Measurement of differential and integrated fiducial cross sections of Higgs boson production in the $H \rightarrow 4\ell$ decay channel in proton-proton collisions at 7, 8 and 13 TeV

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IHEP, CAS , Beijing

ISHBSM, 15-19 Aug 2016 , Shandong University, weihai , China.

Outline

- Introduction
- Event selection and background estimation
- Analysis strategy
- Results
- Conclusions

Introduction

- An important property to measure of the discovered Higgs boson is its (differential) fiducial cross section

  → Important test of SM predictions and probe of BSM effects

- Similar measurements (nearly) available:

  ATLAS $H\rightarrow\gamma\gamma$ (RUN1), 4ℓ (RUN1), combination (RUN1&RUN2)

  ATLAS $H\rightarrow WW$ (RUN1)

  CMS $H\rightarrow\gamma\gamma$ (Run1,RUN2)

- To minimize model dependence, we perform the measurement in a fiducial space close to experimental acceptance
- The definition can be reproduced by theorists/phenomenologists, such that the experimental results can be compared to any theoretical calculation

Datasets and Event Selection(Run 1)

- Datasets, triggers, and event selection follows the legacy H→4ℓ analysis

Phys. Rev. D 89 (2014) 092007

Channel	4e	4μ	$2e2\mu$
	$5.1\ \mathrm{fb}^{-1}$ (7 TeV)		
$q\bar{q} \to ZZ$	0.8 ± 0.1	1.8 ± 0.1	2.2 ± 0.3
$Z + X$	0.3 ± 0.1	0.2 ± 0.1	1.0 ± 0.3
$gg \to ZZ$	0.03 ± 0.01	0.06 ± 0.02	0.07 ± 0.02
Total background expected	1.2 ± 0.1	2.1 ± 0.1	3.4 ± 0.4
$H \to 4\ell$ ($m_H = 125.0$ GeV)	0.7 ± 0.1	1.2 ± 0.1	1.7 ± 0.3
Observed	1	3	6
	$19.7\ \mathrm{fb}^{-1}$ (8 TeV)		
$q\bar{q} \to ZZ$	3.0 ± 0.4	7.6 ± 0.5	9.0 ± 0.7
$Z + X$	1.5 ± 0.3	1.2 ± 0.5	4.2 ± 1.1
$gg \to ZZ$	0.2 ± 0.1	0.4 ± 0.1	0.5 ± 0.1
Total background expected	4.8 ± 0.7	9.2 ± 0.7	13.7 ± 1.3
$H \to 4\ell$ ($m_H = 125.0$ GeV)	2.9 ± 0.4	5.6 ± 0.7	7.3 ± 0.9
Observed	9	15	15

Event counts in the range 105 GeV < m(4ℓ) < 150 GeV

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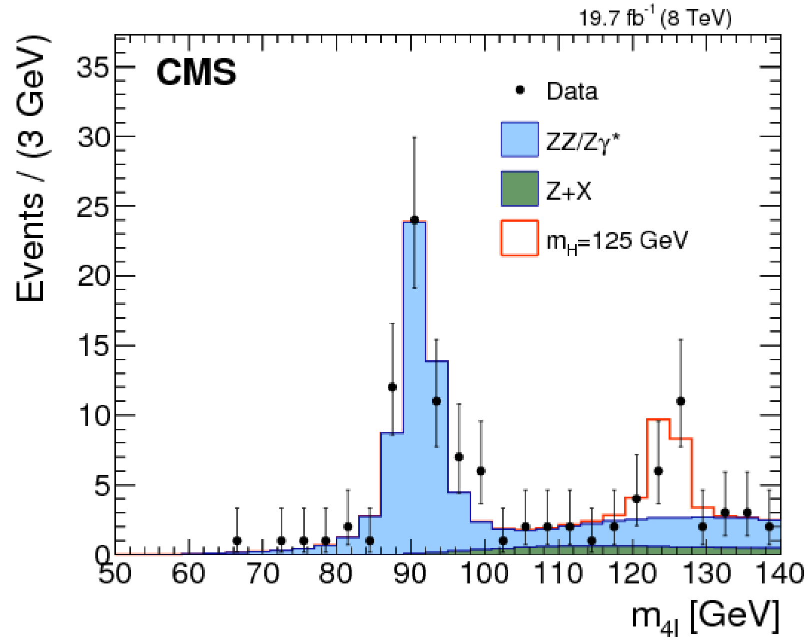
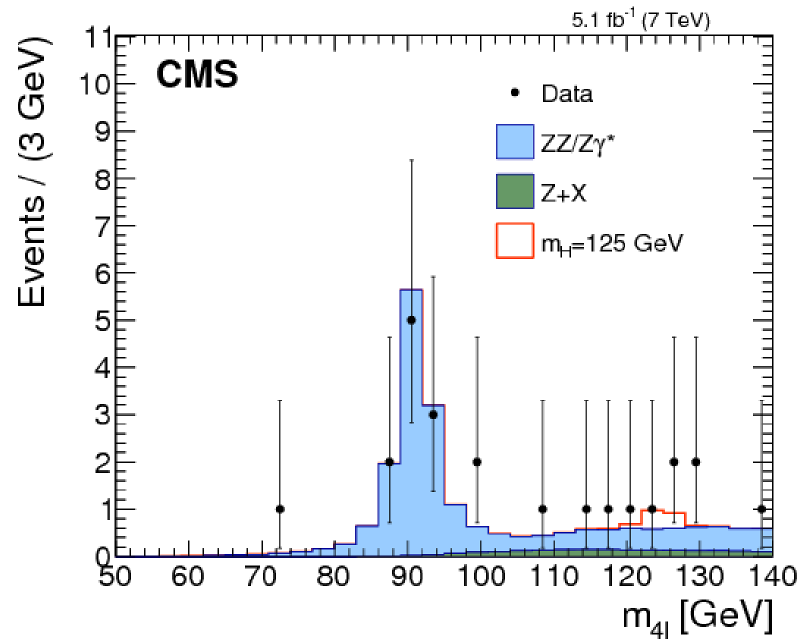
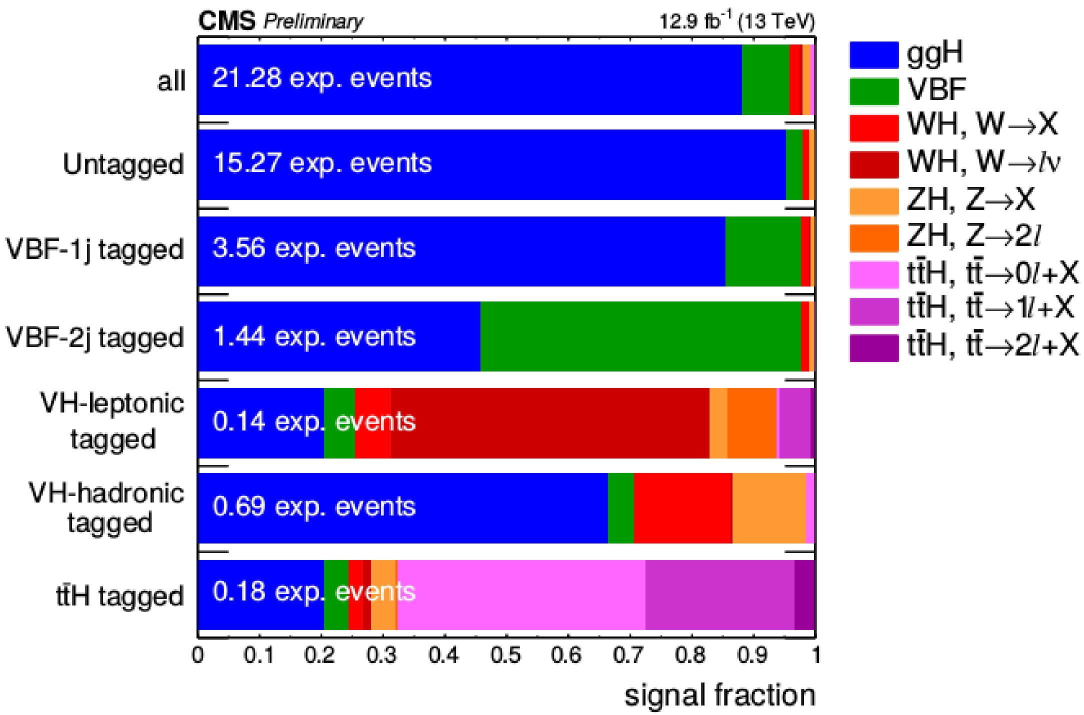
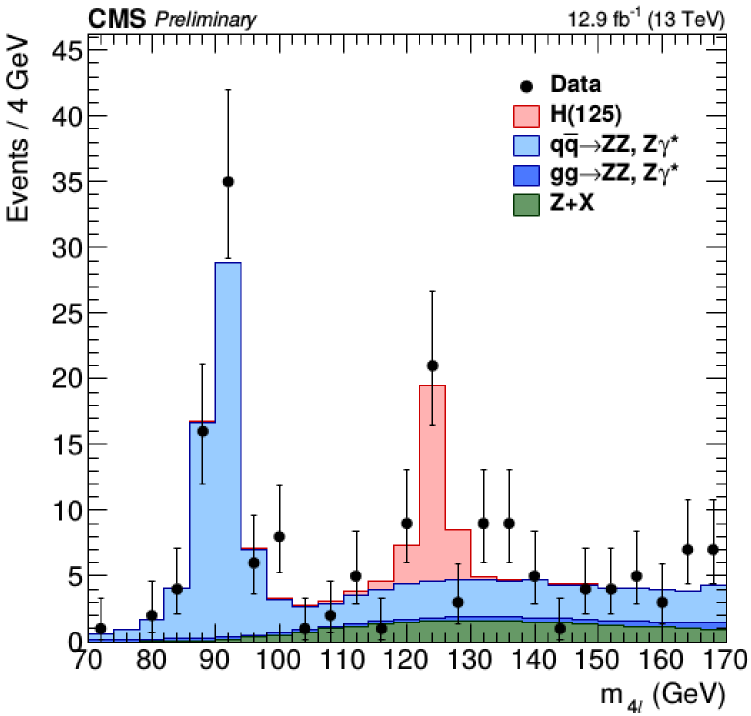




