EFT interpretations in the Higgs and electroweak sectors
-- lecture 1 --

Ecole de Gif 2023 -- Annecy

Saskia Falke (IPHC Strasbourg)

Introduction

- Higgs & electroweak sectors = study of interaction between (SM) particles, excluding strong interaction (QCD)
  - Precision measurement of free parameters of SM ($\sin\theta_W$, Z mass, Higgs mass,…)
  - Precision measurement of interaction rates and properties to probe SM predictions
  - Search for rare processes that could be significantly enhanced in presence of new physics
- Different kind of experiments targeting different properties and energy ranges
  - Low energy probes, e.g. measurement of Fermi contant from muon lifetime
  - “Medium” energy scale, e.g. in B-meson decays at B-factories
  - High energy colliders, e.g. LEP (e^+e^- collisions at Z-pole) or LHC (pp collisions at ~13TeV)

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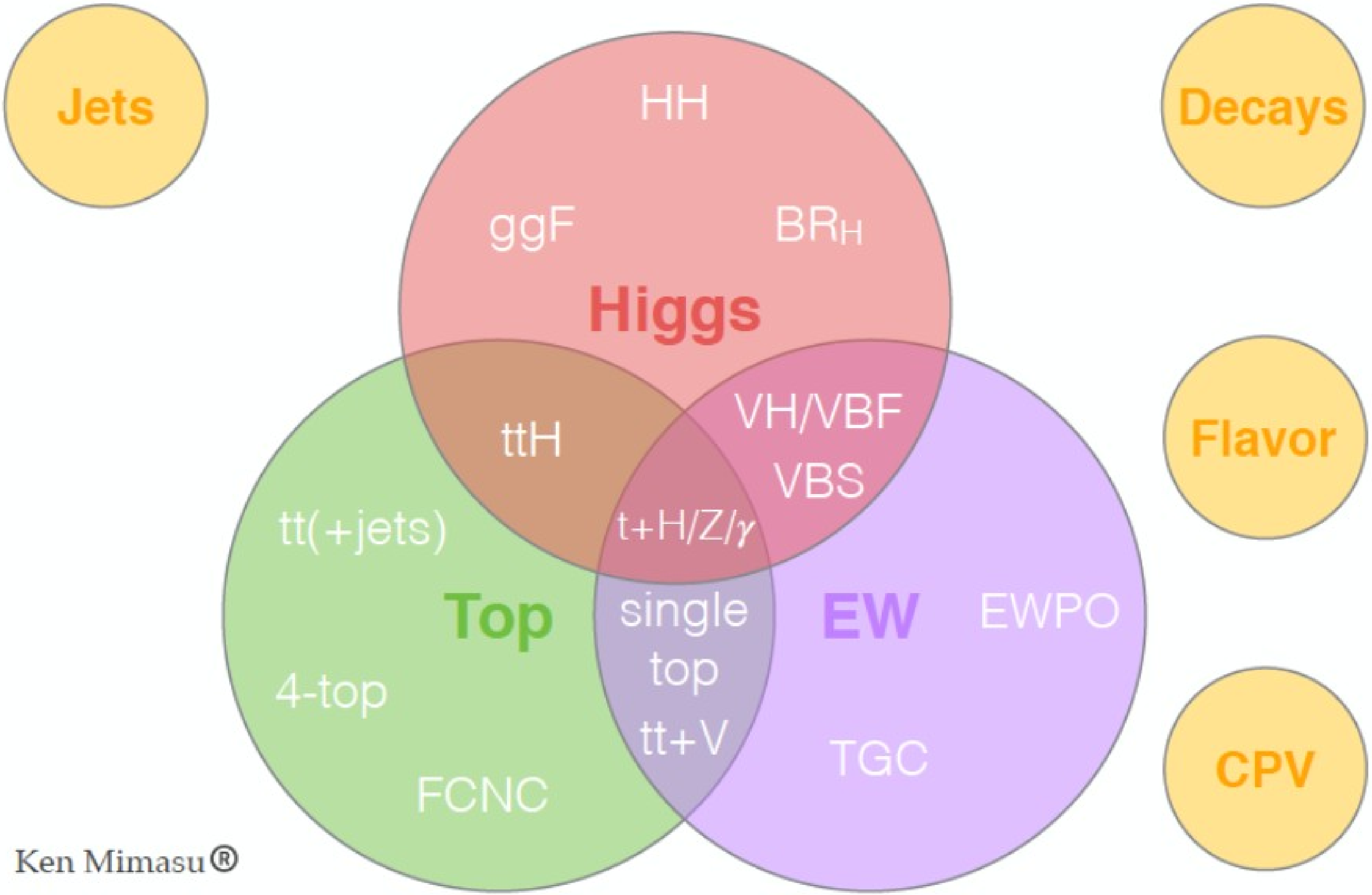
Focus of this session

Precision measurements at the LHC



Content

1st lecture:

- Higgs physics
  - Higgs production and decay channels and their measurement
  - BSM and EFT sensitivity of each channel
- EW physics
  - Anomalous triple gauge couplings and dim-6 EFT interpretation
  - Beyond dim-6: neutral anomalous triple gauge couplings and quartic gauge couplings

2nd lecture:

- Towards a global fit: combining the available information
  - Experimental challenges of combinations
  - Global fit in action: how to ensure generality / model independence of EFT fits
  - Limitations and perspectives for EFT fits – towards HL-LHC and beyond

Content

1st lecture: Overview of Higgs and EW measurements and their EFT sensitivity at the LHC

- Higgs physics
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2nd lecture: "Case study" of a general (global) EFT fit

- Towards a global fit: combining the available information
  - Experimental challenges of combinations
  - Global fit in action: how to ensure generality / model independence of EFT fits
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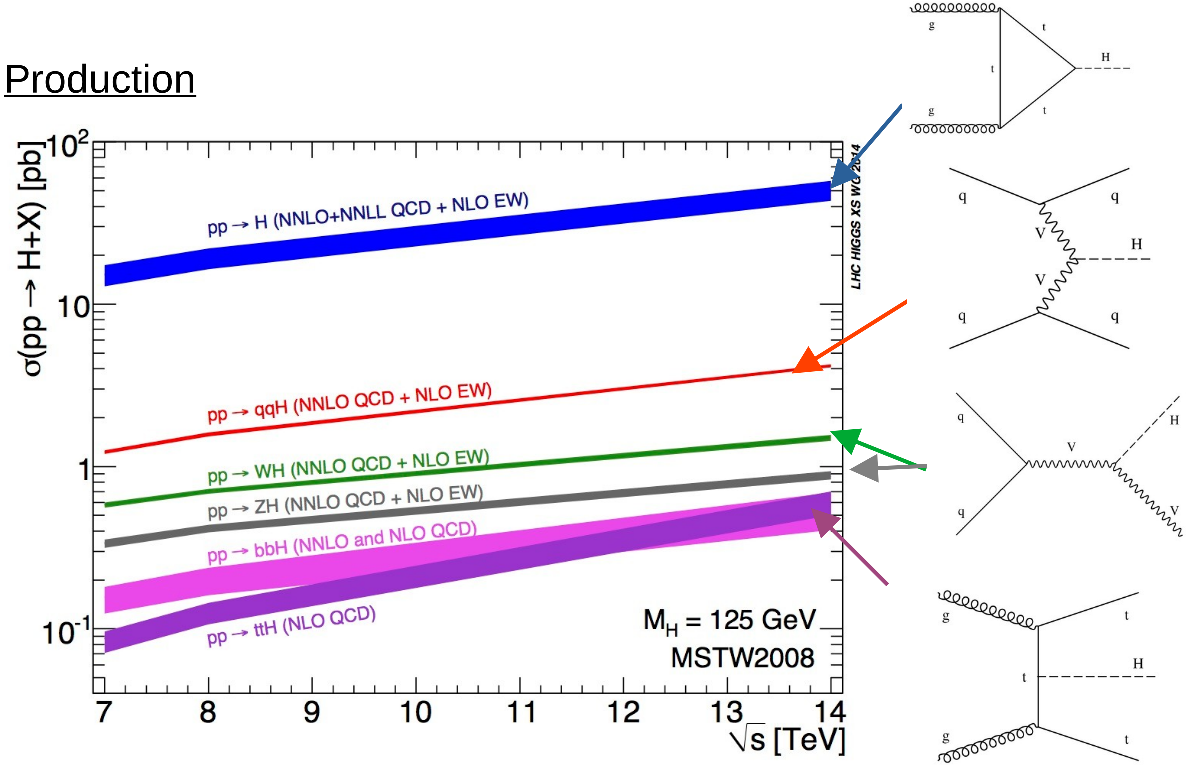
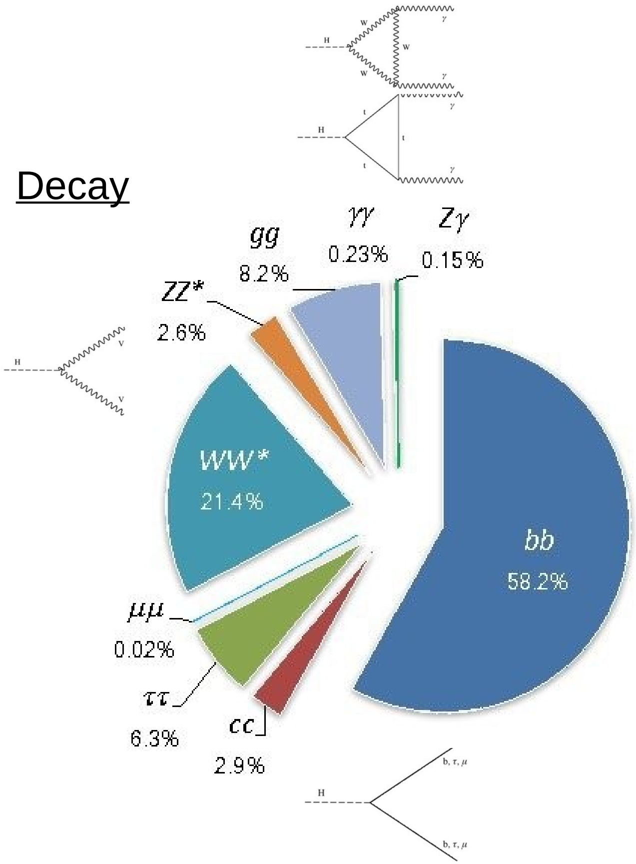
Higgs measurement channels

- Several orders of magnitude between different Higgs production and decay rates
- Many channels probed at LHC – adding new channels with increasing statistics and new reconstruction techniques

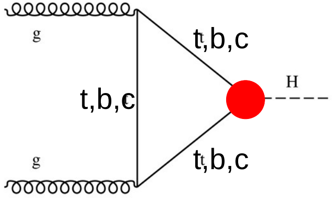
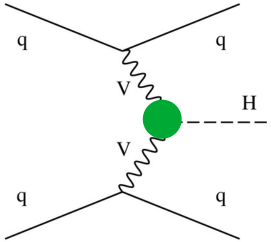
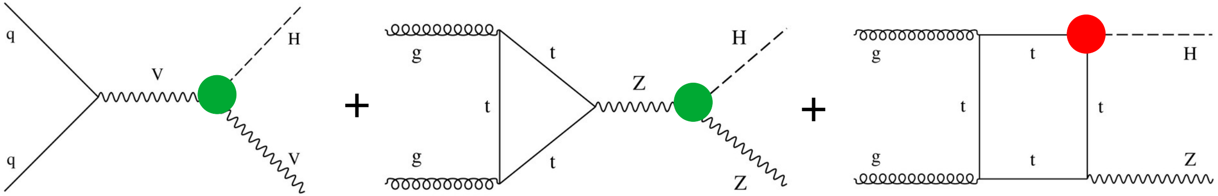
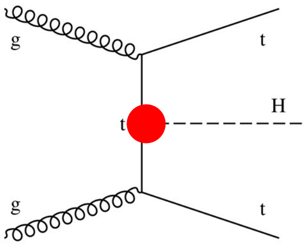
<u>Production</u>



<u>Decay</u>



Couplings through Higgs production

Channel	Experimental signature	Most important diagrams
Gluon fusion (ggF)	Higgs + N-jets (N≥0)	
Vector boson fusion (VBF)	Higgs + 2 jets with large $\Delta\eta_{jj}$ and m_{jj}	
Higgs strahlung (ZH or WH)	Higgs + Z or W boson	
Associated top production (ttH)	Higgs + 2 tops (ttH)	

- Bosonic couplings
- Yukawa couplings

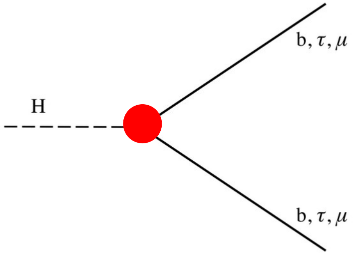
Couplings through Higgs decay

Channel | **Experimental signature** | **Most important diagrams**

- Bosonic couplings
- Yukawa couplings

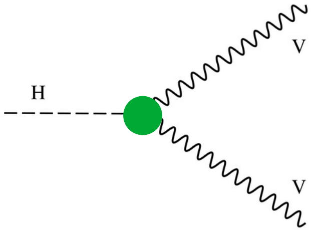
Fermionic decays ($H \to bb$, $H \to cc$, $H \to \tau\tau$, $H \to \mu\mu$)

2 fermions of given type (b-jets, c-jets, τ-lepton or muon)



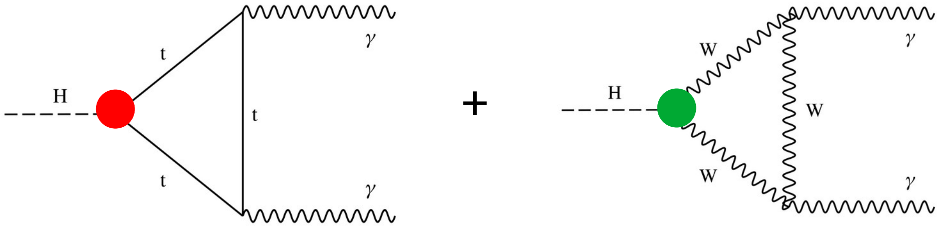
Decay to vector bosons ($H \to ZZ^*$, $H \to WW^*$)

Decay products of vector bosons (usually leptonic decays, i.e. 4l or 2l2v)

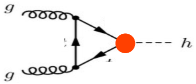
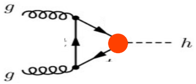
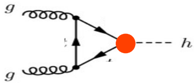
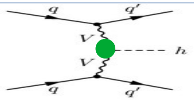
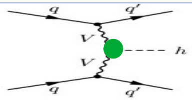
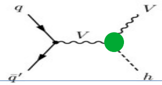
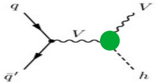
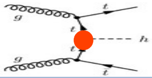
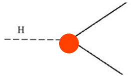
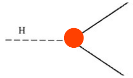
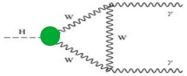
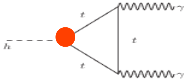
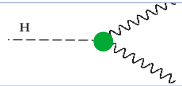
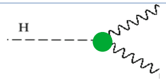
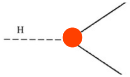
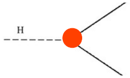


Higgs to diphoton ($H \to \gamma\gamma$)

2 photons



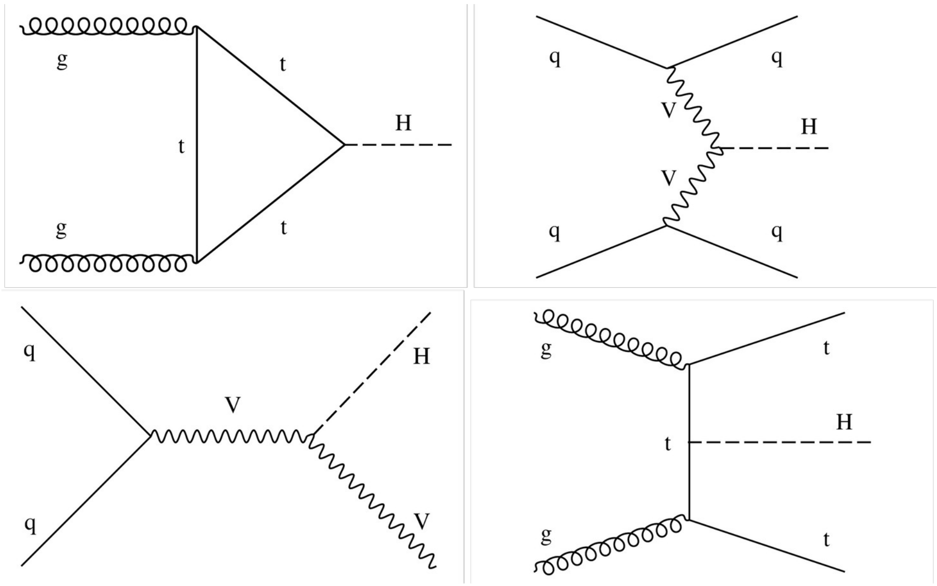
Overview of Higgs couplings to SM particles

Channel \ Coupling	H-W	H-Z	H-t	H-b	H-c	H-τ	H-μ
ggF							
VBF							
WH							
ZH							
ttH, tH							
H→bb							
H→cc							
H→yy							
H→WW							
H→ZZ							
H→ττ							
H →μμ							

Higgs measurements

- Different production modes and decay channels probed at LHC – sensitivity is function of frequency (statistics) and experimental performance (resolution, backgrounds,…)
- Higgs is narrow scalar particle → factorisation of production & decay – convenient for combined measurements of Higgs properties and interpretations

Production



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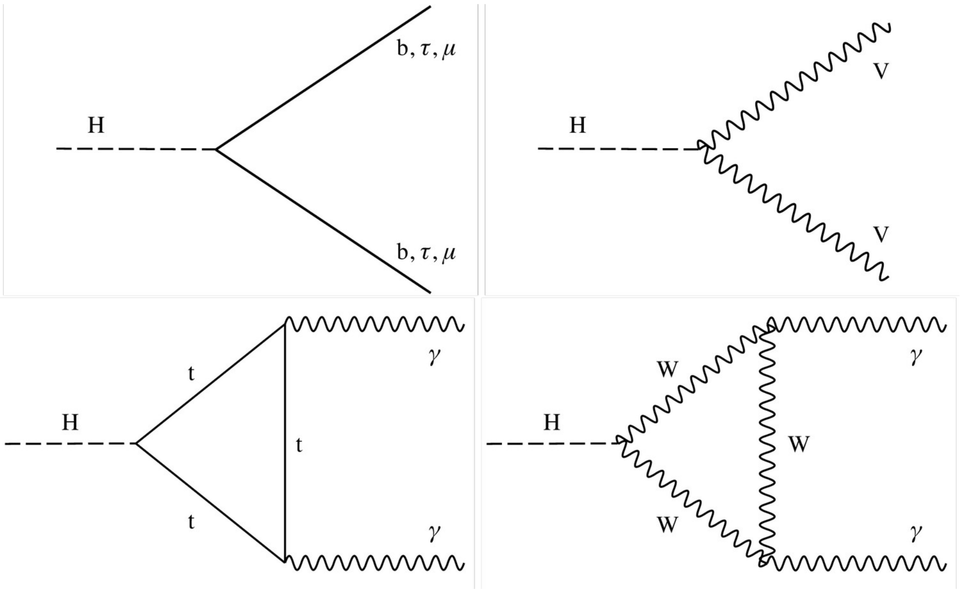
Decay



Experimental channel sensitivity

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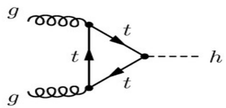
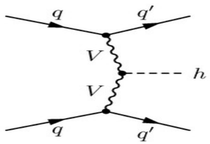
Cross section

ggF



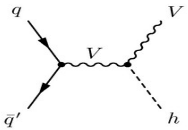
- High stat. (largest prod. mode)
- Higgs + N-jets – hard to tag

VBF



- Rel. high stat.
- 2 forward quark jets with large Δη and high di-jet mass

VH



- Rel. low stat.
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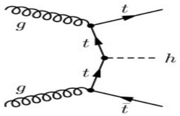
ttH



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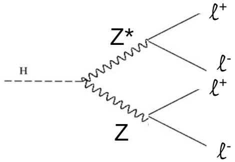
tH

- Very low stat.

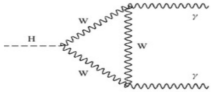
Branching fraction

H → ZZ* → 4l



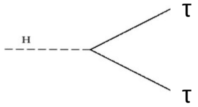
- Very low stat. (leptonic Z decays)
- Excellent purity, efficiency, resolution
- Rel. small or well-modeled bkg.

H → $\gamma\gamma$



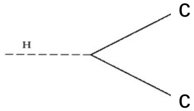
- Low stat.
- Clean signature, good resolution
- Functional background

H → ττ



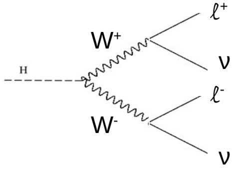
- Rel. high stat.
- τ reconstruction difficult
- Z → ττ background hard to model

H → cc



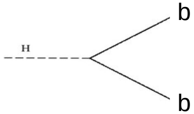
- Rel. high stat.
- c-tagging very challenging
- Badly modeled background

H → WW* → lvlv



- High stat. (leptonic W decays)
- Good lepton reco & resolution
- Missing energy from neutrinos

H → bb



- High stat. (most frequent decay)
- b-tagging challenging
- Large bkg. modeling uncertainty

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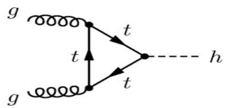
Cross section

ggF



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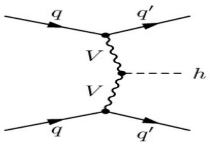

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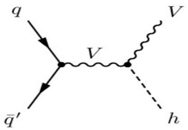

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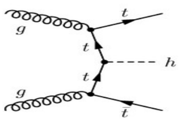

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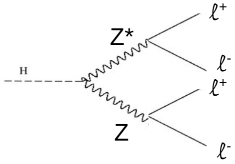
H→ZZ* → 4l



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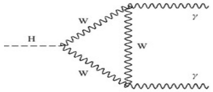

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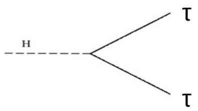

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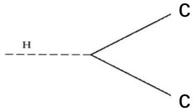

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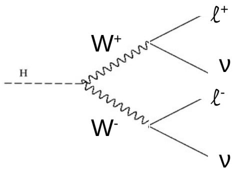

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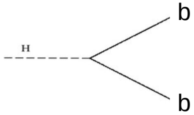

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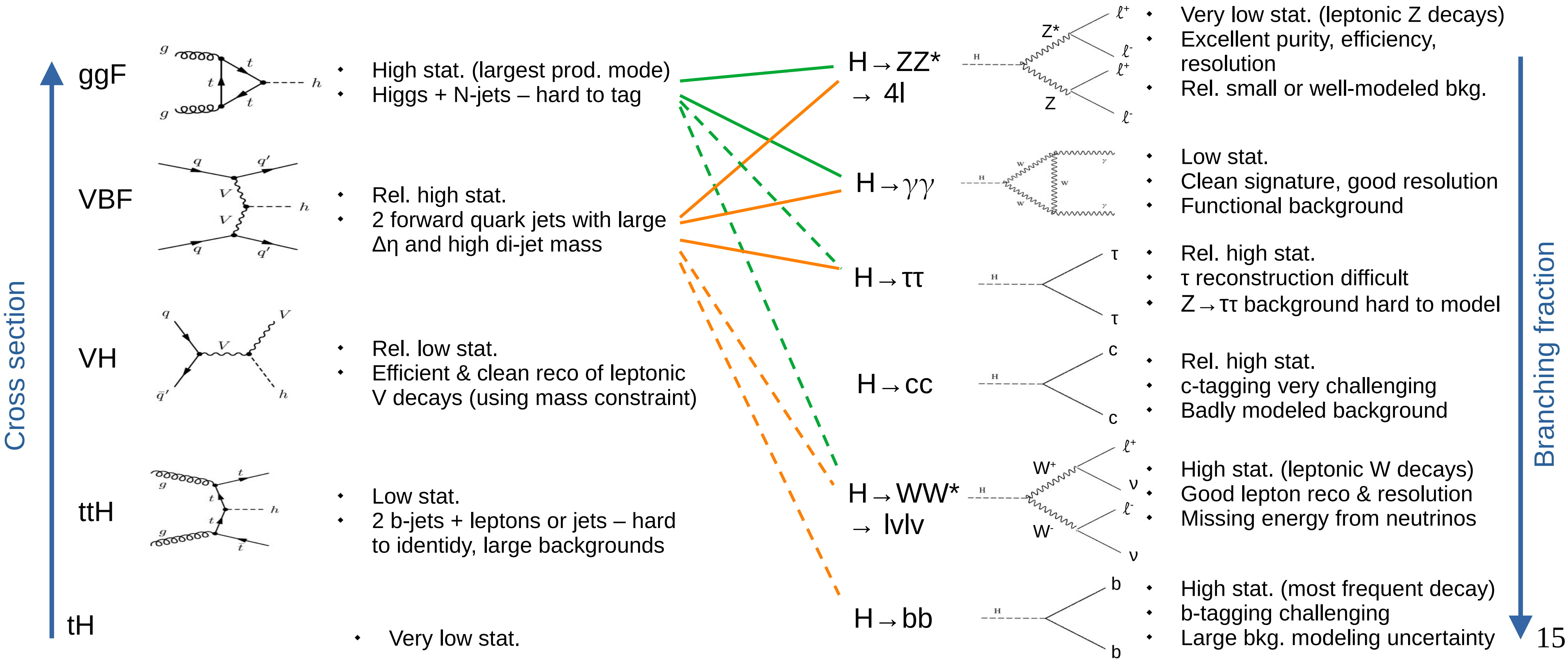

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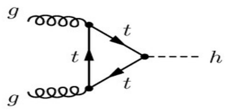

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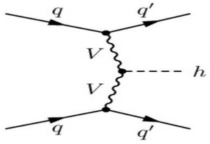

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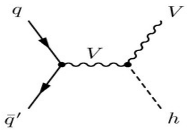

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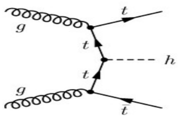

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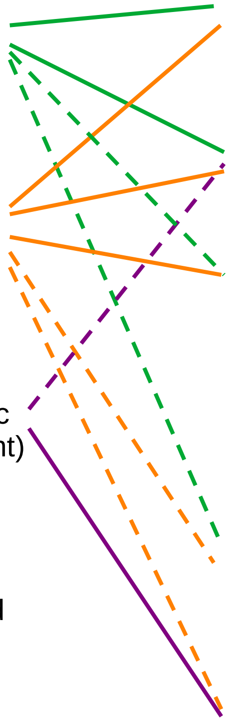

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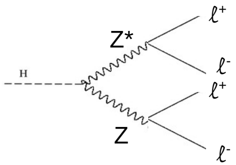
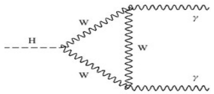
$H \to ZZ^* \to 4l$



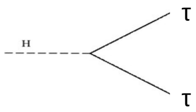
- Very low stat. (leptonic Z decays)
- Excellent purity, efficiency, resolution
- Rel. small or well-modeled bkg.

