Higgs fiducial and simplified template cross sections

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Outline

One ~~*Ring*~~ *framework to rule them all, One* ~~*Ring*~~ *framework to find them,*
One ~~*Ring*~~ *framework to bring them all and in the darkness bind them*

J.R. Tolkien

Outline

Another ~~One~~ framework ~~Ring~~ to rule them all, Another ~~One~~ framework ~~Ring~~ to find them,
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J.R. Tolkien

Introduction

Need of a general framework to present measurements on Higgs:

- Useful to theorist (comparable to theory)
- Measurements valid as long as possible (theory change)
- Separate experimental and theoretical uncertainties (theory improves)

Example

Signal strength measurement:
$\mu = (\sigma \cdot \mathcal{B})^{\text{exp.}} / (\sigma \cdot \mathcal{B})^{\text{theo.}} = 1.2^{+0.9}_{-0.5}$
Problems:

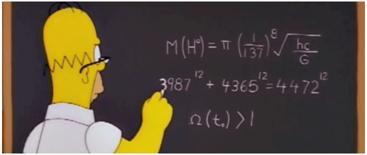
- Theory changes → value should change
- Theory improves → error should reduce

Solution:

- Give measurement of $(\sigma \cdot \mathcal{B})^{\text{exp.}}$
- Can compute μ with whatever modified/improved theory

Example 2

k are not Wilson coefficients (G.Gonella's talk)



Correcting data

Correct data for detector effects to make it usable by theorists!

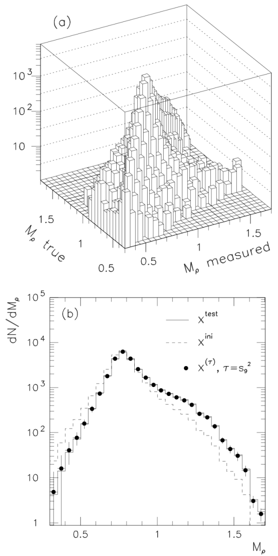
Unfolding procedure

From MC with full detector simulation:

- $X^{\text{det}}_{MC} = \mathcal{M} \otimes X^{\text{truth}}_{MC}$
- compute $\mathcal{M}$

To obtain corrected data:

- $X^{\text{truth}}_{\text{data}} = \mathcal{M}^{-1} \otimes X^{\text{det}}_{\text{data}}$
- Additional correction needed to extrapolate outside detector acceptance.
- Corrected data depends on theoretical assumptions.



arXiv:hep-ph/9509307

The further from detector level, the bigger is the intrinsic theory input on the result.

Fiducial cross sections

Measure cross sections
Correct for detector effects ⟶ fiducial cross sections

$$(\sigma_j)^{\text{fid}}_{\text{exp}} = \frac{N_j^{\text{events}}}{\alpha_j \epsilon_j \mathcal{L}}$$

ϵ_j → unfolding correction → minimise theory dependence by unfolding to suitable truth level

α_j → acceptance correction → extrapolate to phase space outside detector acceptance

- Fiducial cross sections minimise theory dependence on the measurement.
- Exp. and theo. error factorise :

$$\frac{\Delta(\sigma_j)^{\text{fid}}_{\text{exp}}}{(\sigma_j)^{\text{fid}}_{\text{exp}}} = \frac{\Delta N_j^{\text{events}}}{N_j^{\text{events}}} \oplus \frac{\Delta \epsilon_j}{\epsilon_j} \oplus \frac{\Delta \alpha_j}{\alpha_j}$$

Truth levels and unfolding coefficients

Particle level

Objects with lifetime long enough to interact with detector ($\tau > 0.3 \cdot 10^{-10}$s). No interaction with detector is assumed.

- Theo. input in correcting data: "stable" particle interaction with detector
- Directly comparable to theoretical calculation matched to parton shower program.

Parton level

Objects which enter in fixed order calculations, usually generated from the hard process MC generators. Free of shower and hadronisation effects.

- Theo. input in correcting data: "stable" particle interaction with detector, shower&hadronisation modelling.
- Directly comparable to fixed order calculations.

Particle level minimises theory input of unfolding coefficients.

