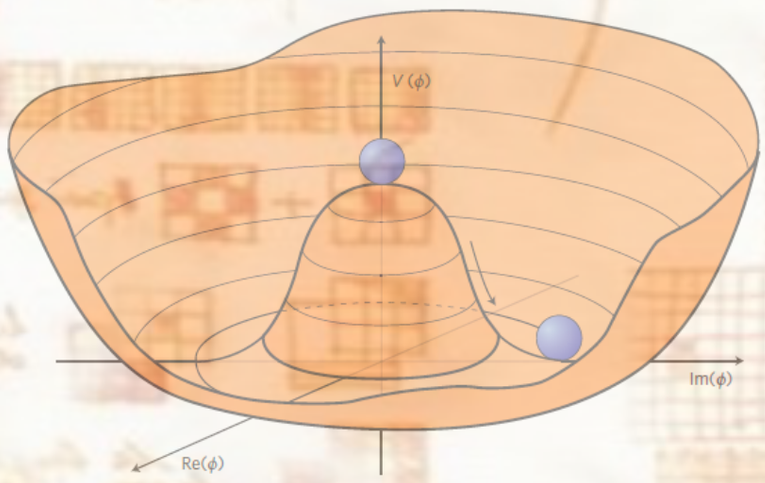
Measurement of the Higgs cross sections in the H → ZZ → 4ℓ channel at CMS

Walaa Elmetenawee[1]
on behalf of The CMS collaboration

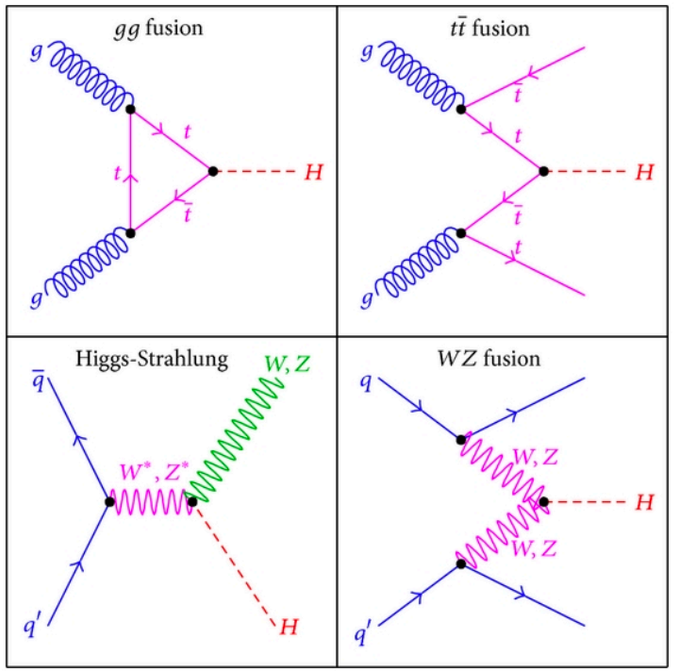


Higgs 2021 (18-22 Oct 2021)

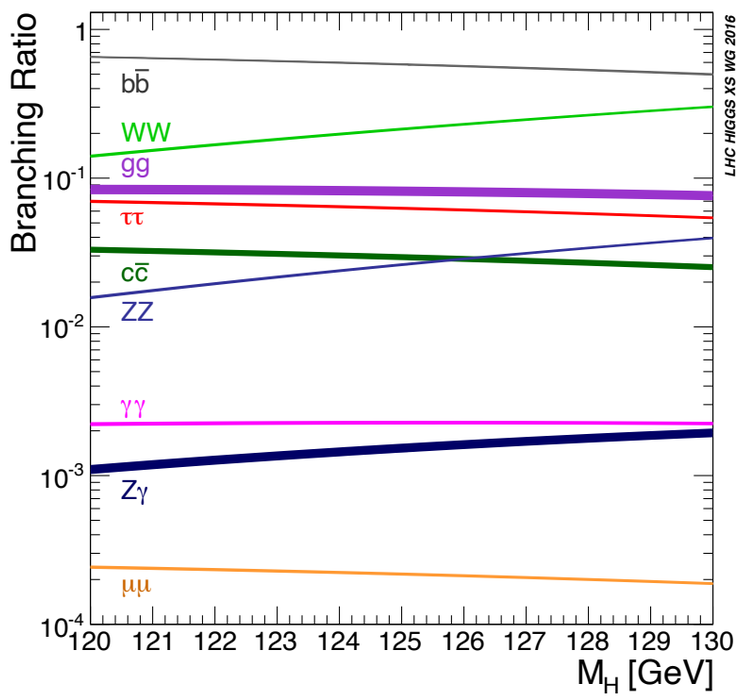
[1] University & INFN Bari

Overview

Mian Higgs production modes



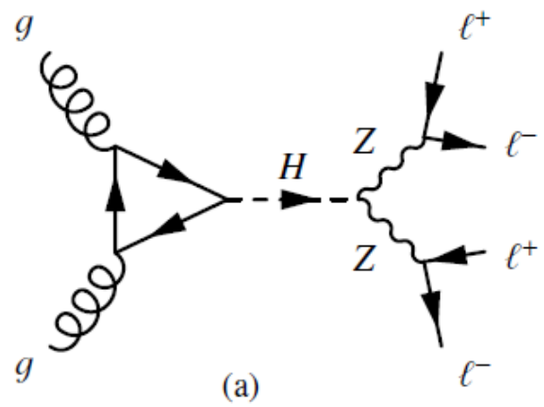
Higgs decay modes and BR



Event Signature:

- **Large signal V.S. bkg ratio**: > 2:1 under the Higgs peak.
- **Signal is fully reconstructed** using four lepton with good momentum resolution.
- Good mass resolution (1-2%).
- Low branching fraction (0.012%) compensated by fully reconstructed final state.

