ggF: experimental status

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Introduction

- Summarise experimental landscape for ggF measurements
  - recent full Run 2 ggF results from ATLAS + CMS collaborations

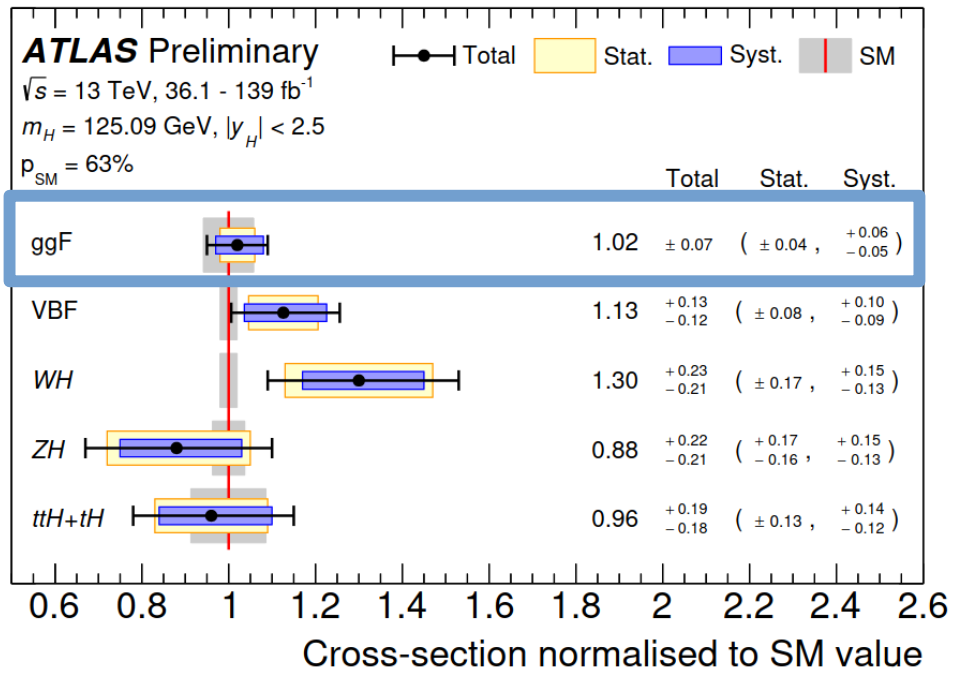
    $\Rightarrow$ not everything, just a select few
  - highlight where theory input will be useful
  - aims for Run 3

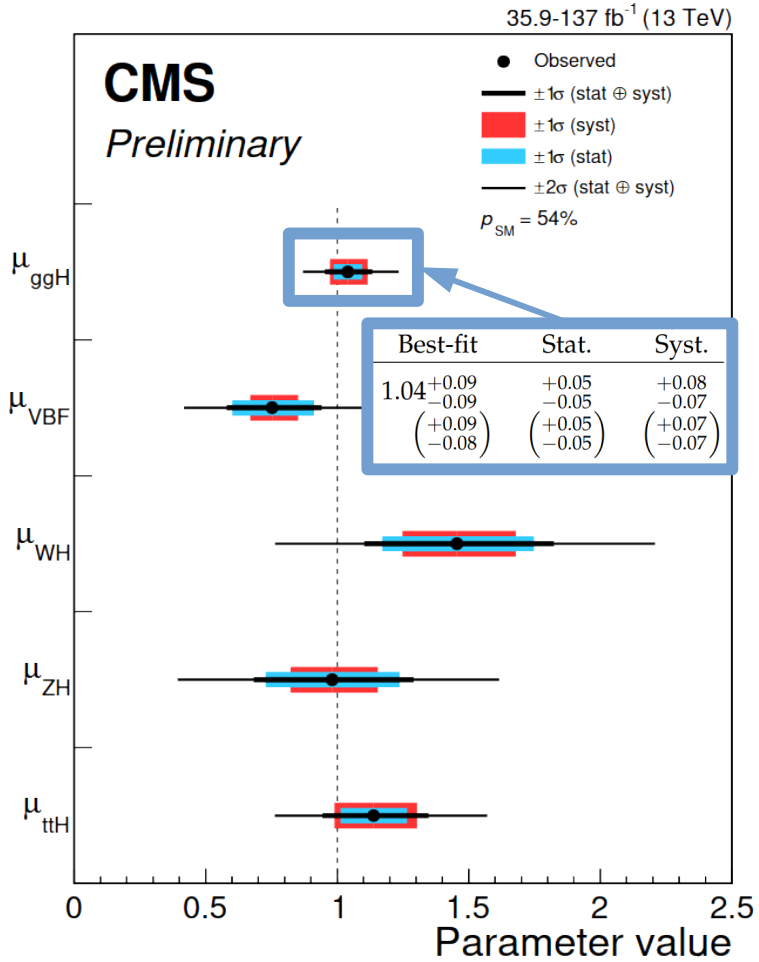
- Wealth of data collected during Run 2 enabled many interesting analyses
  - measure kinematics of ggF production mode: differential/STXS
  - rare phase space regions e.g. boosted ggF(H$\rightarrow$bb)
  - using ggF to probe Higgs properties e.g. CP

- Related ggF talks during this workshop:
  - [theory update] from Stephen
  - [STXS uncertainty scheme] from Haider

Inclusive ggF measurements

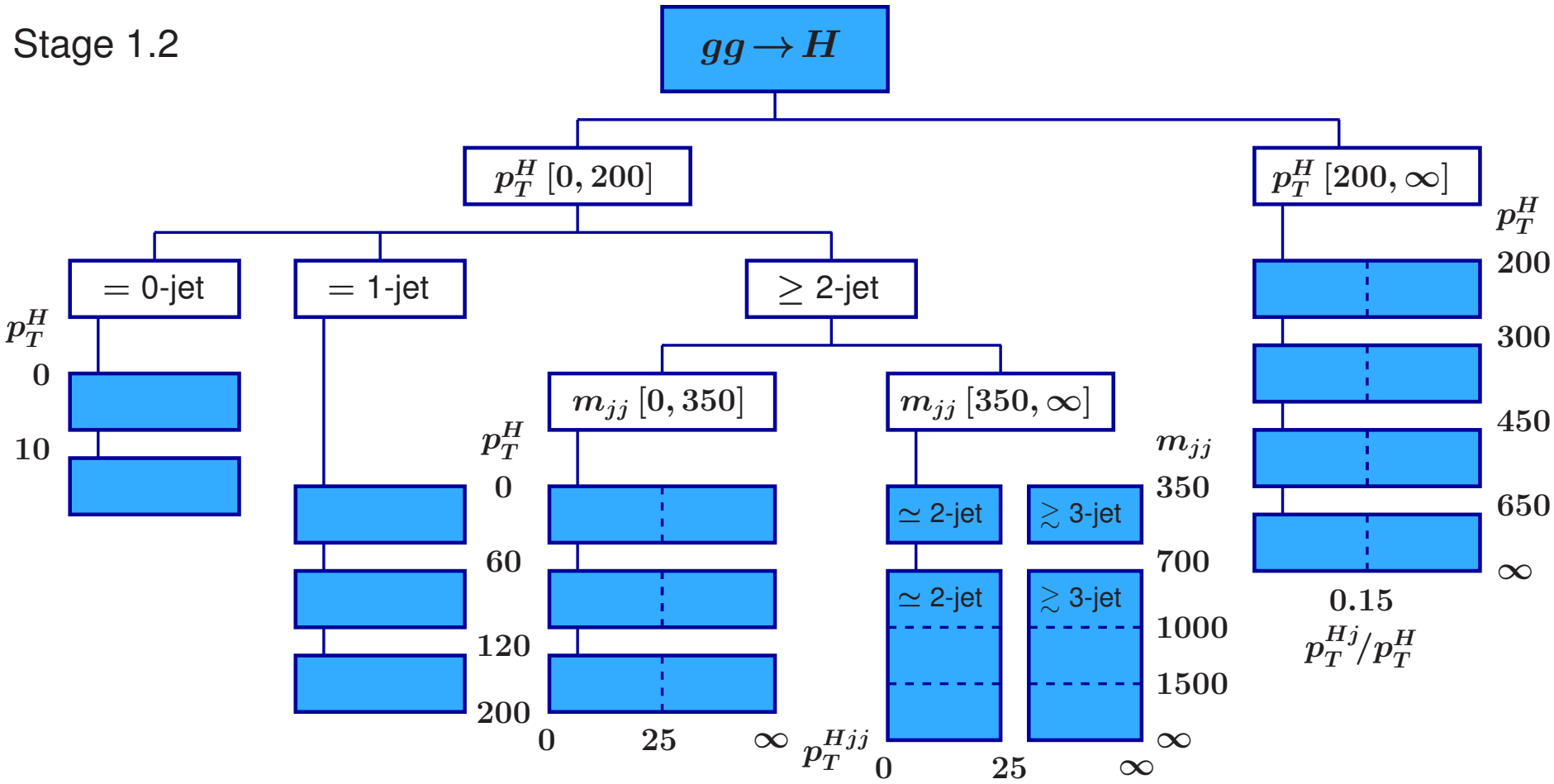
- Highest precision achieved by combining decay channels
  - [ATLAS-CONF-2021-053]: cross-section
  - [CMS-PAS-HIG-19-005]: signal-strength (theory uncertainties folded-in)
  - syst-limited measurements ⇒ requires analysis/theory improvements





