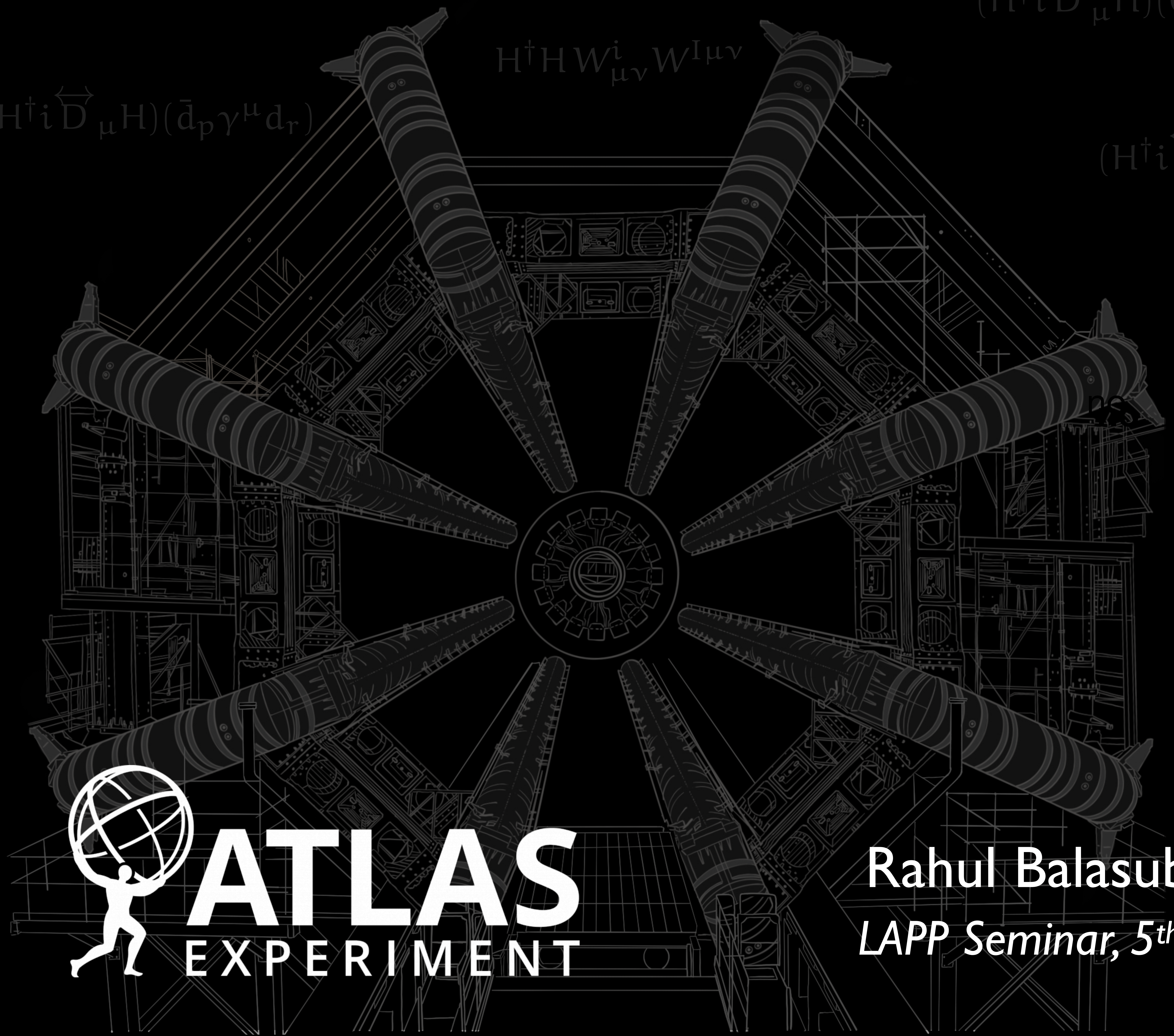
Effectively going beyond the Standard Model with the ATLAS experiment



