Higgs boson fiducial differential cross section measurements at CMS

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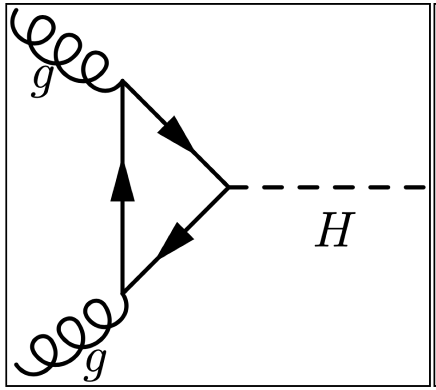
Introduction

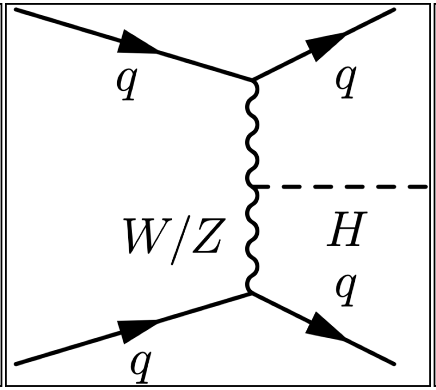
- **The crown jewel of particle physics, the Higgs boson was discovered in 2012 by the ATLAS and CMS Collaborations**
  - All of the following measurements of its properties have shown **a complete agreement** with the **Standard Model (SM)**
  - The Run 2 era of data taking allowed us to open a new chapter in our understanding of the Higgs boson with the advances made in the area of precision measurements
    - In this talk focusing on the fiducial differential cross section measurements

Gluon gluon fusion



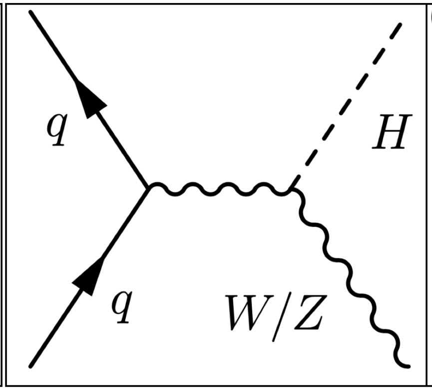
σ (ggH) = 48.6 ± 2.8 pb

Vector boson fusion



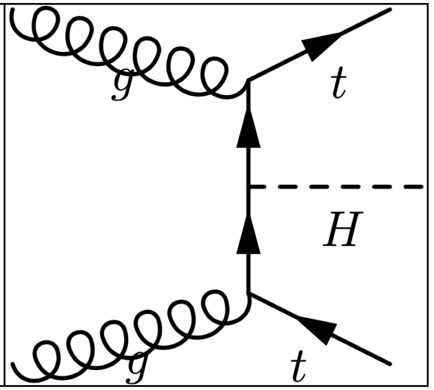
σ (VBF) = 3.78 ± 0.08 pb

Associated Higgs production with W or Z boson



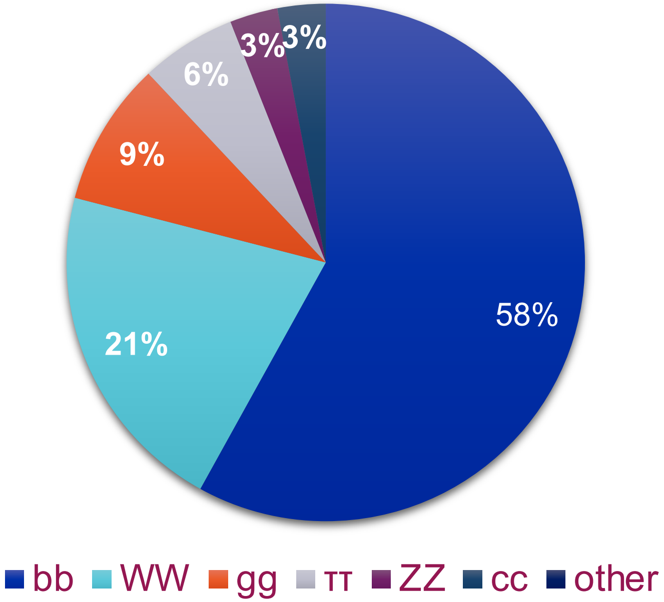
σ (WH, ZH) = 1.37 ± 0.03, 0.88 ± 0.03 pb

Associated Higgs production with a top quark pair



σ (ttH) = 0.50 ± 0.04 pb

Higgs Boson decay modes



Introduction

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  - All of the following measurements of its properties have shown **a complete agreement** with the **Standard Model (SM)**
  - The Run 2 era of data taking allowed us to open a new chapter in our understanding of the Higgs boson with the advances made in the area of precision measurements
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Measurements presented in this talk

Decay mode:	$H \rightarrow bb$	$H \rightarrow WW$	$H \rightarrow \gamma\gamma$	$H \rightarrow \tau\tau$	$H \rightarrow ZZ$
DOI/link:	Phys. Rev. D 105, 092003	JHEP 03 (2021) 003	arXiv:2208.12279 Acc. for pub. in JHEP	Phys. Rev. Lett. 128 (2022) 081805	arXiv:2305.07532 Submitted to JHEP

Introduction

- **Motivation:** Fiducial differential Higgs measurements allow us to test the SM Higgs boson properties as well as to probe for BSM contributions
  - **Fiducial region is defined to closely match the detector-level analysis and object selections**
    - Allowing for less model-independent measurements

  - A differential cross section measurement aims to quantify how the cross section of a given process varies with respect to one or more observables:
    - Usually involving $\boldsymbol{p_T^H}$, $\boldsymbol{\eta_T^H}$, the **invariant mass** of the final-state particles, etc.
    - They are providing a measure of **how the process rate changes as a function of that observable**
      - Differential cross section measurements are crucial for testing theoretical predictions
    - Allowing us to **look for new physics effects** in the **corners of the phase space**
    - **Complementary** to the **simplified template cross section** approach
- **The following measurements were performed using the complete Run 2 dataset collected by the CMS experiment**

$H \rightarrow ZZ^*$ decay mode: Introduction

- **Topology:** Focusing on three different final states: $4e, 4\mu, 2e2\mu$
  - Even though it has a small BR, this final state is well reconstruced
  - Narrow peak over a flat background
  - Looking for events containing 4 leptons (e/μ), grouped into same-flavour opposite-charge pairs to form Z candidates
- **Background processes:**
  - **Non-resonant $ZZ/Z\gamma$ production (dominant):**
    - Shape and normalization estimated from simulation
  - **$Z + jets, tt, WZ$ (subdominant):**
    - Estimated in dedicated control regions
- **Core observables:**
  - Fiducial cross sections are extracted from a fit of the observed m_{4l}
    - **Measured: $\sigma_{fid} = 2.73 \pm 0.22(\text{stat.}) \pm 0.15(syst.)$ fb**
      - Comparable uncertainties
    - **SM prediction: $\sigma_{fid}^{SM} = 2.86 \pm 0.1$ fb**