H → ZZ → 4ℓ channel



Analysis Strategy

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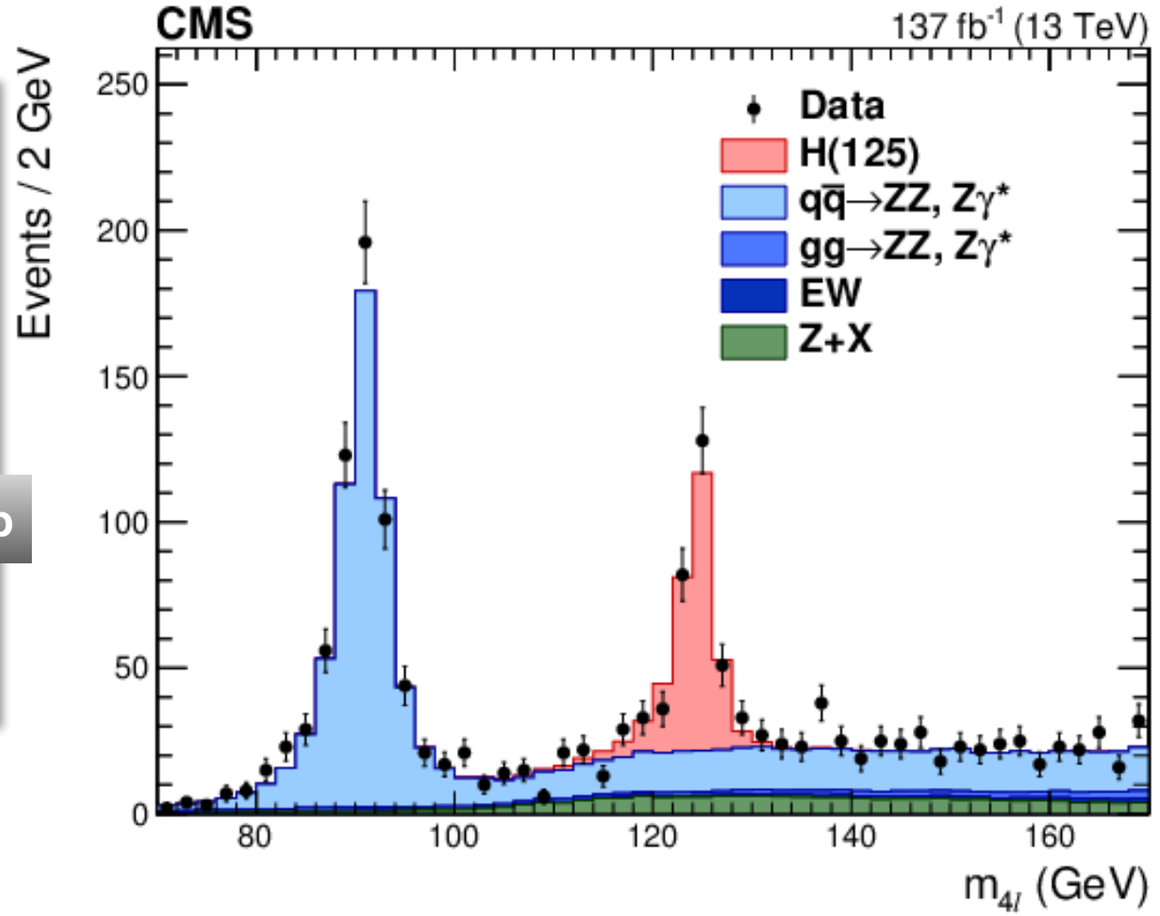
Selection strategy

- Electrons (muons) reconstructed down to 7 (5) GeV.
- **Selected leptons:** lepton identification, isolation, SIP cut & final gamma radiation recovery algorithms .
- **Z candidates:** OSSF pairs of fully selected leptons $12 < m_{ll(\gamma)} < 120$ GeV.
- **ZZ candidates:** apply series of selection cuts. ▶Backup
- **corrections** for efficiencies in data measured by Tag&Probe.



Background and signal modelling:

- **Irreducible:** qq→ZZ and gg→ZZ from simulation with additional QCD and EW k-factors as a function of m4l.
- **Reducible**: Z+X estimated using data-driven method in control regions using 2 independent methods.
- **Signal**: ggH, VBF, WH, ZH, ttH, production modes considered from simulation.

Fiducial and Simplifies template cross-section

Fiducial cross-section

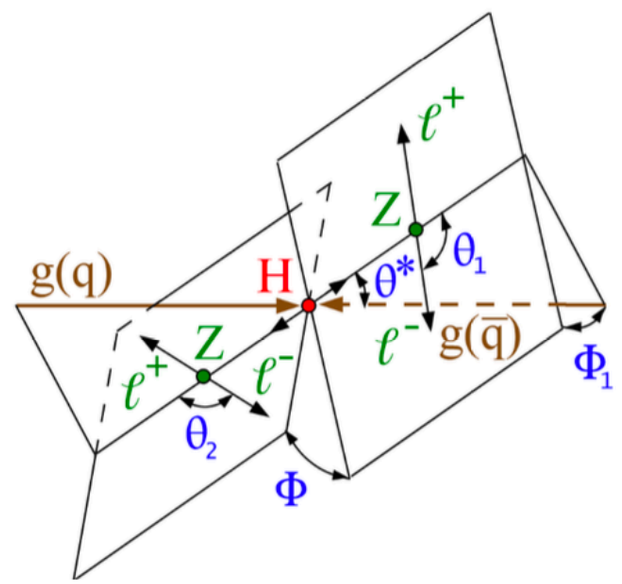
- Optimized for maximal theoretical independence.
- Fiducial in Higgs decay.
- Agnostic to production mode.
- Simple signal cuts.
- Exact fiducial volume.
- Can be done with single and differential distributions.
- Combination not straightforward.