Datasets and Event Selection(Run 2)





Event counts in the range
118 GeV < m(4ℓ) < 130 GeV

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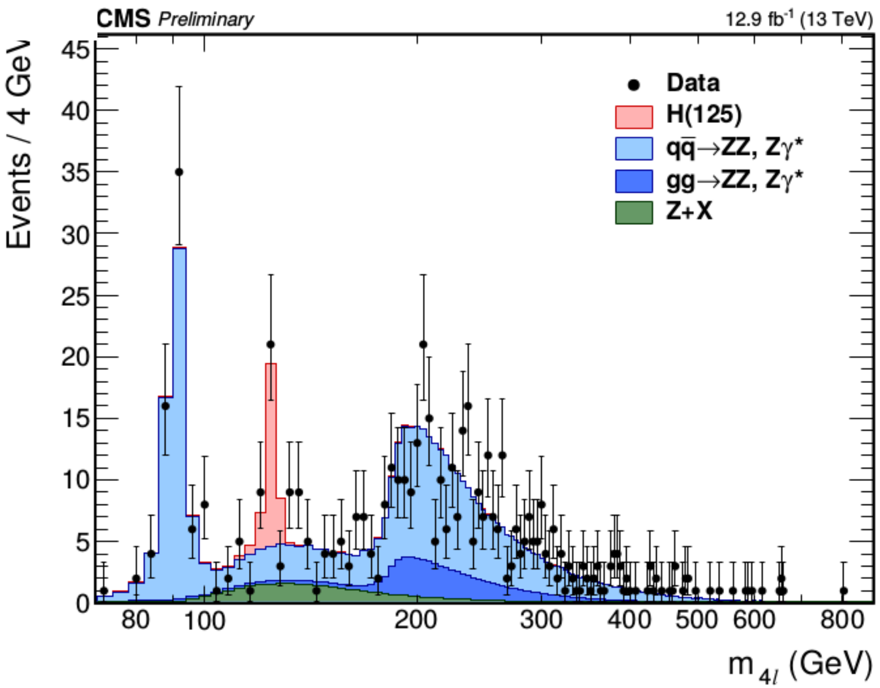


