Higgs boson differential cross-section measurements at CMS

Alessandra Cappati
(LLR, École Polytechnique, in2p3, CNRS)

On behalf of the **CMS Collaboration**

31st International Workshop on Deep Inelastic Scattering
9 April 2024

Laboratoire Leprince-Ringuet

École Polytechnique IP Paris

EuroTechPostdoc2 Programme
Excellence in Science and Technology

CMS

Introduction

Differential cross-sections measurements → key to Higgs boson properties characterization

test of SM predictions for full spectra of variable of interest

probe possible **BSM hints**

Measured in **fiducial phase space** → largely **model independent** → results can be compared between channels and experiments, and with multiple theoretical models

Full Run 2 results from CMS in different decay channels

H→ ZZ* → 4l: JHEP 08 (2023) 040
H→$\gamma\gamma$: JHEP 07 (2023) 091
H→WW: JHEP 03 (2021) 003
H→bb: JHEP 12 (2020) 085
H→$\tau\tau$: Phys. Rev. Lett. 128 (2022) 081805, CMS-PAS-HIG-21-017

Presented in Johannes Erdmann's talk!

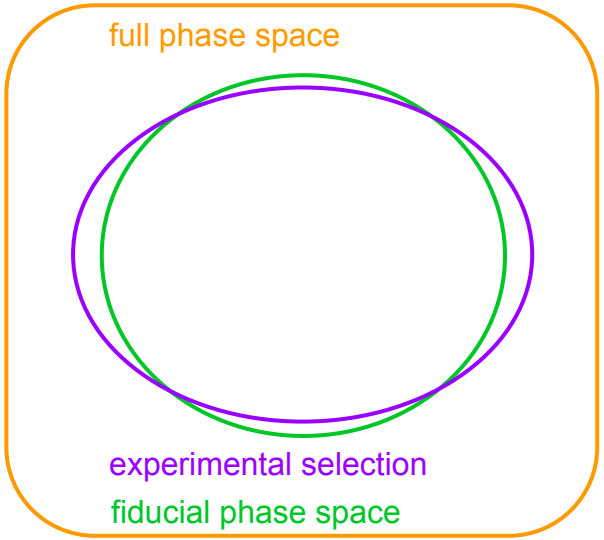
Fiducial Cross-Sections

Aim: provide **model independent** characterization of the Higgs boson properties
(even if SM is assumed when calculating the acceptance)

Data **unfolded** to correct for the detector effects → allow **direct comparison** with different **theoretical predictions**

Fiducial phase space defined to closely **match experimental acceptance** and **analysis selection**

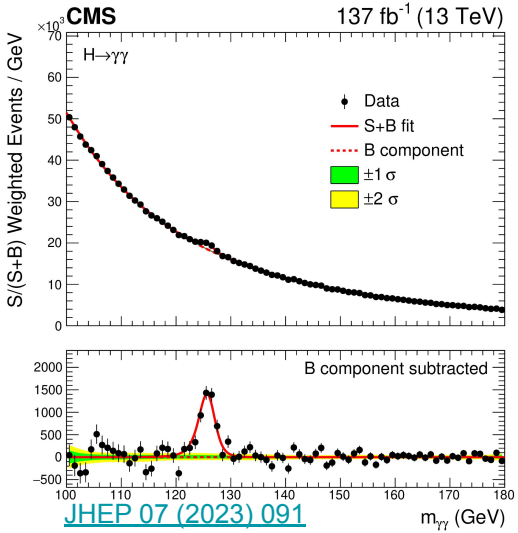
Fiducial cross-section also measured **differentially**
→ many kinematical variables sensitive to possible BSM



H→bosons

H→$\gamma\gamma$

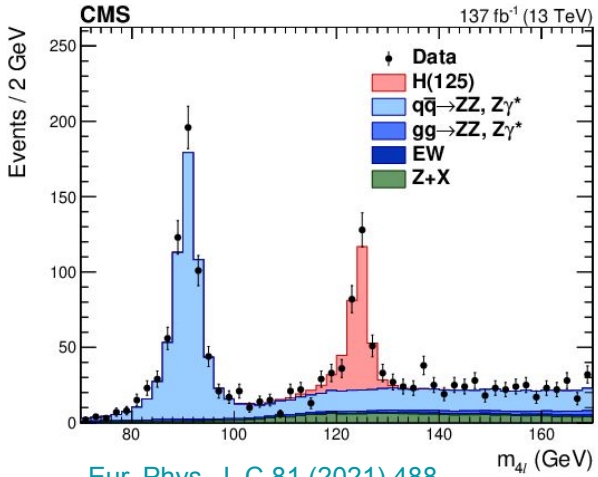
- Signal: events with 2 energetic photons
- Bkg: SM $\gamma\gamma$, γj, jj
- Results: ML fits on $m_{\gamma\gamma}$



JHEP 07 (2023) 091

H→ZZ

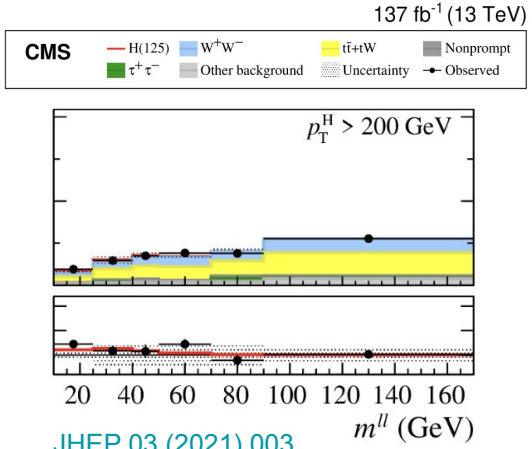
- Signal: events with 4 OS SF leptons (e, μ)
- Bkg: qqZZ, ggZZ, Z+X
- Results: ML fits on m_{ZZ}



Eur. Phys. J. C 81 (2021) 488

H→WW

- Signal: events with 1e+1μ + p^{T}_{miss} > 20 GeV
- Bkg: SM WW, tt+tW, $\tau\tau$, nonprompt leptons
- Results: fits on (m_{ll}, m_{T}^{H})



JHEP 03 (2021) 003

H→bosons: inclusive results

H→γγ

$\sigma_{\text{fid}} = 73.4^{+5.4}_{-5.3}(\text{stat})^{+2.4}_{-2.2}(\text{sys})$ fb