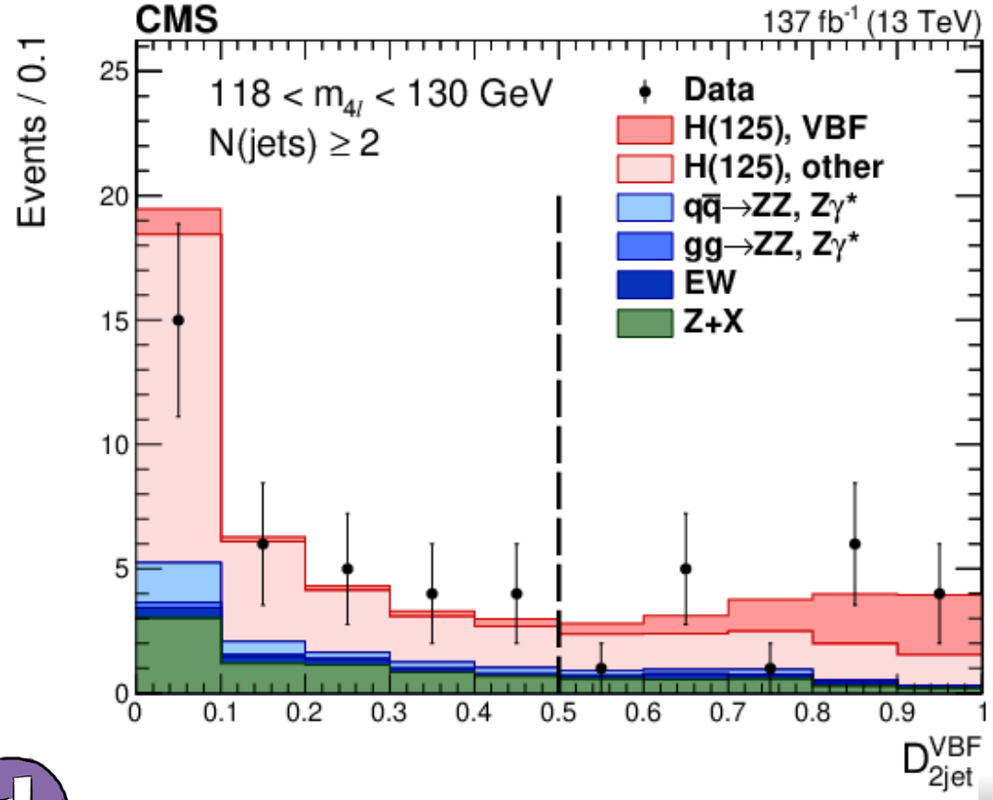
Simplified templates cross-section

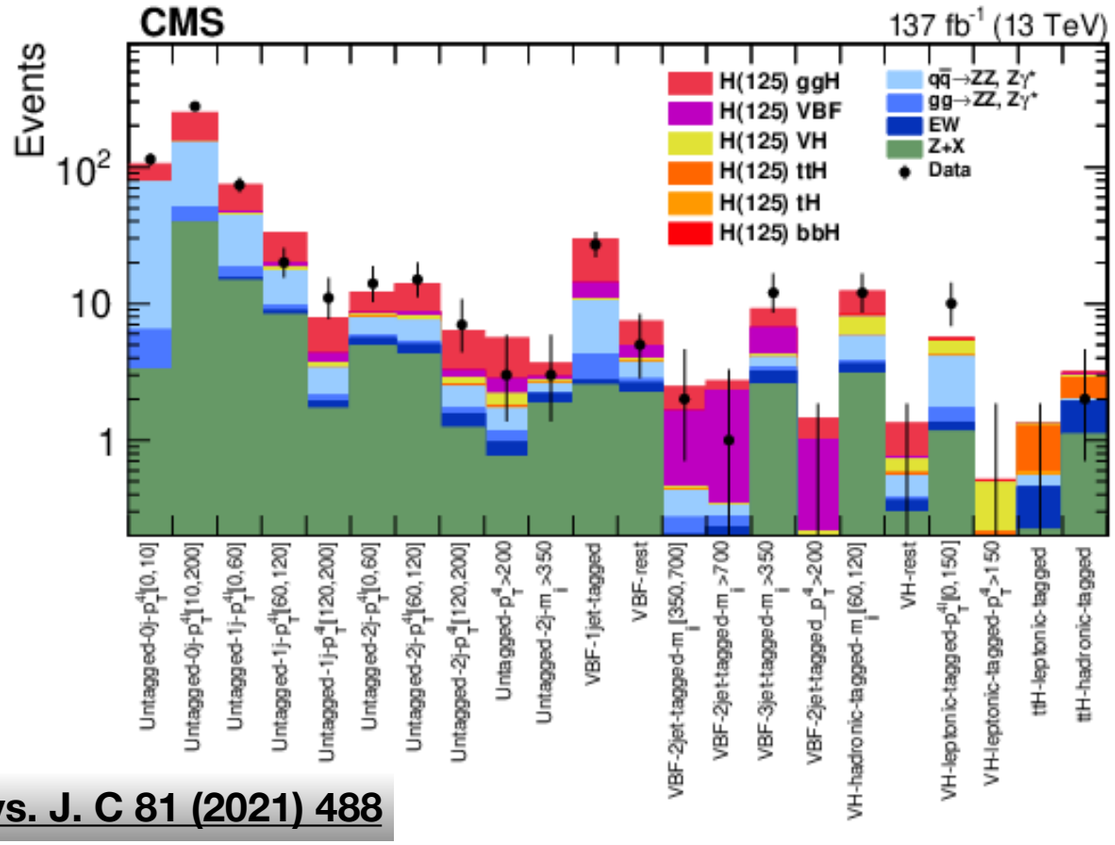
- Target maximum sensitivity, while keeping theoretical dependence as small as possible.
- Cross section split by production mode
- Cross section divided in **exclusive** regions of phase space (bins).
- Inclusive in Higgs decay.
- Allows complex event selections, categorisation.
- Explicitly designed for combination.

STXS Measurement Strategy

- Matrix-element based kinematic discriminants calculated with **MELA**.
- **Categorization:**
  - split events into mutually exclusive production mode categories.
  - split production mode categories into 22 kinematic regions.
  - using equivalent reco quantities e.g. $p^{4\ell} \Leftrightarrow p^{H}$







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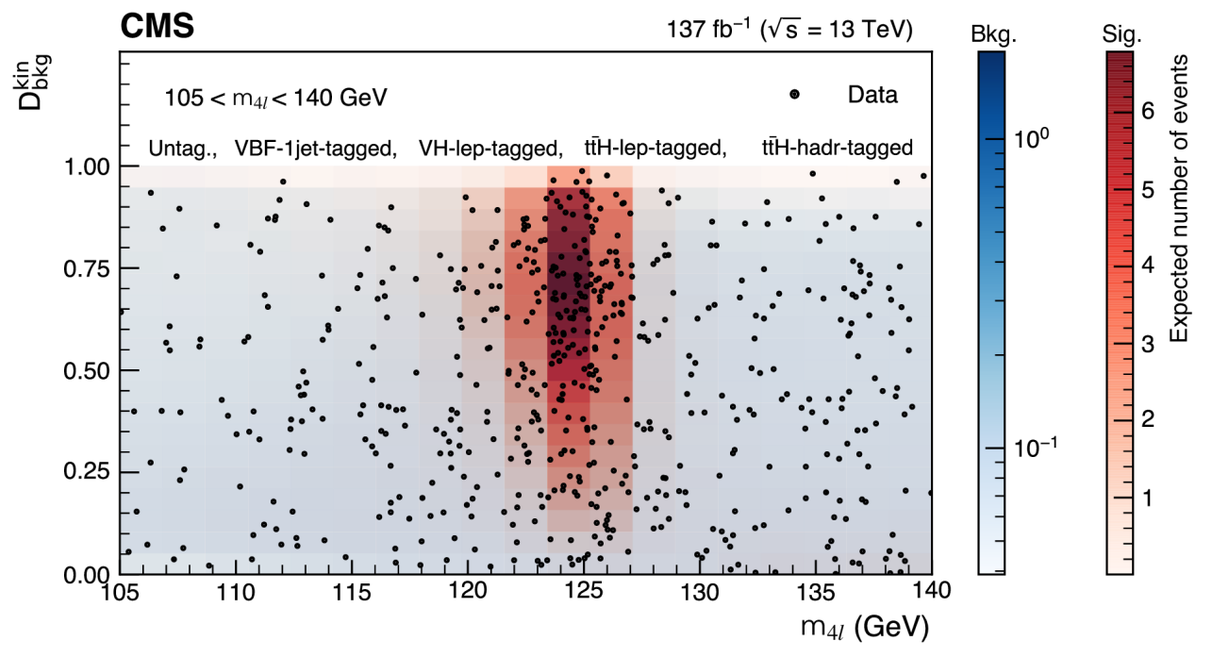
STXS Measurement Strategy

