Exploring the CP-sensitive STXS staging in the H→WW* decay channel by the ATLAS experiment

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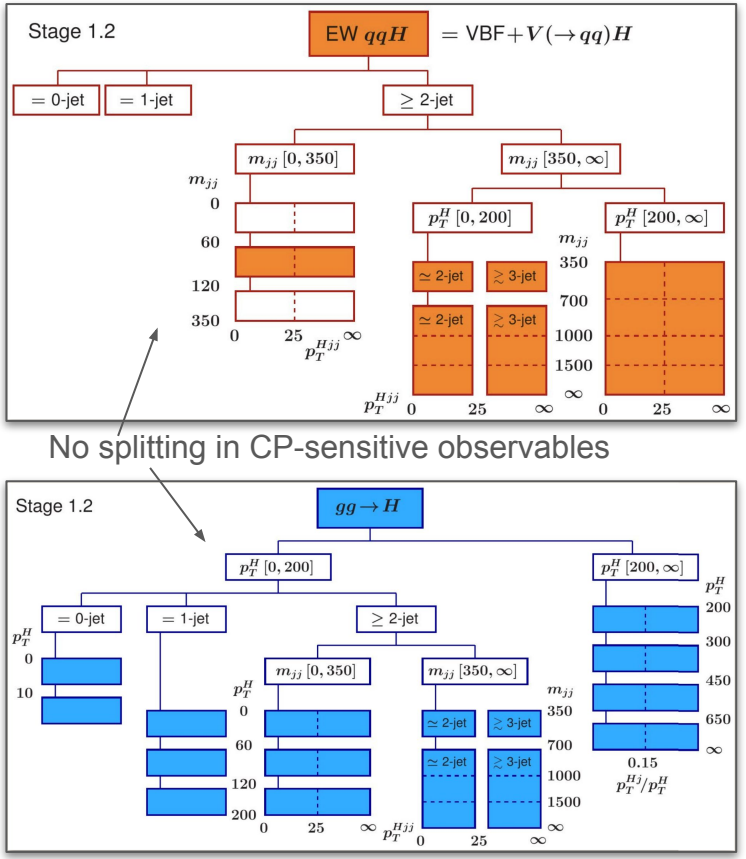
https://indico.cern.ch/event/1442025/contributions/6174083/

Introduction

- Current **STXS Stage 1.2** binning is **not** sensitive to the Charge-Parity (CP) properties of the Higgs boson
- Plans for **STXS Stage 1.3** binning include **CP-sensitive bins**
  - Most recent discussion in LHCHWG found here
- In this talk, we discuss a ***similar*** implementation in measurements of vector-boson fusion (VBF) and gluon-gluon fusion (ggF) in H→WW* decays

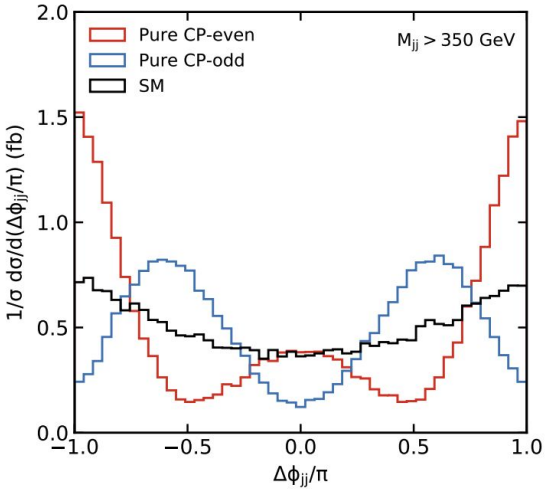


CP sensitive observable

- Independent of the Higgs decay mode, CP properties of HVV couplings can be investigated by additionally splitting the 2-jet phase space by the **signed azimuthal separation between the two leading jets** that characterize the VBF process:

$$\Delta\phi_{jj}^{\pm} = \text{remainder}(\phi_j^{\text{forward}} - \phi_j^{\text{backward}} + 2\pi)/2\pi,$$

  - $\varphi_j^{\text{forward}}$ and $\varphi_j^{\text{backward}}$ chosen such that $\eta_j^{\text{forward}} > \eta_j^{\text{backward}}$
  - Maps to $[0, 2\pi]$
- Same observable considered for splitting EW qqH in Stage 1.3 STXS

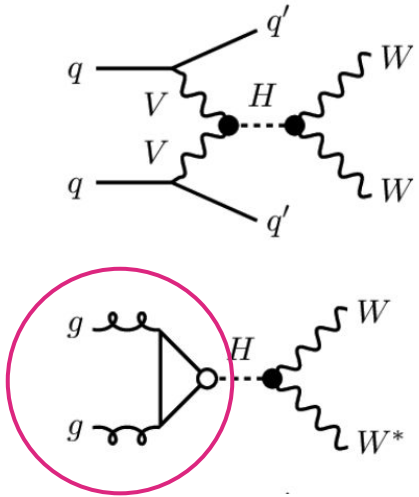


$\Delta\varphi_{jj}$ observable for pure CP-even, pure CP-odd, and SM couplings (source) at parton level

N.B. when we write $\Delta\varphi_{jj}$ in this talk, we are always referring to the signed quantity

Overall strategy

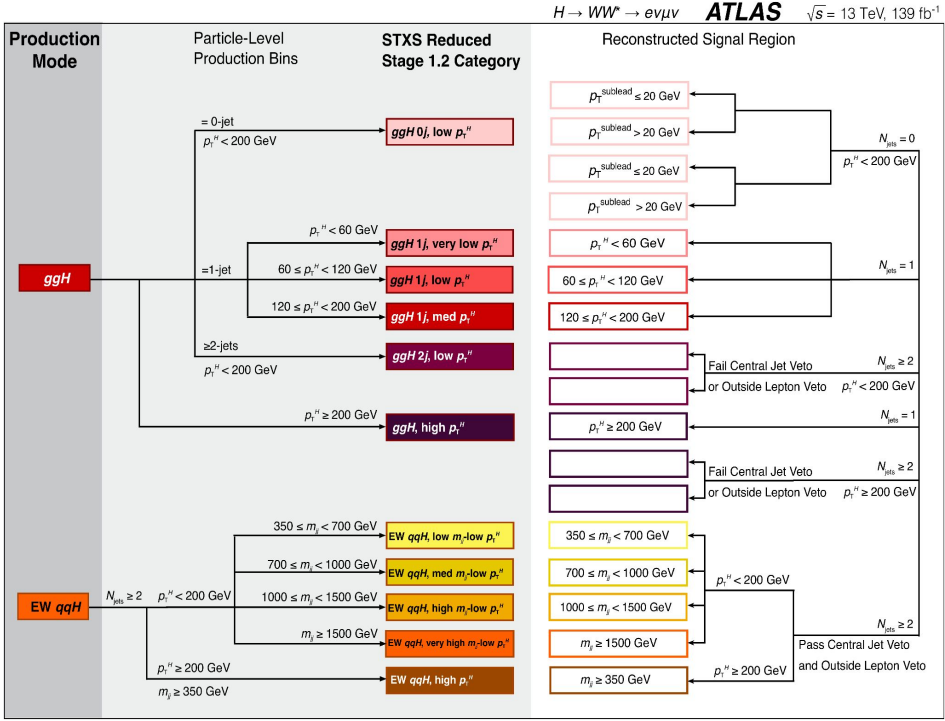
- Explore **both** VBF and ggF production modes to investigate **CP-odd anomalous couplings**
- CP-odd effect characterized by **Standard Model Effective Field Theory** (SMEFT) operators in the Warsaw basis
- Constraints on CP-odd SMEFT operators can reveal **potential CP violation** for the Higgs boson's effective couplings to **vector bosons** and **gluons**



Resolved as effective vertex in SMEFT

Describing VBF+ggF, H→WW* events

- Based on the most recent 139 fb^{-1} measurement from ATLAS: [Phys. Rev. D 108 (2023) 032005]
- H→WW*→$\ell\nu\ell\nu$ decay characterized by 2 (different-flavour) charged leptons and 2 undetected neutrinos in the final state
- Jets can be present, either from the quarks participating in VBF or from initial-state radiation in ggF
- Events divided by number of jets: 0, 1, ≥2
- 0- and 1-jet regions still contribute to CP-even constraints