$\sigma^{\text{th}}_{\text{fid}} = 75.4 \pm 4.1$ fb

JHEP 07 (2023) 091

H→ZZ

$\sigma_{\text{fid}} = 2.73 \pm 0.22(\text{stat}) \pm 0.15(\text{sys})$ fb

$\sigma^{\text{th}}_{\text{fid}} = 2.86 \pm 0.15$ fb

JHEP 08 (2023) 040

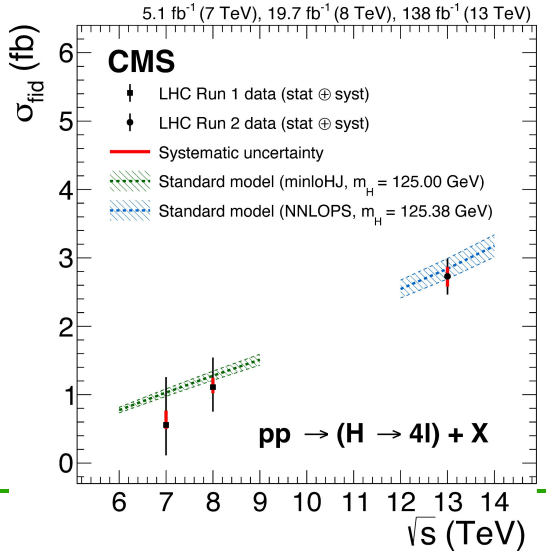
H→WW

$\sigma_{\text{fid}} = 86.5 \pm 9.5$ fb

$\sigma^{\text{th}}_{\text{fid}} = 82.5 \pm 4.2$ fb

JHEP 03 (2021) 003

More results in Johannes Erdmann's talk!



- Overall precision of 10%
- Profit from large S/B ratio and full kinematic information

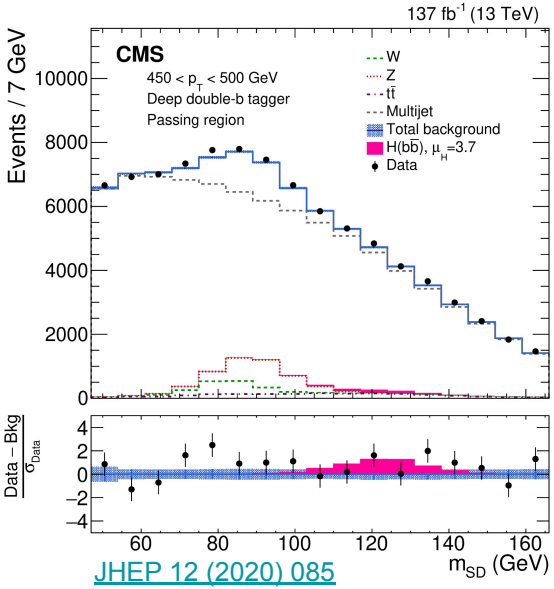
H→fermions

H→bb (boosted)

- Signal: events with 1 AK8 jet
  + veto events with p^T_{miss} > 140 GeV
  + soft drop (SD) algorithm
- Bkg: QCD multijet, tt
- Results: ML fit on m_{SD}

reduce tt bkg

reduce QCD bkg

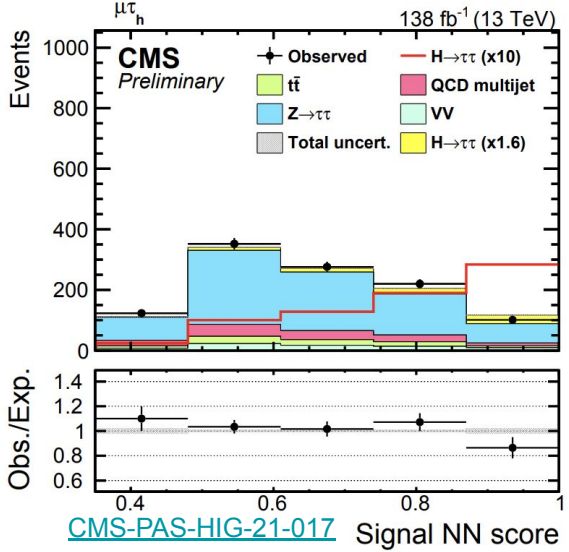


JHEP 12 (2020) 085

H→ττ

- Signal: events with 2 τ (all decays)
  + p^T_{miss} < 60 GeV
  or + $m_{\tau\tau}$ > 50 GeV (boosted)
- Bkg: Z→ττ, tt, VV, j/l/τ_h mis-ID, QCD multijet
- Results: fit on $m_{\tau\tau}$ in observables bins, or fit on NN output (boosted)

