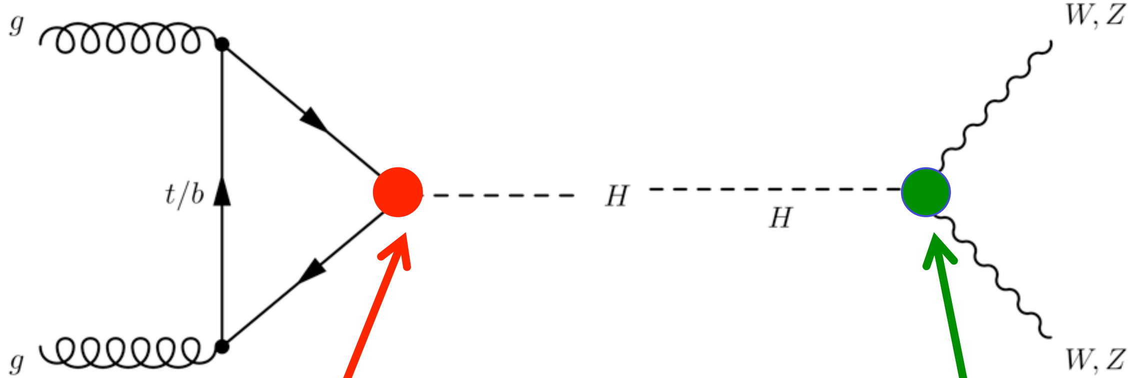
Outline of this presentation

Interpretation beyond signal strengths – the κ framework

- Parameters κ_j correspond to LO degrees of freedom
- Example for ggF production of H→VV



$\sigma_{ggF} = (1.06\,\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_b\kappa_t)\,\sigma_{ggF}(SM)$ $\Gamma_{W,Z} = \kappa^2_{W,Z}\,\Gamma_{W,Z}(SM)$

$$\sigma(i \rightarrow H \rightarrow f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

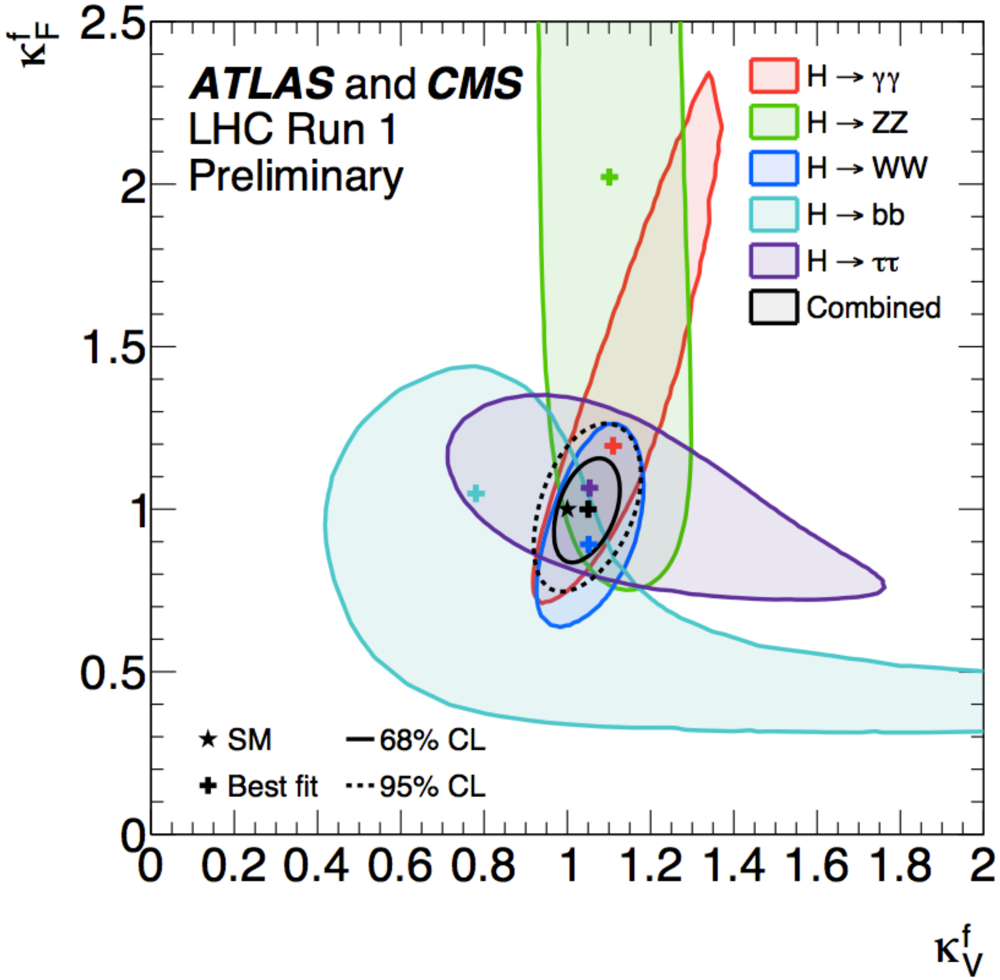
NB: σ_{ggF}(SM) from NNLO(QCD) + NLO(EW) calculation!

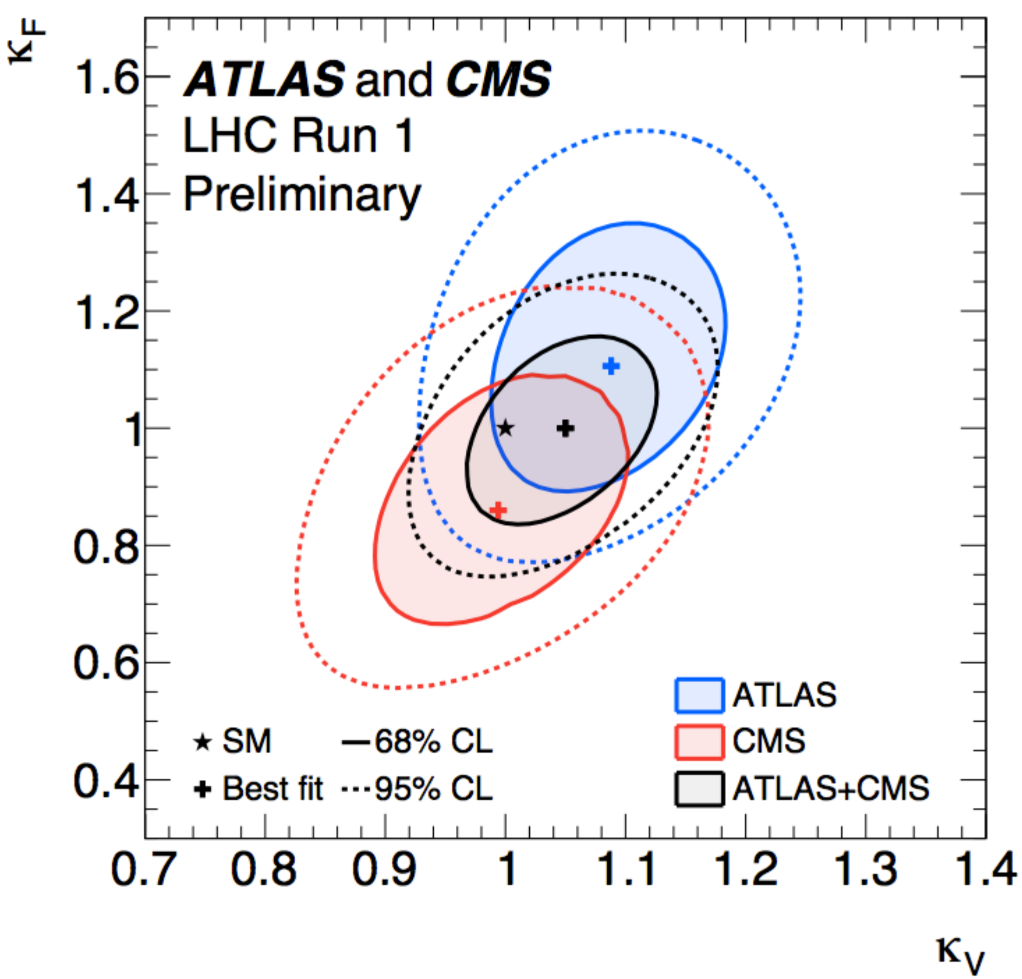
Constraints for Higgs couplings to fermions, bosons

- Assume universal scaling parameters for Higgs couplings to fermions (κ_F), bosons (κ_V)

$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

- Assume only SM physics in loops, no invisible Higgs decays, $\kappa_{F,V} \geq 0$





Constraints on tree-level Higgs couplings

- Assume only SM physics in loops, no invisible Higgs decays
- Fit for scaling parameters for Higgs couplings to

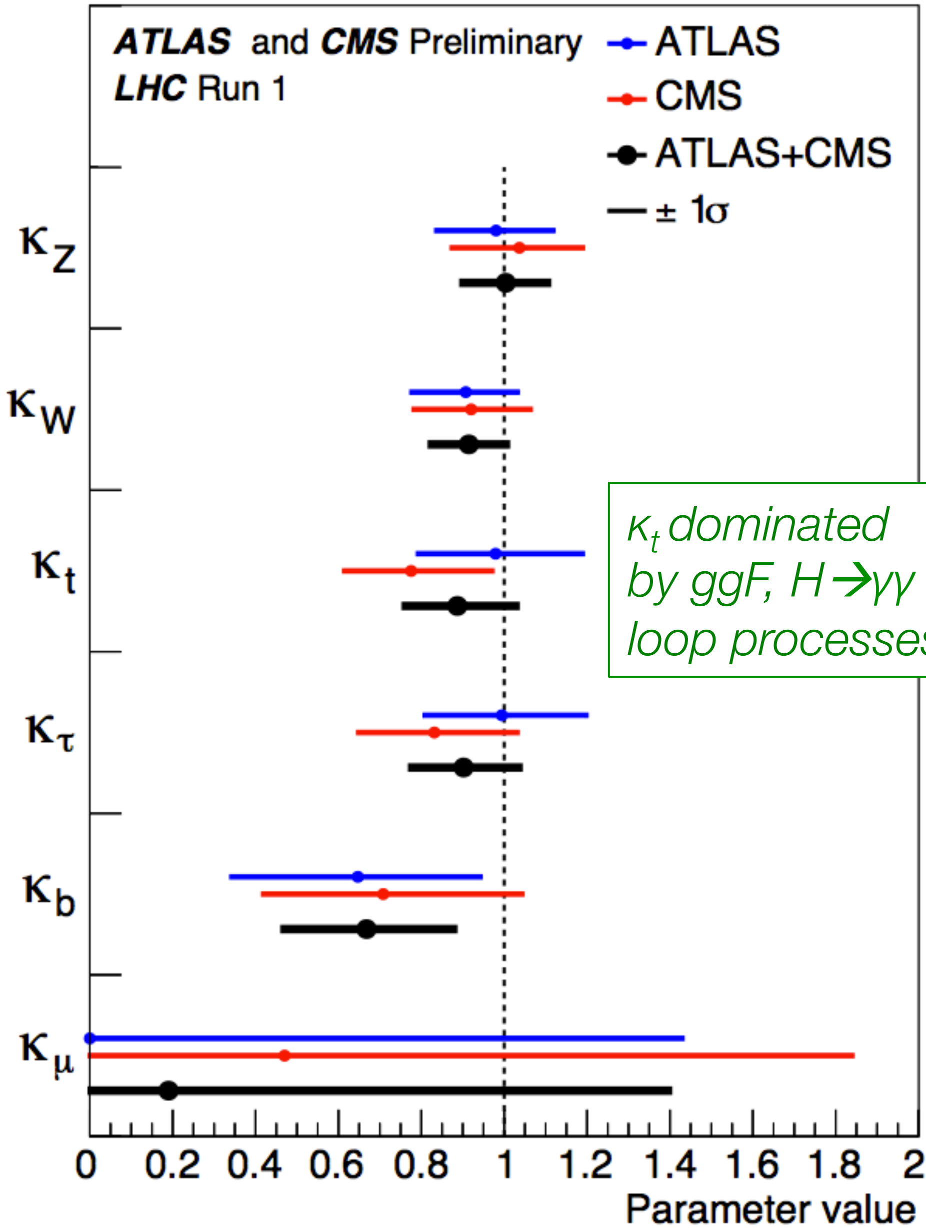
  W, Z, b, t, τ, μ

- *NB: low measured value of κ_b reduces total width Γ_H*

  → all κ_i measured low [w.r.t μ=1.09]

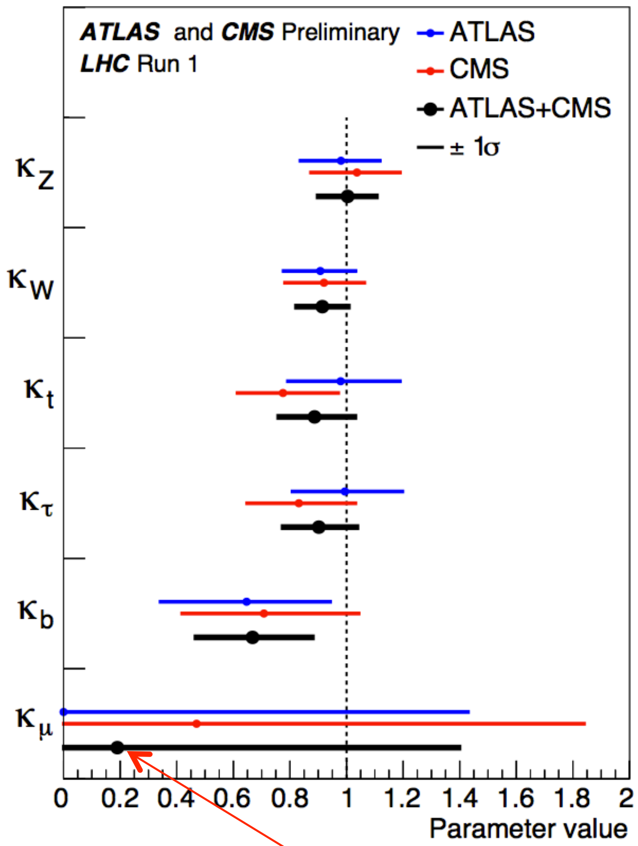
$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

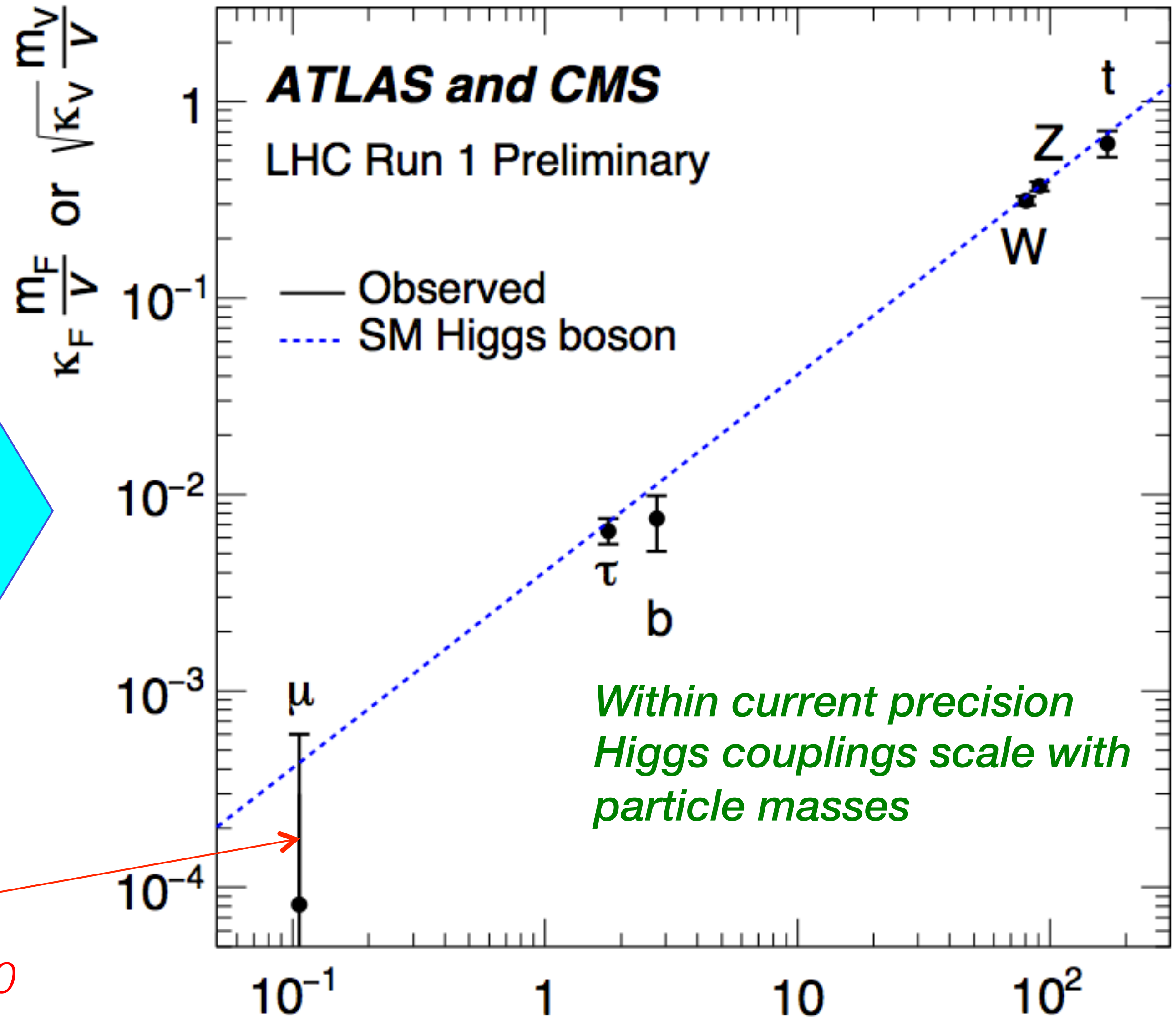
$$\kappa_H^2 \sim \begin{array}{l} \boxed{0.57 \cdot \kappa_b^2} + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + \\ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + \\ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2 \end{array}$$



κ_t dominated by ggF, H→γγ loop processes

Constraints on tree-level Higgs couplings





Observed κ_μ compatible with 0

Within current precision Higgs couplings scale with particle masses

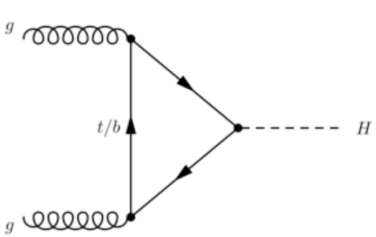
Running masses ($\overline{MS}$ scheme)

Allowing for BSM contributions in Higgs coupling interpretations

- Results shown so far assumed no invisible (BSM) Higgs decays nor BSM contributions to loops. Now drop these assumptions.

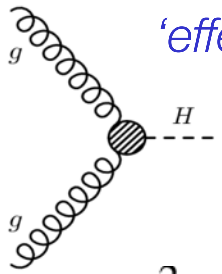
1. Represent loop processes (ggF, H→Z/γγ) with effective params (κ_g,κ_γ), rather than assuming SM content

'SM resolved'



$$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$$

'effective coupling'



$$\kappa_g^2$$

Measurement of κ_t dominated by ttH

2. Allowing BSM Higgs decays (invisible, undetected etc…) to increase the total width

$$\Gamma_\mathrm{H} = \frac{\kappa_H^2 \cdot \Gamma_H^\mathrm{SM}}{1 - \mathrm{BR}_\mathrm{BSM}}$$

If BR_{BSM} >0 then all observed cross-sections lowered by common factor

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

Limit on invisible Higgs decays from Higgs couplings

- Concept: set limit on BR to (invisible, undetected) Higgs decays

$$\Gamma_{\mathrm{H}} = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

- When κ_H is modeled by 6+2 κ_i's it has no strong upper bound
  → $\mathrm{BR}_{\mathrm{BSM}}$ not bounded (Γ_H due to large κ_H or to large BR_{BSM}?)
  → Must introduce some assumptions to bound κ_H
- Scenario 1 – Assume 6 tree-level couplings at SM ($k=1$),
  but leaving 2 effective couplings for loops floating
- Scenario 2 – Keep all 6+2 coupling parameters floating,
  but bound vector boson couplings $\kappa_W,\kappa_Z \leq 1$

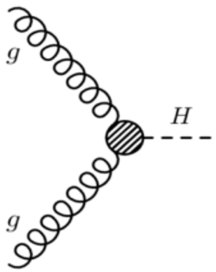
(Bound $k_V \leq 1$ occurs naturally in many BSM physics models, e.g. Electroweak Singlet, 2HDM, MCHM…)

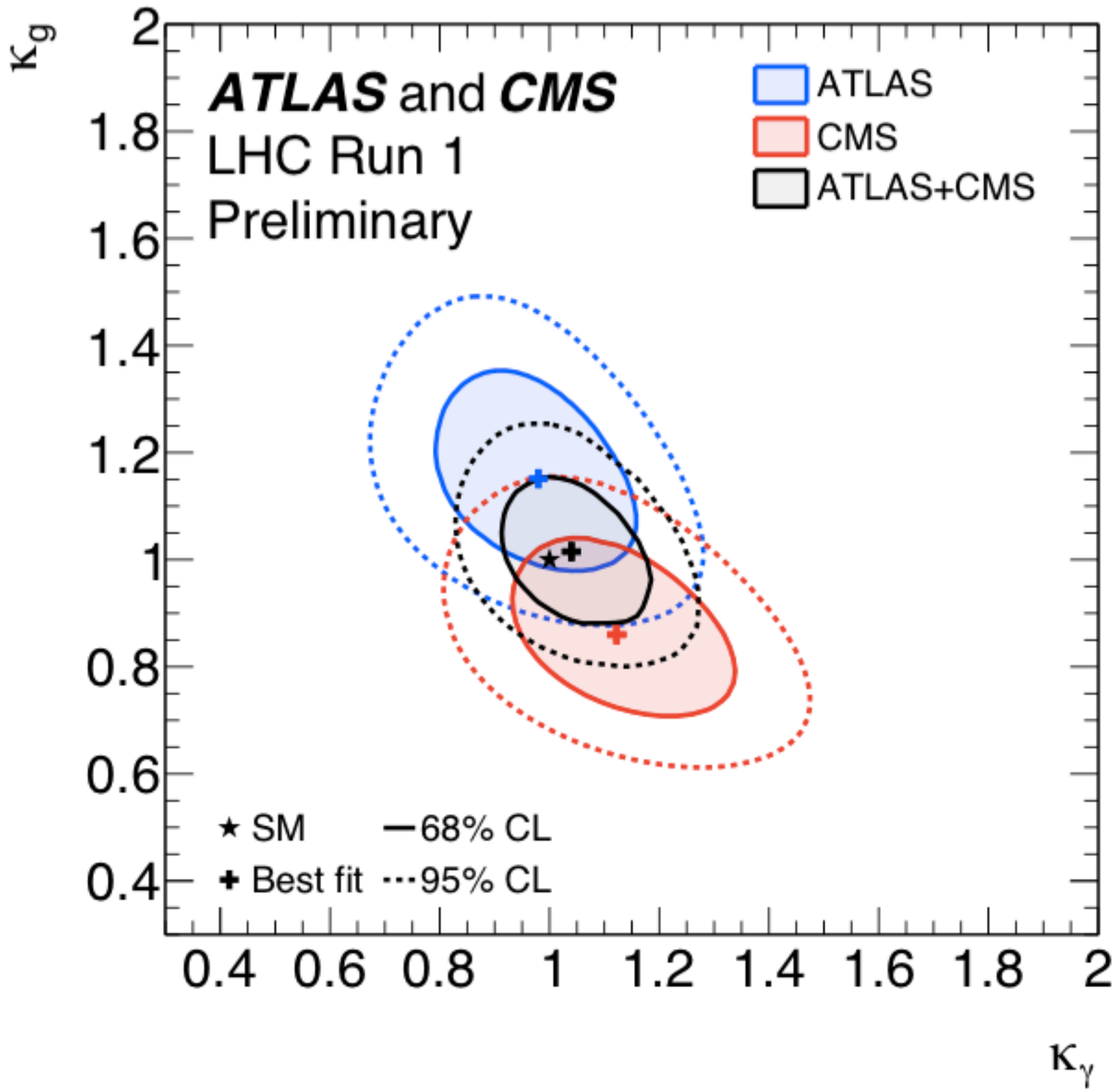
(alternatively, use off-shell coupling strength measurements to constrain Γ_H, albeit with additional assumptions)

Focus on effective couplings for loop processes

‘Scenario 1’

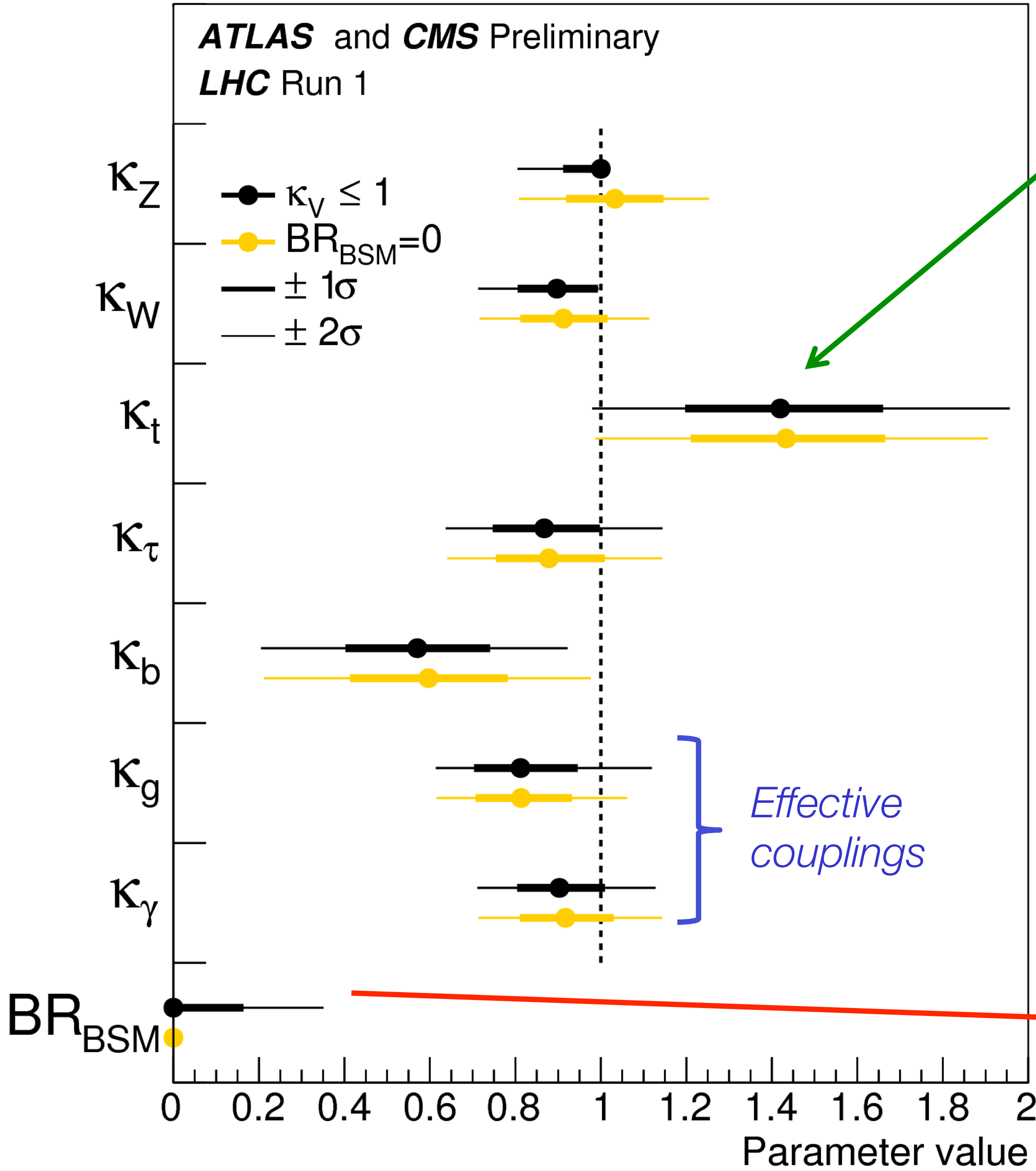
- Fix all tree-level Higgs couplings to SM ($\kappa_W, \kappa_Z, \kappa_b, \kappa_t, \kappa_\mu, \kappa_\tau = 1$) and $BR_{inv} = 0$





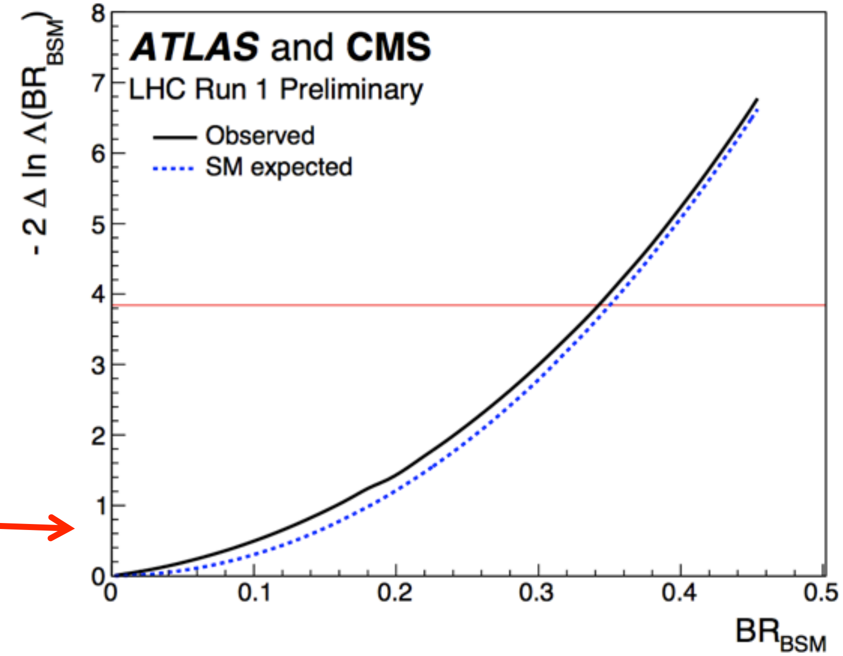
Constraints on Higgs couplings allowing BSM physics in loops & decays

'Scenario 2'



κ_t dominated by ttH process (ggF,H$\gamma\gamma$ loops no longer contribute)

BR_{BSM} < 0.34 at 95% C.L. (assuming $\kappa_V \leq 1$)



What about direct limits on H→inv decays

- Searches for associated (VH) or VBF Higgs productions with H→invisible decays also set limits on Br_{inv}
  - Experimental signature: associated products plus large missing ET
- Individual ATLAS and CMS searches in ZH, WH and VBF channels set limits between 182% and 28%

Reference	Process	Experiment	Observed limit	Expected limit
PRL 112, 201802 (2014)	Z(-> ll) H	ATLAS	75%	62%
EPJC 74 (2014) 2980	Z(-> ll) H	CMS	83%	86%
EPJC 74 (2014) 2980	Z(-> bbar) H	CMS	182%	199%
EPJC (2015) 75:337	V(W/Z -> jets) H	ATLAS	78%	86%
CMS-PAS-EXO-12-055	V/jet + E_T^{miss}	CMS	53%	62%
CMS-PAS-HIG-14-038	VBF H -> inv	CMS	57%	40%
ATLAS-CONF-2015-004	VBF H -> inv	ATLAS	28%	31%

Direct searches assume SM Higgs production rate!