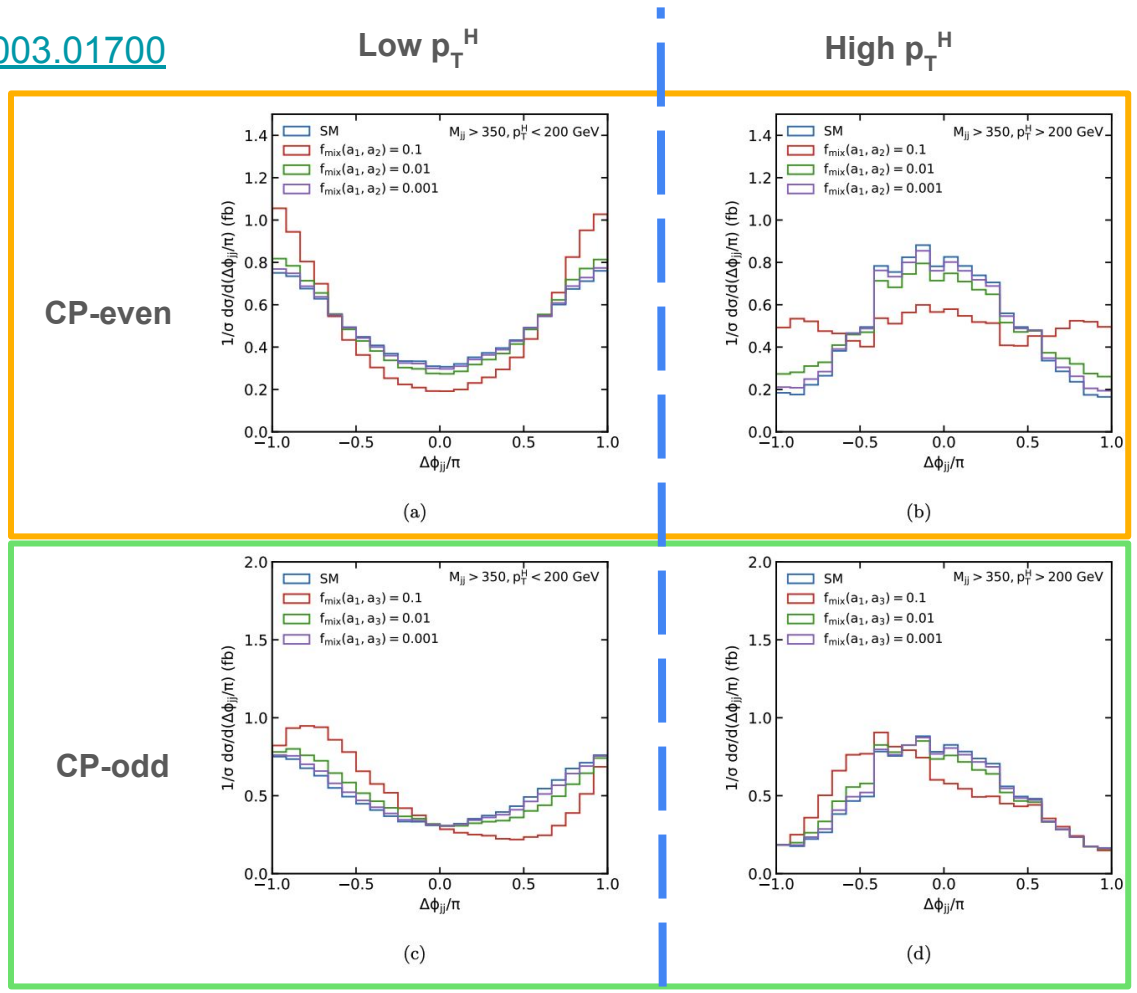


$\Delta\varphi_{jj}$ in different STXS bins

Normalized distributions of $\Delta\varphi_{jj}$ for various amounts of mixing between anomalous CP couplings and the SM at parton level

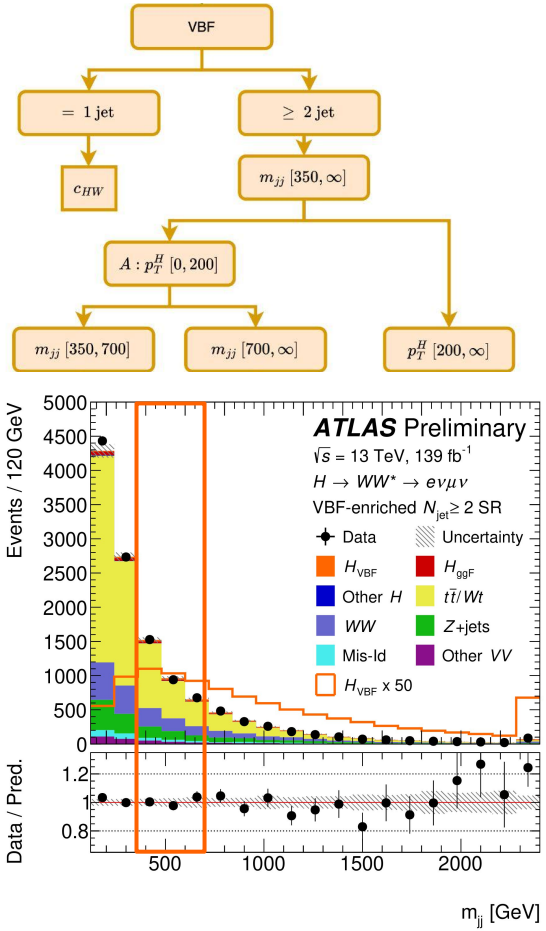
$$T^{\mu\nu}(q_1,q_2) = a_1(q_1,q_2)\, g^{\mu\nu} + a_2(q_1,q_2)\,[q_1\cdot q_2 g^{\mu\nu} - q_1^{\mu}q_2^{\nu}] + a_3(q_1,q_2)\,\epsilon^{\mu\nu\alpha\beta}q_{1,\alpha}q_{2,\beta}$$

arXiv:2003.01700



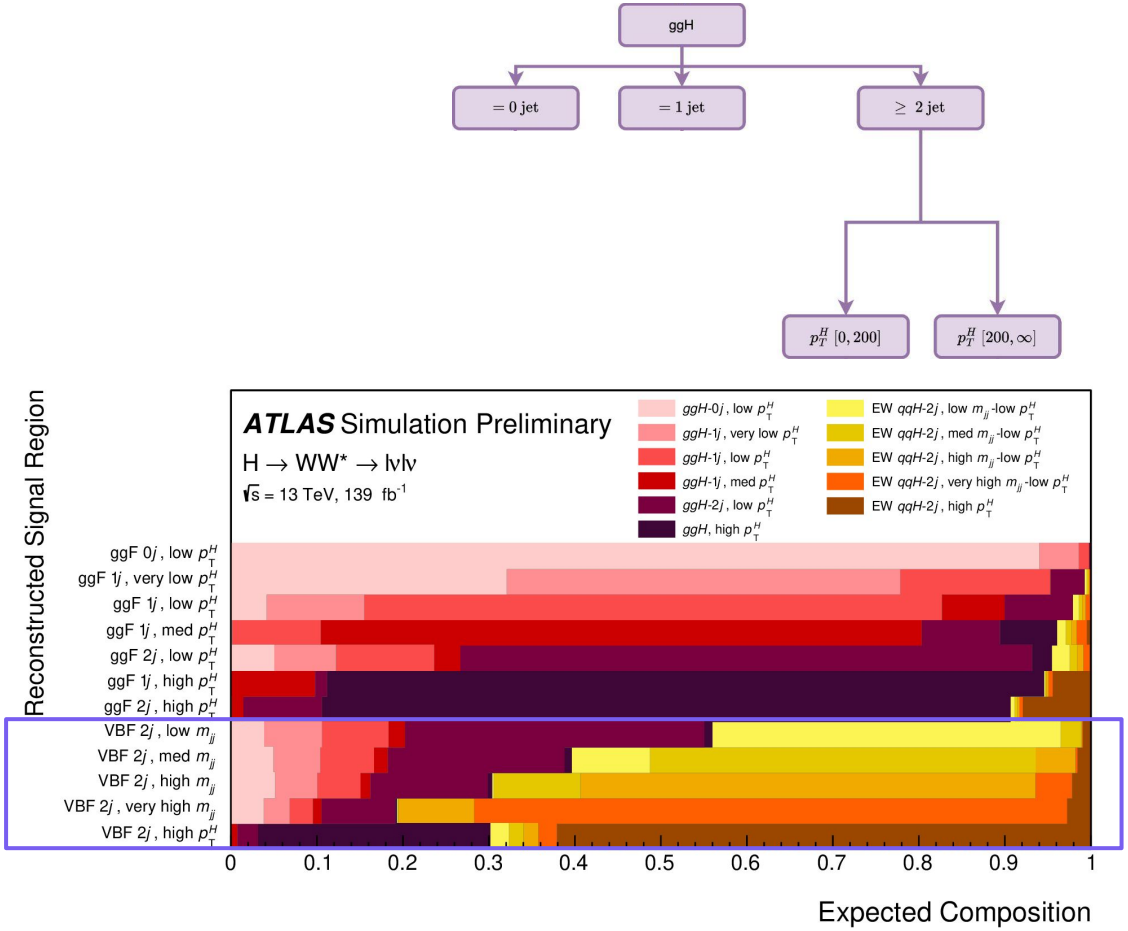
Binning strategy

- **Binning strategy based on STXS Stage 1.2**
  - VBF production split at Higgs p_T of 200 GeV as the EFT effects on the $\Delta\varphi_{jj}$ shape differ significantly between the low and high p_T^H regions
  - VBF production also split at m_{jj} of 700 GeV due to high top-quark contamination in the lower energy region



