Latest CMS results in the H→ZZ→4l channel

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On behalf of **CMS Collaboration**

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Laboratoire Leprince-Ringuet

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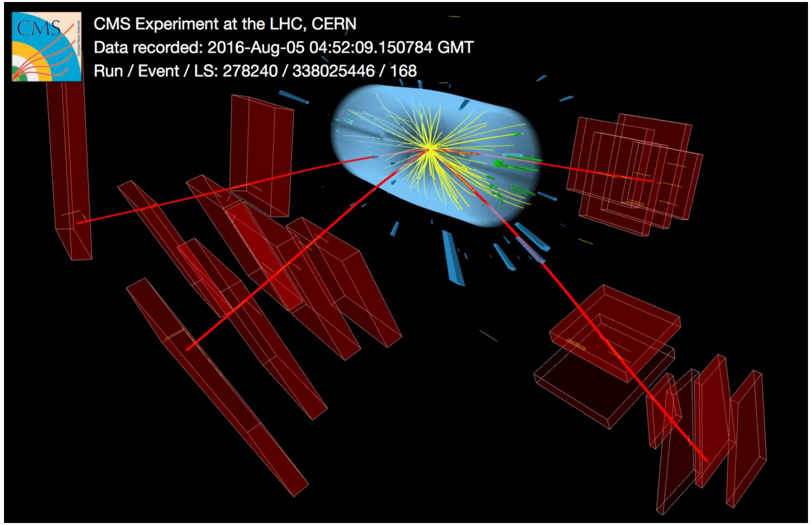
CMS

The H→ZZ→4l Channel

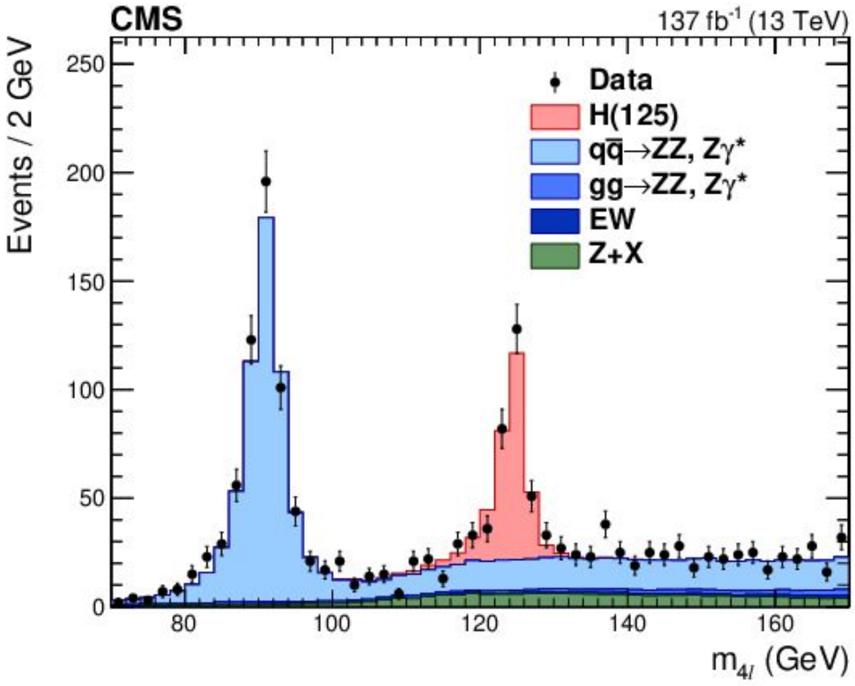
- **Golden channel**: important for the discovery and to study of H properties
  - **Clear** 4 lepton **signature** provides large S/B
  - **Complete reconstruction** of the final state decay products
  - But very small Branching fraction (0.012%)

- Results presented in this talk:
  - Eur. Phys. J. C 81 (2021) 488
  - CMS-PAS-HIG-21-009 New!



The H→ZZ→4l Channel

- Selection:
  →**4l** (e, μ)
  →**Z** candidate
  →**ZZ** candidate
  →**best ZZ** candidate chosen (if more than 1) with:
  - Kinematic discriminant (MELA pkg)
  - Highest p_T of Z_2 (for differential cross sections)
- Background:
  - ZZ estimated from MC
  - Z+X (reducible) from data
- Additional objects for event categorization
- Matrix element discriminants and multidimensional ML fits to extract results



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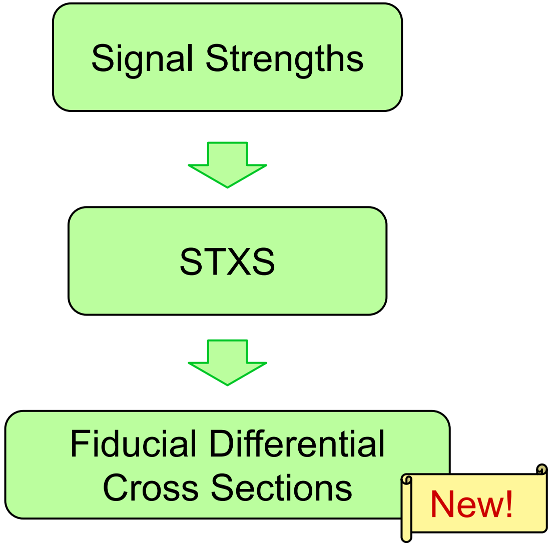
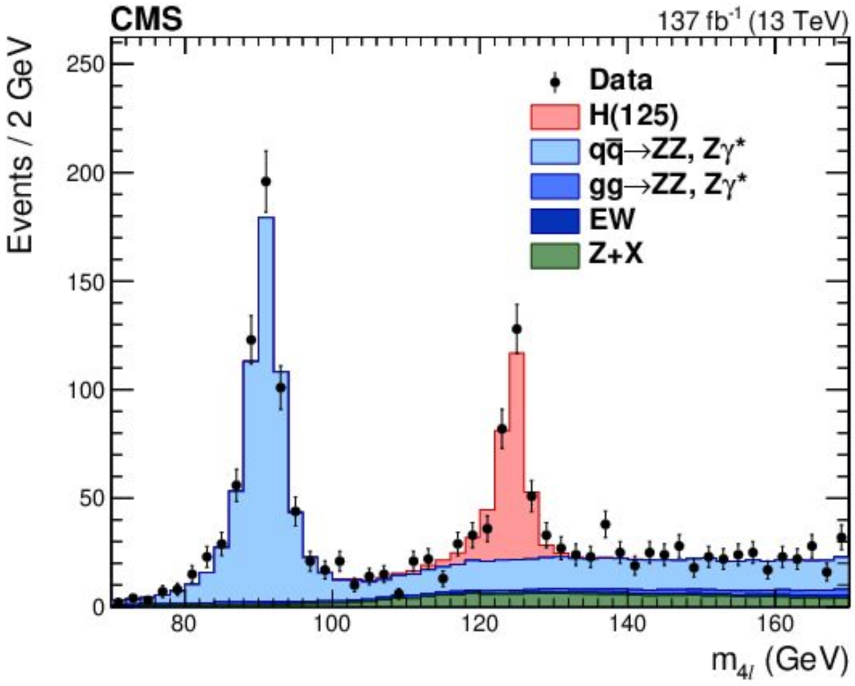
The H→ZZ→4l Results





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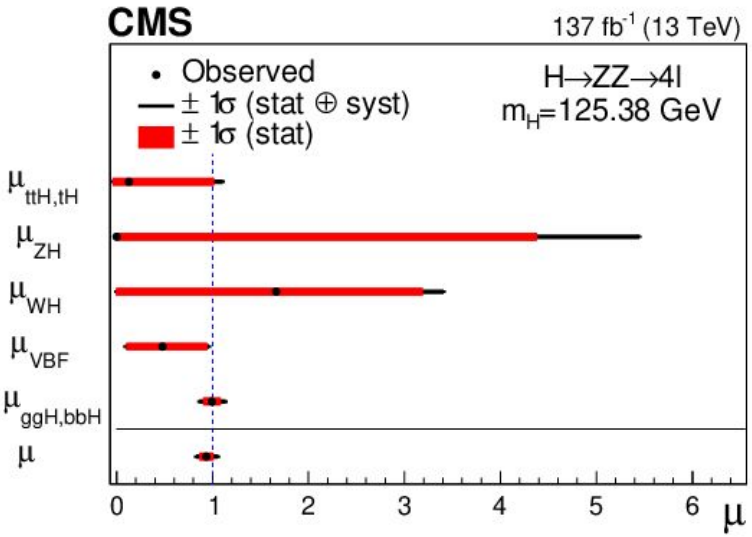
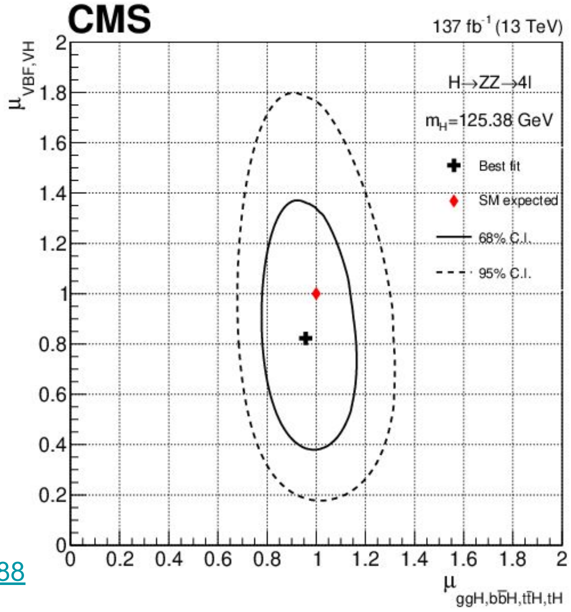
Signal strengths

