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Simplified Template Cross Sections

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+feedback from many people

Summary of the discussion in **Les Houches 2015: Physics at TeV Colliders**
(FERMILAB-CONF-16-175-PPD-T - 1605.04692)

and in the **LHC Higgs Cross Section Working Group 2**
(YR IV in preparation - LHCHXSWG-DRAFT-INT-2016-006)

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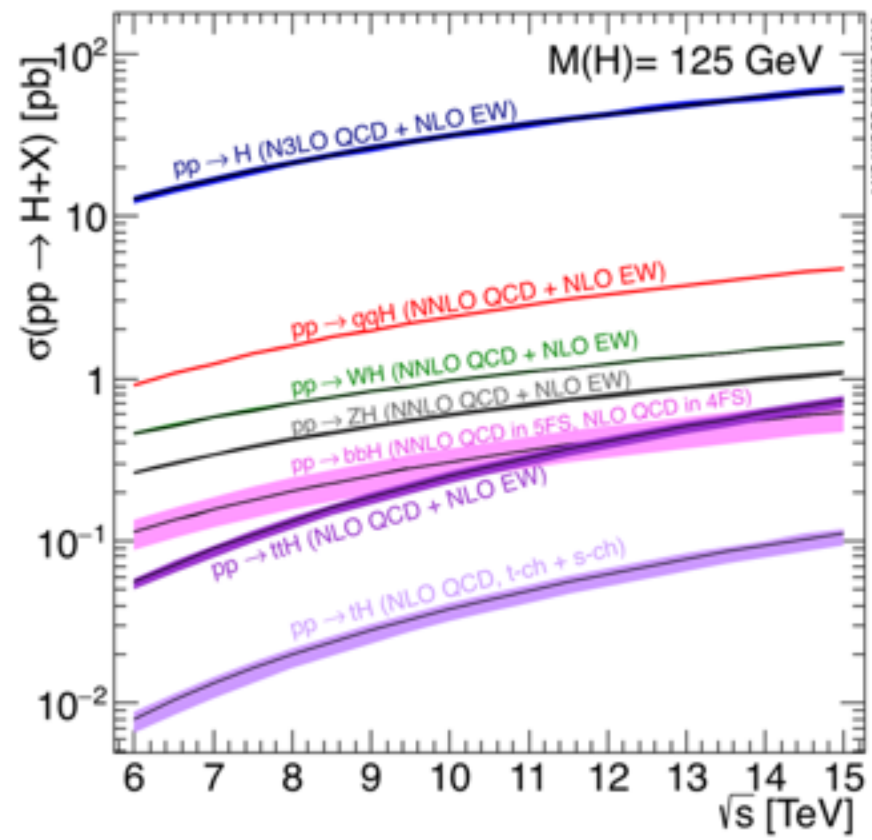
From the discovery to the Higgs properties

- The Run 1 Higgs analyses for the 125 GeV Higgs started as searches
  - To **enhance the sensitivity**, the experimental analysis uses **event categories and multivariate techniques**
- **After discovery, experiments adapted these analysis into first measurements of properties**
- SM Higgs boson has very peculiar production mechanisms:
  - **event categorisation eventually allows the splitting of the production modes in the global fit.**
- Event categories to:
  - **increase the sensitivity of the analysis;**
  - **enrich events of a given Higgs production mode;**
  - **analysis requirements (i.e. trigger selection and bkg estimation);**



an example from ATLAS

$H \to ZZ^* \to 4\ell$ Category	Target	$H \to \gamma\gamma$ Category	Target
VH-leptonic	VHlep	$t\bar{t}H$ leptonic	top
0-jet	ggF	$t\bar{t}H$ hadronic	top
1-jet	ggF	VH dilepton	VHlep
2-jet VBF-like	VBF	VH one-lepton	VHlep
2-jet VH-like	VHhad	VH Emiss	VHlep
		VH hadronic loose	VHhad
		VH hadronic tight	VHhad
		VBF loose	VBF
		VBF tight	VBF
		ggH central low-p_{Tt}	ggF
		ggH central high-p_{Tt}	ggF
		ggH fwd low-p_{Tt}	ggF
		ggH fwd high-p_{Tt}	ggF

From the discovery to the Higgs properties

- Most analyses measure the signal strength μ_{if} for the process i -> H -> f : for a category/bin C of the analysis, the number of measured signal events is

$$n^{C}_{measured} = (\Sigma_f)\ \Sigma_i\ \mu_{if}\ (\sigma \times B)_{if}\ A^{C}_{if}\ L$$

  - σ x B are the SM predictions for production cross section and decay branching ratio
  - A is the acceptance and efficiency for the SM H estimated using MC tools
  - L is the luminosity

- In Red the parts which depend on the SM assumptions calculated/estimated with calculations/tools available at a certain point in time.