Fiducial phase space and acceptance corrections

Define fiducial phase space the most similar possible to the one at detector level.

↓

Minimises theory input on acceptance factors

Cuts definition	ATLAS	CMS
Obj definition		
Electrons	$p_t > 7$ GeV, $\lvert\eta\rvert < 2.47$	$p_t > 7$ GeV, $\lvert\eta\rvert < 2.5$
Muons	$p_t > 6$ GeV, $\lvert\eta\rvert < 2.7$	$p_t > 5$ GeV, $\lvert\eta\rvert < 2.4$
Event selection		
Lep p_t cuts	$p_t > 20, 15, 10, 10$GeV	$p_t > 20, 10, 7(5), 7(5)$GeV
Inv. masses cuts	$50\text{GeV} < m(l^+, l^-) < 106\text{GeV}$ $12\text{GeV} < m(l'^-, l'^+) < 115\text{GeV}$ $118\text{GeV} < m(llll) < 129\text{GeV}$ $m(l^+, l^-) > 5\text{GeV}$	$40\text{ GeV} < m(l^+, l^-) < 120\text{ GeV}$ $12\text{GeV} < m(l'^-, l'^+) < 120\text{GeV}$ $105\text{GeV} < m(llll) < 140\text{GeV}$ $m(l^+, l^-) > 4\text{GeV}$
Lep separation	$\Delta R(l_i, l_j) > 0.1(0.2)$ for same(opposite) sign	$\Delta R(l_i, l_j) > 0.02$ for every $i \neq j$

Differences in the definition of fiducial volumes for H→ 4l in ATLAS and CMS.

Same cuts are applied to detector level objects.

[Phys. Lett. B738 (2014) 234-253 and CMS-PAS-HIG-14-028]

Unfolding and acceptance factors

Signal process	α_i (to whole phase space)	ϵ_j
Higgs production modes		
ggH	0.422 ± 0.001	0.681 ± 0.002
VBF	0.476 ± 0.003	0.678 ± 0.005
WH	0.342 ± 0.002	0.672 ± 0.003
ZH	0.348 ± 0.003	0.679 ± 0.005
ttH	0.250 ± 0.003	0.685 ± 0.010
Non-SM models		
$q\bar{q} \rightarrow H(J^{\mathrm{CP}} = 1^-)$	0.238 ± 0.001	0.642 ± 0.002
$q\bar{q} \rightarrow H(J^{\mathrm{CP}} = 1^+)$	0.283 ± 0.001	0.651 ± 0.002
$gg \rightarrow H \rightarrow Z\gamma^*$	0.156 ± 0.001	0.667 ± 0.002
$gg \rightarrow H \rightarrow \gamma^*\gamma^*$	0.238 ± 0.001	0.671 ± 0.002

Unfolding and extrapolation correction factors, for $H \rightarrow 4l$ analysis (from CMS-PAS-HIG-14-028).

Acceptance factors depend on Higgs production modes.

σ^{fid} limitations

Limitations of fiducial cross sections:

Extrapolation factors depend on production modes.

To combine measurements, need to extrapolate to a common fiducial phase space.
Dependence of acceptance factors on production modes

Advanced event selection

To enhance experimental sensitivity, experiments use advanced techniques (BDT, MVA, NN...), which are not easily reproducible.

- Give simplified version of advanced experimental techniques used.
- Use only cuts on kinematic variables.

Theory side

σ^{fid} theoretical calculations need to be implemented in a MC generator. (M. Boggia talk)
Most of the calculations are NLO QCD + PS .

Simplified template cross sections

Simplified template cross sections (STXS) framework aims to find a good balance between experimental sensitivity and theoretical independence of Higgs cross section measurements.