$H \to \gamma\gamma$



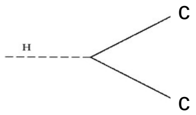
- Low stat.
- Clean signature, good resolution
- Functional background

$H \to \tau\tau$



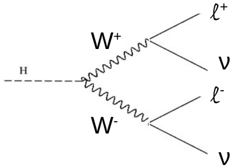
- Rel. high stat.
- τ reconstruction difficult
- $Z \to \tau\tau$ background hard to model

$H \to cc$



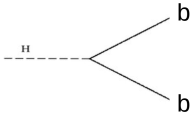
- Rel. high stat.
- c-tagging very challenging
- Badly modeled background

$H \to WW^* \to l\nu l\nu$



- High stat. (leptonic W decays)
- Good lepton reco & resolution
- Missing energy from neutrinos

$H \to bb$



- High stat. (most frequent decay)
- b-tagging challenging
- Large bkg. modeling uncertainty

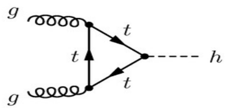
Experimental channel sensitivity

Sensitivity driven by statistics (orders of magnitude between channels) but also experimental performance:

- High statistics processes can have poor reconstruction efficiency or large backgrounds
- Low statistics processes might be reconstructed with good efficiency and resolution

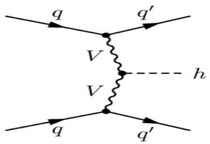
Cross section

ggF



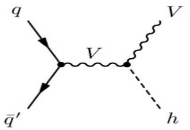
- High stat. (largest prod. mode)
- Higgs + N-jets – hard to tag

VBF



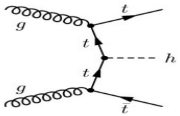
- Rel. high stat.
- 2 forward quark jets with large Δη and high di-jet mass

VH



- Rel. low stat.
- Efficient & clean reco of leptonic V decays (using mass constraint)

ttH



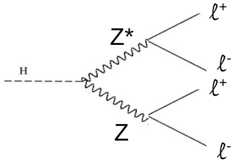
- Low stat.
- 2 b-jets + leptons or jets – hard to identidy, large backgrounds

tH

- Very low stat.

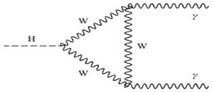
Branching fraction

H→ZZ* → 4l



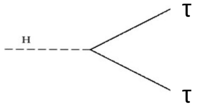
- Very low stat. (leptonic Z decays)
- Excellent purity, efficiency, resolution
- Rel. small or well-modeled bkg.

H→$\gamma\gamma$



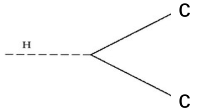
- Low stat.
- Clean signature, good resolution
- Functional background

H→ττ



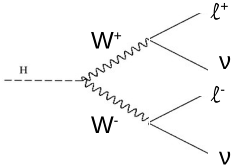
- Rel. high stat.
- τ reconstruction difficult
- Z→ττ background hard to model

H→cc



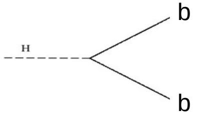
- Rel. high stat.
- c-tagging very challenging
- Badly modeled background

H→WW* → lνlν



- High stat. (leptonic W decays)
- Good lepton reco & resolution
- Missing energy from neutrinos

H→bb



- High stat. (most frequent decay)
- b-tagging challenging
- Large bkg. modeling uncertainty

Measurement

- Most generic Higgs measurement:
  - Production and decay rates as a function of full event kinematics contain all information needed to make any interpretation
  - Only look at final state – no assumptions on production or decay mode
- In practice:
  - Measure differential distributions in most sensitive observables (1 or 2 dimensional) with binning defined by statistical and modeling power
  - Measurement for given decay mode, using Higgs mass constraint (on-shell Higgs)
  - Sometimes useful to measure by Higgs production mode

Overview: Higgs measurements

- **Fiducial (differential) measurements:**

  compute theory prediction in phase space close to experimental acceptance to minimise assumptions on unmeasured phase space

- **Production and decay mode (differential) cross sections:**

  cross sections and branching fractions of channels as defined in SM: extrapolation to full phase space

- **Signal strength:**

  cross sections or branching fractions w.r.t. SM prediction – search deviations from 1

- **Couplings:**

  generic interpretations of results in terms of Higgs couplings to SM particles (coupling modifiers, EFT, etc.)

- **Limits on specific BSM models:**

  typically 2HDM, MSSM, etc.

Higgs fiducial cross sections

- Measure cross section in specific phase space defined to match experimental cuts → reduce uncertainties from phase space extrapolation

Reminder from Methodology lecture

$$N^i_{obs} = \mathscr{L} \times \sigma^i \times BR(H \to ZZ^*) \times \mathscr{A}$$

Selected data events in given p_T^H bin i

Integrated luminosity

POI

Acceptance factor

$$\mathscr{A} = \frac{N_{sel}}{(N_{sel} + N_{cut})}$$

→ Large bias when extrapolating to unmeasured phase space

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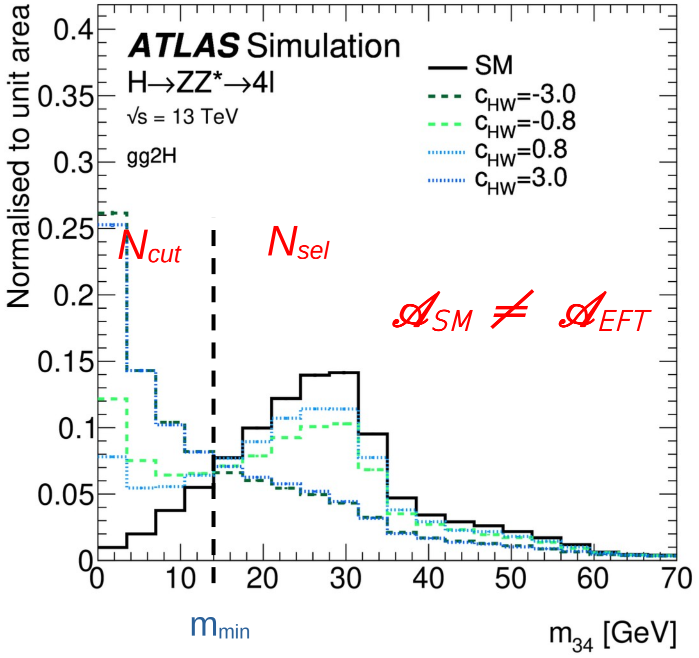


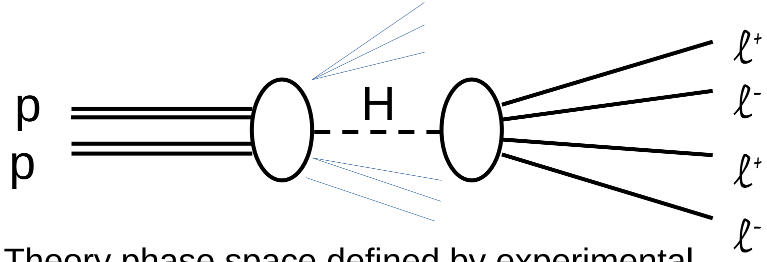
Solution:

Aim at $\mathscr{A}$ **= 1** → define theory with same cuts, so that $N_{cut} = 0$

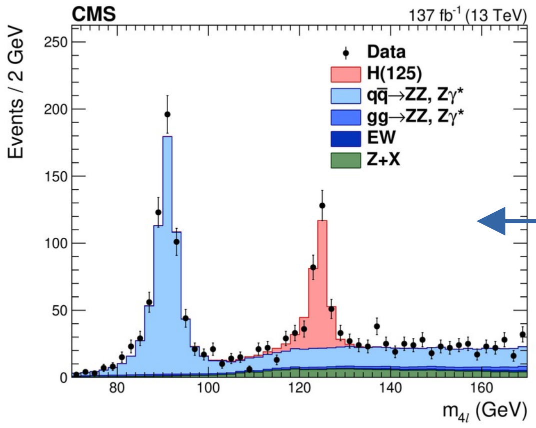
Higgs fiducial cross sections

- Measure cross section in specific phase space defined to match experimental cuts → reduce uncertainties from phase space extrapolation
- Differential measurement in kinematic observables give sensitivity to BSM models
- Unfolded results allow direct comparison to theory outside experiment

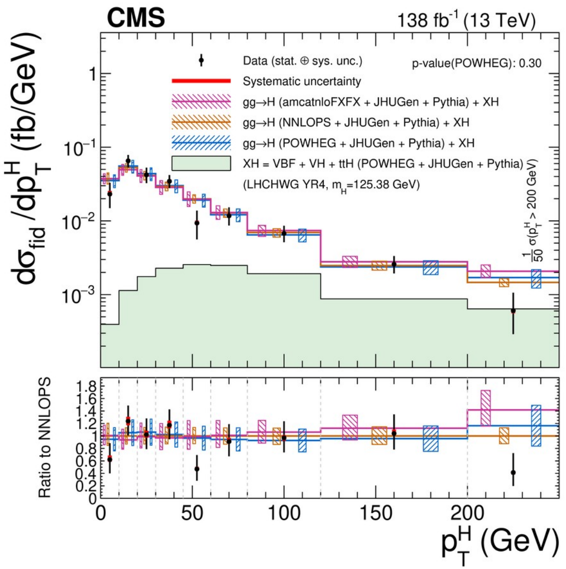
Example: H → 4l decay JHEP 08 (2023) 040

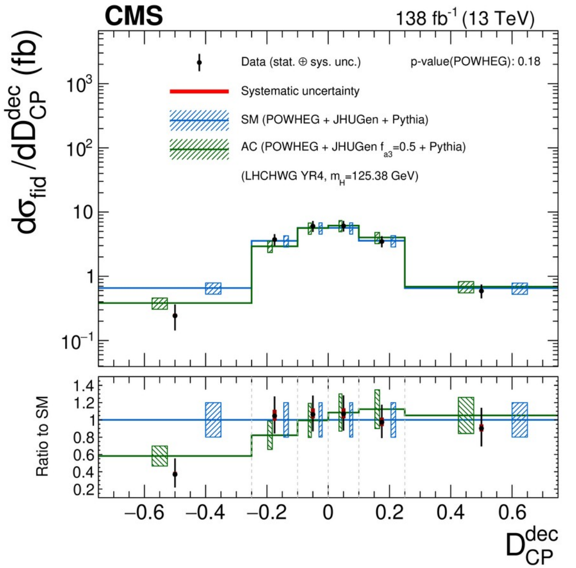


Theory phase space defined by experimental acceptance on lepton and jets selection



Simple observable to separate signal from background without model assumptions

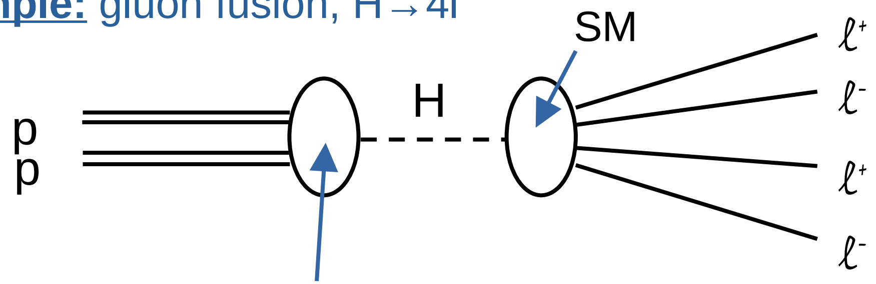


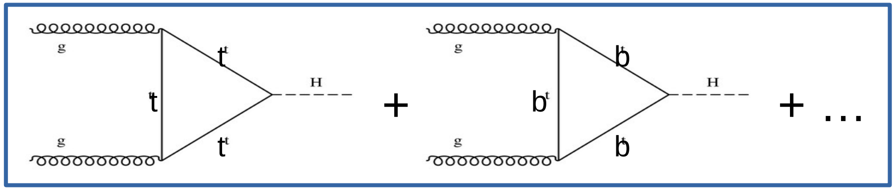


Differential measurement as a function of kinematic variables sensitive to new physics in H → 4l channel

Production mode cross sections & signal strengths

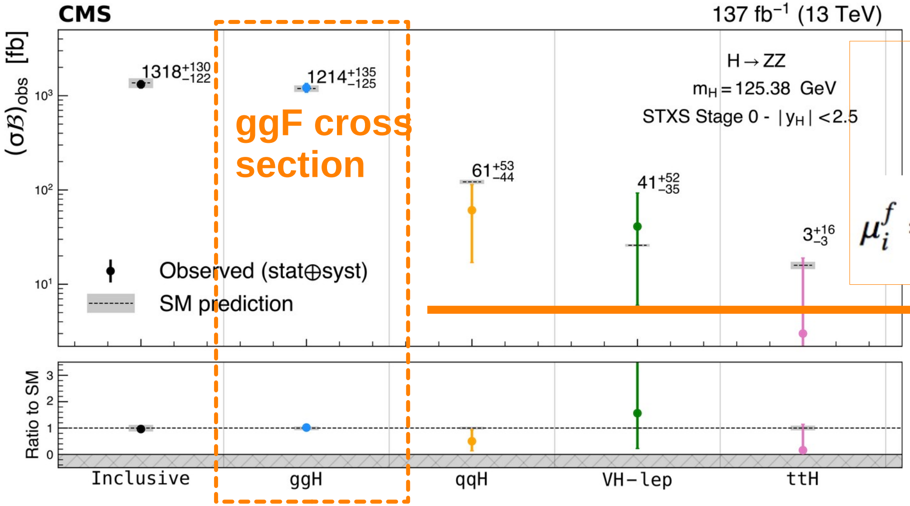
Example: gluon fusion, H→4l





Experimental selection of ggF-like events:

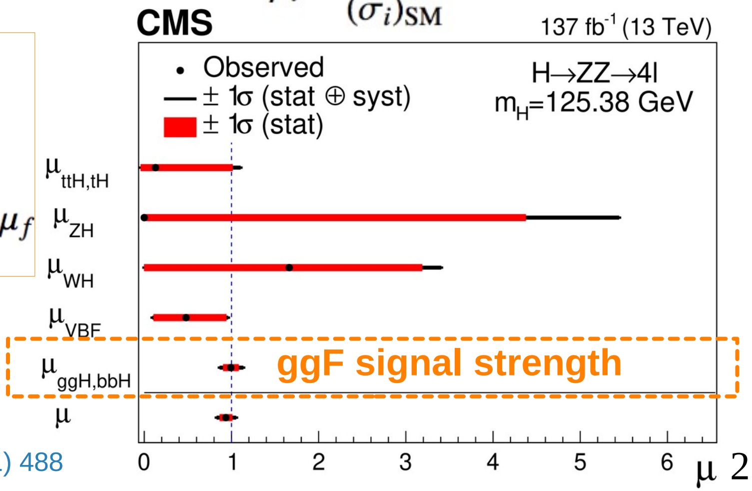
- H→4l + 0, 1, …, N- jets with certain properties
- Mixing with other production modes – purity from MC
- Selection acceptance – extrapolation factor from MC



Rel. to SM prediction

$$\mu_i^f = \frac{\sigma_i \times \mathrm{BR}_f}{(\sigma_i \times \mathrm{BR}_f)_{\mathrm{SM}}} \equiv \mu_i \times \mu_f$$

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}}$$



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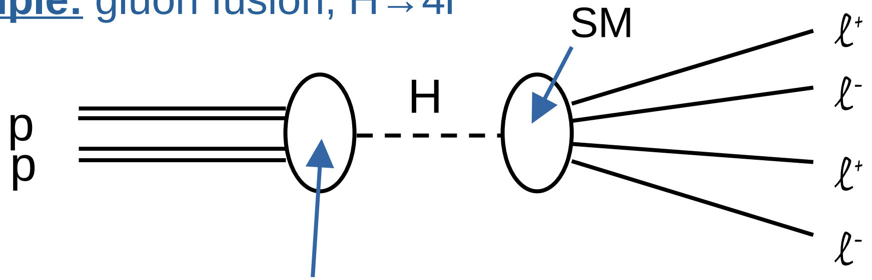
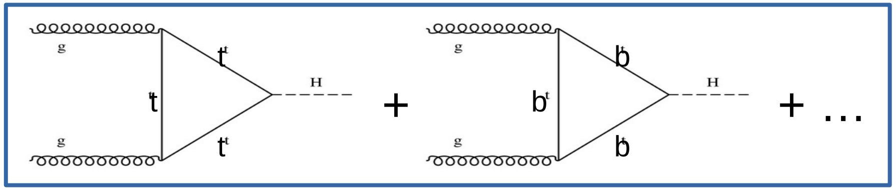
Production mode cross sections & signal strengths

Example: gluon fusion, H → 4l

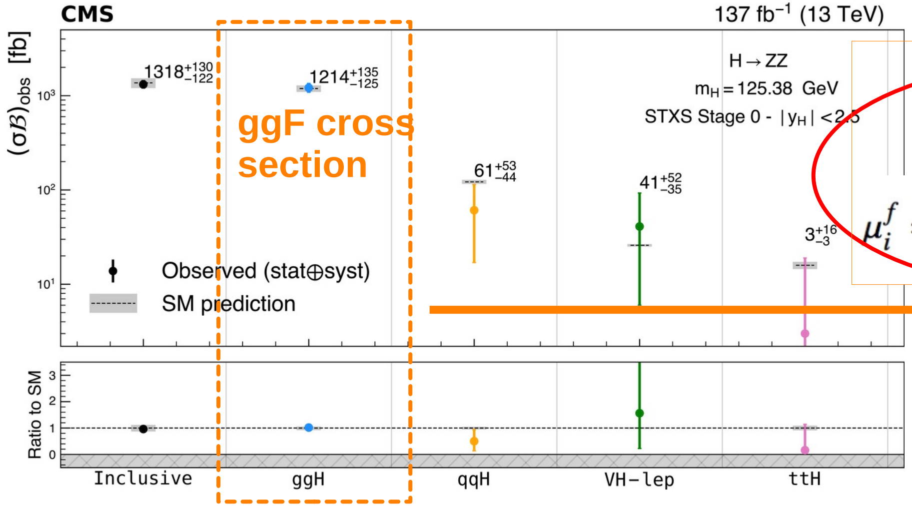




Experimental selection of ggF-like events:

- H → 4l + 0, 1, …, N- jets with certain properties
- Mixing with other production modes – purity from MC
- Selection acceptance – extrapolation factor from MC

Model dependence – larger theory uncertainties



Rel. to SM prediction

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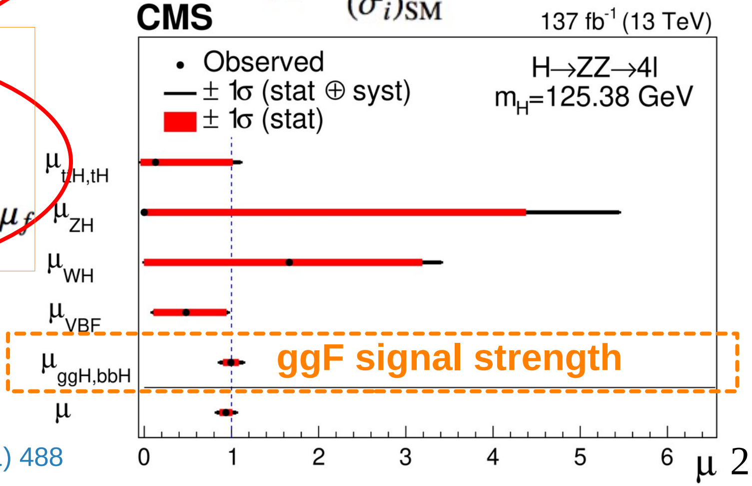
$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}}$$



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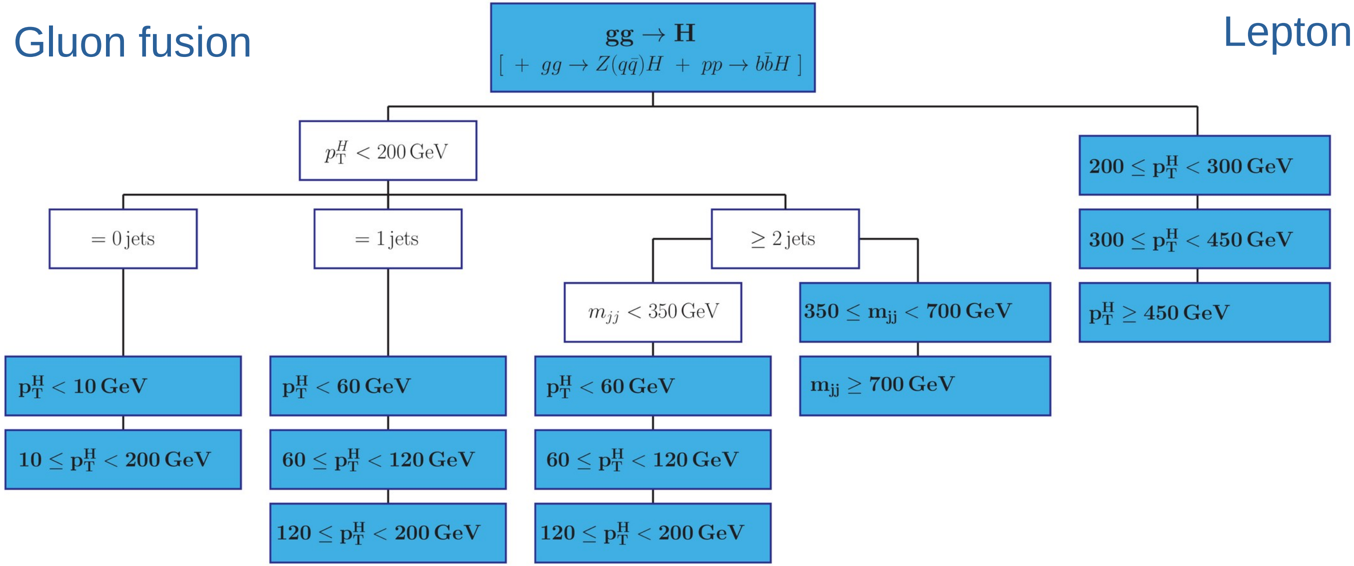
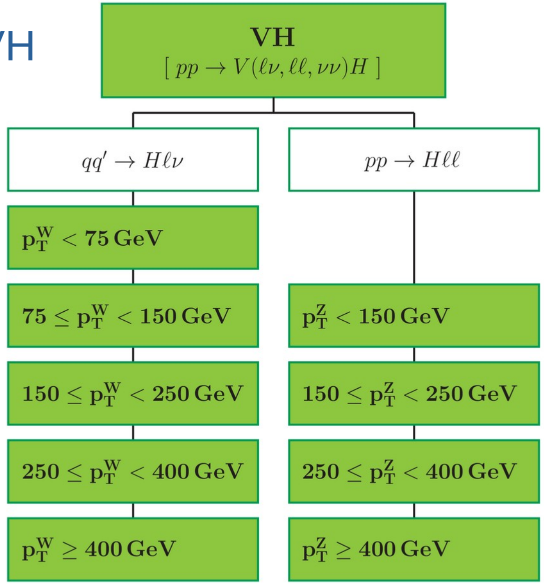
Simplified Template Cross Sections (STXS)

Gluon fusion



Leptonic VH



Similar for VBF & t(t)H

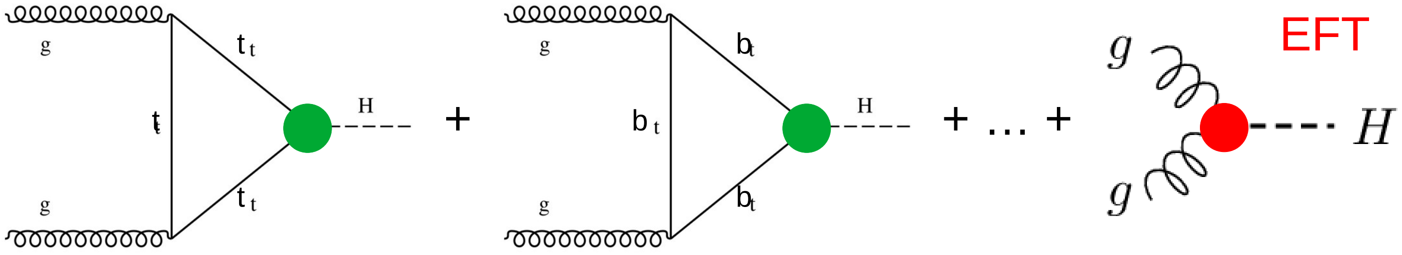
- Split events by (major) production modes
- Differential measurement in BSM sensitive and experimentally well measured observable for each production mode
  - Choice of observable depending on most sensitive decay channel
  - Re-optimise binning with increasing amount of data