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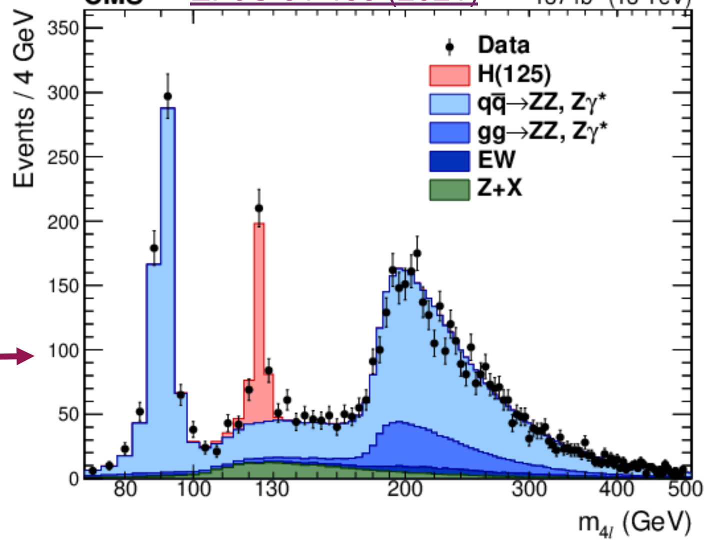
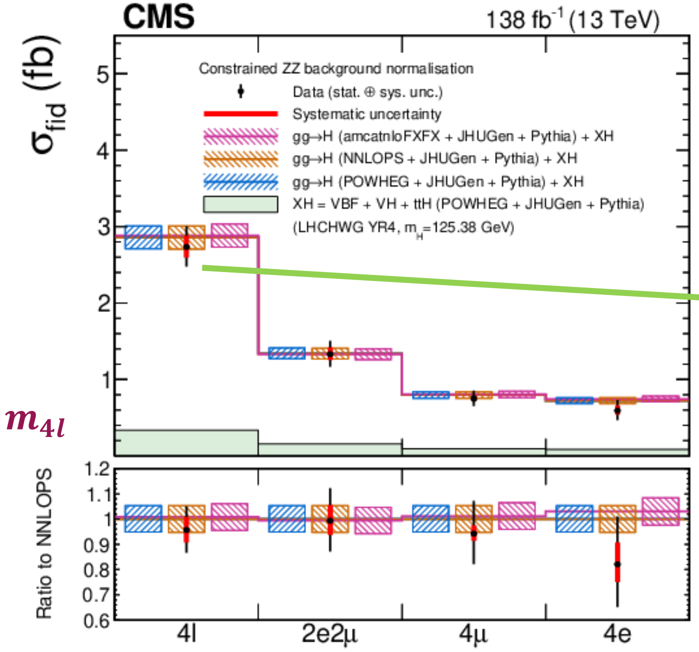
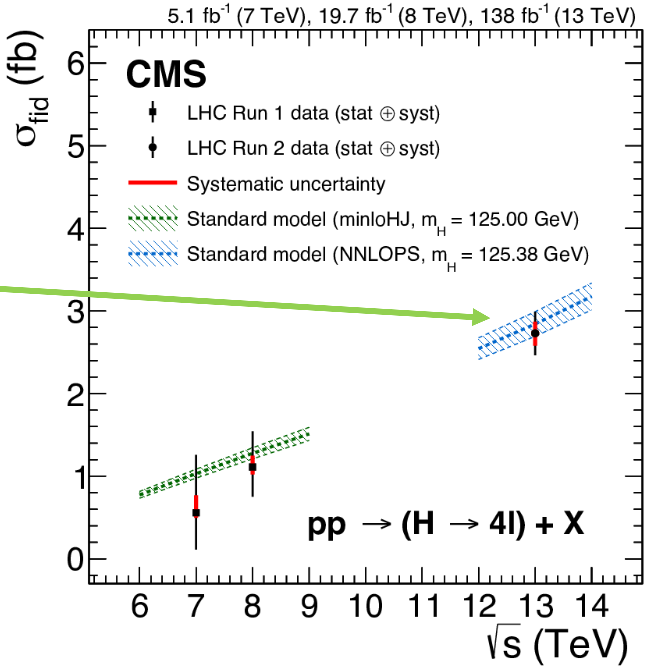


arXiv:2208.12279





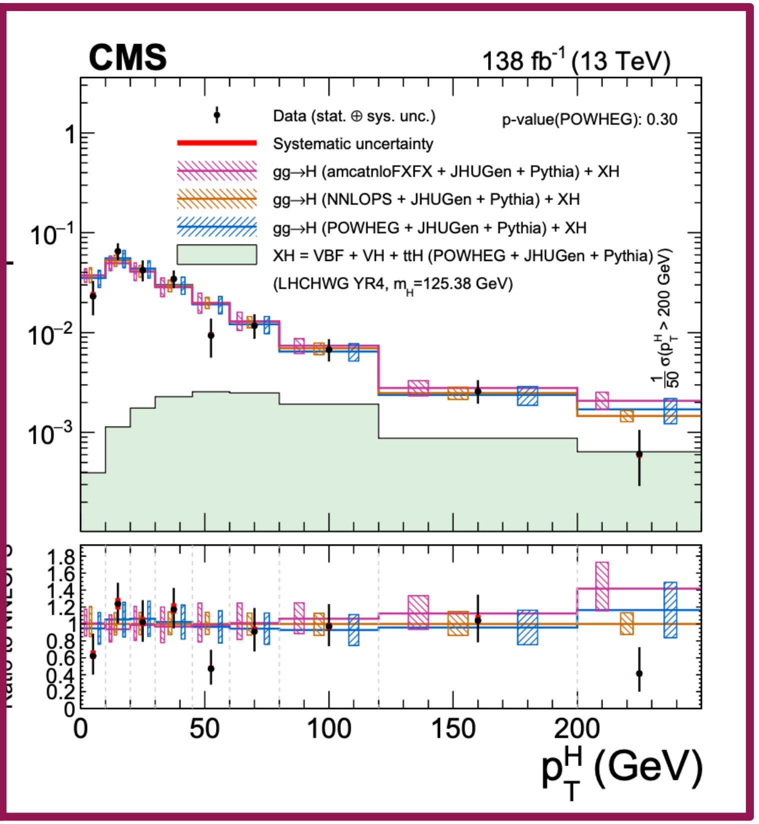
$H \rightarrow ZZ^*$ decay mode: Results

- **Differential cross sections are measured as a function of several kinematic observables sensitive to the Higgs boson production and decay to four leptons.**
  - Results are consistent with theoretical predictions from the Standard Model

Production mode targeting observables

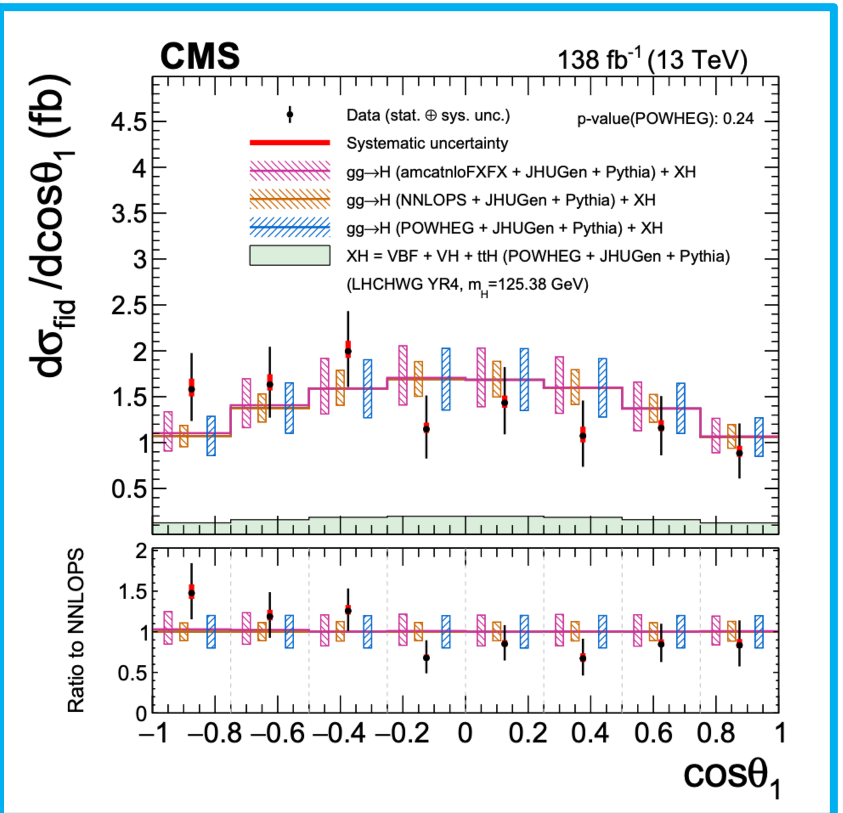
arXiv:2208.12279

Observable
m_{Z_1} (GeV)
m_{Z_2} (GeV)
$\lvert y_H \rvert$
p_T^H (GeV)
N_{jets}
p_T^H (GeV)
$p_T^{j_1}$ (GeV)
$p_T^{j_2}$ (GeV)
p_T^{Hj} (GeV)
p_T^H (GeV)
$\mathcal{T}_C^{max}$ (GeV)
p_T^H (GeV)



Decay mode targeting observables

Observable
$\cos\theta^*$
$\cos\theta_1$, $\cos\theta_2$
Φ, Φ_1
m_{Z_1}
m_{Z_2}
$\mathcal{D}_{0-}^{dec}$
$\mathcal{D}_{0h+}^{dec}$
$\mathcal{D}_{\Lambda1}^{dec}$
$\mathcal{D}_{\Lambda1}^{Z\gamma,dec}$
$\mathcal{D}_{CP}^{dec}$
$\mathcal{D}_{int}^{dec}$