Fiducial Volume Definition

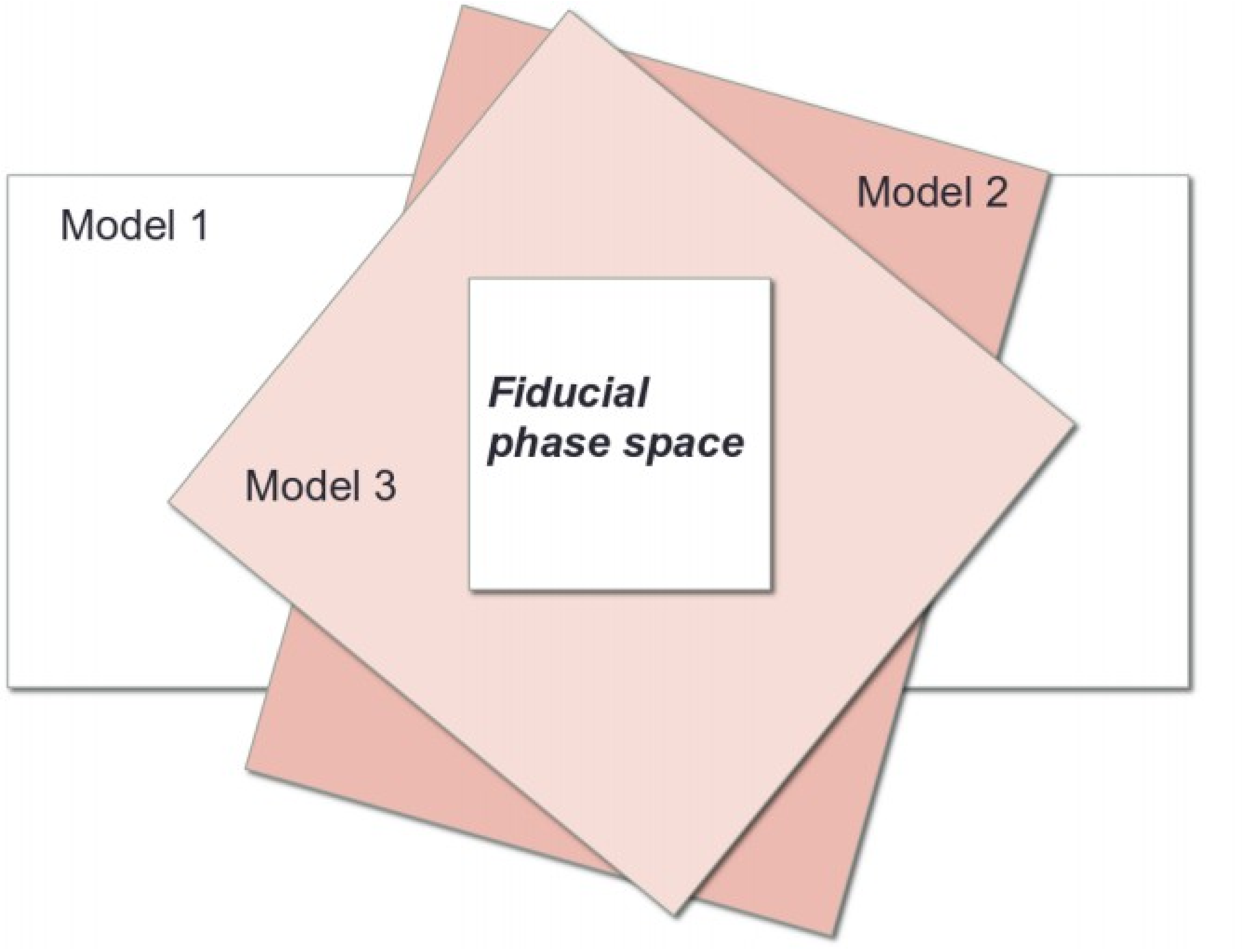
- The fiducial volume definition is chosen to closely match the reconstruction level selection, defined using leptons at the hard scattering level

Requirements for the $H \to 4\ell$ 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)	$\|\eta\| < 2.5\ (2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.4$ from lepton	$< 0.4 p_T$
Event topology	
Existence of at least two SFOS 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	$\Delta R(\ell_i \ell_j) > 0.02$
Inv. mass of any opposite-sign lepton pair	$m(\ell_i^+ \ell_j^-) > 4\,\text{GeV}$
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140\,\text{GeV}$

- For jets, p^T>30 GeV and |η|<4.7
- A crucial point is the inclusion of isolation in the fiducial selection
  - → Does not include neutrinos or FSR photons
  - → Without isolation, the difference in efficiency between production modes can be more than 50%

Fiducial Cross Section Overview

- Fiducial cross sections are necessary because acceptance has a strong model dependence, for example between SM production modes by up to 60%



Fiducial Cross Section Overview

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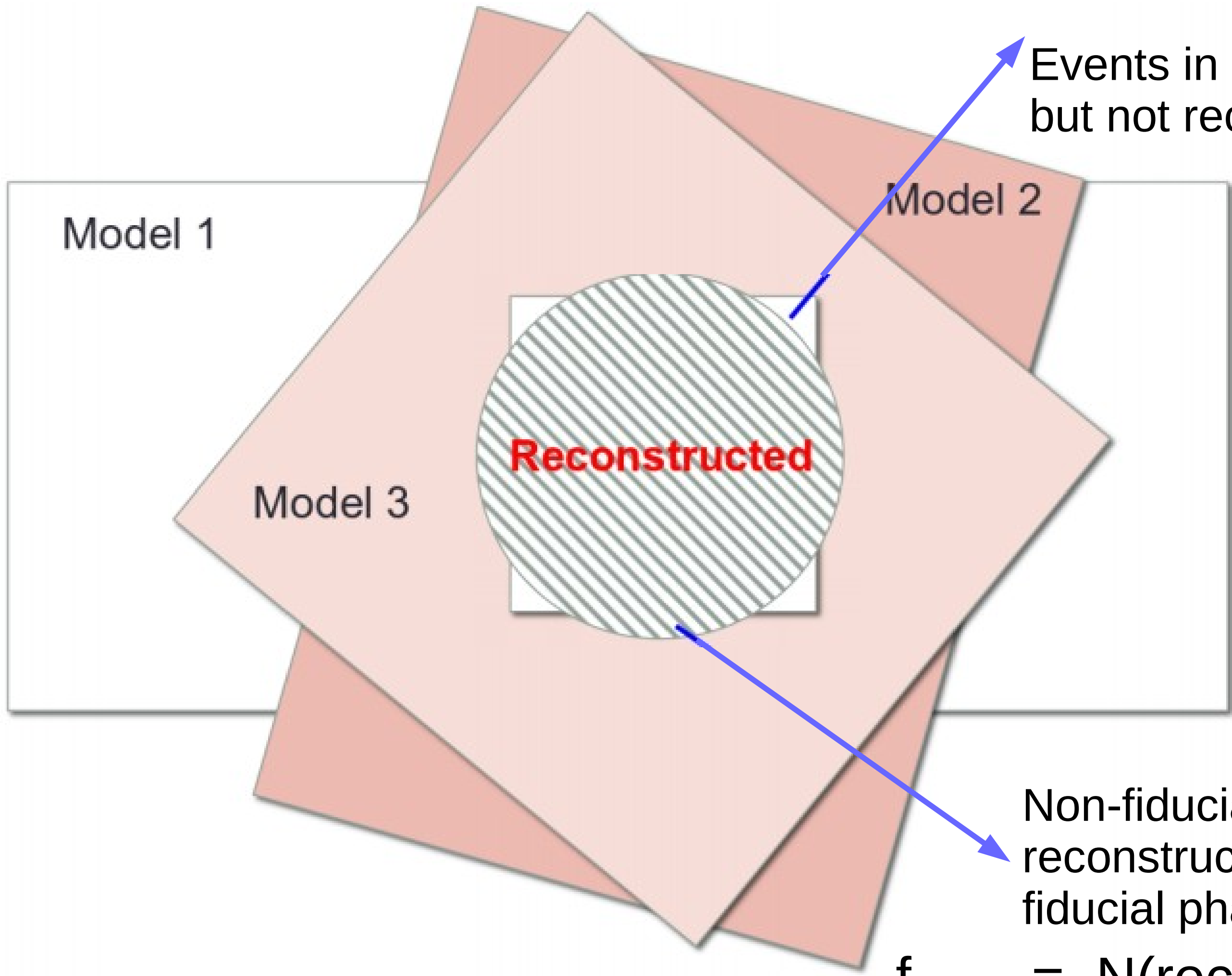
$$\varepsilon = \frac{N(\text{reco} \ \&\& \ \text{fid.})}{N(\text{fid.})}$$

