Simplified Template Cross Sections

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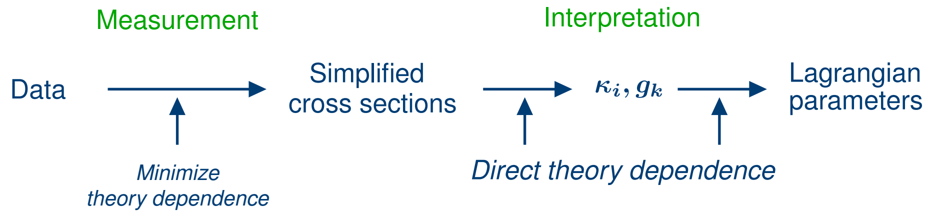
with input from many discussions and people

11th Workshop of the LHC Higgs Cross Section Working Group

January 14, 2016

Evolving the μ measurements.

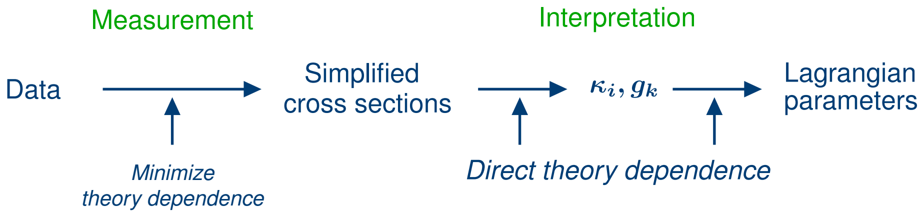


Goal

- Evolution of the μ and κ measurements as Higgs combination
- Serve as input to global interpretations (κ fits, EFT studies, ...)
- Complementary to differential cross section measurements
  - Differential cross sections are optimized for model independence
  - Simplified template cross sections are optimized for sensitivity while also minimizing theory dependence

Introduction to simplified template cross sections at summer 2015 workshop: `link`

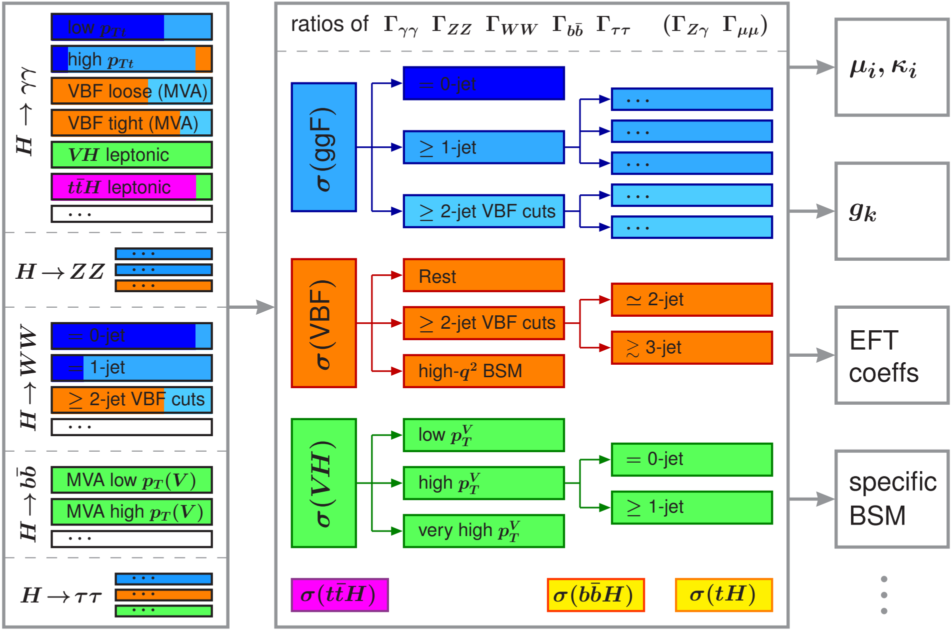
Evolving the μ measurements.