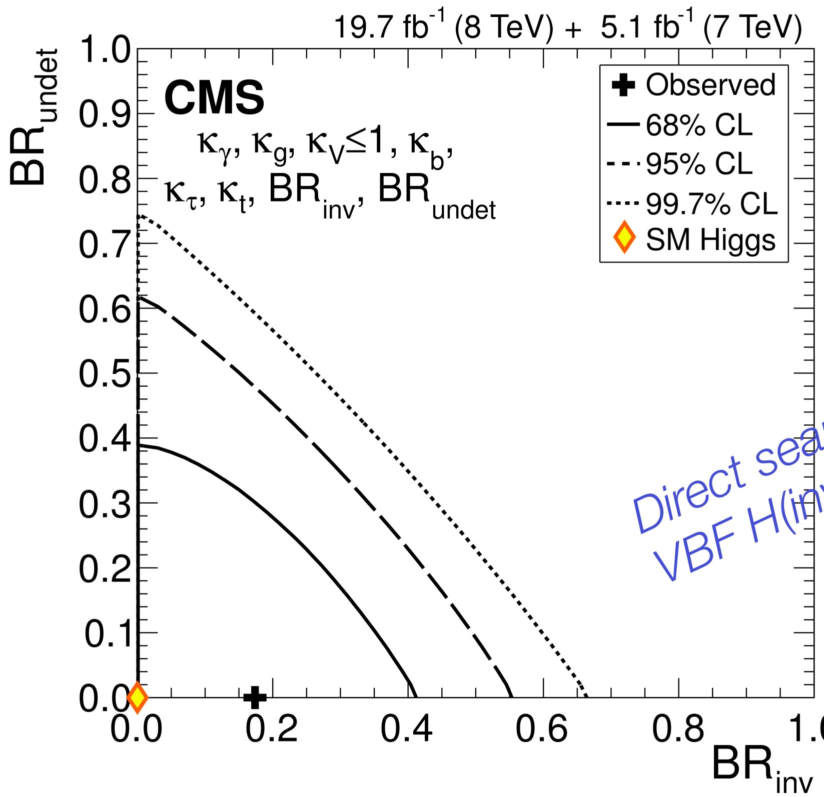
VBF searches most powerful…

ATLAS HIGG-2015-03 ATLAS Direct Combined result: BR_{inv} < 0.25 at 95% C.L. (<0.27 expected)

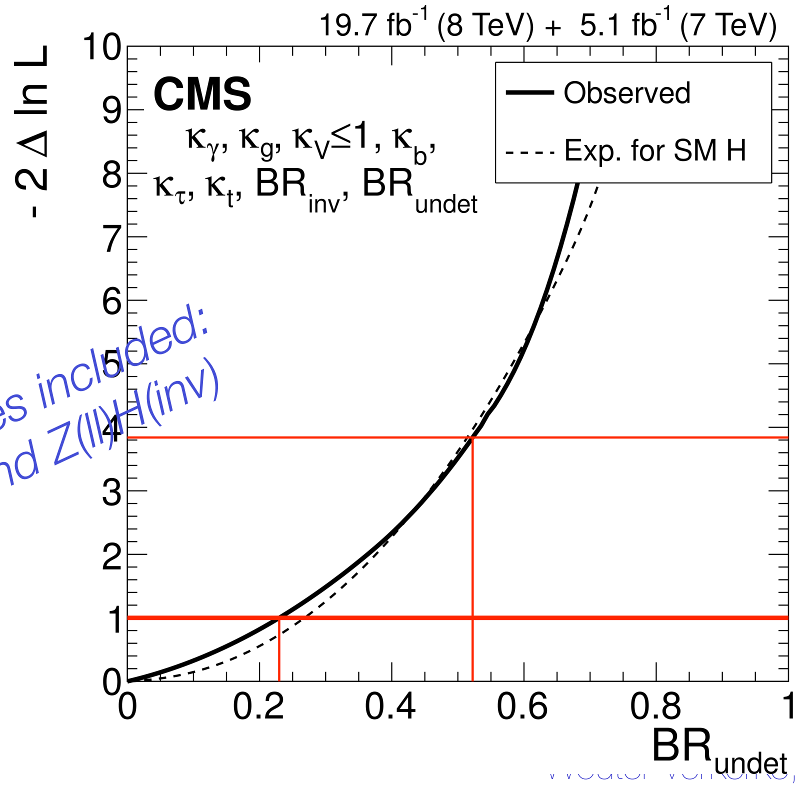
CMS PAS HIG-14-038 CMS Direct Combined result: BR_{inv} < 0.46 at 95% C.L. (<0.35 expected)

Combining direct and indirect measurements

- **Indirect** measurements from couplings measure sum of invisible decays (BR_{inv}) and undetected decays (BR_{undet}, e.g. BSM H decays to lepton+jets)
- **Direct** searches requiring MET only constrain invisible decays (BR_{inv})
- Can (weakly) constrain BR_{undet} by combining direct & indirect measurements



Direct searches included: VBF H(inv) and Z(ll)H(inv)



Combining direct and indirect measurements

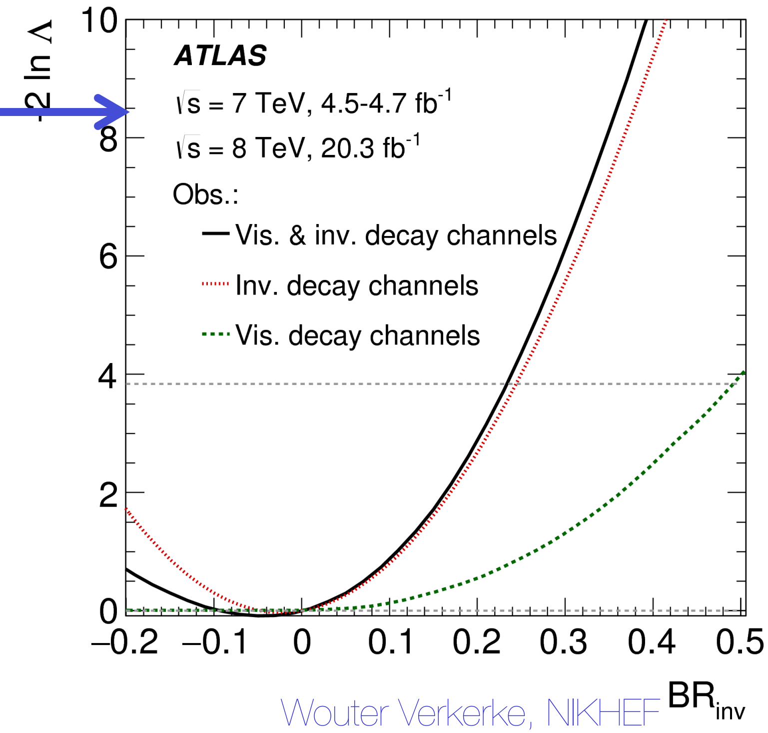
- Alternatively, (conservatively) assume BR_{undet}=0 → Both direct and indirect searches measure BR_{inv}
- In direct searches can release assumption of SM production rate
→ substitute measured rate from couplings fit
- In coupling fit can release assumption k_V<1
→ direct limit on BR_{inv} is sufficiently strong to bound Γ_H

Includes VBFHinv+ZllHinv

Most general result (assumes only BR_{undet}=0)
ATLAS: **BR_{inv}<0.23 at 95% C.L.** (exp <0.24)
CMS: **BR_{inv}< 0.49 at 95% C.L.** (exp<0.32)
(assumes kV<1)

ATLAS

Decay channels	Coupling parameterisation	κ_i assumption	Upper limit on BR_{inv} Obs.	Exp.
Invisible decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}]$	$\kappa_{W,Z,g} = 1$	0.25	0.27
Visible decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}]$	$\kappa_{W,Z} \leq 1$	0.49	0.48
Inv. & vis. decays	$[\boldsymbol{\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}}]$	**None**	**0.23**	**0.24**
Inv. & vis. decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}]$	$\kappa_{W,Z} \leq 1$	0.23	0.23



Generic parameterizations

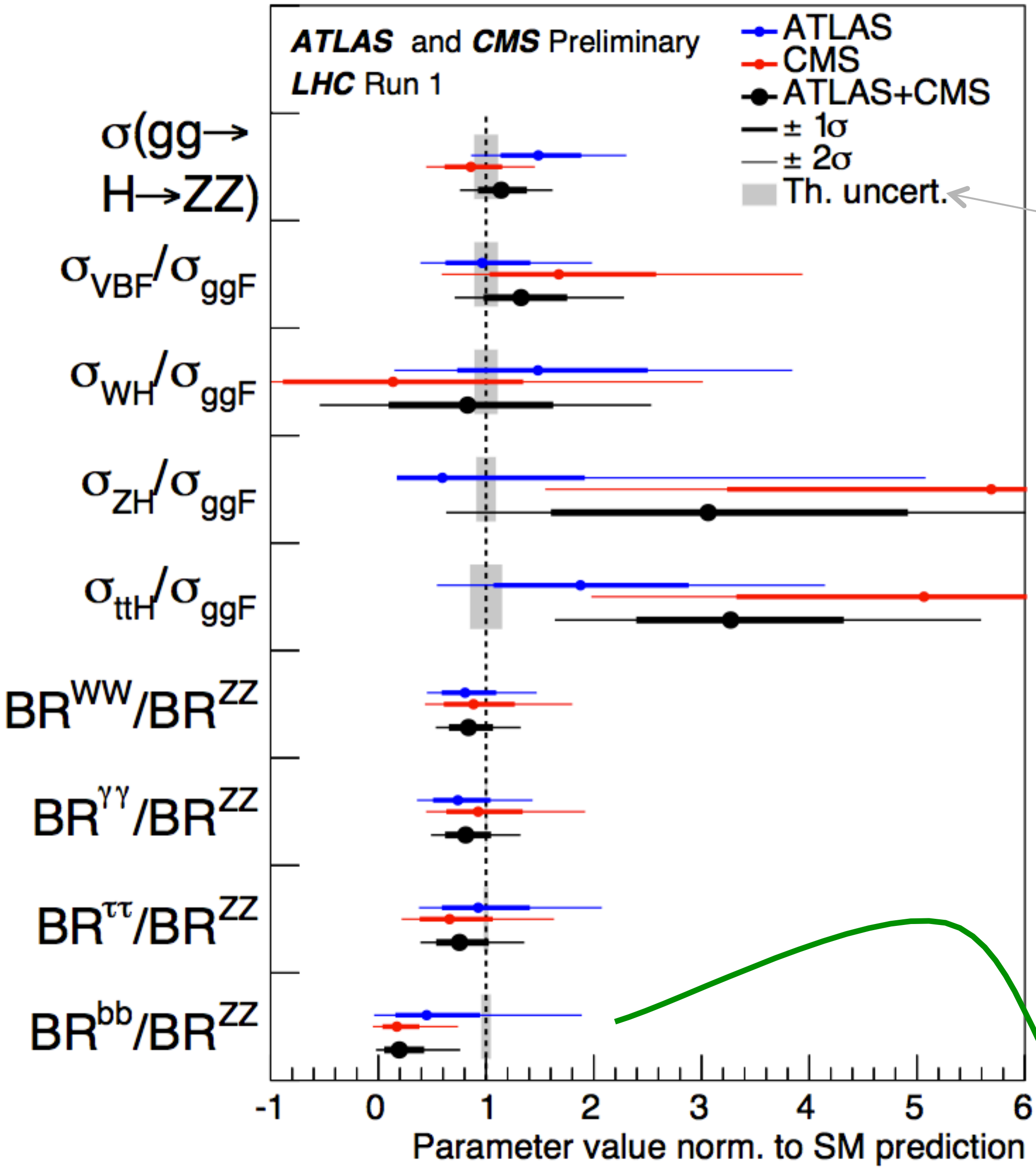
- Goal of (most) generic parameterizations is to provide summary of Higgs coupling constraints while make minimal number of assumptions and with minimal exposure to theory uncertainties
  - **All results shown today can be derived from these generic parametrizations** once correlation matrix is provided
  - Will allow legacy Run-1 Higgs coupling results to be re-evaluated in future, e.g. when new theory calculations are available with reduced uncertainties

- Most generic model is signal strength model with ratios

$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right),$$

  - Choose ggF H→ZZ as reference channel since it is the cleanest channel and has the smallest systematic uncertainty
  - Ratios of cross-sections and BRs reduce exposure to dominant theoretical uncertainties on inclusive cross-sections

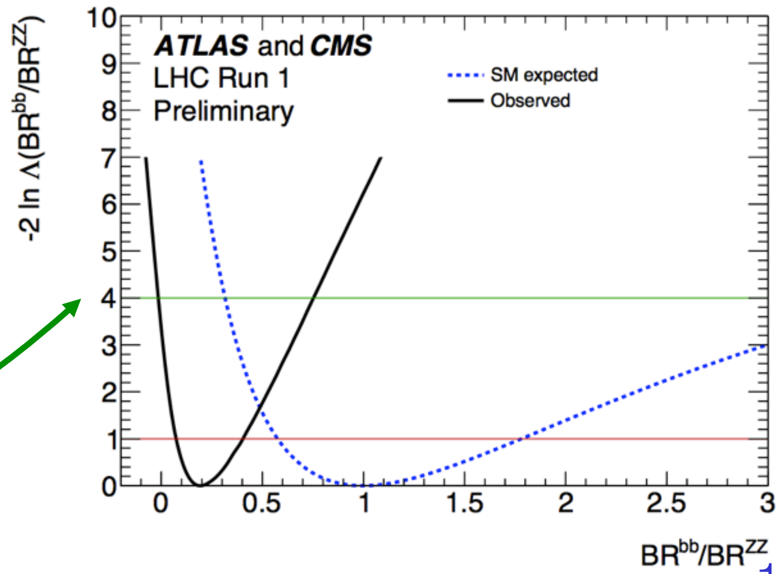
Signal strength models with ratios



Inclusive theory uncertainties shown on SM prediction

Largest discrepancy is seen in BR^{bb}/BR^{ZZ}, at the level of 2.4 σ

Driven by combination of high ttH→leptons, ZH→ZZ, low VH→bb (while ttH→bb is not high)



NB: Correlation matrix will be provided for final paper version

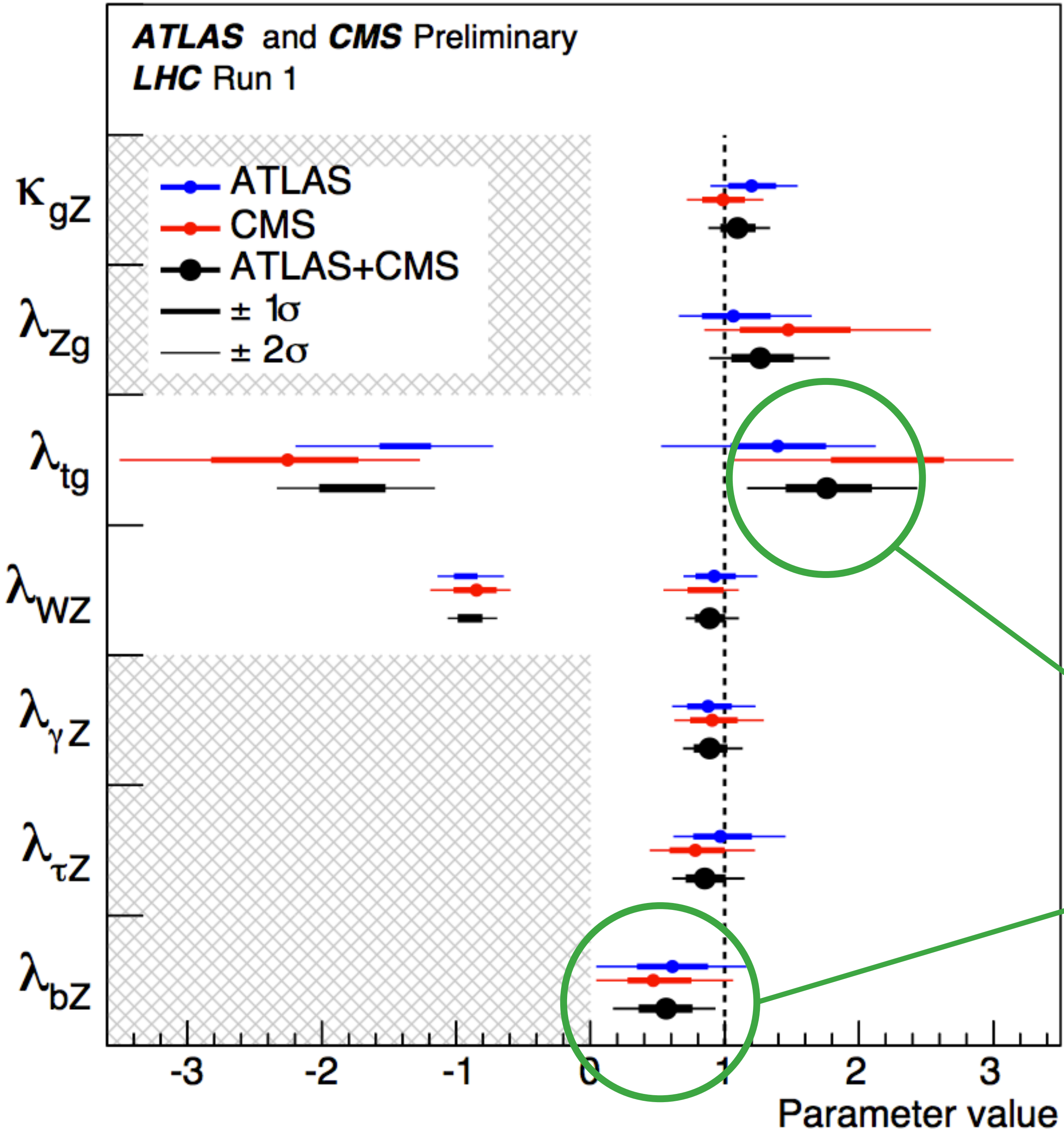
Alternatively, measure **ratio of coupling strengths**

- No assumption on Higgs total width needed, as Γ_H cancels in all expressions

σ and BR ratio model	Coupling-strength ratio model
$\sigma(gg \to H \to ZZ)$	$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$
$\sigma_{VBF}/\sigma_{ggF}$	
σ_{WH}/σ_{ggF}	
σ_{ZH}/σ_{ggF}	$\lambda_{Zg} = \kappa_Z/\kappa_g$
$\sigma_{ttH}/\sigma_{ggF}$	$\lambda_{tg} = \kappa_t/\kappa_g$
BR^{WW}/BR^{ZZ}	$\lambda_{WZ} = \kappa_W/\kappa_Z$
$BR^{\gamma\gamma}/BR^{ZZ}$	$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$
$BR^{\tau\tau}/BR^{ZZ}$	$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$
BR^{bb}/BR^{ZZ}	$\lambda_{bZ} = \kappa_b/\kappa_Z$

(these can be fully expressed in terms of λ_{WZ} and λ_{Zg})

Higgs coupling model with ratios



Same qualitative features as generic signal strength ratio model

NB: Correlation matrix will be provided for final paper version

Summary of Run-1 Higgs coupling measurements

- ATLAS and CMS Higgs boson coupling results have been combined, sensitivity on signal strength improved by almost √2
  - Decay to ττ and VBF production established at more than 5σ level
  - The most precise results on Higgs boson production and decay and constraints on its couplings have been obtained at O(10%) precision
  - Different parameterizations have been studied: all results all consistent with the SM predictions within uncertainties: SM p-value of all combined fits in range 10%-88%

- LHC Run-2 at 13 TeV, precision will be improved during the coming years thanks to higher energy, larger integrated luminosity, progress in the theory predictions, and ability to integrate more measurements (differential σ) when moving beyond κ-framework.

ATLAS+CMS run-1	*stat.unc*	*syst.unc*
$\lambda_{WZ} = \kappa_W / \kappa_Z$	$^{+0.09}_{-0.08}$	$^{+0.04}_{-0.04}$
$\lambda_{tg} = \kappa_t / \kappa_g$	$^{+0.21}_{-0.20}$	$^{+0.23}_{-0.20}$

√s=8 → 13 TeV
σ(ggF) x 2.3
σ(VBF) x 2.4
σ(ttH) x 3.9

What do we need to improve Higgs property measurements

- LHC Run-2 is project deliver 150 fb-1 of data,
  5x more data than Run-1 → >10x more observed Higgs boson decays
- How can we efficiently exploit this data to make precision measurement of Higgs boson properties?
- Address systematic uncertainties
  - Most experimental & theoretical uncertainties will shrink due to more data and/or improved calculations
  - Does current modeling of systematic uncertainties capture true uncertainty?

ATLAS+CMS run-1	stat.unc	syst.unc
$\lambda_{WZ} = \kappa_W / \kappa_Z$	$^{+0.09}_{-0.08}$	$^{+0.04}_{-0.04}$
$\lambda_{tg} = \kappa_t / \kappa_g$	$^{+0.21}_{-0.20}$	$^{+0.23}_{-0.20}$

- Evaluate theoretical models used to describe Higgs properties
  - Implicit theoretical uncertainties in k-framework due to assumptions (LO degrees of freedom, SM kinematics assumptions etc…)
  - Plenty of ideas around (e.g. EFT), but what are implications of such frameworks for experimental Higgs analysis?

Outline of this presentation

① Introduction

② Higgs boson phenomenology & interpretation framework

③ Combination procedure & experimental inputs

④ Signal strength measurements

⑤ Constraints on Higgs boson couplings

⑥ **Improving on systematic uncertainties**

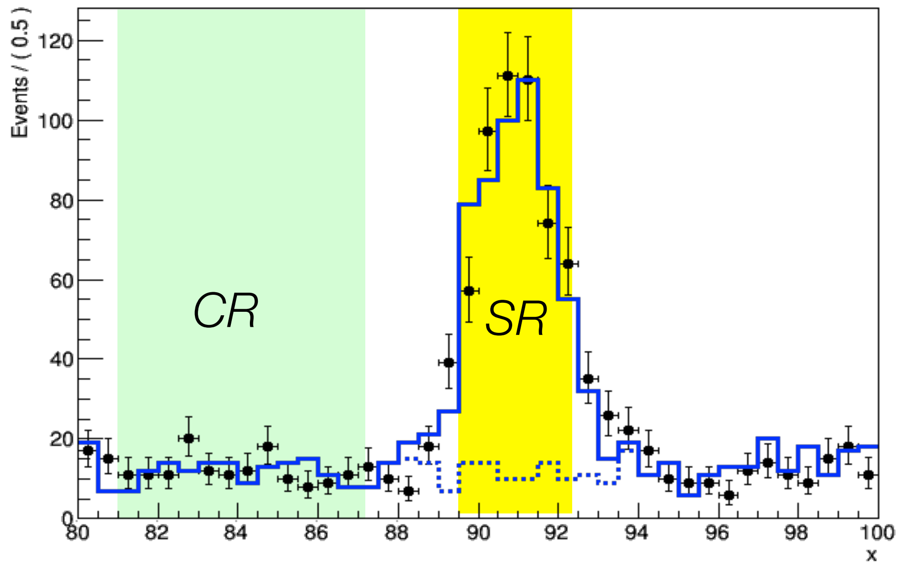
⑦ Improving on Higgs signal models

What are systematic uncertainties?

- Concept & definitions of ‘systematic uncertainties’ originates from physics, not from fundamental statistical methodology.
  - E.g. Glen Cowans (excellent) 198pp book “statistical data analysis” does not discuss systematic uncertainties at all
- A common definition is
  - “Systematic uncertainties are all uncertainties that are not directly due to the statistics of the data”
- But the notion of ‘the data’ is a key source of ambiguity:
  - does it include control measurements?
  - does it include measurements that were used to perform basic (energy scale) calibrations?

