UNIVERSITÀ DEGLI STUDI FIRENZE

Higgs boson cross section measurements at CMS

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On behalf of the CMS Collaboration

Introduction

- Following its discovery, the Higgs boson has been studied in a wide variety of final states
- All accessible production modes have been measured
- Each channel brings complementary information and probes a different phase space

→ **A wide range of decay modes probed with the 13 TeV data set collected during Run2**

Decay channel	Recent results from CMS
$H \to WW$	CMS-HIG-20-013 (acc. in EPJC)
$H \to \tau\tau$	10.1103/PhysRevLett.128.081805, CMS-HIG-19-010 (acc in EPJC)
$H \to \gamma\gamma$	CMS-HIG-19-016 (acc. in JHEP)
$H \to ZZ$	CMS-HIG-21-009 (sub. in JHEP)
$H \to b\bar{b}$	CMS-PAS-HIG-22-009, CMS-PAS-HIG-20-001
$H \to c\bar{c}$	CMS-HIG-21-008 (acc. in PRL)

Covered in this talk

Differential cross sections in $H \rightarrow ZZ$

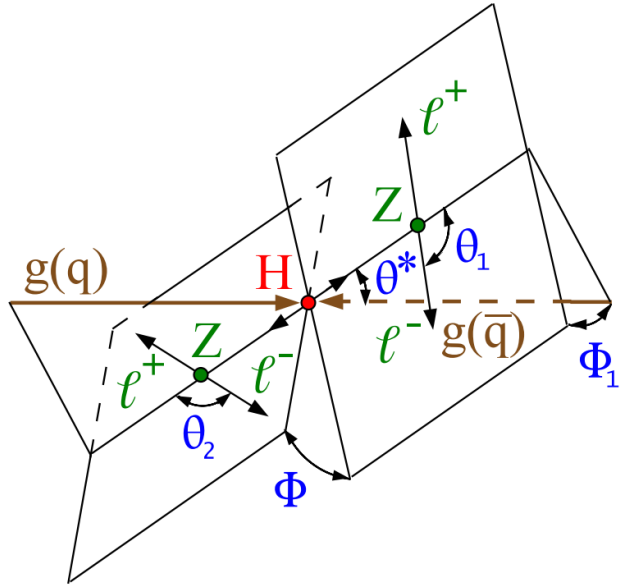
Submitted to JHEP, *Arxiv:2305.07532*

$H \rightarrow ZZ$ - Overview

- Full Run2 measurement ($\mathcal{L} = 138\ \mathrm{fb}^{-1}$)
- $H \rightarrow ZZ \rightarrow 4\ell$ ($\ell = e, \mu$)
- Extend the measurement with respect to the previous Run2 analysis ($4 \rightarrow 31$ observables)

HIGHLIGHTS

- Bins of **kinematics observables defining the decay**
- Bins of **6 matrix element discriminants sensitive to anomalous couplings in the HVV vertex**
- Double-differential results

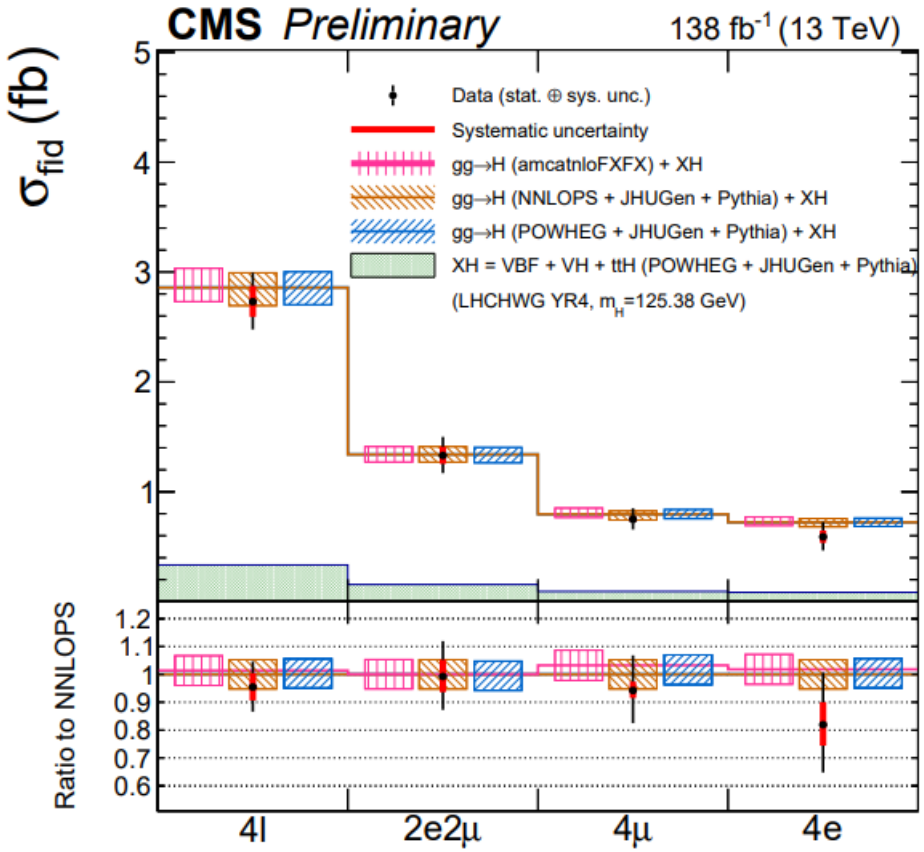


Decay kinematics fully described by:

- Invariant mass of the Z bosons (m_{Z_1}, m_{Z_2})
- 5 angles describing the fermions kinematical properties (Φ, θ_1, θ_2) and the production and decay planes (Φ_1, θ^*)

$H \rightarrow ZZ$ – Results (1)

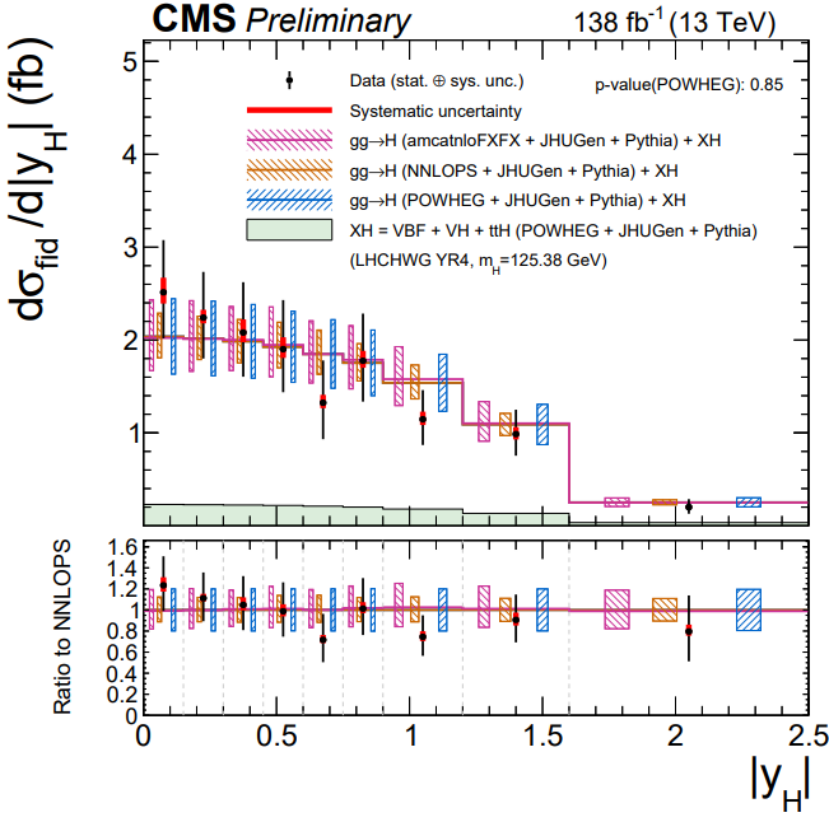
- Definitions of a fiducial phase space to match closely the reco-level selection
- Signal extraction trought fit to the $m_{4\ell}$ distribution
  - All fiducial cross sections in agreement with the SM predictions within uncertainties
  - Inclusive cross section measured with overal precision of 10%
  - Systematic uncertainty dominated by
    - Electrons-related nuisances