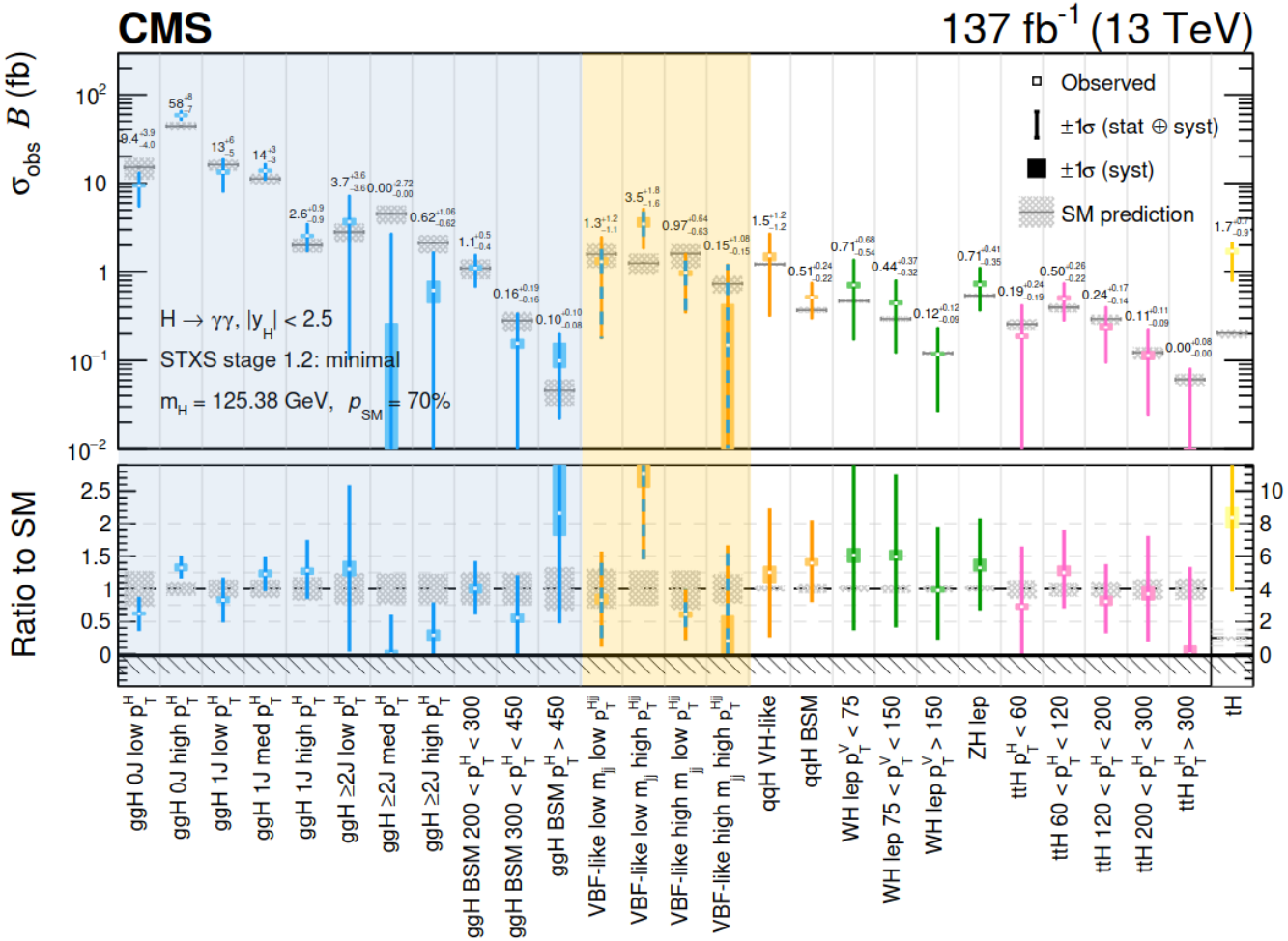
Simplified template cross sections

- Divide inclusive phase space into simplified fiducial volumes (bins)
  - splittings to minimize theory dependence + isolate BSM-sensitive regions
  - no fiducial selection on decay products ⇒ useful for combination



STXS results

- Many ggF stage 1.2 bins measured: splittings in p_T^H, N_{jet}, m_{jj}, (p_T^{Hjj})



- [*JHEP* 07 (2021) 027]: CMS H→ $\gamma\gamma$ analysis, no significant deviations from SM
- cross-sections vary by $\mathcal{O}(10^3)$, most dominated by stat. uncertainty
- high p_T^H measurements approaching theory precision

