STXS and differential Higgs boson cross section measurements at CMS

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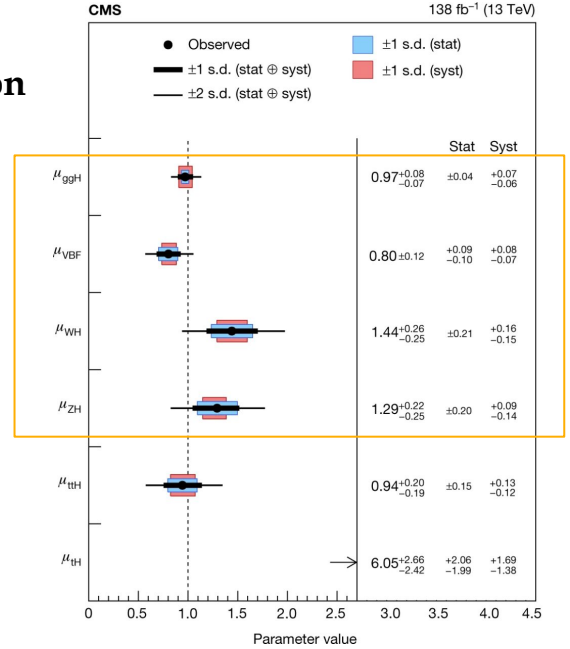
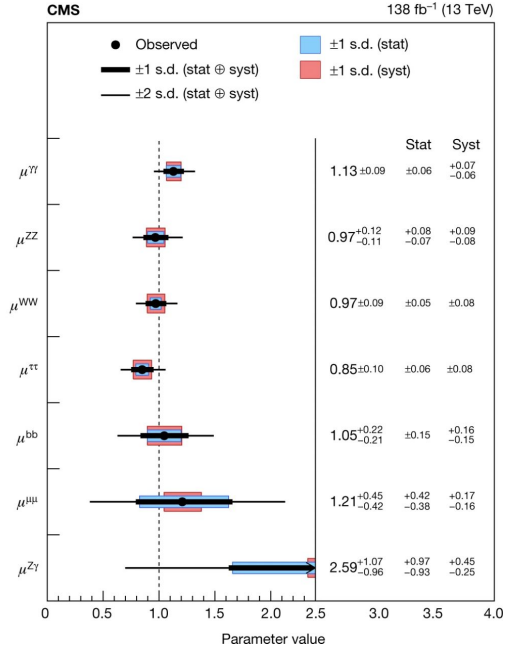
Introduction

- The **Higgs boson discovery** has marked the **LHC Run 1**
- **LHC Run 2 and 3** are the eras of **precision measurements** of the Higgs boson
- A wide variety of final state has been explored
  - Each channel probes a different phase space and brings complementary information
- All main production modes have been measured
  - Significance of 5σ or larger





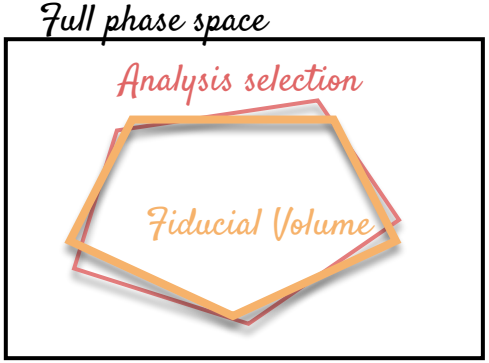
"A portrait of the Higgs boson by the CMS experiment ten years after the discovery", Nature 607, 60-68(2022)

Fiducial and differential measurements

- Fiducial differential measurements play a key role
  - The most model-independent way to measure Higgs boson production cross section
  - Sensitive to BSM effects

- Differential: the cross section is measured in bins of some observables (p_T^H , #jets, …)
  - Provides more information than inclusive measurements

- Fiducial: the extrapolation of the result is limited to a restricted phase space defined close as possible to the experimental selection
  - Minimizes the theoretical assumption for extrapolation to full phase space
  - Easy comparison with different theories

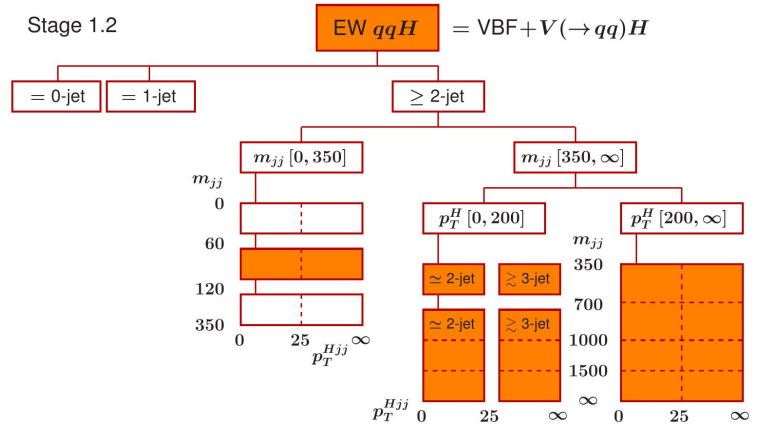


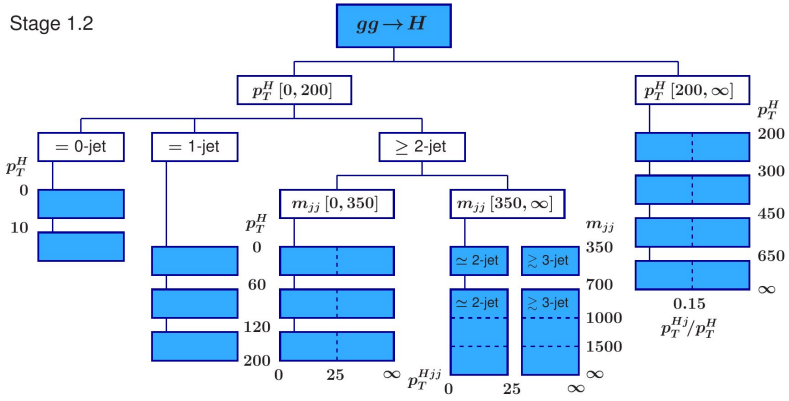
STXS measurements

- *Simplified Template Cross Sections* (**STXS**) framework
  - Complementary to differential measurements