Rahul Balasubramanian

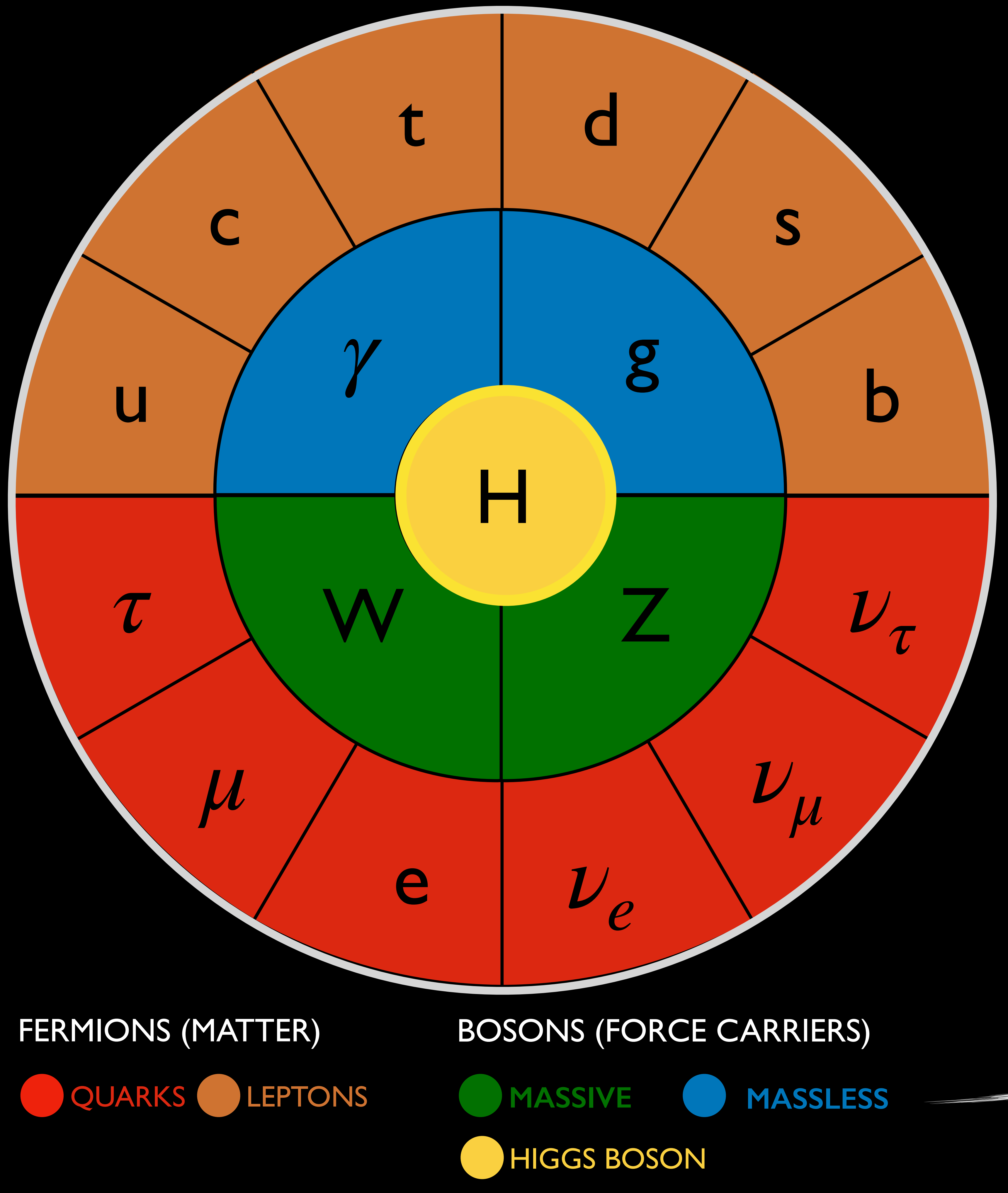
LAPP Seminar, 5th April 2024

ATLAS EXPERIMENT

Nikhef

‘Standard Model’ - The fundamental theory of elementary particles

spin-1/2 particles
fermions

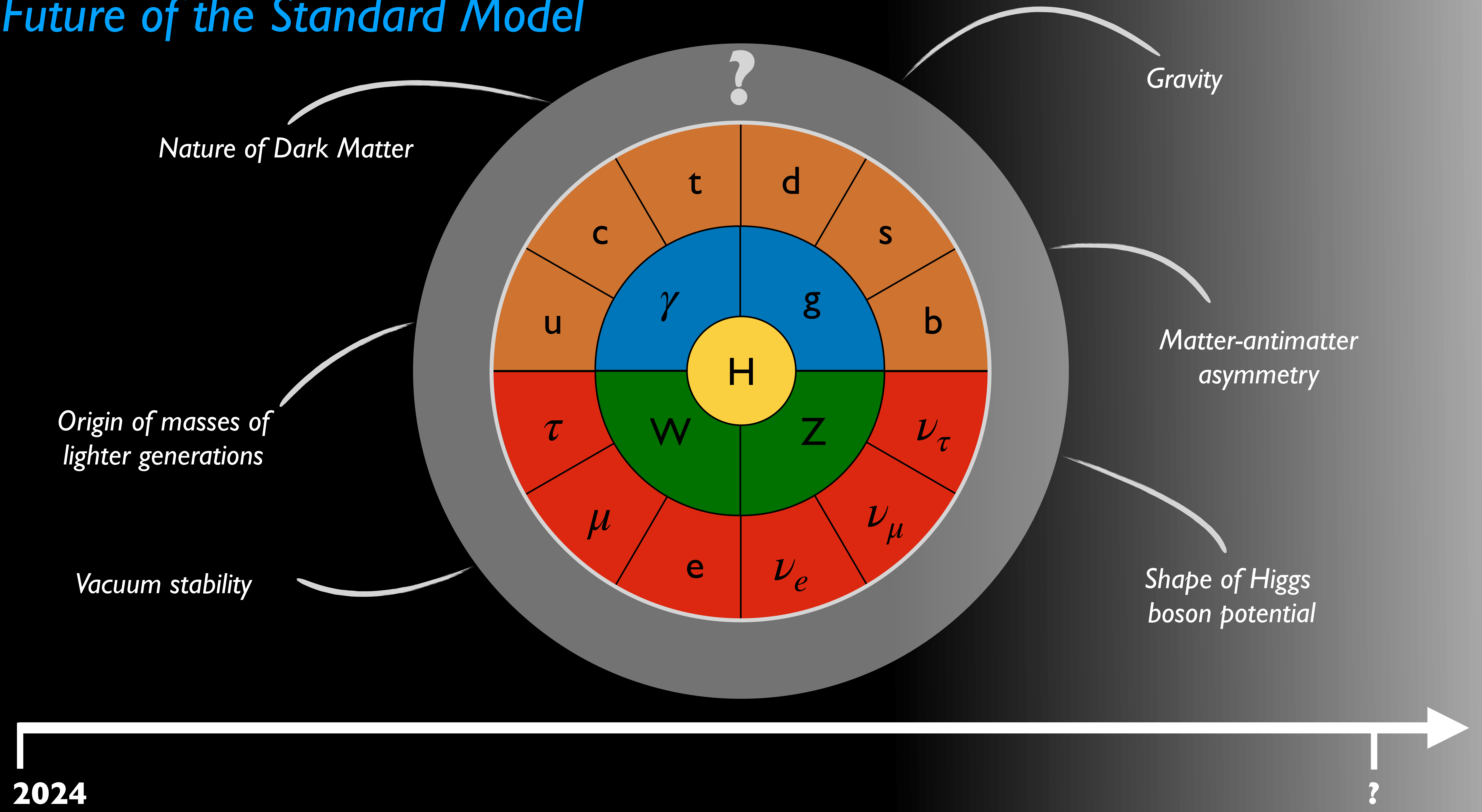


Spin-1 particles
mediating forces
bosons

Mathematical description emerges from underlying symmetries

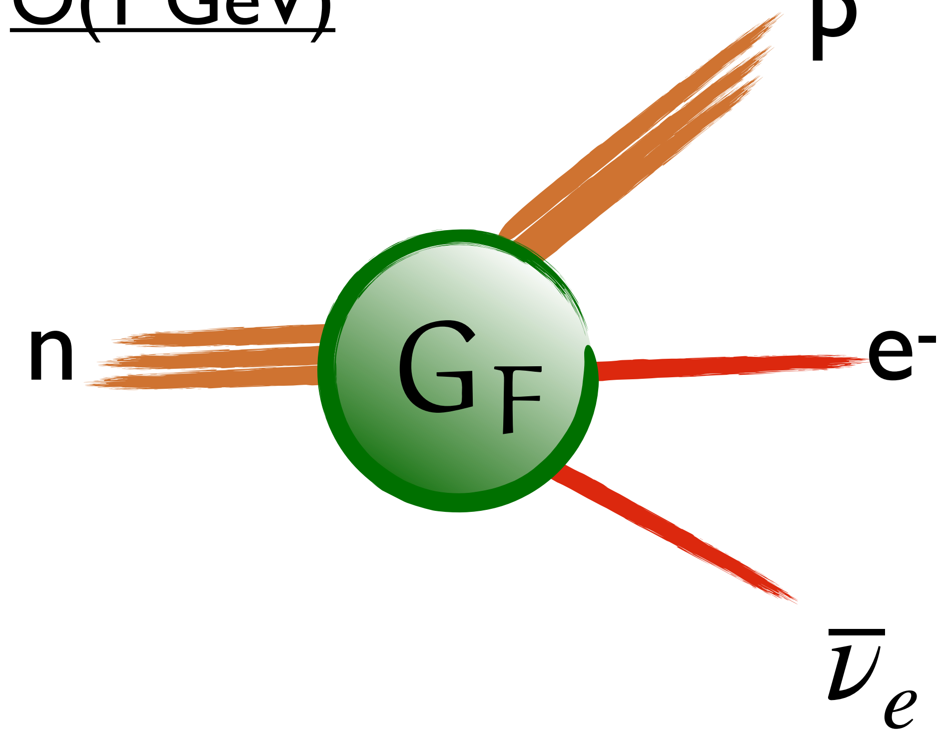
The heart of the Standard Model uncovered