- Defined as ratio of the measured cross section and the SM expectation
- Inclusive: μ **= 0.94 ± 0.07(stat)** $^{+0.07}_{-0.06}$ **(th)** $^{+0.06}_{-0.05}$**(exp)**
- Consistent with SM expectations





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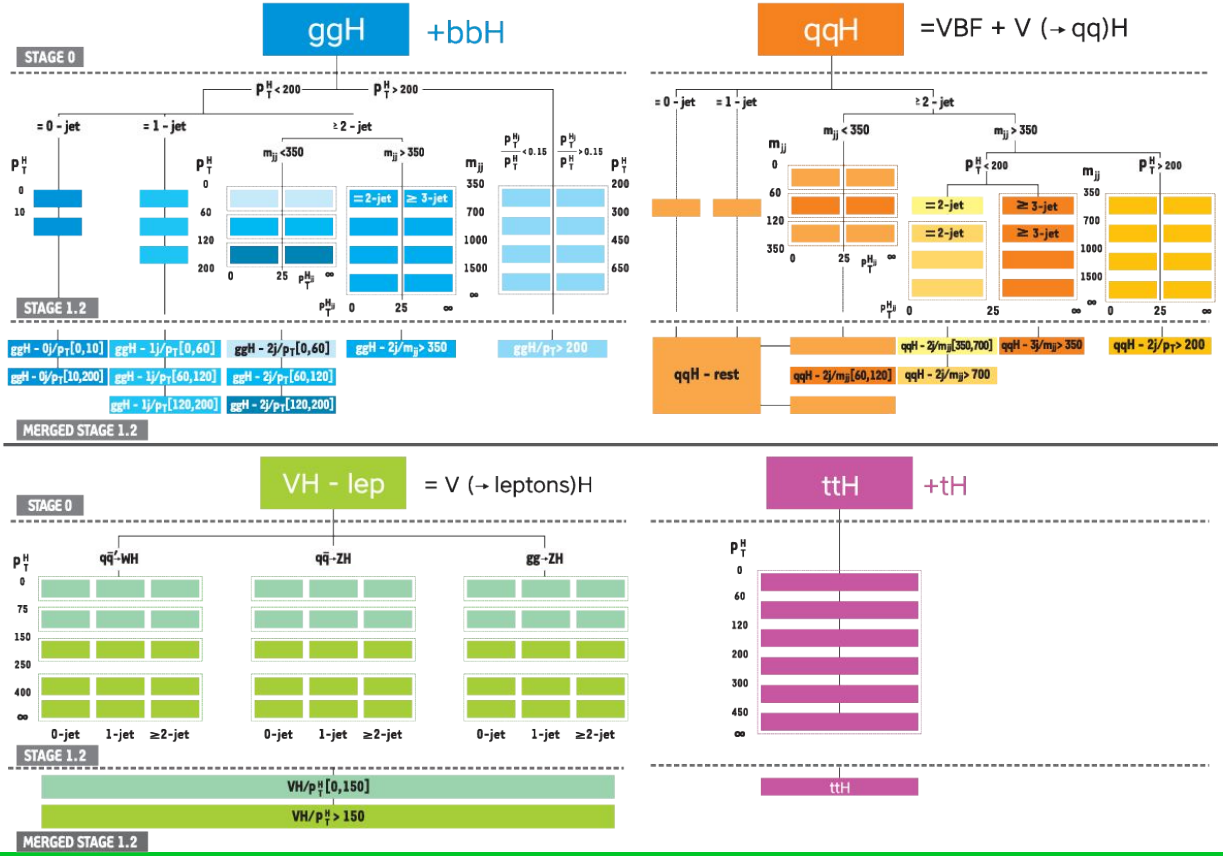
Simplified Template Cross Sections (STXS)

- **kinematic regions based on the production modes of the Higgs** →Built to maximize sensitivity to isolate BSM effects while reducing theory dependence
- Dedicated categories to measure **STXS Stage 1.2** : splitting based on number of jets and kinematic selections (p_T^H)
- Some STXS bins **merged** to avoid large uncertainties or high correlations (reduces model-independence)



Simplified Template Cross Sections (STXS)

- Good sensitivity to ggH process
- Because of low statistics, some bins merged and result to be fit to 0
- Consistent with SM expectations

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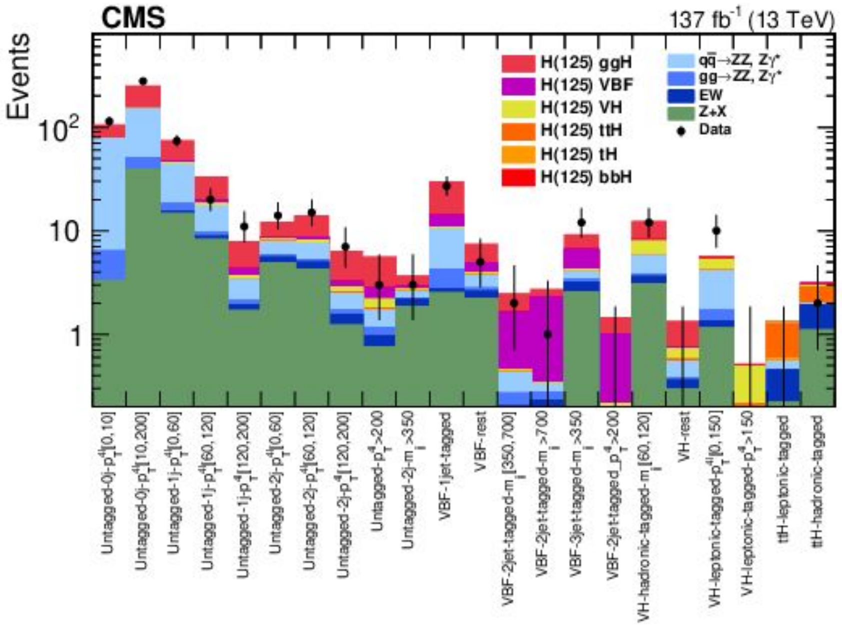
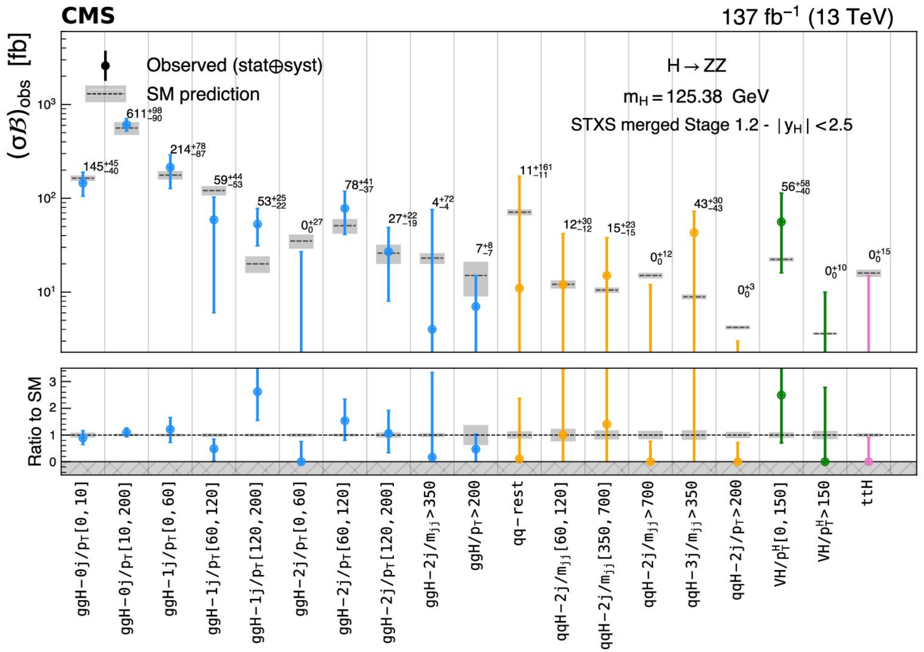


