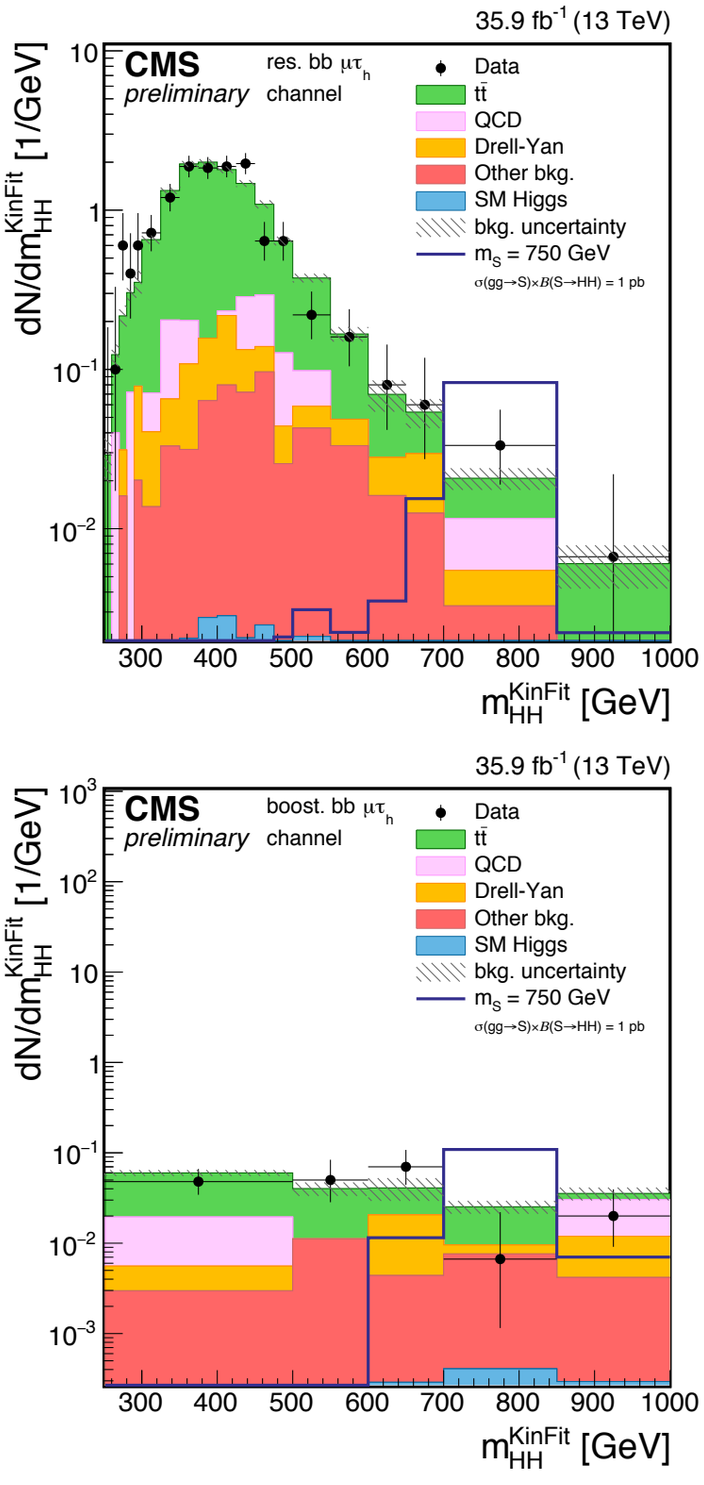
$\sigma_{HH}/\sigma_{SM} < 79$ (89 exp)

similar spin 2 limit





HH production: bb$\tau\tau$, resonant search



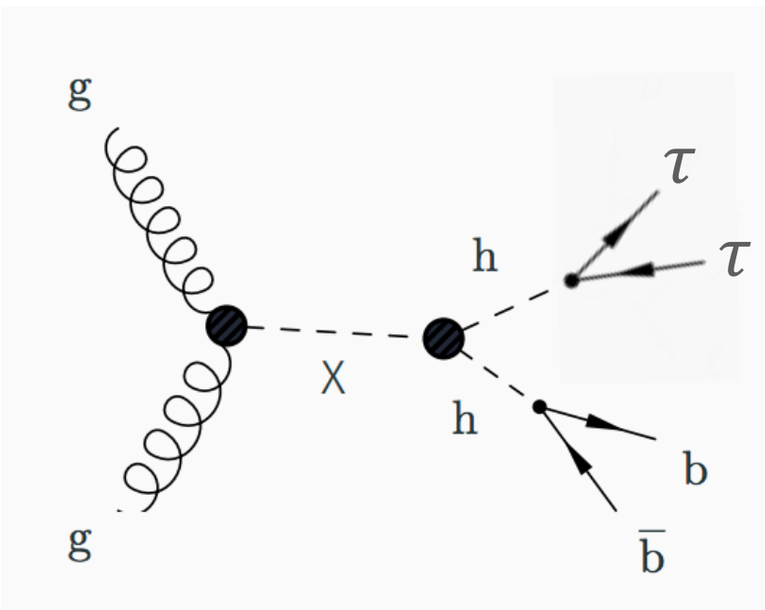
$\tau\tau$: eτ_h, $\mu\tau_h$, $\tau_h\tau_h$

