SnowMass2021

Future perspectives for EFT studies at LHC

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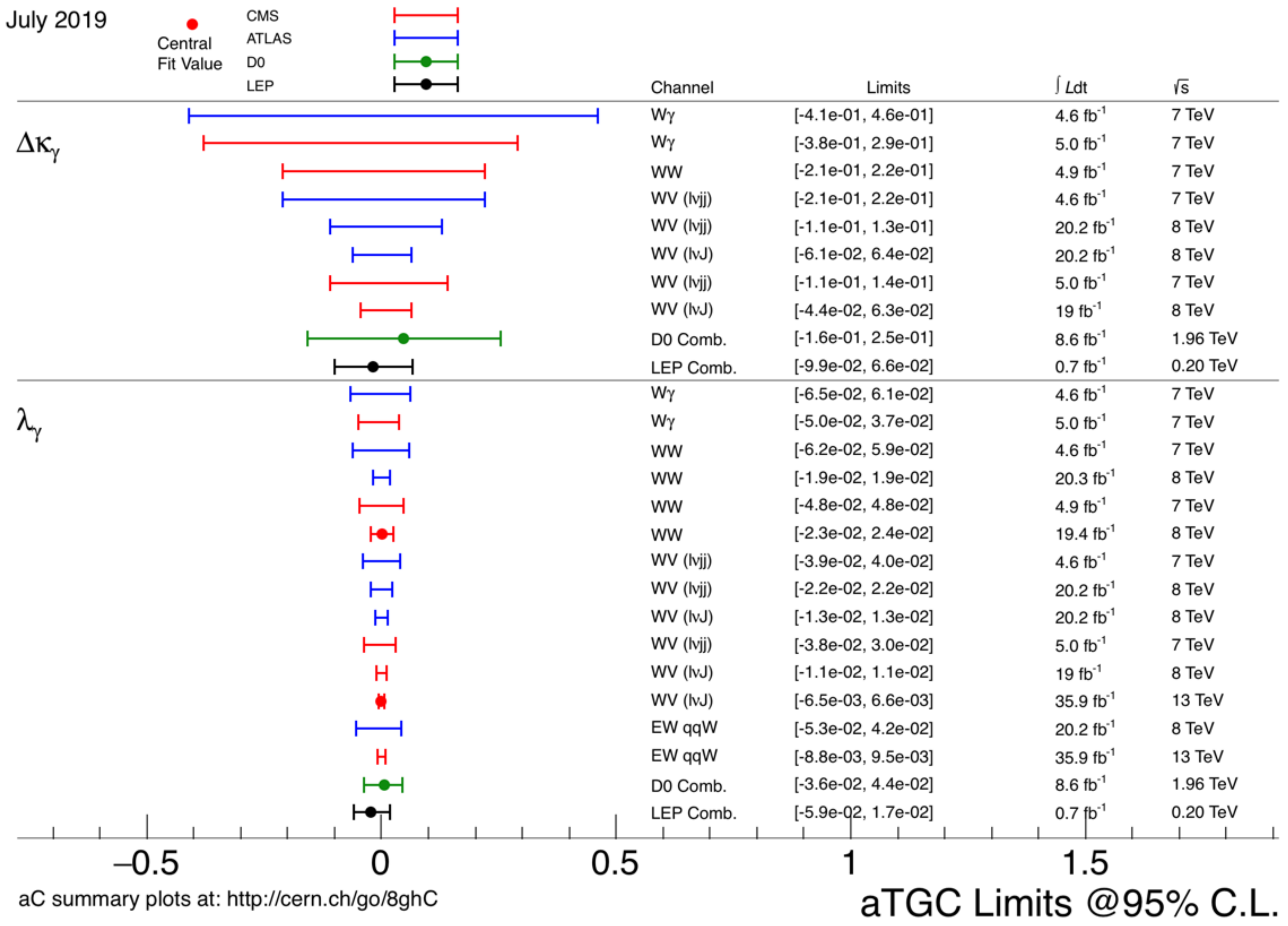
a preliminary disclaimer

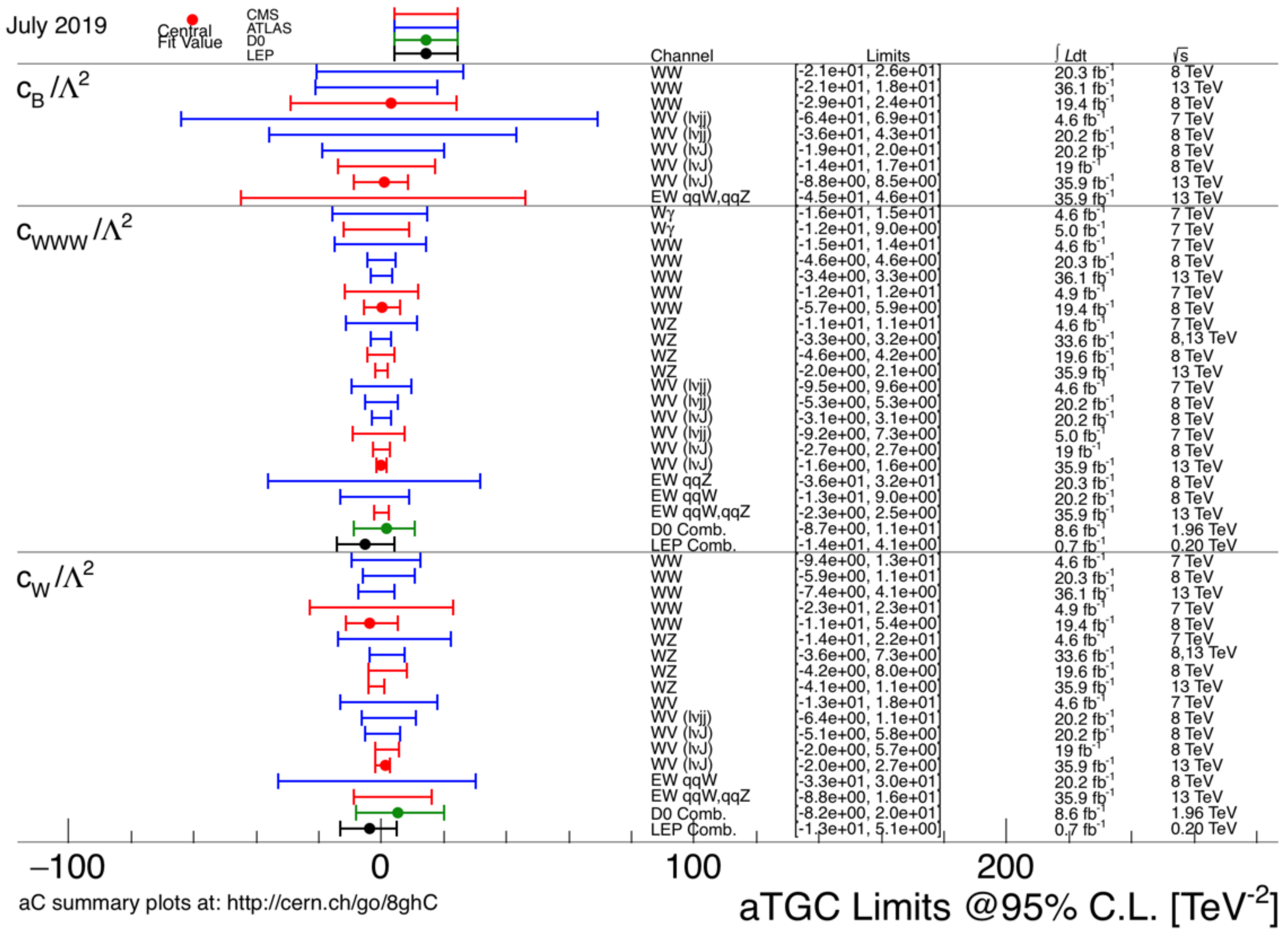
- this is a biased talk: I work in the CMS Collaboration, with some experience in the Higgs boson search and multi-boson processes (VBS)
- in the first part of the talk, an incomplete collection of material is meant as an example to trigger the second part of the presentation,
- a (not exhaustive) **set of questions** useful to start a discussion
- **in view** of the preparation **of a global EFT fit of LHC results**
- (some material stolen from recent talks at LHCP20)