Events in Fiducial phase space but not reconstructed



Non-fiducial events: events reconstructed but not from fiducial phase space

$$f_{\text{nonfid}} = \frac{N(\text{reco} \ \&\& \ !\text{fid.})}{N(\text{reco} \ \&\& \ \text{fid.})}$$

Analysis strategy

- The signal component is extracted from a fit to the m(4ℓ) distribution

Fiducial Signal Shape (P_{res}):

Double Sided Crystal Ball

→ norm proportional to σ_{fid}

→ efficiencies (ε) from simulation

"Non-Fiducial" Signal shape:

Same as fiducial shape

→ fraction of fiducial signal (f_{nonfid})

→ fraction depends on model

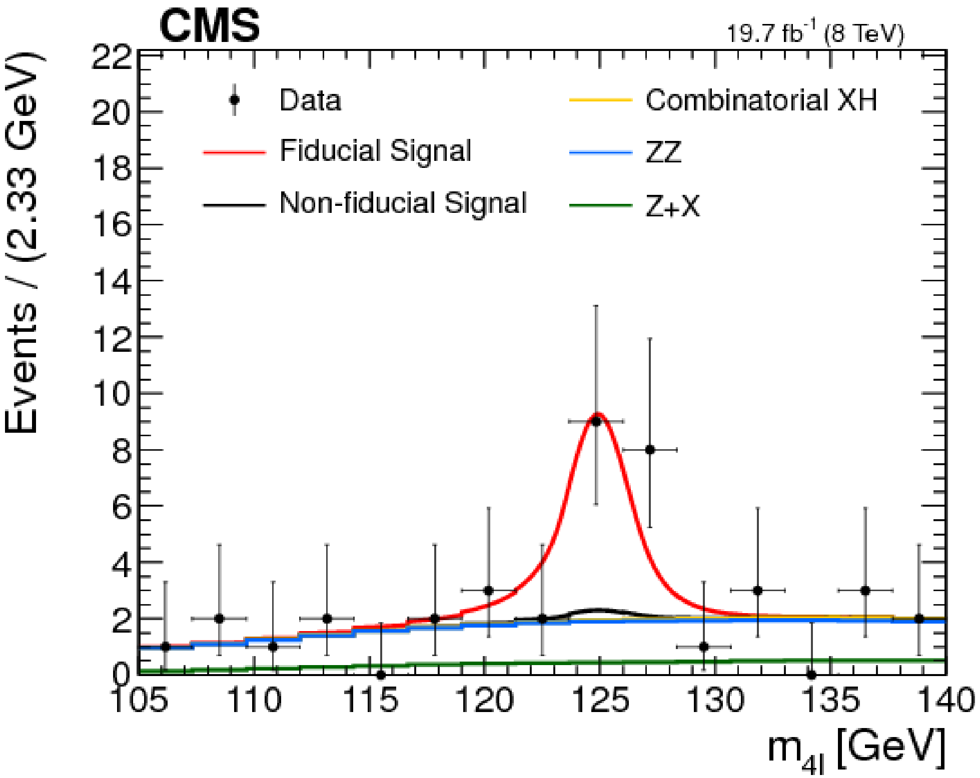
"Non-resonant" Signal Shape (P_{nonres}):

One or more leptons not directly from H decay (e.g. WH, ZH, ttH)

→ Landau distribution

→ shape constrained from simulation

→ norm +/- 10 times SM (uniform prior)



qqZZ,ggZZ shape and norm from MC

Z+X shape and norm from control regions in data

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

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

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

f = final state

i = observable bin at reco level

Systematic Uncertainties

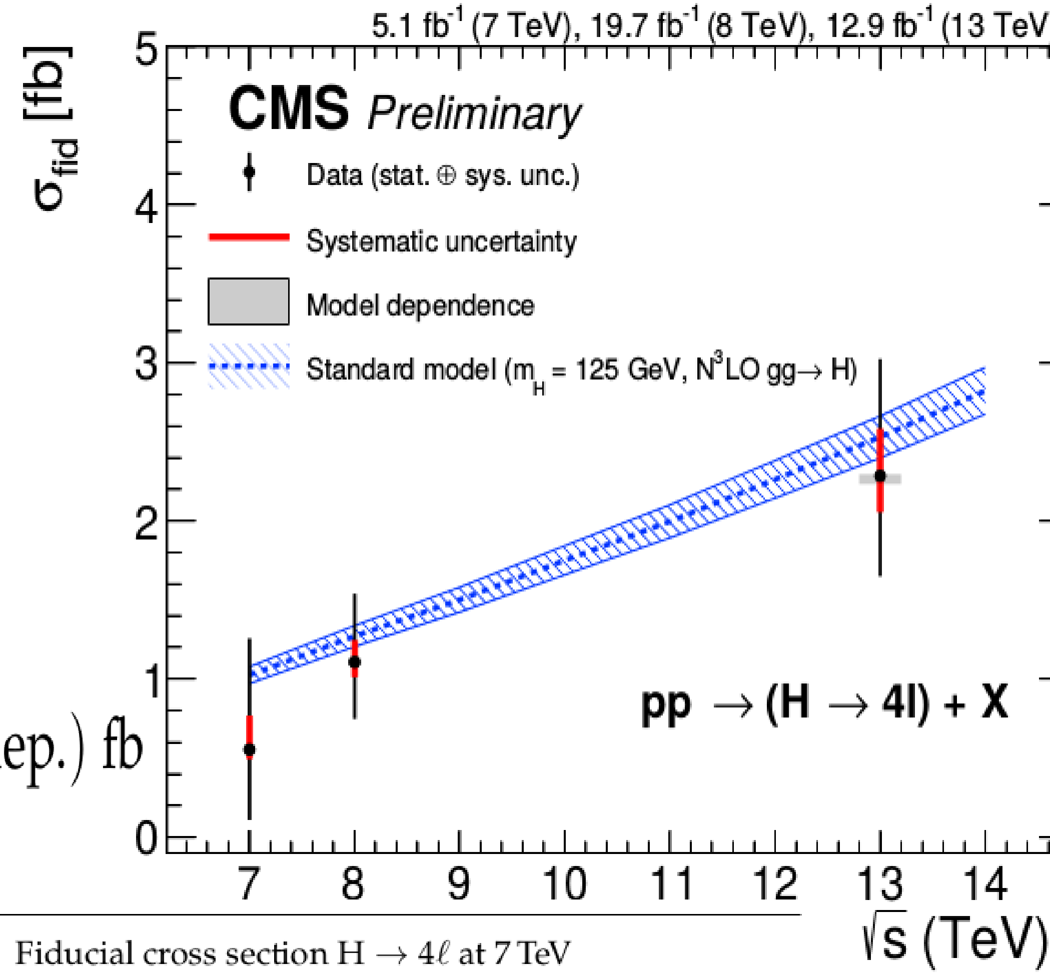
- Experimental systematic uncertainties mostly from Legacy paper:
  - → Background estimation
    - QCD scale (~3% qqZZ, ~24% ggZZ) and PDF (~3% qqZZ, 7% ggZZ)
    - Reducible Background (20%-40%)
  - → Lepton reconstruction efficiency (10% 4e, 4% 4mu)
  - → Signal Shape
    - Lepton energy scale (0.3% 4e, 0.1% 4mu)
    - Lepton energy resolution (20%)
  - → Non-resonant signal contribution
    - Effect on the final measurement is ~+4%/-11%
  - →Integrated Luminosity (2.2% at 7 TeV, 2.6% at 8 TeV)
    - Lepton energy scale (0.3% 4e, 0.1% 4mu)
    - Lepton energy resolution (20%)
- For observables involving jets, Jet Energy Scale
  - → Correlated across differential bins to preserve unity
  - → 3%-12% for signal, 2%-16% for background