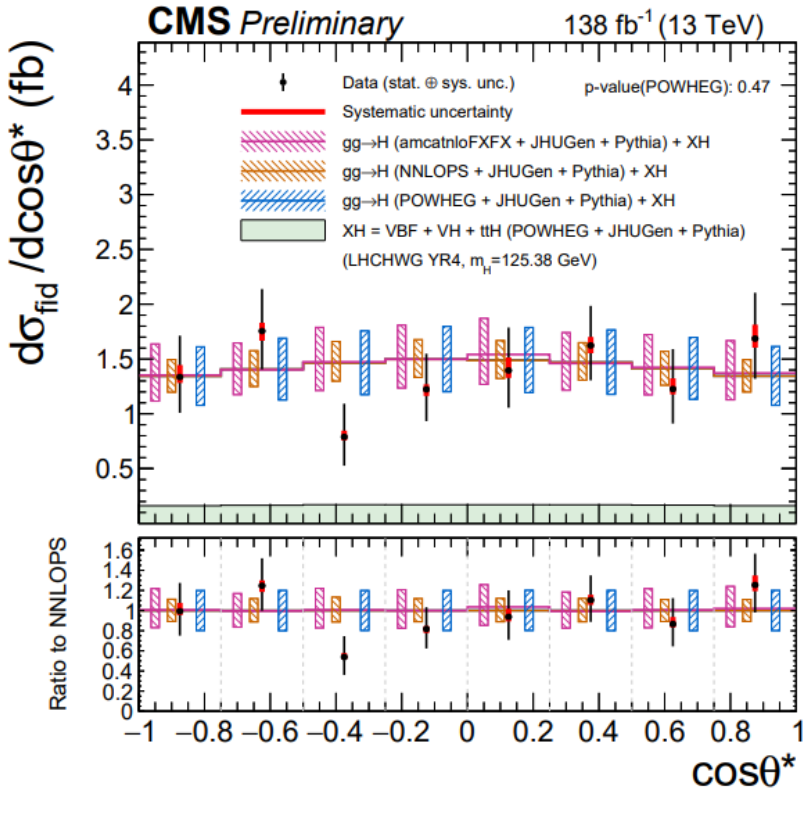


$$\sigma^{fid} = 2.73^{+0.22}_{-0.22}(stat)^{+0.15}_{-0.14}(syst)$$

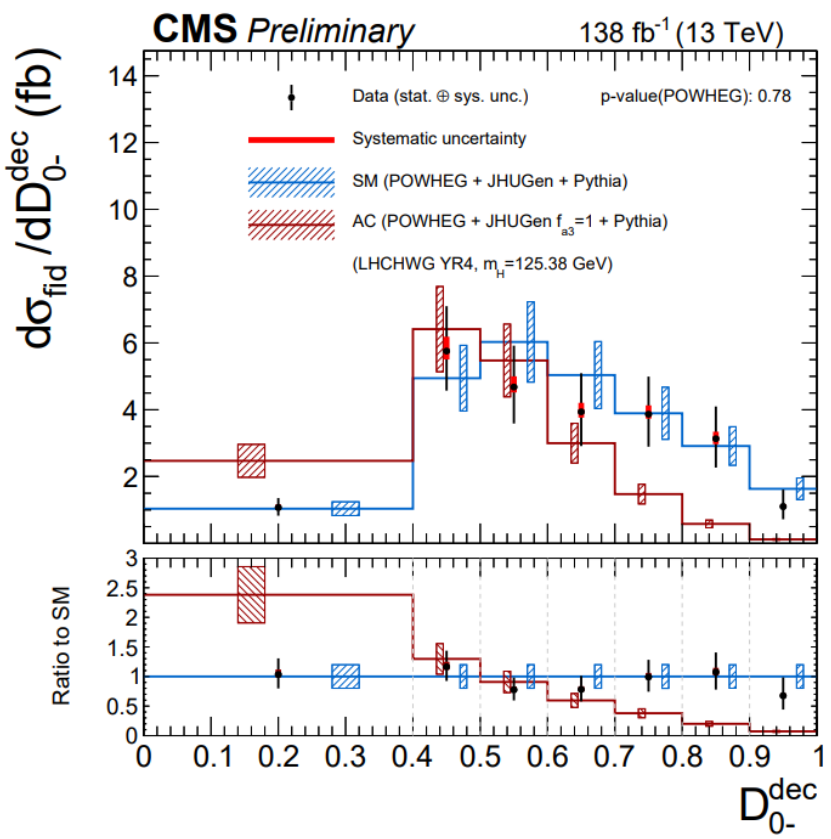
$H \to ZZ$ – Results (2)

Higgs boson kinematics





ME discriminant



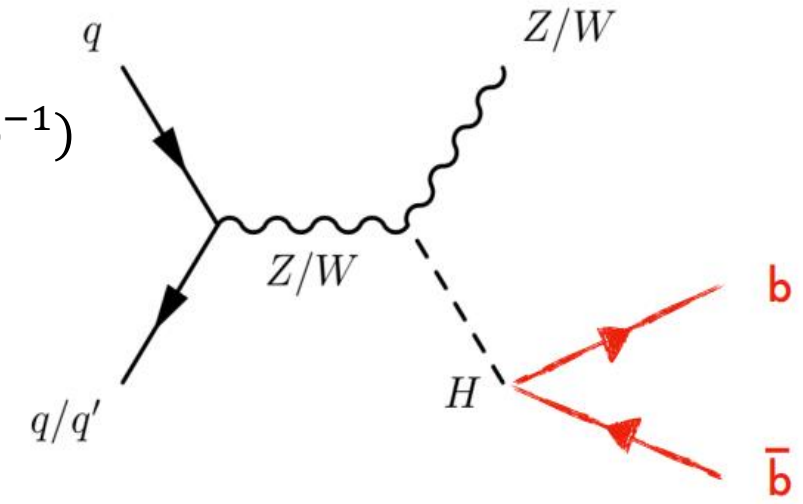
- Differential results consistent with the SM prediction
- Dominated by statistical uncertainty

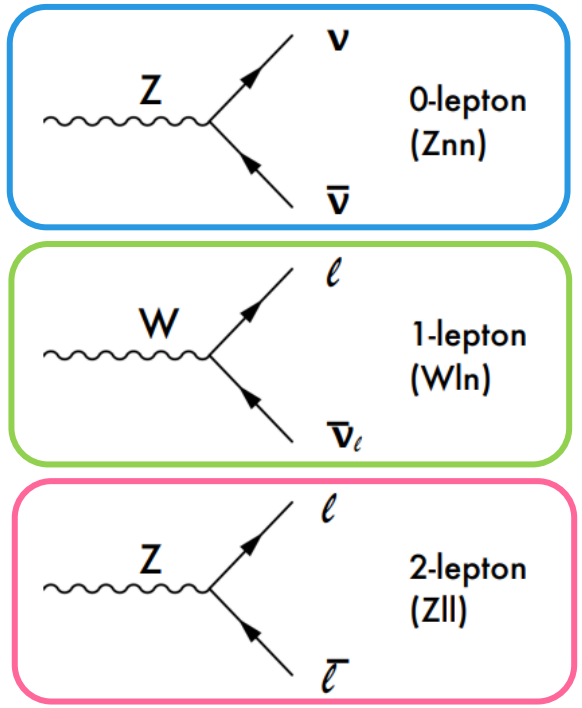
STXS measurement VH in $H \rightarrow b\bar{b}$

CDS:2827421

STXS VH in $H \to b\bar{b}$ - Overview

- Full Run2 measurement ($\mathcal{L} = 138\ \mathrm{fb}^{-1}$)
- 3 analysis channels by decay of the vector boson

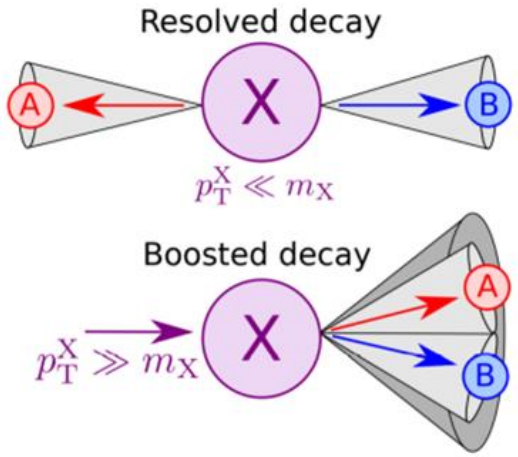




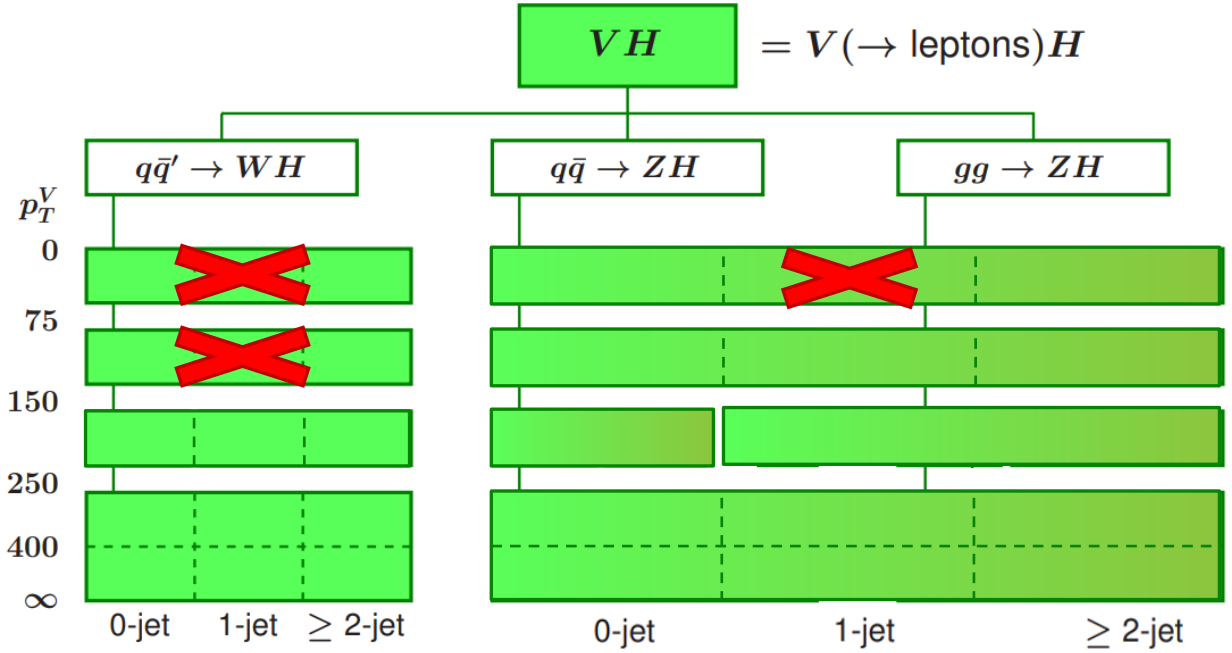
ℓ = e, μ

HIGHLIGHTS

- Within the **S**implified **T**emplate **XS**ection **(STXS)** framework
- **Dedicated categories for *boosted* topology**



STXS VH in $H \to b\bar{b}$ - Strategy



Stage 1.2 scheme with some modifications:

- Merge $qqZH + ggZH$ bins
- Merge WH $150 - 250$ $(0jet +> 0jets)$ bins
- Bin with normalisation fixed to SM expectation

Reco-level categories in $p_T(V)$ and $\#jets$

$0-lepton$				
$p_T(V)$	$(0,250)$		$(250,400)$	$[400,\infty)$
$\#\ of\ additional\ jets$	0	≥ 1		

$1-lepton$			
$p_T(V)$	$(0,250)$	$(250,400)$	$[400,\infty)$

$2-lepton$				
$p_T(V)$	$(75,150)$	$(150,250)$	$(250,400)$	$[400,\infty)$
$\#\ of\ additional\ jets$	0	≥ 1		

