Simplified Template Cross Sections: Status and Plans

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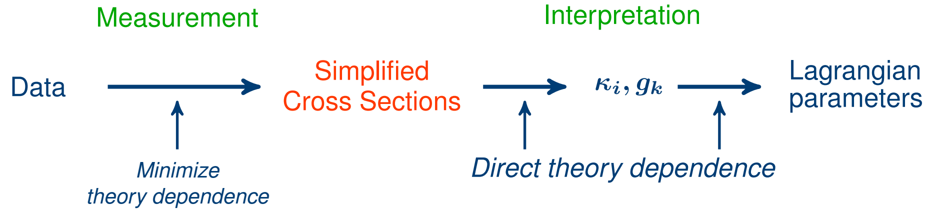
[Michael Dührssen, Paolo Francavilla, FT, Kerstin Tackmann
+ feedback from many people; LH15 (1605.04692), YR4 (1610.soon)]

Introduction.

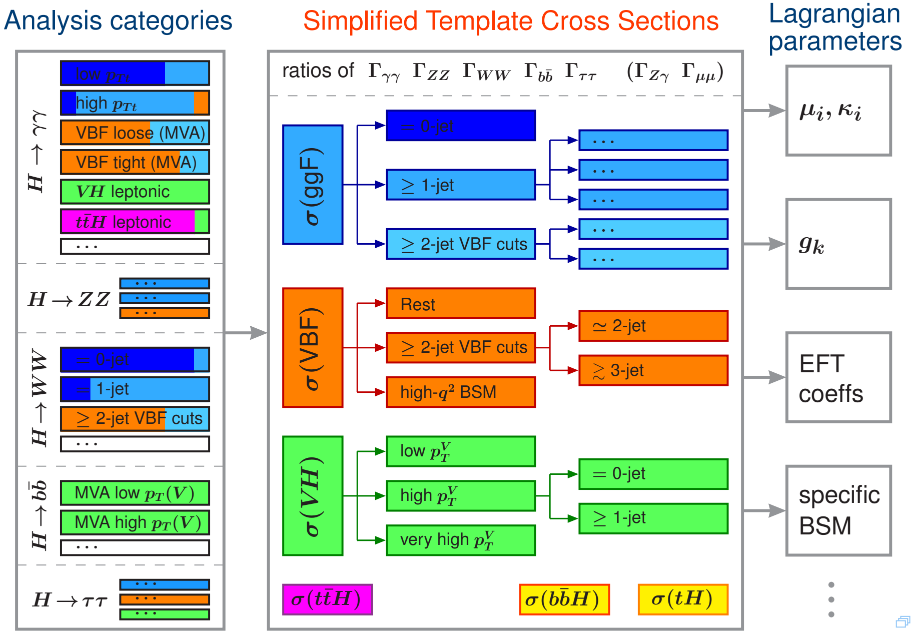
Separating Measurement from Interpretation.



Goals

- Minimize theory systematics in measurements
  - Clearer and systematically improvable treatment at interpretation level
- Minimize model dependence in measurements
  - Decouples measurements from assumption of underlying physics model (SM, (non)linear EFT, BSM models)
- Measurements stay long-term useful
- Allows easy further (re)interpretation with different theory inputs/assumptions
  - Improved theory predictions/uncertainties
  - μ_i, κ_i, anomalous couplings, EFT coefficients, specific BSM scenarios

Simplified Template Cross Section Framework.



Defining Features.

- Measure cross sections but separated into production modes
  - Allows different efficiencies/acceptances without incurring dependence on SM production mode mix
  - SM processes act as kinematic templates
  - Future: Can add more kinematic templates (e.g. CP-odd Higgs)
- Non-Higgs backgrounds are subtracted
  - Future: Can add templates for BSM sensitive backgrounds (e.g. $pp \to WW$)
- Inclusive over the Higgs decays
  - Can perform a global combination of channels
- “Simplified” bin definitions abstracted from the actual measurement categories
  - Allow some acceptance corrections
  - Analyses can use optimized selections at reconstruction level, MVAs ...

$\Rightarrow$ Maximize sensitivity while reducing theory dependence

Current Status.