Model depdence

- Model dependence of the measurement procedure is estimated by repeating the measurement using the efficiencies and non-fiducial ratios from a range of different models of production, decay, and spin-parity
  (exotic models taken from anomalous HVV couplings paper PRD 92 (2015) 012004)
  → In the inclusive measurement the model dependence is less than 7%
  → For differential measurements, in particular jet related observables, can be up to 25% for a particular bin
- If only SM production modes are considered, along with their existing experimental constraints (EPJC 75 (2015) 212), the model dependence is at most 3% for any measurement, and typically much smaller
- We quote the full model dependence without any experimental constraints as a separate systematic effect

Inclusive H → 4ℓ Results

- The acceptance is calclulated using Powheg at 13 TeV and HRes for 7,8 TeV
- The model dependence uses experimental constraints on the relative fraction of the various production modes
- All total cross sections taken from LHCHXSWG



$$\sigma_{\text{fid.}} = 2.29^{+0.74}_{-0.64}(\text{stat.})^{+0.30}_{-0.23}(\text{sys.})^{+0.01}_{-0.05}(\text{model dep.})\ \text{fb}$$

$$\sigma^{\text{SM}}_{\text{fid.}} = 2.53 \pm 0.13\ \text{fb}$$

Fiducial cross section H → 4ℓ at 7 TeV	
Measured	$0.56^{+0.67}_{-0.44}$ (stat) $^{+0.21}_{-0.06}$ (syst) ± 0.02 (model) fb
gg → H(HRES) + XH	$0.93^{+0.10}_{-0.11}$ fb
Fiducial cross section H → 4ℓ at 8 TeV	
Measured	$1.11^{+0.41}_{-0.35}$ (stat) $^{+0.14}_{-0.10}$ (syst) $^{+0.08}_{-0.02}$ (model) fb
gg → H(HRES) + XH	$1.15^{+0.12}_{-0.13}$ fb
Ratio of H → 4ℓ fiducial cross sections at 7 and 8 TeV	
Measured	$0.51^{+0.71}_{-0.40}$ (stat) $^{+0.13}_{-0.05}$ (syst) $^{+0.00}_{-0.03}$ (model)
gg → H(HRES) + XH	$0.805^{+0.003}_{-0.010}$

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H → 4ℓ Differential Results

RUN 1

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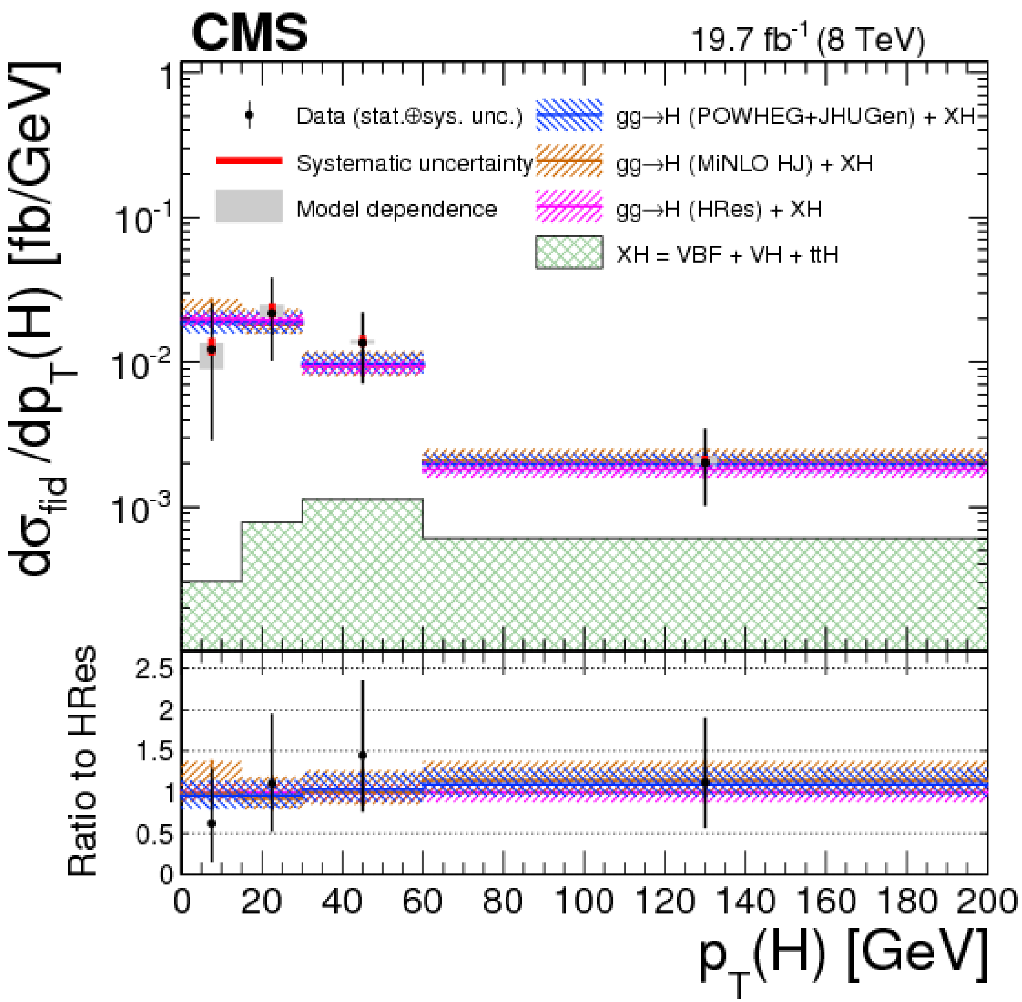

