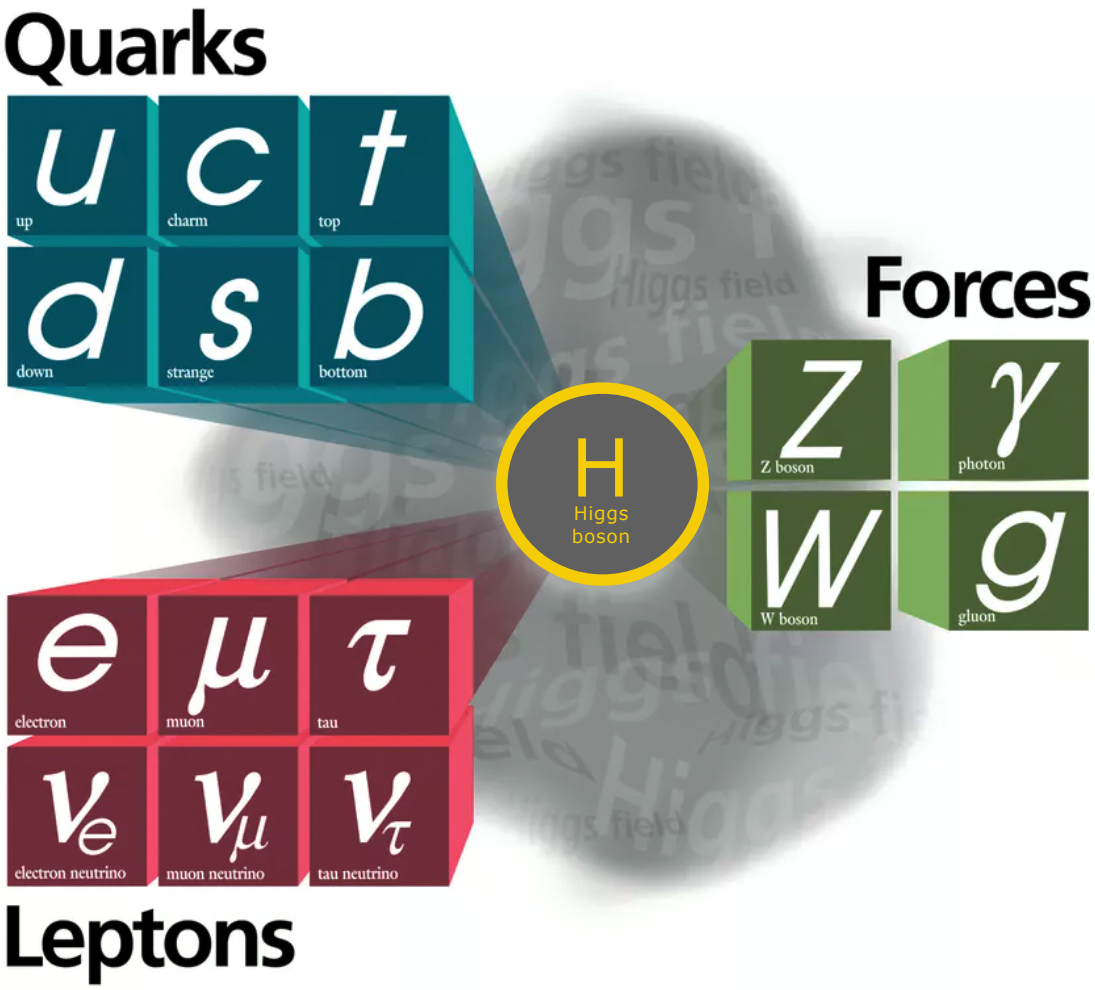
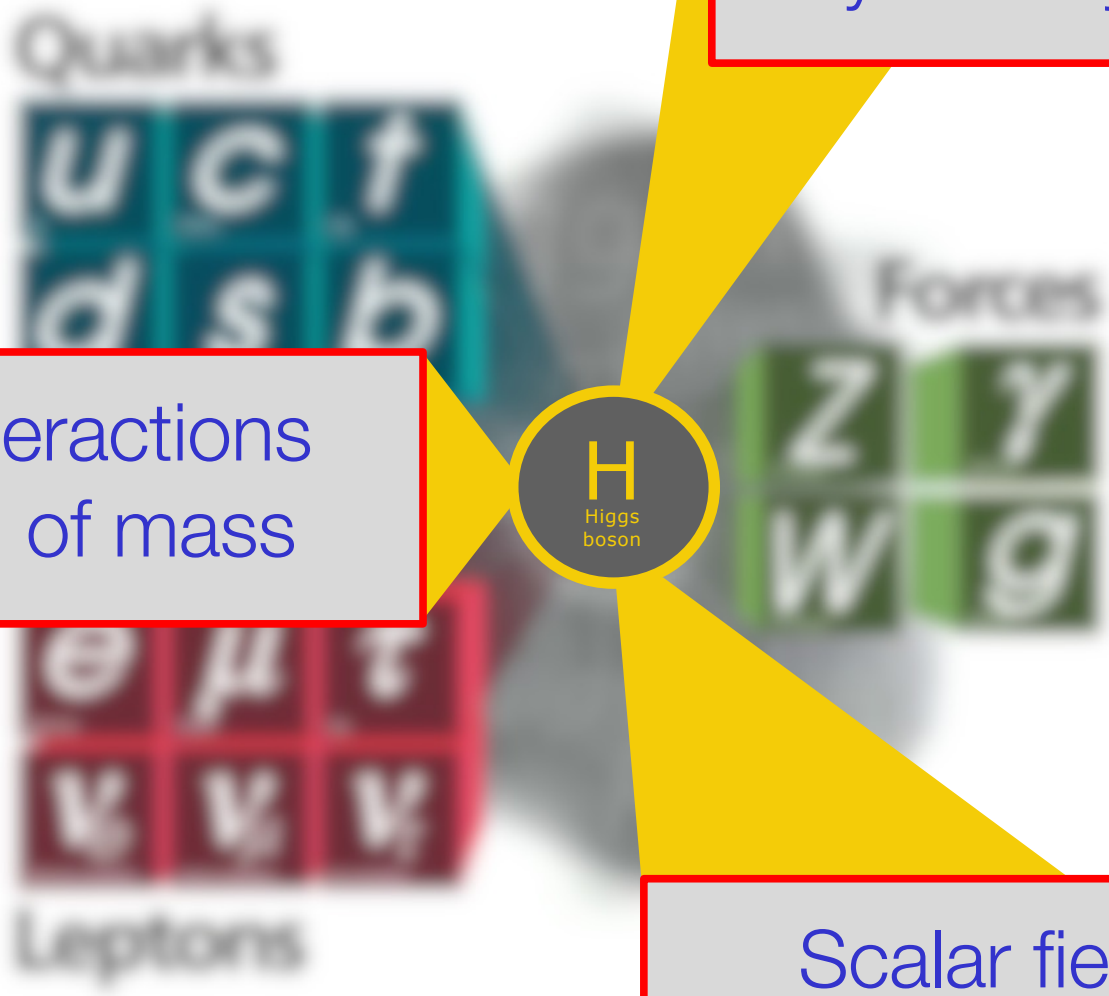
Measuring Higgs properties from combined Higgs data now and in the future

W. Verkerke (Nikhef)

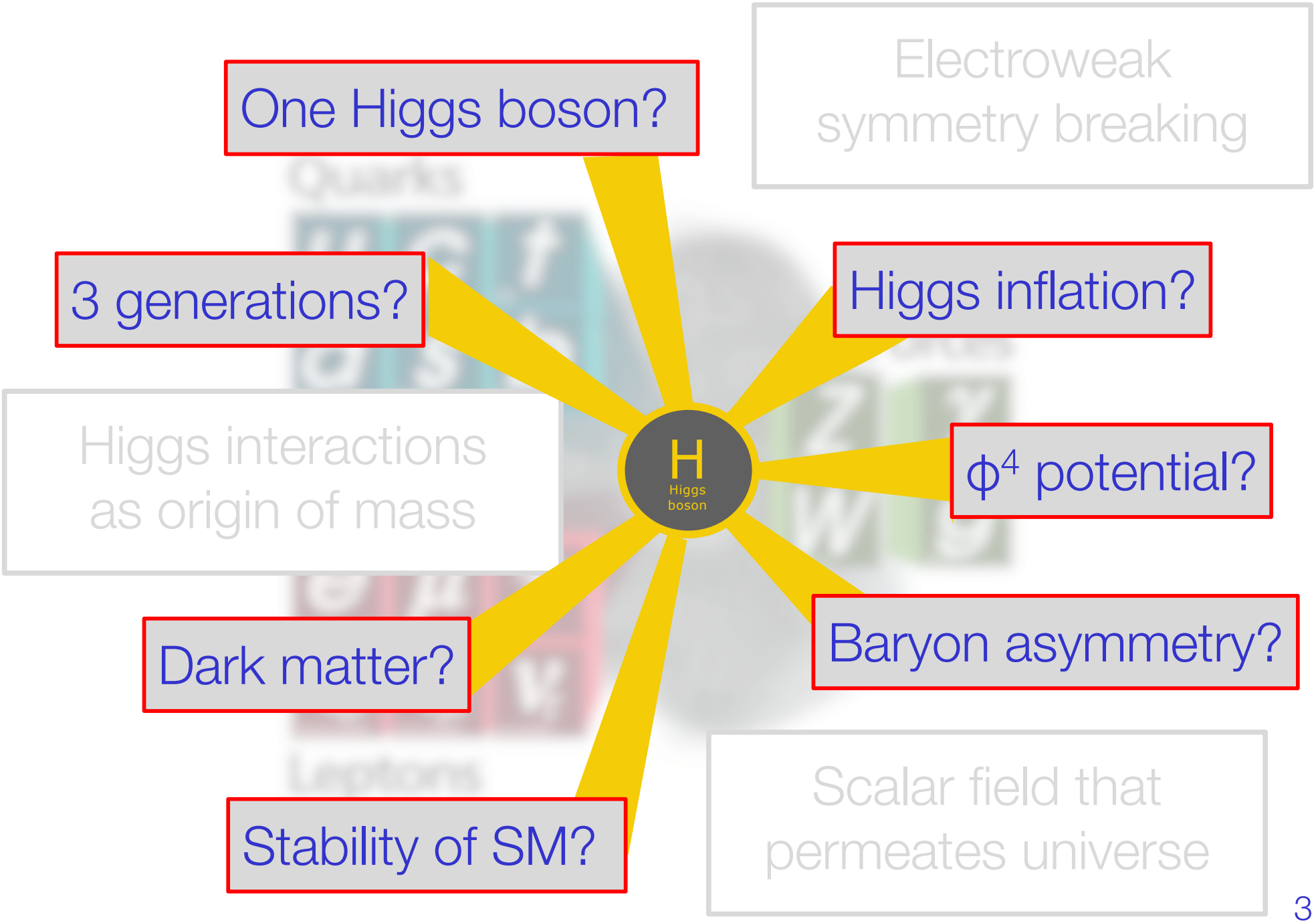

Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs
boson
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons

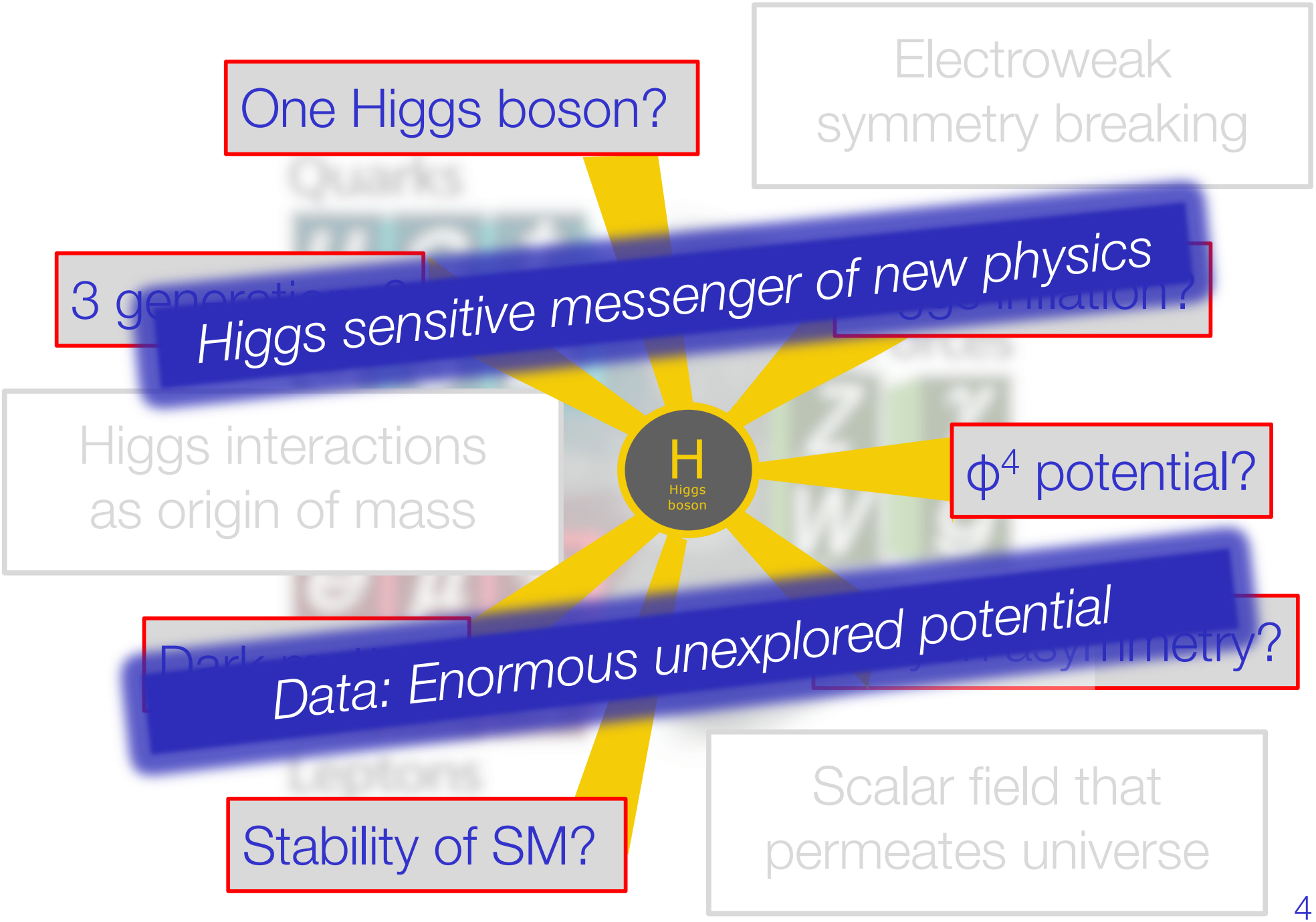


Electroweak symmetry breaking

Higgs interactions as origin of mass

Scalar field that permeates universe

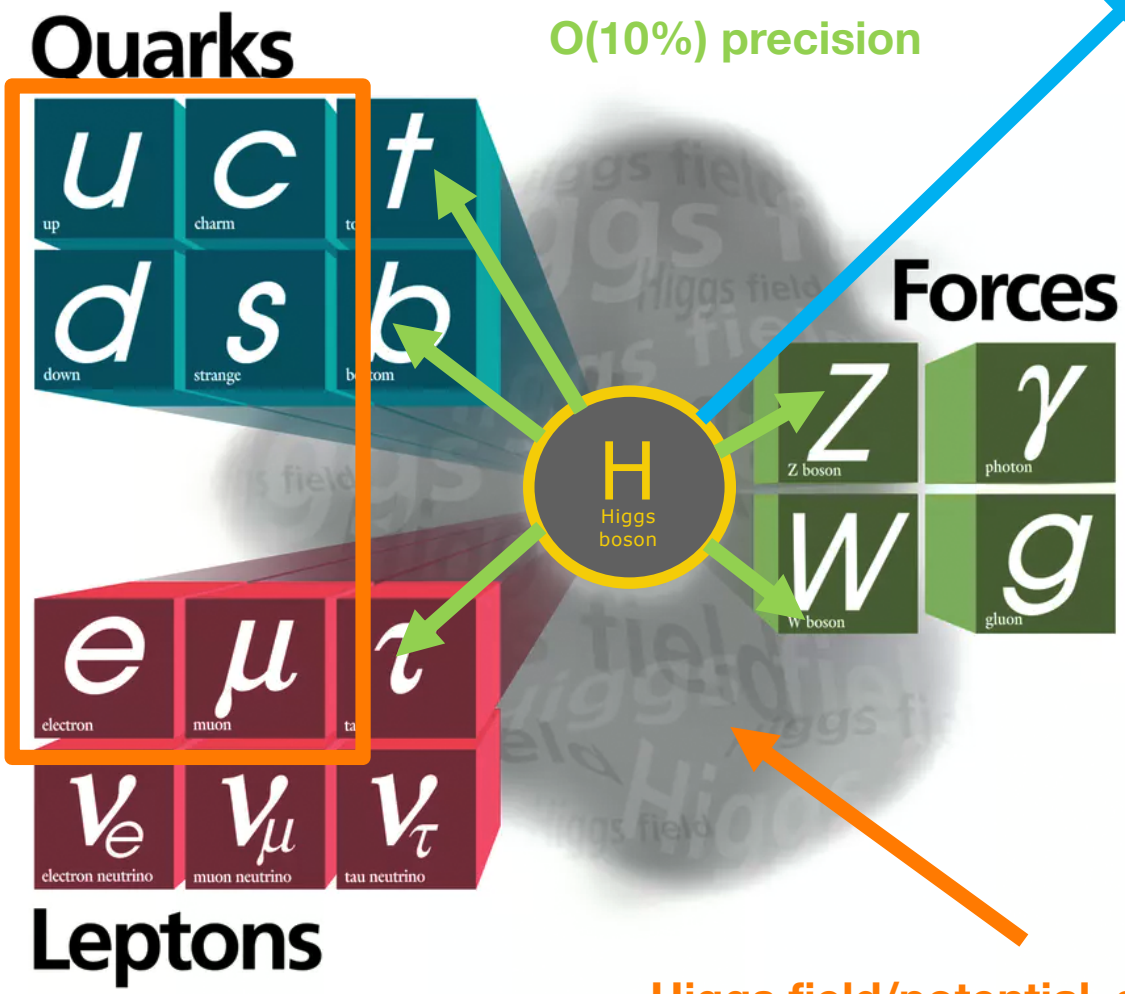

One Higgs boson?
Electroweak symmetry breaking
3 generations?
Higgs inflation?
Higgs interactions as origin of mass
H
Higgs boson
ϕ^4 potential?
Dark matter?
Baryon asymmetry?
Stability of SM?
Scalar field that permeates universe


One Higgs boson?
Electroweak symmetry breaking
Higgs sensitive messenger of new physics
Higgs interactions as origin of mass
H
Higgs boson
ϕ^4 potential?
Data: Enormous unexplored potential
Stability of SM?
Scalar field that permeates universe

Higgs couplings to 3rd gen fermions and W/Z bosons O(10%) precision

Higgs decays to non-SM particles O(30%) [UNPROVEN]

Yukawa couplings to 1st and 2nd generation? [UNPROVEN]

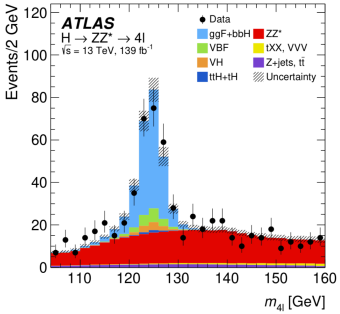


Higgs field/potential, self-couplings? [UNPROVEN]

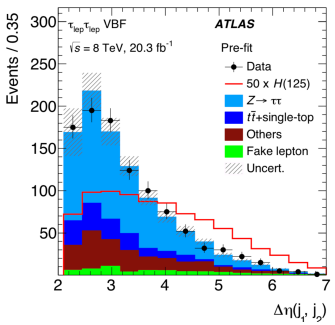
From Higgs measurements to Higgs properties to new Physics

O(100) Measurements

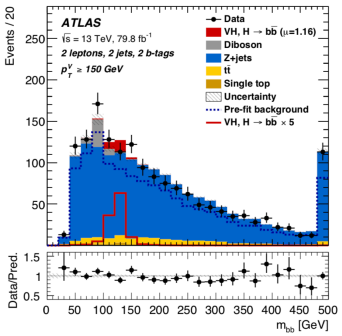
ggF → H → ZZ



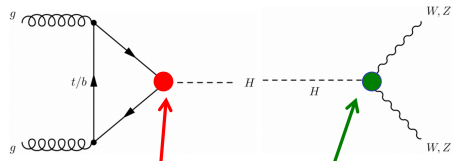
VBF → H → ττ



VH → H → bb

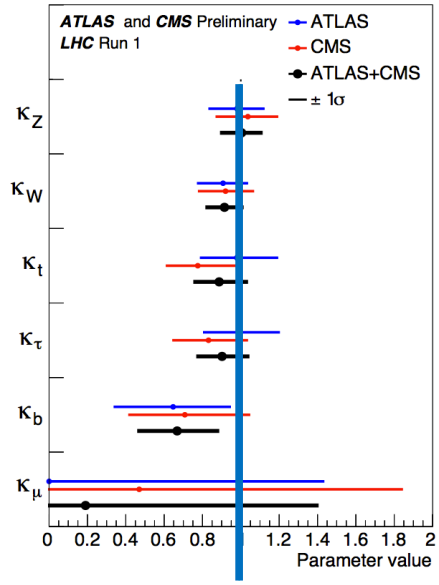


Parametric model to quantify deviations from SM



$\Gamma_{W,Z} = \kappa^2_{W,Z}\,\Gamma_{W,Z}(SM)$

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



SM expectation

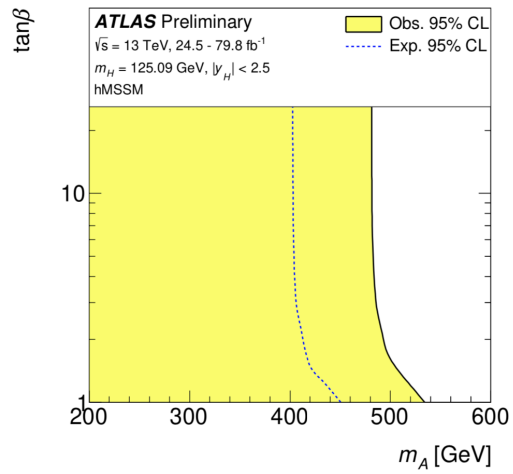
New Physics finger printing

MSSM-like theory

$$\kappa_V = \frac{s_d(m_A,\tan\beta)+\tan\beta\; s_u(m_A,\tan\beta)}{\sqrt{1+\tan^2\beta}}$$

$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

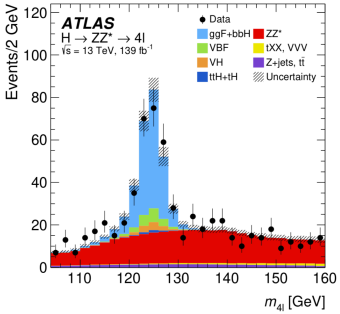
$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta}\quad ,$$



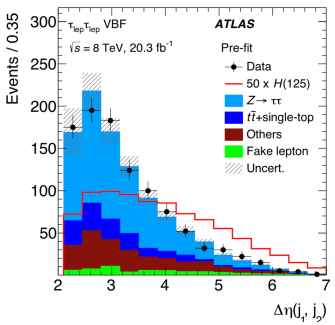
Limiting factors in current approach

O(100) Measurements

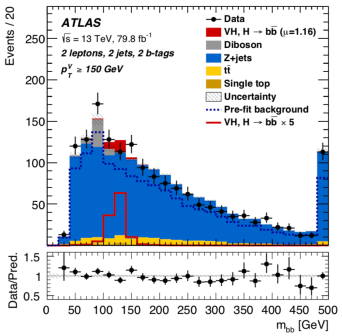
ggF → H → ZZ



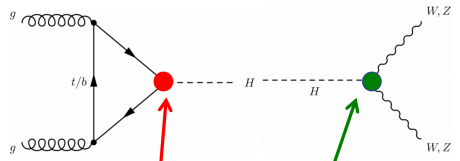
VBF → H → ττ



VH → H → bb



Parametric model to quantify deviations from SM



$\Gamma_{W,Z} = \kappa^2_{W,Z}\,\Gamma_{W,Z}(SM)$

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

Want 'sheep with 5 legs'

- Be able to describe *all* observed data
- Make *no* assumptions about specific features of new physics
- Valid physics model (does not violate known symmetries etc…)

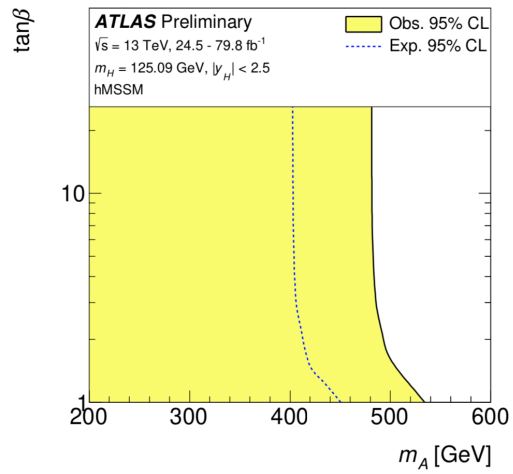
New Physics finger printing

MSSM-like theory

$$\kappa_V = \frac{s_d(m_A,\tan\beta)+\tan\beta\; s_u(m_A,\tan\beta)}{\sqrt{1+\tan^2\beta}}$$

$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

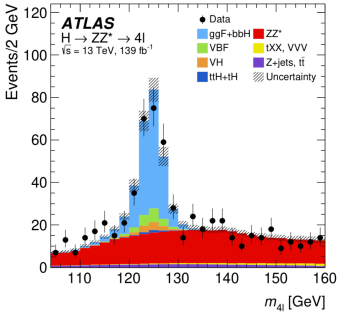
$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta}\quad ,$$