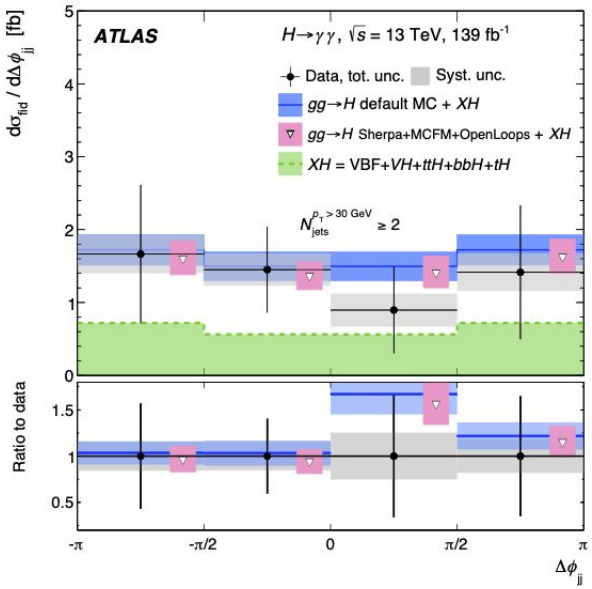
Binning strategy

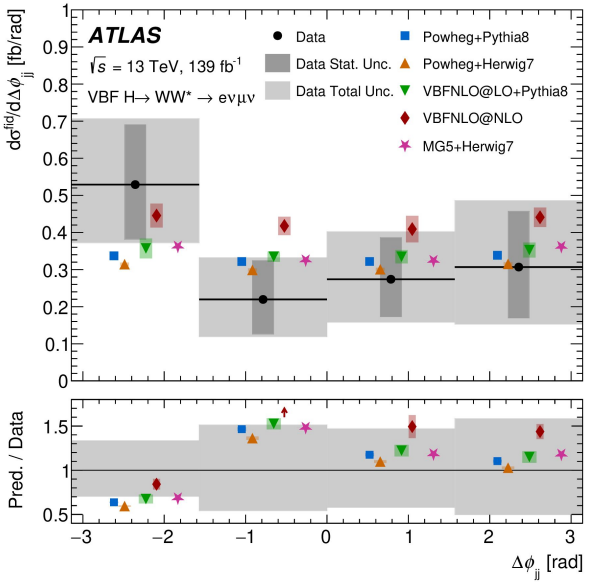
- **Binning strategy based on STXS Stage 1.2**
  - ggF 2-jet production split at Higgs p_T of 200 GeV to account for ggF contamination in VBF categories



Binning strategy

- Each 2-jet region further divided into **4 equal $\Delta\varphi_{jj}$ categories**:
  - $(0, \pi/2)$
  - $(\pi/2, \pi)$
  - $(\pi, 3\pi/2)$
  - $(3\pi/2, 2\pi)$





H→$\gamma\gamma$ differential measurement

VBF differential measurement

- The CP sensitivity of the 0 to 2π scheme is **equivalen**t to a $-\pi$ to $+\pi$ measurement

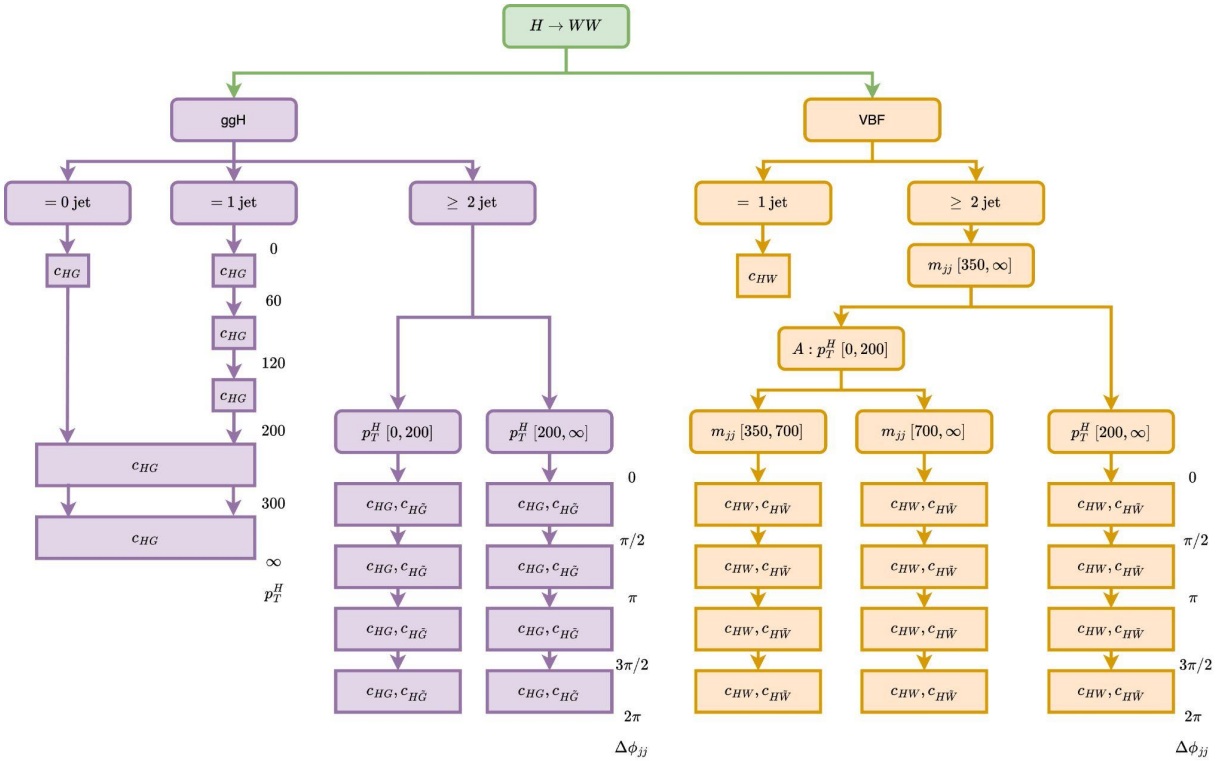
Operators of interest

- As mentioned, interested in anomalous effects modifying the Higgs boson's couplings to vector bosons and gluons → leads to the following set of Wilson coefficients and operators
- When considering these operators, we **only consider** the CP-even/odd SM-BSM interference terms, **not** the CP-even BSM-BSM terms

Wilson coefficient	Operator
c_{HG}	$H^\dagger H G^A_{\mu\nu} G^{A\mu\nu}$
$c_{H\tilde{G}}$	$H^\dagger H \tilde{G}^A_{\mu\nu} G^{A\mu\nu}$
c_{HW}	$H^\dagger H W^I_{\mu\nu} W^{I\mu\nu}$
$c_{H\tilde{W}}$	$H^\dagger H \tilde{W}^I_{\mu\nu} W^{I\mu\nu}$