- **Two types of discriminants used:**
  - Decay only discriminant provides significant discrimination between ggH signal and ZZ background.
  - Decay + production discriminants provide significant discrimination between VBF/ VH and ggH



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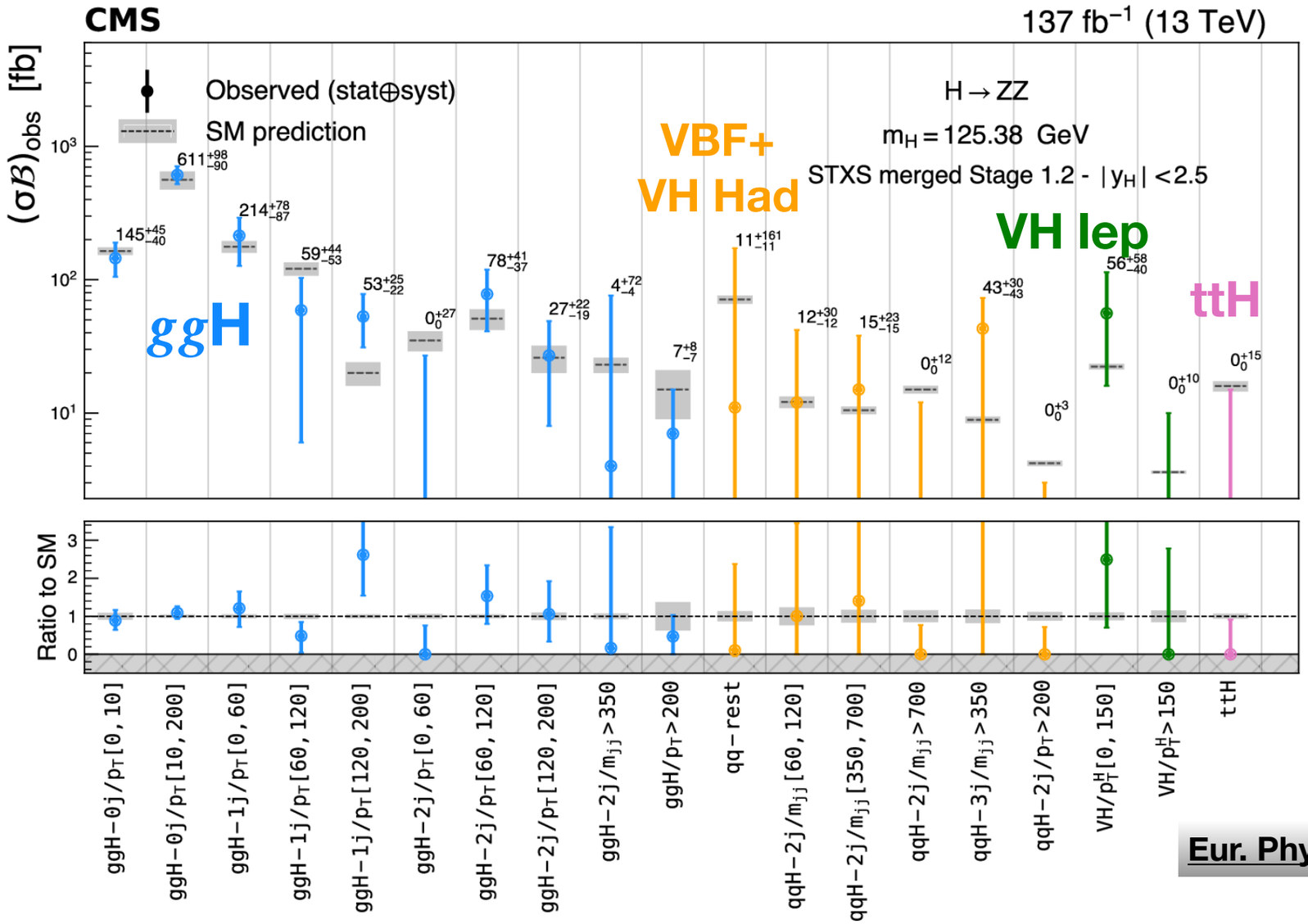
- **Two-dimensional likelihood fit in (m_{4l},$\mathcal{D}_{bkg}$) in all 22 analysis categories**
  - $\mathcal{P}(m_{4\ell})$ Decay unbinned analytic shape for each (STXS bin, category, decay channel)
  - $\mathcal{P}(\mathcal{D}_{bkg}|m_{4\ell})$: binned template, conditional on value of $m_{4\ell}$
  - Systematic included which affect shape and normalisation of S + B models.

STXS Results

- Use likelihood to unfold σ · B in 19 independent kinematic regions. ▶Backup
- Good agreement with SM prediction, statistical uncertainties dominate.



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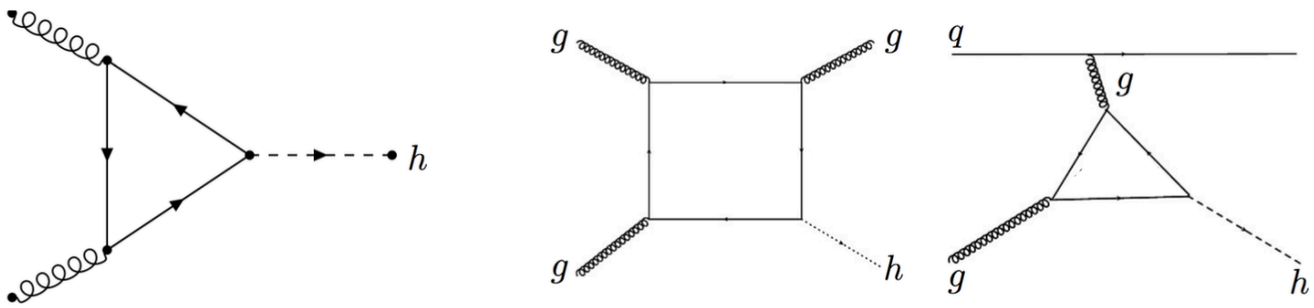
Differential measurements

WHY?

New physics might affect the shape of Higgs distribution, without affecting its overall production. "**Differential measurements**" are needed to identify such effects.

- **Transverse momentum: $p_T(H)$**
  - Sensitive to modifications of effective Higgs Yukawa couplings.
  - Sensitivity to finite top mass effects.
- **Jet multiplicity and p_T**
  - New physics in the quark loop (especially at high jet p_T)
- **Higgs rapidity:**
  - Effects on gluon PDF.



HOW?

▶Backup

Fiducial Volume

Observables and binning

Response matrix

Unfolding

Interpretation

Fiducial cross-section measurements

- Measured by performing a maximum likelihood fit of the signal and background parameterisations to the observed 4l mass distribution.