Features

- Minimize theory uncertainties in measurements
  - Clearer and systematically improvable treatment at interpretation level
- Measurements stay long-term useful
- Decouples measurements from discussions about specific models
- Allows for interpretation with different model assumptions/BSM scenarios
  - μ_i, κ_i, effective couplings, EFT coefficients, specific models
- Can be combined with decay pseudo observables in the interpretation

Simplified template cross section framework.



Comparing fiducial with simplified template.

fiducial	simplified template
Agnostic to production modes	xsec split by production mode
Optimized for theory independence	Optimized for sensitivity while minimizing theory dependence
$\longrightarrow$ Minimize acceptance corrections $\longrightarrow$ Simple (rectangular) acceptance cuts $\longrightarrow$ "Exact" fiducial volume $\longrightarrow$ Fiducial in Higgs decay	$\longrightarrow$ Allow larger acceptance corrections $\longrightarrow$ Allow event categories, MVAs, ... $\longrightarrow$ Abstracted/simplified fiducial volumes $\longrightarrow$ Inclusive in Higgs decay
(Single-)differential distributions (overlapping events)	Split xsec into mutually exclusive regions of phase space
(Now) only $H \rightarrow \gamma\gamma, 4\ell, WW$	Explicitly designed for combination of all decay channels

Basic design principles.

- Identify phase-space regions that are most important to separate out from the theory side
  - Where are largest theory systematics (e.g. ggF jet bins)
  - BSM sensitivity/interpretation
- Try to minimize residual theory dependence
  - Split in production modes eliminates uncertainty from production mode dependence
  - Avoid non-constant acceptance within one bin
    - If not enough statistics to split, assign uncertainties
  - Try to align cuts with experimental categories to reduce extrapolations (e.g. reason to use p_T^V instead of m_{VH})
  - Still have to keep MVAs in check to avoid uncontrolled theory systematics
- Bin definitions can evolve with statistics
  - Individual analyses can quote sum of bins while sensitivity is still limited
  - In BSM "overflow" bins even limits are very interesting
  - Can split into more fine-grained bins as required and allowed by statistics (previous determinations remain useful)

Object definitions.

Higgs boson

- On-shell Higgs boson with $|Y_H| < 2.5$
  - If any sensitivity to higher rapidity e.g. from use of forward electrons, add additional bin for $|Y_H| > 2.5$

Particles produced in addition to the Higgs boson:

Jets (from VBF, $V \to jj$, ...)

- Anti-k_t jets with $R = 0.4$ built from all stable particles, including neutrinos and leptons from hadron decays
  - All Higgs decay products should be removed
- $p_T^j > 25$ or 30 GeV, no rapidity cut
  - 25 GeV would split events more evenly, feedback from experiments welcome

Leptons (from $V \to \ell\ell/\ell\nu$, ...)

- Electrons and muons should be dressed, if ever relevant, τ to be defined from decay products
- No p_T^ℓ or rapidity cut

Staging.

- Impossible to define a set of bins perfect for every analysis
- Aim to find a good compromise
  - Only split into bins with “sufficiently good reason”
  - Typically some decay channels will only be able to constrain the sum of certain bins
- Define different “stages”
  - Evolution of different production modes can take place independently
- Stage 0: closest correspondence to Run1
- Stage 1
  - All “minimally hoped-for” splits
  - Intermediate steps to get there indicated by “(+)” for possible merging of bins
  - Early measurements will show if adjustments are needed, but should try to avoid changes unless serious problems arise
- Stage 2
  - Difficult to do without any real-life experience
  - Here: indications of what could be interesting

Comments on practical implementation.

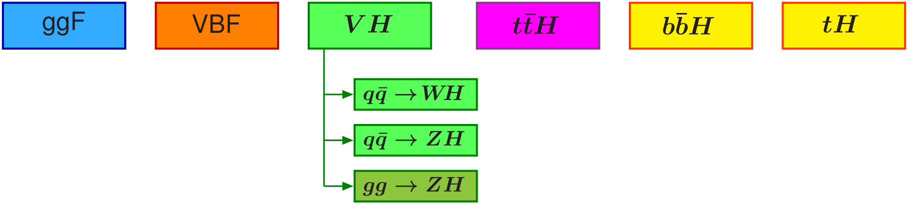
Ideally...