STXS/$\Delta\varphi_{jj}$ binning and operators of interest

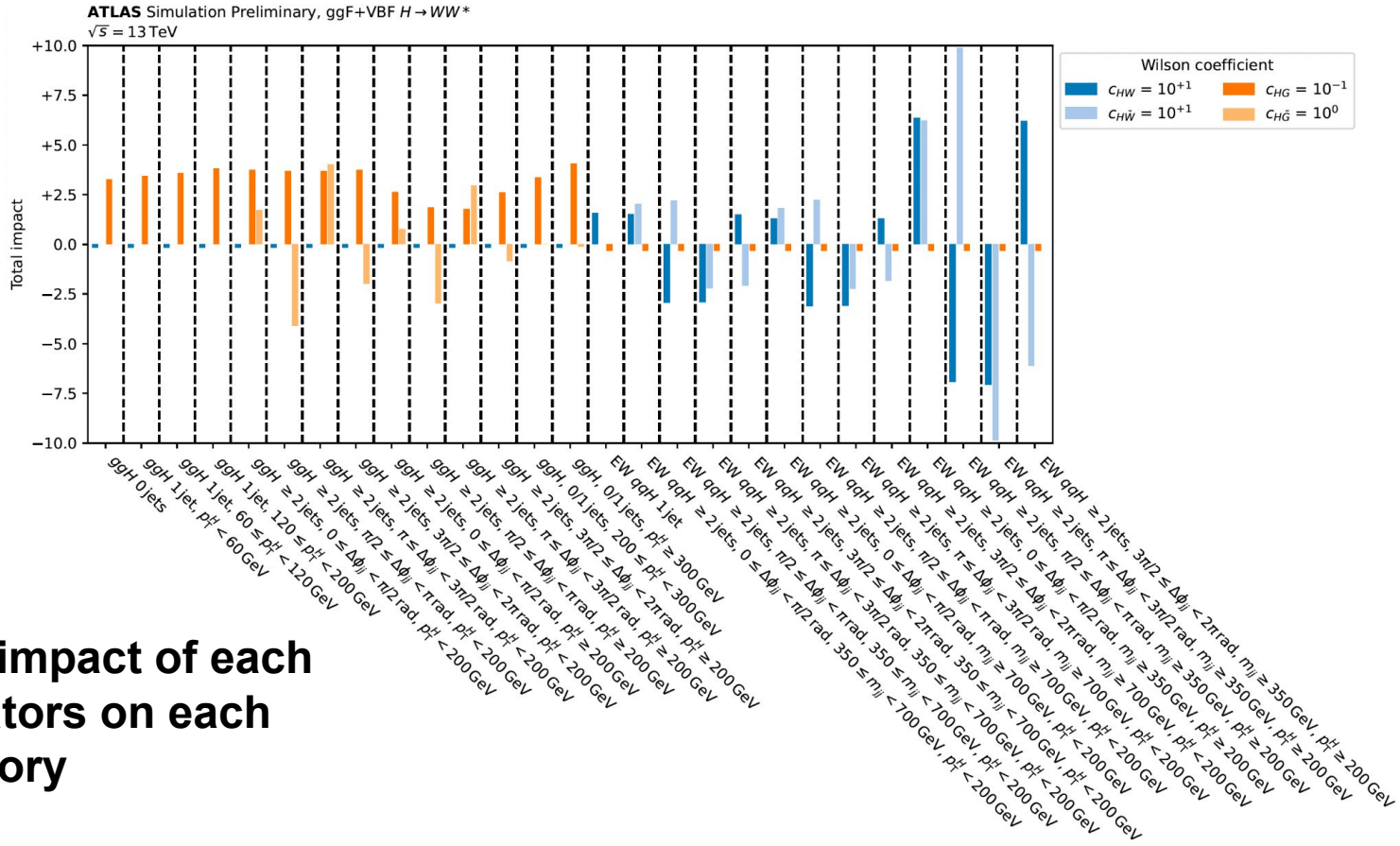
Each of the purple (orange) square boxes representing the ggF (VBF) bins is labeled with the Wilson coefficients whose corresponding operators affect the production bin through the production vertex



Deriving a parameterization

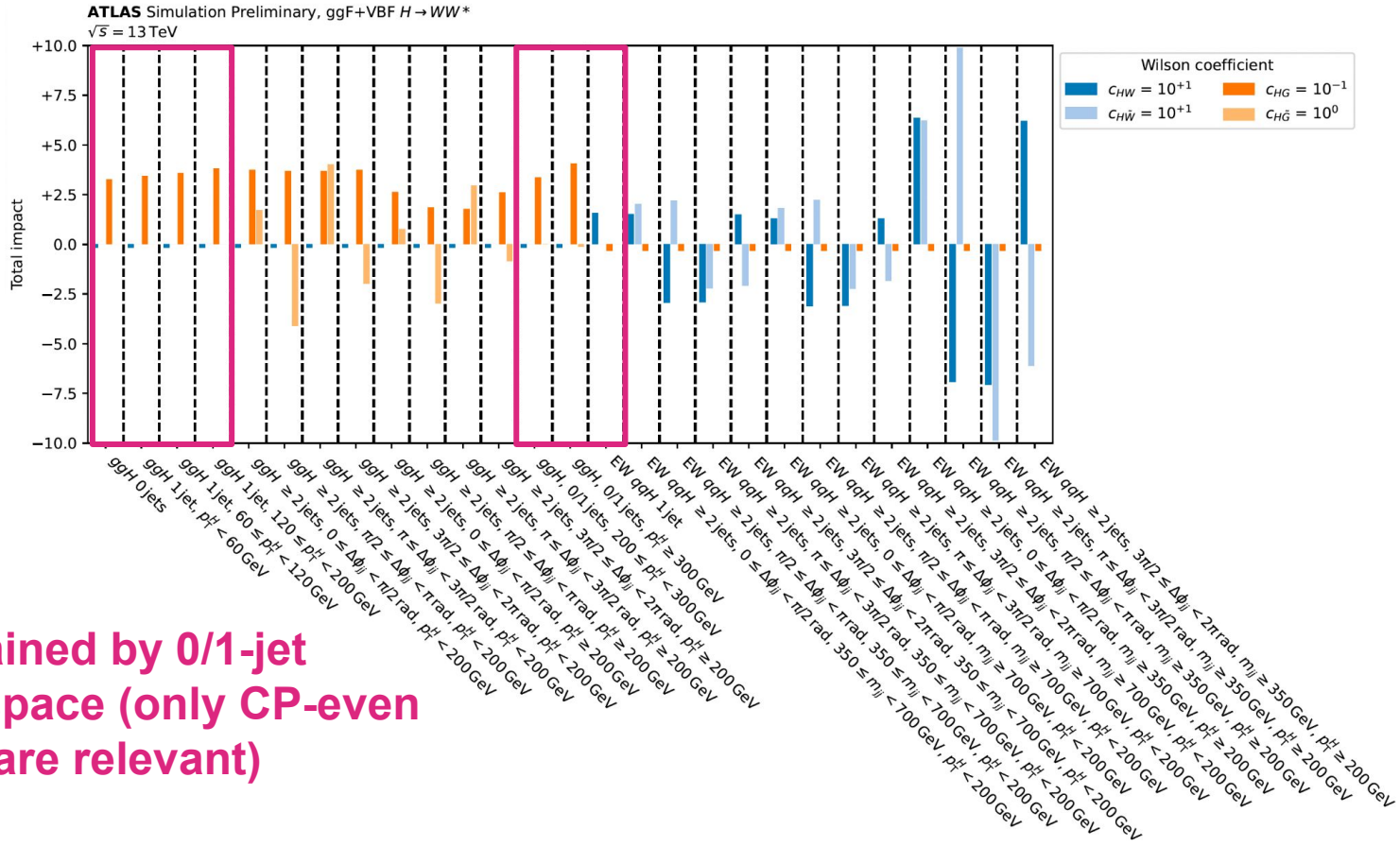
- Procedure closely follows that of the recent ATLAS SMEFT interpretation
- **Impact** of each operator on **Higgs production**, **partial width**, and **total width** in STXS and/or $\Delta\varphi_{jj}$ bins estimated using MadGraph with the SMEFTsim UFO with a new physics scale Λ = 1 TeV
  - Except for ggF+0/1j, where the impact on production is estimated using the SMEFT@NLO UFO (only includes CP-even operators, so cannot be used for $\Delta\varphi_{jj}$ parameterization)
- Events are showered using Pythia 8
- Impact for each operator is parameterized as a function of the corresponding Wilson coefficient
  - **CP-odd operators only affect production**, not partial or total widths