RUN 2

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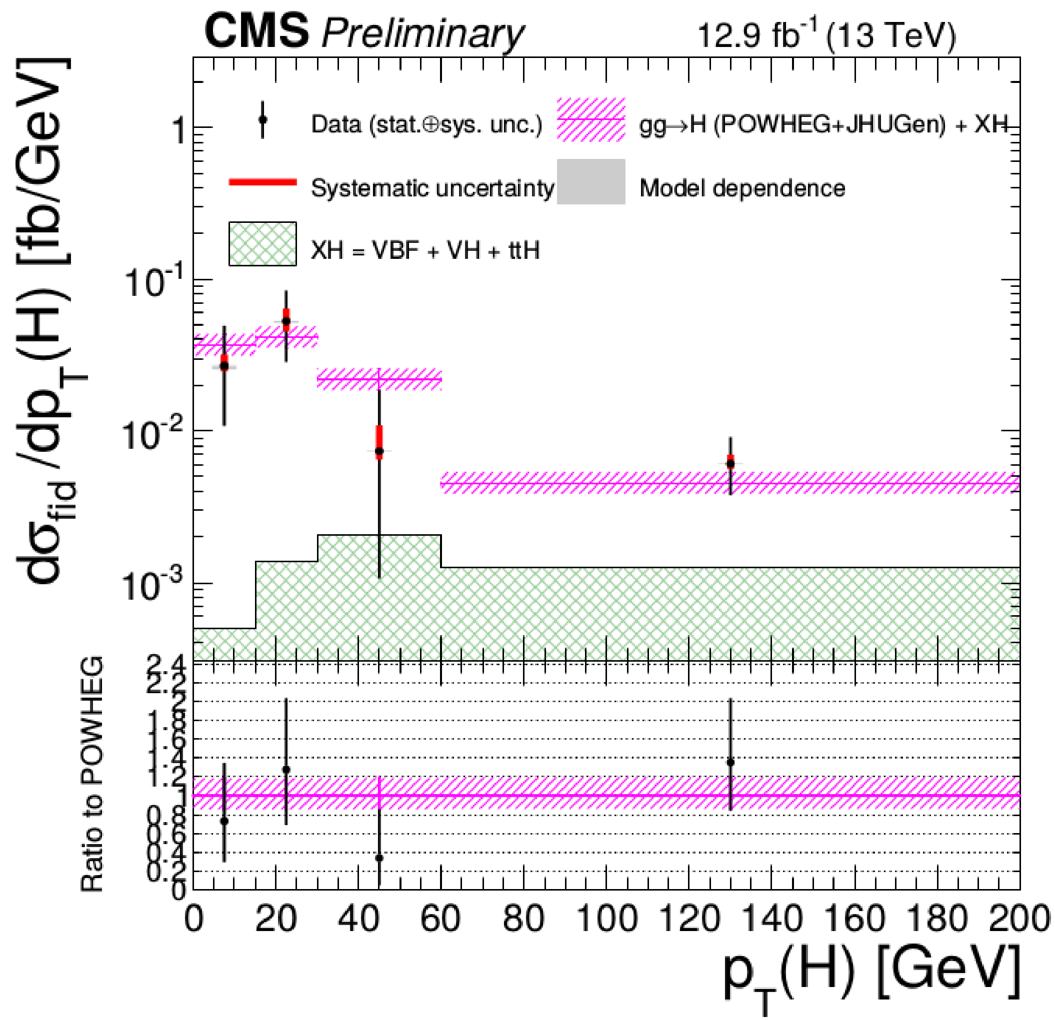

Differential observable p^T(H),Y(H)

- Sensitive to gluon fusion production mechanism and PDFs of colliding proton

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H → 4ℓ Differential Results

RUN 1

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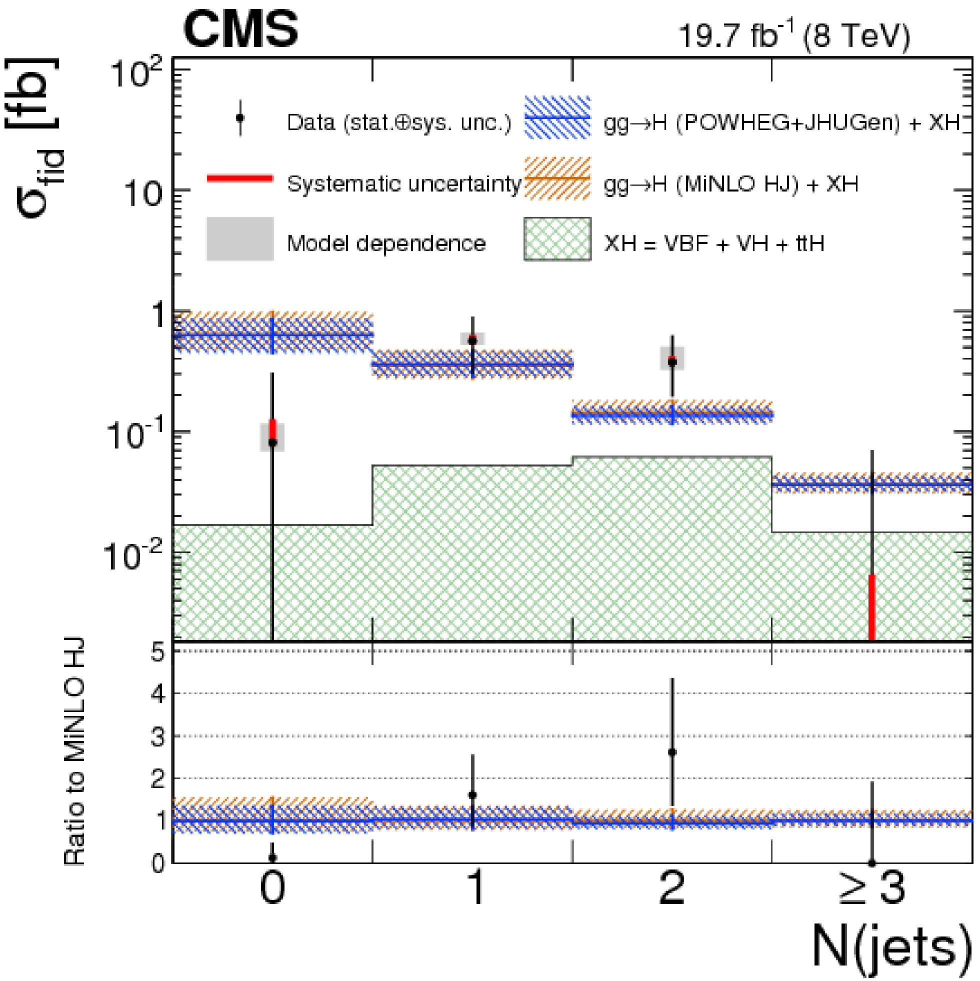