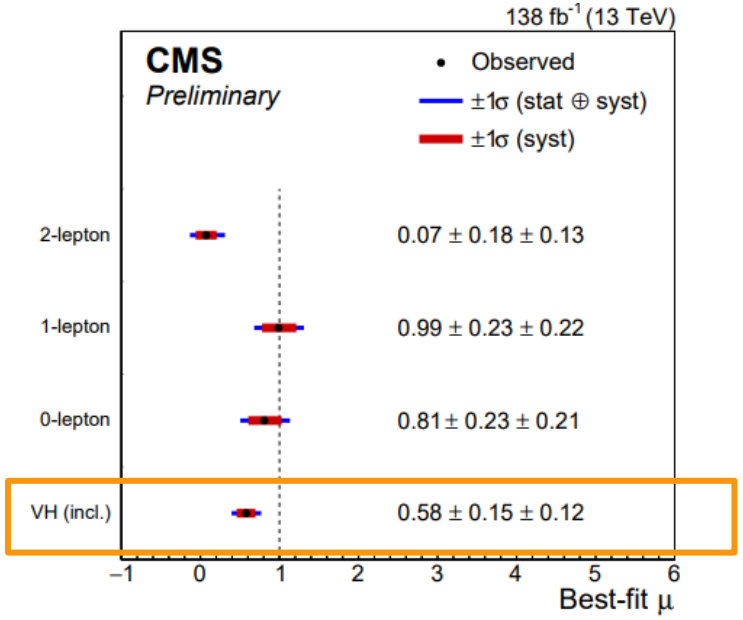
- For each category, one SR and 3 CRs enriched in the main background processes are defined

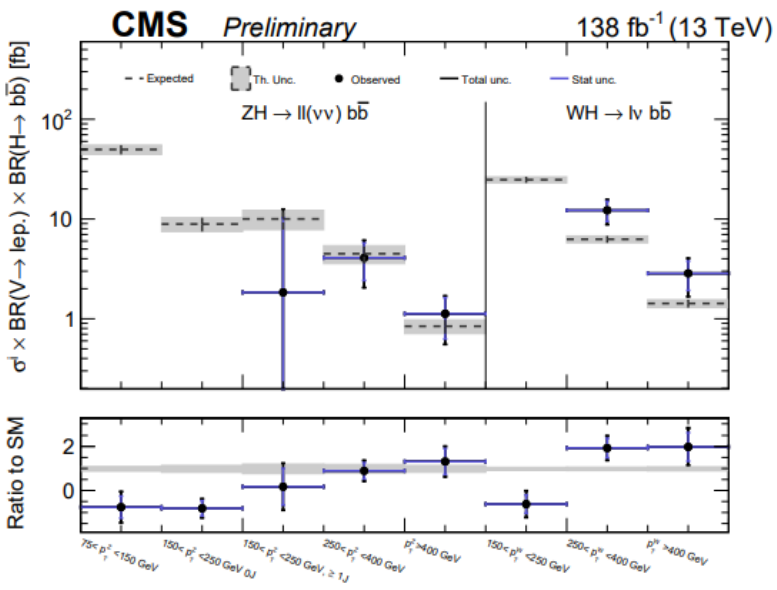
STXS VH in $H \to b\bar{b}$ - Results

	SR	$t\bar{t}$ CR	V+LF CR	V+HF CR
0-lepton, resolved	DNN	$p_T(V)$	$p_T(V)$	HFDNN
0-lepton, boosted	BDT	DeepAK8bbVsLight	DeepAK8bbVsLight	DeepAK8bbVsLight
1-lepton, resolved	DNN	$p_T(V)$	$p_T(V)$	HFDNN
1-lepton, boosted	BDT	DeepAK8bbVsLight	DeepAK8bbVsLight	DeepAK8bbVsLight
2-lepton, resolved	DNN	$p_T(V)$	$p_T(V)$	DeepCSV scores
2-lepton, boosted	BDT	DeepAK8bbVsLight	DeepAK8bbVsLight	DeepAK8bbVsLight

Overall signal strength extracted from a simultaneous fit in SRs and CRs

- Combining all analysis categories
  $\mu = 0.58 \pm 0.18$
- Observed (expected) significance of 3.3 (5.2) standard deviations





Cross sections in $H \rightarrow WW$

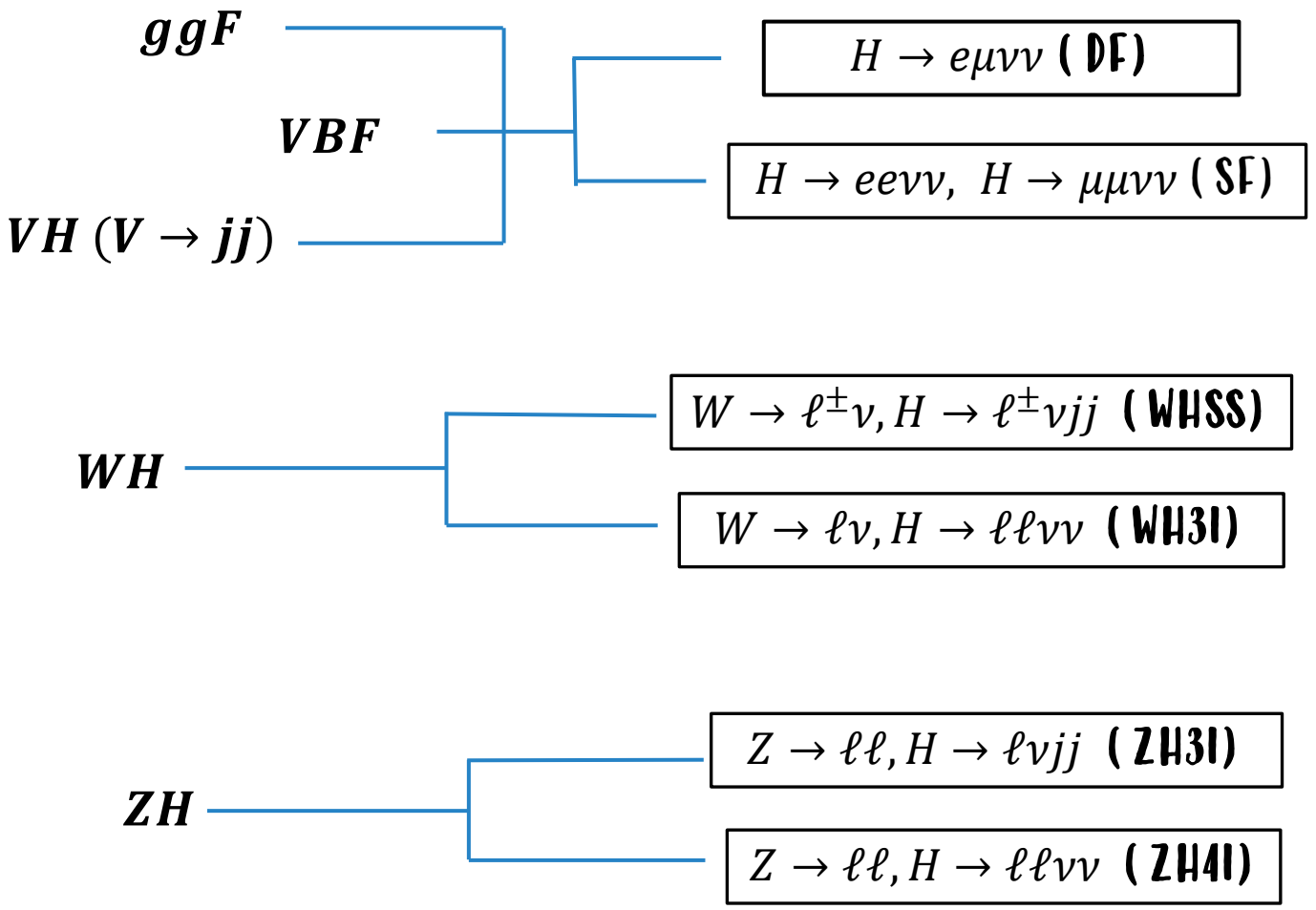
Accepted in EPJC, *Arxiv:2206.09466*

$H \to WW$ - Overview

- Full Run2 measurement
- 3 Higgs boson production modes

HIGHLIGHTS

- **10 final states**
  - fully leptonic, except for **WHSS** and **ZH3l**
  - $W \to \ell\nu$ has a high BR but neutrino is not detected
- **Simultaneous measurement of 14 STXS bins**



$H \rightarrow WW$ – Signal extraction

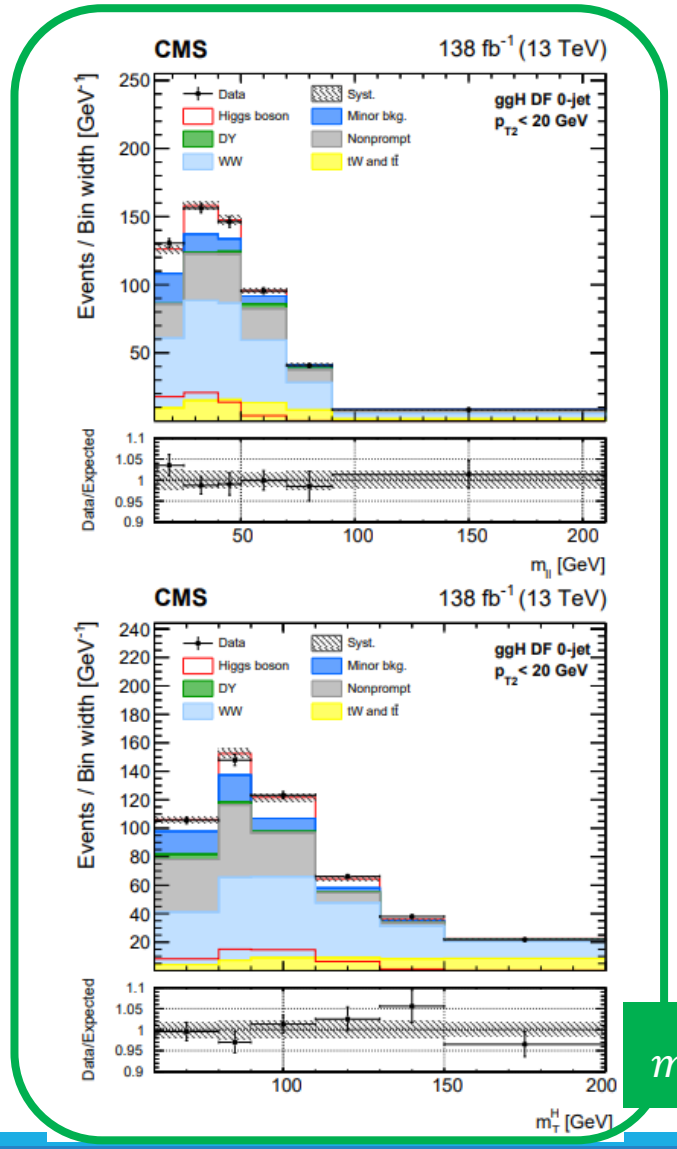
- Simultaneous maximum likelihood template fit to all analysis categories:

