Differential fiducial measurements: next steps and combination

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The 18th Workshop of the LHC Higgs Working Group

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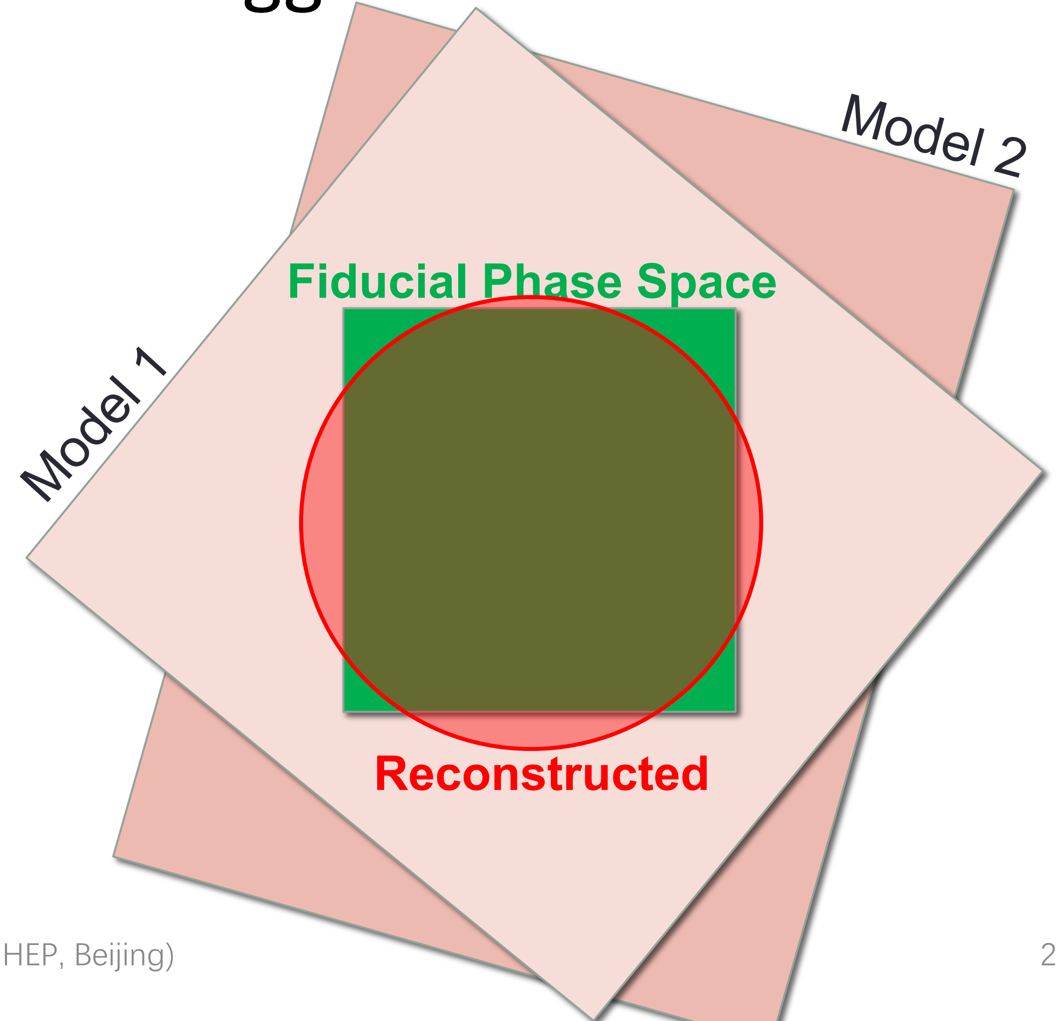
Introduction

Differential fiducial cross section measurements – A complementary framework to probe Higgs kinematics

- Target fiducial region closely matching experimental selection
- Unfolded to particle-level quantities
- Largely model-independent measurements
- Long measurement lifetime and easy comparison with different theories