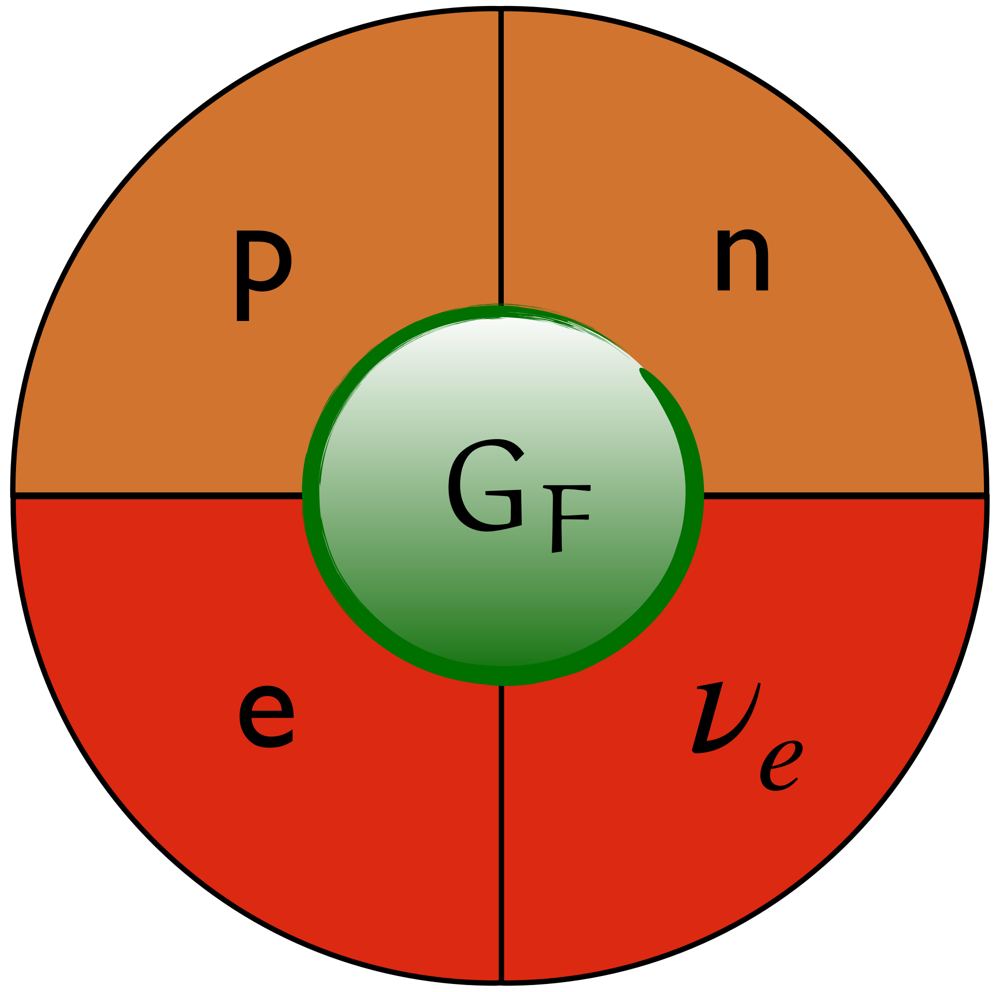
Future of the Standard Model



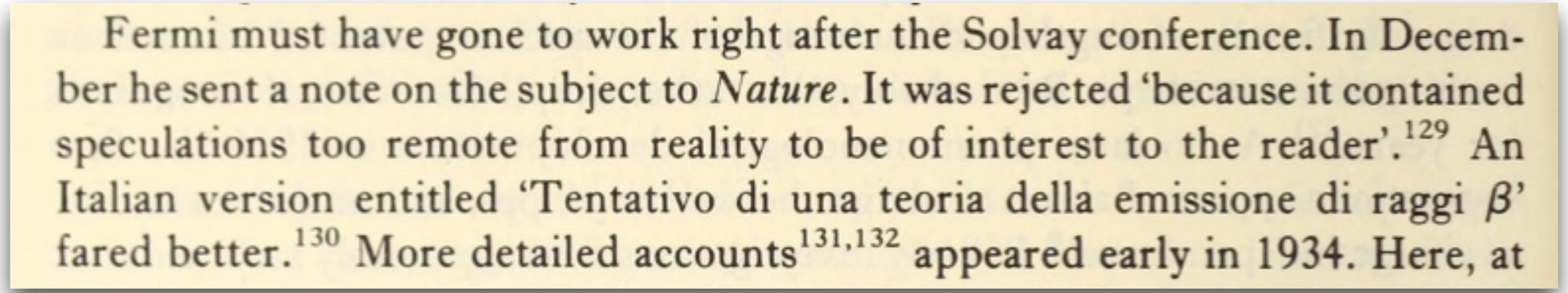
Going before the current Standard Model

O(1 GeV)





un tentativo (an attempt)



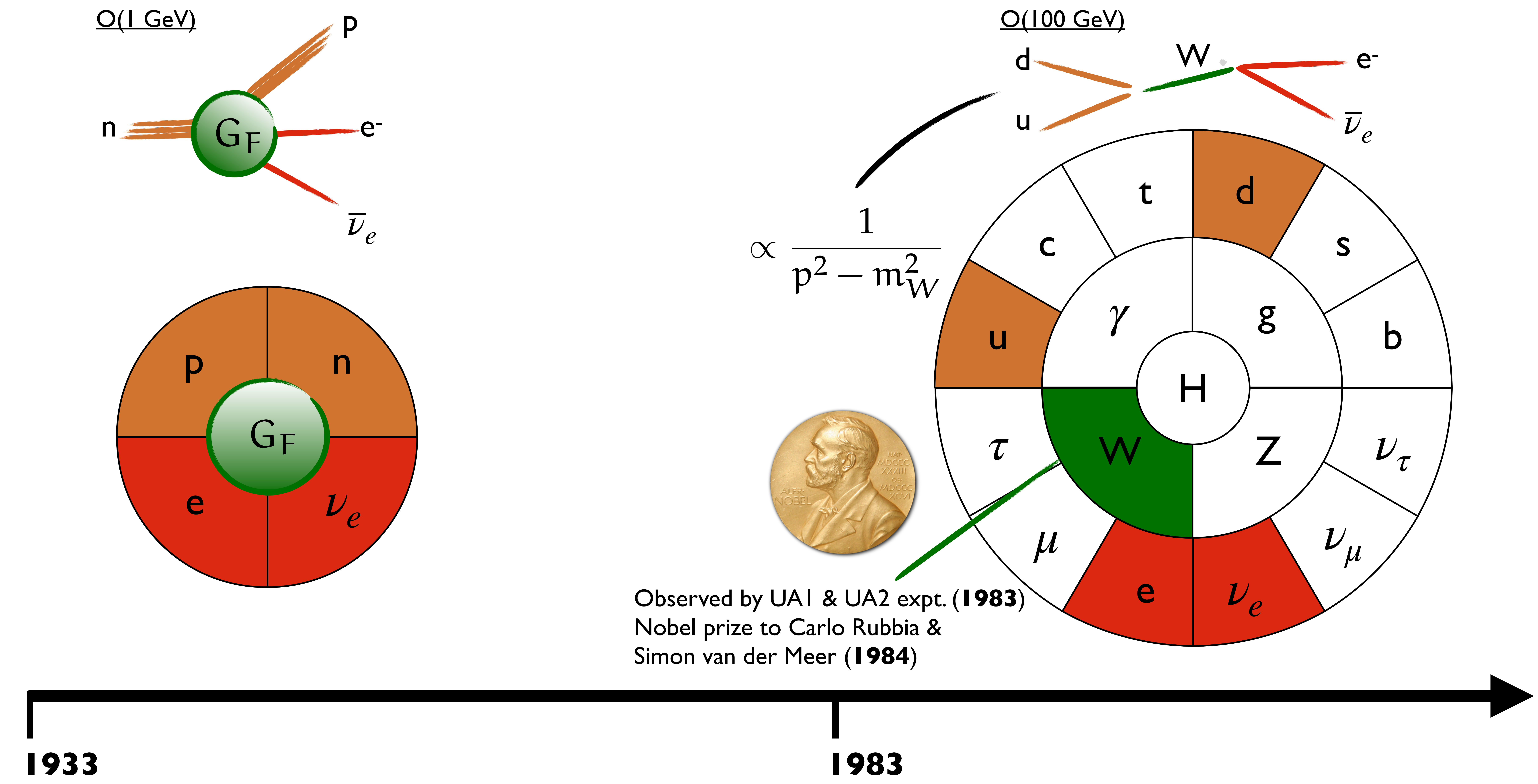
Fermi must have gone to work right after the Solvay conference. In December he sent a note on the subject to *Nature*. It was rejected 'because it contained speculations too remote from reality to be of interest to the reader'.[129] An Italian version entitled 'Tentativo di una teoria della emissione di raggi β' fared better.[130] More detailed accounts[131,132] appeared early in 1934. Here, at