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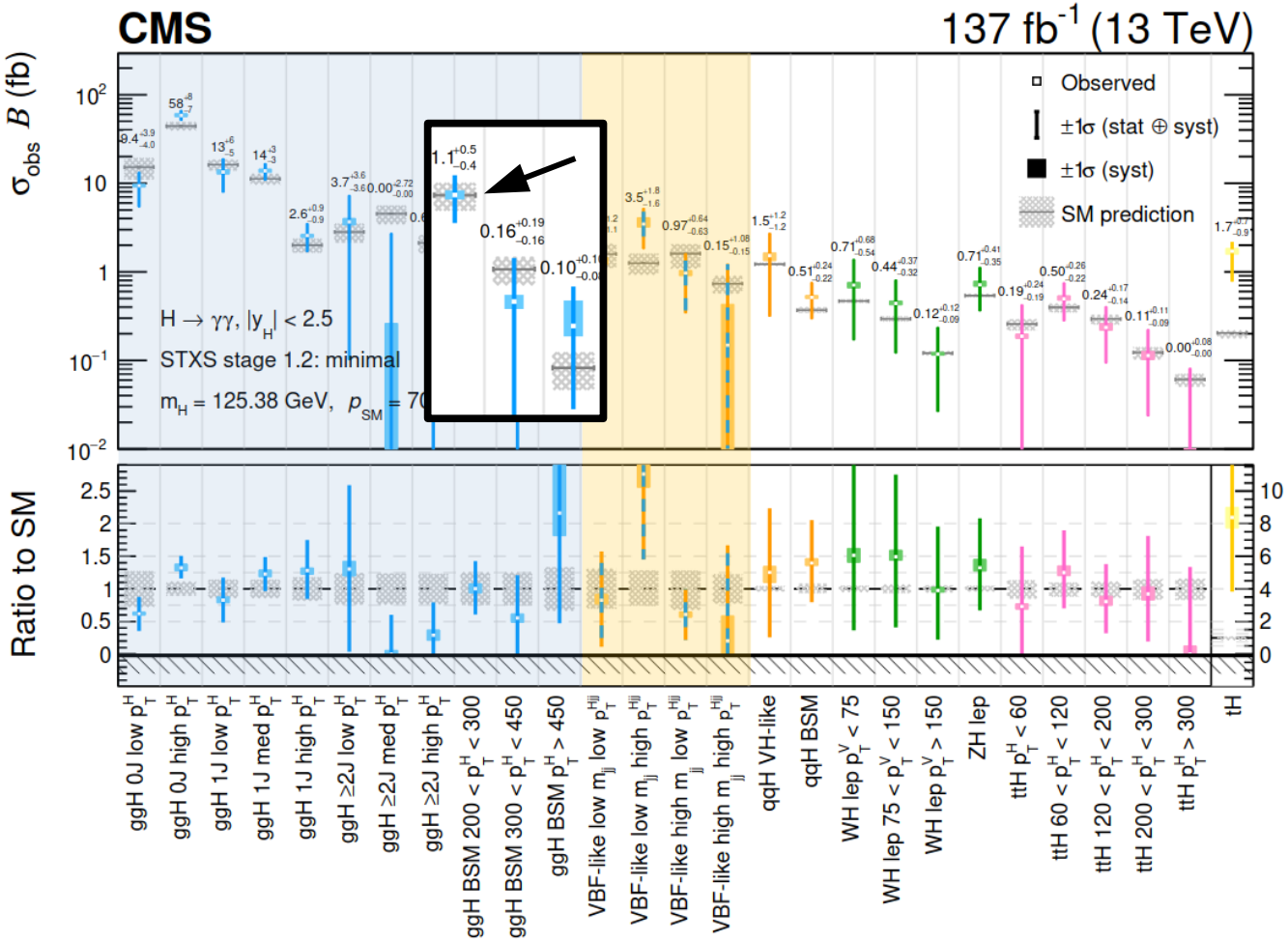

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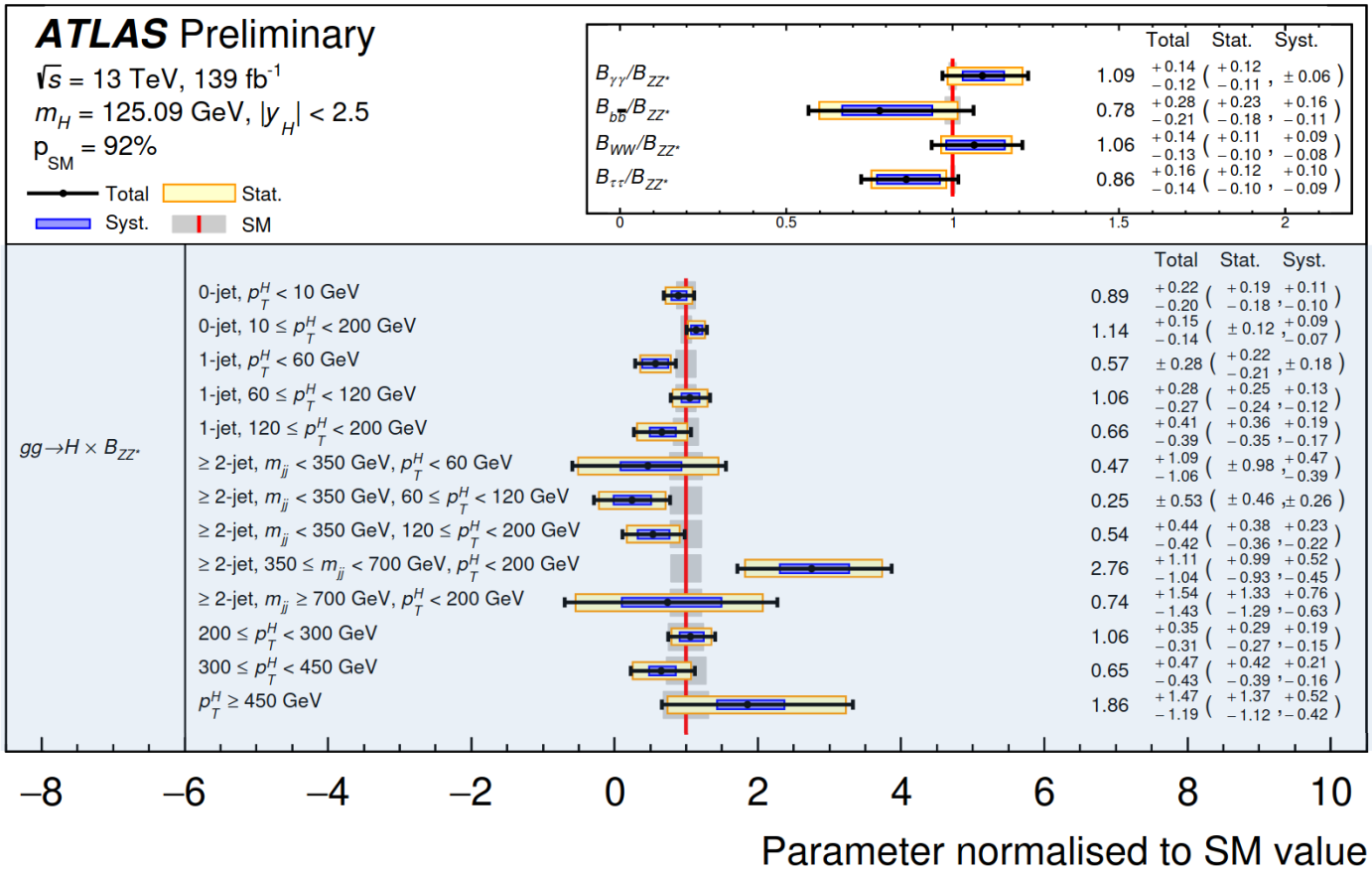
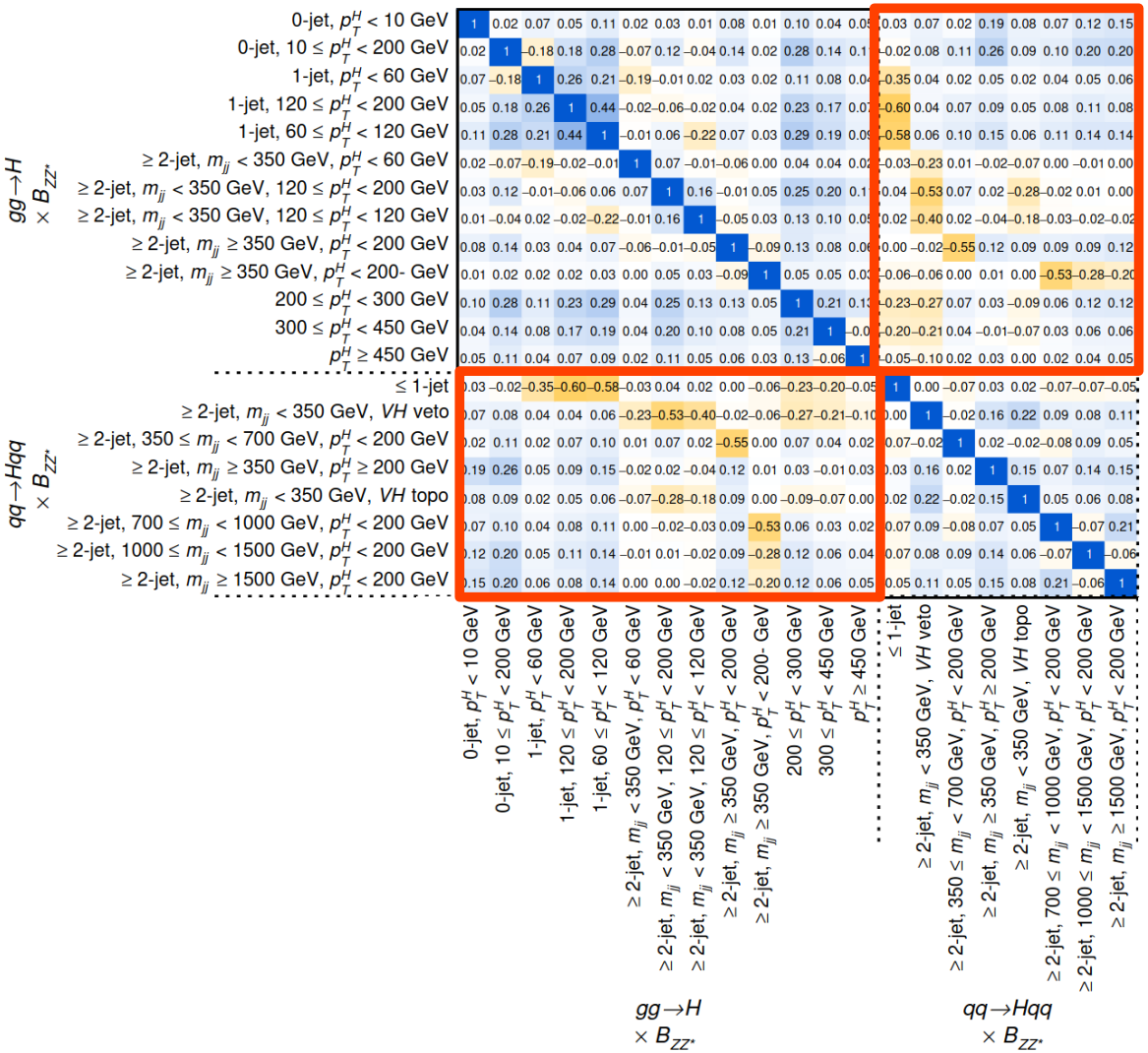
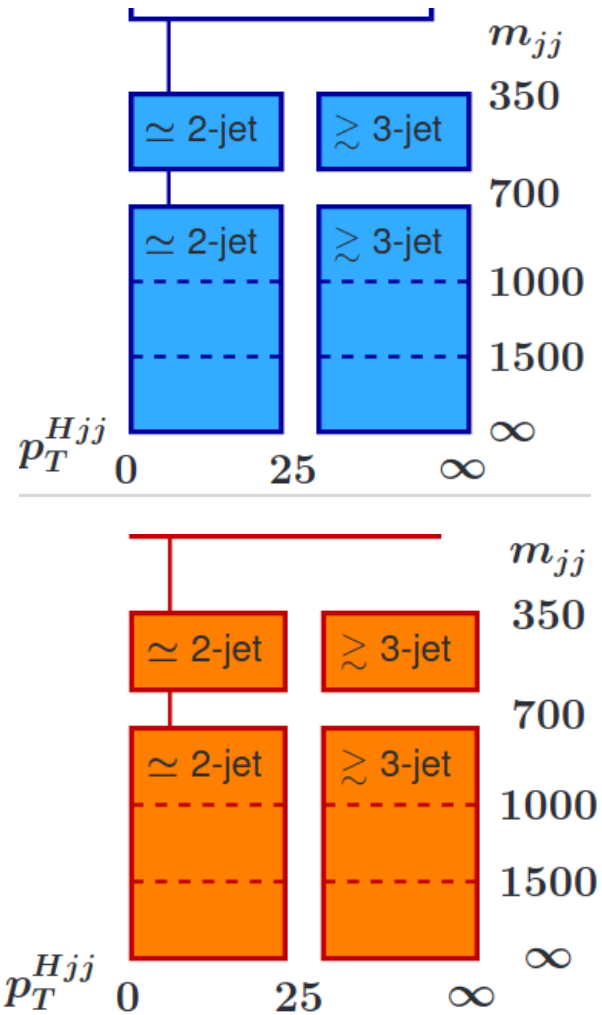