EFT at the LHC

CMS Standard Model Twiki

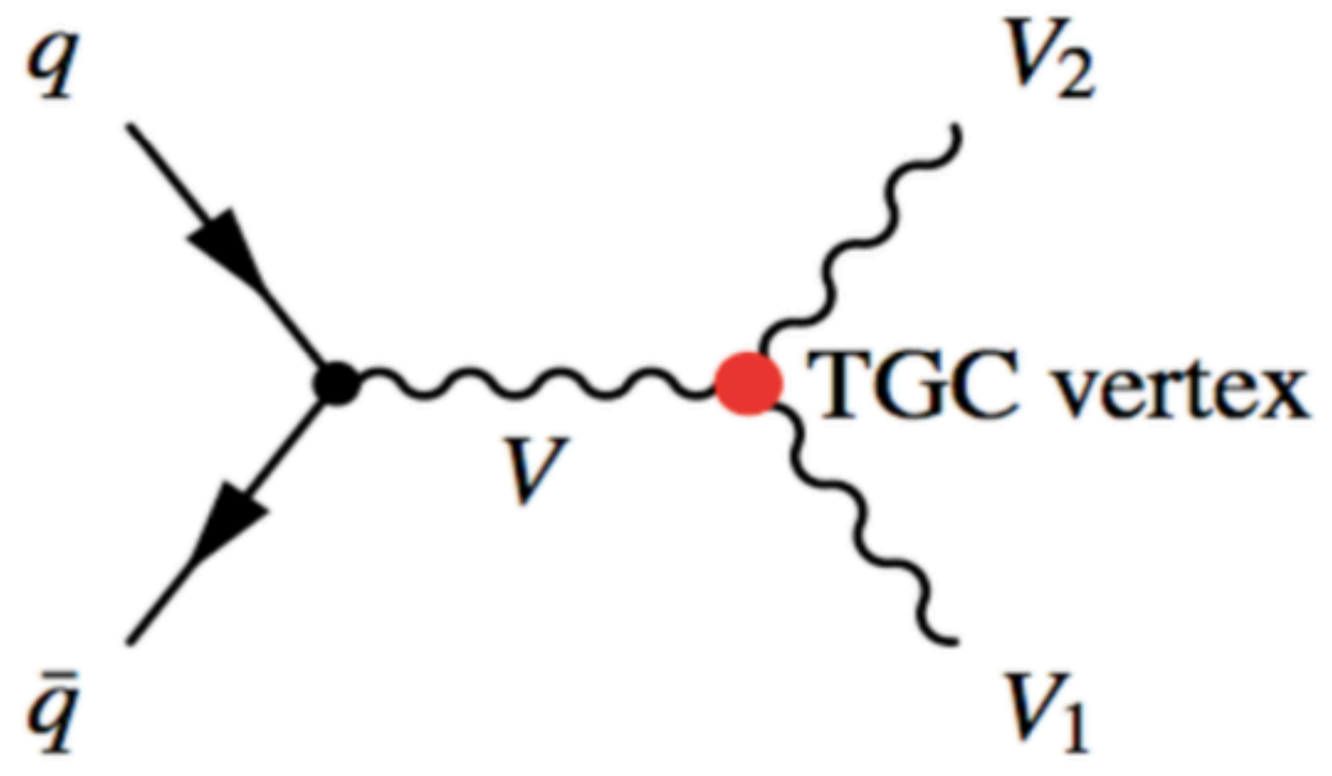
- BSM physics as **search for unexpected deviations** is studied at the LHC since the beginning of the data taking
- the first version of these plots in our Twiki pages dates back to **26.02.2013**

