Simplified Template Cross Sections

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YR4 section: Michael Duehrssen, Paolo Francavilla, FT, Kerstin Tackmann

Contributions and feedback from many people in Les Houches and WG2

Particular thanks to Dag Gillberg and Jim Lacey for feedback

Goals and Features.

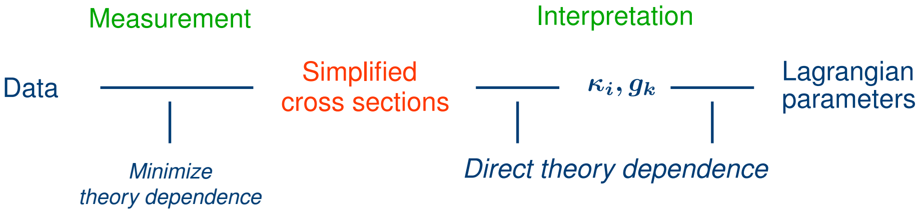
Measurement | Interpretation

Data — Simplified cross sections — κ_i, g_k — Lagrangian parameters

Minimize theory dependence | *Direct theory dependence*

- Provide interface between Measurement and Interpretations
  - Evolution of the μ and κ measurements as Higgs combination
  - Serve as input to global interpretations (κ fits, EFT studies, ...)
- Minimize theory dependence in measurements
  - Shift treatment of (dominant) theory uncertainties to interpretation level
  - Decouples measurements from specific interpretation/model assumptions/BSM scenarios
  - Measurements stay long-term useful

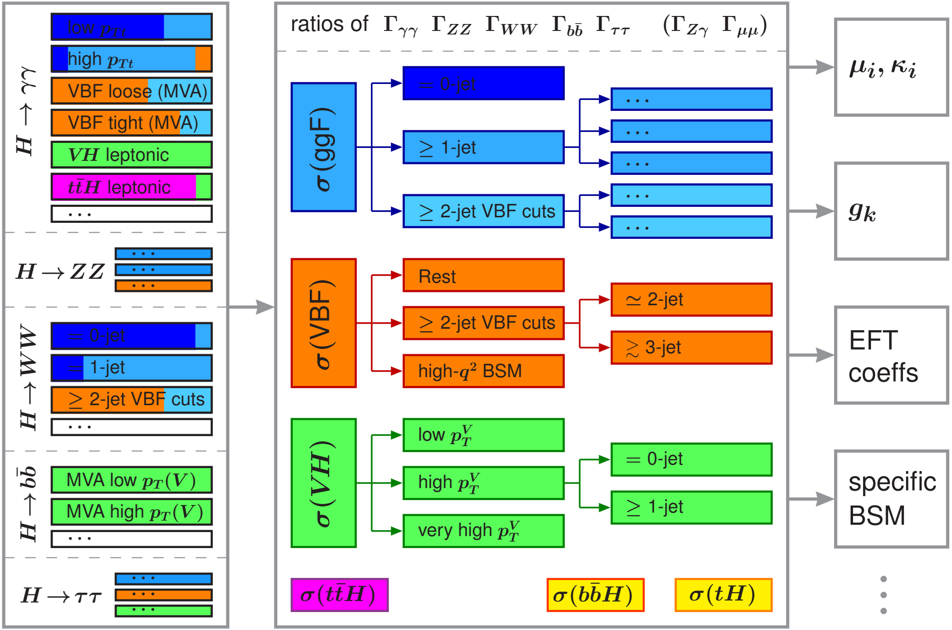
Goals and Features.



- 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

$\Rightarrow$ For more detailed intro see talks at previous workshops `here` and `here` and YR4 section.

