Fiducial and Simplified Cross Sections

Discussions for Run 2

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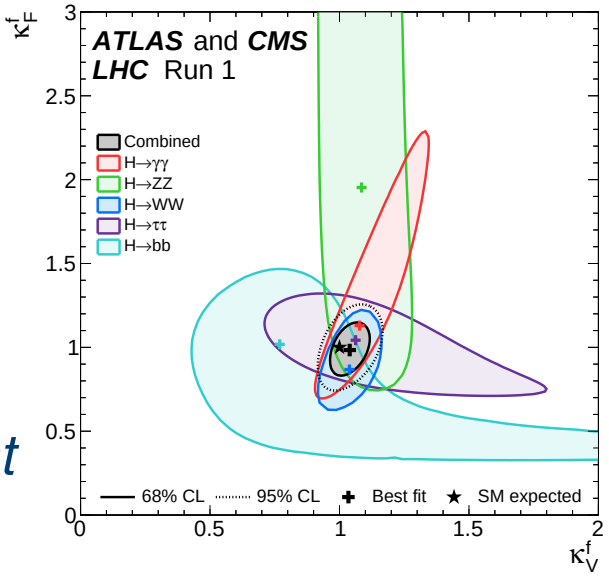
Deutsches Elektronen-Synchrotron

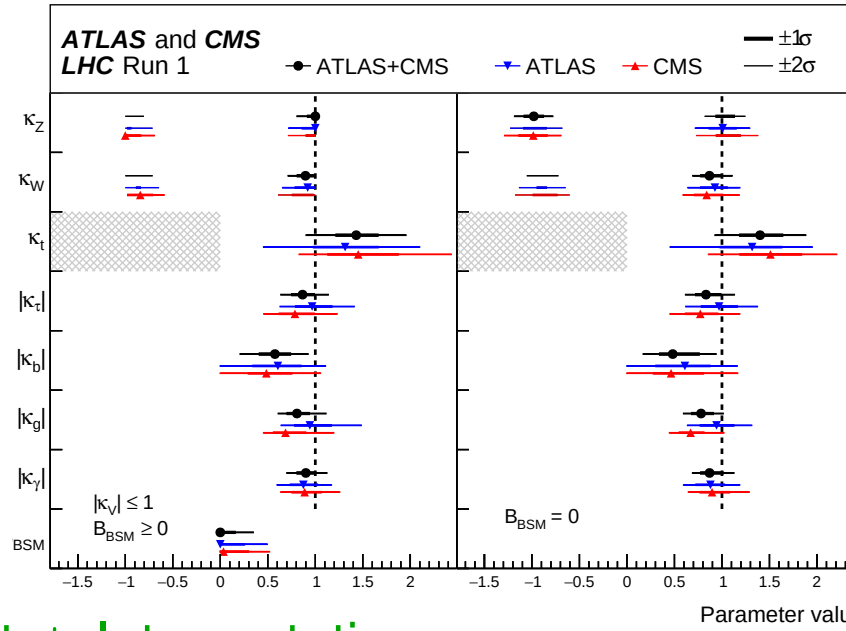
Higgs Hunting, Paris
September 1, 2016

Introduction.

Direct Coupling Fits.

Data → *theory-dependent*





Measurement + Interpretation

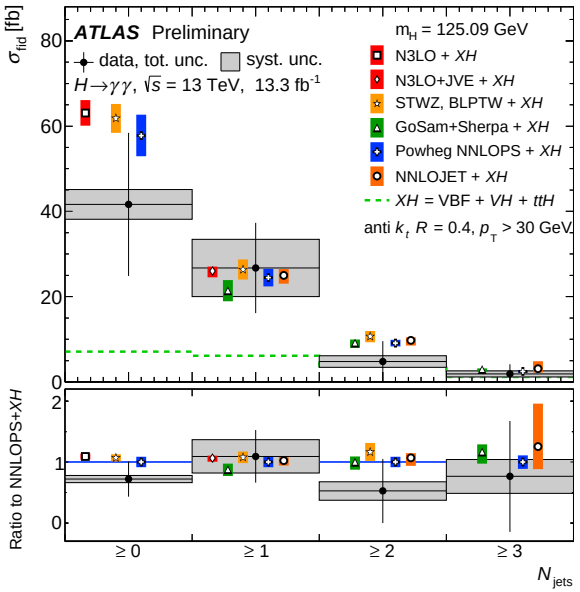
Pros

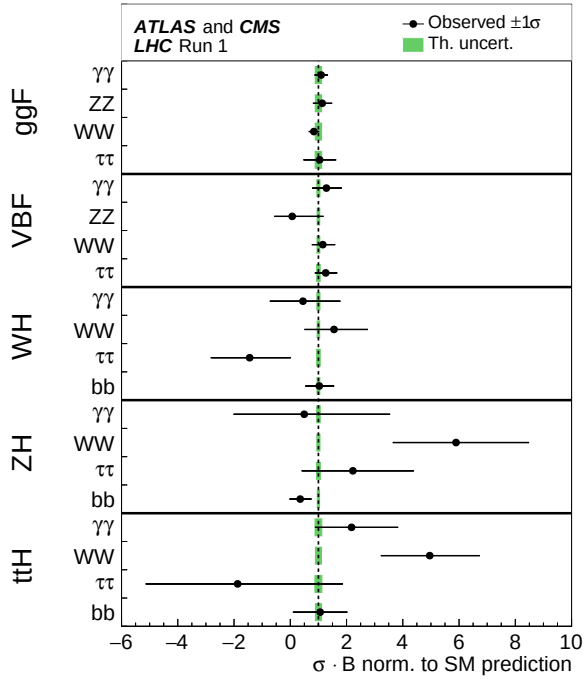
- Maximum possible sensitivity
- Allows use of advanced selection techniques (MVAs, black magic, ...)
- Can benefit from kinematic correlations among production modes across all decay channels in combination

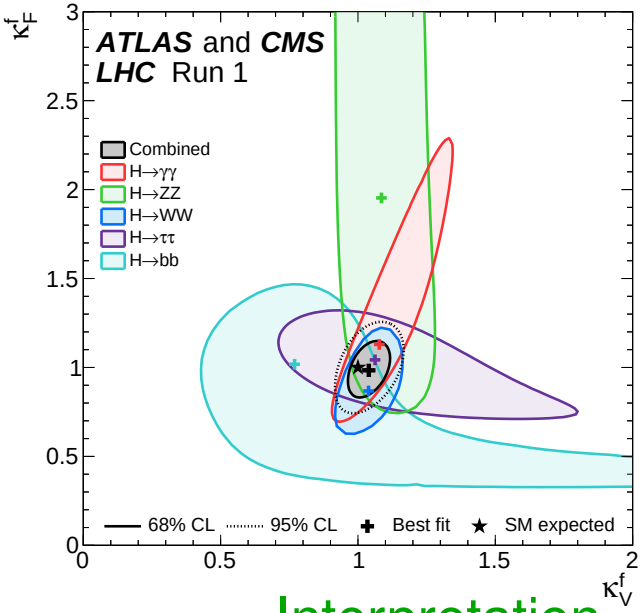
Cons

- Theory predictions and *uncertainties* maximally entangled in results
- Any nontrivial theory changes require new results from experiments

Measurement vs. Interpretation.







Measurement

Interpretation

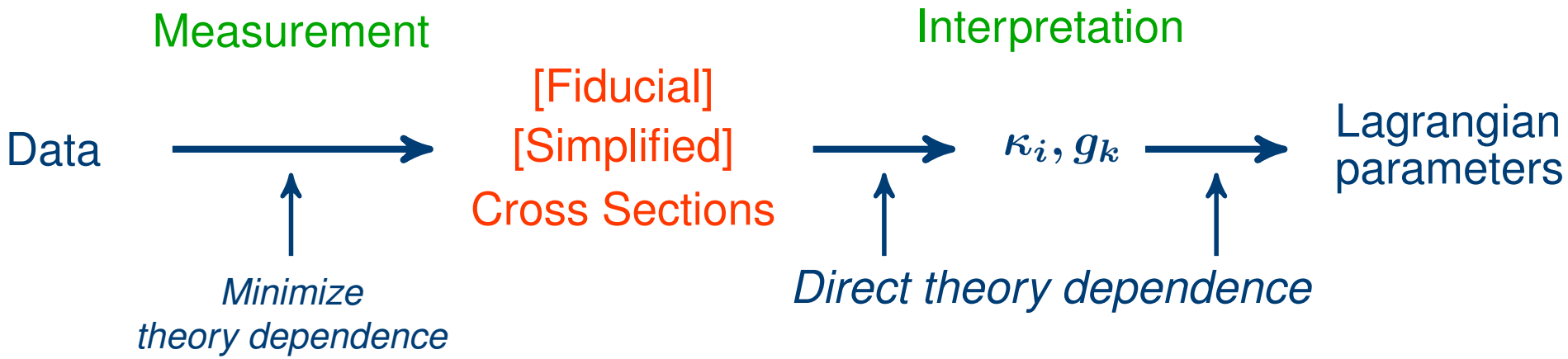
theory-independent

theory-dependent

"Theory dependence" includes 2 aspects

- Dependence on underlying physics model:
  - Assume/test a specific Lagrangian (SM, (non)linear EFT, BSM models)
  - Dependence on kinematic distributions
- Dependence on theory systematics/uncertainties
  - Acceptance corrections and extrapolations to total xsec taken from theory
  - Perturbative and parametric (PDFs, α_s, ...) uncertainties

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 discussions about specific 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

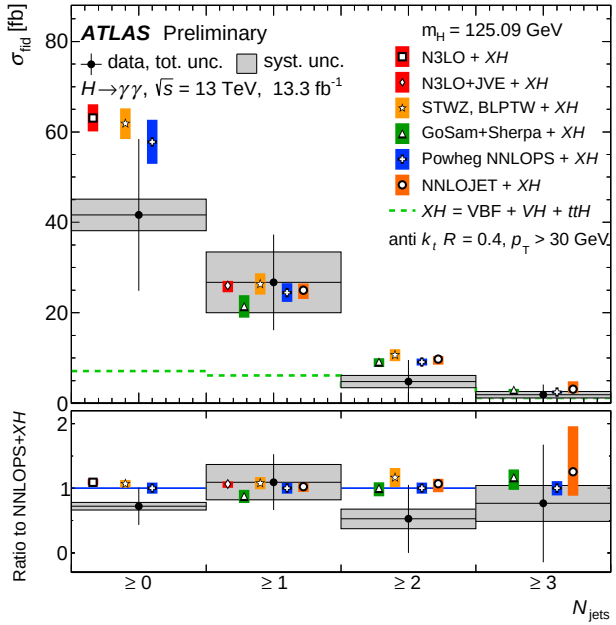
Fiducial Cross Sections.

