STXS Uncertainty Parametrization for VBF

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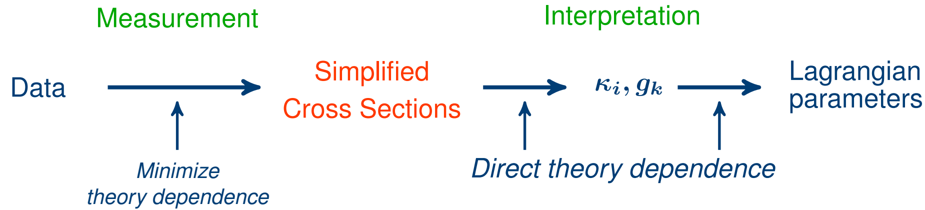
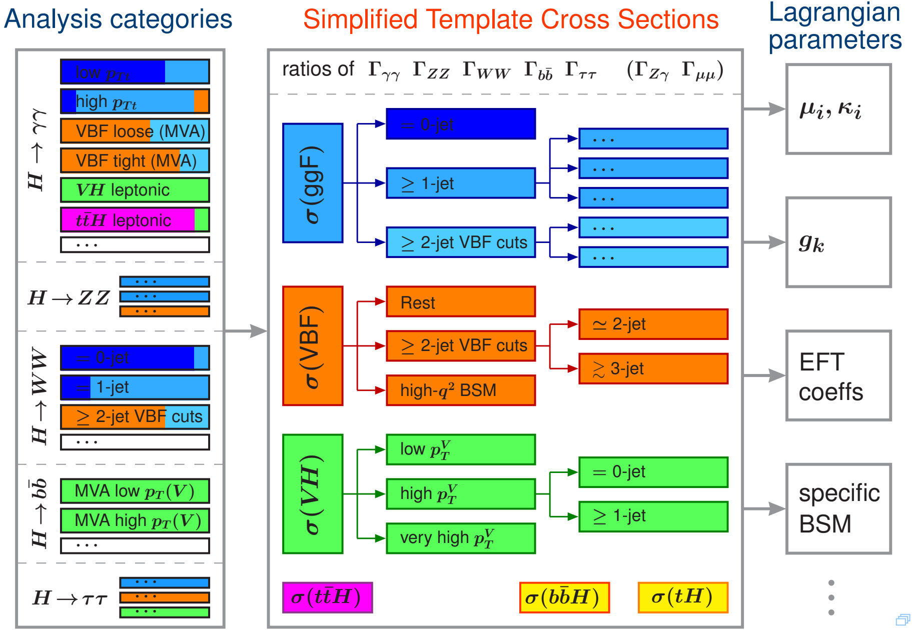
Separating Measurement from Interpretation.



Goals

- Minimize dependence on theory systematics in measurements
  - Clearer and systematically improvable treatment at interpretation level (acceptance corrections, extrapolations to total xsec, ...)
- Minimize model dependence in measurements
  - Decouples measurements from discussions about specific models (SM, linear/nonlinear EFT, BSM models, ...)
- Measurements stay long-term useful
- Allows easy (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 for different production modes 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 would be relevant for VBF)
- 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 exp. categories
  - Allow some acceptance corrections
  - Analyses can use optimized selections at reconstruction level, MVAs ...
  - Avoid extrapolations that are unnecessary or nontrivial (i.e. theory sensitive)

$\Rightarrow$ Maximize sensitivity while reducing theory dependence

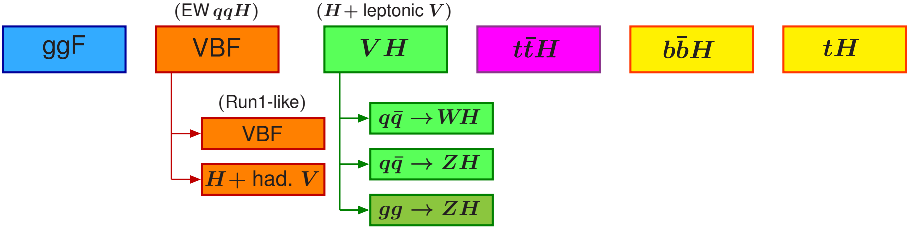
Staging.