- Every analysis implements the full binning from the beginning (even if there is no sensitivity for a full fit)

Realistically...

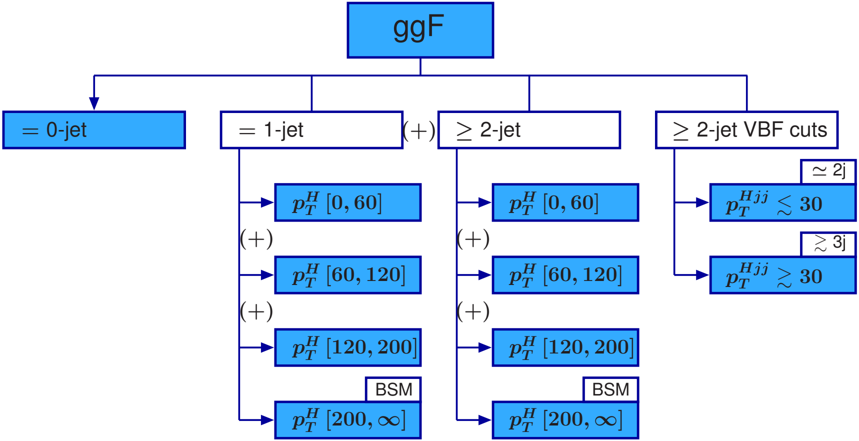
- Each analysis implements the binning according to the appropriate stage
- Bins will be merged compared to the full binning
  - Signal acceptance for the merged bins is $\sim$the same: bin can be split in the combination
    - Unbiased, only some loss in sensitivity
  - Signal acceptence for the merged bins is not the same: estimation of induced uncertainties
    - If at all possible, prefer to implement the split

Stage 0.



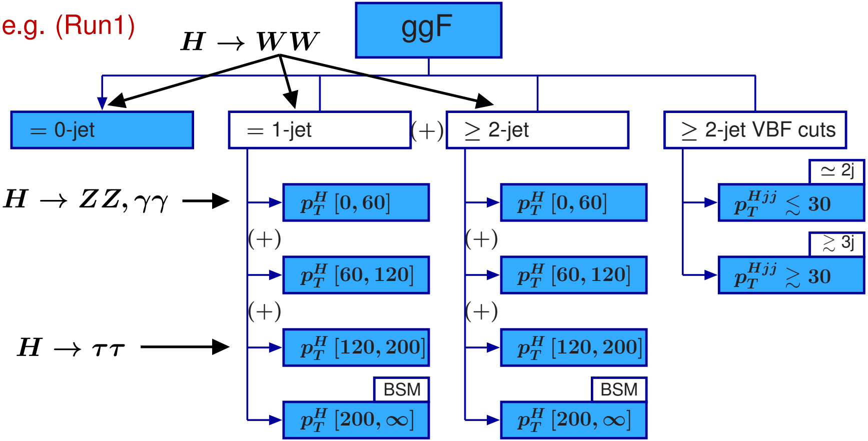
- Inclusive cross section per production mode
  - ggF, VBF, VH and $t\bar{t}H$
    - Split VH into WH and ZH, and/or $q\bar{q} \to VH$ and $gg \to VH$
  - Once meaningful, $b\bar{b}H$ and tH
- Closest correspondence to production-mode μ measurements, but expressed in terms of cross sections and restricted to $|Y_H| < 2.5$

Gluon fusion – Stage 1.



- Jet bins motivated by experimental needs, split reduces theory dependence
  - Run1 analyses needed to apply ggF signal uncertainties related to jet binning
- Stage 2 to be defined

Gluon fusion – Stage 1.