Fiducial signal — **Non-fiducial signal** — **Non-resonant signal** — **Background contribution**

$$N^{f,i}_{\text{exp}}(m_{4\ell}) = N^{f,i}_{\text{fid}}(m_{4\ell}) + N^{f,i}_{\text{nonfid}}(m_{4\ell}) + N^{f,i}_{\text{nonres}}(m_{4\ell}) + N^{f,i}_{\text{bkg}}(m_{4\ell})$$

$$= \sum_j \epsilon^f_{i,j} \left(1 + f^{f,i}_{\text{nonfid}}\right) \sigma^{f,j}_{\text{fid}} \mathcal{L} \mathcal{P}_{\text{res}}(m_{4\ell})$$

Response matrix — **Parameter of interest**

$$+ N^{f,i}_{\text{nonres}} \mathcal{P}_{\text{nonres}}(m_{4\ell}) + N^{f,i}_{\text{bkg}} \mathcal{P}_{\text{bkg}}(m_{4\ell}).$$

Probability density function for resonant, non-resonant and background

Inclusive cross-section Results

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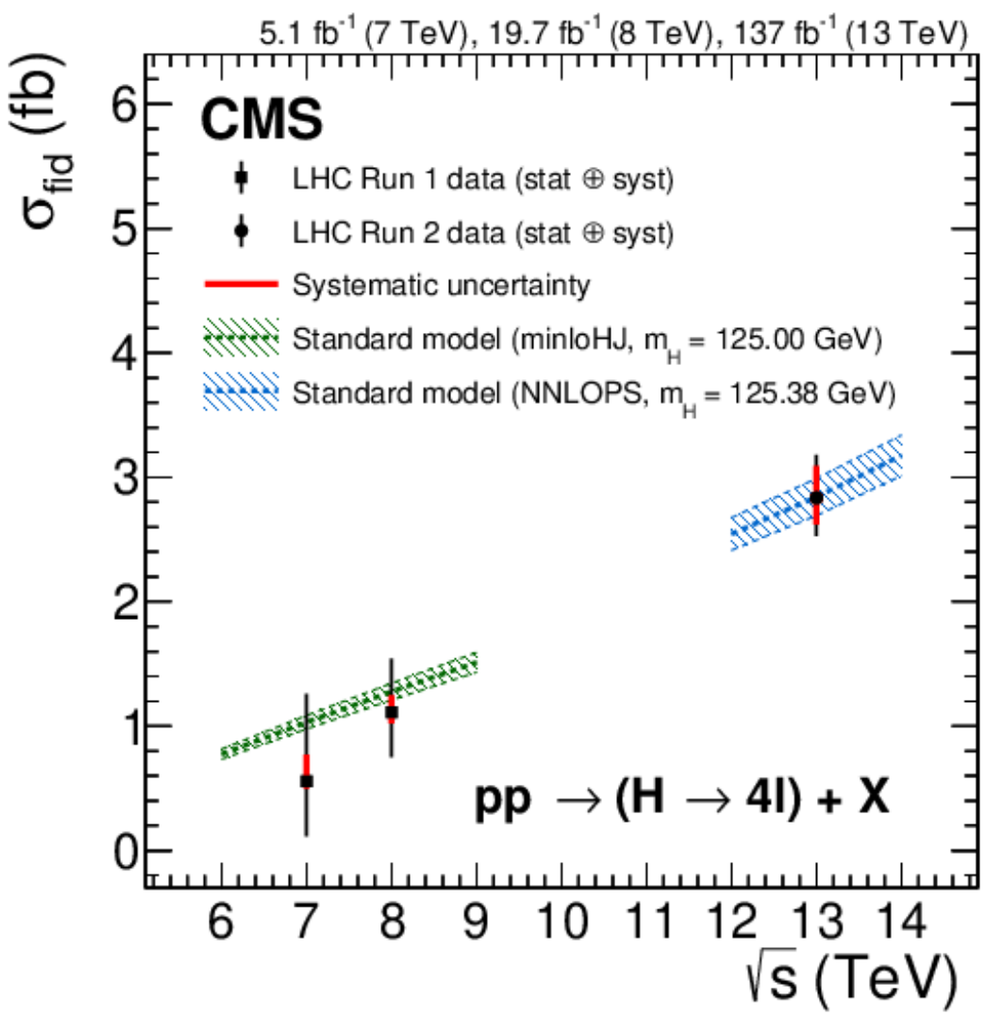
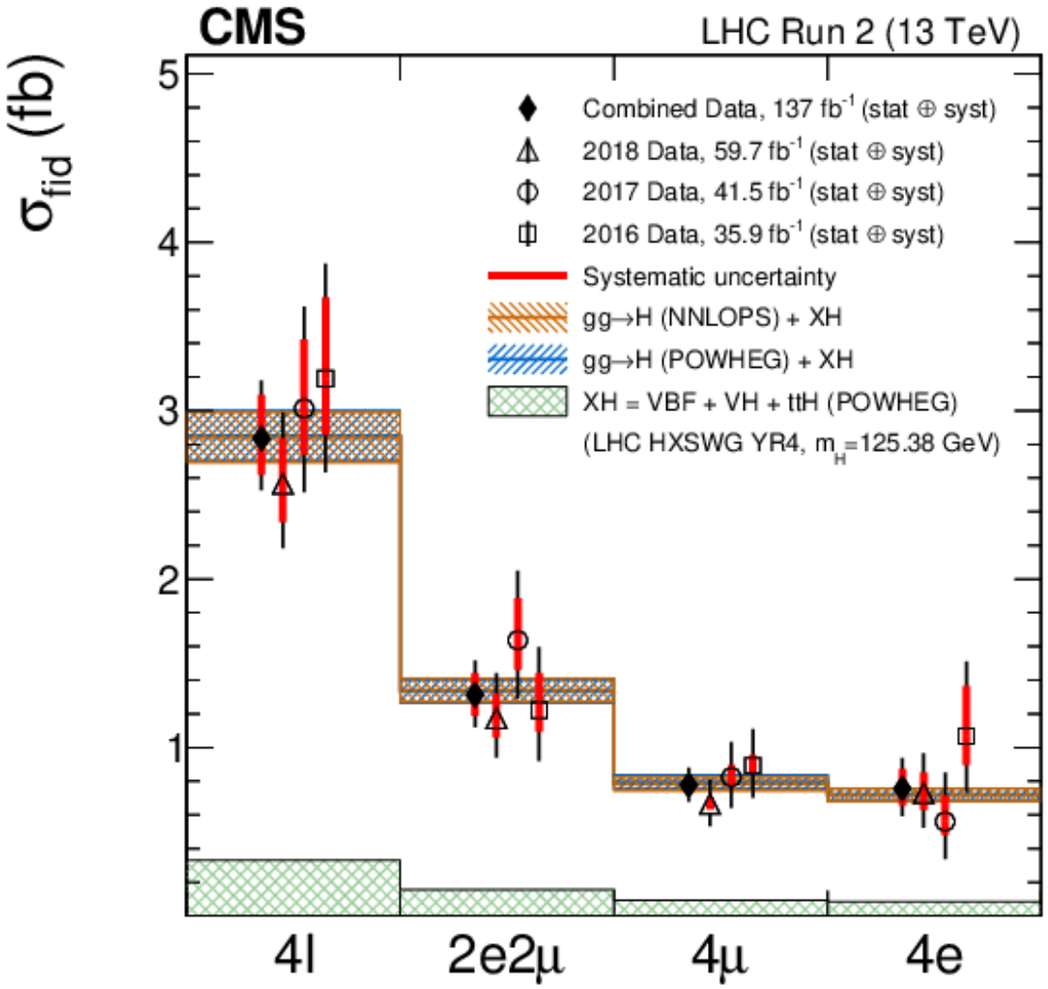