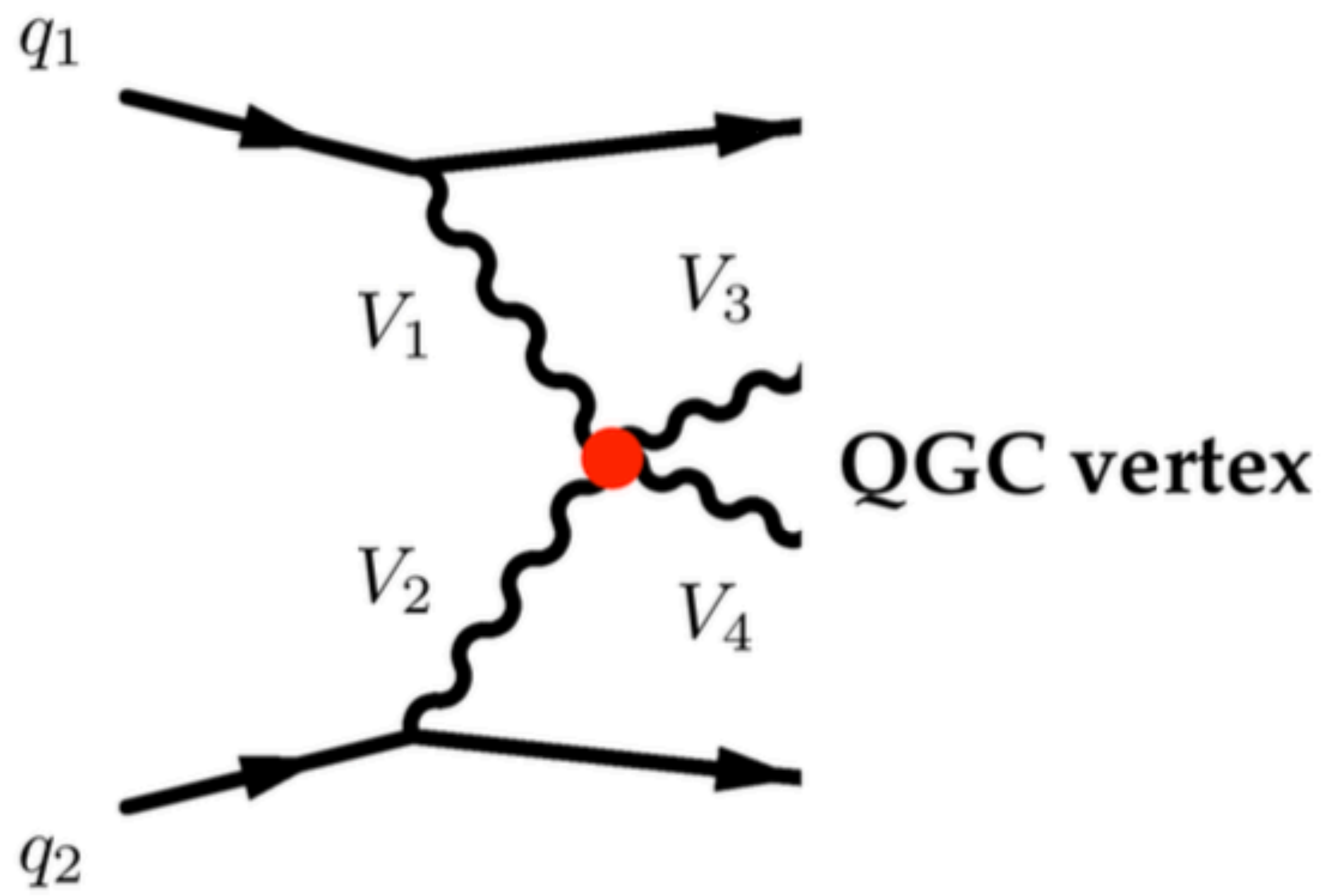




anomalous couplings

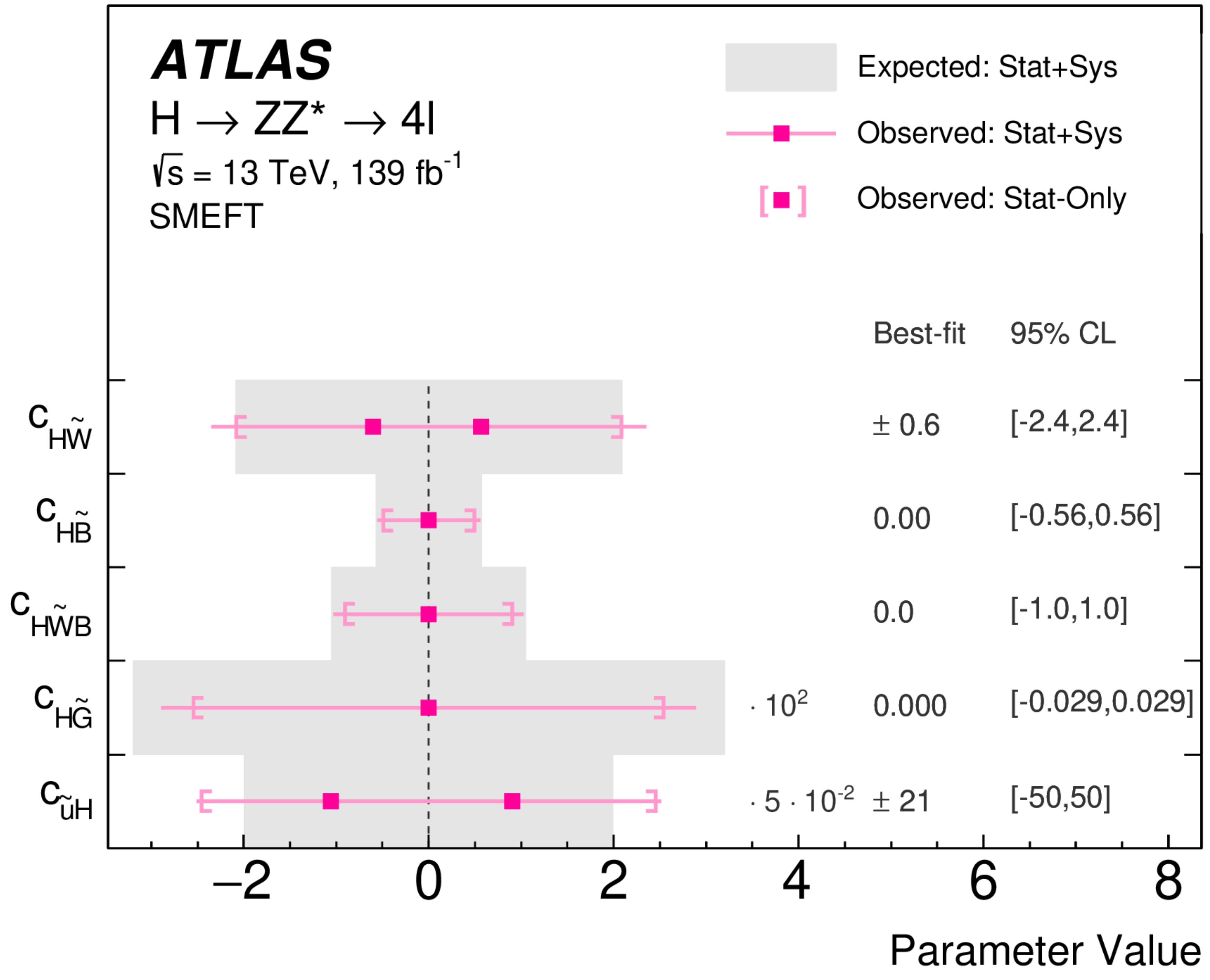
- many results have been expressed in terms of **anomalous couplings**
- assume that any new physics is summarised as a **multiplicative modification of one coupling** in a single vertex in Feynman diagrams
- typically divided into two categories: anomalous Triple Gauge Couplings (**aTGC**) or anomalous Quartic Gauge Couplings (**aQGC**)
- **historically**, aTGCs have been associated to di-boson final states, aQGCs to tri-boson final states and vector boson scattering (VBS)

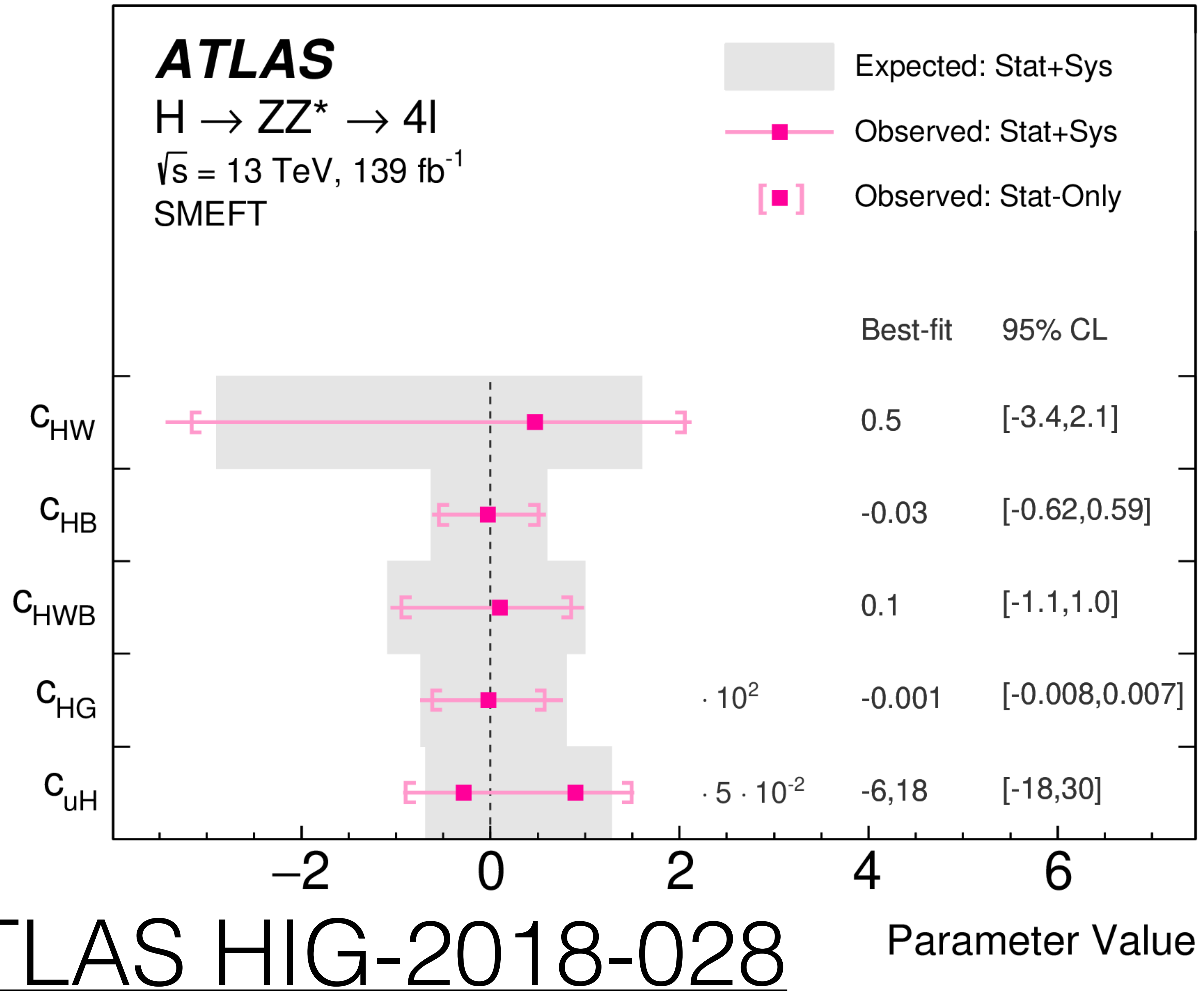




In the Higgs sector

- searches for **anomalies wrt the SM** started before the Higgs boson discovery, putting limits on signal strengths not compatible with unity
- continued after the Higgs discovery, to ascertain the SM-nature of the newly discovered resonance