Overview.



low p_{Tt}
high p_{Tt}
VBF loose (MVA)
VBF tight (MVA)
VH leptonic
$t\bar{t}H$ leptonic
...
$H \to \gamma\gamma$
$H \to ZZ$
= 0-jet
= 1-jet
≥ 2-jet VBF cuts
$H \to WW$
MVA low $p_T(V)$
MVA high $p_T(V)$
$H \to b\bar{b}$
$H \to \tau\tau$
ratios of $\Gamma_{\gamma\gamma}$ Γ_{ZZ} Γ_{WW} $\Gamma_{b\bar{b}}$ $\Gamma_{\tau\tau}$ ($\Gamma_{Z\gamma}$ $\Gamma_{\mu\mu}$)
σ(ggF)
= 0-jet
≥ 1-jet
≥ 2-jet VBF cuts
σ(VBF)
Rest
≥ 2-jet VBF cuts
high-q^2 BSM
≃ 2-jet
≳ 3-jet
$\sigma(VH)$
low p_T^V
high p_T^V
very high p_T^V
= 0-jet
≥ 1-jet
$\sigma(t\bar{t}H)$
$\sigma(b\bar{b}H)$
$\sigma(tH)$
μ_i, κ_i
g_k
EFT coeffs
specific BSM

Basic Design Principles.

- Identify phase-space regions that are most important to separate out from the theory side
  - Where are largest theory systematics
  - 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 in measurement)
  - Try to align cuts with experimental categories to reduce extrapolations
  - Still have to keep MVAs in check to avoid uncontrolled theory systematics
- Staging: 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)

Staging.

- Impossible to define a set of bins perfect for every analysis, so 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 and merge bins compared to the full binning
- Define different “stages”
  - Each analysis implements the binning according to the appropriate stage
  - 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: to be defined (after gaining more real-life experience)

Since January Meeting.

YR4 writeup

- Discuss basic framework, guiding principles in bin definitions, staging and practical considerations
- Final-state object definitions
- Complete bin definitions for stages 0 and 1
  - Experimental and/or theoretical reasons/motivations are given for each bin
- Outline possibilities for stage 2

Rivet reference implementation (see next talk by Jim Lacey)

- Has been very helpful to iron out some remaining issues

Object Definitions.

- Definitions of “truth” final-state objects (adapted to current scope)
- Explicitly kept simpler and more idealized than in fiducial cross section measurements
  - Allow comparison with theoretical predictions from both analytic calculations and MC simulations

Higgs boson

- All bins are for an on-shell Higgs boson with a cut $|Y_H| < 2.5$
  - Current measurements have no sensitivity beyond this
  - Once sensitivity to higher rapidity (e.g. using forward leptons in $H \to ZZ \to 4\ell$) add an additional otherwise inclusive bin for $|Y_H| > 2.5$
- Treating Higgs as final-state particle is what allows combination of decay channels

Object Definitions.

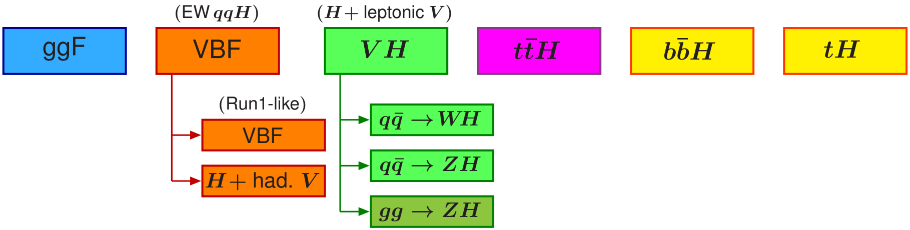
Leptons from decays of signal vector bosons (i.e. VH)

- Electrons and muons are defined as dressed
- τ defined from sum of decay products (for any decay mode)
- No restriction on lepton p_T or rapidity

Signal jets

- Anti-k_t jets with $R = 0.4$
  - built from all stable particles, including neutrinos, photons, leptons from hadron decays
  - All particles arising from Higgs decay are removed
  - All particles from leptonic decays of signal V bosons are removed
  - Decay products from hadronic decays of signal V are included
- Common p_T^j threshold of 30 GeV
- Truth jets are defined with no restriction on jet rapidity
  - Rapidity cuts can be included in bin definitions if needed

