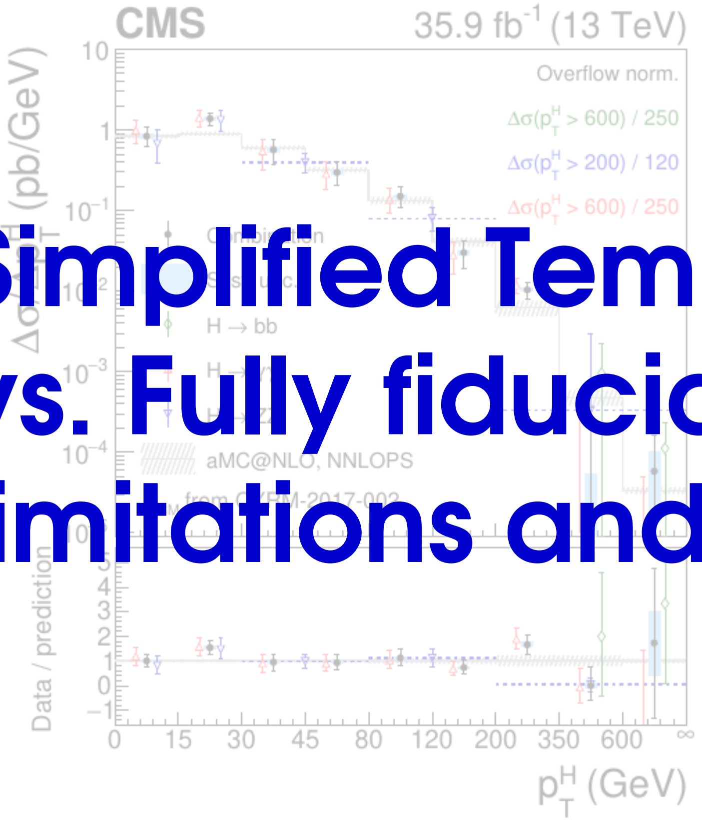
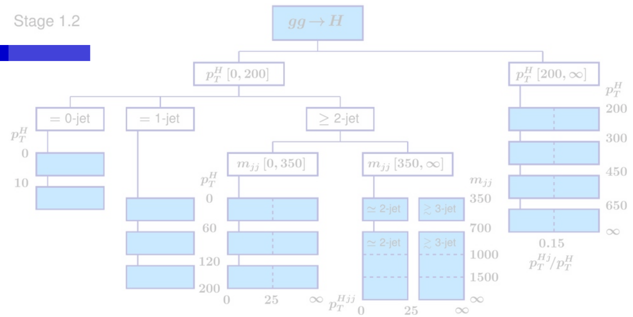
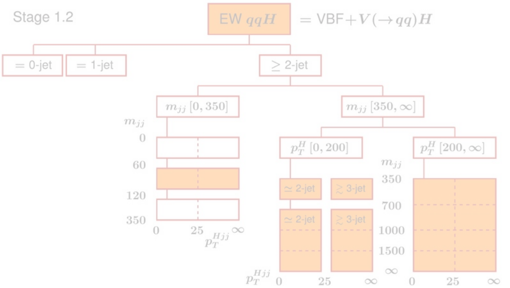
Simplified Template Cross-sections vs. Fully fiducial measurements: limitations and future improvements



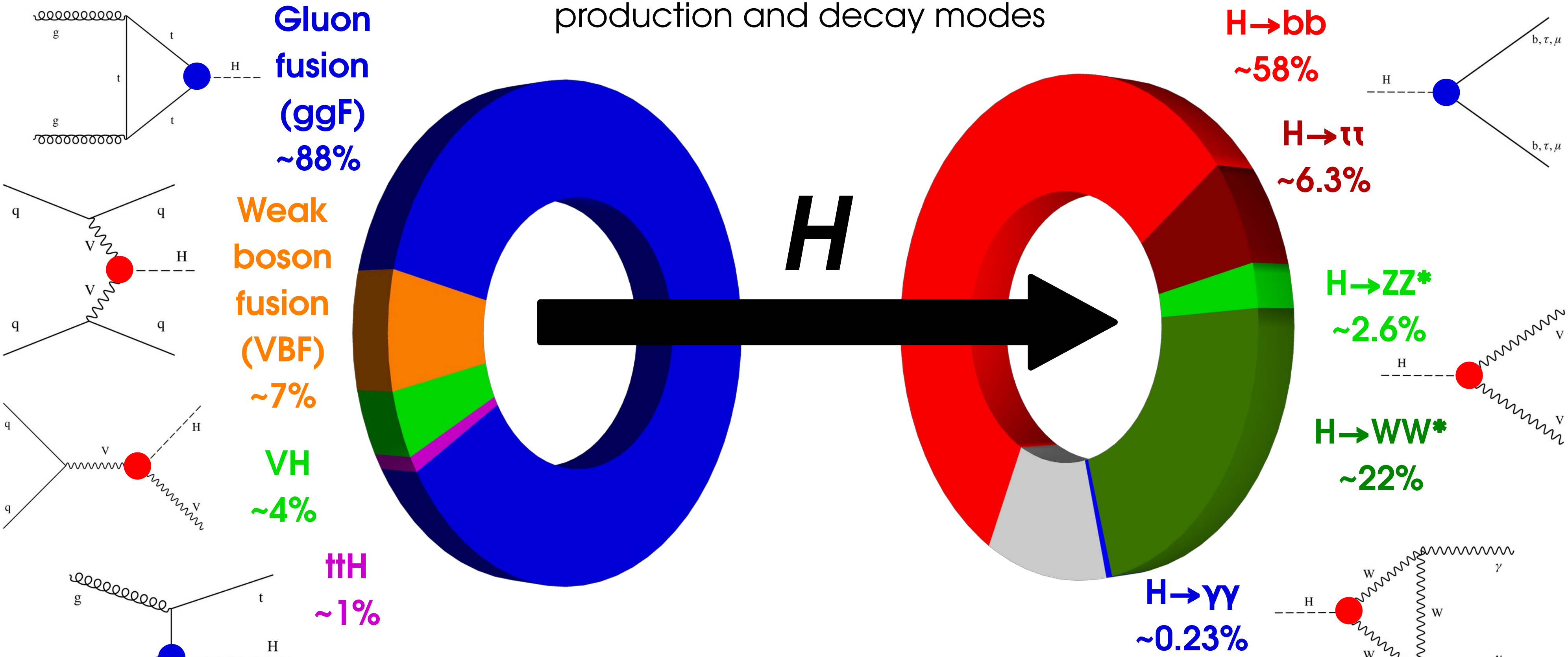




Nicolas Berger (LAPP Annecy)
on behalf of the ATLAS and CMS collaborations

Higgs boson production and decay

ATLAS/CMS: many accessible production and decay modes



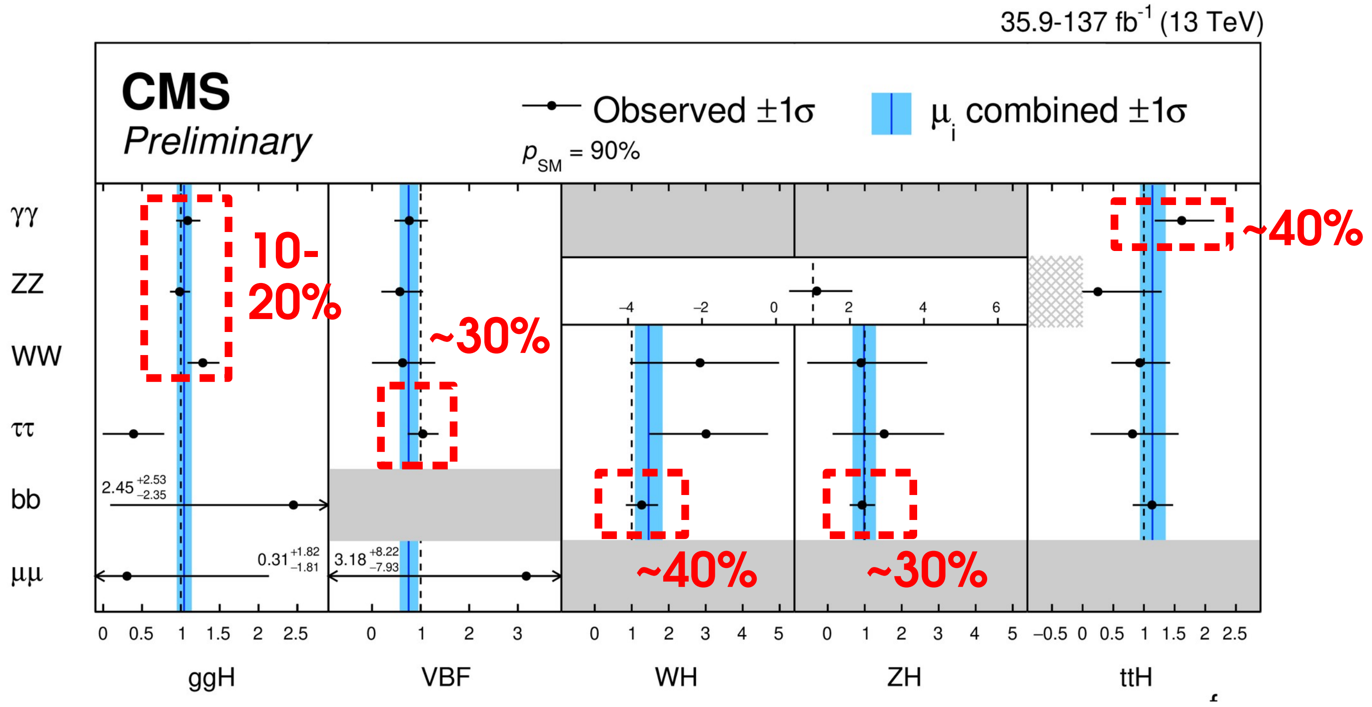
⇒ Window to Higgs properties, in particular couplings to SM particles

Inclusive Higgs boson measurements @ LHC

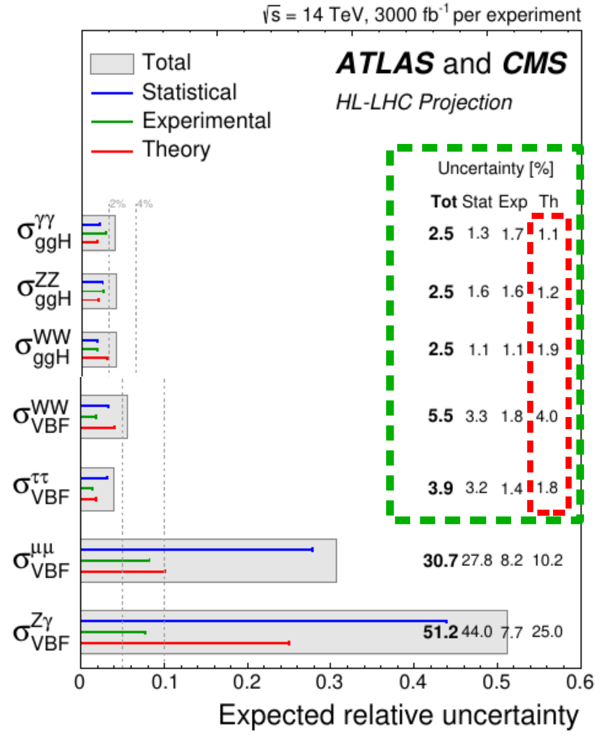
CERN-LPCC-2018-04

LHC Run 2

CMS-PAS-HIG-19-005



HL-LHC



All main production and decay modes observed in Runs 1 and 2

Precision ~10-40% (per experiment) in all processes

Systematics comparable to statistical uncertainties for some modes

Precision reaches <3%

Large theory uncertainties

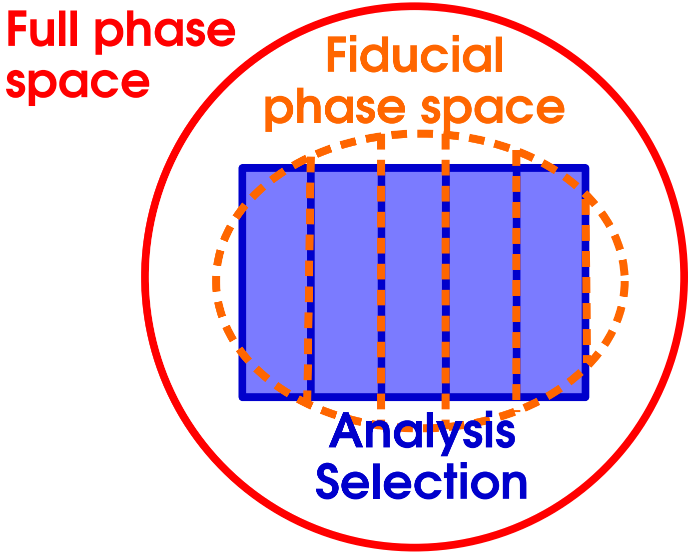
Fiducial Differential cross-section measurements

Cross-section measurement:

$$\sigma = \frac{N_{\text{reco}}}{(A \times \epsilon)\, L}$$

Phase-space acceptance

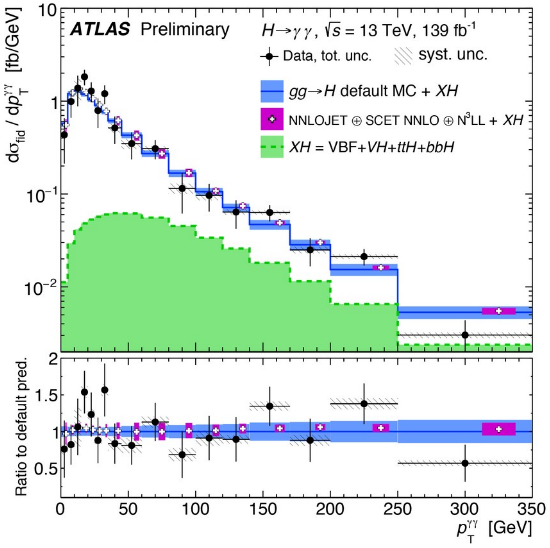
Reconstruction efficiency



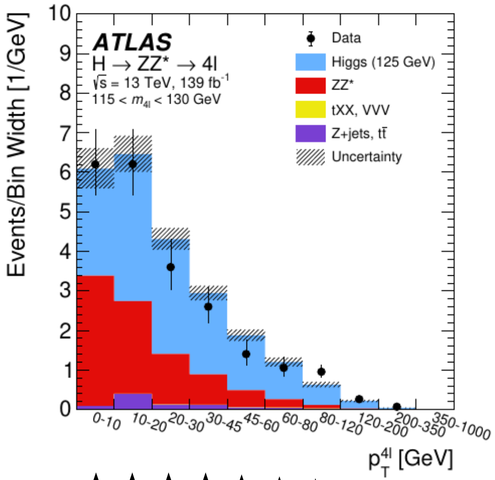
Fiducial differential cross-sections

→ **Fiducial** : target phase-space region matching experimental selection (A≈1)