- [ATLAS-CONF-2021-053]: ATLAS STXS combination ($\gamma\gamma$, 4ℓ, WW, $\tau\tau$, bb)
- excellent precision in rare phase space (e.g. $N_{\text{jet}} \geq 2$). Again SM holds true!
- Run 2 summary: building up an accurate, granular description of ggF production

STXS correlations

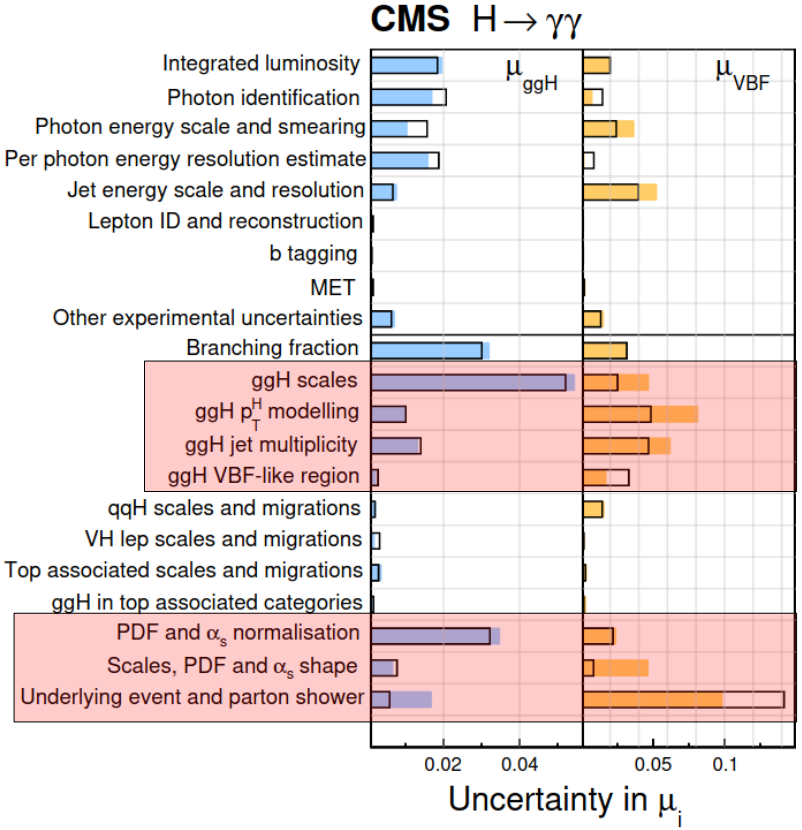
- [ATLAS-CONF-2021-053]: in general, correlations between ggF bins are small
  - larger correlations with some qqH (=VBF+VH had) bins
  - difficult to disentangle production modes with similar event topologies





High-ranking systematics

- Theoretical uncertainties dominate ggF signal-strength measurement
  - missing higher-order QCD terms
  - modelling of ggF kinematics in VBF phase space important for μ_{VBF}
- Parton shower now dominant th. unc in ggF cross-section measurement
  - worth investing time + effort in consistent scheme (and reducing!) PS uncertainties