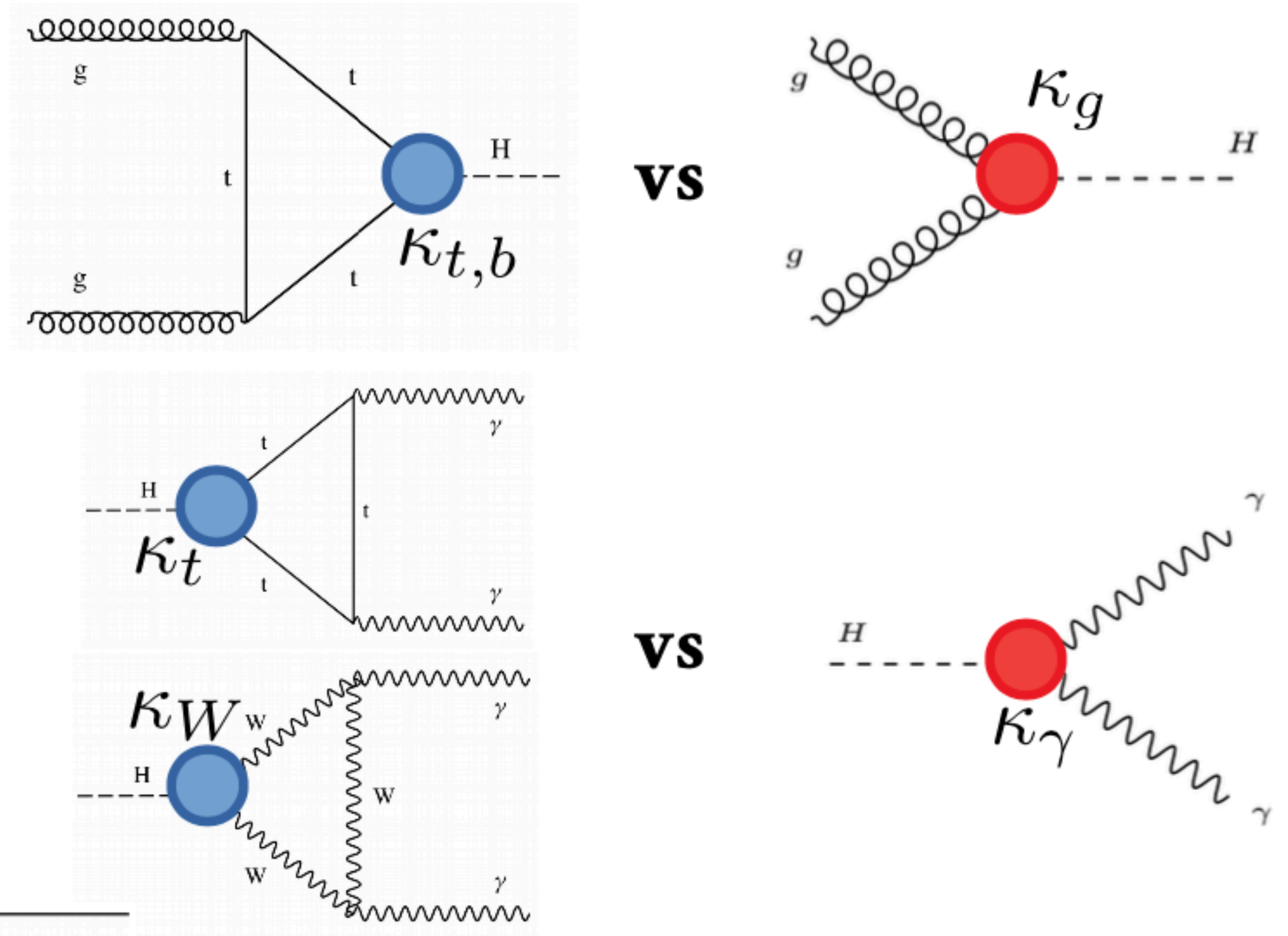
ATLAS HIG-2018-028

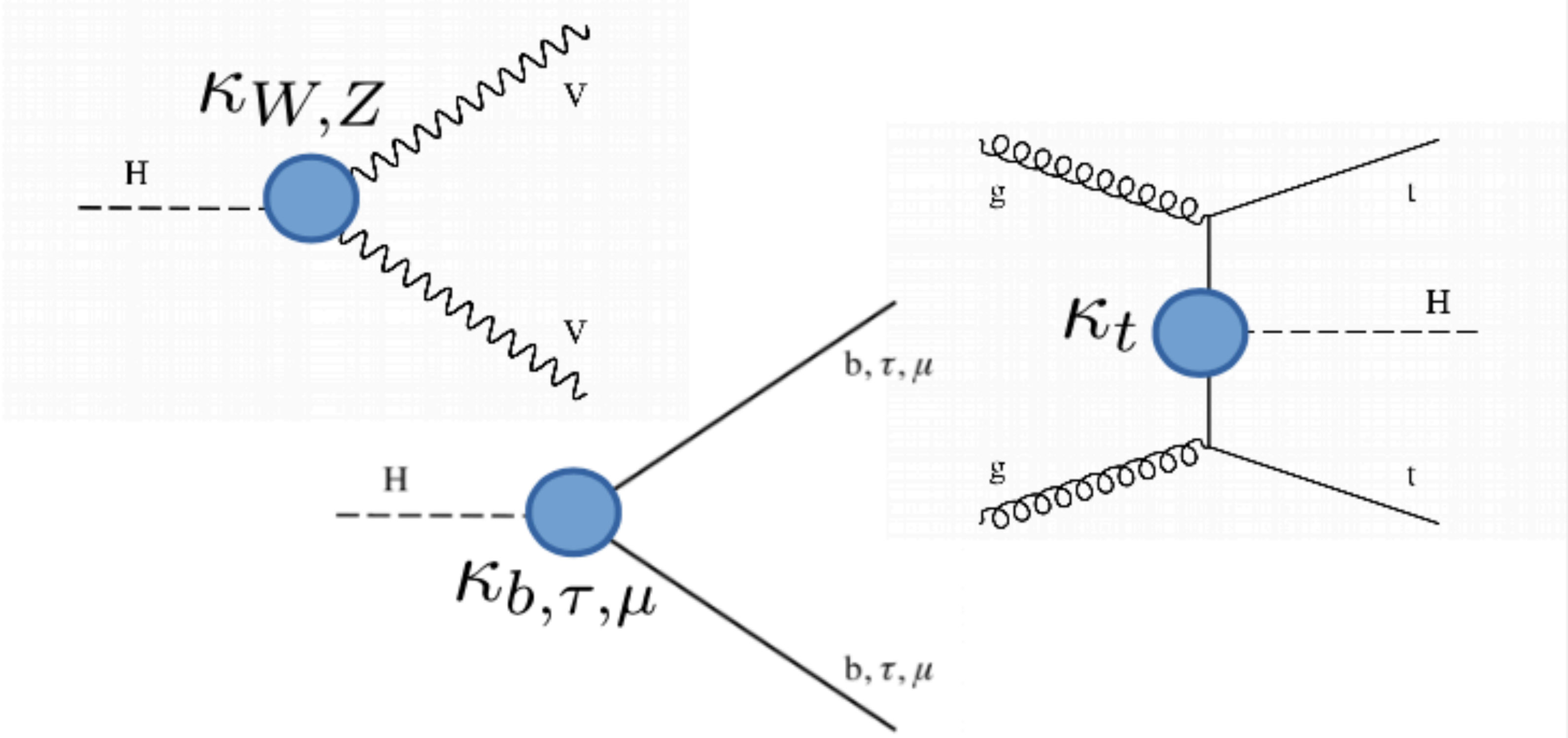
the kappa framework

- Multiplicative coupling modifiers
  ⇒ SM: positive + equal to unity
- Two possible treatments for loop diagrams:
  - resolved into SM components
  - effective vertices

$$\mu \rightarrow \mu(\kappa)$$

	Loops	Interference	Effective scaling factor	Resolved scaling factor
Production				
$\sigma(\mathrm{ggH})$	✓	g-t	κ_g^2	$1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	—	—		$0.73\kappa_W^2 + 0.27\kappa_Z^2$
$\sigma(\mathrm{WH})$	—	—		κ_W^2
$\sigma(\mathrm{qq/qg} \to \mathrm{ZH})$	—	—		κ_Z^2
$\sigma(\mathrm{gg} \to \mathrm{ZH})$	✓	Z-t		$2.46\kappa_Z^2 + 0.47\kappa_t^2 - 1.94\kappa_Z\kappa_t$
$\sigma(\mathrm{ttH})$	—	—		κ_t^2
$\sigma(\mathrm{gb} \to \mathrm{WtH})$	—	W-t		$2.91\kappa_t^2 + 2.31\kappa_W^2 - 4.22\kappa_t\kappa_W$
$\sigma(\mathrm{qb} \to \mathrm{tHq})$	—	W-t		$2.63\kappa_t^2 + 3.58\kappa_W^2 - 5.21\kappa_t\kappa_W$
$\sigma(\mathrm{bbH})$	—	—		κ_b^2
Partial decay width				
Γ^{ZZ}	—	—		κ_Z^2
Γ^{WW}	—	—		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W-t	κ_γ^2	$1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	—	—		κ_τ^2
Γ^{bb}	—	—		κ_b^2
$\Gamma^{\mu\mu}$	—	—		κ_μ^2
Total width for $\mathcal{B}_{\mathrm{BSM}} = 0$				
Γ_H	✓	—	κ_H^2	$0.58\kappa_b^2 + 0.22\kappa_W^2 + 0.08\kappa_g^2 + 0.06\kappa_\tau^2 + 0.026\kappa_Z^2 + 0.029\kappa_c^2 + 0.0023\kappa_\gamma^2 + 0.0015\kappa_{Z\gamma}^2 + 0.00025\kappa_s^2 + 0.00022\kappa_\mu^2$