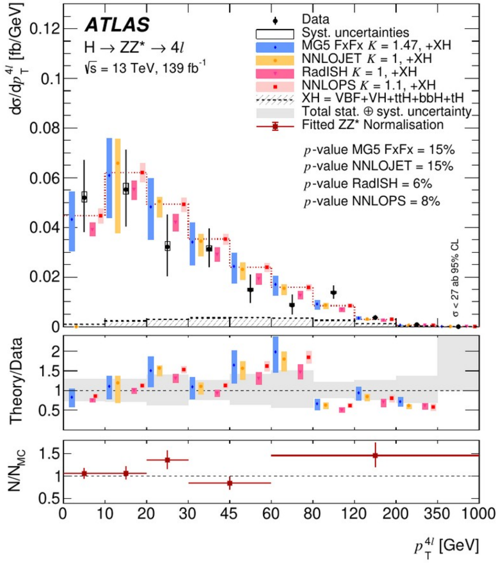
→ **Differential**: in bins of a variable (p_T^H, N_{jets}, ...), typically unfolded to particle-level quantities

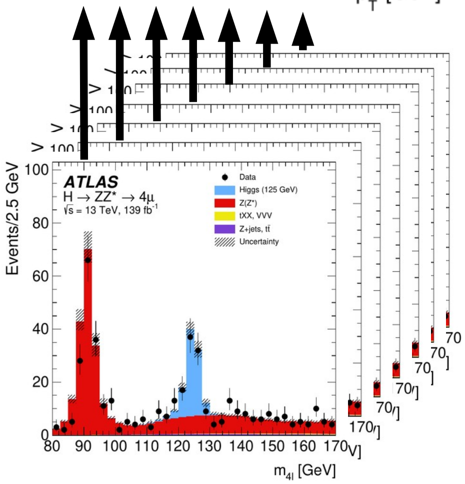


Fiducial differential measurements



Unfold





Perform analysis in each bin of the reco variable

Variables:

Production kinematics
p_T^H, y^H

Associations
N_{jets}, m_{jj}, p_T^{j1}

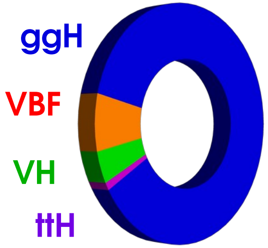
Decay kinematics
m_{12}, m_{34} ($H \rightarrow ZZ^*$)
$\cos\theta^*$ ($H \rightarrow \gamma\gamma$)

Probe:
- pQCD modeling
- Production mode composition
- BSM effects

Less sensitivity to SM model assumptions thanks to fiducial matching and kinematic binning

⇒ Lower theory uncertainties.

Production modes to Simplified Template Cross-sections

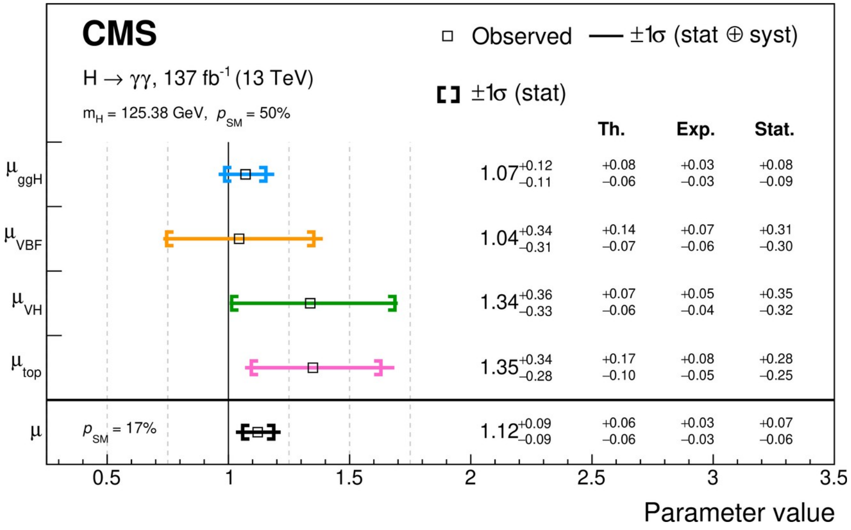


Multiple relevant Higgs production modes, sensitive to different couplings,
⇒ Important to separately measure

Per-mode total cross-section measurements

- Assume SM kinematics valid within each mode
  ⇒ model dependence
- No sensitivity to kinematics

$$\mu = \frac{\sigma_{\text{observed}}}{\sigma^{\text{SM}}_{\text{expected}}}$$



How to improve further ?

- Better match to measurement acceptance
- Measure in smaller kinematic regions within each mode

⇒ Simplified Template Cross-sections (STXS)

Number of STXS results

2017	2018	2019	2020
5	4	6	10

Simplified Template Cross-sections

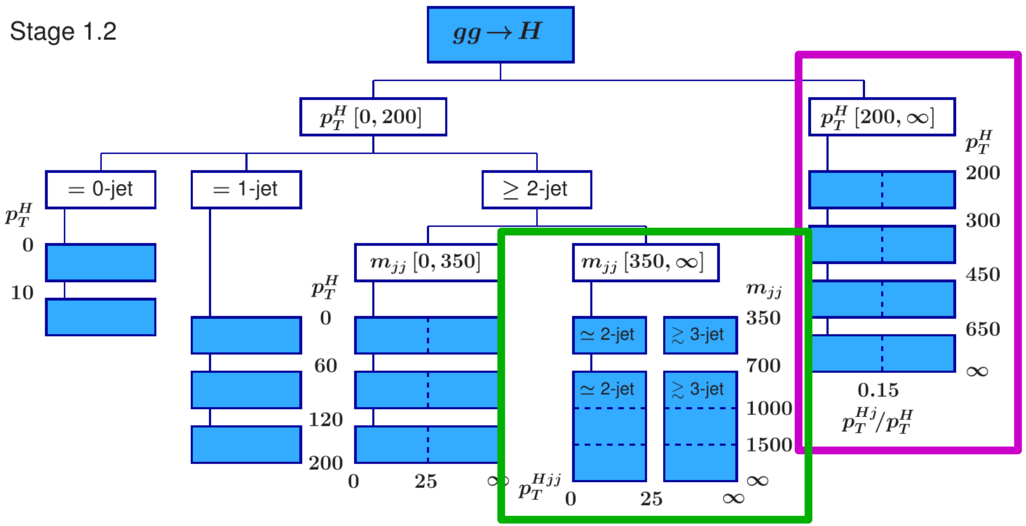
In practice, by just taking subsets of signal MC samples.

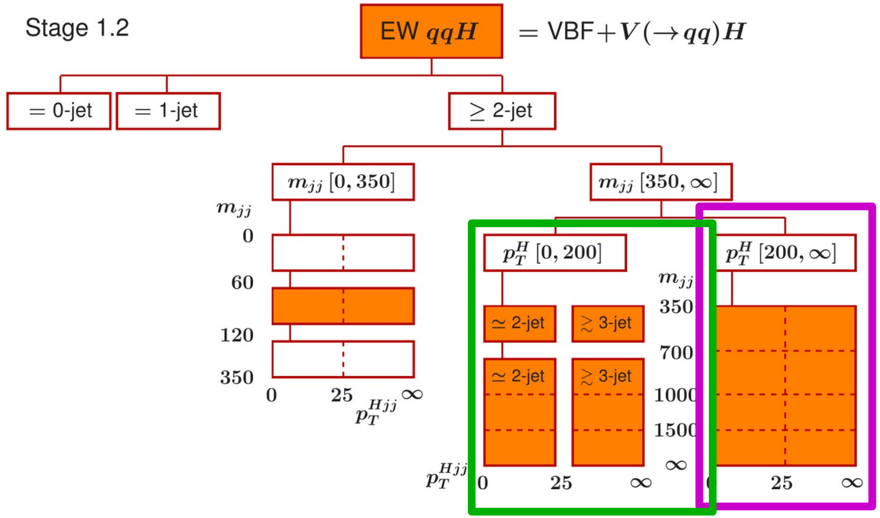
Break up each production mode into smaller **templates** within $|y_H|<2.5$ (~ ATLAS/CMS acc.)

Assume **SM behavior within each bin**

Multi-variable split to compromise between:

- → **Stronger BSM sensitivity** (high-mass, etc.)
- → **Weaker theory extrapolations** (e.g. VBF-like ggF)
- → **Match to experimental selections**





gg→ H : Bins in p_T^H, N_{jets}, m_{jj} and p_T^{Hjj}.

→ Isolate VBF-like region (hard to extrapolate)

EW qqH : Bins in p_T^H, N_{jets}, m_{jj} and p_T^{Hjj}.

→ Both VBF and (V→jj)H (same initial/final states)

Simplified Template Cross-sections

Break up each production mode into smaller **templates** within **$|y_H|<2.5$** (~ ATLAS/CMS acc.)

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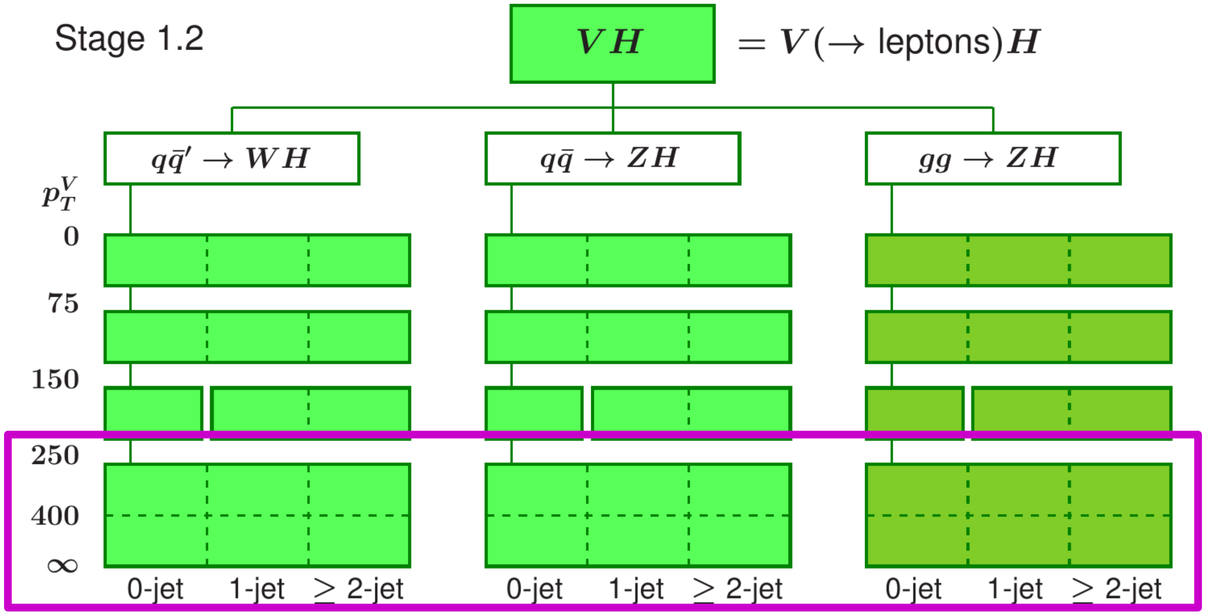
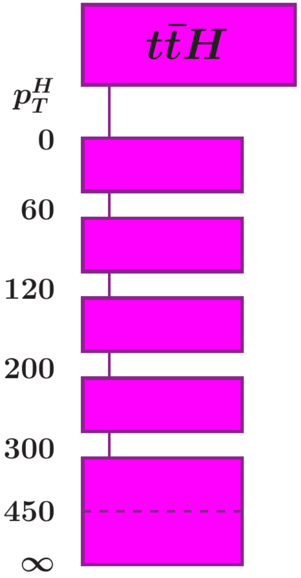


VH: Bin in process, p_T^V and N_{jets}.



ttH : bin in p_T^H

Simplified Template Cross-sections

Break up each production mode into smaller **templates** within **$|y_H|<2.5$** (~ ATLAS/CMS acc.)