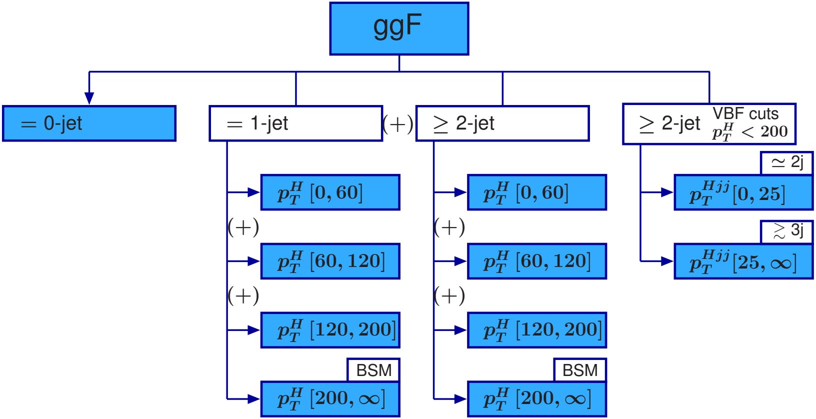
Stage 0.



Inclusive cross section per production mode

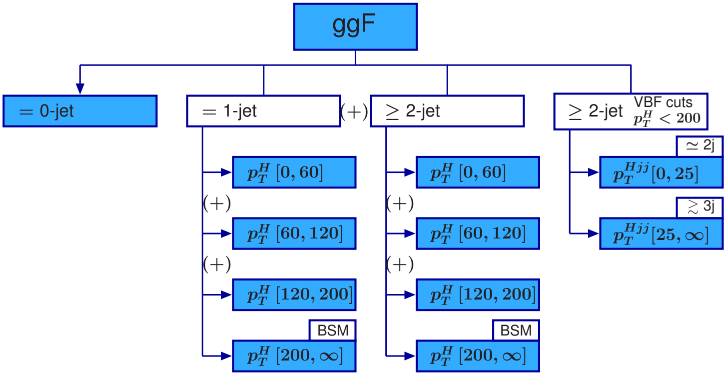
- Closest correspondence to Run1 production-mode μ measurements, but expressed in terms of cross sections and restricted to $|Y_H| < 2.5$
- "VBF" defined as electroweak qqH
  - Split into Run1-like VBF and hadronic VH
- "VH" defined as $H +$ leptonic V
  - Split into WH and ZH, and/or $q\bar{q} \to ZH$ and $gg \to ZH$
- Once meaningful, $b\bar{b}H$ and tH

Gluon Fusion – Stage 1



- Experimental and theoretical motivations for each cut value given in YR4
- Finalized bin with VBF topology cuts
  - Fixed jet-veto like cut to p_T^{Hjj} at 25 GeV
  - Includes cut on $p_T^H < 200\,\mathrm{GeV}$ (giving priority to inclusive $N_j \geq 2$ bin)

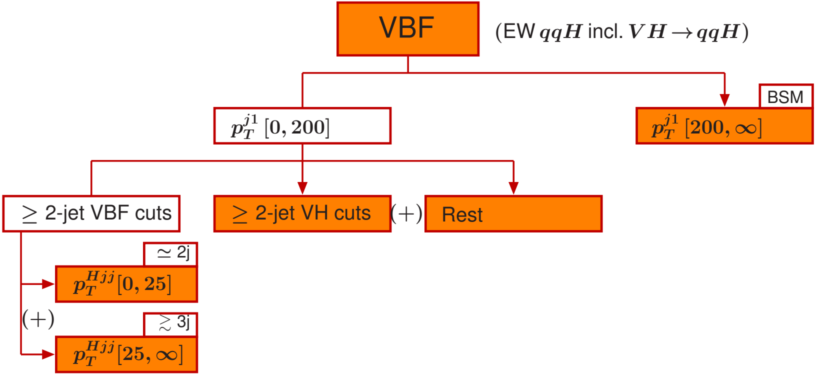
Gluon Fusion – Stage 2.