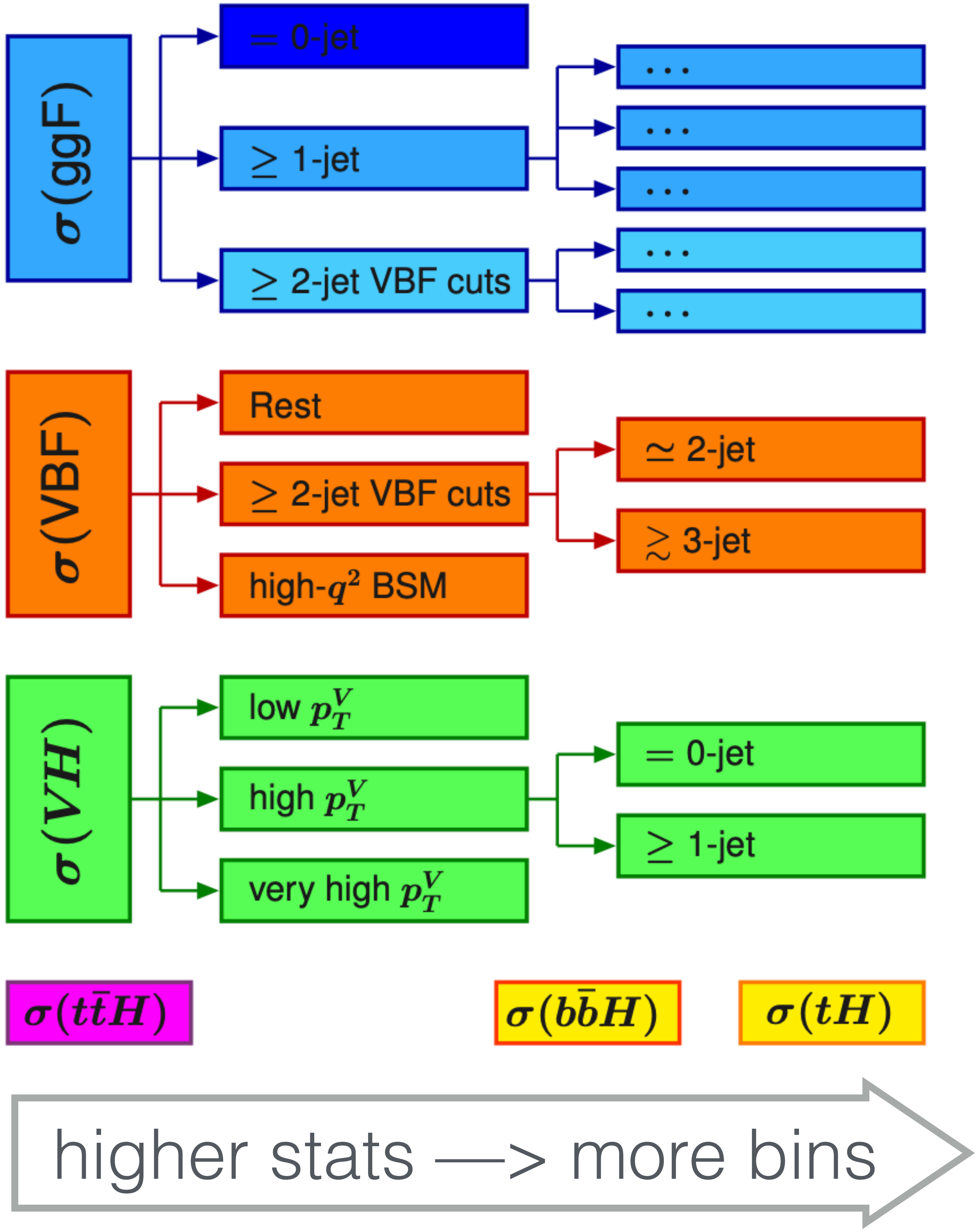
Limitations

1. LO framework
2. Ignores shape effects
3. Specific to H physics

J. Langford | Higgs combination | LHCP 29.05.20 8 / 14

standard template cross-sections

- **set of bins** in Higgs searches, agreed between experiments and theory, where to provide cross-section values, at different levels of refinement (the so-called versions)
- they may be used to **fit BSM models** on experimental results differentially
- **simple to use** also for global combinations in case of small deviations, with **theory uncertainties minimised**
- assume **SM selection efficiencies**, as the results are based on SM Monte Carlo simulations
- the **granularity is limited** by the binning itself



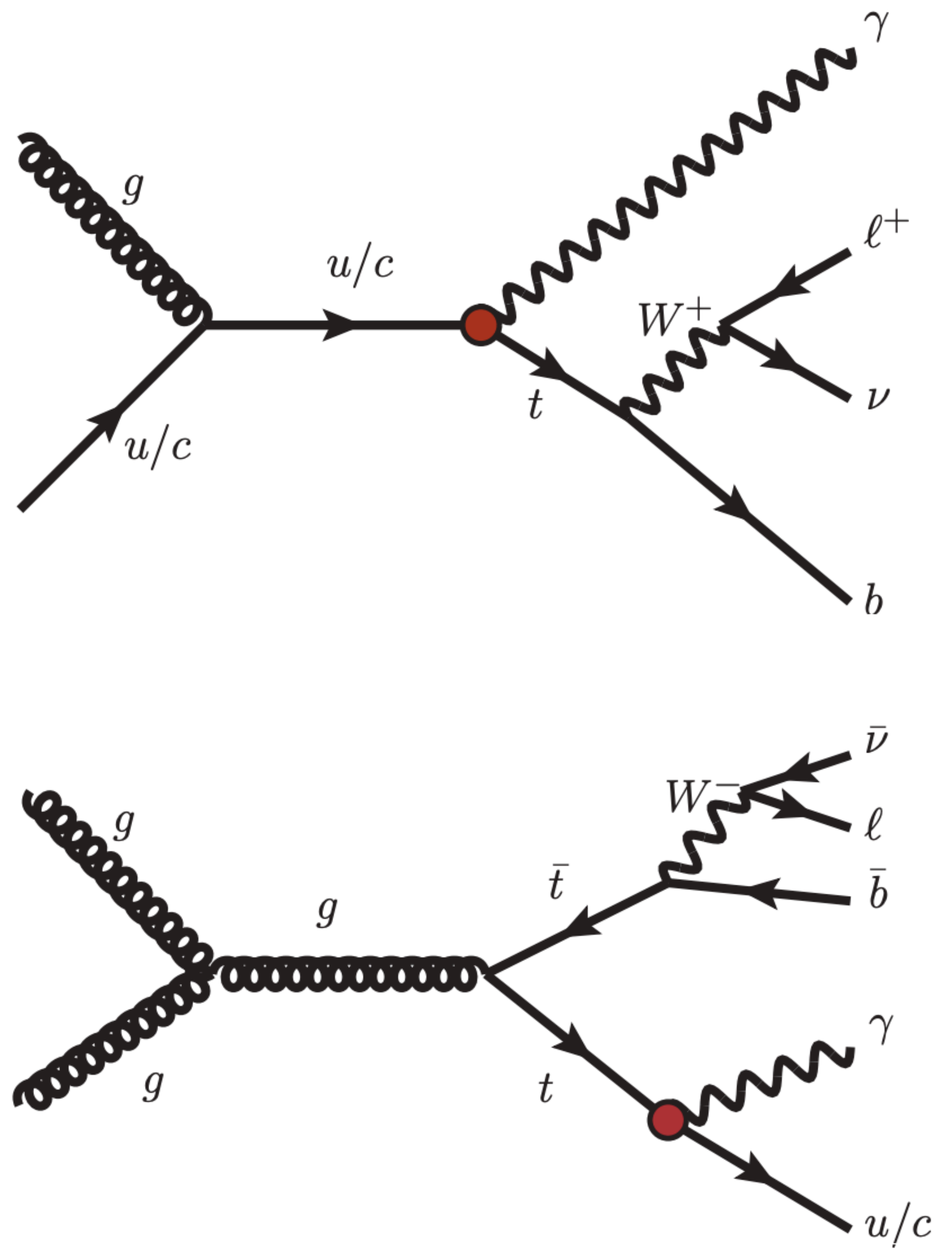
EFT fits

- Higgs boson data analysis results also published in terms of **limits on additional EFT operators** to the SM Lagrangian
- **several different ways** of obtaining and publishing results depending on the experiments and single publications:

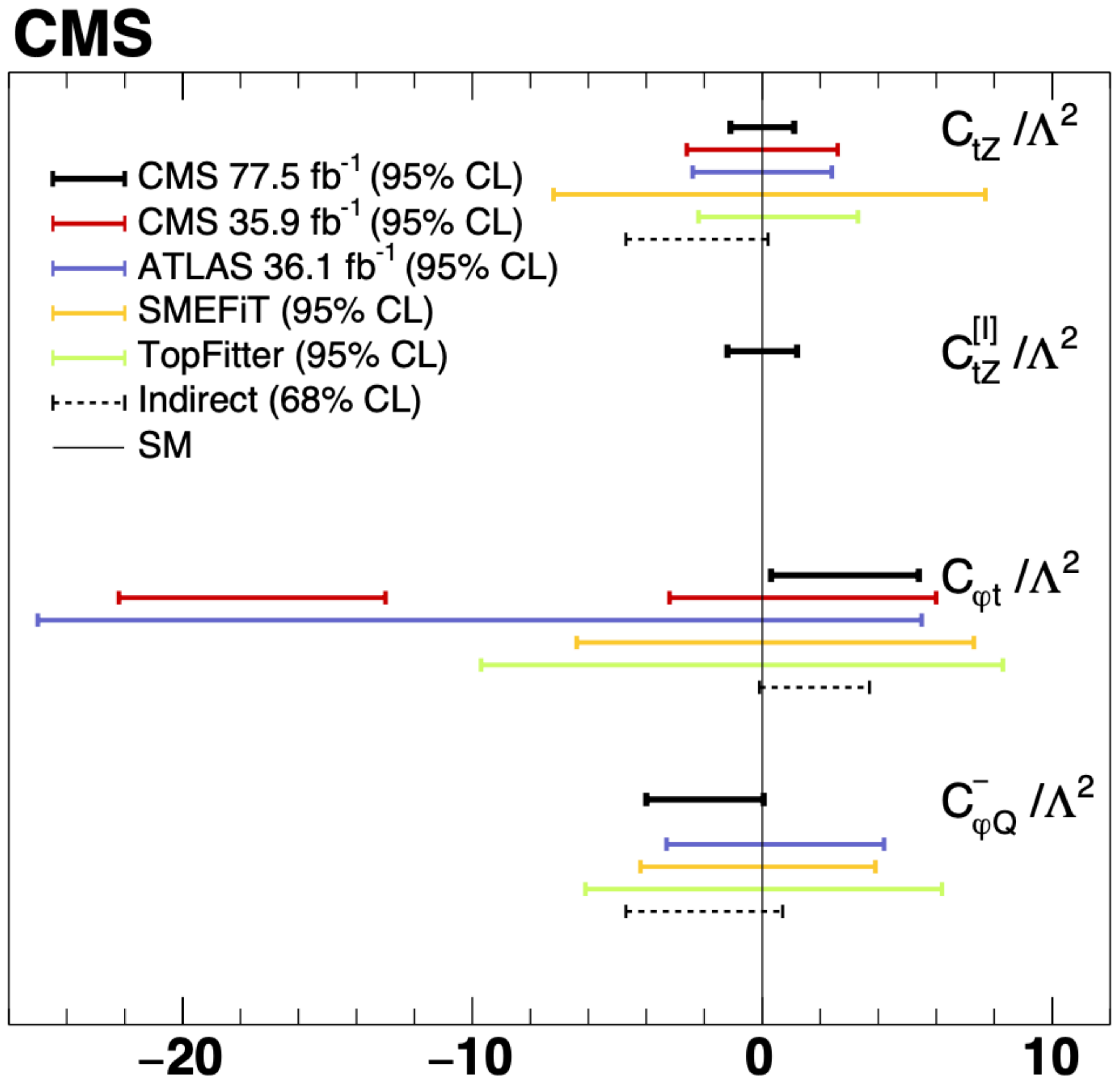
- CMS HZZ HIG-13-002 (HVV effective amplitude)
- ATLAS HZZ HIG-2018-28 (Warsaw basis)
- ATLAS HYY ATLAS-CONF-2019-029 (SILH and Warsaw basis)
- ATLAS Htautau HIG-17-004 (HEL basis)
- CMS HIG-19-005 Higgs combination (based on STXS, kappa fwk and HEL basis)

in the top sector

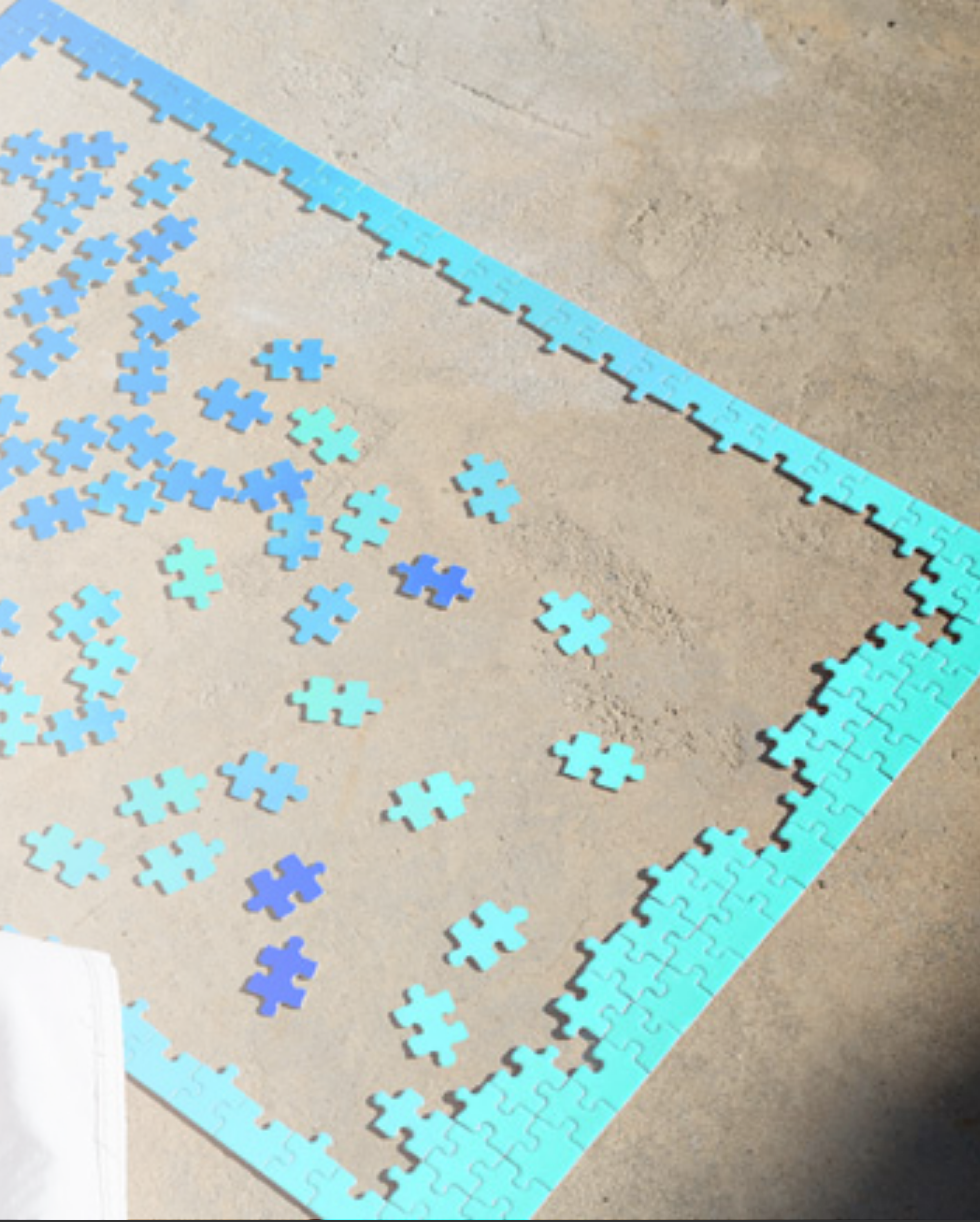
- Flavour-Changing Neutral Currents (e.g. in ATLAS Phys. Lett. B 800 (2019) 135082)
- charged lepton flavour violation (ATLAS-CONF-2018-044)
- additional general anomaly searches in ttbar final states (e.g. in CMS 1903.11144) or exclusive ones (CMS ttZ 1907.11270)