Status on the experimental results

Details in Ed Scott's talk at Higgs2021 and J. Langford's talk in WG1 session

Differential results based on Full Run-2 data

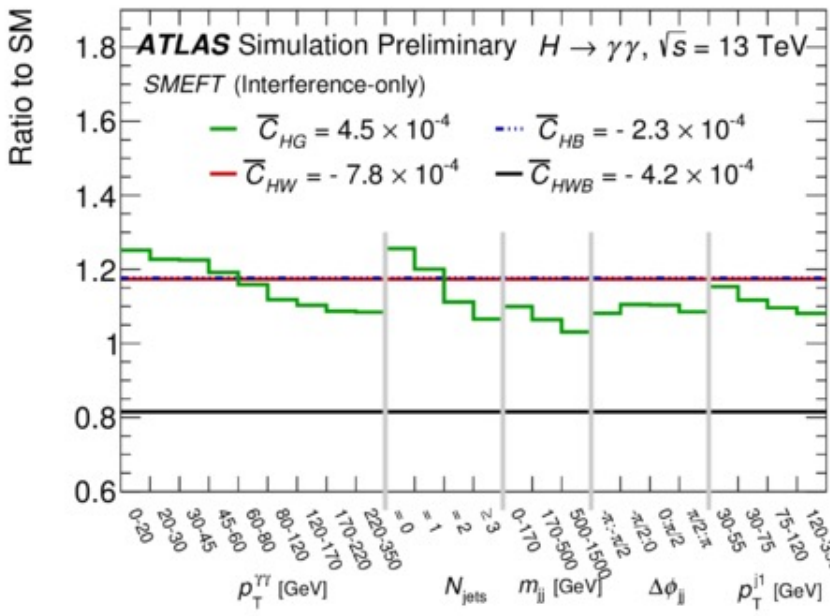
	H->ZZ*->4l	H->γγ	H->WW	H->ττ	H->bb
ATLAS	✅	☑			✅
CMS	✅		✅	✅	✅

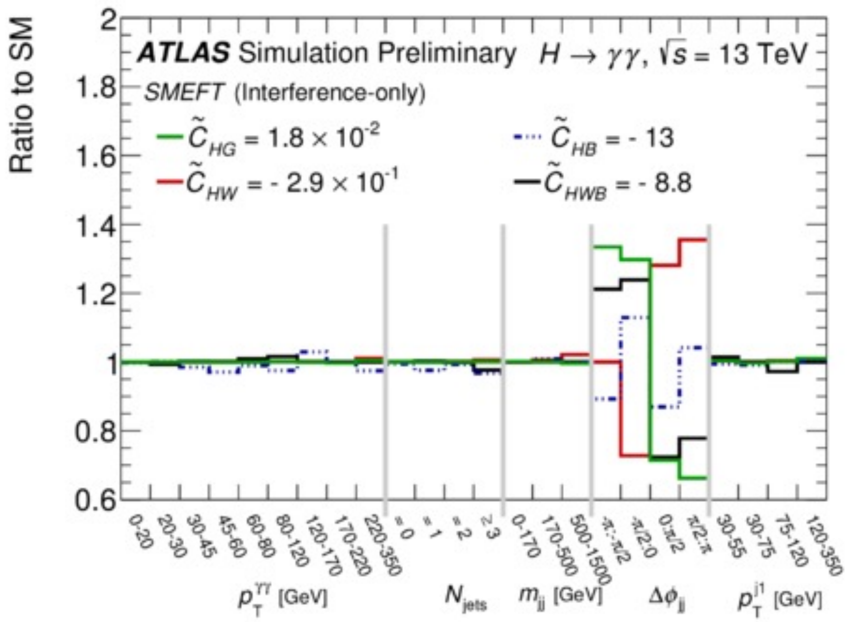
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