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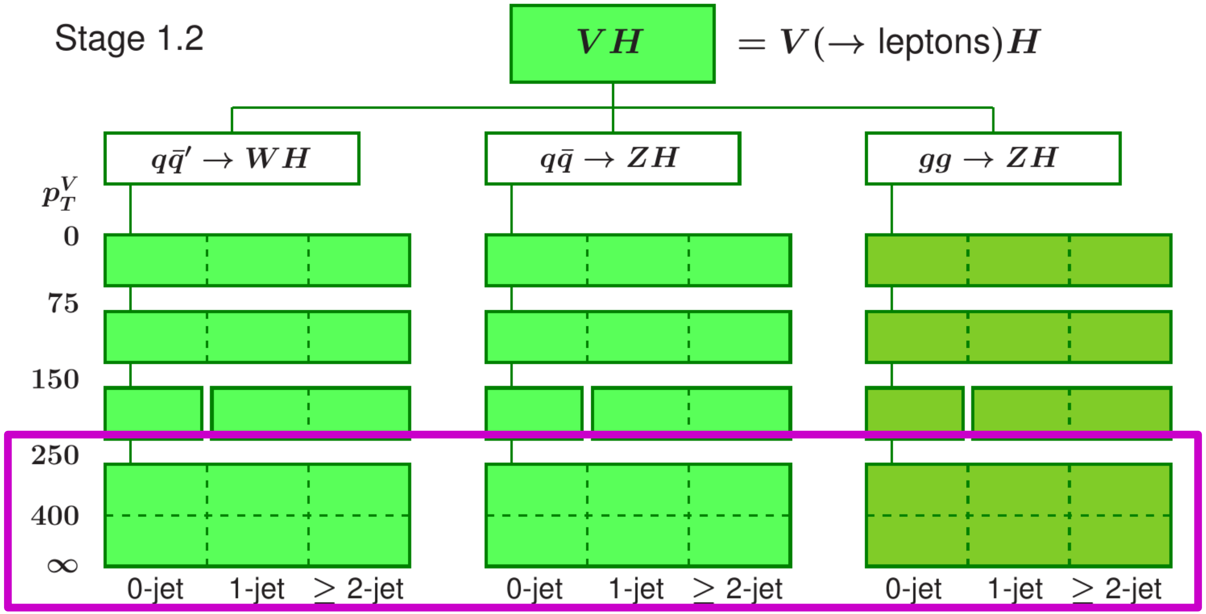

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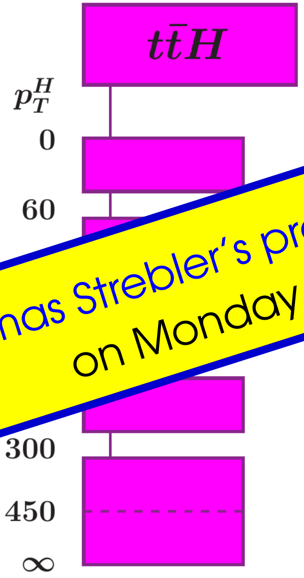


See Thomas Strebler's presentation on Monday

ttH : bin in p_T^H

Simplified Template Cross-sections

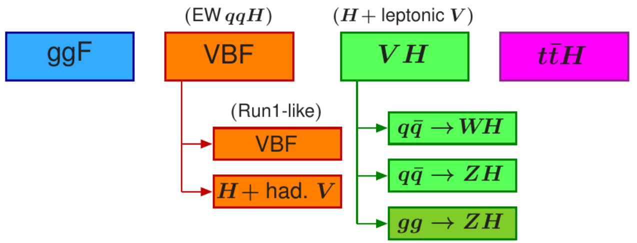
Break up each production mode into smaller **templates** within **$|y_H|<2.5$** (~ ATLAS/CMS acc.)

Assume **SM behavior within each bin**
Multi-variable split to compromise between:

- → **Stronger BSM sensitivity** (high-mass, etc.)
- → **Weaker theory extrapolations** (e.g. VBF-like ggF)
- → **Match to experimental selections**

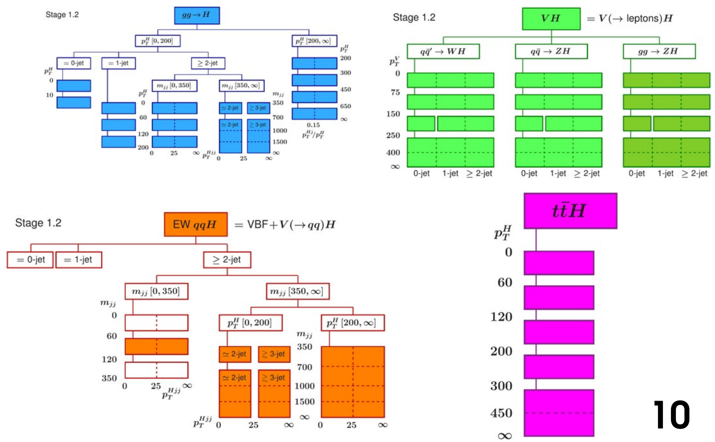
Only partially fiducial on production side
⇒ Same binning for all Higgs decay modes

Stage 0



Increase granularity with measurement precision
⇒ More detailed measurements
⇒ Reduce SM model assumptions

Stage 1.2

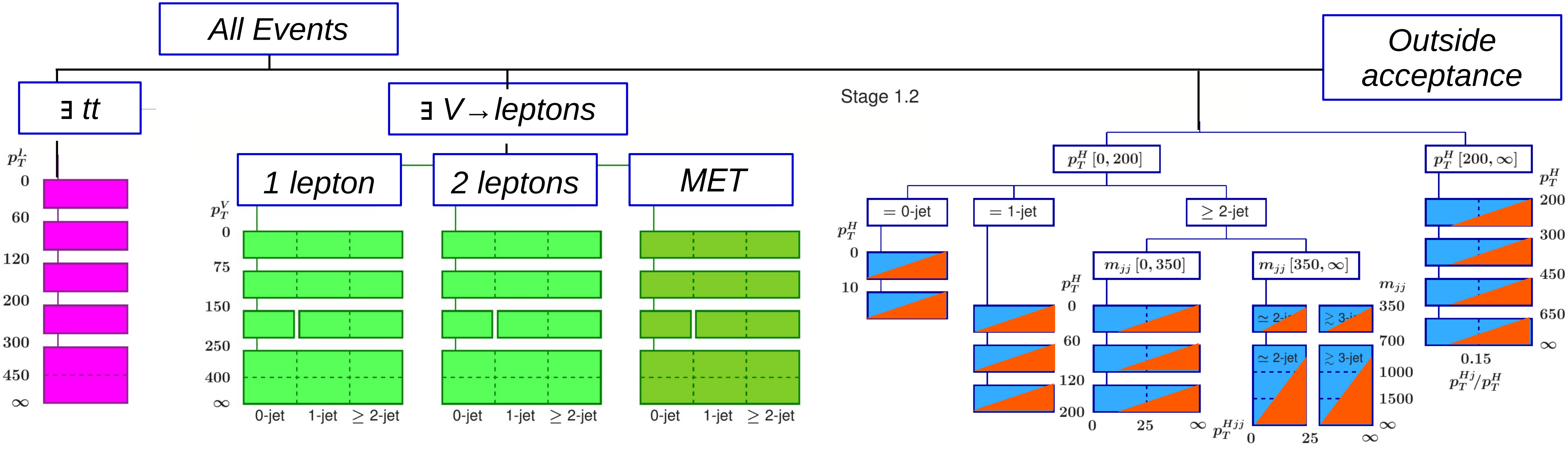


Perform measurement through implicit matrix unfolding

$$N_{SR1} = (A_{11}\ \sigma_{STXS1} + A_{12}\ \sigma_{STXS2} + \dots)\ \varepsilon_1\ L$$

$$N_{SR2} = (A_{21}\ \sigma_{STXS1} + A_{22}\ \sigma_{STXS2} + \dots)\ \varepsilon_2\ L$$

Fiducial STXS measurements ?



→ Similar to regular STXS for VH & ttH, but no ggF/VBF/VH separation

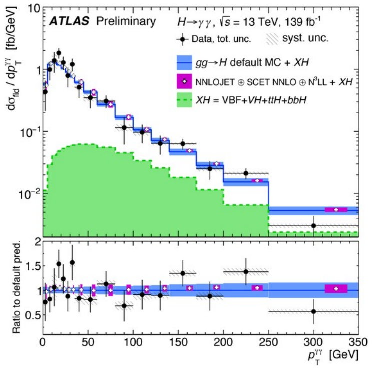
⇒ Need additional assumptions to separate production modes and measure couplings

→ Analysis selections must match truth-level binning ⇒ simple selections only

Regular STXS: assume SM within each bin ⇒ can use information in MVAs **⇒ Stronger sensitivity**

Pros and Cons

dif/fid XS



⊕ Minimizes model-dependence

→ Small extrapolations and SM assumptions (mainly through unfolding)

→ Reinterpretable in models with similar A ⇒ Long measurement lifetime

⊖ Simple experimental selection only (should match truth-level selection)

⊕ Can be performed for any measurement variable

⊖ Only 1 or 2 variables at a time **(but can have fine binning)**

o **Works best for "clean" modes** : good resolution, manageable backgrounds

⊖ Fiducial region depends on final state ⇒ cannot trivially combine different modes

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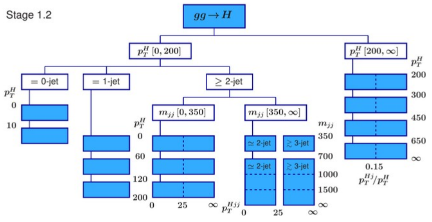
STXS



⊖ SM description within each bin ⇒ Larger model-dependence

⊕ SM description within each bin ⇒ Can use MVAs/NNs/ML.

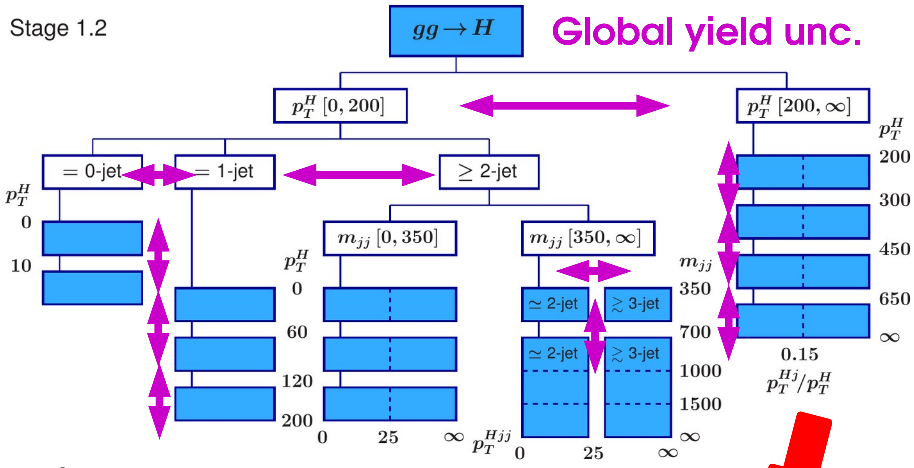
⊕ Well-suited to measure perturbations from SM (e.g. SMEFT)

⊕ Common binning includes information from multiple variables

⊖ Larger bins, only limited number of variables

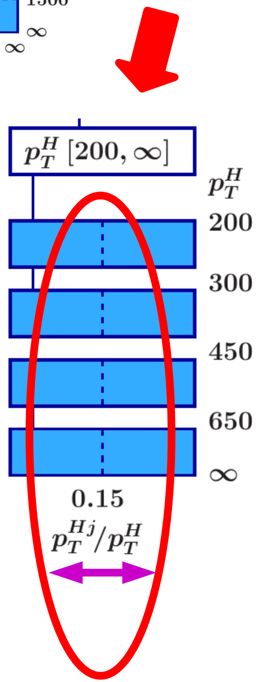
⊕ Common binning for all decay modes ⇒ simplifies combination

Theory Uncertainties



STXS: Unified treatment of theory uncertainties:

- Global "**yield**" uncertainties + "**migrations**" between bins (See Higgs YR3, YR4, BLPTW paper)
  → Implements correlations across bins and analyses
  → *Very* convenient for combinations across different analyses and experiments.
- Only between-bin uncertainties. what about within-bin ?
  - "**dotted**" boundaries covering largest effects
  - Additional ad-hoc uncertainties where needed
  - Increase binning granularity to keep uncertainties manageable!



fiducial/differential XS

- Fiducial matching of reco/truth ⇒ residual theory effects typically small
- Typically implemented within the unfolding procedure