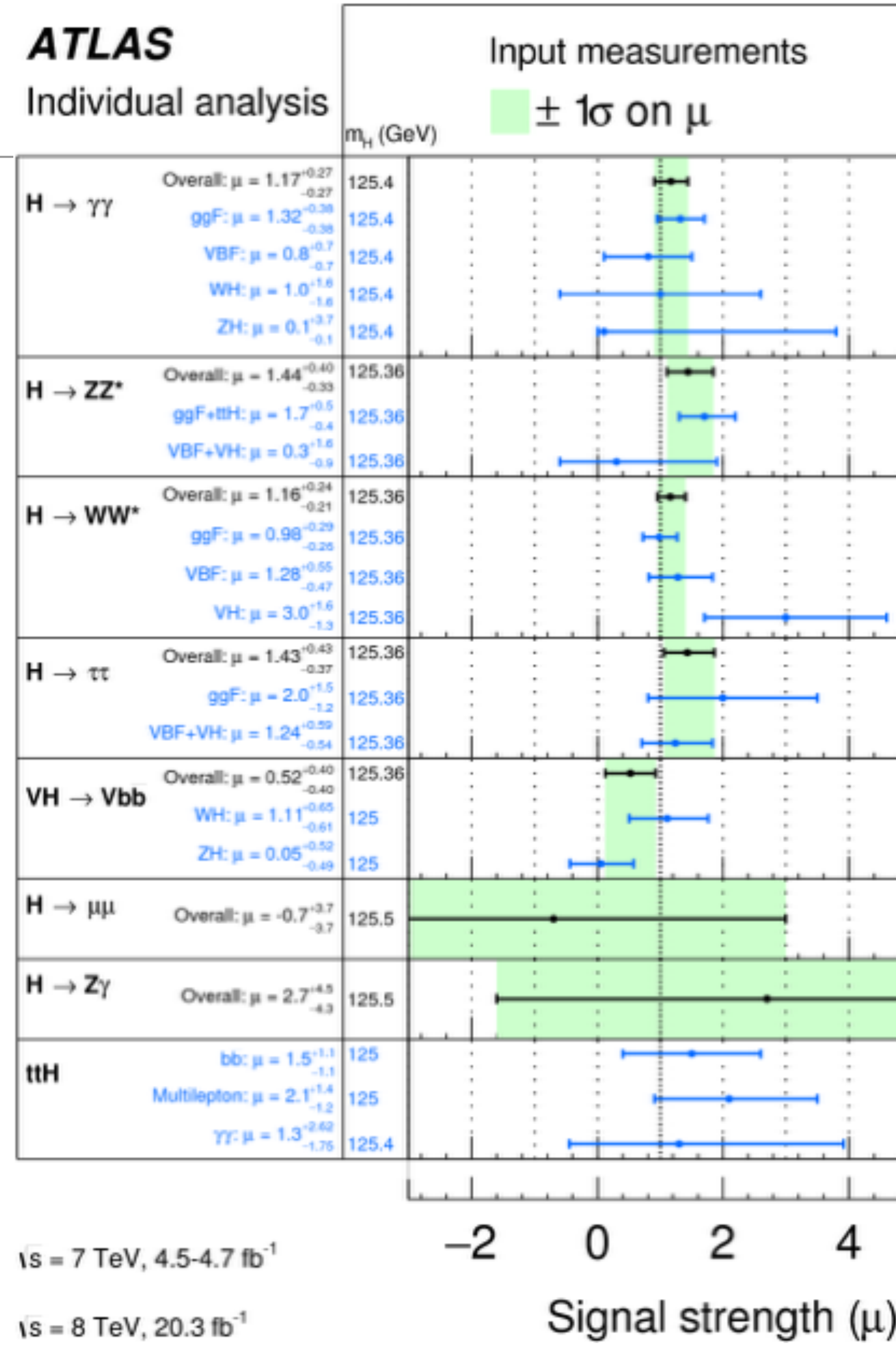
Some considerations

- Run 1 results on the Higgs characterisation are a big success, which combine all the decay channels
    - analyses with event categorisation optimised sensitivity and allowed for separating the production modes
- In these results the Higgs boson signal theory uncertainties are folded in the measurements of μ_{if}:
    - **Systematic uncertainties on SM calculation of (σ x B).** *NOTE: this comes with questions about PDF and scale correlations*
    - **Uncertainties on the SM H estimations of A.** *NOTE: this adds uncertainties and correlations between categories.*

→ *Better calculations cannot easily be compared to these measurements (e.g. N3LO gg→H, …)*

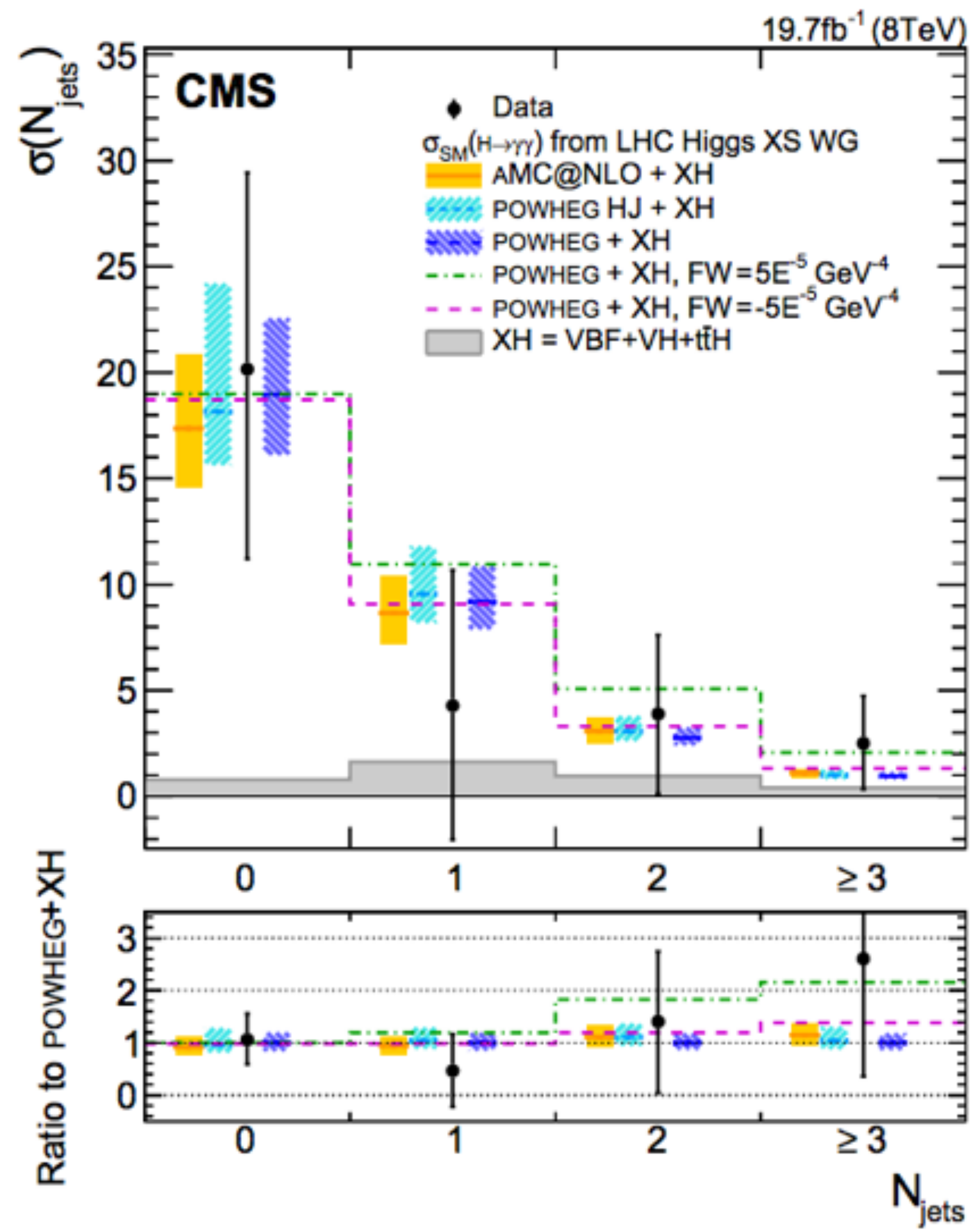
- Analyses usually **assume properties of a SM Higgs boson**, especially in the Higgs boson production and decay **kinematics**.

→ *What if we have deviations in the kinematic distributions as foreseen in BSM scenarios?*



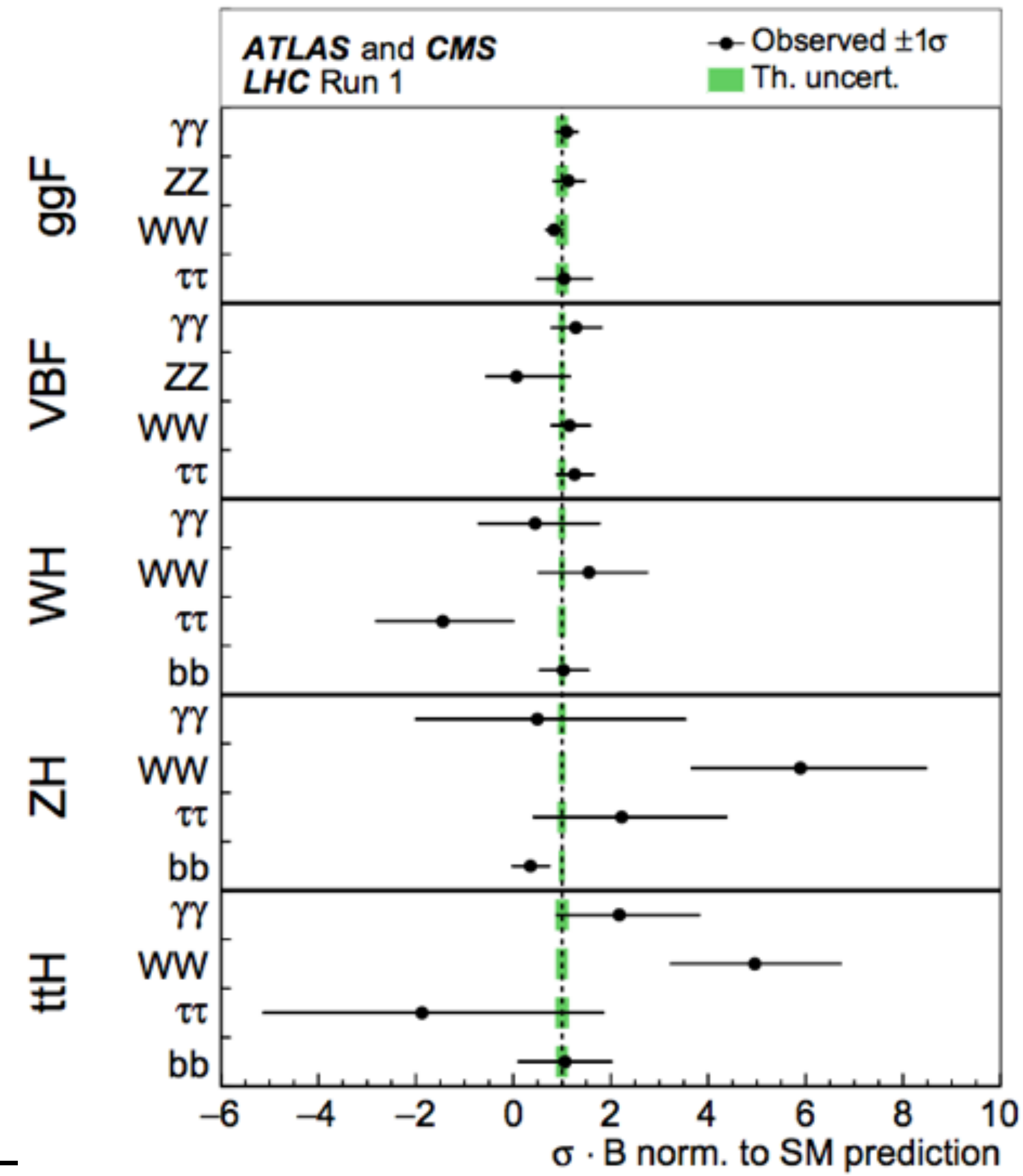
Changing paradigm?