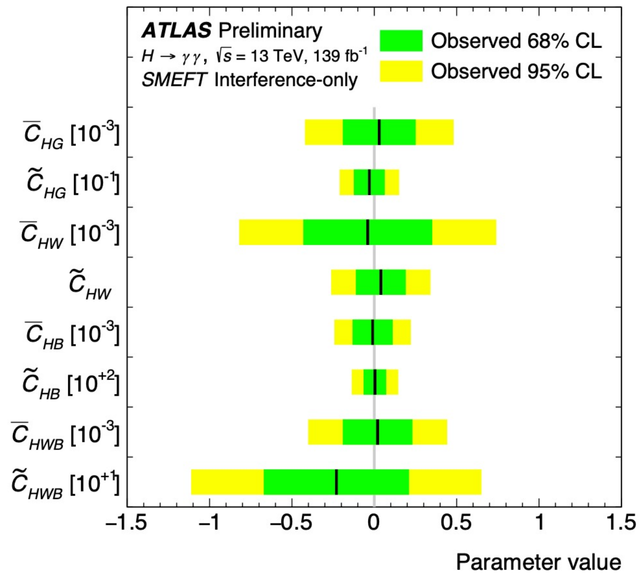
- Excellent array of results, also interpretations in EFT, κ-framework, pseudo-observables
- Still ongoing efforts in experiments to provide more measurements

Interpretations: constraints on EFT operators

- **What observables to be used**
  - Different sensitivities on different operators from different observables
- Lots of discussion on common aspects is ongoing in LHC EFT WG
- SMEFT(sim|@NLO) as a starting point





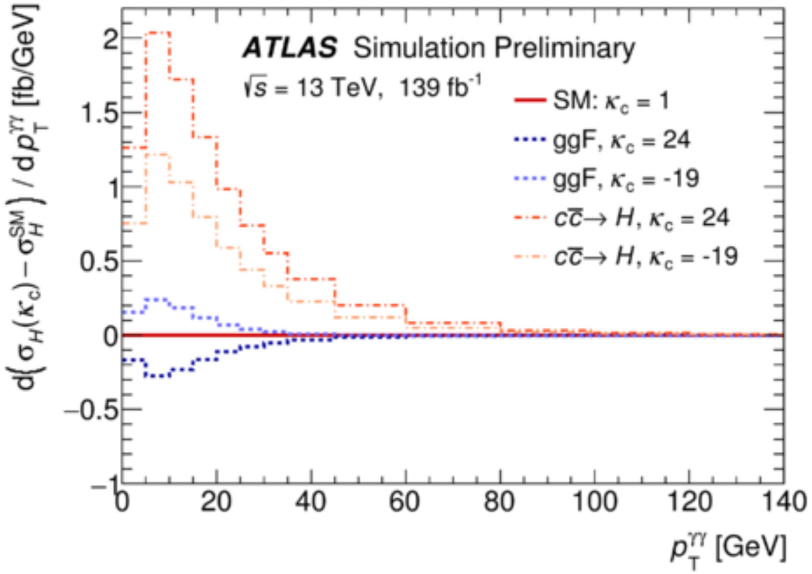


ATLAS-CONF-2019-029

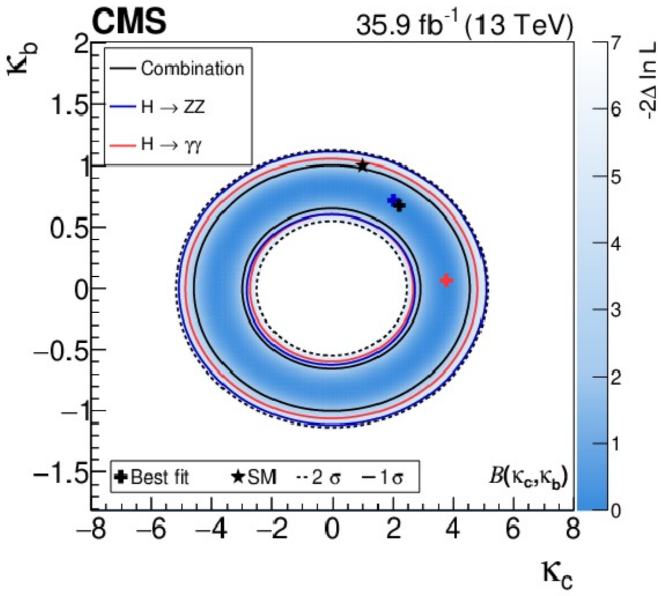
Interpretations: constraints on $\kappa_c\kappa_b$ in κ-framework