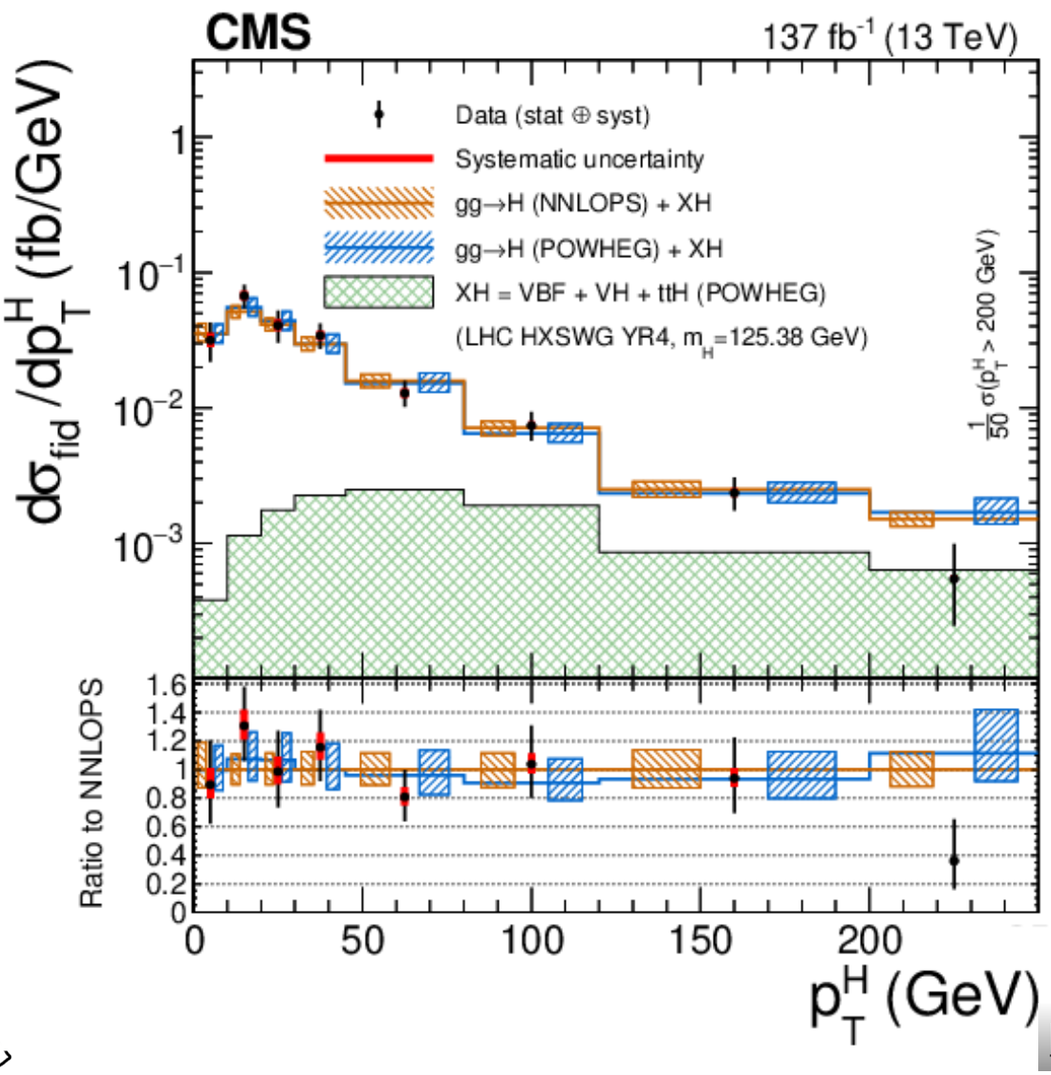


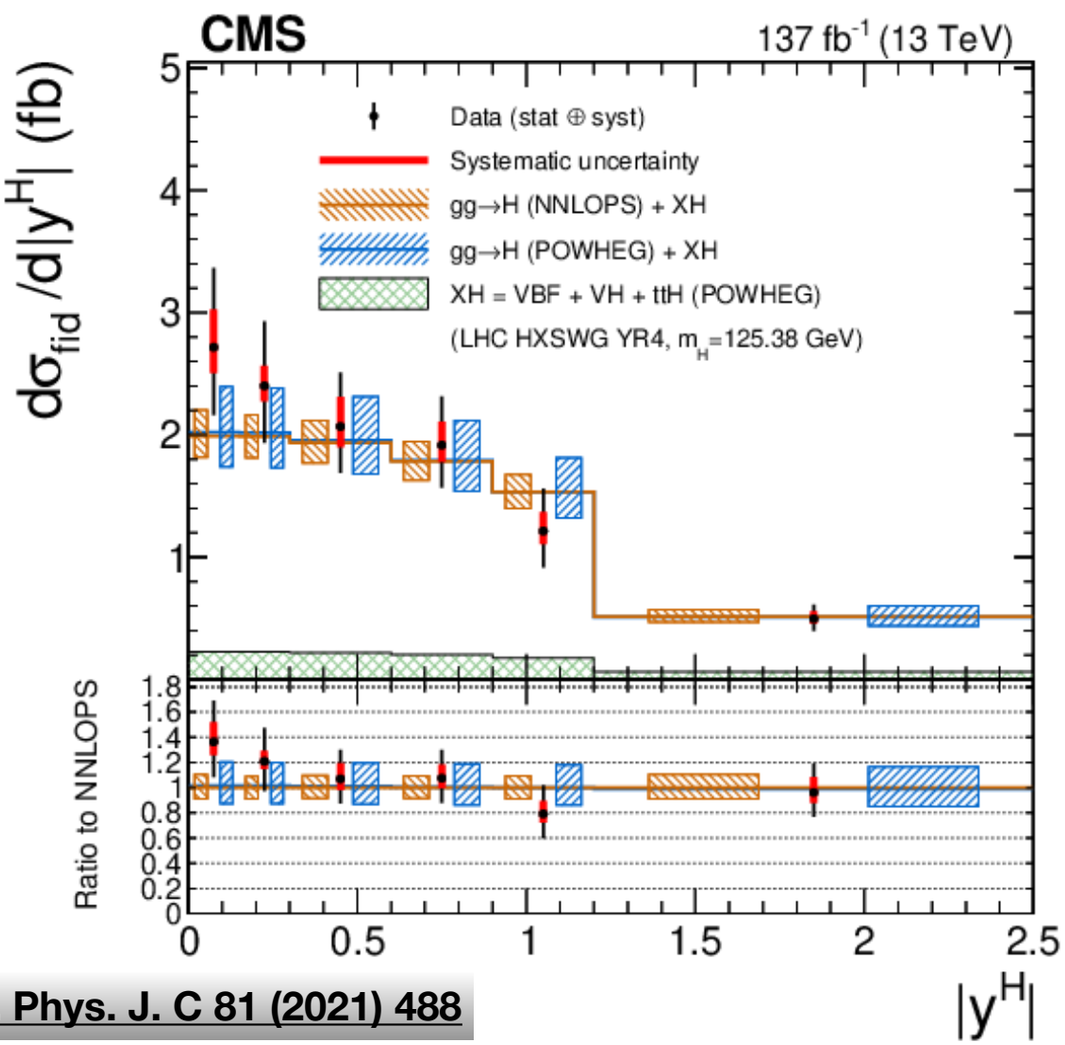
$$\sigma_{\text{fid}} = 2.84^{+0.34}_{-0.31} = 2.84^{+0.23}_{-0.22}\,(\text{stat})^{+0.26}_{-0.21}\,(\text{syst})\ \text{fb}$$