Visualizing the parameterization



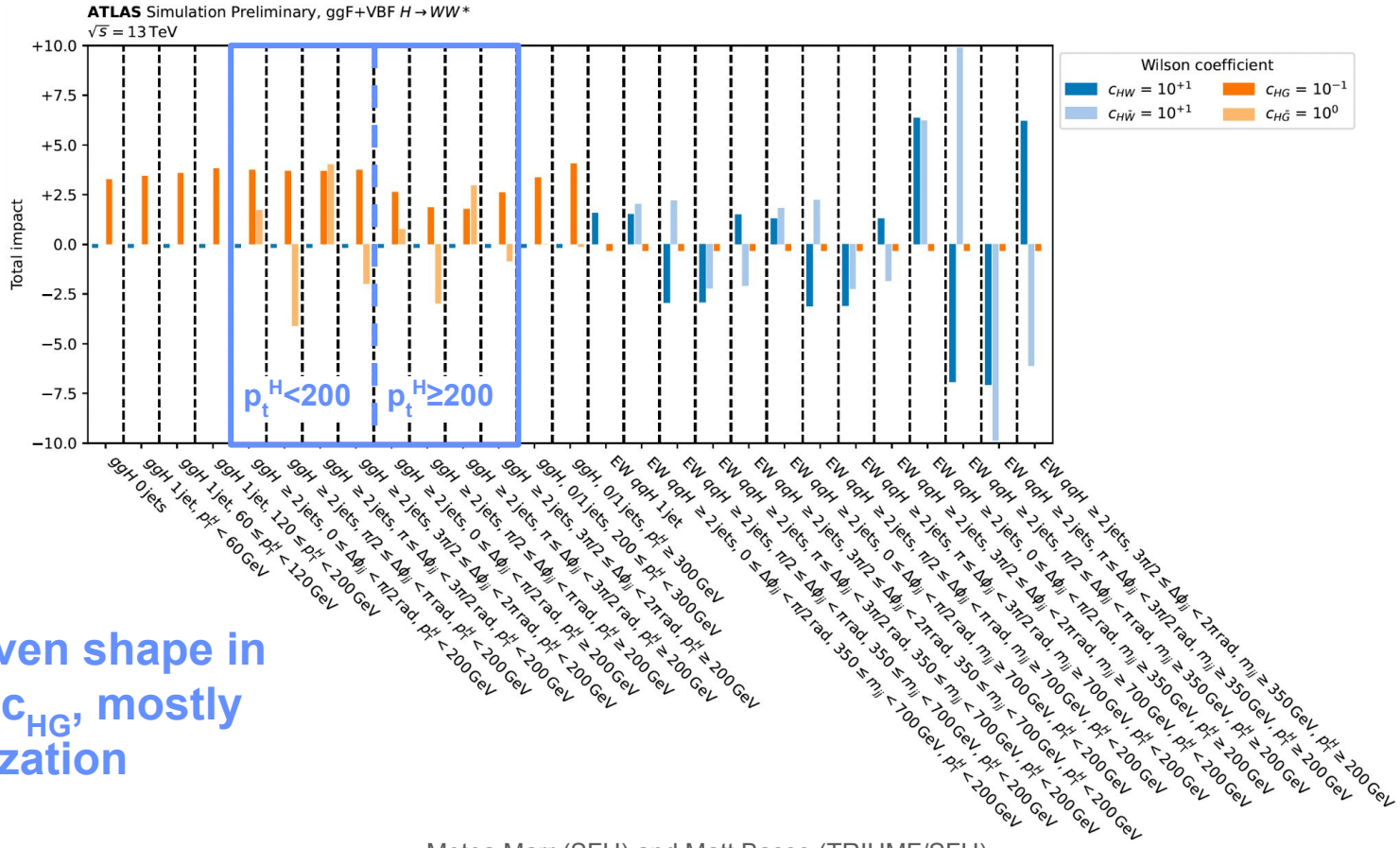
Total impact of each operators on each category

Visualizing the parameterization



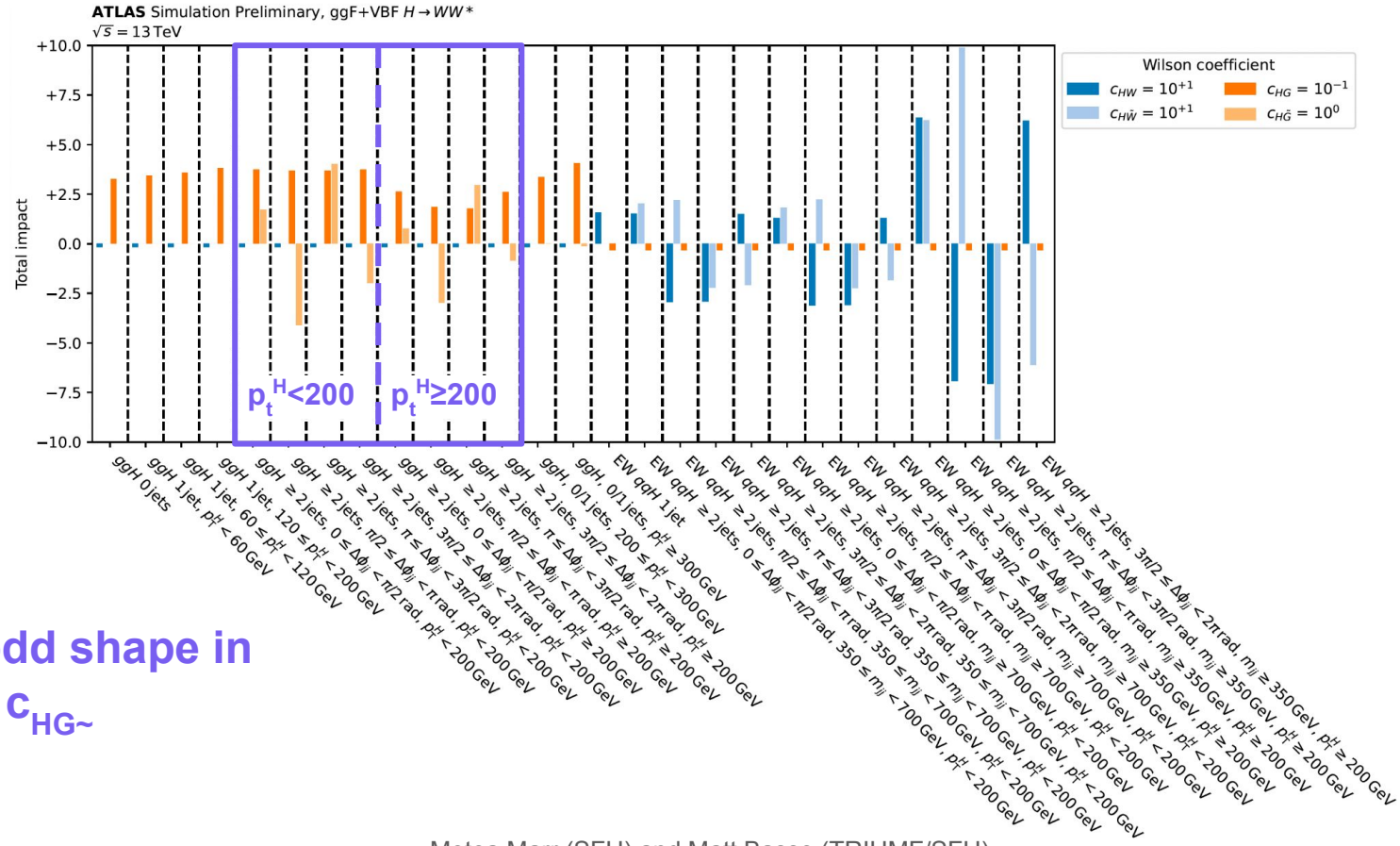
Constrained by 0/1-jet phase space (only CP-even effects are relevant)