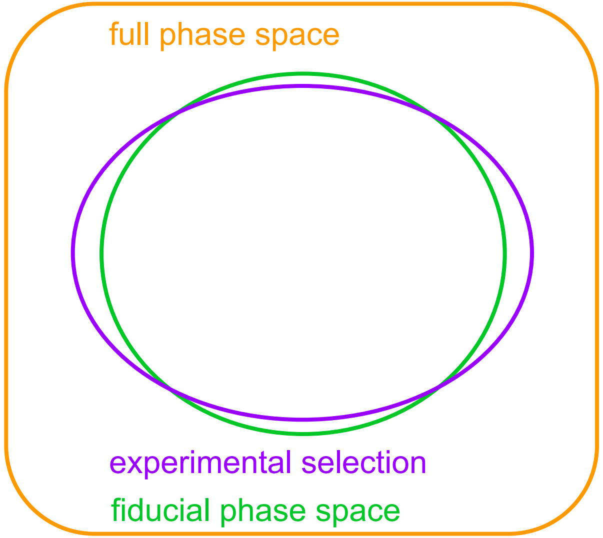


Fiducial Differential Cross sections

New results!
→ Alessandro's talk

- **Fiducial volume** defined to match experimental selections
  →achieve model-independence

- Large number of **new observables** considered
- Differential xsec **bin boundaries** chosen to:
  - Be aligned for the combination with other channels
  - Have enough data for low expected uncertainties
  - Ensure a good level of S/B
- **Improved** event reconstruction, object calibration, systematics estimate
- **Interpretation** of p_T^H spectrum (k_λ, k_b, k_c)

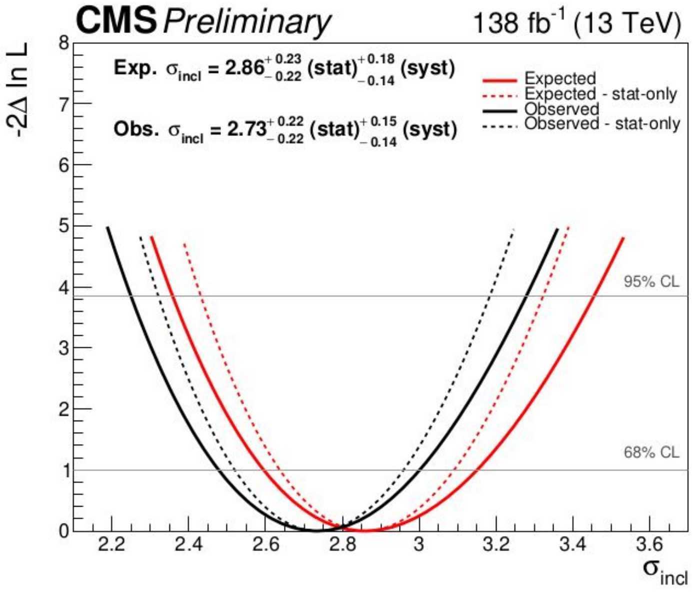


Inclusive Fiducial Cross Section

$$\sigma^{\mathrm{fid}} = 2.73^{+0.22}_{-0.22}\,(\mathrm{stat})^{+0.15}_{-0.14}\,(\mathrm{syst})\ \mathrm{fb}$$
$$= 2.73^{+0.22}_{-0.22}\,(\mathrm{stat})^{+0.12}_{-0.12}(\mathrm{electrons})^{+0.06}_{-0.05}(\mathrm{lumi})^{+0.04}_{-0.04}(\mathrm{bkg})^{+0.03}_{-0.02}(\mathrm{muons})\ \mathrm{fb}$$

CMS-PAS-HIG-21-009

- Overall **precision of 10%**
- Good agreement with SM expectations
- 40% decrease of systematic uncertainties w.r.t. previous measurements!
- Systematic component dominated by electron reconstruction efficiency



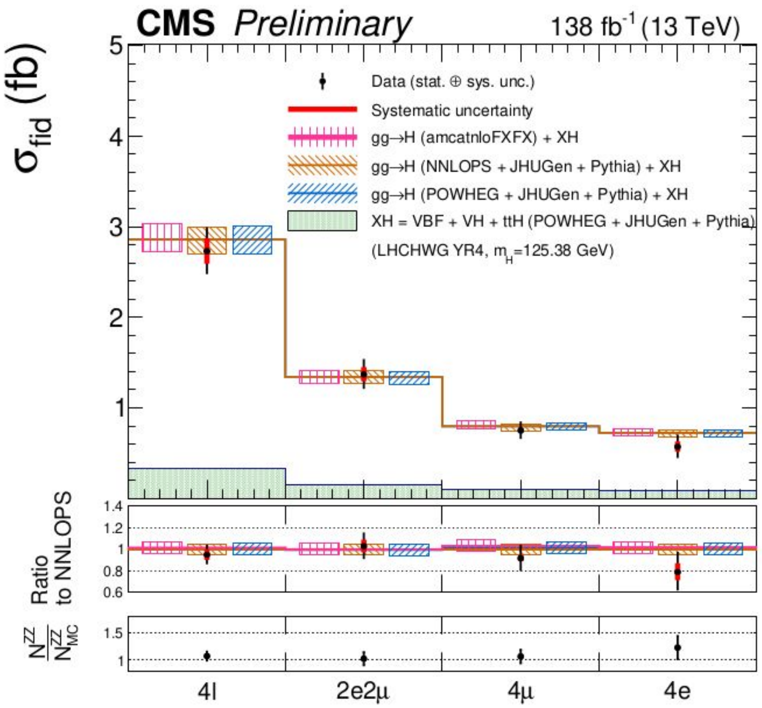
Inclusive Fiducial Cross Section: Floating ZZ normalization

CMS-PAS-HIG-21-009

New strategy investigated: measure the **ZZ** irreducible bkg normalization together with the inclusive fiducial xsec

- Standard approach: ZZ shape and normalization from MC
- Useful to:
    - Reduce uncertainty on ZZ normalization
    - Be **sensitive to possible BSM effects in the bkg**

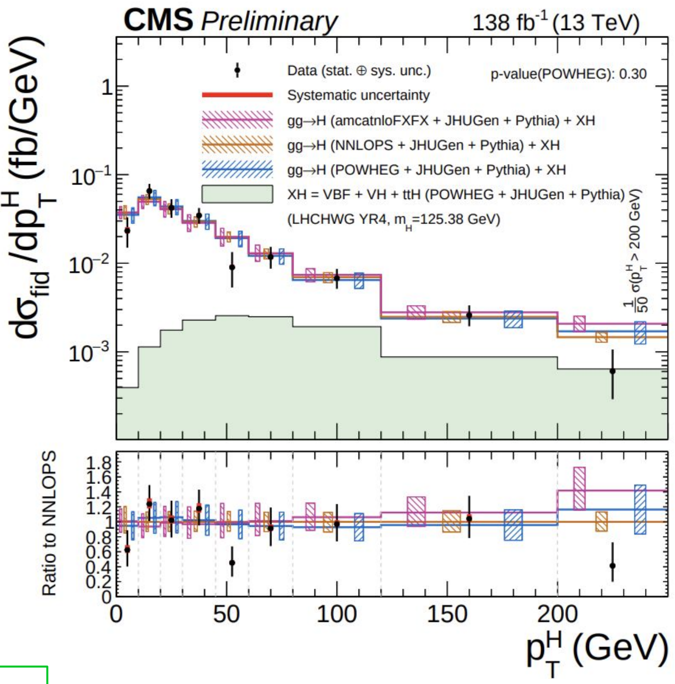
- Results consistent with standard approach
- But not yet enough data to profit from this method in differential measurements

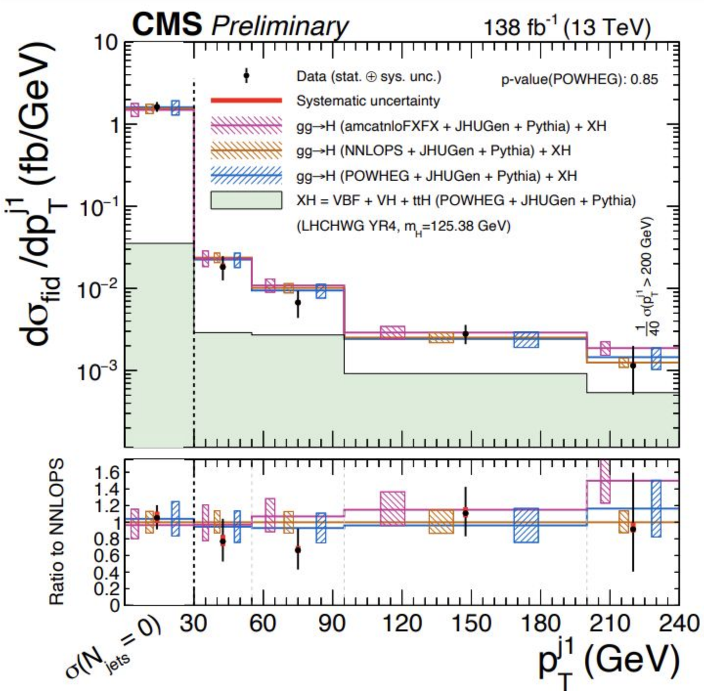


Production Observables

CMS-PAS-HIG-21-009

- New **bin** boundaries choice
- **p_T^H spectrum** measurement precision improved
- **jets** phase space extension (up to $|\eta_j| < 4.7$) thanks to improved CMS jet reconstruction