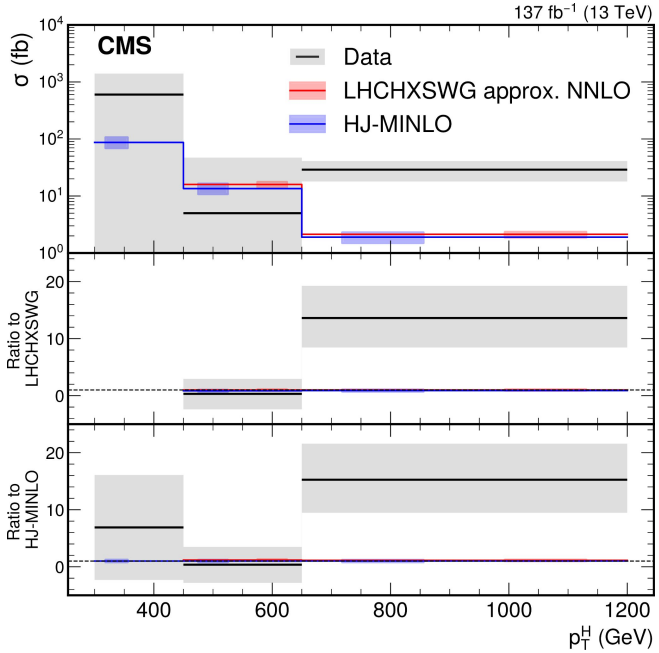
remove overlap w/ H→WW



CMS-PAS-HIG-21-017

H→fermions: inclusive results

- both channels **statistically dominated**



H→bb

fiducial results given in p_T^H bins

JHEP 12 (2020) 085

- **First** differential results in H→$\tau\tau$

H→$\tau\tau$

$\sigma_{\text{fid}} = 426 \pm 102\,\text{fb}$

$\sigma_{\text{fid}}^{\text{th}} = 408 \pm 27\,\text{fb}$

Phys. Rev. Lett. 128 (2022) 081805

$\sigma_{\text{fid}} = 1.96^{+0.86}_{-0.69}\,\text{fb}$

$\sigma_{\text{fid}}^{\text{th}} = 1.20 \pm 0.20\,\text{fb}$

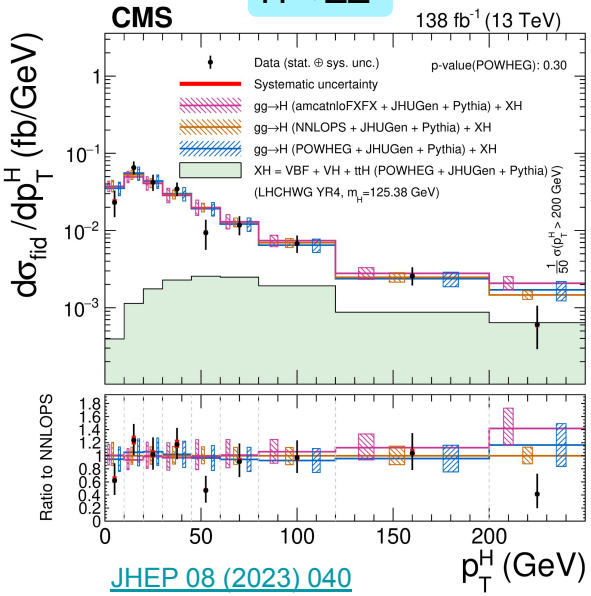
(boosted)

CMS-PAS-HIG-21-017

Higgs boson p_T

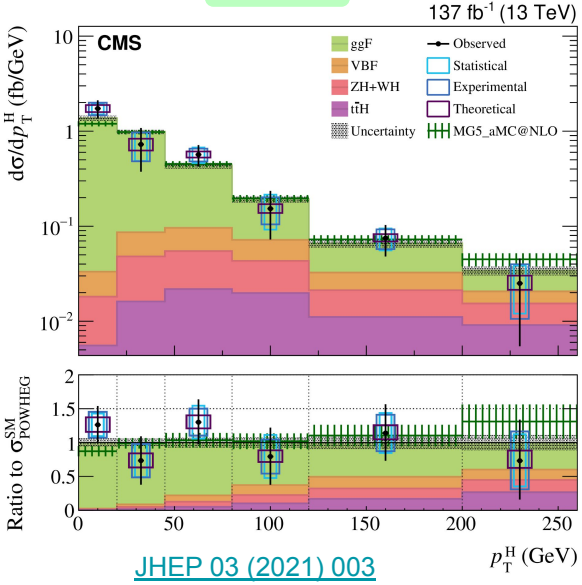
- p_T^H distribution probes perturbative **QCD modelling** of Higgs production
- Variations of couplings can **distort shape** of p_T^H spectrum
- Different **models** provided by theorists to describe shape distortions

H→ZZ



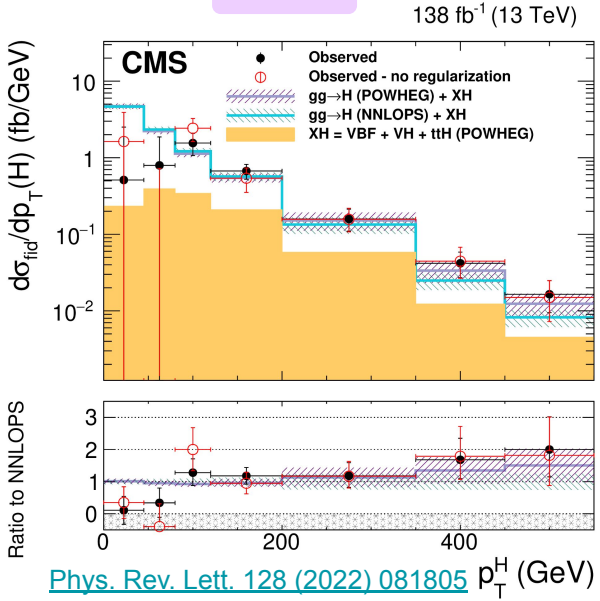
JHEP 08 (2023) 040

H→WW



JHEP 03 (2021) 003

H→ττ



Phys. Rev. Lett. 128 (2022) 081805

Higgs boson p_T: interpretations

p_T^H → set limits on **H self-coupling** and constraints on **couplings modifiers** to **b** and **c quarks**

- sizable contributions from **ttH** and **VH** for $\mathbf{k_\lambda}$
  → thanks to larger V and top masses
- **ggH** used to set constraints on $\mathbf{k_b}$ and $\mathbf{k_c}$
  → possible modification from b and c quarks in ggH loop

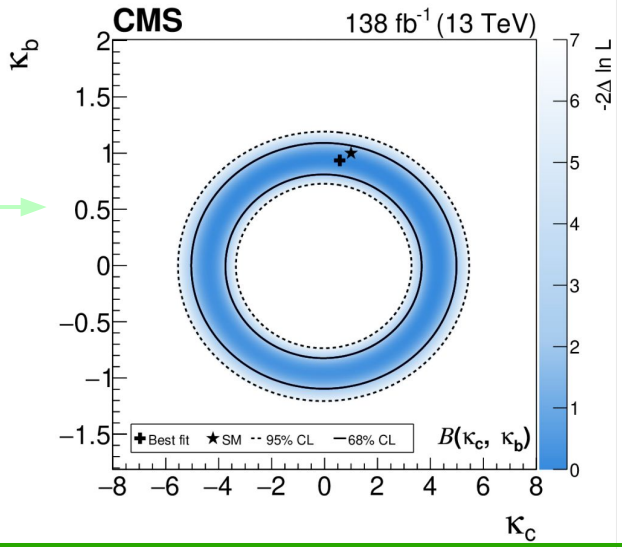
H→ZZ
JHEP 08 (2023) 040

95% CL limits assuming **BR dependent on k_b, k_c**

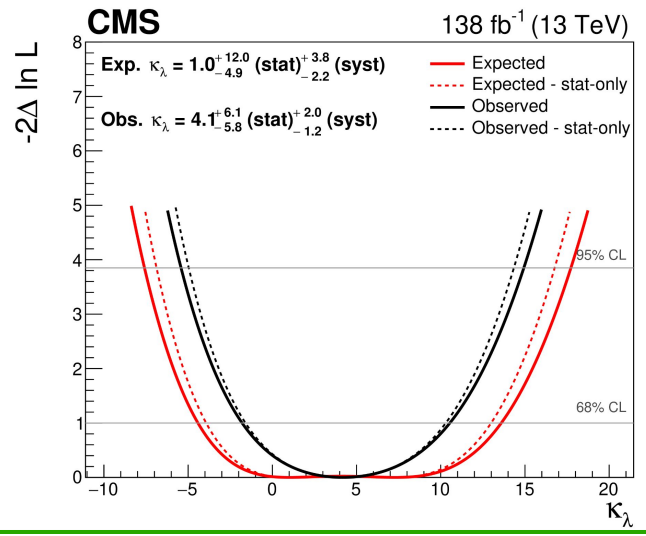
-1.1 (-1.3) < k_b < 1.1 (1.2)
-5.3 (-5.7) < k_c < 5.2 (5.7)