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
  - All “minimally hoped-for” splits
  - Intermediate steps to get there indicated by “$(+)$” for possible bin merging
  - Early measurements will show if adjustments are needed (will not make any changes unless serious problems arise)
- Stage 2: to be defined (after gaining more real-life experience)

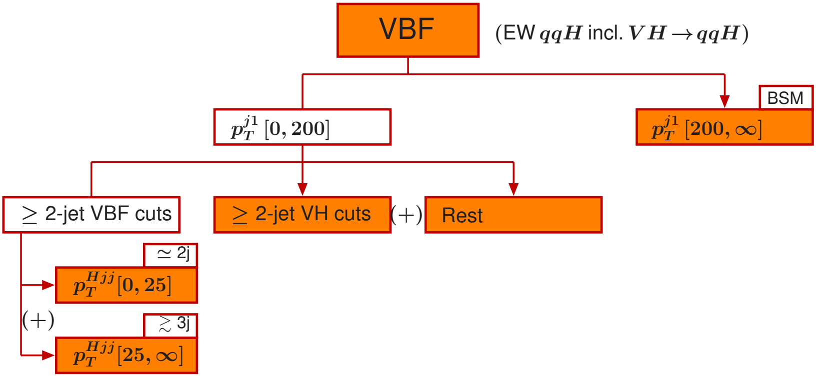
Stage 0.



Template processes are defined for a stable Higgs but decayed V

- "VBF" is defined as electroweak qqH production
  - hadronic VH $q\bar{q} \to V(\to qq)H$ is part of "VBF"
  - Targeted via dedicated "VBF" bin with $V(\to jj)H$ topology cuts ($60\,\mathrm{GeV} < m_{jj} < 120\,\mathrm{GeV}$)
  - VBF-like-looking ggF is part of ggF (and separating the two is one of the main challenges)
  - Note: At sufficiently high order virtual EW corrections to "ggF" production Higgs coming from HVV vertex in principle becomes ambiguous with "VBF" (should be way beyond the level we currently care)

VBF – Stage 1.



- 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)

Theory Uncertainties.

Two aspects to theory uncertainties

- Residual theoretical uncertainties related to “unfolding” experimental event categories to STXS bins
- Uncertainties in interpretation of STXS bins, i.e. in SM (or beyond) cross section predictions for each bin
  - Also enter as “residual” uncertainties in measurement whenever bins with different sensitivities are merged

Implementation of uncertainties (in measurement or interpretation)

- Requires uncertainties per bin and their correlations
  - Particularly important when binning cut itself introduces a source of uncertainty that affects each bin but cancels in their sum
  - Experimental implementation in terms of $\pm$100% correlated or uncorrelated nuisance parameters

$\rightarrow$ Need to identify and distinguish different sources of uncertainties and evaluate also their correlations between kinematic bins

  - Use generic parametrization of uncertainties in kinematic bins as discussed in `YR4` Section 1.4.2a

Uncertainties With Multiple Bin Boundaries.

- Each bin can have multiple boundaries, and each boundary can be shared by different bins
- Consider given bin boundary when all additional subdivisions are removed and parametrize in terms of independent yield and migration uncertainties
- Consider binning cut "a/b" with $\sigma_{ab} = \sigma_a + \sigma_b$ and associated $\Delta_{a/b}$ (anticorrelated between σ_a and σ_b)
  - Allow for additional subbins such that $\sigma_a = \sum_i \sigma_a^i$ and $\sigma_b = \sum_j \sigma_b^j$
  - Consider binning uncertainty as fully correlated among subbins and implement with a single nuisance parameter

$$\theta_{a/b}: \quad \Delta_{a/b} \times \big\{\{x_a^i\}, -\{x_b^j\}\big\} \qquad \text{with} \qquad \sum_i x_a^i = \sum_j x_b^j = 1$$

where x_a^i and x_b^j specify how $\Delta_{a/b}$ gets distributed among the subbins