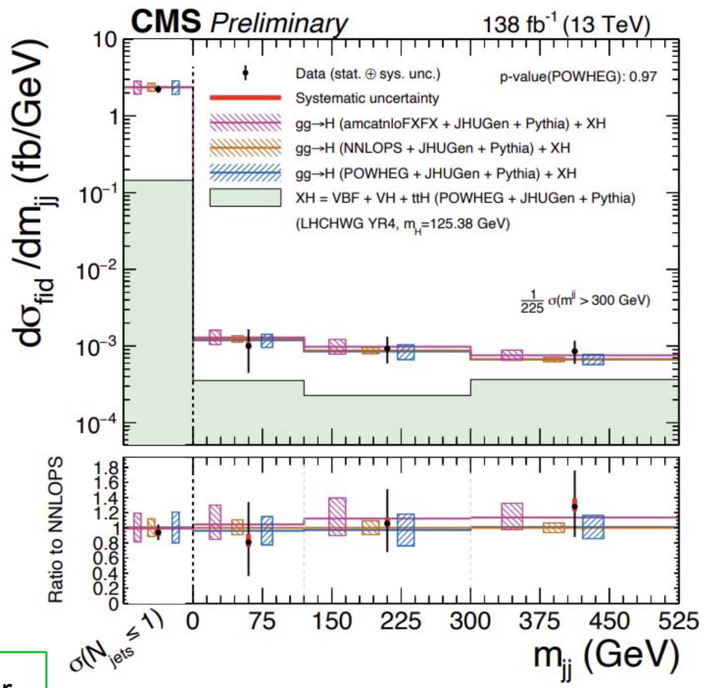


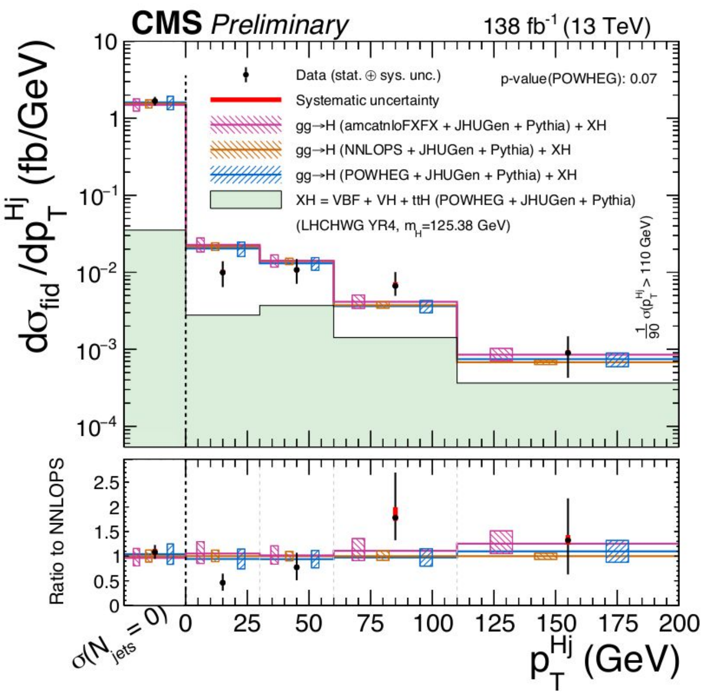
→ more variables in the paper

Production Observables

CMS-PAS-HIG-21-009

- **New** observables
- Information on **di-jet** and **H+jet** system
- First bin contains events for which the observables are not defined





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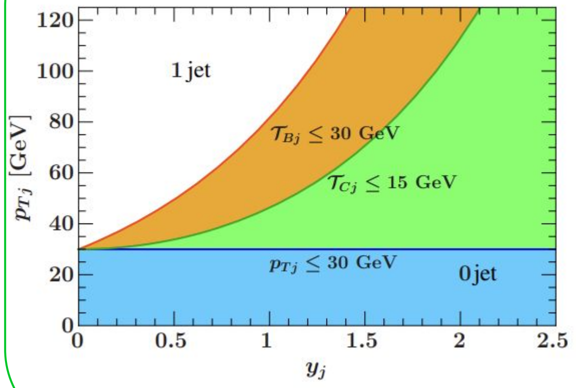
Production Observables

CMS-PAS-HIG-21-009

- **New** observables
- Jet transverse momentum **weighted** by a **function of jet rapidity**
- Useful to test QCD resummation
- 0-jet phase space redefinition

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

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



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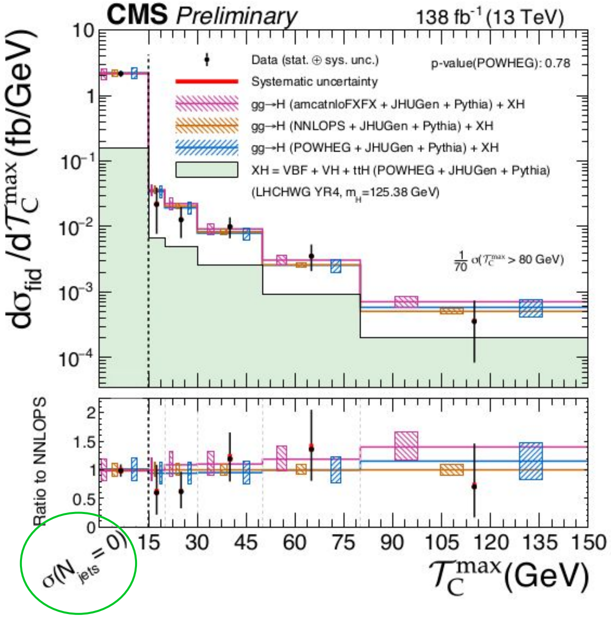
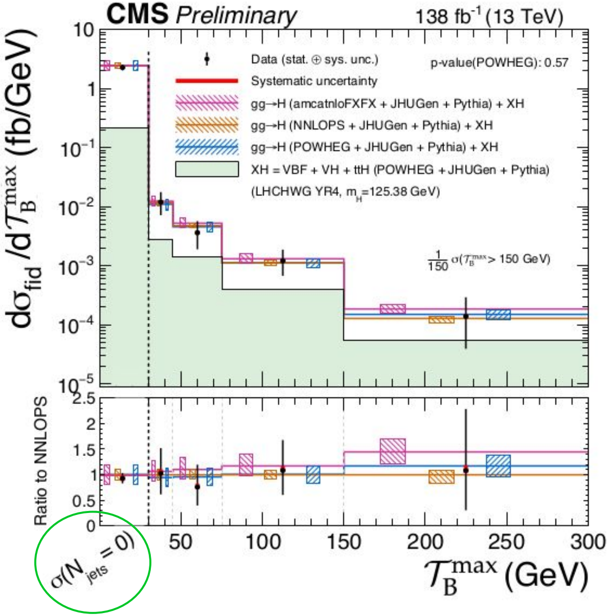
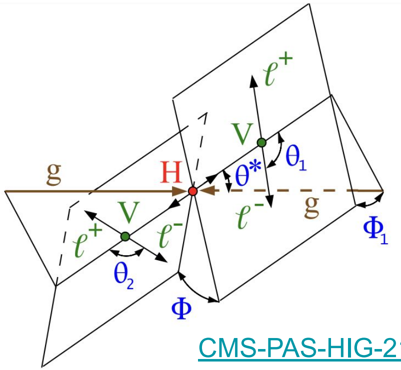