- The cross section is measured in **pre-defined template bins per production mode**
  - Reduces theoretical uncertainties
  - Enhances sensitivity to possible deviations from the SM

- No fiducial phase space defined ($|y_H| < 2.5$)
  - Larger extrapolation uncertainties but possibility to combine different decay modes





Some recent highlights from CMS

Decay channel	Data set	Results
H→WW	Full Run 2	Eur. Phys. J. C 83 (2023) 667
H→ττ	Full Run 2	CMS-HIG-21-017 (**sub. in PLB**)
H→γγ	Full Run 2 Run 3 (2022)	JHEP 07 (2023) 091 CMS-PAS-HIG-23-014
H→ZZ	Full Run 2 Run 3 (2022)	JHEP 08 (2023) 040 CMS-PAS-HIG-24-013
H→bb	Full Run 2 Full Run 2 Full Run 2	(STXS VH(bb)) Phys. Rev. D 109 (2024) 092011 (Boosted Hbb) CMS-PAS-HIG-21-020 (**sub. in JHEP**) (ttH(bb)) CMS-PAS-HIG-19-011
H→cc	Full Run 2	Phys. Rev. Lett. 131 (2023) 061801
Combination & Interpretation	Full Run 2 in process	

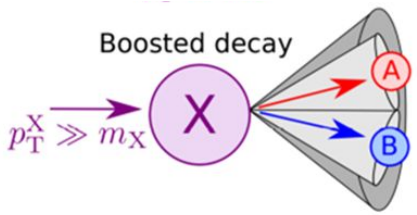
New for ICHEP2024

Covered in this talk

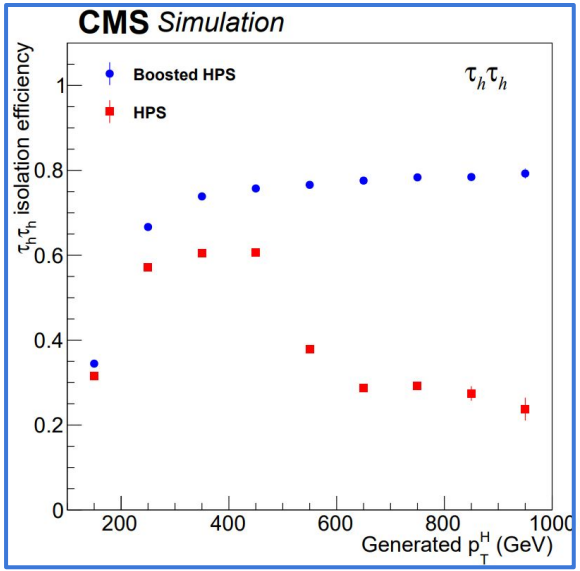
Boosted H→ττ

Overview

- Full Run 2 *fiducial* measurement targeting the production of a **boosted Higgs boson** $p_T^H > 250$ GeV
  - First H→ττ measurement in a boosted regime
  - Test BSM effects to which inclusive measurements could be insensitive, especially *Higgs boson couplings with massive particle*



- τ leptons are produced spatially closed with their decay products overlapping
  - Dedicated algorithm is developed to reconstruct the boosted τ leptons



- Four final states targeted: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$

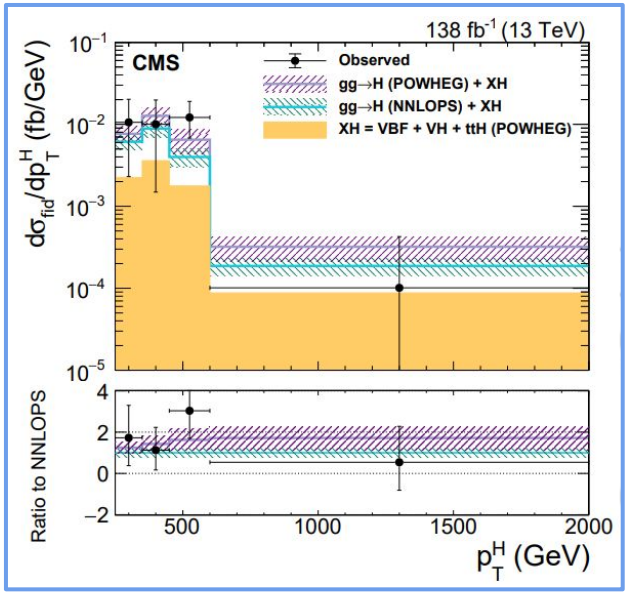
- **Multiclass NN** used to discriminate signal from major backgrounds in each final state

Boosted H→ττ

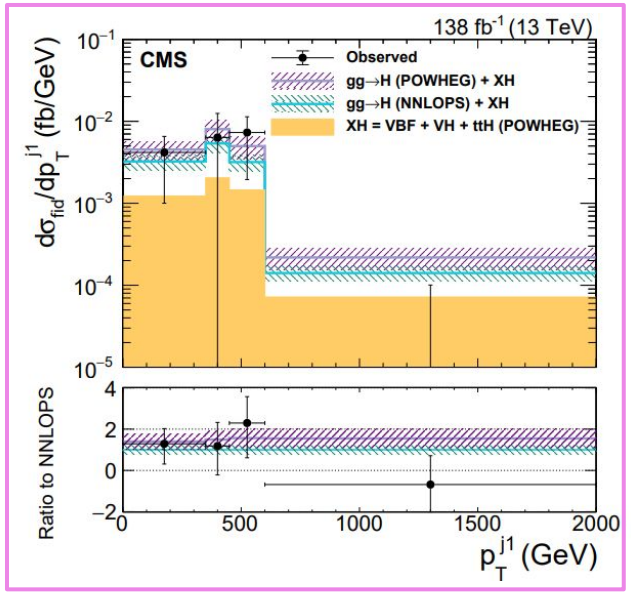
Results

- Cross section of the **four main production modes** measured in bins of p_T^H and p_T^{j1}
- Results dominated by statistical uncertainty, especially in the highest-p_T bins
- Leading systematic uncertainty in the boosted τ_h candidate identification

Higgs boson transverse momentum



Leading jet transverse momentum

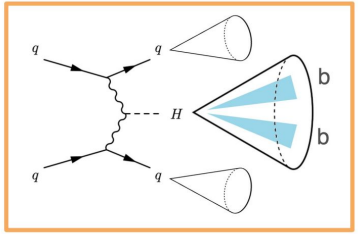


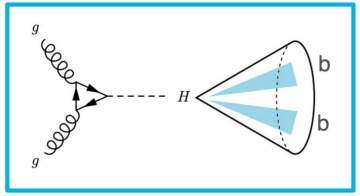
- No significant deviations with respect to the SM predictions, **probed large-p_T phase space extended to region beyond 600 GeV**