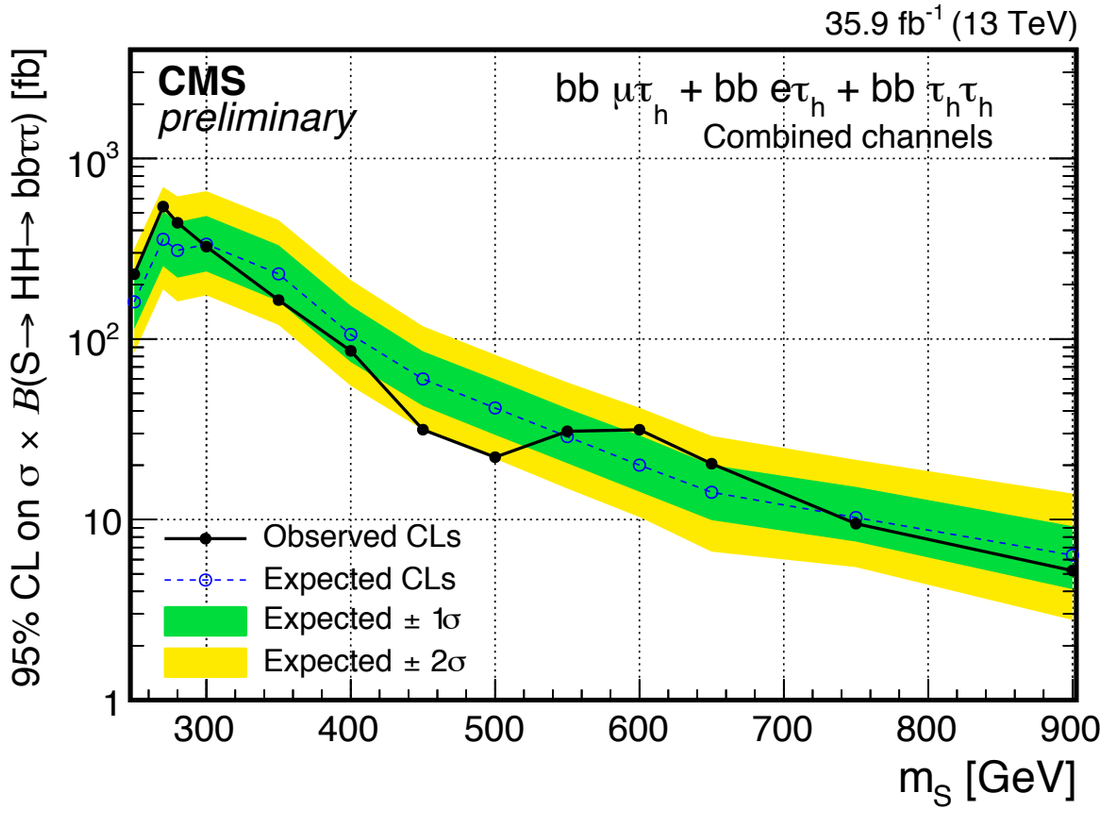
bb: 2 btag, 1 btag, 1 boosted ak8 jet

Reduce ttbar background

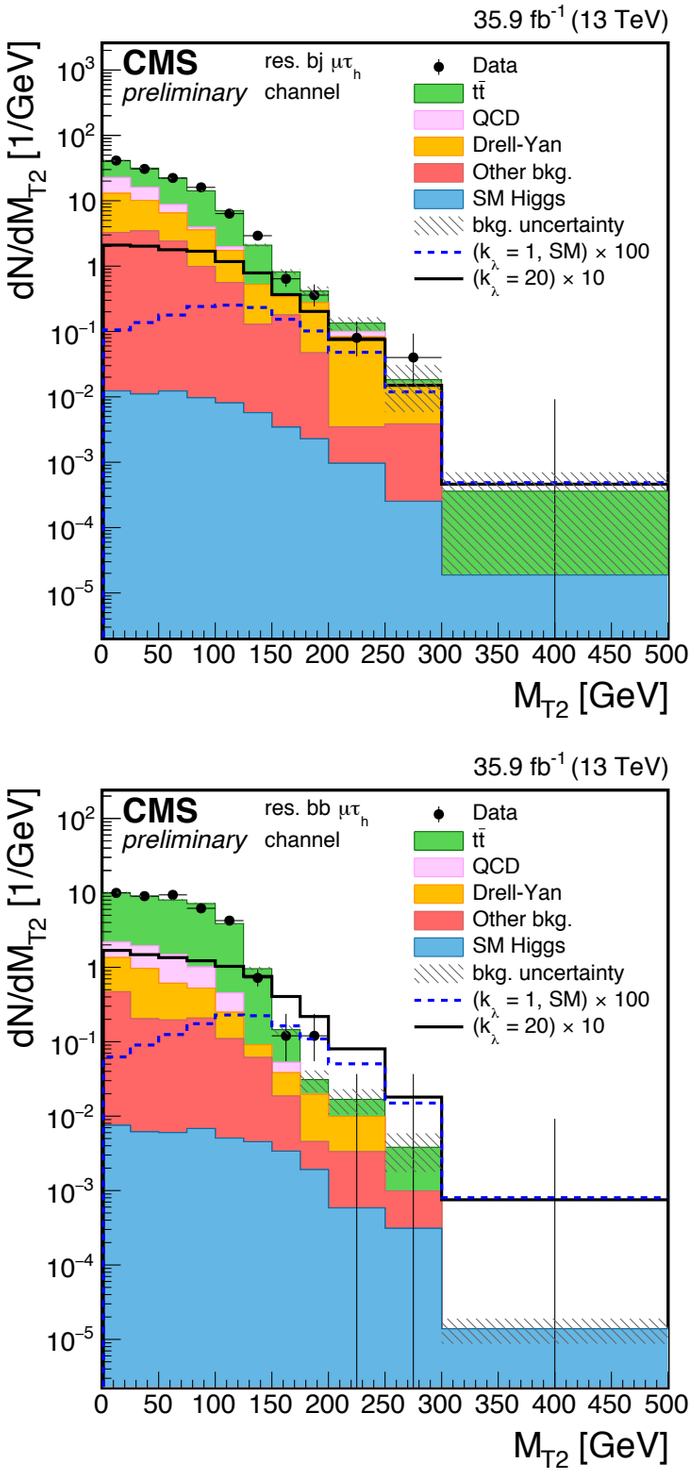
- cut $m_{\tau\tau}$ and m_{bb}
- cut BDT discriminant

1D analysis: m_{HH}

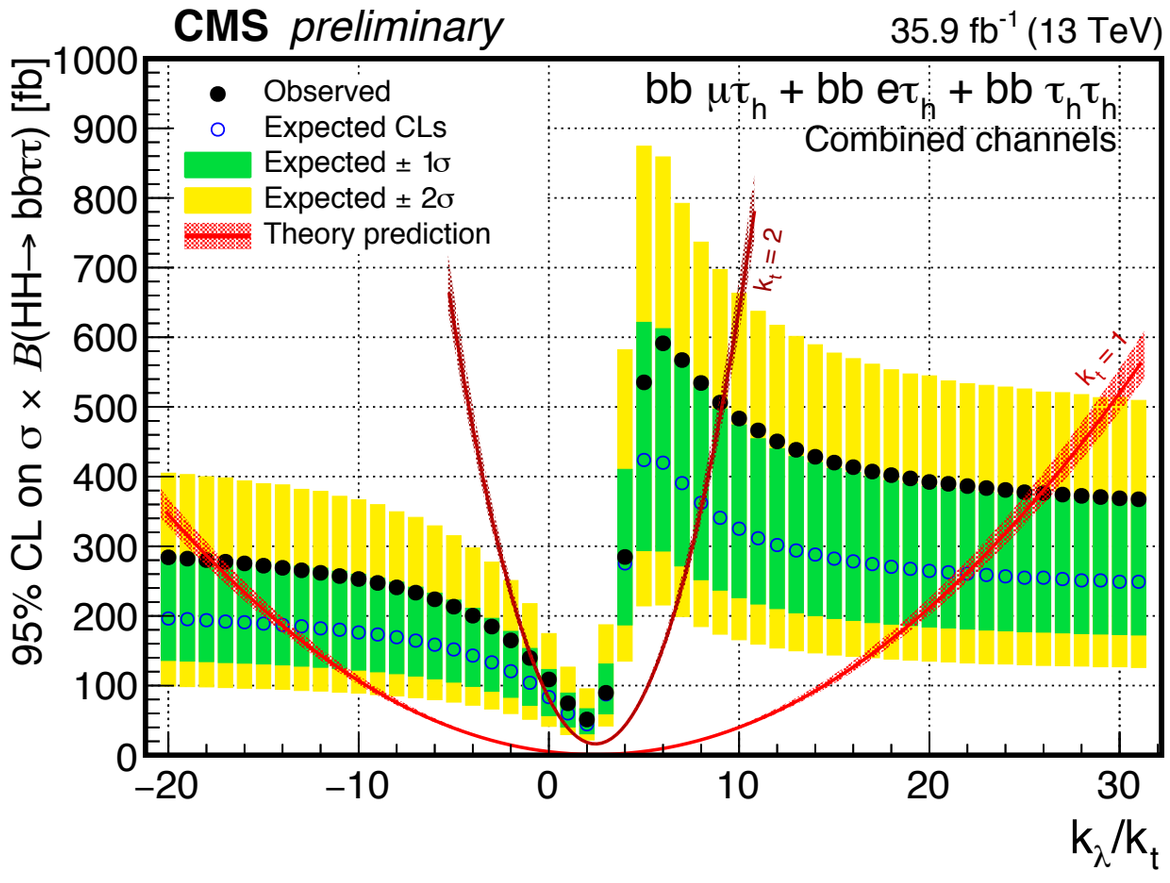




HH production: bb$\tau\tau$, non-resonant



1D analysis: m_{T2}, better than m_{HH}



$\sigma_{HH}/\sigma_{SM} < 28$ (25 exp)