RUN 2

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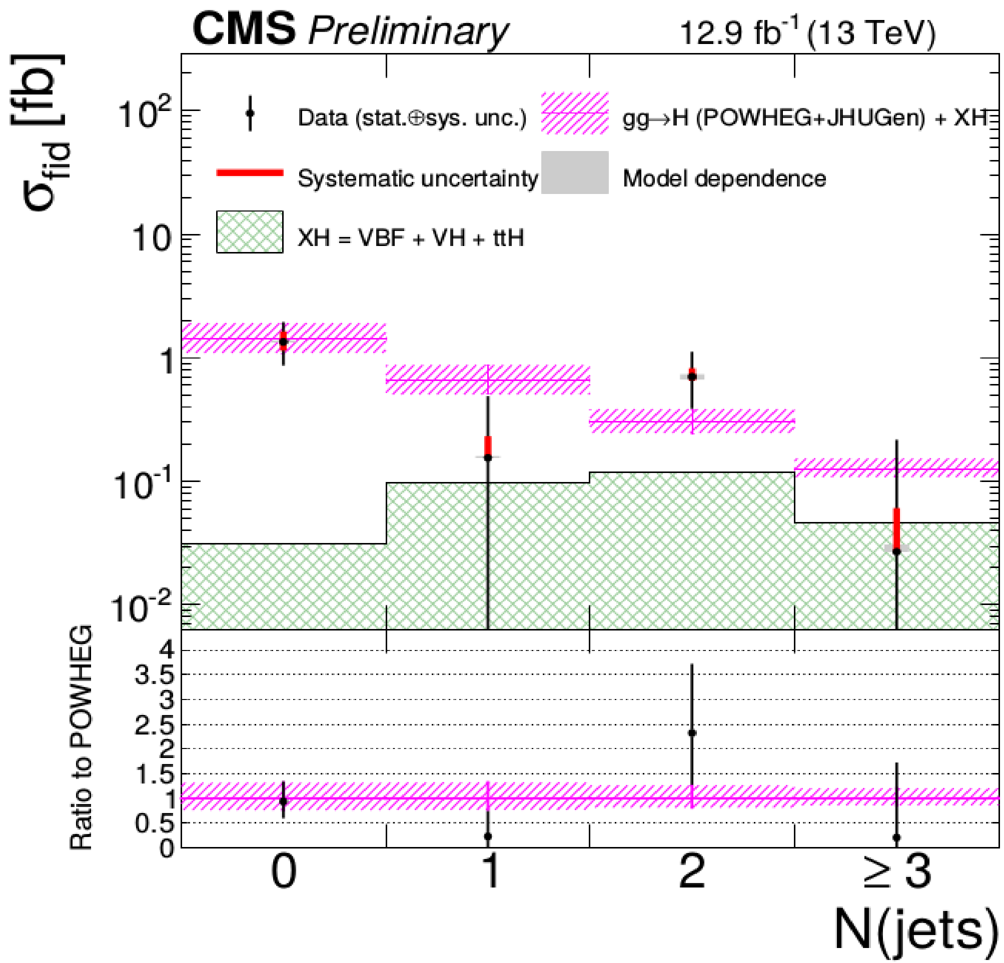
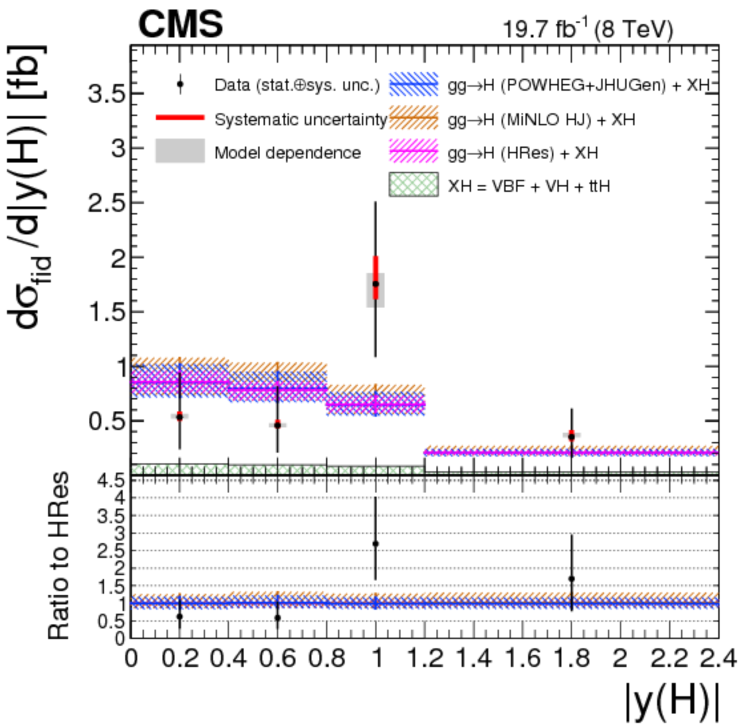
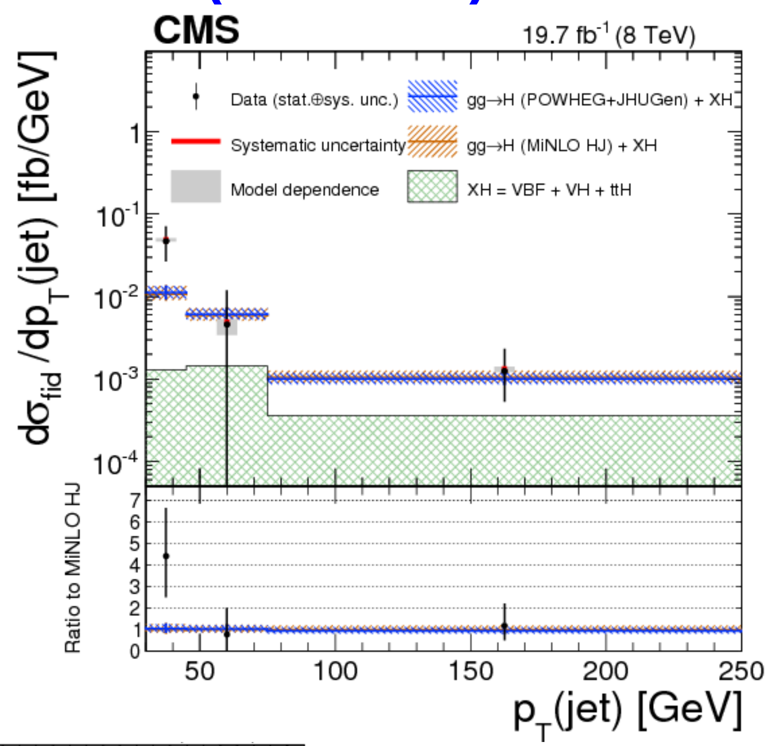