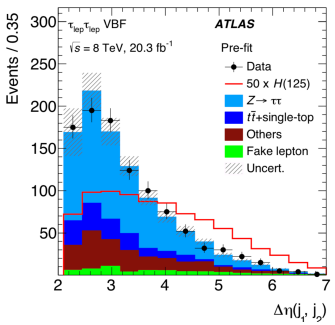
Limiting factors in current approach

O(100) Measurements

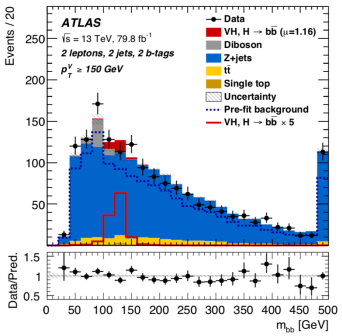
ggF → H → ZZ



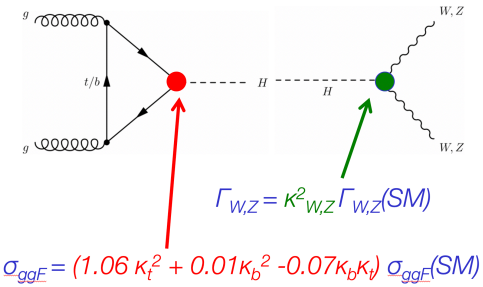
VBF → H → ττ



VH → H → bb



κ-framework to quantify deviations from SM



Have 'sheep with 3 legs'

- Can't model distributions, nor self-couplings
- Make no assumptions about specific features of new physics
- Ad-hoc model that does not respect known physics features

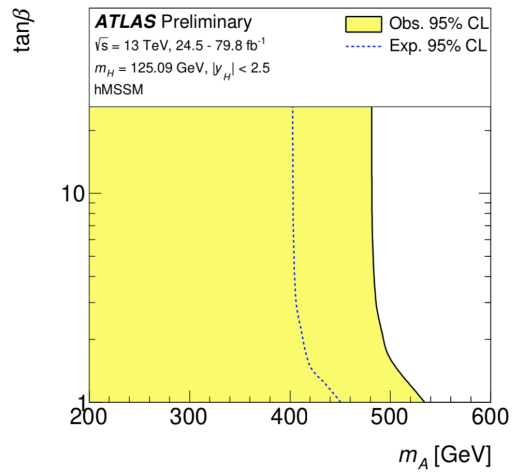
New Physics finger printing

MSSM-like theory

$$\kappa_V = \frac{s_d(m_A,\tan\beta)+\tan\beta\ s_u(m_A,\tan\beta)}{\sqrt{1+\tan^2\beta}}$$

$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

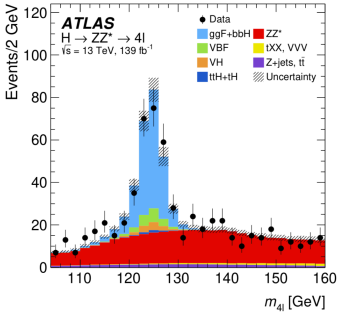
$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta} \quad ,$$



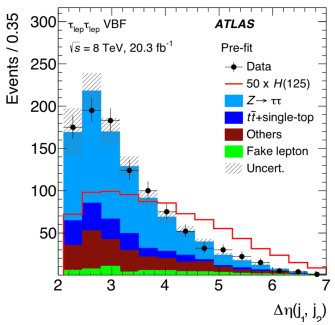
Limiting factors in current approach

O(100) Measurements

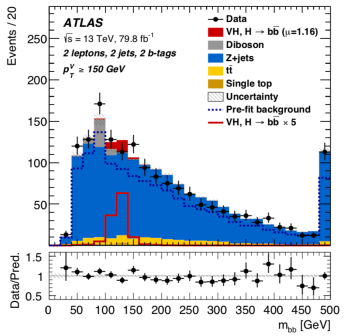
ggF → H → ZZ



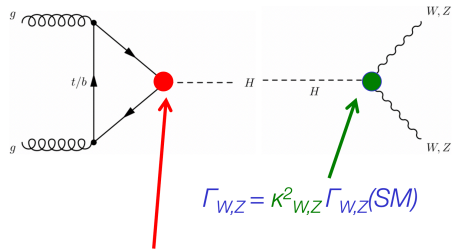
VBF → H → ττ



VH → H → bb



κ-framework to quantify deviations from SM



$\Gamma_{W,Z} = \kappa^2_{W,Z}\,\Gamma_{W,Z}(SM)$

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

Have 'sheep with 3 legs'

- Intuitive Leading Order interpretation
- Driving model for all LHC Run-1/2 coupling measurements
- Theoretical inaccuracies not been very limiting *up to now*

New Physics finger printing

MSSM-like theory

$$\kappa_V = \frac{s_d(m_A,\tan\beta)+\tan\beta\; s_u(m_A,\tan\beta)}{\sqrt{1+\tan^2\beta}}$$

$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

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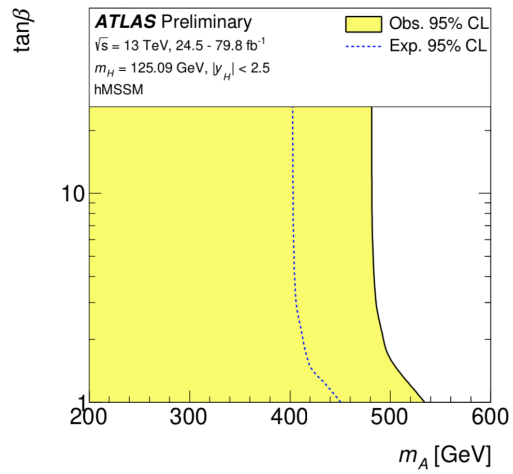


Outline of this presentation

① Introduction

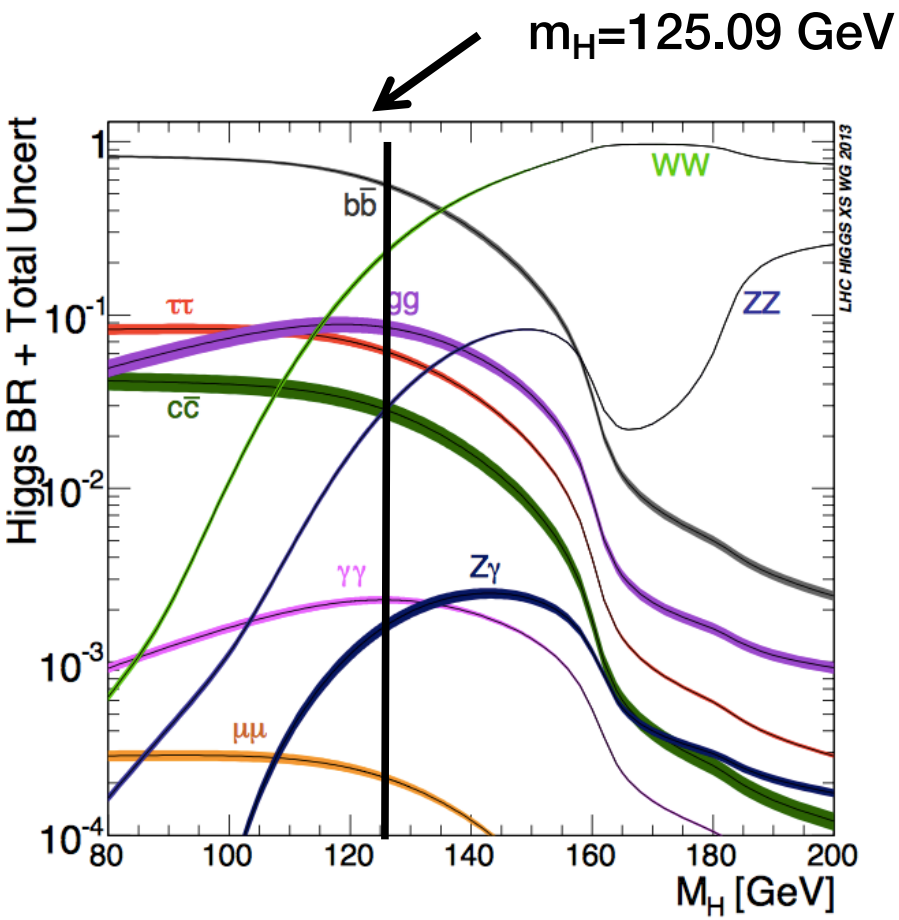
② **Higgs boson phenomenology & the κ-framework interpretation**

③ Combination procedure & experimental inputs

④ Current couplings results from combined measurements

⑤ From rates to distributions, connecting the pieces with SM(EFT)

Standard Model Higgs boson decays



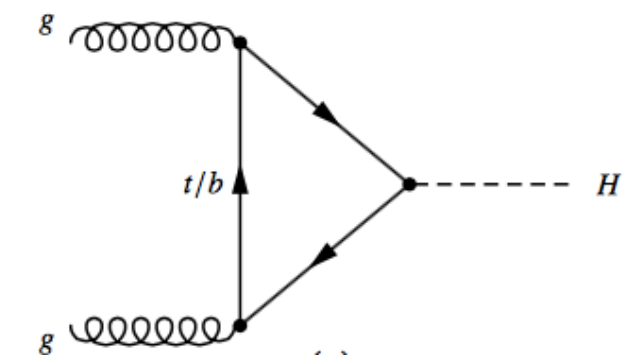
Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

SM BR theory uncertainties
2-5% for most important decays

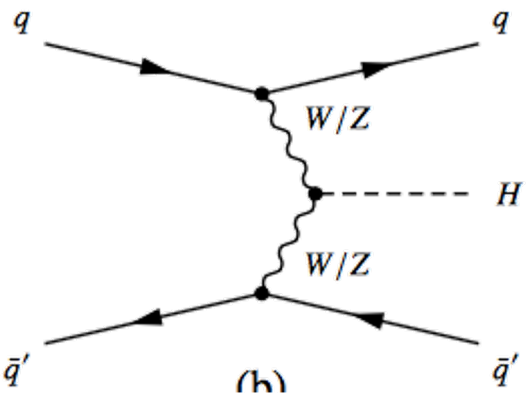
The natural width of the Higgs boson is expected to be very small (<< resolution)

See "Handbook of LHC Higgs Cross Sections: 3. Higgs Properties" (arXiv:1307.1347) for further details on Higgs phenomenology

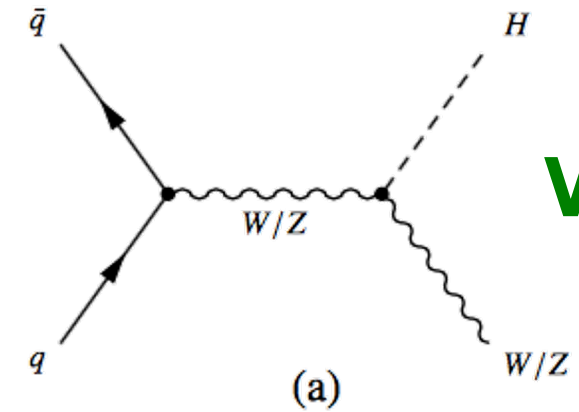
Higgs boson production in the SM



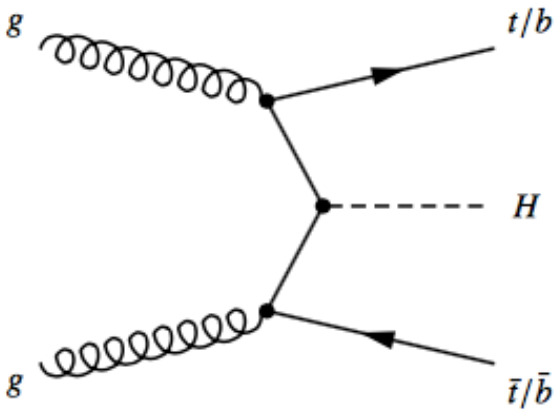
ggF



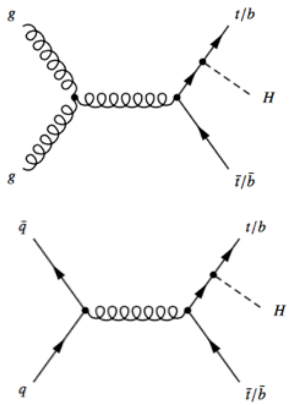
VBF



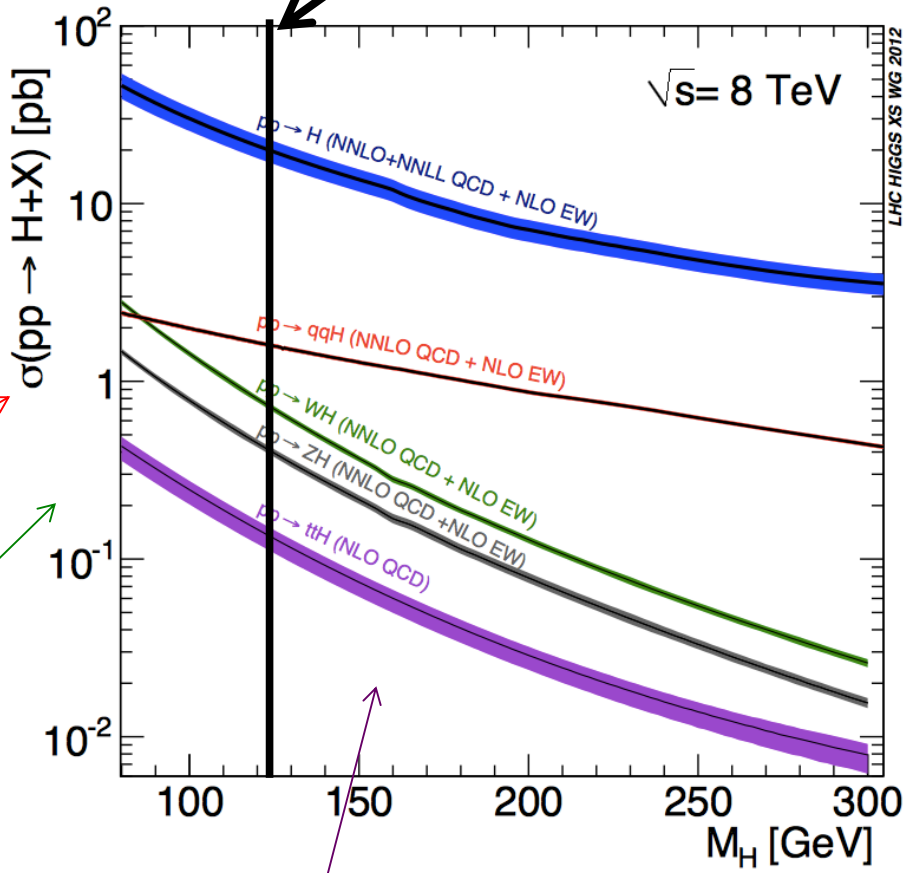
VH



ttH



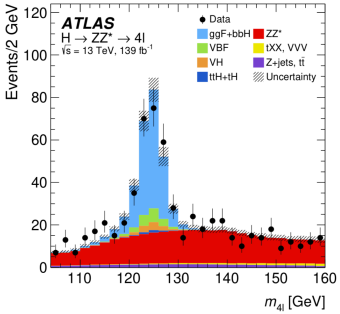
m_H=125.09 GeV

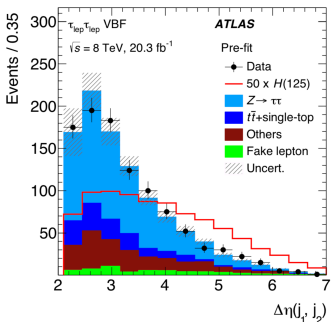


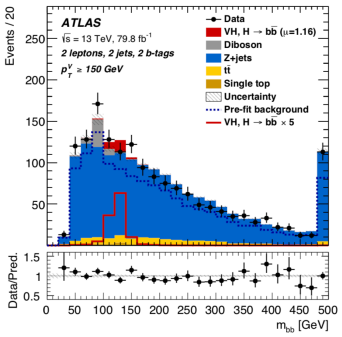
Higgs production and decay – Run 2 measurements

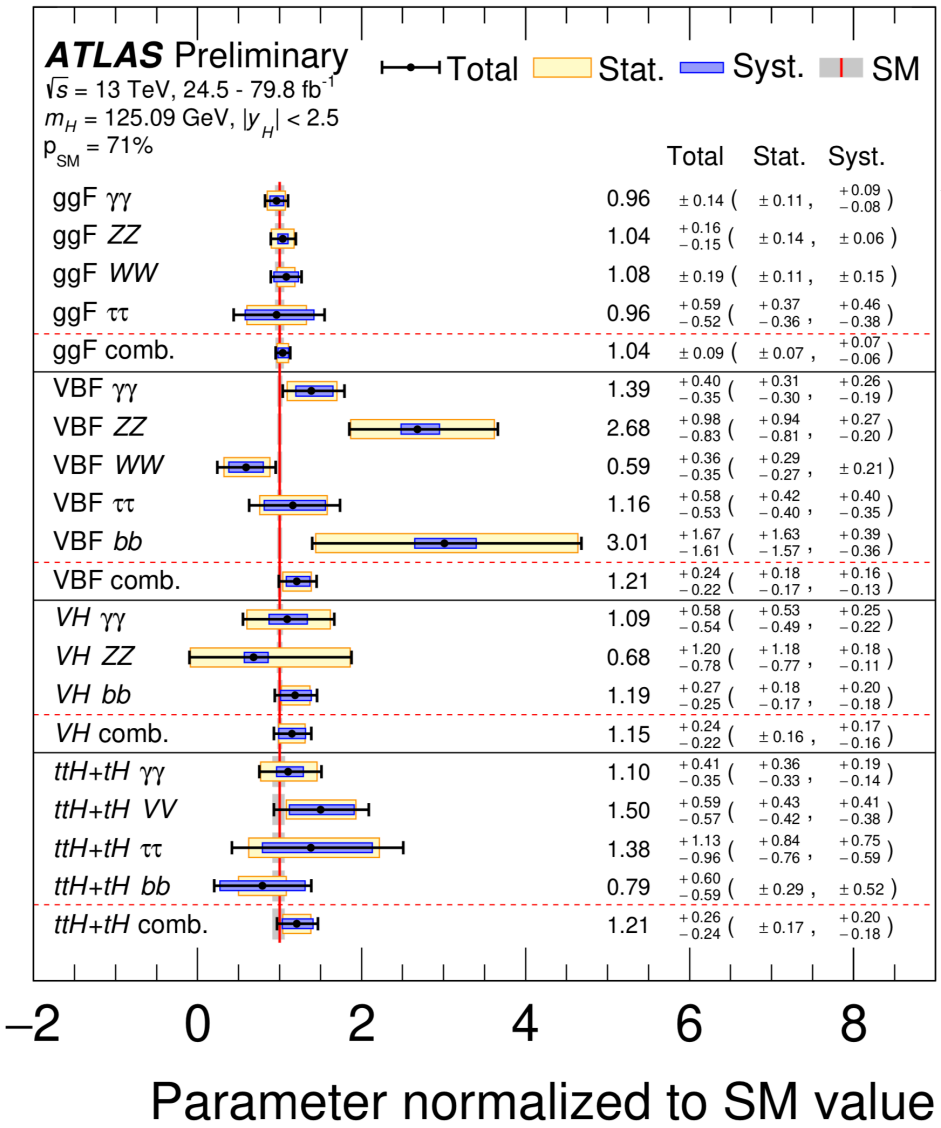
O(100) Measurements

ggF → H → ZZ







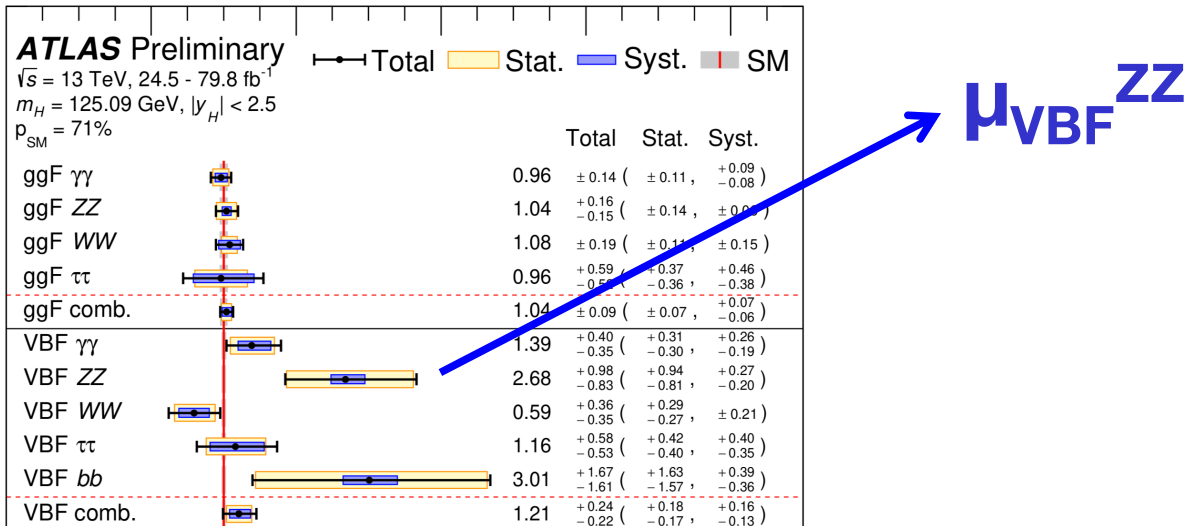


Finer splitting of measurements often available (e.g. + n jets)

Understanding signal strengths for process i → H → f

- Signal strength μ is observed rated normalized by SM prediction

$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$



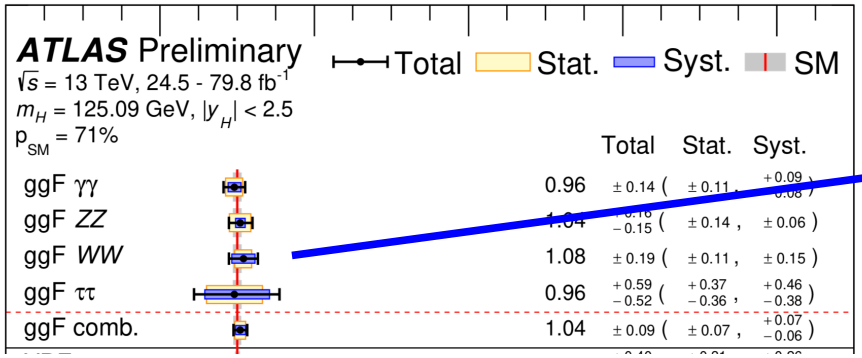
μ_{VBF}^{ZZ}

- Disentangling production (μ_i) & decay (μ_f) always **requires assumption of narrow Higgs width.**

Interpretation beyond signal strengths – **the κ framework**

See "Handbook of LHC Higgs Cross Sections: 3. Higgs Properties" (arXiv:1307.1347) for further details κ framework

- Alternative one can disentangle deviations in production and decay with explicit modeling of Higgs width



μ_{ggF}^{WW}

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

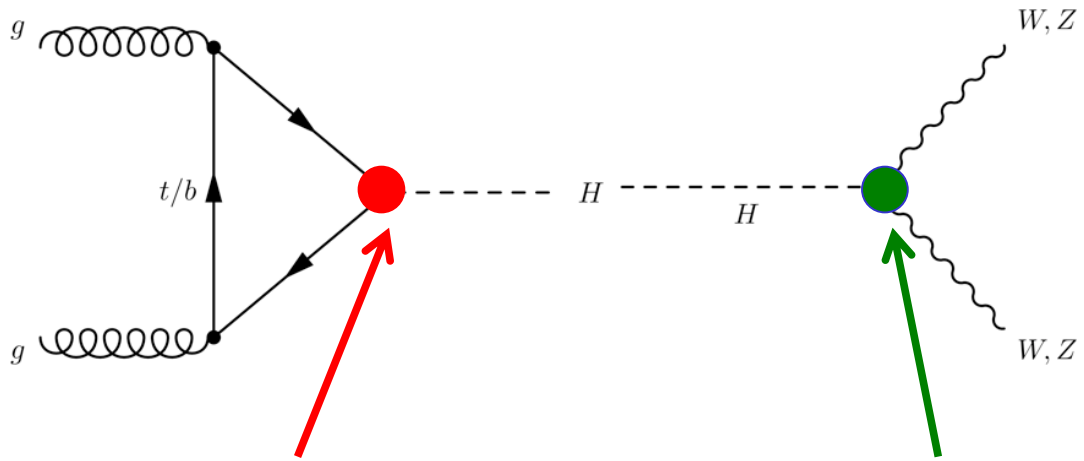
- **Introduce functions κ_j** → describe deviations from SM predictions.

$$\sigma_i = \kappa_i^2(\vec{\kappa}) \cdot \sigma_i^{SM} \qquad \Gamma^f = \kappa_f^2(\vec{\kappa}) \cdot \Gamma^{f,SM}$$

so that for κ_j=1 → σ_i, Γ_f, Γ_H give SM prediction

Interpretation beyond signal strengths – the κ framework

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



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

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

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

The κ framework – the total width

- Note that total *H* width scales all observed cross-sections

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

- Since Γ_H is not yet directly measured with a meaningful precision, must make an assumption on Γ_H to interpret cross-sections in terms of Higgs couplings.