Examples: CMS H→γγ STXS

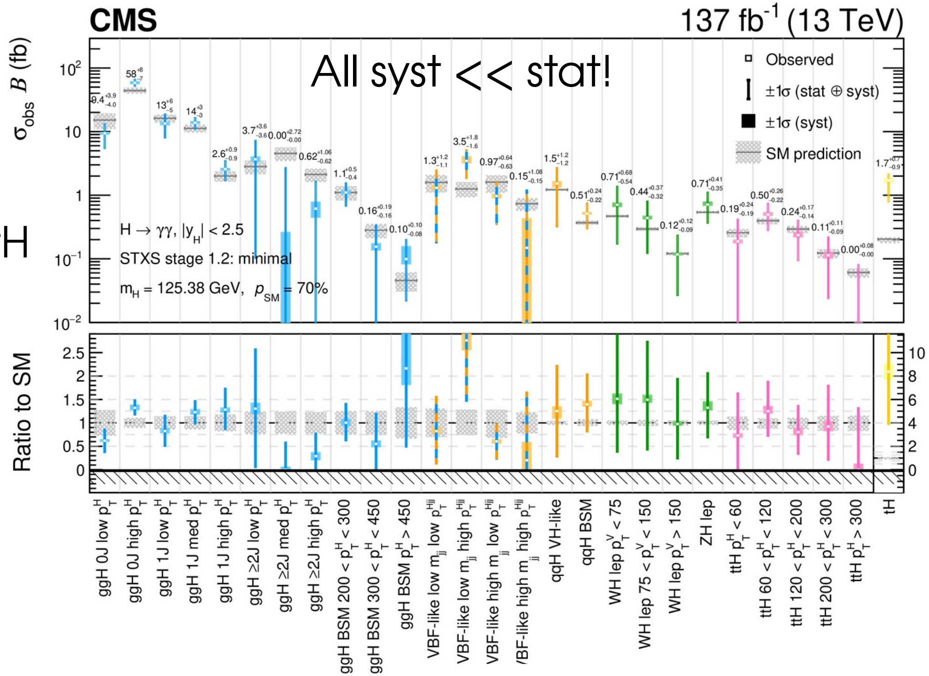
arXiv:2103.06956

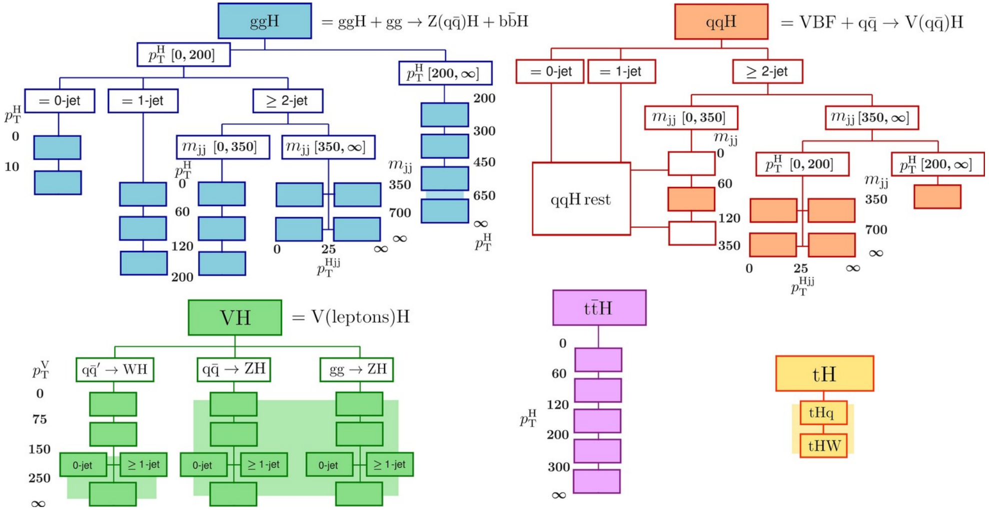
CMS H→γγ

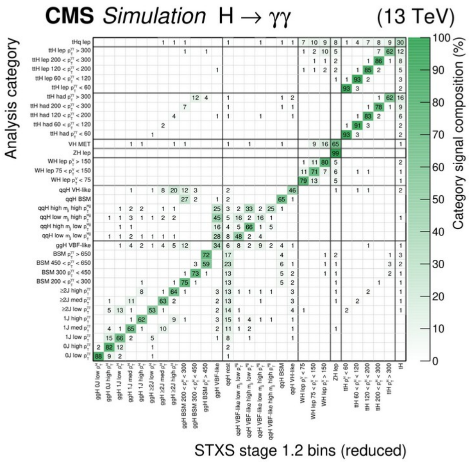
- Measure 27 STXS bins in gg→H, qqH, WH, ZH, ttH, tH
- 80 analysis regions

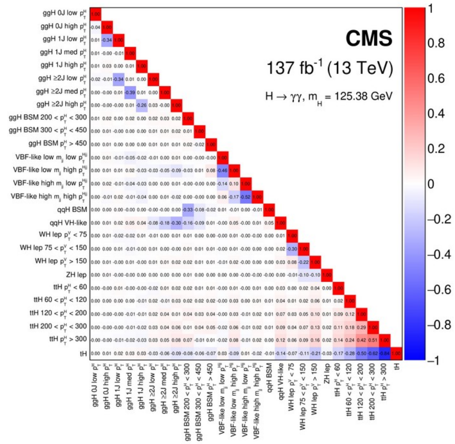
→ Fine-grained kinematic information, useful for SMEFT interpretations

→ Similar ATLAS result: ATLAS-CONF-2020-026









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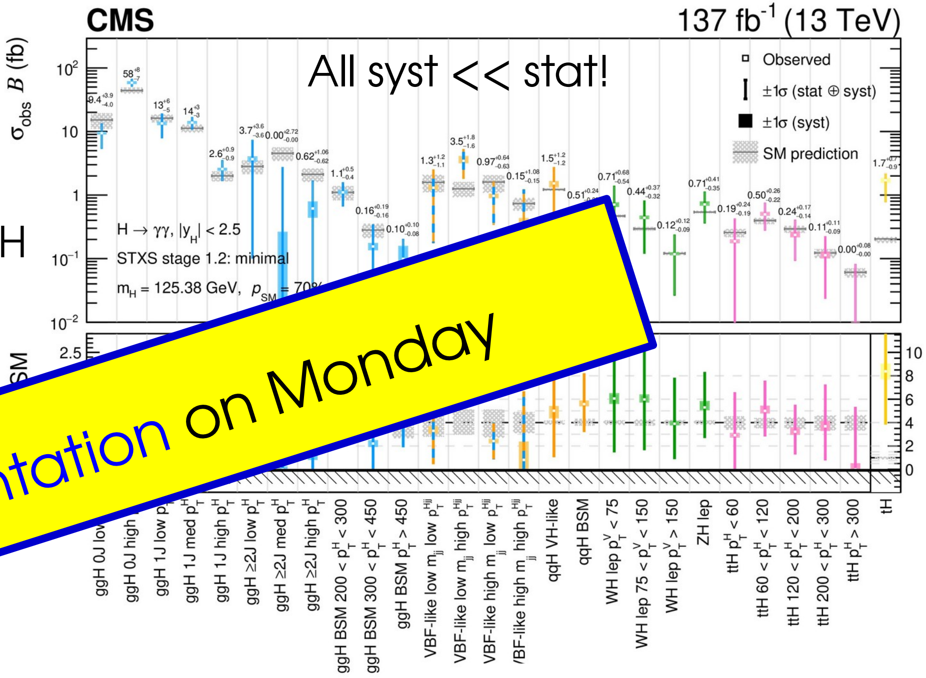
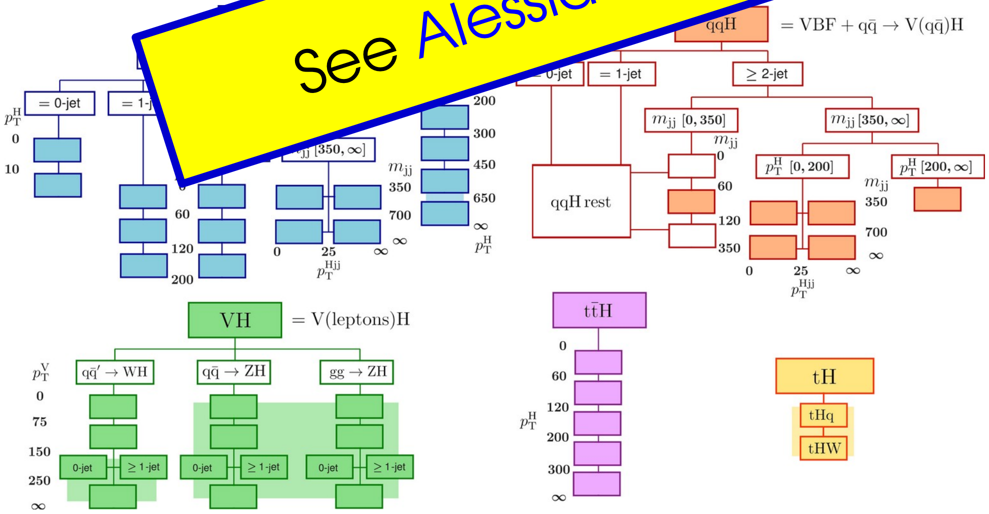
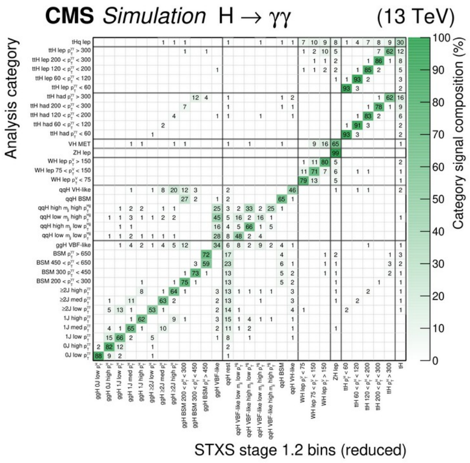
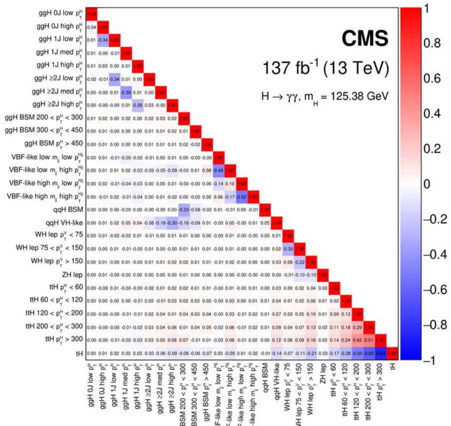
See Alessia Murrone's presentation on Monday





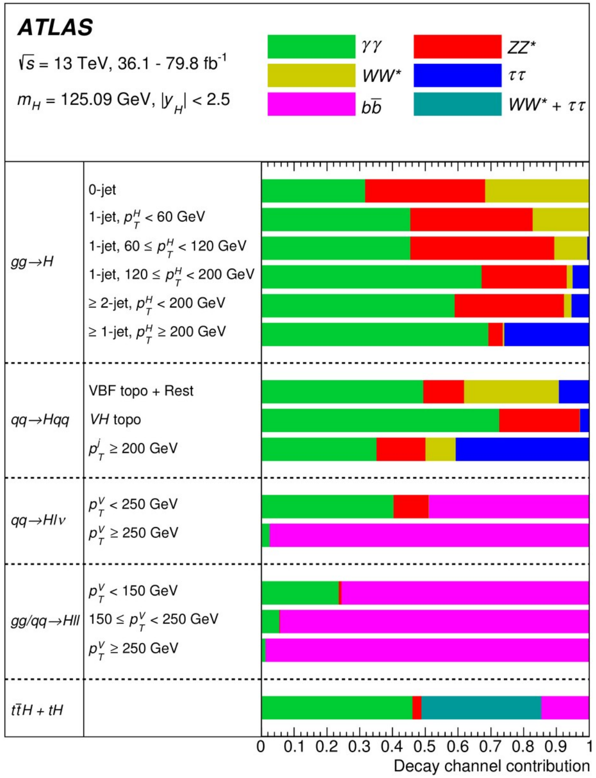


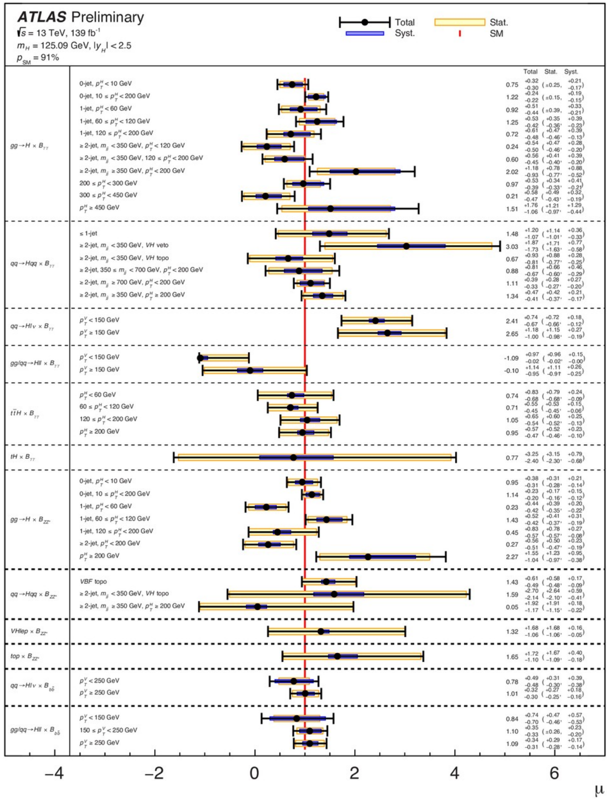


Combinations and reinterpretations : STXS

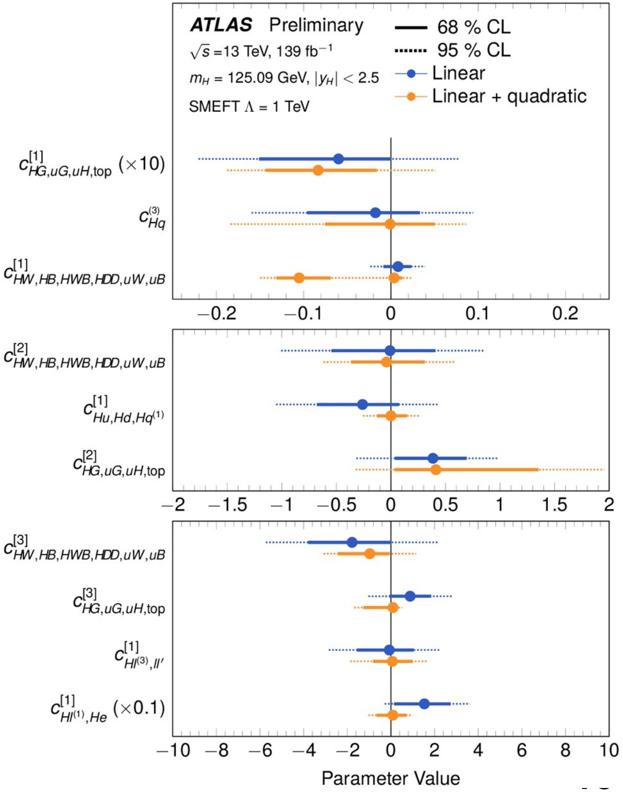
Phys. Rev. D 101 (2020) 012002

- Combining information from multiple sources typically improves BSM sensitivity
- Combining multiple modes/experiments : main difficulty is properly correlating systematics
- STXS : independent measurements along multiple variables by construction
- Multiple modes contribute to various sectors





SMEFT Interpretation



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See the presentation by Thomas Calvet tomorrow