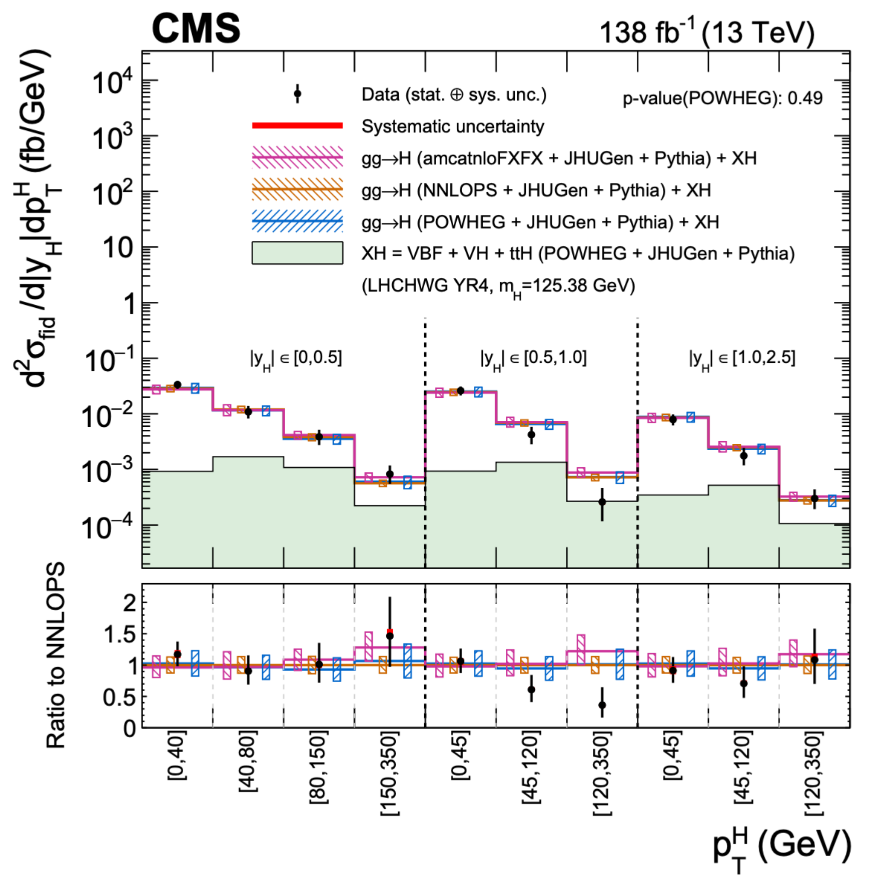


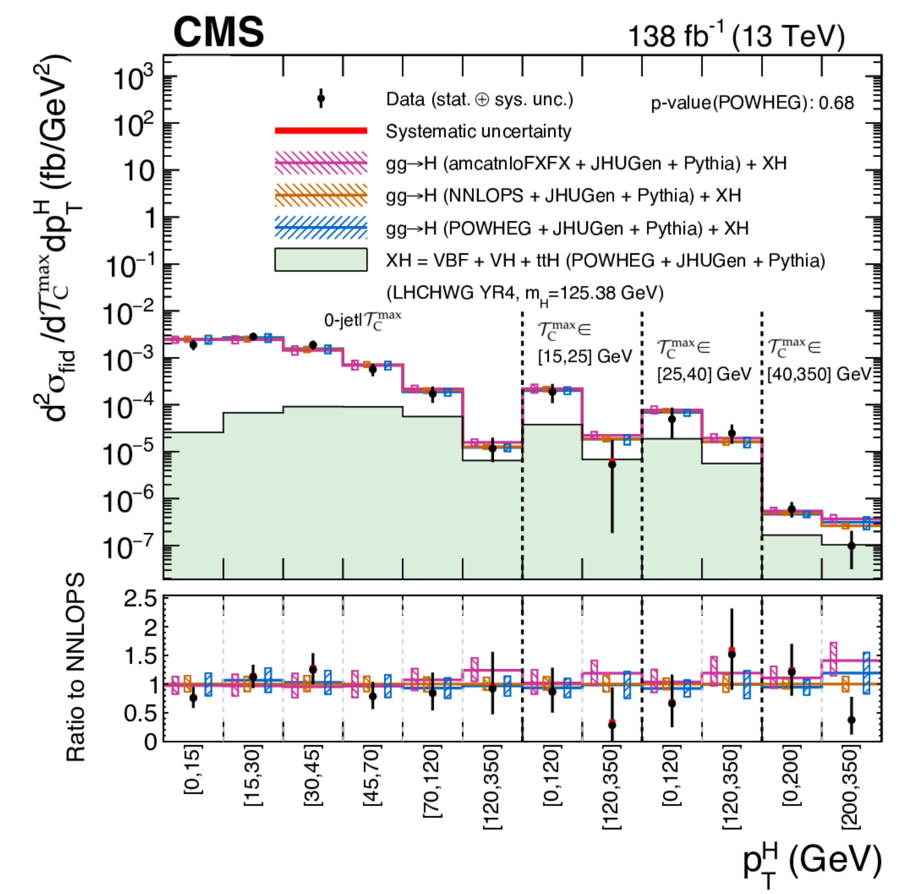
$H \to ZZ^*$ decay mode: Results

- **A set of double differential measurements is also performed**
  - Maximizing the coverage and separation of the different phase space regions

arXiv:2208.12279

Observable
m_{Z_1} (GeV) m_{Z_2} (GeV)
$\lvert y_H \rvert$ p_T^H (GeV)
N_{jets} p_T^H (GeV)
$p_T^{j_1}$ (GeV) $p_T^{j_2}$ (GeV)
p_T^{Hj} (GeV) p_T^H (GeV)
$\mathcal{T}_C^{max}$ (GeV) p_T^H (GeV)

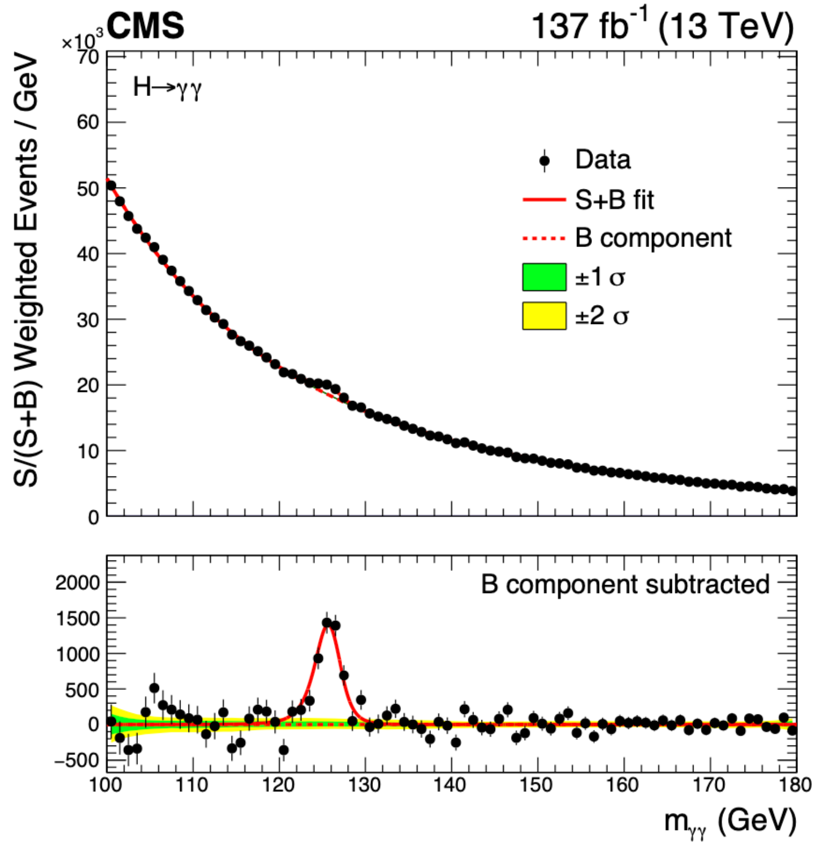




$H \to \gamma\gamma$ decay mode: Introduction

arXiv:2208.12279

- **Topology:** Two reconstructed photons represent a clean signature that overcomes the small BR of ~0.23%
  - High precision of the diphoton invariant mass reconstruction
  - Narrow peak over a smoothly falling background