- Some Run 1 analyses already changed the approach:
  - Fiducial and differential cross section measurements in H→γγ, H→ZZ and H→WW
    - almost model independent measurements



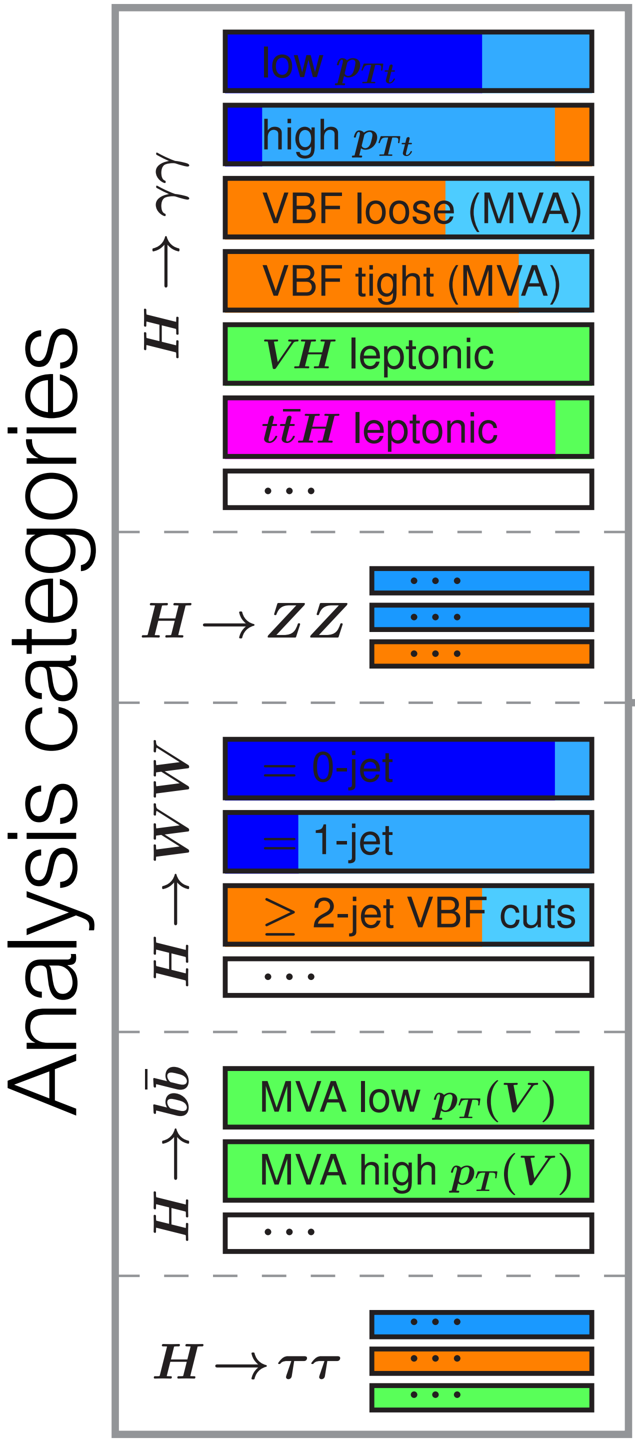
Changing paradigm?

- Some Run 1 analyses already changed the approach:
  - Fiducial and differential cross section measurements in H→γγ, H→ZZ and H→WW
    - almost model independent measurements
  - Cross section (σ x B) results (in ATLAS/CMS coupling combination papers)
    - Removes theory dependence on inclusive xsec



$$n^{C}_{measured} = (\Sigma_f\ )\ \Sigma_i (\sigma \times B)_{if}\, A^{C}_{if}\ L$$

Changing paradigm?



Requirements:

- **Make a measurement in the phase spaces covered by the experimental setup.**
- **Reduce the impact of the theory assumptions/bias on the measurement.**
    - Smaller uncertainty coming from predictions, more open to measure deviations from predictions

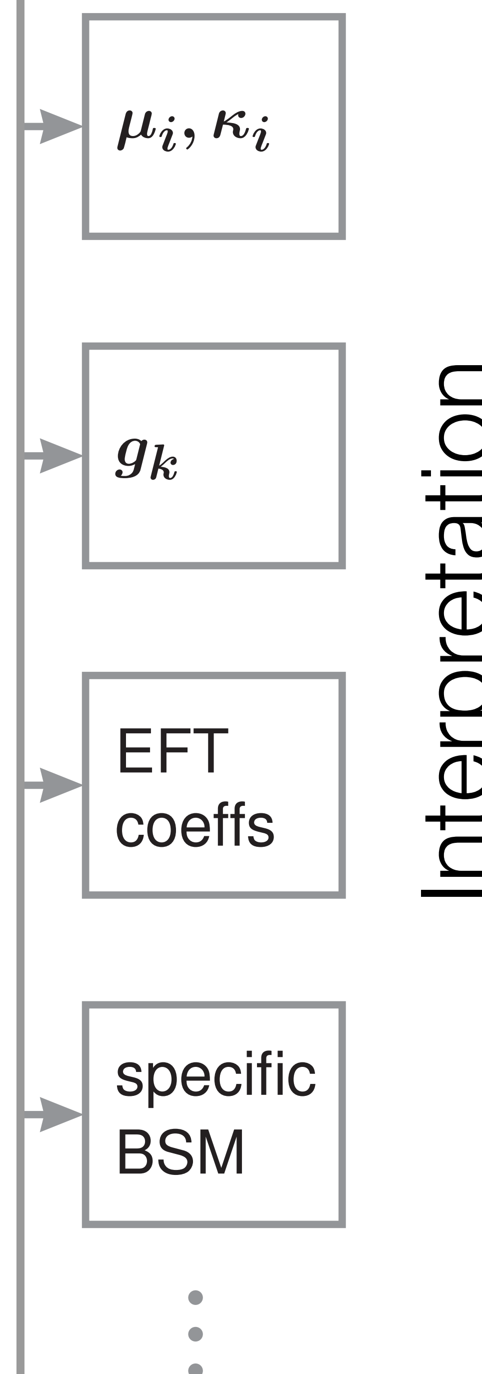
Wishlist:

- ***Maintain sensitivity to production modes***
- ***Doable for all the channels, including the one using multi-variate techniques, and allowing their combination***
- ***Easy to implement at the analysis level***
  —> more likely to happen quickly.
- ***Easy definition (i.e. not ambiguous)***
  —> easier to be compared to different theoretical predictions

Fiducial and differential measurements?