- E.g. in absence of BSM *H* decays (invisible, undetected etc…), can assume SM width, adjusted by effect of k-rescaled couplings

$$\Gamma_H(\vec{\kappa}) = \kappa_H^2(\vec{\kappa}) \cdot \Gamma_H^{\mathrm{SM}}$$

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

The kappa framework – the dictionary

Production	Loops	Interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	$t-b$	κ_g^2	$1.04\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.04\,\kappa_t\kappa_b$
$\sigma(\text{VBF})$	-	-	-	$0.73\,\kappa_W^2 + 0.27\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	$t-Z$	$\kappa_{(ggZH)}$	$2.46\,\kappa_Z^2 + 0.46\,\kappa_t^2 - 1.90\,\kappa_Z\kappa_t$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	$t-W$	-	$2.91\,\kappa_t^2 + 2.31\,\kappa_W^2 - 4.22\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	$t-W$	-	$2.63\,\kappa_t^2 + 3.58\,\kappa_W^2 - 5.21\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	$t-b$	κ_g^2	$1.11\,\kappa_t^2 + 0.01\,\kappa_b^2 - 0.12\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	$t-W$	κ_γ^2	$1.59\,\kappa_W^2 + 0.07\,\kappa_t^2 - 0.67\,\kappa_W\kappa_t$
Total width ($B_{inv} = B_{undet} = 0$)				
Γ_H	✓	-	κ_H^2	$0.58\,\kappa_b^2 + 0.22\,\kappa_W^2$ $+0.08\,\kappa_g^2 + 0.06\,\kappa_\tau^2$ $+0.03\,\kappa_Z^2 + 0.03\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

Factors depend on

- *Assumed value m_H,*
- *Calculations of σ, Γ*
- *Kinematic selections*

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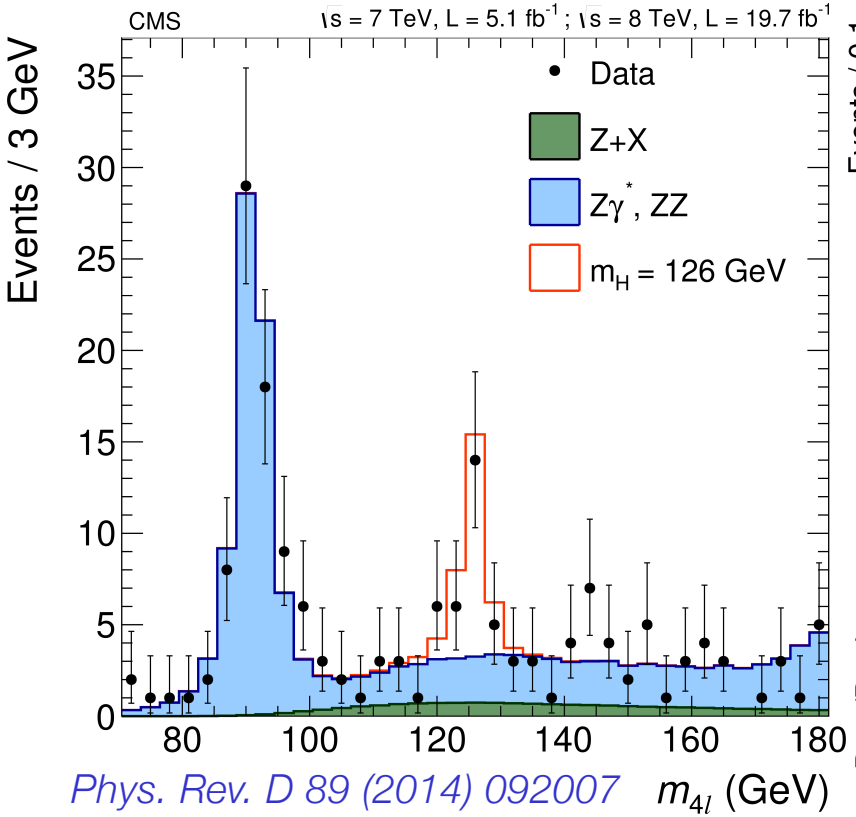
④ Current couplings results from combined measurements

⑤ From rates to distributions, connecting the pieces with SM(EFT)

Anatomy of a single measurement

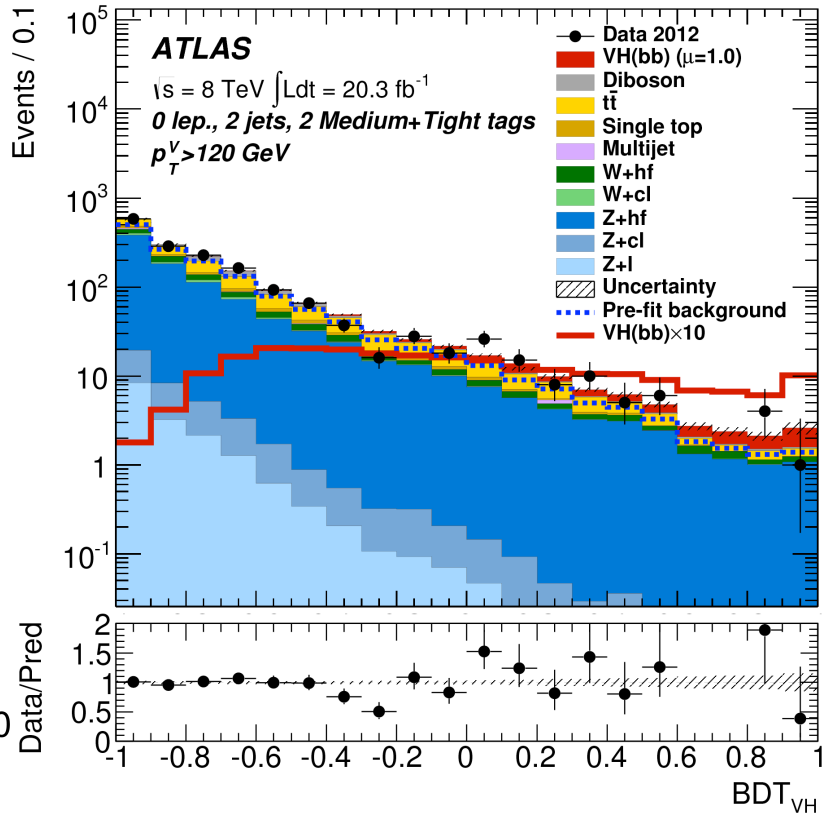
- Every measurement consists of one or more signal regions, designed to selected target Higgs production/decay
- Distribution of a (multivariate) discriminant is interpreted in terms of sum of signal and background contributions

"Low bkg / high mass resol." (H→ZZ*)



Phys. Rev. D 89 (2014) 092007

"High bkg / worse resol." (WH→bb)



JHEP01(2015)069

Profile likelihood formalism for (systematic) uncertainties

- Build likelihood function for *each* signal, control region of the data

i→H→f *Background*

$$L(\vec{N} \mid \vec{\mu}_i, \vec{\mu}_f, \vec{\theta}) = \prod_{k=0,nbins} Poisson\left(N_k \mid \sum_{i,f} \mu_i \cdot \mu^f \cdot S^f_{i,k}(\vec{\theta}) + \sum_m B_m(\vec{\theta}) \right)$$

Inclusive SM cross-section

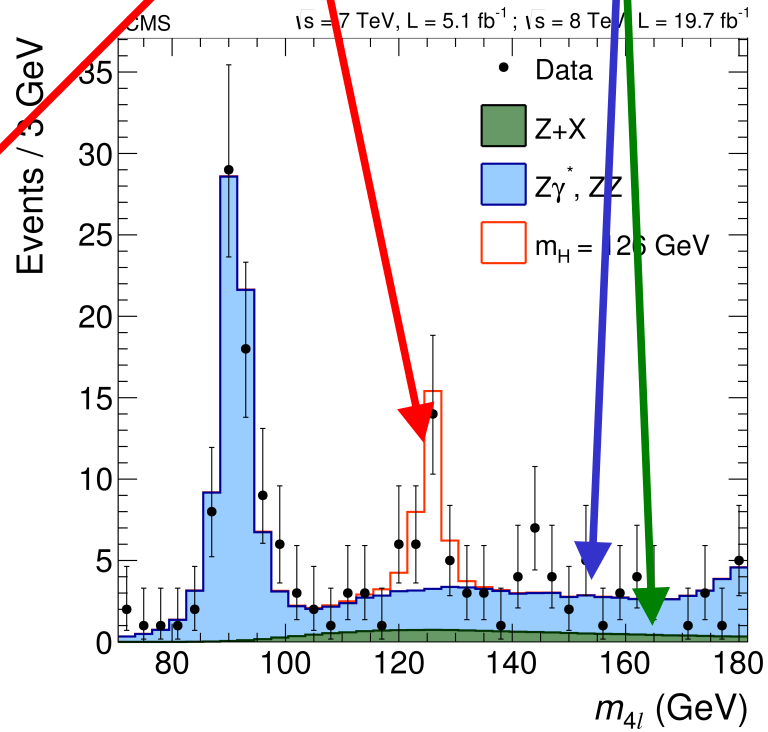
Acceptance (from MC)

Efficiency (from MC)

Higgs BR

Luminosity

$$\mathcal{L}(k) \times \left\{ \sigma_i^{\mathrm{SM}} \times A_i^f(k) \times \varepsilon_i^f(k) \times \mathrm{BR}^f_{\mathrm{SM}} \right\}$$



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Inclusive SM cross-section

Acceptance (from MC)

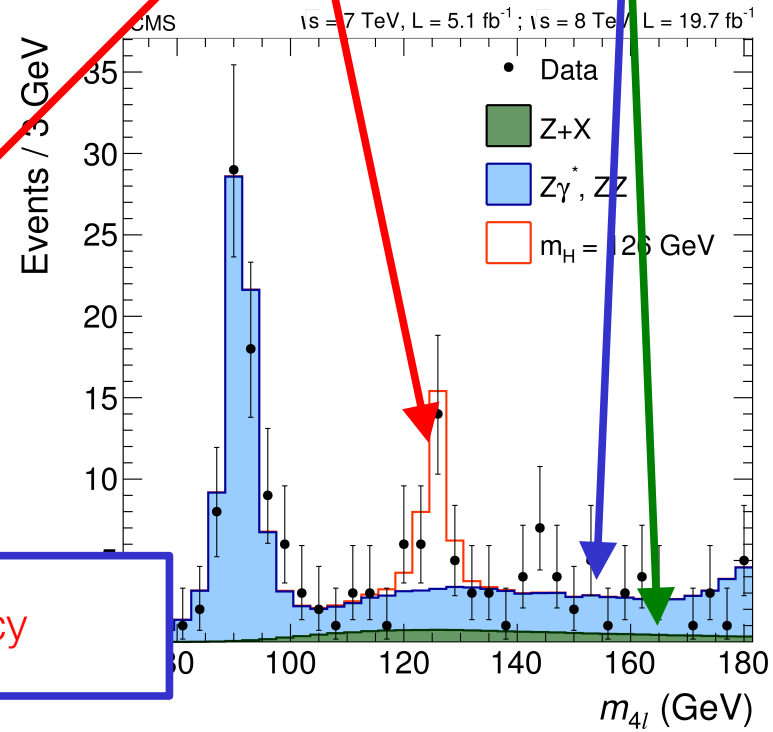
Efficiency (from MC)

Higgs BR

Luminosity

$$\mathcal{L}(k) \times \left\{ \sigma_i^{SM} \times A_i^f(k) \times \varepsilon_i^f(k) \times BR^f_{SM} \right\}$$

Assume **SM Higgs boson** for acceptance & efficiency

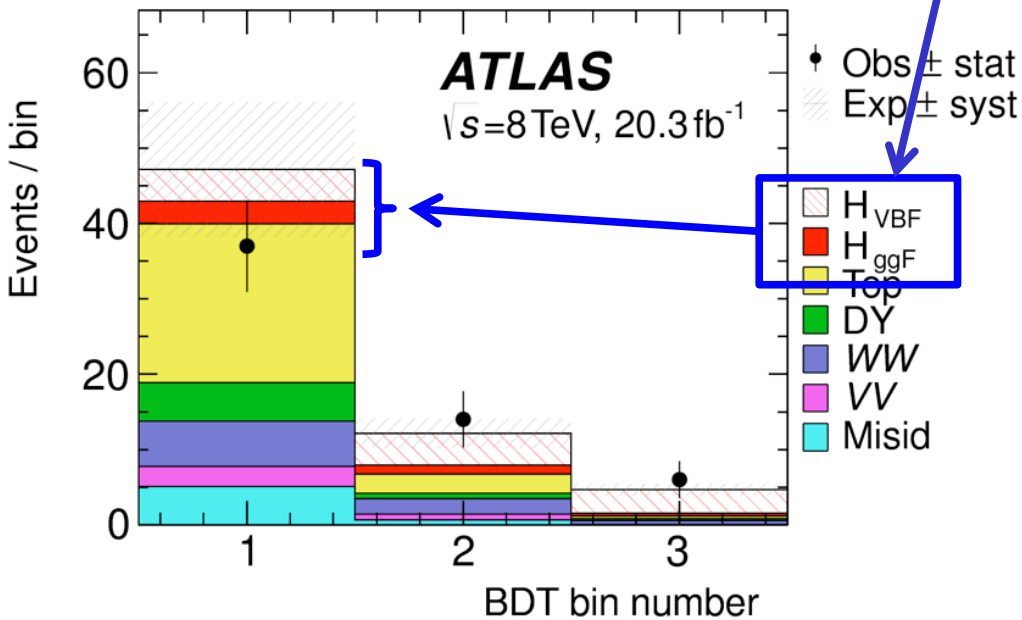


Decomposition of Higgs signal contributions in channels

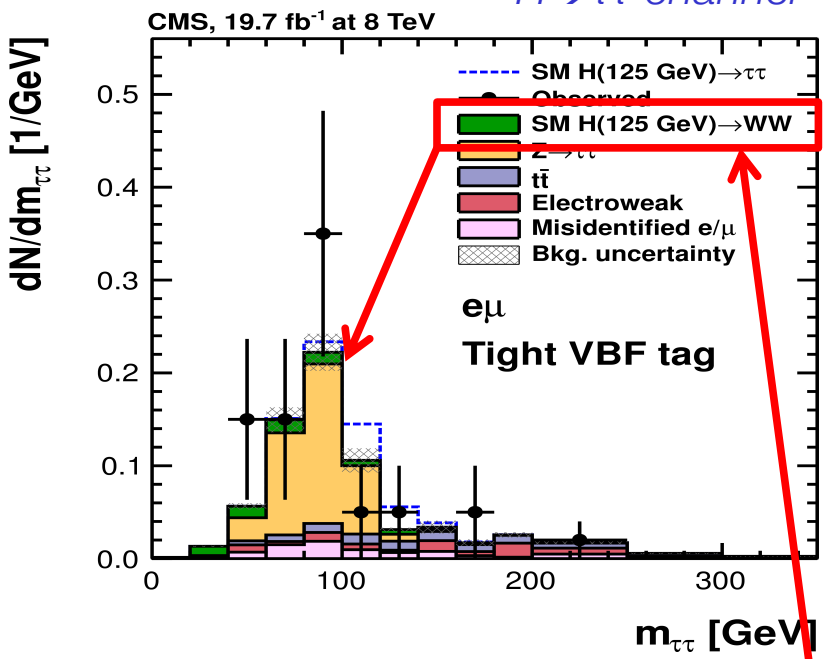
- Channels selections hardly ever 100% pure in production process (especially 'untagged') → separately model distributions from all contributing Higgs production processes

Phys. Rev. D 92, 012006 (2015)

"Untagged" H→WW channel



H→ττ channel

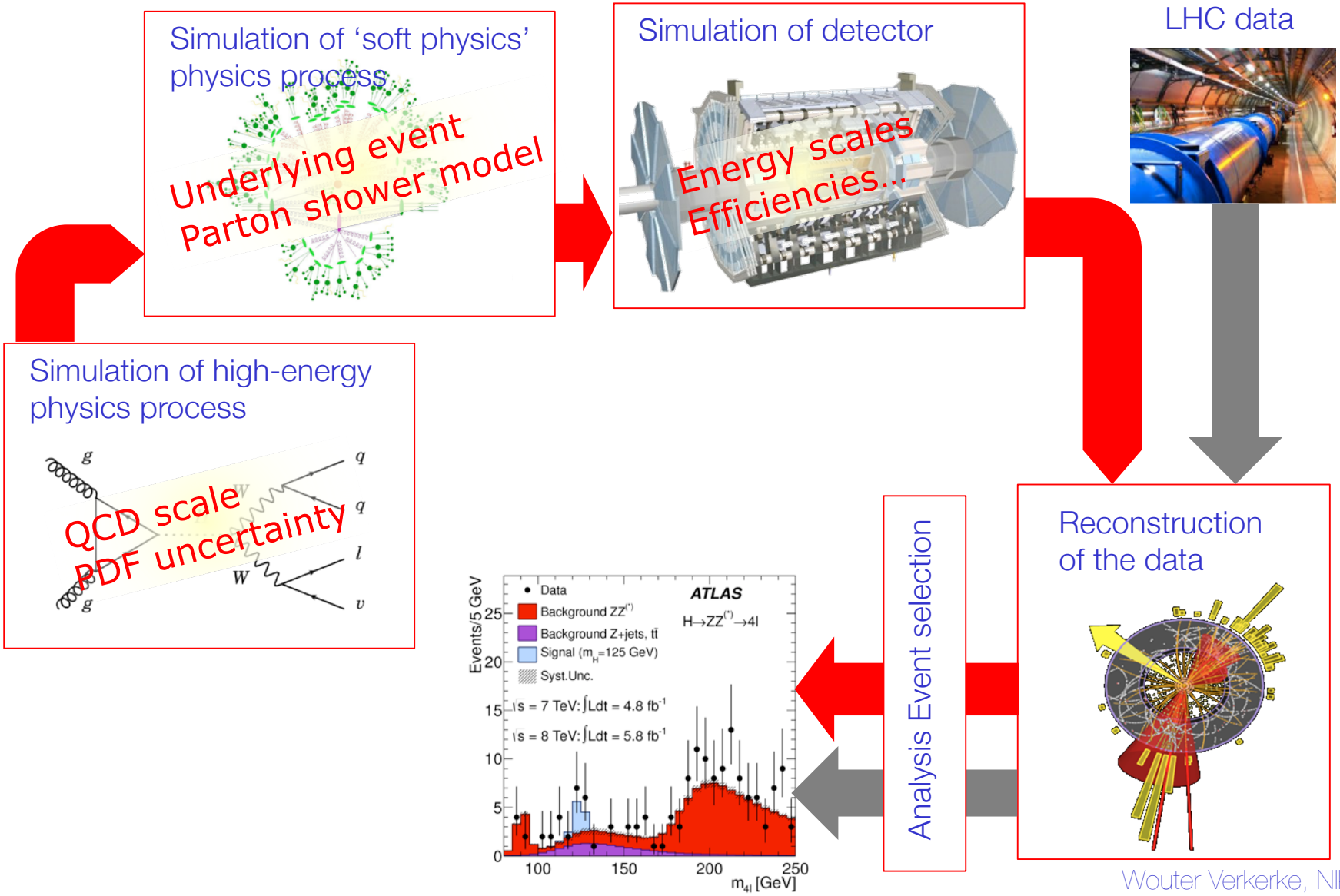


J. High Energy Phys. 05 (2014)

- Some channels also not 100% pure in decay mode (e.g. H→WW selection has contributions of H→ττ decays). Interpret such contributions as Higgs signal (of appropriate type) in coupling analysis

Most expected distributions subject to ***systematic uncertainties***

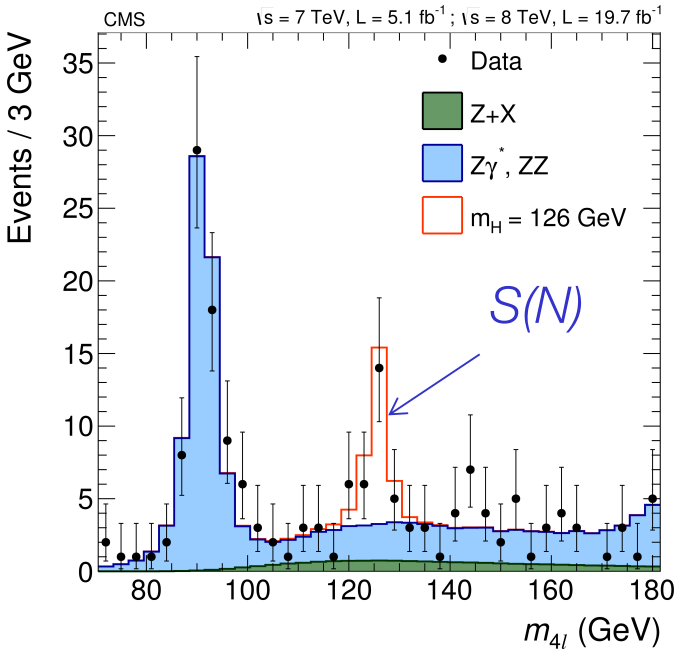
- Expected distributions mostly derived from simulation chain

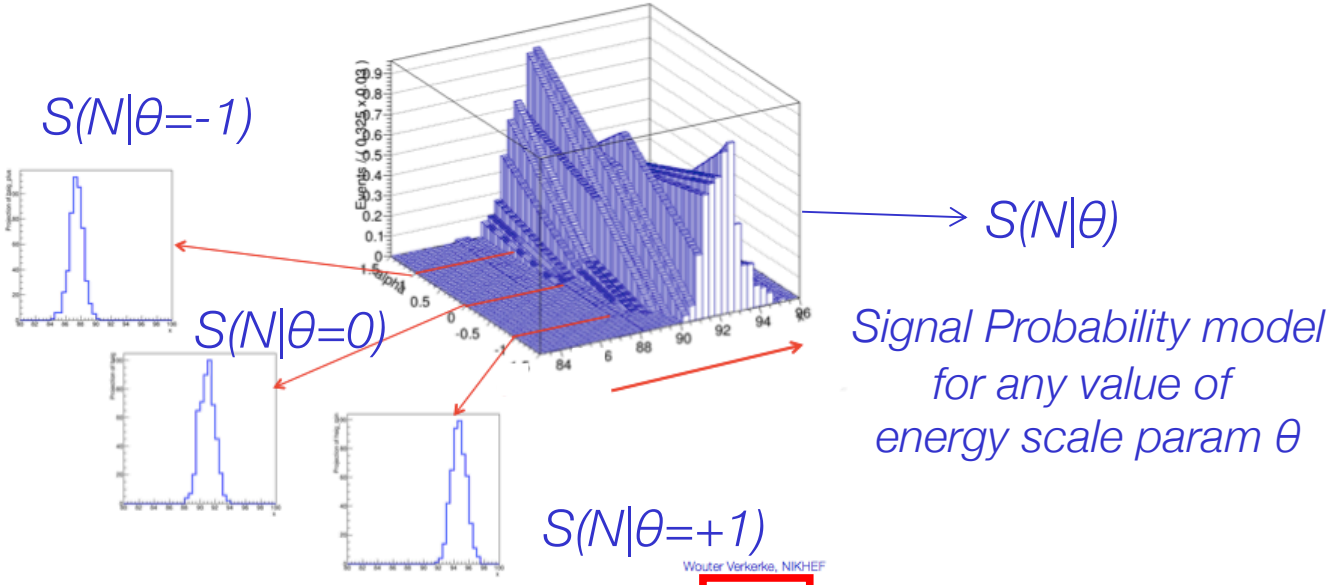


Profile likelihood formalism for (systematic) uncertainties

- **Extend description of each signal/background distribution** so that it can *describe distribution under a wide range of parameters* for which the true values are unknown (energy scales, QCD scales…)

Illustration: modeling of energy scale uncertainty



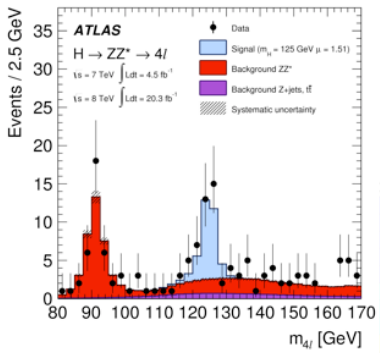


$$L(\vec{N} \mid \vec{\mu}_i, \vec{\mu}_f, \vec{\theta}) = \prod_{k=0,nbins} Poisson\left(N_k \mid \sum_{i,f} \mu_i \cdot \mu^f \cdot S^f_{i,k}(\vec{\theta}) + \sum_m B_m(\vec{\theta}) \right)$$

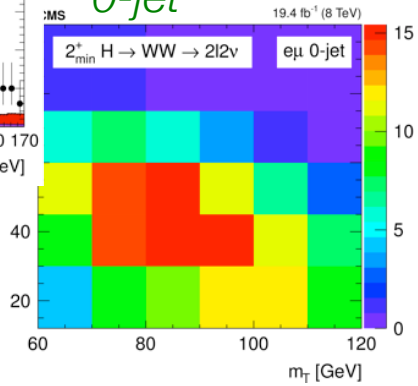
Profile likelihood formalism for (systematic) uncertainties

- Correlated parameters as needed between channels, experiments

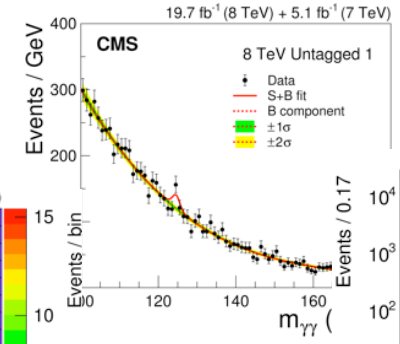
ATLAS ZZ



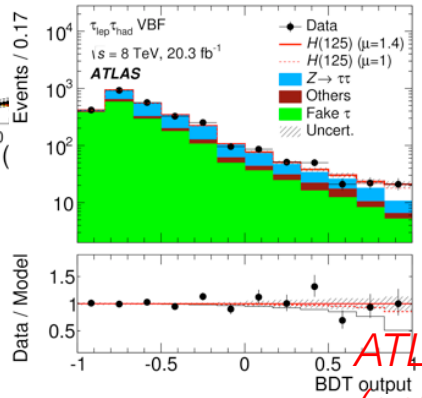
CMS WW 0-jet



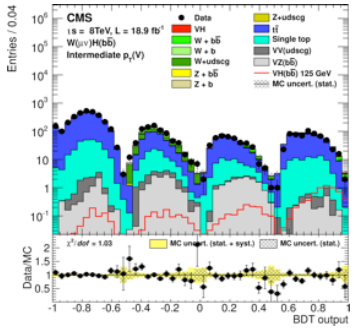
CMS γγ untagged



ATLAS ττ VBF μ-τ$_{had}$



CMS bb



ATLAS detector systematic (only correlated between ATLAS measurements)