→ More details in 2nd lecture

Measuring the Higgs couplings

- BSM contribution possible in any Higgs vertex: modification of coupling strength and/or kinematics
- Possible contributions from new heavy particle loops -- additional (effective) couplings (= new diagrams), e.g. effective Higgs to gluon coupling
- Usually, several anomalous couplings or EFT operators contribute to same experimental final state
- Note: BSM might contribute to
  - non-Higgs couplings (“easy” to consider in EFT approach)
  - backgrounds (usually neglected for now)

Example: gluon fusion



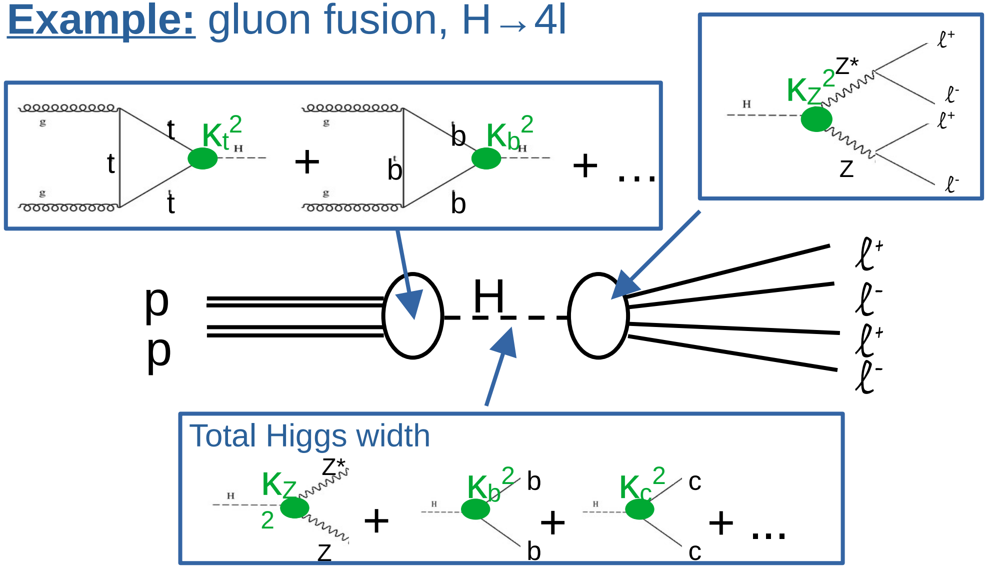
Coupling modifiers -- κ-framework

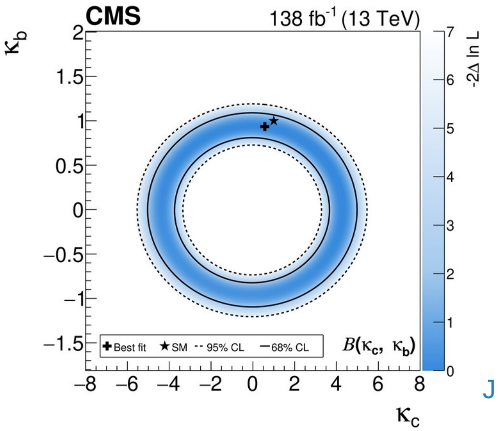
Simple scaling of Higgs-SM couplings: $\kappa_i = \dfrac{g_i}{g_{i,SM}}$

$$\sigma \cdot B(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} = \frac{\sigma_i^{SM} \cdot \Gamma_f^{SM}}{\Gamma_H^{SM}} \cdot \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}$$

- For generality of results:
  - Float as many coupling modifiers as possible in fit
  - Can allow for new couplings and invisible Higgs decays
  - Global picture through combination of channels
- Limitations:
  - Single narrow Higgs with $J^{CP}=0^{++}$ (SM-like)
  - No change of process kinematic

Example: gluon fusion, H→4l





- b- versus c-Yukawa coupling from ggF in H→4l analysis; all other couplings assumed to be SM-like
- significant from impact of κ_b & κ_c in total decay width

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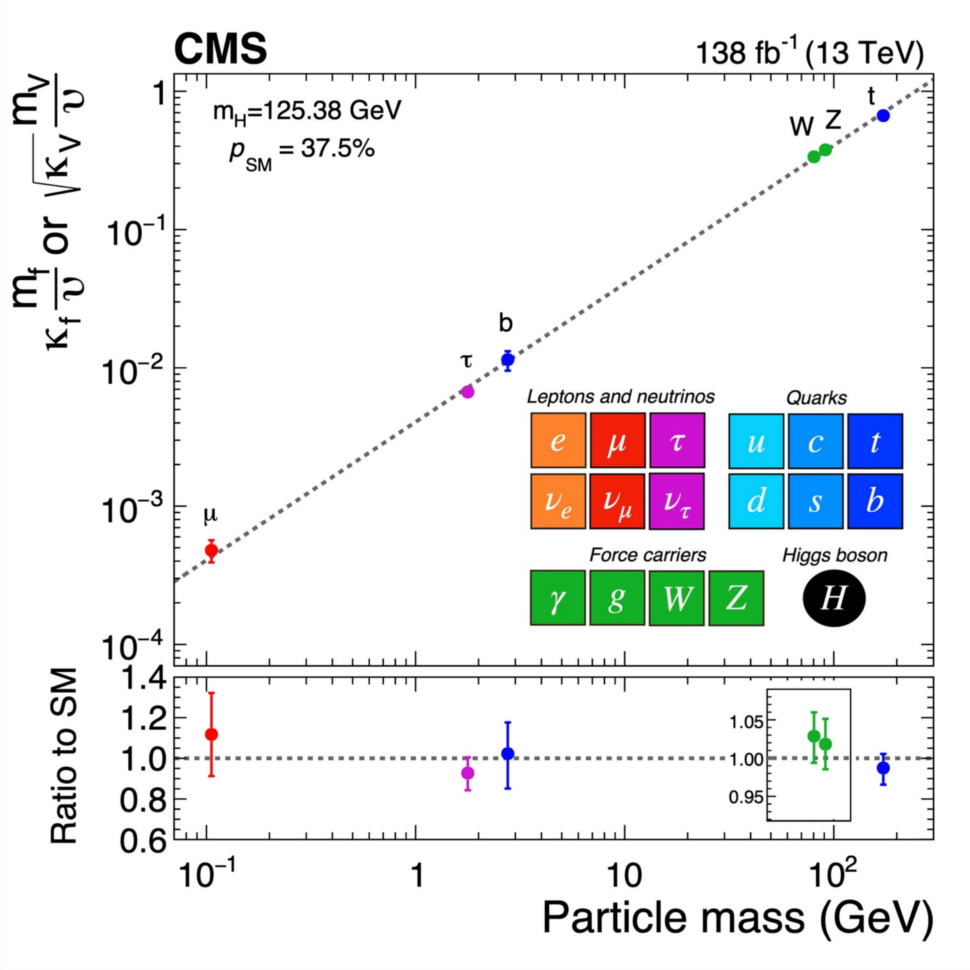
Coupling modifiers -- κ-framework



- So far, excellent agreement with SM prediction
- Strong limits on many BSM couplings, e.g. on Higgs couplings to “invisible” particles (neutrinos or new particles)

Anomalous couplings

Most general Lorentz-invariant scattering amplitude between a spin-0 boson (SM Higgs or light Higgs) and

- 2 vector bosons:

$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

Tree-level couplings (CP-even)
SM: only a_1^{ZZ} and $a_1^{WW} \neq 0$

Higher order + anomalous couplings (CP-even)

CP-even anomalous couplings

CP-odd anomalous couplings

- 2 fermions:

$$\mathcal{A}(\mathrm{Hff}) = -\frac{m_f}{v} \bar{\psi}_{\mathrm{f}} \left(\kappa_{\mathrm{f}} + \mathrm{i} \tilde{\kappa}_{\mathrm{f}} \gamma_5 \right) \psi_{\mathrm{f}}$$

CP-even coupling

CP-odd coupling

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$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

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CP-even anomalous couplings

CP-odd anomalous couplings

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CP-even coupling

CP-odd coupling

Note:

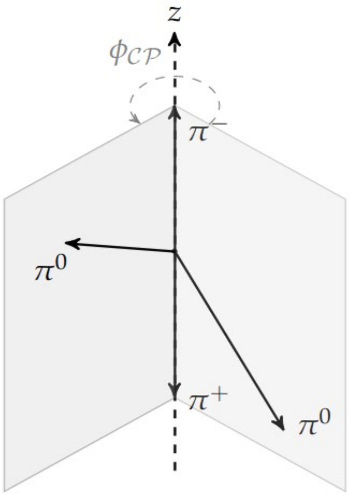
This is a “simple” effective theory to describe Higgs interactions with certain assumptions

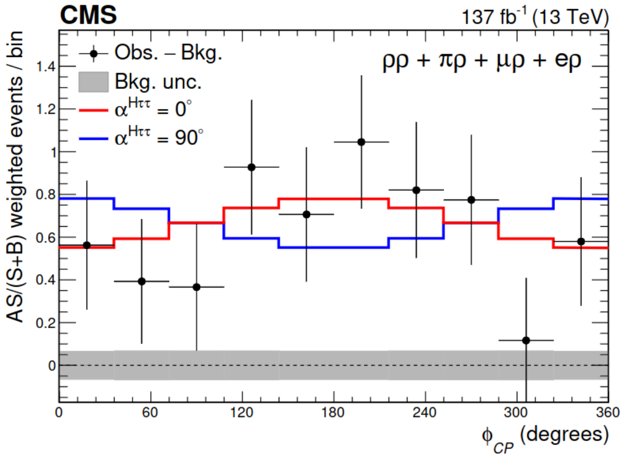
Example: CP in H→ττ decay

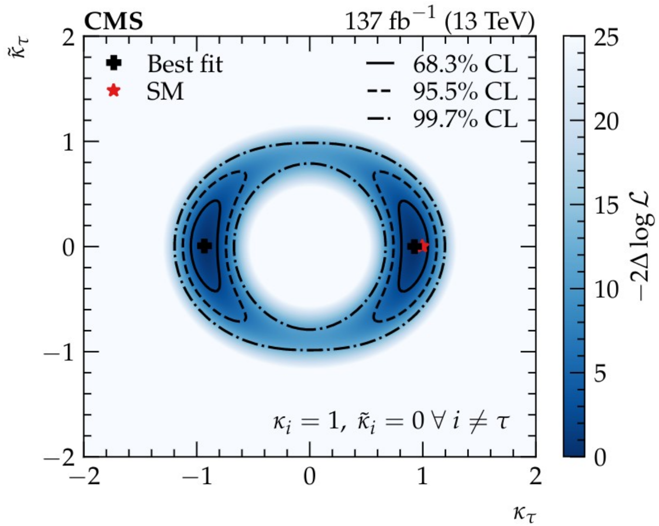
CMS-HIG-20-006

- Direct probe of CP structure of H to fermion coupling from H→ττ decay
  - Measuring effective mixing angle: $\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$
- Requirement: measure spin correlation between Higgs decay products – this is possible since τ's decay
  - Observable: angle between τ decay planes directly related to CP mixing angle

$$\frac{d\Gamma}{d\phi_{CP}}(H \to \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$







$$\alpha^{H\tau\tau} = -1 \pm 19\,(\text{stat}) \pm 1\,(\text{syst}) \pm 2\,(\text{bin-by-bin}) \pm 1\,(\text{theo})^\circ$$

Exclusion of pure CP-odd coupling at 3σ

Overview: Higgs measurements used for EFT

- **Fiducial (differential) measurements:**
  compute theory prediction in phase space close to experimental acceptance to minimise assumptions on unmeasured phase space

- **Production and decay mode (differential) cross sections:**
  cross sections and branching fractions of channels as defined in SM: extrapolation to full phase space

In particular STXS

- **Signal strength:**
  cross sections or branching fractions w.r.t. SM prediction – search deviations from 1

- **Couplings:**
  generic interpretations of results in terms of Higgs couplings to SM particles (coupling modifiers, EFT, etc.)

In particular anomalous couplings

- **Limits on specific BSM models:**
  typically 2HDM, MSSM, etc.

EFT interpretation of Higgs measurements

- General EFT assumptions:
  - Linear EFT (e.g. SMEFT, HEL): Higgs included in doublet, linear under SU(2)
  - Non-linear EFT (e.g. HEFT): Higgs transforms as gauge single, chiral perturbation theory
- Basis:
  - Equivalent sets of complete and non-redundant operators designed for different target processes
  - Choice on case-by-case basis; translation between bases possible

SMEFT, HEL:

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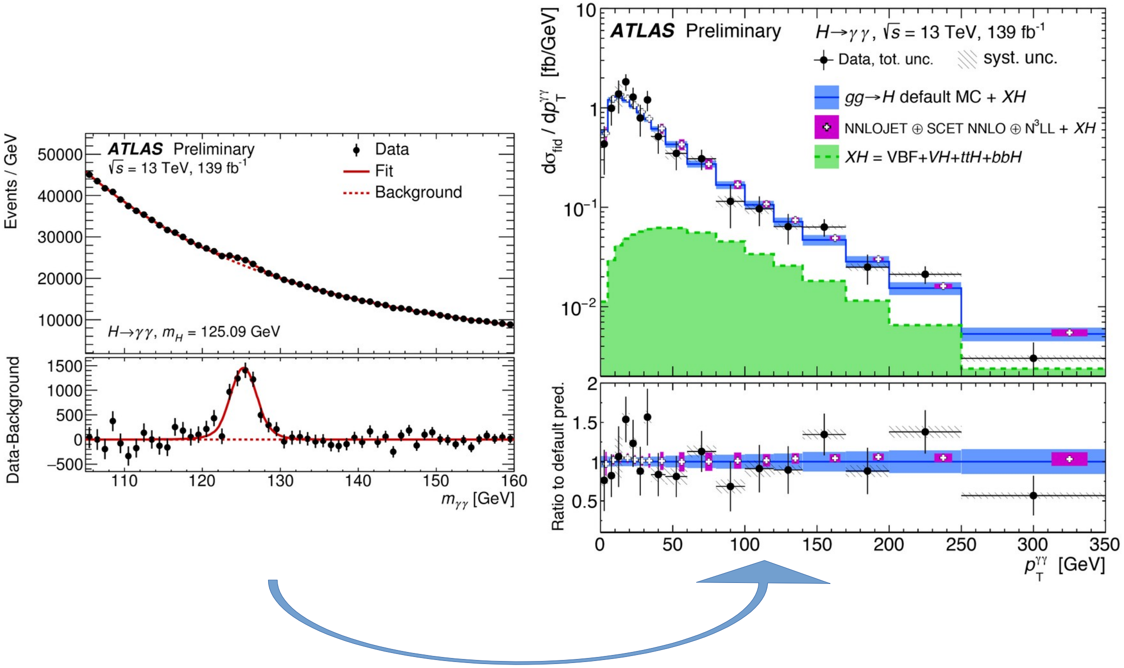
Basis	Underlying gauge symmetry	Fields used in the Lagrangian
Warsaw, SILH	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Gauge-eigenstates
BSM primaries, Higgs	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Mass-eigenstates
Higgs/BSM characterisation	$SU(3)_C \times U(1)_{EM}$	Mass-eigenstates

- Warsaw: very general – comparison with BSM theories modifying fermion interactions
- SILH (Strongly Interacting Light Higgs) in HEL: good matching to BSM modifying boson interactions
- Higgs: in terms of mass eigenstates – operators aligned with Higgs observables (couplings)

Example 1: H→γγ

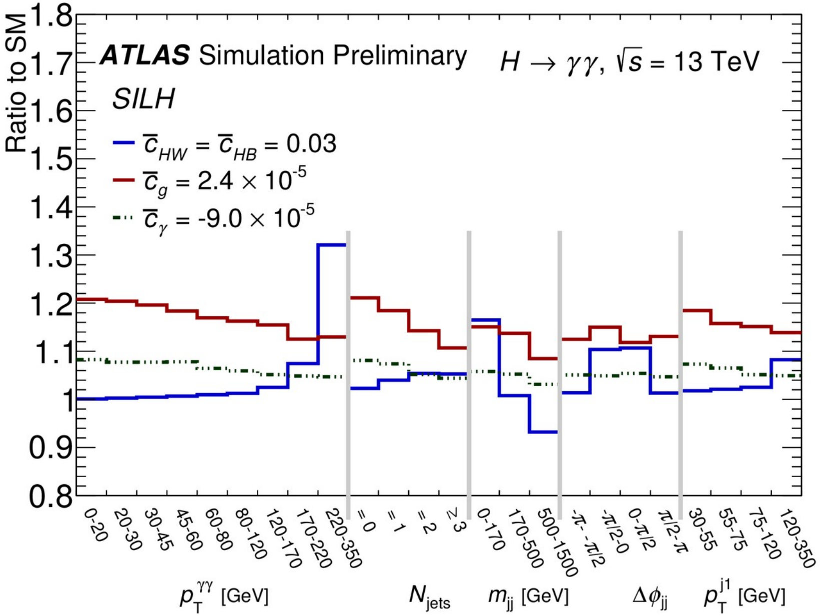
Well resolved signal peak over falling background
→ good prerequisite for differential & fiducial cross sections



- Fit of diphoton invariant mass in each pT bin to extract signal and reject background
- Unfolding to correct detector resolution

Many differential distributions measured

- Complementary sensitivity to BSM / EFT operators
- Plot: impact of CP even operators in SILH basis
- Additional sensitivity to CP odd operators, mainly from $\Delta\Phi_{jj}$



Example 1: H→γγ

Also constrain SMEFT operators in Warsaw basis

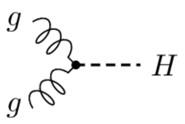
Sensitivity from ggF production vertex

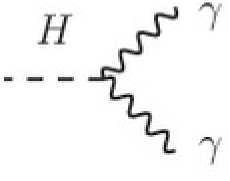
$$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$$

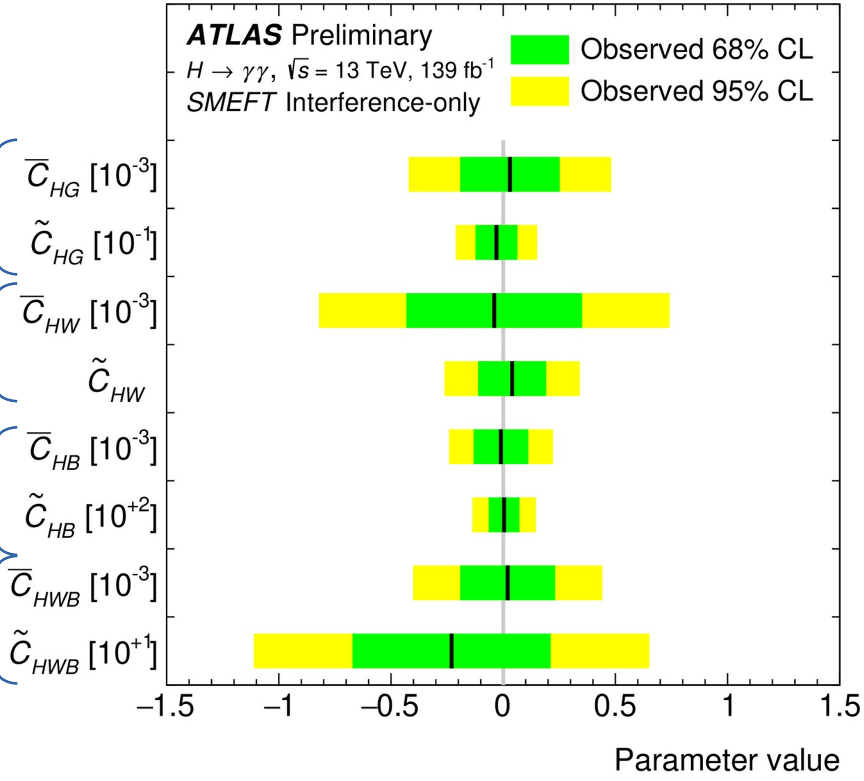
- Main sensitivity from H→ γγ decay vertex
- Additional sensitivity from VBF -- through mjj distribution in this analysis

c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$

Example diagram







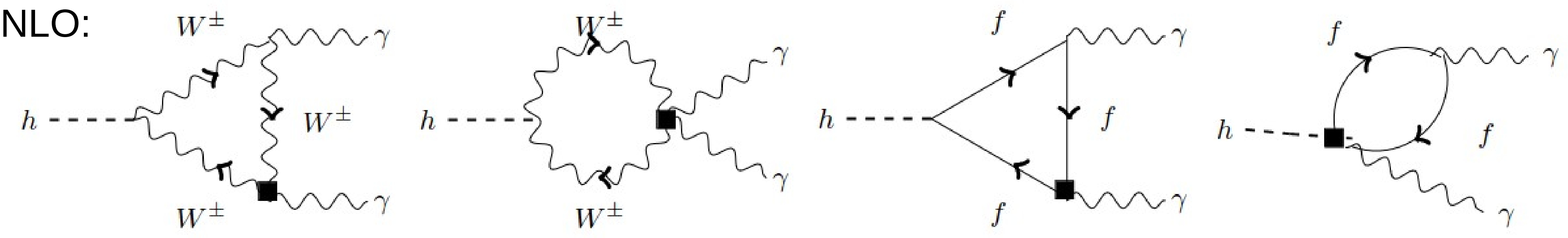
Example 1: H→yy

NOTE: LO EFT

- c_{HG} affecting ggH vertex – no modification of couplings in loop (top Yukawa etc.)
- c_{HW}, c_{HB}, c_{HWB} affecting H→yy at tree level – additional contributions in loops

LO: $\Gamma_{H\to yy}^{int} / \Gamma_{H\to yy}^{SM} = -13.996 \cdot c_{HW} - 48.809 \cdot c_{HB} + 26.144 \cdot c_{HWB}$

NLO:



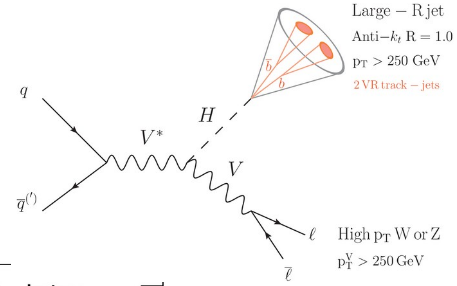
C.Hartmann, M. Trott

$$\Gamma_{H\to yy}^{int} / \Gamma_{H\to yy}^{SM} = -40.15c_{HB} - 13.08c_{HW} + 22.4c_{HWB} - 0.9463c_W + 0.12c_{H\Box} - 0.2417c_{HDD} + 0.03447c_{uH} - 1.151c_{uW} - 2.150c_{uB} - 0.3637c^{(3)}_{Hl} + 0.1819c'_{ll}$$

→ important to consider **higher orders in EFT**!