95% CL limits w/ H→ZZ BR as unconstrained parameters in fit

-5.6 (-5.5) < k_b < 8.9 (7.4)
-20 (-19) < k_c < 23 (20)



-5.5 (7.7) < k_λ < 15.1 (17.9) @95% CL



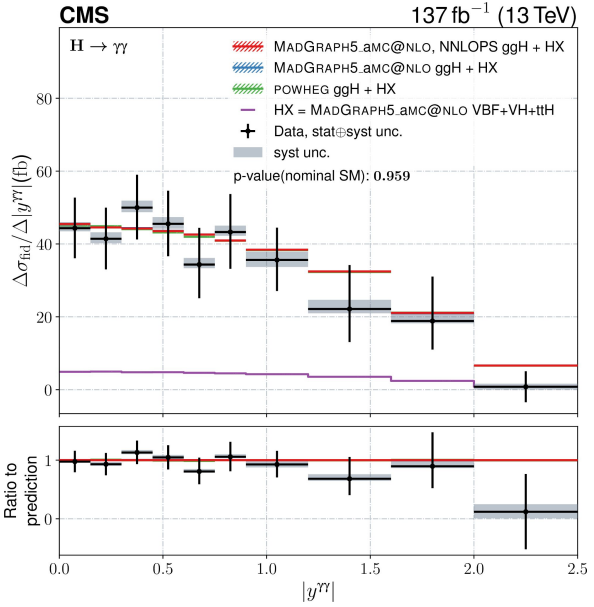
Higgs boson rapidity

y^H probes the **PDFs** and Higgs boson **production** modes

- measurement statistically dominated
- 20-30 % precision with full Run2 statistics

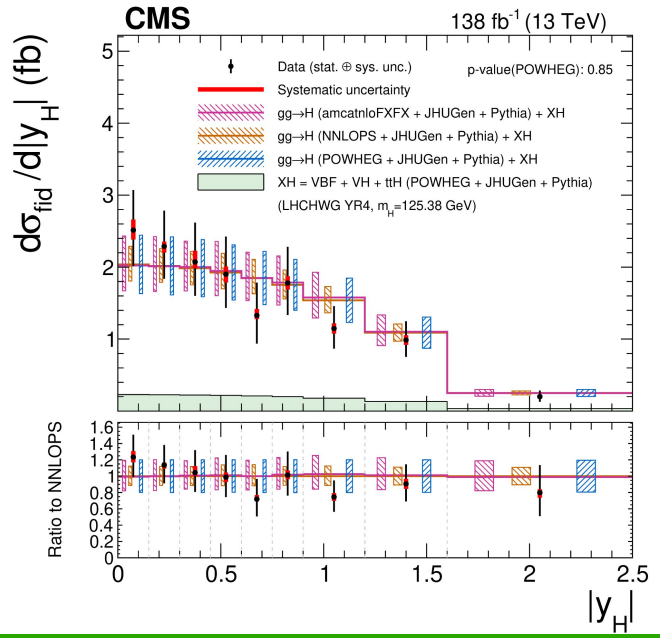
H→ZZ

JHEP 08 (2023) 040



H→$\gamma\gamma$

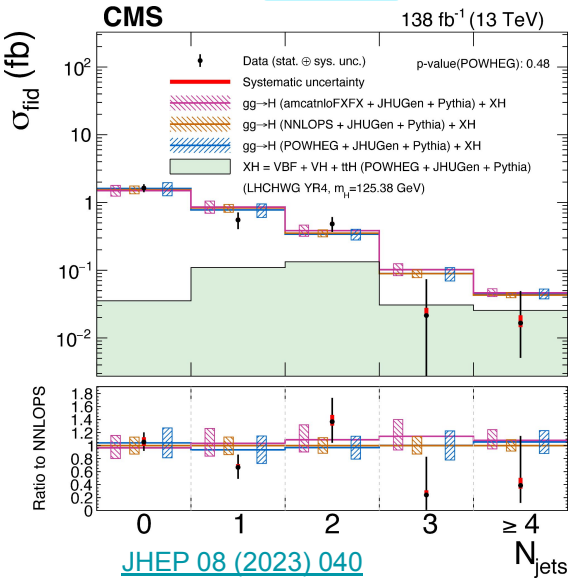
JHEP 07 (2023) 091



Number of Jets

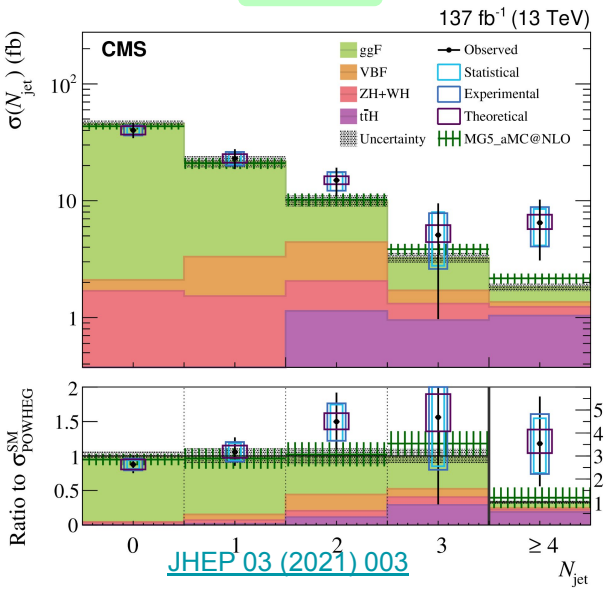
Jet variables useful to test **modelling** of **QCD radiation** and **production mechanisms**
→ H→$\tau\tau$ channel great handle for large jet multiplicity region