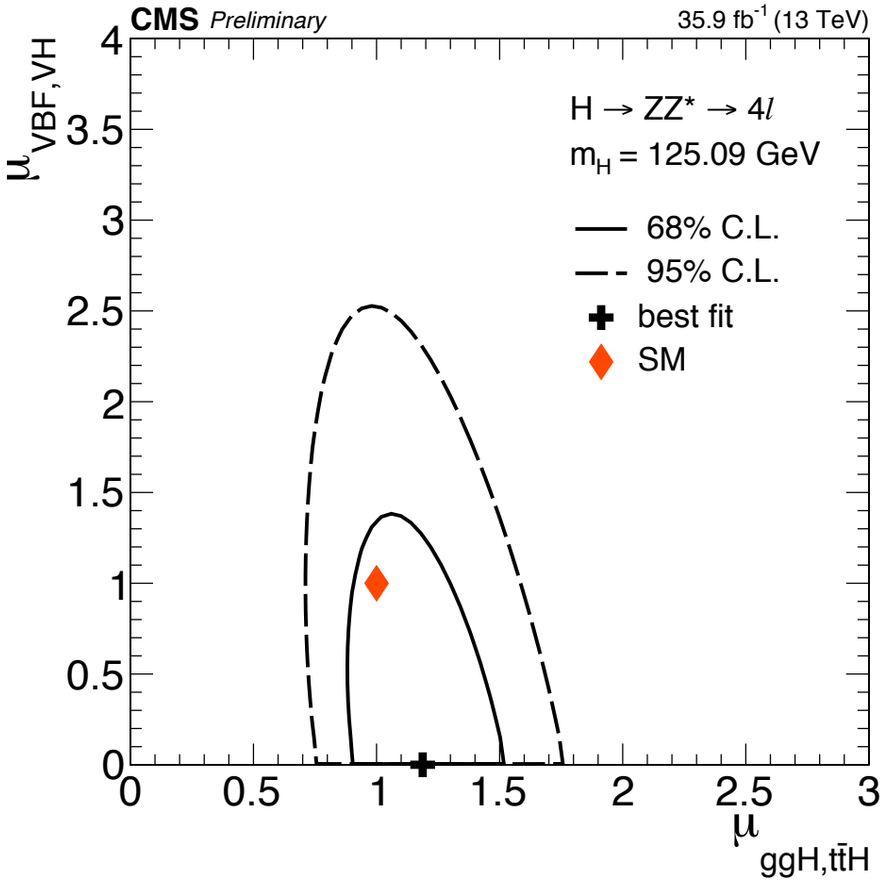
$\sigma_{HH}/\sigma_{SM} < 70$ (48 exp) from Run 1 ATLAS combination

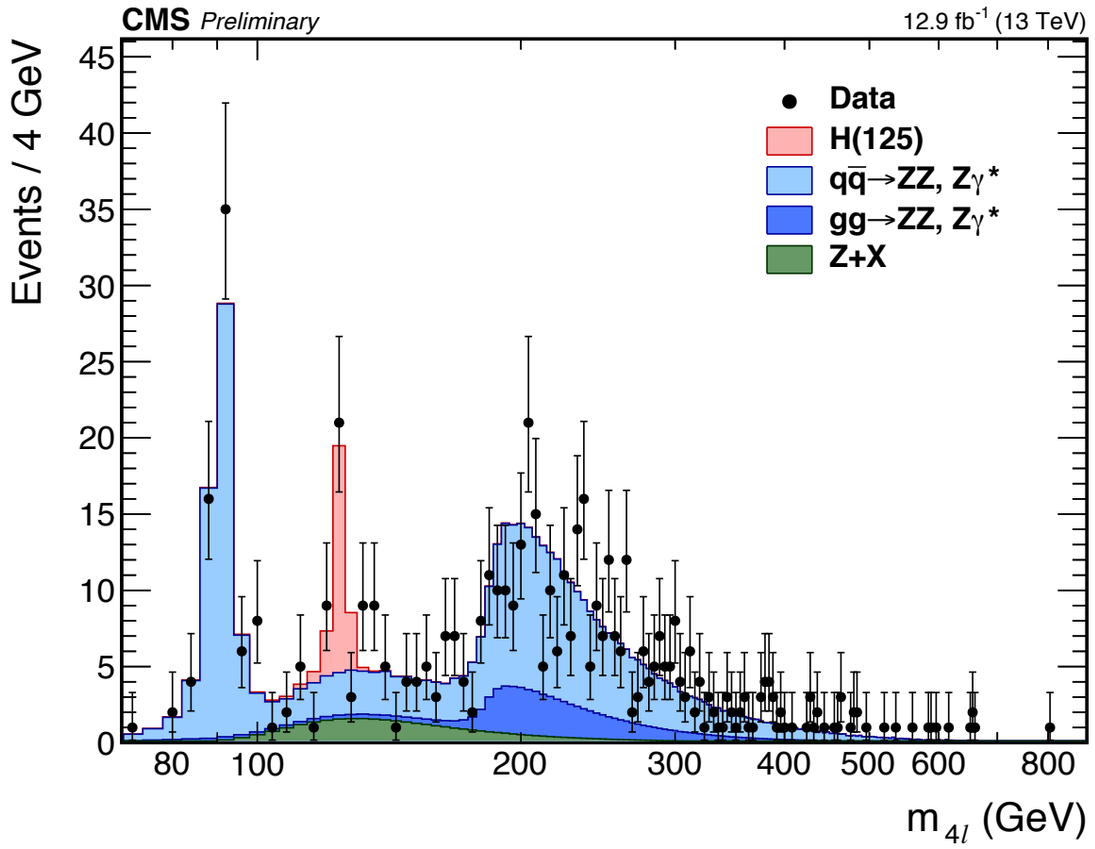
Summary

- Nice new results with Run2 data:
  - confirm the SM Higgs: coupling, cross section, mass, width
  - start to probe the Higgs production: VBF, VH, ttH
    - rare process and indirect probe: self-couplings, anomalous coupling
    - significant improvement compared to Run1
- Looking forward to more results and new data