Fiducial Cross Sections.

Pros: Staying as close as possible to what is actually measured

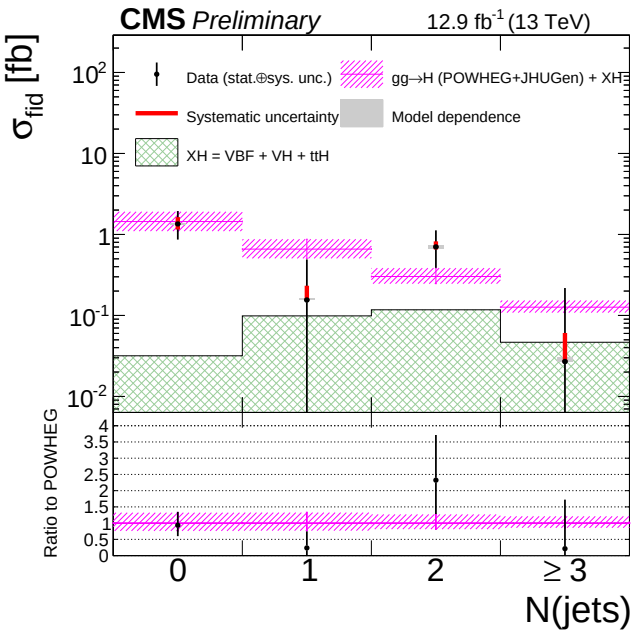
- Allows maximally theory-independent measurements
- Representation of the data that remains long-term useful

⇒ Of course nothing new and routinely done in other SM measurements



However, Higgs is quite different from (other) SM measurements

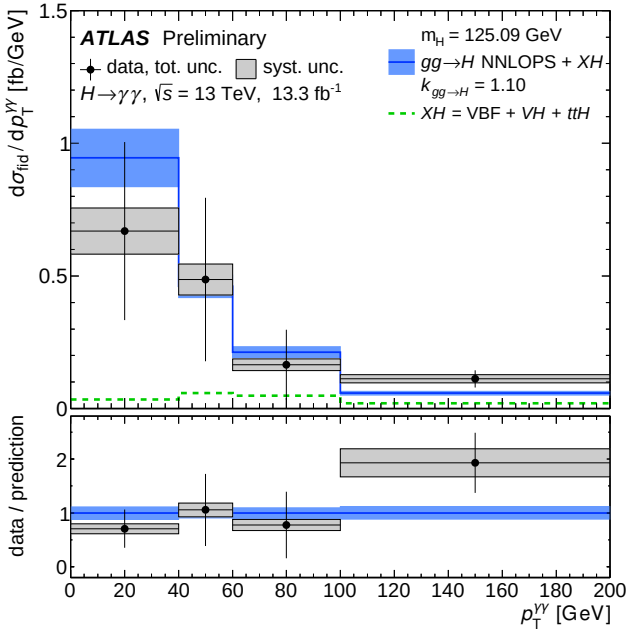
- Many different production and decay modes with large differences in
  - Statistics
  - Relative signal/background
  - Theory uncertainties
  - BSM sensitivity

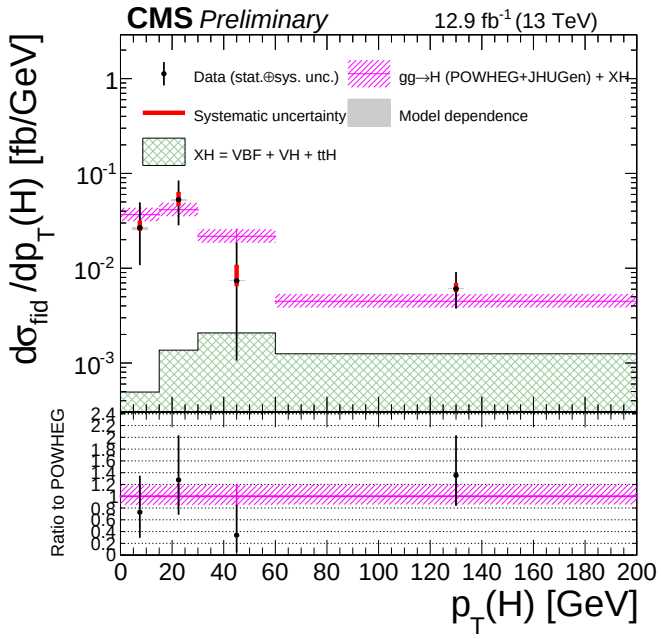


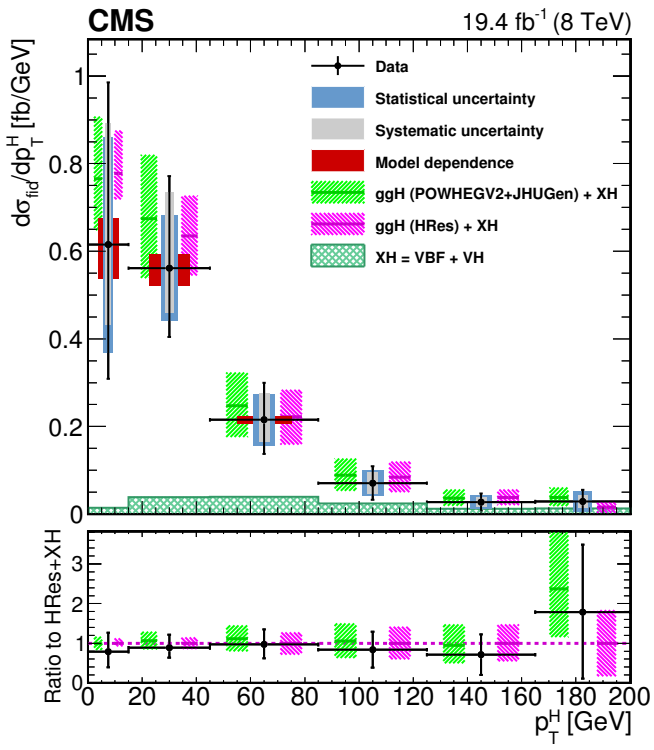
Fiducial Cross Sections.

Many measurements starting to come in

- Still very much statistics limited
  - Nevertheless very important for sharpening exp. and theory tools and minds







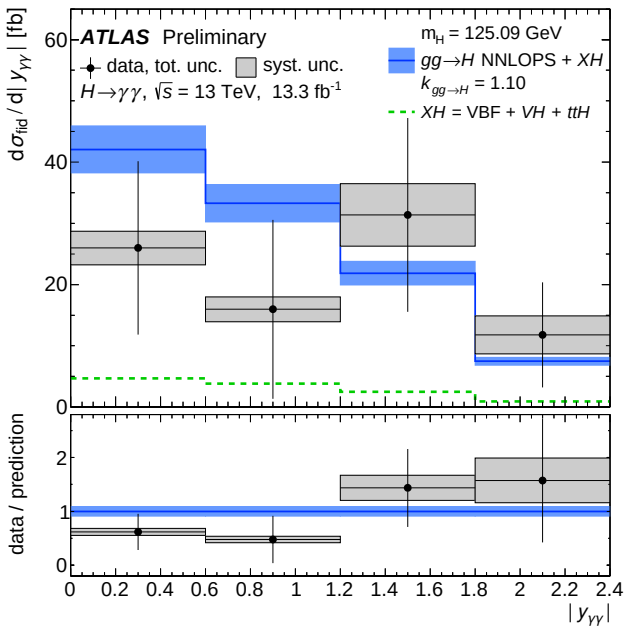
- Higgs p_T spectrum measured in $\gamma\gamma$, ZZ, and even WW
  - Would be great if systematics in WW reduce
  - Would be interesting (especially with limited statistics) to also directly measure first moment in ZZ

Fiducial Cross Sections.

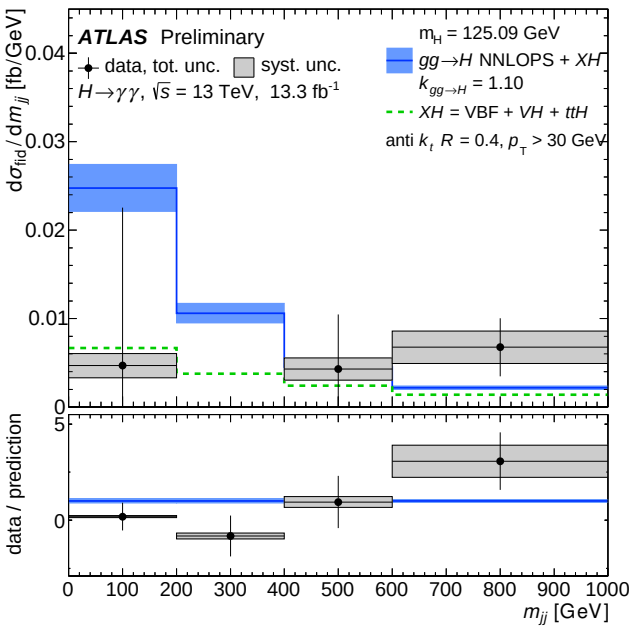
Many measurements starting to come in

- Still very much statistics limited
  - Nevertheless very important for sharpening exp. and theory tools and minds