Boosted H→bb

Overview

- Search for a **boosted Higgs boson** $p_T^H > 450$ GeV via *vector boson fusion* (VBF) and *gluon gluon fusion* (ggH) using the **full Run 2 data set**
  - ggH becomes less dominant, direct probe to Higgs bosons couplings to vector bosons

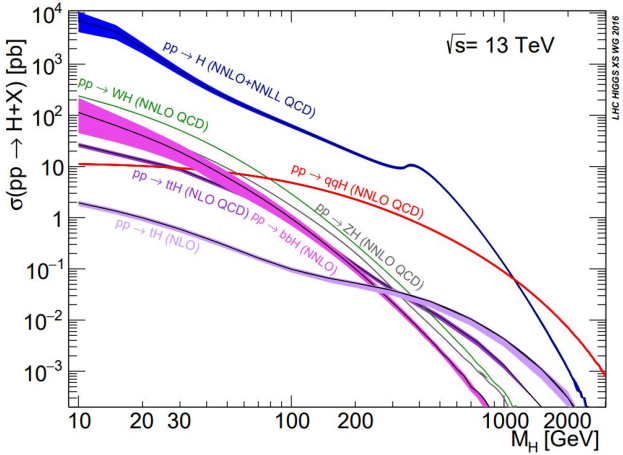




- Higgs boson identified by two-prong substructure and using a multivariate jet tagger [1]

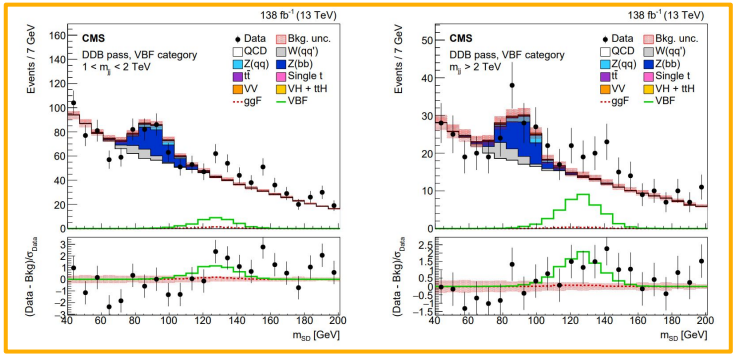
- VBF-jets are used to distinguish VBF from ggH production

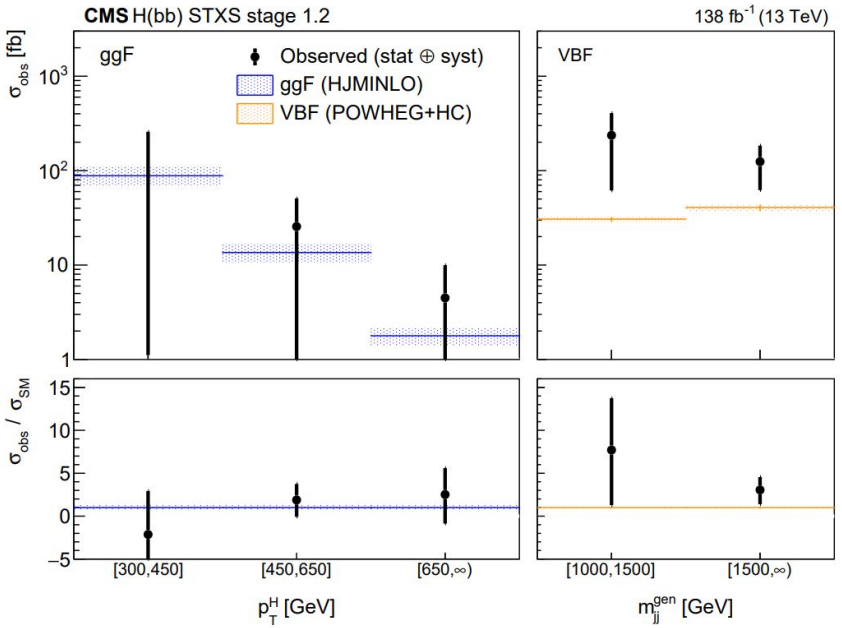
- Signal extraction using soft-drop mass of Higgs-jets



Boosted H→bb

Results





- VBF and ggH cross sections are measured in bins of m_{jj} of VBF-jets and p_T^H respectively

- Largest uncertainty:
  - Uncertainty on the background estimation
  - Theory uncertainty on Higgs boson production
  - Uncertainty on the jet tagger selection

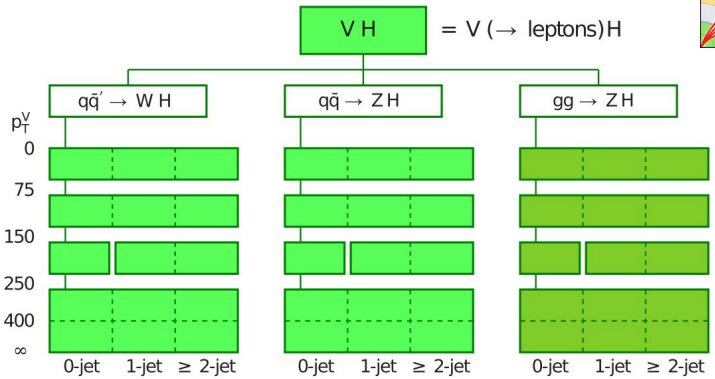
STXS H→bb

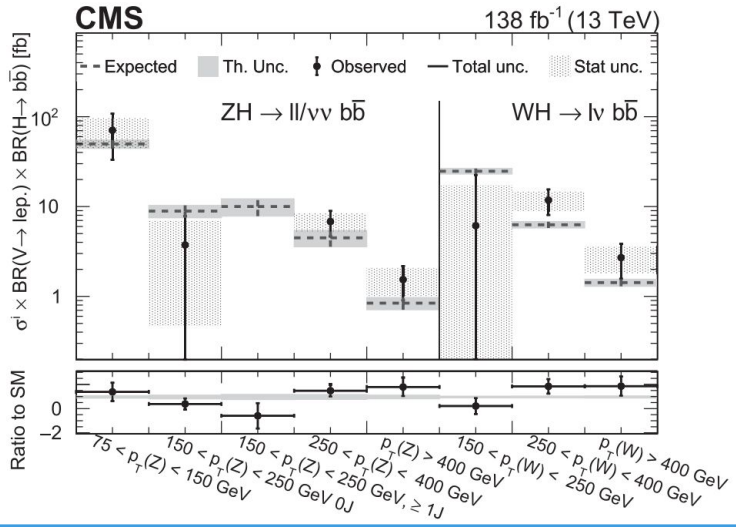
Overview

- Full Run 2 measurement targeting the Higgs boson production via *vector boson associated production* (VH) using **full Run 2 data**
  - 3 analysis channel based on the decay of the vector bosons