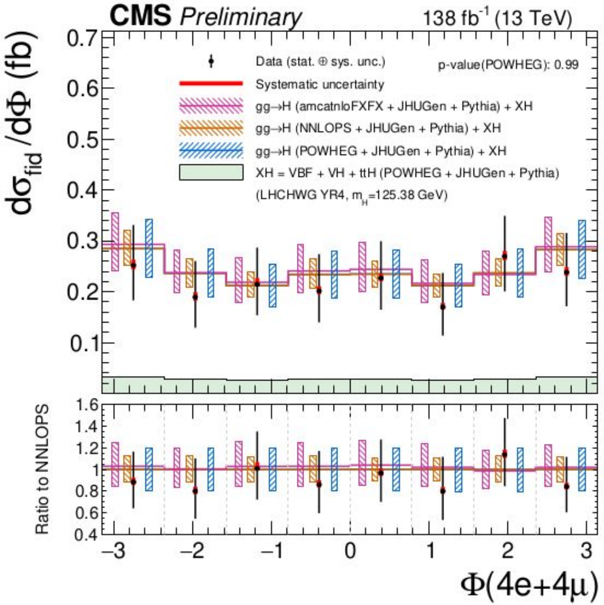
Decay Observables

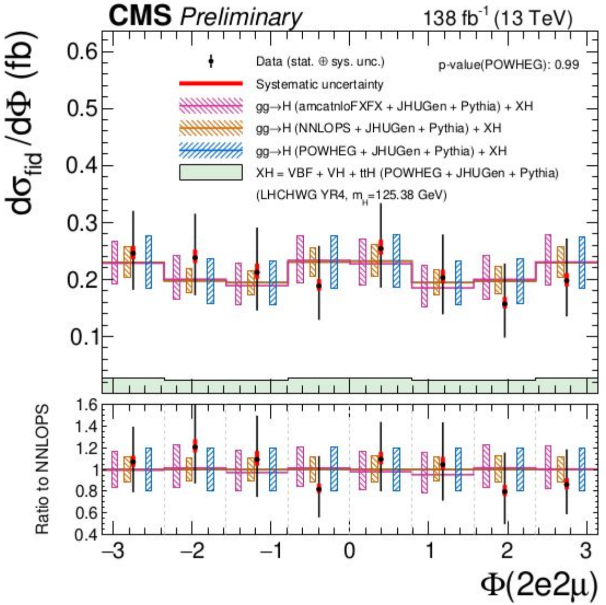
- 7 parameters fully describing the H→4l decay:
  - **Z masses** (m_{Z1}, m_{Z2})
  - Angular variables for **fermion kinematics** (Φ, cos Θ_1, cos Θ_2)
  - Angular **variables connecting production and decay** (Φ_1, cos Θ^*)



CMS-PAS-HIG-21-009

- **New** observables
- Results divided for identical (4e+4μ) and different (2e2μ) flavour final states
  → highlight sensitivity of identical flavour final state to interference effects





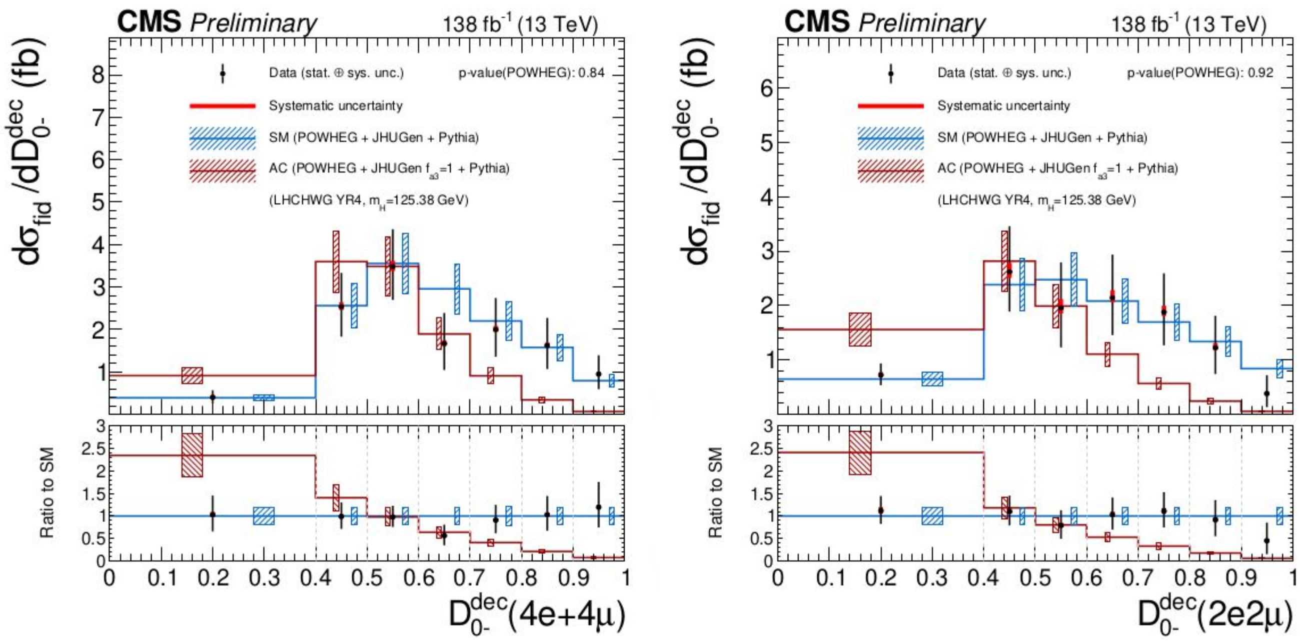
→ more variables in the paper

Decay Observables: ME Discriminants

CMS-PAS-HIG-21-009

Sensitive to possible CP-violation effects

- **New** observables
- ME **discriminants** sensitive to **HVV anomalous couplings**
- Results compared to **different BSM hypotheses**
- Presented separately for identical ($4e+4\mu$) and different ($2e2\mu$) flavour final states



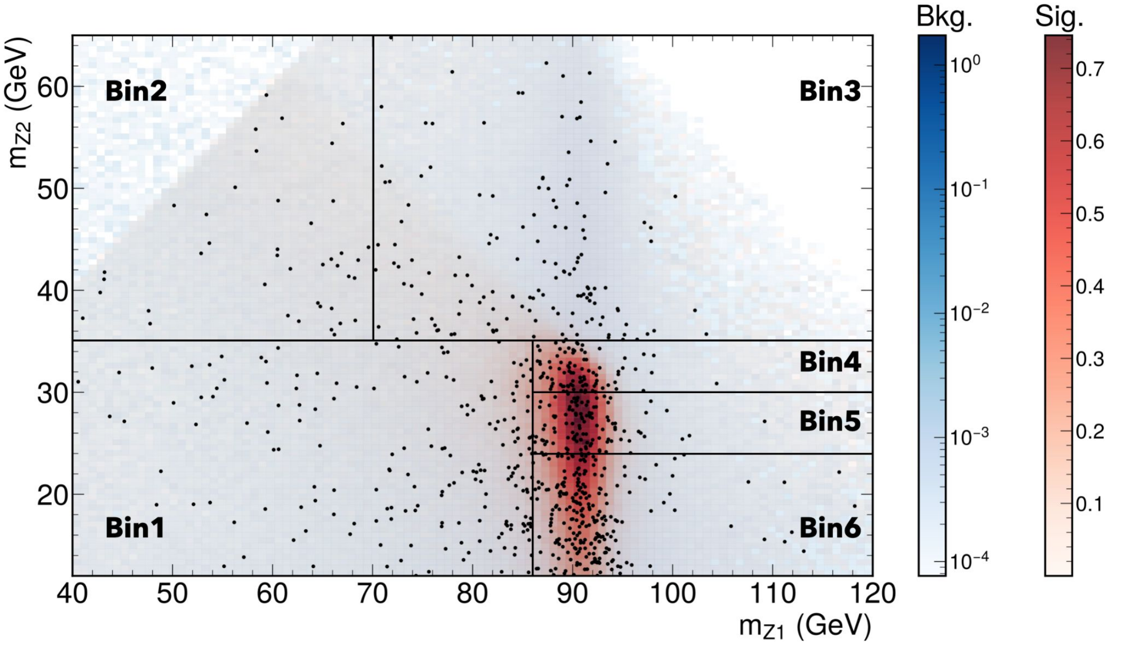
→ more variables in the paper

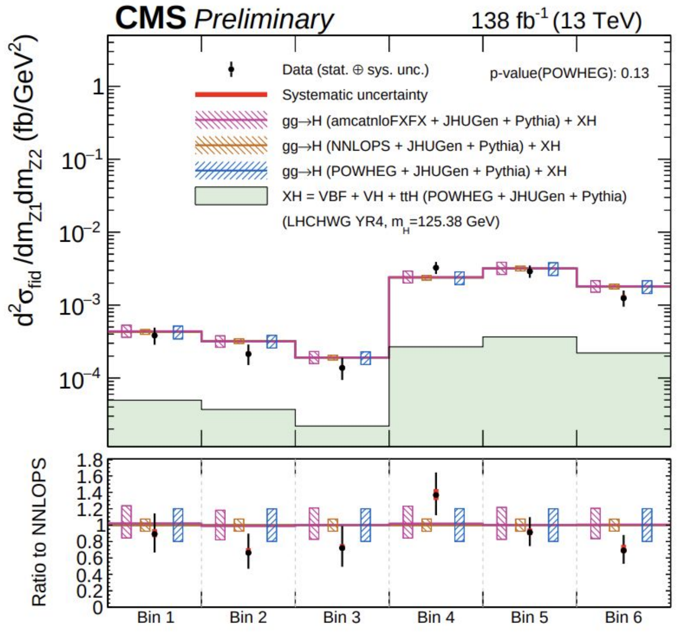
Double Differential Observables

CMS-PAS-HIG-21-009

- **New** observables
- Large set of observables to improve characterization of the decay channel and maximize coverage of different phase space regions