$L_{ATLAS,ZZ}(N|\mu,\boldsymbol{\theta}_{\mathbf{QCDscale}},\boldsymbol{\theta}_{\mathbf{ATLASDet}},\theta,\theta,\theta,\ldots)$

$L_{ATLAS,\tau\tau\tau}(N|\mu,\boldsymbol{\theta}_{\mathbf{QCDscale}},\boldsymbol{\theta}_{\mathbf{ATLASDet}},\theta,\theta,\theta,\ldots)$

Fully correlated theory uncertainty

$L_{CMS,WW}(N|\mu,\boldsymbol{\theta}_{\mathbf{QCDscale}},\boldsymbol{\theta}_{\mathbf{CMSDet}},\theta,\theta,\theta,\ldots)$

Correlated uncertainties in Run-1 ATLAS/CMS combination

- Full combination describes ~580 signal regions & control regions from both experiments. Grand total of ~4200 nuisance parameters, related to (systematic) uncertainties
- Correlation strategy of nuisance parameters a delicate and complicated task
  - **Detector systematic uncertainties** → follow strategy of ATLAS and CMS internal combinations (**generally correlated within, not between experiments)**
  - **Signal theory uncertainties** (QCD scales, PDF, UEPS) on **inclusive cross-sections** generally **correlated between experiments.**
  - **Signal theory uncertainties on acceptance and selection efficiency** are **uncorrelated between experiments**, as these are small and estimation procedures are generally different.
  - **PDF uncertainties on signal cross-sections** **uncorrelated between channels**, except WH/ZH = correlated (effect of ignoring other correlations is ≤1%)
  - **No correlations assumed between Higgs BRs** (except for WW/ZZ).
    Effect of ignoring correlations shown to be generally small, except for a few specific measurements, in which case full correlation structure is retained

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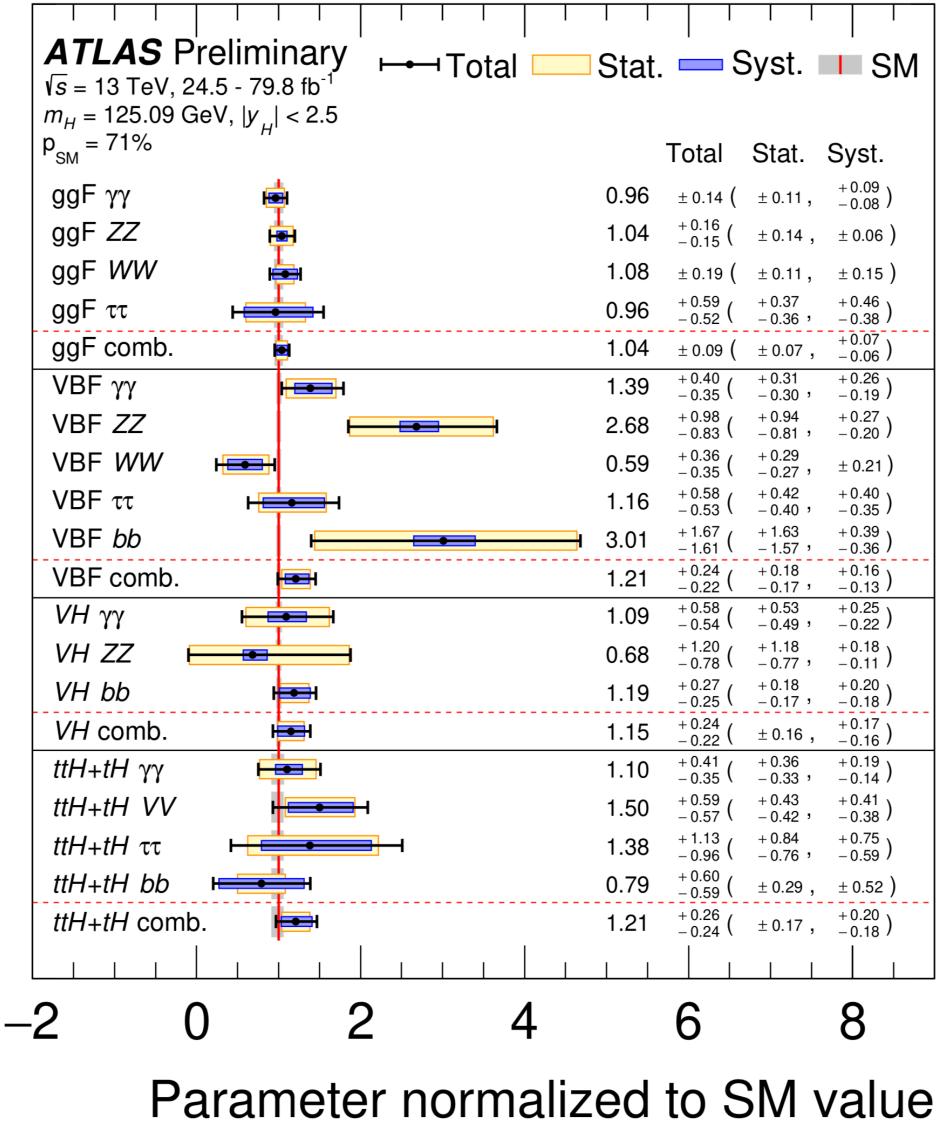
④ **Current couplings results from combined measurements**

⑤ From rates to distributions, connecting the pieces with SM(EFT)

Simplest combined fit – global signal strength fit



Assume all measurements measure
SM Higgs boson
modulo a *global signal strength modifier*

(Effectively the Higgs discovery strategy)

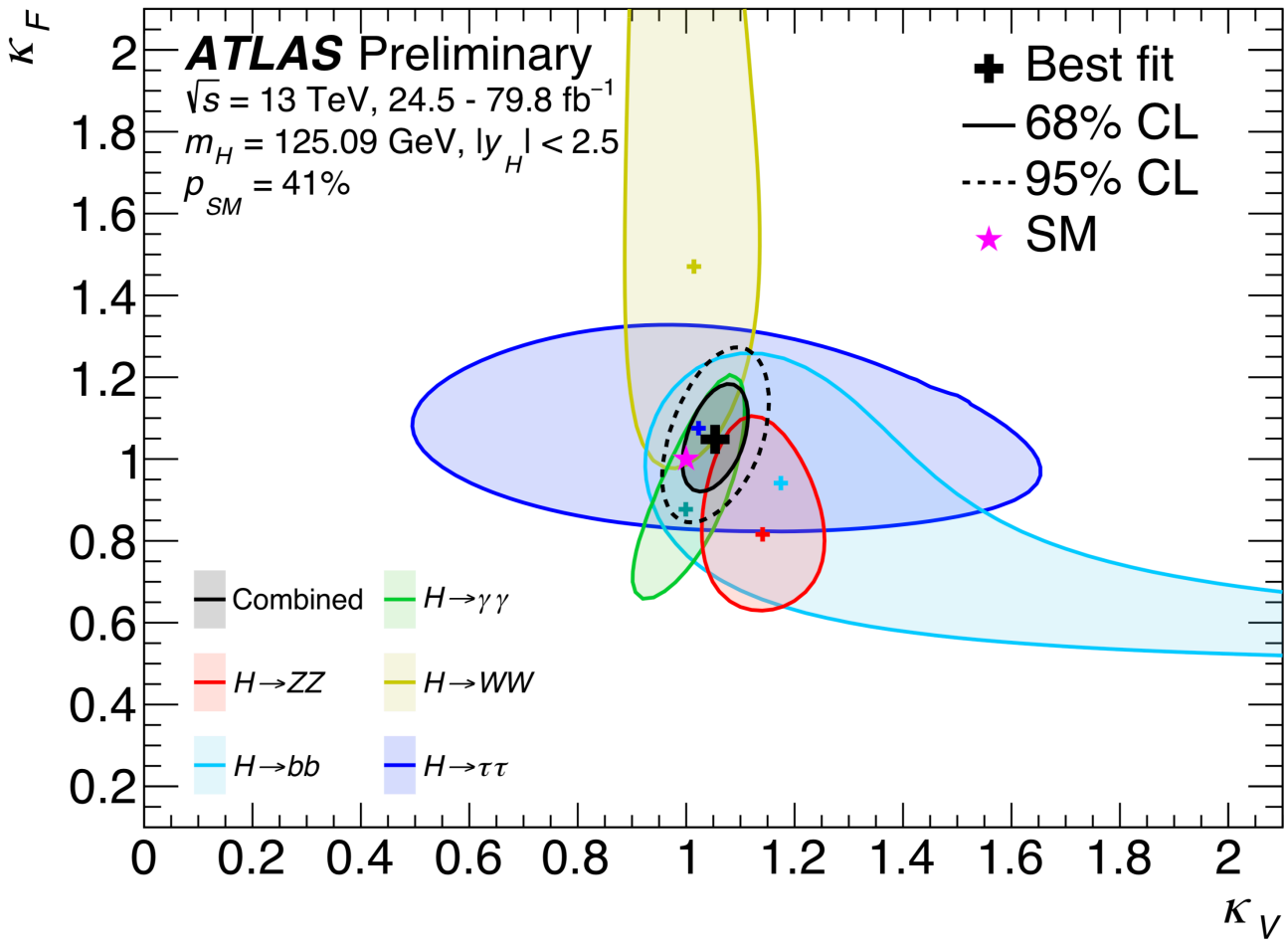
- Run 1 combination: $\mu = 1.09 \pm 0.11$
- Run 2 ATLAS: $\mu = 1.11 \pm 0.09$
- Run 2 CMS: $\mu = 1.17 \pm 0.10$

Constraints for Higgs couplings to fermions, bosons

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

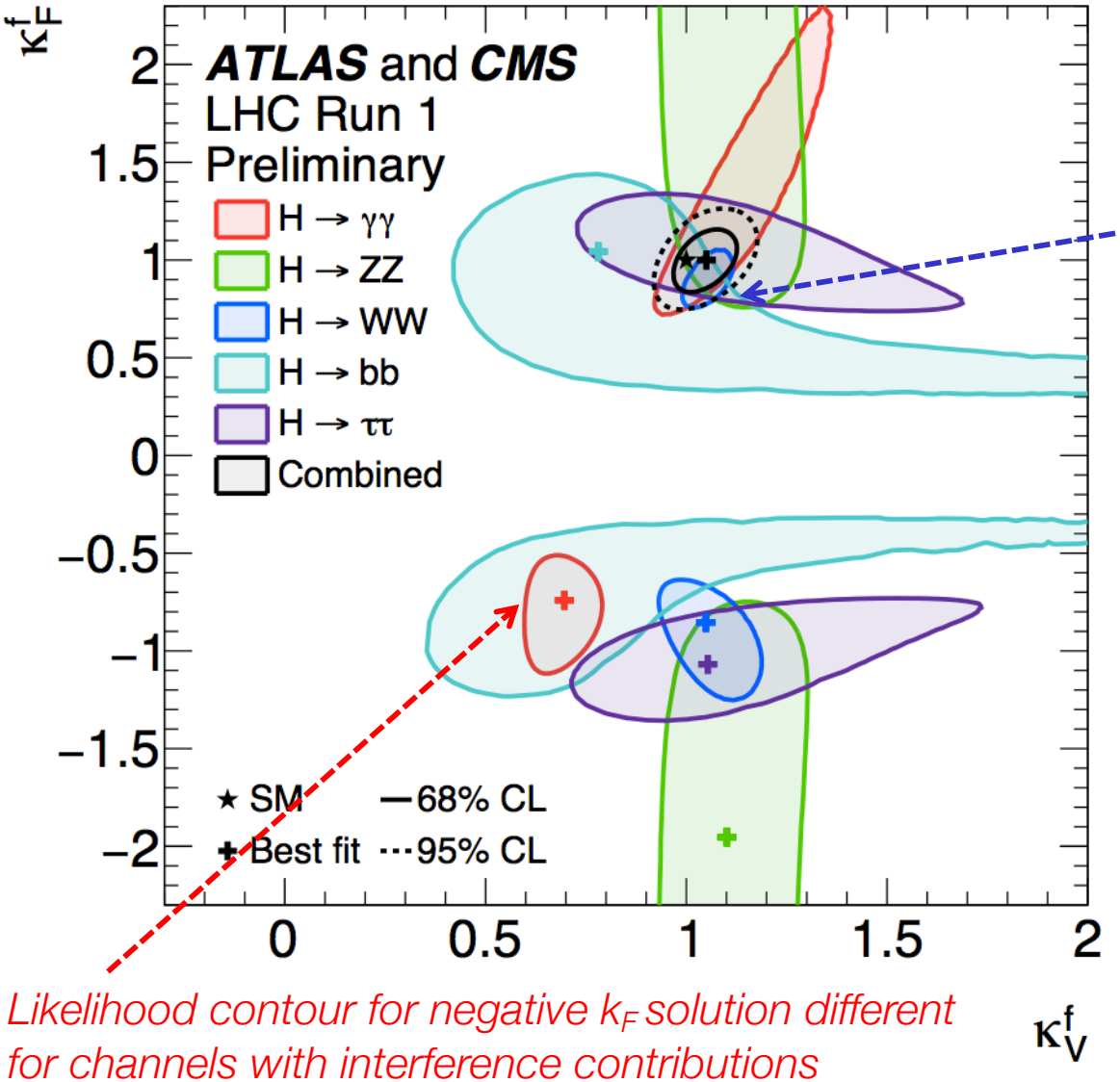
$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

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

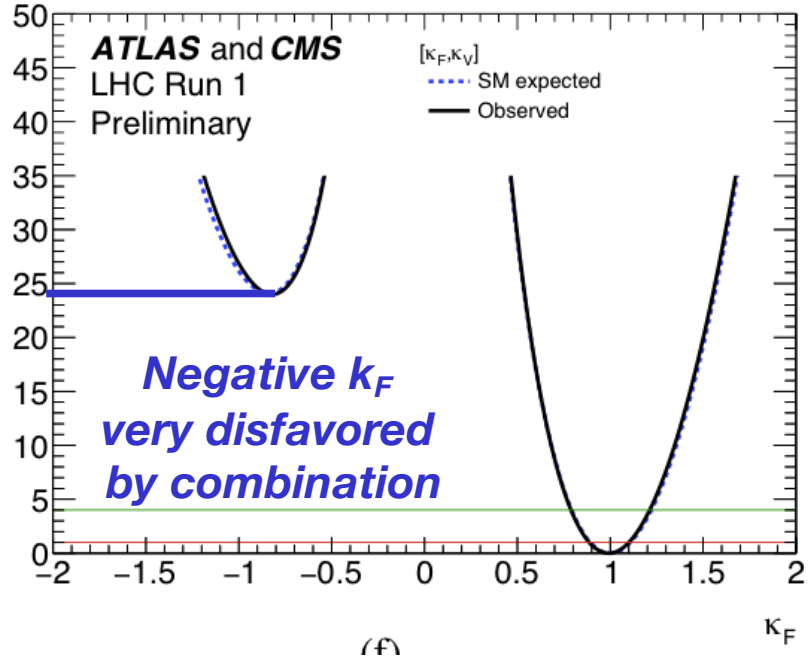


Constraints for Higgs couplings to fermions, bosons

- Expanding parameter ranges to include negative couplings



Positive WW contour reduced due to preferred negative solution



Likelihood contour for negative k_F solution different for channels with interference contributions

Constraints on Higgs couplings

- Assuming *no* BSM Higgs decays

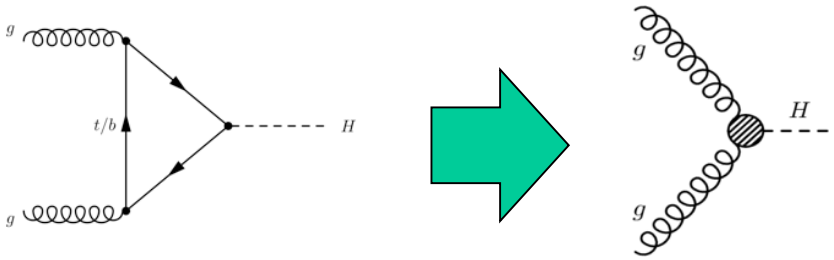
$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

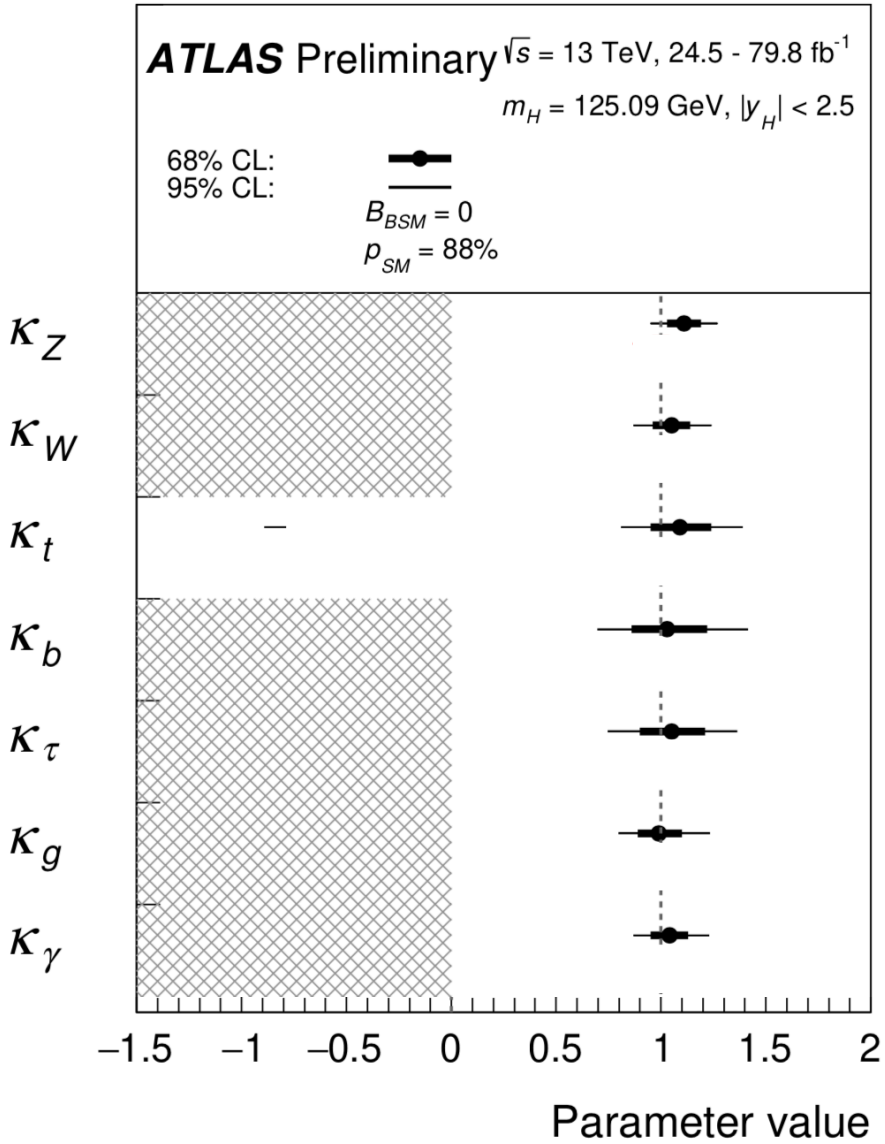
$$\kappa_H^2 \sim \begin{array}{l} 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + \\ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + \\ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2 \end{array}$$

- Fit for scaling parameters for Higgs couplings to

  W, Z, b, t, τ, μ, g, γ

- *Effective* couplings for g, γ





Constraints on Higgs couplings

- Allowing for BSM Higgs decays

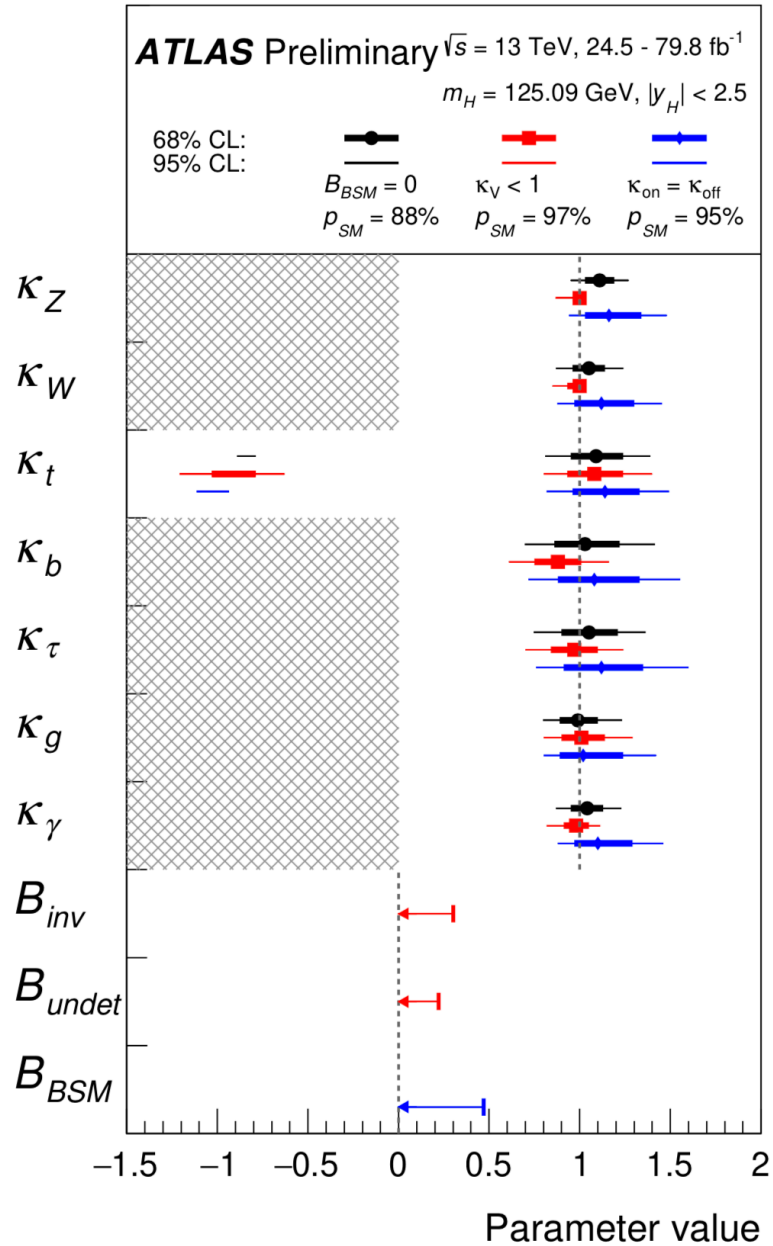
$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$$

- Fit for for additional parameters

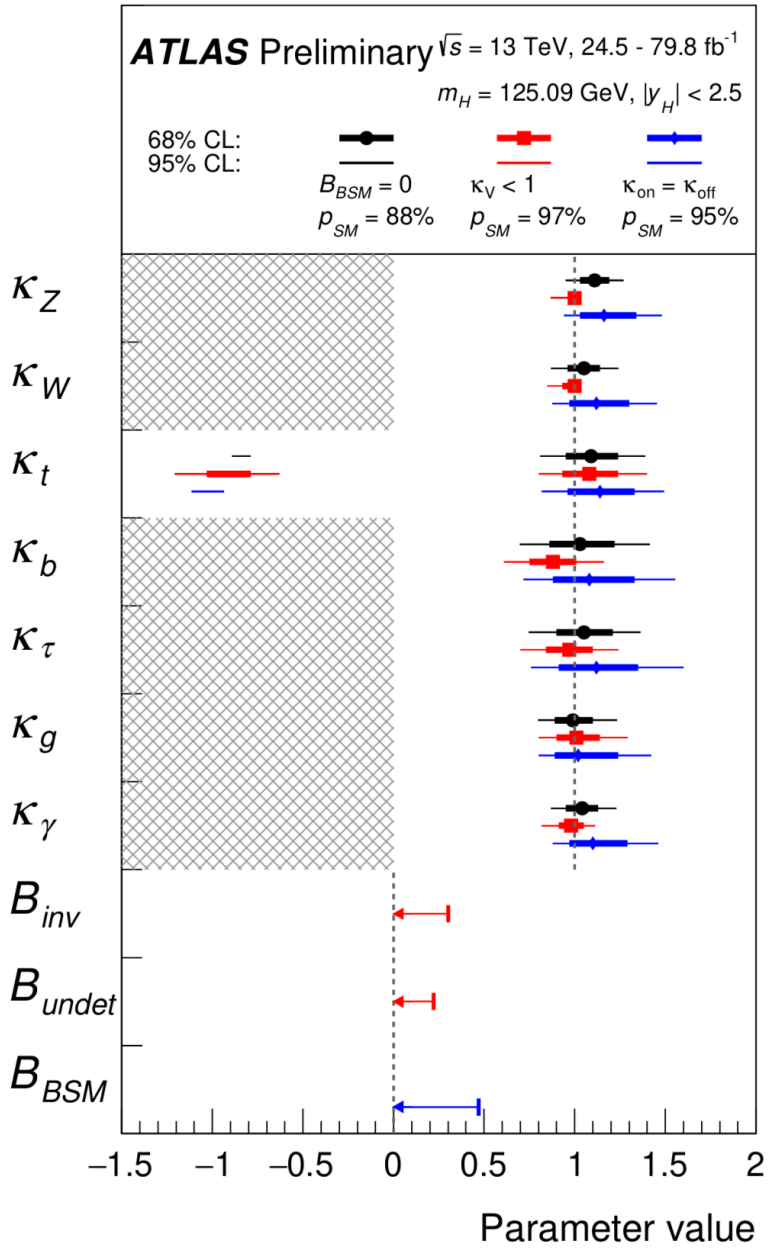
  BR_{inv},
  BR_{undet}
  or
  ($BR_{BSM}=BR_{inv}+BR_{undet}$)