$$\sigma^{\text{SM}}_{\text{fid}} = 2.84 \pm 0.15\ \text{fb}.$$

Differential cross-section results

- Differential cross section measured for $p_T(H)$, $|y(H)|$, N(jet), $p_T(jet)$
- Unfolding performed by including response matrix in the likelihood
- Compared to predictions from POWHEG and NNLOPS





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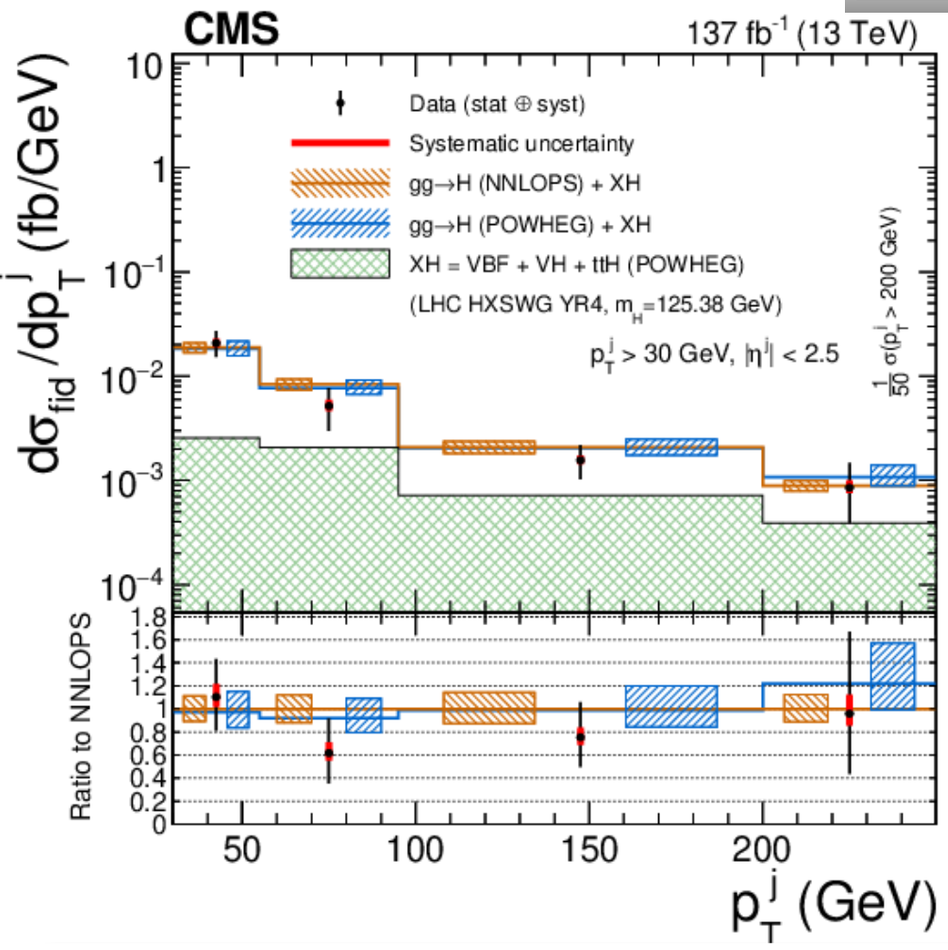
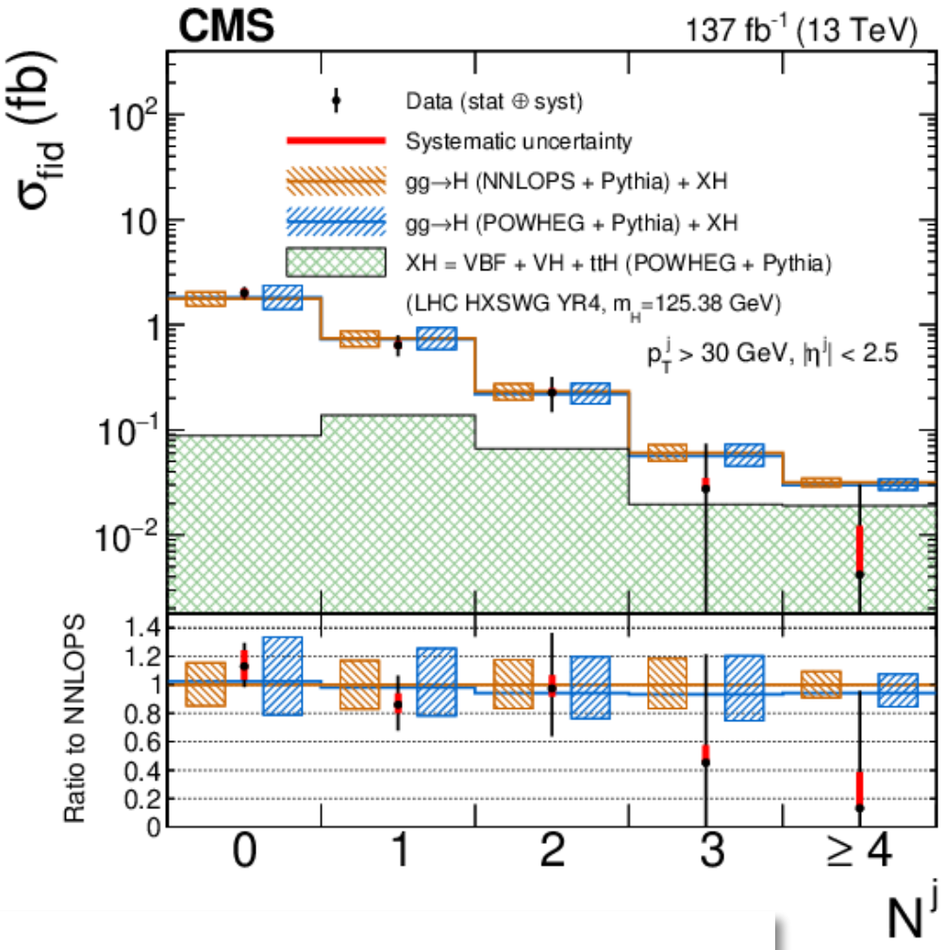