The sideband measurement

- Suppose your data
  in reality looks like this ➔



Can estimate level of background in the 'signal region' from event count in a 'control region' elsewhere in phase space

$$L_{SR}(s,b) = Poisson(N_{SR} \mid s+b)$$

$$L_{CR}(b) = Poisson(N_{CR} \mid \tilde{\tau} \cdot b)$$

NB: Define parameter 'b' to represents the amount of bkg is the SR.

Scale factor τ accounts for difference in size between SR and CR

"Background uncertainty constrained from the data"

- Full likelihood of the measurement ('simultaneous fit')

$$L_{full}(s,b) = Poisson(N_{SR} \mid s+b) \cdot Poisson(N_{CR} \mid \tilde{\tau} \cdot b)$$

Generalizing the concept of the sideband measurement

- Background uncertainty from sideband clearly clearly not a 'systematic uncertainty'

$$L_{full}(s,b) = Poisson(N_{SR} \mid s+b) \cdot Poisson(N_{CR} \mid \tilde{\tau} \cdot b)$$

- Now consider scenario where *b* is not measured from a sideband, but is taken from MC simulation **with an 8% cross-section 'systematic' uncertainty**

'Measured background rate by MC simulation'

$$L_{full}(s,b) = Poisson(N_{SR} \mid s+b) \cdot \underbrace{Gauss(\tilde{b} \mid b, 0.08)}_{\text{'Subsidiary measurement' of background rate}}$$

  - *We can model this in the same way, because the cross-section uncertainty is also (ultimately) the result of a measurement*

Generalize: 'sideband' → 'subsidiary measurement'

Generalizing the concept of the sideband measurement

- Background uncertainty from sideband clearly clearly not a 'systematic uncertainty'

$$L_{full}(s,b) = Poisson(N_{SR} \mid s+b) \cdot Poisson(N_{CR} \mid \tilde{\tau} \cdot b)$$

- Now consider scenario where *b* is not measured fro[illegible], but is taken from MC simulation **with an 8%** [illegible] **'systematic' uncertainty**

This exactly how all systematic uncertainties are modeled!

'M[illegible]nd rate by MC simulation'

$$L[illegible](N_{SR} \mid s+b) \cdot \underbrace{Gauss(\tilde{b} \mid b, 0.08)}$$

'**Subsidiary measurement**' of background rate

  - *We can model this in the same way, because the cross-section uncertainty is also (ultimately) the result of a measurement*

Generalize: 'sideband' → 'subsidiary measurement'

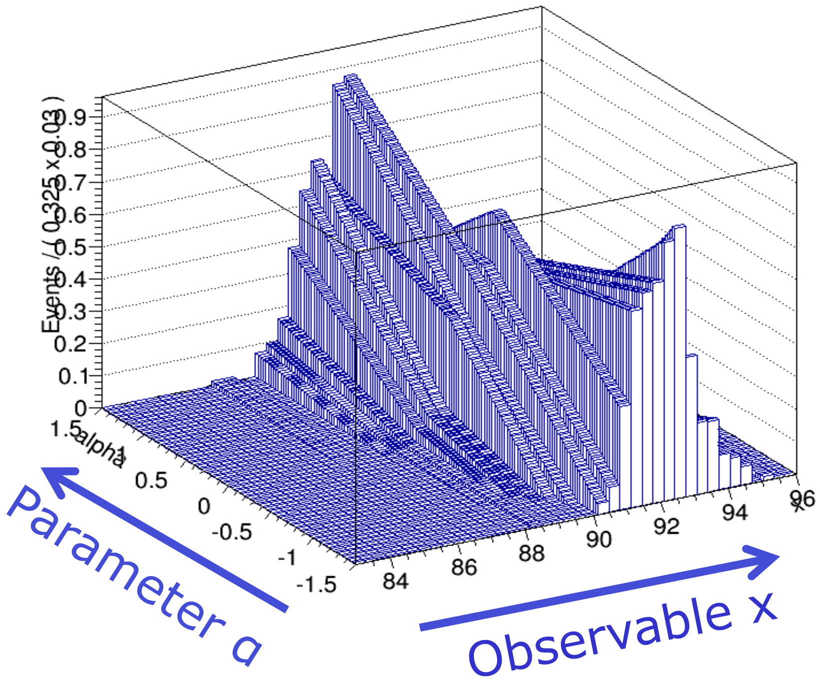
Systematics modeling in the likelihood

- How do we model systematic uncertainties in a measurements/limit of a physics quantity μ. ‘Profile Likelihood’ approach:

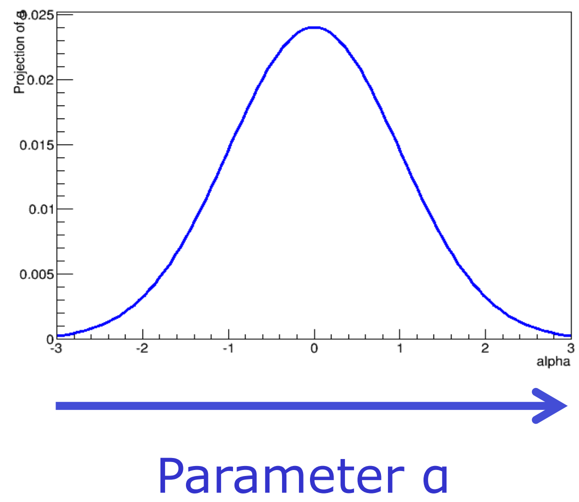
Example systematic ‘Energy Scale’ described by one uncertainty parameter α

$$L_{full}(x \mid \mu, \alpha) = L_{physics}(x \mid \mu, \alpha) \cdot L_{subsidiary}(0 \mid \alpha)$$

Likelihood of physics measurement



Likelihood of (simplified) calibration measurement



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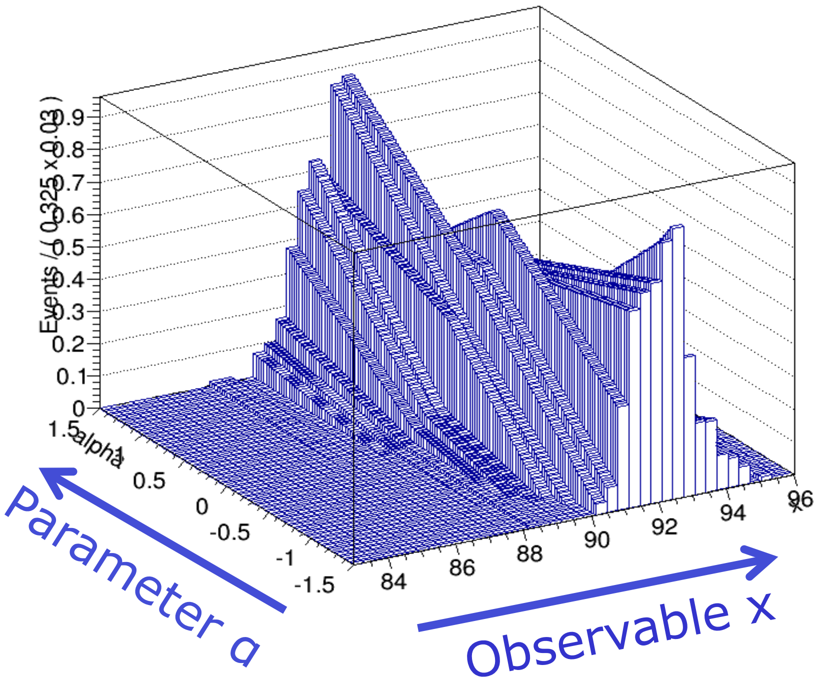
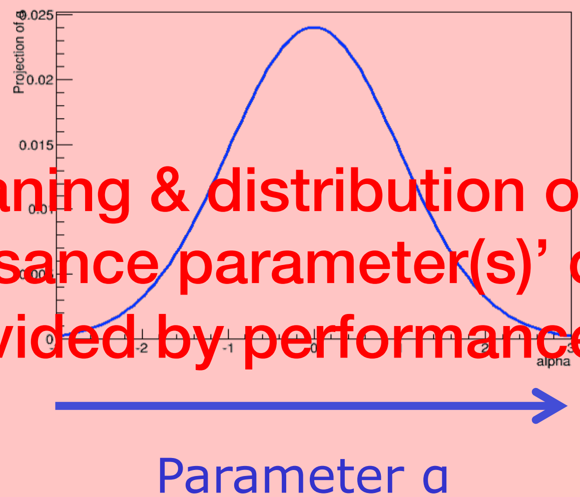


Likelihood of (simplified) calibration measurement



Meaning & distribution of 'nuisance parameter(s)' α provided by performance group

Systematics modeling in the likelihood

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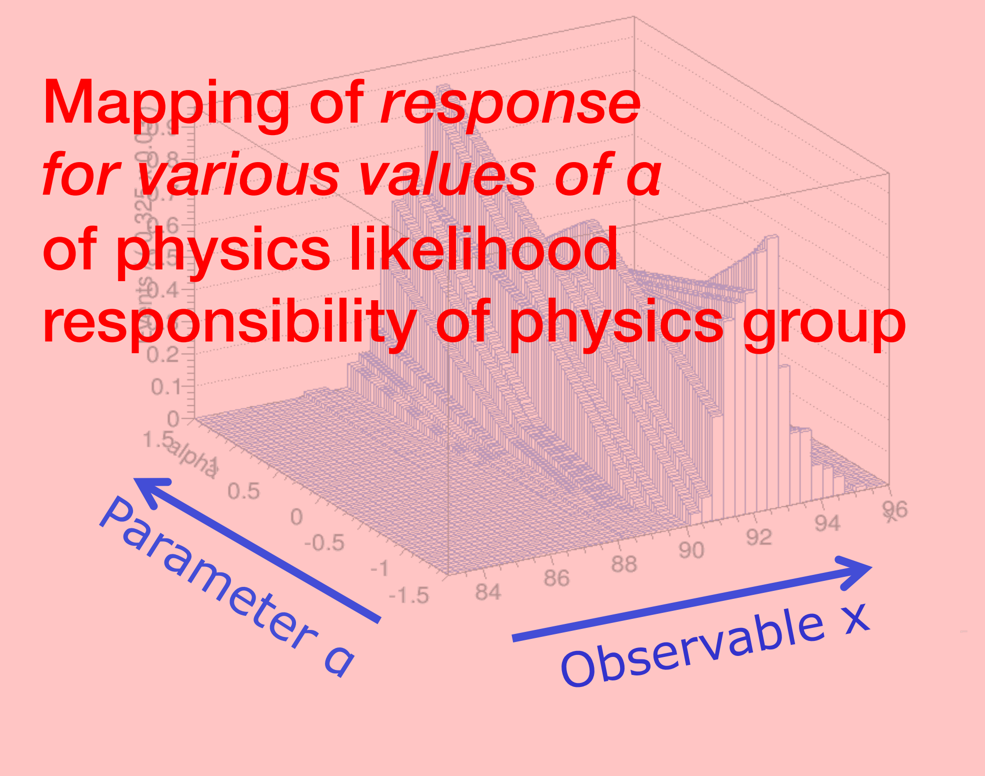
Example systematic 'Energy Scale' described by one uncertainty parameter α

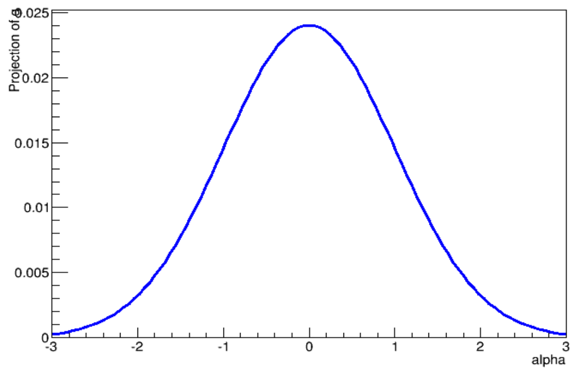
$$L_{full}(x \mid \mu,\alpha) = L_{physics}(x \mid \mu,\alpha) \cdot L_{subsidiary}(0 \mid \alpha)$$

Likelihood of physics measurement

Mapping of *response for various values of α* of physics likelihood responsibility of physics group



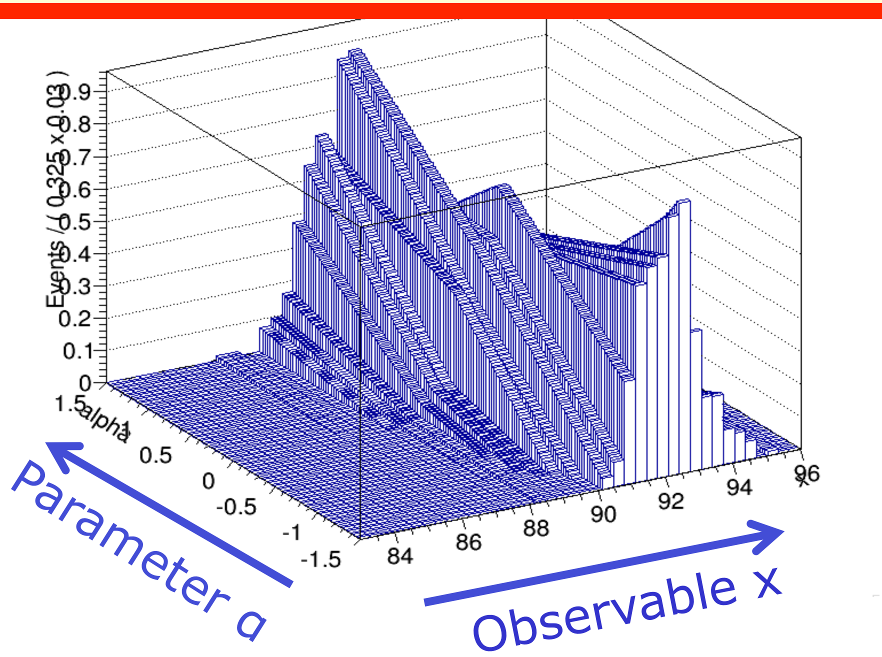
Likelihood of (simplified) calibration measurement



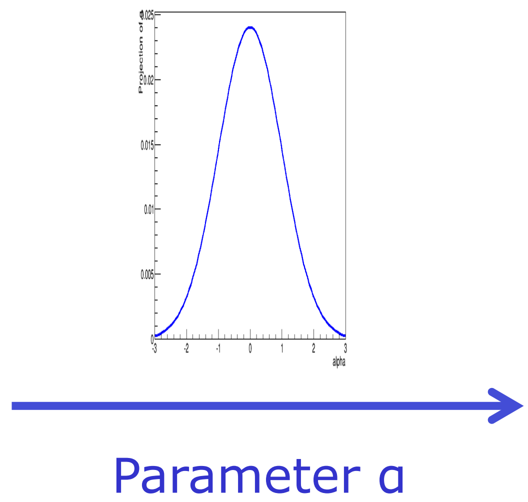
Parameter α

Systematics modeling in the likelihood

- Experimental systematics will (generally) shrink in future as more data becomes available for calibration measurement
- Theoretical systematic will (generally) shrink in future as more precise (higher order) calculations become available
- Propagation of smaller uncertainties will lead to more precise Higgs properties measurements. *Just sit back and relax?*



measurement



Systematics modeling in the likelihood

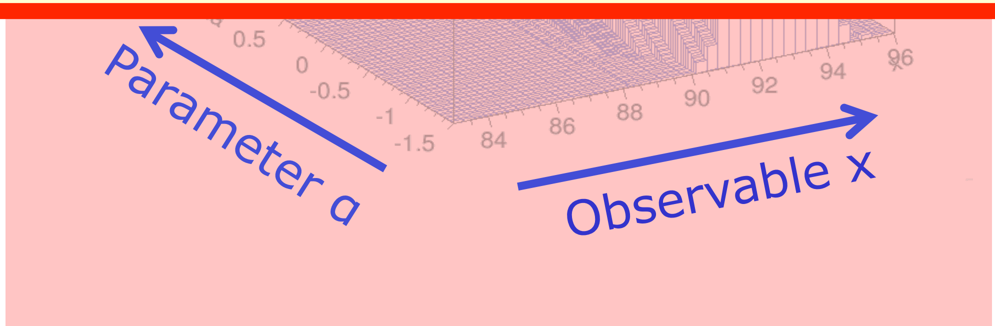
- How do we model systematic uncertainties in a measurements/limit of a physics quantity μ. 'Profile Likelihood' approach:

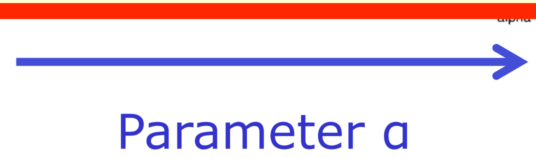
Well no… propagation of (shrinking) systematic uncertainties *is only correct if*

1) **Subsidiary measurements of nuisance parameters are correct**

2) Parametrization of a systematic uncertainty is sufficiently flexible for distribution to cover true (but unknown distribution).
   - Do you need 1 parameter α for JES, or 60?
   - Can you describe fragmentation/hadronization uncertainty with single parameter

3) Are the interpolation procedures for response mapping sufficiently accurate to describe systematic-induced deviation between sampling points?





Reminder – profile likelihood formalism for systematic uncertainties

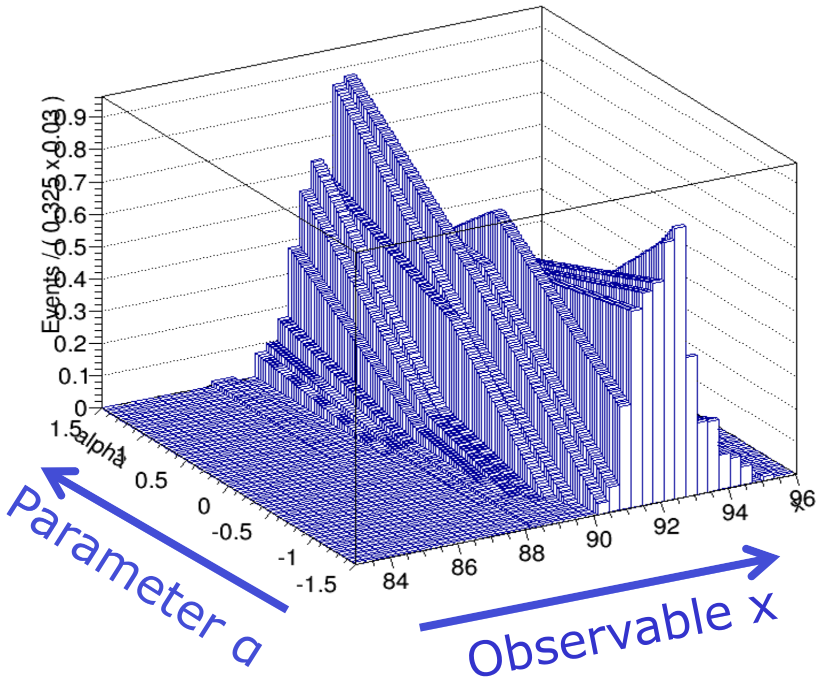
- Uncertainties with a theoretical origin are modeled in the same way as experimental uncertainties

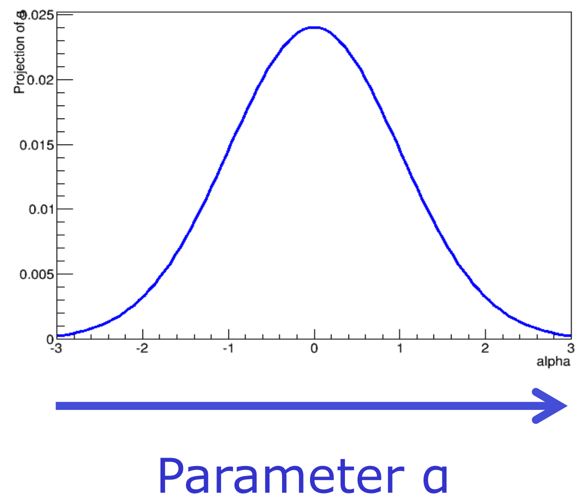
E.g. 'inclusive cross-section uncertainty' described by one uncertainty parameter α

$$L_{full}(x \mid \mu, \alpha) = L_{physics}(x \mid \mu, \alpha) \cdot L_{subsidiary}(0 \mid \alpha)$$

Likelihood of physics measurement

'theory' measurement of cross-section





What is the distribution when information is based on calculation rather than data?

Modeling theory uncertainties in probability models

- **Difficulty 1 – What is distribution of the subsidiary measurement?**
- Easy example – Top cross-section "uncertainty is 8%"

$$L_{full}(s,\sigma_{tt}) = Poisson(N_{SR} \mid s + \varepsilon_{tt} \cdot \sigma_{tt}) \cdot Gauss(\tilde{\sigma}_{tt} \mid \sigma_{tt}, 0.08)$$

→ Gaussian subsidiary with 8% uncertainty
(because XS uncertainty is ultimately from a measurement)

- Difficult example – QCD scale "Vary Scale by x0.5 and x2"

$$L_{full}(s,\sigma_{tt}) = Poisson(N_{SR} \mid s + b(\alpha_{FS})) \cdot F(\tilde{\alpha}_{FS} \mid \alpha_{FS})$$

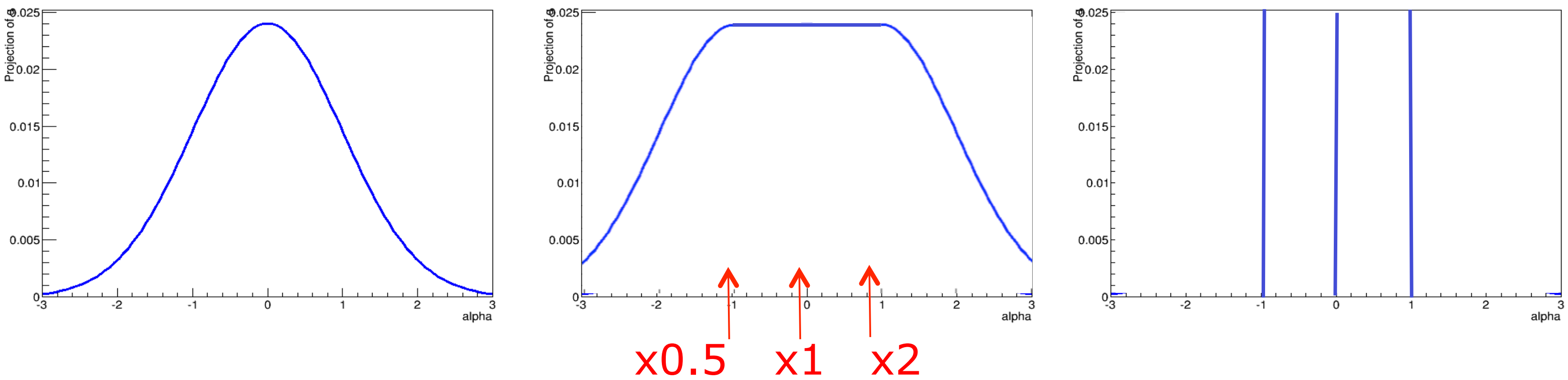
F(α) is probably not Gaussian
So what distribution was meant?

Modeling theory uncertainties

- Difficult example – Factorization scale uncertainty

$$L_{full}(s,\sigma_{tt}) = Poisson(N_{SR} \mid s + b(\alpha_{FS})) \cdot F(\tilde{\alpha}_{FS} \mid \alpha_{FS})$$

"Vary Factorization Scale by x0.5 and x" → F(α) is probably not Gaussian
So what distribution was meant?



- Difficult arises from imprecision in original prescription.
  - NB: Issue is *physics* question, not a statistical procedure question.
- Note that you *always* assume some distribution (explicitly or implicitly)
- If 'difficult'uncertainty has small effect on POI, you don't care too much, but as experimental precision increases, modeling difficult uncertainty will start to be important

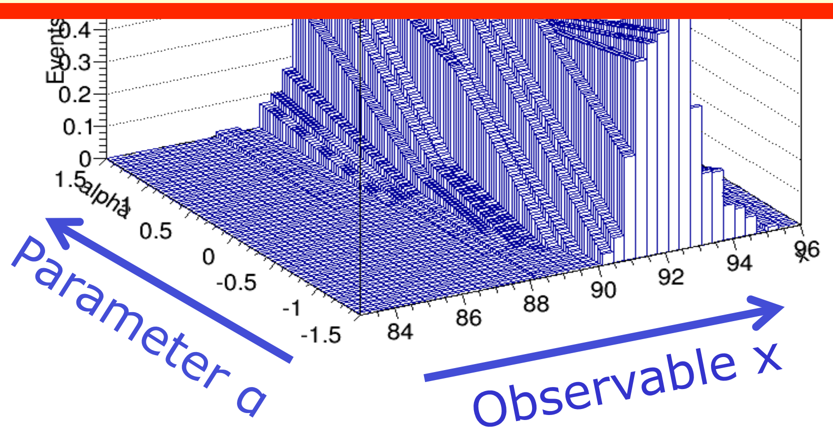
Systematics modeling in the likelihood

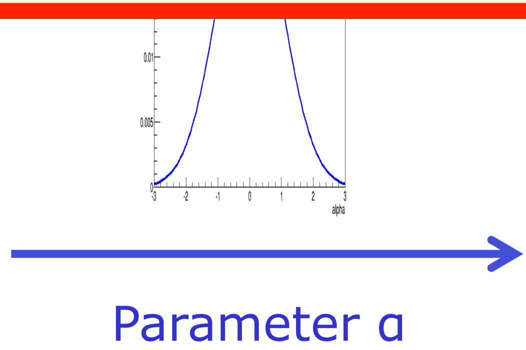
Propagation of (shrinking) systematic uncertainties only correct if

1) Subsidiary measurements of nuisance parameters are correct

2) Parametrization of a systematic uncertainty is sufficiently flexible for distribution to cover true (but unkwown distribution).
   - Do you need 1 parameter α for JES, or 60?
   - Can you describe fragmentation/hadronization uncertainty with single parameter

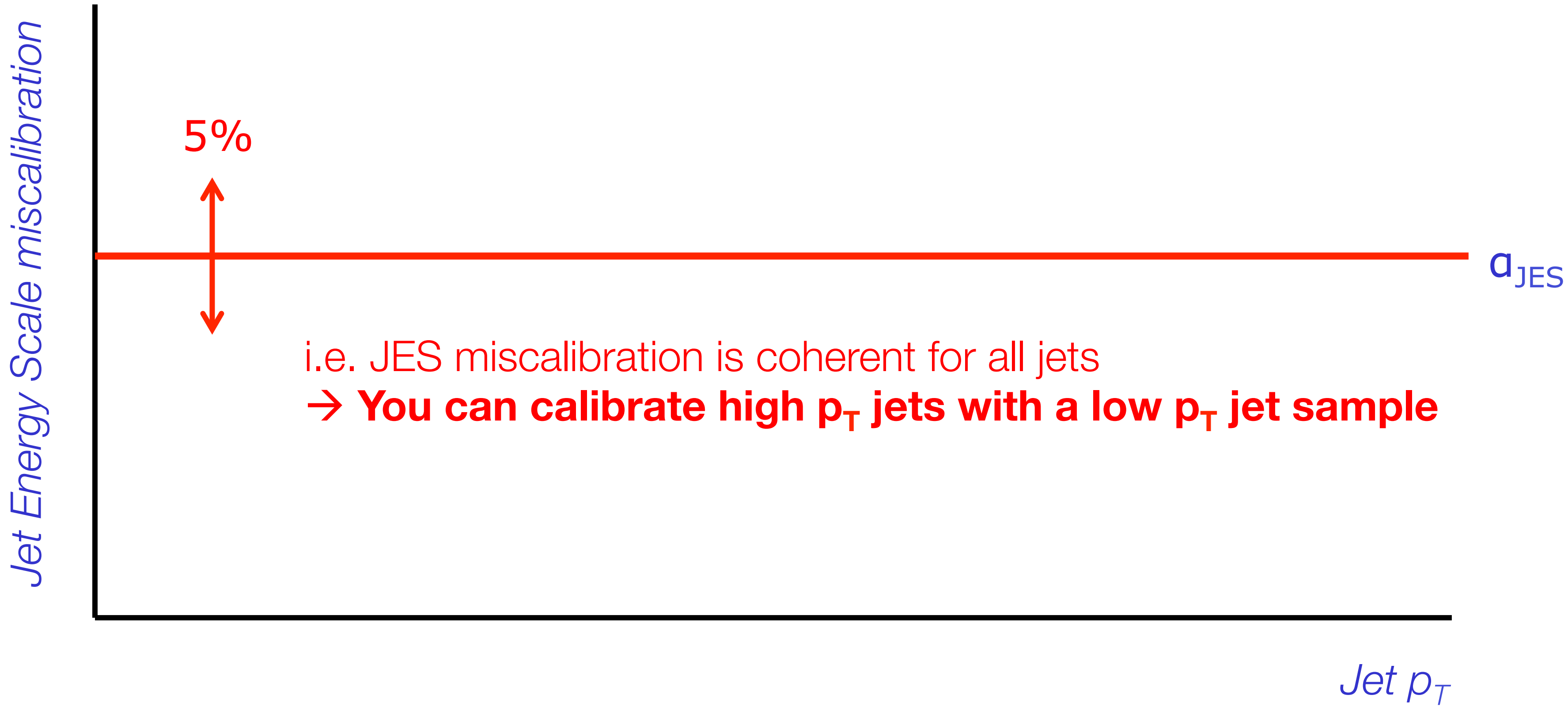
3) Are the interpolation procedures for response mapping sufficiently accurate to describe systematic-induced deviation between sampling points?