- pT spectrum sensitive to the change of lighter quark Yukawa couplings (primarily low p_T^H regions, arXiv:1606.09253)

ATLAS-CONF-2019-029



Phys. Lett. B 792 (2019) 369



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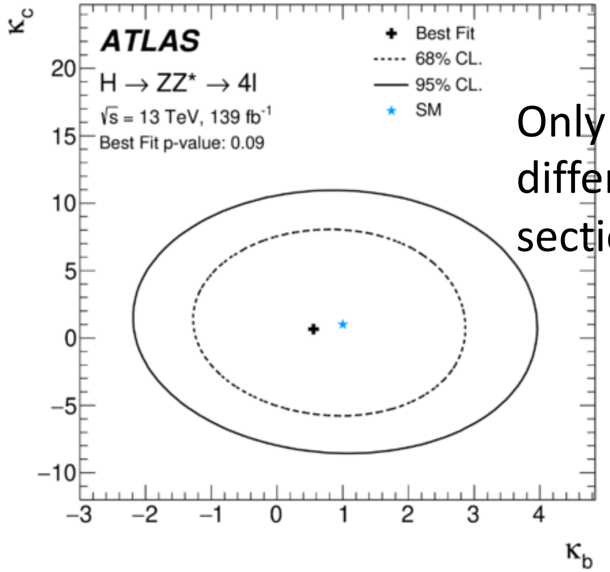
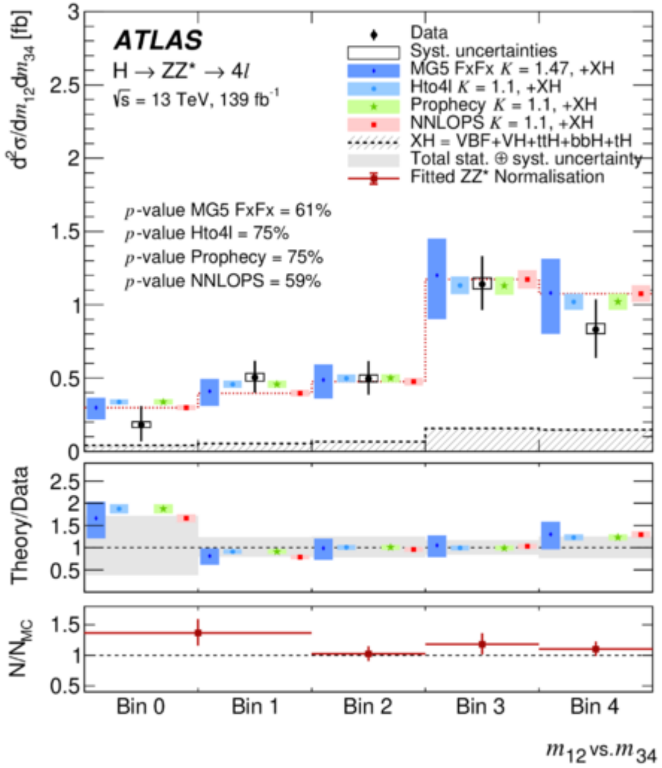


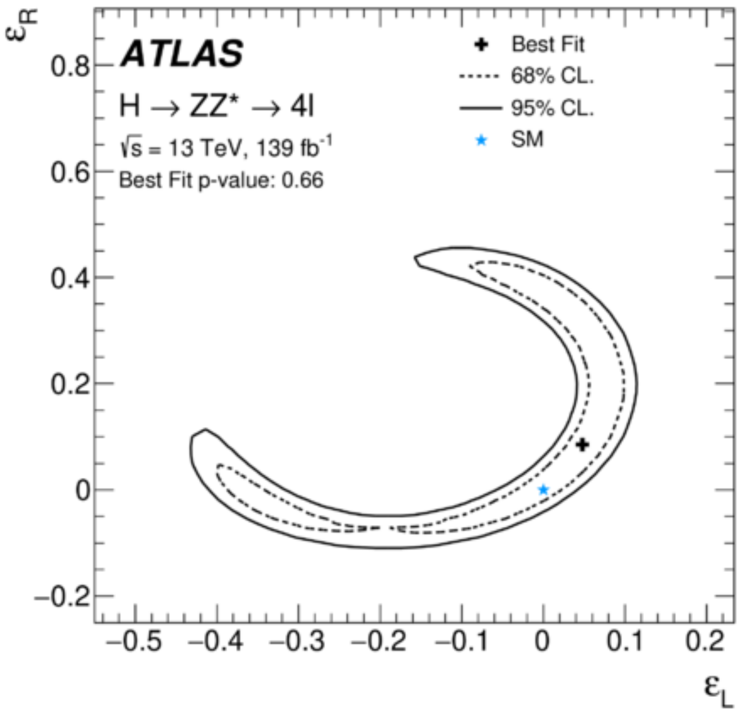
Only predicted $p_T^{4\ell}$ differential cross section is used