- Performed within the **STXS framework**

- Dedicated category**:**
  - **boosted topology**: large-radius b-jet, BDT used for signal extraction
  - **resolved topology**: 2 b-tagged jets, DNN used for signal extraction





First Run 3 results at √s=13.6 TeV

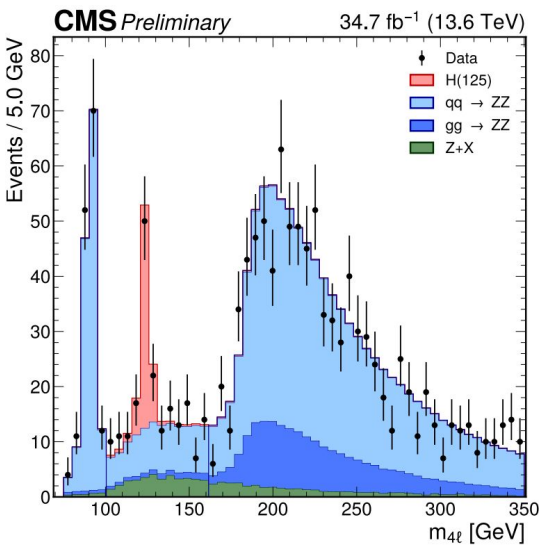
2022 data set (34.7 fb^{-1})

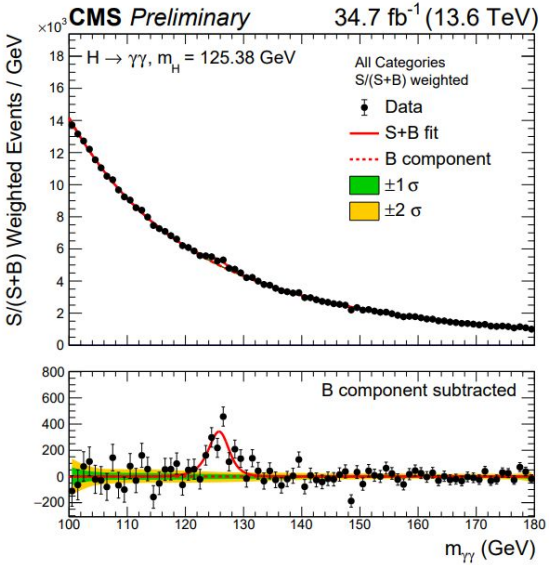
H→ZZ→4ℓ & H→γγ

Overview

New for ICHEP2024

- *Fiducial* measurements of the Higgs boson production cross section using **2022 data** (34.7 fb^{-1}) at **$\sqrt{s}$ = 13.6 TeV**
- Low BRs but clean final state topology
- Quoted both inclusive and **differential cross sections**





More details on the analysis strategy in Jan Lukas' talk

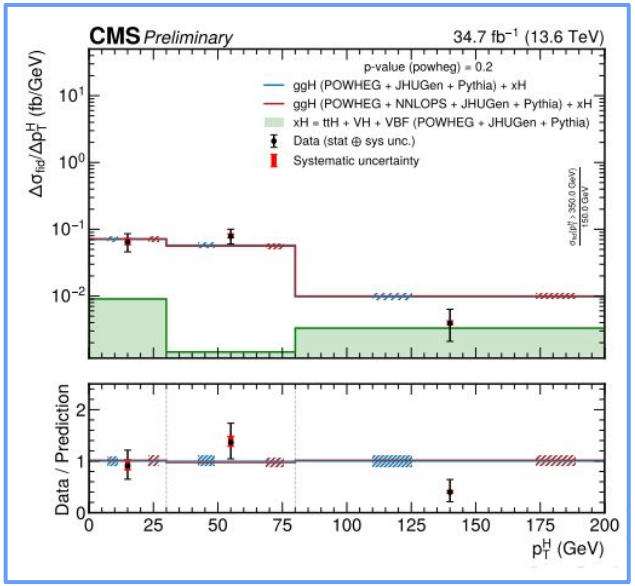
H→ZZ
Results

New for ICHEP2024

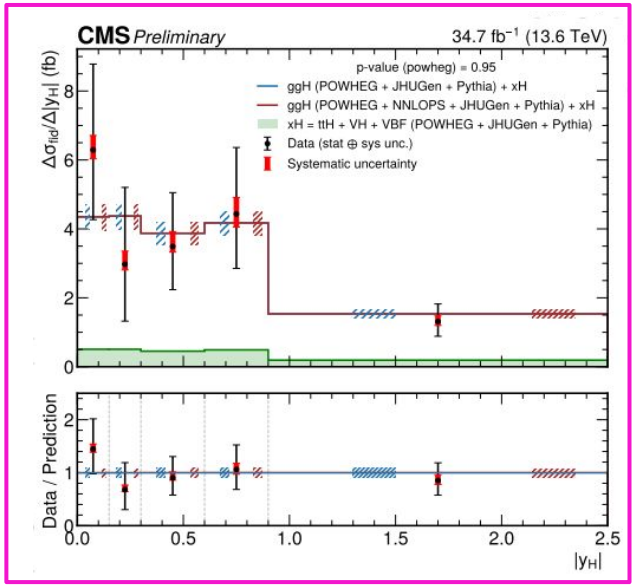
- Differential measurements as a function of p_T^H and $|y^H|$

- Differential results are **consistent with the SM prediction** and **dominated by statistical uncertainty**