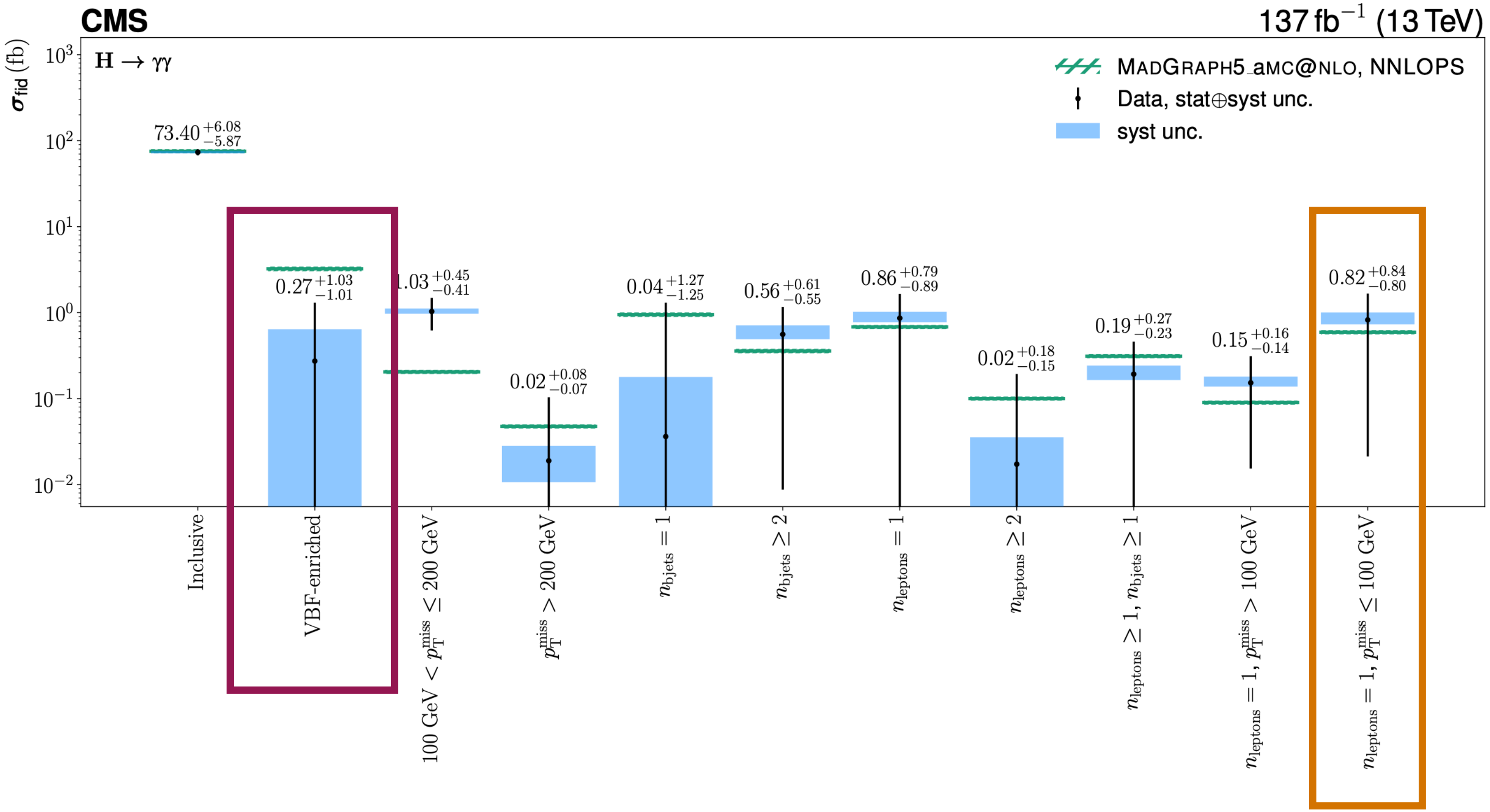


- **Background processes:**
  - **QCD diphoton production (dominant):**
  - **γ + *jets*, dijet events - misidentified as photons (subdominant):**
    - Normalisation and invariant mass shape are estimated from data

- **Total fiducial cross section:**
  - **Measured:** $\sigma_{fid} = 73.4^{+6.1}_{-5.3}(stat)^{+2.4}_{-2.2}\,(syst.)\mathrm{fb}$
  - **SM prediction:** $\sigma^{SM}_{fid} = 75.4 \pm 4.1\ \mathrm{fb}$
  - The uncertainty is **dominated** by the **statistical component** of about 7%, while the systematic uncertainty amounts to about 3%

$H \to \gamma\gamma$ decay mode: Results

arXiv:2208.12279

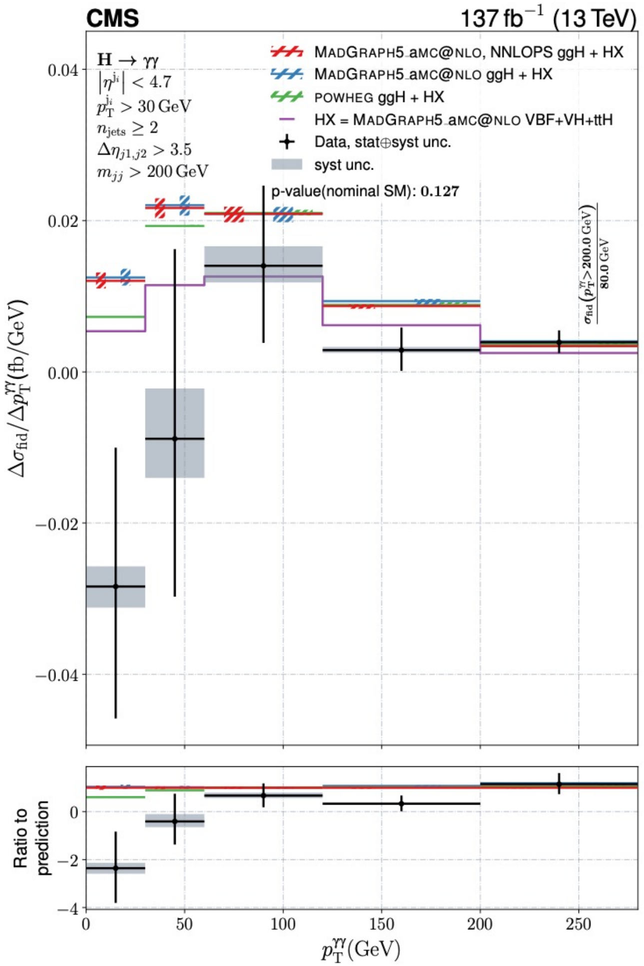


- **Cross section measurement in dedicated regions of the fiducial phase space:**
  - MadGraph5 amc@NLO + NNLOPS
- **Examples:**
  - **VBF-enriched phase space**
    - $N_{jets} \geq 1$
    - $\Delta\eta_{jj} \geq 3.5$
    - $m_{jj} \geq 200$ GeV
  - **VH-like phase space**
    - $N_{lep} \geq 1$
    - $p_{T,miss} < 100$ GeV