→ more variables in the paper





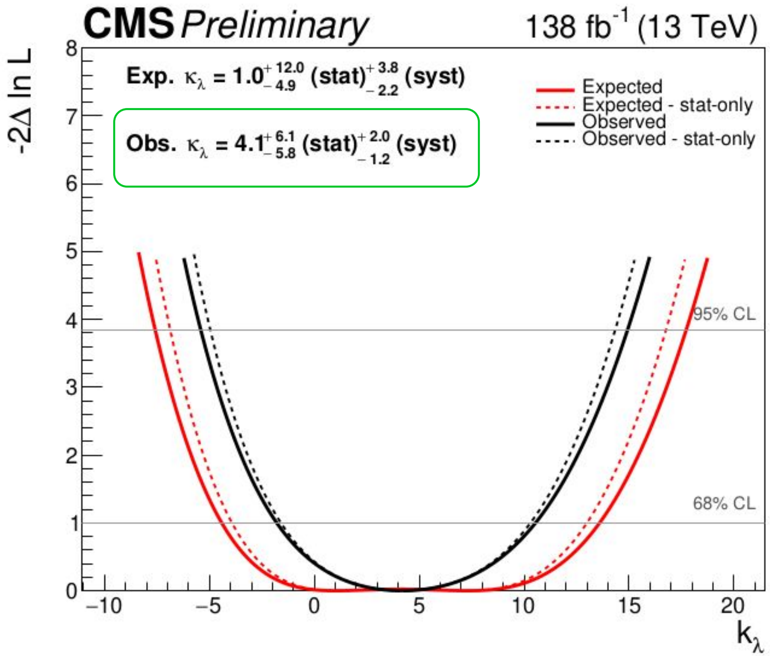
Interpretation

CMS-PAS-HIG-21-009

- NLO EW corrections induce dependence of single-H cross sections on λ_{HHH} → extract information from **p_T^H spectrum**
- Large contribution from ttH and VH
- **H cross section parametrized as function of $k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$:**
  - Cross section and BR fixed to SM values
  - Scaling function $\mu(\lambda)$ in each bin of p_T^H spectrum for all production mechanisms
- Observed (expected) limits at 95% CL:

$-5.5\ (7.7) < k_\lambda < 15.1\ (17.9)$

Competitive with many limits from HH direct searches!



Interpretation

CMS-PAS-HIG-21-009

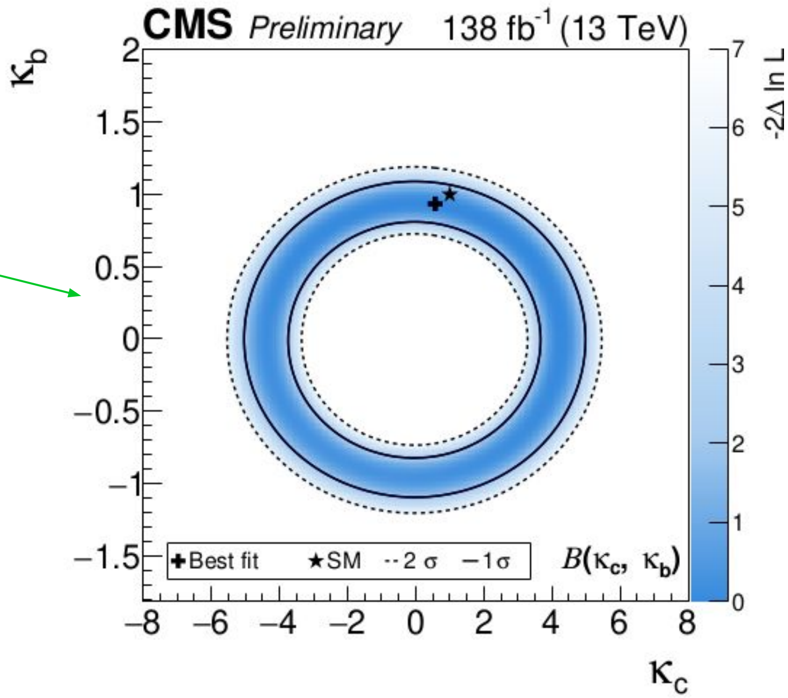
- ggH p_T^H **spectrum** used to set constraints on k_b, k_c coupling modifiers
  → Quadratic polynomials to parametrize simultaneous variations of H couplings in each bin

- Observed (expected) 95% CL limits assuming **branching fractions dependent on k_b, k_c**

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

- Observed (expected) 95% CL limits if treating H→ZZ branching fraction as unconstrained parameters in fit

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



Summary

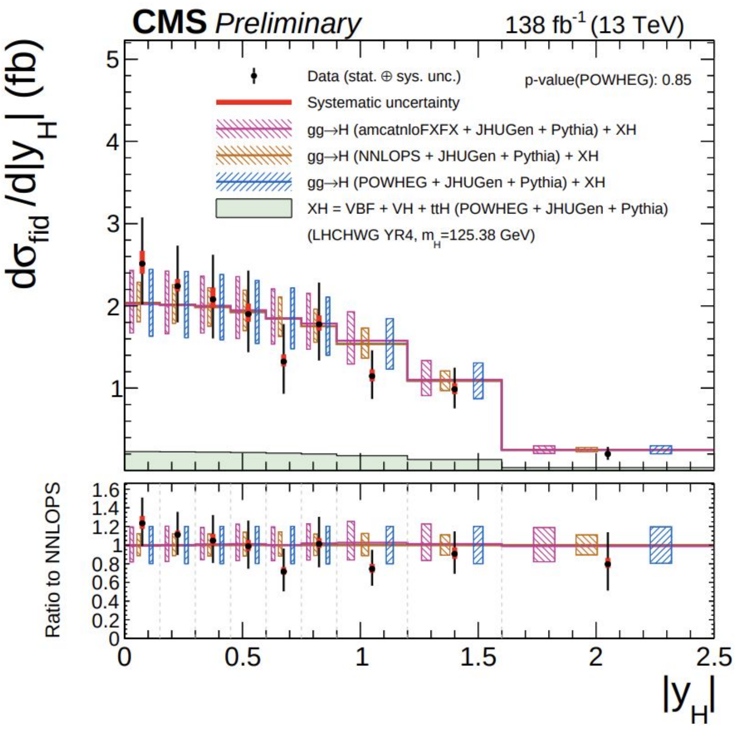
- $H \to ZZ \to 4l$ is a fundamental channel to study the Higgs boson
- Most recent full Run2 results presented, overall **good agreement with SM**
- Super fresh results from **differential fiducial cross section measurements**
  - Comprehensive characterization of the $H \to 4l$ channel
  - Many **new observables** considered
  - 3 **interpretation** performed
  - **Improved** event reconstruction, object calibration, systematics estimate
    → Very precise measurements (10% inclusive)!

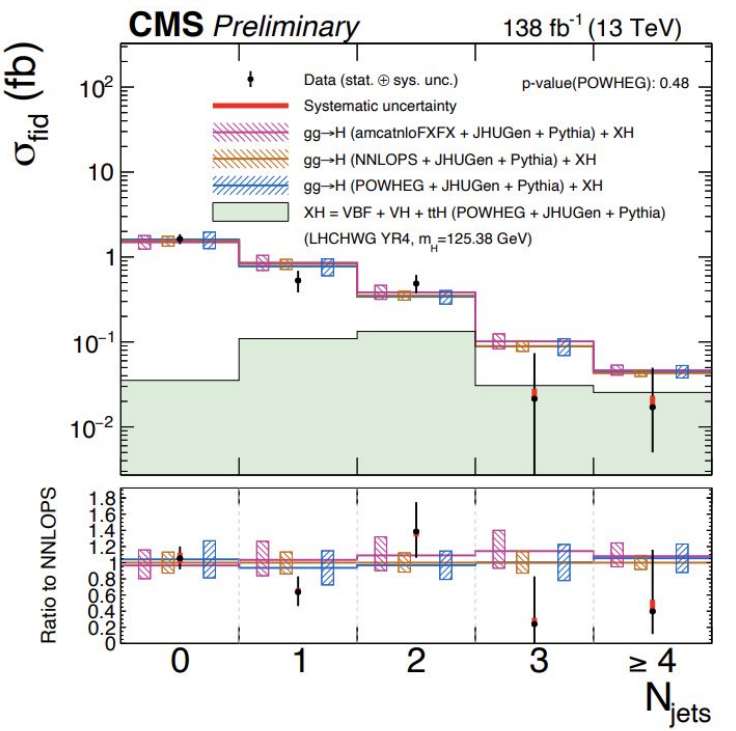
The precision exploration of the scalar sector has just started!