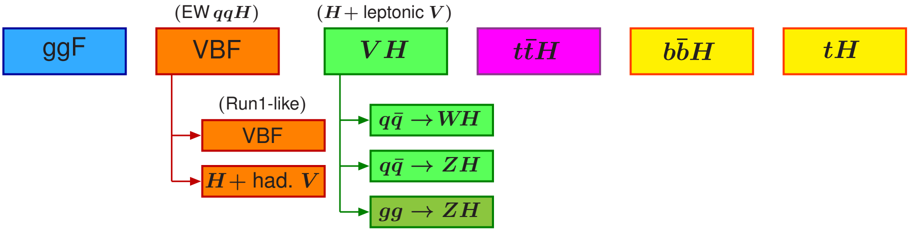
Staging.

Define different "stages" for each production mode

- Each analysis implements the binning according to the appropriate stage
- Evolution of different production modes can take place independently
- 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)

- Stage 0: closest correspondence to Run1
- Stage 1: fully defined in YR4
  - All "minimally hoped-for" splits
  - Intermediate steps to get there indicated by "$(+)$" for possible bin merging
  - Currently: Being implemented by experiments, support/feedback loop for first stage 1 measurements (changes only for serious problems)
- Future: Define Stage 2 (after gaining more real-life experience)

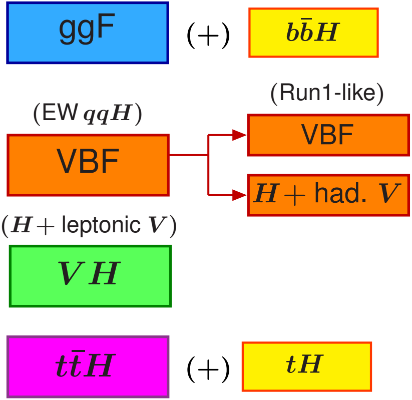
Stage 0.

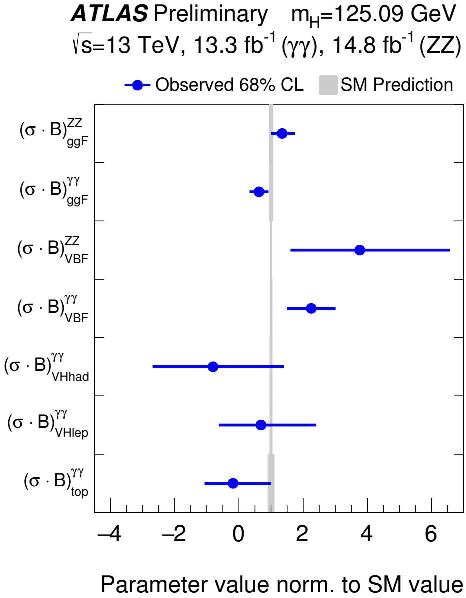


Inclusive cross section per production mode

- 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

First Stage-0 Measurements from ATLAS.





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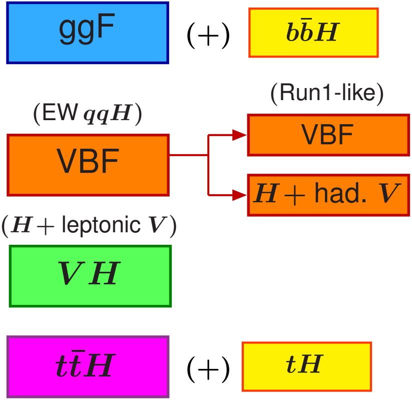
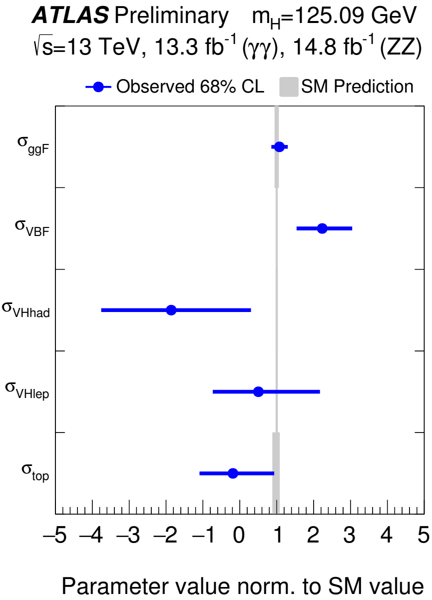


(Combined $\gamma\gamma$ and ZZ assuming SM BR)