Higgs boson transverse momentum



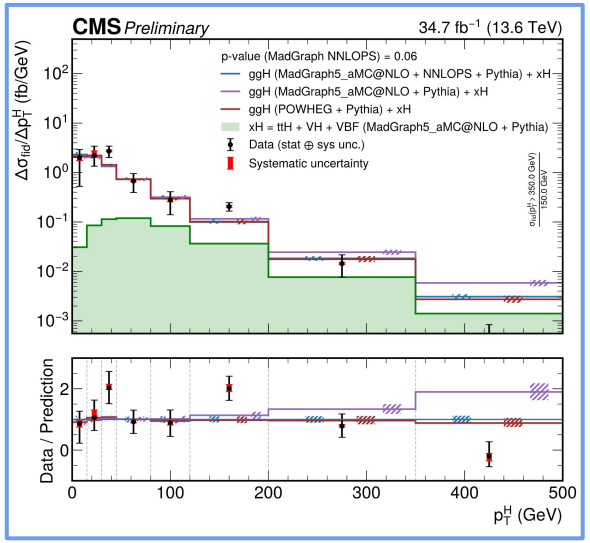
Higgs boson rapidity

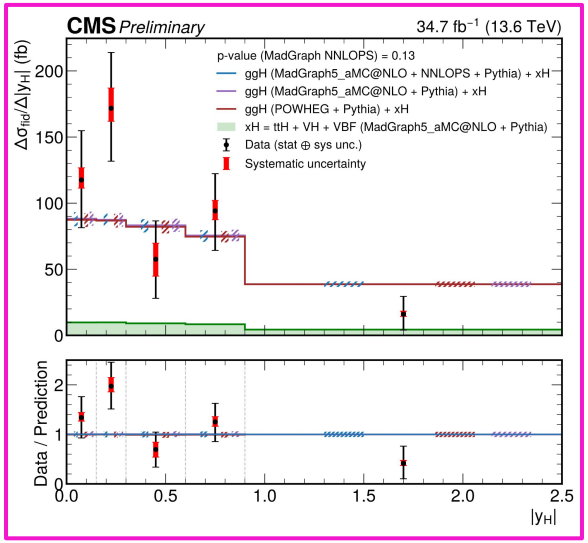


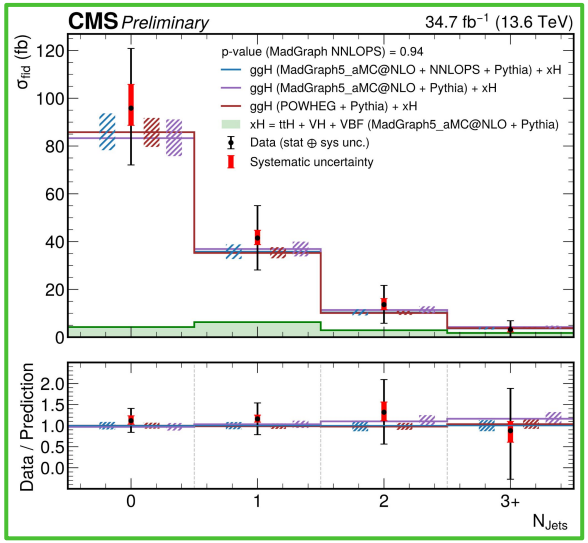
H→γγ
Results

New for ICHEP2024

- **Differential results** as a function of p_T^H, $|y^H|$ and N_{jets} **agree with the SM predictions**
- Systematics dominated by photon scale/resolution







Conclusions

- The LHC Run 2 made it possible to conduct an extensive set of fiducial and differential Higgs boson cross section measurements
- Recents results from the CMS Collaboration have been presented, including the very first measurements with Run 3 data
- So far, all measurements are consistent within the uncertainties with the Standard Model expectations
- Precision in measurements is still largely statistically limited
- The LHC Run 3 will allow even more precise measurements with more granular binning

Thanks for your attention

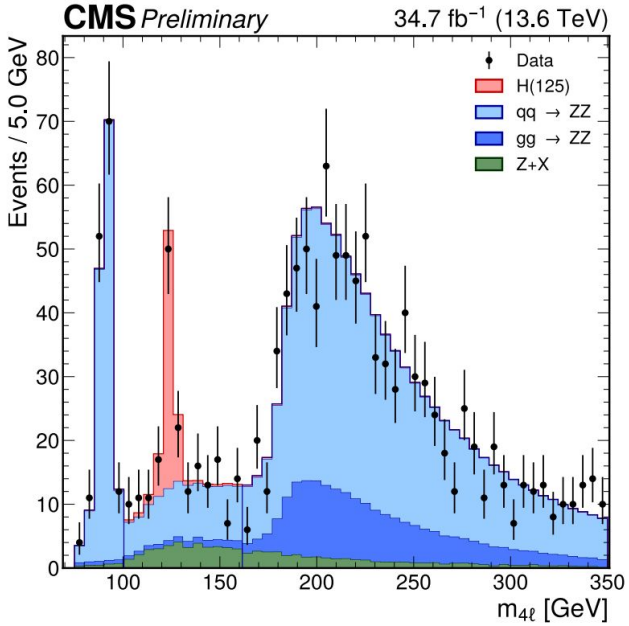
Back up

H→ZZ @ 13.6 TeV

Overview

New for ICHEP2024

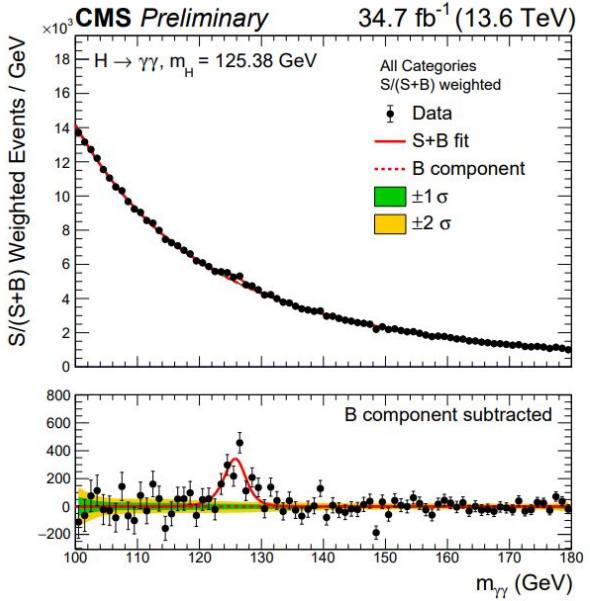
- *Fiducial* measurement in the **4 leptons final state** (H→ZZ→4l, l=e,μ) using **2022 data** (34.7 fb^{-1}) at **$\sqrt{s}$ = 13.6 TeV**
  - Low BR but clear signature, large S/B and final state kinematics fully reconstructed
- Main backgrounds are non-resonant ZZ production and Z+X
- Signal extraction through a fit to the $\mathbf{m_{4l}}$ distribution, unfolding embedded in the likelihood fit
- Inclusive results in agreement with the SM expectation