Additional materials

H→ ZZ, couplings



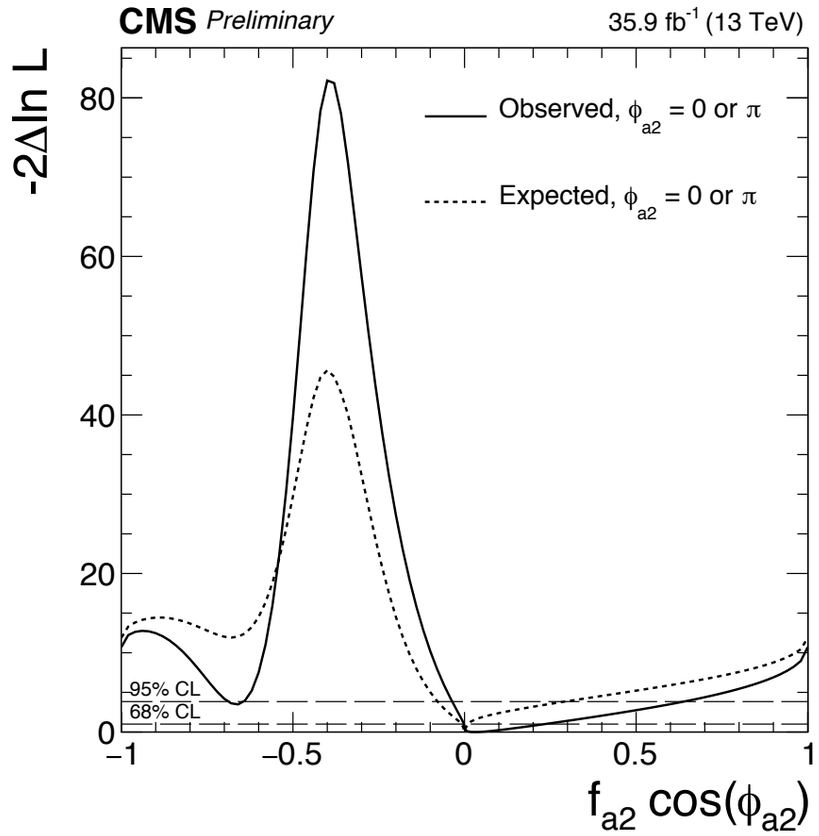


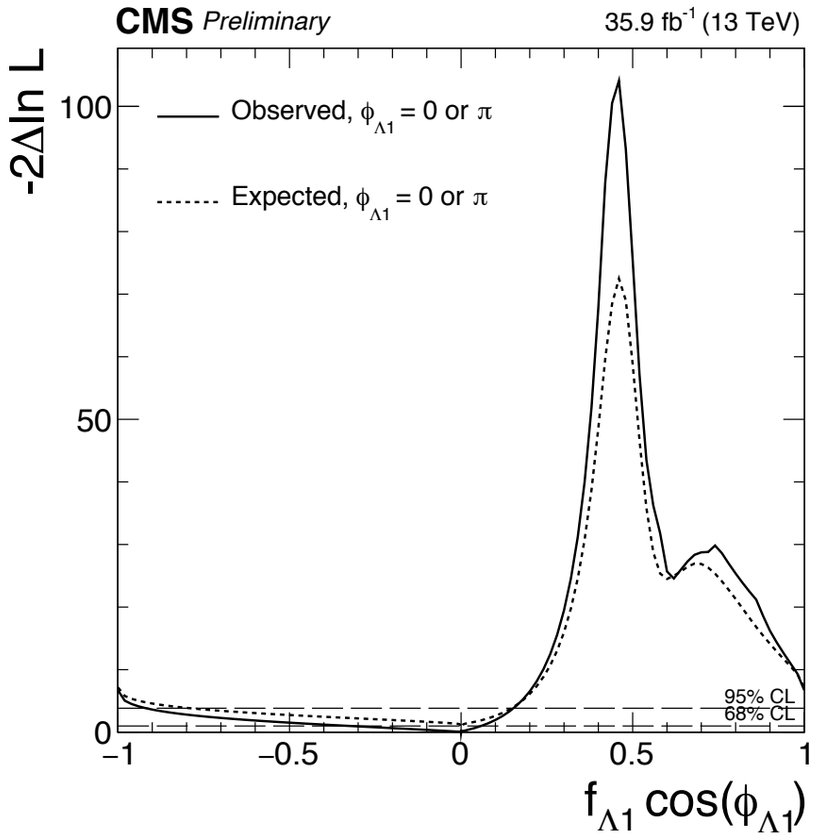
	Event category							
	Untagged	VBF-1j	VBF-2j	VH-hadr.	VH-lept.	VH-MET	ttH	Inclusive
gg → H	38.78	8.31	2.04	1.41	0.08	0.02	0.10	50.74
VBF	1.08	1.14	2.09	0.09	0.02	< 0.01	0.02	4.44
WH	0.43	0.14	0.05	0.30	0.21	0.03	0.02	1.18
ZH	0.41	0.11	0.04	0.24	0.04	0.07	0.02	0.93
ttH	0.08	< 0.01	0.02	0.03	0.02	< 0.01	0.35	0.50
Signal	40.77	9.69	4.24	2.08	0.38	0.11	0.51	57.79
qq̄ → ZZ	19.18	2.00	0.25	0.30	0.27	0.01	0.01	22.01
gg → ZZ	1.67	0.31	0.05	0.02	0.04	0.01	< 0.01	2.09
Z+X	10.79	0.88	0.78	0.31	0.18	0.30	0.27	13.52
Total expected	72.41	12.88	5.32	2.71	0.86	0.43	0.79	95.41
Observed	73	13	4	2	1	1	0	94

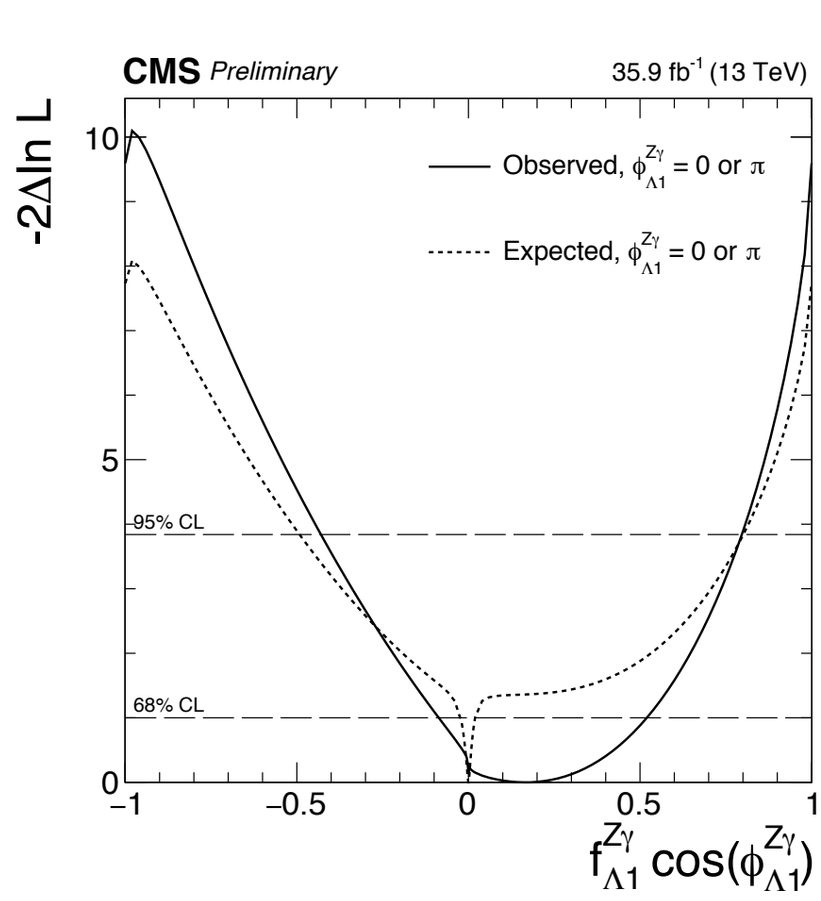
	Inclusive	μ_{ggH}	μ_{VBF}	μ_{VHhad}	μ_{VHlep}	$\mu_{t\bar{t}H}$
Expected	$1.00^{+0.15}_{-0.14}(\text{stat.})^{+0.10}_{-0.09}(\text{sys.})$	$1.00^{+0.23}_{-0.21}$	$1.00^{+1.25}_{-0.97}$	$1.00^{+3.97}_{-1.00}$	$1.00^{+3.94}_{-1.00}$	$1.00^{+3.24}_{-1.00}$
Observed	$1.05^{+0.15}_{-0.14}(\text{stat.})^{+0.11}_{-0.09}(\text{sys.})$	$1.20^{+0.22}_{-0.21}$	$0.06^{+1.03}_{-0.06}$	$0.00^{+2.85}_{-0.00}$	$0.00^{+2.78}_{-0.00}$	$0.00^{+1.19}_{-0.00}$

Channel	4e	4μ	2e2μ	4ℓ
qq̄ → ZZ	$192.7^{+18.6}_{-20.1}$	$360.2^{+24.9}_{-27.3}$	$471.0^{+32.6}_{-35.7}$	$1023.9^{+68.9}_{-76.0}$
gg → ZZ	$41.2^{+6.3}_{-6.1}$	$69.0^{+9.5}_{-9.0}$	$101.7^{+14.0}_{-13.3}$	$211.8^{+28.9}_{-27.5}$
Z+X	$21.1^{+8.5}_{-10.4}$	$34.4^{+14.5}_{-13.2}$	$59.9^{+27.1}_{-25.0}$	$115.4^{+31.9}_{-30.1}$
Sum of backgrounds	$255.0^{+23.9}_{-25.1}$	$463.5^{+31.9}_{-33.7}$	$632.6^{+44.2}_{-46.1}$	$1351.1^{+85.8}_{-91.2}$
Signal ($m_H = 125$ GeV)	$12.0^{+1.3}_{-1.4}$	23.6 ± 2.1	30.0 ± 2.6	65.7 ± 5.6
Total expected	$267.0^{+24.9}_{-26.1}$	$487.1^{+33.1}_{-34.9}$	$662.6^{+45.7}_{-47.5}$	$1416.8^{+89.1}_{-94.3}$
Observed	293	505	681	1479