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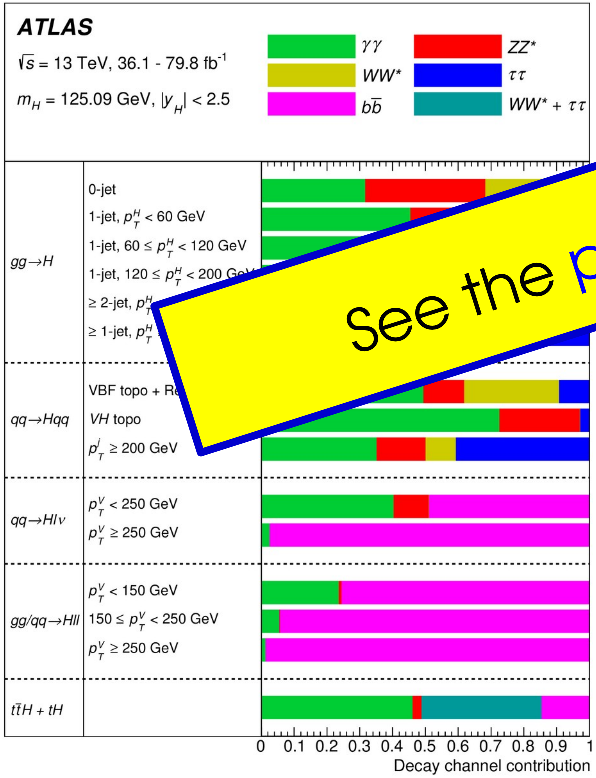

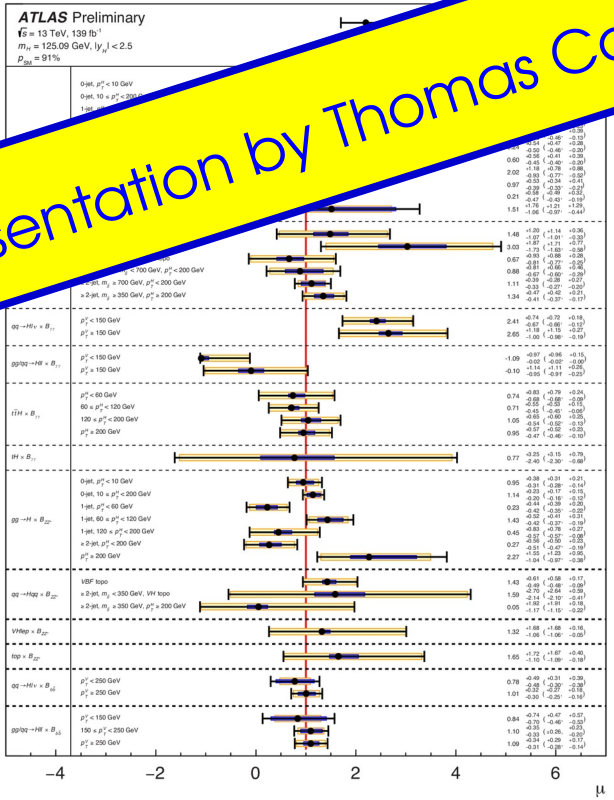

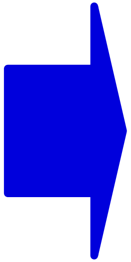

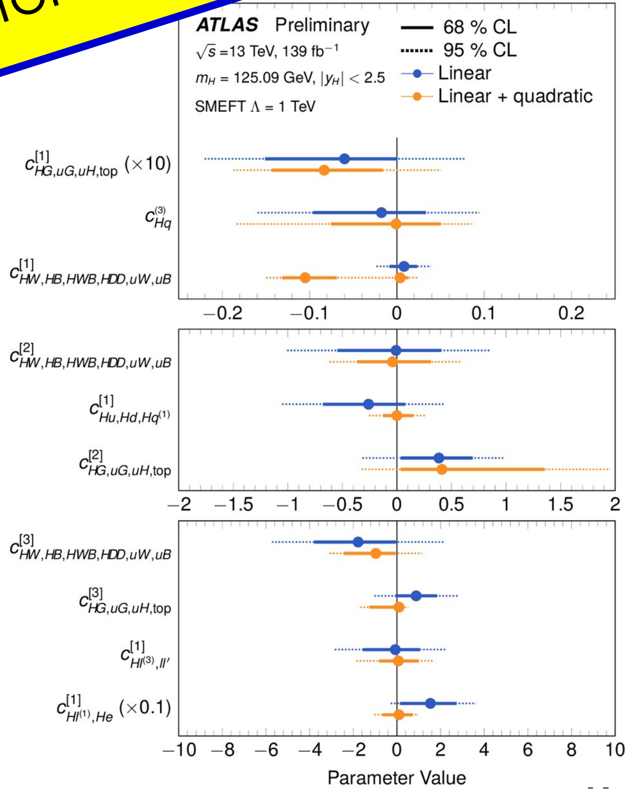

Combinations and reinterpretations of fiducial/differential XS

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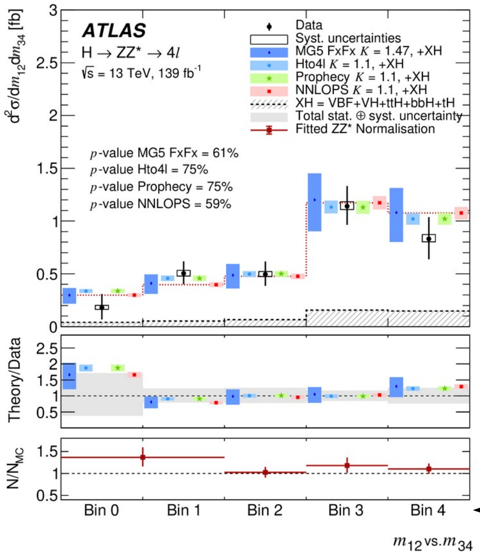
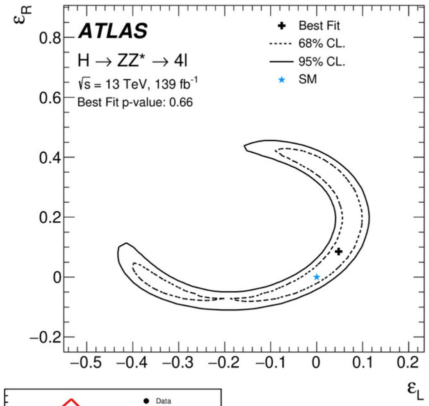
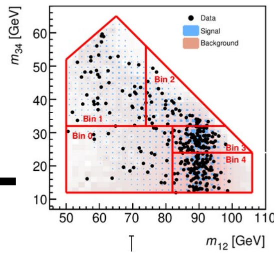
ATLAS H→4l :

PO interpretation of m_{12} vs. m_{34} 2D distribution

Eur. Phys. J. C 80 (2020) 942



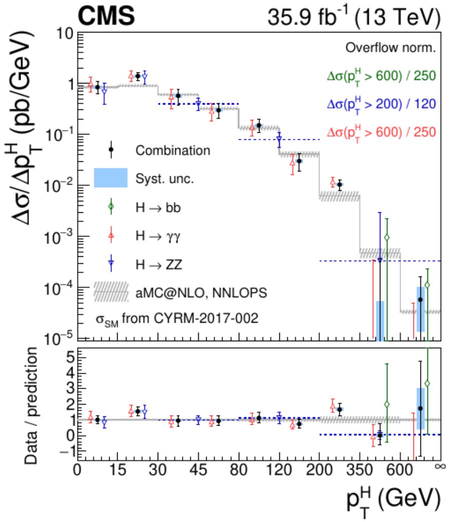




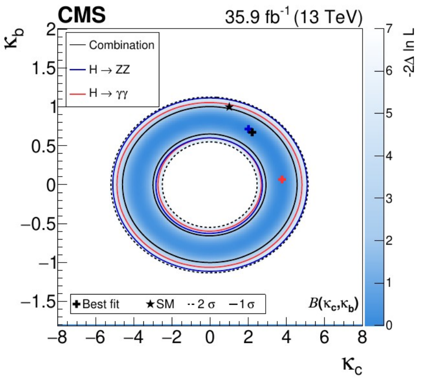
CMS H→γγ + H→4l + H→bb

Couplings interpretation of p_T^H distribution

PLB 792 (2019) 369



Coupling-modifier Interpretation



Combinations and reinterpretations of fiducial/differential XS

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See the presentation by Fabio Lucio Alves after this one

ATLAS H→4l :

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H→bb

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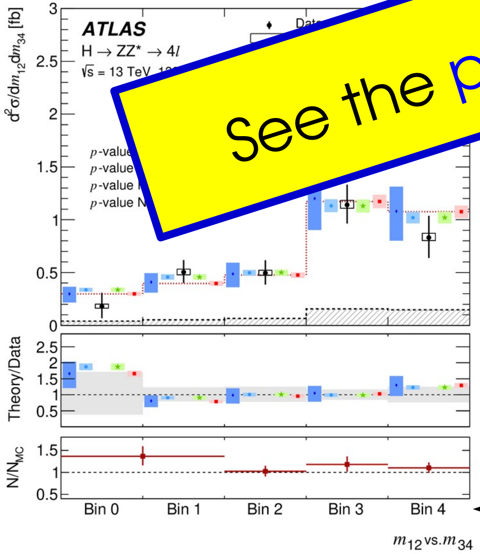

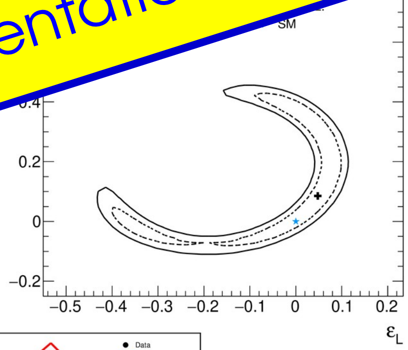

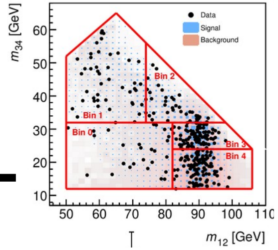

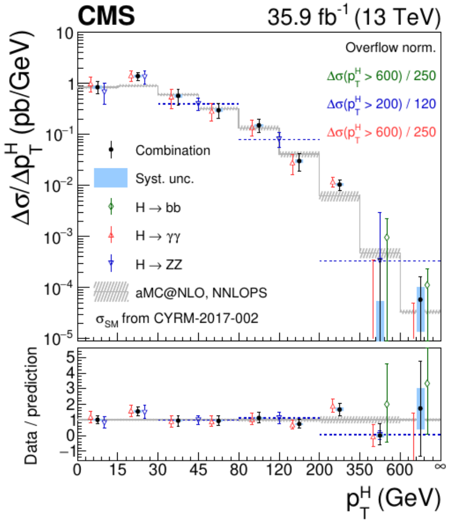

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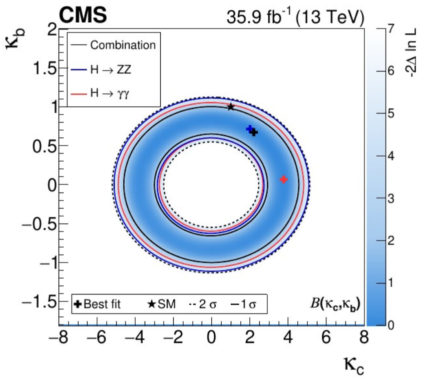


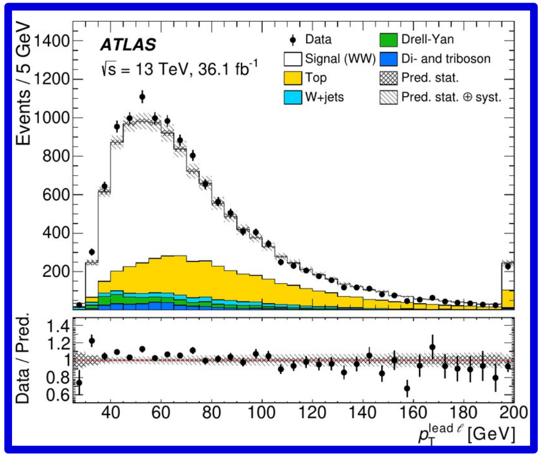
Combined H→WW* + SM WW SMEFT interpretation

SM WW:

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

Measure pp→WW→ lνlν in bins of $p_T^{lead\ l}$.

Fiducial differential cross-sections $d\sigma/dp_T^{lead\ l}$.

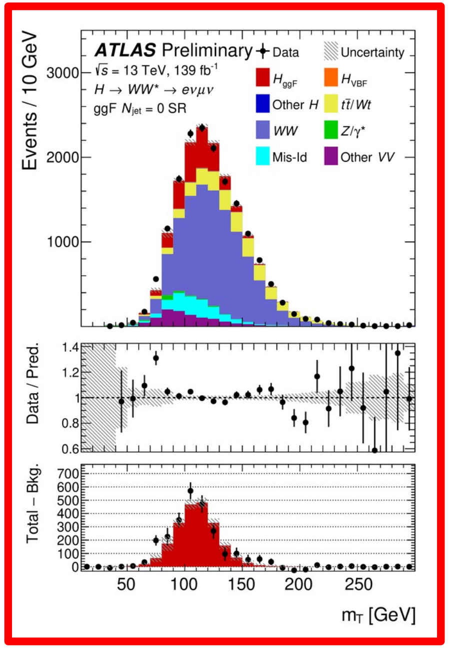


H→WW*

ATLAS-CONF-2021-014

Measure STXS in ggF and VBF modes, with H→WW*→eνμν decay

pp→WW is the main analysis background



Combination

Correlate systematic uncertainties

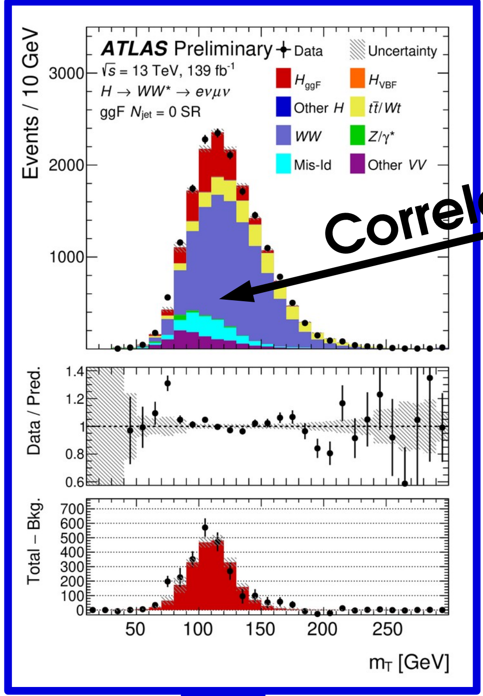
Use pp→WW to constrain backgrounds to H→WW*

Interpret the results in the context of SMEFT.