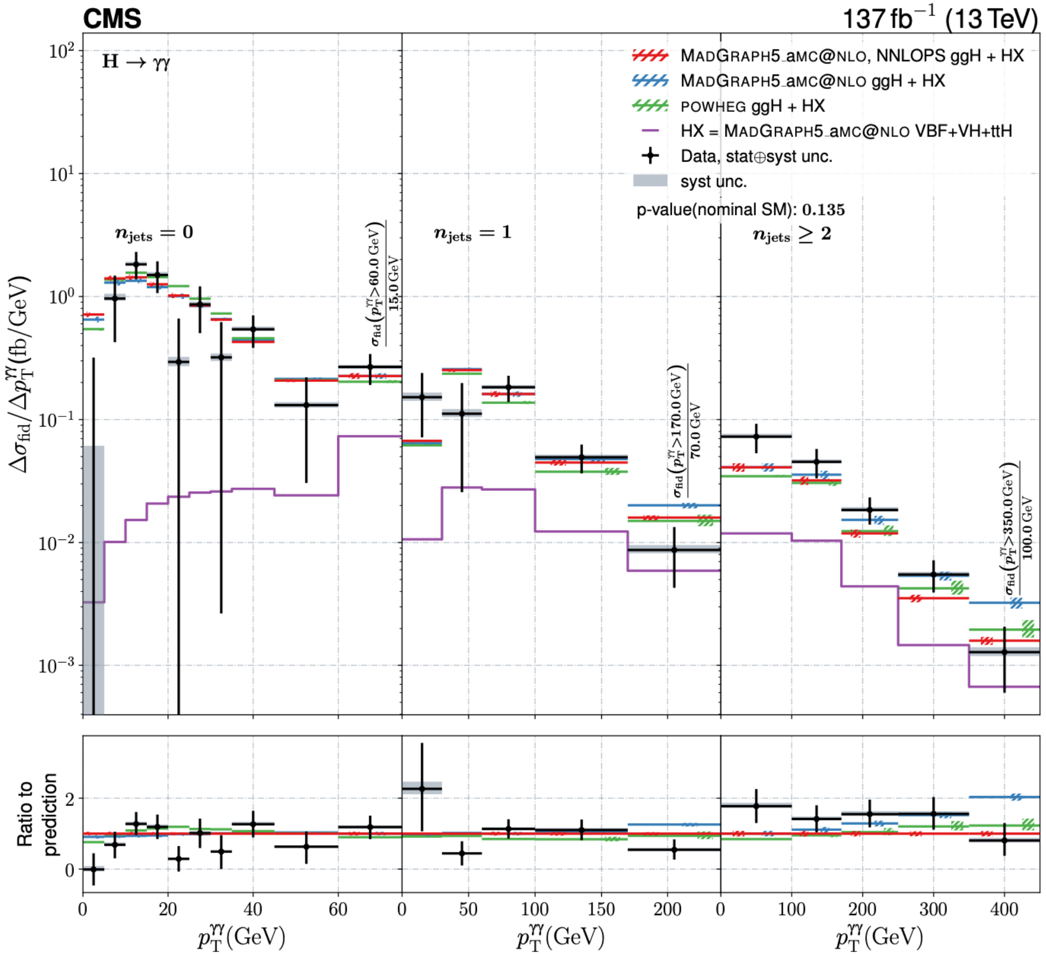
$H \rightarrow \gamma\gamma$ decay mode: Results

arXiv:2208.12279

- **VBF-enriched phase space**

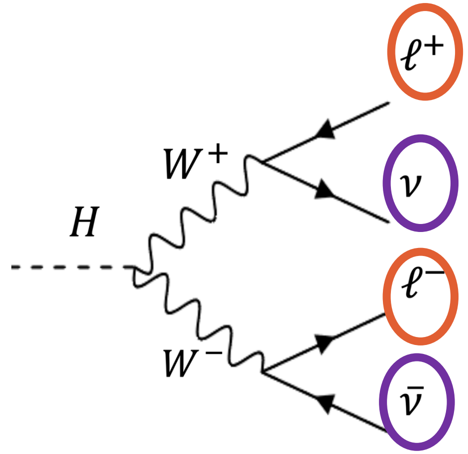


- **Double-differential fiducial measurement ($p_T^{\gamma\gamma}, n_{jets}$)**



$H \to WW$ decay mode: Introduction

- **Topology:** Focusing on scenarios with at least two isolated opposite sign leptons ($e^{+/-}\mu^{-/+}$) and $E_{T,miss}$ ($\nu\nu$)
  - $H \to W^+W^- \to e^{+/-}\mu^{-/+}\nu\bar{\nu}$ state provides the best sensitivity
  - Highest BR out of bosonic decays (second overall)



- **Background processes:**
  - **Non-resonant WW, tt, W+jets (dominant)** → Normalization obtained from data
  - **Non-prompt leptons – originating from heavy flavour hadron decays (subdominant):**
    - Normalisation measured via a control region
    - Lepton misidentification probability estimated from data
  - **Di- and tri-boson production (minor contribution)** → Estimated using simulation samples

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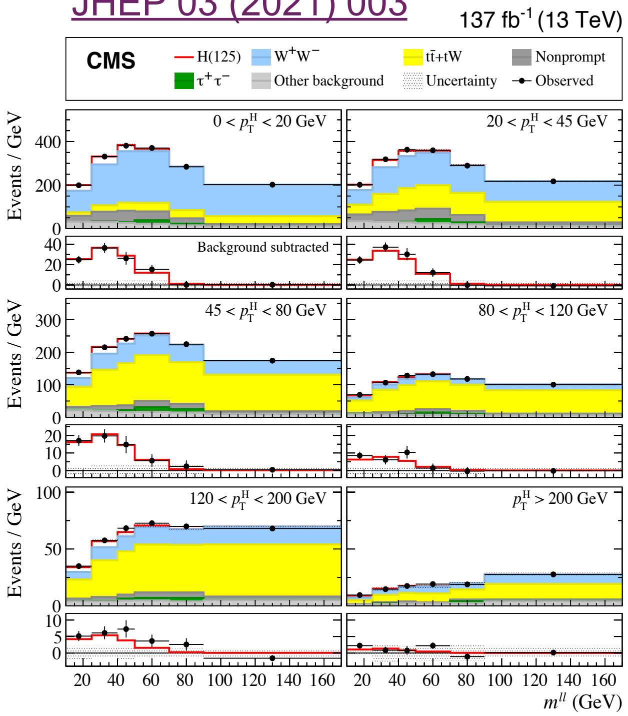
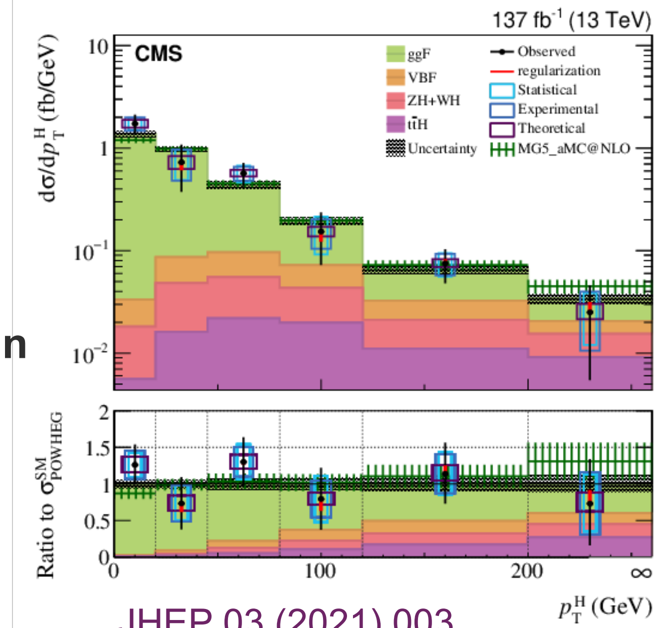


- **Core observables:**
  - The dilepton mass (m_{ll}) and transverse mass of the Higgs boson (m_T^H) are found to have a strong discrimination power against background processes

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

$H \rightarrow WW$ decay mode: Results

- **Taking all production mechanisms under consideration for the final measurement:**
  - Signal extraction is performed by fitting 2D distributions (m_{ll}, m_T^H) in **each observable bin**
  - **Dominant systematic uncertainties:**
    - Lepton reconstructions and identification, lepton momentum, jet and $E_{T,miss}$ scale
  - Measurement displayed a **good agreement with the SM prediction**
    - The largest excess was for the $N_{jets} \geq 4$, standing at **1.4 σ**



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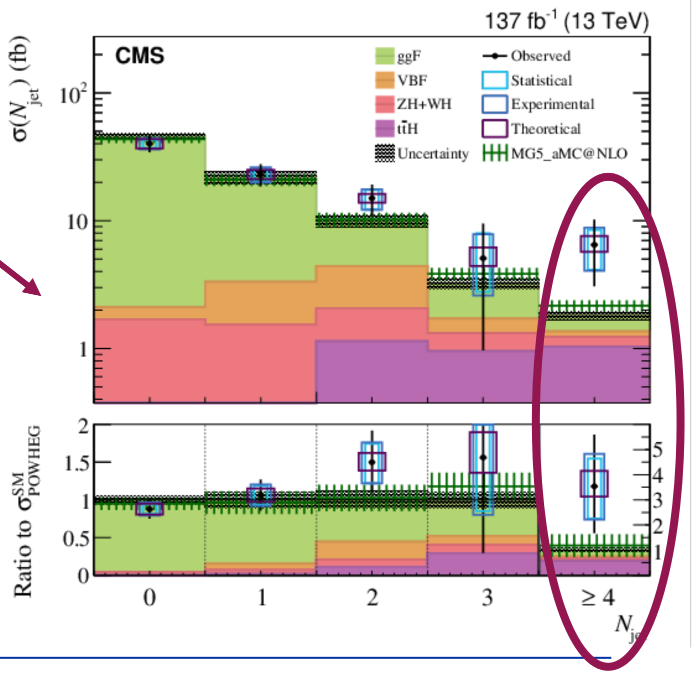
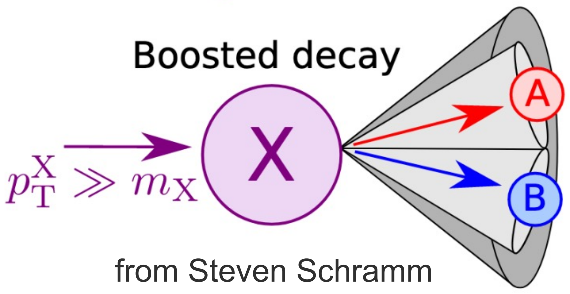