- Not easy to perform for all channels, usually can't use most powerful techniques (MVAs)

Would be good to find a doable compromise...



Simplified template cross sections

- *Starting point:*
  instead of measuring μ_{if}, measure directly $(\sigma \times B)_{if}$
  (done for the ATLAS/CMS combination paper in Run1)

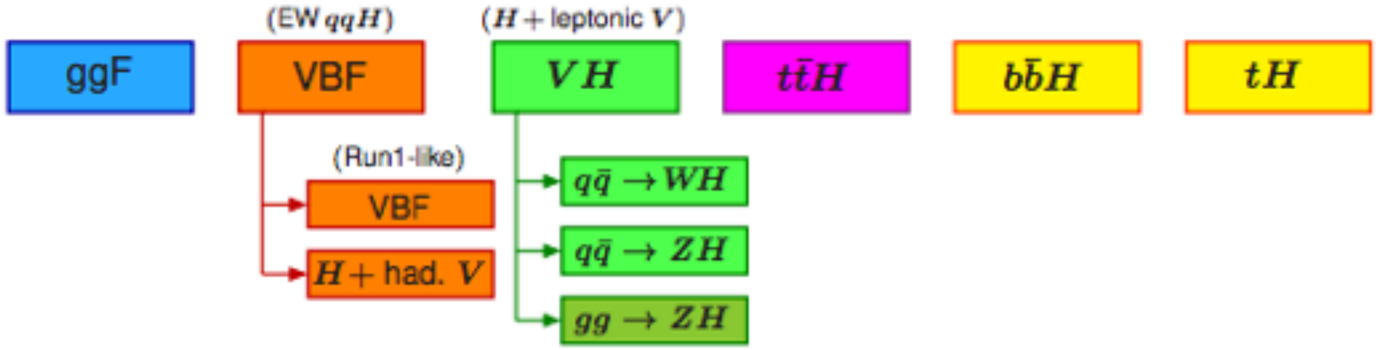
- ***stage 0 - intermediate step:*** for most of the analysis, the experimental setup has a negligible acceptance for Higgs boson rapidity $|y_H| > 2.5$.

Measure $(\sigma \times B)_{if}$ for $|y_H| < 2.5$

If some analysis can cover $|y_H| > 2.5$, perform a second measurement there

- Uncertainties on $(\sigma \times B)_{if}$ SM predictions and their correlations are not anymore affecting the measurement.

- Assumptions on SM predictions and uncertainties remains in A^{C}_{if}



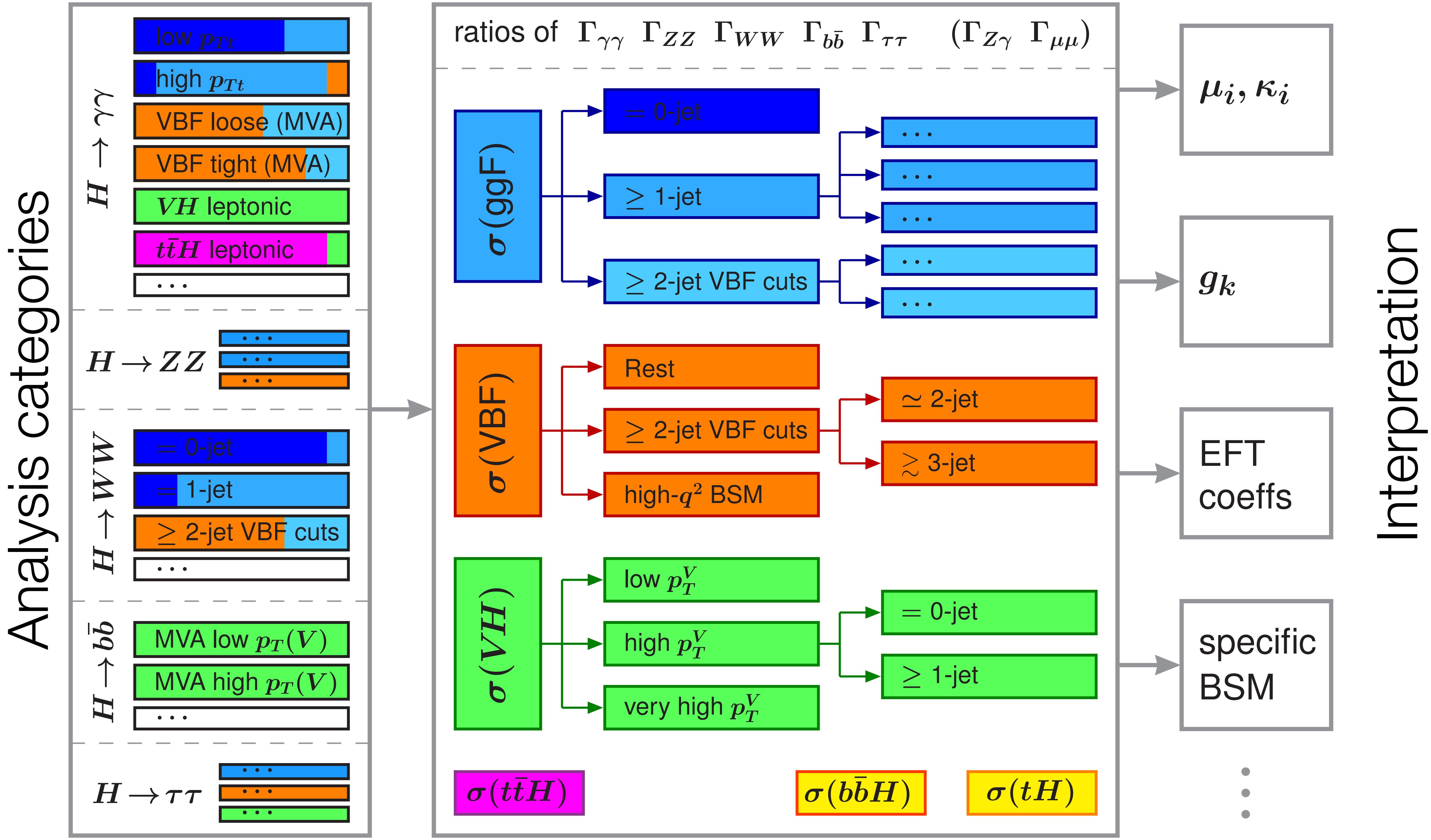
Designing the next stages

- **In stage 0, the uncertainties remains in A^{C}_{if}**
  - Are these negligible? No. i.e.: systematics due to the categorisation in #jets still important contribution. Can we do better?
- **Measure (σ x B) in well defined kinematic bin *b* : $(\sigma \times B)^{b}_{if}$ and split in sufficiently fine granular binning.**
- *Example:* measure the ggF in 0, 1, 2 jets:

$$(\sigma \times B)^{0\text{-}jets}_{ggF\,f} \qquad (\sigma \times B)^{1\text{-}jets}_{ggF\,f} \qquad (\sigma \times B)^{2\text{-}jets}_{ggF\,f}$$

- Provide correlations between these measurements
- Split in kinematic bins is production mode specific
- Connecting all the $(\sigma \times B)^{b}_{if}$ with SM assumption can still provide measurements a la Run1.
- SM theory uncertainties on $A^{C\,b}_{if}$ are still present, but much smaller due to the split in bins:
  - They depend only on the SM kinematics inside the bin.
  - If uncertainties remain, and not negligible, use them to guide how to split more granularly.
  - SM prediction acts as **template** for each bin.

Simplified template cross sections



Pros

- **No changes to experimental analysis code needed:**
  - but one can anytime decide to improve the analysis to measure a specific kinematic bin
- **No change to MC production needed:**
  - just need to split MC samples by applying the generator cuts that define the kinematic bins
- **Well defined kinematic bins (proposed in YR4):**
  - it should be unambiguous how to get SM and BSM predictions for each of these bins

How to define the bins?