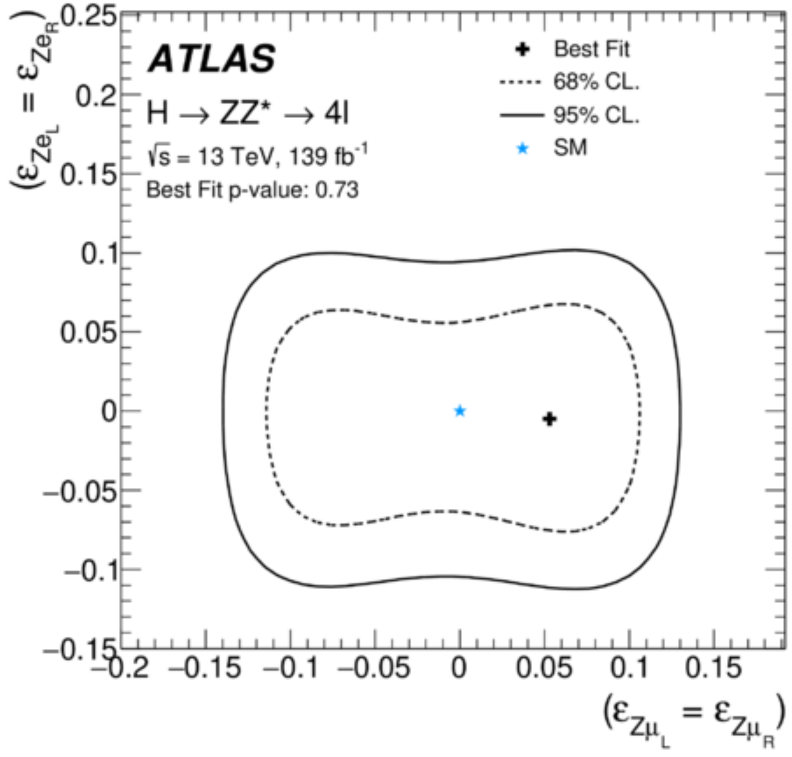
- Improved ggH computation/modeling in low/medium/high pT regions has emerged since 2017
  - We could benefit from these improvements with full run2 dataset
  - Need to discuss and converge on a common prescription (on a timescale expected for Run 2 LHC combination)

Interpretations in pseudo-observables framework

- Constraints on modified contact terms between H/Z bosons and left- and right-handed leptons ($\varepsilon_{Z,lL}$, $\varepsilon_{Z,lR}$)
  - m12 vs m34 (leading vs sub-leading Z boson mass) used







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Towards combinations

- Combination of multiple channels within one experiment is already ongoing within the single collaborations
- ATLAS+CMS combinations
  - Multiple channels: full blown combination with extrapolation to full phase space
  - Single channel: try to get to a common phase space, minimizing the extrapolation uncertainties
- There have been efforts to harmonize on several aspects towards these combinations
  - Choice and definition of variables
  - Binning for differential variables
  - Signal extraction and unfolding
  - Common regions for single-channel combination
- A twiki page has been created to summarize all the key information
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/DifferentialRun2