- Note that fit is degenerate!
  - With $BR_{BSM}>0$ and all $\kappa<1$
    all observables may be identical to SM ($BR_{BSM}=0$ and $\kappa=1$)



Constraints on Higgs couplings

- Need additional information to resolve degeneracy
- Option 1 – Assumptions from theory:
  → assume bounds $k_W, k_Z < 1$
  → these bounds occur in many concrete BSM theories
- Option 2 – Measured Higgs width
  → Direct measurement not possible ($\Gamma H \sim 4$ MeV << resolution)
  → Indirect measurement possible from off-shell Higgs production
  → Involves theory assumptions too notably $\kappa_{on} = \kappa_{off}$



- Note that fit is degenerate!
  - With $BR_{BSM} > 0$ and all $\kappa < 1$ all observables may be identical to SM ($BR_{BSM} = 0$ and $\kappa = 1$)

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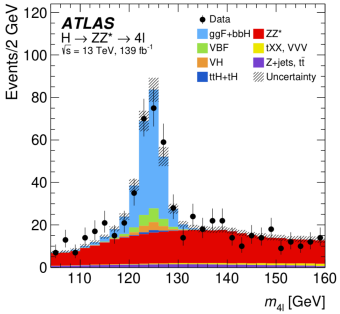
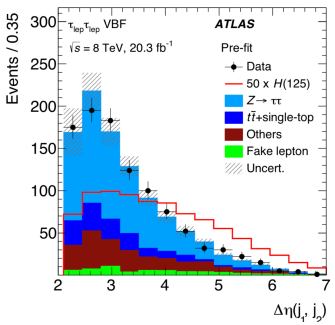
Limiting factors in current approach

O(100) Measurements

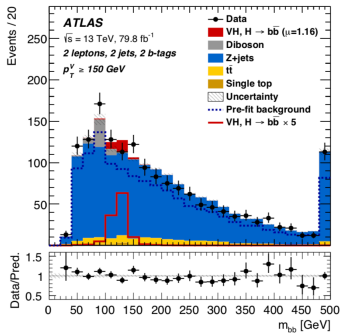
ggF → H → ZZ



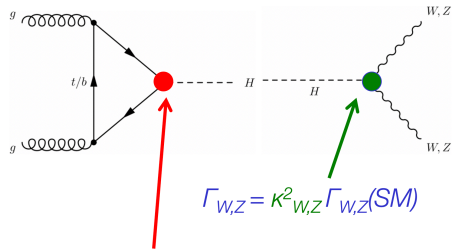
VBF → H → ττ



VH → H → bb



Parametric model to quantify deviations from SM



$\Gamma_{W,Z} = \kappa^2_{W,Z}\,\Gamma_{W,Z}(SM)$

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

Have 'sheep with 3 legs'

- Can't model distributions, nor self-couplings
- Make no assumptions about specific features of new physics
- Ad-hoc model that does not respect known physics features

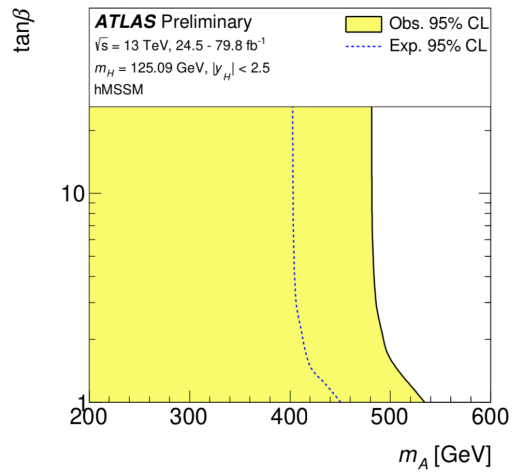
New Physics finger printing

MSSM-like theory

$$\kappa_V = \frac{s_d(m_A,\tan\beta)+\tan\beta\; s_u(m_A,\tan\beta)}{\sqrt{1+\tan^2\beta}}$$

$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

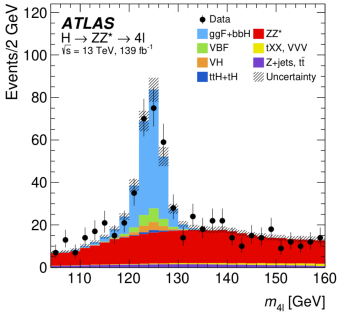
$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta}\quad ,$$



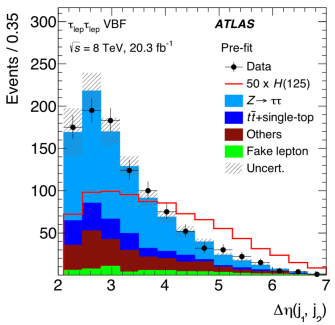
How can we improve in the future

O(100) Measurements

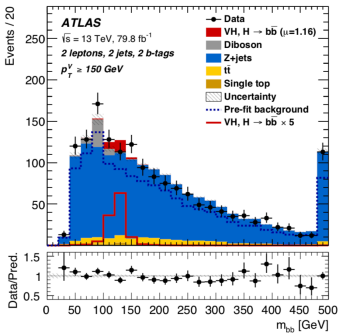
ggF → H → ZZ



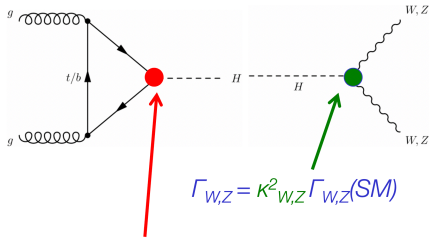
VBF → H → ττ



VH → H → bb



A new parametric model
to quantify deviations
in **all our data**



$\Gamma_{W,Z} = \kappa^2_{W,Z}\,\Gamma_{W,Z}(SM)$

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

Have 'sheep with 4 legs'

- **Model distributions**
- **Describe self-couplings**
- Sound theoretical basis
- Make few assumptions about specific features of new physics

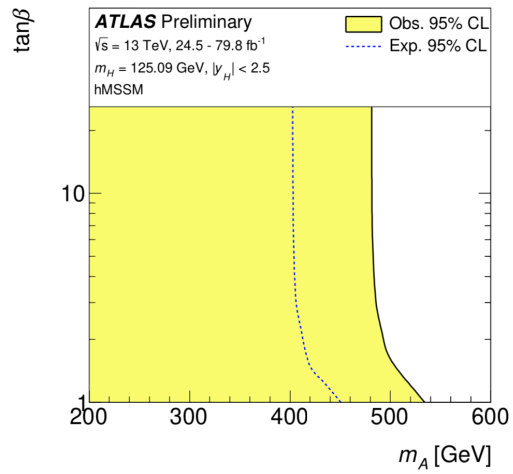
New Physics finger printing

MSSM-like theory

$$\kappa_V = \frac{s_d(m_A,\tan\beta)+\tan\beta\; s_u(m_A,\tan\beta)}{\sqrt{1+\tan^2\beta}}$$

$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

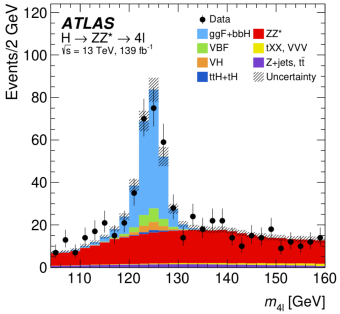
$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta}\quad ,$$



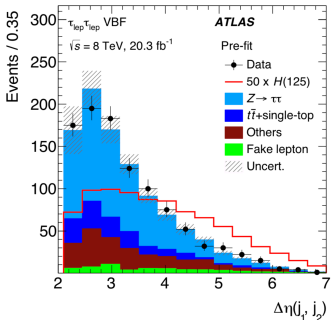
How can we improve in the future

O(100) Measurements

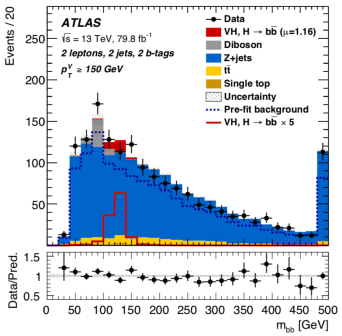
ggF → H → ZZ



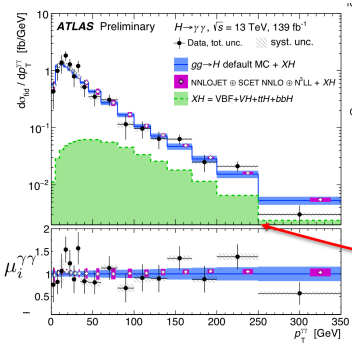
VBF → H → ττ



VH → H → bb

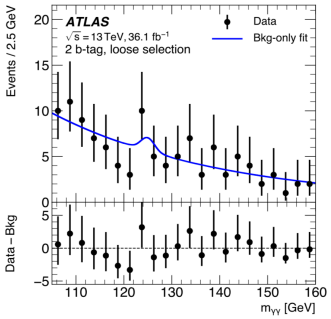


ggF → H → γγ *differential*

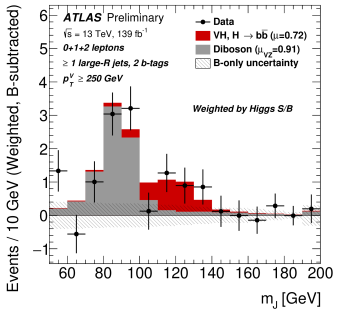


+ ...

HH → bbγγ (self-couplings)

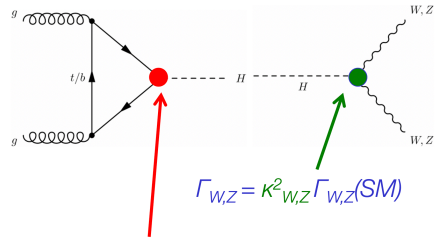


boosted (high-pT) VH→bb



+ ...

A new parametric model
to quantify deviations
in **all our data**



$\Gamma_{W,Z} = \kappa^2_{W,Z}\,\Gamma_{W,Z}(SM)$

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

Have 'sheep with 4 legs'

- **Model distributions**
- **Describe self-couplings**
- Sound theoretical basis
- Make few assumptions about specific features of new physics

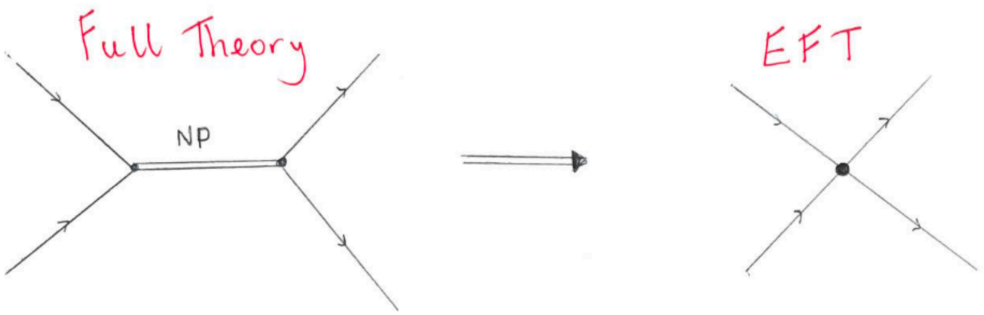
Wouter Verkerke, NIKHEF

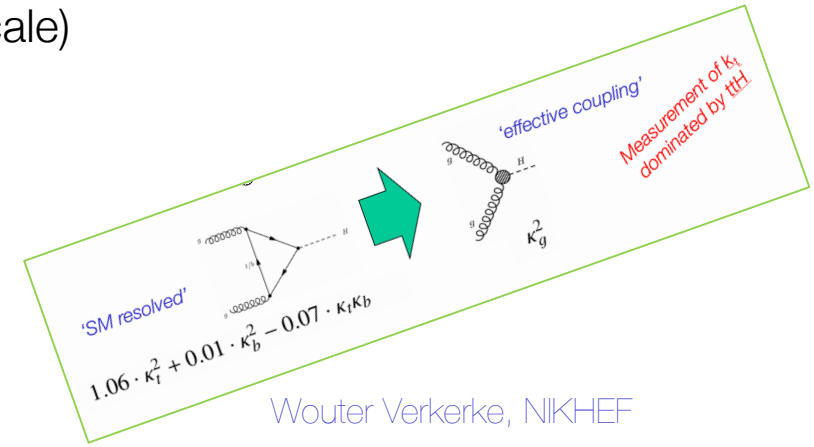
A different approach to modeling deviations – (SM)EFT

- New theory framework for measurements: SM Effective Field Theory

$$\mathcal{L} = L_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_i^{d=8} + \ldots$$

- Essence of the idea
  - Take full SM Lagrangian (dim-4 operators)
  - Extend theory by adding new operators (dim-6, dim-8) that allow novel interactions between SM particles, suppressed by a (large) energy scale Λ
  - Describes BSM physics as *effective* operators between SM fields (only assumption on BSM physics is high energy scale)





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- New experimental goal is to constrain the (Wilson) coefficients c_i (instead of Higgs couplings scale factors κ_i)
- *How many parameters c_i / operators O_i exist?* In principe many, but can restrict scope to those involving Higgs sector → Managable

		Operator	Notation	Operator	Notation
Class 1	X^3	$\varepsilon_{abc} W_\mu^{a\,\nu} W_\nu^{b\,\rho} W_\rho^{c\,\mu}$	$\mathscr{O}_W$		
	ϕ^6	$(\phi^\dagger\phi)^3$	$\mathscr{O}_\phi$		
	$\phi^4 D^2$	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathscr{O}_{\phi\Box}$	$(\phi^\dagger D_\mu\phi)((D^\mu\phi)^\dagger\phi)$	$\mathscr{O}_{\phi D}$
	$X^2\phi^2$	$\phi^\dagger\phi B_{\mu\nu}B^{\mu\nu}$	$\mathscr{O}_{\phi B}$	$\phi^\dagger\phi W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathscr{O}_{\phi W}$
		$\phi^\dagger\sigma_a\phi W^a_{\mu\nu}B^{\mu\nu}$	$\mathscr{O}_{\phi WB}$	$\phi^\dagger\phi G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathscr{O}_{\phi G}$
Class 2	$\psi^2\phi^2$	$(\phi^\dagger\phi)(\bar{l}_L\phi e_R^j)$	$(\mathscr{O}_{e\phi})_{ij}$		
		$(\phi^\dagger\phi)(\bar{q}_L^i\phi d_R^j)$	$(\mathscr{O}_{d\phi})_{ij}$	$(\phi^\dagger\phi)(\bar{q}_L^i\tilde{\phi}u_R^j)$	$(\mathscr{O}_{u\phi})_{ij}$
Class 3	$\psi^2\phi^2 D$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{l}_L^i\gamma^\mu l_L^j)$	$\left(\mathscr{O}_{\phi l}^{(1)}\right)_{ij}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{l}_L^i\gamma^\mu\sigma_a l_L^j)$	$(\mathscr{O}_{\phi l}^{(3)})_{ij}$
		$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}_R^i\gamma^\mu e_R^j)$	$(\mathscr{O}_{\phi e})_{ij}$		
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		$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}_R^i\gamma^\mu u_R^j)$	$(\mathscr{O}_{\phi u})_{ij}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{d}_R^i\gamma^\mu d_R^j)$	$(\mathscr{O}_{\phi d})_{ij}$
		$(\tilde{\phi}^\dagger iD_\mu\phi)(\bar{u}_R^i\gamma^\mu d_R^j)$	$(\mathscr{O}_{\phi ud})_{ij}$		

For details see (tomorrows) lectures by Pilar

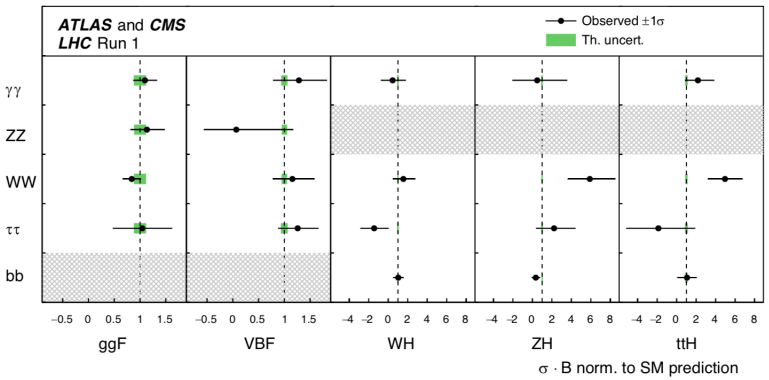
Experimental bottom line (SM)EFT provides a BSM-agnostic theory framework that can describe all observable distributions (including self-couplings)*

The power of distributions – according to (SM)EFT

Effective field theory

$$\mathcal{L} = L_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6}$$

On-shell

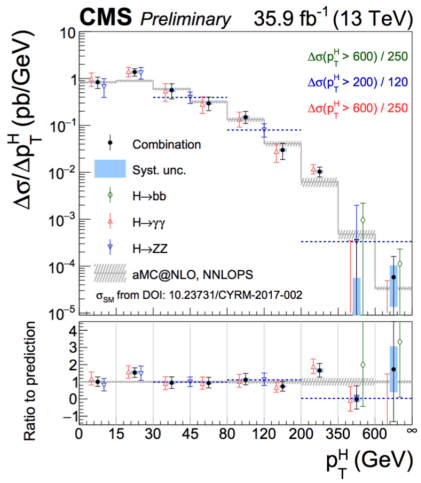


$$\delta\mu \approx \left(\frac{v}{\Lambda}\right)^2$$

Inclusive $\mu/\varkappa$: high-precision yields precision on new physics scale

δμ = 1% → Λ ~ 2.5 TeV)

Off-shell / large q^2



$$\delta\mu \approx \left(\frac{q}{\Lambda}\right)^2$$

Differential: High momentum production sensitive to new physics

δσ = 15% (q=1TeV) → Λ ~ 2.5 TeV

Need to use differential measurements to exploit sensitivity at LHC!

What experimentalist do with these new possibilities?

- 1) Which distributions to measure?
  - Potentially hundreds of differential Higgs signal distributions that can be measured.
  - Which ones provide (large) sensitivity to c_i?
  - For which have good experimental resolution/sensitivity?

  Promising new (theory) ideas popping up non-stop these days

- 2) What is the 'interface' between data and theory for future measurements?
  - For κ framework the interface was trivial: SM-normalized cross-sections for each process
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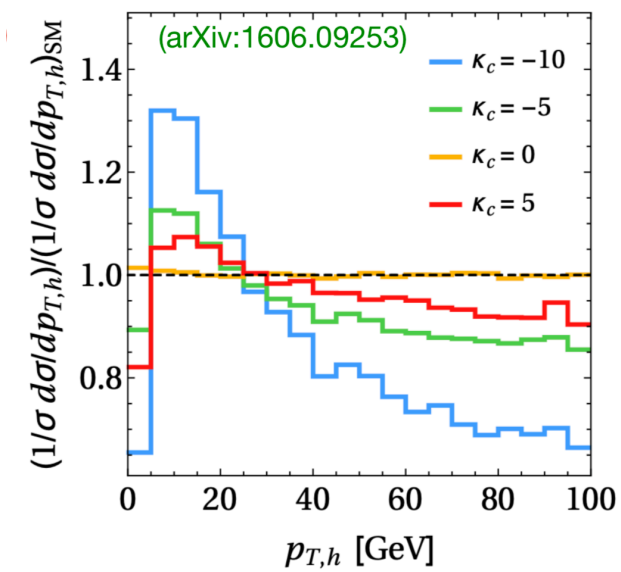
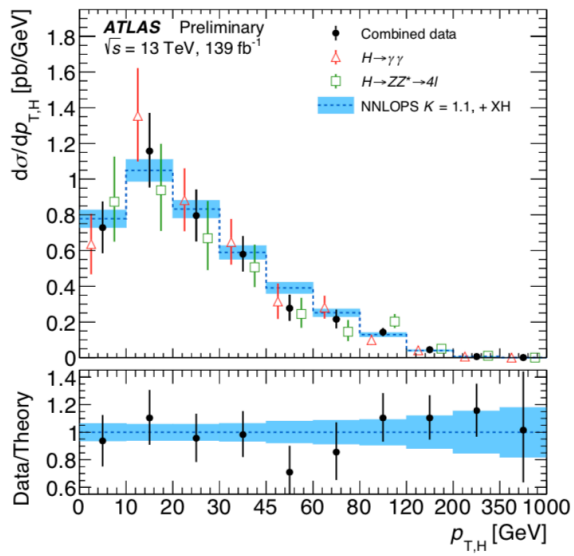
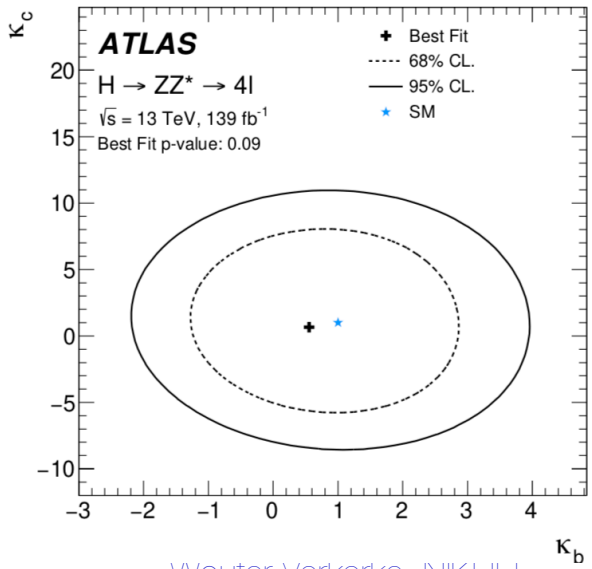
Theory studies:
$p_T(H)$ distribution predicted to be sensitive to e.g. Higgs-charm coupling



ATLAS
Run-2 measurements



Extraction of κ_c,κ_b
(under optimistic assumption of all other κ_i fixed at SM)



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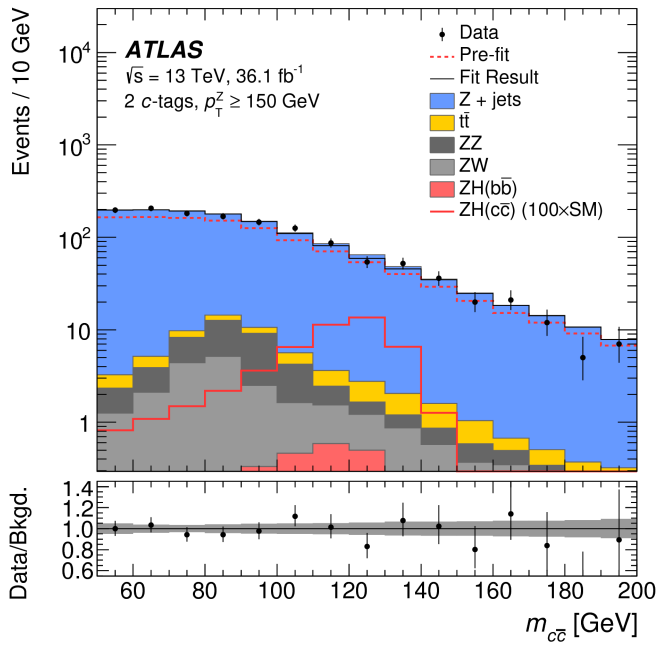
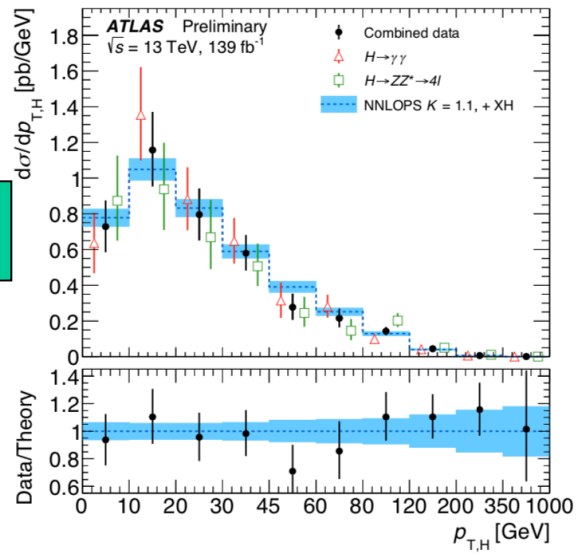
ATLAS Run-2 data
direct search for H→cc



Joint extraction of charm coupling

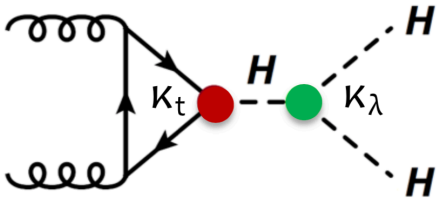
ATLAS Run-2 data
pT(H) distribution

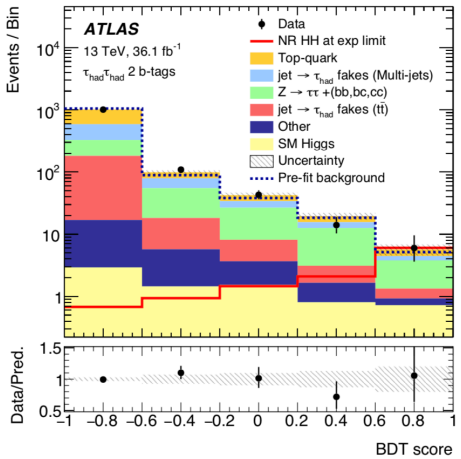


Which distributions to measure – many other opportunities!