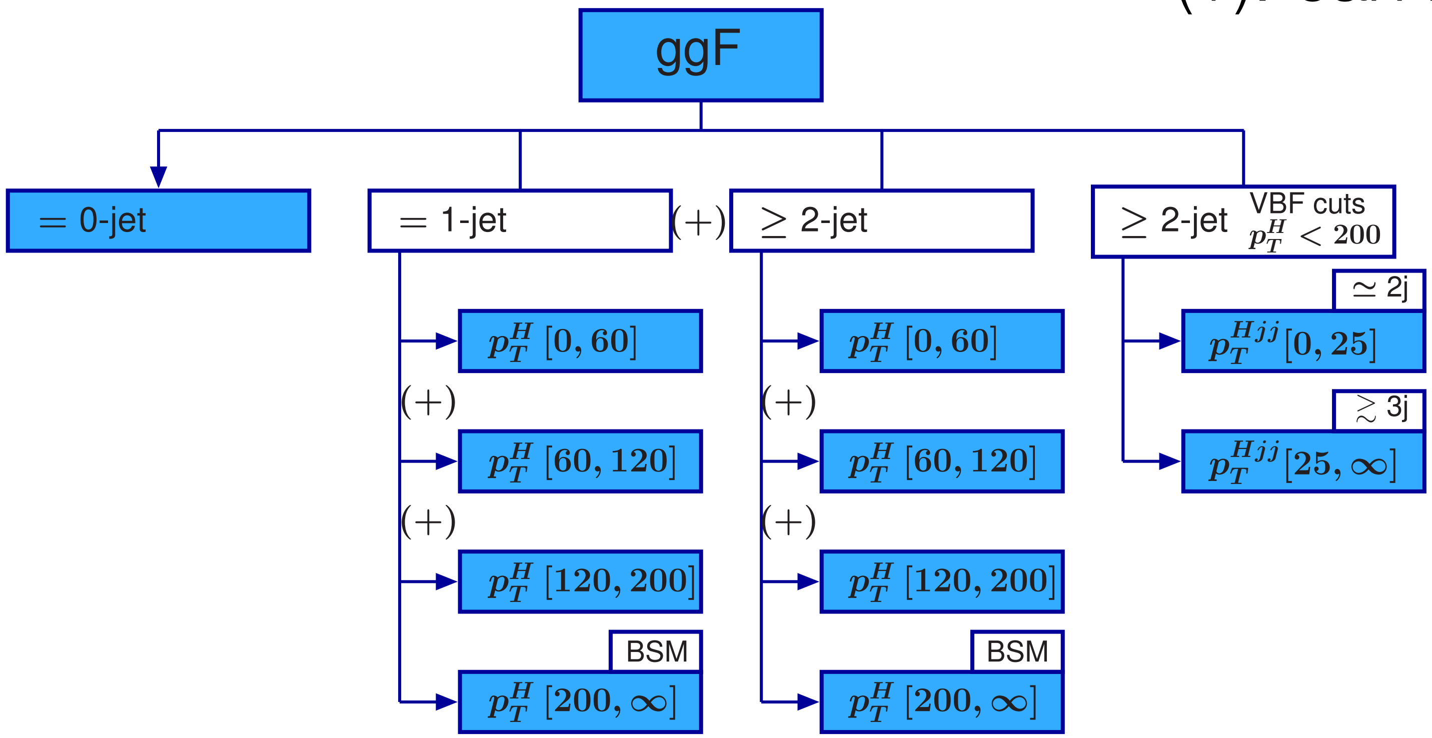
- **Identify kinematic bins that are more important to separate out from theory side**
  - Largest theory systematics
  - BSM sensitivity
- **Minimise residual theory dependence**
  - Try to align bins with analysis cuts to minimise the extrapolations
- **Bin definition can evolve with statistics**
  - Individual analysis can quote sum of bins while sensitivity is still limited
  - Limits on overflow bins are interesting for BSM even with limited statistics

Truth final state particles

- **Truth final state particles need to be defined unambiguously for the binning**
    - Definition kept **simpler and more idealised** than in the fiducial cross section measurements.
- **Higgs boson:**
    - on-shell Higgs boson, $|y_H| < 2.5$, treated as final state particle, to allow the combination of different decay channels.
- **Leptons:**
    - **Electrons and muons** from decays of signal vector bosons, e.g. from VH production, are defined as dressed i.e. FSR photons should be added back to the electron or muon.
    - **τ leptons** are defined from the sum of their decay products (for any τ decay mode).
    - No restriction on the transverse momentum or the rapidity of the leptons.
- **Jets:**
    - **anti-kt jets** with a jet radius **R = 0.4, p_T> 30 GeV**, no restriction on rapidity
    - All stable particles included (lifetime greater than 10 ps),
      but decay products from the **Higgs boson decay**, and **leptons** from **decays of signal vector bosons**

ggF - Stage 1

(+): can be merged together



- The #jets bins are motivated by the use of jet bins in the experimental analyses.
    - Introducing them also for the simplified template cross sections avoids folding the associated theoretical uncertainties into the measurement.
- The bins with VBF topology cuts are motivated by the wish to separately measure the gluon fusion contamination in the VBF selection
    - The #jets >= 2 with VBF topology cuts is excluded from the #jets >= 2 bins.

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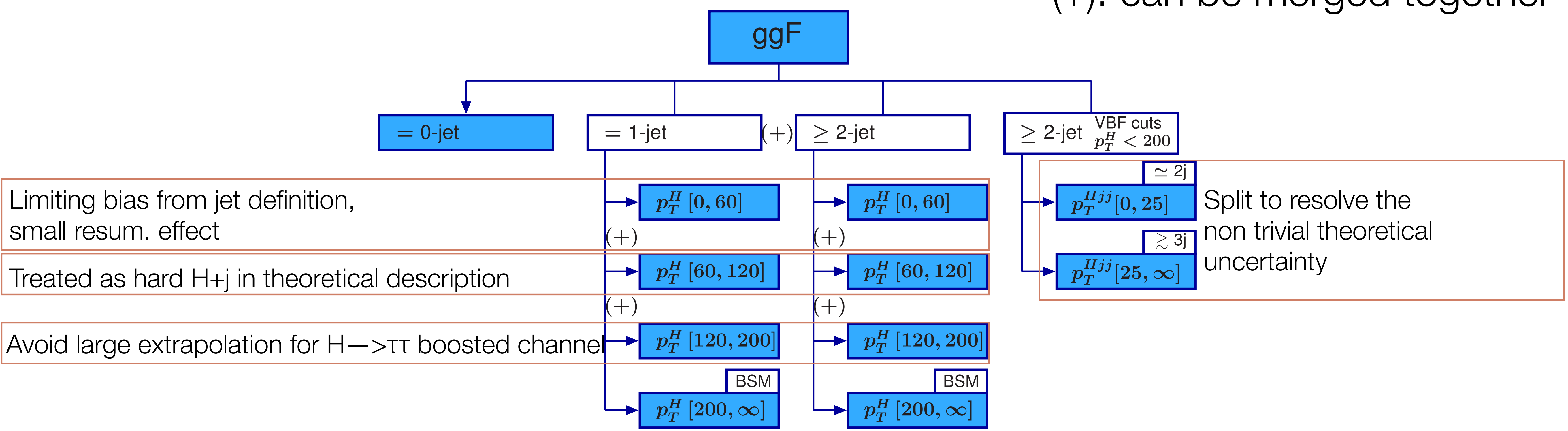