Combined H→WW* + SM WW SMEFT interpretation

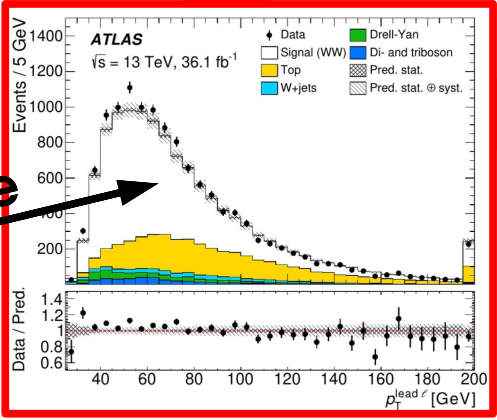
ATL-PHYS-PUB-2021-010

H→WW*

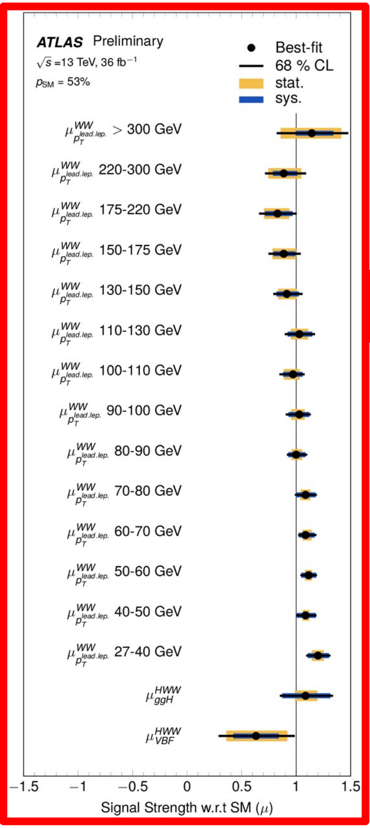


Correlate

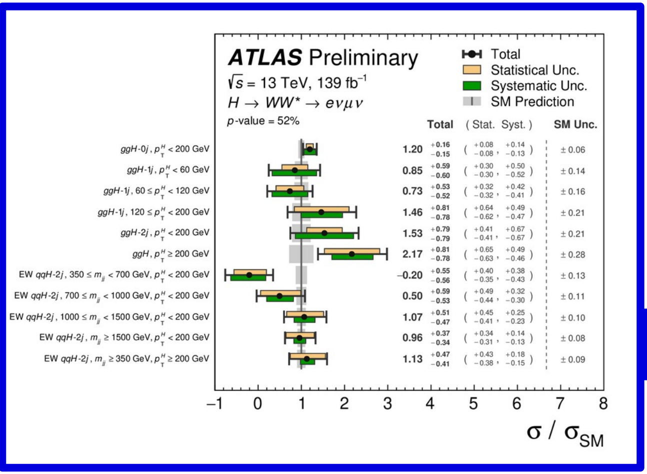
SM WW

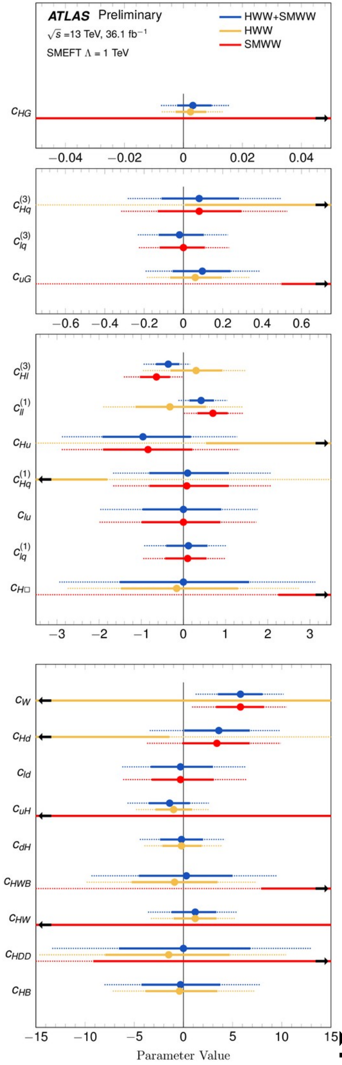


fid/dif XS



STXS





Combined H→WW* + SM WW SMEFT interpretation

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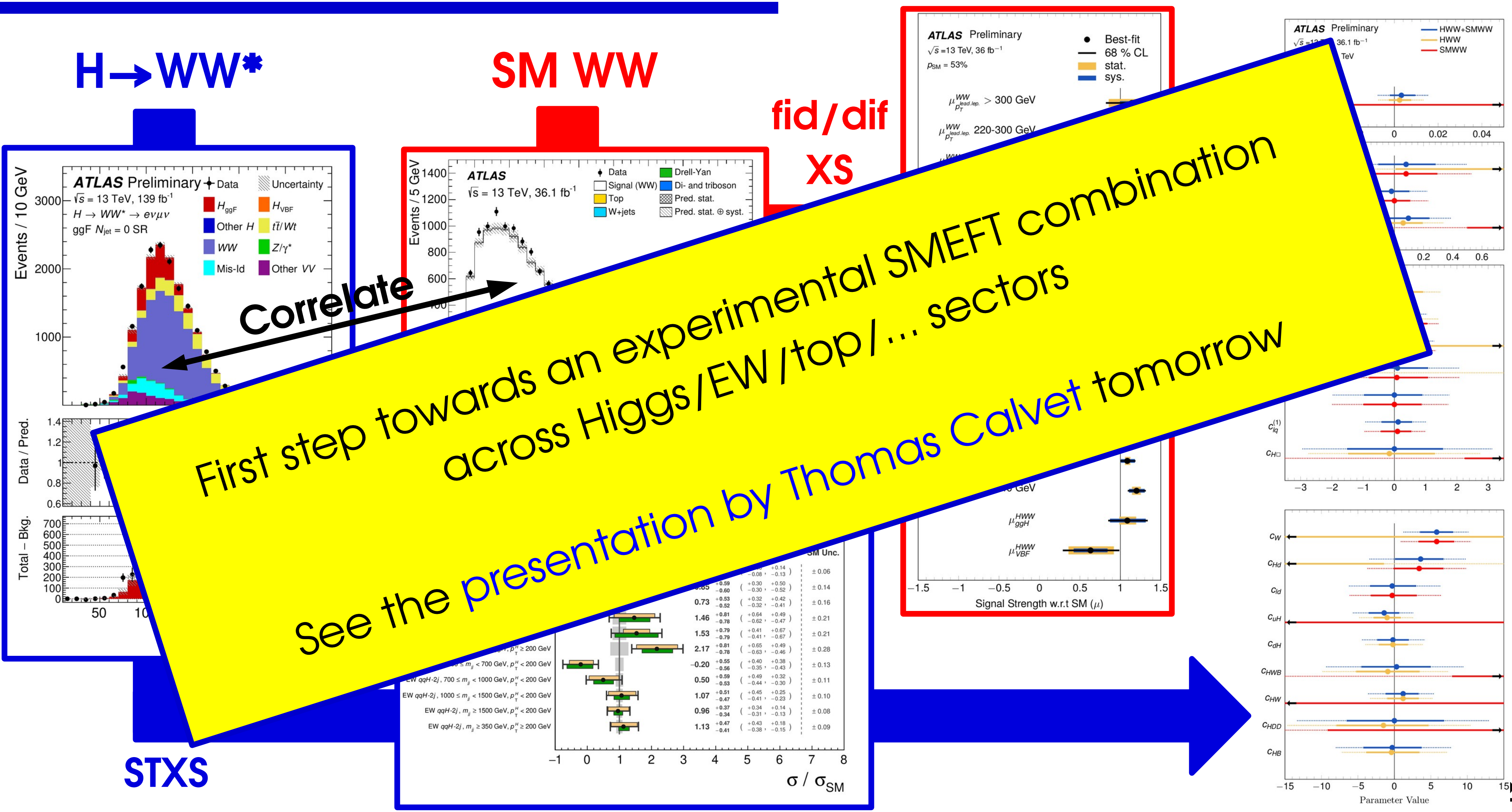
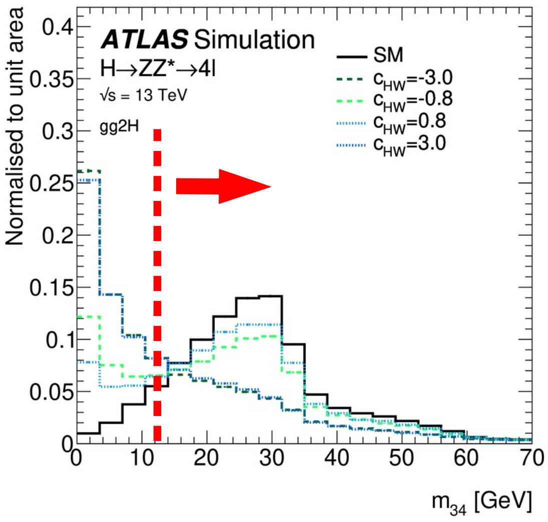


First step towards an experimental SMEFT combination across Higgs/EW/top/... sectors

See the presentation by Thomas Calvet tomorrow

Acceptance effects in H→4l STXS



H→ 4l STXS measured under SM assumptions.

SMEFT interpretation: some modifications change kinematics

⇒ **also changes analysis acceptance & reconstruction efficiency.**

⇒ **Partially invalidate the STXS measurement**

e.g. H→4l : m_{34} > 12 GeV cut, and m_{34} strongly depends on c_{HV}

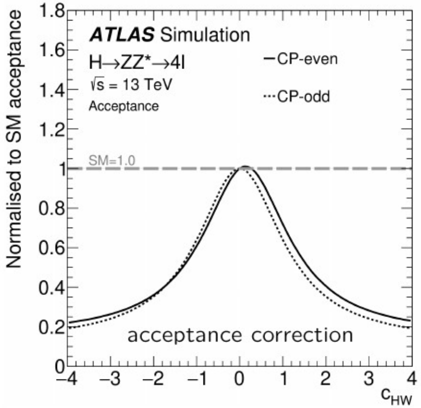
$$\frac{A(\vec{c})}{A_{\rm SM}} = \alpha_0 + (\alpha_1)^2 \cdot \left[\alpha_2 + \sum_i \delta_i \cdot (c_i + \beta_i)^2 + \sum_{\substack{ij \\ i \neq j}} \delta_{(i,j)} \cdot c_i c_j + \delta_{(i,j,k)} \cdot c_i c_j c_k \right]^{-1}_{i \neq j \neq k}$$

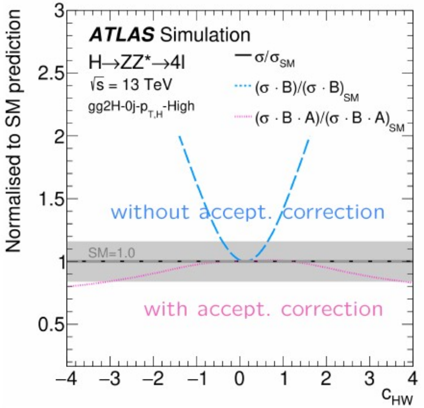
⇒ **Parameterize acceptance A(c) :**

Need to include the (model-dependent) correction when performing the interpretation

Similar effects also in H→WW*   ATL-PHYS-PUB-2021-010

Could be mitigated with STXS binning of final state (here in m_{34}) ⇒ Also provides BSM sensitivity



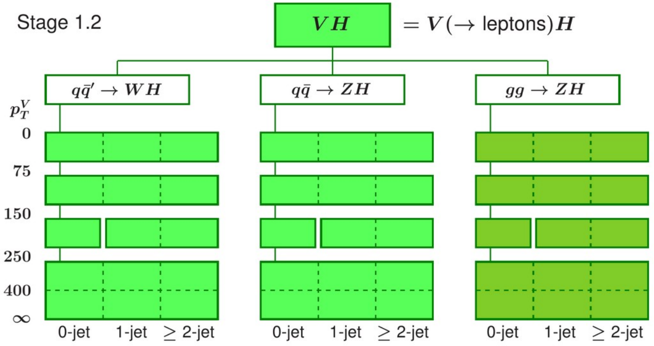


STXS Optimality and Future Evolutions

STXS measurements generally more sensitive than fid/diff XS due to additional assumptions

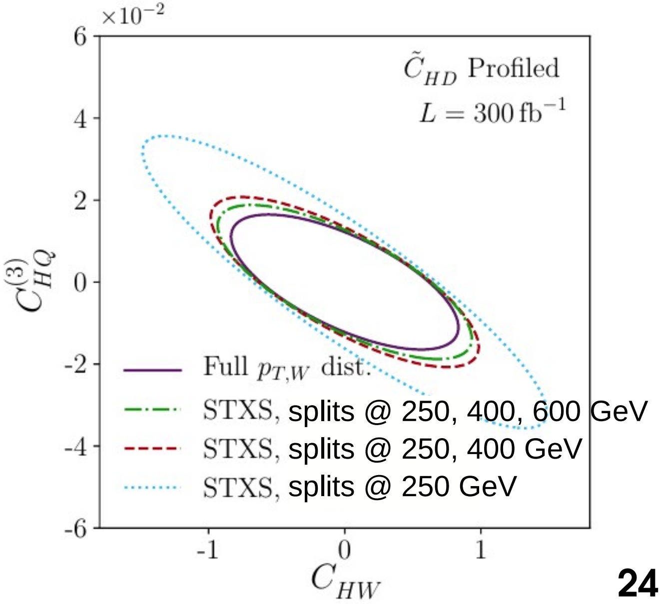
How close to optimal sensitivity achieved by dedicated analyses ?

→ Affected by choice of binning variables, binning granularity



JHEP 1911 (2019) 034 : study of SMEFT interpretations of STXS in pp→WH mode

→ More bins at high-p_T^V improve sensitivity



⇒ Important to improve binning granularity as more data becomes available, in particular in BSM-sensitive regions.