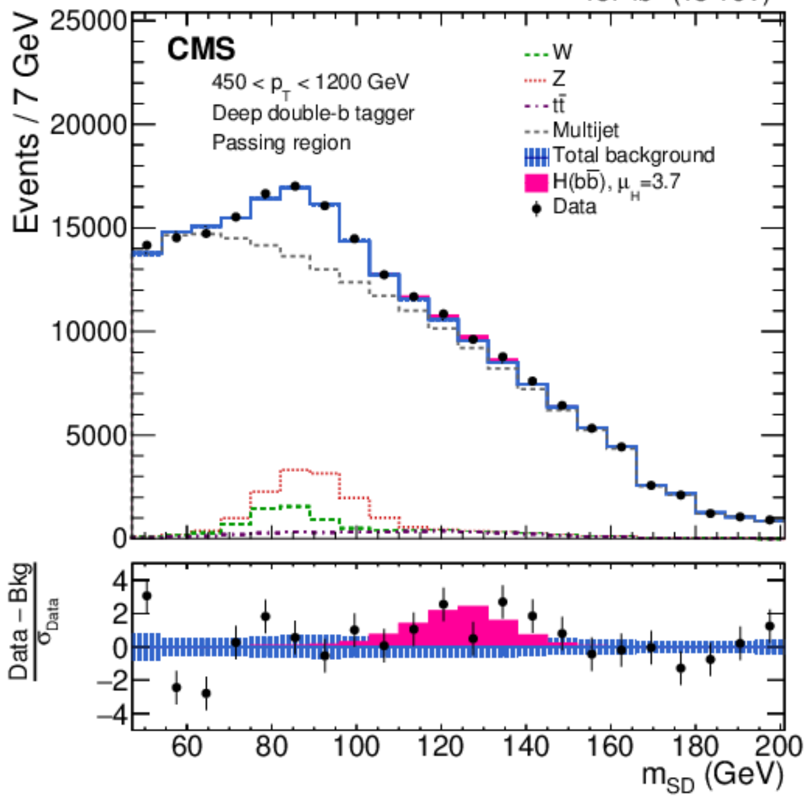
- **Total fiducial cross section is obtained by fitting P_T^H**
  - **Measured: $\sigma_{fid} = 86.5 \pm 9.5$ fb**
  - **SM prediction: $\sigma_{fid}^{SM} = 82.5 \pm 4.2$ fb**
  - $\mu^{fid} = 1.03^{+0.12}_{-0.11}\ (\pm 0.05\ (stat.)^{+0.08}_{-0.07}(theory) \pm 0.03(lumi.) \pm 0.07(exp.))$
- Dominated by systematic uncertainties

$H \to bb$ decay mode: Introduction



- **Topology: Higgs boson produced with high transverse momentum (p_T):**
  - Boosted studies of this mode provide better sensitivity due to BR($H \to b\bar{b}$) = 58% (highest)
  - Looking for a jet candidate with $p_T > 450$ GeV
    - Jet substructure (SD) and double tagger (DDBT) techniques are being utilised
- **Background processes:**
  - **QCD multijet production (dominant)** → Estimated using data
    - QCD control region is defined by inverting the b-tagging requirement
      - designed to have reduced correlation with jet mass and p_T
  - **V+jets (resonant) and tt (non-resonant)** → Estimated using simulation
  - **Di- and tri-boson production, ttV**→ Estimated using simulation samples and found to be negligible
- **Core observables:**
  - Signal is extracted by fitting the jet mass (m_{SD}) observable

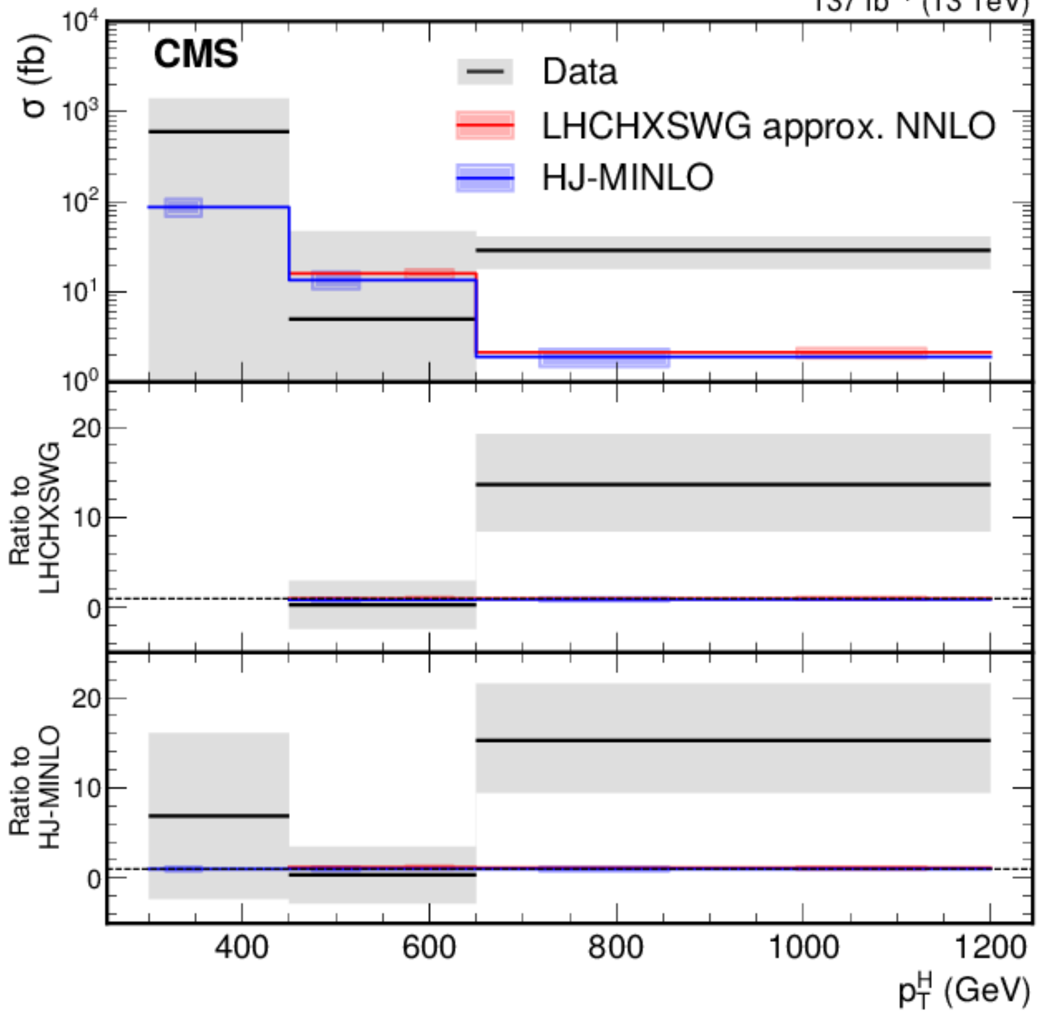
Phys. Rev. D 105, 092003



$H \rightarrow bb$ decay mode: Results

- **The approach taken for the extraction of the differential cross section:**
  - Focusing on **ggH** production mode, while other modes are treated as background processes
    - Predictions are taken from HJ-MINLO and compared to NNLO calculations from LHCHXSWG
    - Statistically dominant uncertainty, followed by jet systematic uncertainty