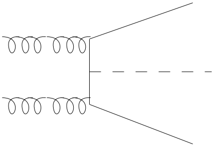
- σ-like measurements (and not μ-like)
- Combine decay channels
  - reduce stat. unc. (main unc. for most Higgs σ)
  - reduce fluctuations
  - introduce theoretical dependence
- Allow using advanced experimental techniques
  - use simplified fiducial volumes (*bins*)
- Distinguish different production modes

Truth level for STXS

Optimised definition of truth level for STXS:

- Particle level objects → minimise theory dependence in unfolding
- Higgs stable → agnostic to Higgs decay

Parton level



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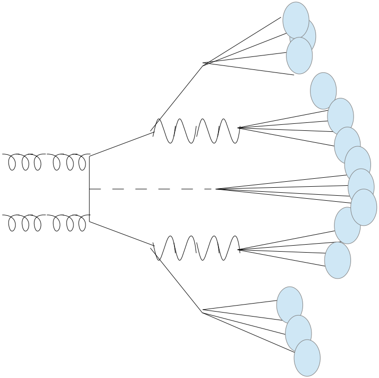
Particle level



Truth level for STXS

Optimised definition of truth level for STXS:

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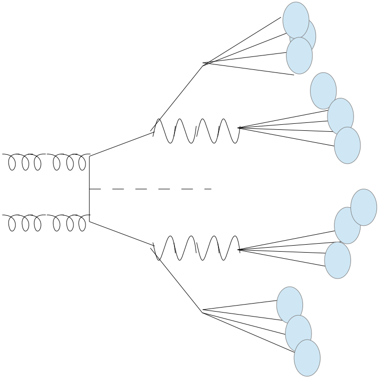
- Higgs stable → agnostic to Higgs decay

STXS truth level



STXS formula

Stage 0 simplied template cross sections $\sigma_i^{\alpha_1}$:

$$\sigma^f_{\text{exp}} = \sum_{i,\alpha_0} A^f{}_{i,\alpha_0} \cdot \overbrace{\sigma^{\alpha_0}{}_i} \qquad (\textit{stage } 0)$$
$$= A^f_{ggH} \cdot \sigma_{ggH} \; + \; A^f_{VBF} \cdot \sigma_{VBF} + \ldots$$

- f : final states / experimental categories
- i: Higgs production modes
- α_0: *bins* (simplified fiducial volume indices)

At stage 0, STXSs are total production cross sections
(close to signal strength fits)

A^f_{i,α_0} computed within SM

Stages 1 and 2

Divide *stage* 0 simplified fiducial volumes in smaller ones, and so on:

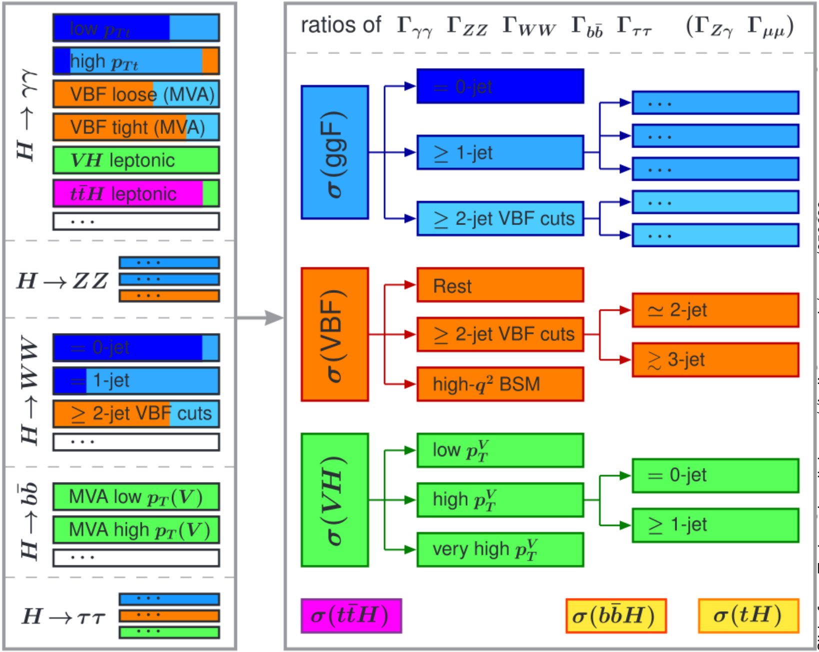
↓

stage 1 and *stage* 2 STXSs

$$\sigma^f_{\text{exp}} = \sum\nolimits_{i,\alpha_0\alpha_1} A^f_{i,\alpha_0\alpha_1} \cdot \sigma_i^{\alpha_0\alpha_1} \qquad (\textit{stage } 1)$$

$$\sigma^f_{\text{exp}} = \sum\nolimits_{i,\alpha_0\alpha_1\alpha_2} A^f_{i,\alpha_0\alpha_1} \cdot \sigma_i^{\alpha_0\alpha_1\alpha_2} \qquad (\textit{stage } 2)$$

- α_1, α_2 indices running on sub-*bins*
- Does not make sense to continue staging, because of limited statistics.