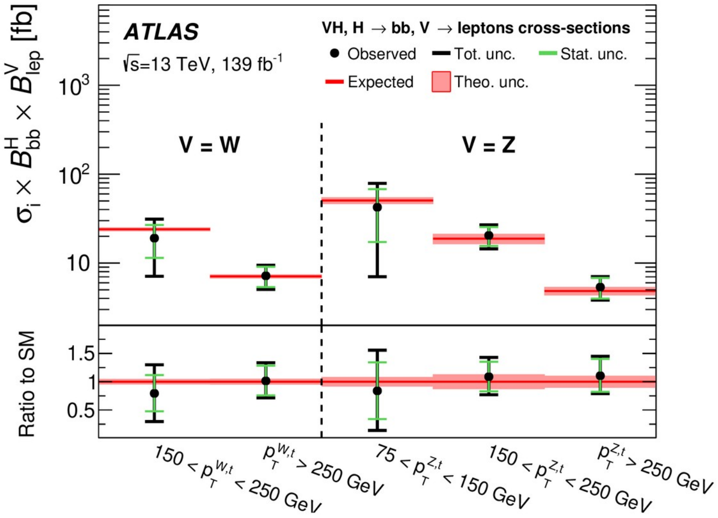
Example 2: VH(→bb)

- Associated production of Higgs with vector boson (W or Z)
- Analysis performed in 3 categories: 0, 1 or 2 leptons (depending on V decay)
- Higgs decaying to 2 b-jets (low Higgs-p_T region) or 1 merged larged radius b-jet (boosted Higgs)
- MVA techniques for signal vs. background separation, large background modeling uncertainties



Resolved regime

2 well-separated b-jets



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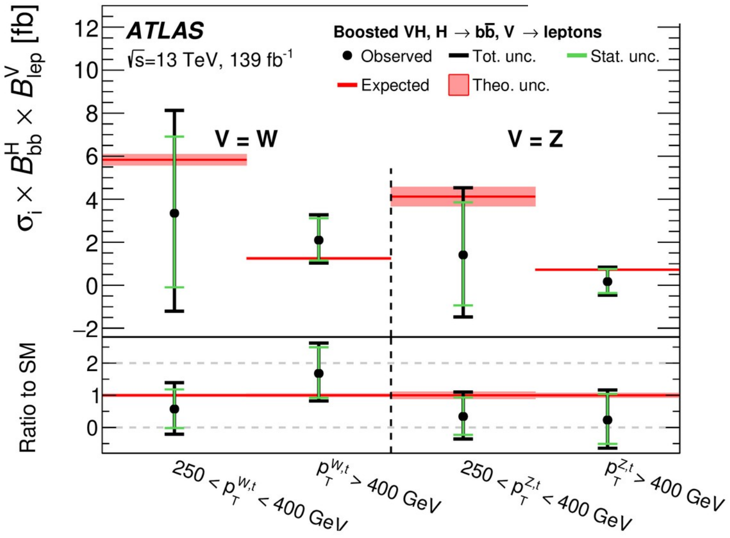
Boosted regime

Additional split at p_T^H = 400 GeV



Phys. Lett. B 816 (2021) 136204

Example 2: VH(→bb)

Phys. Lett. B 816 (2021) 136204

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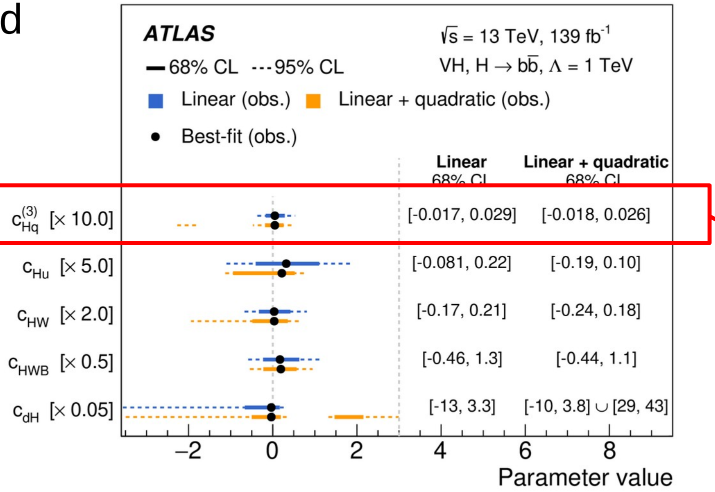
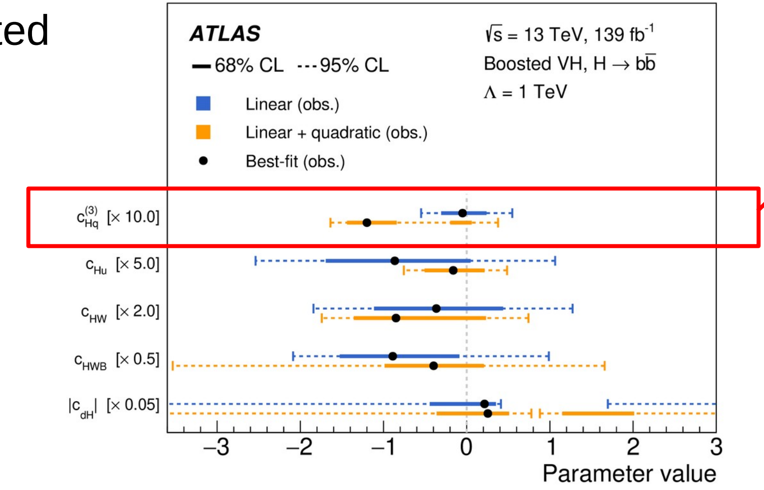
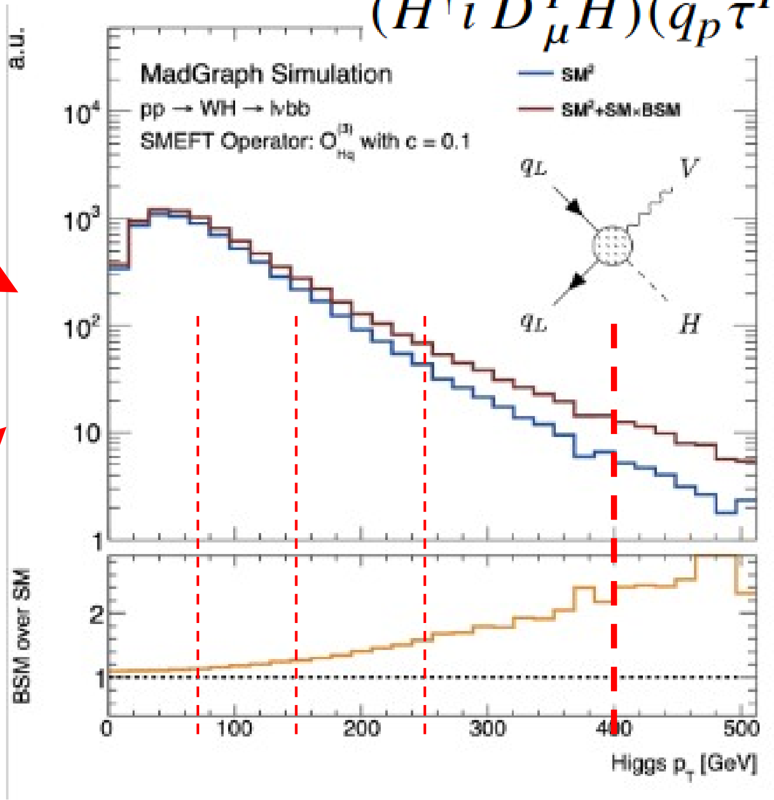
Resolved



Boosted



$$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$$



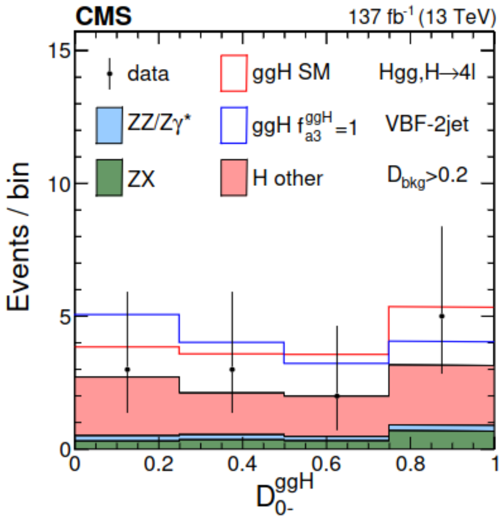
~ factor 2 improvement from split at 400 GeV

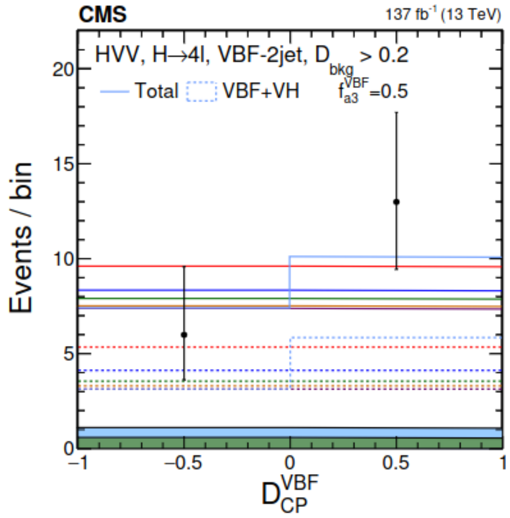
Example 3: H→4l MELA analysis

CMS-HIG-19-009

- Analysis in many categories targeting different production modes and maximising signal purity
- Matrix Element Likelihood Approach: high dimensional fit in observable separating signals and backgrounds as well as anomalous couplings

Category	Selection	Observables $\vec{x}$ for fitting
Scheme 1		
VBF-1jet	$\mathcal{D}^{\mathrm{VBF}}_{\mathrm{1jet}} > 0.7$	$\mathcal{D}_{\mathrm{bkg}}$
VBF-2jet	$\mathcal{D}^{\mathrm{VBF}}_{\mathrm{2jet}} > 0.5$	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{VBF}}_{\mathrm{2jet}}, \mathcal{D}^{\mathrm{ggH}}_{0-}, \mathcal{D}^{\mathrm{ggH}}_{CP}$
VH-hadronic	$\mathcal{D}^{\mathrm{VH}}_{\mathrm{2jet}} > 0.5$	$\mathcal{D}_{\mathrm{bkg}}$
VH-leptonic	see Section 3	$\mathcal{D}_{\mathrm{bkg}}$
$\mathrm{t\bar{t}H}$-hadronic	see Section 3	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{t\bar{t}H}}_{0-}$
$\mathrm{t\bar{t}H}$-leptonic	see Section 3	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{t\bar{t}H}}_{0-}$
Untagged	none of the above	$\mathcal{D}_{\mathrm{bkg}}$
Scheme 2		
Boosted	$p_{\mathrm{T}}^{4\ell} > 120\,\mathrm{GeV}$	$\mathcal{D}_{\mathrm{bkg}}, p_{\mathrm{T}}^{4\ell}$
VBF-1jet	$\mathcal{D}^{\mathrm{VBF}}_{\mathrm{1jet}} > 0.7$	$\mathcal{D}_{\mathrm{bkg}}, p_{\mathrm{T}}^{4\ell}$
VBF-2jet	$\mathcal{D}^{\mathrm{VBF}}_{\mathrm{2jet}} > 0.5$	$\mathcal{D}^{\mathrm{EW}}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{VBF+dec}}_{0h+}, \mathcal{D}^{\mathrm{VBF+dec}}_{0-}, \mathcal{D}^{\mathrm{VBF+dec}}_{\Lambda1}, \mathcal{D}^{Z\gamma,\mathrm{VBF+dec}}_{\Lambda1}, \mathcal{D}^{\mathrm{VBF}}_{\mathrm{int}}, \mathcal{D}^{\mathrm{VBF}}_{CP}$
VH-hadronic	$\mathcal{D}^{\mathrm{VH}}_{\mathrm{2jet}} > 0.5$	$\mathcal{D}^{\mathrm{EW}}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{VH+dec}}_{0h+}, \mathcal{D}^{\mathrm{VH+dec}}_{0-}, \mathcal{D}^{\mathrm{VH+dec}}_{\Lambda1}, \mathcal{D}^{Z\gamma,\mathrm{VH+dec}}_{\Lambda1}, \mathcal{D}^{\mathrm{VH}}_{\mathrm{int}}, \mathcal{D}^{\mathrm{VH}}_{CP}$
VH-leptonic	see Section 3	$\mathcal{D}_{\mathrm{bkg}}, p_{\mathrm{T}}^{4\ell}$
Untagged	none of the above	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{dec}}_{0h+}, \mathcal{D}^{\mathrm{dec}}_{0-}, \mathcal{D}^{\mathrm{dec}}_{\Lambda1}, \mathcal{D}^{Z\gamma,\mathrm{dec}}_{\Lambda1}, \mathcal{D}^{\mathrm{dec}}_{\mathrm{int}}, \mathcal{D}^{\mathrm{dec}}_{CP}$

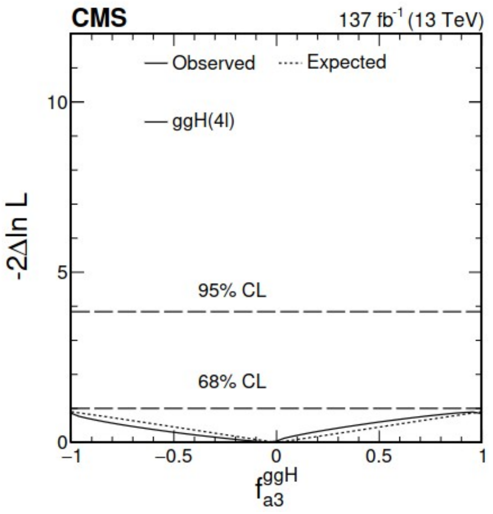


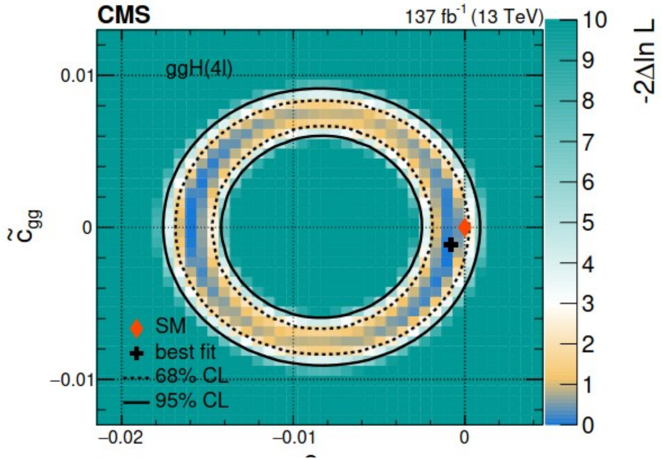


Example 3: H→4l MELA analysis

CMS-HIG-19-009

Fit of cross section ratios to reduce systematic uncertainties – reparametrisation in terms of EFT operators



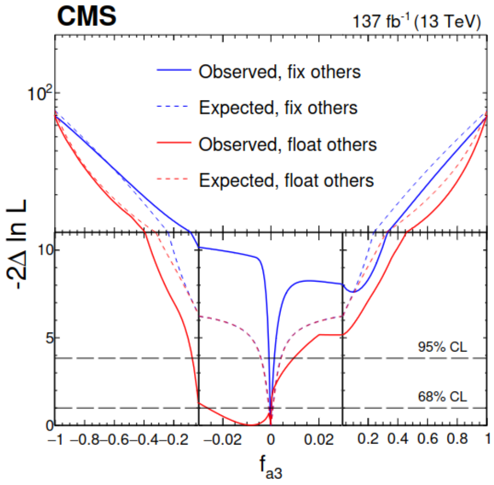


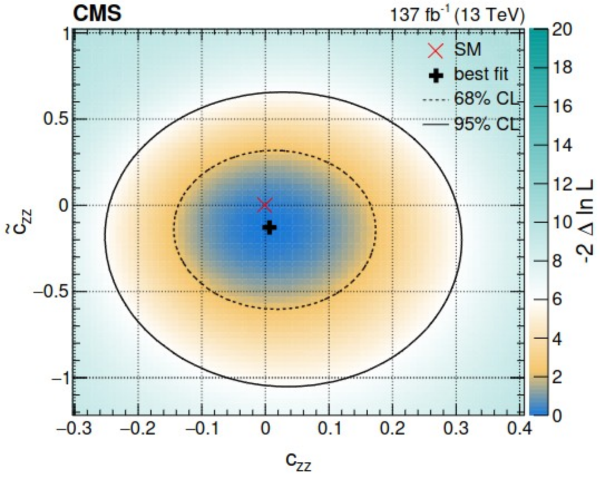
Hgg couplings

- No resolution of top loop in this measurement (κ_t absorbed in c_{gg})

HVV couplings

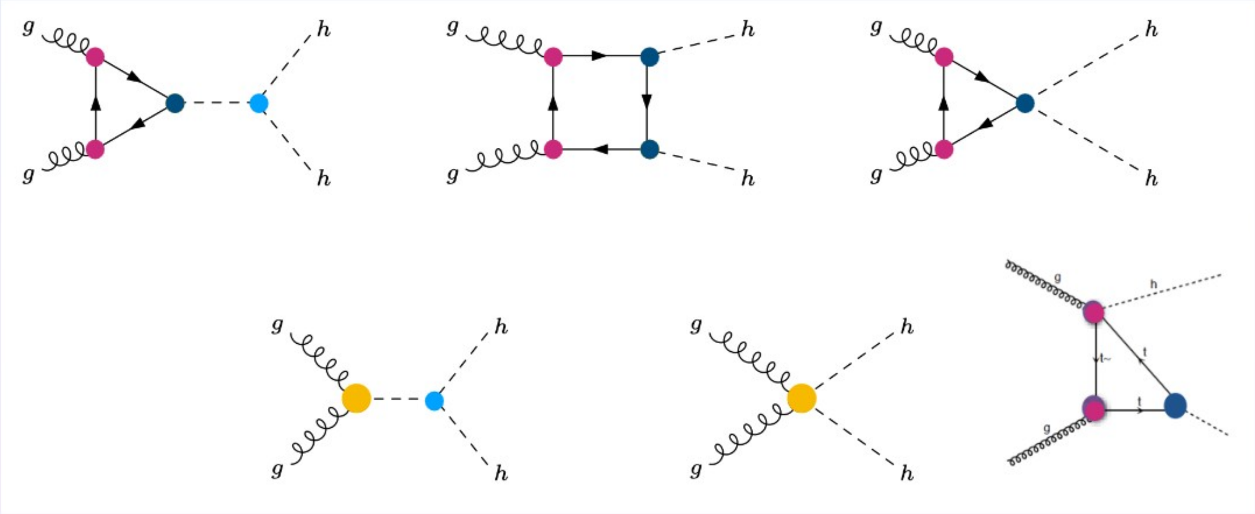
- Different scenarios (assumptions) on anomalous coupling (relations)





Non-resonant di-Higgs production

- SM predicts Higgs self-coupling – coupling provides sensitivity to Higgs potential
- Many BSM models modifying self-coupling strength – can be probed in terms of EFT



SMEFT:

$$\mathscr{L} = C_{H,\Box}(H^\dagger H)\Box(H^\dagger H) + C_{HD}D_\mu(H^\dagger H)D^\mu(H^\dagger H)^* \quad + \quad C_H|H|^6 \quad +$$

$$C_{HG}|H|^2 G_{\mu\nu}G^{\mu\nu} \quad + \quad C_{uH}\bar{Q}_L\tilde{H}t_R|H|^2 + h.c. \quad + \quad C_{uG}\bar{Q}_L\sigma_{\mu\nu}T^a\tilde{H}t_R G^a_{\mu\nu} + h.c.$$

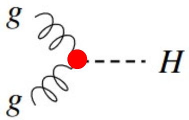
Warsaw basis

coefficients of $\mathcal{O}(1/\Lambda^2)$

R. Groeber

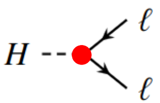
EFT operators relevant for Higgs physics

Higgs self-coupling → $c_{H\Box}$



ggF
H→γγ
(+ VBF, VH)

H→ττ

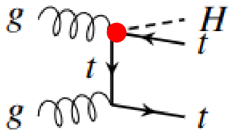


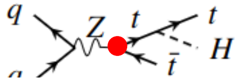
Top-Higgs: ggF, ttH, tH

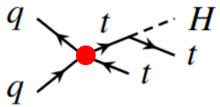
H-l-Z interactions: mainly H→4l (+ZH)

H-q-V interactions: mainly VH

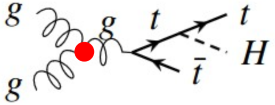
Wilson coefficient	Operator	Wilson coefficient	Operator
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	c_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\,G^A_{\mu\nu}$
c_{HDD}	$\left(H^\dagger D^\mu H\right)^*\left(H^\dagger D_\mu H\right)$	c_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\,W^I_{\mu\nu}$
c_{HG}	$H^\dagger H\,G^A_{\mu\nu}G^{A\mu\nu}$	c_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\,B_{\mu\nu}$
c_{HB}	$H^\dagger H\,B_{\mu\nu}B^{\mu\nu}$	c'_{ll}	$(\bar{l}_p\gamma_\mu l_t)(\bar{l}_r\gamma^\mu l_s)$
c_{HW}	$H^\dagger H\,W^I_{\mu\nu}W^{I\mu\nu}$	$c^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{HWB}	$H^\dagger\tau^I H\,W^I_{\mu\nu}B^{\mu\nu}$	$c^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	c_{qq}	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{uH}	$(H^\dagger H)(\bar{q}_p u_r\widetilde{H})$	$c^{(31)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_t)(\bar{q}_r\gamma^\mu\tau^I q_s)$
c_{dH}	$(H^\dagger H)(\bar{q}_p d_r\widetilde{H})$	c_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	$c^{(1)}_{uu}$	$(\bar{u}_p\gamma_\mu u_t)(\bar{u}_r\gamma^\mu u_s)$
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$	$c^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{u}_r\gamma^\mu u_s)$
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	$c^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	$c^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$	$c^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	c_W	$\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	c_G	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$







Couplings involving H-top (+gluons): ggF, ttH, tH



Content

1st lecture:

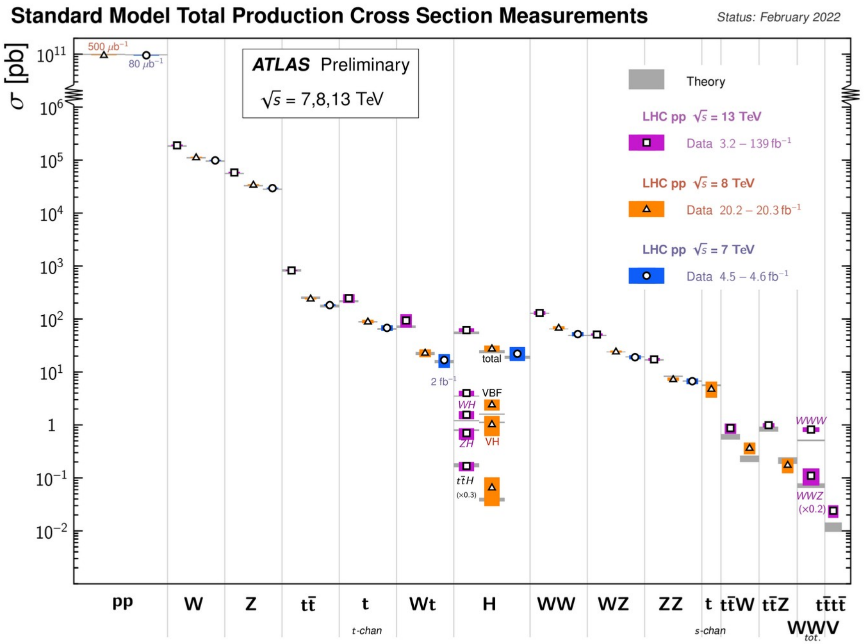
- Higgs physics
  - Higgs production and decay channels and their measurement
  - BSM and EFT sensitivity of each channel
- EW physics
  - Anomalous triple gauge couplings and dim-6 EFT interpretation
  - Beyond dim-6: neutral anomalous triple gauge couplings and quartic gauge couplings

2nd lecture:

- Towards a global fit: combining the available information
  - Experimental challenges of combinations
  - Global fit in action: how to ensure generality / model independence of EFT fits
  - Limitations and perspectives for EFT fits – towards HL-LHC and beyond

Electroweak measurements

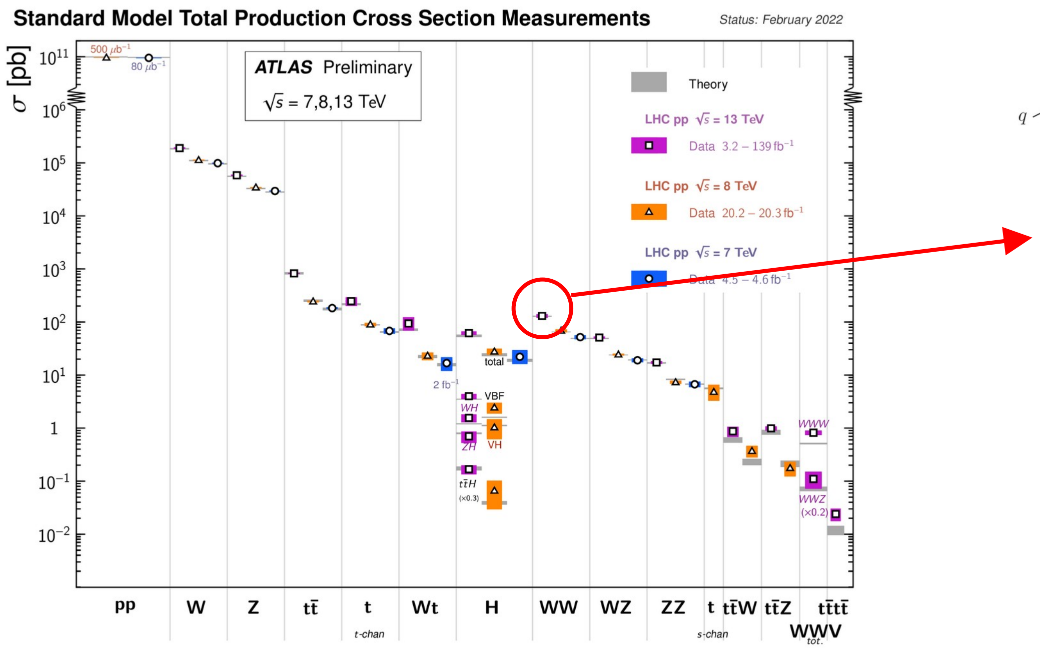
- Many SM processes measured with great precision at the LHC
- Search for rare processes that can be significantly enhanced in BSM
- Study interactions of gauge bosons or leptons with well known decays – focus on production side
- Often measure fiducial & differential cross section

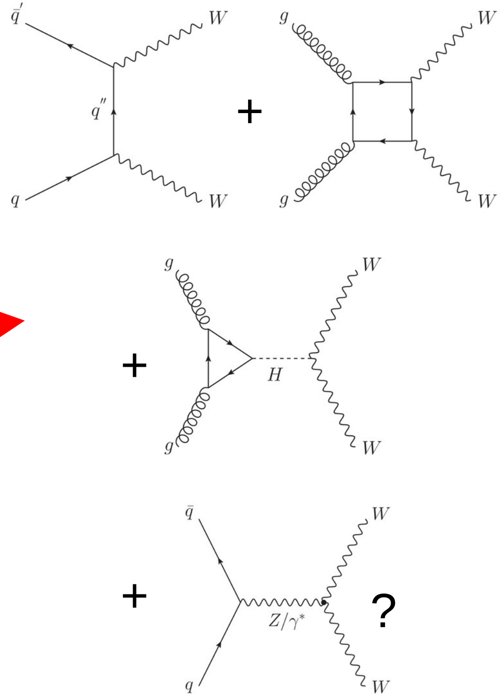


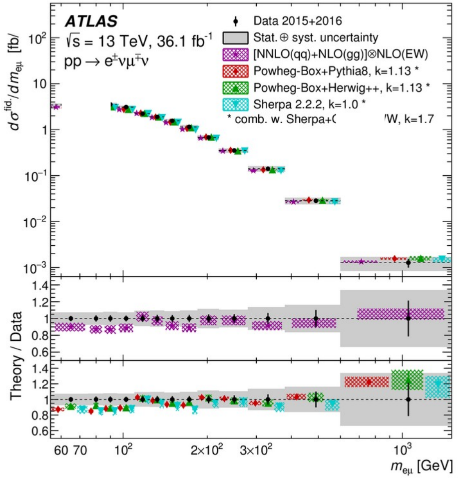
Electroweak measurements

- Many SM processes measured with great precision at the LHC
- Search for rare processes that can be significantly enhanced in BSM
- Study interactions of gauge bosons or leptons with well known decays – focus on production side
- Often measure fiducial & differential cross section