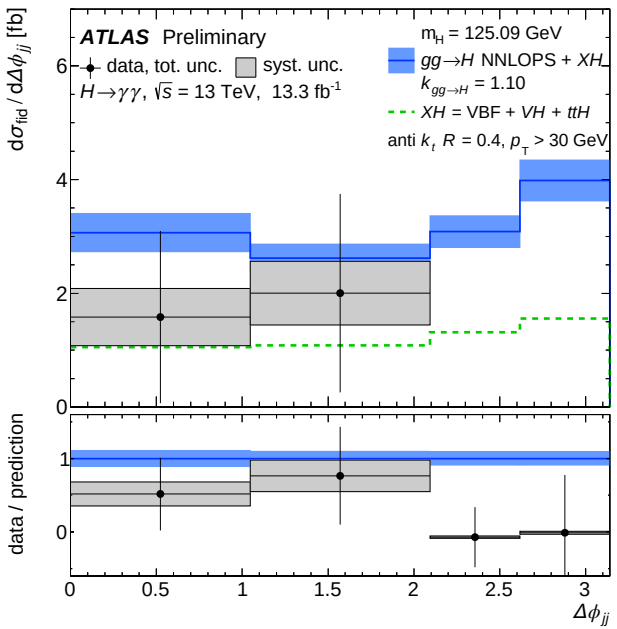
Higgs rapidity



m_{jj}

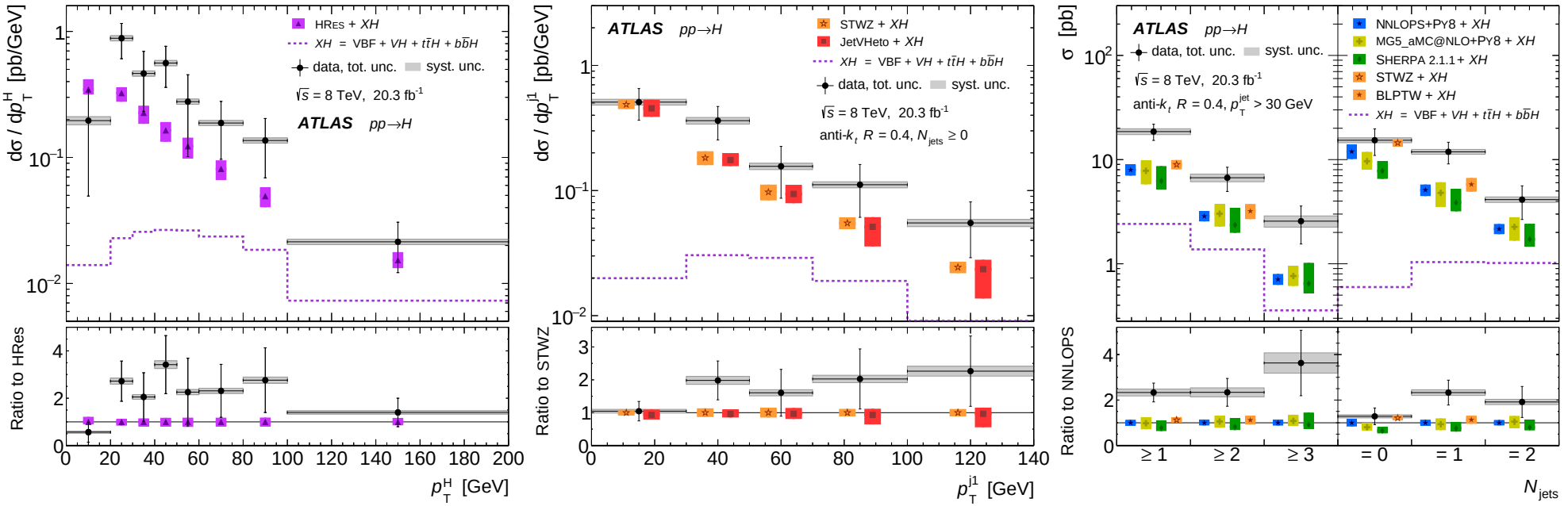


$\Delta\phi_{jj}$



- Also various other interesting observables

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 $H \to ZZ$
- Still agnostic about production mode (mostly, due to $gg \to H$ dominance)

Disadvantages of Fiducial Cross Sections.

Optimizing for maximal theory independence requires sacrificing sensitivity

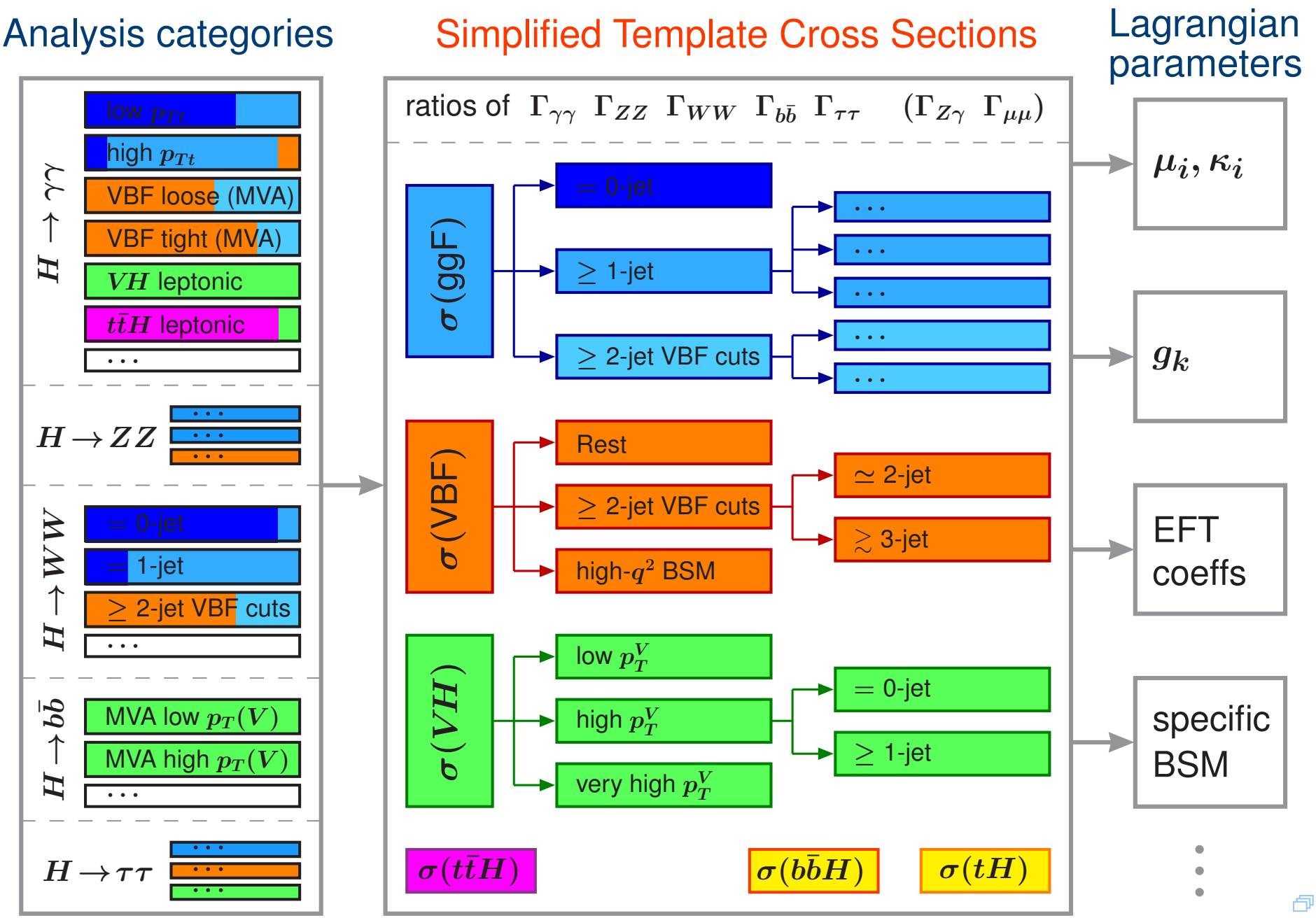
- Requires clean decay channels: $H \to \gamma\gamma, ZZ, (WW)$
- Requires signal definitions such that all experimental efficiencies are independent of production mode
  - Otherwise, efficiency corrections introduce dependence on assumed SM production mode mix
  - Often cannot use MVAs to optimize kinematic signal selection cuts but need simple (rectangular) cuts
  - Sometimes this is just not possible
- Projecting onto several single-differential spectra looses information compared to fully-differential level and introduces statistical overlap

$\Rightarrow$ Simplified template cross sections

Simplified Template Cross Sections.

[Michael Duehrssen-Debling, Paolo Francavilla, FT, Kerstin Tackmann
+ feedback from many people
Les Houches 2015 1605.04692, WG2 YR4 LHCHXSWG-DRAFT-INT-2016-006]

Simplified Template Cross Section Framework.



Construction.

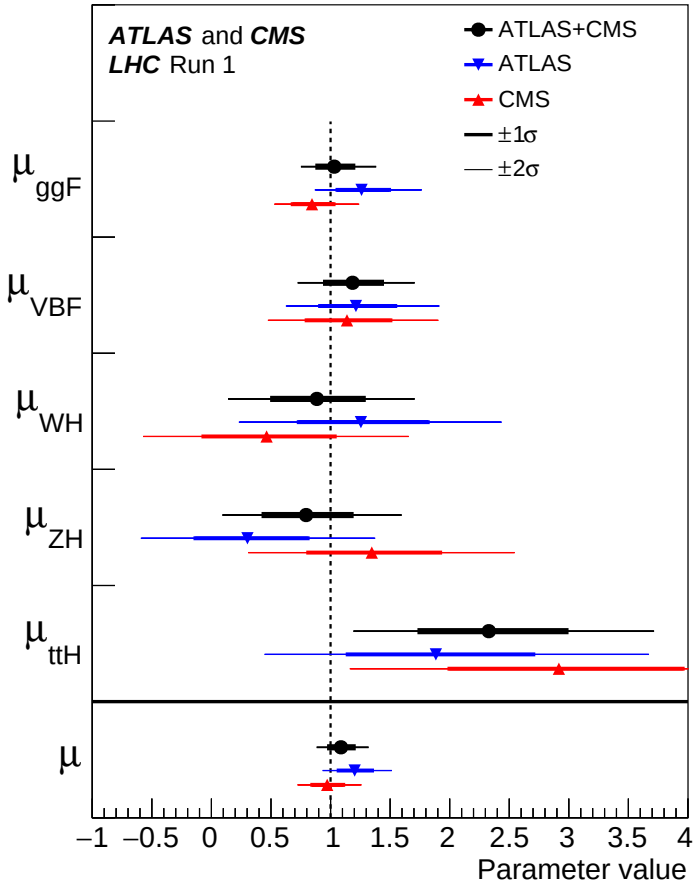
Consider schematic μ fits:

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

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

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

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



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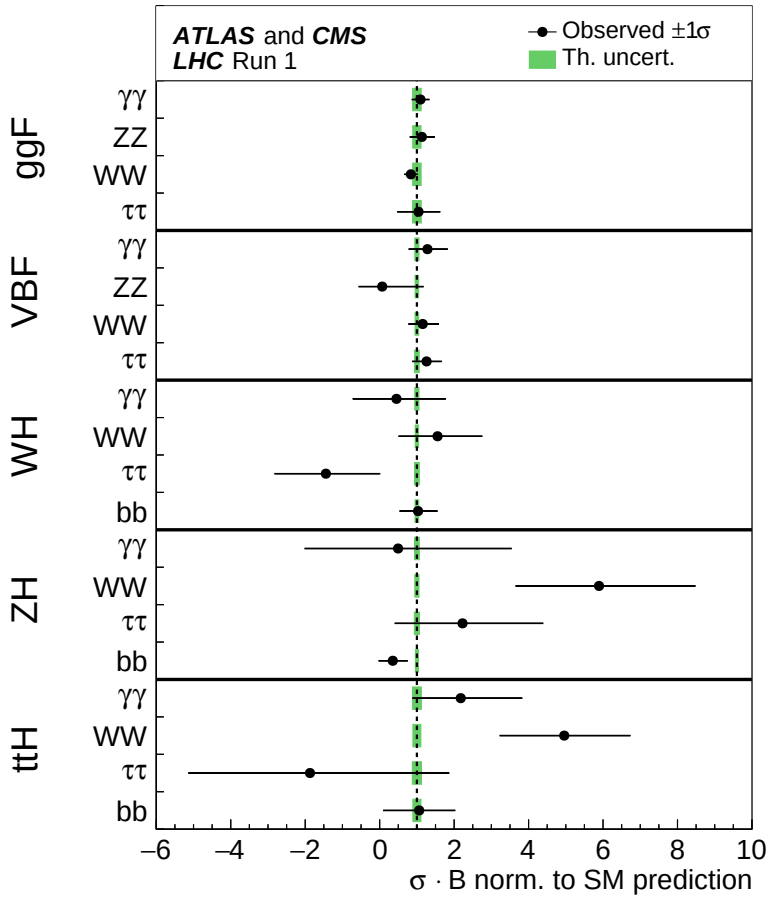
$$\sigma_3^{\text{meas}} = \cdots$$

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

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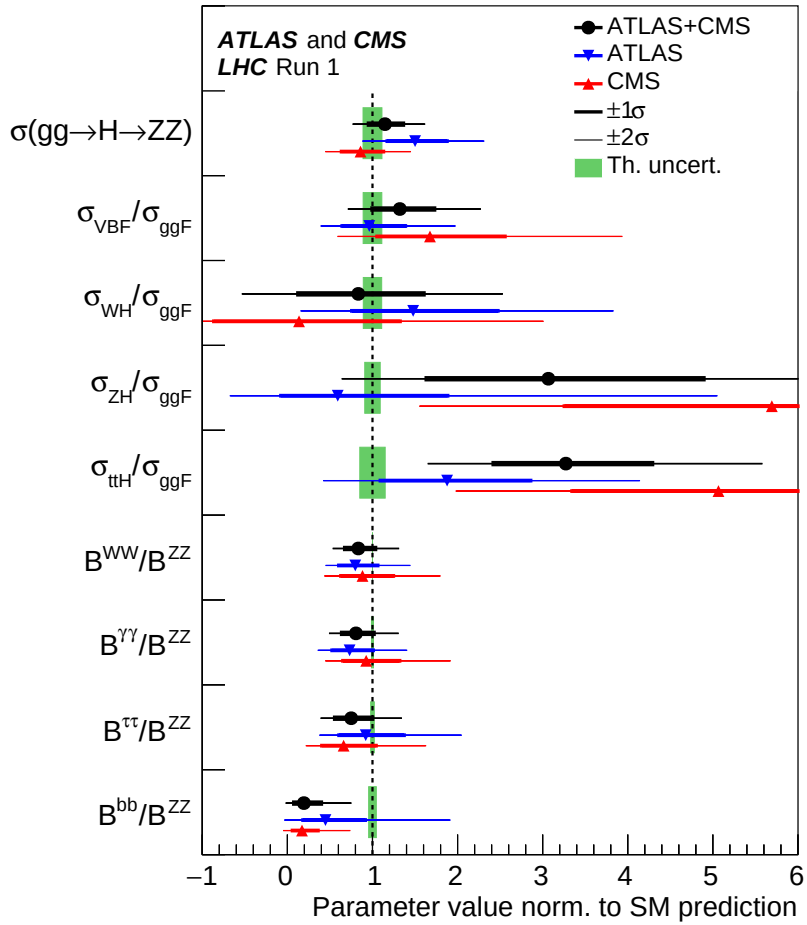


Construction.

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

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

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

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

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 (SM acts as “simplified model”)
  - 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

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

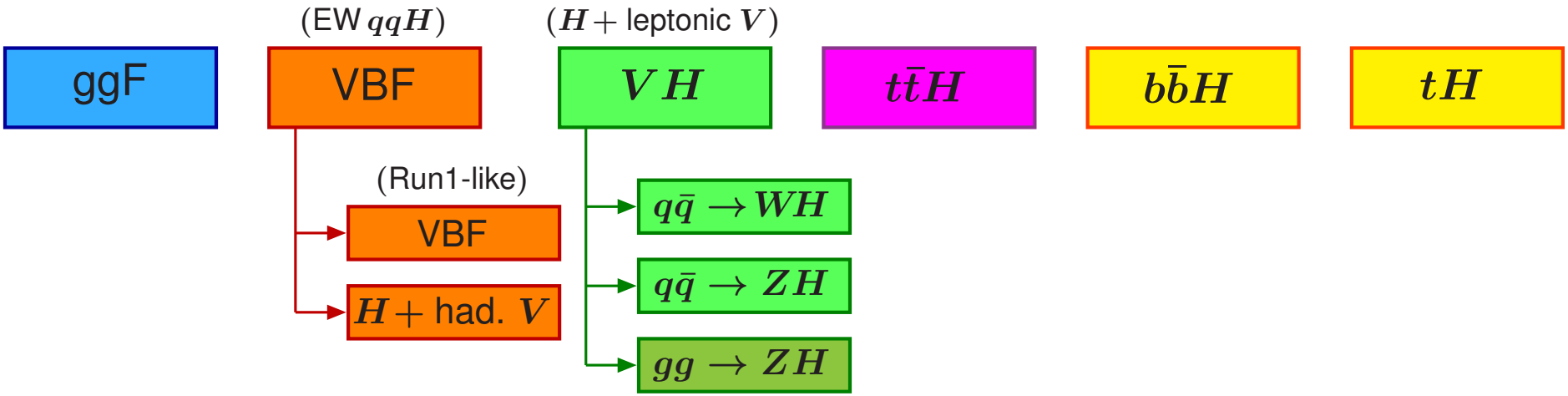
Staging.

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)

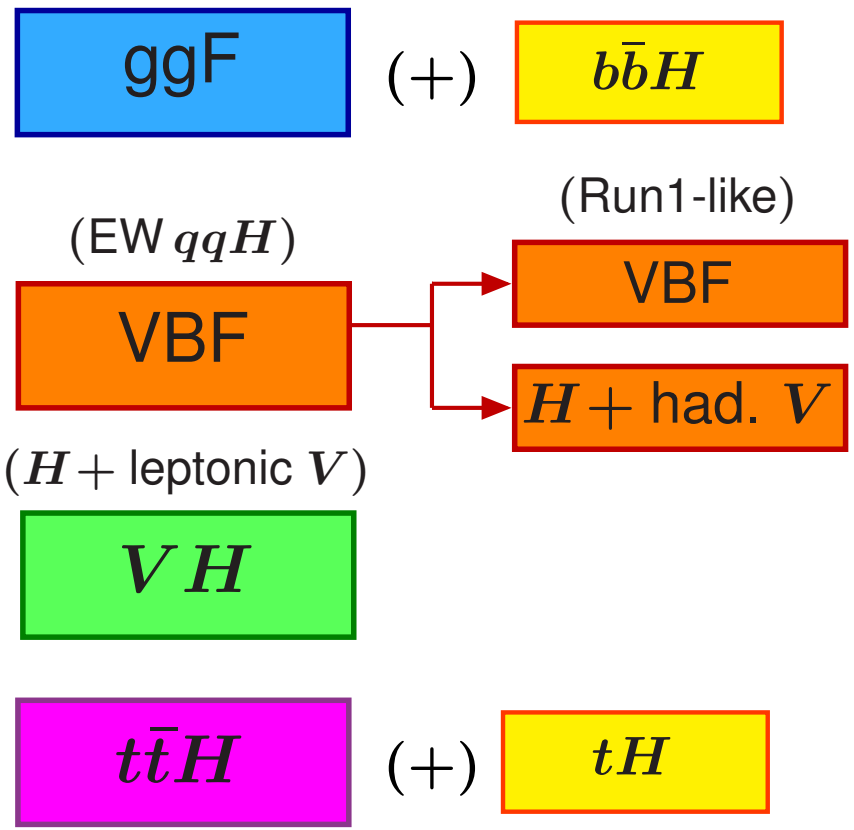
Stage 0.