$H \to \gamma\gamma$

low p_{Tt}

high p_{Tt}

VBF loose (MVA)

VBF tight (MVA)

VH leptonic

$t\bar{t}H$ leptonic

...

$H \to ZZ$

...

...

...

$H \to WW$

= 0-jet

= 1-jet

$\geq$ 2-jet VBF cuts

...

$H \to b\bar{b}$

MVA low $p_T(V)$

MVA high $p_T(V)$

...

$H \to \tau\tau$

...

...

...

ratios of $\Gamma_{\gamma\gamma}$ Γ_{ZZ} Γ_{WW} $\Gamma_{b\bar{b}}$ $\Gamma_{\tau\tau}$ $(\Gamma_{Z\gamma}$ $\Gamma_{\mu\mu})$

σ(ggF)

= 0-jet

$\geq$ 1-jet

...

...

...

$\geq$ 2-jet VBF cuts

...

...

σ(VBF)

Rest

$\geq$ 2-jet VBF cuts

$\simeq$ 2-jet

$\gtrsim$ 3-jet

high-q^2 BSM

$\sigma(VH)$

low p_T^V

high p_T^V

= 0-jet

$\geq$ 1-jet

very high p_T^V

$\sigma(t\bar{t}H)$ $\sigma(b\bar{b}H)$ $\sigma(tH)$

Slide from Tackman's talk https://indico.cern.ch/event/350628

Binning choice

bins = simplified fiducial volumes

- Theory independent (BSM also)
- Cuts apply to truth level objects
- Isolate regions sensitive to BSM
- Allow for *bins* combination

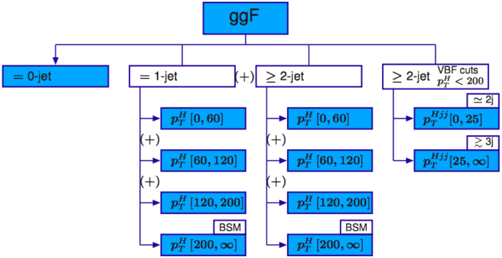


Figure 219: Stage 1 binning for gluon fusion production.

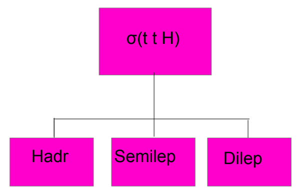
From YR4 (arXiv:1610.07922)

$t\bar{t}H$ binning: proposals

- Experiments are now starting to fill *bins* of stage 1.
- No consensuos proposal for $t\bar{t}H$ binning (still *stage* 0 though).
- No proposal for $b\bar{b}H$, Ht (far from being discovered)

YR4 proposal

- Distinguish between $t\bar{t}$ decays
- Highly model independent
- Not really BSM sensitive



σ(t t H)

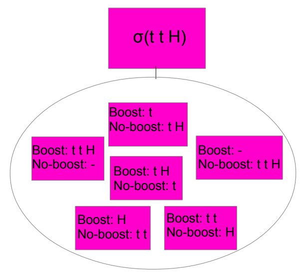
Hadr

Semilep

Dilep

last week LHCXWG2 proposal

- Use $t\bar{t}H$ kinematic regimes (defined via decay products (also H)
- *bins* sensitive to BSM



σ(t t H)