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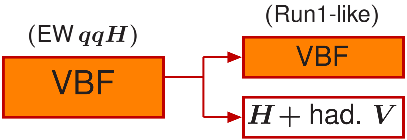
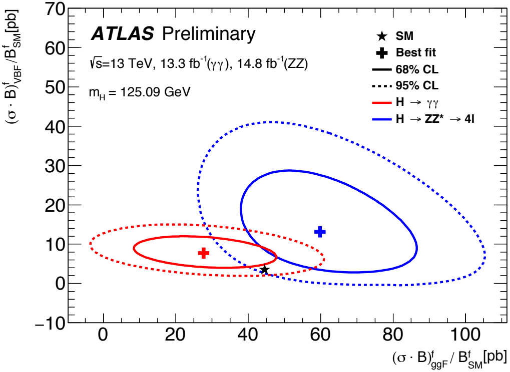
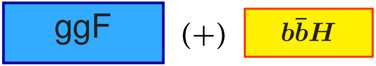
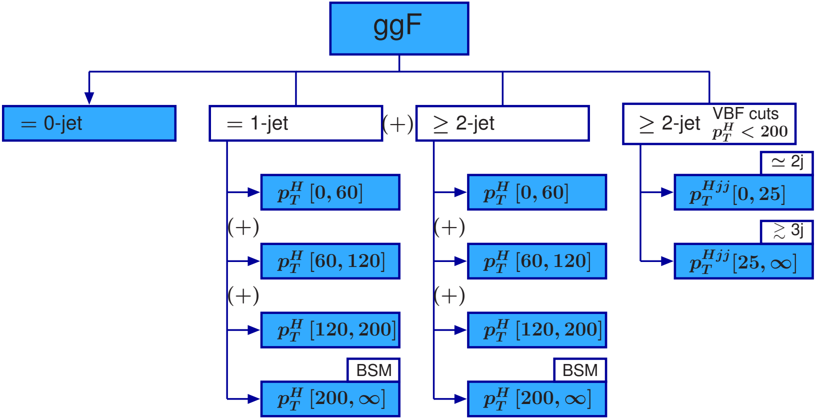






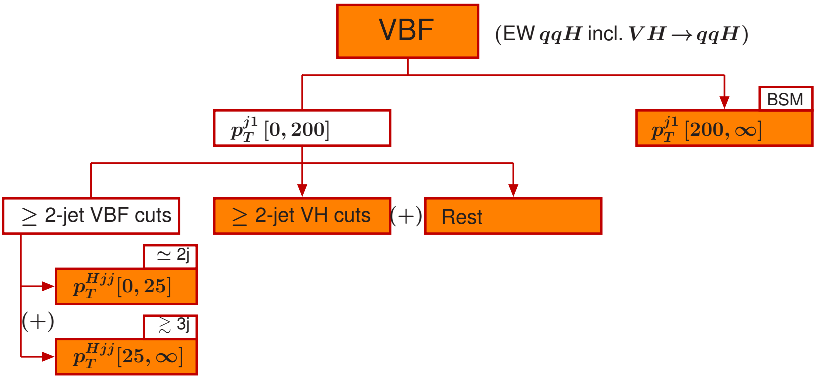
- Normalized to SM branching ratios for plotting purposes only

Gluon Fusion – Stage 1.



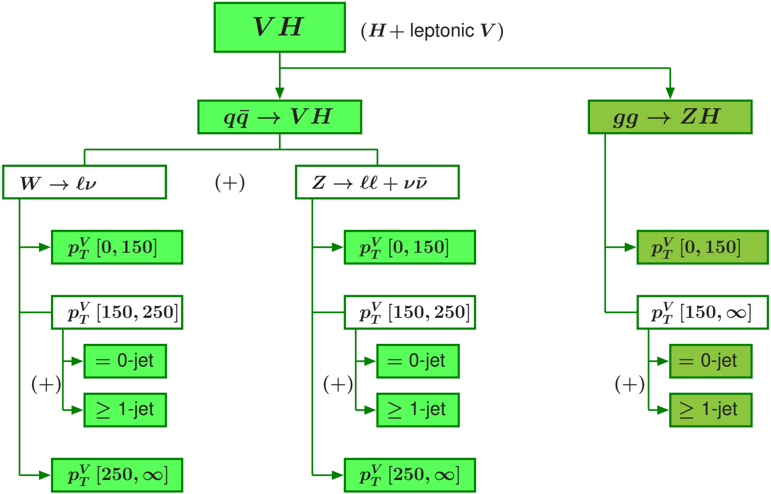
- Jet bins motivated by experimental analyses
- High p_T^H bins target boosted categories ($\tau\tau$) and BSM overflow
- VBF-like cuts to constrain ggF contribution in VBF categories

VBF – Stage 1.