H→γγ @ 13.6 TeV
Overview

New for ICHEP2024

- *Fiducial* **differential Higgs boson cross section measurement** using **2022 data** (34.7 fb^{-1}) at **√s = 13.6 TeV**
  - Small BR but excellent energy resolution, narrow peak over a smoothly falling background
- Clean final state:
  - Signal is reconstructed by two energetic photons
  - Main backgrounds are QCD γγ production and γ+jets
- Signal extraction through a fit to the diphoton invariant mass spectrum (**$m_{\gamma\gamma}$**)
- Unfolding embedded in the likelihood fit
- Inclusive cross section statistically limited and systematic uncertainty dominated by per-photon energy resolution

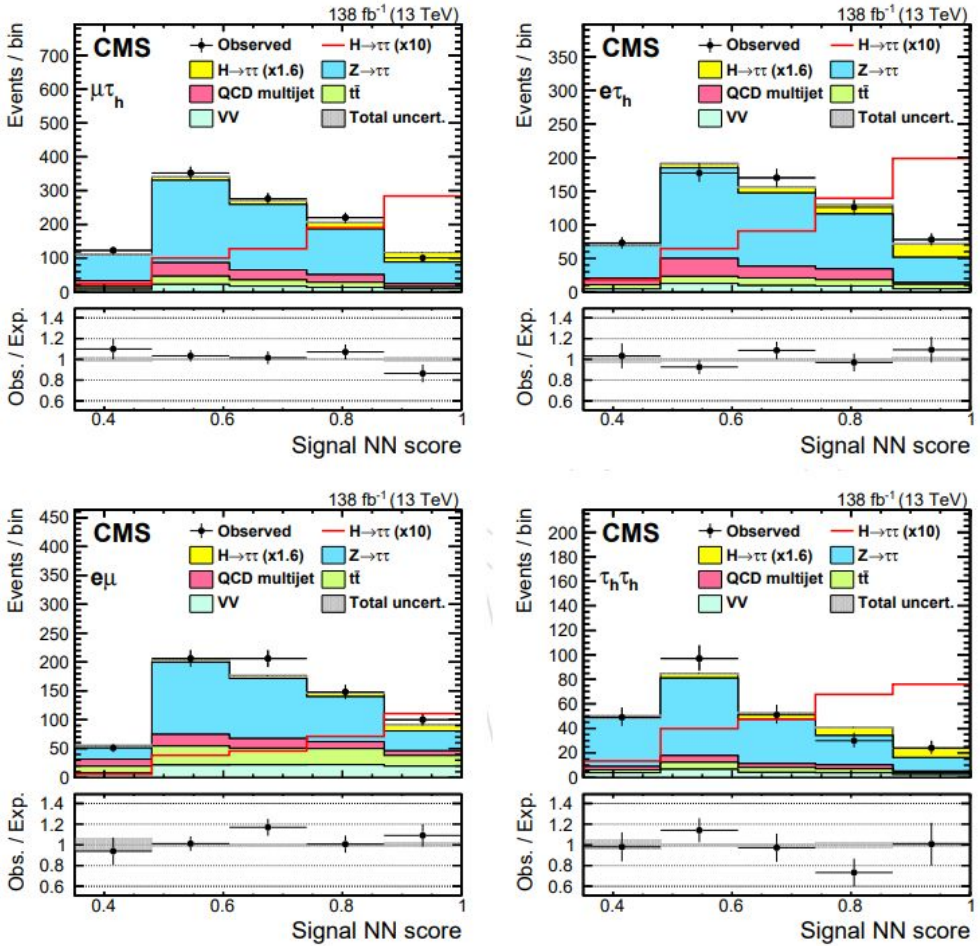


Boosted H→ττ

Multiclass NN

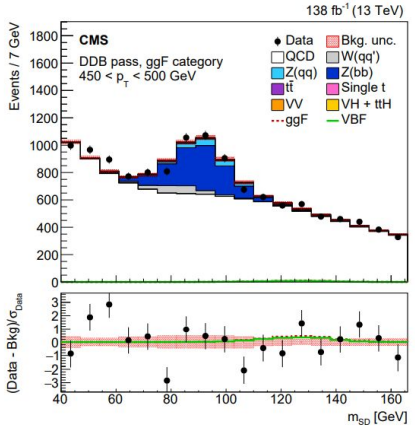
Multiclass NN that separates the signal from DY and mis-ID backgrounds

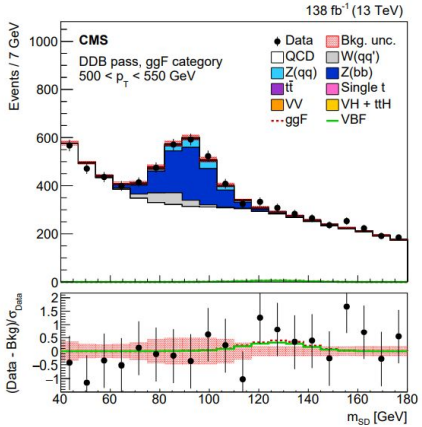
Observed and expected NN distributions in the signal-enriched region, after combining all four p_T^H bins