Visualizing the parameterization



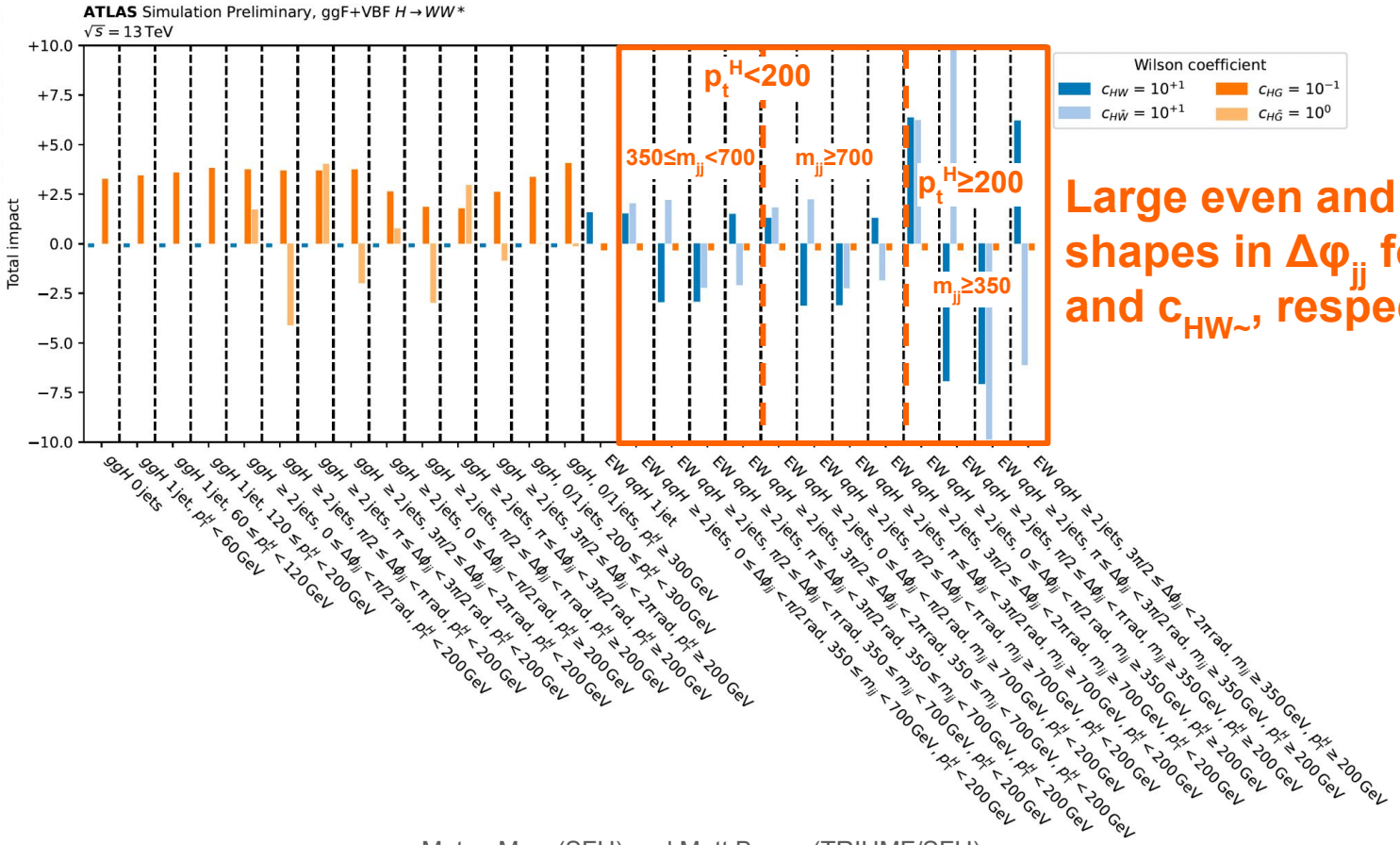
Small even shape in $\Delta\varphi_{jj}$ for c_{HG}, mostly normalization

Visualizing the parameterization



Large odd shape in $\Delta\varphi_{jj}$ for $c_{HG\tilde{}}$

Visualizing the parameterization



Large even and odd shapes in $\Delta\varphi_{jj}$ for c_{HW} and $c_{HW\sim}$, respectively

Applying a parameterization

Example for ggH, p_T^H < 200 GeV region

$$(\sigma \times \mathcal{B})_{0-200,\alpha} \rightarrow (\sigma \times \mathcal{B})_{0-200,\alpha} \times \mu_{0-200} \frac{1 + \sum_i^N \left(A_{\alpha i}^{0-200} + A_i^{\Gamma^{HWW}} \right) \times c_i}{1 + \sum_i^N A_i^{\Gamma^H} \times c_i}$$

- Nominal measurement has a **signal strength (σ×B)** scaling the yield for each STXS and $\Delta\varphi_{jj}$ bin (labelled α = 1, 2, 3, 4) measured
- For each operator, the parameterization of its **impact** on each of **production**, **partial width**, and **total width** is applied to each signal strength → shifts free parameters from signal strengths to Wilson coefficients
- Including **signal normalization factors (NFs)**, shared among the $\Delta\varphi_{jj}$ bins of a given p_T^H/m_{jj} region, can **remove normalization effects**
  - This allows us to isolate pure CP violating effects and avoid introducing bias into the results

Some comments

- **Impacts plots inspire the expected sensitivity**
  - $c_{HW}/c_{HW\sim}$ operators affect VBF cross sections with **similar magnitudes** but **different shapes** → expect **similar sensitivity** to both operators, with **minimal correlation**
  - c_{HG} operator has a **large normalization effect on 0/1-jet bins** and a small shape in $\Delta\varphi_{jj}$ → **expect sensitivity to be driven by Stage 1.2 0/1-jet bins**
  - Sensitivity to $c_{HG\sim}$ operator will come entirely from 2-jet bins
- Making the statement stronger: the shapes in STXS/$\Delta\varphi_{jj}$ for each operator are distinct, so minimal correlations are expected between all of them
- We expect the correlation between $c_{HG\sim}$ and $c_{HW\sim}$ to be small because the ggF contamination is smaller at high p_T^H and the EFT effect is much more prominent in this region

Summary

- Presented a proposal for measuring CP-violating effects in bins of VBF+ggF production and the H→WW* decay channel
  - Proposal is based on an STXS-like splitting of VBF and ggF into bins of $\Delta\varphi_{jj}$, which is similar (but not identical) to that proposed for Stage 1.3
- Proposal has the potential to measure CP-even and odd SMEFT operators modifying the Higgs-V and Higgs-gluon couplings in a relatively decorrelated way

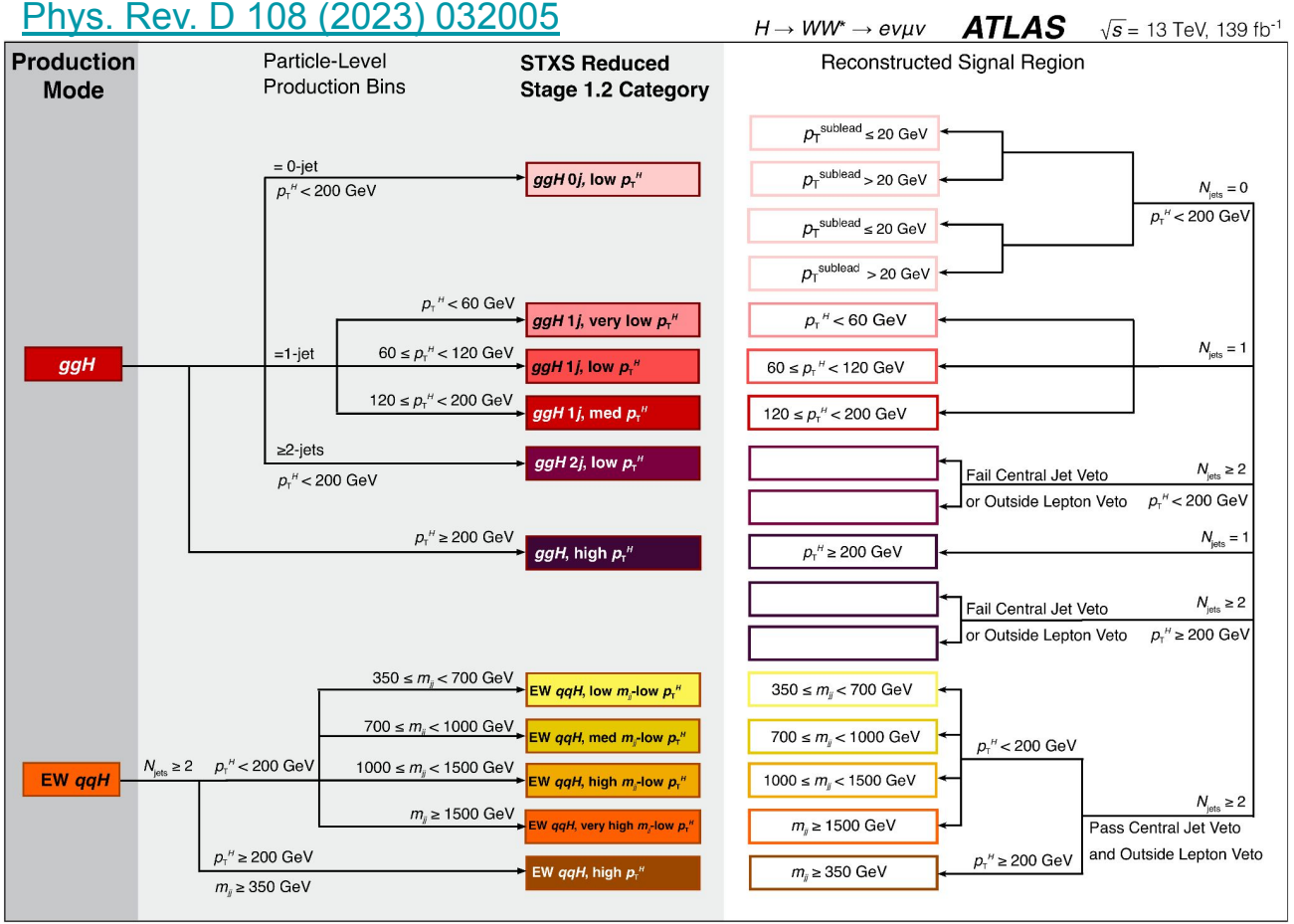
Thank you for your attention! Questions?