Boost: t
No-boost: t H

Boost: t t H
No-boost: -

Boost: t H
No-boost: t

Boost: -
No-boost: t t H

Boost: H
No-boost: t t

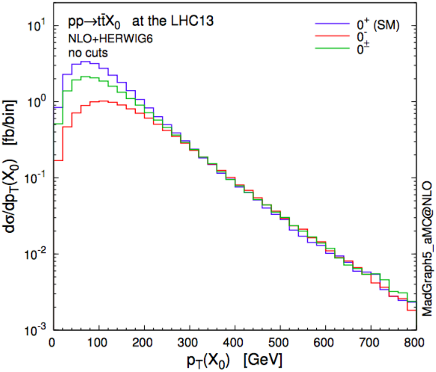
Boost: t t
No-boost: H

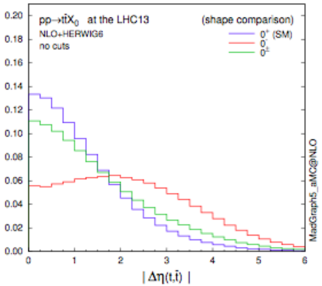
$t\bar{t}H$ binning: our proposal

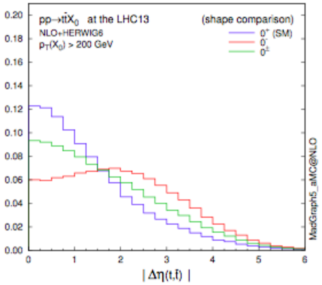
Motivations - Phys. J. C (2014) 74: 3065

- NP at high(er) scale
- CP properties of $t - H$ interaction:

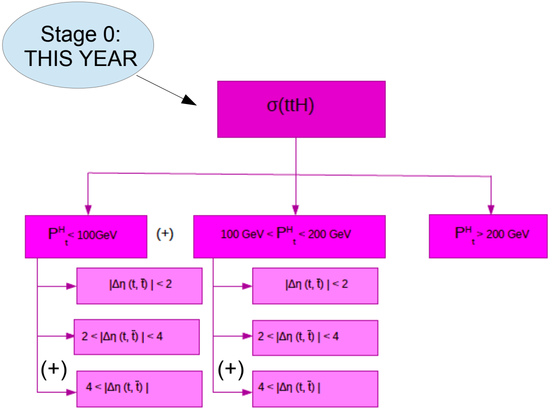
$$\mathcal{L} \propto t(a + b\gamma^5)tH$$





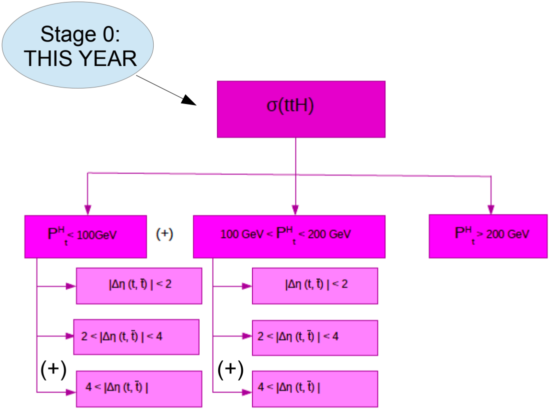


$t\bar{t}H$ binning: our proposal



Presented for the first time

$t\bar{t}H$ binning: our proposal



Stage 0: THIS YEAR

σ(ttH)

P_t^H < 100GeV (+) 100 GeV < P_t^H < 200 GeV

P_t^H > 200 GeV

$|\Delta\eta(t,\bar{t})| < 2$

$2 < |\Delta\eta(t,\bar{t})| < 4$

(+) $4 < |\Delta\eta(t,\bar{t})|$

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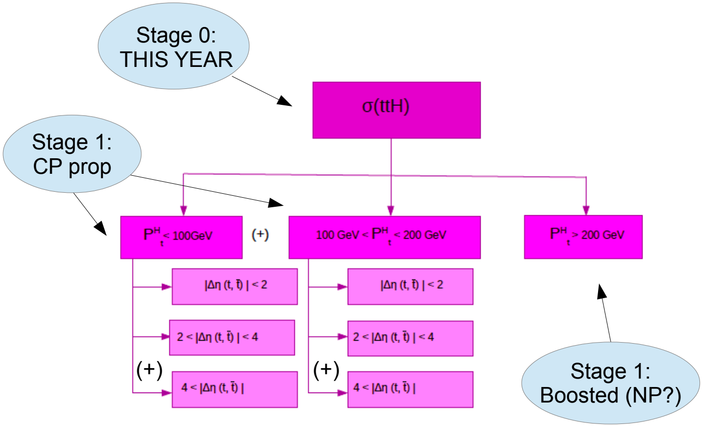
(+) $4 < |\Delta\eta(t,\bar{t})|$