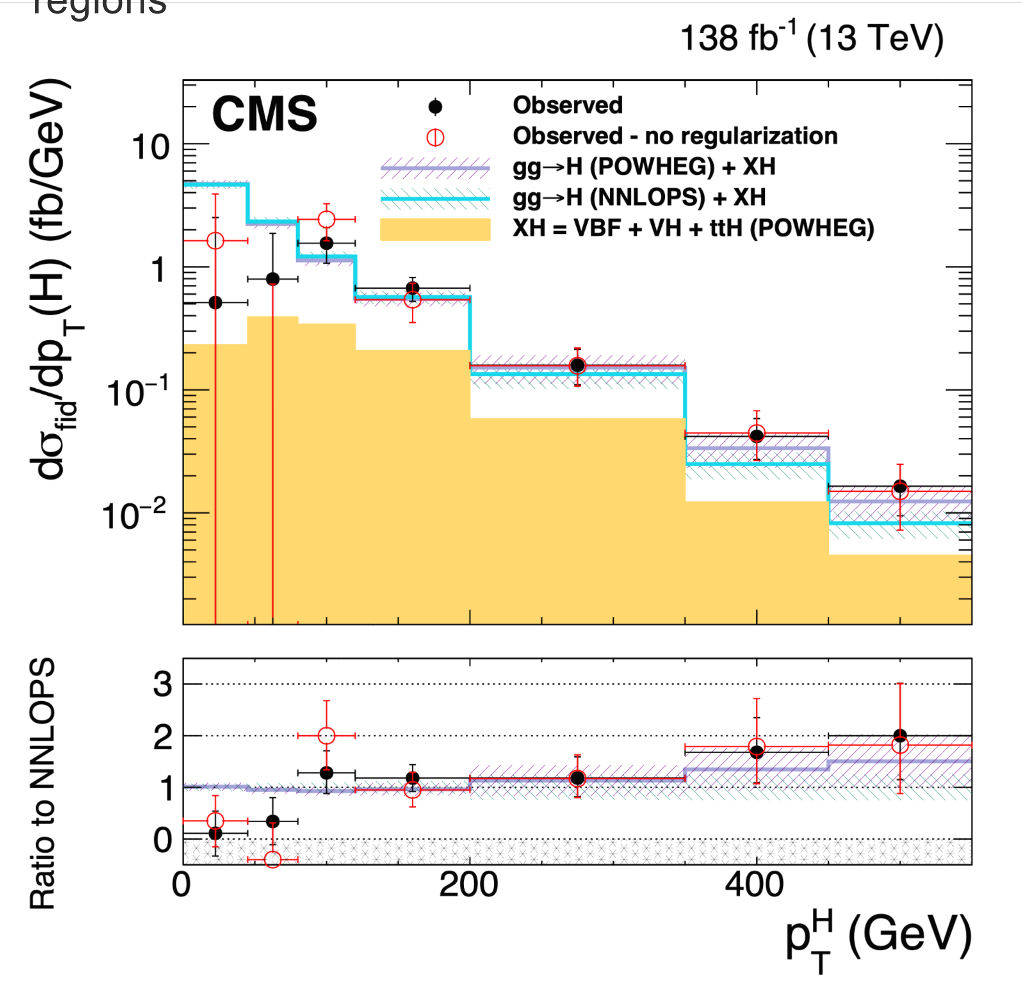
Phys. Rev. D 105, 092003



$H \to \tau\tau$ decay mode

- **Topology:** Focusing on the majority of ττ decay combinations, excluding $ee/\mu\mu + 4\nu$
  - $e\mu, e\tau_{had}, \mu\tau_{had}, \tau_{had}\tau_{had}$ final states, further categorised in different $p_T^{\tau_{had}}$ regions
  - **First differential measurement in this decay channel**
- **Background processes:**
  - **$Z \to \tau\tau$, leptonically decaying tt, diboson production**
    - Di-τ events are estimated from "embedded sample" using data
  - **Jets misidentified as τ_{had}**
    - Misidentification probability is estimated using data
- **Good agreement with the SM prediction:**
  - $\sigma_{fid}^{tot} = 426 \pm 102$ fb
  - $\sigma_{fid}^{tot,SM} = 408 \pm 27$ fb
  - Dominated by statistical and theoretical uncertainties
- **Core observables:**
  - Fit is performed on the di-τ mass ($m_{\tau\tau}$) reconstructed through a simplified matrix-element algorithm

Phys. Rev. Lett. 128 (2022) 081805



Summary and outlook

- **The Run 2 era of data taking provided us with the necessary input for detailed precision studies:**
    - Allowed for measurements of the fiducial differential cross section in several decay modes of the Higgs boson with good precision
        - Increased statistical precision opened doors for many variables to be considered for the first time
        - There is a very good agreement between what was measured and the SM predictions
- **If we consider that Run 2 opened a new chapter for Higgs precision measurements, the ongoing Run 3 and future phases are going to be first steps into a new era of precision:**
    - Probing for new physics effects in far corners of the phase space in the Higgs sector
    - Stay tuned for more exiting results!

Measurements presented in this talk

Decay mode:	$H \rightarrow bb$	$H \rightarrow WW$	$H \rightarrow \gamma\gamma$	$H \rightarrow \tau\tau$	$H \rightarrow ZZ$
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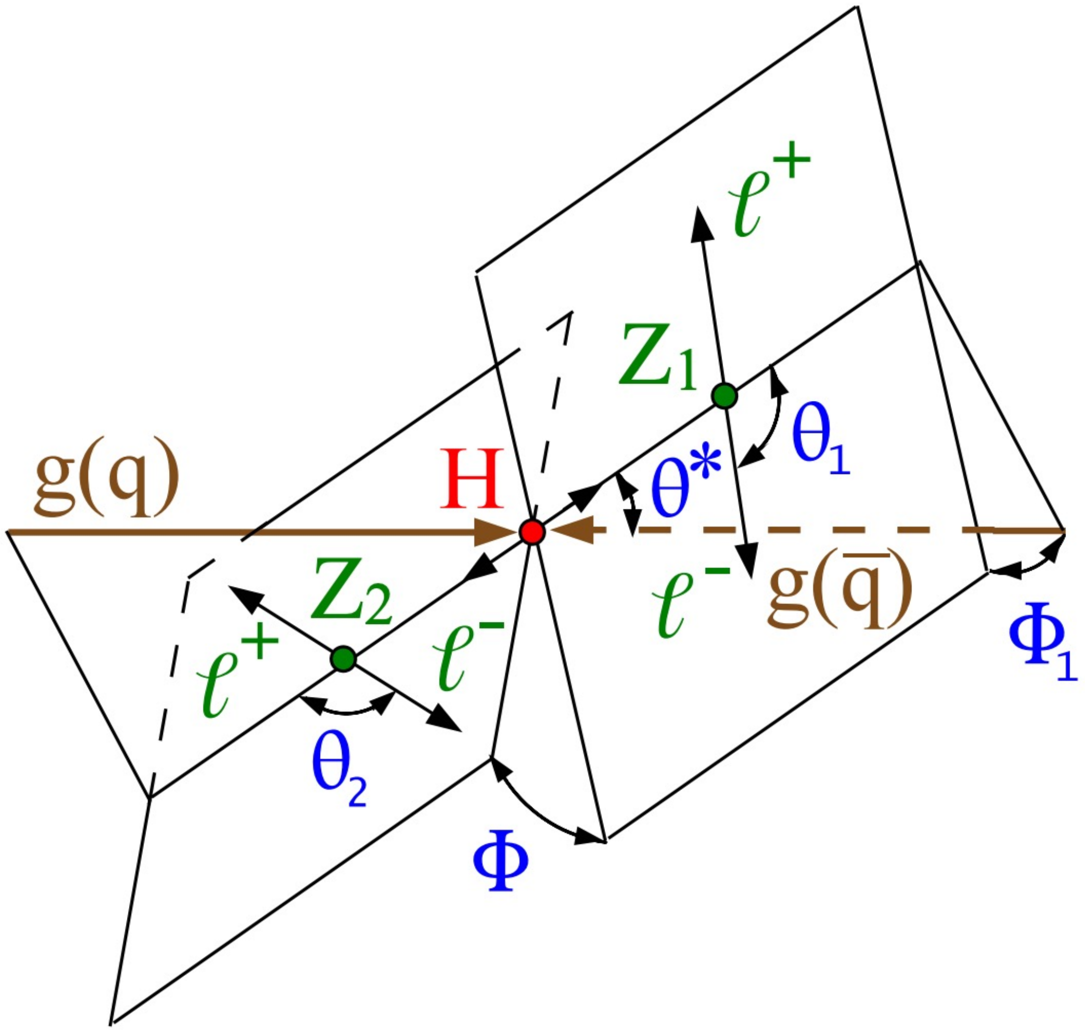
Thank you for your time!