Example: pp → WW production with WW → eνμν

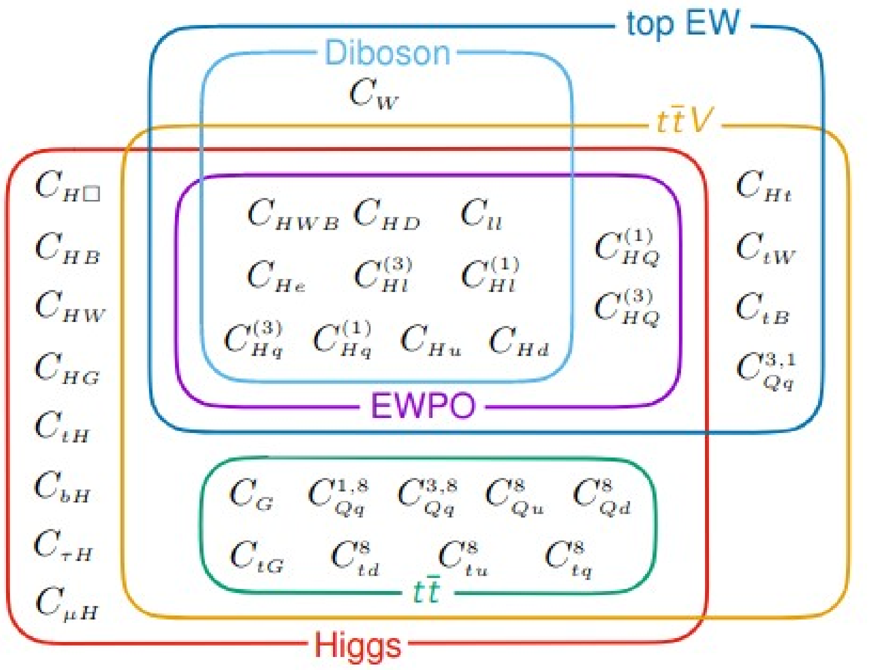






EFT sensitivity of EW measurements

- Dim-6:
  - Gauge boson and lepton coupling modifications from cross sections & EW precision observables
  - Anomalous triple gauge couplings (aTGC) from diboson production & VBF
  - Heavy flavour couplings from measurements with top quarks

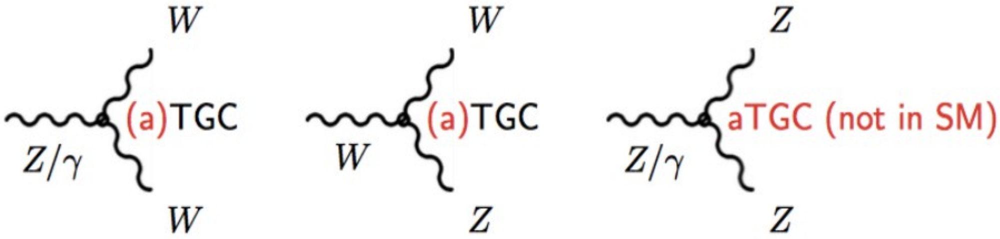


- Dim-8:
  - Sensitivity to neutral TGCs and anomalous quartic gauge couplings (aQGC) from vector boson scattering and tri-boson production

Anomalous triple gauge couplings

Anomalous gauge couplings formalism: SM deviations in gauge bosons couplings

- aTGC at dim-6



- simple extension of Lagrangian with additional interactions of 3 gauge bosons:

$$
\begin{aligned}
\mathcal{L} \;=\; & i g_{WWV} \Big(g_1^V (W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}) V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho \\
& + i g_4^V W^+_\mu W^-_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) - i g_5^V \epsilon^{\mu\nu\rho\sigma} (W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu) V_\sigma \\
& + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho \Big)
\end{aligned}
$$

} C- or P-violating

Notes:

- aTGC considered independent of BSM scale – no cut-off scale Λ as in EFT
- No complete field theory

From aTGC to EFT

5 EFT operators relevant in HISZ basis:

$$\begin{aligned} \mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] \\ \mathcal{O}_{W} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\ \mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) \end{aligned}$$

(C- & P- conserving)

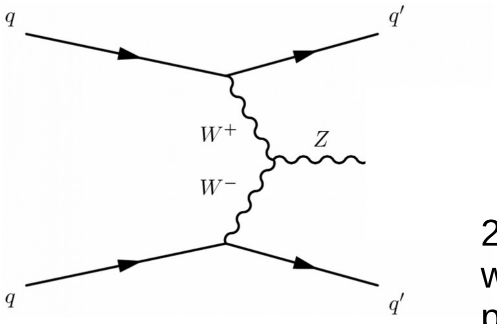
$$\begin{aligned} \mathcal{O}_{\tilde{W}WW} &= \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] \\ \mathcal{O}_{\tilde{W}} &= (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi) \end{aligned}$$

(C- &/or P- violating)

- Only operators affecting interaction between gauge bosons – generating aTGC and modifying boson kinematics
- More operators for boson to fermion interactions – neglected since well constrained from EW precision observables by LEP experiments

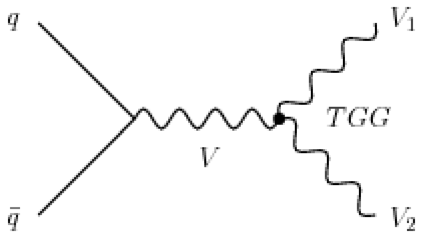
Experimental channels:

Vector boson fusion



2 forward quark jets with large separation in pseudo-rapidity

Diboson production



Production of 2 gauge bosons (W, Z or photon)

aTGC from VBF production

Example: EW Z+2jet production

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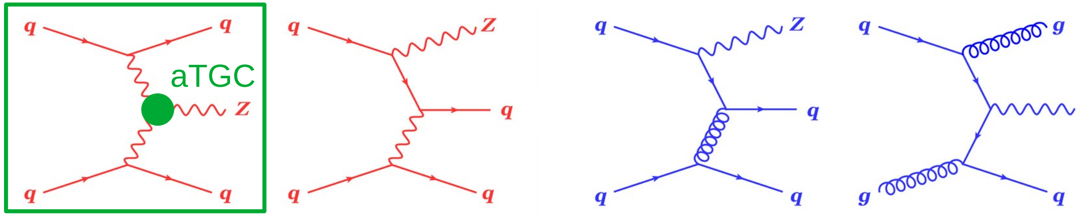
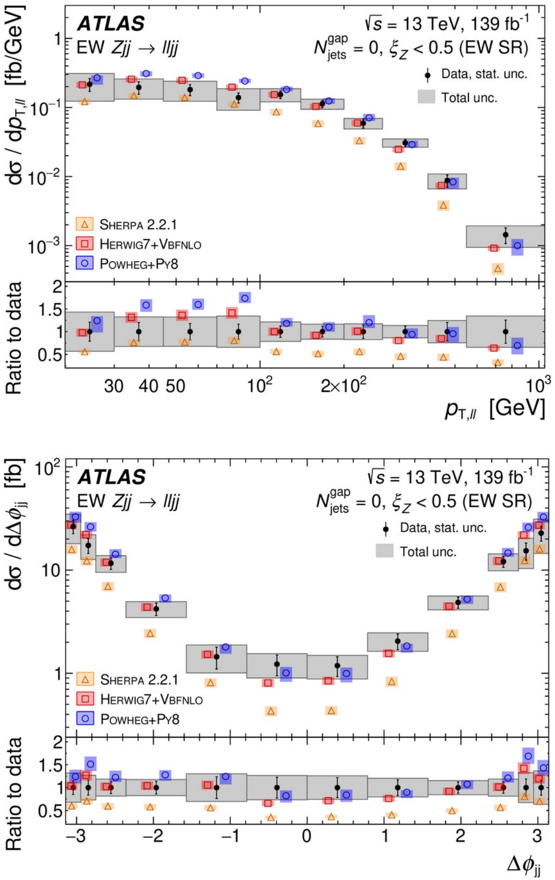
EW production

Strong production

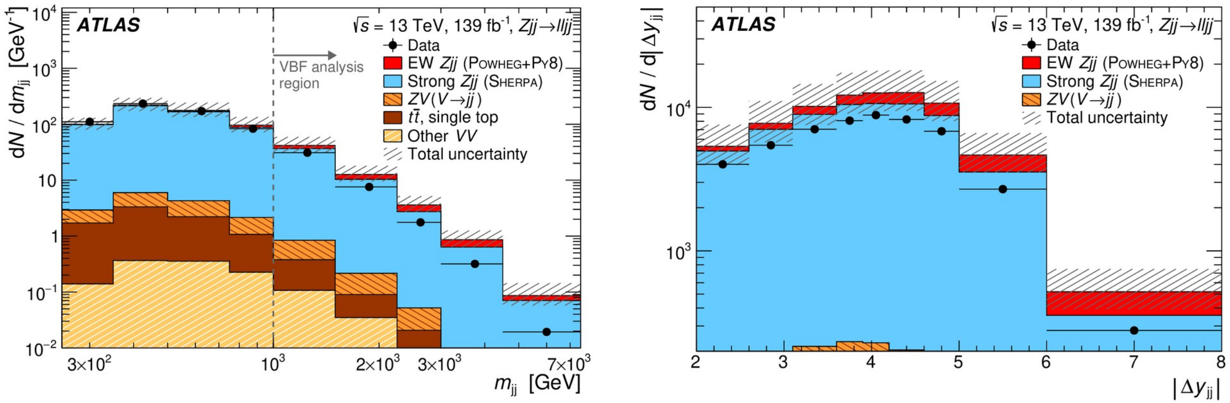


Differential cross sections measured in several kinematic variables



Several observables considered to discriminate between

- VBF Z+2j production and background processes
- EW production (sensitive to aTGC) and strong production – definition of signal and control regions



aTGC from VBF production

Example: EW Z+2jet production

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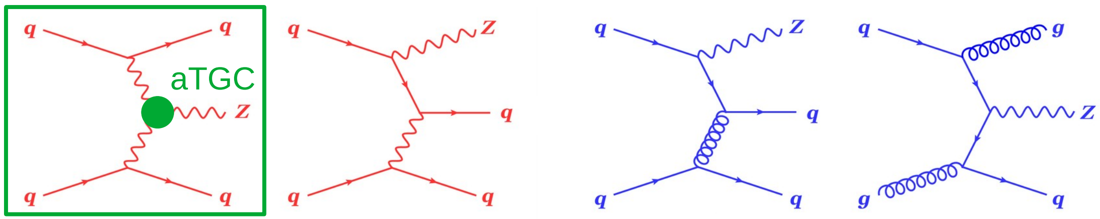
EW production

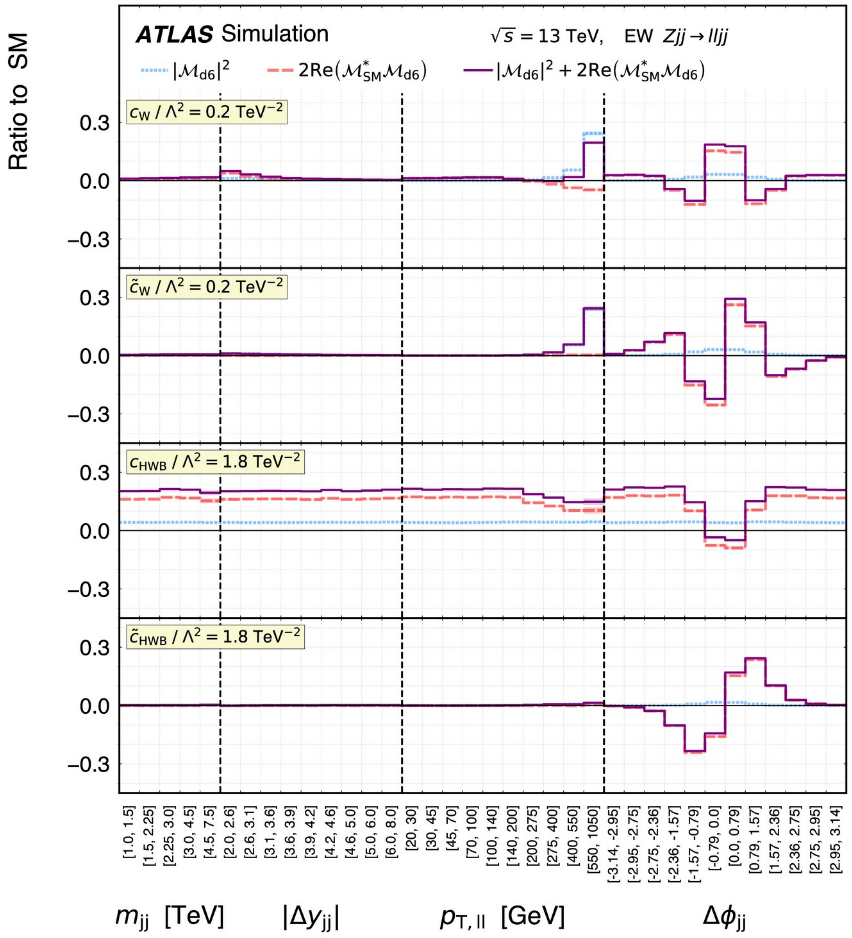
Strong production



- EFT sensitivity from high momentum tails – CP nature from signe ΔΦ between 2 jets
- Simultanous fit on diff. cross sections in 4 observables

Wilson coefficient	Includes $\|\mathcal{M}_{d6}\|^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

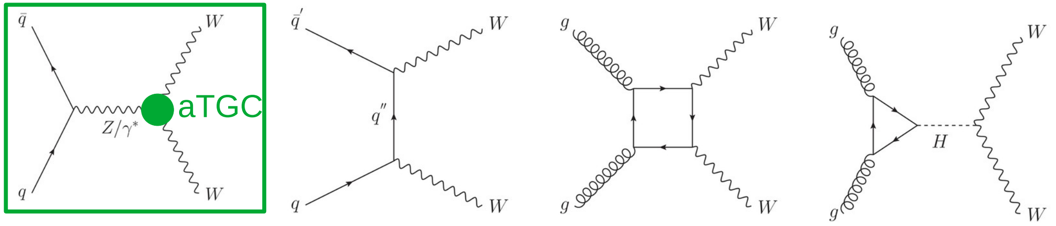
* Parametrisation in terms of Warsaw basis operators



aTGC from diboson production

Example: WW production

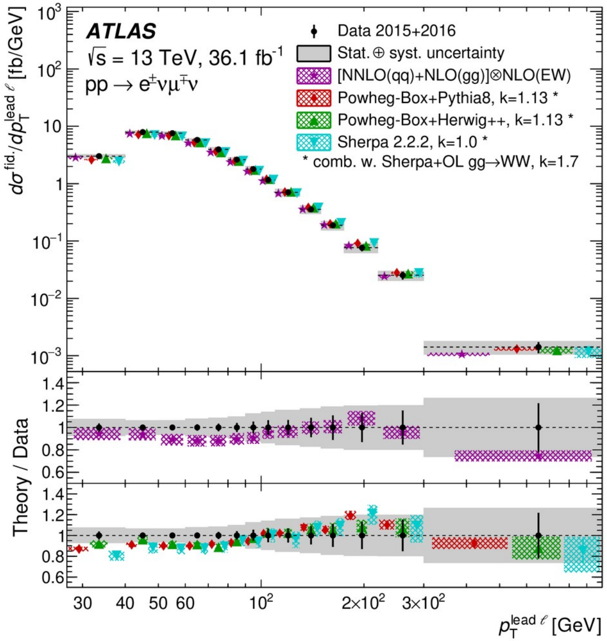
Eur. Phys. J. C 79 (2019) 884



Channel with large SM backgrounds

- Fiducial phase space defined to minimise bkg (e.g. jet-veto against ttbar)
- Data driven techniques with control and validation regions to constrain dominant backgrounds

Differential cross sections measured in many kinematic observables



Good limits on aTGC / EFT parameters – better limits achieved by adding more channels (e.g. WW + 1-jet)

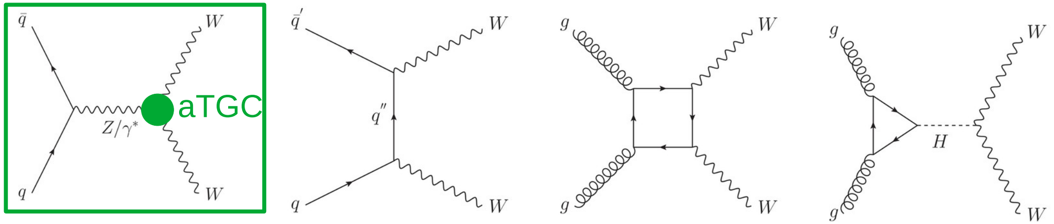
Operator	95% CL (linear and quadratic terms)	95% CL (linear terms only)
c_{WWW}/Λ^2	$[-3.4\ \text{TeV}^{-2}, 3.3\ \text{TeV}^{-2}]$	$[-179\ \text{TeV}^{-2}, -17\ \text{TeV}^{-2}]$
c_W/Λ^2	$[-7.4\ \text{TeV}^{-2}, 4.1\ \text{TeV}^{-2}]$	$[-13.1\ \text{TeV}^{-2}, 7.1\ \text{TeV}^{-2}]$
c_B/Λ^2	$[-21\ \text{TeV}^{-2}, 18\ \text{TeV}^{-2}]$	$[-104\ \text{TeV}^{-2}, 101\ \text{TeV}^{-2}]$

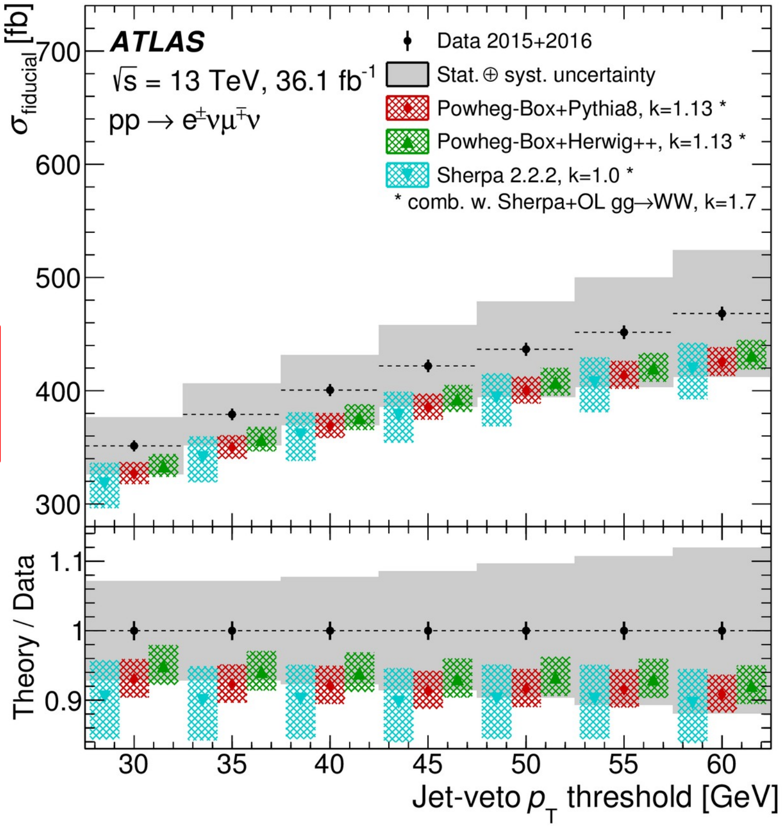
Note: Largest sensitivity from pure BSM contributions (quadratic terms) on p_T of leading leptons

aTGC from diboson production

Example: WW production

Eur. Phys. J. C 79 (2019) 884





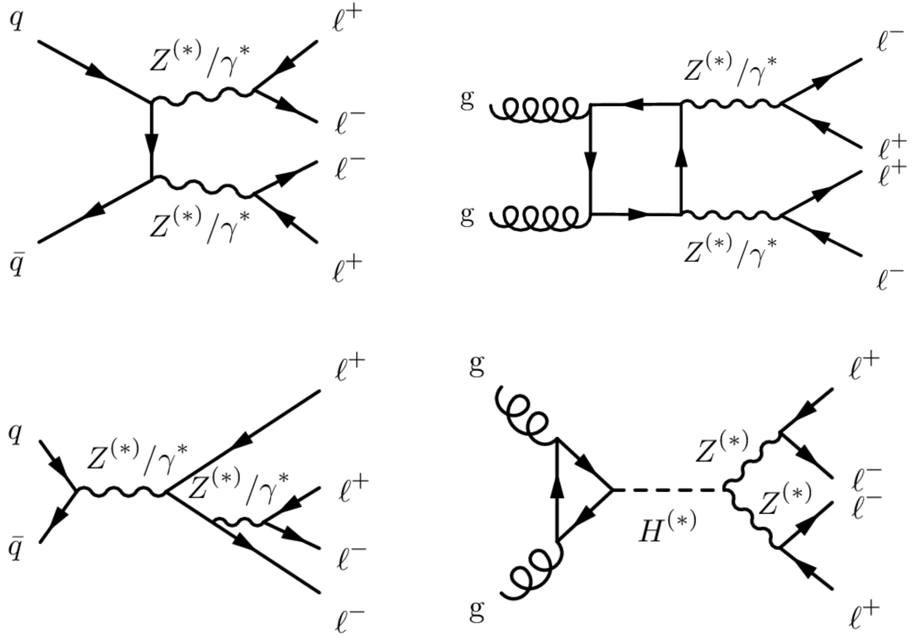
Note:
aTGC / EFT interpretation from unfolded cross section results

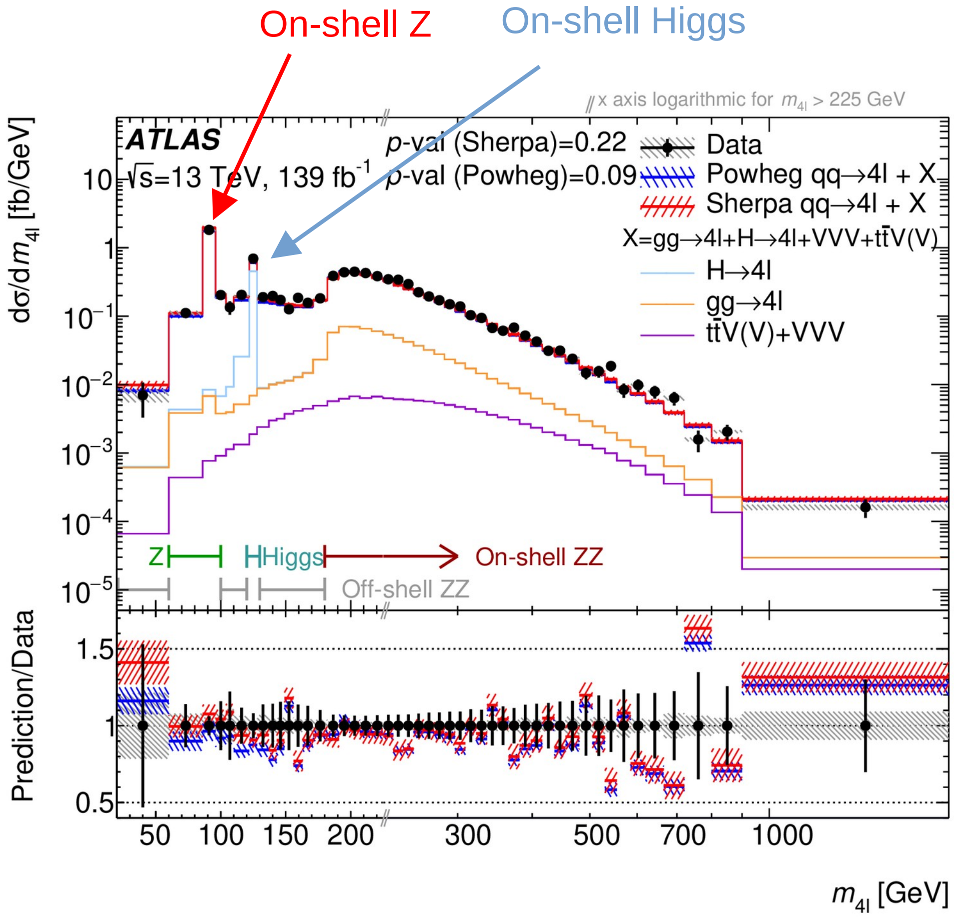
- Significant dependence of cross section on fiducial phase space definition – can be very different for SM vs. BSM
- Important to define fiducial phase space as close as possible to experimental selection to avoid acceptance effects
  - response matrix should only quantify detector resolution