Presented for the first time

$t\bar{t}H$ binning: our proposal



Stage 0:
THIS YEAR

σ(ttH)

Stage 1:
CP prop

$P_t^H < 100$GeV

(+)

100 GeV < P_t^H < 200 GeV

$P_t^H > 200$ GeV

$|\Delta\eta\,(t,\bar{t})| < 2$

$2 < |\Delta\eta\,(t,\bar{t})| < 4$

(+)

$4 < |\Delta\eta\,(t,\bar{t})|$

$|\Delta\eta\,(t,\bar{t})| < 2$

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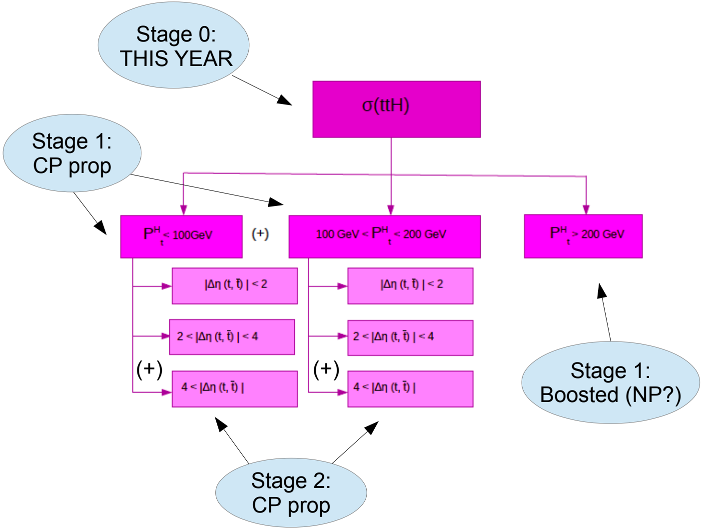
(+)

$4 < |\Delta\eta\,(t,\bar{t})|$

Stage 1:
Boosted (NP?)

Presented for the first time

$t\bar{t}H$ binning: our proposal



Stage 0: THIS YEAR

$\sigma(ttH)$

Stage 1: CP prop

$P_t^H < 100$GeV

(+)

100 GeV < P_t^H < 200 GeV

$P_t^H > 200$ GeV

$|\Delta\eta\,(t,\bar{t})| < 2$

$2 < |\Delta\eta\,(t,\bar{t})| < 4$

(+)

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$2 < |\Delta\eta\,(t,\bar{t})| < 4$

(+)

$4 < |\Delta\eta\,(t,\bar{t})|$

Stage 1: Boosted (NP?)

Stage 2: CP prop

Presented for the first time

Interplay with pseudobservables

See A. Ilnicka's talk on proper definition of POs.
For what we are interested in here:

POs for STXSs

- Model indep. way to parametrize particle interactions
- Linear in amplitude → quadratic in cross section
- Need proxy to check expansion arounde physical poles
- Interaction modelling enters in both production and decays → correlations

POs available for EW production and deacy modes, not yet for all QCD modes

Higgs (EW) production amplitudes

Amplitudes	Flavour + CP	Flavour Non Univ.	CPV
VBF neutral curr. and Zh	$[\,\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}\,]$ $\epsilon_{Zu_L}, \epsilon_{Zu_R}, \epsilon_{Zd_L}, \epsilon_{Zd_R}$	$\epsilon_{Zc_L}, \epsilon_{Zc_R}$ $\epsilon_{Zs_L}, \epsilon_{Zs_R}$	$\left[\,\epsilon^{CP}_{ZZ}, \delta^{CP}_{Z\gamma}, \delta^{CP}_{\gamma\gamma}\,\right]$
VBF charged curr. and Wh	$[\,\kappa_{WW}, \epsilon_{WW}\,]$ $\mathrm{Re}(\epsilon_{Wu_L})$	$\mathrm{Re}(\epsilon_{Wc_L})$	$[\epsilon^{CP}_{WW}]$, $\mathrm{Im}(\epsilon_{Wu_L})$ $\mathrm{Im}(\epsilon_{Wc_L})$