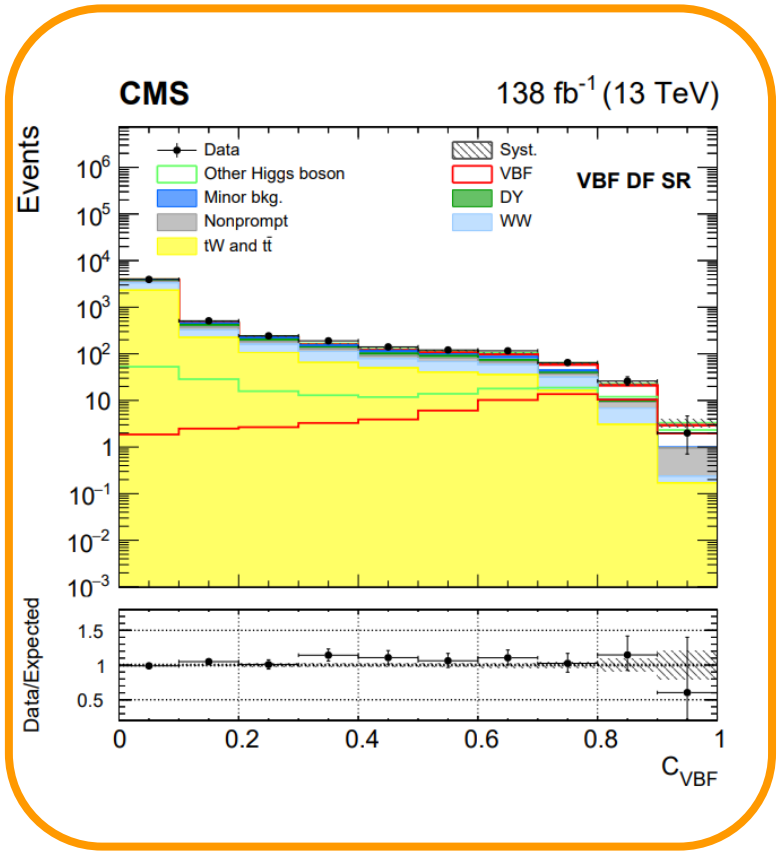
ggH
  - DF: template 2D $(m_{\ell\ell}, m_T)$
  - SF: N_{events}

VBF
  - DF: DNN output
  - SF: N_{events}

VH $(V \rightarrow jj)$
  - DF: $m_{\ell\ell}$
  - SF: N_{events}

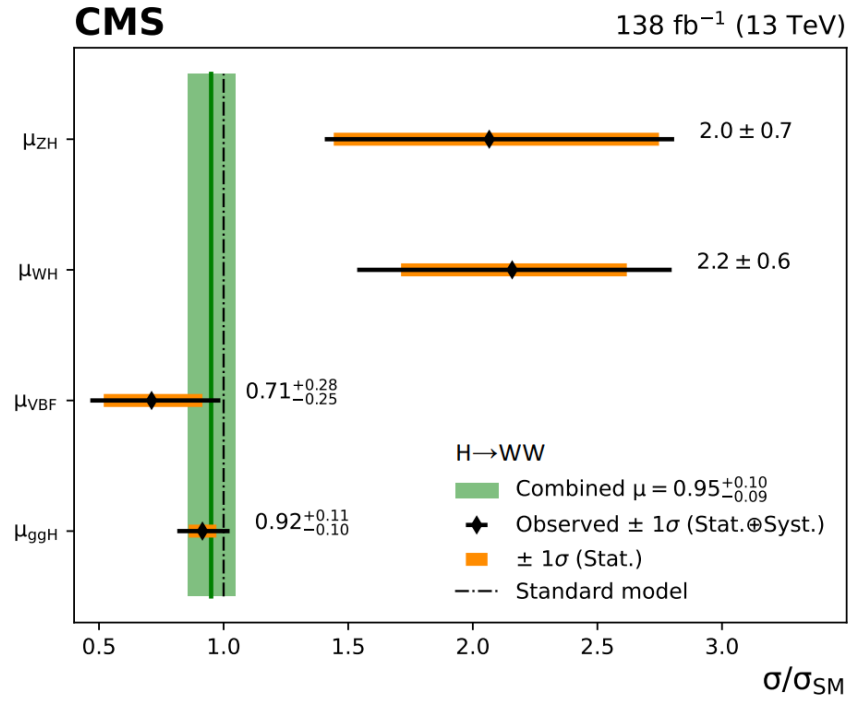
VH $(V \rightarrow leptons)$
  - WHSS: $m_{\ell\ell j(j)}$
  - WH3l: BDT output
  - ZH3l: m_T
  - ZH4l: BDT output

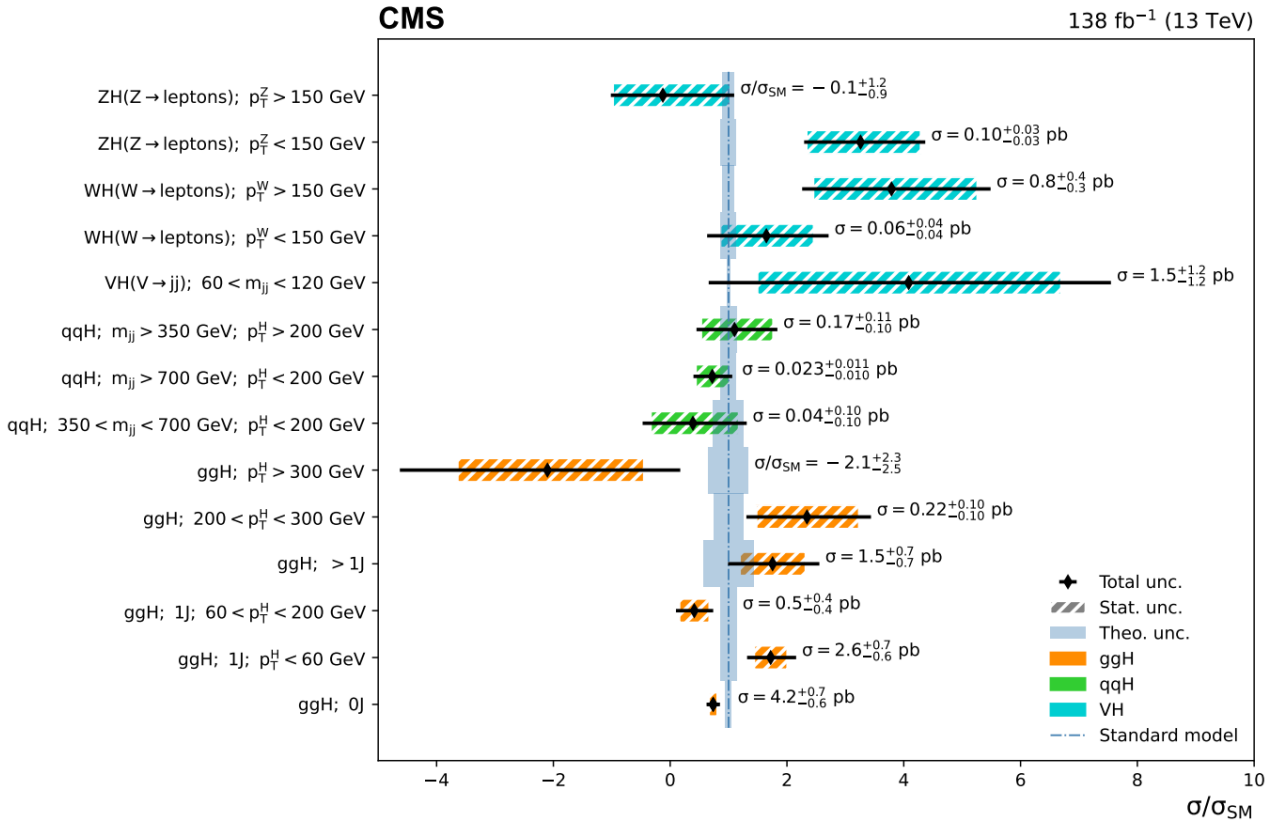




$$m_T^H = \sqrt{2 p_T^{\ell\ell} E_T^{miss} [1 - cos\Delta\phi(\vec{p}_T^{\ell\ell}, E_T^{miss})]}$$

$H \rightarrow WW$ – Results





- Overall signal strength at 10% precision
- Nice improvement on 2016 result thanks to more data and new channels/techniques
- **μ_{ggH} and μ_{WH} among the most precise measurement in a single channel**

- Some bins merged together for lack of sensitivity
- Among the most precise measurements in low p_T^H STXS bins to date

Inclusive and differential cross section in $H \rightarrow \gamma\gamma$

Accepted in JHEP, *Arxiv:2208.12279*

$H \to \gamma\gamma$ - Overview

- Full Run2 measurement ($\mathcal{L} = 137\ \mathrm{fb}^{-1}$)
- Clean final-state topology and precise reconstruction of the diphoton invariant mass
- Small branching ratio but high selection efficiency

HIGHLIGHTS

- Differential fiducial cross sections as a function of **20 observables**
  - VBF-like phase space
- **2 double-differential cross sections**

Observables of interest

Diphoton system

$p_T^{\gamma\gamma}$, $|y^{\gamma\gamma}|$, $|\phi_\eta^*|$, $\cos(\theta^*)$

Event-level observables

p_T^{miss}, N_{bjets}, $N_{leptons}$, N_{jets}, τ_C^j

Leading jet

$p_T^{j_1}$, $|\Delta\phi^{\gamma\gamma j_1}|$, $|y^{j_1}|$, $|\Delta y^{\gamma\gamma j_1}|$

Subleading jet and dijet system

$p_T^{j_2}$, $|\Delta\phi^{j_1 j_2}|$, $|\Delta\phi^{\gamma\gamma j_1 j_2}|$, $|\eta^{j_1 j_2} - \eta^{\gamma\gamma}|$, m^{jj}, $|\Delta\eta^{j_1 j_2}|$, $|y^{j2}|$