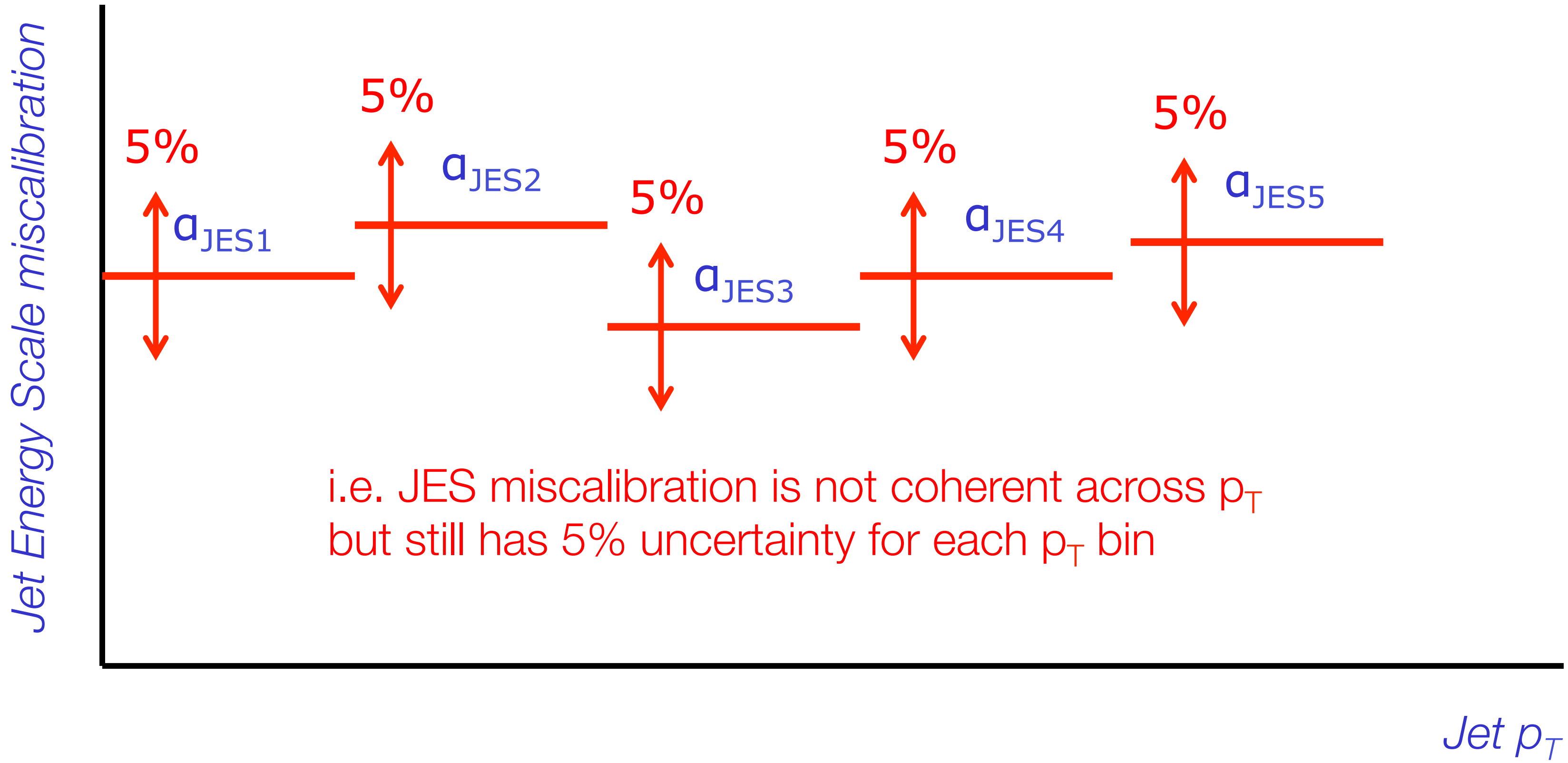
Dealing with over-constraining – introducing more NPs

- Some systematic uncertainties are not captured well by one nuisance parameter.
- Written prescription often not clear on *number* of nuisance parameters:
- Does "*the JES uncertainty is 5% for all jets*" mean one NP



Dealing with over-constraining – introducing more NPs

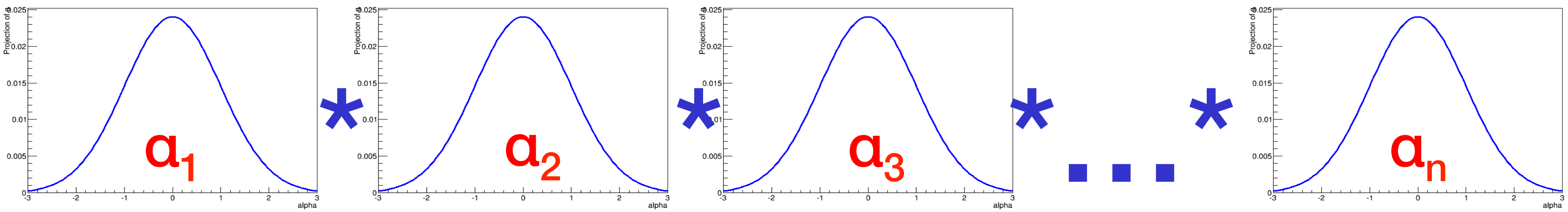
- Some systematic uncertainties are not captured well by one nuisance parameter.
- Written prescription often not clear on *number* of nuisance parameters:
- Or does "*the JES uncertainty is 5% for all jets*" mean 5 NPs?



How many NPs you need to capture a systematic uncertainty?

- Detector systematics (calibrations, efficiencies) are complex entities, mapping det. performance measurements with variable resolution of the detector phase space → **Need >>1 parameter**

$$L_{full}(x \mid \mu,\alpha_1,\ldots,\alpha_n) = L_{physics}(x \mid \mu,\alpha_1,\ldots,\alpha_n) \cdot L_{subsidiary}(0 \mid \alpha_1,\ldots,\alpha_n)$$



Different α_i parameters can represent components of a systematic uncertainty (MC simulation, Flavor content, in-situ calibration uncertainties in any number of p_T bins)

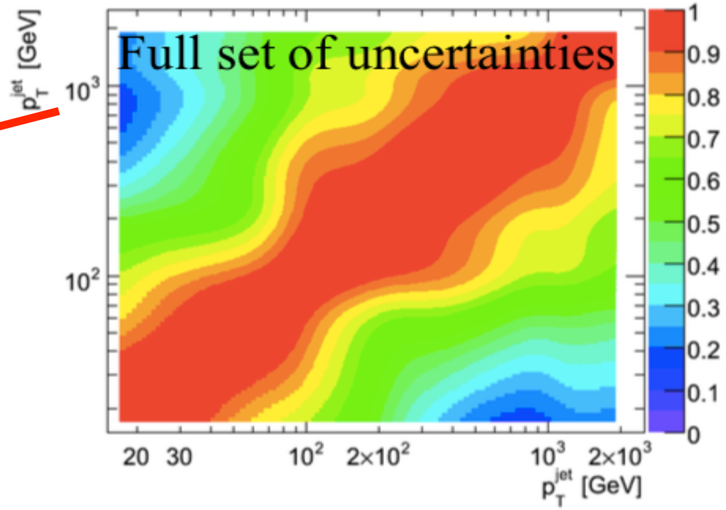
How many NPs you need to capture a systematic uncertainty?

- Detector systematics (calibrations, efficiencies) are complex entities, mapping det. performance measurements with variable resolution of the detector phase space → **Need >>1 parameter**

$$L_{full}(x \mid \mu, \alpha_1, \ldots, \alpha_n) = L_{physics}(x \mid \mu, \alpha_1, \ldots, \alpha_n) \cdot L_{subsidiary}(0 \mid \alpha_1, \ldots, \alpha_n)$$

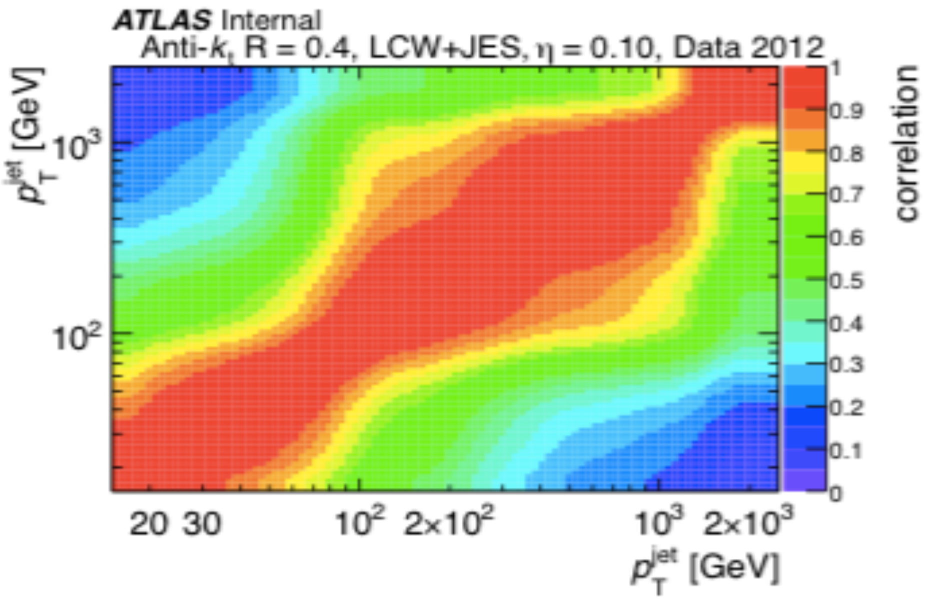
Some α_i parameters can also be *correlated* by subsidiary calibration measurement
(typical for in-situ calibration measurements)

$$L_{subsidiary}(0 \mid \alpha_1, \ldots, \alpha_n)$$
$$= \exp(-0.5 \cdot \vec{\alpha}^T \cdot V^{-1} \cdot \vec{\alpha})$$



How to cleverly tune NPs of a systematic uncertainty?

- Common feature of description of detector systematics is that in-situ calibration uncertainties result in nuisance parameters that are strongly correlated.

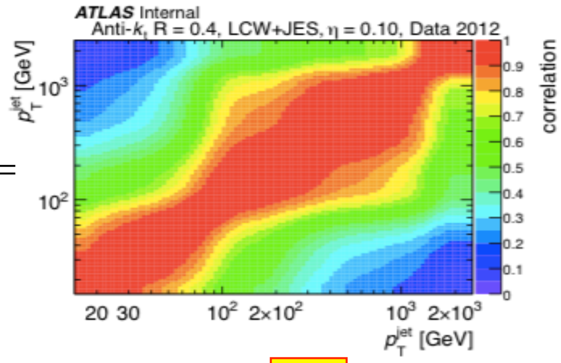


- *What is the right level of detail for an analysis?*
- Can neglect uncertain parameters with least impact on analysis.
- But if parameters are a priori strongly correlated, no obvious least important parameters

Item 1 - Modeling detector uncertainties – EV decomposition

- Correlation issues solved with an eigenvector decomposition constructs a *rotated set of NPs* that are largely uncorrelated and can be ranked in importance using the eigenvalues
  - EV decomposition doesn't reduce #NPs in its own, but simplifies subsequent merging or pruning of NPs
- CP-provided solution for NP reduction: combine weakest *n* NPs into a single NP
  - Makes ad-hoc assumption that weak modes can be treated as fully correlated
  - But you can test this assumption by providing variants where different correlations are assumed among collapsed weak modes
- Effectively can easily produce sets of NP models for a complex experimental systematics with varying level of detail {simple,medium,detailed}

$V=$



$$V' = \begin{pmatrix} V_{11} & & & \\ & V_{22} & & \\ & & V_{33} & \\ & & & V_{44} \end{pmatrix}$$

$$V'' = \begin{pmatrix} V_{11} & \\ & V_{mm} \end{pmatrix}$$

Item 1 - Mod omposition

- Correlation
  decomposi
  are largely u
  importance
  - EV decom
    simplifies
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  combine w
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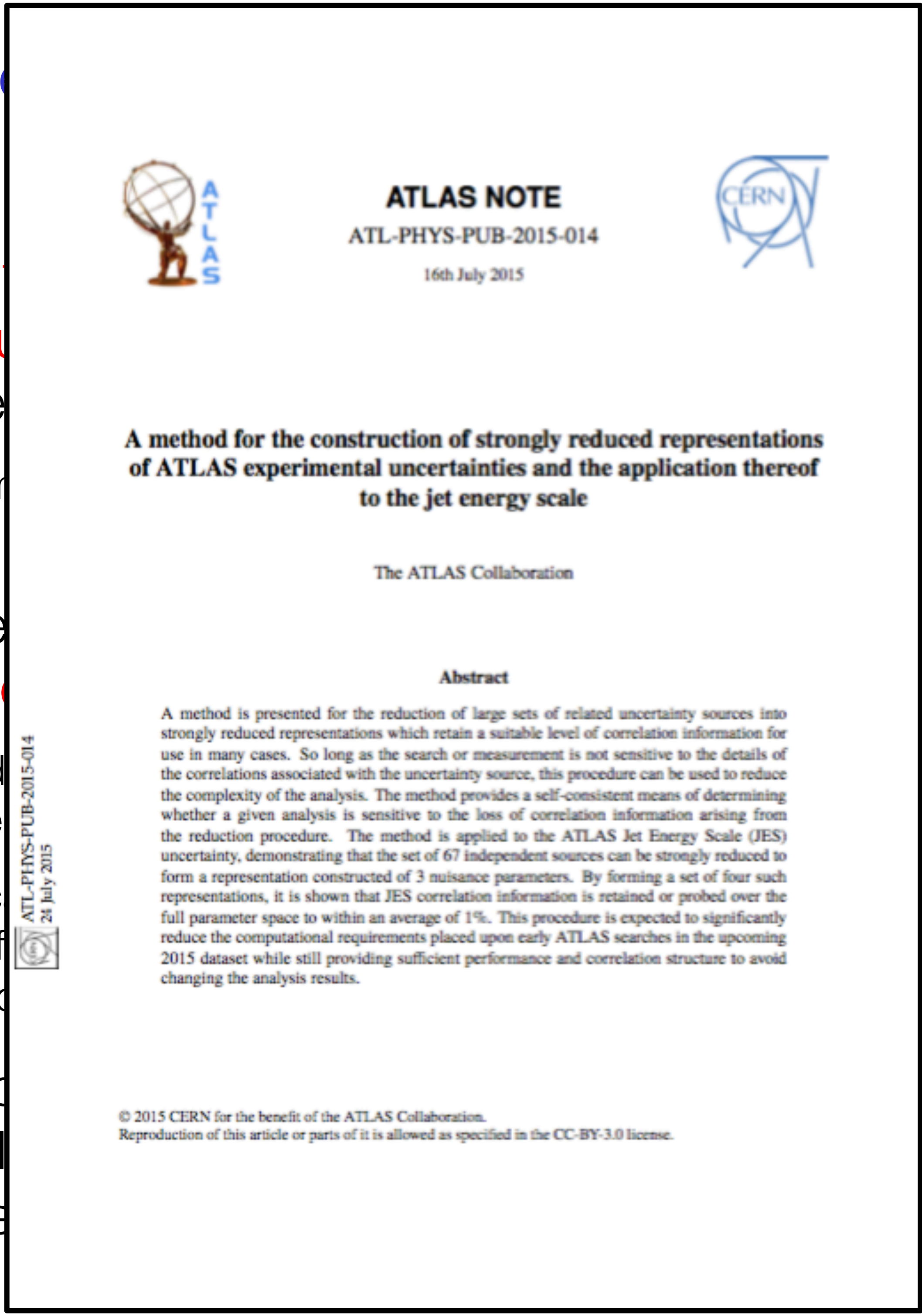


ATLAS NOTE

ATL-PHYS-PUB-2015-014

16th July 2015

A method for the construction of strongly reduced representations of ATLAS experimental uncertainties and the application thereof to the jet energy scale

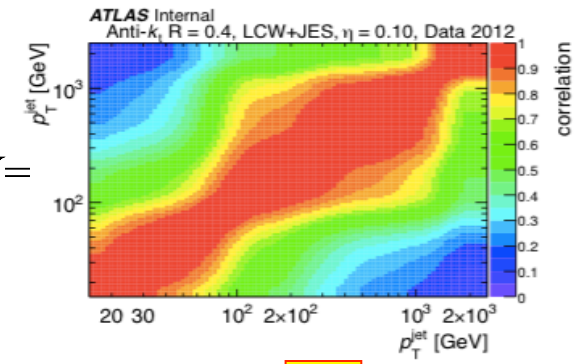
The ATLAS Collaboration

Abstract

A method is presented for the reduction of large sets of related uncertainty sources into strongly reduced representations which retain a suitable level of correlation information for use in many cases. So long as the search or measurement is not sensitive to the details of the correlations associated with the uncertainty source, this procedure can be used to reduce the complexity of the analysis. The method provides a self-consistent means of determining whether a given analysis is sensitive to the loss of correlation information arising from the reduction procedure. The method is applied to the ATLAS Jet Energy Scale (JES) uncertainty, demonstrating that the set of 67 independent sources can be strongly reduced to form a representation constructed of 3 nuisance parameters. By forming a set of four such representations, it is shown that JES correlation information is retained or probed over the full parameter space to within an average of 1%. This procedure is expected to significantly reduce the computational requirements placed upon early ATLAS searches in the upcoming 2015 dataset while still providing sufficient performance and correlation structure to avoid changing the analysis results.

ATL-PHYS-PUB-2015-014
24 July 2015

$V=$



$$V' = \begin{pmatrix} V_{11} & & & \\ & V_{22} & & \\ & & V_{33} & \\ & & & V_{44} \end{pmatrix}$$

$$V'' = \begin{pmatrix} V_{11} & & \\ & V_{mm} & \\ & & \\ & & \end{pmatrix}$$

Parametrization of theoretical uncertainties

- **Difficulty 2 – What are the *parameters* of the systematic model?**
- Easy example – Factorization scale uncertainty

$$L_{full}(s,\sigma_{tt}) = Poisson(N_{SR} \mid s + b(\alpha_{FS})) \cdot F(\tilde{\alpha}_{FS} \mid \alpha_{FS})$$

  - One parameter: the factorization scale → Clearly described and connected to the underlying theory model
  - You can ask yourself if there are additional uncertainties in the theory model (renormalization scale etc), this a valid, but distinct issue.

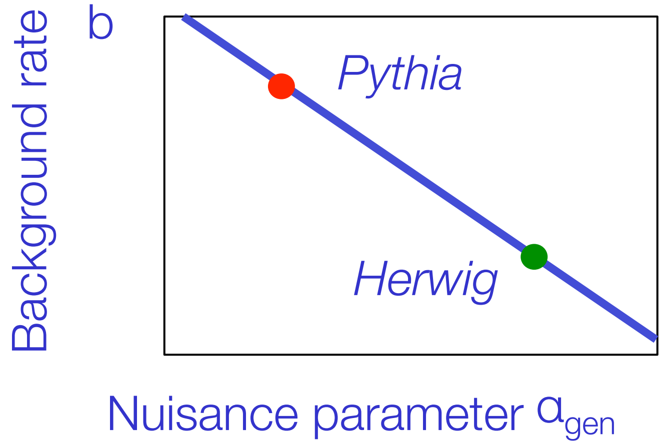
- Difficult example – Hadronization/Fragmentation model
  - Source uncertainty**: you run different showering MC generators (e.g. HERWIG and PYTHIA)** and you observe you get different results from your physics analysis
  - **How do you model this in the likelihood?**

Specific issues with theory uncertainties

- Pragmatic solutions to likelihood modeling of '2-point systematics'
- Final solution will need to follow usual pattern

$$L(N \mid s, \alpha) = Poisson(N \mid s + b(\alpha)) \cdot SomePdf(0 \mid \alpha)$$

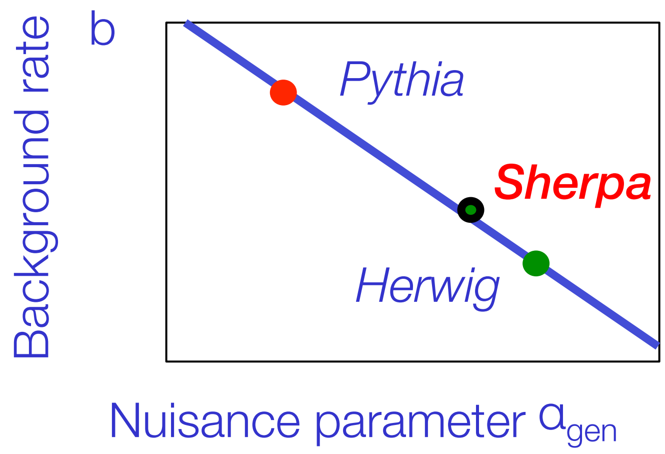
- Defining an (empirical) response function *b(α)* is the easy part



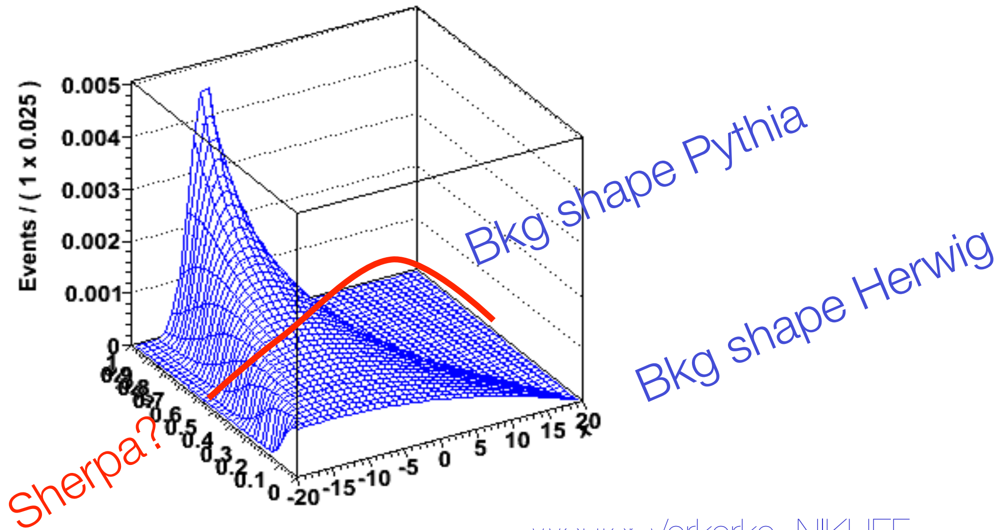
- A thorny question remains:
  What is the subsidiary measurement for α?
  This should reflect you current knowledge on α.

Two-point systematics on non-counting measurements

- In a counting experiment you can argue that for every conceivable background rate there exists a value of the NP that corresponds to that rate
  - Even if 'SHERPA' was never used to construct the model, you can still represent its outcome



- This is not generally true for distributions. A shape interpolation between 'pythia' and 'herwig' does not necessarily describe shape of 'sherpa' (or of Nature!)
  - Fundamental modeling problem!
  - You may need more parameters…



Systematics modeling in the likelihood

- How do we model systematic uncertainties in a measurements/limit of a physics quantity μ. 'Profile Likelihood' approach:

Propagation of (shrinking) systematic uncertainties only correct if

1) Subsidiary measurements of nuisance parameters are correct

2) Parametrization of a systematic uncertainty is sufficiently flexible for distribution to cover true (but unkwown distribution).
   - Do you need 1 parameter α for JES, or 60?
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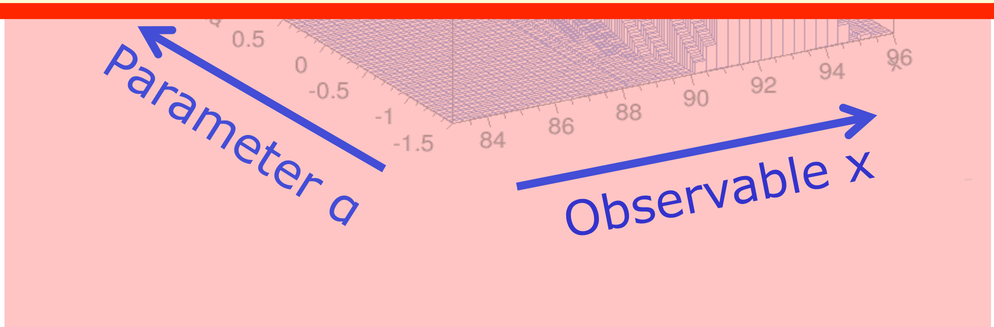
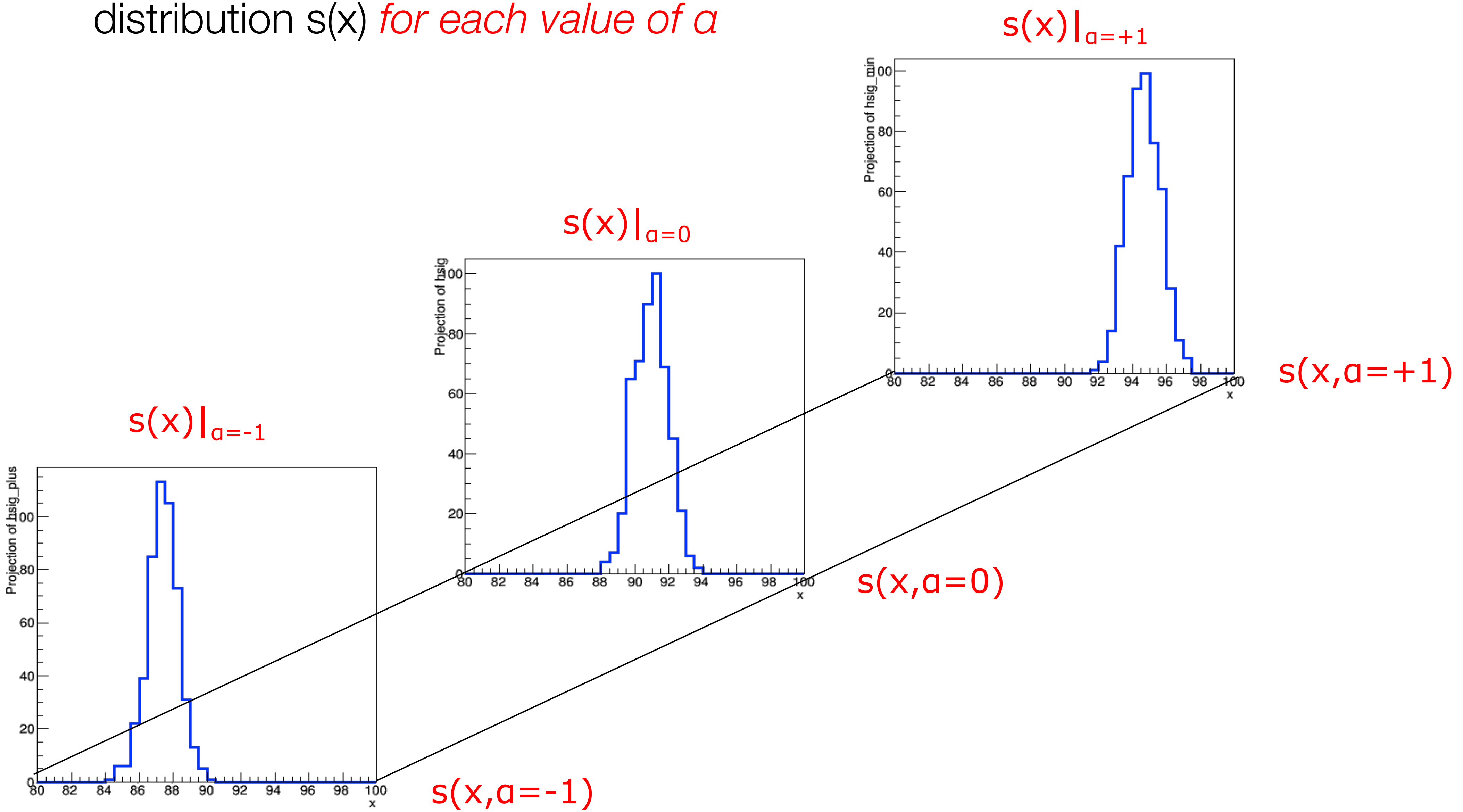
3) Are the **interpolation procedures for response mapping sufficiently accurate** to describe systematic-induced deviation between sampling points?