Higgs (QCD) production modes

κ_g	$\sigma(pp \to h)_{gg-\text{fusion}} = \sigma(pp \to h)^{\text{SM}}_{gg-\text{fusion}} \kappa_g^2$
κ_t	$\sigma(pp \to t\bar{t}h)_{\text{Yukawa}} = \sigma(pp \to t\bar{t}h)^{\text{SM}}_{\text{Yukawa}} \kappa_t^2$

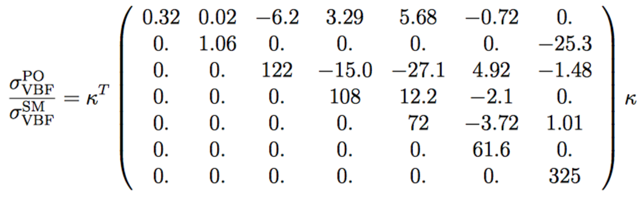
PO: Branching ratios vs STXS

Writing STXSs in terms of POs (theo):

$$\underbrace{\sigma_i^{\alpha_j}}_{\text{STXS, prod } i\text{, bin } \alpha_j} = \sum_{a,b} \underbrace{\left[\mathcal{C}_i^{\alpha_j}\right]_{ab}}_{\text{theo computed coeff.}} \underbrace{k_a k_b}_{POs}$$

"Example" for $\left[\mathcal{C}_i^{\alpha_j}\right]_{ab}$ in VBF

arXiv:1512.06135



$$\frac{\sigma_{\rm VBF}^{\rm PO}}{\sigma_{\rm VBF}^{\rm SM}} = \kappa^T \begin{pmatrix} 0.32 & 0.02 & -6.2 & 3.29 & 5.68 & -0.72 & 0. \\ 0. & 1.06 & 0. & 0. & 0. & 0. & -25.3 \\ 0. & 0. & 122 & -15.0 & -27.1 & 4.92 & -1.48 \\ 0. & 0. & 0. & 108 & 12.2 & -2.1 & 0. \\ 0. & 0. & 0. & 0. & 72 & -3.72 & 1.01 \\ 0. & 0. & 0. & 0. & 0. & 61.6 & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. & 325 \end{pmatrix} \kappa$$

Global fits

Determination of all POs / Wilson coefficients in a global fit
by combining all STXSs / decay widths measurements.

Requirements

- Generators producing theoretical predictions (M. Boggia's talk)
- Need all the correlations between the measurements
- Observables - coupling relations
- Impact of NP on event selections, acceptances, efficiencies
- Software performing the fit

Usually global fits performed by theorists, but not all the information is publicly available

Challenges

Observables to couplings relations

- Higgs POs and EFT have $\mathcal{O}(50)$ coefficients.
- Only $\mathcal{O}(1) - \mathcal{O}(10)$ enter in observables calculations
- Need simulation to detector level to check NP effect on data correction

$n^p \cdot X$ GB , with n variations, p parameters, X is MC output weight

10^6 events events in .LHE file $\rightarrow$ $X \approx 500$MB
$n = 4$ variations for each coefficient
$p = 5$ coefficients in observable calculation
≈ 500 GB , for each independent observable

The Worldwide LHC computing grid (WLCG) handles $\approx 2 \cdot 10^8$ GB disk storage

Reduce MC size

- Morphing techiniques reduce n^p: $\mathcal{R}(\vec{k}_{\text{new}}) = \sum_{i=1}^{n} w\left(\vec{k}_{\text{new}}, \vec{k}_i\right) \cdot \mathcal{R}(\vec{k}_i)$
- Detector simulation smearing .lhe output (no need for full det sim)

Challenges

Fit framework

- Global fit is usually a likelihood ($\mathcal{L}$) minimisation
- Lots of observables, correlations and multiple parameters to fit
- $\mathcal{L}$ difficult to compute
- Usually multivariate Gaussian model

$$p(x;\mu,\Sigma) = \frac{1}{(2\pi)^{\frac{n}{2}}|\Sigma|^{\frac{1}{2}}}\exp\left(-\frac{1}{2}(x-\mu)^T\Sigma(x-\mu)\right) \qquad \text{with } \Sigma_{ij} = \sigma_i\sigma_j\rho_{ij}$$