- Observable of Higgs self-coupling is now the 'holy grail'

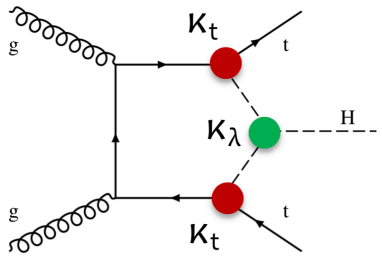
diHiggs production

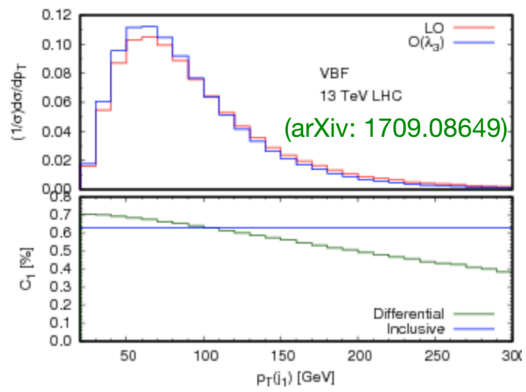




Traditional approach
Extremely low rates
make it super challenging

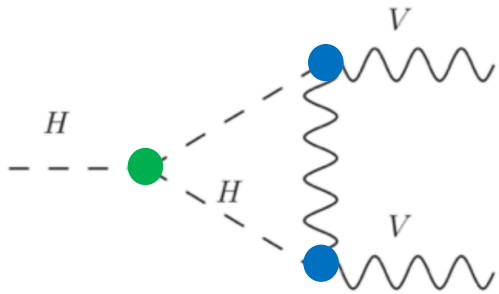
ttH production p_T distribution

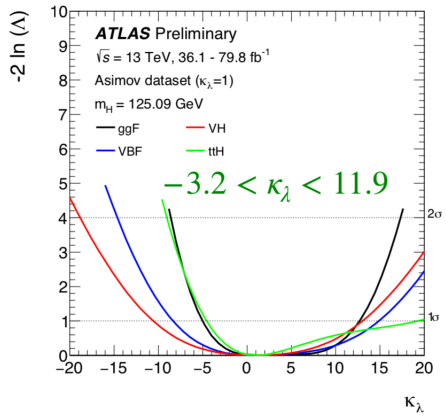




Substantial expected
sensitivity in ttH data
(channel observed at 5σ)

loop correction to single Higgs prod.





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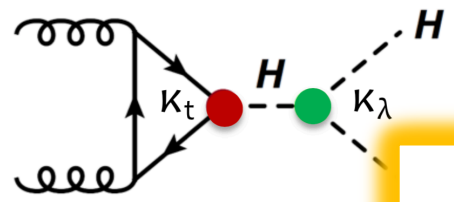

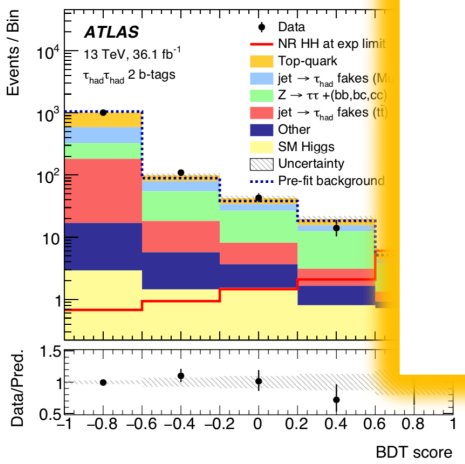

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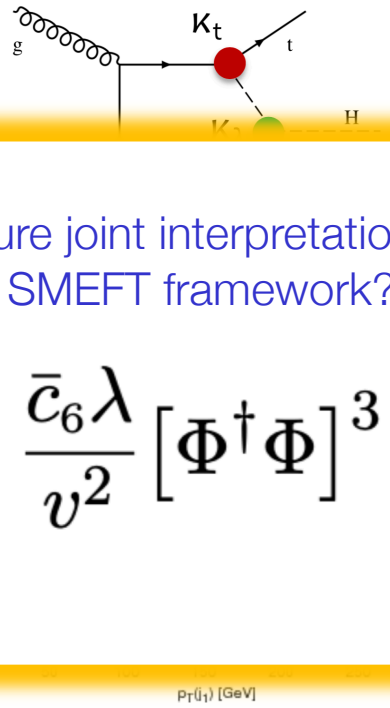

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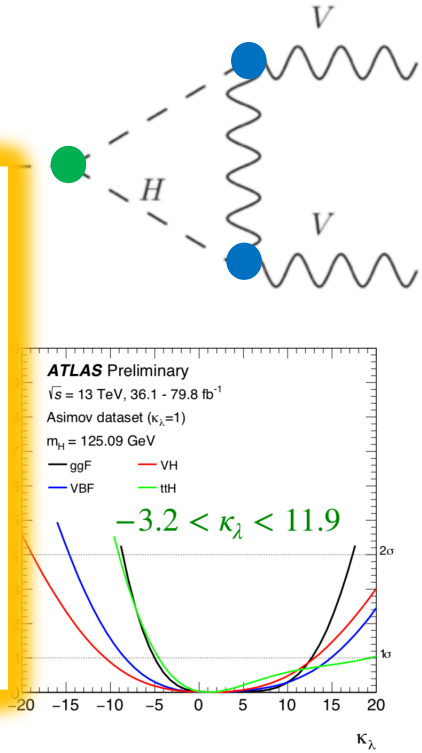

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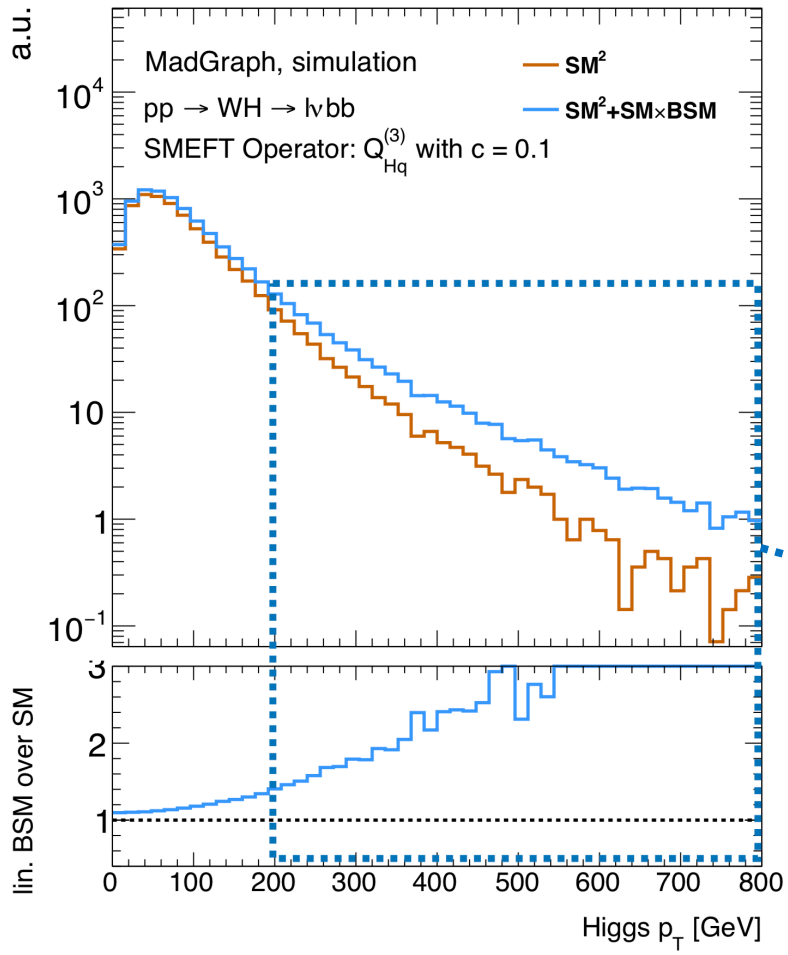
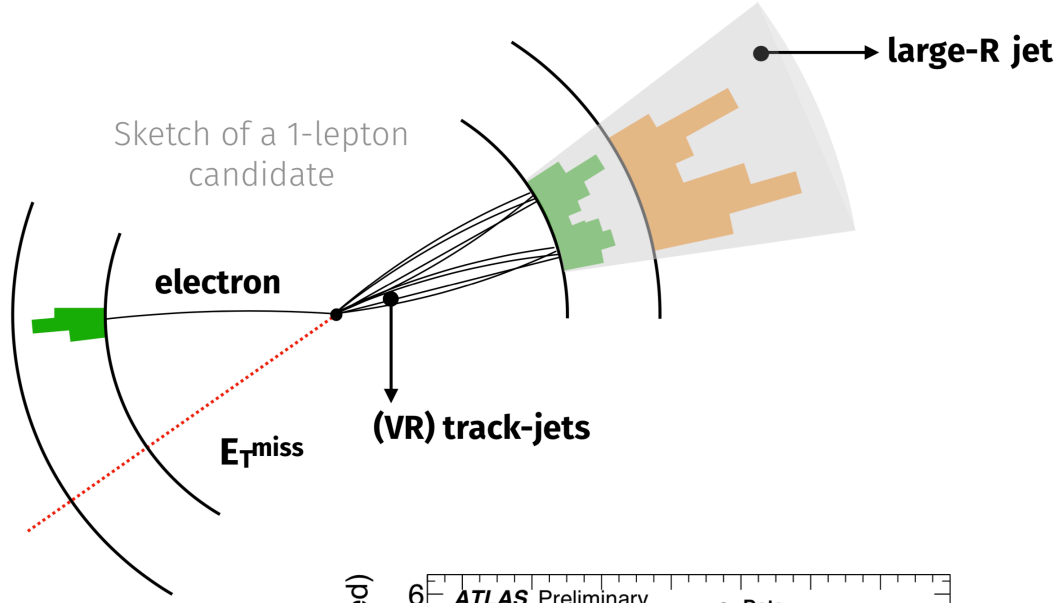
Future joint interpretation
in SMEFT framework?

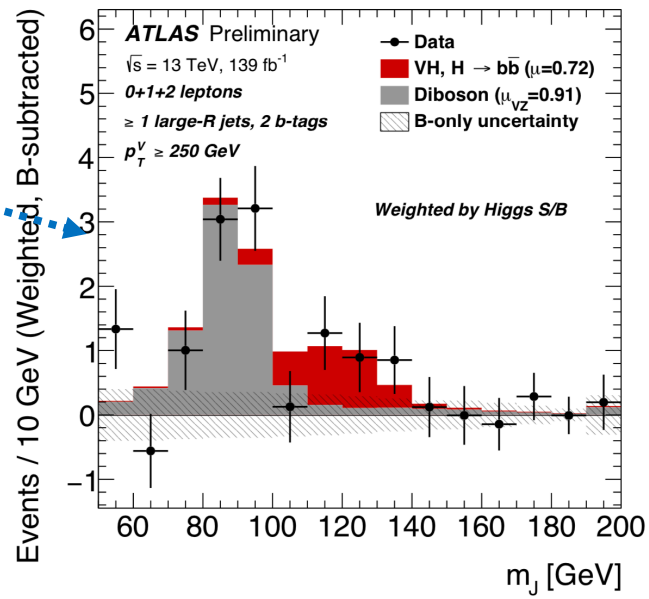
$$\frac{\bar{c}_6 \lambda}{v^2}\left[\Phi^\dagger \Phi\right]^3$$

Which distributions to measure – many opportunities!

- High energy tails of Higgs production have largest sensitivity to new physics contributions







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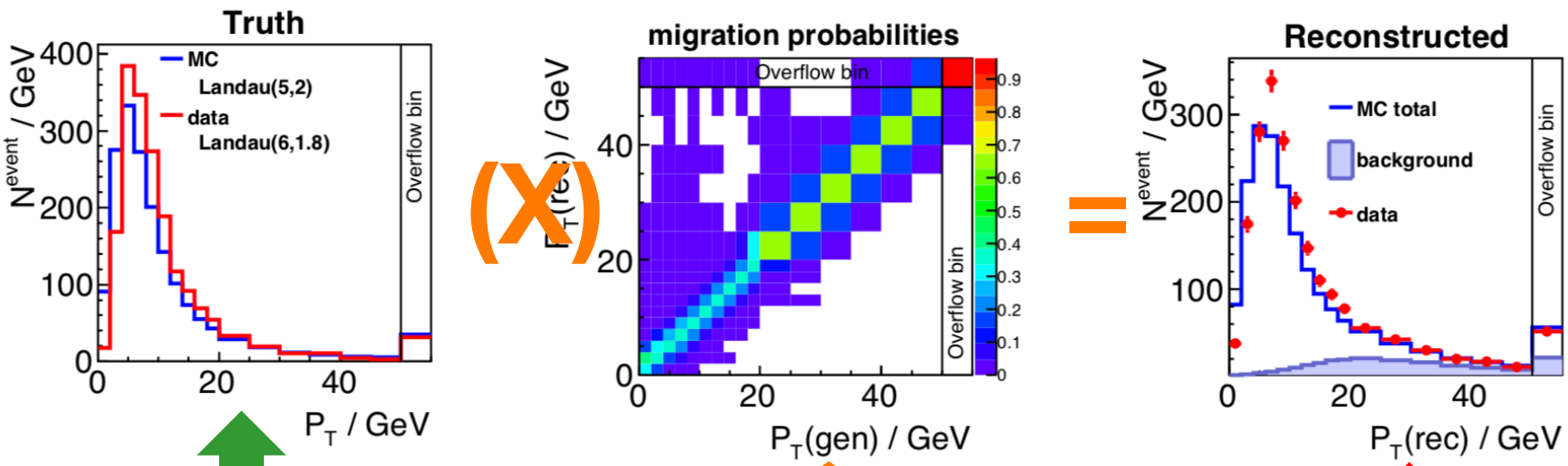
Publishing distributions 1 - the cleanest & hardest way

- Observed event rates and observed distributions cannot be trivially interpreted in terms of fundamental theories
  - Rates → need to substract backgrounds, account for acceptance effects
  - Distribution → substract backgrounds, account for acceptance *and migration effects*



Theory predicts distribution in terms of c_i

Detector resolution and efficiency

Experimental measurement

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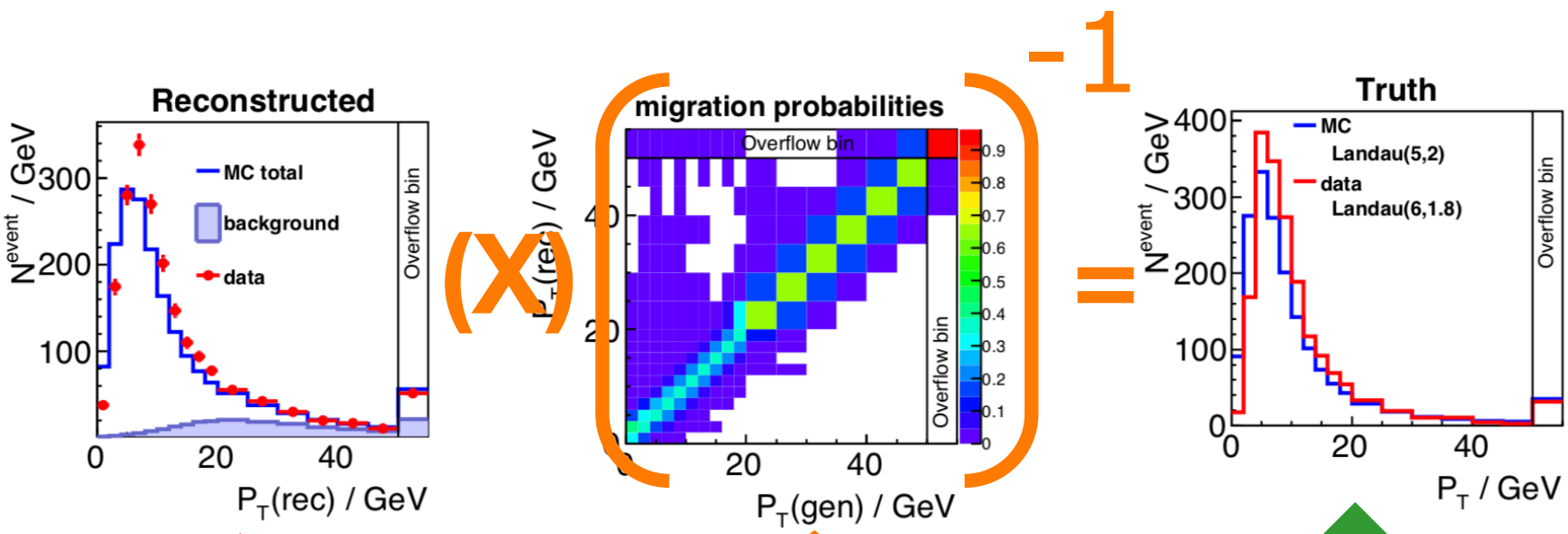


Experimental measurement

Inverse of detector resolution and efficiency (deconvolution/unfolding

Theory predicts distribution in terms of c_i

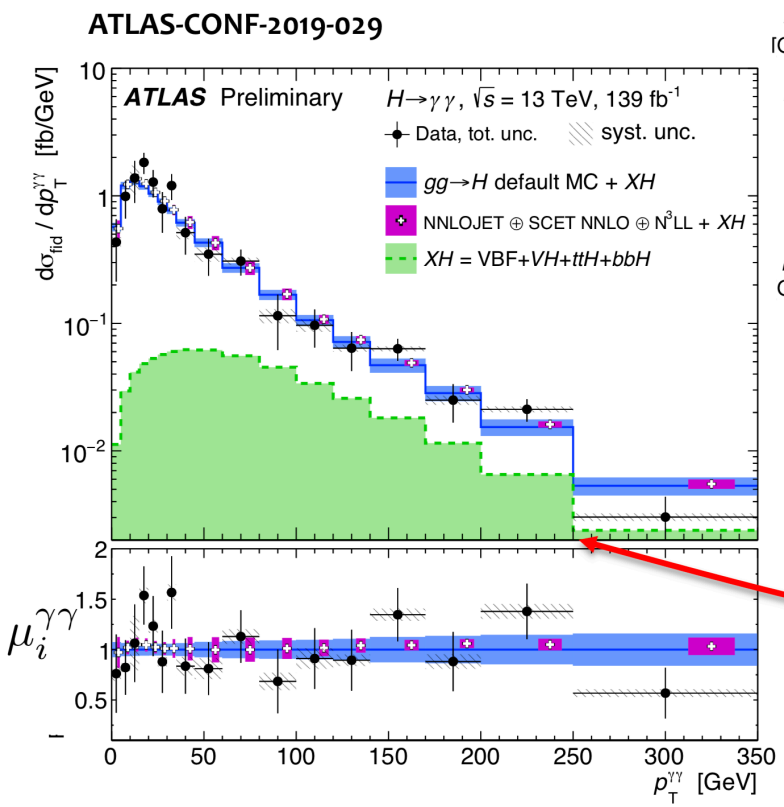
Publishing distributions 1 - the cleanest & hardest way

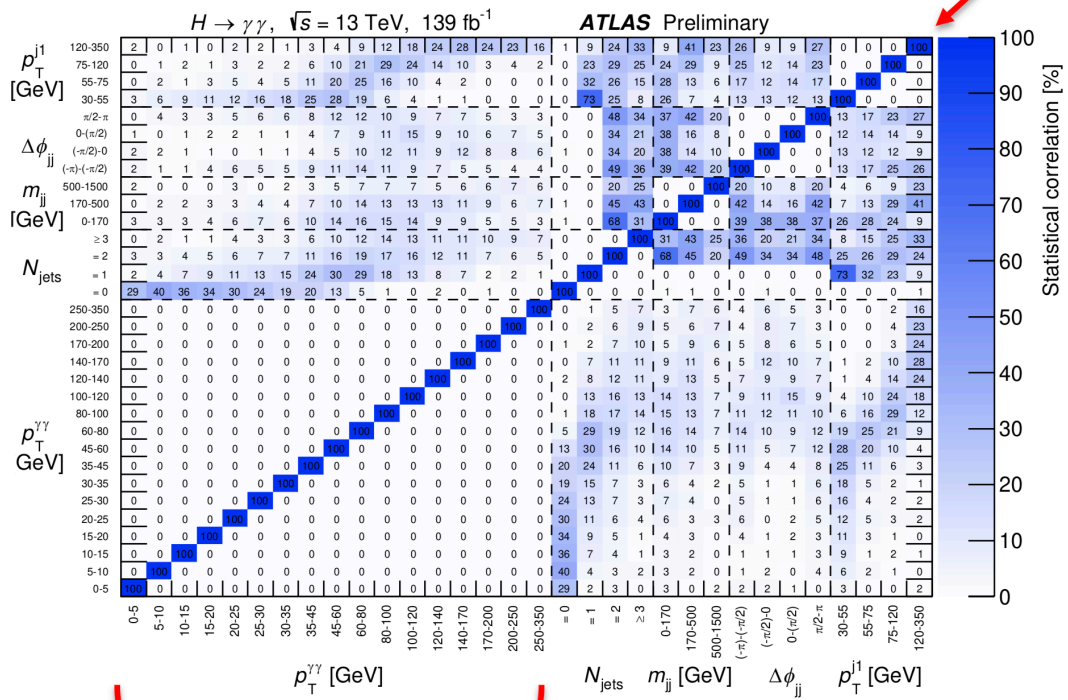
- Example ATLAS result with full unfolding procedure

Fiducial differential Higgs measurements in several (1D) variables with H→γγ

- $p_T^{\gamma\gamma}$, $\Delta\varphi_{jj}$, p_T^{j1}, m_{jj}, N_{jets}

$$\rho(\mu_i^{\gamma\gamma}, \mu_j^{\gamma\gamma})$$



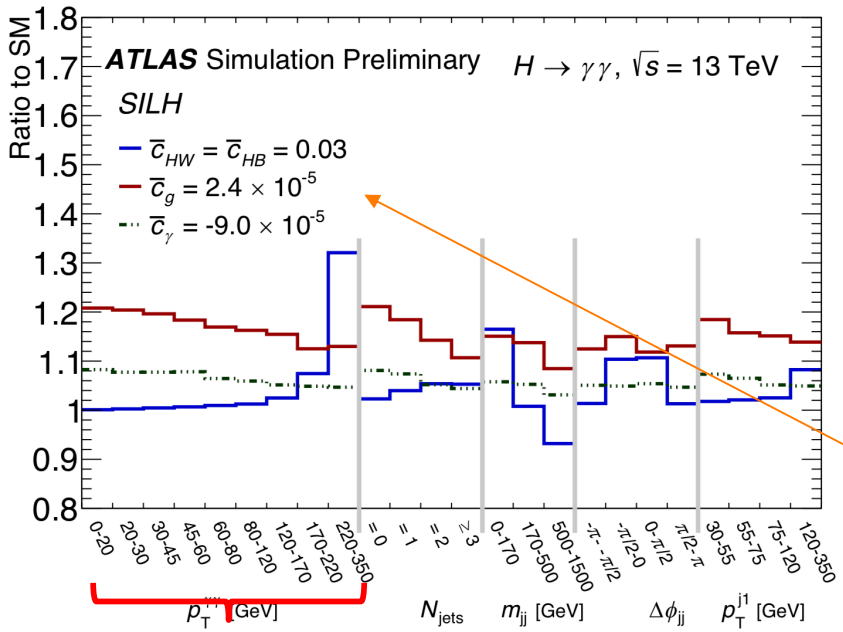


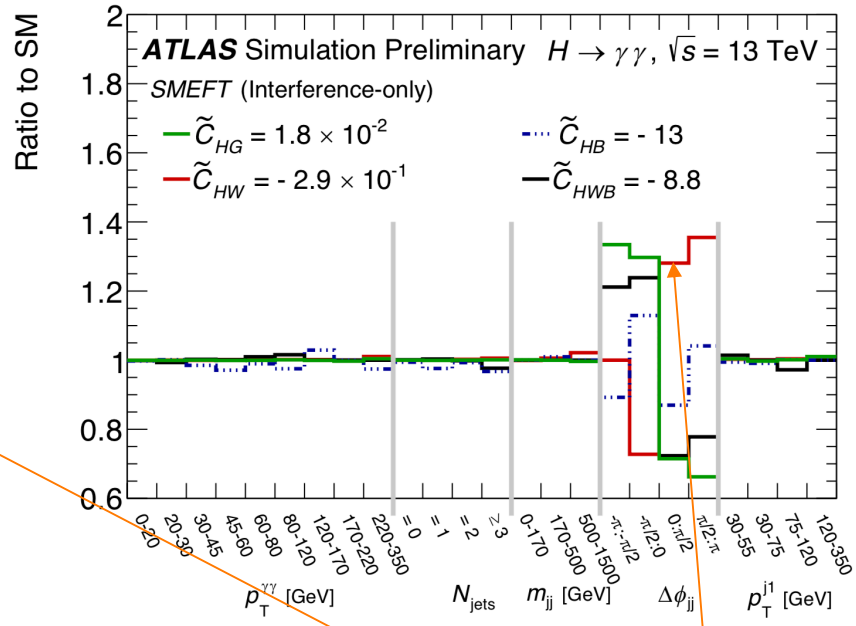
Extremely labour intensive measurement…

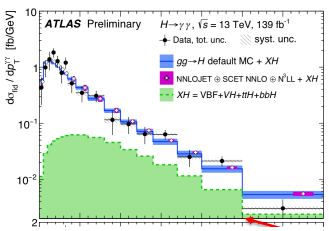
Publishing distributions 1 - the cleanest & hardest way