Observable	Vertex	Coupling	Obs.	Exp.
$\left\|C_{uW}^{(13)*} + C_{uB}^{(13)*}\right\|$	$tu\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$\left\|C_{uW}^{(31)} + C_{uB}^{(31)}\right\|$	$tu\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
$\left\|C_{uW}^{(23)*} + C_{uB}^{(23)*}\right\|$	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
$\left\|C_{uW}^{(32)} + C_{uB}^{(32)}\right\|$	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	LH	36	52^{+21}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	RH	78	75^{+31}_{-21}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}



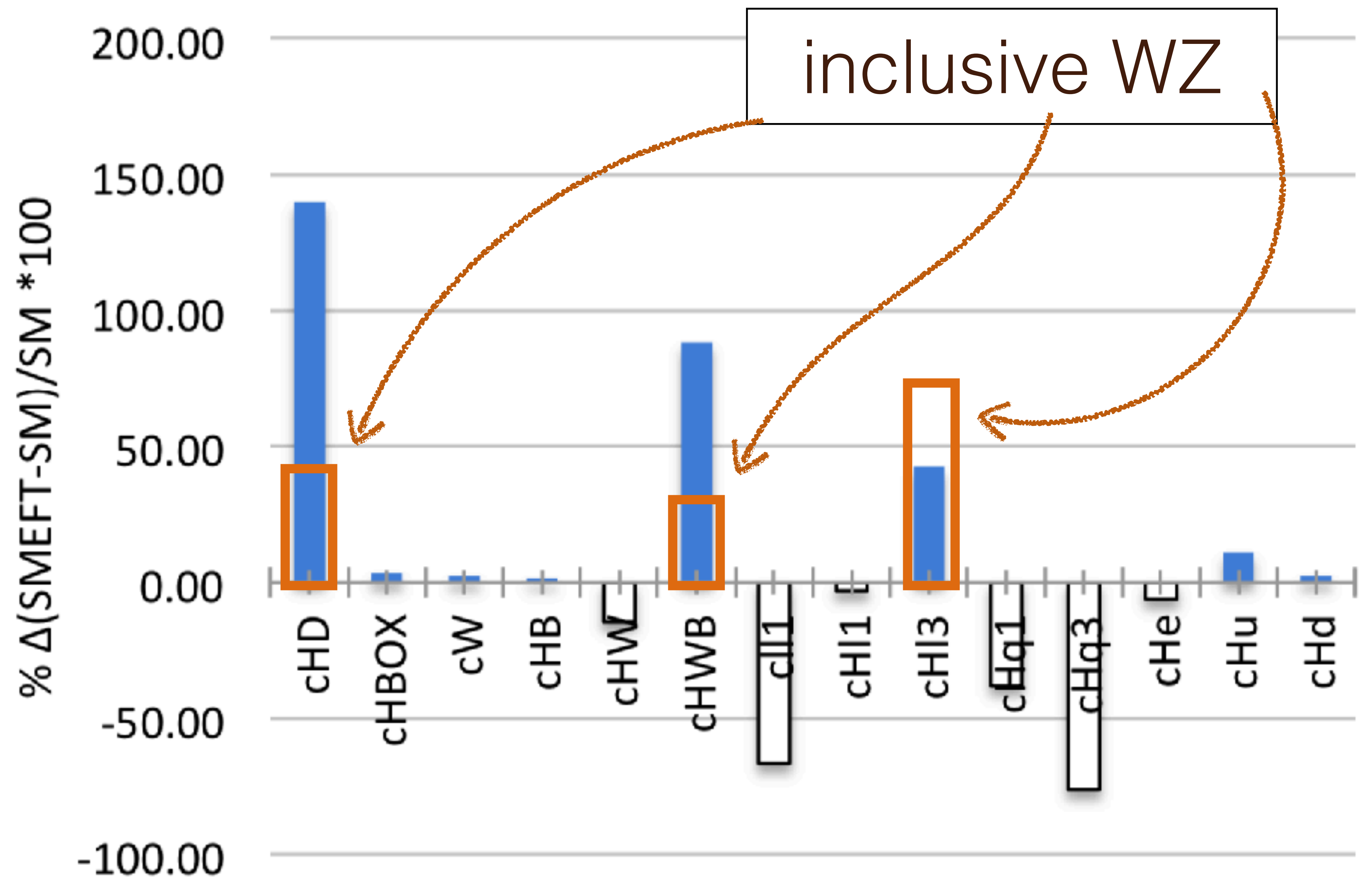
towards a global fit



- several pieces already existing and **experience well rooted in the experimental collaborations**
- **different approaches** exist on how to model BSM effects and what to fit
- connected also to **what operators get tested** with each final state
- different choices exist on how to treat **EFT unitarity issues**

how to perform a fully blown EFT study?

- from anomalous couplings to a fully blown EFT study:
- shift from the question "*what operators may be associated to a modified behaviour of a vertex?*" to "***which operators produce a measurable effect in the final state of the study?***"
- overcome the traditional categorisation of analyses into dim-6 and dim-8 probes: for a global fit, **lower terms** in the perturbative Lagrangian expansion are more important in general
- **need for phenomenological studies** for guidance, in particular for sophisticated final states like VBS



impact on VBS **WZ cross-section**
studied at generator level ($c_i/\Lambda = 0.3$)
D. Sampsonidou, MBI 2019

which EFT to rule them all?

- **several different bases** are used so far, either for historical reasons or to adapt to the specific final state under study
- **a common reference**, together with practical indications on how to **translate results into that basis**, would help a lot the combination of results wherever meaningful
- would ease the re-interpretation of several results with the same BSM models
- how do we treat **loop-induced processes**?
- what can we give for granted?
  - how to make sure that **we do not absorb new physics effects in the fit of proton structure** when new high energy data are included?
  - how would the bounds change if PDFs were fitted by consistently including the same operators that are included in EFT fits?

M. Ubiali, PDF and EFT Fits Interplay

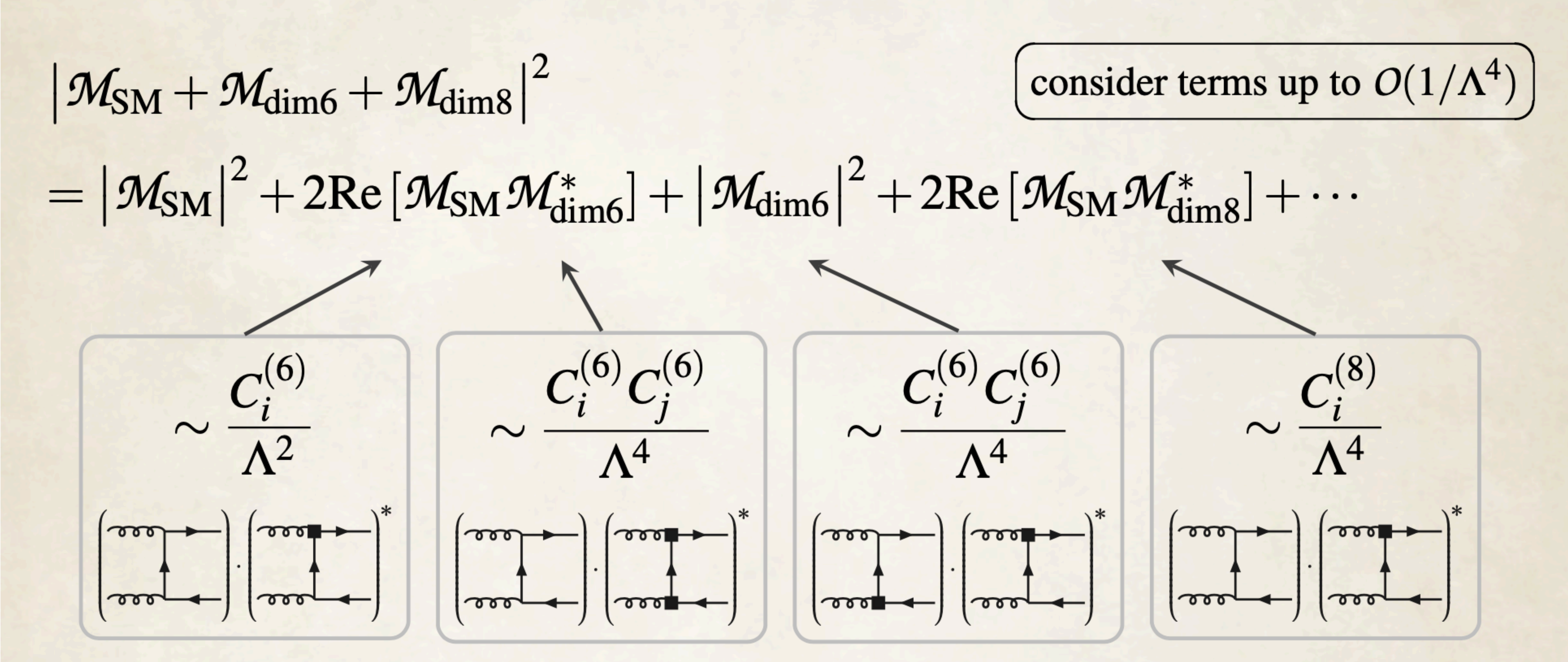
what do we learn from BSM models?