- VBF defined as electroweak $qq'H$ production
  - including usual VBF process and VH with hadronic V decays
- First split by p_T^{j1}
  - 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 < 2 jets)

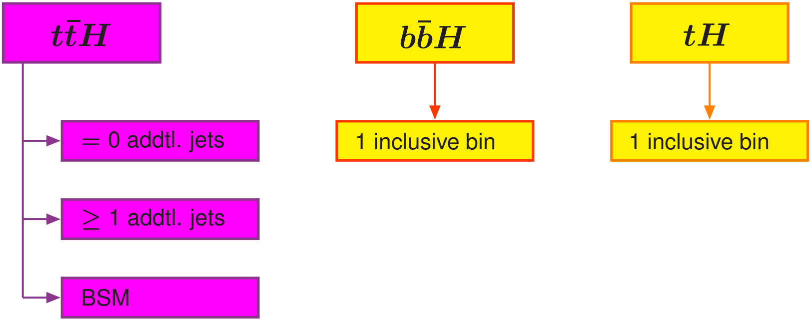
VH – Stage 1.



- VH defined as Higgs 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 ggF)
- Binning in p_T^V aligned with $H \to b\bar{b}$ (which is main contributor)

What's Next.

Other Production Modes.



Stage 1

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

Evaluate possibilities and needs for stage 2

- Possibly split $t\bar{t}H$

Interplay with Fiducial Cross Sections.

Fiducial: Optimized for maximal theory independence

- Minimize acceptance corrections
- Simple (rectangular) signal cuts
- “Exact” fiducial volume
- Fiducial in Higgs decay
- Targeted object definitions

Agnostic to production modes

(Single-)differential distributions
(overlapping events)

Only $H \to \gamma\gamma, ZZ, (WW)$
(by default no combination of channels)

Simplified: Maximize sensitivity while reducing theory dependence

- Allow larger acceptance corrections
- Allow event categories, MVAs, ...
- Abstracted/simplified fiducial volumes
- Inclusive in Higgs decay
- Common idealized object definitions

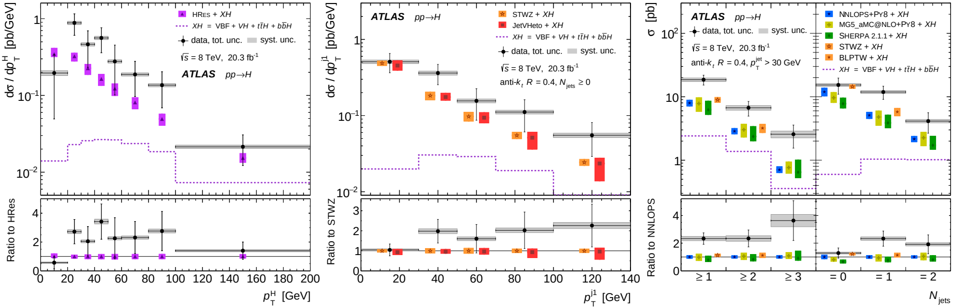
Xsec split by production mode

Xsec split into mutually exclusive regions of phase space

Explicitly designed for combination of all decay channels

- Despite different focus, should discuss/identify common areas of interest
  - Residual theory/model uncertainties in measurements
  - Presentation of measurement results

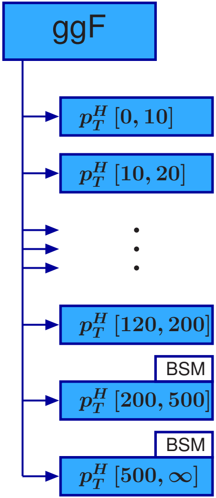
Combined Differential Spectra.



Combined differential spectra for inclusive Higgs production

- Going one step away from being fully fiducial
  - Adds in some theory dependence by extrapolating to inclusive Higgs decay phase space and assuming SM branching ratio
- Allows combining $H \to \gamma\gamma$ and $H \to ZZ$
  - Useful if statistics is still limited, perhaps not needed once spectra from single channel are precise enough on their own
- Still agnostic about production mode (mostly, due to $gg \to H$ dominance)

Simplified Template Differential Spectra.



Could use the same framework to measure single-differential spectra *per production mode*

- One more step away from fiducial toward simplified template
- Would be interesting e.g. for precision QCD studies in ggF
- Supplementary to primary bins
  - Would need to evaluate correlations with primary bins due to statistical overlap in case both are used for specific interpretation

Theory Inputs for Interpretation Step.