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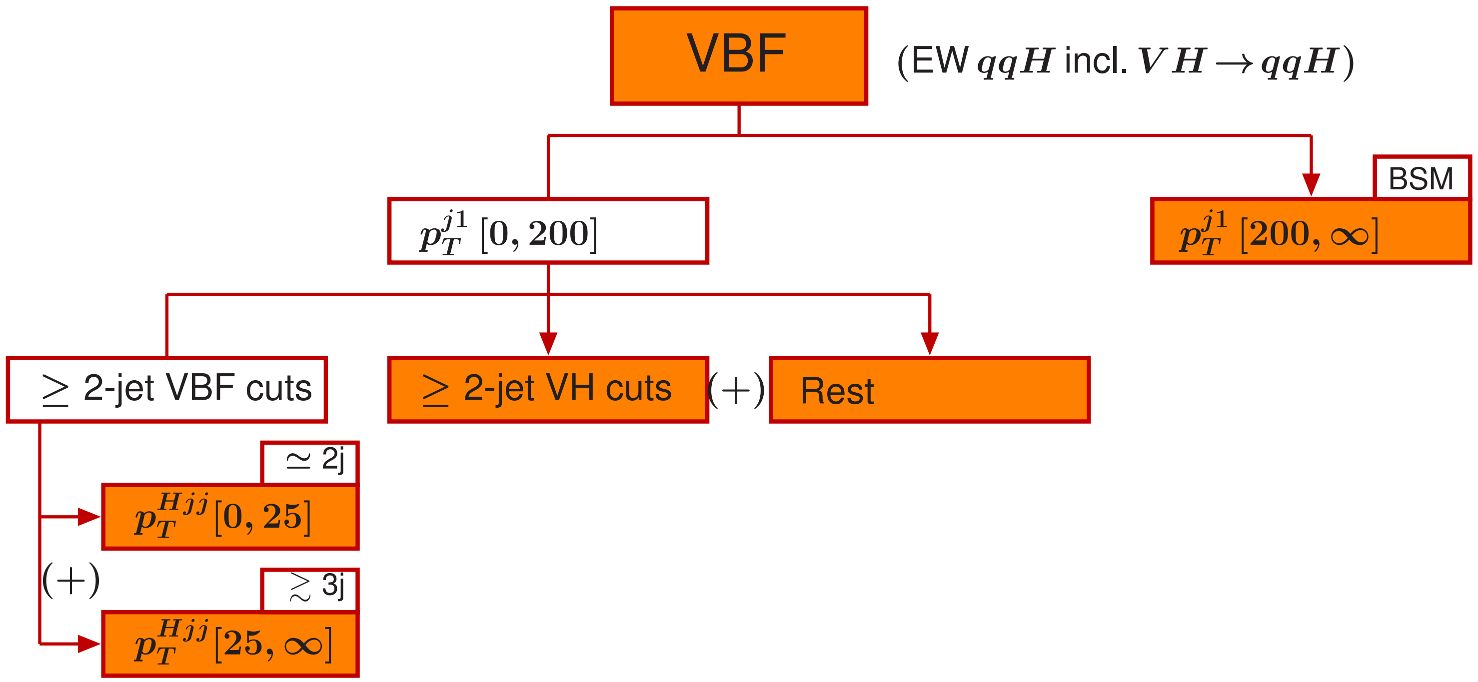
VBF - Stage 1

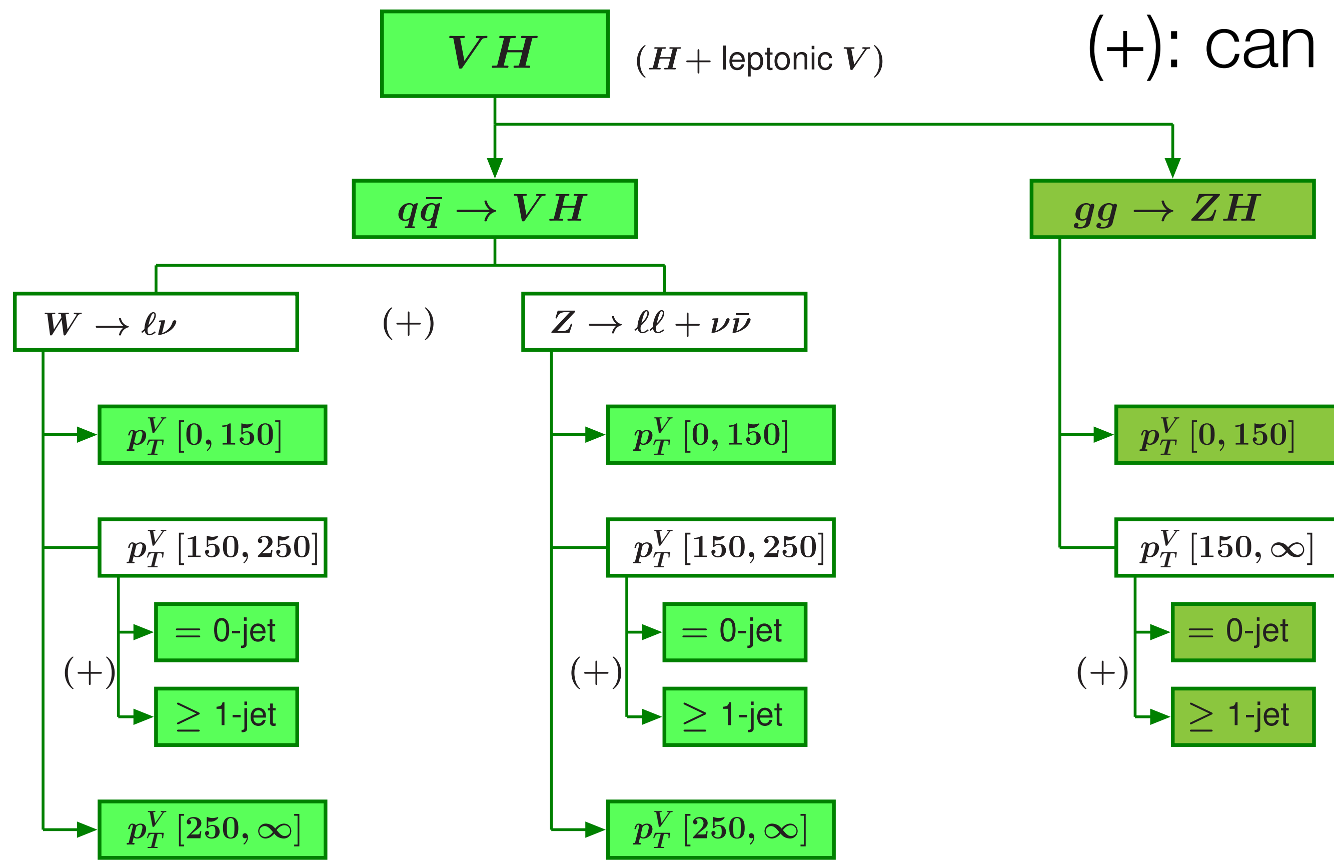
(+): can be merged together



- VBF defined as as electroweak qqH production, which includes both VBF and VH with hadronic V decays
- VBF cuts: m_{jj} > 400 GeV, $d\phi_{jj}$ > 2.8 (compromise among the various VBF selection in analyses)
  - p_T^{Hjj} is chosen as a compromise between the different kinematic variables used by different channels to enrich VBF production (p_T^{j3}, $d\phi_{H-jj}$)
- VH cuts: 60 < m_{jj} < 120

VH leptonic - Stage 1

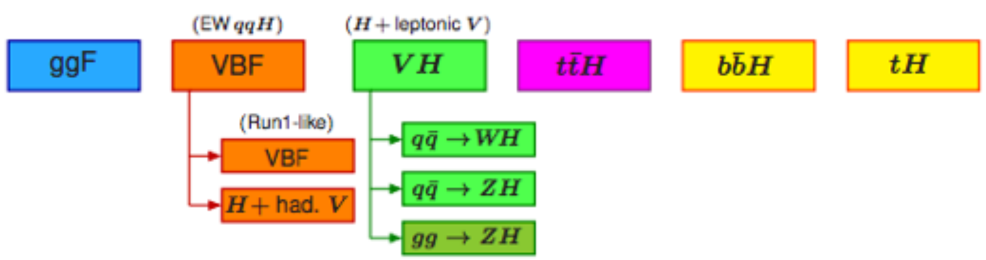
(+): can be merged together



- Split in qq->VH and gg->ZH
  - ambiguous at higher order - defined according to the MC samples used in the analyses
- Separation for p_T^V = 150 GeV to avoid large extrapolation for ZH->vvbb channel (which uses an EtMiss trigger with efficiency above ~150 GeV).
- The split #jets reflecting the different experimental sensitivity and reduces the theoretical dependence
- Bins for p_T^V >250 GeV particularly sensitive to BSM scenarios.