Parameter α

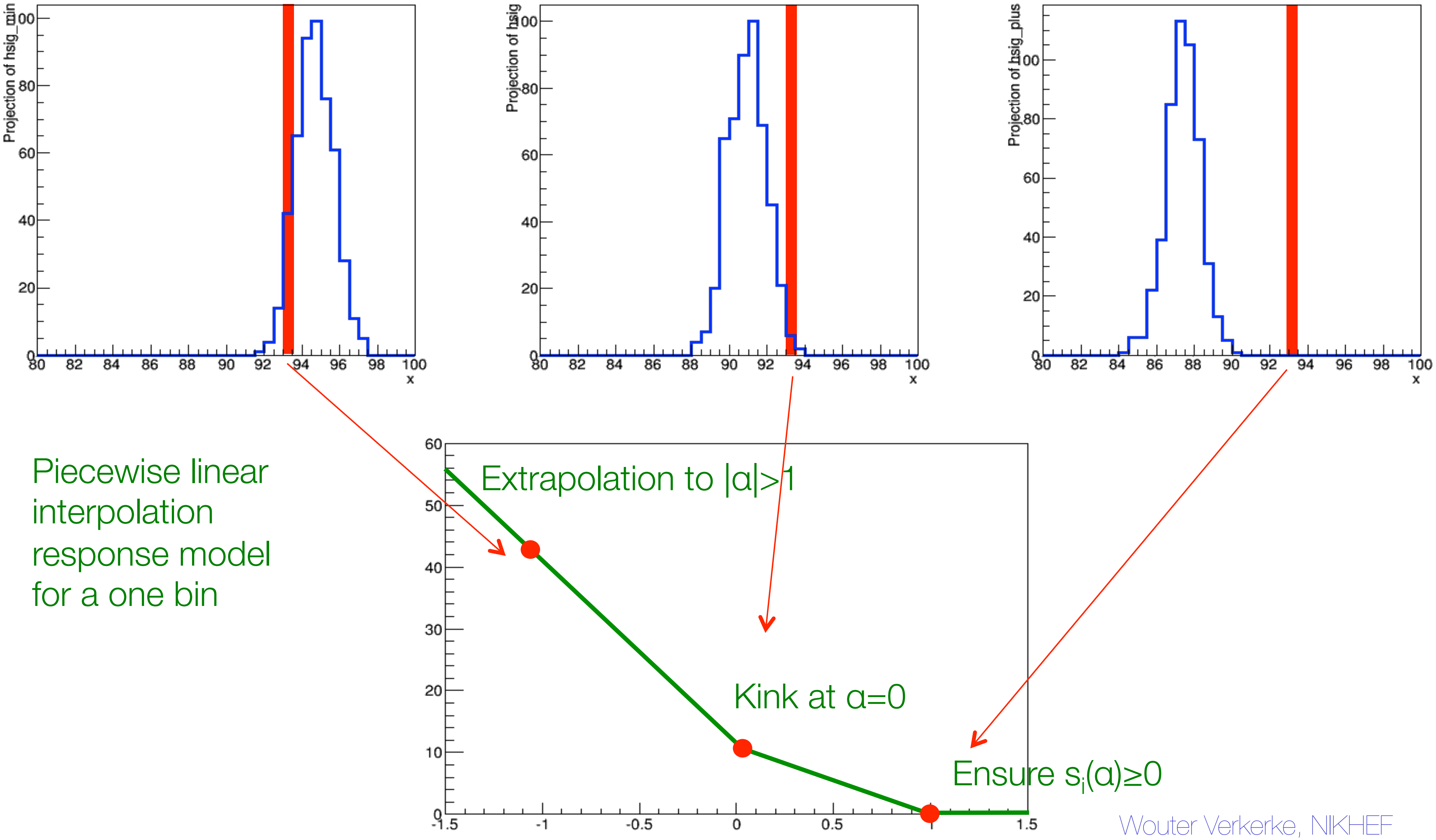
Need to interpolate between template models

- Need to define 'morphing' algorithm to define distribution s(x) *for each value of α*

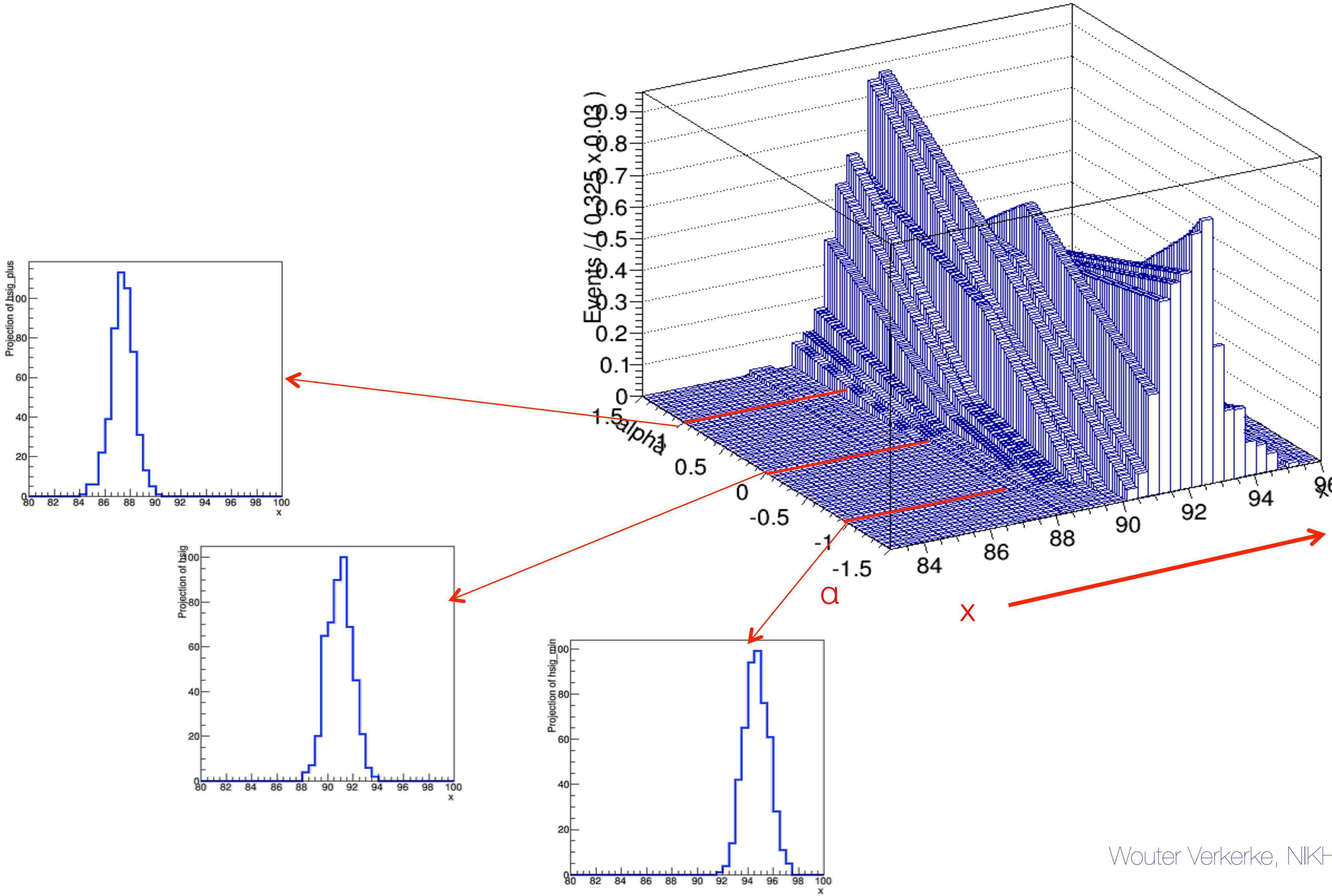


Piecewise linear interpolation

- Simplest solution is piece-wise linear interpolation for each bin



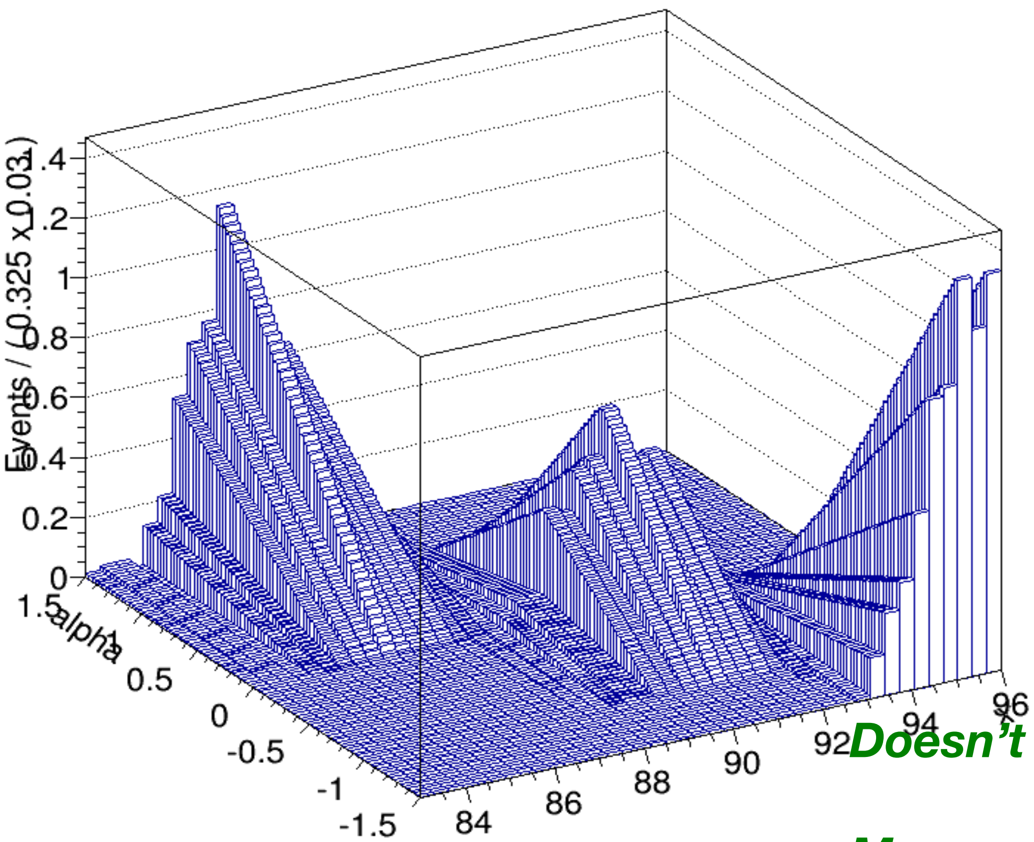
Visualization of bin-by-bin linear interpolation of distribution

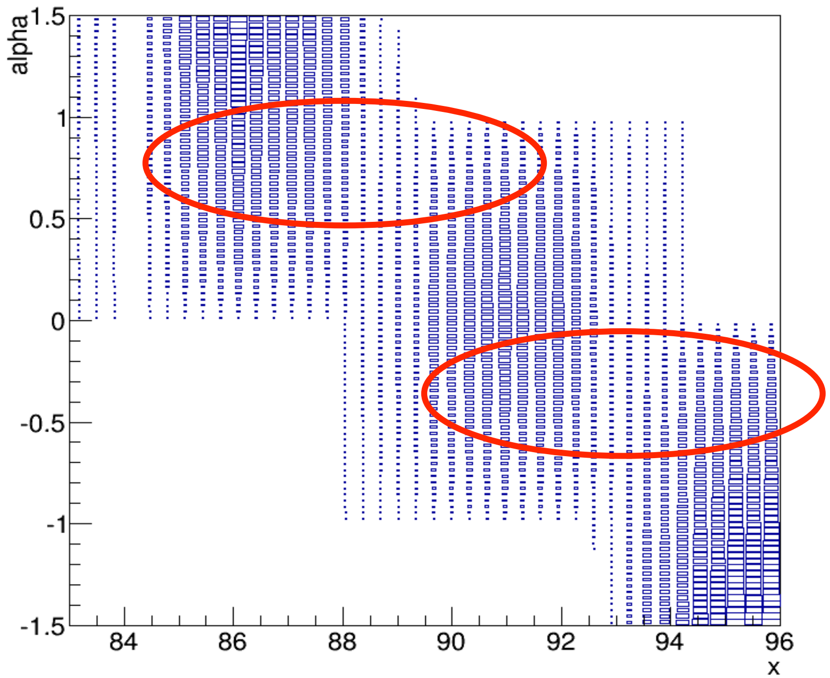


Limitations of piece-wise linear interpolation

- Bin-by-bin interpolation looks spectacularly easy and simple, but be aware of its limitations
  - Same example, but with larger 'mean shift' between templates

Note double peak structure around |α|=0.5





Doesn't work for all shape changes in distributions

May need more sophisticated interpolation algorithms
→ will show solutions later

Summary on systematic uncertainties

- A lot of effort is underway in experiments and theory community reduce many of the uncertainties that currently limit Higgs property measurements
- This will help to interpret future large LHC Run-2 data samples to obtain more precise coupling measurements
- But need to be careful what will be limiting measurements in future

→ Are parametrizations of future reduced systematic uncertainties sufficiently flexible to capture true uncertainty?

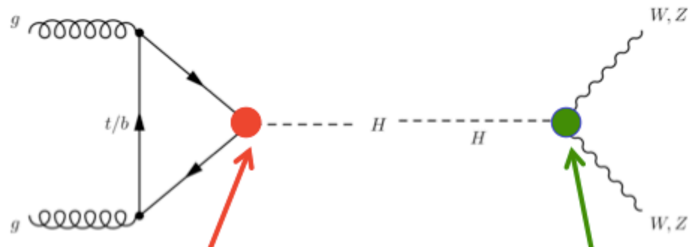
→ Do we understand distributions of subsidiary measurements of (theoretical) uncertainties that are no based on measurements?

→ Are the interpolation techniques we use to map response of uncertainties in physics measurement accurate enough?

Outline of this presentation

Improving Higgs signal models

- Present k-framework for interpreting Higgs Couplings sufficient within current experimental precision



$\sigma_{ggF} = (1.06\,\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_b\kappa_t)\;\sigma_{ggF}(SM)$ $\Gamma_{W,Z} = \kappa^2_{W,Z}\,\Gamma_{W,Z}(SM)$

$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

NB: σ_{ggF}(SM) from NNLO(QCD) + NLO(EW) calculation!

Wouter Verkerke, NIKHEF

2

- But several problems on the horizon
  - Validity: assumption that differential distributions of observables are always SM-like when couplings are rescaled clearly not realistic (but OK with current precision)
  - Interpretation: Framework does not guarantee that every configuration of k-parameters is a consistent theory. What does a deviation mean?

Two routes for improved Higgs signal descriptions

- 1) Assume a particular class of BSM theory.

  Most BSM theories have additional unconstrained theory parameters that can be introduced in the interpretation of the data (will not cover this due to lack of time)

- 2) Assume no particular type of BSM theory,
  but aim to extend SM in a generic and consistent way.

  Must always make some assumption on New Physics, but can e.g. assume that NP lives at high energy scale Λ.

  For description of physics below scale Λ, no need to introduce propagators etc of new physics, just see them as 'contact interactions'. Effect of NP is expressed in modified coefficients of such SM-like terms in the Lagrangian → Effective Field Theory.

Future precision measurements with minimal assumptions

- Starting point – formulate model to be tested against data as an **(effective) field theory**.
- Start with SM Lagrangian and add higher-order operators

$$\mathcal{L}_{\rm EFT} = \mathcal{L}^{\rm SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \cdots .$$

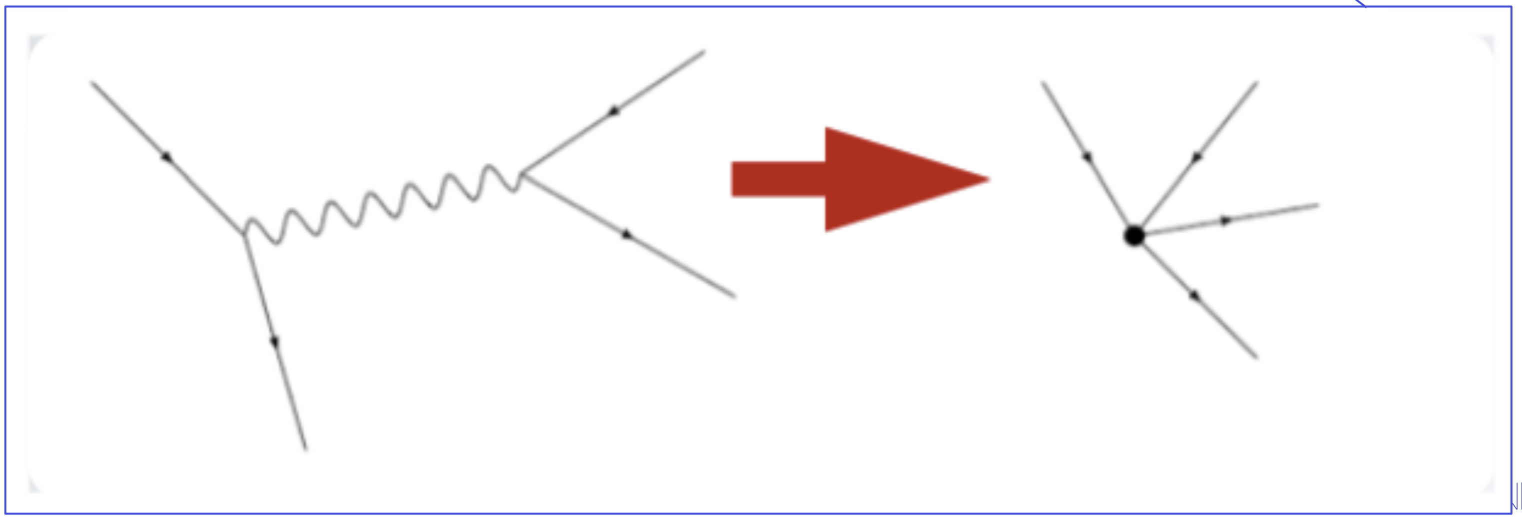
$$\begin{aligned}\mathcal{L}^{\rm SM} &= -\frac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^i_{\mu\nu} - \frac{1}{4}B_{\mu\nu}B_{\mu\nu} + D_\mu H^\dagger D_\mu H + \mu_H^2 H^\dagger H - \lambda(H^\dagger H)^2 \\ &+ \sum_{f\in q,\ell} i\bar{f}_L\gamma_\mu D_\mu f_L + \sum_{f\in u,d,e} i\bar{f}_R\gamma_\mu D_\mu f_R \\ &- \left[\tilde{H}^\dagger \bar{u}_R y_u q_L + H^\dagger \bar{d}_R y_d V^\dagger_{\rm CKM} q_L + H^\dagger \bar{e}_R y_e \ell_L + \text{h.c.}\right] . \qquad (2.1)\end{aligned}$$

EFT Higgs measurements

- Starting point – formulate model to be tested against data as an (effective) field theory.
- Start with SM Lagrangian and add higher-order operators

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}^{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \cdots .$$

Mass scale Λ of non-SM physics is assumed to be >>v



EFT Higgs measurements

- Starting point – formulate model to be tested against data as an (effective) field theory.
- Start with SM Lagrangian and add higher-order operators

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}^{\text{SM}} + \cancel{\sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \cancel{\cdots}$$

All dim-5 operators that can be constructed from SM fields violate lepton number. Experimental constraints → $c_i^{(5)}$ very small, ignorable at LHC

The contribution of each O(d) to amplitudes of physical processes at the energy scale of order v scales as (v/Λ)d−4. Since v/Λ < 1 by construction, EFT typically describes small deviations from the SM predictions

EFT Higgs measurements

- A **basis** of dimension-6 operators is a complete, non-redundant set of O(6) operators

$$\sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}$$

- There is no unique decomposition → there exist multiple bases
- Examples: Warsaw basis, SILH basis, Higgs basis (there are more)

EFT Basis choices

$$\sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}$$

dim-6 operators in Warsaw basis (! 4-fermion)

H^4D^2 and H^6		f^2H^3		V^3D^3	
O_H	$[\partial_\mu(H^\dagger H)]^2$	$[O_e]_{ij}$	$-\frac{\sqrt{m_i m_j}}{v}(H^\dagger H - \frac{v^2}{2})\bar e_i H^\dagger \ell_j$	O_{3G}	$g_s^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	$[O_u]_{ij}$	$-\frac{\sqrt{m_i m_j}}{v}(H^\dagger H - \frac{v^2}{2})\bar u_i \tilde H^\dagger q_j$	$O_{3\widetilde{G}}$	$g_s^3 f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$
O_{6H}	$(H^\dagger H)^3$	$[O_d]_{ij}$	$-\frac{\sqrt{m_i m_j}}{v}(H^\dagger H - \frac{v^2}{2})\bar d_i H^\dagger q_j$	O_{3W}	$g^3 \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
				$O_{3\widetilde{W}}$	$g^3 \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$

V^2H^2		f^2H^2D		f^2VHD	
O_{GG}	$\frac{g_s^2}{4} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$[O_{H\ell}]_{ij}$	$i\bar\ell_i \gamma_\mu \ell_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{eW}]_{ij}$	$g \bar\ell_i \sigma^k H \sigma_{\mu\nu} e_j W^k_{\mu\nu}$
$O_{\widetilde{G}G}$	$\frac{g_s^2}{4} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$	$[O'_{H\ell}]_{ij}$	$i\bar\ell_i \sigma^k \gamma_\mu \ell_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$	$[O_{eB}]_{ij}$	$g' \bar\ell_i H \sigma_{\mu\nu} e_j B_{\mu\nu}$
O_{WW}	$\frac{g^2}{4} H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$[O_{He}]_{ij}$	$i\bar e_i \gamma_\mu e_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uG}]_{ij}$	$g_s \bar q_i \tilde H \sigma_{\mu\nu} T^a u_j G^a_{\mu\nu}$
$O_{\widetilde{W}W}$	$\frac{g^2}{4} H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$	$[O_{Hq}]_{ij}$	$i\bar q_i \gamma_\mu q_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uW}]_{ij}$	$g \bar q_i \sigma^k \tilde H \sigma_{\mu\nu} u_j W^k_{\mu\nu}$
O_{BB}	$\frac{g'^2}{4} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$[O'_{Hq}]_{ij}$	$i\bar q_i \sigma^k \gamma_\mu q_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$	$[O_{uB}]_{ij}$	$g' \bar q_i \tilde H \sigma_{\mu\nu} u_j B_{\mu\nu}$
$O_{\widetilde{B}B}$	$\frac{g'^2}{4} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$	$[O_{Hu}]_{ij}$	$i\bar u_i \gamma_\mu u_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dG}]_{ij}$	$g_s \bar q_i H \sigma_{\mu\nu} T^a d_j G^a_{\mu\nu}$
O_{WB}	$g g' H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$[O_{Hd}]_{ij}$	$i\bar d_i \gamma_\mu d_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dW}]_{ij}$	$g \bar q_i \sigma^k H \sigma_{\mu\nu} d_j W^k_{\mu\nu}$
$O_{\widetilde{W}B}$	$g g' H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$	$[O_{Hud}]_{ij}$	$i\bar u_i \gamma_\mu d_j \tilde H^\dagger D_\mu H$	$[O_{dB}]_{ij}$	$g' \bar q_i H \sigma_{\mu\nu} d_j B_{\mu\nu}$

SILH basis (incomplete)

$$
\begin{aligned}
O_W &= \frac{ig}{2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu},\\
O_B &= \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu},\\
O_{HW} &= ig\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu},\\
O_{HB} &= ig'\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu},\\
O_{\widetilde{HW}} &= ig\left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu},\\
O_{\widetilde{HB}} &= ig'\left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu},\\
O_{2W} &= D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu},\\
O_{2B} &= \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu},\\
O_{2G} &= D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}.
\end{aligned}
$$

EFT Basis choices

$$\sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}$$

dim-6 operators in Warsaw basis (! 4-fermion)

H^4D^2 and H^6		f^2H^3		V^3D^3
O_H	$\left[\partial_\mu(H^\dagger H)\right]^2$	$[O_e]_{ij}$	$-\frac{\sqrt{m_i}}{v}$ …	
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	$[O_u]_{ij}$	$-\frac{\sqrt{m_i m_j}}{v}$ …	
O_{6H}	$(H^\dagger H)^3$	$[O_d]_{ij}$	$-\frac{\sqrt{m_i}}{v}$ …	

V^2H^2		
O_{GG}	$\frac{g_s^2}{4}H^\dagger H\, G^a_{\mu\nu}G^a_{\mu\nu}$	$[O_{H\ell}]$ …
$O_{\widetilde{GG}}$	$\frac{g_s^2}{4}H^\dagger H\, \widetilde{G}^a_{\mu\nu}G^a_{\mu\nu}$	$[O'_{H\ell}]$ …
O_{WW}	$\frac{g^2}{4}H^\dagger H\, W^i_{\mu\nu}W^i_{\mu\nu}$	$[O_{He}]$ …
$O_{\widetilde{WW}}$	$\frac{g^2}{4}H^\dagger H\, \widetilde{W}^i_{\mu\nu}W^i_{\mu\nu}$	$[O_{Hq}]$ …
O_{BB}	$\frac{g'^2}{4}H^\dagger H\, B_{\mu\nu}B_{\mu\nu}$	$[O'_{Hq}]$ …
$O_{\widetilde{BB}}$	$\frac{g'^2}{4}H^\dagger H\, \widetilde{B}_{\mu\nu}B_{\mu\nu}$	$[O_{Hu}]$ …
O_{WB}	$gg'H^\dagger\sigma^i H\, W^i_{\mu\nu}B_{\mu\nu}$	$[O_{Hd}]$ …
$O_{\widetilde{WB}}$	$gg'H^\dagger\sigma^i H\, \widetilde{W}^i_{\mu\nu}B_{\mu\nu}$	$[O_{Hud}]$ …