In retrospective, was quite the oversight not to publish this work

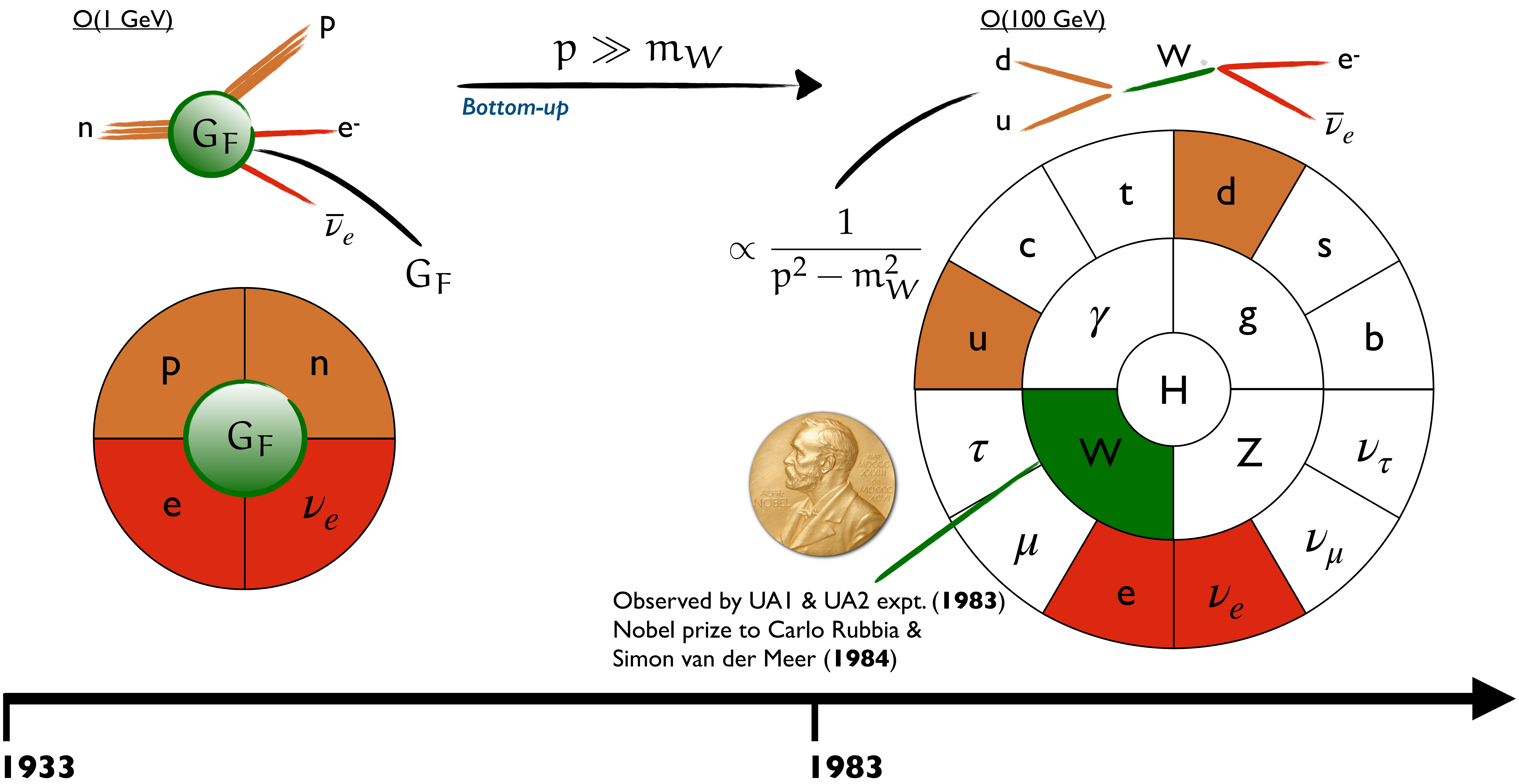
Tentativo di una teoria dell'emissione dei raggi beta,
E. Fermi, La Ricerca Scientifica 4 (**1933**) 491-495