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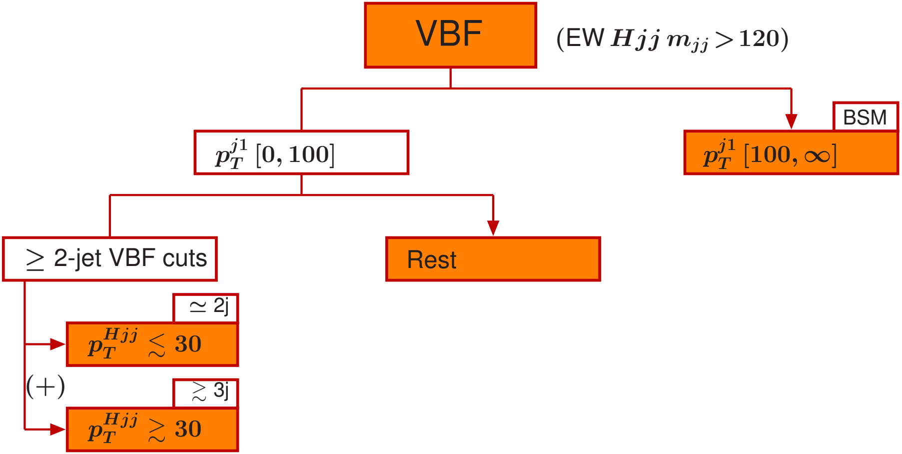
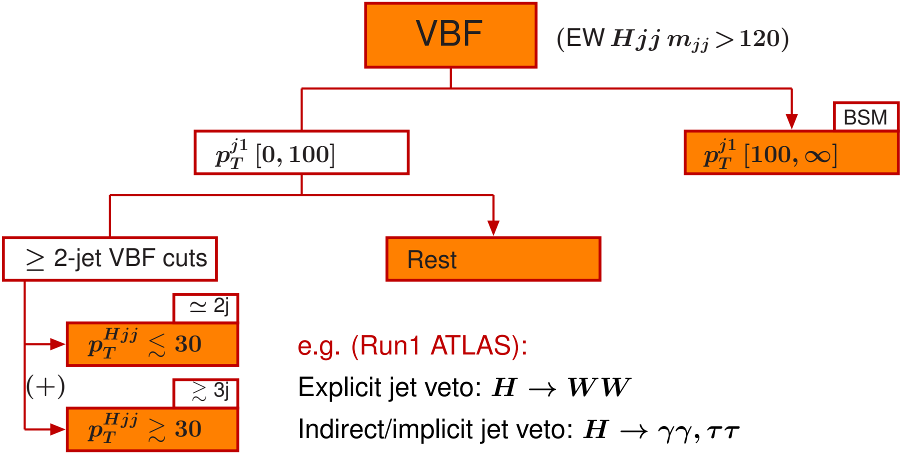
VBF – Stage 1



- Truth definition $m_{jj} > 120$ GeV to separate from $V(\to jj)H$
- VBF cuts: m_{jj} and $\Delta\eta_{jj}$, cut values **to be defined**
- p_T^{Hjj} cut might be 25 GeV, in sync with truth jet definition



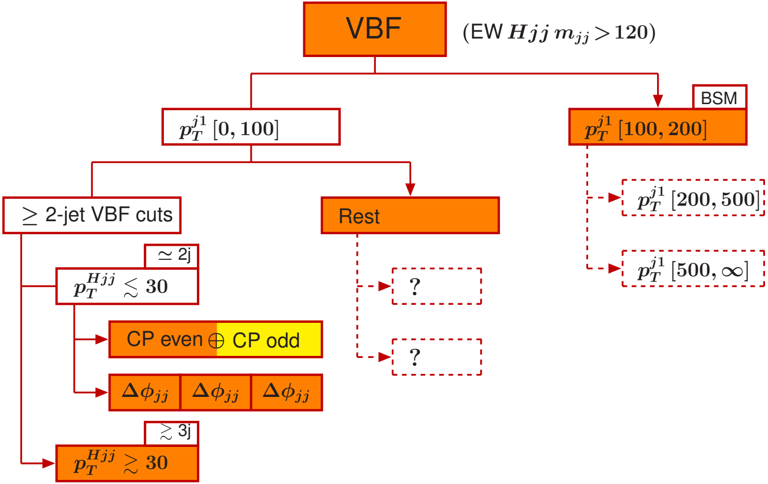
e.g. (Run1 ATLAS):