Backup

STXS categories

ggF and VBF production bins at particle level (left) and the corresponding reconstructed signal regions (right)

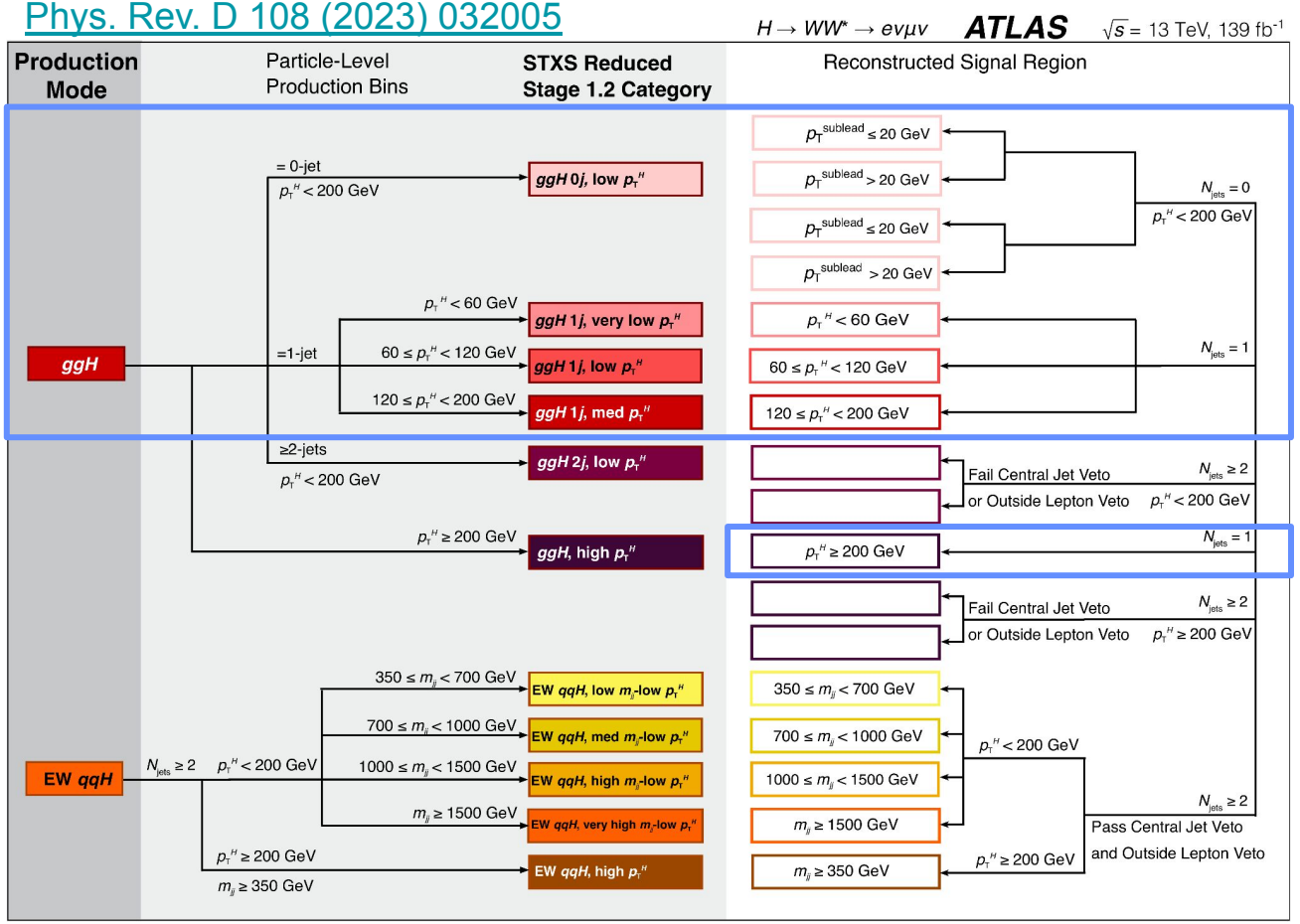
Phys. Rev. D 108 (2023) 032005



STXS categories

0- and 1-jet categories are not susceptible to the interference of the SM and CP-odd operators (from terms linear in the Wilson coefficients)