1933

Going before the Standard Model

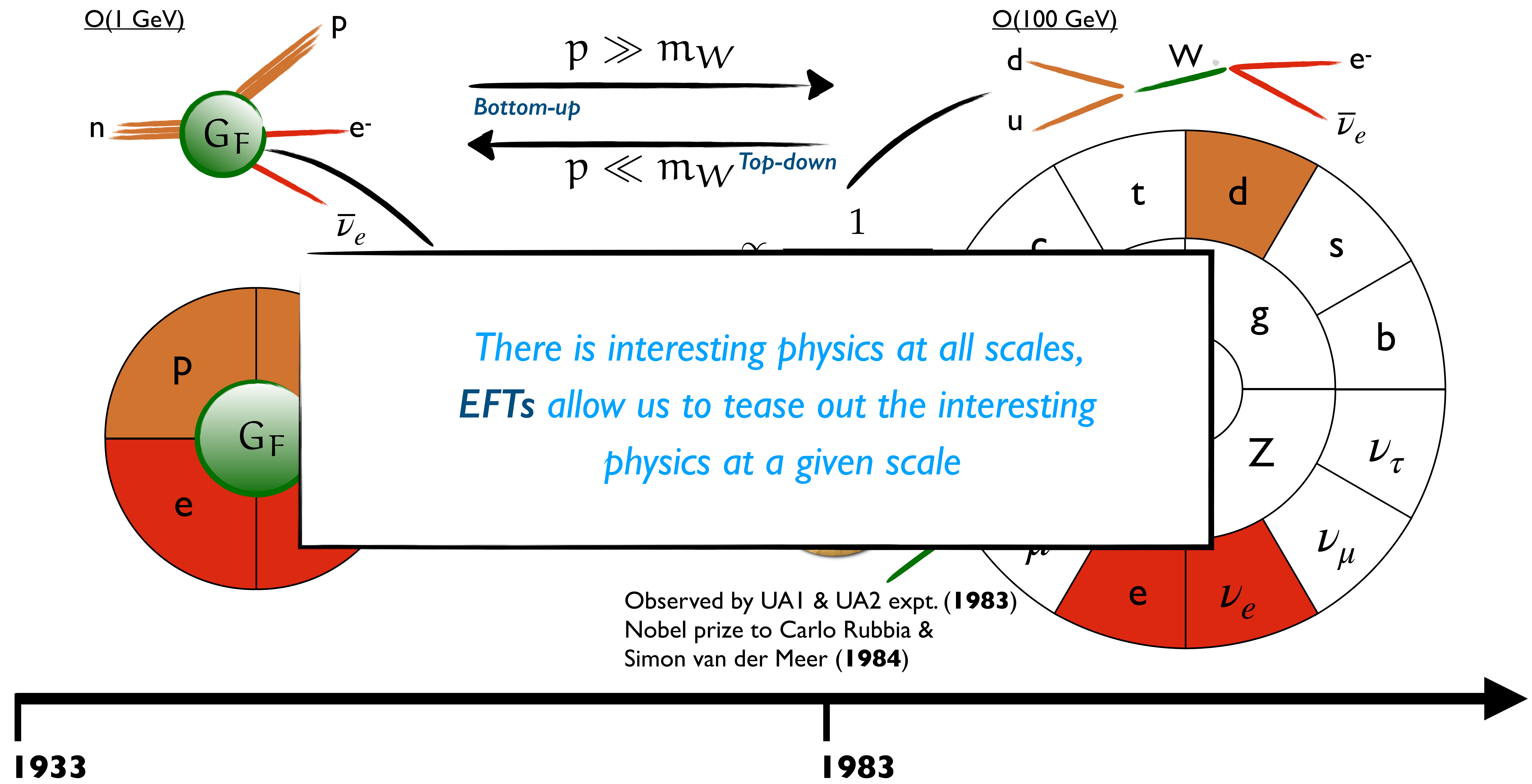


Going before the Standard Model



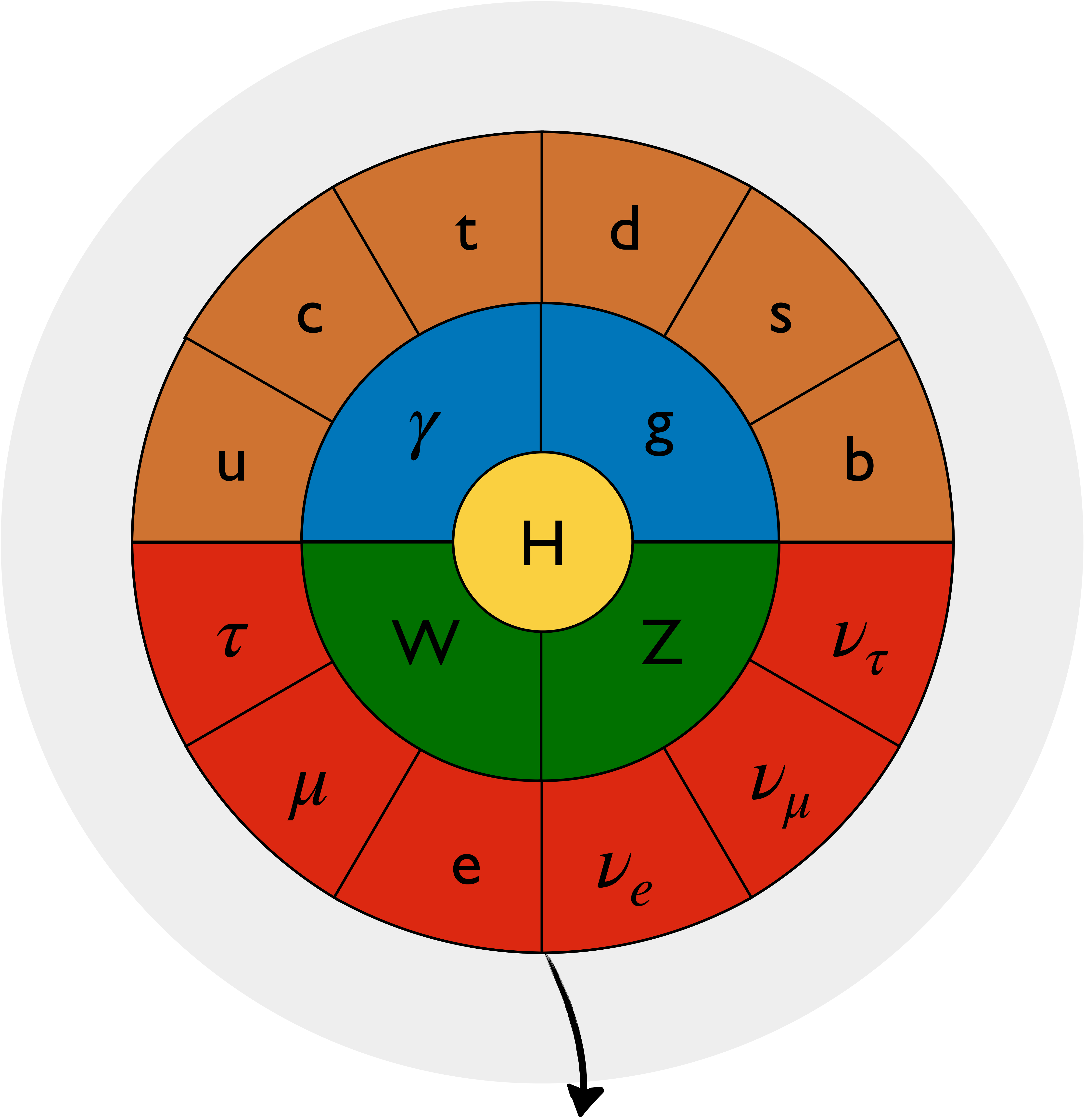
Going before the Standard Model

Going before the Standard Model



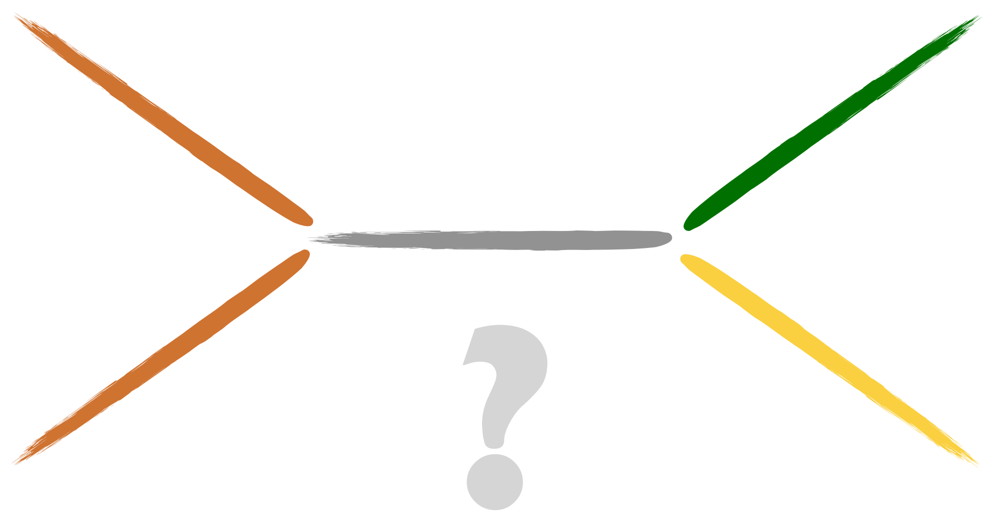
There is interesting physics at all scales,
***EFTs** allow us to tease out the interesting*
physics at a given scale