Complicated $\mathcal{L}$ could need seconds to be computed.
Minimisation require multiple calls (exponential with dimension of parameters)
Multidimensional minimisation often has empty bins

Profiling

Extract one fitted value at a time, by profiling on others
Repeat procedure for each value

Summary and conclusions

Strategies to catalogise Higgs measurements has been presented.
Several aspects have been taken into account:

- Data unfolding
- Truth levels and fiducial phase spaces
- STXSs binning ($t\bar{t}H$ in particular)
- STXSs connection with POs
- Global fits challenges

Efforts started toward a global fit for Higgs physics.
Most of the ongoing work require a theoretical-experimental collaboration.

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Thanks for your attention!

Back-up

POs and BRs

PO	*Physical* PO	Relation to the eff. coupl.
$\kappa_f,\ \delta_f^{\mathrm{CP}}$	$\Gamma(h \to f\bar{f})$	$= \Gamma(h \to f\bar{f})^{(\mathrm{SM})}[(\kappa_f)^2 + (\delta_f^{\mathrm{CP}})^2]$
$\kappa_{\gamma\gamma},\ \delta_{\gamma\gamma}^{\mathrm{CP}}$	$\Gamma(h \to \gamma\gamma)$	$= \Gamma(h \to \gamma\gamma)^{(\mathrm{SM})}[(\kappa_{\gamma\gamma})^2 + (\delta_{\gamma\gamma}^{\mathrm{CP}})^2]$
$\kappa_{Z\gamma},\ \delta_{Z\gamma}^{\mathrm{CP}}$	$\Gamma(h \to Z\gamma)$	$= \Gamma(h \to Z\gamma)^{(\mathrm{SM})}[(\kappa_{Z\gamma})^2 + (\delta_{Z\gamma}^{\mathrm{CP}})^2]$
κ_{ZZ}	$\Gamma(h \to Z_L Z_L)$	$= (0.209\ \mathrm{MeV}) \times \lvert\kappa_{ZZ}\rvert^2$
ϵ_{ZZ}	$\Gamma(h \to Z_T Z_T)$	$= (1.9 \times 10^{-2}\ \mathrm{MeV}) \times \lvert\epsilon_{ZZ}\rvert^2$
$\epsilon_{ZZ}^{\mathrm{CP}}$	$\Gamma^{\mathrm{CPV}}(h \to Z_T Z_T)$	$= (8.0 \times 10^{-3}\ \mathrm{MeV}) \times \lvert\epsilon_{ZZ}^{\mathrm{CP}}\rvert^2$
ϵ_{Zf}	$\Gamma(h \to Z f\bar{f})$	$= (3.7 \times 10^{-2}\ \mathrm{MeV}) \times N_c^f\ \lvert\epsilon_{Zf}\rvert^2$
κ_{WW}	$\Gamma(h \to W_L W_L)$	$= (0.84\ \mathrm{MeV}) \times \lvert\kappa_{WW}\rvert^2$
ϵ_{WW}	$\Gamma(h \to W_T W_T)$	$= (0.16\ \mathrm{MeV}) \times \lvert\epsilon_{WW}\rvert^2$
$\epsilon_{WW}^{\mathrm{CP}}$	$\Gamma^{\mathrm{CPV}}(h \to W_T W_T)$	$= (6.8 \times 10^{-2}\ \mathrm{MeV}) \times \lvert\epsilon_{WW}^{\mathrm{CP}}\rvert^2$
ϵ_{Wf}	$\Gamma(h \to W f\bar{f}')$	$= (0.14\ \mathrm{MeV}) \times N_c^f\ \lvert\epsilon_{Wf}\rvert^2$

NP impact on data correction

Efficiencies and accpetance factors could depend on the underlying event.
Need to check that this is minimised → generate NP MC samples to detector level

Time to generate an event at detector level (tipically needed $10^8 - 10^9$ events)

- Experiments fast simulations: ≈ 100 s/evt
- Delphes: ≈ 1 s/evt
- Smearing .lhe file: $\approx 10^{-3}$ s/evt