Double-differential

$p_T^{\gamma\gamma}$ vs N_{jets}, $p_T^{\gamma\gamma}$ vs τ_c^j

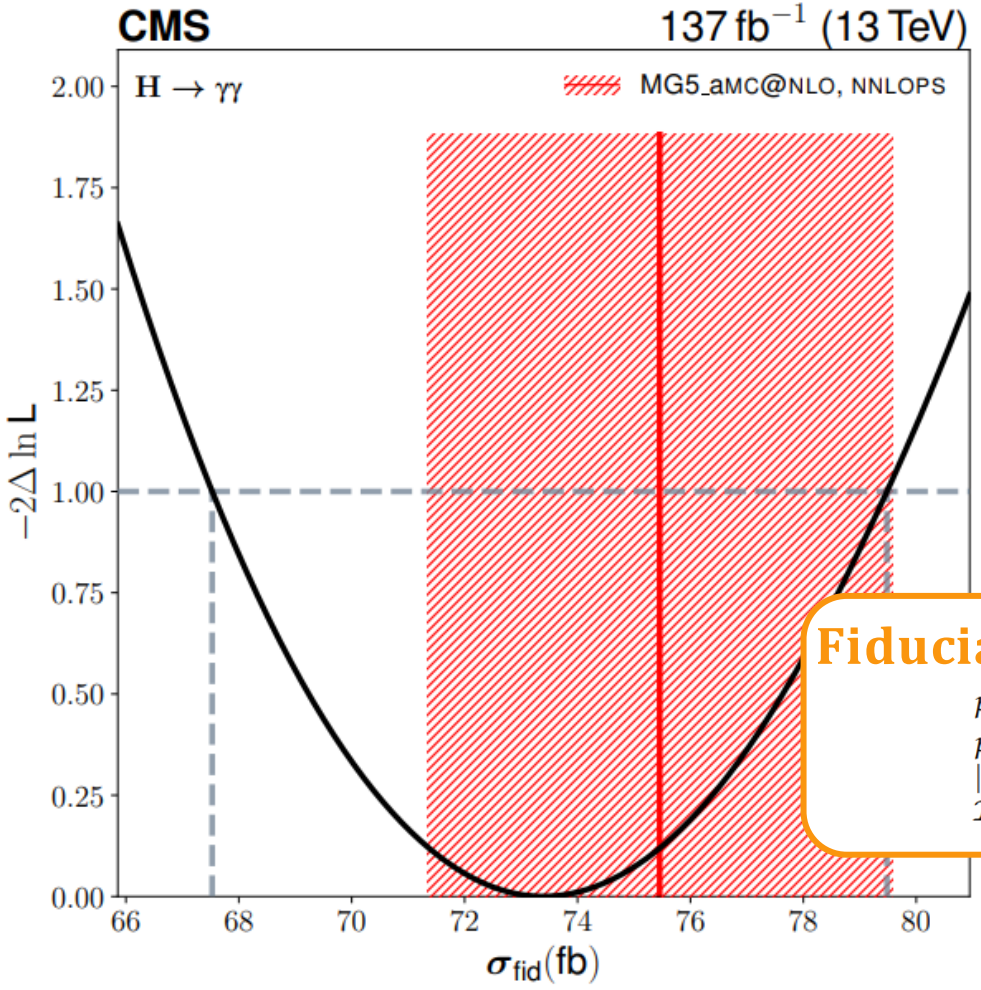
$H \to \gamma\gamma$ – Results (1)

- Signal extraction through a fit to the diphoton invariant mass spectrum

- Unfolding embedded in the likelihood fit signal extraction

- Cross section measured within the fiducial volume consistent with the SM value (75.4 ± 4.1 fb) within one standard deviation

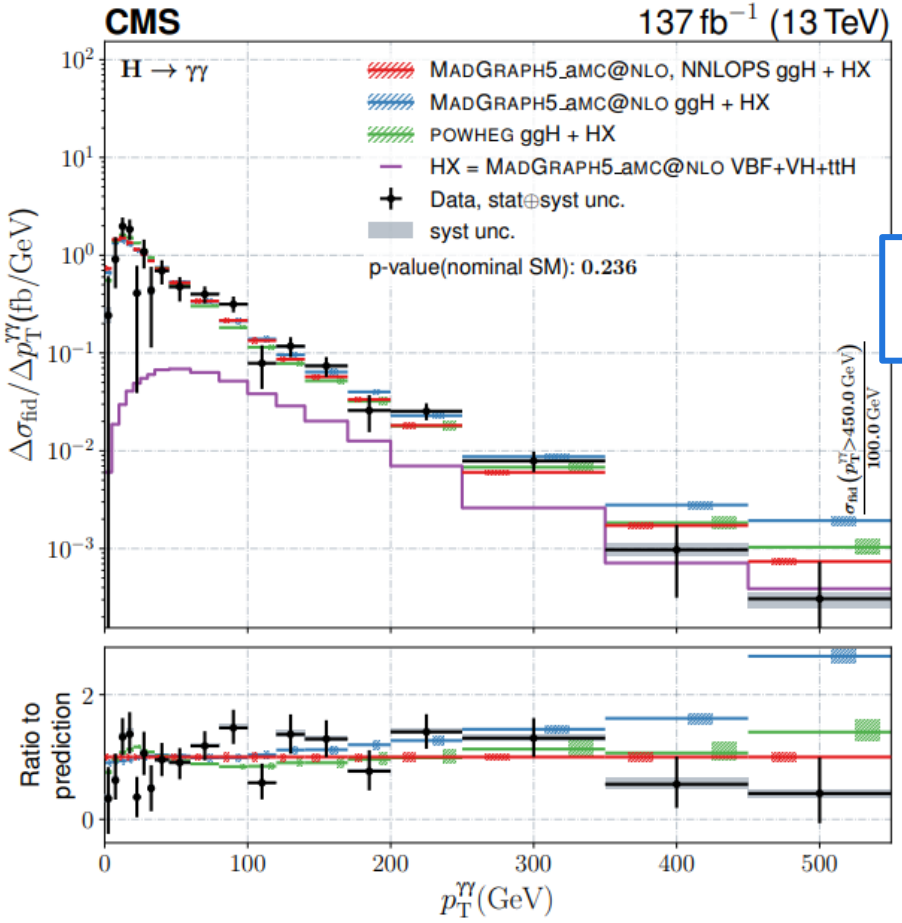
$$\sigma^{\text{fid}} = 73.40^{+5.4}_{-5.3}(\text{stat})^{+2.4}_{-2.2}(\text{syst})\ \text{fb}$$



Fiducial phase space

$p_T^{\gamma_1}/m_{\gamma\gamma} > 1/3$
$p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$
$|\eta^{\gamma}| < 2.5$
$\mathcal{I}^{\gamma}_{\text{gen}} < 10\,\text{GeV}$

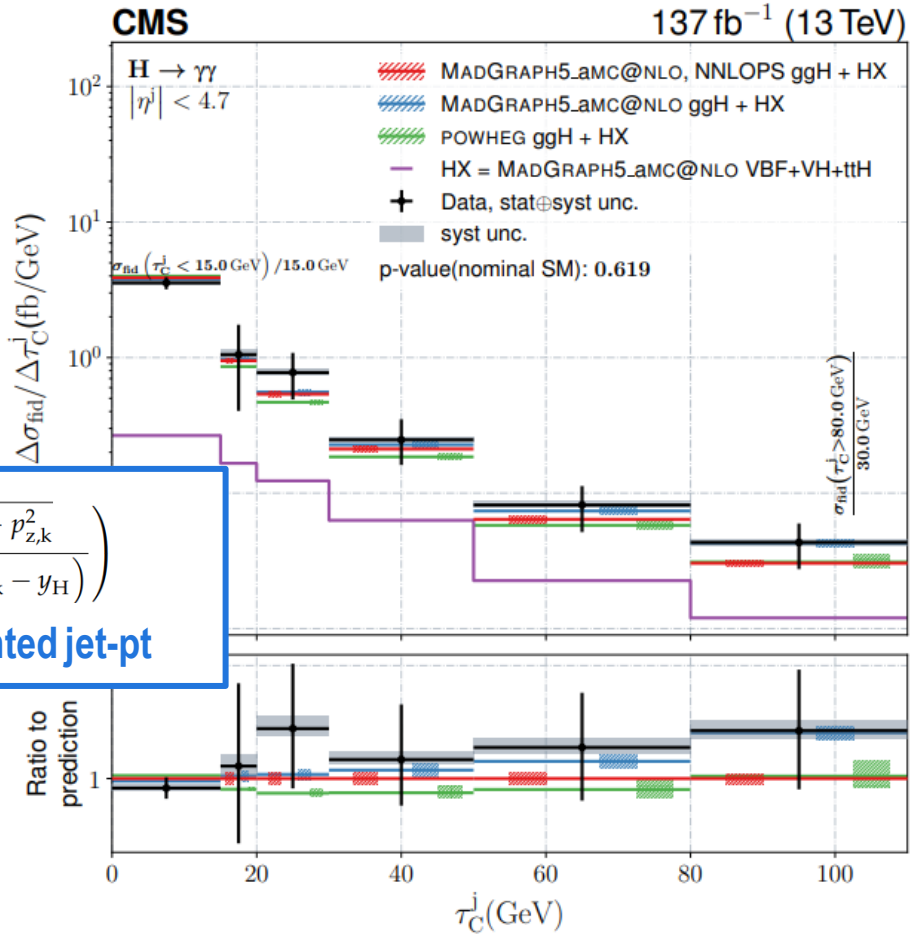
$H \to \gamma\gamma$ –Results (2)



Higgs p_T

$$\tau_C^j = \max_{k \in jets}\left(\frac{\sqrt{E_k^2 - p_{z,k}^2}}{2\cosh\left(y_k - y_H\right)}\right)$$

Rapidity weighted jet-pt

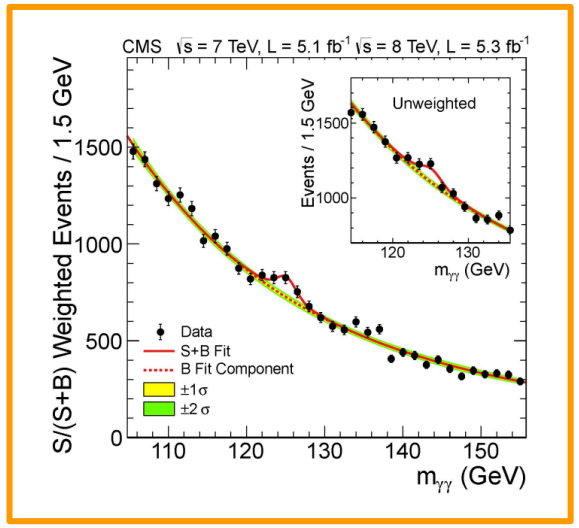


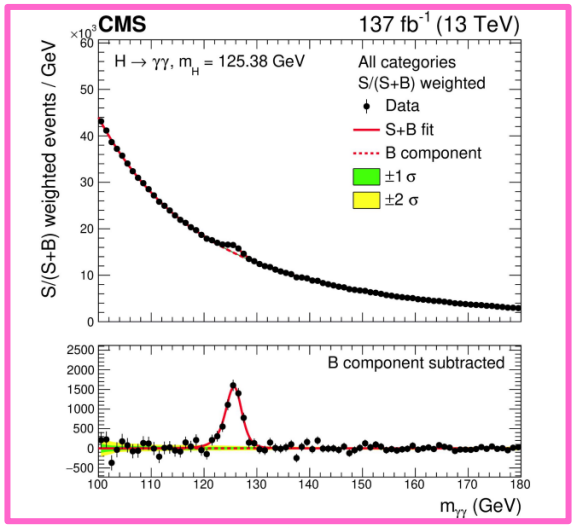
Showing just a few examples from the extensive set!