- Consider each binning cut/bin boundary as potential uncertainty source
  - Migration uncertainty between σ_a and σ_b, and yield uncertainty inside each
  - Limiting case: Global yield uncertainty for total xsec

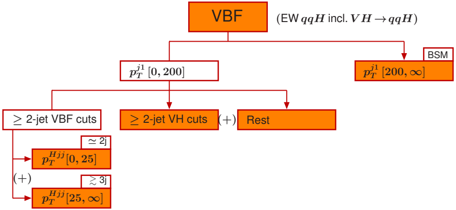
Parametrization of VBF uncertainties: Sources.

QCD uncertainties

- Q: How are unc. in different m_{jj} regions correlated?
  - Option 1: single overall yield Δ_μ plus m_{jj} shape/migration Δ_{mjj}
  - Option 2: uncorrelated sources Δ_{low} and Δ_{high} for low and high m_{jj}
  - Option 3: ???
- Δ_μ^{VH} uncertainty for the VH bin induced by hadronic VH process
  - Correlated with leptonic VH (i.e. same nuisance parameters as in VH)
- Δ_{200} migration uncertainty related to p_T^{j1} cut
- Δ_{25} migration uncertainty related to 2/3-jet separation

EW uncertainties

- Δ_{Sud}: EW Sudakov effects
  - correlated with $q\bar{q} \to VH$ (?)
- Δ_{hard}
  - uncorrelated with $q\bar{q} \to VH$ (?)



Parametrization of VBF uncertainties.

Bin	QCD uncertainties (Option 2)					EW uncertainties		
	Δ_{low}	Δ_{high}	Δ_{μ}^{VH}	Δ_{200}	Δ_{25}	Δ_{Sud}	Δ_{hard}	$\Delta_{W,Z,\gamma}^{\text{VH}}$
p_T^j [0,200]	≈ 1	≈ 1	≈ 1	-1		y_1	$*$	
VBF cuts	≈ 0	≈ 1	≈ 0	$-x_1$	0	y_2	$*$	
p_T^{Hjj} $[0, 25]$		z		$-x_1 z$	$+1$	$\cdots$	$*$	
p_T^{Hjj} $[25, \infty]$		$1 - z$		$-x_1(1-z)$	-1	$\cdots$	$*$	
VH cuts	?	?	≈ 1	$-x_2$		y_3	$*$	1
Rest	≈ 1	≈ 0	?	$-x_3$		y_4	$*$	
p_T^j $[200, \infty]$	?	?	?	$+1$		$1 - y_i$	$*$	

To estimate the actual numbers, there are two aspects

- The overall impact/uncertainty: Δ_i
  - Could come from appropriate calculation or estimatee.g. be evaluated via MC reweighting
- The distribution inside subbins: x_i
  - Could e.g. be evaluated via MC reweighting

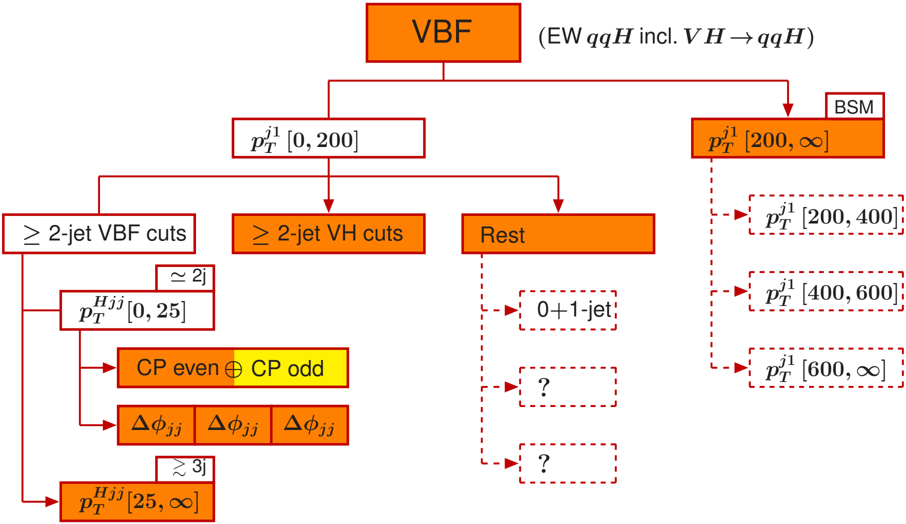
Summary.