Explicit jet veto: $H \to WW$

Indirect/implicit jet veto: $H \to \gamma\gamma, \tau\tau$

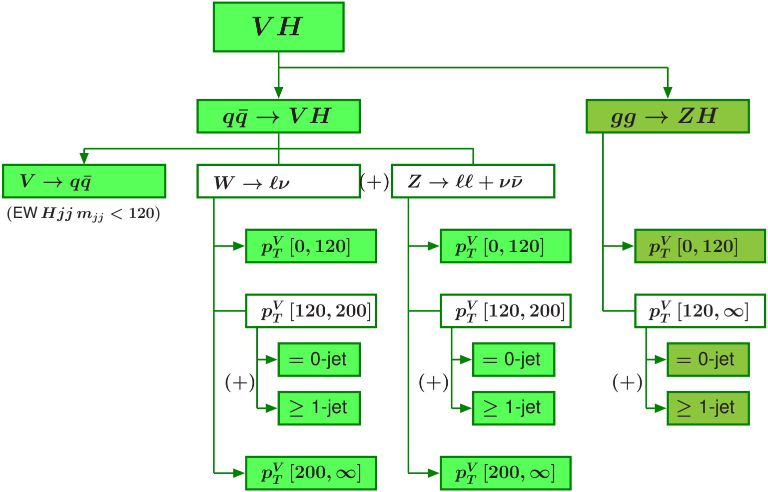
- Truth definition $m_{jj} > 120$ GeV to separate from $V(\to jj)H$
- VBF cuts: m_{jj} and $\Delta\eta_{jj}$, cut values **to be defined**
- p_T^{Hjj} cut might be 25 GeV, in sync with truth jet definition

VBF – Stage 2.



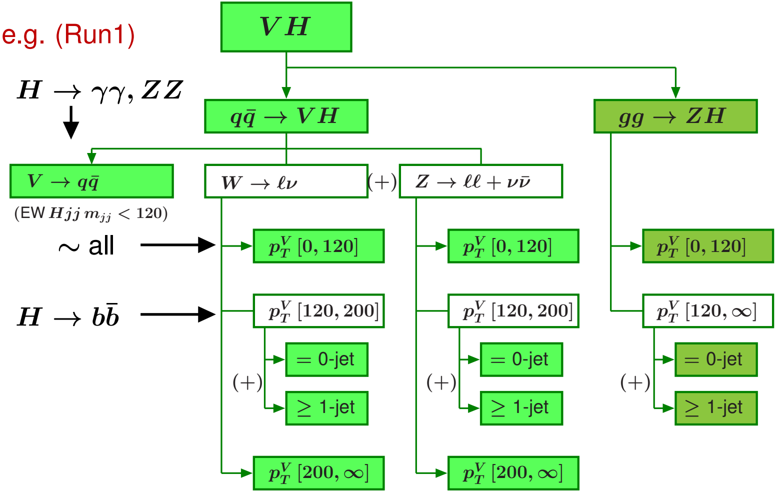
- Add sensitivity to CP odd
  - Details need studies, could be bins in $\Delta\phi_{jj}$ or a continuous parameter
- Separate into “tight” and “loose” VBF cuts

VH – Stage 1.