Phys. Rev. D 108 (2023) 032005



STXS categories

2-jet categories follow STXS Stage 1.2 scheme

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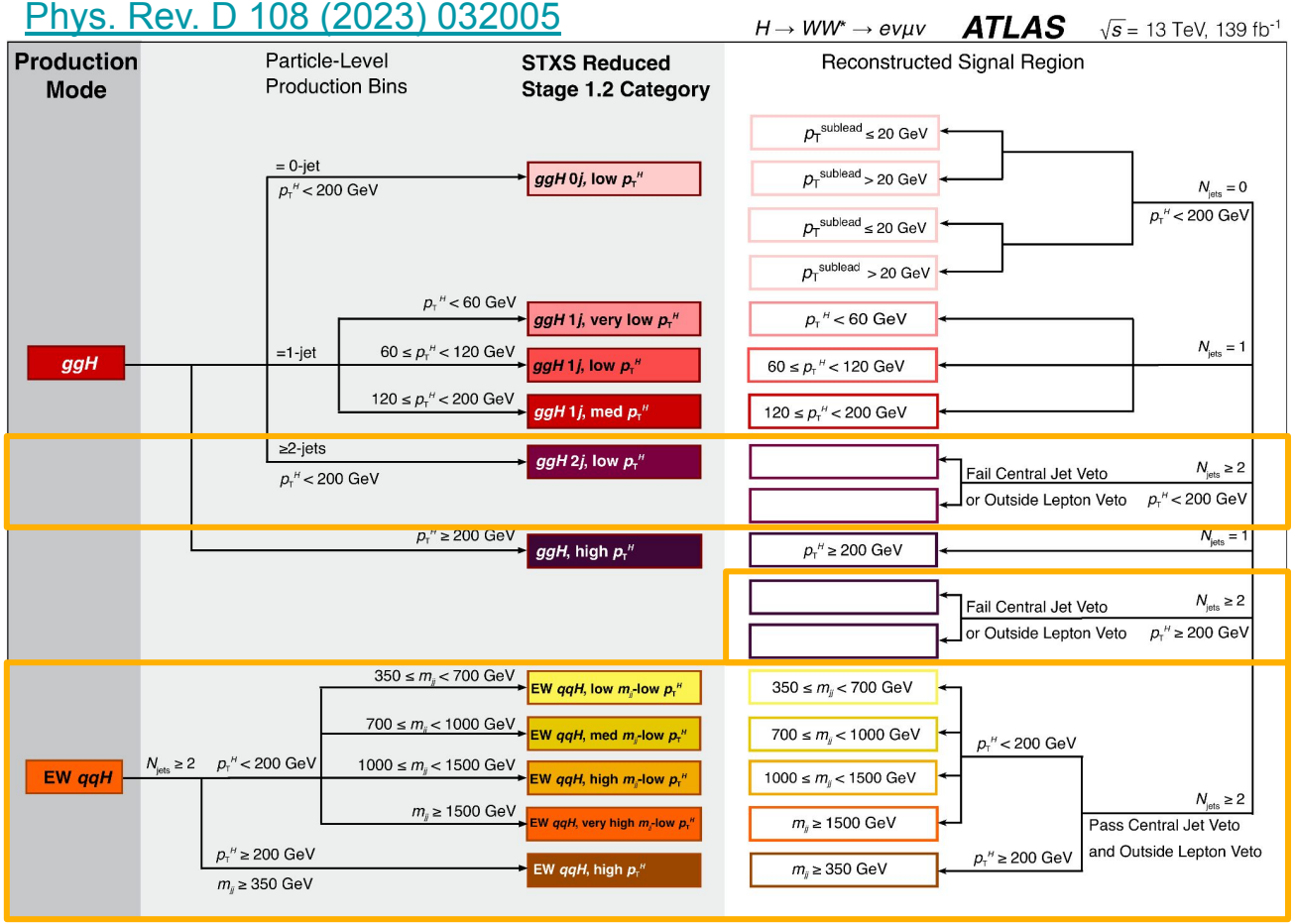
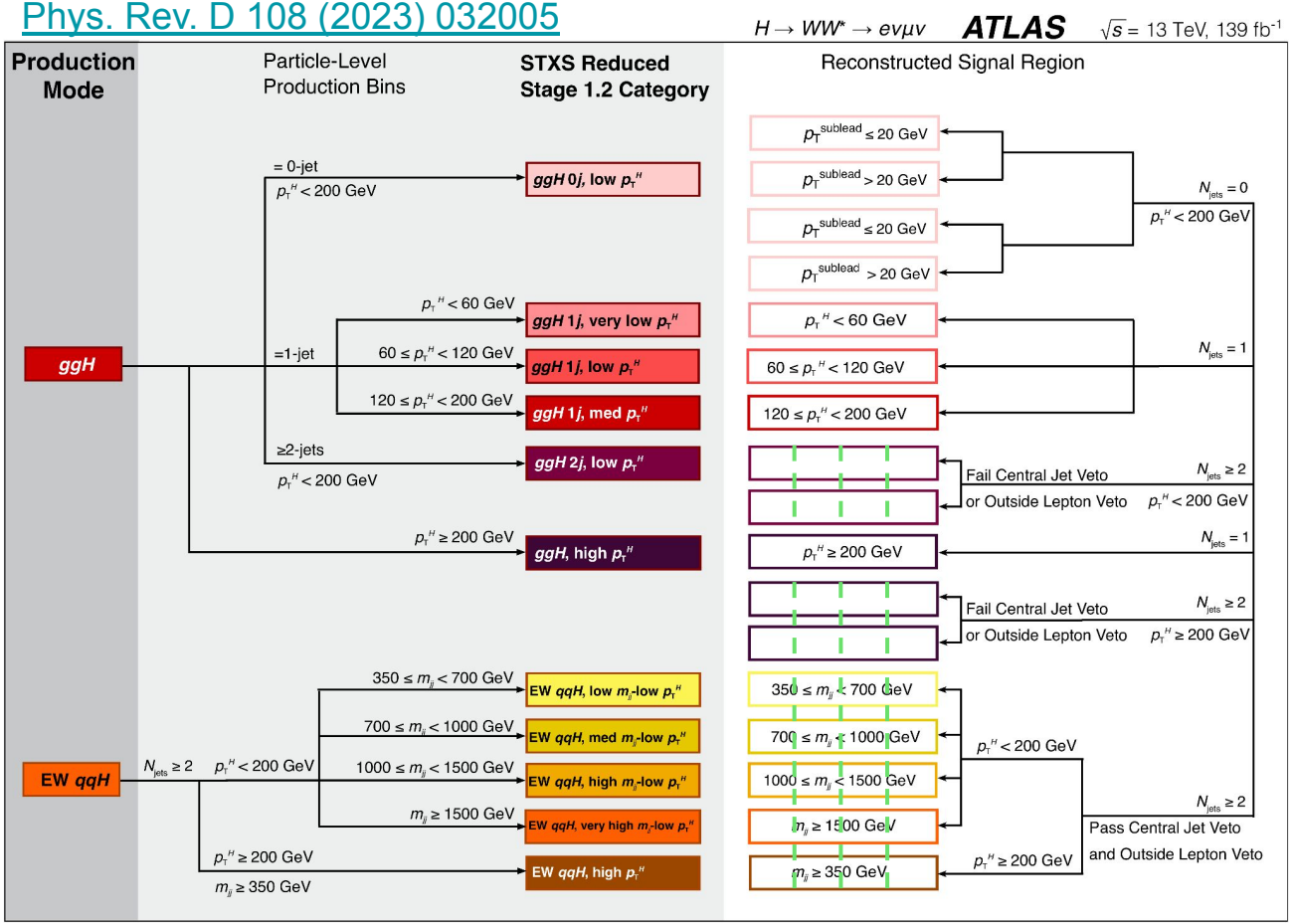


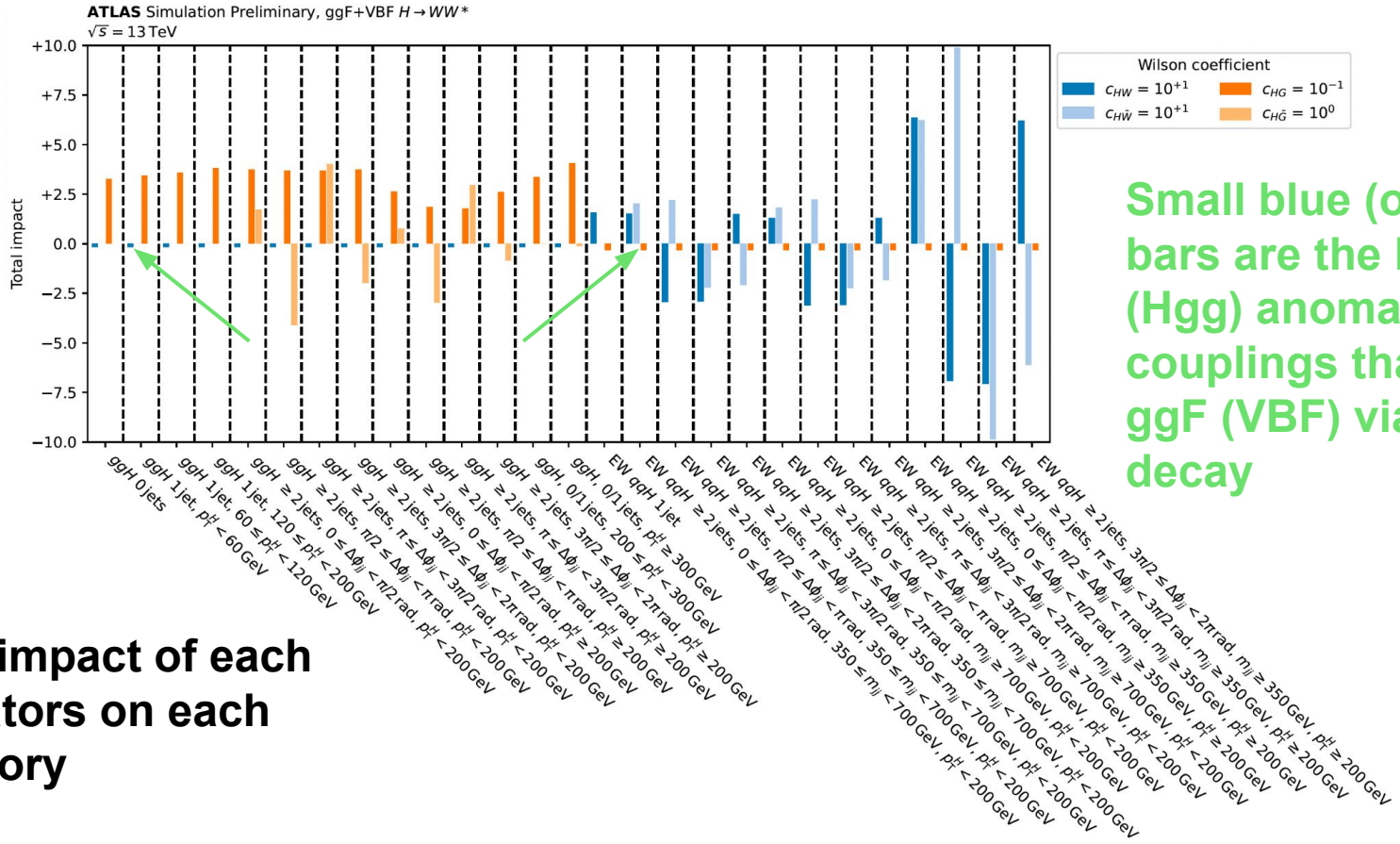
STXS categories

2-jet categories could be further divided into 4 equal $\Delta\varphi_{jj}$ bins

Phys. Rev. D 108 (2023) 032005



Visualizing the parameterization



Small blue (orange) bars are the HVV (Hgg) anomalous couplings that affect ggF (VBF) via HWW decay

Total impact of each operators on each category

Reasoning for $\Delta\varphi_{jj}$ being signed

Phys. Rev. D 74, 095001 (2006)