- does an explicit connection between EFT operators and UV-complete BSM models exist?
- can we derive limits on BSM models starting from constraints on EFT operators?
- can we infer, from reasonable assumptions on the BSM models nature, …
  - what **operators are relevant**?
  - what **operator correlations** to study?

A. David, G. Passarino
SMEFT bookkeeping

what are the do’s and don’ts?

- how should the EFT models used?
- e.g. (when) should we consider **double insertions** in the data analysis?
- e.g. (when) should we **mix dim-6 and dim-8** operators in the fits? if so, how?



talk by Peter Geller at LHCP20

how should we cure the unitarity problem?

- In SMEFT, scattering amplitudes generally grow with energy leading to a **breakdown of unitarity at some critical energy**
- **EFT validity stops at the energy Λ**, which represents the scale of new physics
  - if this effect is neglected in data analyses, resulting limits on Wilson coefficients are typically too stringent
- **what technique** should be applied to provide results that are not too optimistic, if unitarity questions are neglected?
- how is the unitarity issue treated **when combining several analyses**?
- how do we balance the accounting of unitarity bounds with the **need for an easily-usable result**?

M. Szleper
EFT validity issues in Vector Boson Scattering data analysis

how will we cope with samples simulation?

- investigating several directions in the hyper-volume of Wilson coefficients is **costly** in terms of MC generation and of event simulation and reconstruction
- can we **generate** linear, interference and quadratic **terms separately** in a safe manner?
- up to what extent may we use **event weights**?

$$
\begin{aligned}
f_{\mathrm{EFT}}(v) = f_{\mathrm{SM}}(v) &+ \frac{c_i}{\Lambda^2} f_{\mathrm{INT},i}(v) + \frac{c_i^2}{\Lambda^4} f_{\mathrm{BSM},i}(v) \\
&+ \frac{c_j}{\Lambda^2} f_{\mathrm{INT},j}(v) + \frac{c_j^2}{\Lambda^4} f_{\mathrm{BSM},j}(v) \\
&+ \frac{c_i c_j}{\Lambda^4} f_{\mathrm{INT},ij}(v) \ ,
\end{aligned}
$$

- **how much do we lose**, relying on differential distributions or STXS only?

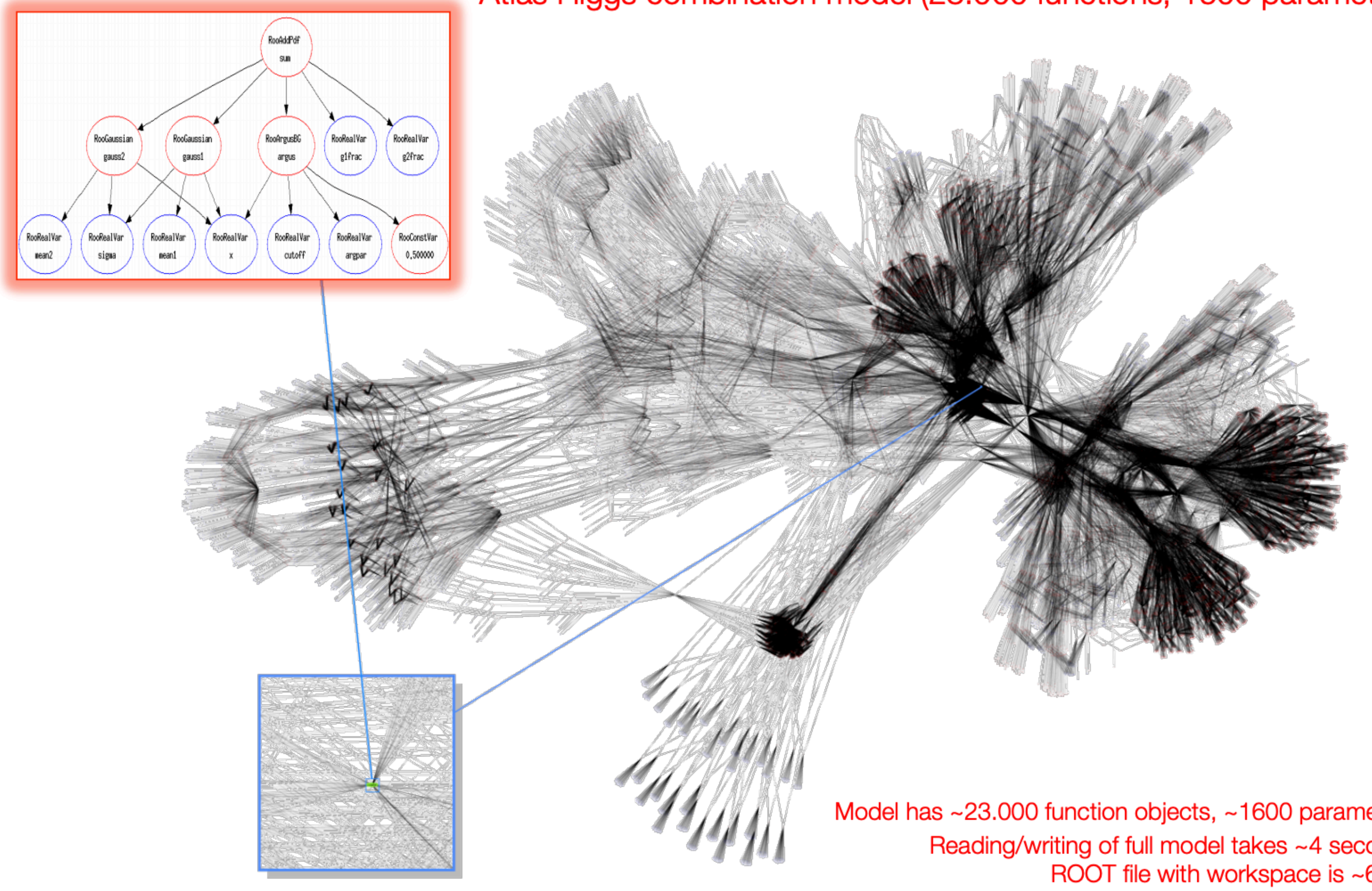
what is the interplay with N^{X}LO calculations?

- QCD and EW higher order corrections may be of **the same size of EFT effects**
- the more precisely we take them into account for, the better it is
  - agreed **generation tools**,
  - prescriptions for **combining different calculations** and
  - for calculation of **uncertainties** are probably needed
- how do **EFT terms enter in the NLO** corrections?
  - how much is this effect relevant?
- what are the **theory uncertainties** that need to be considered?
  - besides missing higher order EW and QCD ones, how do we include uncertainties from choices made in the **dim-6 EFT expansion** truncation?

how will we perform experimental fits?

- **Several tools exist** on the market, both from theory and experiments
- **Combinations of experimental results** in global fits involve thousands of events, hundreds of nuisance parameters, measurement bins, tens of parameters of interest
- **Implementing the proper fitting tool** may be a crucial aspect of a global EFT fit

Atlas Higgs combination model (23.000 functions, 1600 parameters)



Model has ~23.000 function objects, ~1600 parameters
Reading/writing of full model takes ~4 seconds
ROOT file with workspace is ~6 Mb

W. Verkerke
Statistical model building at the LHC

J. Bendavid,
Differential W measurements in run 2

summary

- the interest of the community on systematic EFT fits is increasing rapidly
- involving the **largest number of players and final states** is possible
- the **interplay between theory and experiments**
  - for physics discussions
  - and agreement on tools and prescriptions
- will be fundamental to create the necessary **order for an inclusive global fit**
- a global LHC EFT Working Group, involving theory, ATLAS and CMS is <u>starting</u>