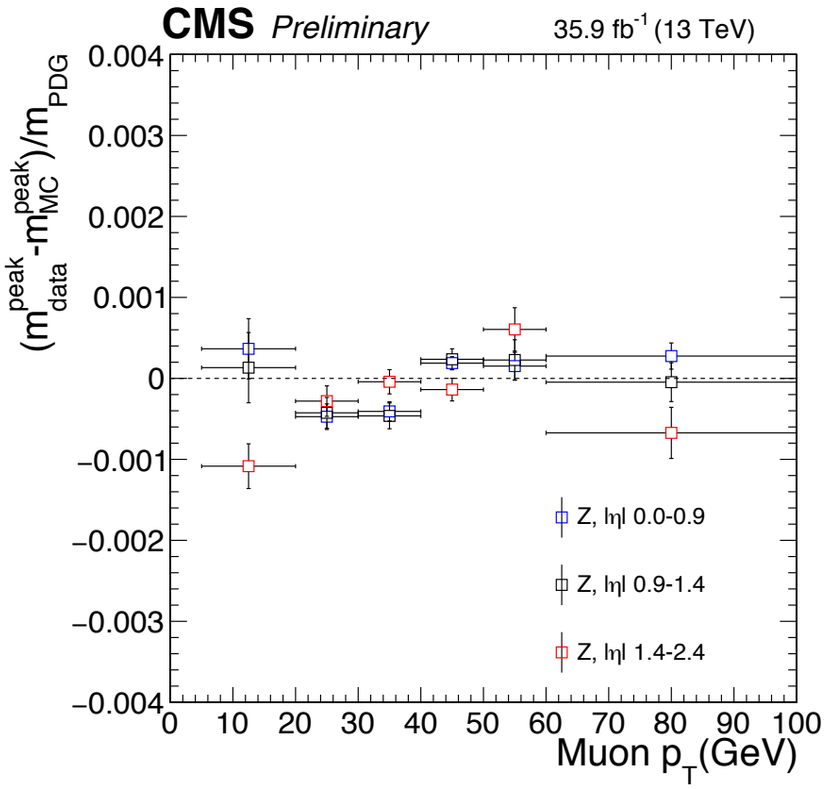
H→ 4l, anomalous couplings



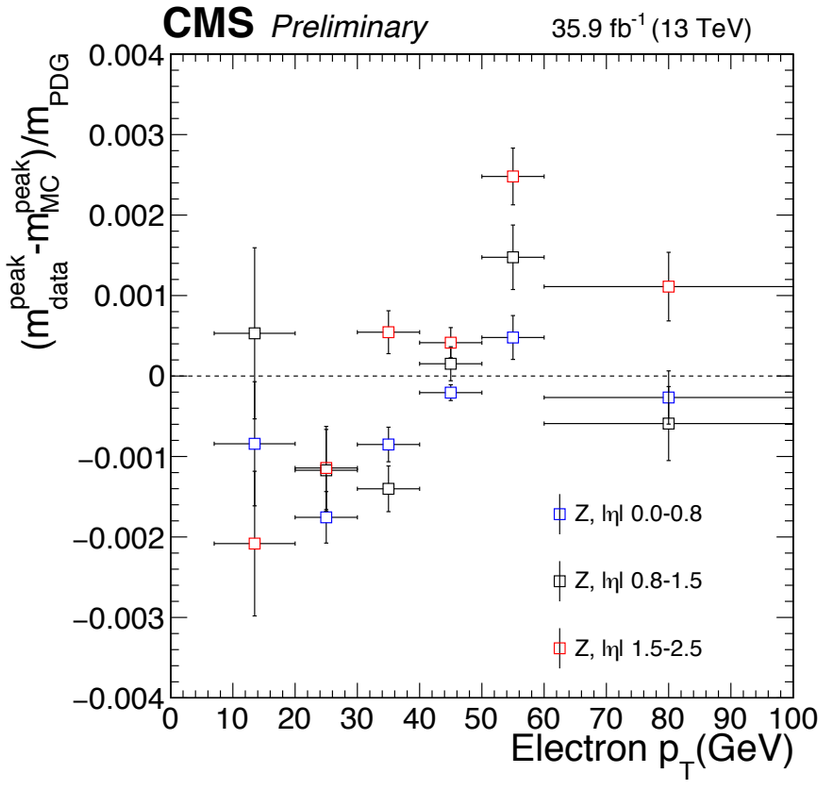




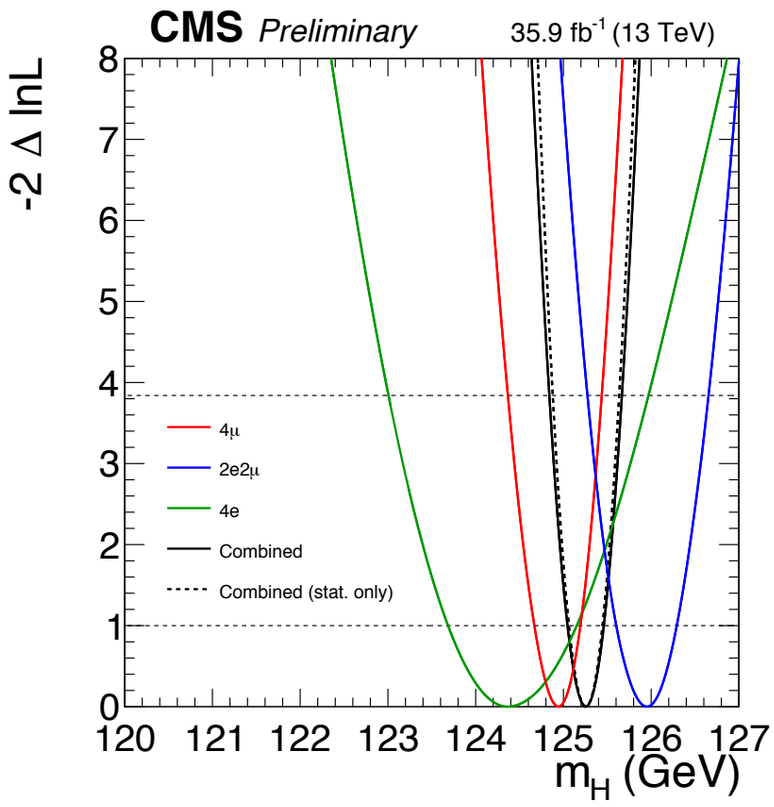
H→ ZZ, mass



Muon



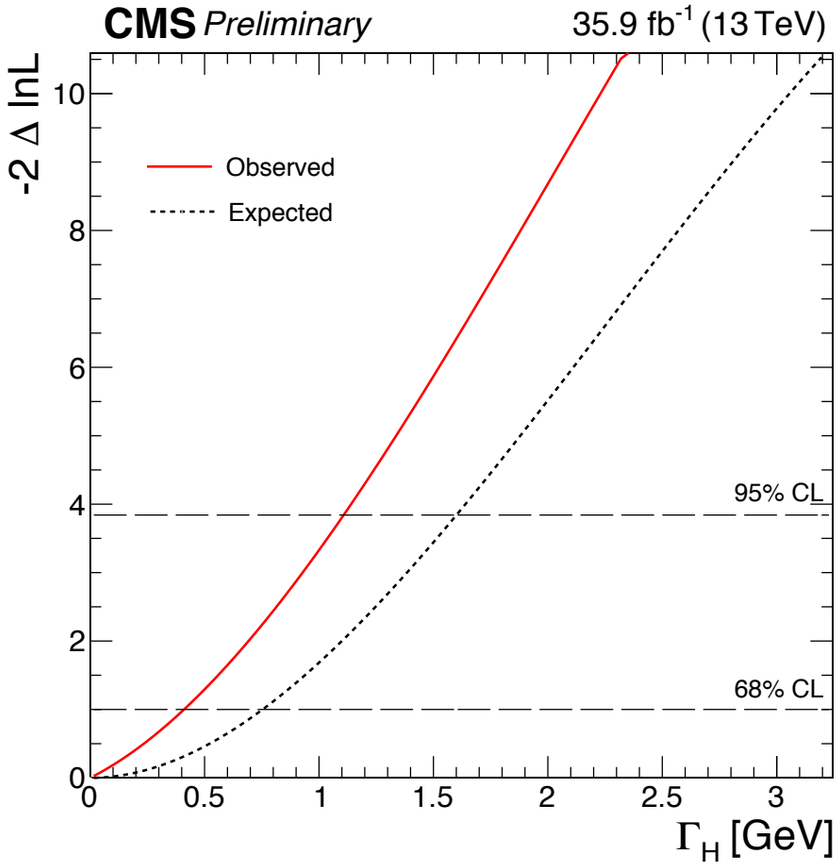
Electron

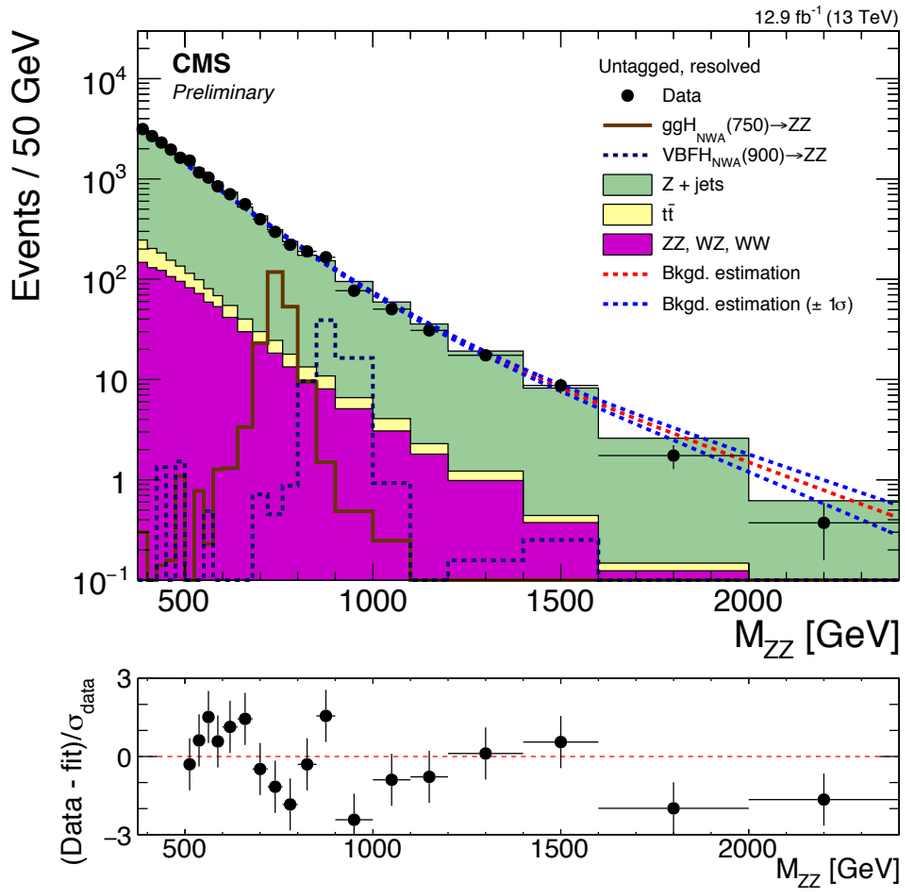


No $m(\mathrm{Z}_1)$ constraint	3D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\mathrm{mass}}, \mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}})$	2D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\mathrm{mass}})$	1D: $\mathcal{L}(m_{4l})$