- Overall, differential cross section results agree within the uncertainties with the SM prediction

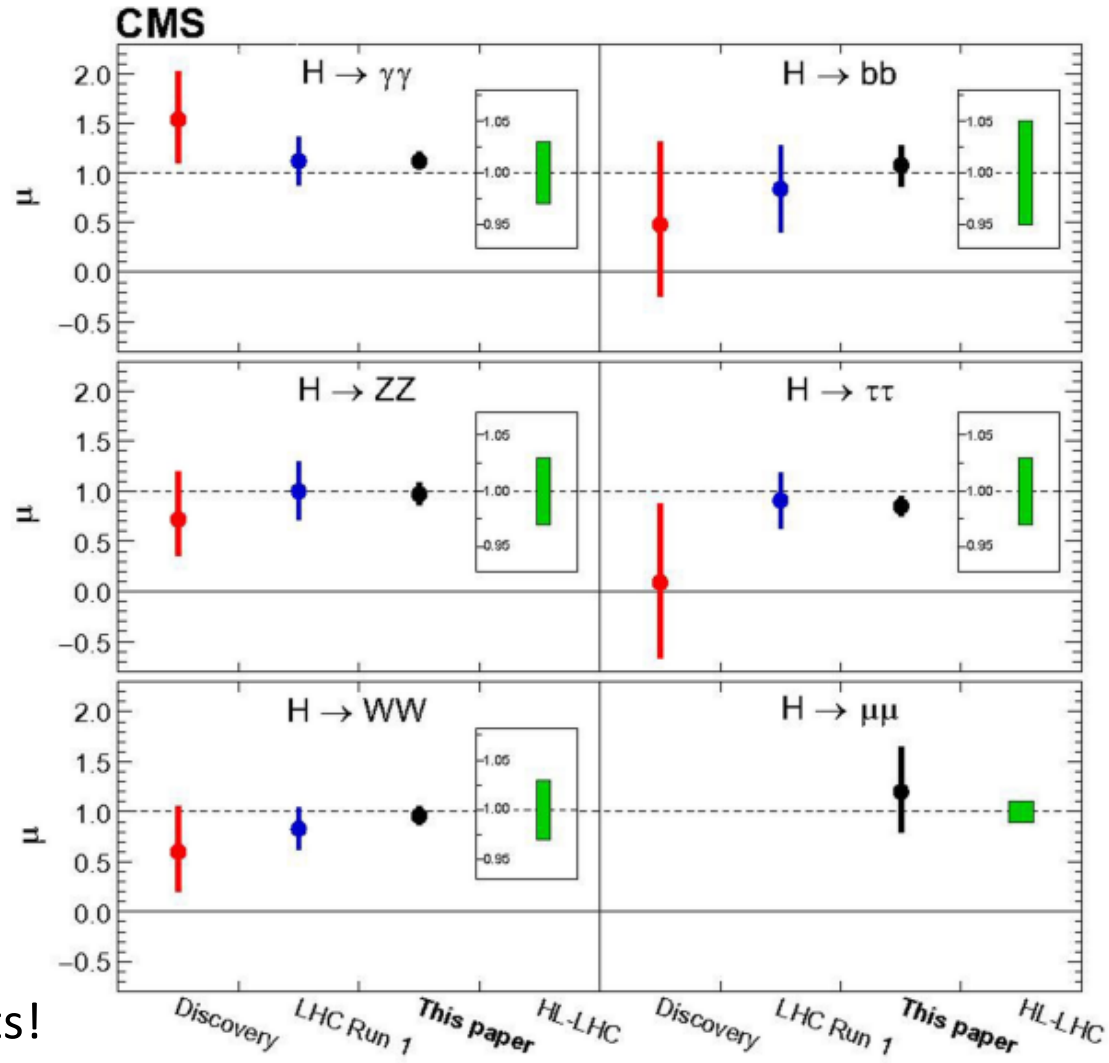
Higgs turns 10!

On July 2022 the CMS collaboration has published the most up-to-date combination of Higgs boson results for the 10 years of its discovery (*Nature 607, 60-68(2022)*)





2012 → Today



From searching for a new particle to precision measurements!

Higgs combination

Combination of production modes and decay channels:

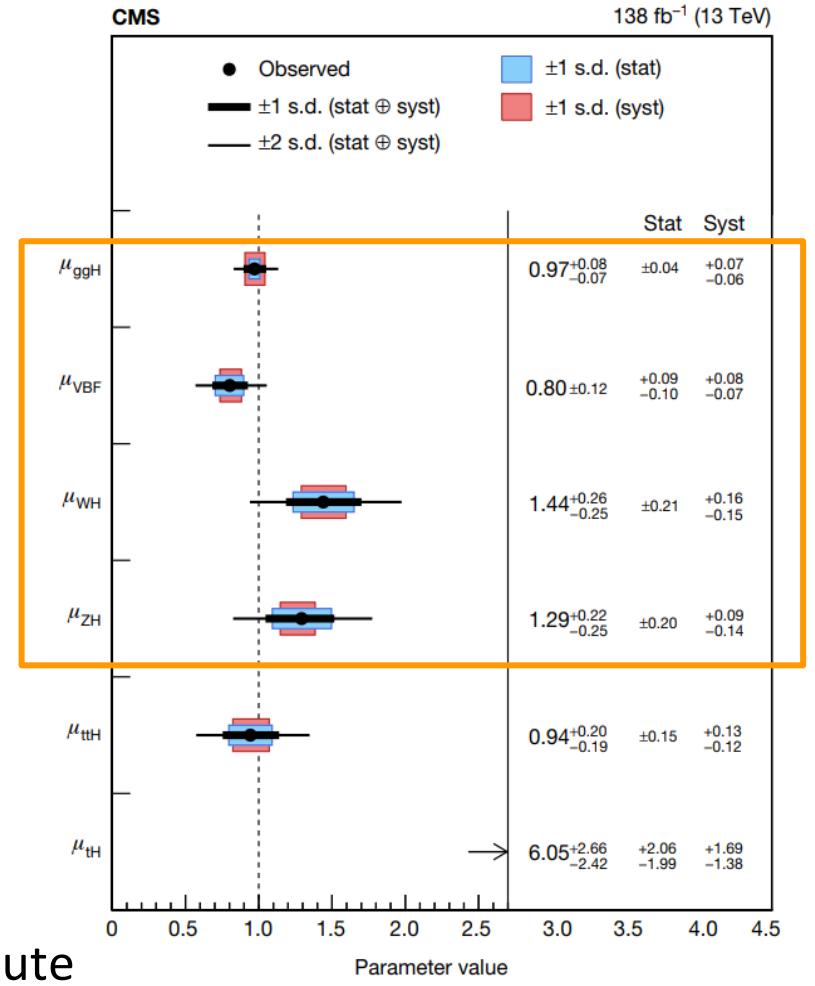
$$\mu = 1.002 \pm 0.057$$

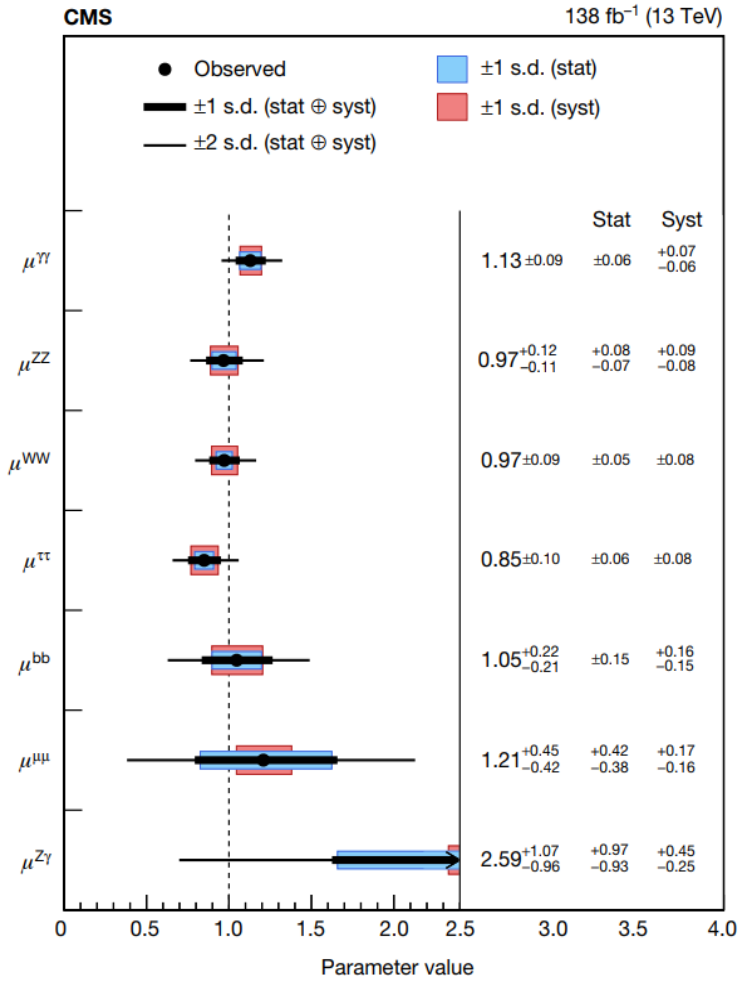
- Excellent agreement with SM expectation
- At the time of discovery

$$\mu = 0.87 \pm 0.23$$

→ Improvement of the uncertainties by a factor of 4.5 in precision

  - Theoretical, statistical and systematical uncertainties contribute at a similar level