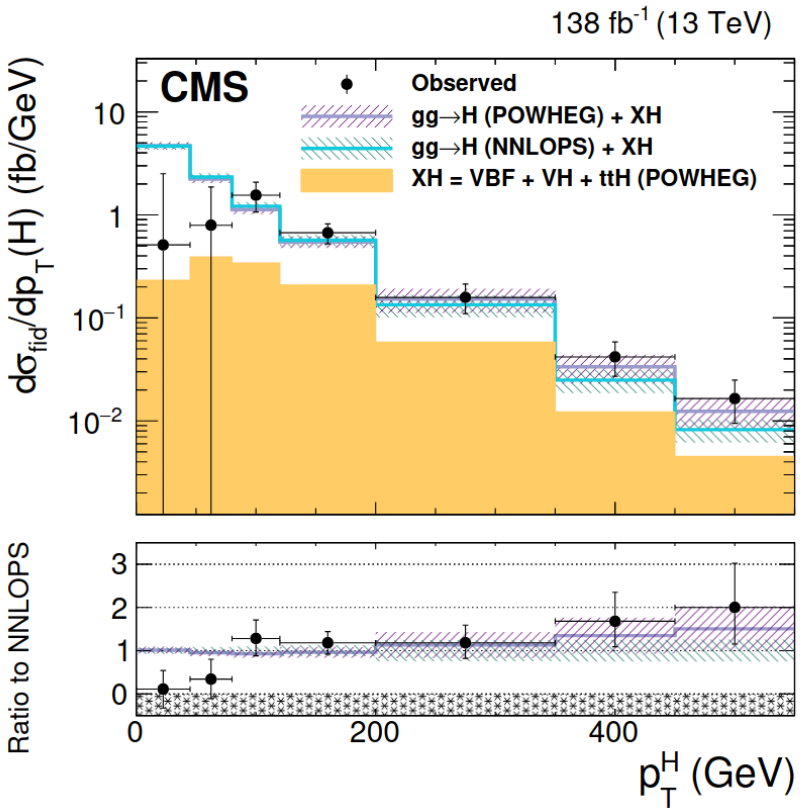


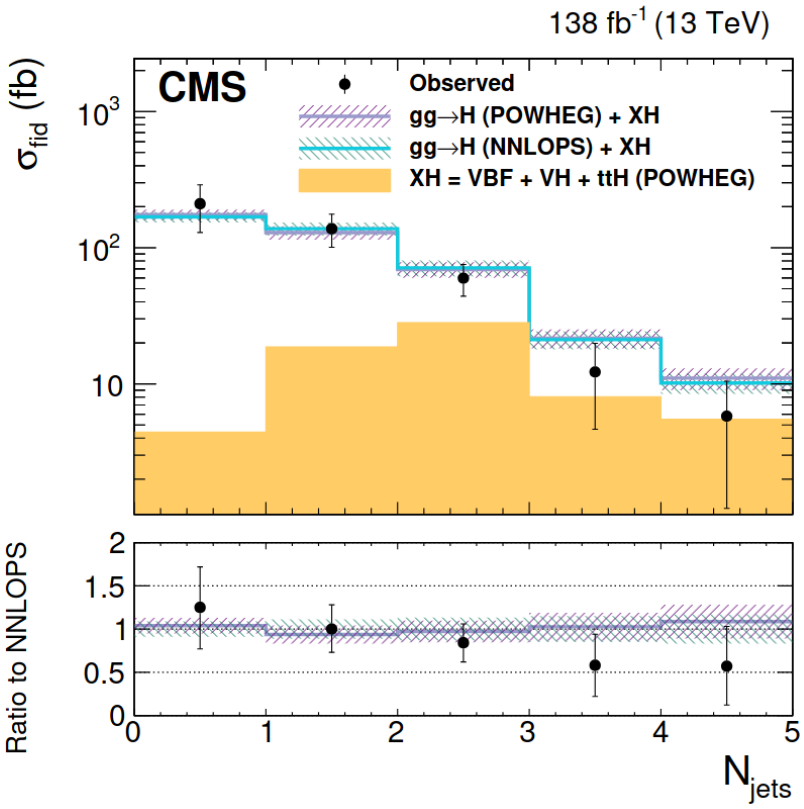
ATLAS $H \to \gamma\gamma$

Uncertainty source	ggF+ bbH $\Delta\sigma[\%]$	VBF $\Delta\sigma[\%]$
Underlying Event and Parton Shower (UEPS)	± 2.3	± 10
Modeling of Heavy Flavor Jets in non-$t\bar{t}H$ Processes	$< \pm 1$	$< \pm 1$
Higher-Order QCD Terms (QCD)	± 1.6	$< \pm 1$
Parton Distribution Function and α_S Scale (PDF+α_S)	$< \pm 1$	± 1.1
Photon Energy Resolution (PER)	± 2.9	± 2.4
Photon Energy Scale (PES)	$< \pm 1$	$< \pm 1$
Jet/$E_{\mathrm{T}}^{\mathrm{miss}}$	± 1.6	± 5.5
Photon Efficiency	± 2.5	± 2.3
Background Modeling	± 4.1	± 4.7
Flavor Tagging	$< \pm 1$	$< \pm 1$
Leptons	$< \pm 1$	$< \pm 1$
Pileup	± 1.8	± 2.7
Luminosity and Trigger	± 2.1	± 2.1
Higgs Boson Mass	$< \pm 1$	$< \pm 1$

Differential cross-sections

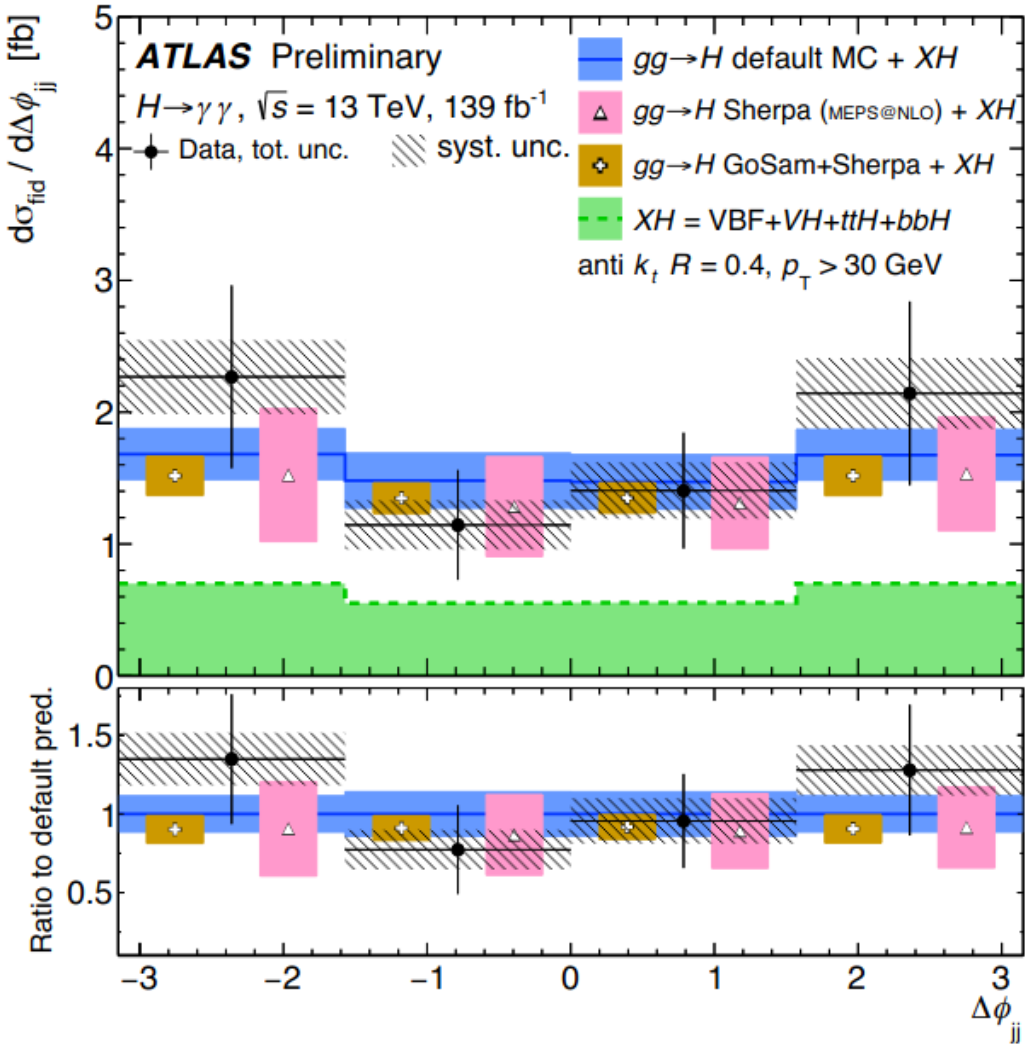
- Fiducial selection on Higgs decay products to match experimental acceptance
  - more model-independent than STXS
  - use distribution to probe new physics, CP structure, precision SM calculations, ...
- [Submitted to Phys. Rev. Lett.]: CMS first differential measurement in $\tau\tau$ decay
  - sensitivity particularly good in high p_T^H/high N_{jets} regions