Expected m_{H} uncertainty change	+8.1%	+11.2%	+21%
Observed m_{H} (GeV)	125.28±0.22	125.36±0.24	125.39±0.25

With $m(\mathrm{Z}_1)$ constraint	3D: $\mathcal{L}(m'_{4l}, \mathcal{D}'_{\mathrm{mass}}, \mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}})$	2D: $\mathcal{L}(m'_{4l}, \mathcal{D}'_{\mathrm{mass}})$	1D: $\mathcal{L}(m'_{4l})$
Expected m_{H} uncertainty change	—	+3.2%	+10.7%
Observed m_{H} (GeV)	125.26±0.21	125.30±0.21	125.34±0.23

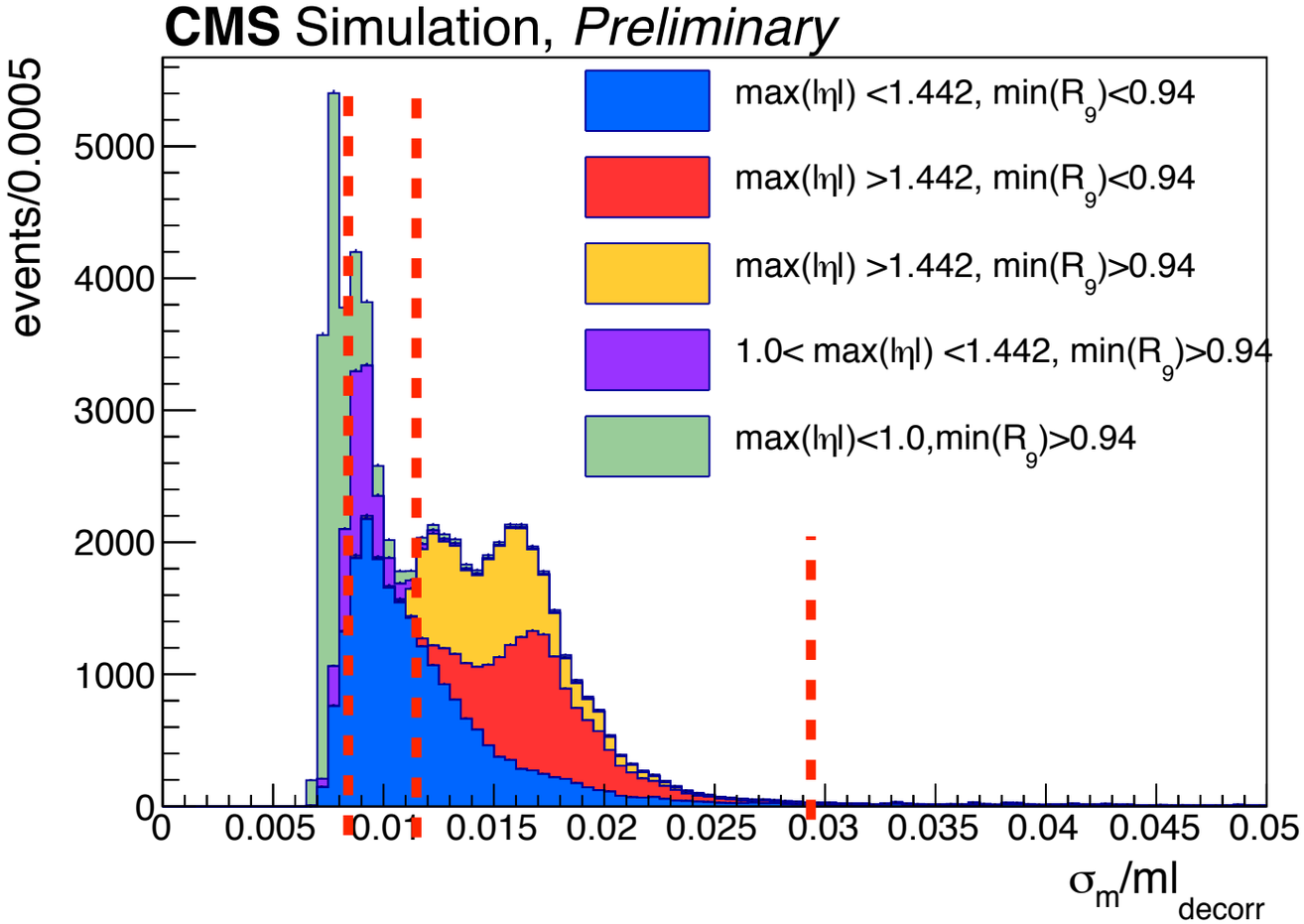
H→ ZZ


CMS Preliminary
35.9 fb-1 (13 TeV)
-2 Δ lnL
Observed
Expected
95% CL
68% CL
ΓH [GeV]