⇒ Future evolution: additional splits to include new observables:

e.g. signed $\Delta\varphi_{jj}$ in gg→H+2 jets and qq→Hqq, sensitive to Higgs CP

Challenges: a partial list

Fiducial differential	STXS

Refined binnings adapted to larger datasets

Reduced theory uncertainties (for acceptances and interpretations)

Better control of experimental uncertainties (e.g. through more data-driven methods)

Fiducial differential:

Measurements in $H\rightarrow bb$, $H\rightarrow WW$, $H\rightarrow \tau\tau$

Multidimensional measurements

Combinations with other sectors (top/EW/QCD/...)

STXS:

Decay-side bins:
- Additional information
- Avoid model-dependence in acceptance in $H\rightarrow 4l$ and $H\rightarrow WW$

New variables (e.g. sensitive to Higgs CP)

Possible extension to top/EW/... sectors:
- Could improve BSM sensitivity
- Easier combinations across Higgs/ EW/top measurements

Conclusions

- **Fiducial differential cross-sections and STXS provide complementary frameworks to characterize kinematics**
  - differential/fiducial measurements more model-independent
  - STXS higher sensitivity to BSM effects

- **Both increasingly useful as we move towards (even) higher-precision measurements**
  → Crucial in particular to set contraints on SMEFT parameters

- **STXS binning designed to evolve with dataset size**
  Finer bins ⇒ lower model-dependence, higher BSM sensitivity

- **STXS also could be useful in non-Higgs measurements (e.g. top, pp→VV, QCD vs. EW production)**
  → Could improve measurement sensitivity (at the cost of some model-dependence)
  → Could also make for easier combinations across multiple analyses.
  e.g. SM EW/Higgs/Top, SMEFT interpretations.

Backup

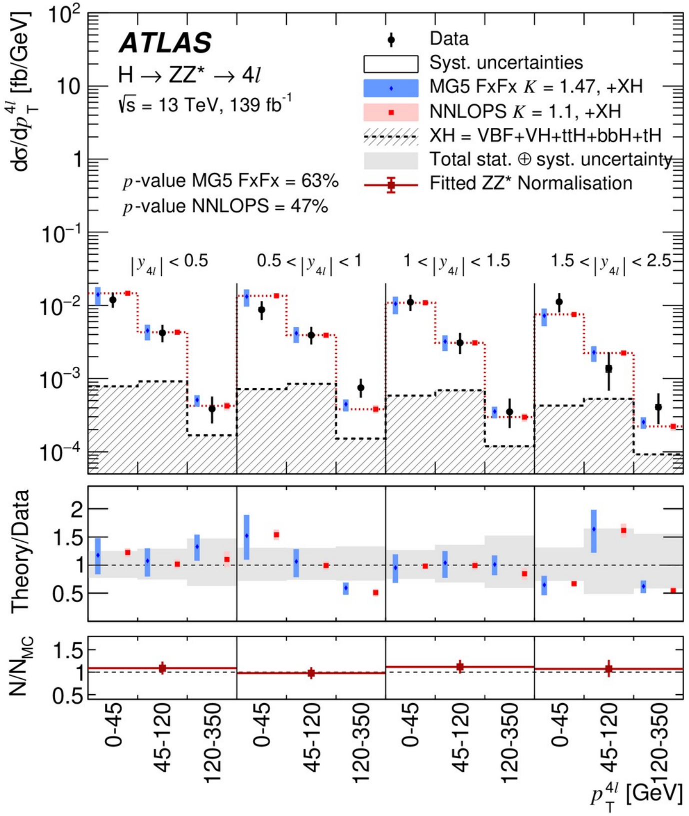
Decay mode	Production Process																			
	ggH				VBF				WH				ZH				ttH			
			Uncertainty				Uncertainty				Uncertainty				Uncertainty				Uncertainty	
	Best-fit		Stat.	Syst.	Best-fit		Stat.	Syst.	Best-fit		Stat.	Syst.	Best-fit		Stat.	Syst.	Best-fit		Stat.	Syst.
$H \to bb$	2.45	$^{+2.53}_{-2.35}$ $\left(^{+2.11}_{-1.95}\right)$	$^{+2.04}_{-2.01}$ $\left(^{+1.92}_{-1.91}\right)$	$^{+1.51}_{-1.22}$ $\left(^{+0.86}_{-0.34}\right)$	— (—)				1.27	$^{+0.42}_{-0.40}$ $\left(^{+0.42}_{-0.41}\right)$	$^{+0.32}_{-0.31}$ $\left(^{+0.33}_{-0.32}\right)$	$^{+0.27}_{-0.25}$ $\left(^{+0.27}_{-0.26}\right)$	0.93	$^{+0.33}_{-0.31}$ $\left(^{+0.32}_{-0.31}\right)$	$^{+0.27}_{-0.26}$ $\left(^{+0.26}_{-0.26}\right)$	$^{+0.19}_{-0.17}$ $\left(^{+0.19}_{-0.17}\right)$	1.13	$^{+0.33}_{-0.30}$ $\left(^{+0.32}_{-0.30}\right)$	$^{+0.16}_{-0.16}$ $\left(^{+0.16}_{-0.16}\right)$	$^{+0.29}_{-0.25}$ $\left(^{+0.28}_{-0.25}\right)$
$H \to \tau\tau$	0.39	$^{+0.38}_{-0.39}$ $\left(^{+0.39}_{-0.36}\right)$	$^{+0.16}_{-0.16}$ $\left(^{+0.16}_{-0.16}\right)$	$^{+0.35}_{-0.35}$ $\left(^{+0.36}_{-0.33}\right)$	1.05	$^{+0.30}_{-0.29}$ $\left(^{+0.31}_{-0.30}\right)$	$^{+0.25}_{-0.24}$ $\left(^{+0.25}_{-0.25}\right)$	$^{+0.18}_{-0.17}$ $\left(^{+0.18}_{-0.17}\right)$	3.01	$^{+1.65}_{-1.51}$ $\left(^{+1.52}_{-1.40}\right)$	$^{+1.37}_{-1.27}$ $\left(^{+1.27}_{-1.16}\right)$	$^{+0.92}_{-0.81}$ $\left(^{+0.82}_{-0.78}\right)$	1.53	$^{+1.60}_{-1.37}$ $\left(^{+1.45}_{-1.25}\right)$	$^{+1.41}_{-1.25}$ $\left(^{+1.32}_{-1.17}\right)$	$^{+0.75}_{-0.55}$ $\left(^{+0.59}_{-0.46}\right)$	0.81	$^{+0.74}_{-0.67}$ $\left(^{+0.72}_{-0.64}\right)$	$^{+0.57}_{-0.53}$ $\left(^{+0.57}_{-0.53}\right)$	$^{+0.46}_{-0.40}$ $\left(^{+0.43}_{-0.36}\right)$
$H \to WW$	1.28	$^{+0.20}_{-0.19}$ $\left(^{+0.17}_{-0.16}\right)$	$^{+0.11}_{-0.11}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.17}_{-0.15}$ $\left(^{+0.14}_{-0.12}\right)$	0.63	$^{+0.65}_{-0.61}$ $\left(^{+0.61}_{-0.58}\right)$	$^{+0.58}_{-0.54}$ $\left(^{+0.55}_{-0.52}\right)$	$^{+0.30}_{-0.29}$ $\left(^{+0.27}_{-0.26}\right)$	2.85	$^{+2.11}_{-1.87}$ $\left(^{+1.48}_{-1.20}\right)$	$^{+1.78}_{-1.60}$ $\left(^{+1.33}_{-1.09}\right)$	$^{+1.13}_{-0.96}$ $\left(^{+0.64}_{-0.51}\right)$	0.90	$^{+1.77}_{-1.43}$ $\left(^{+1.67}_{-1.37}\right)$	$^{+1.70}_{-1.41}$ $\left(^{+1.61}_{-1.36}\right)$	$^{+0.50}_{-0.24}$ $\left(^{+0.43}_{-0.21}\right)$	0.93	$^{+0.48}_{-0.45}$ $\left(^{+0.45}_{-0.41}\right)$	$^{+0.37}_{-0.36}$ $\left(^{+0.35}_{-0.35}\right)$	$^{+0.30}_{-0.26}$ $\left(^{+0.27}_{-0.22}\right)$
$H \to ZZ$	0.98	$^{+0.12}_{-0.11}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.09}_{-0.09}$ $\left(^{+0.10}_{-0.09}\right)$	$^{+0.08}_{-0.07}$ $\left(^{+0.08}_{-0.07}\right)$	0.57	$^{+0.46}_{-0.36}$ $\left(^{+0.57}_{-0.47}\right)$	$^{+0.44}_{-0.35}$ $\left(^{+0.52}_{-0.44}\right)$	$^{+0.15}_{-0.09}$ $\left(^{+0.23}_{-0.14}\right)$			1.10	$^{+0.96}_{-0.74}$ $\left(^{+0.99}_{-0.73}\right)$	$^{+0.94}_{-0.74}$ $\left(^{+0.96}_{-0.72}\right)$	$^{+0.19}_{-0.10}$ $\left(^{+0.21}_{-0.11}\right)$			0.25	$^{+1.03}_{-0.25}$ $\left(^{+1.12}_{-0.67}\right)$	$^{+1.00}_{-0.25}$ $\left(^{+1.10}_{-0.67}\right)$	$^{+0.21}_{-0.00}$ $\left(^{+0.22}_{-0.06}\right)$
$H \to \gamma\gamma$	1.09	$^{+0.15}_{-0.14}$ $\left(^{+0.14}_{-0.13}\right)$	$^{+0.11}_{-0.11}$ $\left(^{+0.11}_{-0.11}\right)$	$^{+0.10}_{-0.08}$ $\left(^{+0.09}_{-0.07}\right)$	0.77	$^{+0.37}_{-0.29}$ $\left(^{+0.41}_{-0.36}\right)$	$^{+0.32}_{-0.27}$ $\left(^{+0.33}_{-0.32}\right)$	$^{+0.18}_{-0.09}$ $\left(^{+0.25}_{-0.18}\right)$	— (—)				— (—)				1.62	$^{+0.52}_{-0.43}$ $\left(^{+0.41}_{-0.35}\right)$	$^{+0.44}_{-0.40}$ $\left(^{+0.39}_{-0.35}\right)$	$^{+0.27}_{-0.14}$ $\left(^{+0.15}_{-0.07}\right)$
$H \to \mu\mu$	0.31	$^{+1.82}_{-1.81}$ $\left(^{+1.78}_{-1.79}\right)$	$^{+1.80}_{-1.80}$ $\left(^{+1.76}_{-1.79}\right)$	$^{+0.22}_{-0.22}$ $\left(^{+0.28}_{-0.07}\right)$	3.18	$^{+8.22}_{-7.93}$ $\left(^{+8.13}_{-7.95}\right)$	$^{+7.99}_{-7.90}$ $\left(^{+8.01}_{-7.88}\right)$	$^{+1.93}_{-0.76}$ $\left(^{+1.41}_{-1.05}\right)$	— (—)				— (—)				— (—)			

CMS-PAS-HIG-19-005

Examples: Differential XS

ATLAS H→4l :

2D differential XS in (p_T^{4l}, N_{jets}), (p_T^{4l}, y^{4l}), (m_{12}, m_{34})...

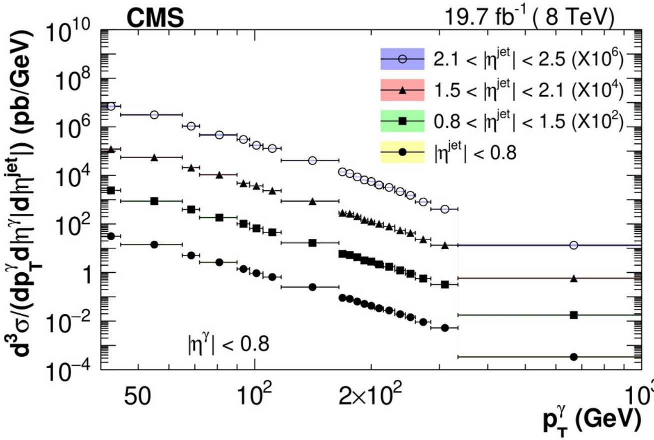


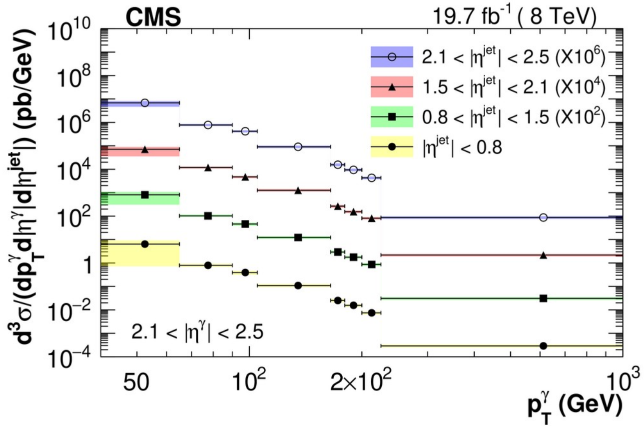
Eur. Phys. J. C 80 (2020) 942

CMS Inclusive pp→γ + jets :

3D diff. XS in (p_T^γ, η_γ, η_j) (18×4×4 bins)

Eur. Phys. J. C 79 (2019) 969





Combinations and reinterpretations : fid/dif XS

- Combining information from multiple sources typically improves BSM sensitivity
- Combining multiple modes/experiments : main difficulty is properly correlating systematics
- fid/dif measurements typically 1 or 2 variables at a time

ATLAS H→4l :