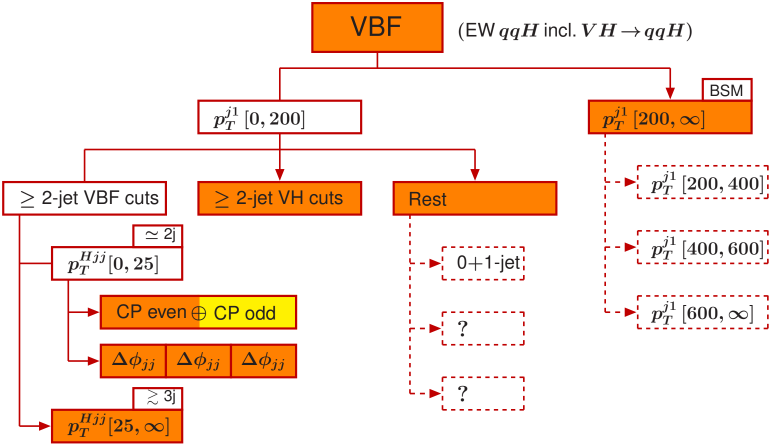
Possible options for stage 2

- High p_T^H bin can be split further (in particular if evidence for new heavy particles arises)
- Low p_T^H region can be split further to further reduce any theory dependence there
- Further split $N_j \geq 2$ into $N_j = 2$ and $N_j \geq 3$

VBF – Stage 1.



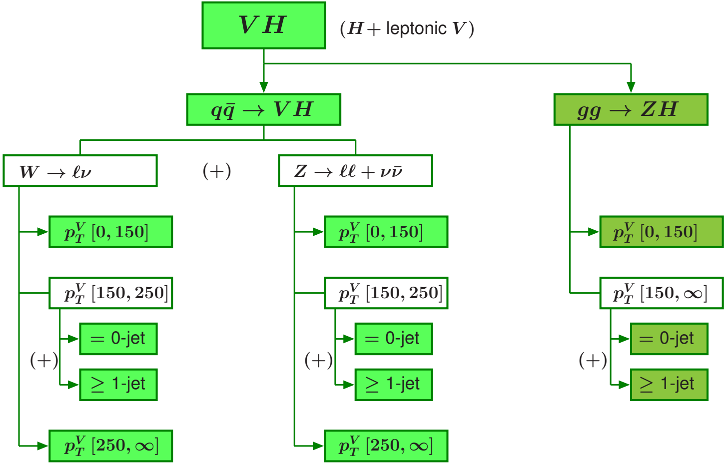
- VBF now defined as electroweak $qq'H$ production
  - including usual VBF process and VH with hadronic V decays
- First split by p_T^{j1} (increased to 200 GeV)
  - VBF topology cuts: $m_{jj} > 400\,\mathrm{GeV}$ and $\Delta\eta_{jj} > 2.8$ (no other cuts)
  - $V(\to jj)H$ topology cuts: $60\,\mathrm{GeV} < m_{jj} < 120\,\mathrm{GeV}$
  - Rest: Everything not passing above, including events with $N_j < 2$



Possible options for stage 2

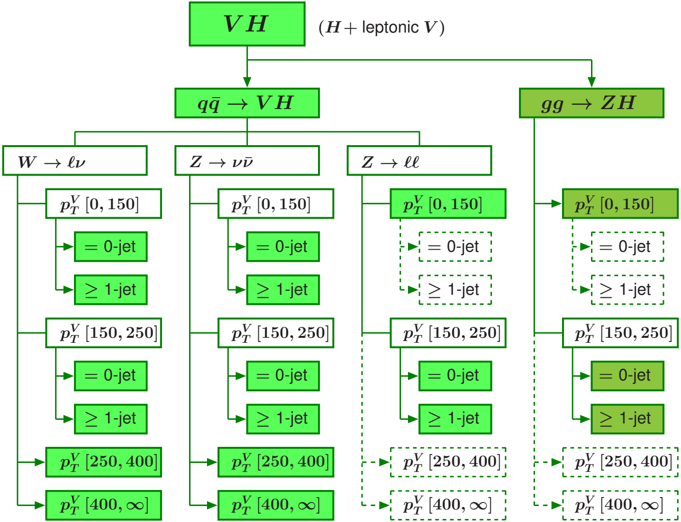
- Add sensitivity to CP odd contributions
- Rest: Further separate out looser VBF cuts and/or 0+1 jet
- Further separate high p_T^{j1}

VH – Stage 1.