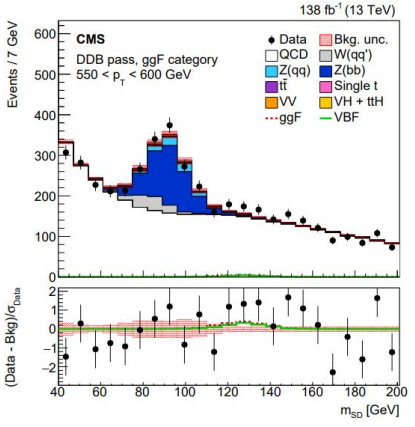


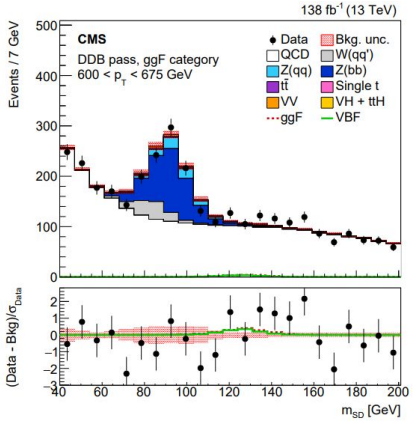
Boosted H→bb

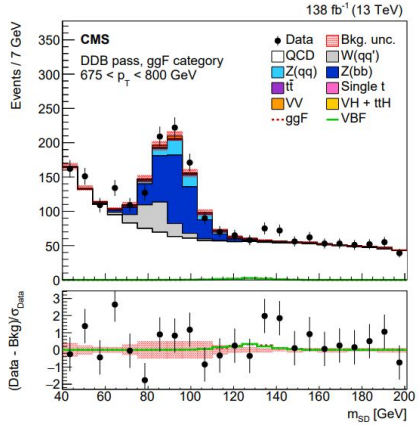
ggF category

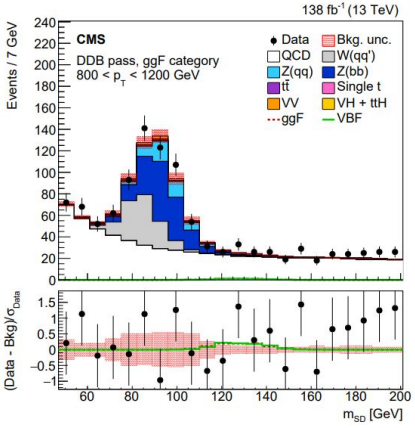






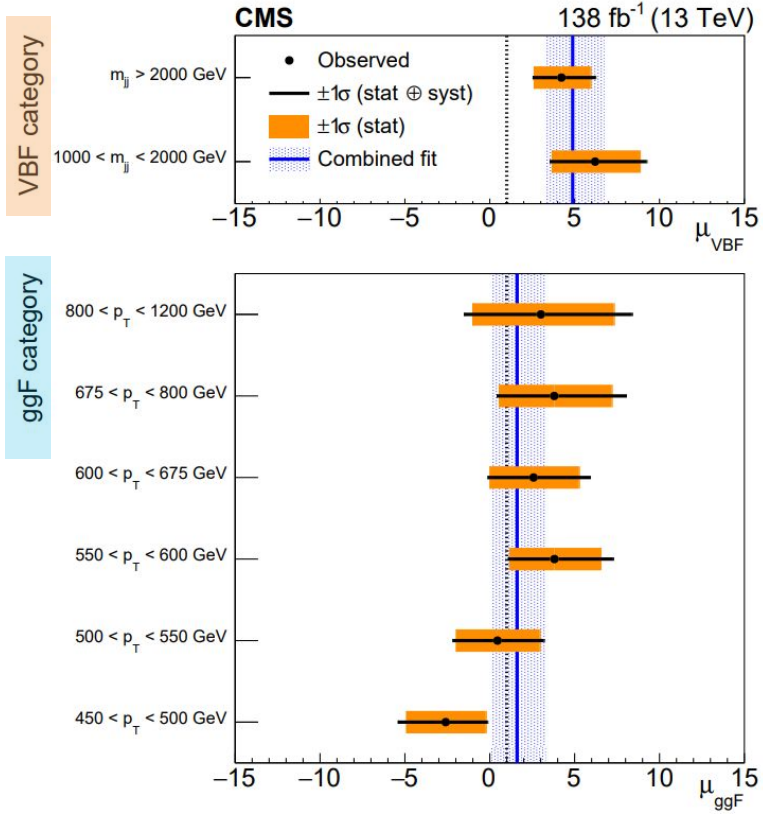




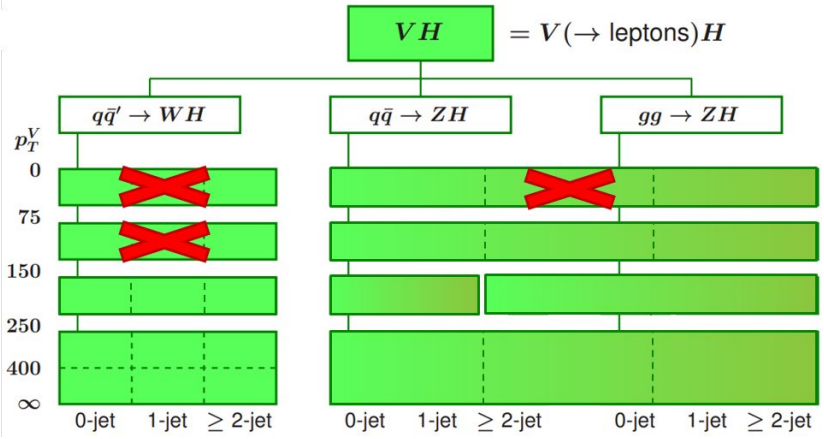


Boosted H→bb

Measured signal strength



H→bb
Strategy



- Stage 1.2 scheme with some modifications:
  - Merge *qqZH*+*ggZH* bins
  - Merge *WH* 150−250 (0*jet*+>0*jets*) bins
  - Bin with normalisation fixed to SM expectation

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

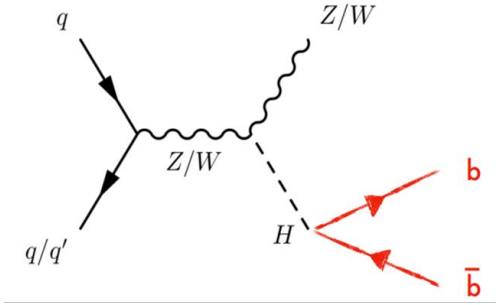
$0-lepton$				
$p_T(V)$	(0,250)		(250,400)	[400,∞)
# of additional jets	0	≥ 1		

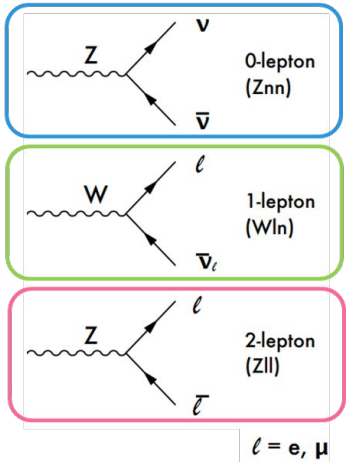
$1-lepton$			
$p_T(V)$	(0,250)	(250,400)	[400,∞)