H→ZZ



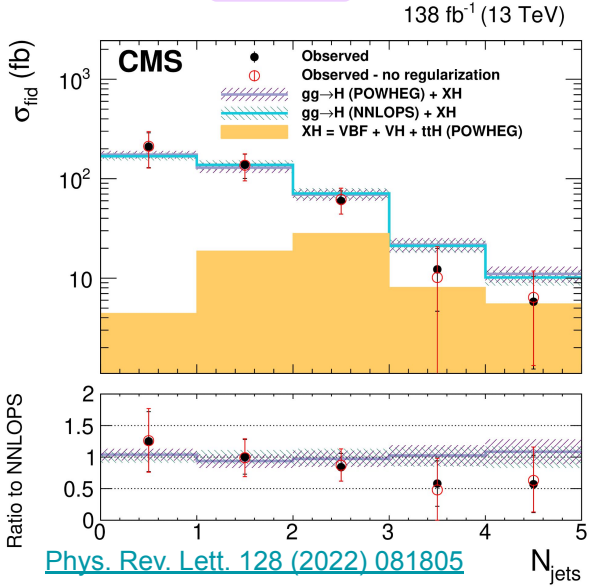
JHEP 08 (2023) 040

H→WW



JHEP 03 (2021) 003

H→$\tau\tau$

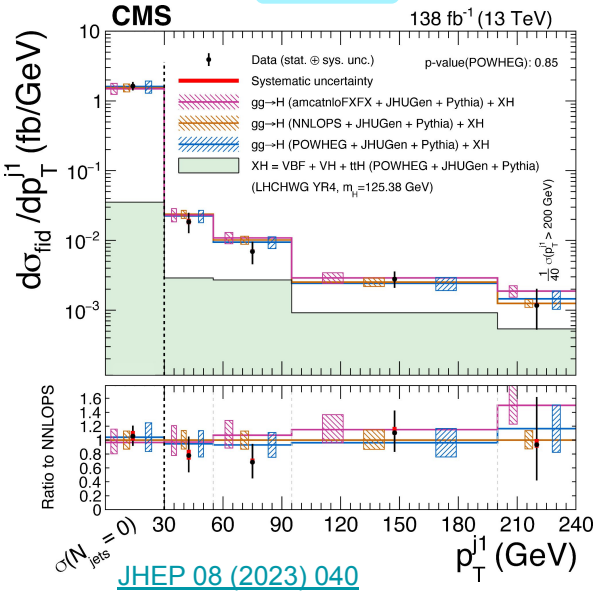


Phys. Rev. Lett. 128 (2022) 081805

Leading jet p_T

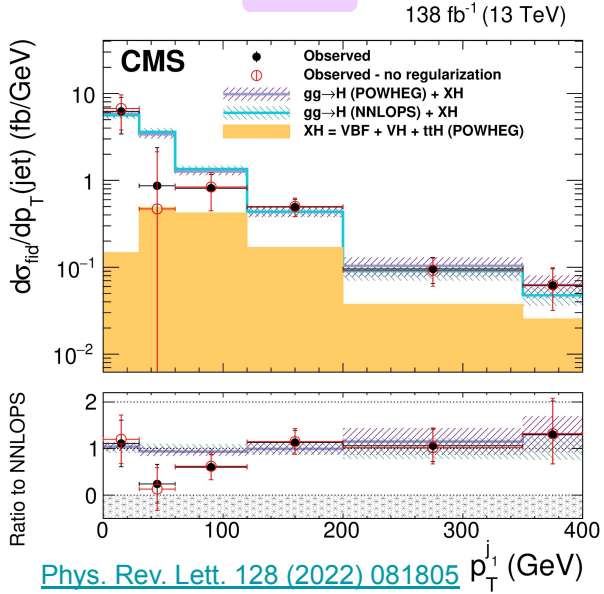
Jet variables useful to test **modelling** of **QCD radiation** and **production mechanisms**
→ H→$\tau\tau$ channel great handle for high p_T region

H→ZZ



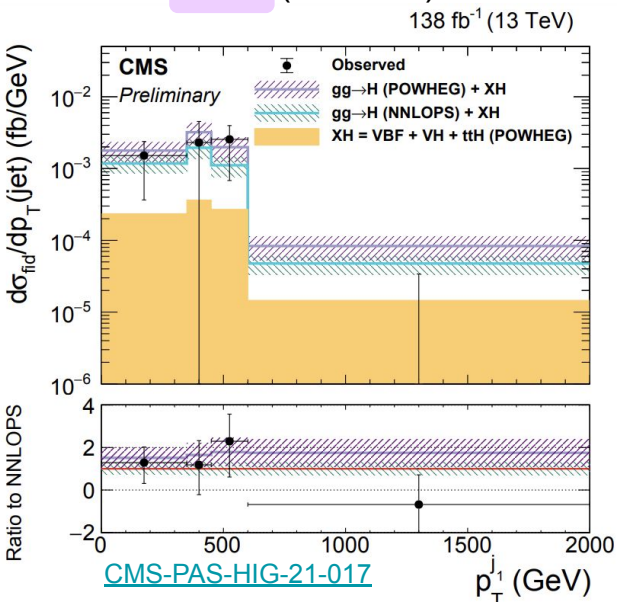
JHEP 08 (2023) 040

H→$\tau\tau$



Phys. Rev. Lett. 128 (2022) 081805

H→$\tau\tau$ (boosted)