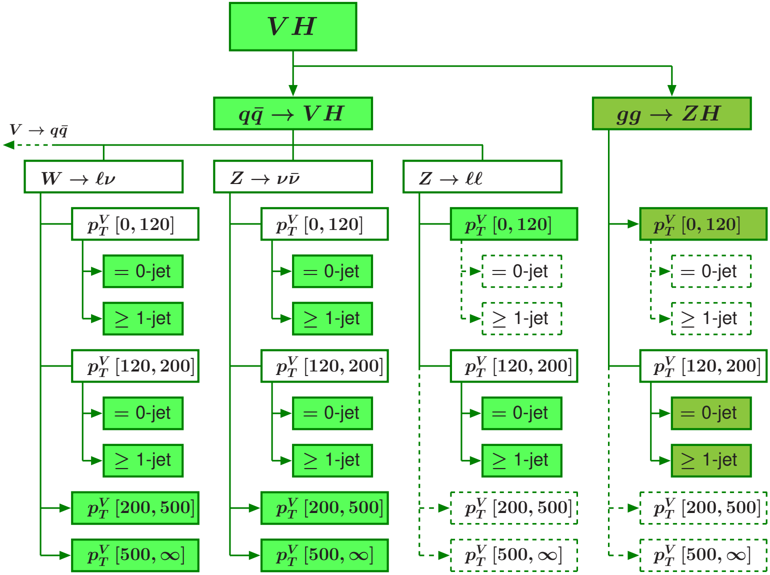
- Numerical values (120 and 200 GeV) might be adjusted following ongoing studies

VH – Stage 1.



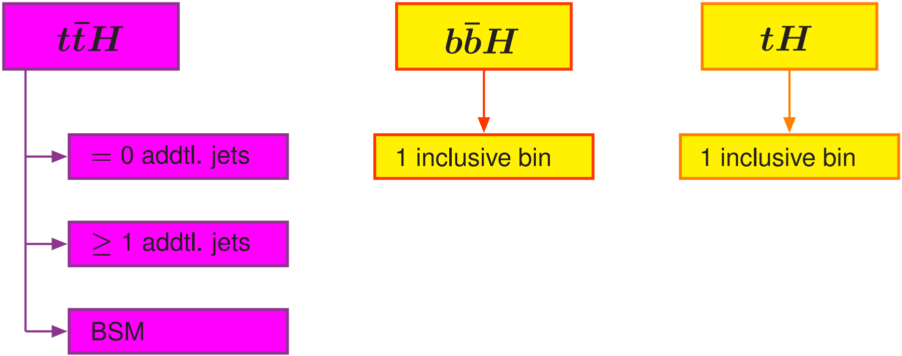
- Numerical values (120 and 200 GeV) might be adjusted following ongoing studies

VH – Stage 2.

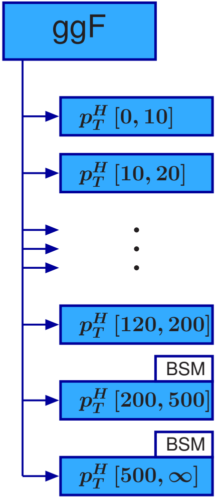


VH
$q\bar{q} \to VH$
$gg \to ZH$
$V \to q\bar{q}$
$W \to \ell\nu$
$Z \to \nu\bar{\nu}$
$Z \to \ell\ell$
p_T^V [0, 120]
= 0-jet
≥ 1-jet
p_T^V [120, 200]
= 0-jet
≥ 1-jet
p_T^V [200, 500]
p_T^V [500, ∞]

Other production modes – Stage 2.



Simplified template differential cross sections.



Supplementary to primary bins

- Same framework can be used to extract differential cross sections per production mode, e.g. p_T^H for ggF
  - Interesting e.g. for QCD studies in ggF
  - Need to evaluate correlations with simplified template cross sections in case both are used for specific interpretation
- Might be an interesting application, but not meant as a replacement for fiducial differential cross section measurements

Status and plans for YR4.

- Introduction and motivation for simplified template cross sections
- Discussion of object definitions
- Discussion of design principles for bins and staging
- As detailed as possible description of stage 1 (with intermediate stages)
  - Concrete numbers whereever possible, with notes for cases where feedback is expected from early analyses
  - Short experimental or theoretical motivation for each bin
- Ideas and thoughts on stage 2
- First draft under way, to be finalized until the end of February

Backup

Trying to get the best of "both worlds".

More differential/fine-grained compared to current μ fits

- Further split production modes into kinematic bins
- Fit for cross sections instead of μ_i

Simplified template compared to full-fledged fiducial cross sections

- Inclusive over the Higgs decays
  - Can perform global combination of channels
- Bin definitions are *per production mode* and simplified/abstracted from the actual measurement categories
  - Analyses can use optimized selections at reconstruction/analysis level
  - Different production modes can have different efficiencies/acceptances *without* incurring dependence on SM production mode mix

$\Rightarrow$ Maximize sensitivity while reducing theory dependence

Definition of simplified template cross sections.