Operator map between Warsaw and SILH bases

$$
\begin{aligned}
O_{HB} &= O_B - \frac{1}{4}O_{WB} - O_{BB},\\
O_{HW} &= O_W - \frac{1}{4}O_{WB} - O_{WW},\\
O_{\widetilde{HB}} &= -\frac{1}{4}O_{\widetilde{WB}} - O_{\widetilde{BB}},\\
O_{\widetilde{HW}} &= -\frac{1}{4}O_{\widetilde{WB}} - O_{\widetilde{WW}},\\
O_B &= g'^2\left[-\frac{1}{4}O_T + \frac{1}{2}\sum_{f\in q,u,d,\ell,e} Y_f \sum_i [O_{Hf}]_{ii}\right],\\
O_W &= g^2\left[-\frac{1}{4}O_H + O_{HD} + \frac{1}{4}\sum_{f\in q,\ell}\sum_i [O'_{Hf}]_{ii}\right],\\
O_{2B} &= g'^2\left[-\frac{1}{4}O_T + \sum_{f\in q,u,d,\ell,e} Y_f \sum_i [O_{Hf}]_{ii} + \sum_{f_1 f_2\in q,u,d,\ell,e} Y_{f_1}Y_{f_2}\sum_{i,j}[O_{f_1 f_2}]_{ii;jj}\right],\\
O_{2W} &= g^2\left[-\frac{1}{4}O_H + O_{HD} + \frac{1}{2}\sum_{f\in q,\ell}\sum_i [O'_{Hf}]_{ii}\right.\\
&\quad \left. + \sum_{ij}\left(\frac{1}{2}[O_{\ell\ell}]_{ij;ji} - \frac{1}{4}[O_{\ell\ell}]_{ii;jj} + \frac{1}{2}[O_{\ell q}]_{ii;jj} + \frac{1}{4}[O_{qq}]_{ii;jj}\right)\right],\\
O_{2G} &= g_s^2\sum_{i,j}\left[\frac{1}{4}[O'_{qq}]_{ij;ji} + \frac{1}{4}[O_{qq}]_{ij;ji} - \frac{1}{6}[O_{qq}]_{ii;jj} + 2[O'_{qu}]_{ii;jj} + 2[O'_{qd}]_{ii;jj}\right.\\
&\quad \left. + 2[O'_{ud}]_{ii;jj} + \frac{1}{2}[O'_{uu}]_{ij;ji} - \frac{1}{6}[O'_{uu}]_{ii;jj} + \frac{1}{2}[O'_{dd}]_{ij;ji} - \frac{1}{6}[O'_{dd}]_{ii;jj}\right]. \qquad (3.4)
\end{aligned}
$$

…H basis (incomplete)

$\sigma^i \overleftrightarrow{D}_\mu H\big)\, D_\nu W^i_{\mu\nu},$

$\overleftrightarrow{D}_\mu H\big)\, \partial_\nu B_{\mu\nu},$

$H^\dagger\sigma^i D_\nu H\big)\, W^i_{\mu\nu},$

$H^\dagger D_\nu H\big)\, B_{\mu\nu},$

$H^\dagger\sigma^i D_\nu H\big)\, \widetilde{W}^i_{\mu\nu},$

$H^\dagger D_\nu H\big)\, \widetilde{B}_{\mu\nu},$

$D_\rho W^i_{\rho\nu},$

$_\rho B_{\rho\nu},$

$$O_{2G} = D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}.$$

EFT Basis choices

$$\sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}$$

dim-6 operators in Warsaw basis (! 4-fermion)

H^4D^2 and H^6		f^2H^3		V^3D^3
O_H	$\left[\partial_\mu(H^\dagger H)\right]^2$	$[O_e]_{ij}$	$-\frac{\sqrt{m_i}}{v}$	
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	$[O_u]_{ij}$	$-\frac{\sqrt{m_i m_j}}{v}$	
O_{6H}	$(H^\dagger H)^3$	$[O_d]_{ij}$	$-\frac{\sqrt{m_i m_j}}{v}$	

V^2H^2		
O_{GG}	$\frac{g_s^2}{4}H^\dagger H\, G^a_{\mu\nu}G^a_{\mu\nu}$	$[O_{H\ell}]_{ij}$
$O_{\widetilde{GG}}$	$\frac{g_s^2}{4}H^\dagger H\, \widetilde{G}^a_{\mu\nu}G^a_{\mu\nu}$	$[O'_{H\ell}]_{ij}$
O_{WW}	$\frac{g^2}{4}H^\dagger H\, W^i_{\mu\nu}W^i_{\mu\nu}$	$[O_{He}]_{ij}$
$O_{\widetilde{WW}}$	$\frac{g^2}{4}H^\dagger H\, \widetilde{W}^i_{\mu\nu}W^i_{\mu\nu}$	$[O_{Hq}]_{ij}$
O_{BB}	$\frac{g'^2}{4}H^\dagger H\, B_{\mu\nu}B_{\mu\nu}$	$[O'_{Hq}]_{ij}$
$O_{\widetilde{BB}}$	$\frac{g'^2}{4}H^\dagger H\, \widetilde{B}_{\mu\nu}B_{\mu\nu}$	$[O_{Hu}]_{ij}$
O_{WB}	$gg'H^\dagger\sigma^i H\, W^i_{\mu\nu}B_{\mu\nu}$	$[O_{Hd}]_{ij}$
$O_{\widetilde{WB}}$	$gg'H^\dagger\sigma^i H\, \widetilde{W}^i_{\mu\nu}B_{\mu\nu}$	$[O_{Hud}]_{ij}$

Coefficient map between Warsaw and SILH bases

$$
\begin{aligned}
c_H &= s_H - \frac{3g^2}{4}\left(s_W + s_{HW} + s_{2W}\right),\\
c_T &= s_T - \frac{g'^2}{4}\left(s_B + s_{HB} + s_{2B}\right),\\
c_{6H} &= s_{6H} + 2\lambda g^2\left(s_W + s_{HW} + s_{2W}\right),\\
c_{WB} &= -\frac{1}{4}\left(s_{HB} + s_{HW}\right),\\
c_{BB} &= s_{BB} - s_{HB},\\
c_{WW} &= -s_{HW},\\
\tilde{c}_{WB} &= -\frac{1}{4}\left(\tilde{s}_{HB} + \tilde{s}_{HW}\right),\\
\tilde{c}_{BB} &= \tilde{s}_{BB} - \tilde{s}_{HB},\\
\tilde{c}_{WW} &= -\tilde{s}_{HW},
\end{aligned}
$$

$$
\begin{aligned}
[c_{Hf}]_{ij} &= [s_{Hf}]_{ij} + \frac{g'^2 Y_f}{2}\left(s_B + s_{HB} + 2s_{2B}\right)\delta_{ij},\\
[c'_{Hf}]_{ij} &= [s'_{Hf}]_{ij} + \frac{g^2}{4}\left(s_W + s_{HW} + 2s_{2W}\right)\delta_{ij},
\end{aligned}
$$

$$[c_f]_{ij} = [s_f]_{ij} - \delta_{ij}\frac{g^2}{\sqrt{2}}\left(s_W + s_{HW} + s_{2W}\right),$$

$$
\begin{aligned}
[c_{\ell\ell}]_{iiii} &= [s_{\ell\ell}]_{iiii} + \frac{1}{4}\left(g'^2 s_{2B} + g^2 s_{2W}\right),\\
[c_{\ell\ell}]_{iijj} &= [s_{\ell\ell}]_{iijj} + \frac{1}{2}\left(g'^2 s_{2B} - g^2 s_{2W}\right), \qquad i<j,\\
[c_{\ell\ell}]_{ijji} &= [s_{\ell\ell}]_{ijji} + g^2 s_{2W}, \qquad i<j,
\end{aligned}
$$

LH basis (incomplete)

$\sigma^i \overleftrightarrow{D}_\mu H\big)\, D_\nu W^i_{\mu\nu},$

$\overleftrightarrow{D}_\mu H\big)\, \partial_\nu B_{\mu\nu},$

$H^\dagger\sigma^i D_\nu H\big)\, W^i_{\mu\nu},$

$H^\dagger D_\nu H\big)\, B_{\mu\nu},$

$H^\dagger\sigma^i D_\nu H\big)\, \widetilde{W}^i_{\mu\nu},$

$H^\dagger D_\nu H\big)\, \widetilde{B}_{\mu\nu},$

$D_\rho W^i_{\rho\nu},$

$\partial_\rho B_{\rho\nu},$

$D_\rho G^a_{\rho\nu}.$

Choice of basis & alignment of EFT params with observables

- Complete bases like Warsaw and SILH have a large number of parameters (coefficients c(i))
- But LHC Higgs observables depend only on a smaller number of linear combinations of the Wilson coefficients
- But some of these linear combinations are already stringently constrained by electroweak precisions tests, such that they cannot yield observable effects at the LHC.
- Other bases are being developed that address these issues, e.g. 'Higgs basis'
  - The goal is to parameterize the d=6 operators in a way that can be more directly connected to observable quantities in Higgs physics
  - Needs only 9 parameters to describe LO EFT corrections existing Higgs signal strength measurements at the LHC

$$c_{gg},\ \delta c_z,\ c_{\gamma\gamma},\ c_{z\gamma},\ c_{zz},\ c_{z\Box},\ \delta y_u,\ \delta y_d,\ \delta y_e.$$

Impact on experiment procedures

- Modeling of (SM) Higgs degrees of freedom in EFT clearly appealing from theoretical perspective
- Theoretical guidance on how to interpret coefficients c(i) with non-SM values (whereas kappa-model only has clear interpretation at k=1)
- But what does EFT deployment it mean *in practice* for experimental Higgs measurements? Things to watch:

1. No agreed-upon choice of basis (yet).
2. Experimental result formulation becomes strongly intertwined with a particular choice of theory model / choice of basis. Longevity of results.
3. Need to understand alignment of observables/measurements with theory parameters (relation $k_i,k_f \rightarrow \mu_i^f$ clear, small #params describing single measurements). Which coefficients c(i) contribute measurable to which μ_i^f?
4. Operators c(i) will generally change rates and kinematic distributions of observables → invasive change in analysis procedure (but this is a good thing → eliminates a limiting assumption of kappa-model)
5. Need to understand range of validity. At sufficiently large parameter deviations, one will violate assumption $v \ll \Lambda$. Also need to be careful with high-p_T tails of distributions (e.g. when pT no longer $\ll \Lambda$)

EFT is already used in Higgs property measurements

- For example for measurement of CP state of h(125)
- Langrangian of 'Higgs characterization framework' for spin-0 X^0
  - Assumes X^0 is admixture of 3 states: SM CP-even, BSM CP-even, BSM-CP-odd

coupling constant for SM CP-even

$$\begin{aligned}\mathcal{L}_0^V = \; & \Big\{ \cos(\alpha)\kappa_{\rm SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] \\ & -\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ & -\tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\} X_0.\end{aligned}$$

Energy scale of non-SM physics

coupling constant for BSM CP-even

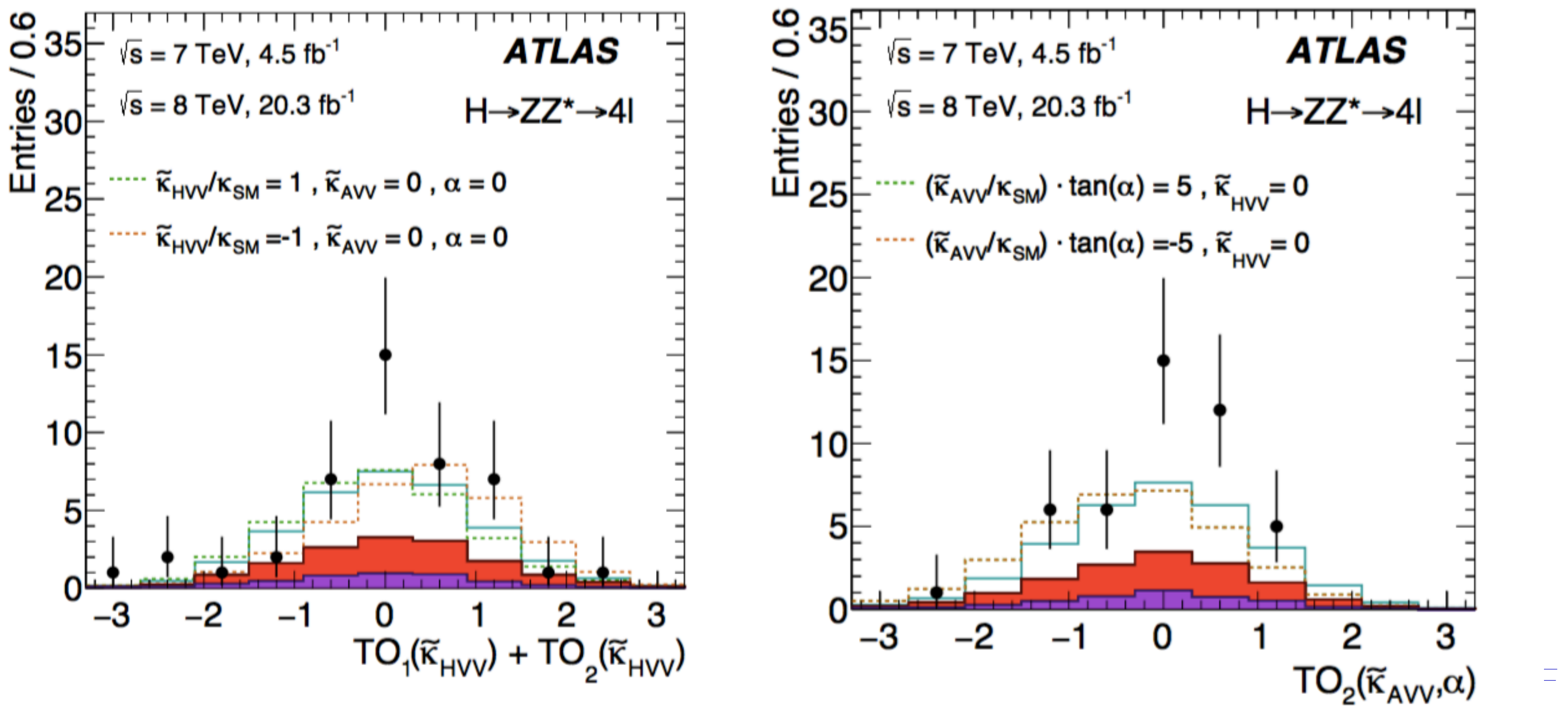
coupling constant for BSM CP-odd

mixing angle (value ≠0 allows for production of mixed states)

Constructing the probability model

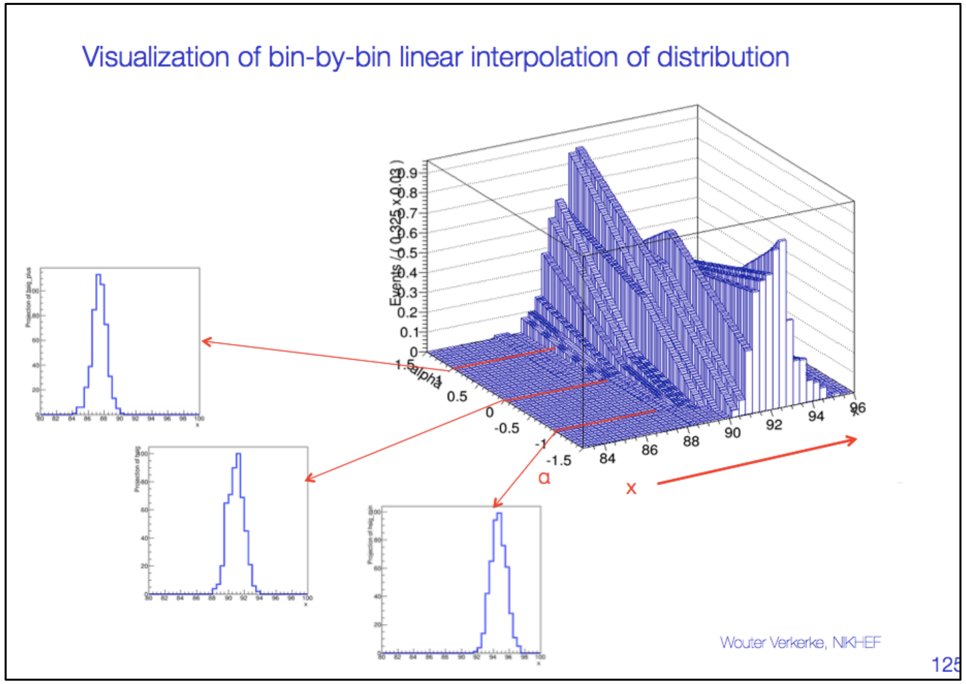
- Probability models for (EFT) CP measurements more complex than for coupling measurements
  - Generally, multiple discriminant observables used (n-Dim analysis)
  - Unlike coupling analysis in k-framework
    theory parameters affect both rate and distributions of observables

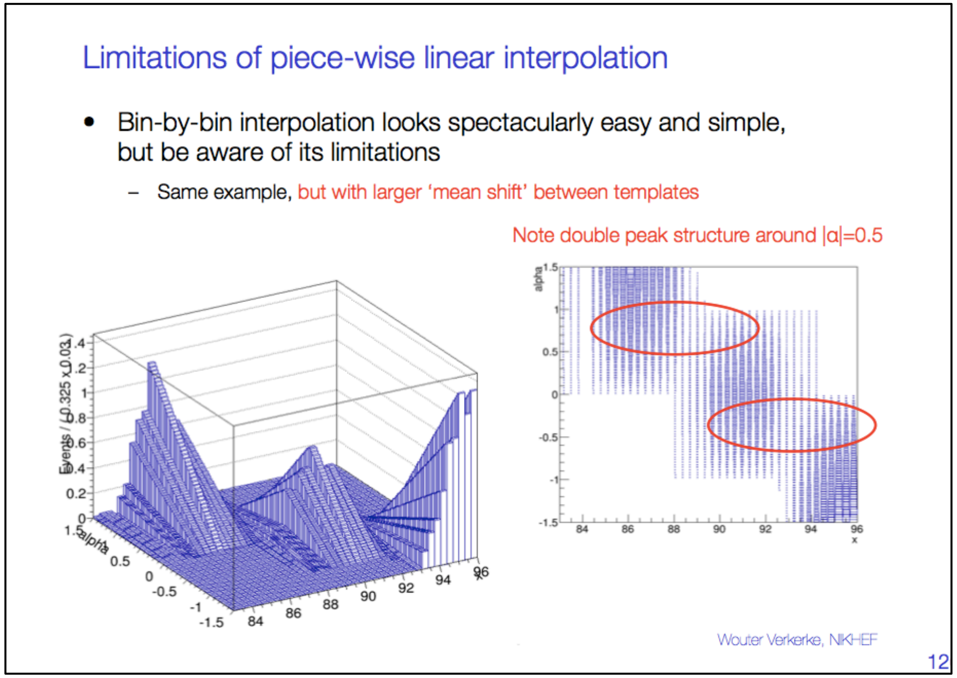
Two example observables from ATLAS H→ZZ analysis



Parameterizing shapes changes in signal distributions

- For shape changes due to systematic uncertainties (nuisance parameters) 'vertical interpolation' is mostly used





- But procedure is ad-hoc and has limitations → Dubious to use this for modeling of signal shape changes related to physics parameters of interest.
- Can we do better?

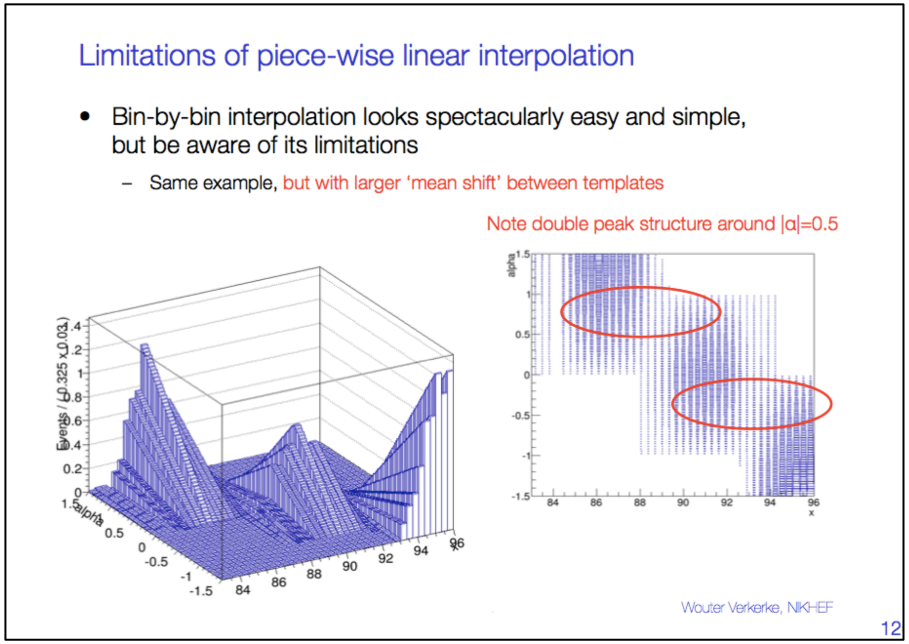
Improved strategy for interpolation – moment morphing

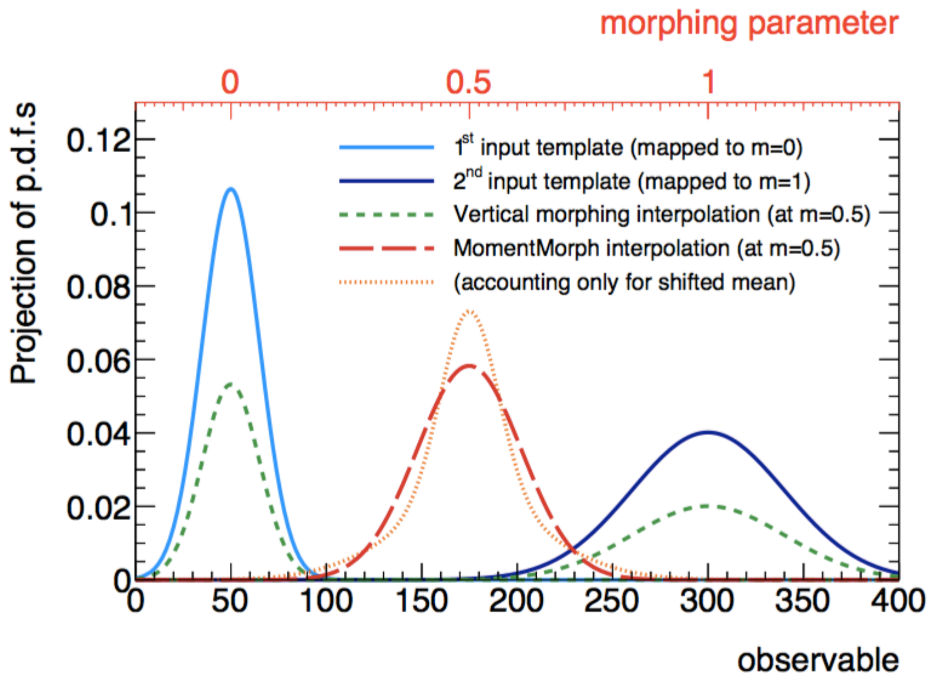
- Key deficiency of vertical interpolation is that it doesn't account well for shifting distributions

  $T_{out}(x|\alpha) = \alpha^* T_{low}(x) + (1-\alpha)^* T_{high}(x)$

- Alternative strategy is "moment morphing"

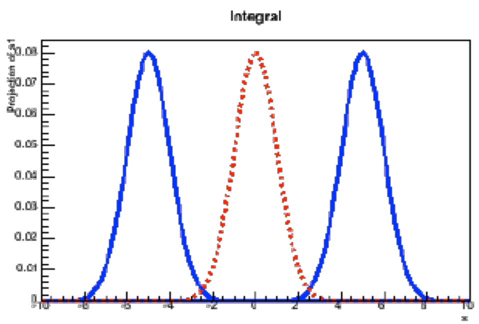
- Basic idea is the same, but adjust mean, r.m.s of $T_{low}(x), T_{high}(x)$ through transformation $x \rightarrow x'$ function of α so that mean, r.m.s. of components $T(x')$ match for any α



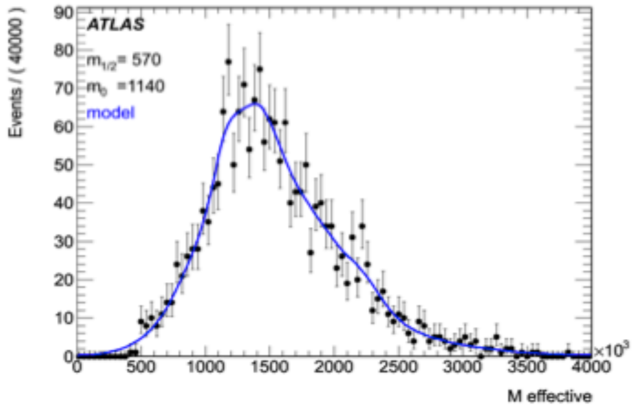


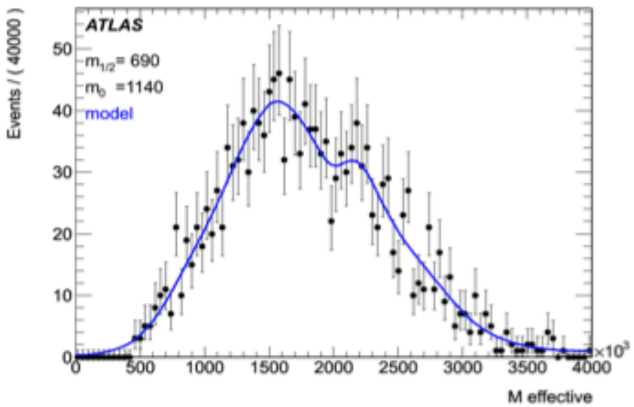
Yet another morphing strategy – ‘Moment morphing’

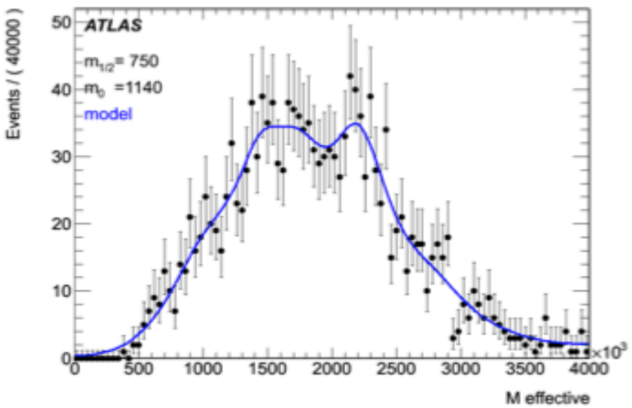
- For a Gaussian probability model with linearly changing mean and width, moment morphing of two Gaussian templates is the exact solution