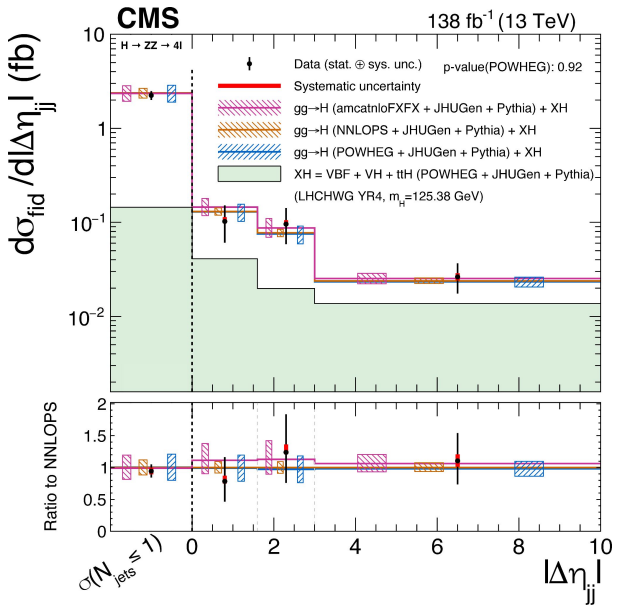
CMS-PAS-HIG-21-017

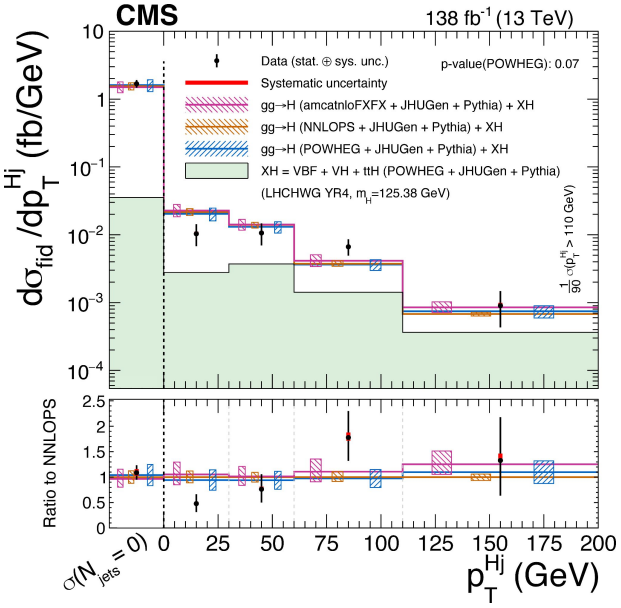
Other jet observables

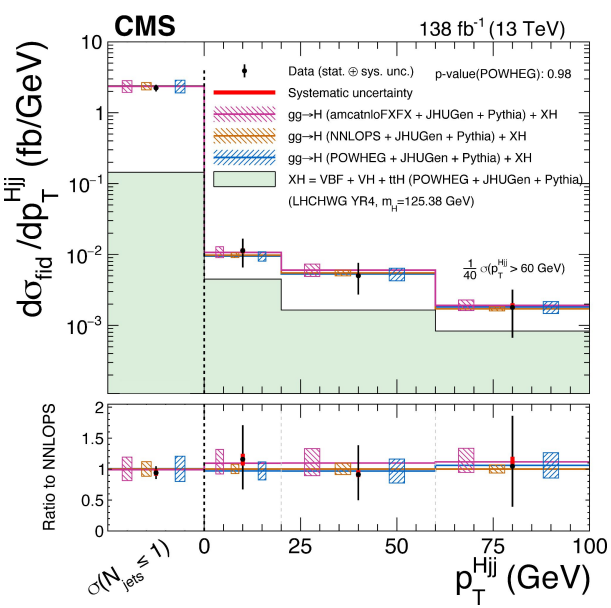
Jet variables useful to test **modelling** of **QCD radiation** and **production mechanisms**
→ kinematics of **di-jet**, **H+j**, **H+jj** systems
→ 0-jet bin defined

H→ZZ

JHEP 08 (2023) 040







Rapidity-weighted jet observables

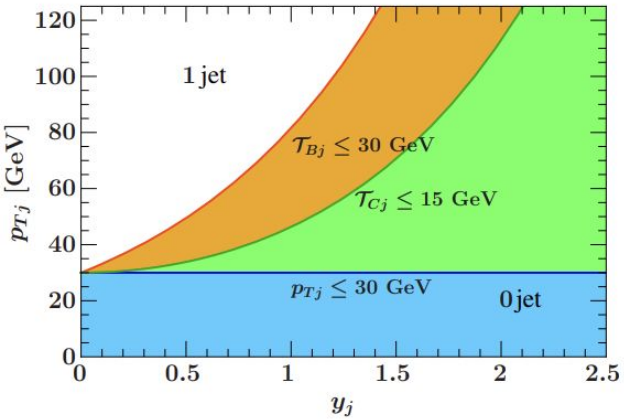
H→ZZ

JHEP 08 (2023) 040

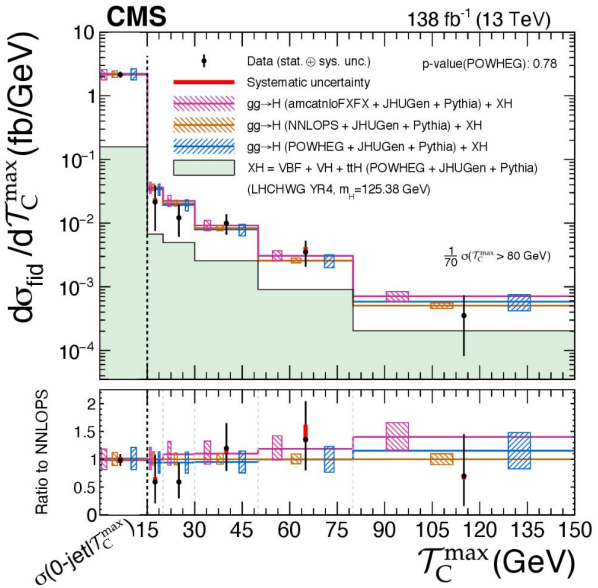
Jet transverse momentum **weighted** by a **function of jet rapidity**
→ useful to **test QCD resummation**
→ 0-jet bin defined

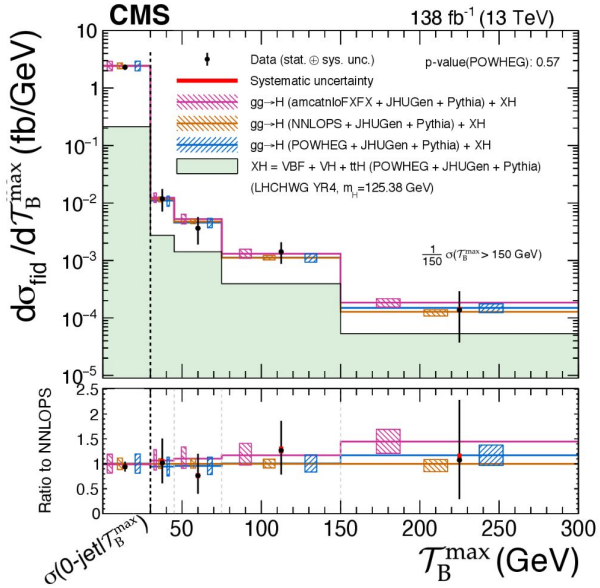
$$\mathcal{T}_C^{\max} = \max_j \left(\frac{\sqrt{E_j^2 - p_{z,j}^2}}{2\cosh\left(y_j - y_H\right)} \right)$$

$$\mathcal{T}_B^{\max} = \max_j \left(m_T^j e^{-|y_j - y_H|} \right)$$



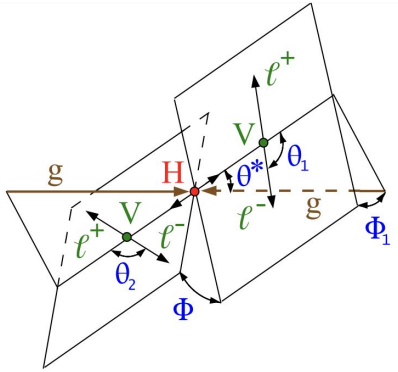
Phys. Rev. D 91, 054023





Decay observables

- 7 parameters fully describing the H→4l decay:
  - **Z masses** (m_{Z1}, m_{Z2})
  - Angular variables for **fermion kinematics** (Φ, $\cos\Theta_1$, $\cos\Theta_2$)
  - Angular **variables connecting production and decay** (Φ_1, $\cos\Theta^*$)