Lepton interactions

JHEP 07 (2021) 005

Example: 4 lepton production



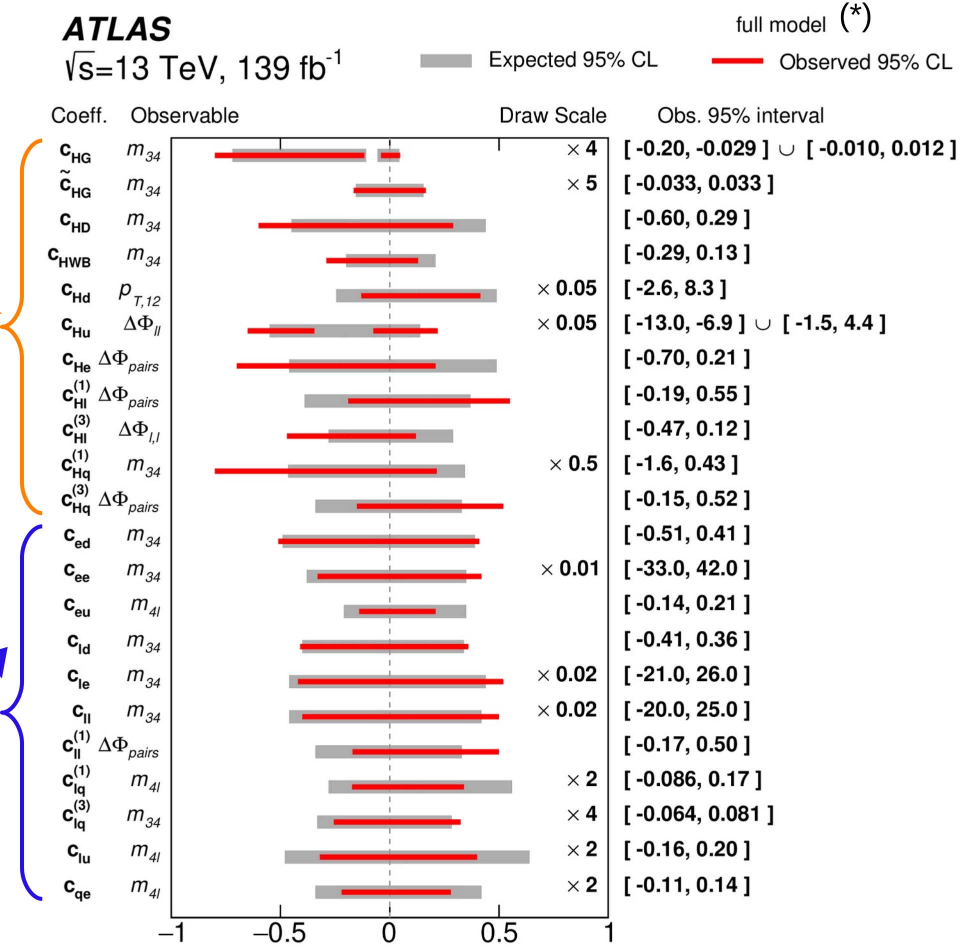


Lepton interactions

JHEP 07 (2021) 005

Example: 4 lepton production

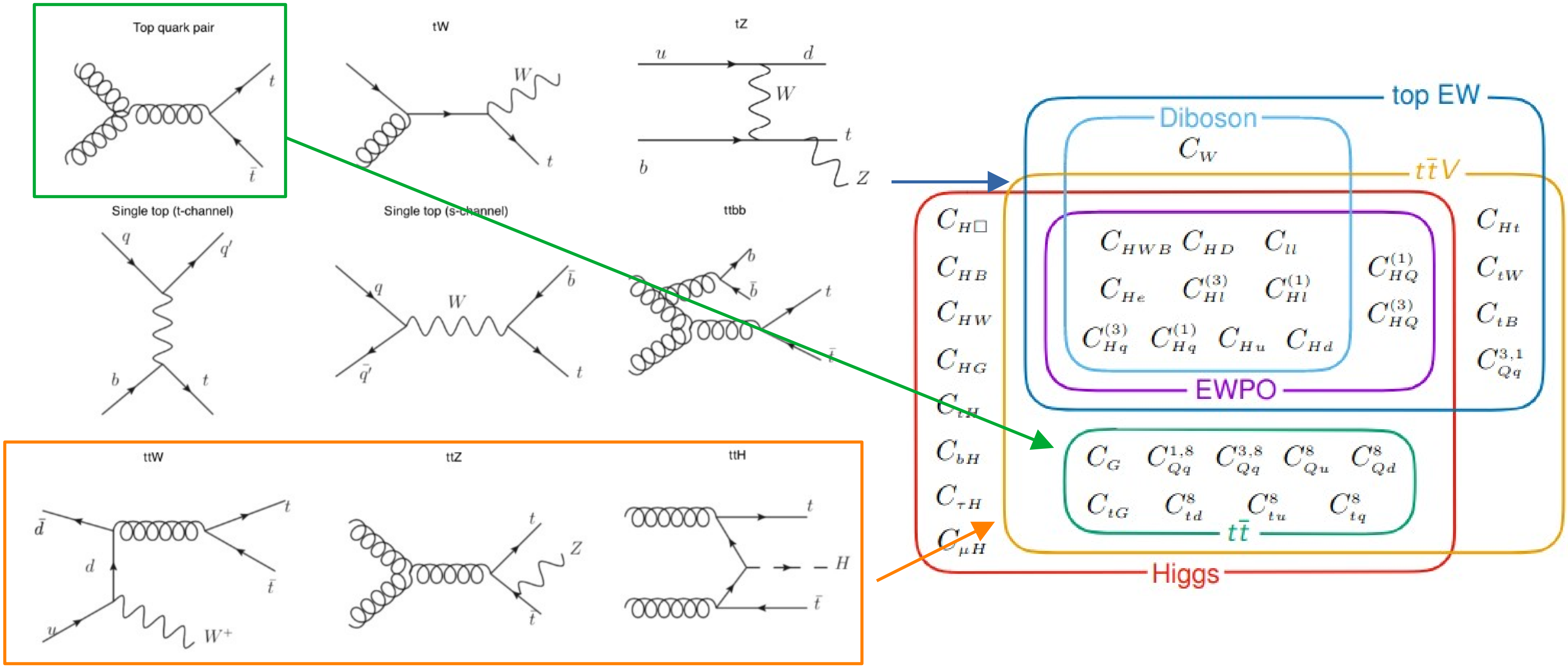
- Diff. cross sections in several kinematic observables
- SMEFT interpretation in Warsaw basis
  - Sensitivity to operators modifying Higgs couplings (gluon fusion production and 4l decay)
  - Sensitivity to large number of operators generating contact interactions between fermions
  - $Z \rightarrow ll$ couplings much better constrained from LEP data
- Complementarity to $H \rightarrow 4l$ analysis
  - Better limit in some Higgs operators from generic measurement
  - Large overlap of events would need to be treated in order to profit from combination



(*) linear + quadratic terms

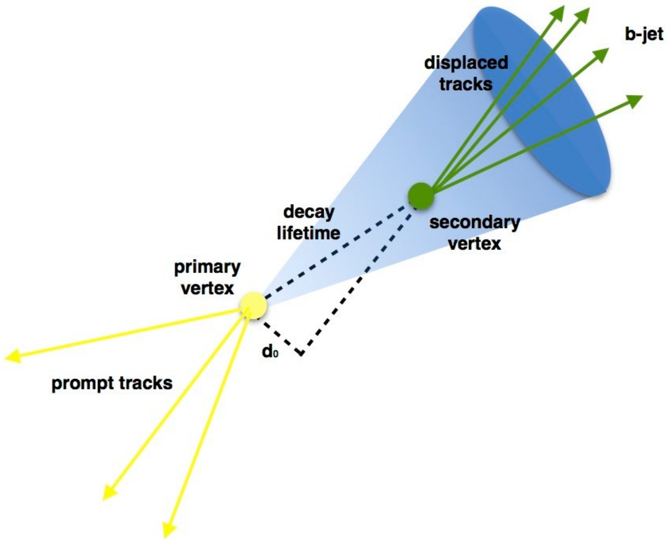
Top quark production

- Top quark is (by far) heaviest particle in SM – special role in many BSM models
- Sensitivity from processes involving top quarks to many EFT operators (top-boson or 4-fermion couplings)



Top quark production

- Experimentally challenging: top decays to b-quark and W boson (in ~100% of cases)
  - b-jet identification: use finite life time → measurable secondary vertex
  - W can decay leptonically or hadronically – leptons more easy to find and trigger, but then energy from neutrino is missing



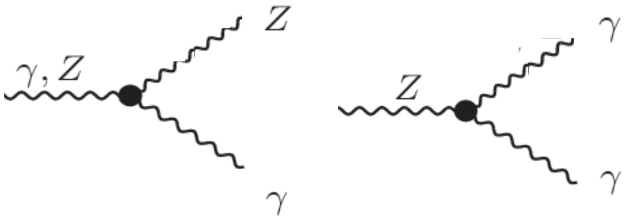
- Even harder to identify charm or strange jets → measurements with top and b-quarks are the only way to (currently) break U(3)5 flavour symmetry from experimental side

Beyond dimension 6

Neutral triple gauge couplings (nTGC) and **anomalous quartic gauge couplings** (aQGC) at dim. ≥ 8

nTGC at dim-8

Trilinear coupling between Z's and photons



$$\mathcal{O}_{BW} = i\, H^\dagger B_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\}\, H,$$
$$\mathcal{O}_{WW} = i\, H^\dagger W_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\}\, H,$$
$$\mathcal{O}_{BB} = i\, H^\dagger B_{\mu\nu} B^{\mu\rho} \{D_\rho, D^\nu\}\, H.$$
$$\mathcal{O}_{\widetilde{B}W} = i\, H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\}\, H,$$

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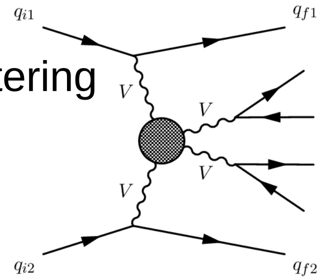
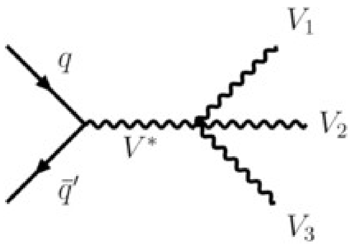
aQGC at dim-8

Vector boson scattering



Triboson production



3 types of operators:

- O_S: contain derivation of scalar Higgs field
- O_T: contain EW field strength tensor derivatives
- O_M: mixed -- contain both

	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	✓	✓			✓				
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$					✓	✓	✓	✓	✓

P. Calfayan

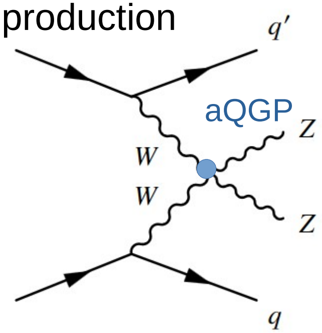
aQGC from vector boson scattering

ATLAS-CONF-2023-024

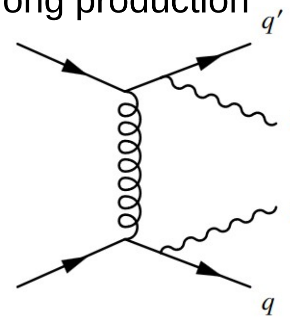
Example: ZZ + 2 jet production ($ZZ \rightarrow$ 4 leptons)

- Fiducial phase space defined at particle level and based on detector level cuts
- Measurement of differential cross sections with sensitivity to EW vs. strong ZZ+2j production

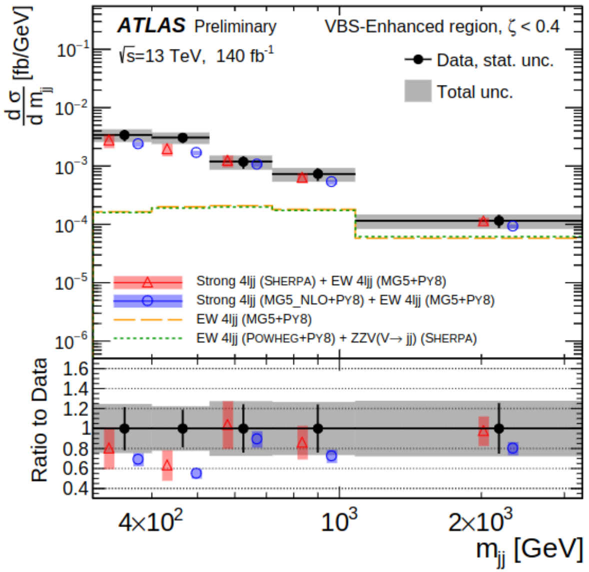
EW production

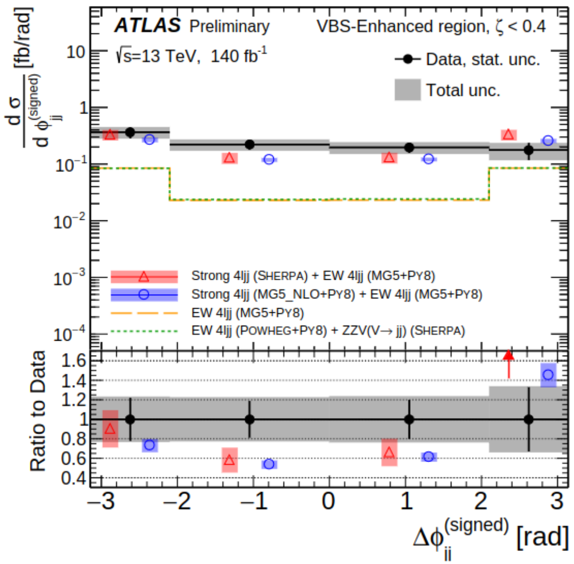


Strong production



Signature: 2 leptonically decaying Z bosons and 2 forward jets with large separation in η





Other channels: WZ, WW, Wγ, Zγ in association with 2 jets

aQGC from vector boson scattering

ATLAS-CONF-2023-024

Example: ZZ + 2 jet production (ZZ→ 4 leptons)

Dim-8 EFT interpretation

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{f_{T,i}}{\Lambda^4} O_{T,i}$$

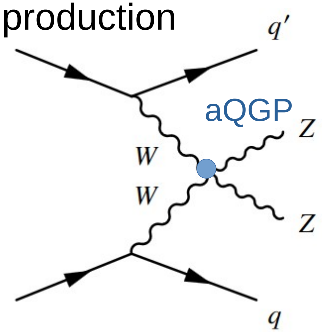
Introduce anomalous quartic weak boson self-interactions

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\,\mathrm{Re}(\mathcal{M}_{SM}{}^* \mathcal{M}_{d8}) + |\mathcal{M}_{d8}|^2$$

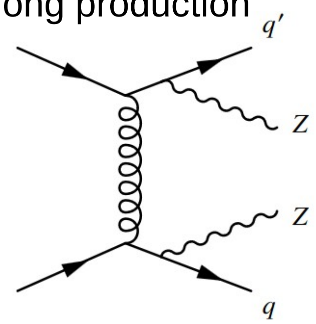
Wilson coefficient	$\|\mathcal{M}_{d8}\|^2$ Included	95% confidence interval [TeV^{-4}] Expected	Observed
$f_{T,0}/\Lambda^4$	yes	[-0.98,0.93]	[-1.0,0.97]
	no	[-23, 17]	[-19, 19]
$f_{T,1}/\Lambda^4$	yes	[-1.2, 1.2]	[-1.3, 1.3]
	no	[-160, 120]	[-140, 140]
$f_{T,2}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-74, 56]	[-63, 62]
$f_{T,5}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-79, 60]	[-68, 67]
$f_{T,6}/\Lambda^4$	yes	[-3.9, 3.9]	[-4.1, 4.1]
	no	[-64, 48]	[-55, 54]
$f_{T,7}/\Lambda^4$	yes	[-8.5, 8.1]	[-8.8, 8.4]
	no	[-260, 200]	[-220, 220]
$f_{T,8}/\Lambda^4$	yes	[-2.1, 2.1]	[-2.2, 2.2]
	no	[-4.6, 3.1]$\times10^4$	[-3.9, 3.8]$\times10^4$
$f_{T,9}/\Lambda^4$	yes	[-4.5, 4.5]	[-4.7, 4.7]
	no	[-7.5, 5.5]$\times10^4$	[-6.4, 6.3]$\times10^4$

Major contribution from pure BSM terms

EW production



Strong production



aQGC from vector boson scattering

ATLAS-CONF-2023-024

Example: ZZ + 2 jet production (ZZ → 4 leptons)

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$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f_{\mathrm{T},i}}{\Lambda^4} O_{\mathrm{T},i}$$

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Wilson coefficient	$\lvert\mathcal{M}_{\mathrm{d8}}\rvert^2$ Included	95% confidence interval [TeV^{-4}] Expected	Observed
$f_{\mathrm{T},0}/\Lambda^4$	yes	[-0.98,0.93]	[-1.0,0.97]
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$f_{\mathrm{T},1}/\Lambda^4$	yes	[-1.2, 1.2]	[-1.3, 1.3]
	no	[-160, 120]	[-140, 140]
$f_{\mathrm{T},2}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
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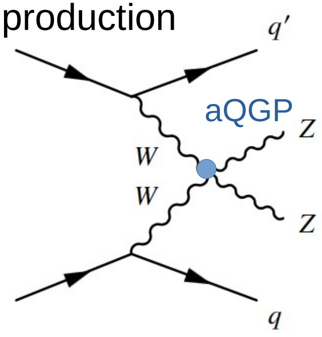
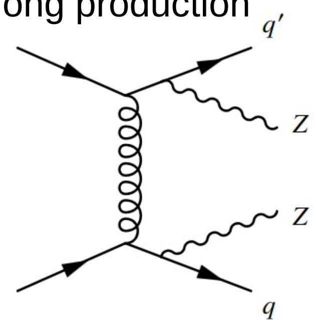
$f_{\mathrm{T},6}/\Lambda^4$	yes	[-3.9, 3.9]	[-4.1, 4.1]
	no	[-64, 48]	[-55, 54]
$f_{\mathrm{T},7}/\Lambda^4$	yes	[-8.5, 8.1]	[-8.8, 8.4]
	no	[-260, 200]	[-220, 220]
$f_{\mathrm{T},8}/\Lambda^4$	yes	[-2.1, 2.1]	[-2.2, 2.2]
	no	[-4.6, 3.1]$\times10^4$	[-3.9, 3.8]$\times10^4$
$f_{\mathrm{T},9}/\Lambda^4$	yes	[-4.5, 4.5]	[-4.7, 4.7]
	no	[-7.5, 5.5]$\times10^4$	[-6.4, 6.3]$\times10^4$

Major contribution from pure BSM terms

EW production

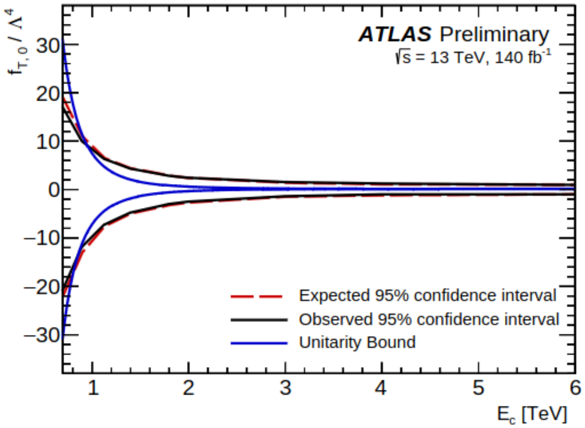


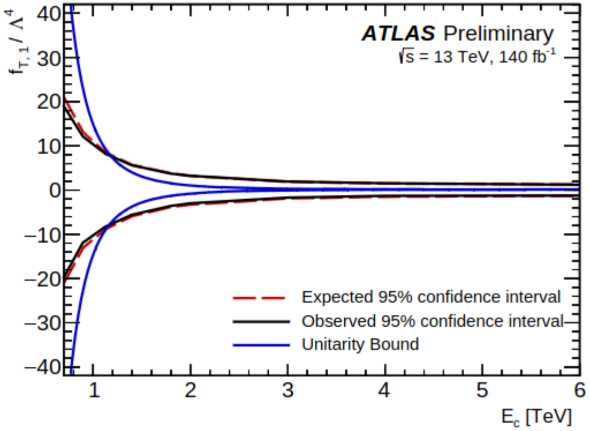
Strong production



Unitarity violation at high energy scales:

- Prevented by reducing theory phase space to $m_{4l} < E_c$ (cut-off)
- Constraints significantly looser in phase space without unitarity violation





aQGC from photon scattering

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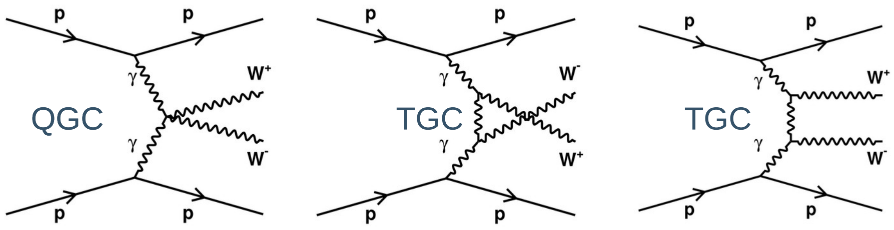
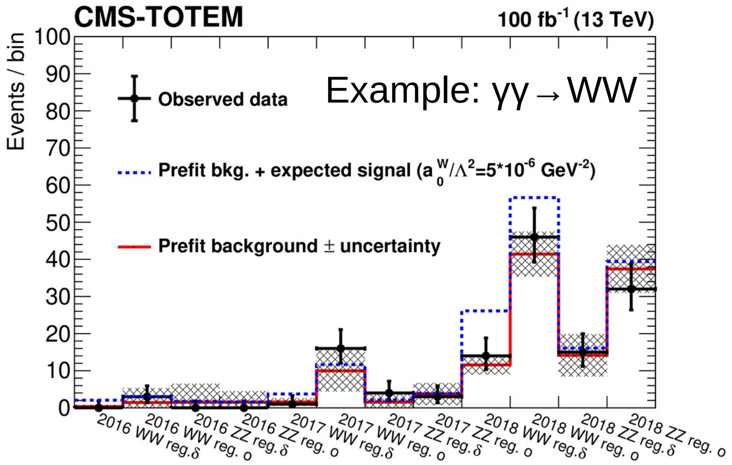
Example: γγ→ZZ & γγ→WW production

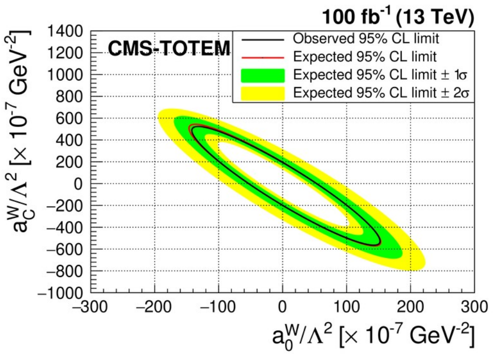


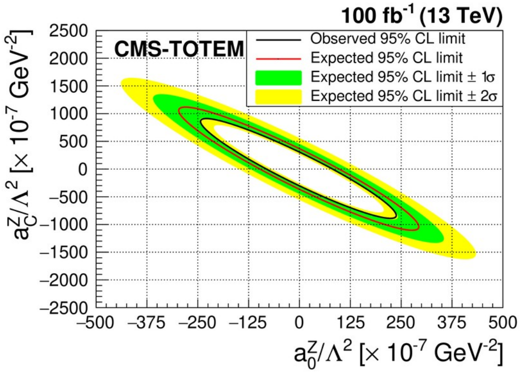
- Both TGC and QGC interactions present in SM
  - Mainly at low VV masses
  - Very low cross section
- Enhancement w.r.t. possible from BSM
  - In particular at high VV masses

- Interacting photons radiated from protons
- Protons remain intact and can be measured in very forward region close to CMS



Limits on non-linear dim-6 aQGC parameters $a_0^{W,Z}$ & $a_C^{W,Z}$

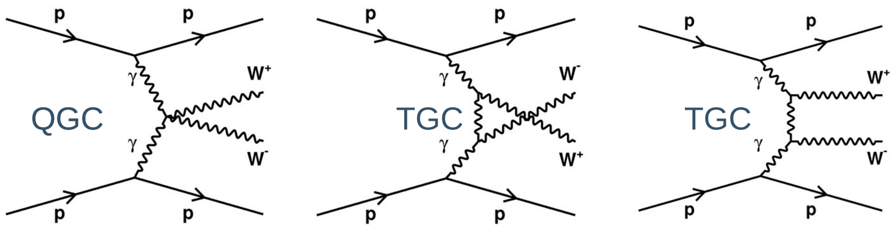




aQGC from photon scattering

JHEP 07 (2023) 229

Example: γγ→ZZ & γγ→WW production



Conversion into linear dim-8 EFT operators

$$a_0^W = -\frac{m_W}{\pi\alpha_{em}}\left[s_w^2\frac{f_{M,0}}{\Lambda^2} + 2c_w^2\frac{f_{M,2}}{\Lambda^2} + s_w c_w\frac{f_{M,4}}{\Lambda^2}\right]$$

Assuming no anomalous WWZγ contributions:

Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert f_{M,0}/\Lambda^4\rvert$	16.2 (14.7) TeV^{-4}	19.5 (19.2) TeV^{-4}
$\lvert f_{M,4}/\Lambda^4\rvert$	90.9 (82.6) TeV^{-4}	110 (108) TeV^{-4}

Note:

- impact from unitarisation smaller than in VBS: natural upper mass limit of ~ 2TeV from proton reconstruction in detector
- Unitarised limits comparable to VBS limits

aQGC from photon scattering

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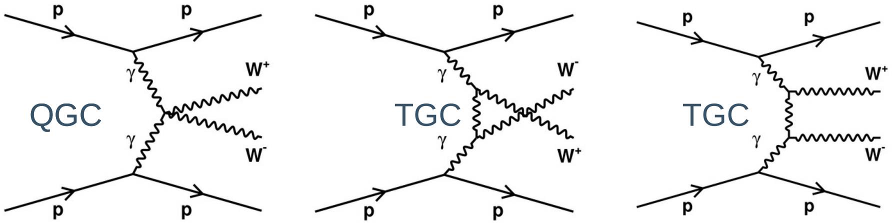
Example: γγ → ZZ & γγ → WW production



Conversion into linear dim-8 EFT operators

$$a_0^W = -\frac{m_W}{\pi\alpha_{em}}\left[s_w^2\frac{f_{M,0}}{\Lambda^2} + 2c_w^2\frac{f_{M,2}}{\Lambda^2} + s_w c_w\frac{f_{M,4}}{\Lambda^2}\right]$$

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$\lvert f_{M,4}/\Lambda^4\rvert$	90.9 (82.6) TeV^{-4}	110 (108) TeV^{-4}

Alternative fit: all operators except one are zero
→ strong dependence of limits on assumptions!

Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert f_{M,0}/\Lambda^4\rvert$	66.0 (60.0) TeV^{-4}	79.8 (78.2) TeV^{-4}
$\lvert f_{M,1}/\Lambda^4\rvert$	245.5 (214.8) TeV^{-4}	306.8 (306.8) TeV^{-4}
$\lvert f_{M,2}/\Lambda^4\rvert$	9.8 (9.0) TeV^{-4}	11.9 (11.8) TeV^{-4}
$\lvert f_{M,3}/\Lambda^4\rvert$	73.0 (64.6) TeV^{-4}	91.3 (92.3) TeV^{-4}
$\lvert f_{M,4}/\Lambda^4\rvert$	36.0 (32.9) TeV^{-4}	43.5 (42.9) TeV^{-4}
$\lvert f_{M,5}/\Lambda^4\rvert$	67.0 (58.9) TeV^{-4}	83.7 (84.1) TeV^{-4}
$\lvert f_{M,7}/\Lambda^4\rvert$	490.9 (429.6) TeV^{-4}	613.7 (613.7) TeV^{-4}

Note:
- impact from unitarisation smaller than in VBS: natural upper mass limit of ~ 2TeV from proton reconstruction in detector
- Unitarised limits comparable to VBS limits

aQGC from triboson production

Example: Zγγ & W±γγ production

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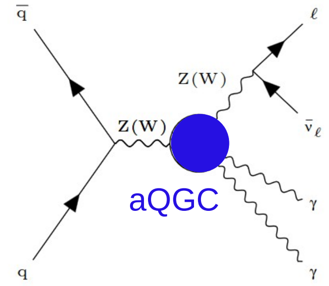
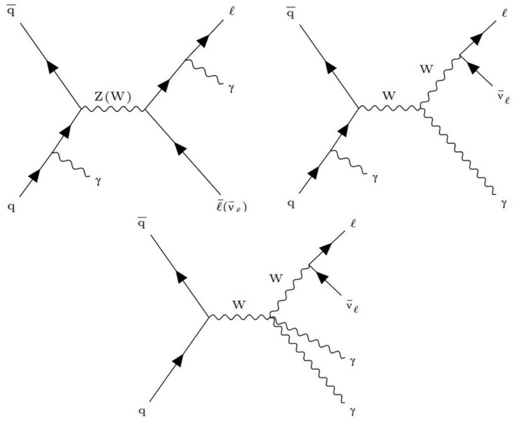
BSM production

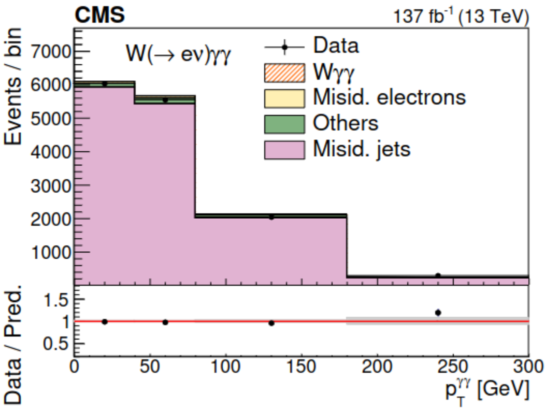


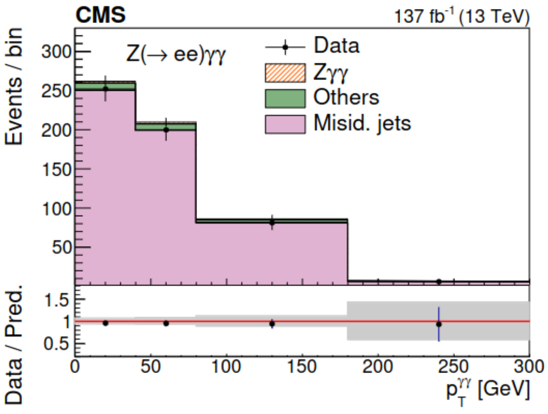
SM production



- EFT interpretation of diphoton p_T spectrum
- Assume no contributions from aTGC (dim-6)
- Strongest aQGC contributions at high $p_T^{\gamma\gamma}$

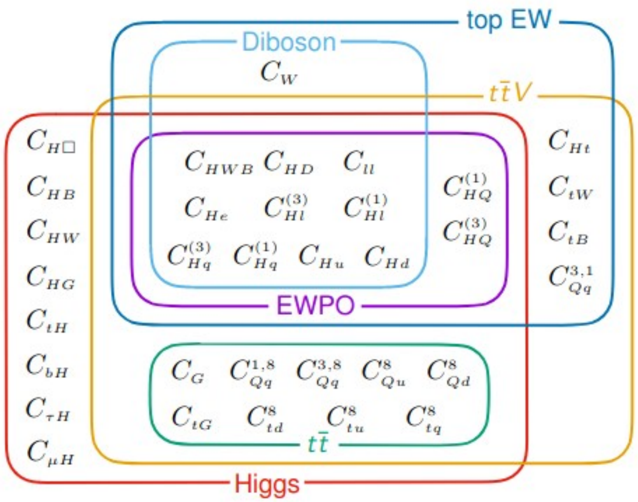
	$W\gamma\gamma$ (TeV^{-4})		$Z\gamma\gamma$ (TeV^{-4})	
Parameter	Expected	Observed	Expected	Observed
f_{M2}/Λ^4	[−57.3, 57.1]	[−39.9, 39.5]	—	—
f_{M3}/Λ^4	[−91.8, 92.6]	[−63.8, 65.0]	—	—
f_{T0}/Λ^4	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T1}/Λ^4	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T2}/Λ^4	[−5.16, 5.16]	[−3.64, 3.64]	[−9.72, 9.32]	[−11.4, 10.9]
f_{T5}/Λ^4	[−0.76, 0.84]	[−0.52, 0.60]	[−2.44, 2.52]	[−2.92, 2.92]
f_{T6}/Λ^4	[−0.92, 1.00]	[−0.60, 0.68]	[−3.24, 3.24]	[−3.80, 3.88]
f_{T7}/Λ^4	[−1.64, 1.72]	[−1.16, 1.16]	[−6.68, 6.60]	[−7.88, 7.72]
f_{T8}/Λ^4	—	—	[−0.90, 0.94]	[−1.06, 1.10]
f_{T9}/Λ^4	—	—	[−1.54, 1.54]	[−1.82, 1.82]

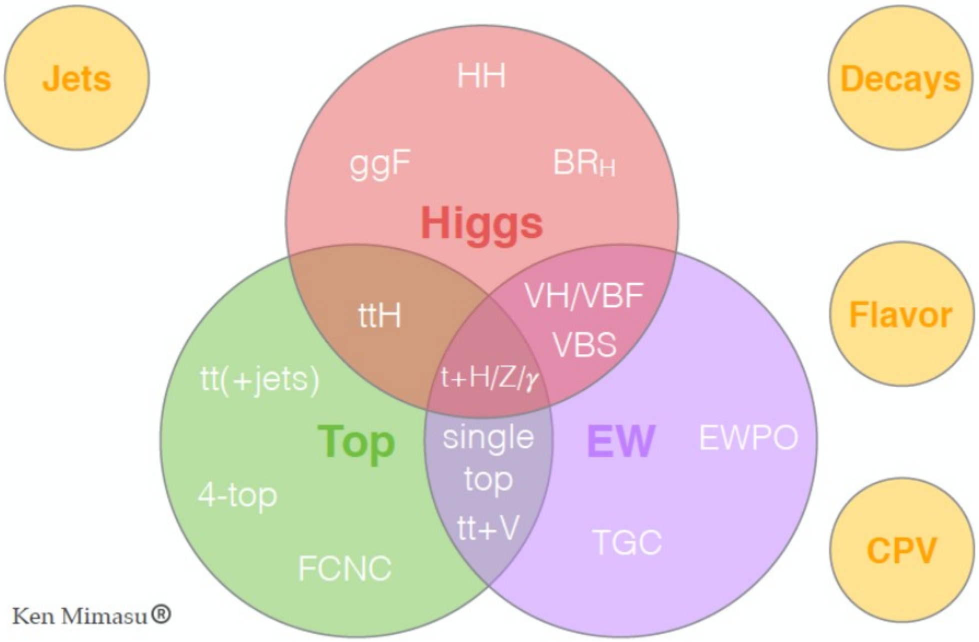




Interplay between EW and Higgs

- Similar event kinematics, e.g. for VBS / VBF – common experimental techniques
- EW might be dominant Higgs analyses backgrounds, e.g. ttW is main background of ttH in multilepton channel





Global EFT fit

→ 2^{nd} lecture

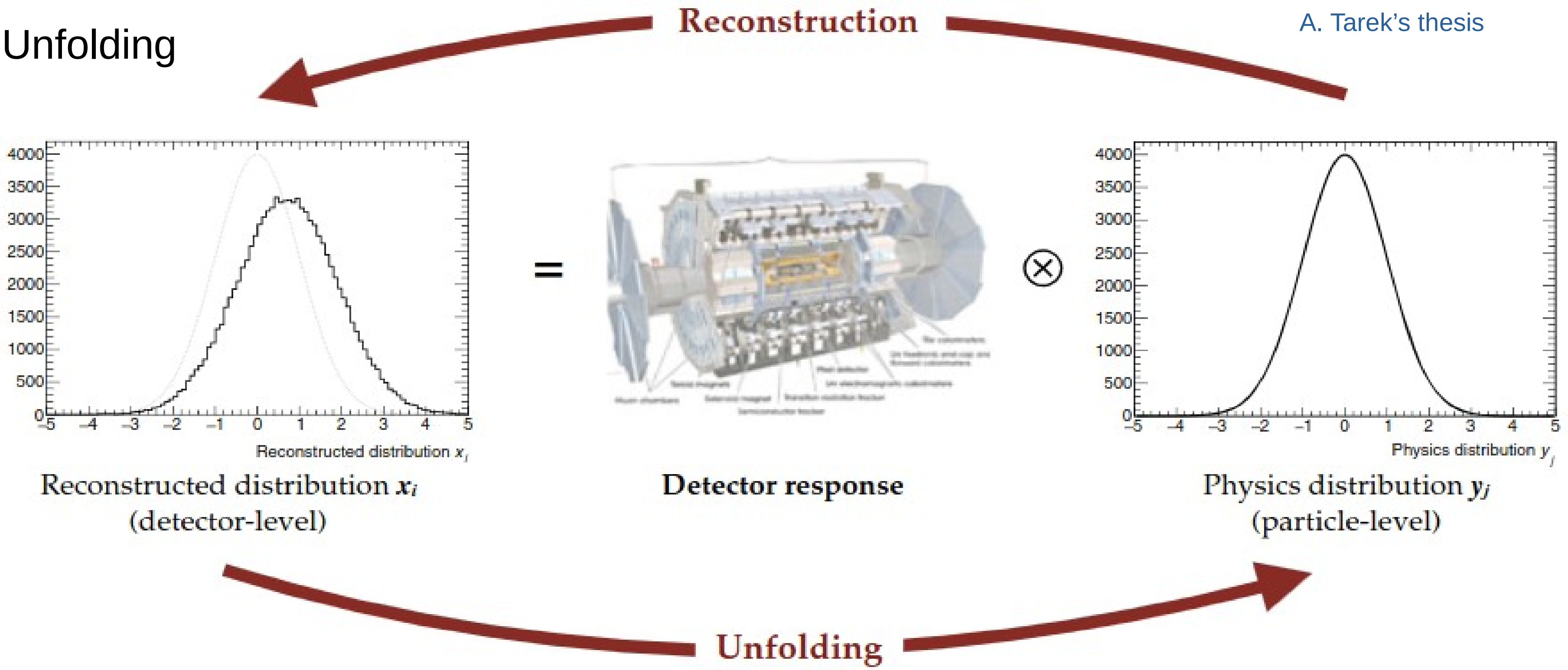
BACKUP

Excursion: unfolding

- Inversion of detector effects to allow comparison of measurements with theory prediction
- Unfolded results allow direct comparison to theory outside experiment

Unfolding

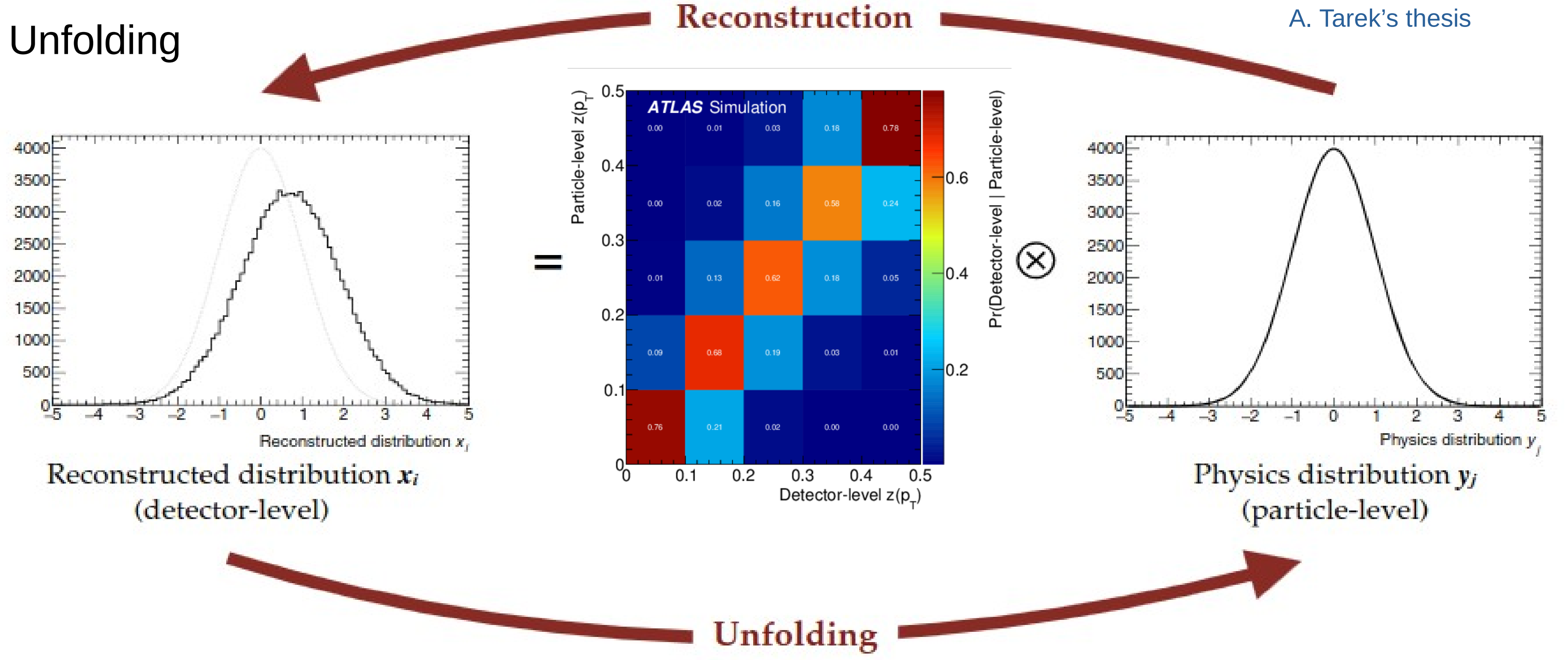
A. Tarek's thesis



Excursion: unfolding

- Inversion of detector effects to allow comparison of measurements with theory prediction
- Unfolded results allow direct comparison to theory outside experiment

A. Tarek's thesis



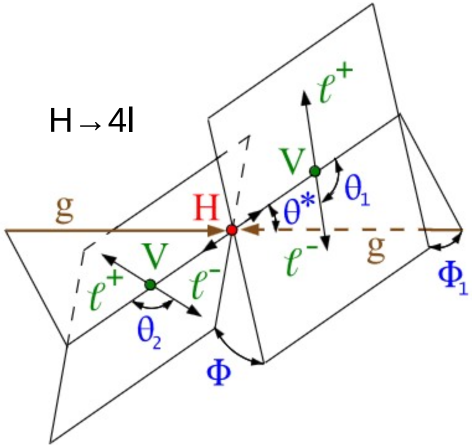
Matrix element observables

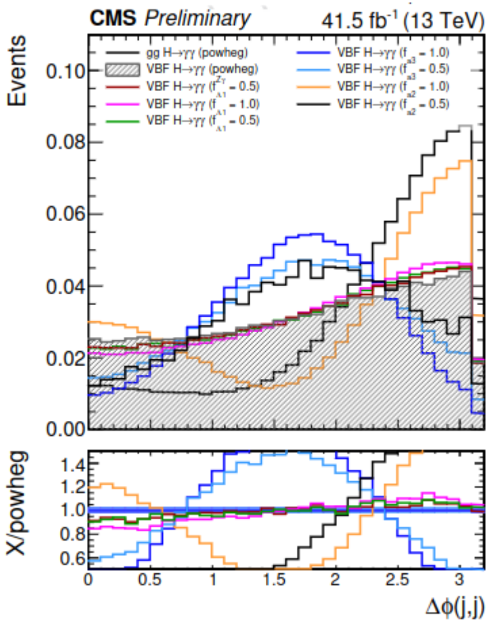
- Matrix element based observables for optimal sensitivity
- Probability ratios for alternative model versus signal model
  - “sig”: SM Higgs signal (possibly specific production mode)
  - “alt”: background, production modes or BSM
  - “int”: interference terms
  - Ω: full kinematic description of process

$$\mathcal{D}_{\text{alt}}(\boldsymbol{\Omega}) = \frac{\mathcal{P}_{\text{sig}}(\boldsymbol{\Omega})}{\mathcal{P}_{\text{sig}}(\boldsymbol{\Omega}) + \mathcal{P}_{\text{alt}}(\boldsymbol{\Omega})}$$

$$\mathcal{D}_{\text{int}}(\boldsymbol{\Omega}) = \frac{\mathcal{P}_{\text{int}}(\boldsymbol{\Omega})}{2\sqrt{\mathcal{P}_{\text{sig}}(\boldsymbol{\Omega})\ \mathcal{P}_{\text{alt}}(\boldsymbol{\Omega})}}$$

Example of kinemetic variables for MELA calculation

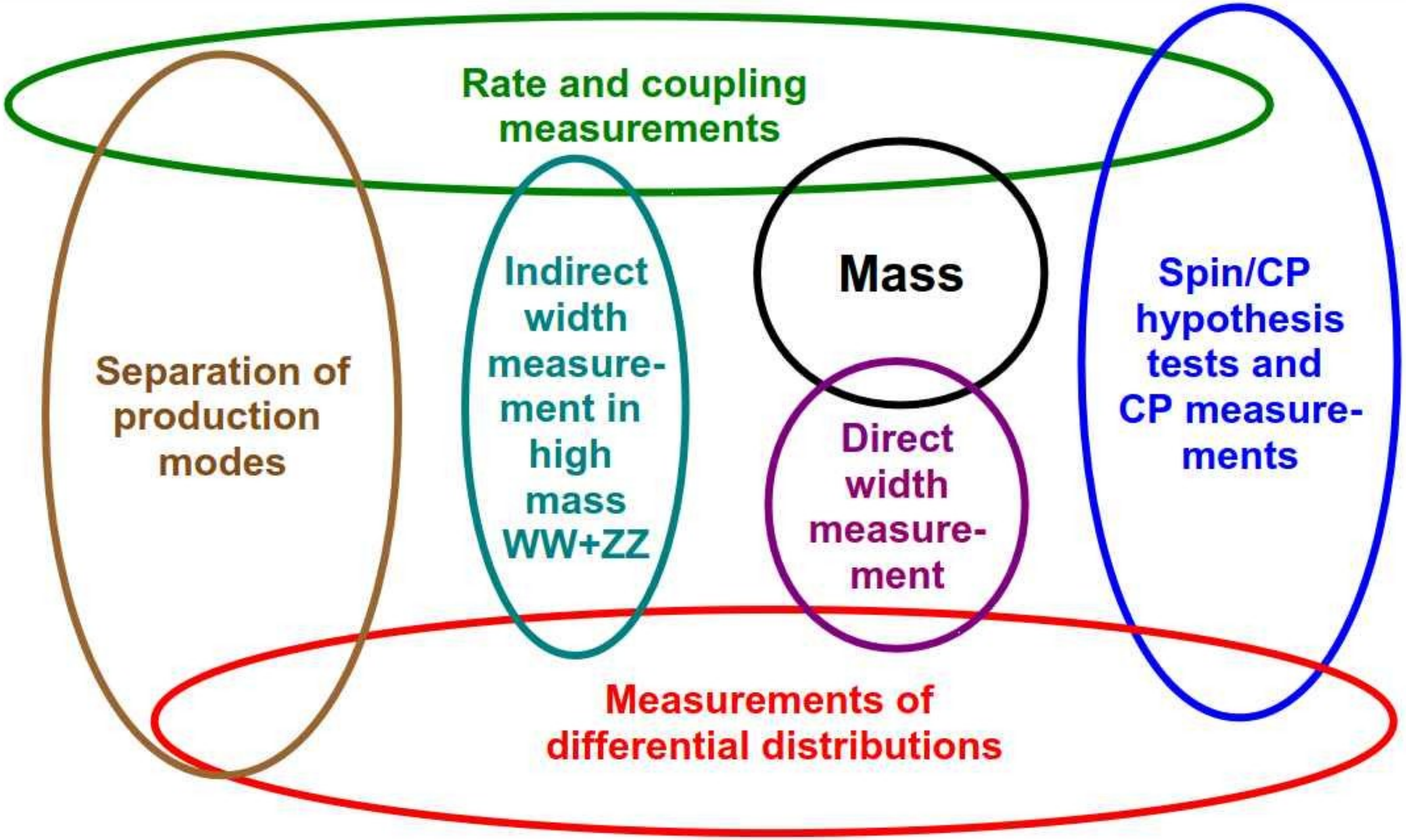




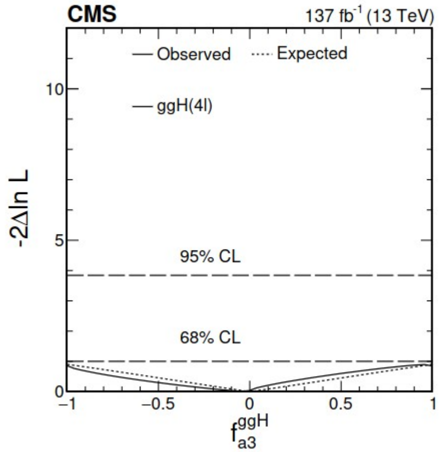
CP-related observables:

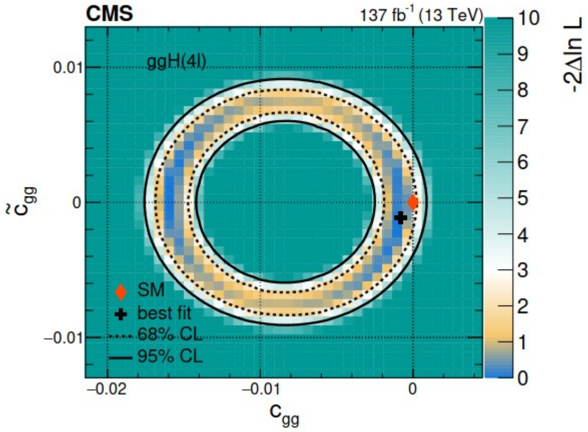
- D_{0-} : CP-even versus CP-odd probability ratio
- D_{CP}: includes interference between CP-even and CP-odd models

Higgs measurements from the experimental point of view



Anomalous couplings in H→4l





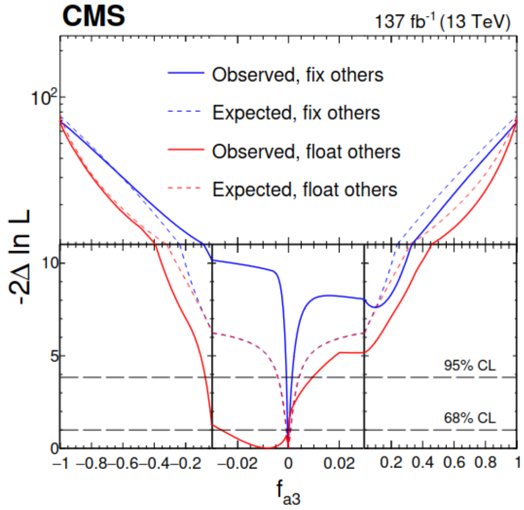
HIG-19-009

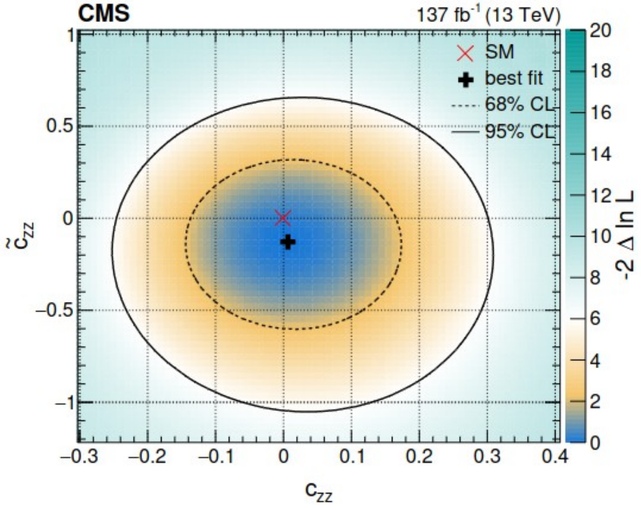
Hgg couplings

- Good agreement with SM
- No resolution of top loop in this measurement (κ_t absorbed in c_{gg})