Differential observable N(jets), p^T (leading jet), y(H)-y(jet)

- Sensitive to theoretical modeling of hard quark radiation and relative contribution of different Higgs Boson production mechanism

H → 4ℓ Differential Results(RUN1)





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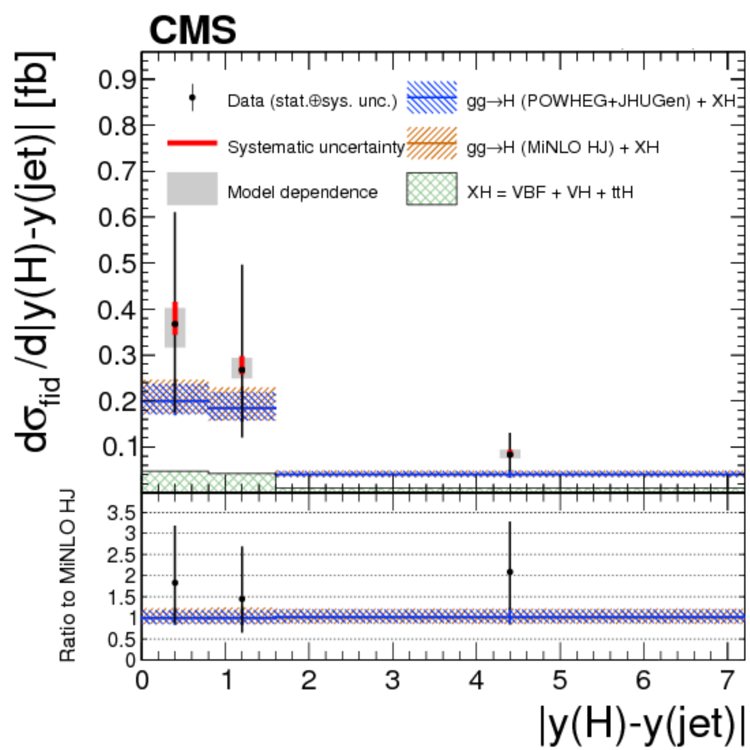


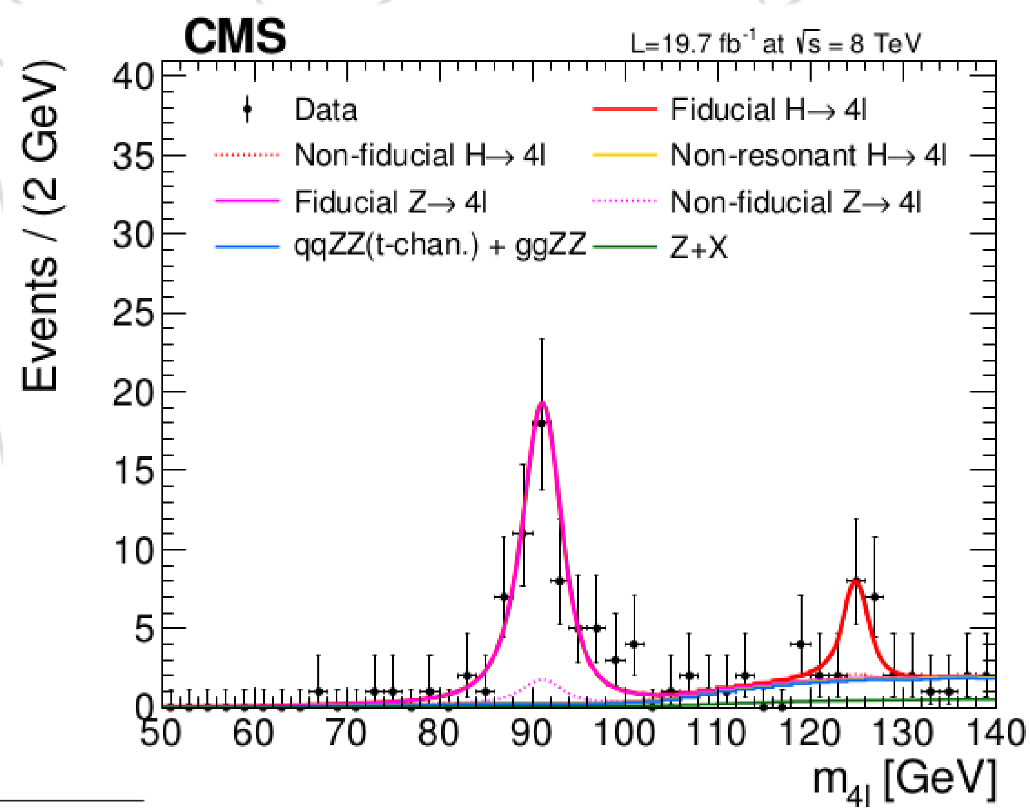
Simultaneous measurement of H→4ℓ and Z→4ℓ cross sections (RUN1)

The H→4ℓ and Z→4ℓ are measured independently using mass range [105-140 GeV] and [50-105 GeV]

In addition the methodology is generalized to measure H→4ℓ and Z→4ℓ simultaneously using mass range [50-140 GeV]

Part of systematics to be canceled (still dominated by statical uncertainty

S channel and t/u channel of qqZZ are treated independently Interference is account In systematics



Fiducial cross section $Z \to 4\ell$ at 8 TeV ($50 < m_{4\ell} < 105$ GeV)	
Measured	$4.81^{+0.69}_{-0.63}$ (stat) $^{+0.18}_{-0.19}$ (syst) fb
POWHEG	4.56 ± 0.19 fb

Ratio of fiducial cross sections of $H \to 4\ell$ and $Z \to 4\ell$ at 8 TeV ($50 < m_{4\ell} < 140$ GeV)	
Measured	$0.21^{+0.09}_{-0.07}$ (stat) ± 0.01 (syst)
$gg \to$ H(HRES) + XH and $Z \to 4\ell$ (POWHEG)	0.25 ± 0.04

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Conclusion

- Performed inclusive and differential measurement fiducial cross sections and several ratios using $H \rightarrow 4\ell$ decay and compared to different theoretical predictions using Run 1 and Run 2 data
  → Differential observable
    - p^T(H), Y(H), p^T(leading jet), Y(H)-Y(leading jet), N(jets) (RUN1)
    - p^T(H), N(jets) (RUN 2)

  → Estimated model dependence using wide range of models
- The measurements are found to be compatible with theoretical calculations based on the standard model