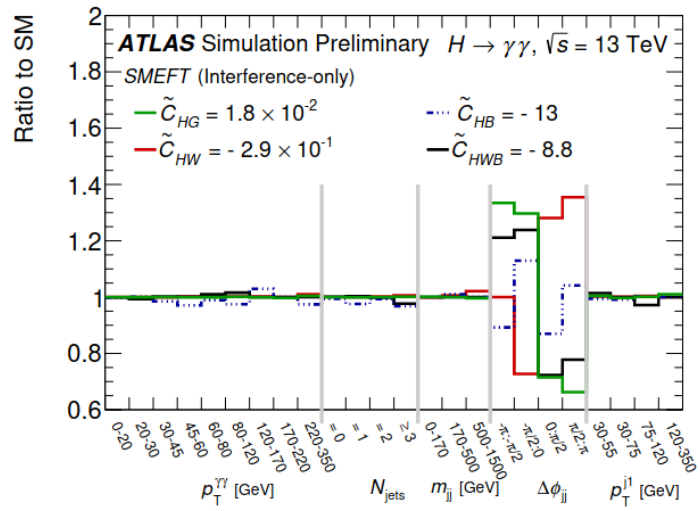


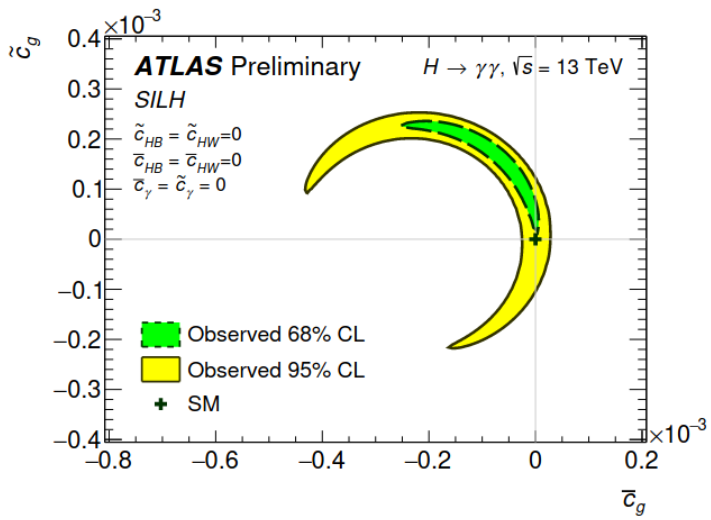


Differential cross-sections

- Also target variables sensitive to Higgs CP e.g. $\Delta\phi_{jj}$
  - [ATLAS-CONF-2019-029]: ATLAS H$\to\gamma\gamma$ differential analysis
  - interpret as constraints on CP-nature of effective Hgg vertex

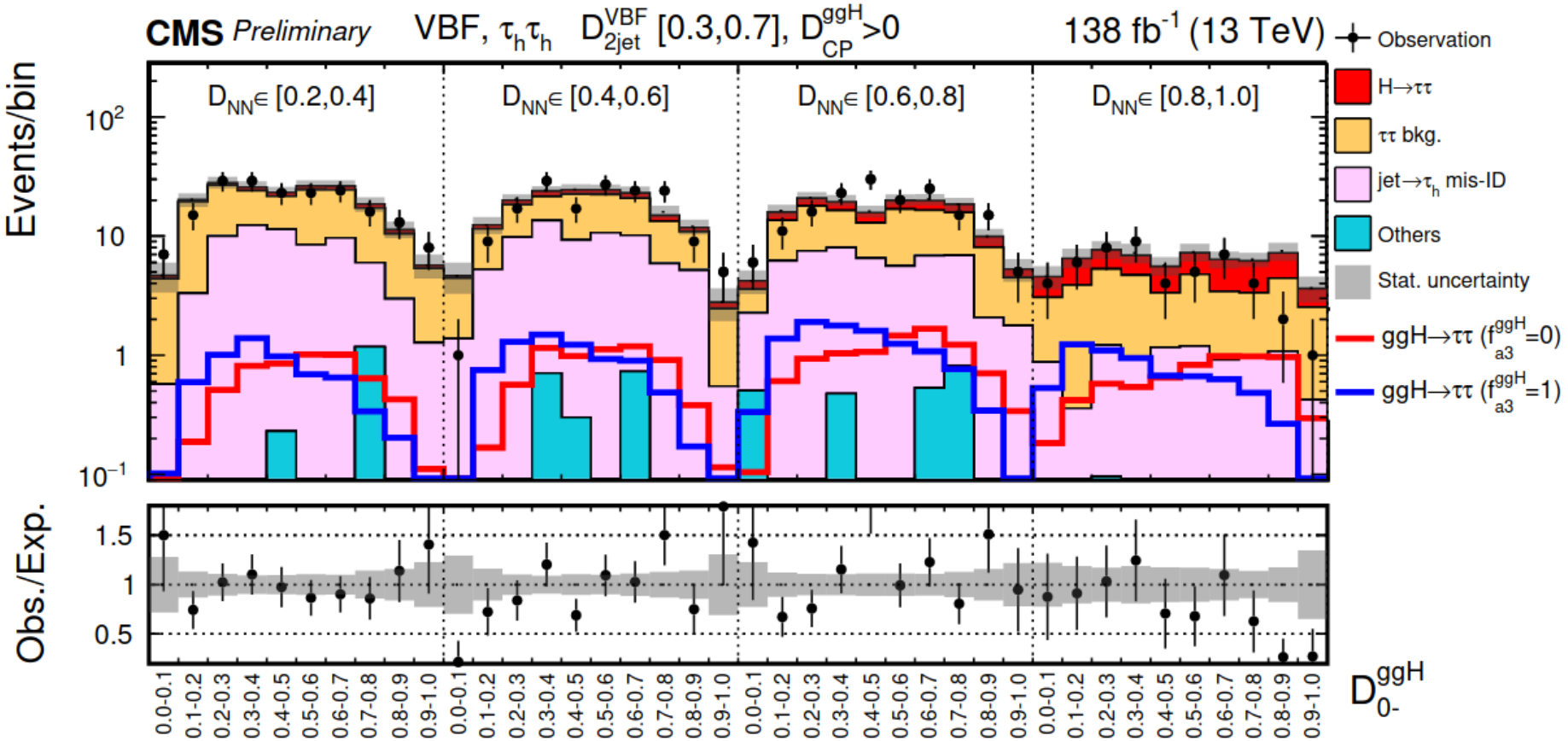






Probing Higgs CP with ggF + 2-jets

- Can also probe CP-structure of Hgg directly e.g. [CMS-PAS-HIG-20-007] ($\tau\tau$)
  - isolate VBF-like ggF+2j events $\Rightarrow$ sensitive to CP
  - MELA: $\mathcal{D}_{0-}^{\mathrm{ggF}}$: CP-odd vs CP-even ggF, $\mathcal{D}_{\mathrm{CP}}^{\mathrm{ggF}}$: CP-odd/CP-even interference, $\mathcal{D}_{\mathrm{2jet}}^{VBF}$: ggF-vs-VBF
  - + neural network ($\mathcal{D}_{\mathrm{NN}}$) separate VBF-like H signal from bkg
  - 4D binned template fit