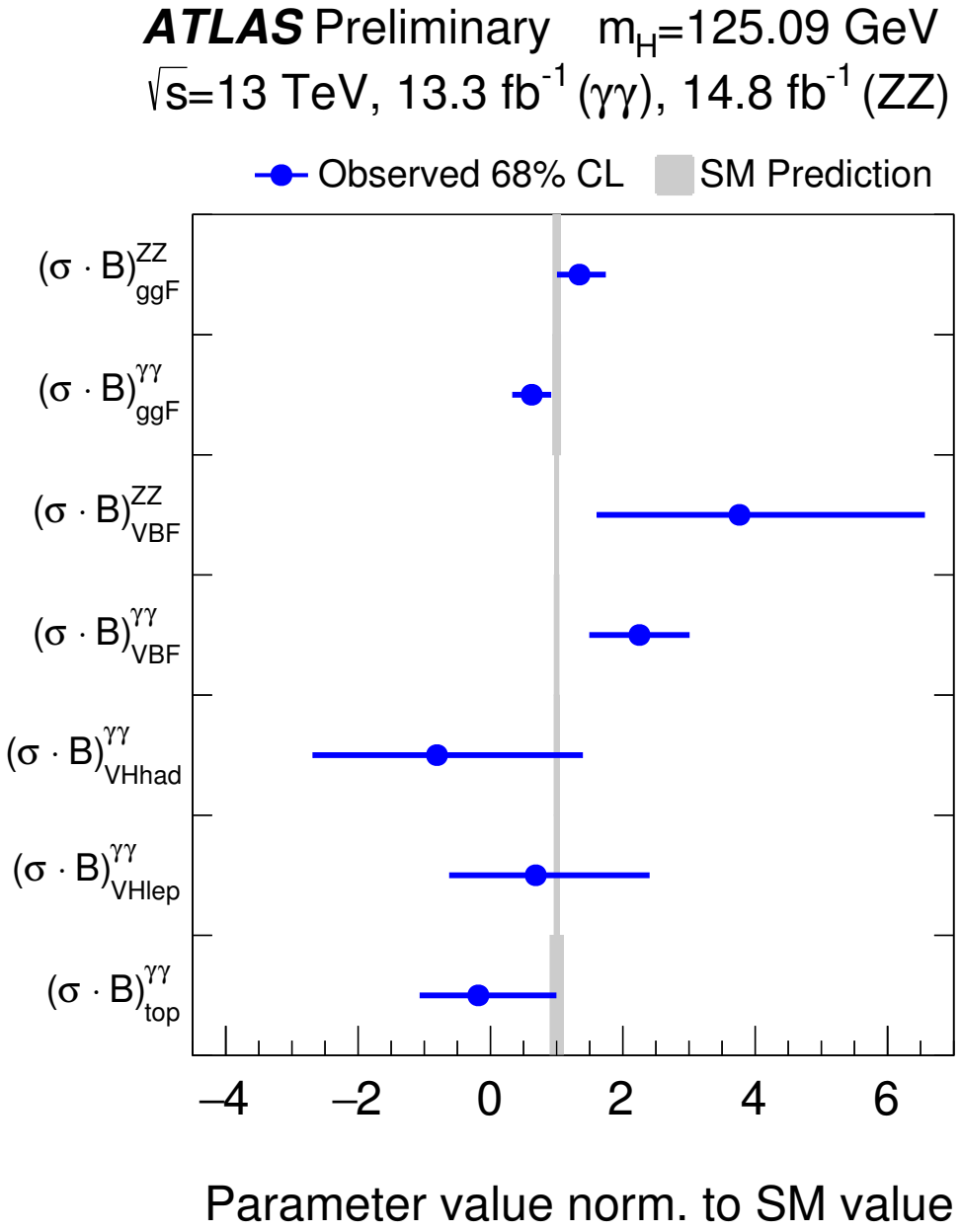


Inclusive cross section per production mode

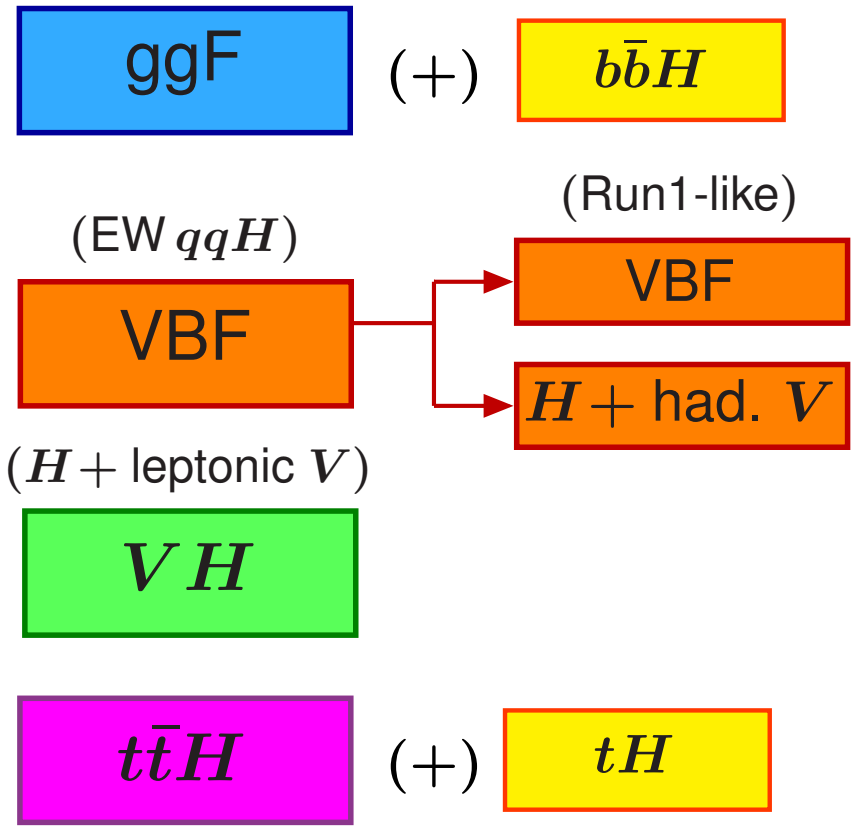
- Closest correspondence to Run1 production-mode μ measurements, *but* expressed in terms of cross sections and restricted to $|Y_H| < 2.5$
- "VBF" defined as electroweak qqH
  - Split into Run1-like VBF and hadronic VH
- "VH" defined as H + leptonic V
  - Split into WH and ZH, and/or $q\bar{q} \to ZH$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

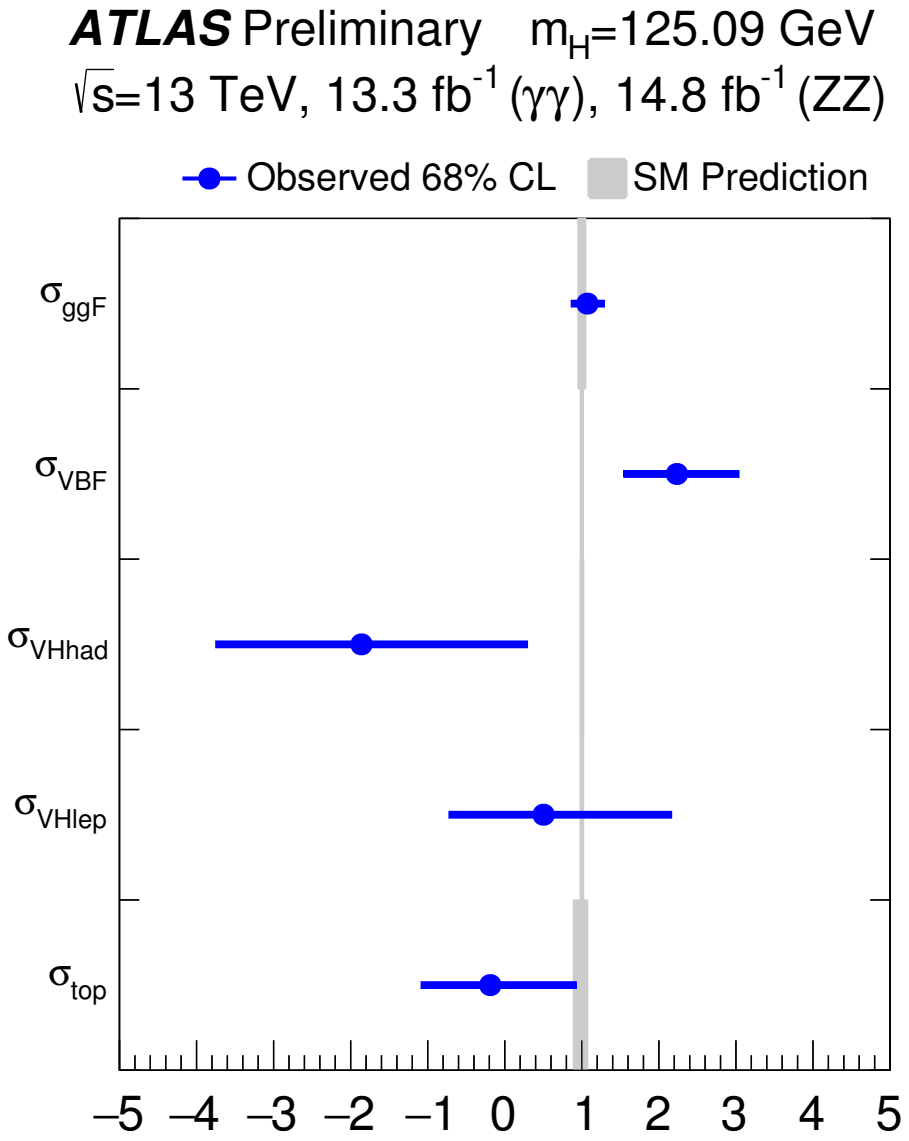
First Stage-0 Measurements from ATLAS.





First Stage-0 Measurements from ATLAS.





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

First Stage-0 Measurements from ATLAS.

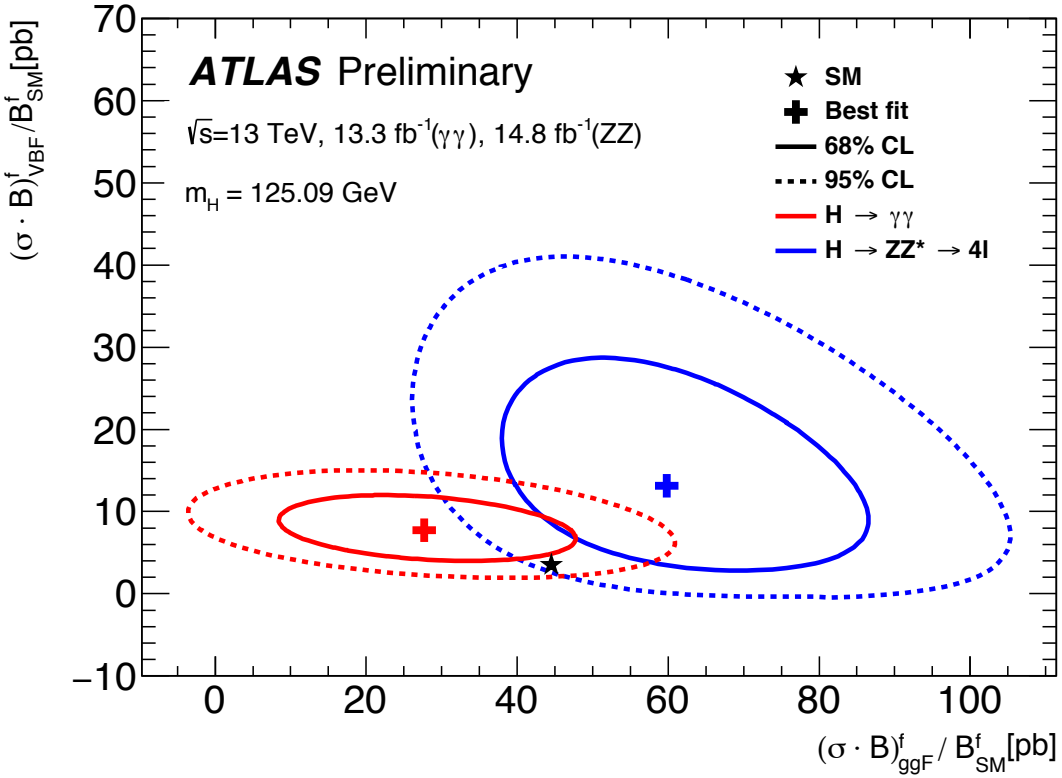
(EW qqH)