Choice of variables

Differential results (being) produced for many variables in golden channels

$H4\ell$	$H\gamma\gamma$
Higgs-related variables	
$p_T^{4\ell}$, $\|y_{4\ell}\|$	$p_T^{\gamma\gamma}$, $\|y^{\gamma\gamma}\|$
m_{12}, m_{34}	$p_T^{\gamma 1}/m_{\gamma\gamma}$, $p_T^{\gamma 2}/m_{\gamma\gamma}$
$\|\cos\theta *\|, \cos\theta_1, \cos\theta_2$	
ϕ, ϕ_1	
Jet-related variables	
$N_{\mathbf{jets}}$, $N_{b-\mathbf{jets}}$	$N_{\mathbf{jets}}$, $N_{b-\mathbf{jets}}$
$p_T^{\mathbf{lead.\ jet}}$ $p_T^{\mathrm{sublead.\ jet}}$	$p_T^{\mathbf{lead.\ jet}}$, τ, τ_1
m_{jj}, $\|\Delta\eta_{jj}\|$, $\Delta\phi_{jj}$	m_{jj}, $\Delta\phi_{jj}$, H_T
$p_T^{4\ell j}$, $p_T^{4\ell jj}$	$p_T^{\gamma\gamma j}$, $p_T^{4\gamma\gamma jj}$
$m_{4\ell j}$, $m_{4\ell jj}$	$m_{\gamma\gamma j}$ $\Delta\phi_{\gamma\gamma jj}$

+ Double Differential

Only a couple variables produced in other channels

To agree on which channels will be included for which variables

- Multiple-channels ATLAS+CMS combinations
  - Higgs production variables, i.e. Higgs pT and rapidity
  - Jet-related variables, e.g. Njets, pT of leading jet, etc
- Single-channel ATLAS+CMS combinations
  - + some decay side variables

Definition of the fiducial phase space

e.g. in H4l channel

ATLAS

EPJC 80 (2020) 942

Leptons and jets	
Leptons	$p_T > 5$ GeV, $\|\eta\| < 2.7$
Jets	$p_T > 30$ GeV, $\|y\| < 4.4$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34})	Remaining SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection (at most one quadruplet per event)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and 12 GeV$< m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\ell_i, \text{jet}) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	105 GeV$< m_{4\ell} <$ 160 GeV
If extra lepton with $p_T > 12$ GeV	Quadruplet with largest matrix element value

CMS

EPJC 81 (2021) 488

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Next-to-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\|\eta\| < 2.5$ (2.4)
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m_{Z_1} < 120$ GeV
Inv. mass of the Z_2 candidate	$12 < m_{Z_2} < 120$ GeV
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4$ GeV
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140$ GeV

- Different thresholds in decay object selection, whether cut on isolation, H candidate selection
  - Relevant for single-channel combinations
- Main issue is jet definition - which particles are clustered and what η restriction
  - Currently jet in CMS not including neutrinos in the clustering (similar to reco level -> less model dependence)
  - Discussed use of STXS definition: anti-kT R=0.4 jets (including neutrinos) with pT > 30 GeV and no η restriction

Which regions we unfold to

- Unfold to full phase spaces
  - Acceptance and correction factors computed from SM predictions
  - In case of EFT interpretations, need to parametrize acceptance as function of operators
- Common fiducial regions for single-channel combination
  - Differences in event selection complicate defining a common region
  - Still envelop of two experiments (extrapolated to the looser selection region) ➞ likely small change in model-dependence
  - **Need inputs from the theory side**
    - Motivations for a common fiducial region
    - Requirements from the theory side
- A common RIVET routine would be useful
  - To ensure we unfold to same thing
  - ATLAS H->$\gamma\gamma$ already use Rivet routine to obtain the fid. diff. predictions