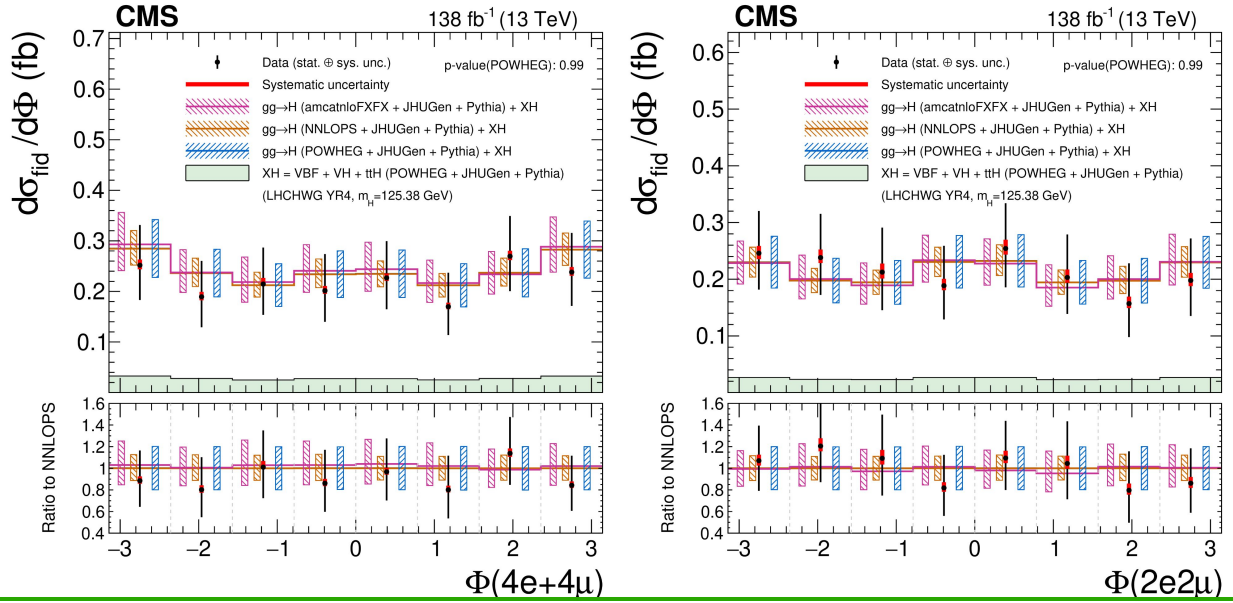


Results divided for identical (4e+4μ) and different (2e2μ) flavour final states

→ highlight sensitivity of same-flavour lepton interference effects

H→ZZ

JHEP 08 (2023) 040



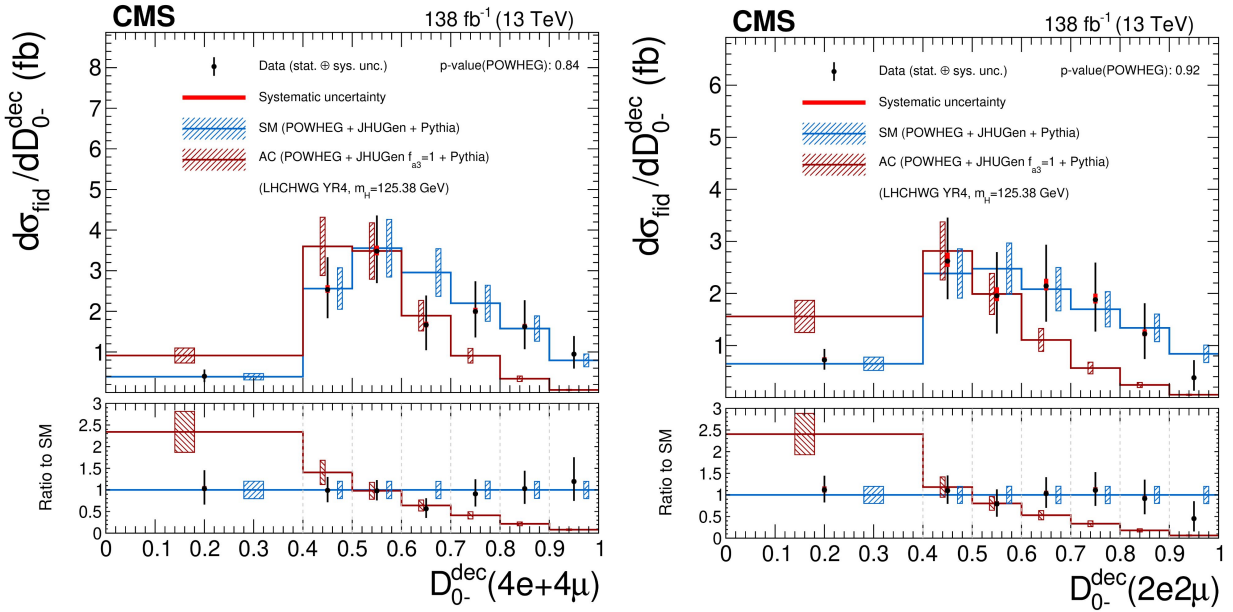
Decay observables: ME discriminants

ME **discriminants** sensitive to **HVV anomalous couplings**
→ $D_{0^-}^{dec}$ sensitive to possible CP-violation effects
→ more discriminants in the paper

H→ZZ

JHEP 08 (2023) 040

- Results compared to **different BSM hypotheses**
- Presented separately for identical (4e+4μ) and different (2e2μ) flavour final states