VBF

(Run1-like)

VBF

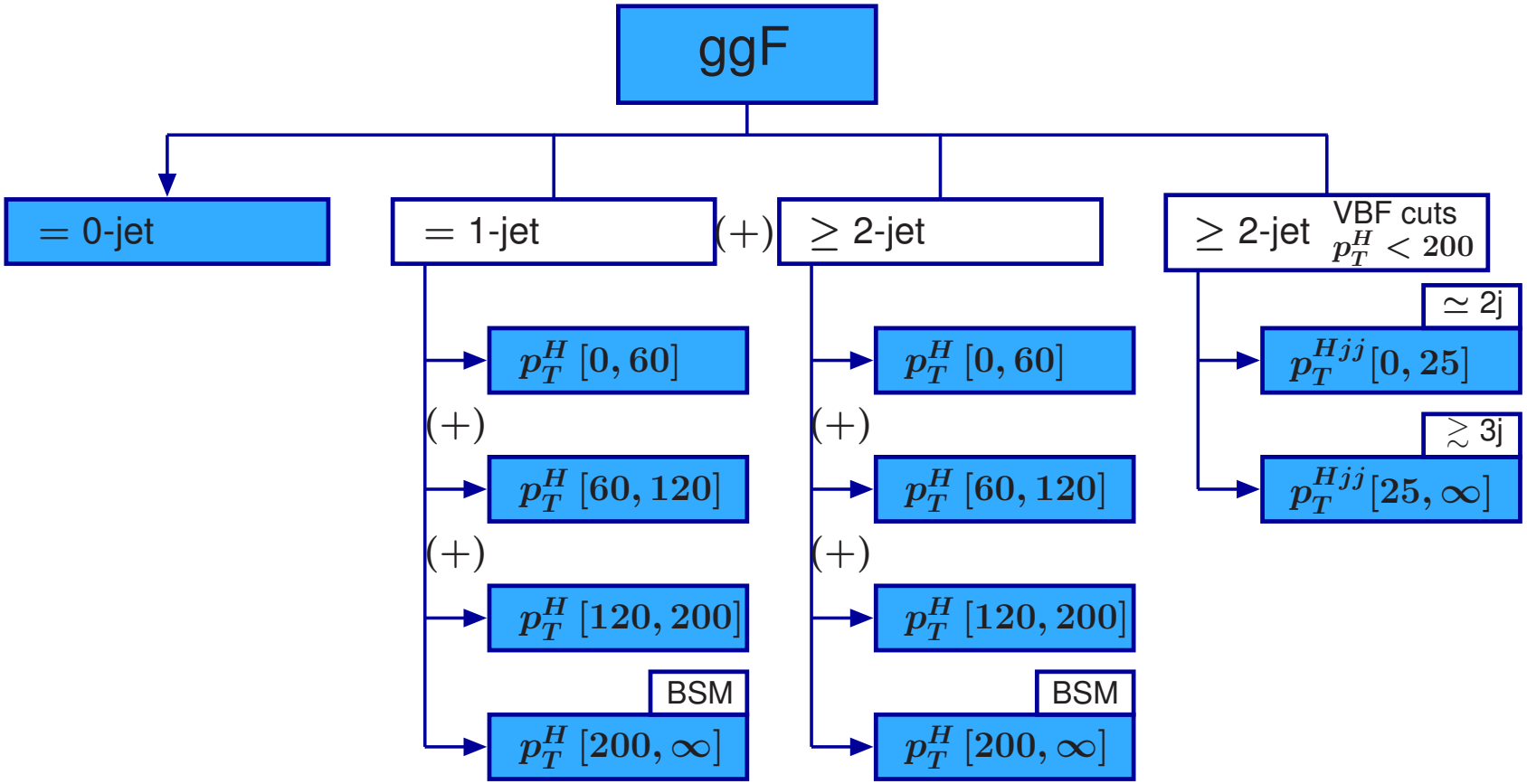
H + had. V



ggF (+) $b\bar{b}H$

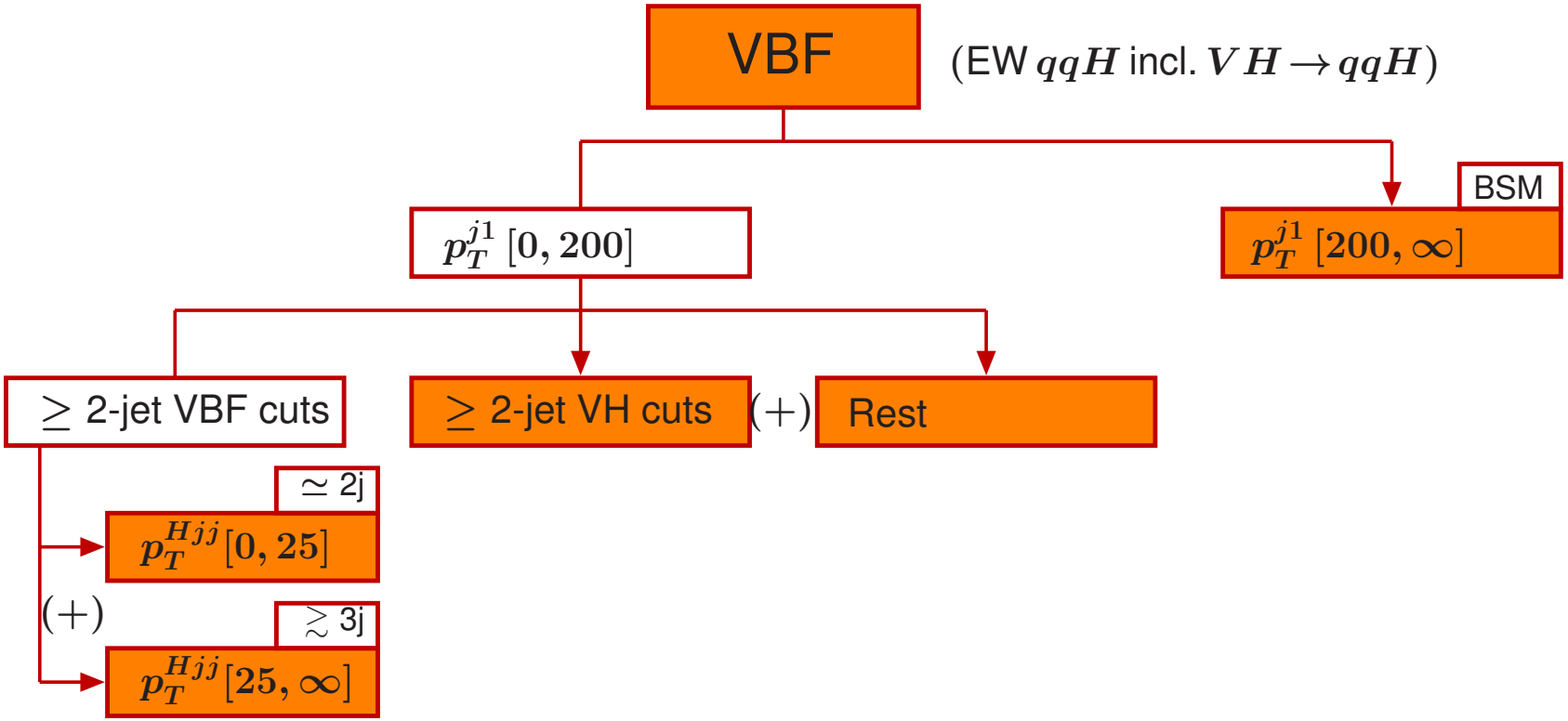
- Normalized to SM branching ratios for plotting purposes only

Gluon Fusion – Stage 1.