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

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

H→bb
Strategy





	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

H→bb
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)	∈[90-150]	∉[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]	∉[90,150]	[90,150]	-
$\vec{p}_T^{miss}$	-	<60	-	-
$\Delta\phi(H,V)$	-	> 2.5	> 2.5	-

H→bb
Resolved topology

Input variables of the DNN trained in resolved SRs

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

Most discriminating variables

H→bb
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→ZZ
Overview

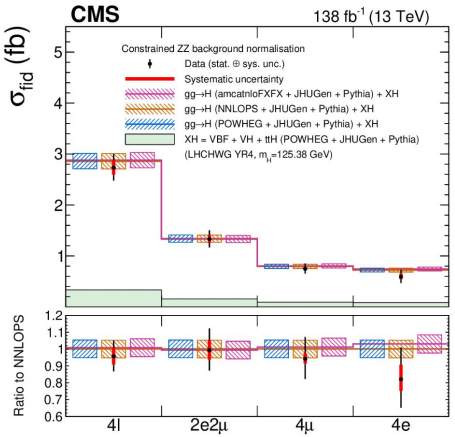
- **Full Run 2** *fiducial* measurement considering the **4 leptons final state** (H→ZZ→4l)
  - Clean final state, excellent mass resolution and large S/B

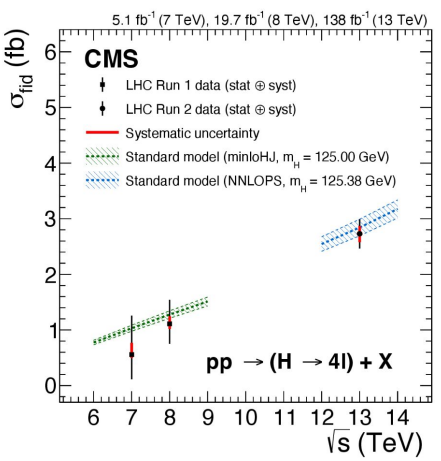
- Extend the measurement with respect to the previous Run 2 analysis

- Set of **31 observables**
  - Production and decay variables, jet related variable,..
  - **Matrix element (ME) discriminant** sensitive to anomalous couplings in the HVV vertex

For the first time!

  - Double differential results





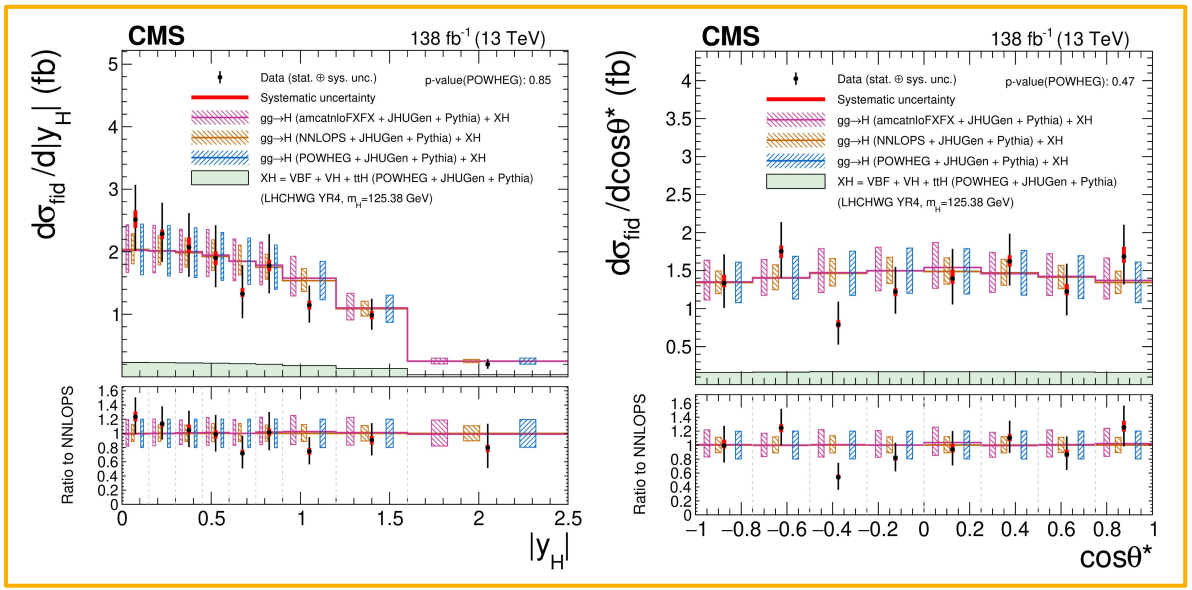
- Signal extraction through a fit to the m_{4l} distribution

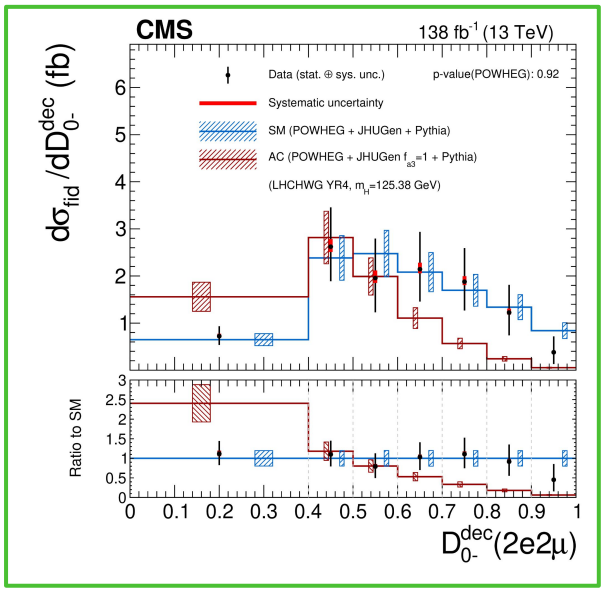
- Inclusive results in agreement with the SM expectation and measured with overall precision of 10%

H→ZZ
Results

Higgs boson kinematics

ME discriminant





- Differential results are **consistent with the SM prediction** and **dominated by statistical uncertainty**