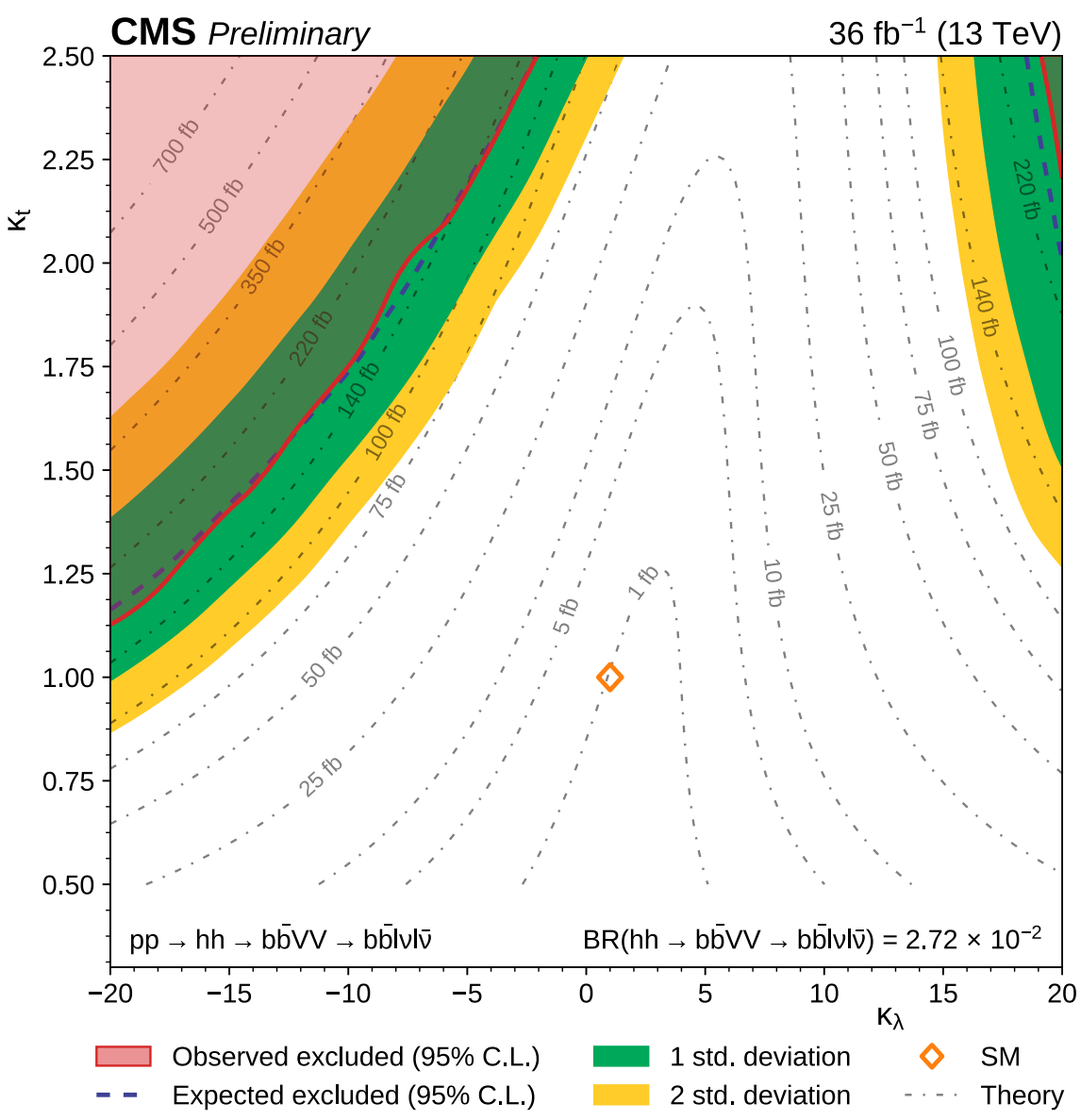

12.9 fb-1 (13 TeV)
CMS
Preliminary
Untagged, resolved
Data
ggHNWA(750)→ZZ
VBFHNWA(900)→ZZ
Z + jets
tt̄
ZZ, WZ, WW
Bkgd. estimation
Bkgd. estimation (± 1σ)
Events / 50 GeV
MZZ [GeV]
(Data - fit)/σdata
MZZ [GeV]

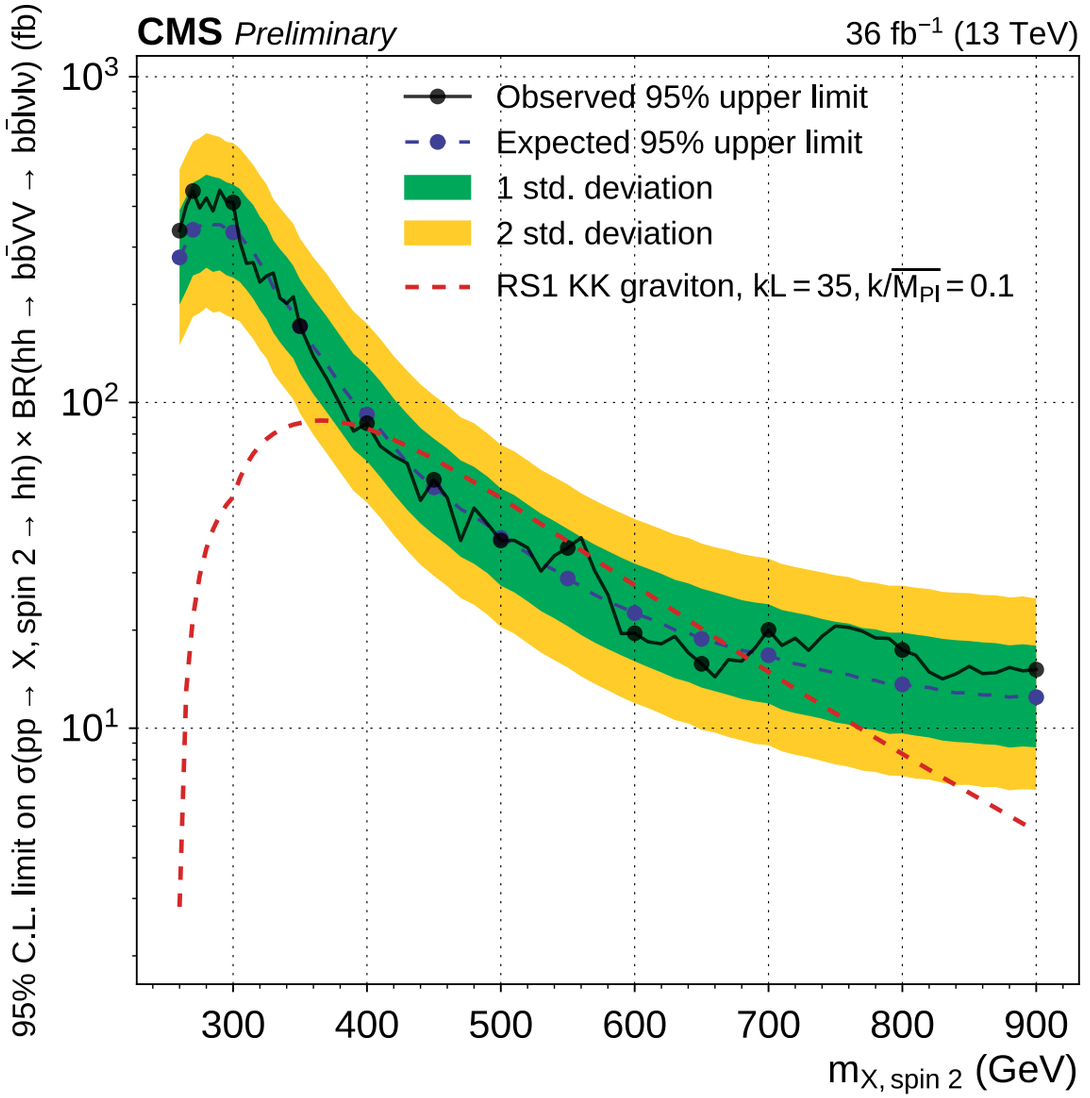
H→ γγ: fiducial cross section

- 3 categories to optimize signal significance
  - based on mass resolution estimator