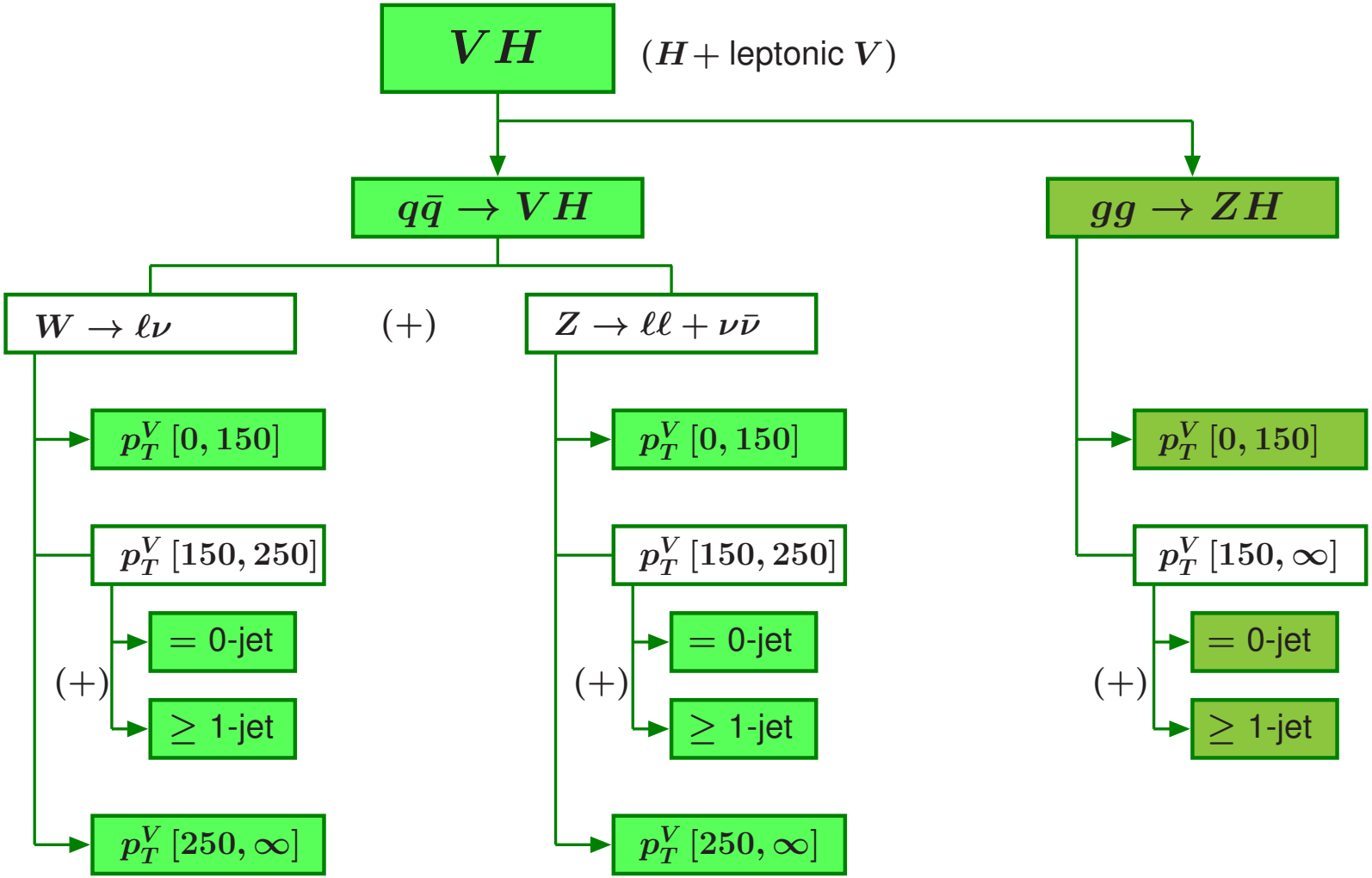
- Jet bins motivated by experimental analyses
- High p_T^H bins target boosted categories ($\tau\tau$) and BSM overflow
- VBF-like cuts to constrain ggF contribution in VBF categories

VBF – Stage 1.



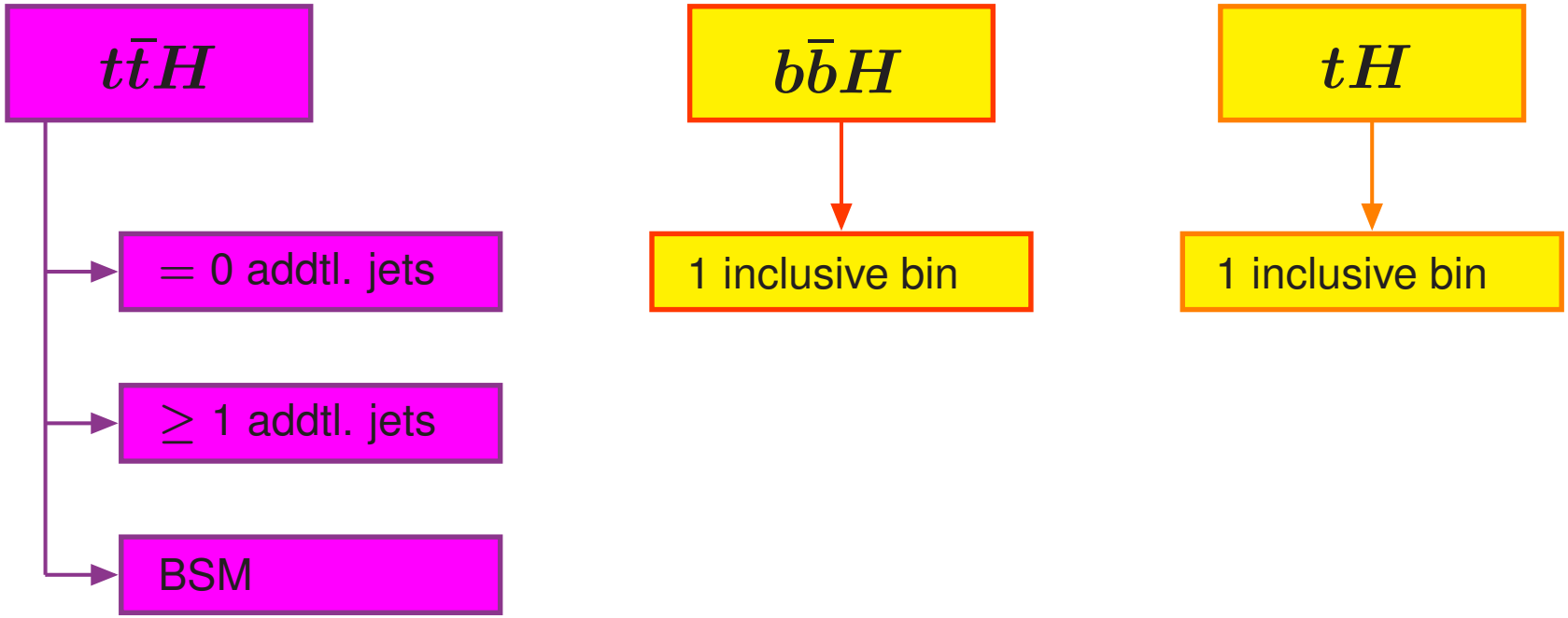
- VBF defined as electroweak $qq'H$ production
  - including usual VBF process and VH with hadronic V decays
- First split by p_T^{j1}
  - VBF topology cuts: $m_{jj} > 400\,\text{GeV}$ and $\Delta\eta_{jj} > 2.8$ (no other cuts)
  - $V(\to jj)H$ topology cuts: $60\,\text{GeV} < m_{jj} < 120\,\text{GeV}$
  - 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)

Other Production Modes.



Stage 1

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

Possible options for stage 2

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

Summary.

Fiducial: Optimized for maximal theory independence

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

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

Agnostic to production modes

(Single-)differential distributions

(overlapping events)

Only $H \to \gamma\gamma, ZZ, (WW)$

(by default no combination of channels)

Xsec split by production mode

Xsec split into mutually exclusive regions of phase space

Explicitly designed for combination of all decay channels

Summary.

Separating measurement from interpretation is key

- ... to manage theory systematics
- ... to make experimental results long-term useful

Simplified cross sections

- Developed as evolution from and eventual replacement of μ fits
  - Provide more fine-grained measurements while benefitting from combination of all channels
  - Reduce theory assumptions/bias folded into experimental results
- Lowest layer of how experiments publish results for individual channels, combination of channels, and ATLAS+CMS combination
  - Can perform κ fits (or any other interpretations) with these as input layer
  - Experimental publications should include full covariance (or if insufficient full likelihood) among all bins

They *do not*

- replace full-fledged fiducial cross section measurements
- exclude optimized analyses for specific purposes
  (e.g. spin or CP measurements, off-shell studies, dedicated BSM searches, etc.)

Backup Slides

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.

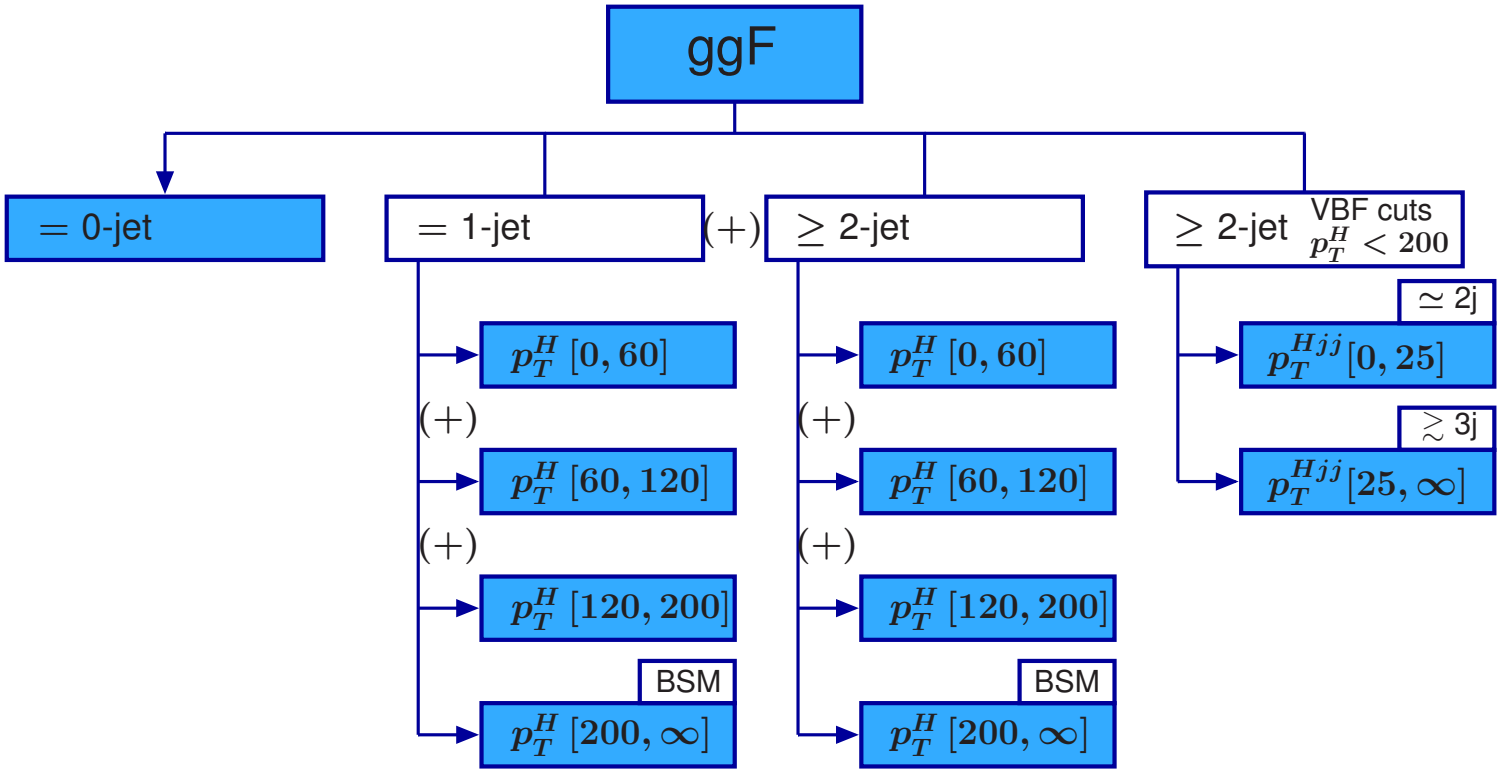
Leptons from decays of signal vector bosons (i.e. VH)