- Example ATLAS result with full unfolding procedure

Deviation from SM expressed in terms of Wilson coefficients $\mu_i^{\gamma\gamma} \rightarrow \mu_i^{\gamma\gamma}(\bar{\mathbf{c}}, \tilde{\mathbf{c}})$
(using SILH / SMEFT basis @ LO)



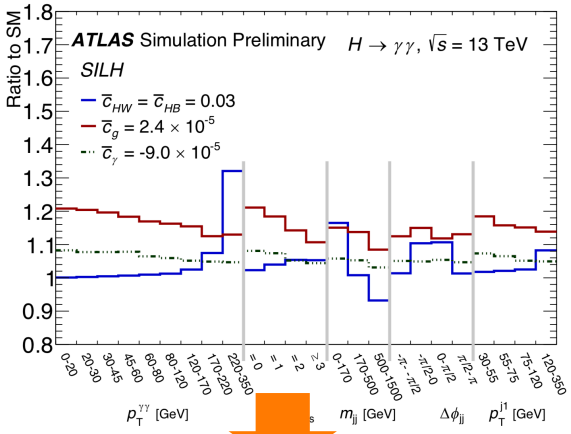




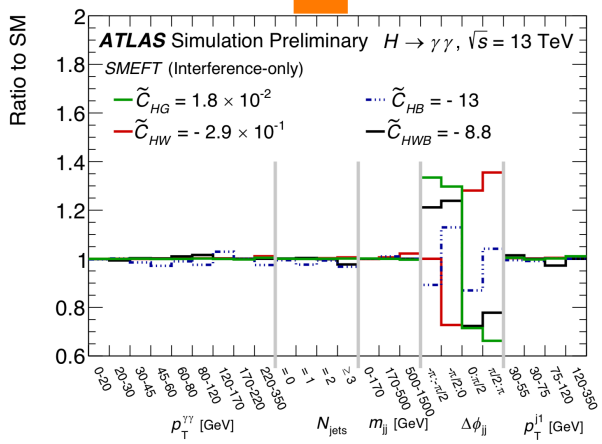
Extremely labour intensive measurement…
but result directly interpretable in EFT c_i's

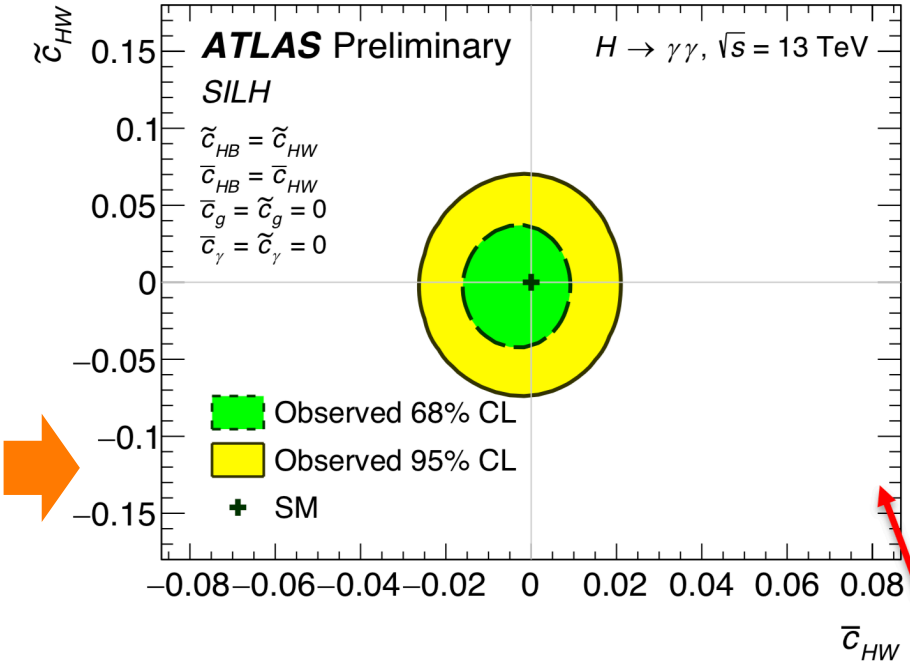
Publishing distributions 1 - the cleanest & hardest way

- Example ATLAS result with full unfolding procedure & interpretation



$$-2\log L = (\hat{\boldsymbol{\mu}}^{\gamma\gamma} - \boldsymbol{\mu}^{\gamma\gamma}(\bar{\boldsymbol{c}}, \tilde{\boldsymbol{c}}))^T V^{-1} (\hat{\boldsymbol{\mu}}^{\gamma\gamma} - \boldsymbol{\mu}^{\gamma\gamma}(\bar{\boldsymbol{c}}, \tilde{\boldsymbol{c}}))$$





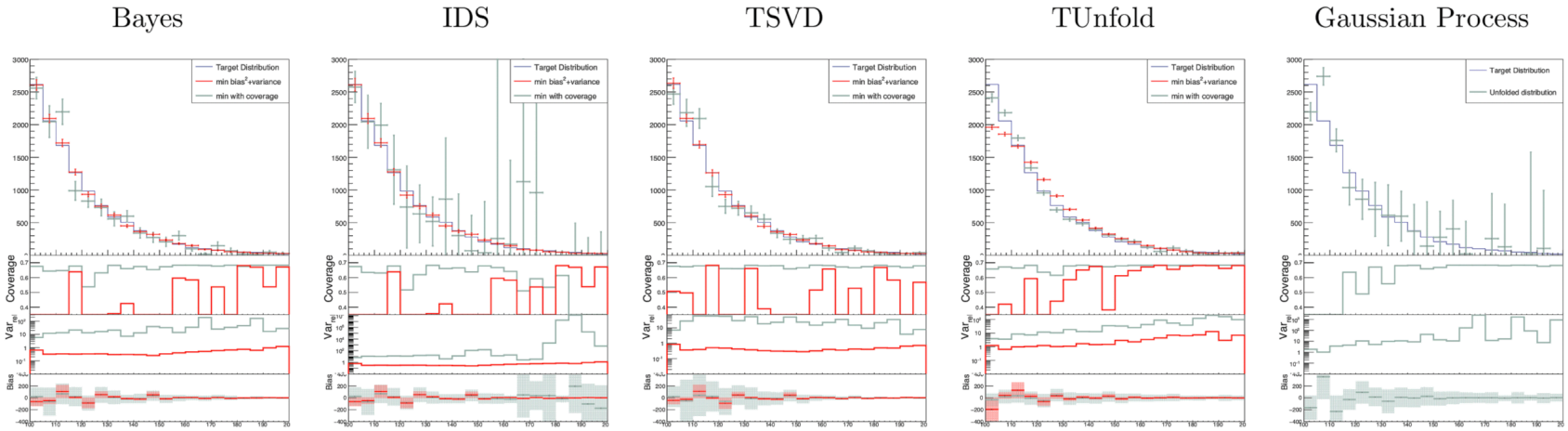
Sensitivity to both CP-even and CP-odd contributions through inclusion of distributions like $\Delta\varphi_{jj}$

Extremely labour intensive measurement…
but result directly interpretable in EFT c_i's

Unfolding is really difficult!

- Unfolding is a numerically very difficult problem that requires ‘regularization’ to make deconvolution step numerically stable
- Many algorithms on the market – with variable sensitivity to assumptions, biases, etc

Unfolding a simply toy distribution – results vary…



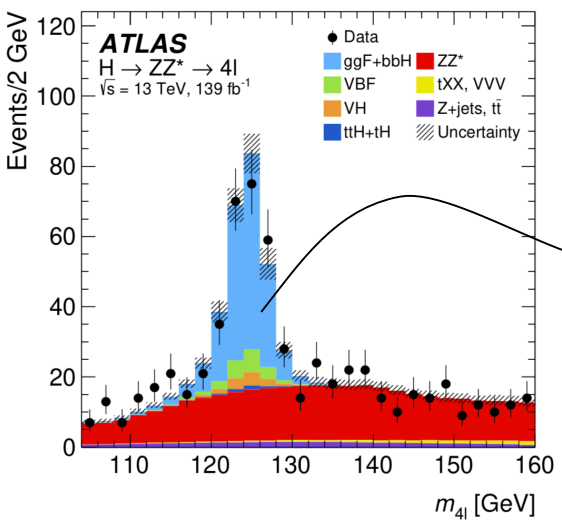
- Unfolded physics distributions are *extremely* time and resource intensive for collaborations to produce!

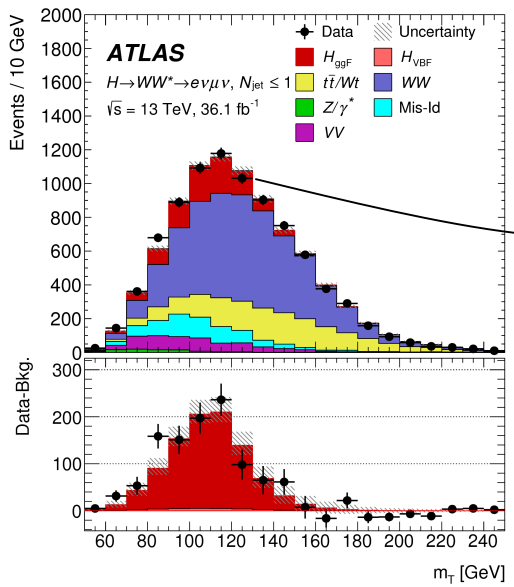
Publishing distributions 2 – the simple & 'ugly' way

- "Simplified Template Cross-Sections"
- Idea – distributions of interest largely originate from H production
  → publish production rates (normalized to SM)

ggF → H → ZZ
VBF → H → ZZ
VH → H → ZZ
} μ(H→ZZ)

ggF → H → WW
VBF → H → WW
VH → H → WW
} μ(H→WW) $\stackrel{\text{def}}{=} \frac{\sigma(H\to WW)}{\sigma(H\to WW)_{SM}}$





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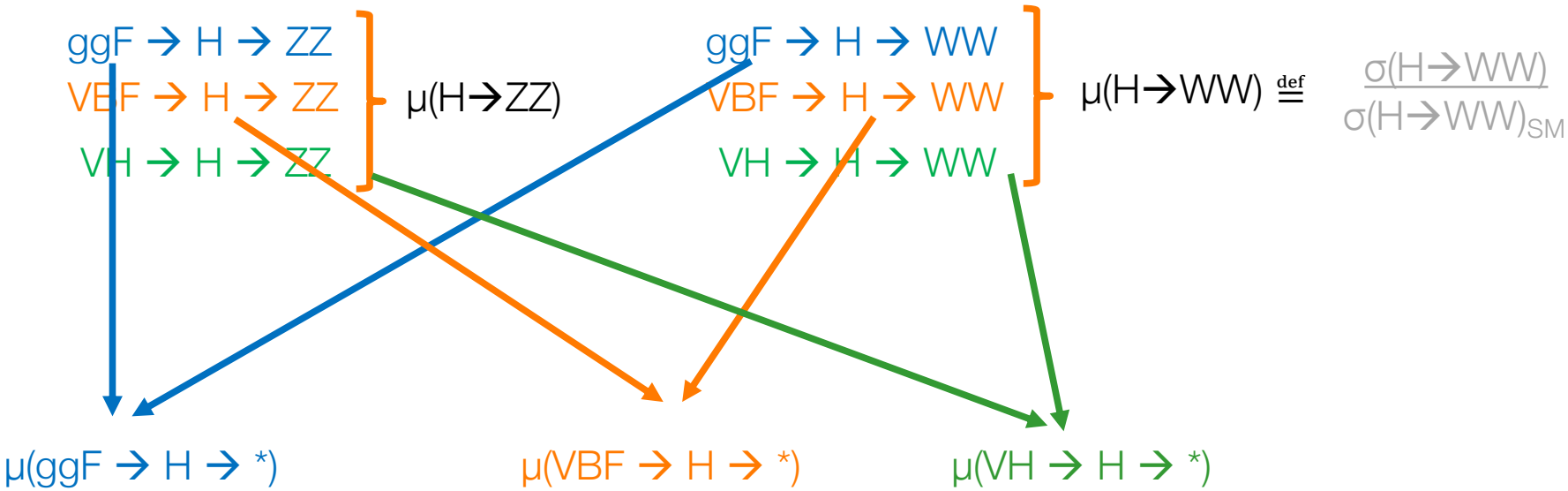

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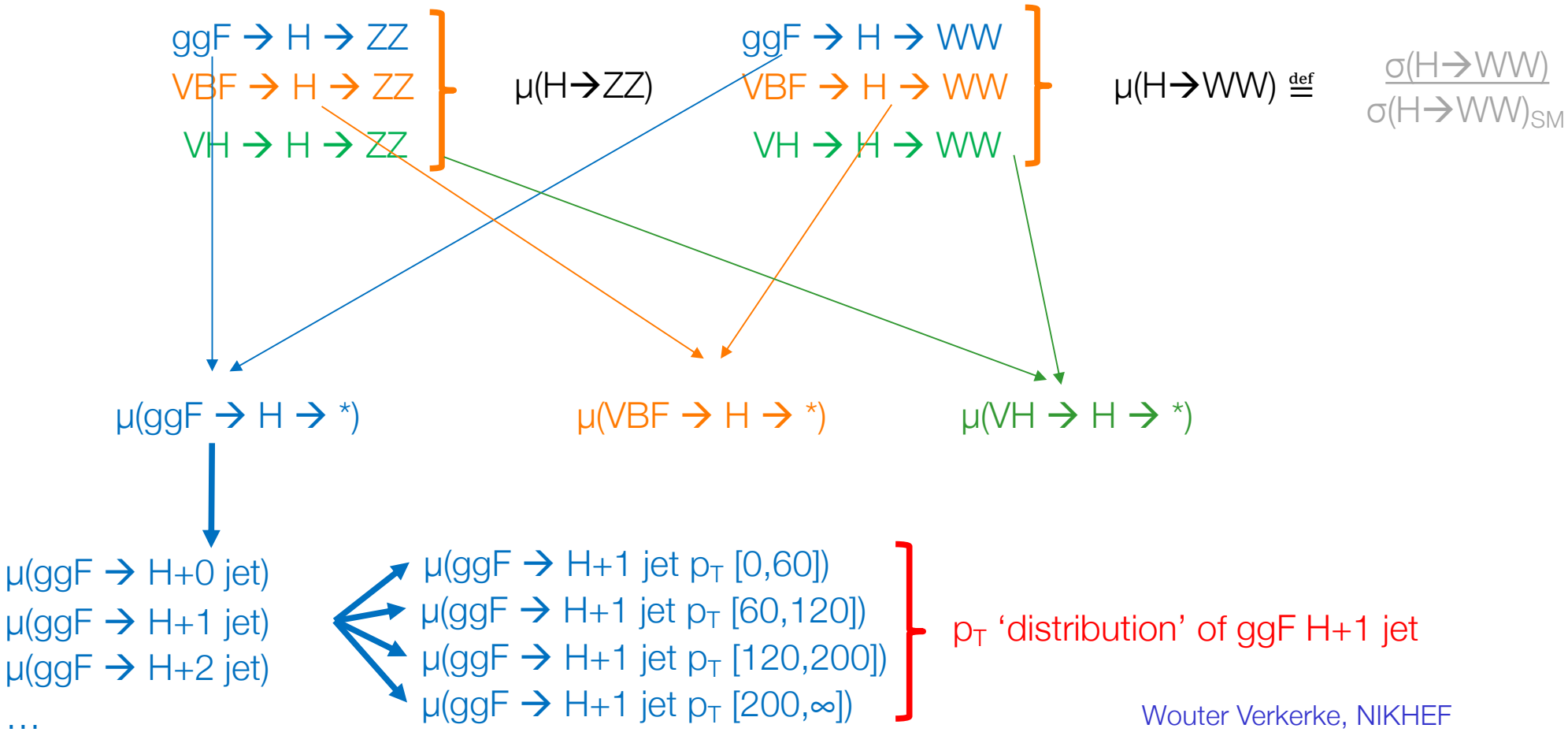

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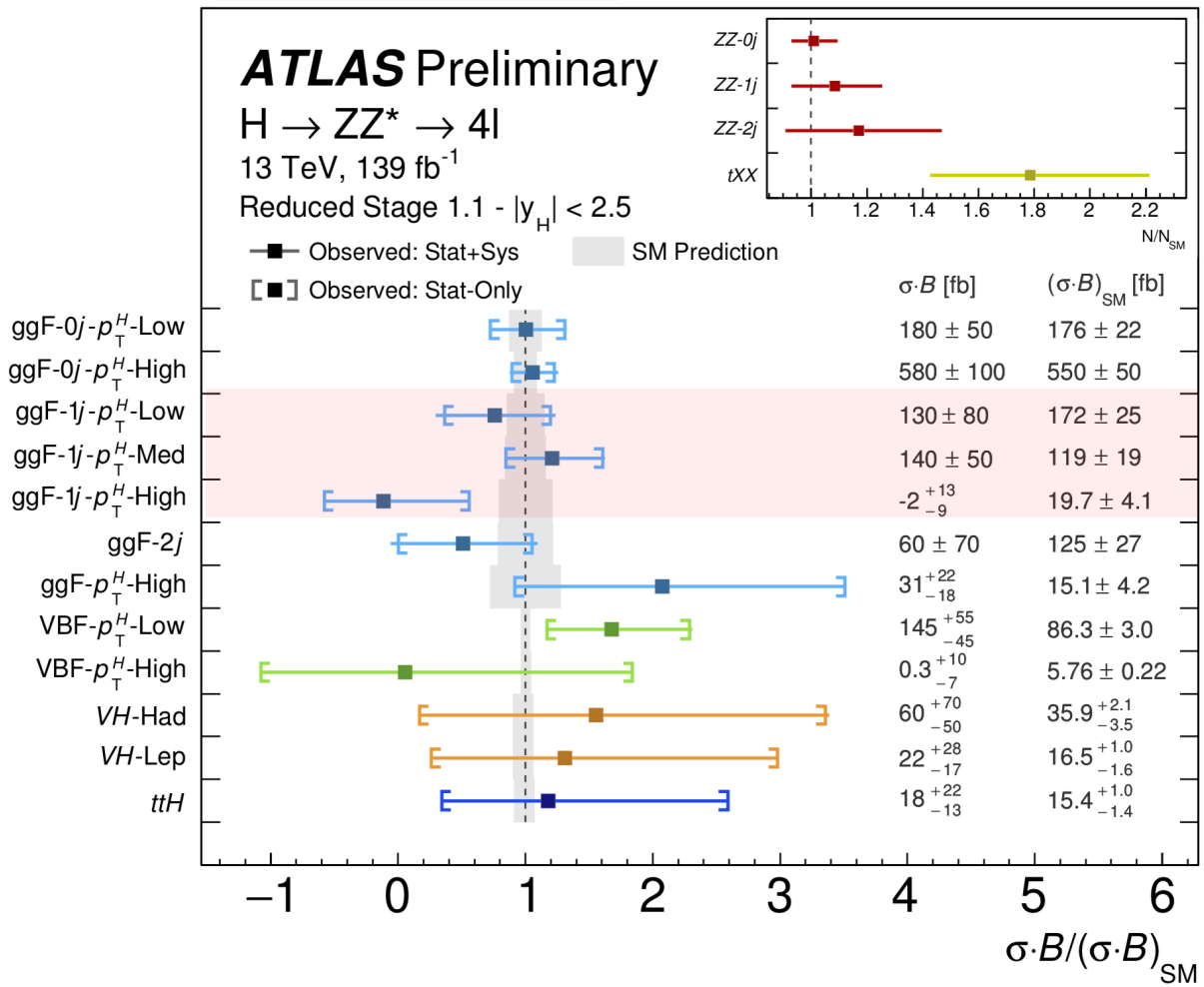


p_T 'distribution' of ggF H+1 jet

Less labour intensive measurement…

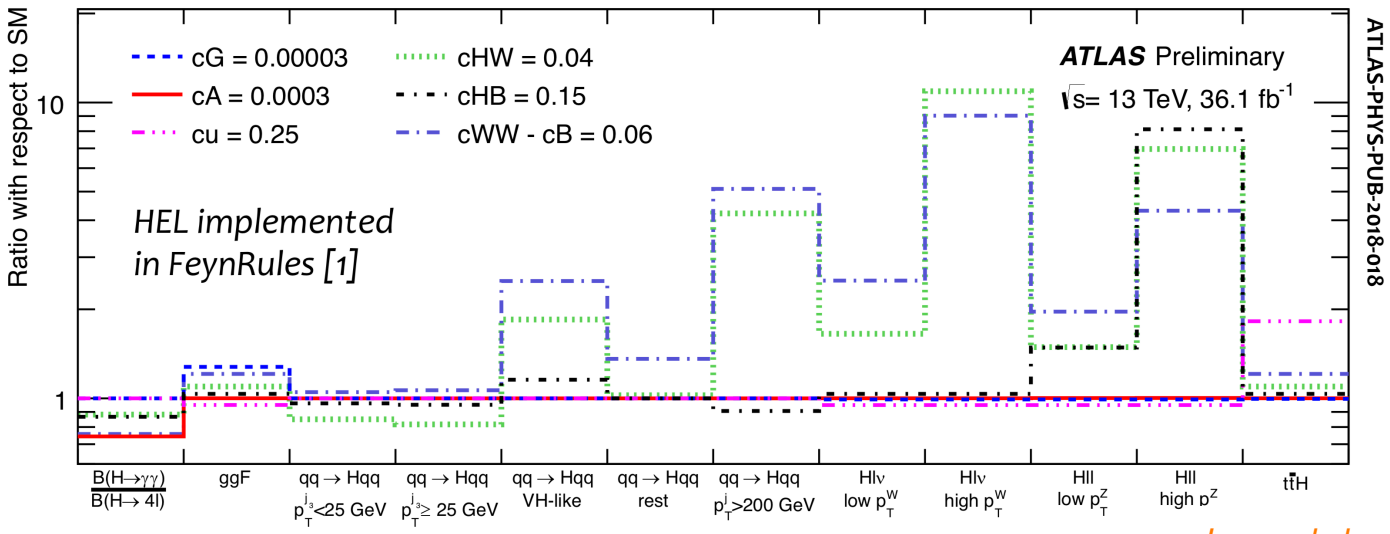
EFT interpretation possible (more more difficult)

Publishing distributions 2 – the simple & 'ugly' way

- Extra work needed to interpret 'STXS distribution' → need MC simulation to map each measured bin μ to expression in c_i
  - STXS distributions → reco-level information → **must account for acceptance effects**

Calculated from MC with MadGraph+STXS Rivet routine

$$\mu = \frac{\sigma}{\sigma_{\mathrm{SM}}} = 1 + \sum_i A_i \bar{c}_i + \sum_{ij} B_{ij} \bar{c}_i \bar{c}_j$$



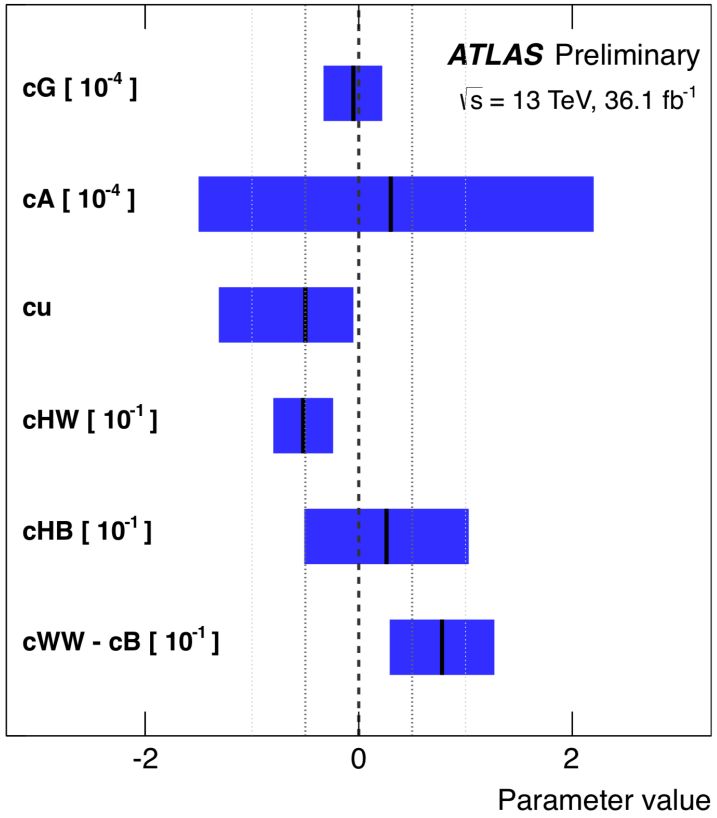
Less labour intensive measurement…

EFT interpretation possible (more more difficult)

Publishing distributions 2 – the simple & 'ugly' way

- Extra work needed to interpret 'STXS distribution' → need MC simulation to map each measured bin μ to expression in c_i
  - First results in effort to make EFT/STXS combinations

Observed HEL constraints with H → ZZ* and H → γγ



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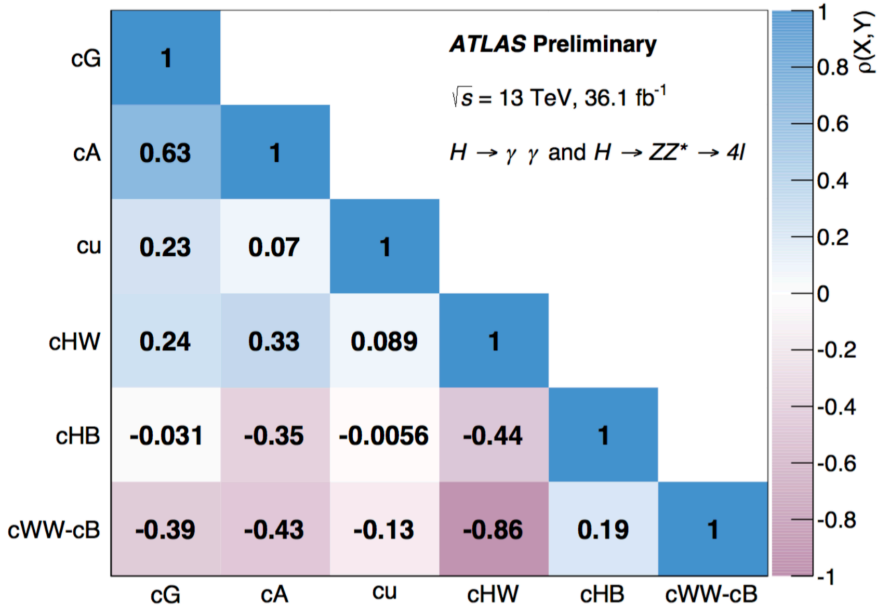


Less labour intensive measurement…

EFT interpretation possible (more more difficult)

Direct modeling of distributions in terms of (SM)EFT c_i

- It is actually *not* needed to (quasi) unfold data to be able to measure EFT coefficients that modify the shapes of distributions
- Consider a measurement of a process with two operators labeled SM and BSM, with strengths g_{SM} and g_{BSM} respectively. Matrix Element is

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

- Transition amplitude is $|M|^2$:

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

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

Resulting distribution described by coefficient-weighted sum of three fixed-shape template distributions!