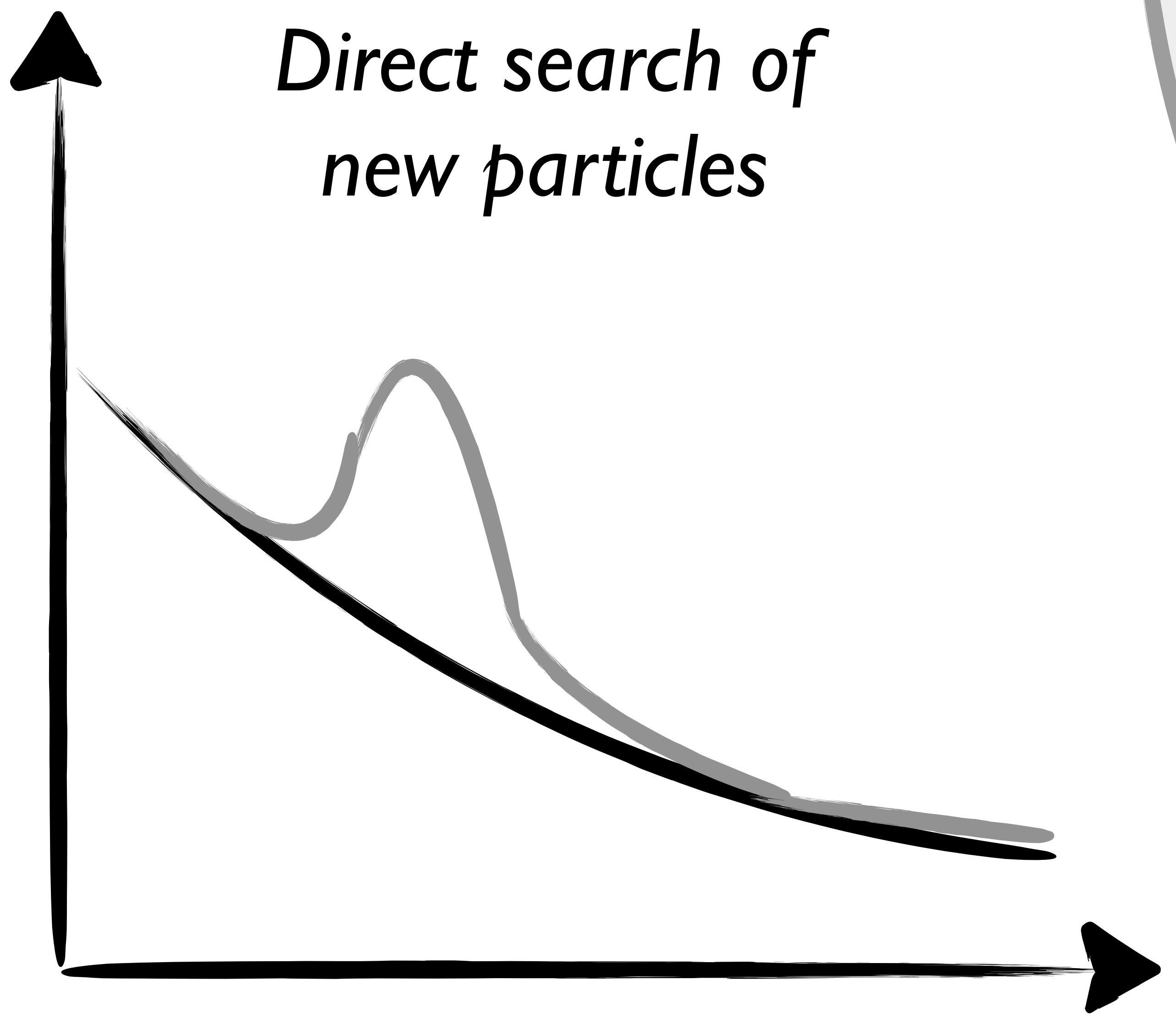
Going beyond the Standard Model

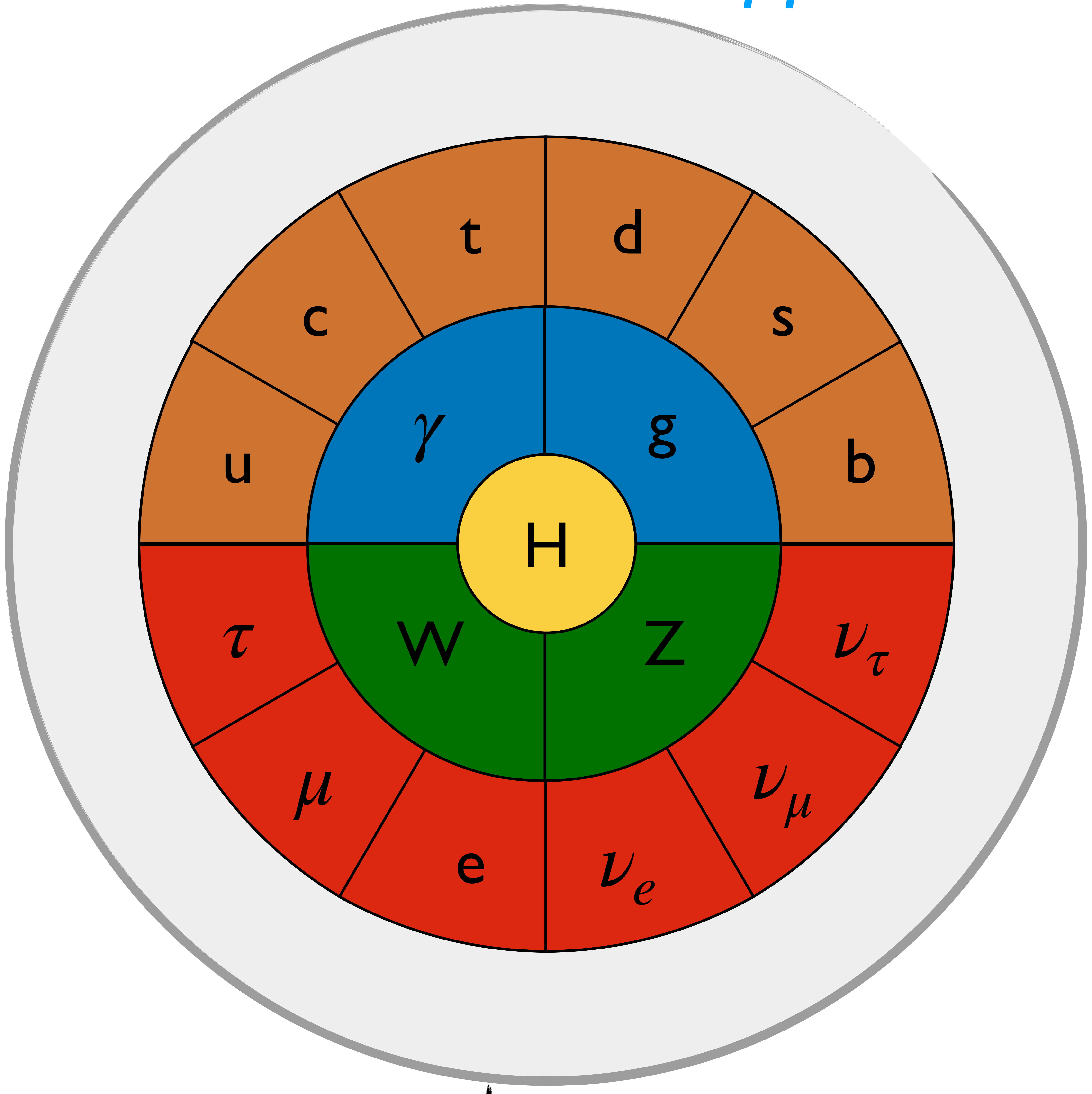


SM provides no parameter that can be measured in data to extend it

Going beyond the Standard Model - direct approach

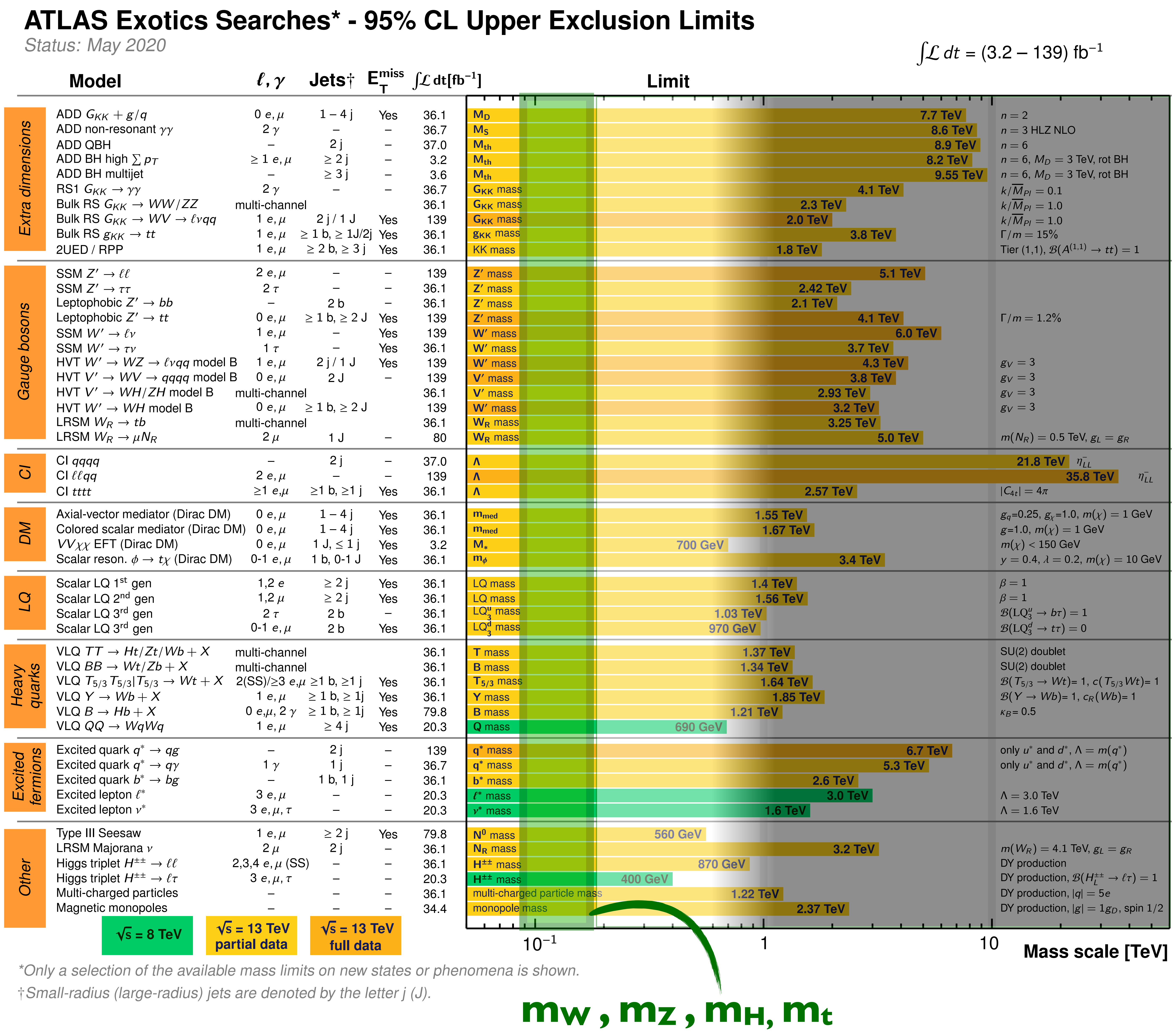






Introduce measurable parameters

Do we need an effective approach ?