Significance of 5σ or larger

Conclusions

- Several Higgs boson cross section measurements have been performed in CMS
- Some of the most recent results have been presented
- ZZ, bb, WW and $\gamma\gamma$ decay channel covered
- Good agreement between standard model predictions and experimental results is observed for all the decay modes
- A new set of measurements will be performed using Run3 data set, allowing to reach an unprecedented level of precision

Thanks for your attention

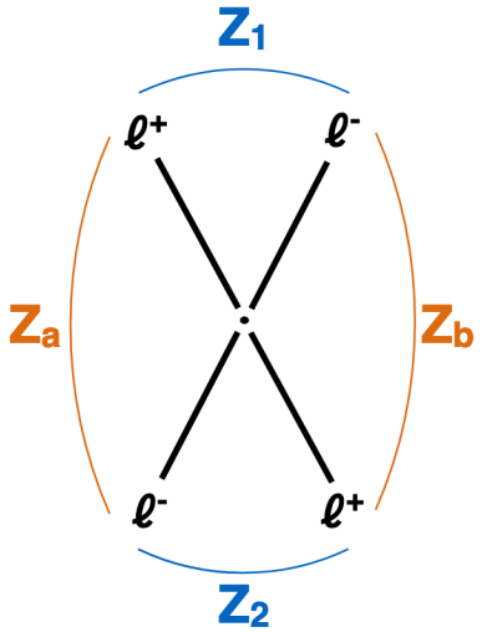
Backup

$H \to ZZ$ – Fiducial volume

Requirements for the $H \to ZZ \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20\,\text{GeV}$
Sub-leading lepton p_T	$p_T > 10\,\text{GeV}$
Additional electrons (muons) p_T	$p_T > 7(5)\,\text{GeV}$
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5\ (2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m_{Z_1} < 120\,\text{GeV}$
Inv. mass of the Z_2 candidate	$12 < m_{Z_2} < 120\,\text{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\text{GeV}$
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 160\,\text{GeV}$

$H \to ZZ$ – Events selections

- Z candidate:
  - Any OSSF pair satisfying $12 < m_{\ell\ell(\gamma)} < 120$ GeV
- ZZ candidates: all possible ZZ pair are built, where the Z_1 is the candidate with $m_{\ell\ell}$ closest to the nominal Z mass
  - $m_{Z_1} > 40$ GeV/c^2
  - $p_{T(l_1)} > 20$ GeV, $p_{T(l_2)} > 10$ GeV
  - $\Delta R(\eta, \phi) > 0.02$ between each of the four leptons
  - $m_{4l} > 4$ GeV for OS pairs
  - Reject 4μ and $4e$ candidates where the alternate pairing $Z_a Z_b$ satisfies $|\, m(Z_a) - m_Z \,| < |\, m_{Z_1} - m_Z \,|$ AND $m_{Z_b} < 12$GeV/c^2
  - $m_{4l} > 70$ GeV/c^2



- If more than one ZZ candidates passes the selection, the one with the highest p_T in retained

STXS VH in $H \to b\bar{b}$ - Resolved topology

Variable	SR	Z + b jets	Z + light jets	$t\bar{t}$
Common selection:				
min(pfMET,H_T^{miss})	> 100	-//-	-//-	-//-
p_T^{miss}	> 170	-//-	-//-	-//-
p_T^{j1}	> 60	-//-	-//-	-//-
p_T^{j2}	> 35	-//-	-//-	-//-
p_T(jj)	> 120	-//-	-//-	-//-
$\Delta\phi$(Z,H)	> 2.0	-//-	-//-	-//-
$\Delta\phi$(pfMET,J)	> 0.5	> 0.5	> 0.5	> 0.5
Different between SR and CRs:				
N_{aj}	≤ 1	≤ 1	≤ 1	≥ 2
M(jj)	$\in$[90-150]	$\notin$[90-150]	-	-
$btag_{max}$	$>$ medium	$>$ medium	$<$ medium	$>$ medium
$btag_{min}$	>loose	>loose	<loose	>loose
$\Delta\phi$(pfMET,trkMET)	< 0.5	< 0.5	< 0.5	-
min $\Delta\phi$(pfMET,J)	-	-	-	$< \pi/2$

Variable	SR	W + b jets	W + light jets	$t\bar{t}$
Common selection:				
p_T(jj)	> 100	-//-	-//-	-//-
$p_T(V)$	> 150	-//-	-//-	-//-
N_{lep}	< 1	-//-	-//-	-//-
p_T^{j1}	> 25	-//-	-//-	-//-
p_T^{j2}	> 25	-//-	-//-	-//-
$\Delta\phi$(lep, pfMET)	< 2	-//-	-//-	-//-
Difference between SR and CRs:				
$btag_{max}$	>medium	>medium	[loose-medium]	>tight
$btag_{min}$	>loose	-	-	-
M(jj)	[90,150]	[150,250] and <90	<250	< 250
N_{aj}	< 2	< 2	-	>1
σ(pfMET)	-	> 2	> 2	-
$\Delta\phi(H,V)$	< 2.5	-	-	-

Variable	SR	Z + b jets	Z + light jets	$t\bar{t}$
$btag_{max}$	>medium	>medium	<loose	>tight
$btag_{min}$	>loose	>loose	<loose	>loose
$M(V)$	[75,105]	[85,97]	[75,105]	[10,75] and <120
M(jj)	[90,150]	$\notin$[90,150]	[90,150]	-
$\vec{p}_T^{miss}$	-	<60	-	-
$\Delta\phi(H,V)$	-	> 2.5	> 2.5	-

STXS VH in $H \to b\bar{b}$ - Resolved topology

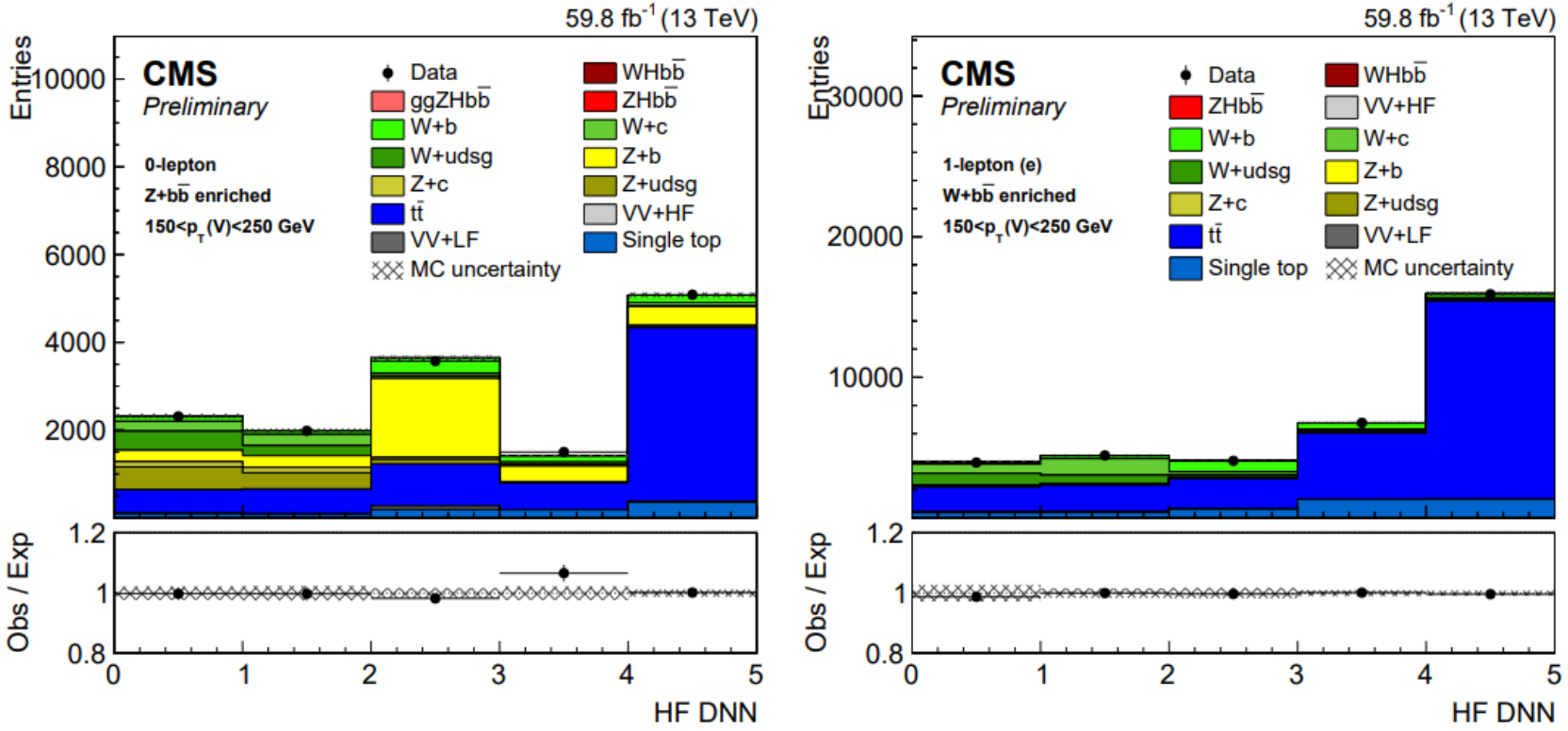
Input variables of the DNN (and HFDNN) trained in resolved SRs