Back up

Production Observables

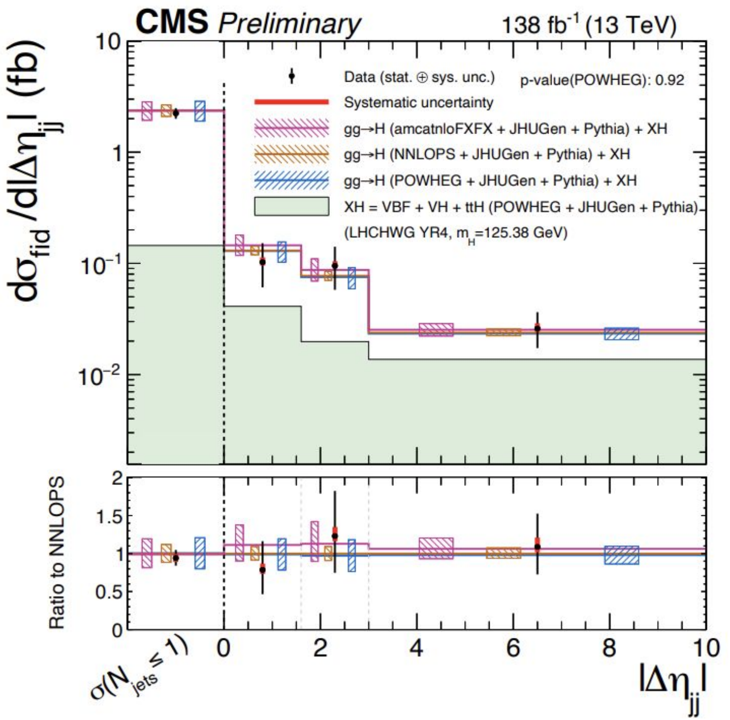
CMS-PAS-HIG-21-009

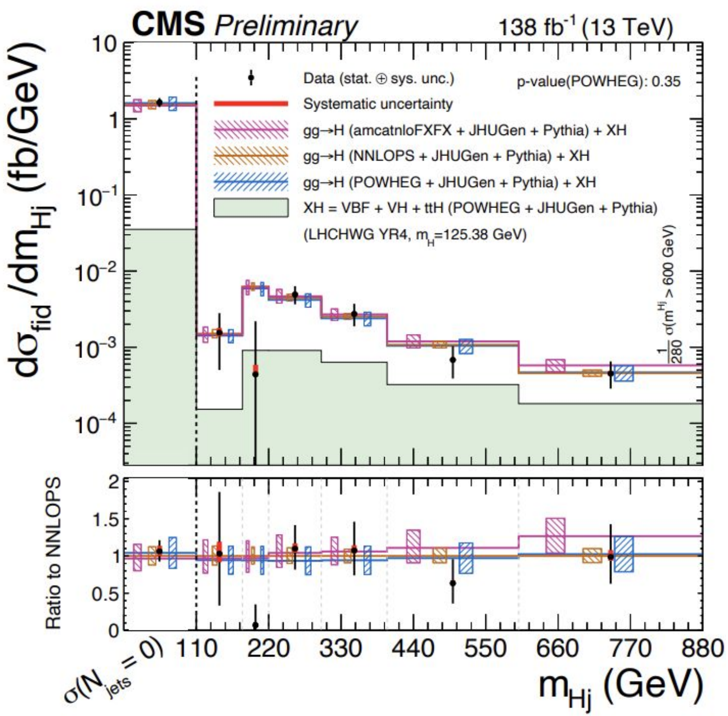




Production Observables

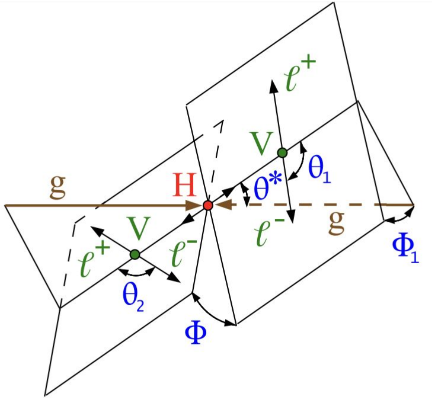
CMS-PAS-HIG-21-009

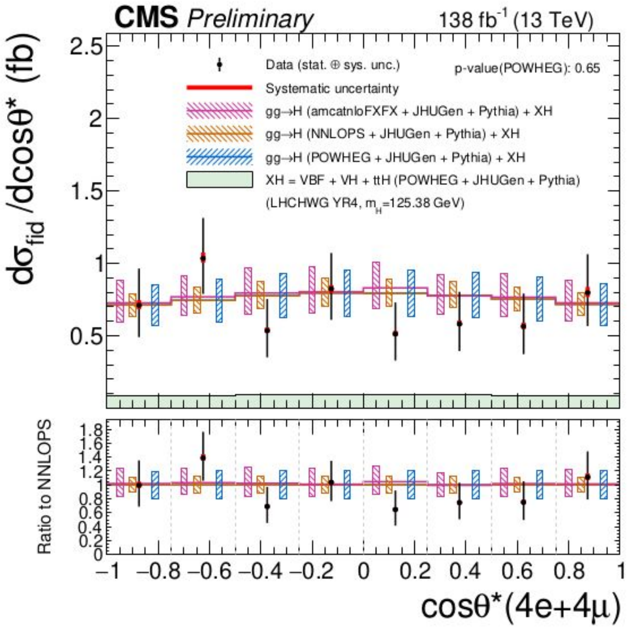


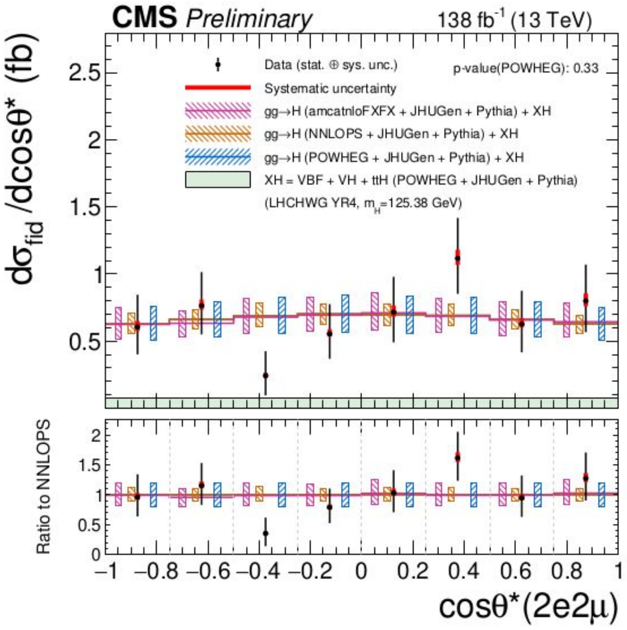


Decay Observables

CMS-PAS-HIG-21-009



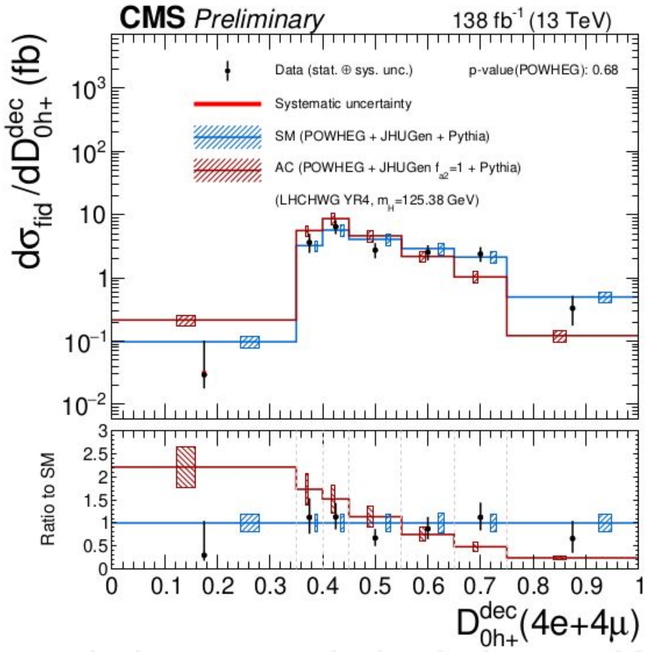


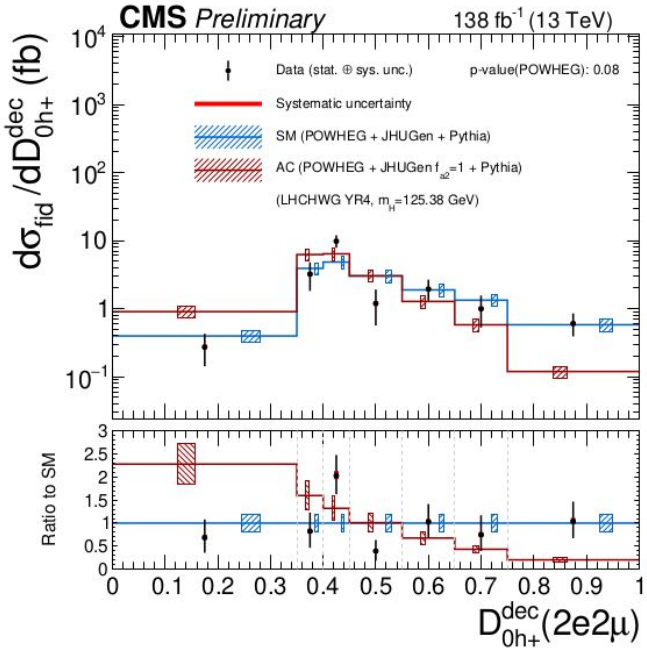


Decay Observables: ME Discriminants

CMS-PAS-HIG-21-009

Sensitive to possible BSM contribution from heavy H bosons

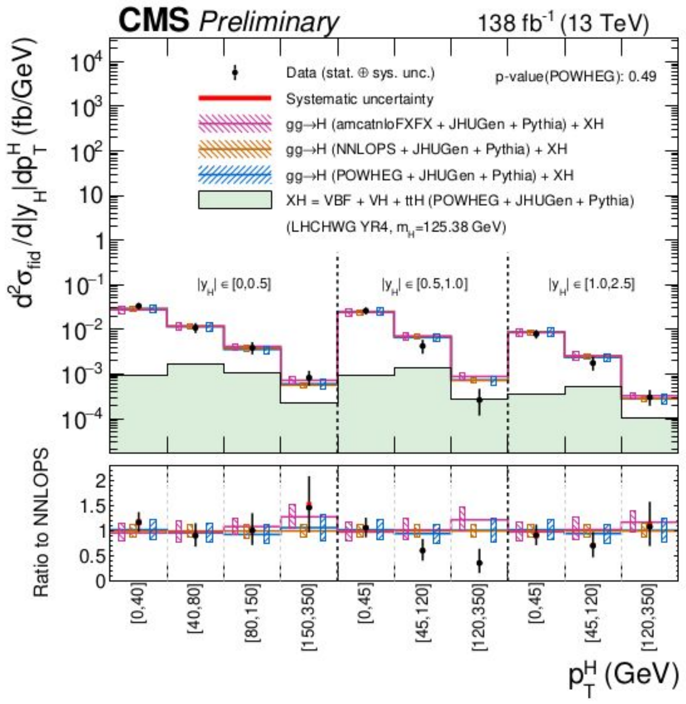




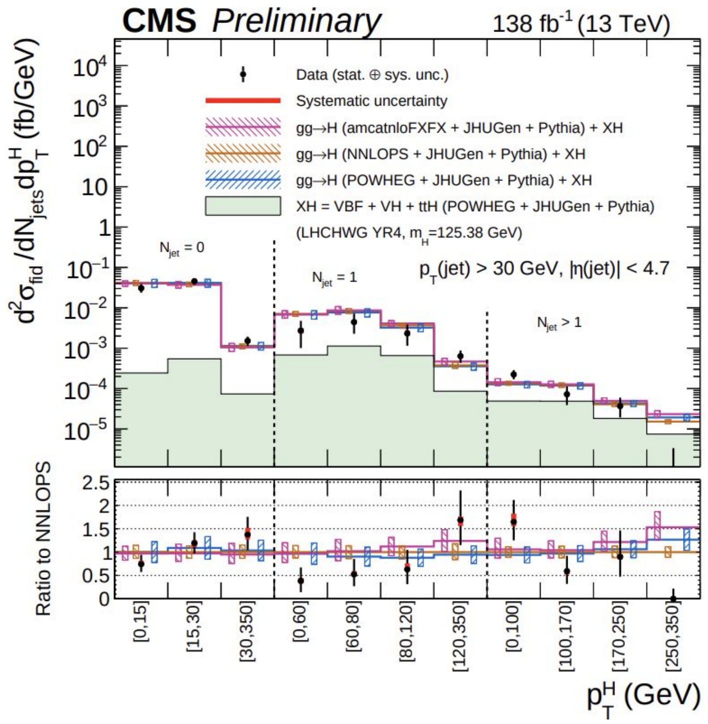
Double Differential Observables

CMS-PAS-HIG-21-009

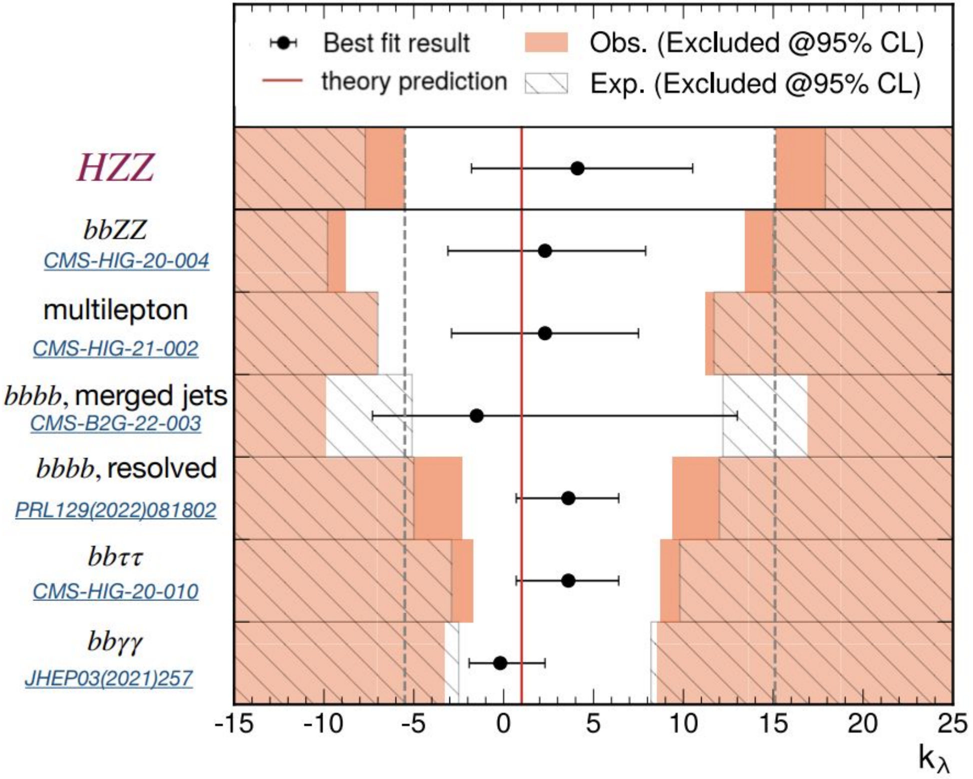
p_T^H , y^H



p_T^H , N_{jets}



Interpretation



Credits: Alessandro Tarabini

Interpretation

production decay

$$\mu_i^f = \mu_i \times \mu^f = \frac{\sigma^{NLO}}{\sigma^{NLO}_{SM}} \frac{BR(H \to ZZ)}{BR^{SM}(H \to ZZ)} = \frac{1 + k_\lambda C_{1,i} + \delta Z_H}{(1 - (k_\lambda^2 - 1)\delta Z_H)(1 + C_{1,i} + \delta Z_H)} \times \left[1 + \frac{(k_\lambda - 1)(C_1^{\Gamma ZZ} - C_1^{\Gamma tot})}{1 + (k_\lambda - 1) C_1^{\Gamma tot}} \right]$$