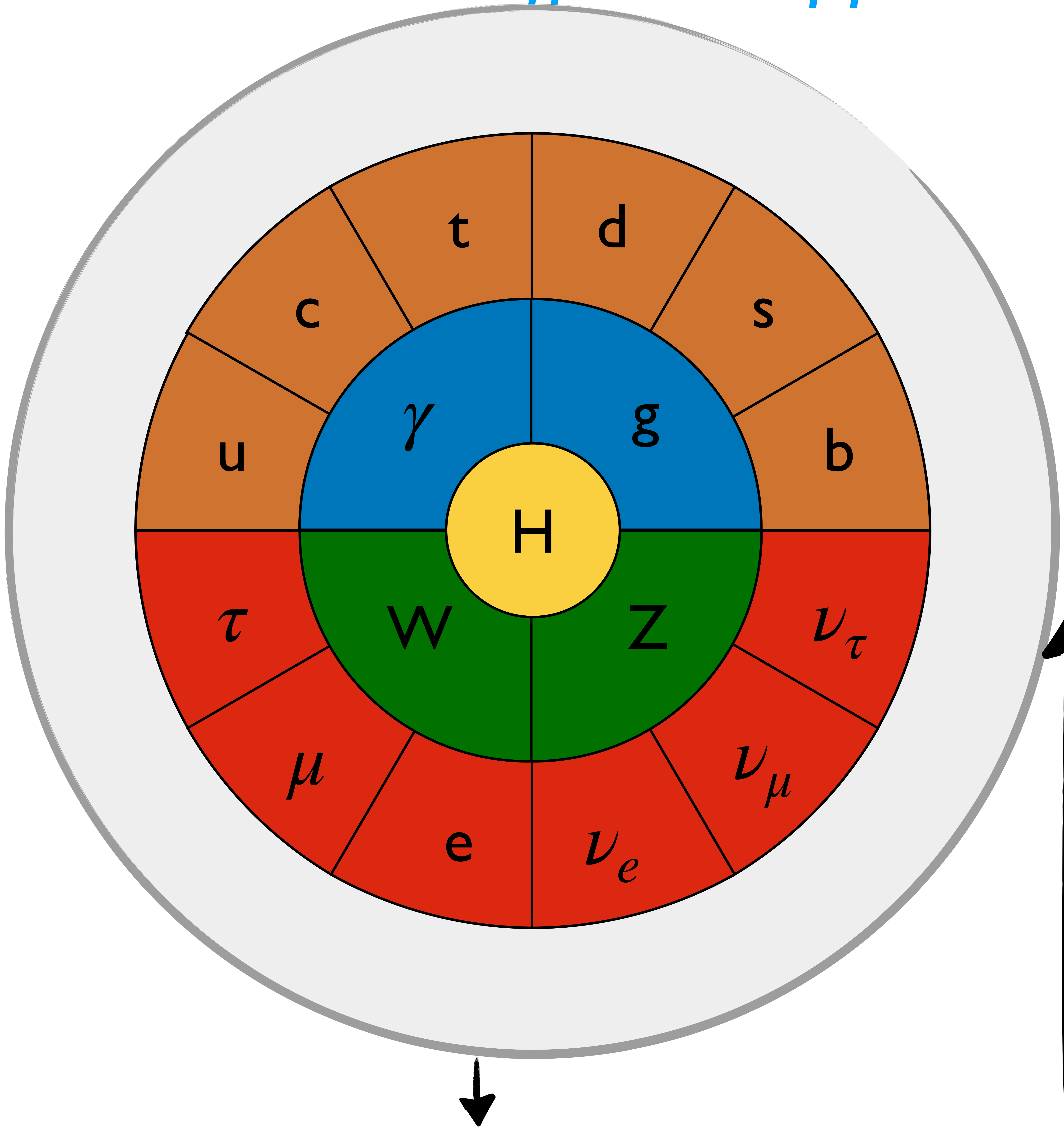
Current data indicates that New Physics likely to be at higher energy scale ($\Lambda \gg v$)

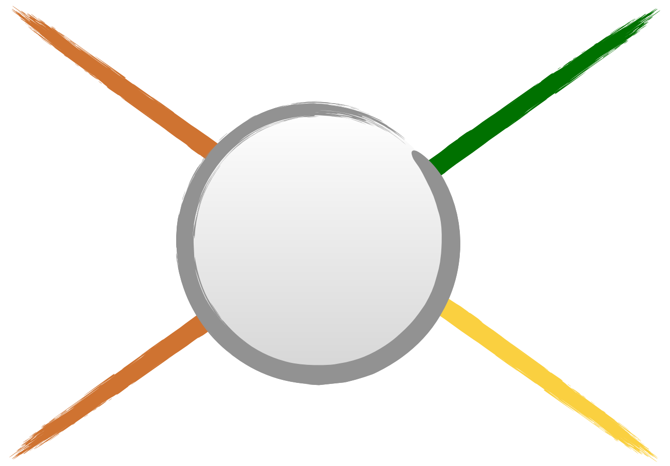
Increasing dataset allows to perform a wide range of measurements

Need a model-agnostic framework that can look for indirect signature of heavy new physics