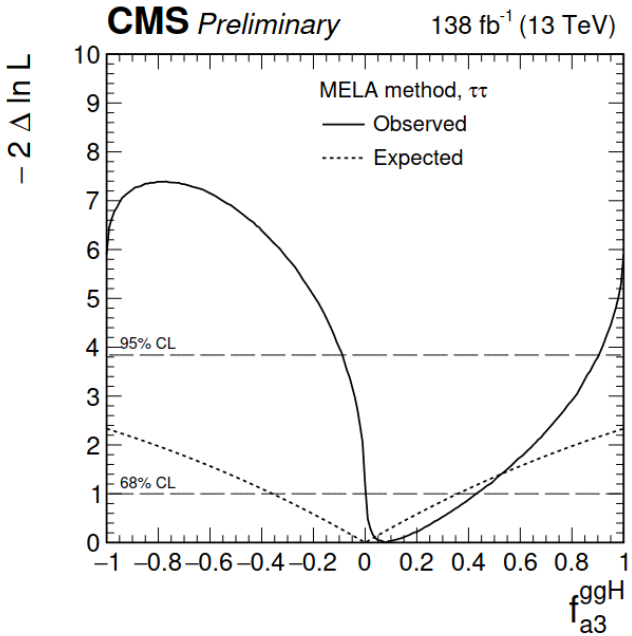


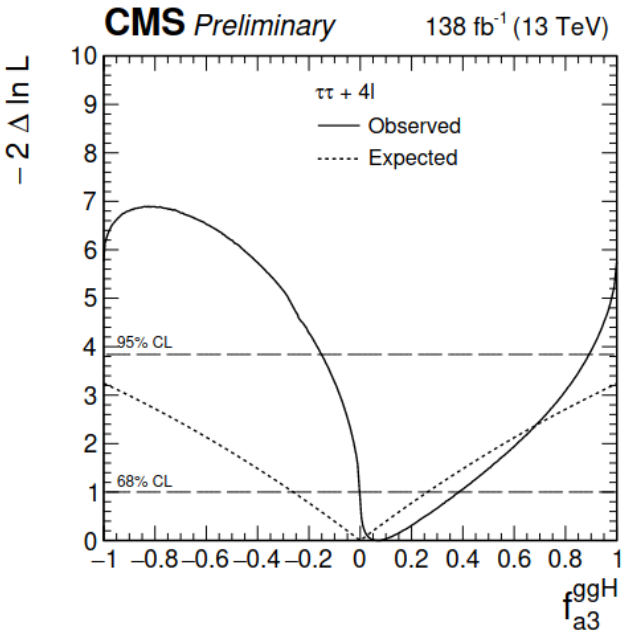
Probing Higgs CP with ggF + 2-jets

$$f_{a3}^{ggF} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2 + |a_3^{gg}|^2} \mathrm{sgn}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$$

- fractional CP-odd contribution to total cross-section

- Combine with AC measurements in H$\to 4\ell$ [Phys. Rev. D 104 052004 (2021)]