- But also works well on ‘difficult’ distributions







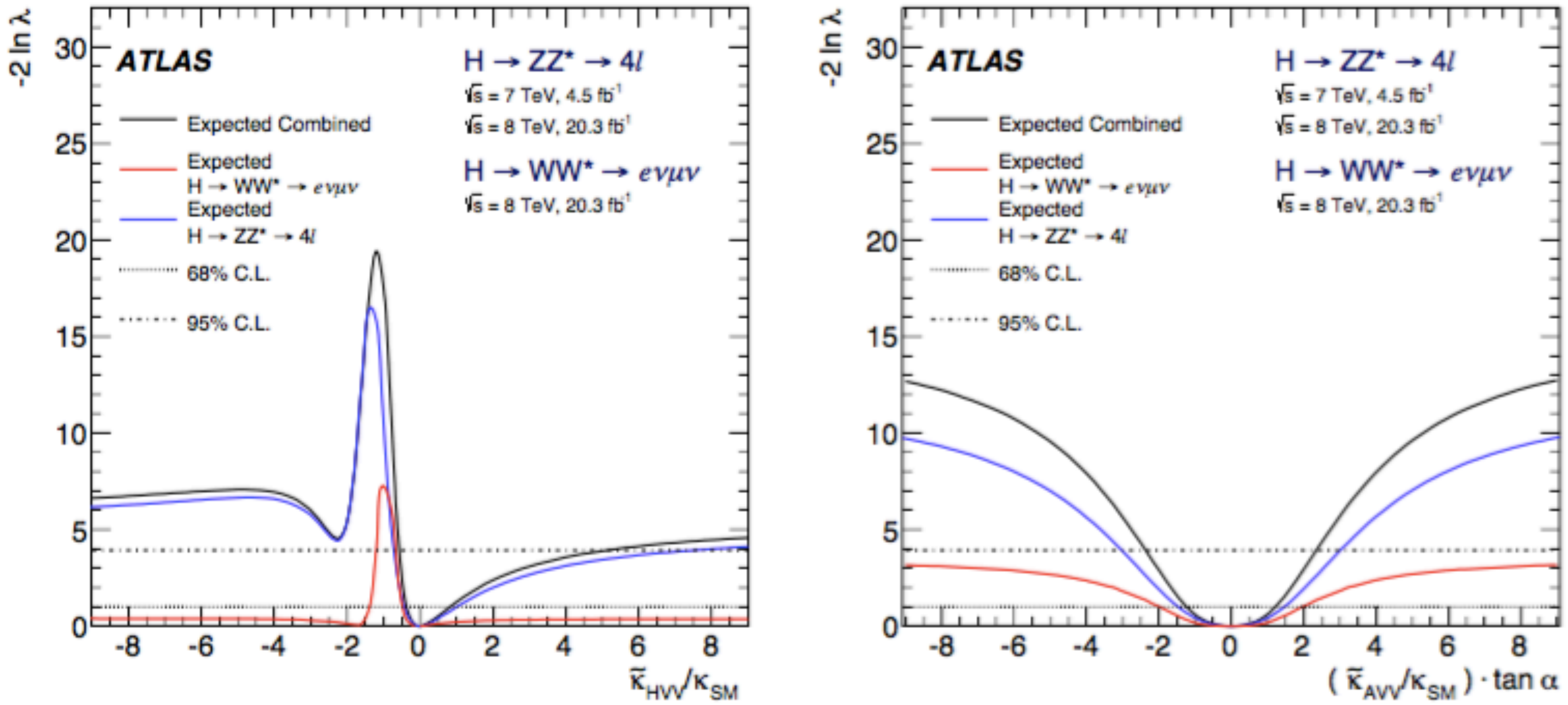
- Good computational performance
  – Calculation of moments of templates is expensive,
    but just needs to be done once, otherwise very fast (just linear algebra)

- Multi-dimensional interpolation strategies exist

- Moment morphing used for signal interpolation for ATLAS CP analysis

Example EFT Results – ATLAS CP constraints

- Individual & combined results of H→WW & H→ZZ channels



Coupling ratio	Best-fit value	95% CL Exclusion Regions	
Combined	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	-0.48	$(-\infty,-0.55]\bigcup[4.80,\infty)$	$(-\infty,-0.73]\bigcup[0.63,\infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM})\cdot\tan\alpha$	-0.68	$(-\infty,-2.33]\bigcup[2.30,\infty)$	$(-\infty,-2.18]\bigcup[0.83,\infty)$

A case study for run-2

- Can we practically describe experimental observable distributions as function of the 15 parameters of the full Higgs Characterization Framework L for Higgs-V interactions

$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{SM} \left[\frac{1}{2} \tilde{g}_{HZZ} Z_\mu Z^\mu + \tilde{g}_{HWW} W^+_\mu W^{-\mu} \right] \\
& - \frac{1}{4} \left[c_\alpha \kappa_{H\gamma\gamma} \tilde{g}_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} \tilde{g}_{A\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu} \right] \\
& - \frac{1}{2} \left[c_\alpha \kappa_{HZ\gamma} \tilde{g}_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} \tilde{g}_{AZ\gamma} Z_{\mu\nu} \tilde{A}^{\mu\nu} \right] \\
& - \frac{1}{4} \left[c_\alpha \kappa_{Hgg} \tilde{g}_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} \tilde{g}_{Agg} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \right] \\
& - \frac{1}{4} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \\
& - \frac{1}{2} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu} \right] \\
& - \frac{1}{\Lambda} c_\alpha \left[\kappa_{H\partial\gamma} Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z} Z_\nu \partial_\mu Z^{\mu\nu} + \kappa_{H\partial W} \left(W^+_\nu \partial_\mu W^{-\mu\nu} + h.c. \right) \right] \Big\} X_0
\end{aligned}
$$

Used in Run 1

Plan Run 2

Consider a new approach to model building (morphing)

- While moment morphing is usually better than vertical morphing, underlying transformations are not rooted in physics principles, but rather assumption on linear adjustments of moments
- If we start from (EFT) assumption that model is built from sum of amplitudes with coefficients, can also build a morphing function based on that physics principle → "EFT morphing"
- Consider first simplest scenario with 1 non-SM coupling in production only (or decay only) → Two parameters g_{SM}, g_{BSM} that affect ME

$$T(g_{\text{SM}}, g_{\text{BSM}}) \propto |\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}})|^2$$

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$$\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}}) = g_{\text{SM}} O_{\text{SM}} + g_{\text{BSM}} O_{\text{BSM}}$$

$$|\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}})|^2 = g_{\text{SM}}^2 |O_{\text{SM}}|^2 + g_{\text{BSM}}^2 |O_{\text{BSM}}|^2 + 2 g_{\text{SM}} g_{\text{BSM}} \mathcal{R}(O_{\text{SM}}^* O_{\text{BSM}})$$

EFT morphing approach

- Number of input distributions needed = number of terms in M^2

$$|\mathcal{M}(g_{\mathrm{SM}}, g_{\mathrm{BSM}})|^2 = g_{\mathrm{SM}}^2 |O_{\mathrm{SM}}|^2 + g_{\mathrm{BSM}}^2 |O_{\mathrm{BSM}}|^2 + 2 g_{\mathrm{SM}} g_{\mathrm{BSM}} \mathcal{R}(O_{\mathrm{SM}}^* O_{\mathrm{BSM}})$$

For this simplest case need 3 templates, e.g.

$$T_{in}(1,0) \propto |O_{\mathrm{SM}}|^2$$
$$T_{in}(0,1) \propto |O_{\mathrm{BSM}}|^2$$
$$T_{in}(1,1) \propto |O_{\mathrm{SM}}|^2 + |O_{\mathrm{BSM}}|^2 + 2\mathcal{R}(O_{\mathrm{SM}}^* O_{\mathrm{BSM}})$$

- Then observable distributions for $|M|^2$ for any value of g_{SM}, g_{BSM} is

$$T_{out}(g_{\mathrm{SM}}, g_{\mathrm{BSM}}) = \underbrace{(g_{\mathrm{SM}}{}^2 - g_{\mathrm{SM}} g_{\mathrm{BSM}})} T_{in}(1,0) + \underbrace{(g_{\mathrm{BSM}}{}^2 - g_{\mathrm{SM}} g_{\mathrm{BSM}})} T_{in}(0,1) + \underbrace{g_{\mathrm{SM}} g_{\mathrm{BSM}}} T_{in}(1,1)$$

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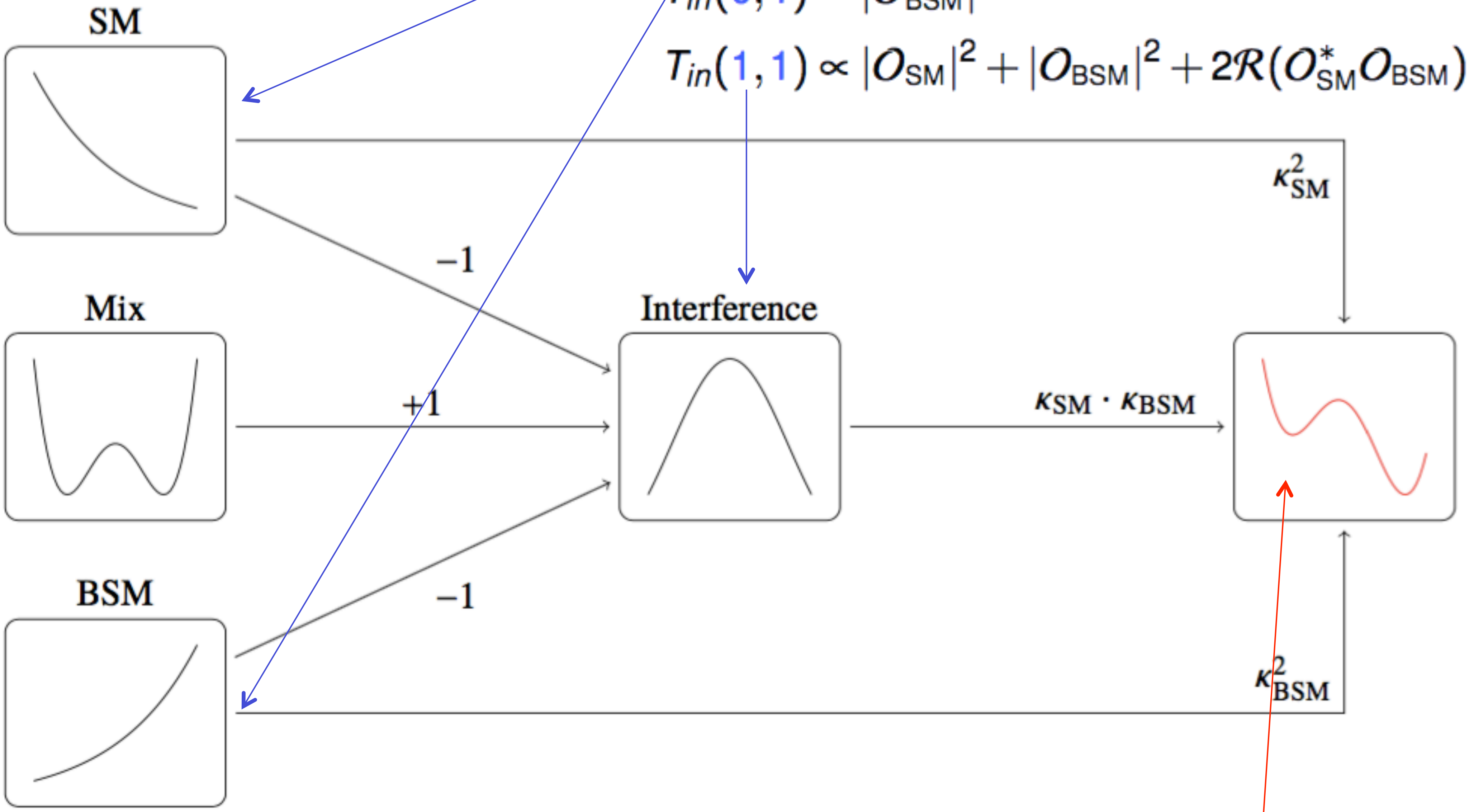
- Interpolation accurate for all values of g_{SM}, g_{BSM}, in limit that $|M|$ is described by formula above

EFT morphing approach

$$T_{in}(1,0) \propto |O_{\mathrm{SM}}|^2$$

$$T_{in}(0,1) \propto |O_{\mathrm{BSM}}|^2$$

$$T_{in}(1,1) \propto |O_{\mathrm{SM}}|^2 + |O_{\mathrm{BSM}}|^2 + 2\mathcal{R}(O^*_{\mathrm{SM}} O_{\mathrm{BSM}})$$

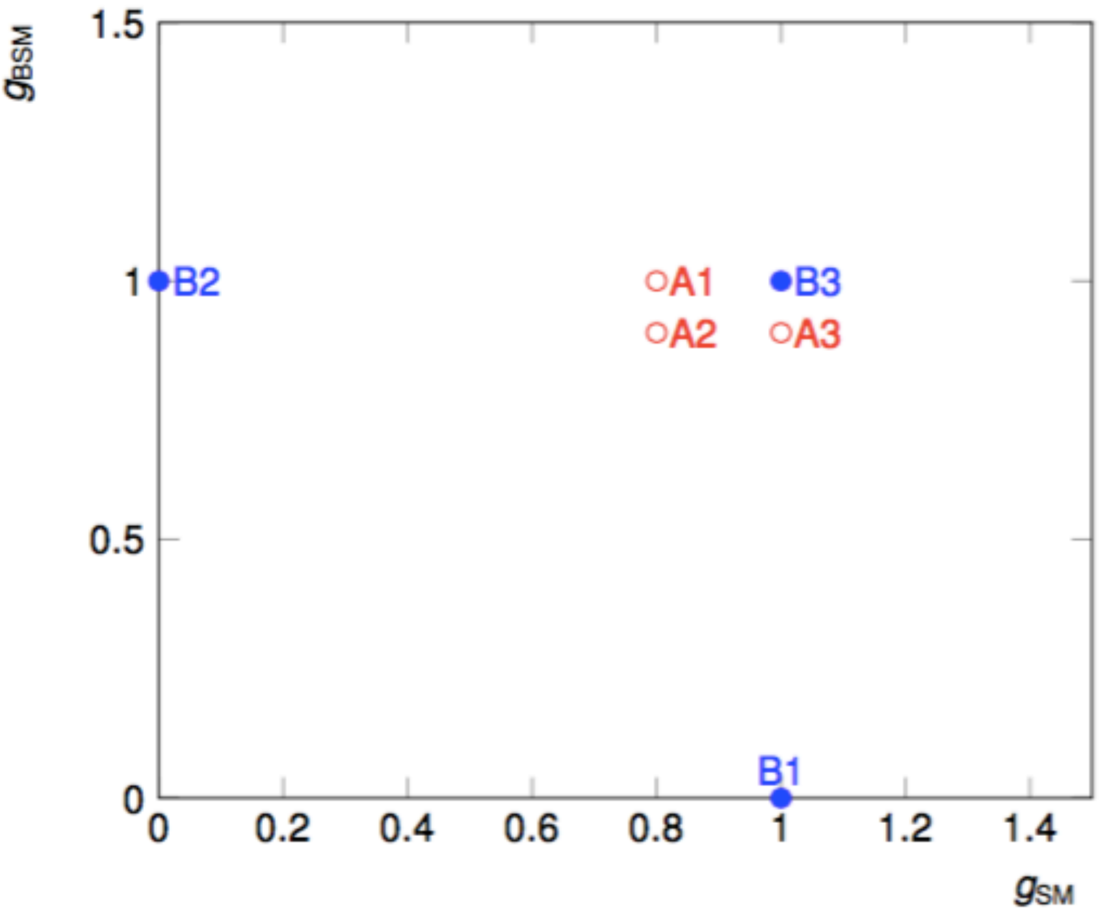


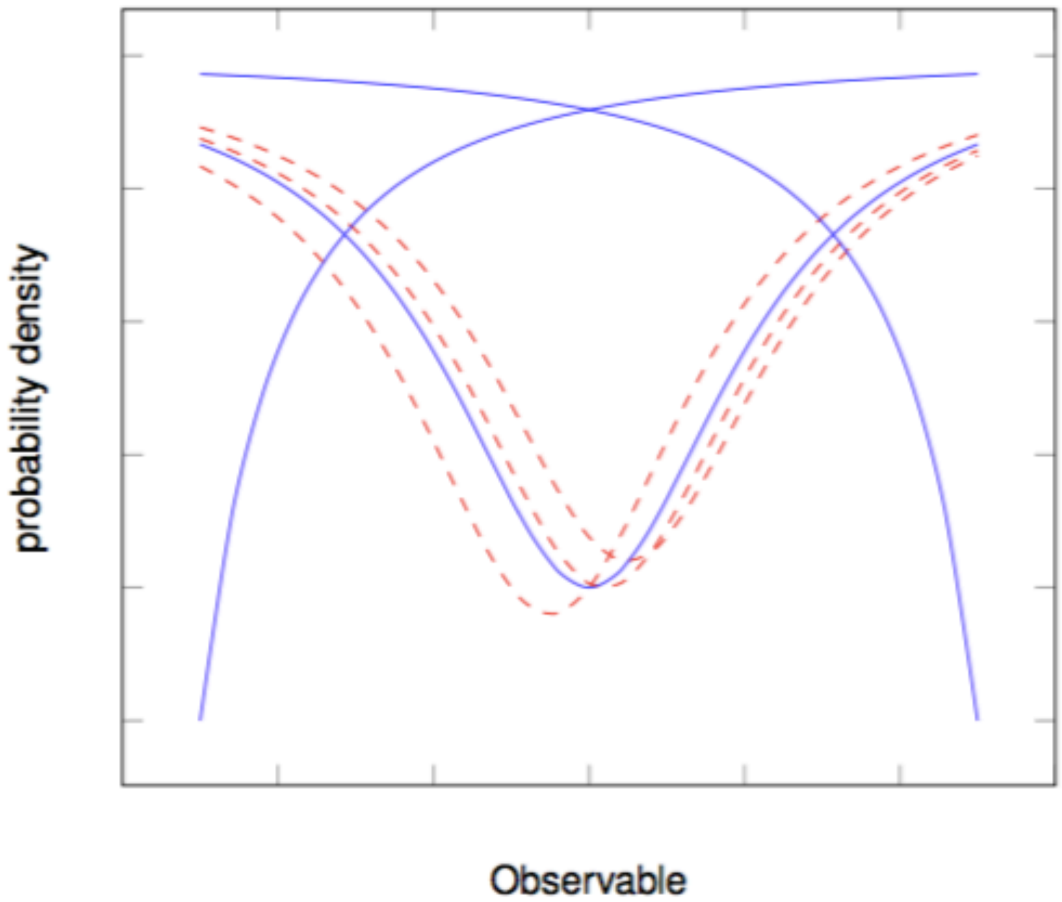
$$T_{out}(g_{\mathrm{SM}}, g_{\mathrm{BSM}}) = \underbrace{(g_{\mathrm{SM}}{}^2 - g_{\mathrm{SM}} g_{\mathrm{BSM}})} T_{in}(1,0) + \underbrace{(g_{\mathrm{BSM}}{}^2 - g_{\mathrm{SM}} g_{\mathrm{BSM}})} T_{in}(0,1) + \underbrace{g_{\mathrm{SM}} g_{\mathrm{BSM}}} T_{in}(1,1)$$

Note that this is effectively 'vertical interpolation' morphing – but with specific choice of sampling points!

Illustration of EFT morphing

- Example of morphing of 1D observable distribution with 2 theory parameters





EFT morphing – non-SM couplings in production & decay

- What happens if both prod. & decay vertices depend on g_{SM}, g_{BSM}
  - Assuming Narrow Width approximation

$$\mathcal{M}(g_{\mathrm{SM}}, g_{\mathrm{BSM}}) = \left(g_{\mathrm{SM}} \cdot O_{\mathrm{SM},p} + g_{\mathrm{BSM}} \cdot O_{\mathrm{BSM},p}\right) \cdot \left(g_{\mathrm{SM}} \cdot O_{\mathrm{SM},d} + g_{\mathrm{BSM}} \cdot O_{\mathrm{BSM},d}\right).$$

$$\Downarrow$$

$$\begin{aligned}
|\mathcal{M}(g_{\mathrm{SM}}, g_{\mathrm{BSM}})|^2 &= \left(g_{\mathrm{SM}} O_{\mathrm{SM},p} + g_{\mathrm{BSM}} O_{\mathrm{BSM},p}\right)^2 \cdot \left(g_{\mathrm{SM}} O_{\mathrm{SM},d} + g_{\mathrm{BSM}} O_{\mathrm{BSM},d}\right)^2 \\
&= g_{\mathrm{SM}}^4 \cdot O_{\mathrm{SM},p}^2 O_{\mathrm{SM},d}^2 + g_{\mathrm{BSM}}^4 \cdot O_{\mathrm{BSM},p}^2 O_{\mathrm{BSM},d}^2 \\
&+ g_{\mathrm{SM}}^3 g_{\mathrm{BSM}} \cdot \left(O_{\mathrm{SM},p}^2 \Re(O_{\mathrm{SM},d}^* O_{\mathrm{BSM},d}) + \Re(O_{\mathrm{SM},p}^* O_{\mathrm{BSM},p}) O_{\mathrm{SM},d}^2\right) \\
&+ g_{\mathrm{SM}}^2 g_{\mathrm{BSM}}^2 \cdot \left(O_{\mathrm{SM},p}^2 O_{\mathrm{BSM},d}^2 + O_{\mathrm{BSM},p}^2 O_{\mathrm{SM},d}^2\right) \\
&+ g_{\mathrm{SM}} g_{\mathrm{BSM}}^3 \cdot \left(O_{\mathrm{BSM},p}^2 \Re(O_{\mathrm{SM},d}^* O_{\mathrm{BSM},d}) + \Re(O_{\mathrm{SM},p}^* O_{\mathrm{BSM},p}) O_{\mathrm{BSM},d}^2\right).
\end{aligned}$$

Now need 5 distribution templates instead of 3,
but otherwise fundamentally not more complicated

EFT morphing – adding parameters

- Morphing method can be generalized to have >2 parameters

$$|\mathcal{M}(\vec{g})|^2 = \underbrace{\left(\sum_{x\in p,b} g_x O(g_x)\right)^2}_{\text{production}} \cdot \underbrace{\left(\sum_{x\in d,b} g_x O(g_x)\right)^2}_{\text{decay}}.$$

- But number of terms in expression (and thus number of input distributions) grows rapidly with number of theory parameters

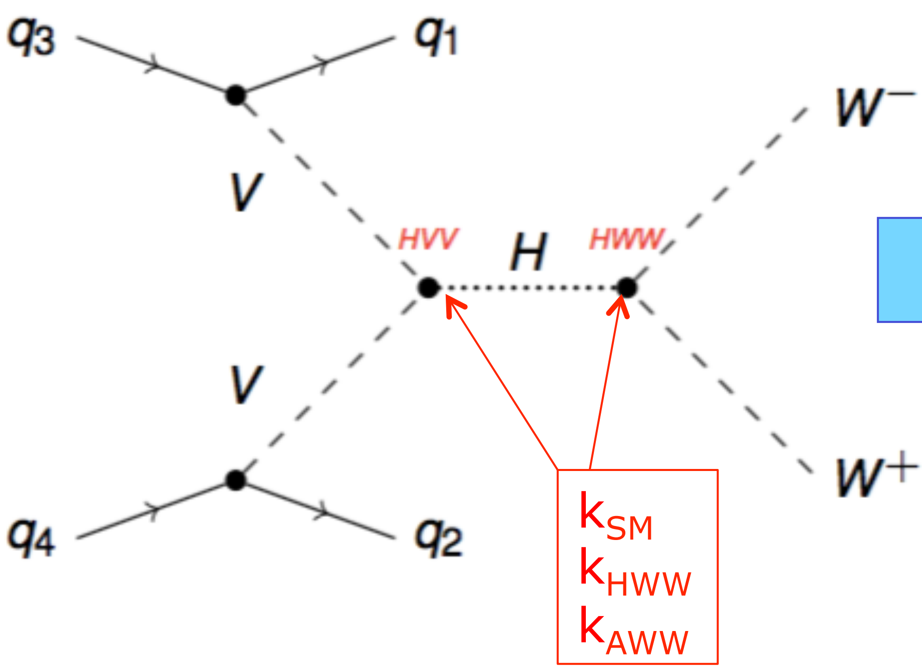
$$N = \frac{n_p\left(n_p+1\right)}{2} \cdot \frac{n_d\left(n_d+1\right)}{2} + \binom{4+n_s-1}{4} + \left(n_p \cdot n_s + \frac{n_s\left(n_s+1\right)}{2}\right) \cdot \frac{n_d\left(n_d+1\right)}{2}$$

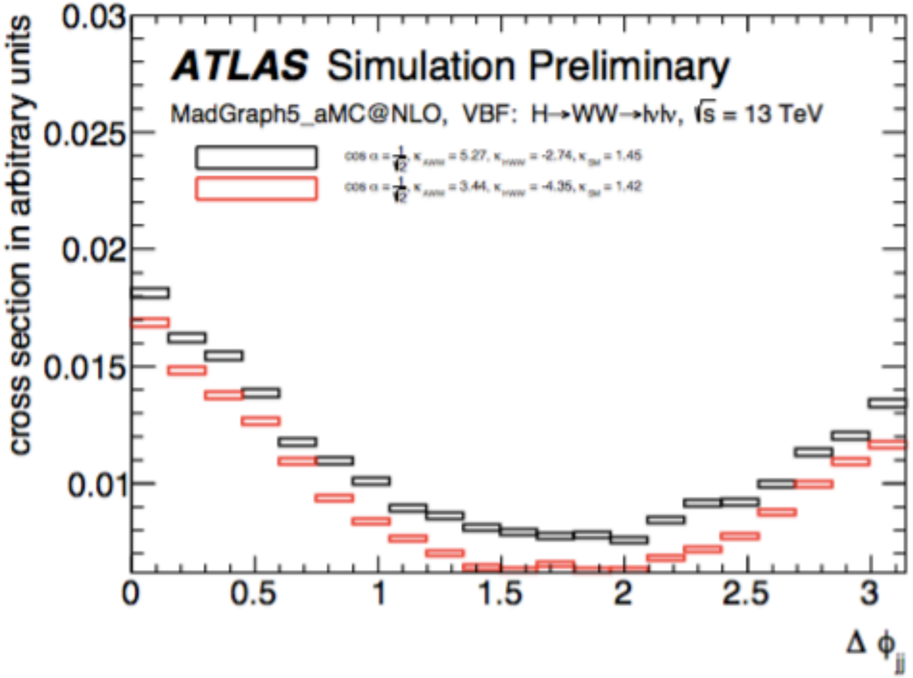
$$+ \left(n_d \cdot n_s + \frac{n_s\left(n_s+1\right)}{2}\right) \cdot \frac{n_p\left(n_p+1\right)}{2} + \frac{n_s\left(n_s+1\right)}{2} \cdot n_p \cdot n_d + \left(n_p+n_d\right)\binom{3+n_s-1}{3}.$$

Process	n_p	n_d	n_s	N
ggF $H \to ZZ^* \to 4\ell$ truth	1	2	0	3
VBF $H \to WW^* \to e\nu\mu\nu$ truth	0	0	3	15
ggF $H \to ZZ^* \to 4\ell$ reconstructed	1	3	0	6
VBF $H \to \mu\mu$ truth	13	1	0	91

n_p = #params in prod only
n_d = #params in decay only
n_s = #params in prod&decay