Where are we? Stage 0

- First preliminary implementation in ATLAS: ATLAS-CONF-2016-081



- **ggF (= ggH+bH), VBF, VHhad, VHlep, top (= ttH+tH)**

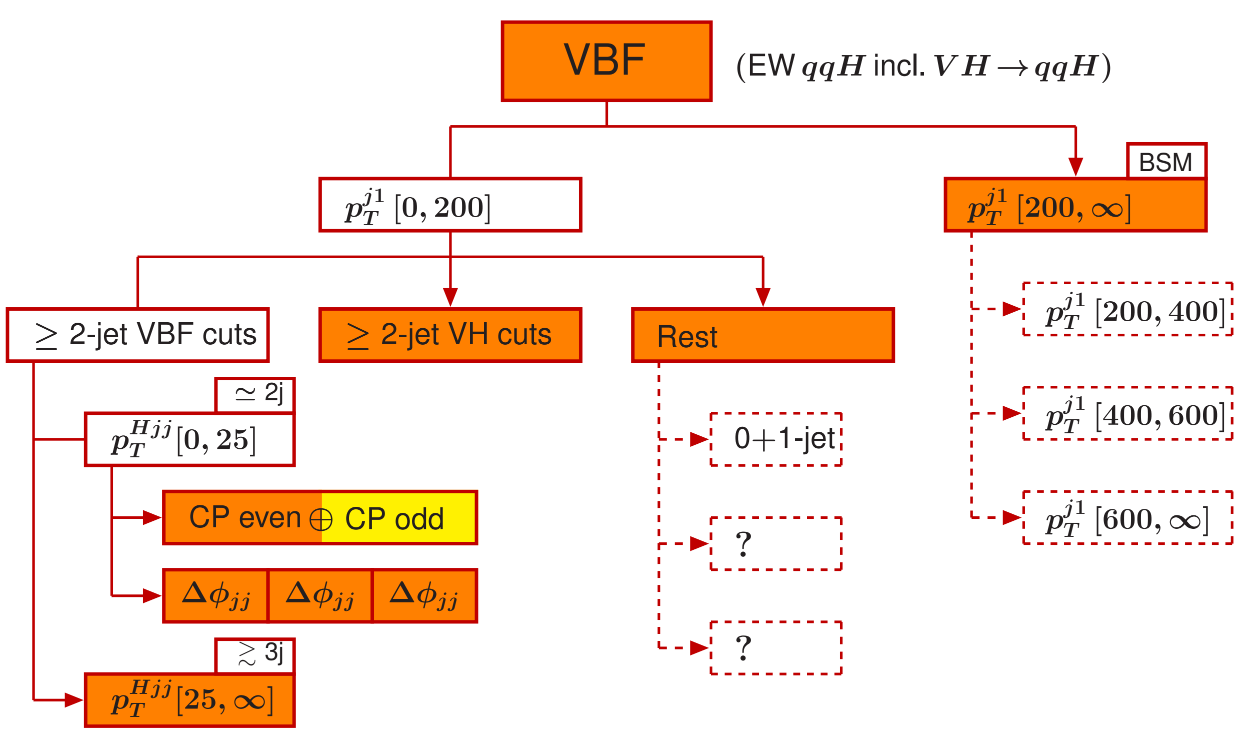
SM predictions with $|y_H| < 2.5$ are needed for comparisons.

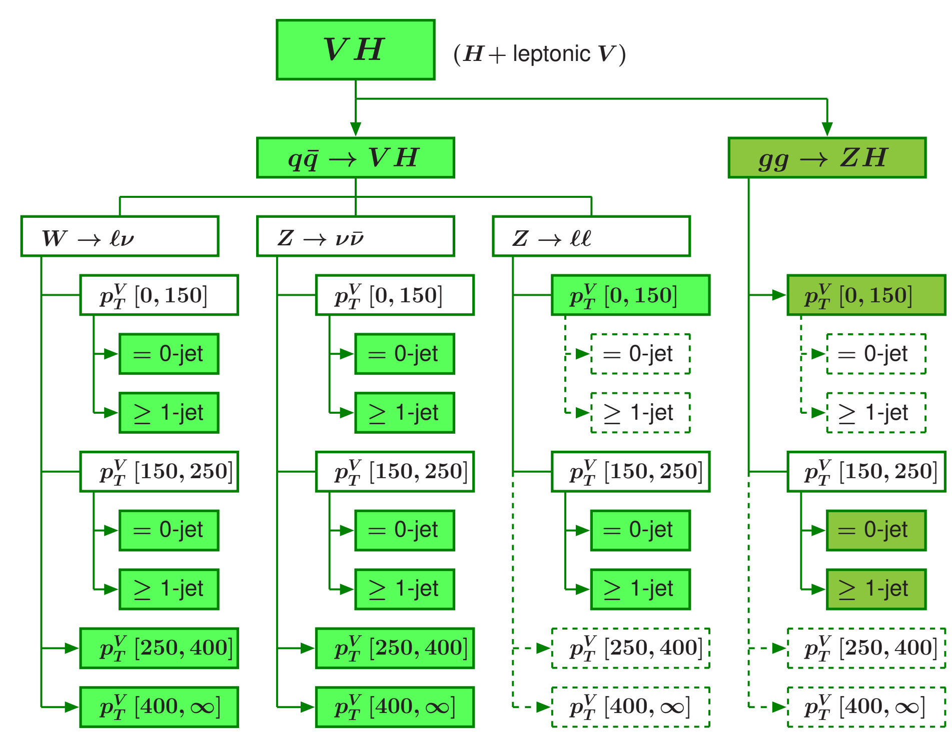
Collecting status-of-art SM predictions and uncertainties for each bin would be useful.

Beyond Stage 1

- Details on how to evolve the binning with higher luminosity is very difficult before having gained experience with the practical implementation of the framework with the stage 1 binning.

- Only indications of interesting further separation of bins that should be considered for the stage 2 binning.