PO interpretation of m_{12} vs. m_{34} 2D distribution

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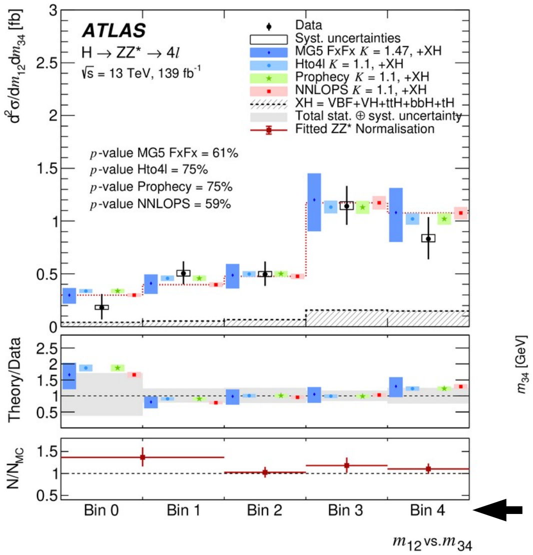
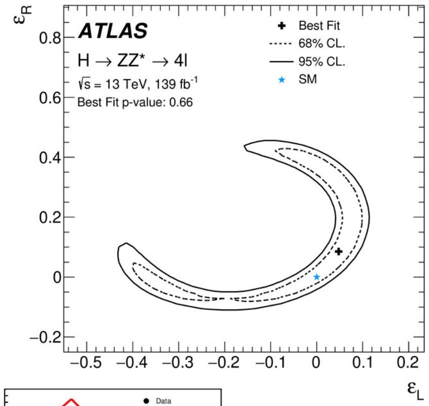
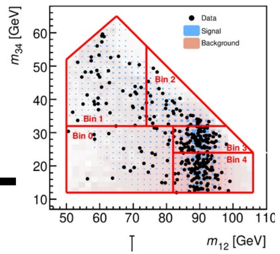


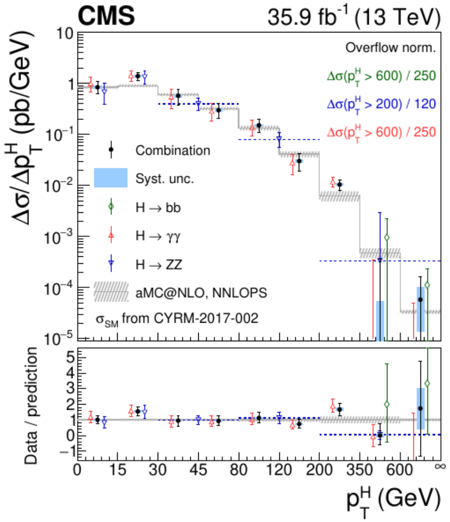




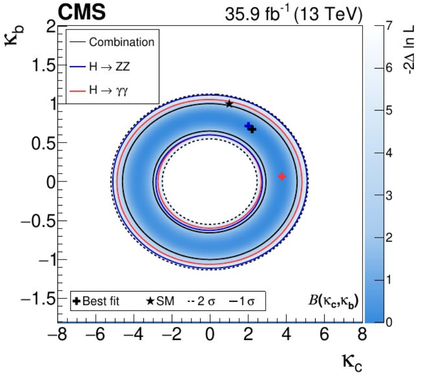
CMS H→γγ + H→4l + H→bb

Couplings interpretation of p_T^H distribution

PLB 792 (2019) 369



Coupling-modifier Interpretation

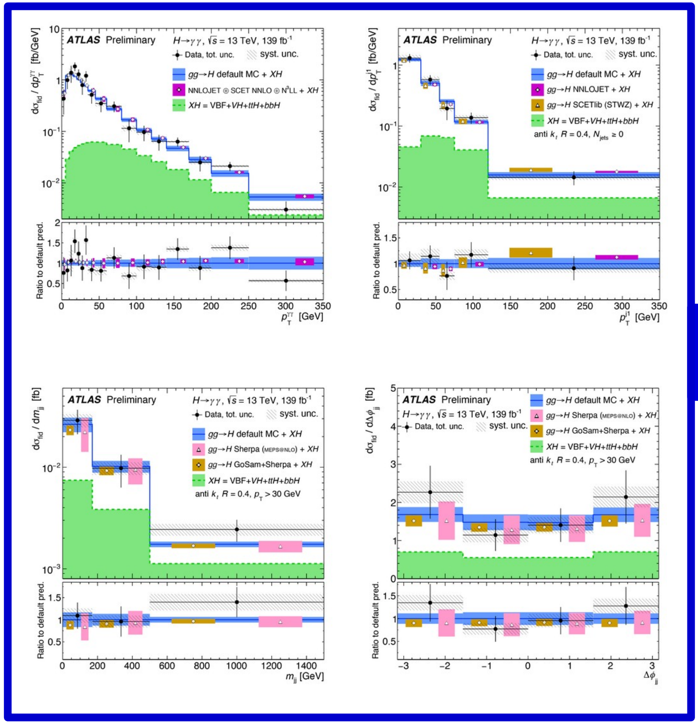


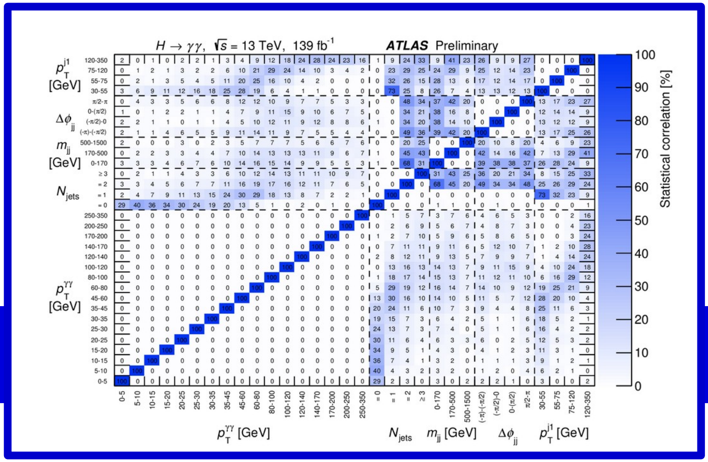
Combinations and reinterpretations : fid/dif XS

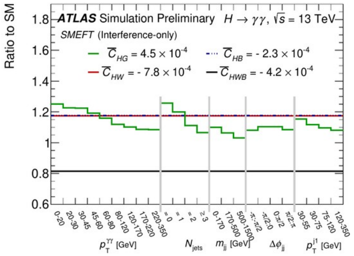
- Combining information from multiple sources typically improves BSM sensitivity
- Combining multiple modes/experiments : main difficulty is properly correlating systematics

$H \to \gamma\gamma$

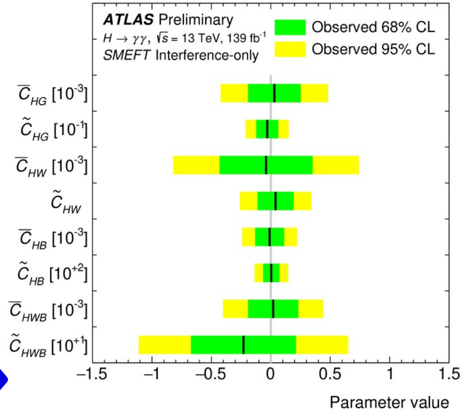
- Large backgrounds ⇒ can measure correlations in data using resampling
- Implement correlations using Gaussian assumptions

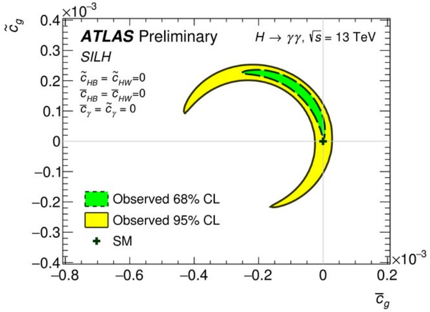






SMEFT Interpretation

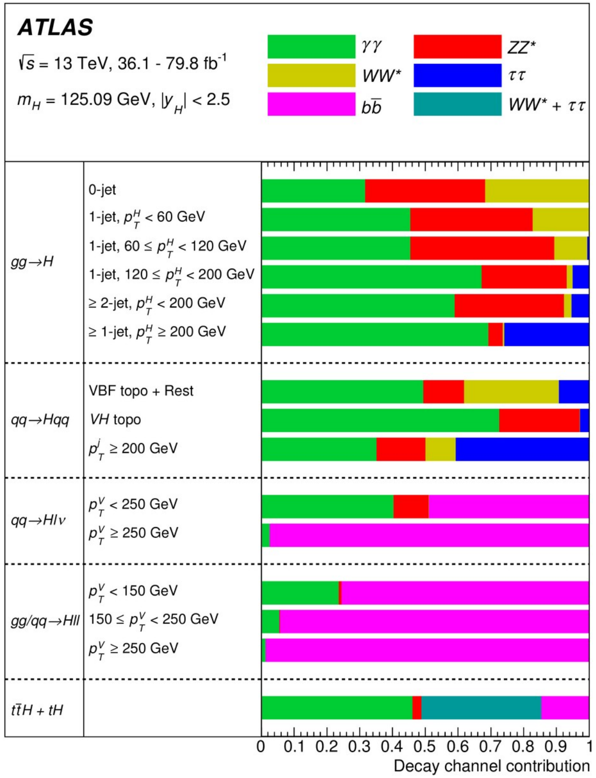


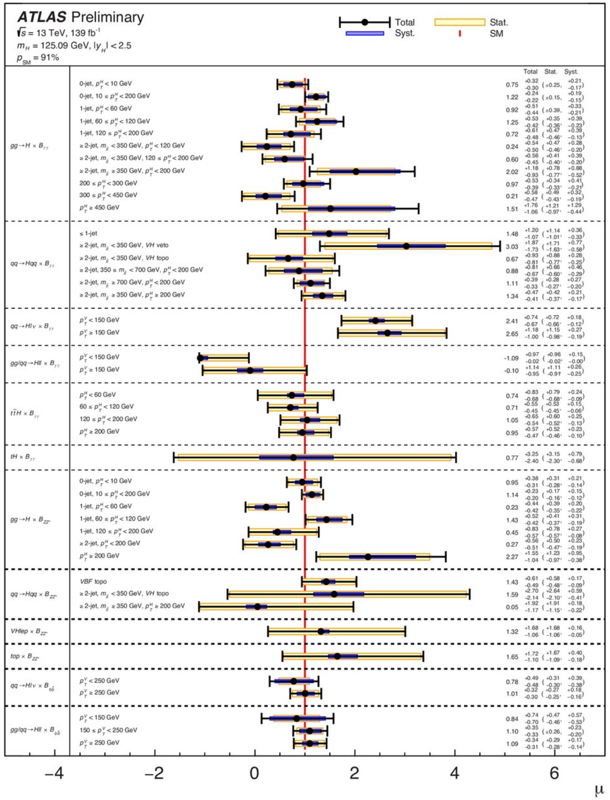


Combinations and reinterpretations : STXS

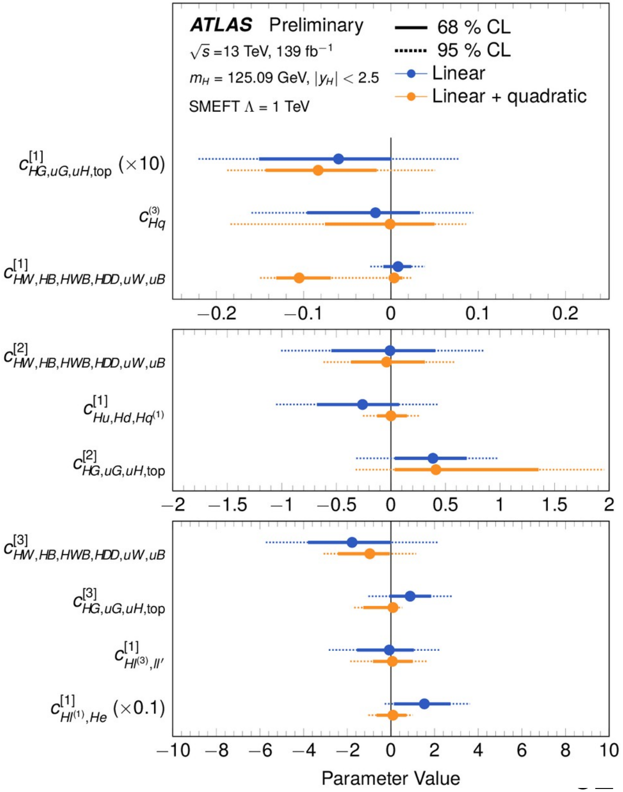
Phys. Rev. D 101 (2020) 012002

- Combining information from multiple sources typically improves BSM sensitivity
- Combining multiple modes/experiments : main difficulty is properly correlating systematics
- STXS : independent measurements along multiple variables by construction
- Multiple modes contribute to various sectors





SMEFT Interpretation



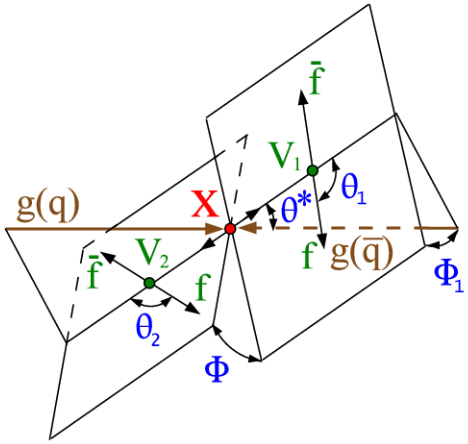
STXS in decays

STXS defined for production in $|y_H| < 2.5$, but can bin *decay* kinematics, in particular for H→4l:

→ Access information in final-state dynamics
→ Decrease model-dependence of experimental acceptance

"Stage 0" : provide fiducial definitions for H→ff, H→ZZ, H→Zγ, H→ γγ... :
a) allows reliable computation of BR predictions
b) can be implemented in MC tools
c) matches the experimental definitions

"Stage 1" : kinematic splits relevant for BSM tests (e.g. m_{34})



m_{34}	[10,20)	[20,35)	[35,m_{12})

Table 2: Bin definitions for $H \to 4\ell$

More details in the draft document and M. Dührssen's presentation @ LHCHWG

Needs input on experimental side (matching truth selection to experiments, Rivet implementation...) ⇒ Contributions welcome!