Experiments will want to continue performing basic μ-like, κ-like (perhaps EFT-like) interpretations but now based on measured bins

- Requires injecting explicit (sets of) theory predictions
  - But now for a well-defined set of bins for each production modes
  - Very easy to explore different scenarios, model assumptions, theory treatments

- First step: Define a framework/interface on how to parametrize/propagate/implement theory uncertainties and correlations
  - Variety of possible sources: parametric (PDFs), perturbative (QCD, EW, resummation, ...), ...
  - Correlations between bins
  - Correlations among production modes
  - There is also some interplay with the residual (and supposed to be subdominant) theory uncertainties in the measurements itself

- Next step: Would need to collect actual numbers from theory groups interested in providing predictions
  - Could be via various subgroups (SM production modes, BSM, EFT, ...)
  - But does not have to be

Summary and Outlook.

Many things to do

- Support and feedback from implementation of Stage 1 measurements
  - Common Rivet routine implementing all Stage 1 bin definitions is available (thanks to Dag Gillberg and Jim Lacey)
  - Happy to get feedback from analyses
  - If desired or deemed useful by experiments could organize discussion of common implementation issues
- Start to think about theory input framework for basic Stage 1 interpretations
- Discuss interplay with fully fiducial measurements
  - Identify/discuss common areas to avoid duplication of effort
- Start to think About Stage 2 definitions
  - Need to wait for experience from Stage 1 measurements
  - Since it will require several iterations, feedback from theoretical studies always useful (e.g. sensitivity of bins/phase-space regions to specific EFT operators, model parameters, ...)
- ...

Backup Slides

Basic Design Principles.

Identify phase-space regions most important to separate out from theory side

- Where are largest theory systematics? BSM sensitivity?
- Try to minimize residual theory dependence in measurements
  - Avoid non-constant signal acceptance within one bin
  - Try to align cuts with dominant channel/categories to reduce extrapolations

Impossible to define one set of bins perfect for every analysis and theory, so aim to find a good compromise

- Only add additional bins with "sufficiently good reason" (see above)
- Some decay channels will only be able to constrain sum of certain bins and must be able/allowed to combine bins
  - Bins are defined to be mutually exclusive and sum up to parent bin
  - If merged bins have similar acceptance $\rightarrow$ Bins can be split in the combination (unbiased, only some loss in sensitivity)
  - If merged bins have different acceptance $\rightarrow$ Split the bins if at all possible, otherwise combine and assign uncertainty in measurement
- Bin definitions can evolve with statistics $\rightarrow$ Staging

Construction.

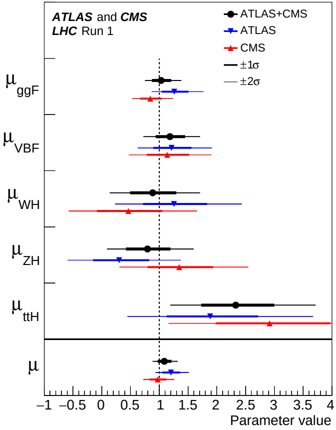
Consider schematic μ fits:

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

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

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

- σ_i^{meas}: measured analysis categories
- A_i^{ggH}, A_i^{VBF}: Acceptances for SM processes (→ theory-dependent)



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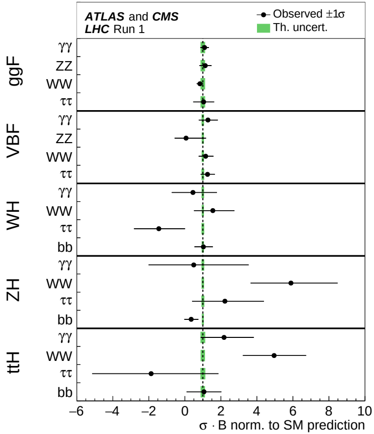
$$\sigma_3^{\text{meas}} = \cdots$$

- σ_i^{meas}: measured analysis categories
- A_i^{ggH}, A_i^{VBF}: Acceptances for SM processes ($\rightarrow$ theory-dependent)
- First step: Fit for σ_{ggH}, σ_{VBF} rather than μ_{ggH}, μ_{VBF}
  - In the SM correspond to total ggF and VBF production cross sections
  - Can combine channels by assuming or fitting ratios of BR
  - Already available



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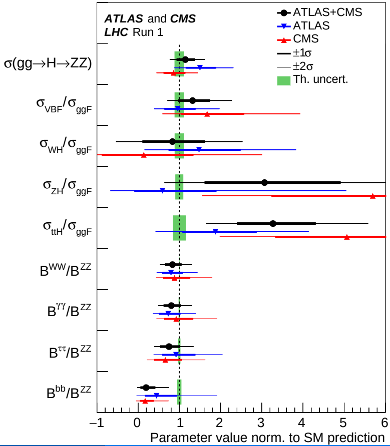


Construction.