Variable	Description	0-lepton	1-lepton	2-lepton
$M(\mathrm{jj})$	Dijet invariant mass	✓	✓	✓
$p_T(\mathrm{jj})$	Dijet transverse momentum	✓	✓	✓
$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$	MET transverse momentum	✓	✓	✓
$\mathrm{M_t(V)}$	Transverse mass of vector boson		✓	
$p_{\mathrm{T}}(\mathrm{V})$	Transverse momentum of vector boson		✓	✓
$p_T(\mathrm{jj})/\ p_{\mathrm{T}}(\mathrm{V})$	Ratio of momentum of vector boson and Higgs boson		✓	✓
$\Delta\phi(V,H)$	Azimuthal angle between vector boson and dijet directions	✓	✓	✓
$\mathrm{btag_{max}}$	Working point b-tagging score of leading jet	✓	✓	✓
$\mathrm{btag_{min}}$	Working point b-tagging score of sub-leading jet	✓	✓	✓
$\Delta\eta(\mathrm{jj})$	Pseudorapidity difference between leading and sub-leading jet	✓	✓	✓
$\Delta\phi(\mathrm{jj})$	Azimuthal angle between leading and sub-leading jet	✓	✓	
$p_T^{max}(\mathrm{j_1},\mathrm{j_2})$	Maximum transverse momentum of jet between leading and sub-leading jet	✓	✓	
$p_T(\mathrm{j_2})$	Transverse momentum of the sub-leading jet	✓	✓	
SA5	Number of soft-track jets with momentum greater than 5 GeV	✓	✓	✓
$\mathrm{N_{aj}}$	Number of additional jets	✓	✓	
$\mathrm{btag_{max}}$ (add)	Maximum btagging discriminant score among additional jets	✓		
p_T^{max}(add)	Maximum transverse momentum among additional jets	✓		
$\Delta\phi$(jet, pfMET)	Azimuthal angle between additional jet and MET	✓		
$\Delta\phi$(lep, pfMET)	Azimuthal angle between lepton and MET		✓	
M_t	Reconstructed top quark mass		✓	
$p_T(\mathrm{j_1})$	Transverse momentum of leading jet			✓
$p_T(\mathrm{j_2})$	Transverse momentum of sub-leading jet			✓
$M(V)$	Reconstructed vector boson mass			✓
$\Delta R(\mathrm{V,H})$	Angular separation between vector boson and Higgs boson			✓
$\Delta R(\mathrm{V,H})$ (kin)	Angular separation between vector boson (reconstructed after kinematic fit) and Higgs boson			✓
$\sigma(\mathrm{m(jj)})$	Resolution of dijet invariant mass			✓
N_{rec}	Number of recoil jets			✓

Most discriminating variables

STXS VH in $H \to b\bar{b}$ - HFDNN

0 lepton (left) and 1 lepton (right) categories



The output nodes target enrichment in the V+light-flavor (first bin), V+c (second bin), V+b (third bin), single-top (fourth bin), and tt (fifth bin) backgrounds.

STXS VH in $H \to b\bar{b}$ - Boosted topology

0-lepton Variable	SR	Z + b jets	Z + light jets	$t\bar{t}$
DeepAK8 (bbVsLight)	> 0.8	> 0.8	< 0.8	> 0.8
$M(jj)$	$\in[90,150]$	$\notin[90,150]$	> 50	> 50
N_{al}	$= 0$	$= 0$	$= 0$	> 0
N_{aj}	$= 0$	$= 0$	$= 0$	> 1

1-lepton Variable	SR	W + b jets	W + light jets	$t\bar{t}$
DeepAK8 (bbVsLight)	> 0.8	> 0.8	< 0.8	> 0.8
$M(jj)$	$\in[90,150]$	$\notin[90,150]$	> 50	> 50
N_{al}	$= 0$	$= 0$	$= 0$	> 0
N_{aj}	$= 0$	$= 0$	$= 0$	> 1

2-lepton Variable	SR	Z + b jets	Z + light jets	$t\bar{t}$
DeepAK8 (bbVsLight)	> 0.8	> 0.8	< 0.8	> 0.8
$M(jj)$	$\in[90,150]$	$\notin[90,150]$	> 50	> 50
$M(V)$	$\in[75,105]$	$\in[75,105]$	$\in[75,105]$	$\notin[90,150]$

$H \rightarrow WW$ - VBF DF

Preselection H → WW DF

$60\ \text{GeV} < m_T^H < 125\ \text{GeV}; m_T^{\ell_2} > 30\ \text{GeV}$
$N_{b-jets} = 0; N_{jets} = 2; m_{jj} > 120\ \text{GeV}$

SR

DNN score

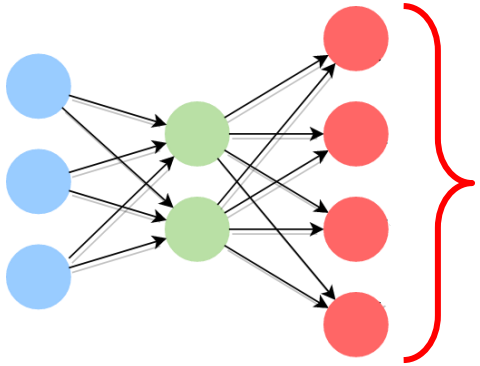
VBF

ggH

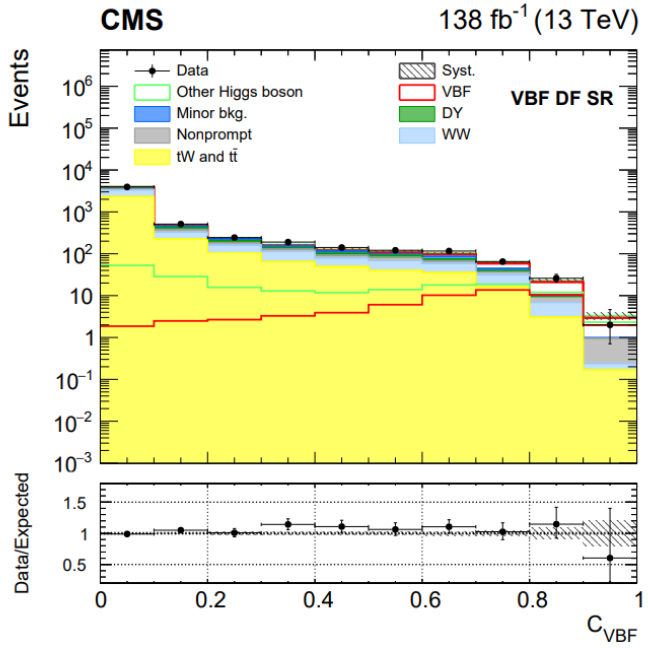
Top

WW

Deep Neural Networks (DNN) to discriminate the signal from the main background process



Used for both event classification and signal extraction



$H \rightarrow WW$ - Uncertainties

Uncertainty source	$\Delta\mu/\mu$	$\Delta\mu_{\mathrm{ggH}}/\mu_{\mathrm{ggH}}$	$\Delta\mu_{\mathrm{qqH}}/\mu_{\mathrm{qqH}}$	$\Delta\mu_{\mathrm{WH}}/\mu_{\mathrm{WH}}$	$\Delta\mu_{\mathrm{ZH}}/\mu_{\mathrm{ZH}}$
Theory (signal)	4%	5%	13%	2%	$< 1\%$
Theory (background)	3%	3%	2%	4%	5%
Fake lepton rate	2%	2%	9%	15%	4%
Integrated luminosity	2%	2%	2%	2%	3%
b-tagging	2%	2%	3%	$< 1\%$	2%
Lepton efficiency	3%	4%	2%	1%	4%
Jet energy scale	1%	$< 1\%$	2%	$< 1\%$	3%
Jet energy resolution	$< 1\%$	1%	$< 1\%$	$< 1\%$	3%
$p_{\mathrm{T}}^{\mathrm{miss}}$ scale	$< 1\%$	1%	$< 1\%$	2%	2%
PDF	1%	2%	$< 1\%$	$< 1\%$	2%
Parton shower	$< 1\%$	2%	$< 1\%$	1%	1%
Backg. norm.	3%	4%	6%	4%	6%
Stat. uncertainty	5%	6%	28%	21%	31%
Syst. uncertainty	9%	10%	23%	19%	11%
Total uncertainty	10%	11%	36%	29%	33%

$\Delta_{syst} > \Delta_{stat}$

$\Delta_{syst} \simeq \Delta_{stat}$

$\Delta_{syst} < \Delta_{stat}$

$H \to \gamma\gamma$ - Strategy

Fiducial phase space

$p_T^{\gamma_1}/m_{\gamma\gamma} > 1/3$
$p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$
$|\eta^\gamma| < 2.5$
$\mathcal{I}^\gamma_{\text{gen}} < 10\,\text{GeV}$

Total hadronic energy within $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ from the photon → mimics the reco level photon ID MVA

1 jet

$p_T^j > 30\,\text{GeV}$
$|\eta^j| < 2.5$

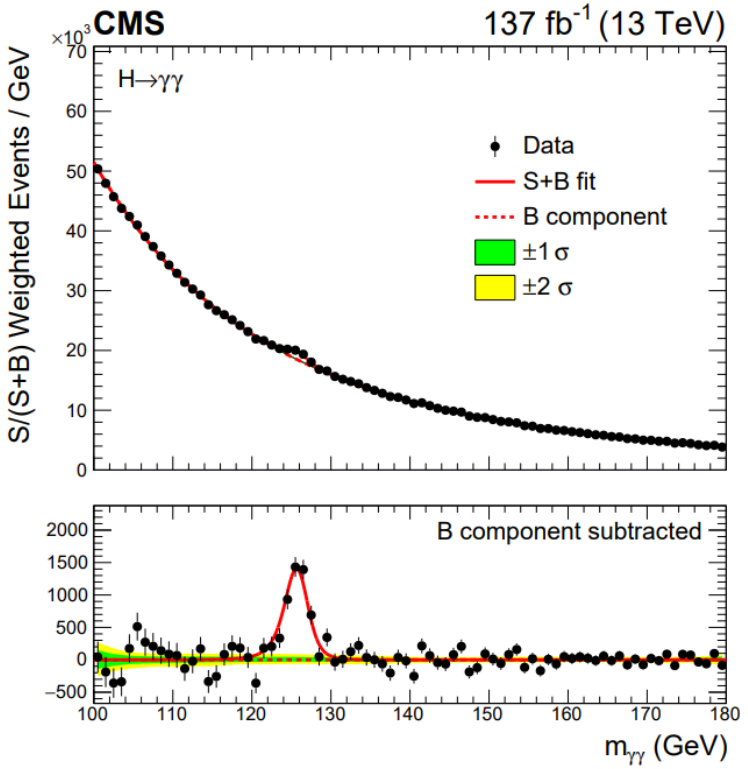
2 jet

$p_T^j > 30\,\text{GeV}$
$|\eta^j| < 4.7$

+ VBF like

$\Delta\eta^{jj} > 3.5$
$m^{jj} > 200\,\text{GeV}$

The $m_{\gamma\gamma}$ *distribution after weighted combination of all categories*



- At reconstructed level, events are categorized in bins of the decorrelated relative mass resolution estimator (σ_m^D)

- Signal extraction through a fit to the diphoton invariant mass spectrum