- 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

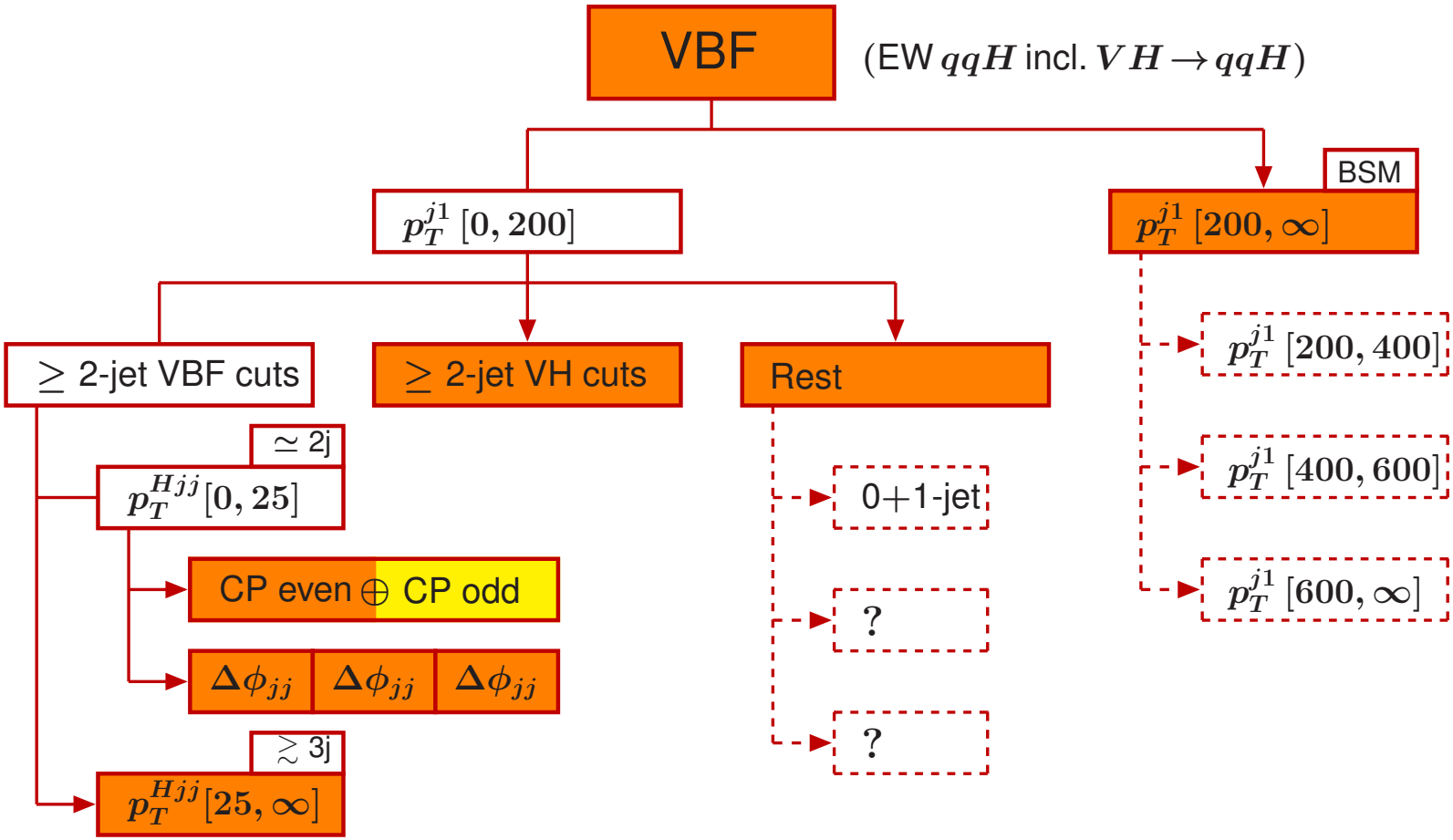
Gluon Fusion – Stage 2.



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 $N_j \geq 3$

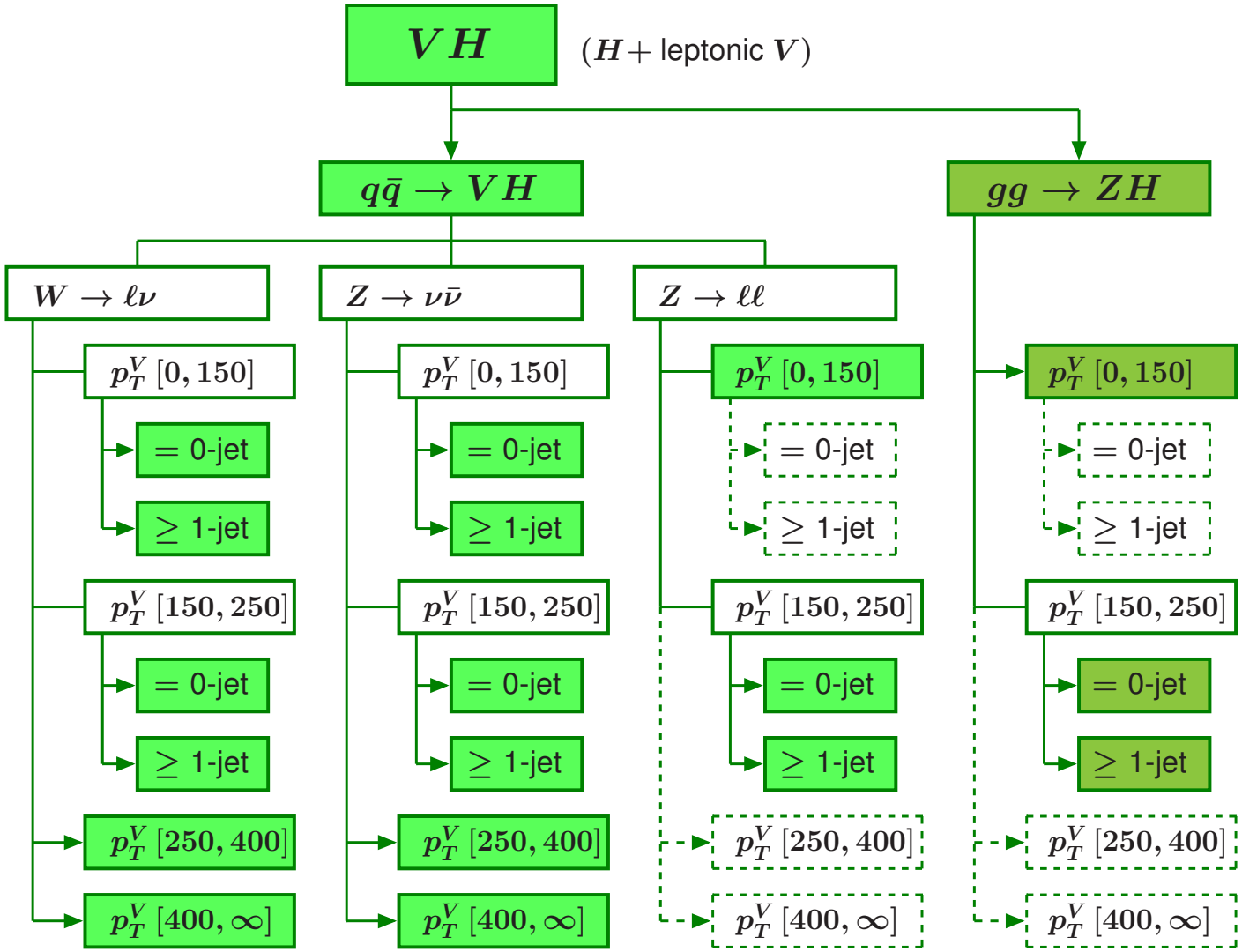
VBF – Stage 2.



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}

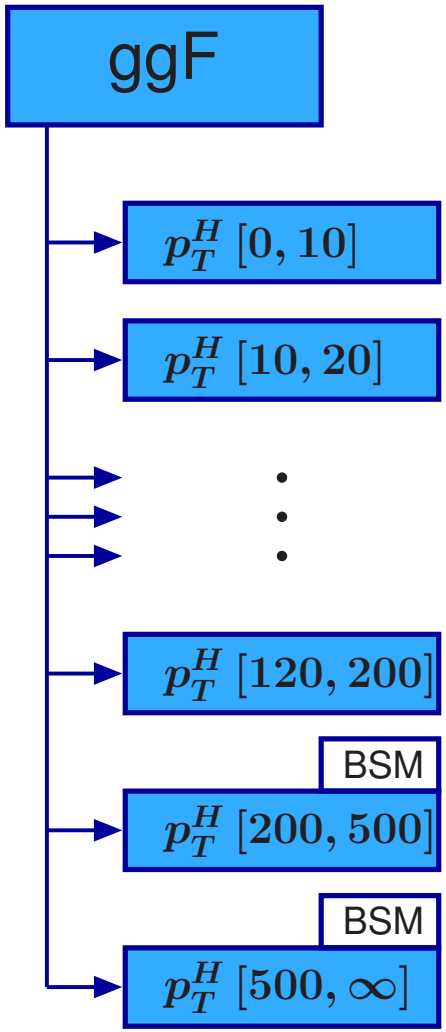
VH – Stage 2.



Possible options for stage 2

- Separate Z decays, further split high p_T^V

Simplified Template Differential Cross Sections.



Supplementary to primary bins

- Same framework can be employed to measure differential spectra per production mode, e.g. p_T^H for ggF
  - Interesting e.g. for QCD studies in ggF
  - Need to evaluate statistical correlations with primary bins in case both are used for specific interpretation
- Could be an interesting application, but must not replace fully fiducial differential cross section measurements