Binning scheme

- Set of bins measured by analysis, i.e. aligned with reco. selection (full Run2 dataset)
- Finer binning (in workspaces) - make sense for the LHC combination, and also for future increase in sensitivity (e.g. Run2+Run3 combination)

e.g. Higgs pT bin boundaries in GeV

Finest binning	0	5	10	15	20	25	30	35	45	60	80	100	120	140	170	200	250	300	350	450	650	1000	inf
ATLAS H->γγ	**0**	5	10	15	20	25	30	35	45	60	80	100	120	140	170	200	250		350			**1000**	
ATLAS H->ZZ	**0**		10		20		30		45	60	80		120			200			350			**1000**	
CMS H->ZZ	**0**		10		20		30		45		80		120			200							**inf**
CMS H->WW	**0**				20				45		80		120			200							**inf**
CMS H->ττ	**0**								45		80		120			200			350	450			**inf**
CMS H->bb																		**300**		450	650		**inf**
ATLAS H->bb																		**300**		450	650	1000	**inf**

pT binning taken from latest public results

Unfolding method

- Two experiments now produce results with common unfolding method: matrix inversion
  - detector response matrix fully built in the likelihood construction

$$N_i(m_{4\ell}) = \sum_j r_{ij} \cdot (1 + f_i^{\text{nonfid}}) \cdot \sigma_j^{\text{fid}} \cdot \mathcal{P}_i(m_{4\ell}) \cdot \mathcal{L} + N_i^{\text{bkg}}(m_{4\ell})$$

background contribution

Events outside the fiducial region reconstructed in bin i

signal shape containing the fraction of events as a function of m4l expected in each reconstruction bin (taken from MC simulation)

detector response matrix

$$\frac{\text{number of events in bin i truth matched to an event in bin j}}{\text{truth events in bin j}}$$

fiducial XS

$$\sigma_j^{\text{fid}} = \sigma_j \cdot A_j \cdot \mathcal{B}$$

MC and modelling uncertainties

Need to survey the generators used in each channels by the two collaborations and discuss possible issues

- e.g. in H4l channel, for ggH
  - CMS: POWHEG(reweighted to NNLOPS, NNLO accuracy)
  - ATLAS: NNLOPS

Systematics uncertainties and model dependence:

- (theoretical) systematics that may be common across channels/experiments
- varying of production process composition within experimental uncertainties

Next steps

Interest of WG2

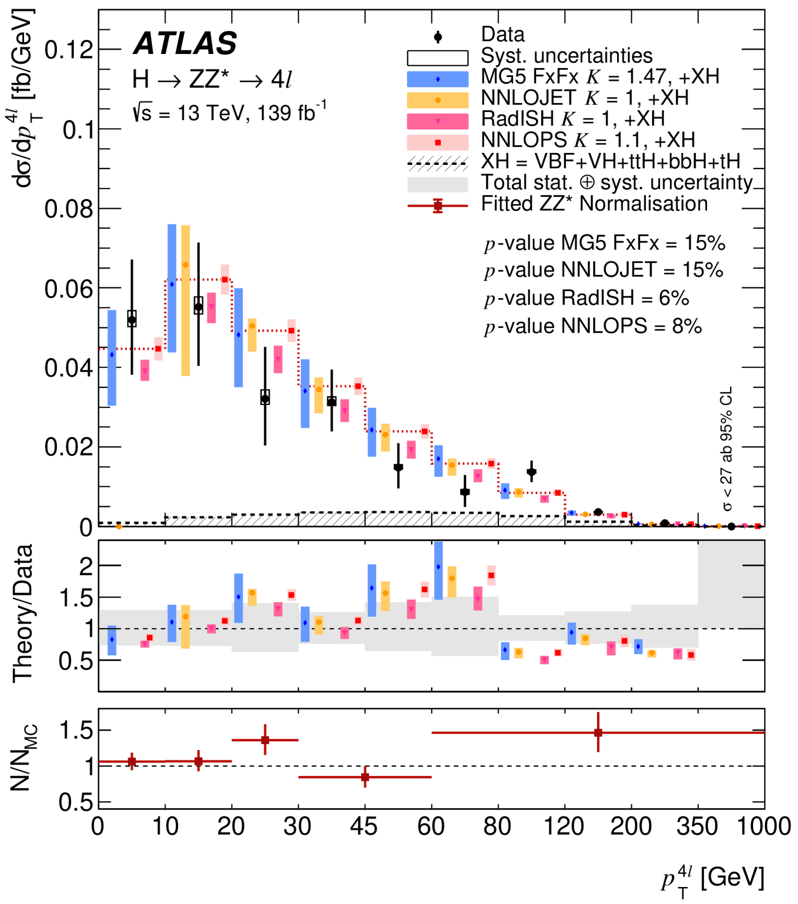
- Agree on a list of variables to be measured
  - also exact definition, bin boundaries
  - any other proposal from theory side to measure additional variables? (previous proposal)
- Agree on what interpretations to provide
  - SMEFT(sim|@NLO) as a starting point ?
    - additional work/studies to be done
  - $\kappa_b\kappa_c$: new updated predictions from theory would be preferred