We need a consistent/common/coherent treatment of theory uncertainties across kinematic regions and across production modes

- Same approach is also followed for ggF bins (already agreed upon) and being discussed for VH bins
- We appreciate your feedback, in particular
  - Any objections? Anything missing?
  - Is this sufficiently general for the EW corrections?
- First step: We (STXS) would like to agree with you (VBF) on a parametrization
  - Should be flexible enough to accomodate most important effects now
  - Important goal is to be able to easily switch between different predictions
- Second step: We strongly rely on your help in providing concrete numbers and estimates

Backup Slides

VBF – Possible Options for Stage 2.



Parametrization of VH Uncertainties: Sources.

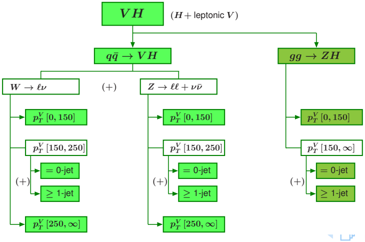
QCD uncertainties

- Δ_μ, Δ_{150}, Δ_{250}
  - Option 1: overall yield uncertainty plus two p_T^V binning (shape) uncertainties
  - Option 2: one uncorrelated uncertainty for each p_T^V bin
- $\Delta_{0/1}$: jet bin migration uncertainty
- Same nuisance parameter for W and Z (i.e. 100% correlated)

EW uncertainties

- Δ_{Sud}: EW Sudakov effects (correlated between W and Z)
- Δ_W, Δ_Z, Δ_γ
  - Separate uncertainties for non-Sudakov contributions

- Separate sources (uncorrelated uncertainties) for $q\bar{q} \to VH$ and $gg \to ZH$
  - Study which sources for $gg \to ZH$ should be correlated with $gg \to H$
- Some of this also impact "VBF" bins through its hadronic VH contribution



Parametrization of VH Uncertainties.

Bin	QCD uncertainties (Option 1)				EW uncertainties			
	Δ_μ	Δ_{150}	Δ_{250}	$\Delta_{0/1}$	Δ_{Sud}	Δ_W	Δ_Z	Δ_γ
W [0,150]	x_1	$-c$	0		y_1	$*$		$*$
W [150,250]	x_2	$+c$	$+d$		y_2	$*$		$*$
=0j [150,250]	$x_2 z$	$+cz$	$+dz$	$+1$	$\cdots$	$*$		$*$
≥1j [150,250]	$x_2(1-z)$	$+c(1-z)$	$+d(1-z)$	-1	$\cdots$	$*$		$*$
W [250,∞]	x_3	0	$-d$		y_3	$*$		$*$
Z [0,150]	x_1	$-c$	0		y_1		$*$	
Z [150,250]	x_2	$+c$	$+d$		y_2		$*$	
=0j [150,250]	$x_2 z$	$+cz$	$+dz$	$+1$	$\cdots$		$*$	
≥1j [150,250]	$x_2(1-z)$	$+c(1-z)$	$+d(1-z)$	-1	$\cdots$		$*$	
Z [250,∞]	x_3	0	$-d$		y_3		$*$	

+ Analogous uncorrelated sources for $gg \to ZH$