HVV couplings

- Different scenarios (assumptions) on anomalous coupling (relations)
- Good agreement with SM

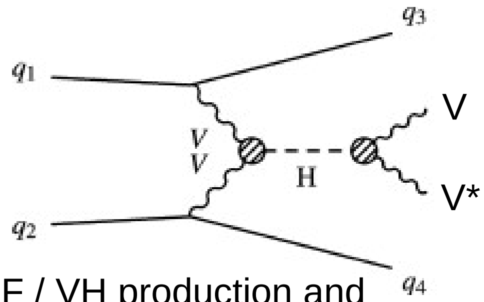




Approach 1: $f_{a2} = f_{\Lambda 1} = f_{\Lambda 1}^{Z\gamma} = 0$

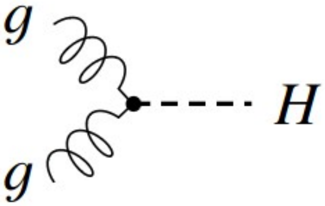
CP in Higgs couplings

H-VV coupling



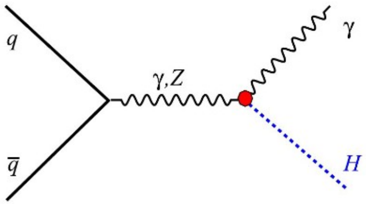
- Probed in VBF / VH production and $H \rightarrow ZZ^*$ / $H \rightarrow WW^*$ decays
- Assumptions on ZZ vs WW (vs Zγ) contributions

Eff. H-gluon coupling



- CP structure of effective H-gluon coupling from ggF
- No resolution of top loop – allow BSM contributions in loop

H-Zγ, H-photon couplings



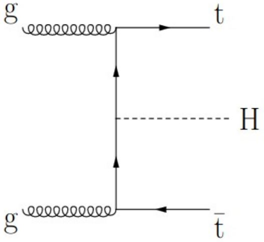
- No sensitivity from decay (no angular information)
- Small sensitivity from production

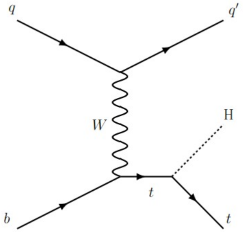
Not covered in this talk, see here for more information on ongoing analyses

Top Yukawa coupling

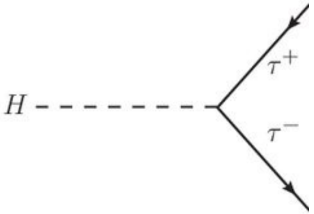
- Direct probe of H-top coupling from ttH / tH production
- Relative sign from tH
- Indirect constraint from ggF assuming top loop domination

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \, \mathrm{sign}(\tilde{\kappa}_t / \kappa_t)$$





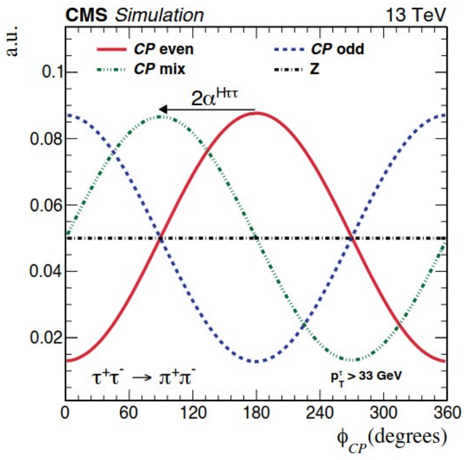
τ Yukawa coupling



- Direct measurement from $H \rightarrow \tau\tau$ decay using relative angular information of τ decay planes

CP in H → ττ decay (1)

HIG-20-006

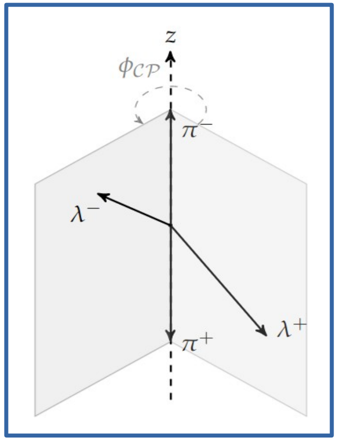


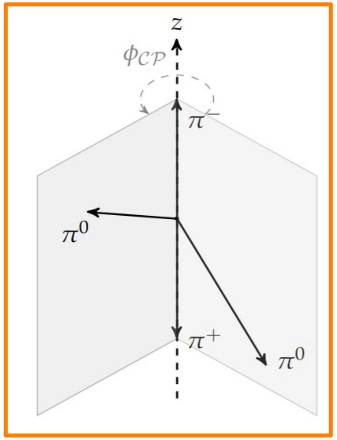
Direct probe of CP structure of H to fermion coupling from H → ττ decay

- Measuring effective mixing angle: $\tan(\alpha^{H\tau\tau}) = \frac{\widetilde{\kappa}_\tau}{\kappa_\tau}$
- Angle between τ decay planes directly related to CP mixing angle

$$\frac{d\Gamma}{d\phi_{CP}}(H \rightarrow \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$

Decay mode dependent Φ_{CP} definition → maximise experimental sensitivity





Impact parameter method
- 1pr τ decays: $\tau \rightarrow \mu^\pm\nu\nu$, $\tau \rightarrow e^\pm\nu\nu$, $\tau \rightarrow \pi^\pm\nu\nu$
- plane from τ impact parameter vector and charged particle

Neutral pion method
- τ to intermediate resonances: $\rho^\pm \rightarrow \pi^\pm\pi^0$, $a_1 \rightarrow \pi^\pm\pi^0\pi^0$, ...
- plane from charged particle and sum of neutral decay products

Polarimetric vector
- all decay modes – sensitive to τ spin
- requires good reco of τ momentum (so far, used in decay via a_1^{3pr})

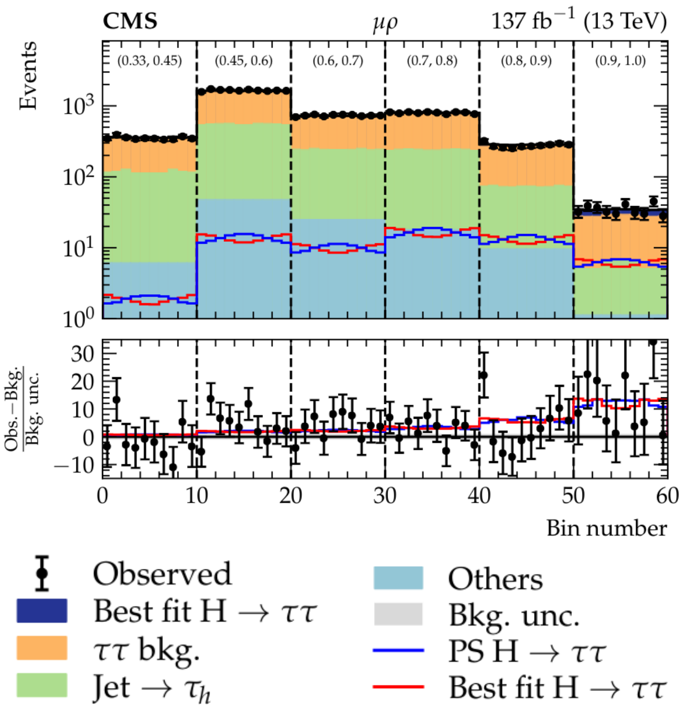
Combination possible

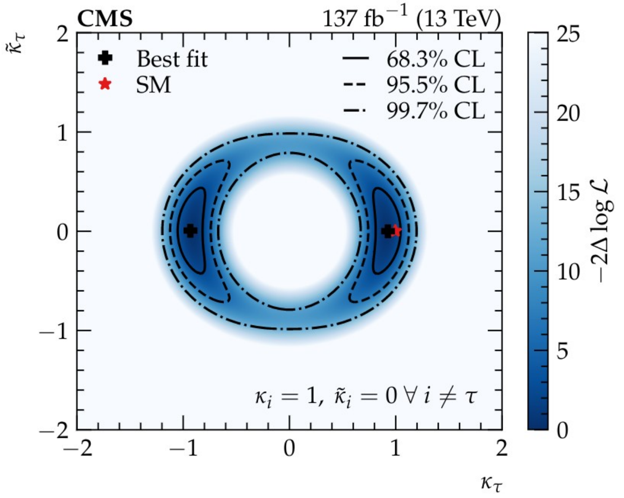
→ Details in this review article

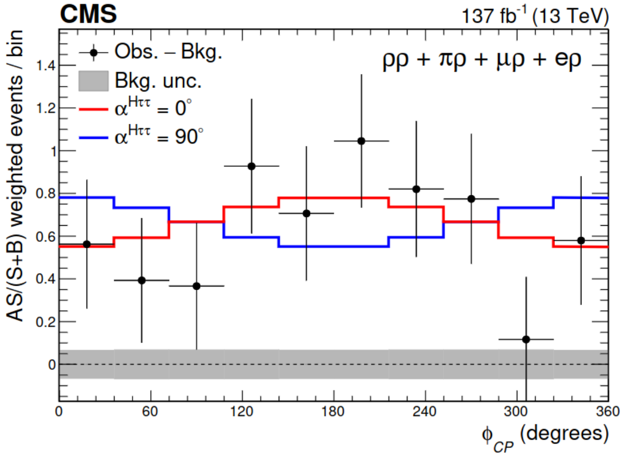
CP in H → ττ decay (2)

HIG-20-006

- MVA analysis in every channel to discriminate between signal (Higgs) from backgrounds (genuine τ's or fakes)
- Combined likelihood fit in all channels of Φ_{CP} in several MVA bins

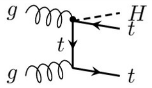
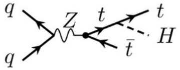
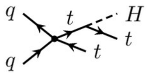
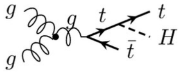


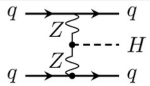
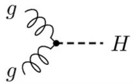
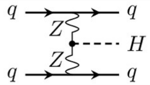
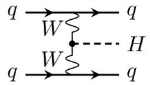
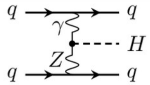
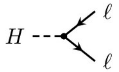
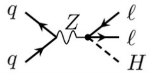
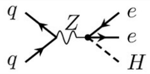
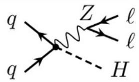
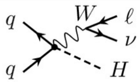
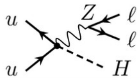
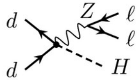




- Pure CP-odd coupling disfavoured at 3σ
- $\alpha^{H\tau\tau} = -1 \pm 19\,(\text{stat}) \pm 1\,(\text{syst}) \pm 2\,(\text{bin-by-bin}) \pm 1\,(\text{theo})^{\circ}$

Impact of Warsaw basis SMEFT operators in Higgs physics

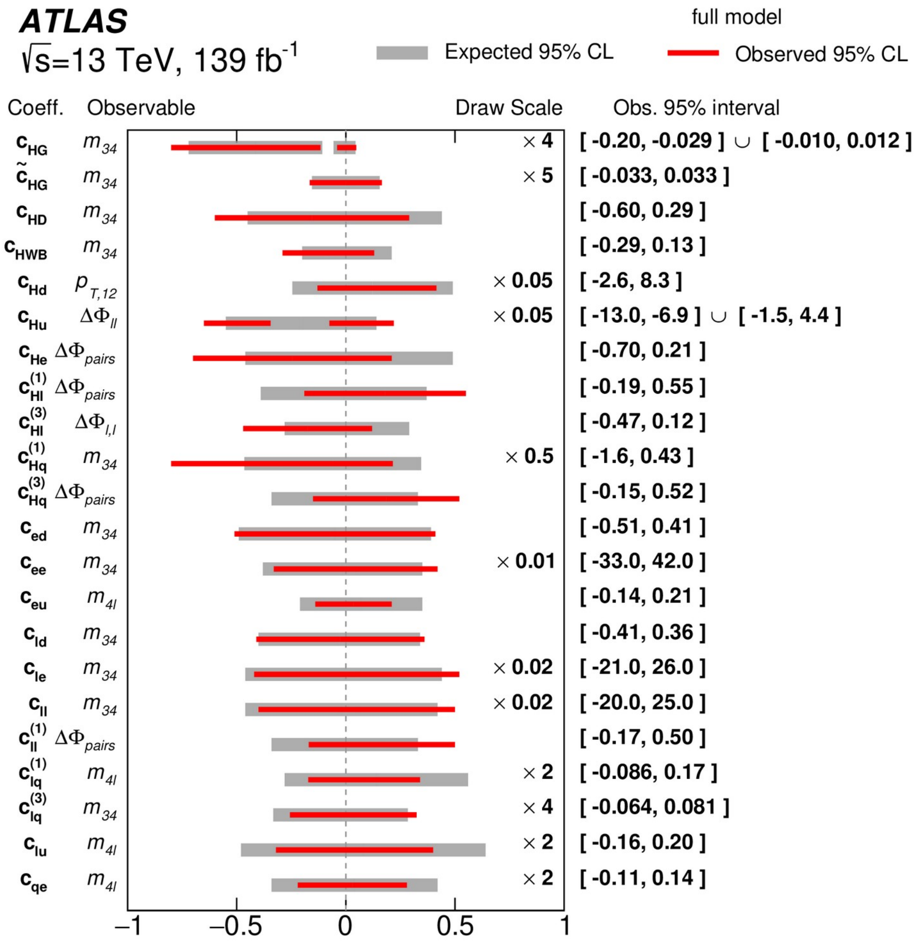
Coefficient	Operator	Example process
c_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	
c_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$	
c_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$	
$c^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$	
$c^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	
c_{qq}	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$	
$c^{(31)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_t)(\bar{q}_r \gamma^\mu \tau^I q_s)$	
c_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	
$c^{(1)}_{uu}$	$(\bar{u}_p \gamma_\mu u_t)(\bar{u}_r \gamma^\mu u_s)$	
$c^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{u}_r \gamma^\mu u_s)$	
$c^{(8)}_{ud}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	
$c^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$	
$c^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$	
c_G	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	

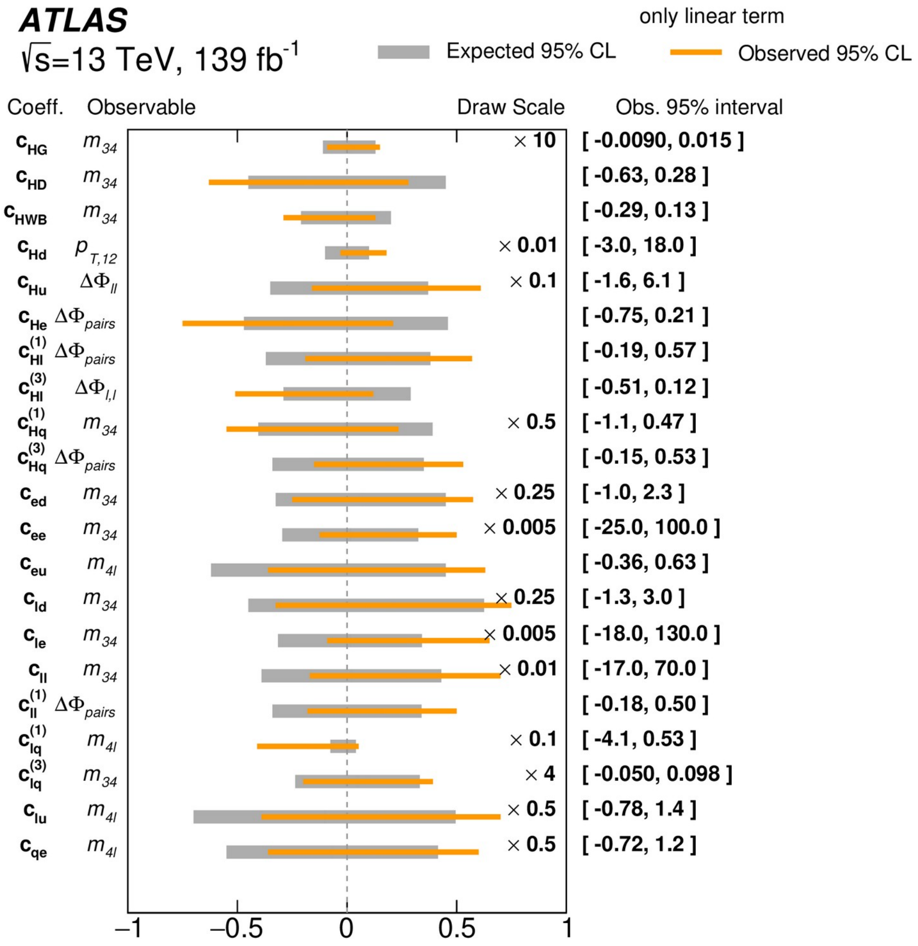
Coefficient	Operator	Example process
c_{HDD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	

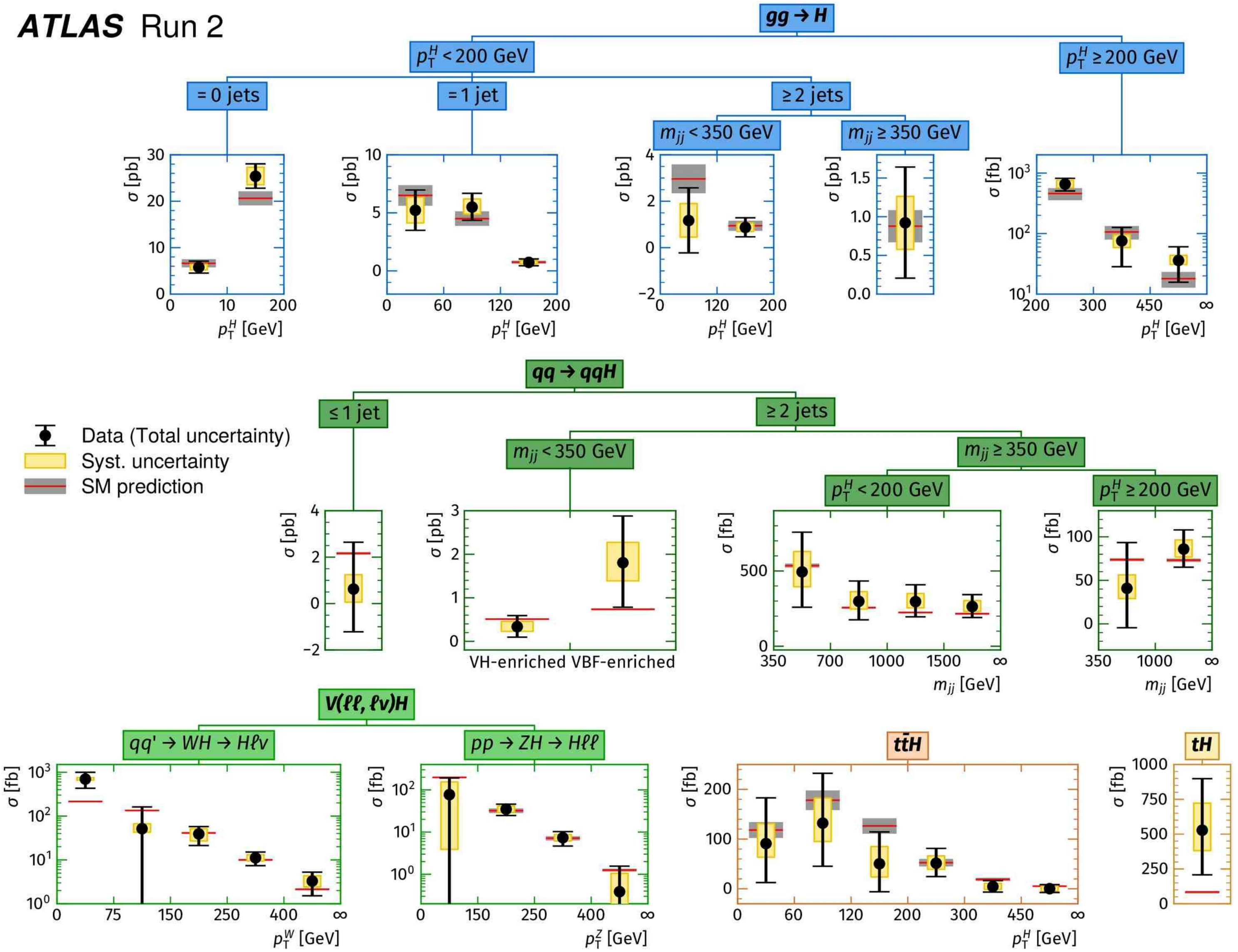
Lepton interactions

JHEP 07 (2021) 005

Example: 4 lepton production





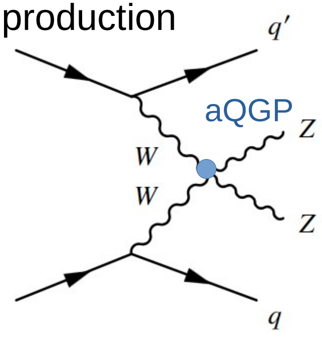

ATLAS Run 2
gg → H
p_T^H < 200 GeV
p_T^H ≥ 200 GeV
= 0 jets
= 1 jet
≥ 2 jets
m_{jj} < 350 GeV
m_{jj} ≥ 350 GeV
σ [pb]
σ [fb]
p_T^H [GeV]
qq → qqH
≤ 1 jet
≥ 2 jets
m_{jj} < 350 GeV
m_{jj} ≥ 350 GeV
p_T^H < 200 GeV
p_T^H ≥ 200 GeV
Data (Total uncertainty)
Syst. uncertainty
SM prediction
VH-enriched VBF-enriched
m_{jj} [GeV]
V(ℓℓ, ℓν)H
qq' → WH → Hℓν
pp → ZH → Hℓℓ
ttH
tH
p_T^W [GeV]
p_T^Z [GeV]

aQGC from vector boson scattering

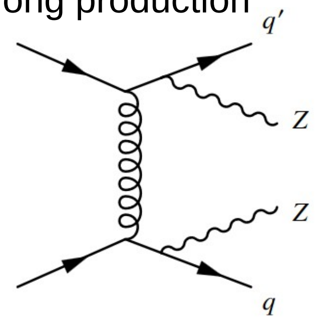
ATLAS-CONF-2023-024

Example: ZZ + 2 jet production (ZZ → 4 leptons)

EW production



Strong production



Dim-8 EFT interpretation

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{f_{T,i}}{\Lambda^4} O_{T,i}$$

Introduce anomalous quartic weak boson self-interactions

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\,\mathrm{Re}(\mathcal{M}_{SM}^* \mathcal{M}_{d8}) + |\mathcal{M}_{d8}|^2$$

Wilson coefficient	$\lvert\mathcal{M}_{d8}\rvert^2$ Included	95% confidence interval [TeV^{-4}] Expected	Observed
$f_{T,0}/\Lambda^4$	yes	[-0.98,0.93]	[-1.0,0.97]
	no	[-23, 17]	[-19, 19]
$f_{T,1}/\Lambda^4$	yes	[-1.2, 1.2]	[-1.3, 1.3]
	no	[-160, 120]	[-140, 140]
$f_{T,2}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-74, 56]	[-63, 62]
$f_{T,5}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-79, 60]	[-68, 67]
$f_{T,6}/\Lambda^4$	yes	[-3.9, 3.9]	[-4.1, 4.1]
	no	[-64, 48]	[-55, 54]
$f_{T,7}/\Lambda^4$	yes	[-8.5, 8.1]	[-8.8, 8.4]
	no	[-260, 200]	[-220, 220]
$f_{T,8}/\Lambda^4$	yes	[-2.1, 2.1]	[-2.2, 2.2]
	no	[-4.6, 3.1]$\times10^4$	[-3.9, 3.8]$\times10^4$
$f_{T,9}/\Lambda^4$	yes	[-4.5, 4.5]	[-4.7, 4.7]
	no	[-7.5, 5.5]$\times10^4$	[-6.4, 6.3]$\times10^4$

Major contribution from pure BSM terms

NOTE:

Dim-6 EFT interpretation

- All operators compatible with 0
- Good constraints from other analyses
- Neglected in dim-8 interpretation

Wilson coefficient	$\lvert\mathcal{M}_{d6}\rvert^2$ Included	95% confidence interval [TeV^{-2}] Expected	Observed
c_W/Λ^2	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-32, 32]	[-37, 28]
$c_{\widetilde{W}}/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-17, 17]*	[0, 30]*
c_{HWB}/Λ^2	yes	[-16, 7]	[-16, 6]
	no	[-12, 12]	[-15, 10]
$c_{H\widetilde{W}B}/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-67, 67]*	[-25, 130]*
c_{HB}/Λ^2	yes	[-13, 13]	[-12, 12]
	no	[-38, 38]	[-38, 38]
$c_{H\widetilde{B}}/\Lambda^2$	yes	[-13, 13]	[-12, 12]
	no	[-420, 420]*	[-200, 790]*