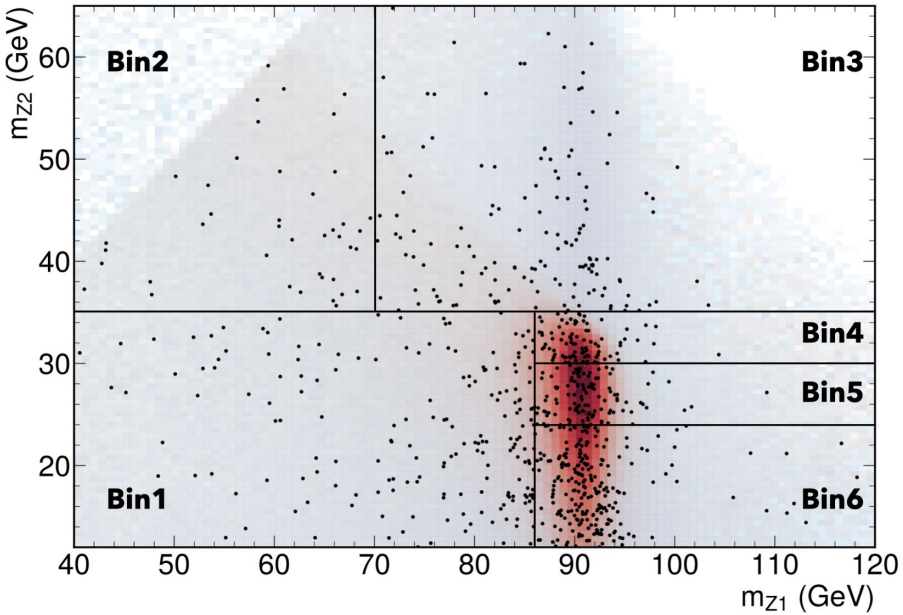
Double differential observables

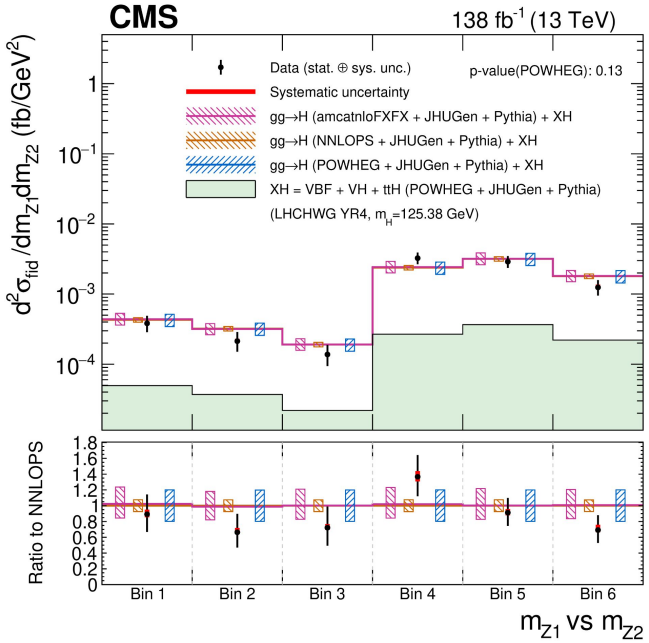
H→ZZ

JHEP 08 (2023) 040

Extensive set of double differential observables to probe specific phase space regions

→ T_C^{max} vs p_T^H | m_{Z1} vs m_{Z2} | N_{jet} vs p_T^H | p_T^H vs p_T^{Hj} | $|y_H|$ vs p_T^H | p_T^{j1} vs p_T^{j2}





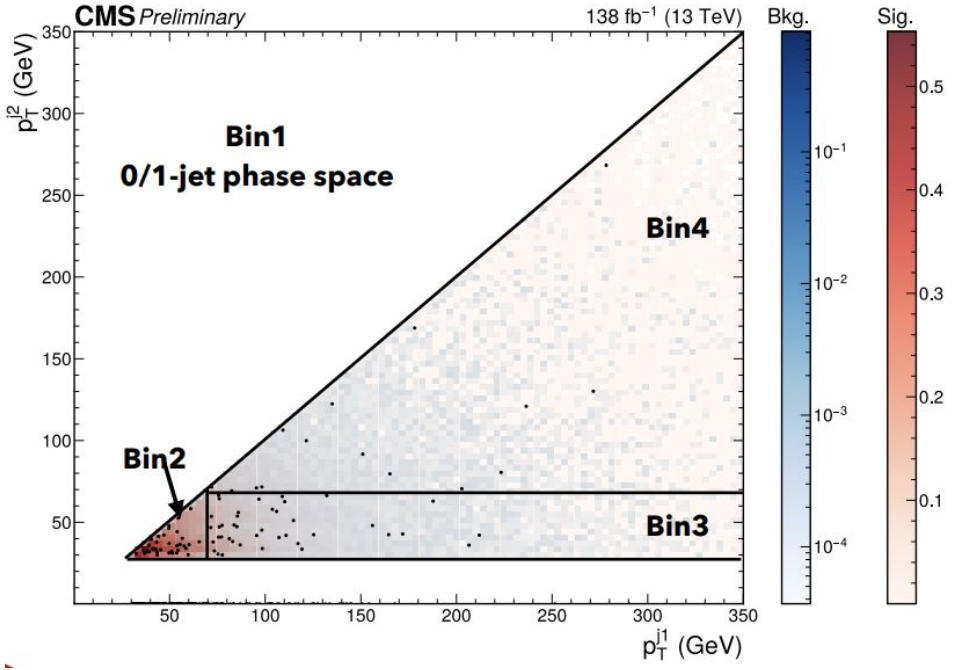
Double differential observables

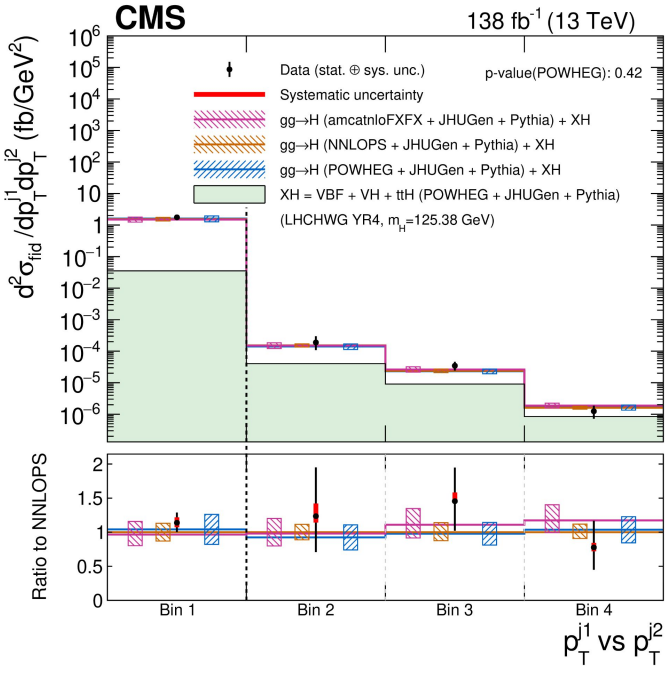
H→ZZ

JHEP 08 (2023) 040

Extensive set of double differential observables to probe specific phase space regions

→ T_C^{max} vs p_T^H m_{Z1} vs m_{Z2} N_{jet} vs p_T^H p_T^H vs p_T^{Hj} $|y_H|$ vs p_T^H p_T^{j1} vs p_T^{j2}





Conclusions

Run2 data allow extensive study of differential Higgs boson cross-sections

Variety of measurement reported in different decay channels:

- observables targeting **production** and **decay**
- **double differential** observables
- **interpretation** of p_T spectrum

→ Differential distributions provide a **handle** to set limits on various **BSM couplings**

No tensions with SM observed

Precision measurement has just started!

- Still **statistically** limited
- **Many improvements** already in place!