- Only central jets with $|\eta|$< 2.5 used in the measurement

Summary

- The CMS Collaboration produced its first results on differential Higgs distributions at 13TeV

- Latest results of Higgs cross-section measurements in four-lepton final state in pp collisions at $\sqrt{s}$ = 13 TeV with integrated luminosity 137 fb^{-1} (full Run2 dataset) are presented:
  - STXS and fiducial differential cross sections have been performed.
  - Measure H production in different kinematic regions.
  - Covered most recent CMS H cross section measurements.
  - Measurements compatible with SM predictions.

- As Run 3 approaches: must continue effort to pin down the Higgs sector
  - leave no stone/region of phase space unturned.

Backup

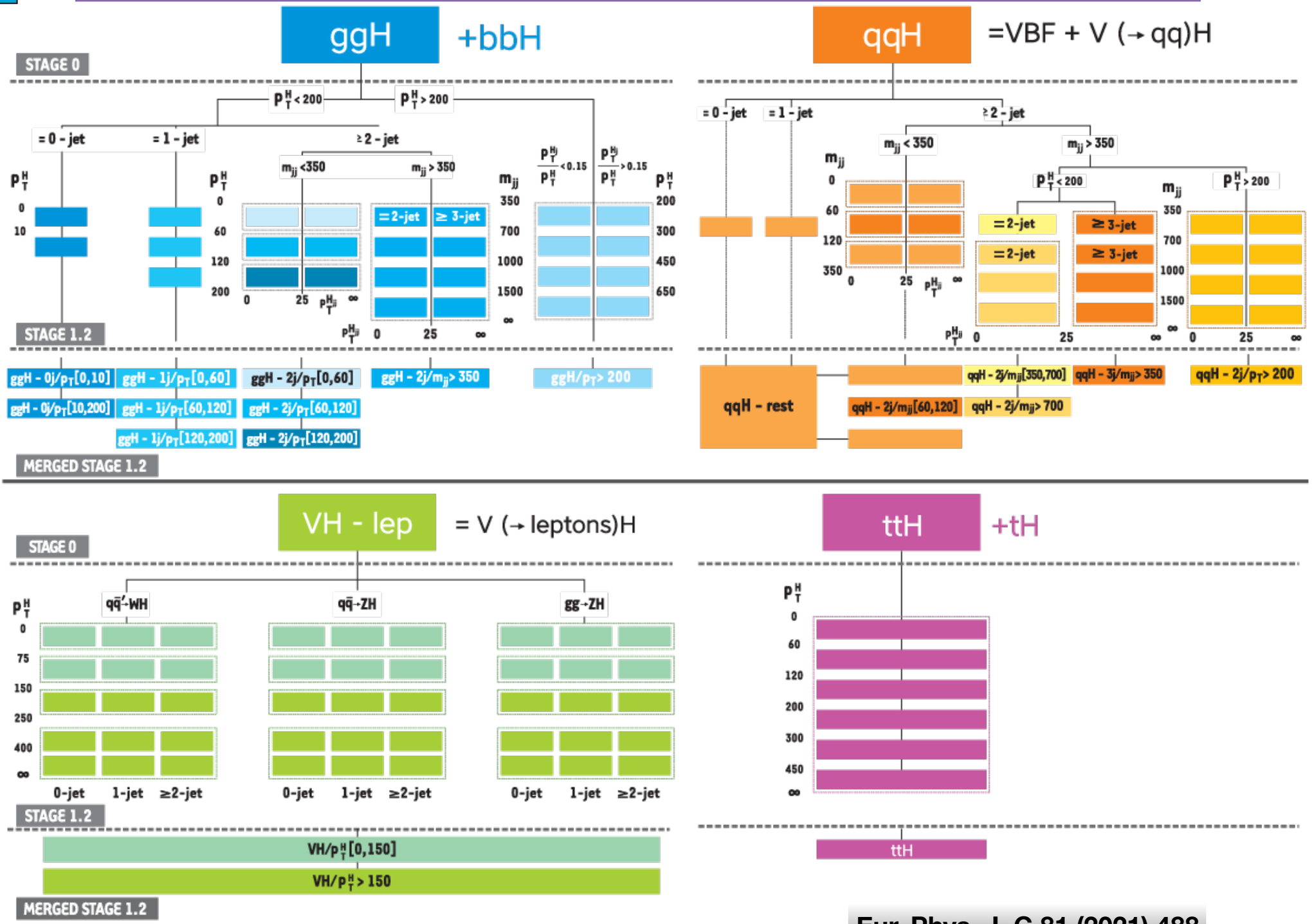
Analysis Strategy

☆SM Higgs selections:

- **Z Candidate**: any OS-SF pair that satisfy $12 < m_{ll(\gamma)} < 120$ GeV.
- Build all possible **ZZ candidates**, define Z1 candidate with mll(γ) closest to the PDG m(Z) mass.
- $M_{Z_1} > 40$ GeV, $p_T(l_1) > 20$ GeV/c, $p_T(l_2) > 10$ GeV/c.
- **Ghost removal**: $\Delta R > 0.02$ between any two leptons.
- **QCD suppression**: $M_{ll} > 4$ GeV for OS pairs, irrespective of flavor.
- Additional **"smart cut"** to reject 4mu/4e pairs where the alternative pairing looks like a on-shell Z+low-mass ll.
- $M_{4l} > 70$ GeV

If more than one ZZ candidates remains, we choose the one with highest D^{kin}_{bkg}, If D^{kin}_{bkg} is the same take the one with Z_1 mass closest to the m(Z).

Simplified template cross sections



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Fiducial region definition

Summary of requirements used in the definition of the fiducial phase space for the H → 4 ℓ cross section measurements

Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20\,\text{GeV}$
Next-to-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	$105 < m_{4\ell} < 140\,\text{GeV}$