$\delta Z_H = -1.536 \times 10^{-3}$ universal quantity

$C_1(p_n)$ dependent on H production model and kinematics

$C_1^{\Gamma ZZ} = 0.0082$

$C_1^{\Gamma tot} = 2.5 \times 10^{-3}$

Interpretation

$$\sigma_{ggH} = \left|\sum_i A_i k_i\right|^2 = Ak_b^2 + Bk_c^2 + Ck_t^2 + Dk_b k_c + Ek_b k_t + Fk_c k_t$$

set $k_t = 1$

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} \kappa_{b,1}^2 & \kappa_{c,1}^2 & \kappa_{t,1}^2 & \kappa_{b,1}\kappa_{c,1} & \kappa_{b,1}\kappa_{t,1} & \kappa_{c,1}\kappa_{t,1} \\ \kappa_{b,2}^2 & \kappa_{c,2}^2 & \kappa_{t,2}^2 & \kappa_{b,2}\kappa_{c,2} & \kappa_{b,2}\kappa_{t,2} & \kappa_{c,2}\kappa_{t,2} \\ \kappa_{b,3}^2 & \kappa_{c,3}^2 & \kappa_{t,3}^2 & \kappa_{b,3}\kappa_{c,3} & \kappa_{b,3}\kappa_{t,3} & \kappa_{c,3}\kappa_{t,3} \\ \kappa_{b,4}^2 & \kappa_{c,4}^2 & \kappa_{t,4}^2 & \kappa_{b,4}\kappa_{c,4} & \kappa_{b,4}\kappa_{t,4} & \kappa_{c,4}\kappa_{t,4} \\ \kappa_{b,5}^2 & \kappa_{c,5}^2 & \kappa_{t,5}^2 & \kappa_{b,5}\kappa_{c,5} & \kappa_{b,5}\kappa_{t,5} & \kappa_{c,5}\kappa_{t,5} \\ \kappa_{b,6}^2 & \kappa_{c,6}^2 & \kappa_{t,6}^2 & \kappa_{b,6}\kappa_{c,6} & \kappa_{b,6}\kappa_{t,6} & \kappa_{c,6}\kappa_{t,6} \end{bmatrix} \begin{bmatrix} A \\ B \\ C \\ D \\ E \\ F \end{bmatrix}$$