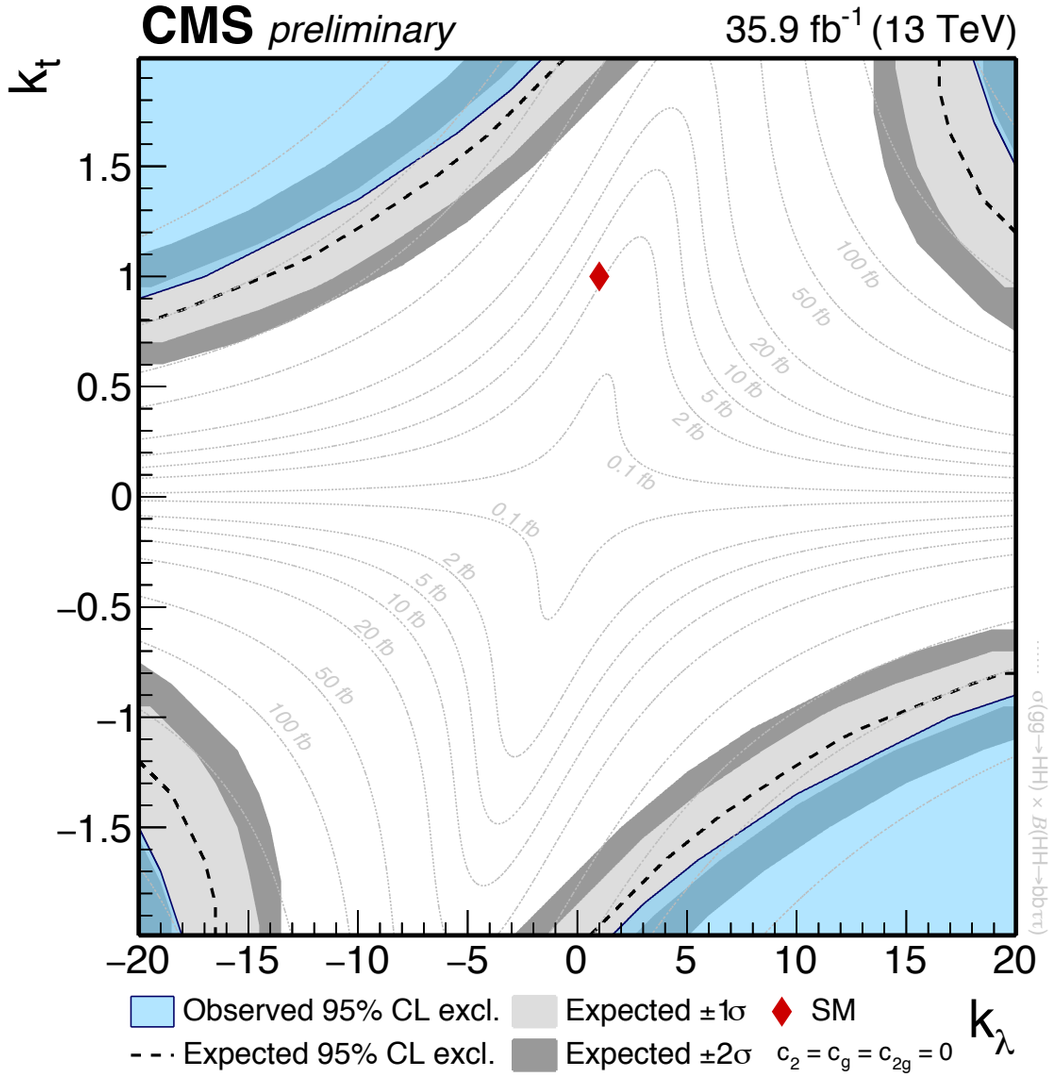


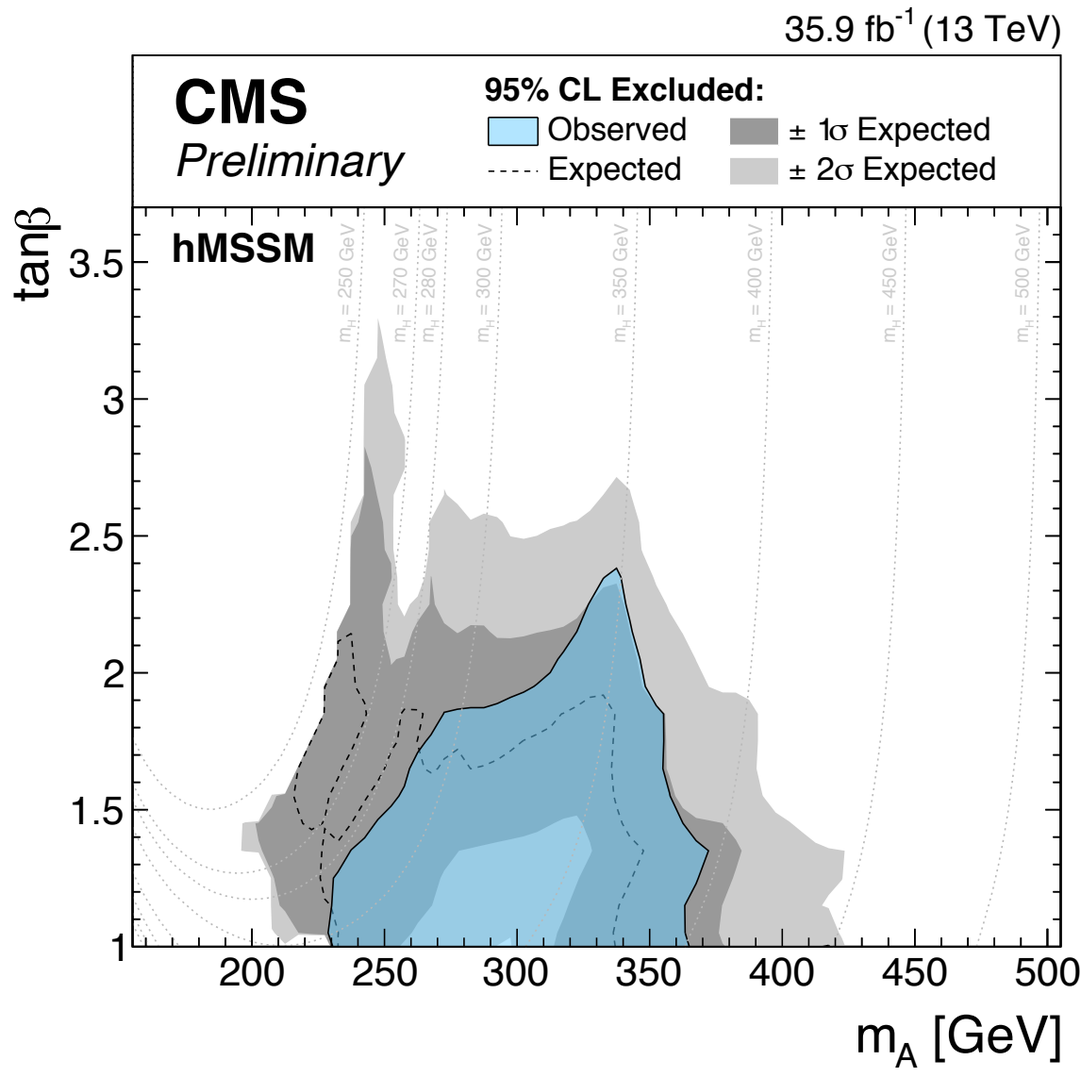
bbVV


CMS Preliminary
36 fb^{-1} (13 TeV)
κ_t
κ_λ
700 fb
500 fb
350 fb
220 fb
140 fb
100 fb
75 fb
50 fb
25 fb
10 fb
5 fb
1 fb
pp → hh → bb̄VV → bb̄lνlν̄
BR(hh → bb̄VV → bb̄lνlν̄) = 2.72 × 10^{-2}
Observed excluded (95% C.L.)
Expected excluded (95% C.L.)
1 std. deviation
2 std. deviation
SM
Theory


CMS Preliminary
36 fb^{-1} (13 TeV)
95% C.L. limit on σ(pp → X, spin 2 → hh) × BR(hh → bb̄VV → bb̄lνlν) (fb)
$m_{X,\ spin\ 2}$ (GeV)
Observed 95% upper limit
Expected 95% upper limit
1 std. deviation
2 std. deviation
RS1 KK graviton, kL = 35, k/$\overline{M_{Pl}}$ = 0.1

bb$\tau\tau$





$$m_{T2} \equiv \min_{\boldsymbol{p}_{T1}+\boldsymbol{p}_{T2}=\boldsymbol{p}_T^{\tau\tau}} \left\{ \max\left[m_T\left(m_{b1}, \boldsymbol{p}_T^{b1}, m_{vis}^{\tau 1}, \boldsymbol{p}_{T1}\right), m_T\left(m_{b2}, \boldsymbol{p}_T^{b2}, m_{vis}^{\tau 2}, \boldsymbol{p}_{T2}\right) \right] \right\}$$

Mass window is chosen accordingly to the resolution and mean value of $m_{\tau\tau}$ and m_{bb} distributions:

$$\left(\frac{m_{\tau\tau}\,[GeV] - 116}{35}\right)^2 + \left(\frac{m_{bb}\,[GeV] - 111}{45}\right)^2 < 1$$

Boosted category:

$$80 < m_{\tau\tau}\,[GeV] < 160, \qquad 90 < m_{fatjet}\,[GeV] < 160$$