$H \rightarrow ZZ$ decay mode: Introduction



$H \to ZZ$ decay mode: Introduction

The rapidity-weighted jet vetoes $\mathcal{T}_{\mathrm{C}}^{\max}$ and $\mathcal{T}_{\mathrm{B}}^{\max}$ are also studied. These are defined, following Ref. [118], as:

$$\mathcal{T}_{\mathrm{C}}^{\max} = \max_{j} \left(\frac{\sqrt{E_j^2 - p_{z,j}^2}}{2\cosh\left(y_j - y_{\mathrm{H}}\right)} \right), \tag{3}$$

$$\mathcal{T}_{\mathrm{B}}^{\max} = \max_{j} \left(m_{\mathrm{T}}^{j} e^{-|y_j - y_{\mathrm{H}}|} \right), \tag{4}$$

where y_j and m_{T}^{j} are the rapidity and transverse mass of the jet, defined from its mass m and momentum p as $m_{\mathrm{T}}^{j} = \sqrt{m^2 + p_{\mathrm{x}}^2 + p_{\mathrm{y}}^2}$, while y_{H} is the rapidity of the H boson. The value of each observable is computed for each jet in the event and its maximum value is taken for each event. Since their resummation structure is different from the canonical p_{T}^{j}, they give complementary information on the properties of jets in an event and can be used as a test of quantum chromodynamics (QCD) resummation. The 0-jet phase space can be redefined using these observables. The events with no jets are defined as the ones with $\mathcal{T}_{\mathrm{C}}^{\max} < 15\,\mathrm{GeV}$ and $\mathcal{T}_{\mathrm{B}}^{\max} < 30\,\mathrm{GeV}$, where the values of these cuts are chosen accordingly to the findings of Ref. [118]. In the following, these events will be defined as 0-jet$|\mathcal{T}_{\mathrm{C}}^{\max}$ and 0-jet$|\mathcal{T}_{\mathrm{B}}^{\max}$, respectively.

$H \rightarrow ZZ$ decay mode: Introduction

$$\begin{aligned}\sigma^{\text{fid}} &= 2.73 \pm 0.22\,(\text{stat}) \pm 0.15\,(\text{syst})\text{ fb}\\ &= 2.73 \pm 0.22\,(\text{stat}) \pm 0.12\,(\text{electrons}) \pm 0.05\,(\text{lumi}) \pm 0.05\,(\text{bkg}) \pm 0.03\,(\text{muons})\text{ fb}\end{aligned}$$

$H \rightarrow \gamma\gamma$ decay mode: Results

Phase space region	Observable	Bin boundaries							
	$p_{\mathrm{T}}^{\gamma\gamma}$	0	5	10	15	20	25	30	35
		45	60	80	100	120	140	170	200
		250	350	450	∞				
	n_{jets}	0	1	2	3	≥ 4			
	$\lvert y^{\gamma\gamma} \rvert$	0.0	0.1	0.2	0.3	0.45	0.6	0.75	0.90
		2.5							
Baseline	$\lvert \cos(\theta^*) \rvert$	0.0	0.07	0.15	0.22	0.35	0.45	0.55	0.75
$p_{\mathrm{T}}^{\gamma_1}/m_{\gamma\gamma} > 1/3$		1.0							
$p_{\mathrm{T}}^{\gamma_2}/m_{\gamma\gamma} > 1/4$	$\lvert \phi_{\eta}^* \rvert$	0.0	0.05	0.1	0.2	0.3	0.4	0.5	0.7
$\lvert \eta^{\gamma} \rvert < 2.5$		1.0	1.5	2.5	4.0	∞			
$\mathcal{I}_{\text{gen}}^{\gamma} < 10\,\text{GeV}$	$p_{\mathrm{T}}^{\gamma\gamma}, n_{\text{jets}} = 0$	0	5	10	15	20	25	30	35
		45	60	∞					
	$p_{\mathrm{T}}^{\gamma\gamma}, n_{\text{jets}} = 1$	0	30	60	100	170	∞		
	$p_{\mathrm{T}}^{\gamma\gamma}, n_{\text{jets}} > 1$	0	100	170	250	350	∞		
	n_{bjets}	0	1	≥ 2					
	n_{leptons}	0	1	≥ 2					
	$p_{\mathrm{T}}^{\text{miss}}$	0	30	50	100	200	∞		
	$p_{\mathrm{T}}^{\mathrm{j}_1}$	30	40	55	75	95	120	150	200
		∞							
	$\lvert y^{\mathrm{j}_1} \rvert$	0.0	0.3	0.6	0.9	1.2	1.6	2.0	2.5
1-jet	$\lvert \Delta\phi_{\gamma\gamma,\mathrm{j}_1} \rvert$	0.0	2.0	2.6	2.85	3.0	3.07	π	
Baseline + $\geq$1 jet	$\lvert \Delta y_{\gamma\gamma,\mathrm{j}_1} \rvert$	0.0	0.3	0.6	1.0	1.4	1.9	2.5	∞
$p_{\mathrm{T}}^{\mathrm{j}} > 30\,\text{GeV}$	$\tau_{\mathrm{C}}^{\mathrm{j}}$	< 15	15	20	30	50	80	∞	
$\lvert \eta^{\mathrm{j}} \rvert < 2.5$	$p_{\mathrm{T}}^{\gamma\gamma}, \tau_{\mathrm{C}}^{\mathrm{j}} < 15$ GeV	0	45	120	∞				
	$p_{\mathrm{T}}^{\gamma\gamma}$, 15 GeV $\leq \tau_{\mathrm{C}}^{\mathrm{j}} < 25$ GeV	0	45	120	∞				
	$p_{\mathrm{T}}^{\gamma\gamma}$, 25 GeV $\leq \tau_{\mathrm{C}}^{\mathrm{j}} < 40$ GeV	0	120	∞					
	$p_{\mathrm{T}}^{\gamma\gamma}$, 40 GeV $\leq \tau_{\mathrm{C}}^{\mathrm{j}}$	0	200	350	∞				
	$p_{\mathrm{T}}^{\mathrm{j}_2}$	30	40	65	90	150	∞		
2-jets	$\lvert y^{\mathrm{j}_2} \rvert$	0.0	0.6	1.2	1.8	2.5	3.5	5.0	
Baseline + $\geq$2 jets	$\lvert \Delta\phi_{\mathrm{j}_1,\mathrm{j}_2} \rvert$	0.0	0.5	0.9	1.3	1.7	2.5	π	
$p_{\mathrm{T}}^{\mathrm{j}} > 30\,\text{GeV}$	$\lvert \Delta\phi_{\gamma\gamma,\mathrm{j}_1\mathrm{j}_2} \rvert$	0.0	2.0	2.7	2.95	3.07	π		
$\lvert \eta^{j} \rvert < 4.7$	$\lvert \overline{\eta}_{\mathrm{j}_1\mathrm{j}_2} - \eta_{\gamma\gamma} \rvert$	0.0	0.2	0.5	0.85	1.2	1.7	∞	
	m^{jj}	0	75	120	180	300	500	1000	∞
	$\lvert \Delta\eta_{\mathrm{j}_1\mathrm{j}_2} \rvert$	0.0	0.7	1.6	3.0	5.0	∞		
VBF-enriched	$p_{\mathrm{T}}^{\gamma\gamma}$	0	30	60	120	200	∞		
2-jets + $n_{\text{jets}} \geq 2$	$p_{\mathrm{T}}^{\mathrm{j}_2}$	30	40	65	90	150	∞		
$\Delta\eta^{\mathrm{jj}} > 3.5$	$\lvert \Delta\phi_{\mathrm{j}_1,\mathrm{j}_2} \rvert$	0.0	0.5	0.9	1.3	1.7	2.5	π	
$m^{\mathrm{jj}} > 200\,\text{GeV}$	$\lvert \Delta\phi_{\gamma\gamma,\mathrm{j}_1\mathrm{j}_2} \rvert$	0.0	2.0	2.7	2.95	3.07	π		