- VH now defined as H in association with leptonically decaying V
  - $q\bar{q} \to V(\to q\bar{q})H$ part of VBF ($gg \to Z(\to q\bar{q})H$ part of gluon fusion)
- Binning in p_T^V aligned with $H \to b\bar{b}$ (which is main contributor)
  - Values increased from 120→150 GeV and 200→250 GeV

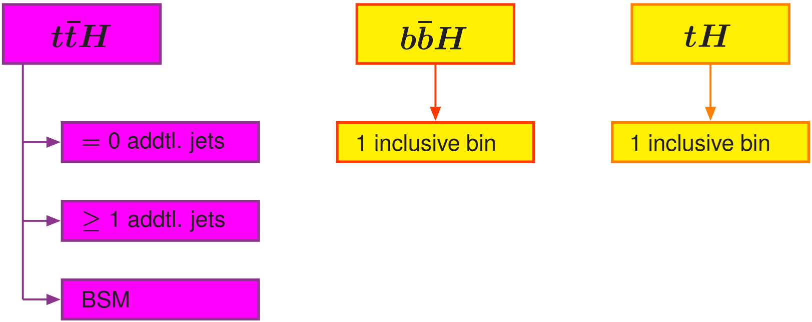
VH – Stage 2.



Possible options for stage 2

- Separate Z decays, further split high p_T^V

Other Production Modes.



Stage 1

- Inclusive production with $Y_H < 2.5$
- No additional split beyond stage 0 forseen

Possible options for stage 2

- Possibly split $t\bar{t}H$, to be seen ...

Outlook.

Next steps

- Probably good to maintain continued feedback loop during experimental implementation of stage 1
  - After first measurements review stage 1 bin definitions and adjust in cases where they turned out to be clearly inadequate
- Discussion of residual theory uncertainties in measurements
  - Compatibility important to facilitate combination of ATLAS and CMS
- Stage 2 bin definitions

(My personal) thoughts on future organizational structure

- Essential to have a single point of convergence for needs/requirements of experimental measurements and theoretical inputs
  - Interface to WG1 subgroups (in particular if we want to provide complete set of theory inputs for a reference SM interpretation/combination)
  - Interface to various beyond SM interpretations (WG3 subgroups, EFT, ...)
  - Direct interface to ATLAS and CMS Higgs combination groups
- Structure should facilitate shorter feedback loops

Backup Slides

Definition of simplified template cross sections.

Consider schematic μ fits:

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

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

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

- $\sigma_i^{\rm meas}$ 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:

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

- 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, ...

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

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

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

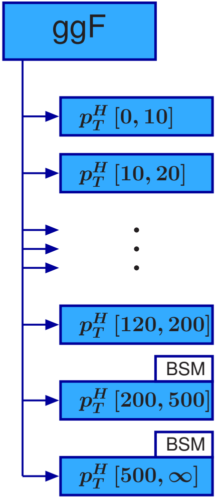
- Separately fit bin cross sections σ_{ggH}^{a}, σ_{ggH}^{b}, $\sigma_{\rm VBF}^{c}$, ...
- A_{ij}^{ggH}, $A_{ij}^{\rm VBF}$ only depend on SM kinematics *inside* a given bin
  - If this becomes a problem, split the bin
  - SM processes act as kinematic templates (SM acts as “simplified model”)
  - If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

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
$\rightarrow$ Minimize acceptance corrections $\rightarrow$ Simple (rectangular) acceptance cuts $\rightarrow$ "Exact" fiducial volume $\rightarrow$ Fiducial in Higgs decay	$\rightarrow$ Allow larger acceptance corrections $\rightarrow$ Allow event categories, MVAs, ... $\rightarrow$ Abstracted/simplified fiducial volumes $\rightarrow$ 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

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