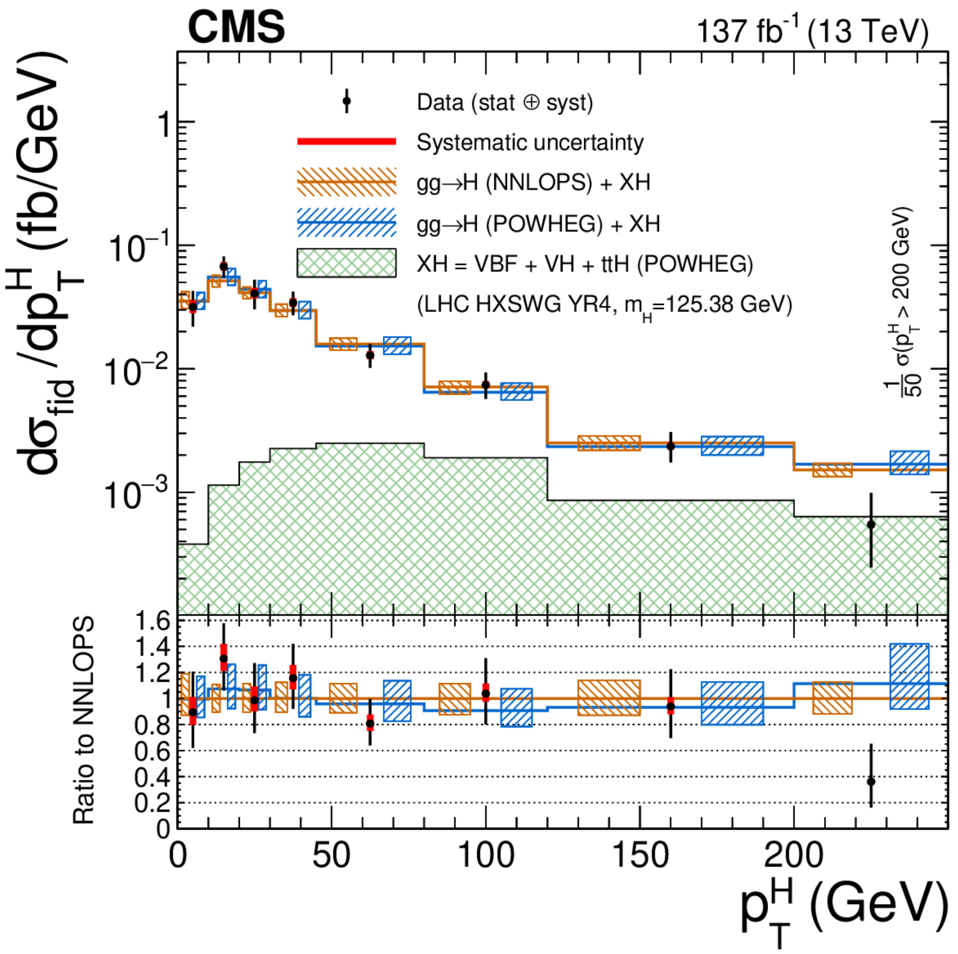
For LHC H Comb

- Exchange the workspaces of published results, start exercise
  - check POIs, conventions used in the workspaces, e.g. fractional or absolute cross sections, etc.
  - produce cross checks - how close the two experiments
  - ....

Back up

Higgs pT





EPJC 80 (2020) 942, EPJC 81 (2021) 488