A concrete example VBH → H → WW





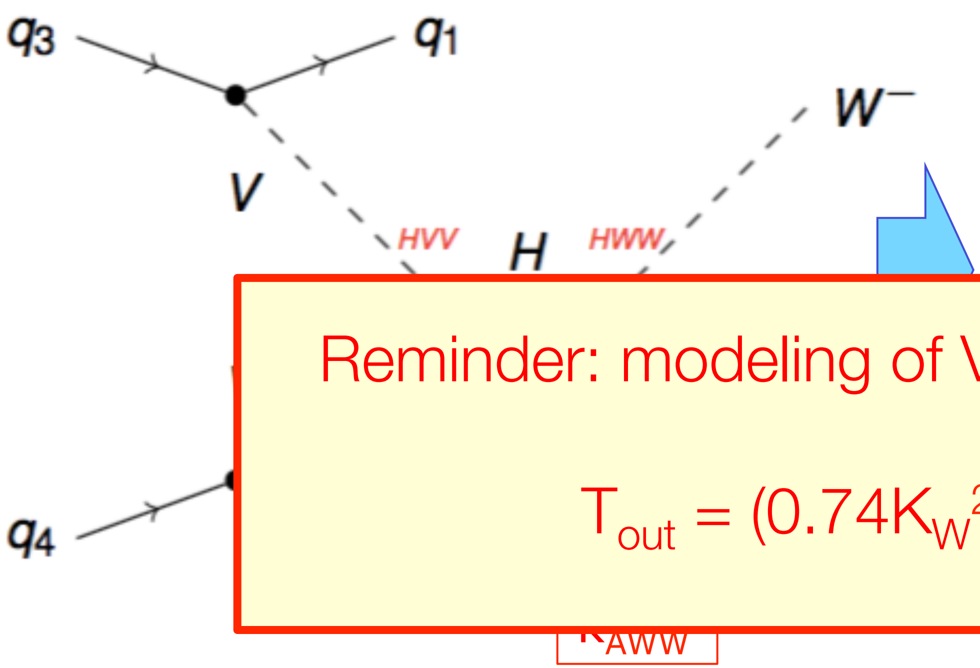
3 shared parameters
→ 15 terms in $|M|^2$ expression
→ 15 input distributions needed

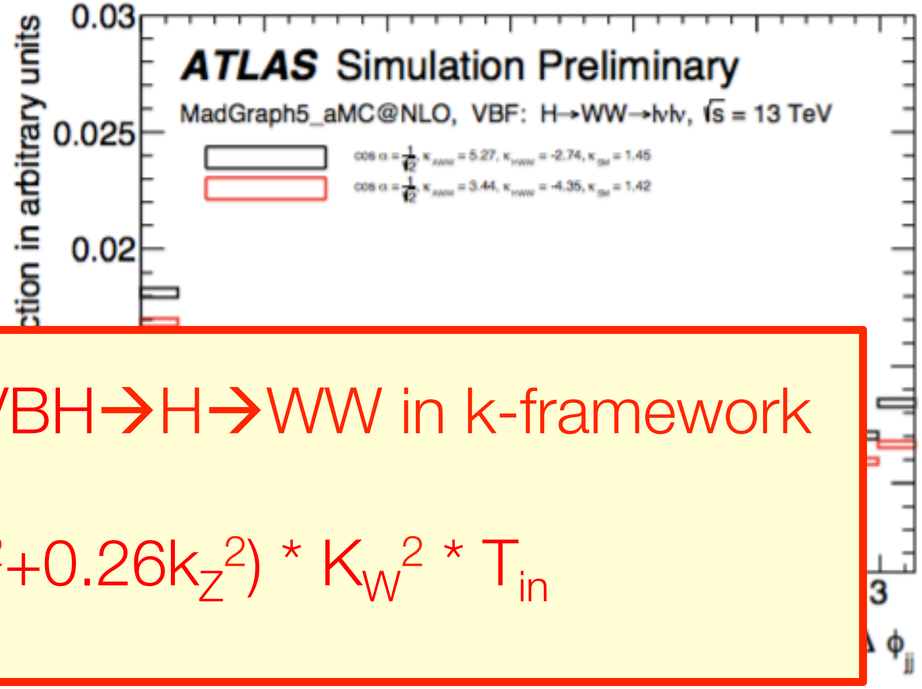
$$T_{out}(k_{SM},k_{HWW},k_{AWW}) = \sum w_i(k_{SM},k_{HWW},k_{AWW}) * T_{in,i}$$

Template weights (polynomials in k_j)

Template histograms

A concrete example VBH → H → WW





Reminder: modeling of VBH→H→WW in k-framework

$$T_{out} = (0.74K_W^2+0.26k_Z^2) * K_W^2 * T_{in}$$

3 shared parameters
→ 15 terms in $|M|^2$ expression
→ 15 input distributions needed

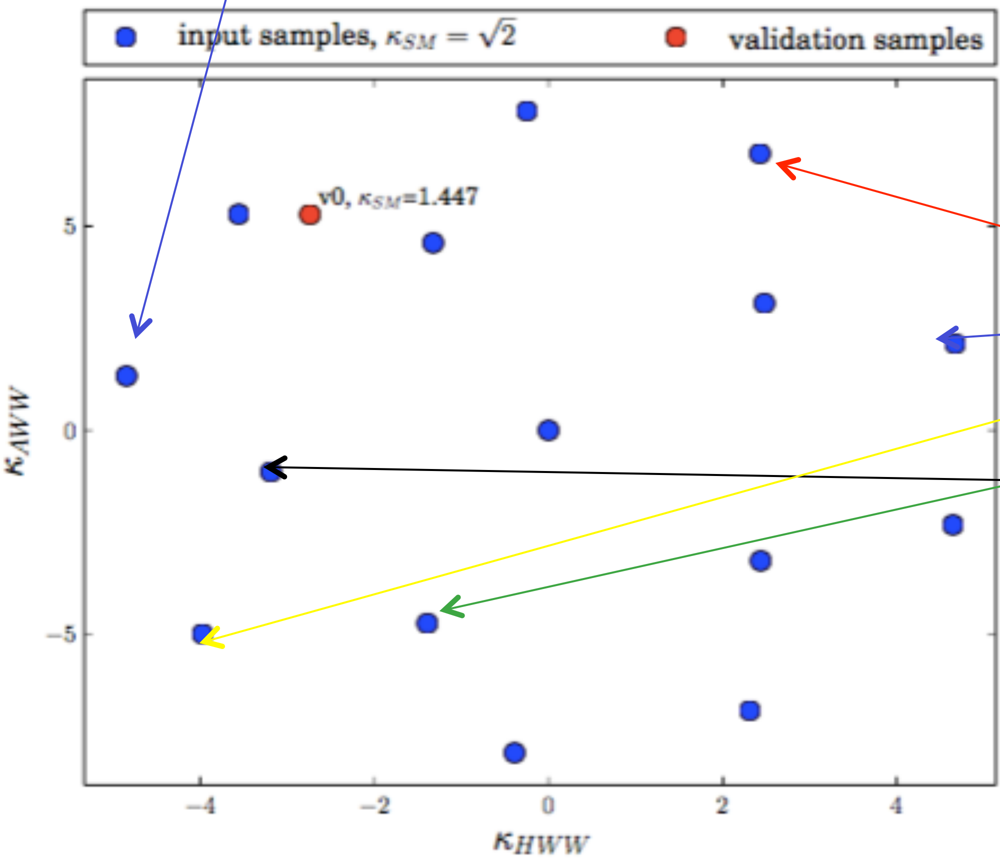
$$T_{out}(k_{SM},k_{HWW},k_{AWW}) = \Sigma\, w_i(k_{SM},k_{HWW},k_{AWW}) * T_{in,i}$$

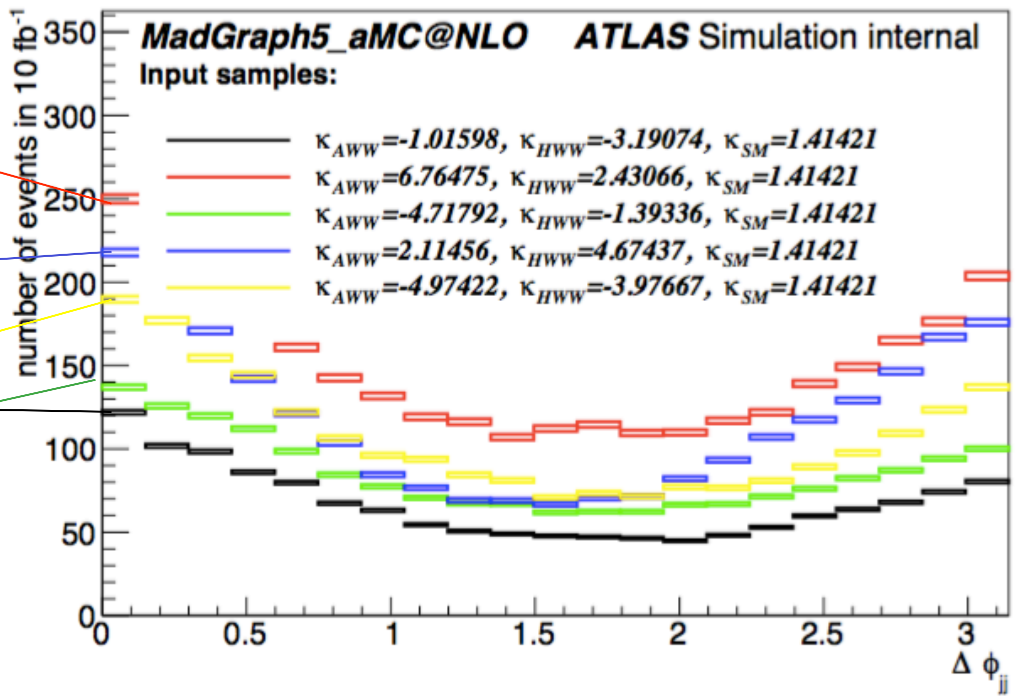
Template weights (polynomials in k_j)

Template histograms

Truth-level validation study on simulation samples

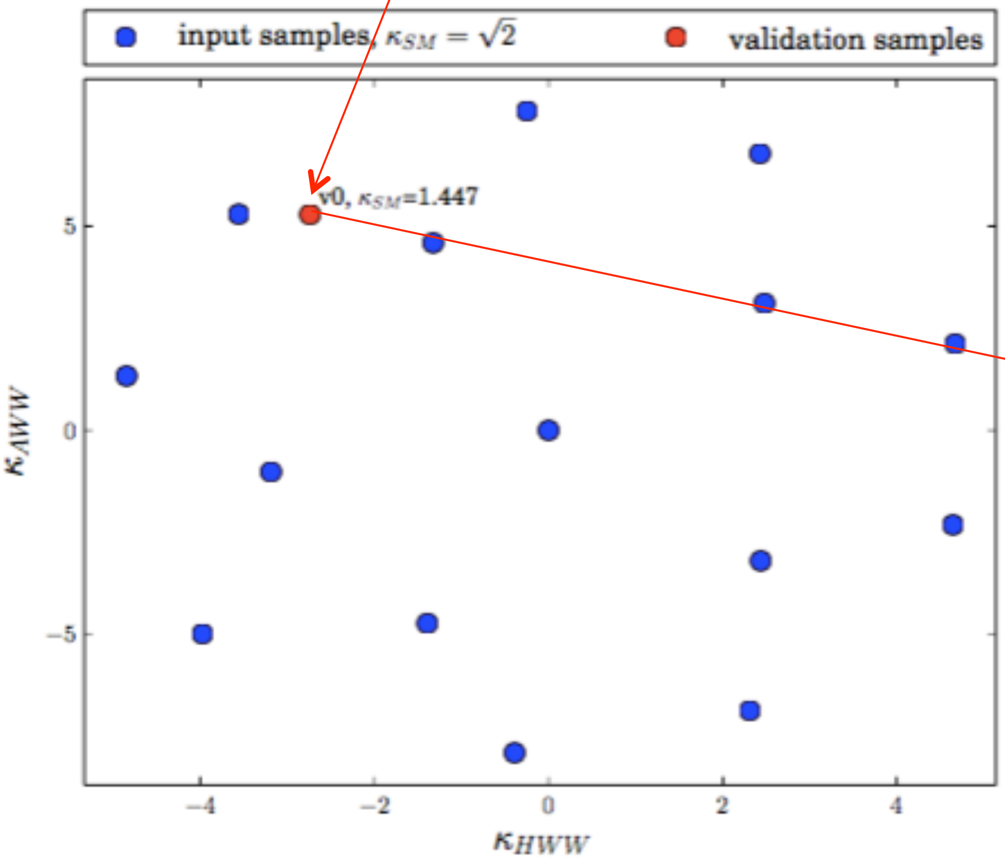
- Procedure
  - VBF H→WW process with **SM** (gSM) and **2 BSM** operators (gHWW, gAWW)
    50k events generated. Kinematic observable used: $\Delta\phi_{jj}$, **Only signal considered**
  - 15 samples with different parameter settings used to construct EFT morphing model

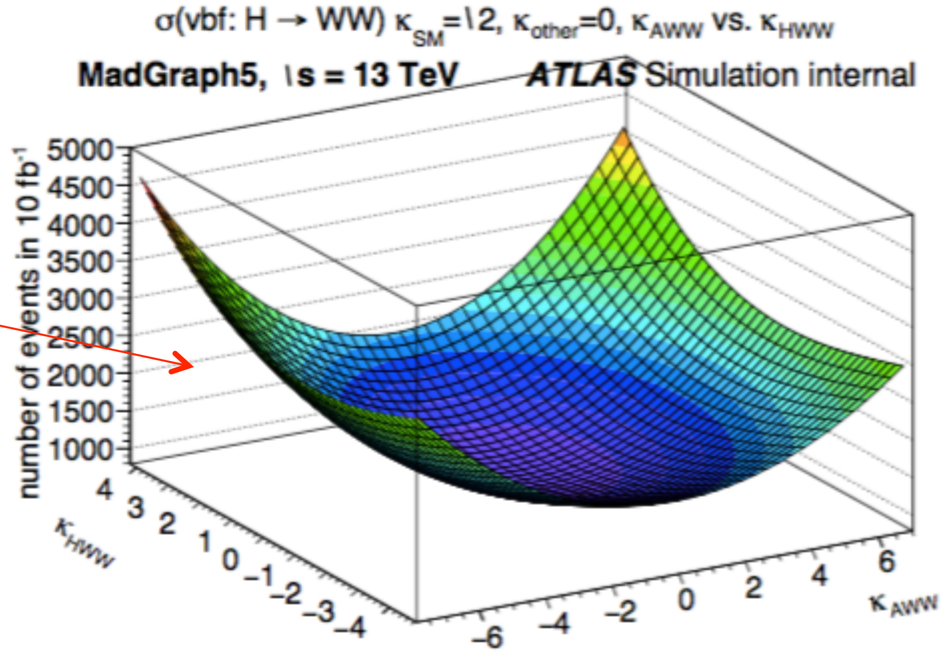




Truth-level validation study on simulation samples

- Procedure
  - VBF H→WW process with **SM** (*g*SM) and **2 BSM** operators (*g*HWW, *g*AWW)
    50k events generated. Kinematic observable used: $\Delta\phi jj$, **Only signal considered**
  - 15 samples with different parameter settings used to construct EFT morphing model
  - Validation sample is fitted to morphing model





A more ambitious example: VBF vertex using full HCF

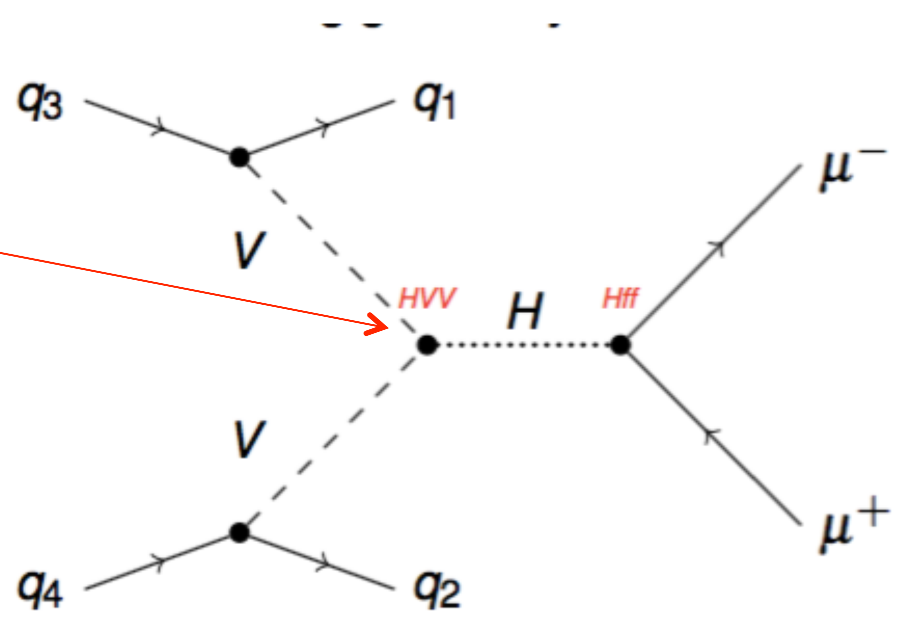
- Implement complete VBF vertex of Higgs Characterization Lagrangian

$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{SM}\left[\frac{1}{2}\tilde{g}_{HZZ} Z_\mu Z^\mu + \tilde{g}_{HWW} W^+_\mu W^{-\mu}\right] \\
& -\frac{1}{4}\left[c_\alpha \kappa_{H\gamma\gamma}\tilde{g}_{H\gamma\gamma} A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma}\tilde{g}_{A\gamma\gamma} A_{\mu\nu}\tilde{A}^{\mu\nu}\right] \\
& -\frac{1}{2}\left[c_\alpha \kappa_{HZ\gamma}\tilde{g}_{HZ\gamma} Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma}\tilde{g}_{AZ\gamma} Z_{\mu\nu}\tilde{A}^{\mu\nu}\right] \\
& -\frac{1}{4}\left[c_\alpha \kappa_{Hgg}\tilde{g}_{Hgg} G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg}\tilde{g}_{Agg} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right] \\
& -\frac{1}{4}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ} Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\
& -\frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HWW} W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right] \\
& -\frac{1}{\Lambda} c_\alpha\left[\kappa_{H\partial\gamma} Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z} Z_\nu \partial_\mu Z^{\mu\nu} + \kappa_{H\partial W}\left(W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\right)\right]\Big\} X_0
\end{aligned}
$$

Used in Run 1

Plan Run 2

κ_{SM}
$\kappa_{H\gamma\gamma}$
$\kappa_{A\gamma\gamma}$
$\kappa_{HZ\gamma}$
$\kappa_{AZ\gamma}$
κ_{HZZ}
κ_{AZZ}
κ_{HWW}
κ_{AWW}
$\kappa_{H\partial WR}$
$\kappa_{H\partial WI}$
$\kappa_{H\partial A}$
$\kappa_{H\partial Z}$



- 13 parameters → 91 terms in $|M|^2$ → 91 input distributions needed

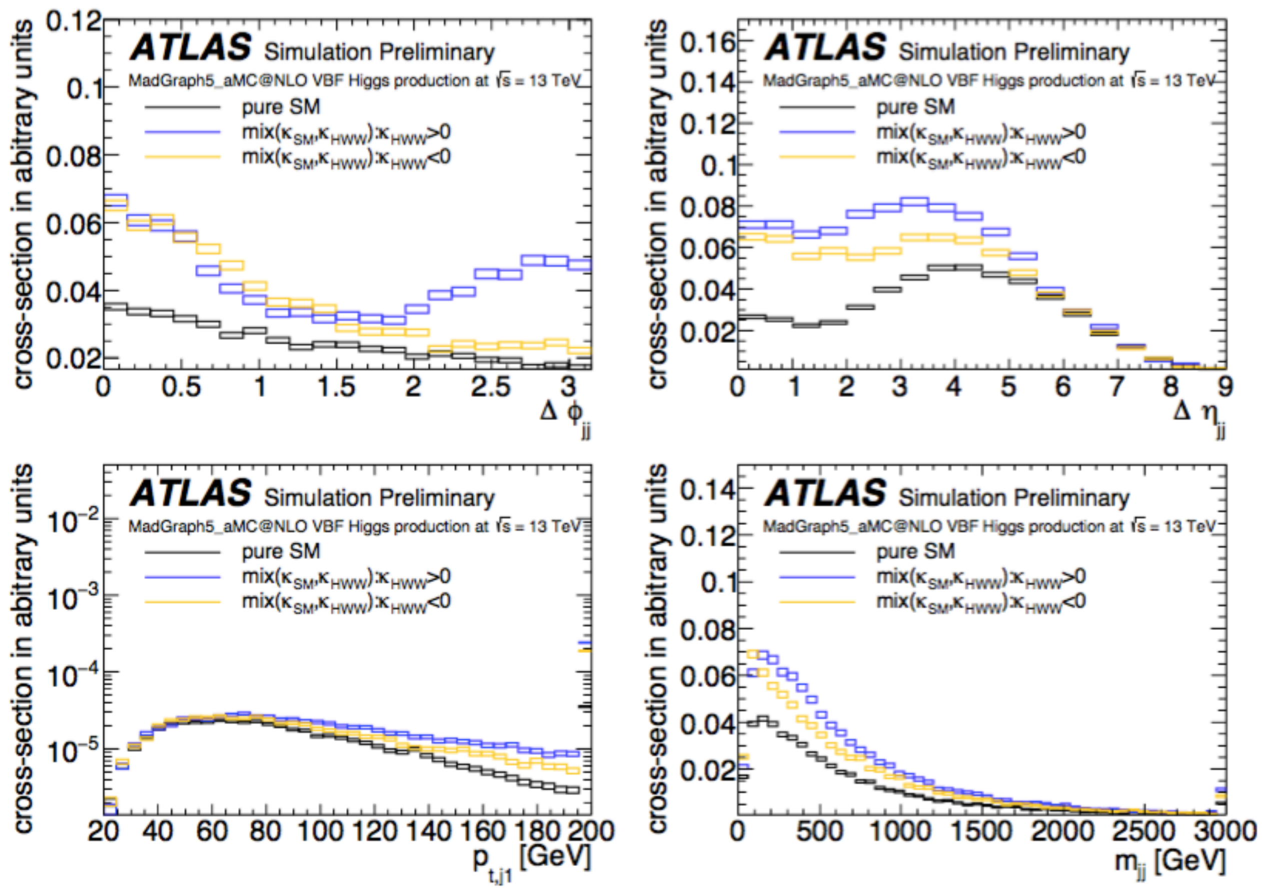
$$T_{out}(k_{SM},k_{HWW},k_{AWW}) = \Sigma\, w_i(k_{SM},k_{HWW},k_{AWW}) * T_{in,i}$$

Generator level, signal only samples used with 30k events each Setup **fit to SM input sample.** Observables: $\Delta\phi_{jj}$, p_T^{j1} , m_{jj} , $\Delta\eta_{jj}$

A more ambitious example: VBF vertex using full HCF

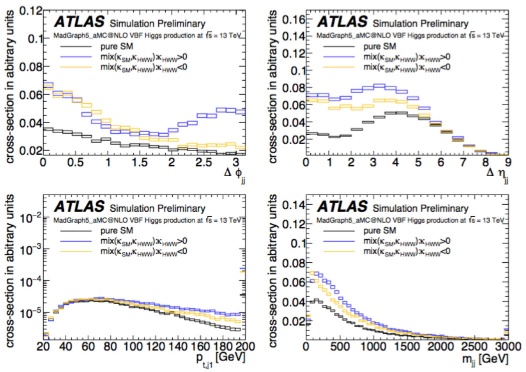
- Example of shape changes in distributions due to k_{HWW}

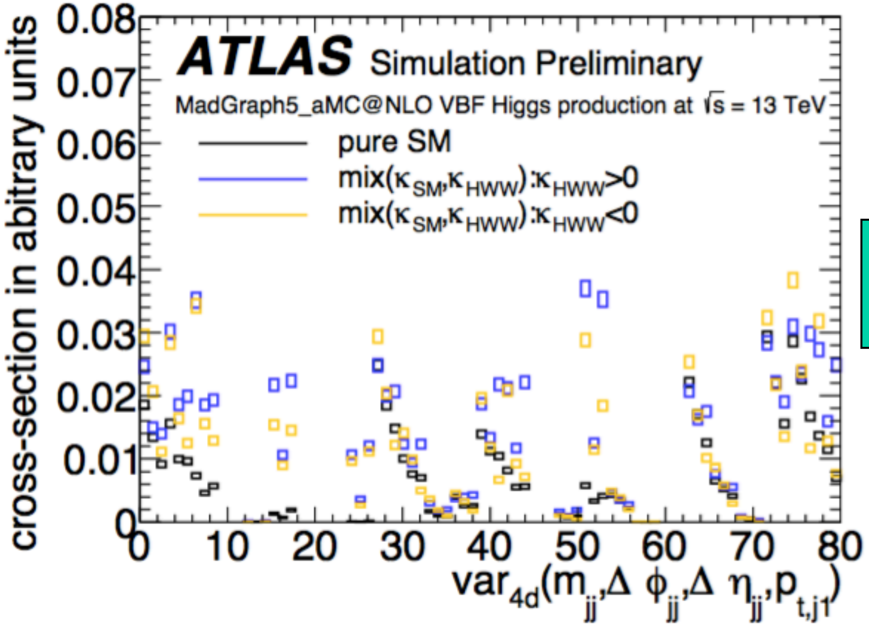
κ_{SM}
$\kappa_{H\gamma\gamma}$
$\kappa_{A\gamma\gamma}$
$\kappa_{HZ\gamma}$
$\kappa_{AZ\gamma}$
κ_{HZZ}
κ_{AZZ}
$\boxed{\kappa_{HWW}}$
κ_{AWW}
$\kappa_{H\partial WR}$
$\kappa_{H\partial WI}$
$\kappa_{H\partial A}$
$\kappa_{H\partial Z}$



Sensivity to 13 parameters of VBF vertex

- Construct simple binned likelihood to combine information of the 4 observables





Fit to pseudo-data sample with 8% cross-section uncertainty

parameter	post-fit value	+	−
Λ	1000.		
$\cos\alpha$	0.71		
$\kappa_{H\ell\ell}$	1.41		
$\kappa_{A\gamma\gamma}$	0	+219	−441
κ_{Aww}	0	+3	−2.6
$\kappa_{Az\gamma}$	0	+441	−398
κ_{Azz}	0	+2.7	−1.3
$\kappa_{H\gamma\gamma}$	0	+236	−91
$\kappa_{H\partial\gamma}$	0	+0.3	−0.6
$\kappa_{H\partial wI}$	0	+1.6	−0
$\kappa_{H\partial wR}$	0	+0.5	−0.3
$\kappa_{H\partial z}$	0	+1.2	−0.5
κ_{Hww}	0	+1.5	−3
$\kappa_{Hz\gamma}$	0	+38	−49
κ_{Hzz}	0	+8	−2.5
κ_{SM}	1.41	+0.22	−0.11

Outlook on Higgs signal models

- EFT-style signal models clearly appealing as future signal models
- First studies performed to show feasibility of implementing such models with many more parameters and implementation of differential signal distributions that depend on EFT parameters.
- But still quite some way to full reconstruction-level implementation and measurement
- In parallel several ideas around to stage progress in intermediate steps
  - 'Simplified cross-sections' break current signal strength measurements in various bins of observables → gives some effective flexibility in modeling shape changes in these distribution without explicit morphing algorithms. Much easier to implement on short term since procedurally very close to k-framework
  - 'Pseudo-observables' aim to break strong dependence of experimental result on parameters of specific theory. E.g. if measurement reports a fiducial cross-section instead of inclusive signal strength → much easier to interpret σ_{fid} in second analysis step in terms of (EFT) theory parameters.
- A lot of work is in progress here!