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

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

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

Next step: Split up production cross sections into kinematic regions a, b, c, ...

- Separately fit bin cross sections σ_{ggH}^{a}, σ_{ggH}^{b}, σ_{VBF}^{c}, ...
- Bin acceptances A_{ij}^{ggH}, A_{ij}^{VBF} now only need to assume/depend on SM kinematics *inside* a given bin
  - If this becomes a limitation $\rightarrow$ further split the bin

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

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.

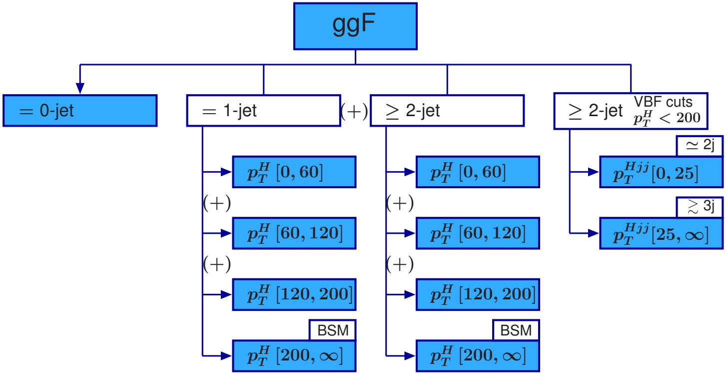
Leptons from decays of signal vector bosons (i.e. VH)

- 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

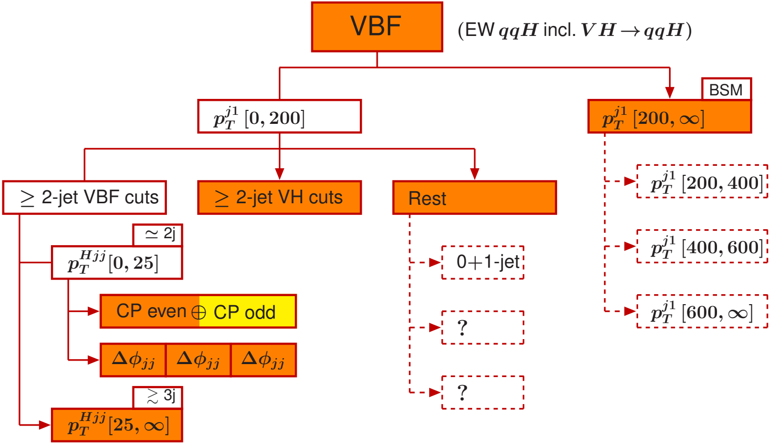
Gluon Fusion – Stage 2.



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 $N_j \geq 3$

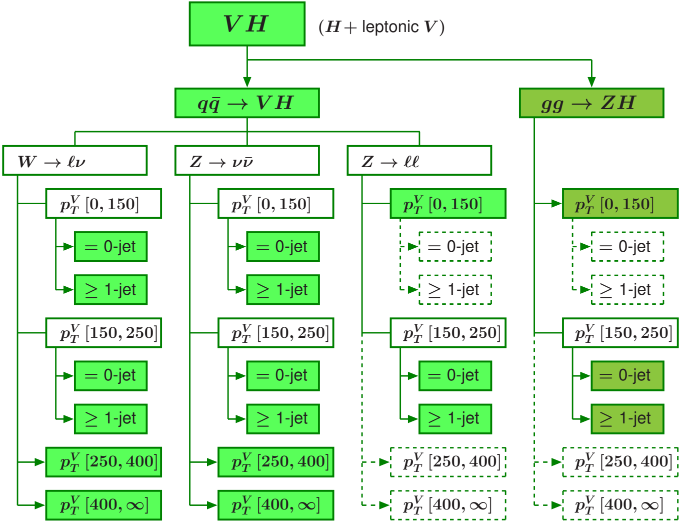
VBF – Stage 2.



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 2.



Possible options for stage 2

- Separate Z decays, further split high p_T^V