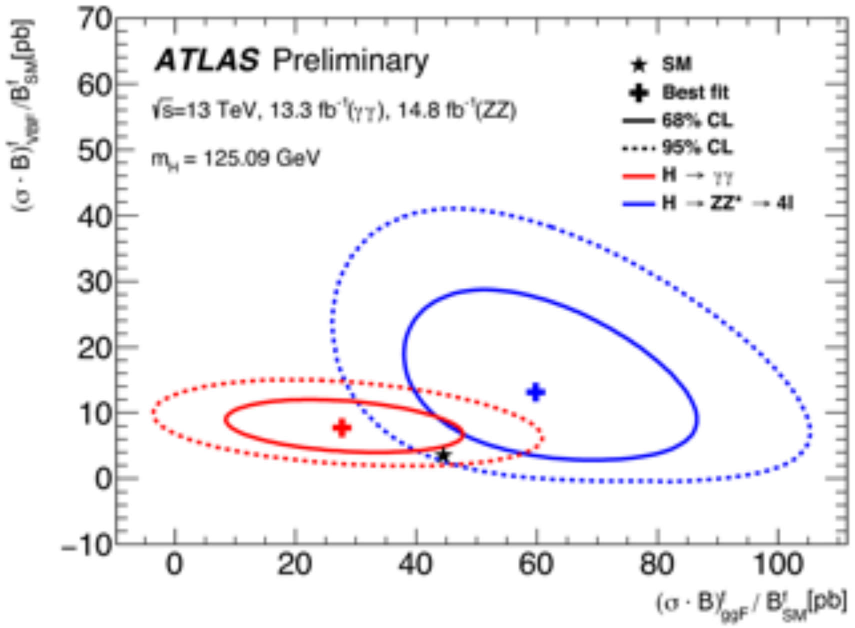


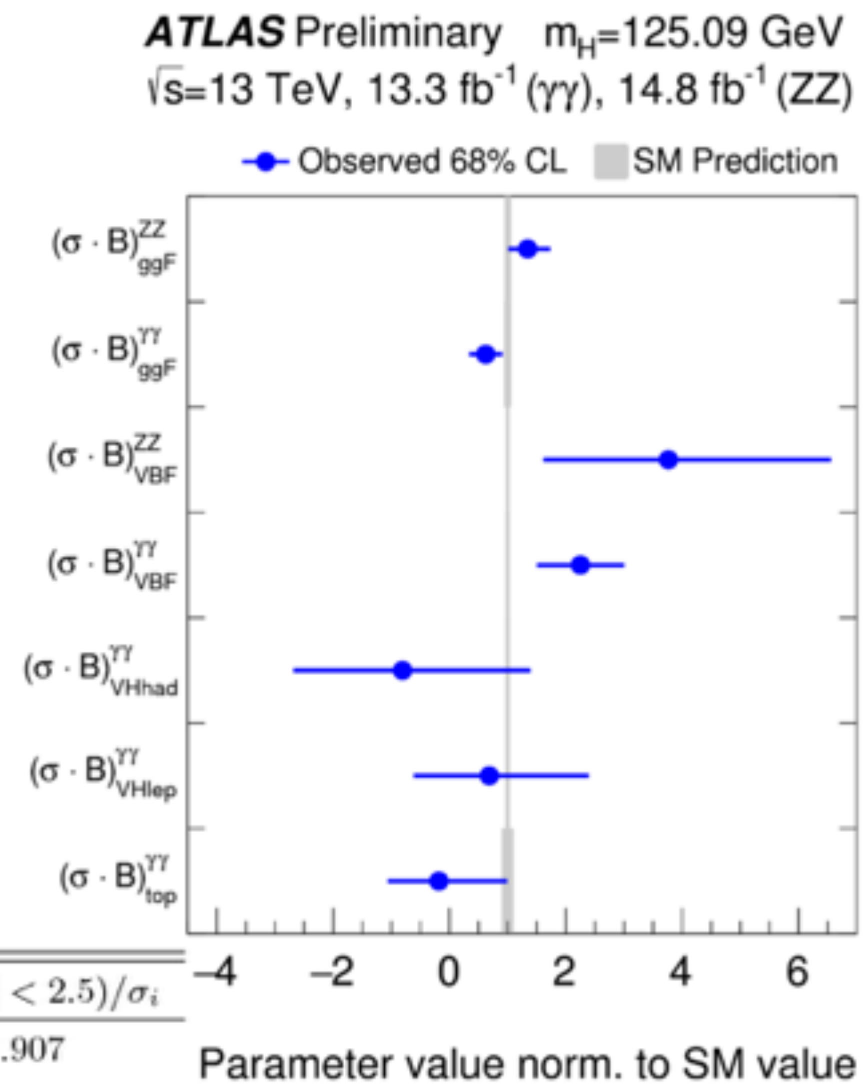
Conclusions

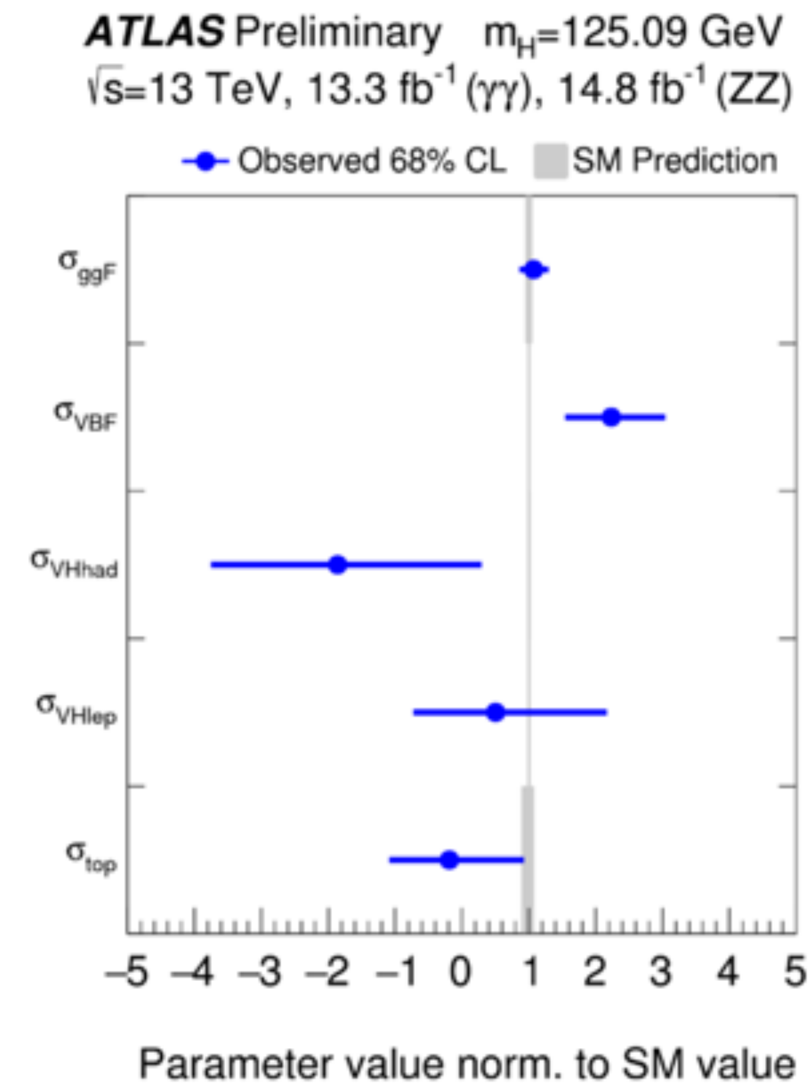
- **Simplified Template Cross Sections are a proposed framework in the path from discovery to precisions measurements.**
- Designed to:
  - provide more **finely-grained measurements**, while at the same time allowing and **benefitting from the global combination** of the measurements in all decay channels
  - make a measurement in kinematic bins covered by the experimental setup, **limiting extrapolations**.
  - **reduce** the impact of the **theory assumptions/bias folded in the measurement**.
    - on the long term, the measurements can still be compared with new theory calculations when available.
  - get measurements/limits in **bins particularly sensitive to BSM scenarios**
  - **easy to implement** at the analysis level (evolution of signal strength measurements)
  - **unambiguous definition** of the kinematic bins
- First LHC measurements for Stage 0 already done, we hope more to come.
  - Collecting SM (and BSM) predictions for the different bins, and providing tools (Rivet?) to share the definition of the binning can be a good way to harmonise the efforts for the next LHC Higgs boson measurements.

Backup

First Run2 results using Simplified Template XS







Process	Contributing to	$\sigma_i(\lvert y_H \rvert < 2.5)/\sigma_i$
$gg \to H$	ggF	0.907
$qq' \to qq'H$	VBF	0.932
$q\bar{q}' \to WH(W \to \text{had.})$	VHhad	0.870
$q\bar{q}/gg \to ZH(Z \to \text{had.})$	VHhad	0.900
$q\bar{q}' \to WH(W \to \text{lep.})$	VHlep	0.869
$q\bar{q} \to ZH(Z \to \text{lep.})$	VHlep	0.900
$gg \to ZH(Z \to \text{lep.})$	VHlep	0.965
$q\bar{q}/gg \to t\bar{t}H$	top	0.985