The mapping of templates to operators

- Note that templates do not need to correspond one-to-one to single operators or pure interference terms

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

- For 2 operator, any three independent pairs of g_{SM},g_{BSM} values can generate templates that will span the whole parameter space. E.g.

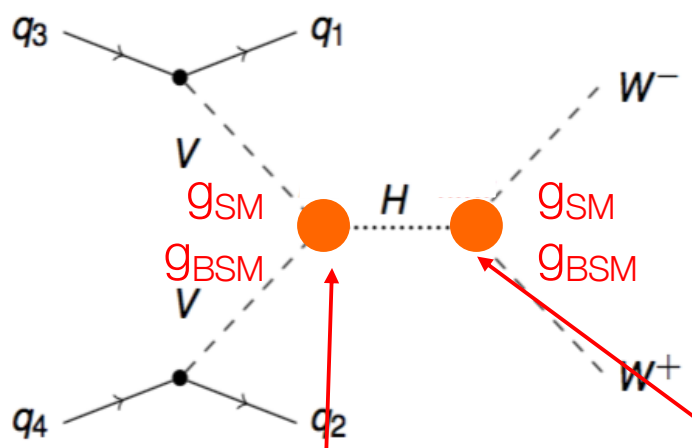
$$T_{in}(1,0) \propto |O_{\mathrm{SM}}|^2$$
$$T_{in}(0,1) \propto |O_{\mathrm{BSM}}|^2$$
$$T_{in}(1,1) \propto |O_{\mathrm{SM}}|^2 + |O_{\mathrm{BSM}}|^2 + 2\mathcal{R}(O_{\mathrm{SM}}^* O_{\mathrm{BSM}})$$

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

Resulting distribution described … sum of three fixed-shape **positive-definite** template distributions **sampled at 'physical' MC generator configurations**

A more realistic physics example

- In many scenarios new physics can enter amplitudes in both the production and decay vertex of a t-channel process



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

A more realistic physics example

- A little math shows we now need 5 independent templates

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

$$\begin{aligned}
|\mathcal{M}(g_{\mathrm{SM}}, g_{\mathrm{BSM}})|^2 &= \left(g_{\mathrm{SM}} O_{\mathrm{SM},p} + g_{\mathrm{BSM}} O_{\mathrm{BSM},p}\right)^2 \cdot \left(g_{\mathrm{SM}} O_{\mathrm{SM},d} + g_{\mathrm{BSM}} O_{\mathrm{BSM},d}\right)^2 && \leftarrow 1 \\
&= g_{\mathrm{SM}}^4 \cdot O_{\mathrm{SM},p}^2 O_{\mathrm{SM},d}^2 + g_{\mathrm{BSM}}^4 \cdot O_{\mathrm{BSM},p}^2 O_{\mathrm{BSM},d}^2 && \leftarrow 2 \\
&+ g_{\mathrm{SM}}^3 g_{\mathrm{BSM}} \cdot \left(O_{\mathrm{SM},p}^2 \Re(O_{\mathrm{SM},d}^* O_{\mathrm{BSM},d}) + \Re(O_{\mathrm{SM},p}^* O_{\mathrm{BSM},p}) O_{\mathrm{SM},d}^2\right) && \leftarrow 3 \\
&+ g_{\mathrm{SM}}^2 g_{\mathrm{BSM}}^2 \cdot \left(O_{\mathrm{SM},p}^2 O_{\mathrm{BSM},d}^2 + O_{\mathrm{BSM},p}^2 O_{\mathrm{SM},d}^2\right) && \leftarrow 4 \\
&+ g_{\mathrm{SM}} g_{\mathrm{BSM}}^3 \cdot \left(O_{\mathrm{BSM},p}^2 \Re(O_{\mathrm{SM},d}^* O_{\mathrm{BSM},d}) + \Re(O_{\mathrm{SM},p}^* O_{\mathrm{BSM},p}) O_{\mathrm{BSM},d}^2\right). && \leftarrow 5
\end{aligned}$$

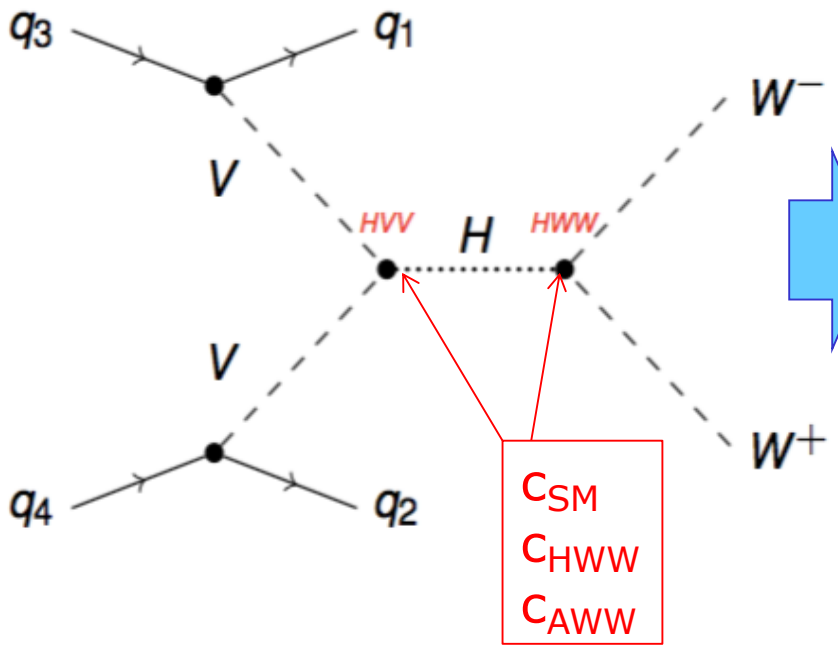
- And the template model can be written as

$$\begin{aligned}
T_{\mathrm{out}}(g_{\mathrm{SM}}, g_{\mathrm{BSM}}) &= \underbrace{\left(a_{11} g_{\mathrm{SM}}^4 + a_{12} g_{\mathrm{SM}}^3 g_{\mathrm{BSM}} + a_{13} g_{\mathrm{SM}}^2 g_{\mathrm{BSM}}^2 + a_{14} g_{\mathrm{SM}} g_{\mathrm{BSM}}^3 + a_{15} g_{\mathrm{BSM}}^4\right)}_{w_1} T_{\mathrm{in}}(g_{\mathrm{SM},1}, g_{\mathrm{BSM},1}) \\
&= \underbrace{\left(a_{21} g_{\mathrm{SM}}^4 + a_{22} g_{\mathrm{SM}}^3 g_{\mathrm{BSM}} + a_{23} g_{\mathrm{SM}}^2 g_{\mathrm{BSM}}^2 + a_{24} g_{\mathrm{SM}} g_{\mathrm{BSM}}^3 + a_{25} g_{\mathrm{BSM}}^4\right)}_{w_2} T_{\mathrm{in}}(g_{\mathrm{SM},2}, g_{\mathrm{BSM},2}) \\
&= \underbrace{\left(a_{31} g_{\mathrm{SM}}^4 + a_{32} g_{\mathrm{SM}}^3 g_{\mathrm{BSM}} + a_{33} g_{\mathrm{SM}}^2 g_{\mathrm{BSM}}^2 + a_{34} g_{\mathrm{SM}} g_{\mathrm{BSM}}^3 + a_{35} g_{\mathrm{BSM}}^4\right)}_{w_3} T_{\mathrm{in}}(g_{\mathrm{SM},3}, g_{\mathrm{BSM},3}) \\
&= \underbrace{\left(a_{41} g_{\mathrm{SM}}^4 + a_{42} g_{\mathrm{SM}}^3 g_{\mathrm{BSM}} + a_{43} g_{\mathrm{SM}}^2 g_{\mathrm{BSM}}^2 + a_{44} g_{\mathrm{SM}} g_{\mathrm{BSM}}^3 + a_{45} g_{\mathrm{BSM}}^4\right)}_{w_4} T_{\mathrm{in}}(g_{\mathrm{SM},4}, g_{\mathrm{BSM},4}) \\
&= \underbrace{\left(a_{51} g_{\mathrm{SM}}^4 + a_{52} g_{\mathrm{SM}}^3 g_{\mathrm{BSM}} + a_{53} g_{\mathrm{SM}}^2 g_{\mathrm{BSM}}^2 + a_{54} g_{\mathrm{SM}} g_{\mathrm{BSM}}^3 + a_{55} g_{\mathrm{BSM}}^4\right)}_{w_5} T_{\mathrm{in}}(g_{\mathrm{SM},5}, g_{\mathrm{BSM},5}).
\end{aligned}$$

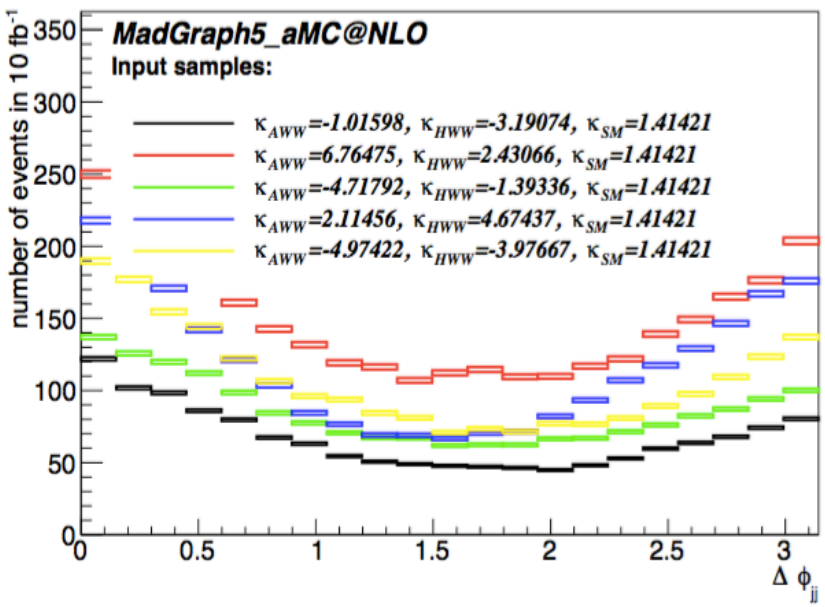
$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{pmatrix} \cdot \begin{pmatrix} g_{\mathrm{SM},1}^4 & g_{\mathrm{SM},2}^4 & g_{\mathrm{SM},3}^4 & g_{\mathrm{SM},4}^4 & g_{\mathrm{SM},5}^4 \\ g_{\mathrm{SM},1}^3 g_{\mathrm{BSM},1} & g_{\mathrm{SM},2}^3 g_{\mathrm{BSM},2} & g_{\mathrm{SM},3}^3 g_{\mathrm{BSM},3} & g_{\mathrm{SM},4}^3 g_{\mathrm{BSM},4} & g_{\mathrm{SM},5}^3 g_{\mathrm{BSM},5} \\ g_{\mathrm{SM},1}^2 g_{\mathrm{BSM},1}^2 & g_{\mathrm{SM},2}^2 g_{\mathrm{BSM},2}^2 & g_{\mathrm{SM},3}^2 g_{\mathrm{BSM},3}^2 & g_{\mathrm{SM},4}^2 g_{\mathrm{BSM},4}^2 & g_{\mathrm{SM},5}^2 g_{\mathrm{BSM},5}^2 \\ g_{\mathrm{SM},1} g_{\mathrm{BSM},1}^3 & g_{\mathrm{SM},2} g_{\mathrm{BSM},2}^3 & g_{\mathrm{SM},3} g_{\mathrm{BSM},3}^3 & g_{\mathrm{SM},4} g_{\mathrm{BSM},4}^3 & g_{\mathrm{SM},5} g_{\mathrm{BSM},5}^3 \\ g_{\mathrm{BSM},1}^4 & g_{\mathrm{BSM},2}^4 & g_{\mathrm{BSM},3}^4 & g_{\mathrm{BSM},4}^4 & g_{\mathrm{BSM},5}^4 \end{pmatrix} = \mathbb{1}$$

A concrete example VBH → H → WW

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



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



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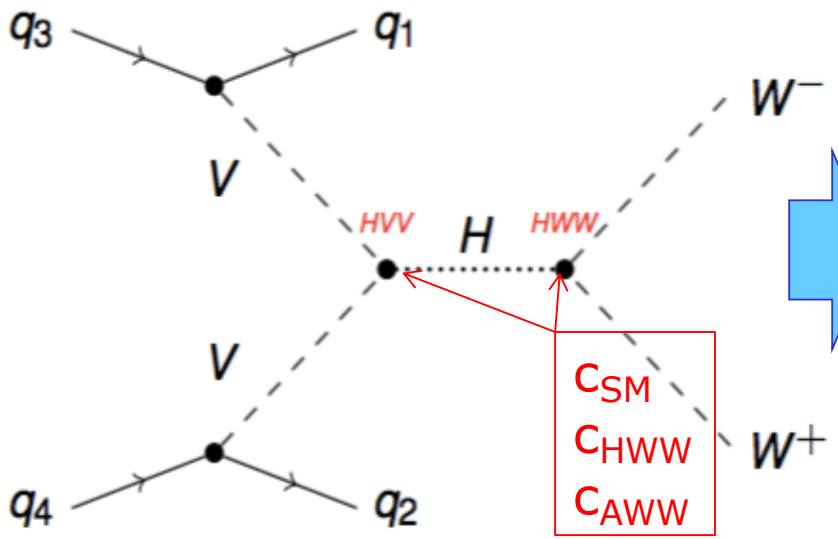

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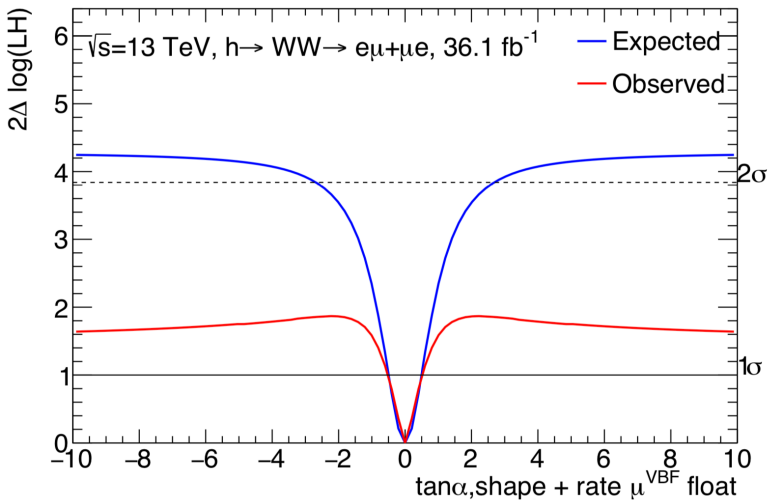
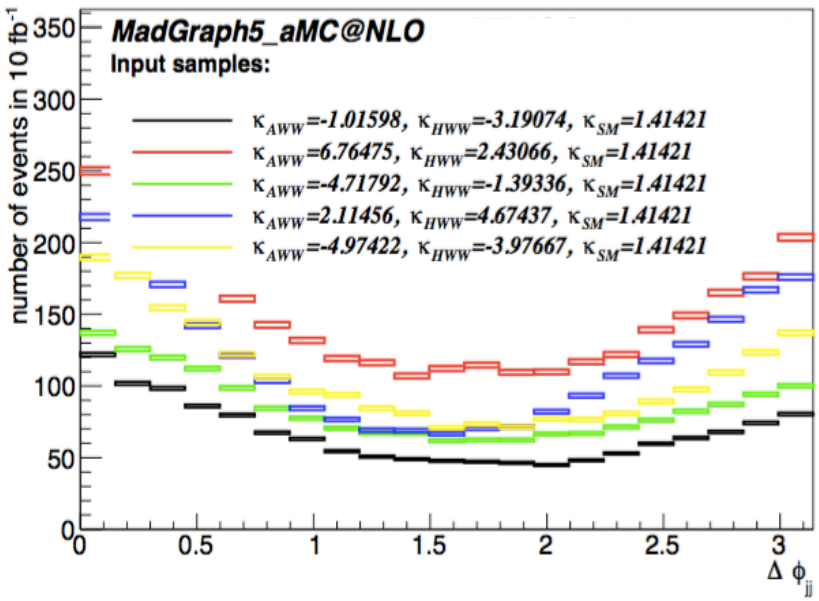
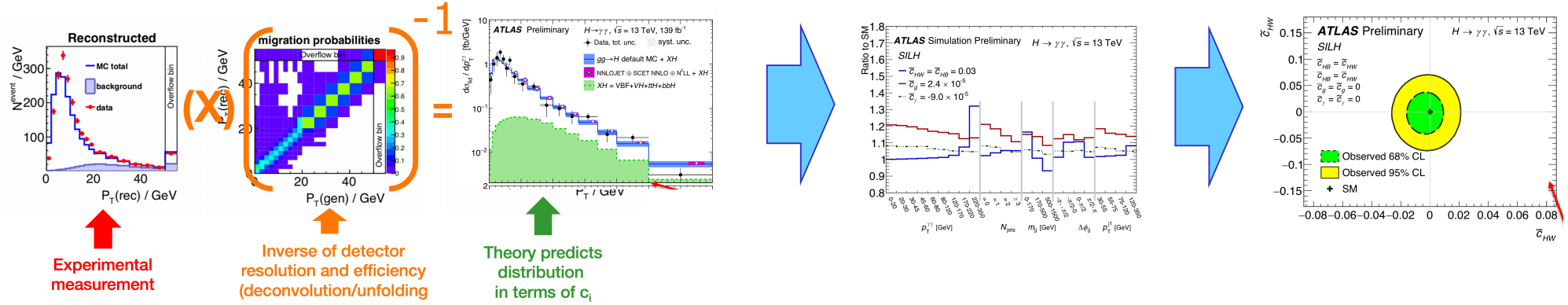


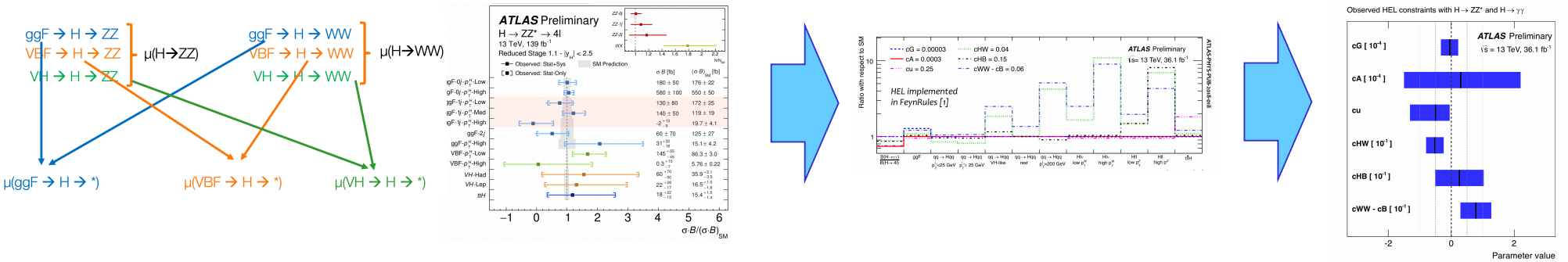


Distributions and their interpretation – 3 ways

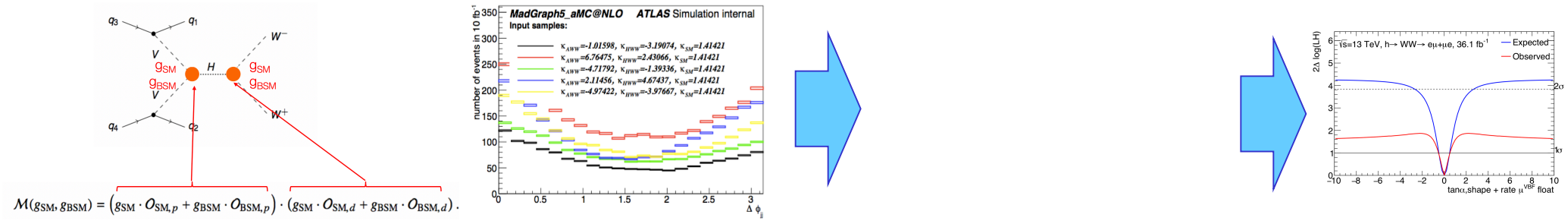
1) **Full unfolding** (very complicated) → SM(EFT) parametrization (easy) → Measurement



2) **Template cross-sections** (med. hard) → SM(EFT) param. (med. hard) →Measurement



3) **Template morphing** with SM(EFT) parametrization (medium) → Measurement

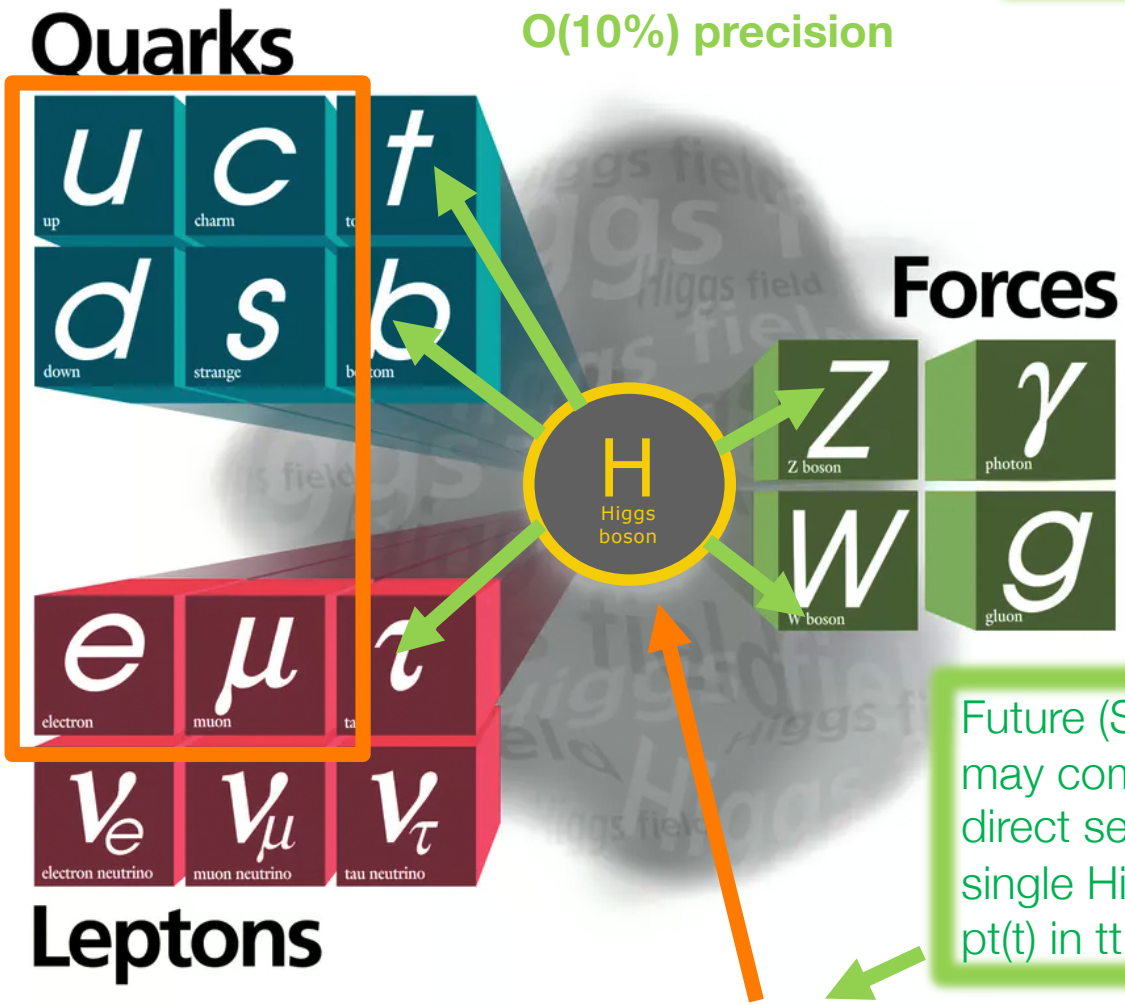


Future (SM)EFT combinations
may combine power of
pt(H) distribution,
direct charm searches and more…

Yukawa couplings to 1st and 2nd generation? [UNPROVEN]

Higgs couplings to 3rd gen fermions and W/Z bosons O(10%) precision

Future (SM)EFT combinations
may leverage power strongly
boosted Higgs production…



Future (SM)EFT combinations
may combine power of
direct searches,
single Higgs production
pt(t) in ttH production and more…

Higgs field/potential, self-couplings? [UNPROVEN]