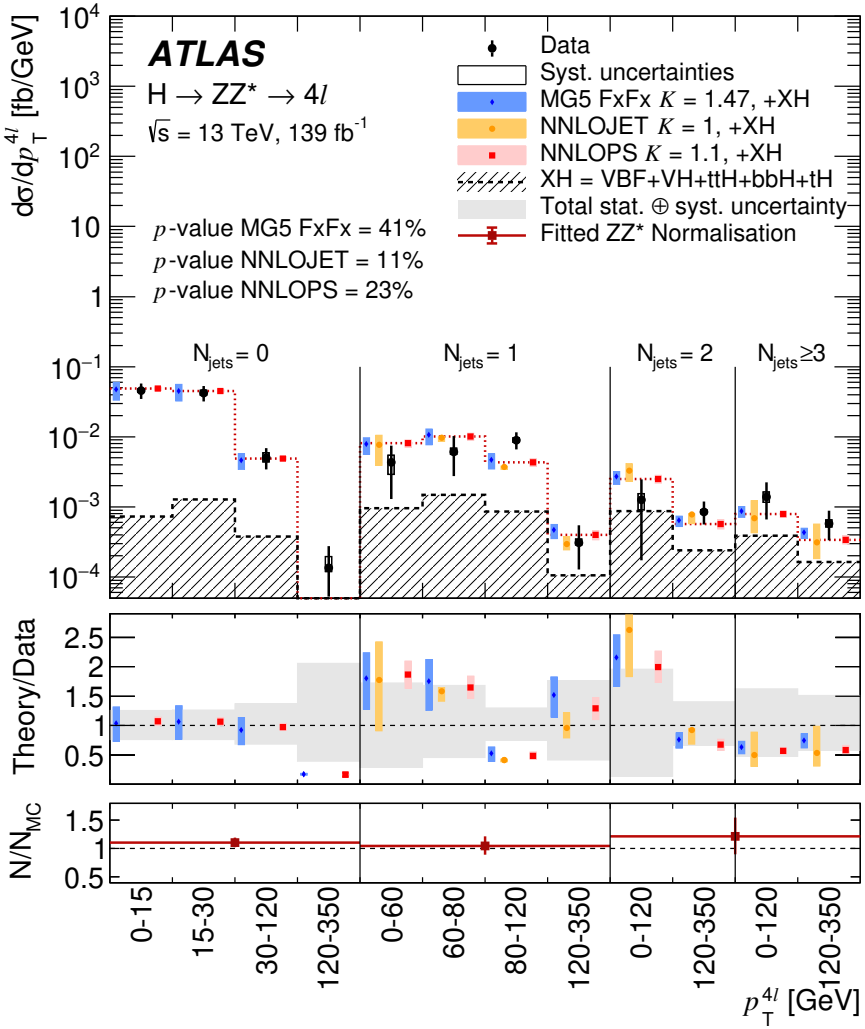


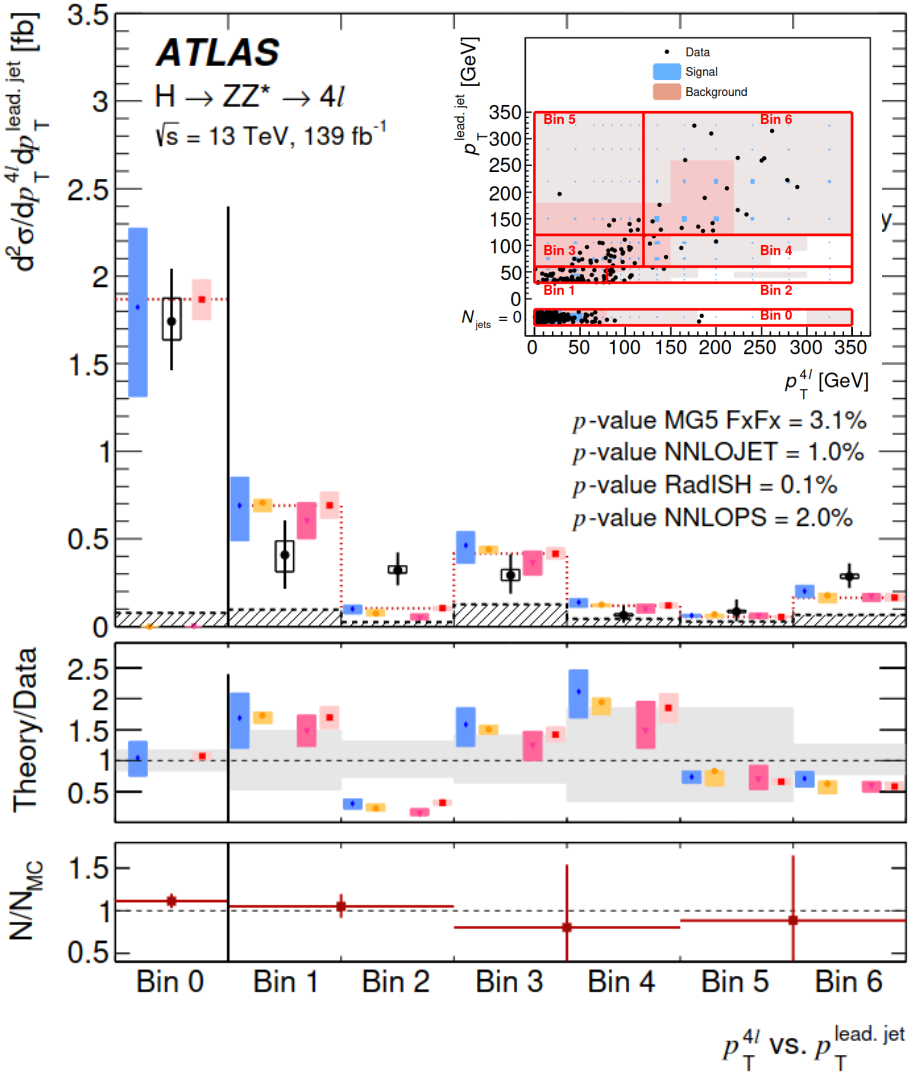


- Analysis selects events in tails of p_T^H: sensitive to quark mass effects
  - would benefit from NLO H+2jet samples with heavy quark mass effects (CP-odd)
  - [JHEP 08 (2016) 006], [arXiv:2110.06953]

Double-differential cross sections

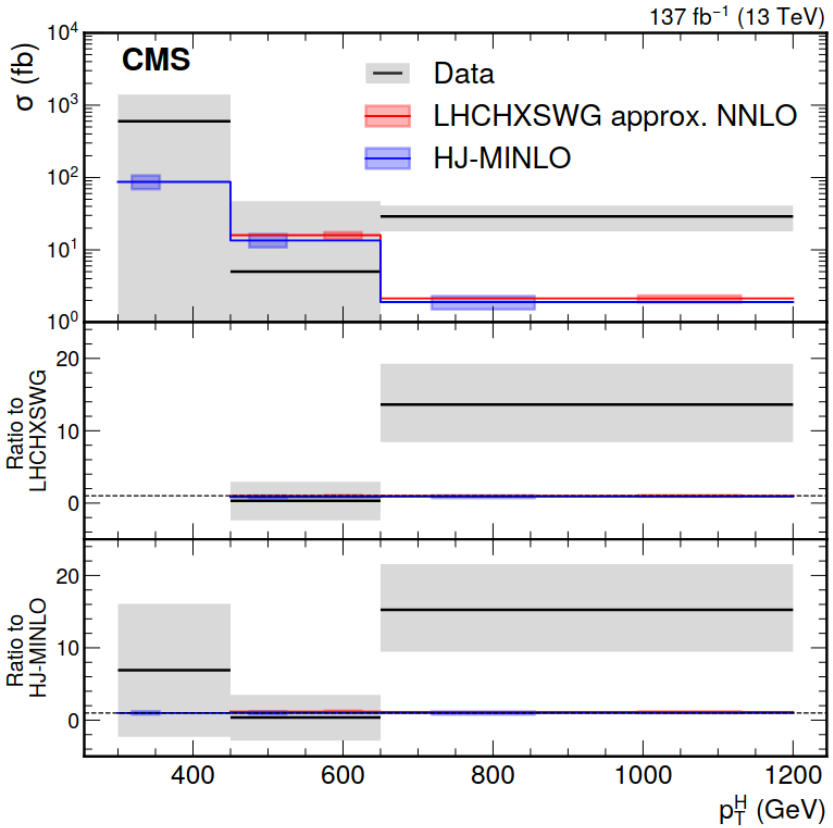
- Sufficient statistics to measure dσ in two variables
  - [Eur. Phys. J. C 80 (2020) 942]: ATLAS H$\to$ 4ℓ differential analysis
  - probe effects of **QCD resummation**!

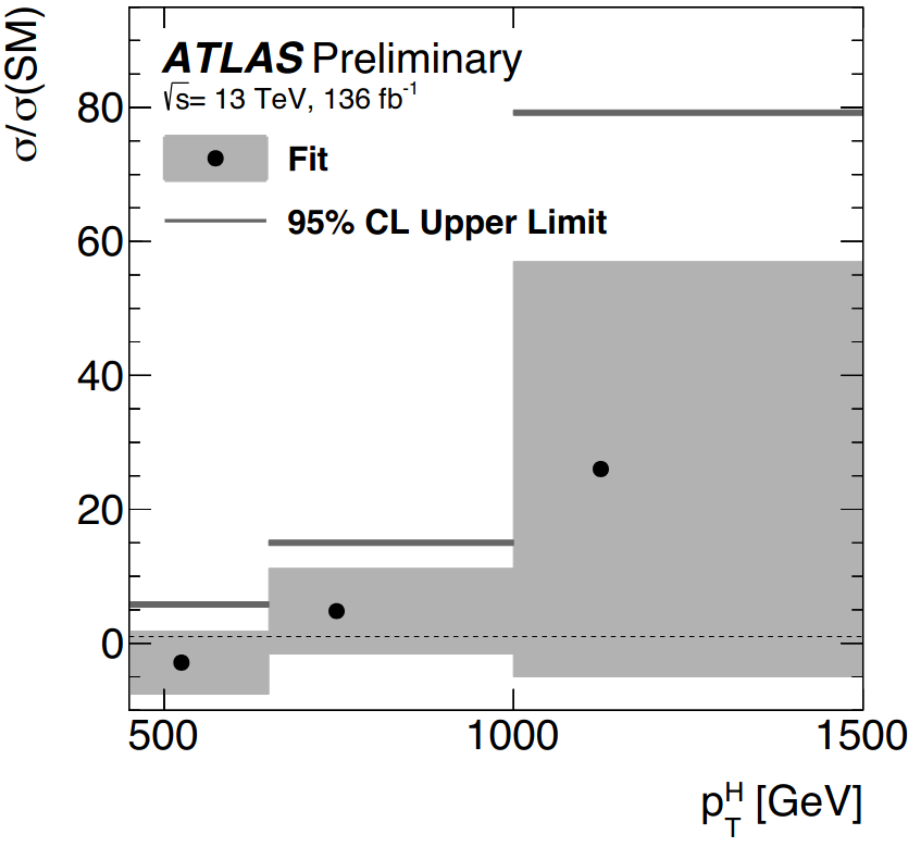




Boosted ggF

- High p_T^H regime sensitive to possible new particles in ggF loop
  - utilise boosted H→bb to reach high p_T^H, tag fat jet consistent with two b quarks
  - CMS: [JHEP 12 (2020) 085], ATLAS: [ATLAS-CONF-2021-010]





- Compared with (recent) state of the art theoretical calculations: [arXiv:2005.07762]
- CMS observe local significance of 2.6σ in $p_T^H > 650$ GeV bin

Experimental plans/wishlist for Run 3

- Will perform ggF cross section measurements at 13.6 TeV
  - require updated theoretical predictions at new c.o.m energy
  - + can include recent advances:

    $\Rightarrow$ exact mixed QCD/EW corrections

    $\Rightarrow$ correct top-quark mass effects at NNLO

    $\Rightarrow$ newer PDFs

    $\Rightarrow$ N^{3}LO not based on threshold expansion

- STXS/differential measurements
  - targeting increasingly-difficult-to-model regions of phase space e.g. H+2jet
  - require state-of-the-art tools for simulation e.g. [MiNNLO$_{\mathrm{PS}}$]
  - STXS uncertainty scheme (see talk by Haider)

- Improved PS modelling: now dominant theory unc. for ggF cross-sections
  - e.g. account for heavy quark masses in PS
  - also require consistent treatment of PS systematics