Consider schematic μ fits:

$$\sigma_1^{\text{meas}} = A_1^{ggH} \times \mu_{ggH} \times \sigma_{ggH}^{\text{SM}} \quad + \quad A_1^{\text{VBF}} \times \mu_{\text{VBF}} \times \sigma_{\text{VBF}}^{\text{SM}}$$

$$\sigma_2^{\text{meas}} = A_2^{ggH} \times \mu_{ggH} \times \sigma_{ggH}^{\text{SM}} \quad + \quad A_2^{\text{VBF}} \times \mu_{\text{VBF}} \times \sigma_{\text{VBF}}^{\text{SM}}$$

$$\sigma_3^{\text{meas}} = \cdots$$

- σ_i^{meas} are the measured analysis categories/selections
- A_i^{ggH}, A_i^{VBF} are acceptances for SM processes
  - theory-dependent

Definition of simplified template cross sections.

Consider schematic μ fits:

$$\begin{aligned}
\sigma_1^{\text{meas}} &= A_1^{ggH} \times \underbrace{\mu_{ggH} \times \sigma_{ggH}^{\text{SM}}}_{} &+& \quad A_1^{\text{VBF}} \times \underbrace{\mu_{\text{VBF}} \times \sigma_{\text{VBF}}^{\text{SM}}}_{} \\
&= A_1^{ggH} \times \quad \sigma_{ggH} &+& \quad A_1^{\text{VBF}} \times \quad \sigma_{\text{VBF}} \\
\sigma_2^{\text{meas}} &= A_2^{ggH} \times \underbrace{\mu_{ggH} \times \sigma_{ggH}^{\text{SM}}}_{} &+& \quad A_2^{\text{VBF}} \times \underbrace{\mu_{\text{VBF}} \times \sigma_{\text{VBF}}^{\text{SM}}}_{} \\
&= A_2^{ggH} \times \quad \sigma_{ggH} &+& \quad A_2^{\text{VBF}} \times \quad \sigma_{\text{VBF}} \\
\sigma_3^{\text{meas}} &= \cdots
\end{aligned}$$

- σ_i^{meas} are the measured analysis categories/selections
- A_i^{ggH}, A_i^{VBF} are acceptances for SM processes
  - theory-dependent
- First: Directly fit for σ_{ggH}, σ_{VBF} rather than μ_{ggH}, μ_{VBF}
  - In the SM: Correspond to total ggH and VBF production cross sections

Definition of simplified template cross sections.

Next: Split each production mode into several kinematic bins a, b, c, ...

$$\sigma_1^{\mathrm{meas}} = A_{1a}^{ggH} \times \sigma_{ggH}^{a} + A_{1b}^{ggH} \times \sigma_{ggH}^{b} + A_{1c}^{\mathrm{VBF}} \sigma_{\mathrm{VBF}}^{c} + \cdots$$

$$\sigma_2^{\mathrm{meas}} = A_{2a}^{ggH} \times \sigma_{ggH}^{a} + A_{2b}^{ggH} \times \sigma_{ggH}^{b} + A_{2c}^{\mathrm{VBF}} \sigma_{\mathrm{VBF}}^{c} + \cdots$$

$$\sigma_3^{\mathrm{meas}} = \cdots$$

- Separately fit bin cross sections σ_{ggH}^{a}, σ_{ggH}^{b}, $\sigma_{\mathrm{VBF}}^{c}$, ...
- A_{ij}^{ggH}, A_{ij}^{VBF} only depend on SM kinematics *inside* a given bin
  - If this becomes a problem, split the bin
  - SM processes act as kinematic templates (SM acts as “simplified model”)
  - If necessary, can add more kinematic templates (e.g. CP-odd Higgs)

⇒ Direct extension of existing framework, can be implemented by experiments straightforwardly on top of existing MC samples