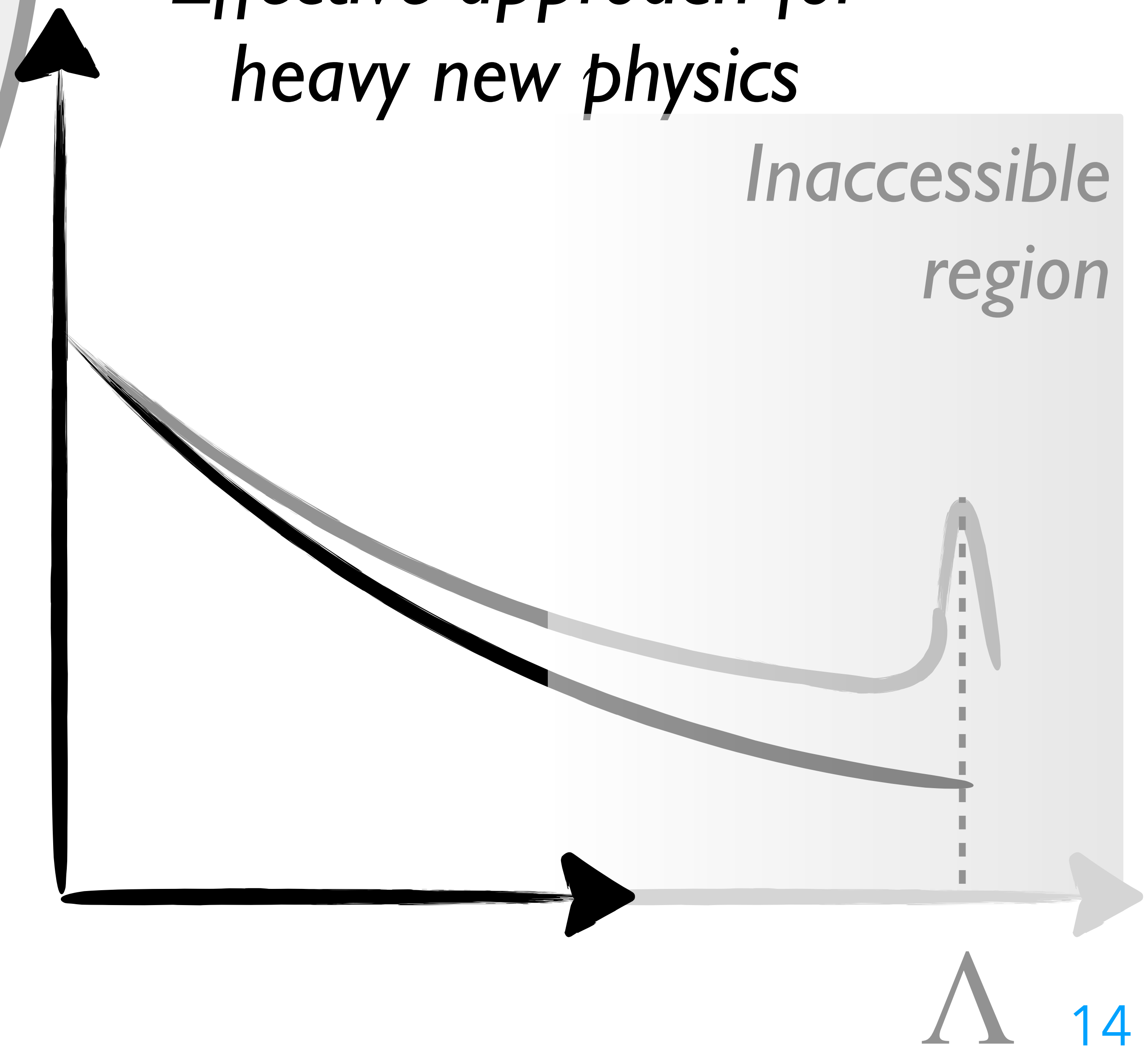
Consistently model deviations across different measurements

Going beyond the Standard Model - effective approach





Effective approach for heavy new physics

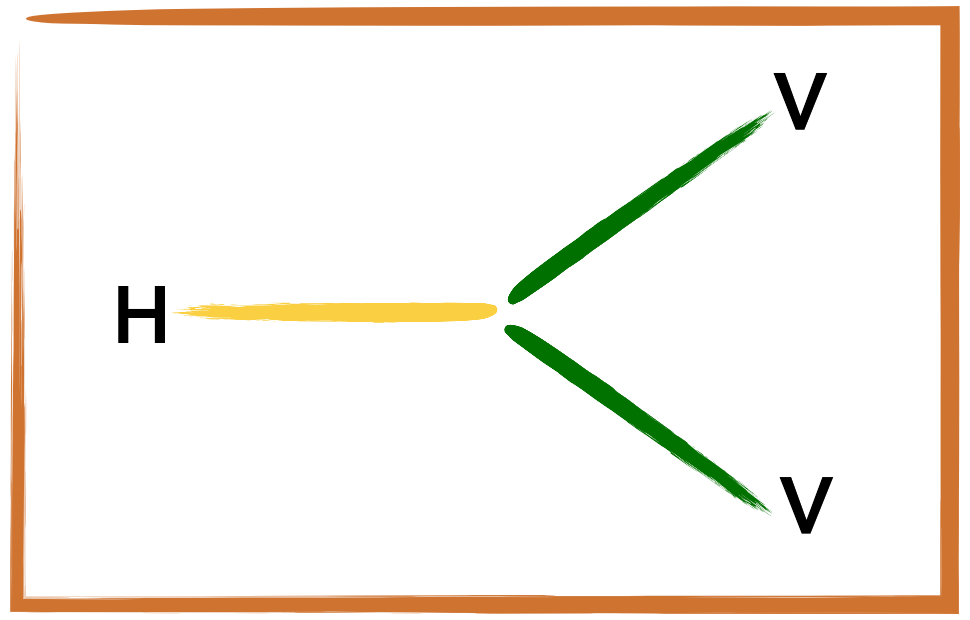


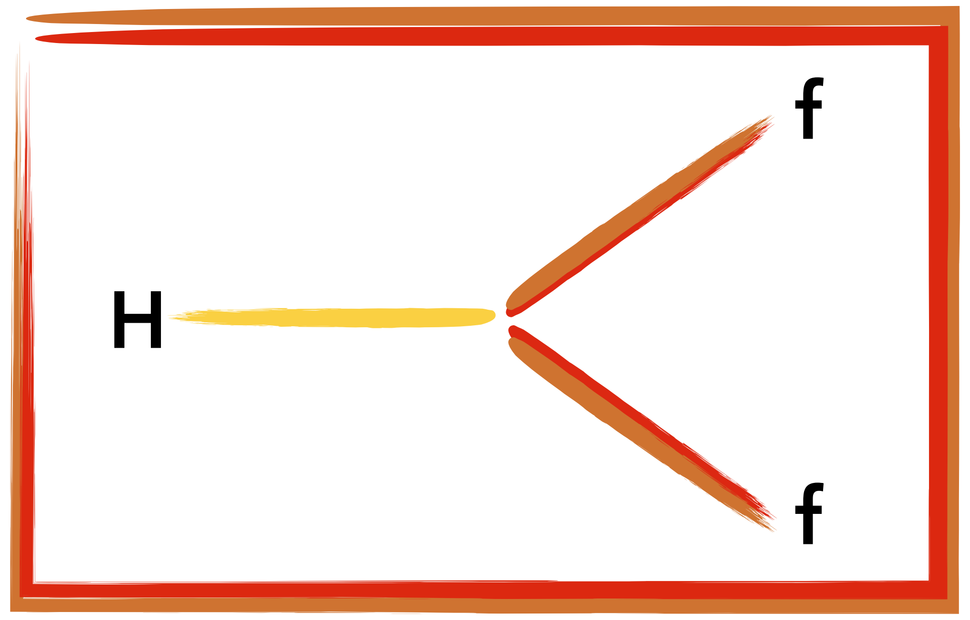
Introduce measurable parameters

Higgs boson - the heart of the Standard Model (SM)

Particle with unique quantum numbers ($J^{CP} = 0^+$), ***needs to be studied in detailed***

15 out of 19 parameters in the SM connected to the Higgs Boson





$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

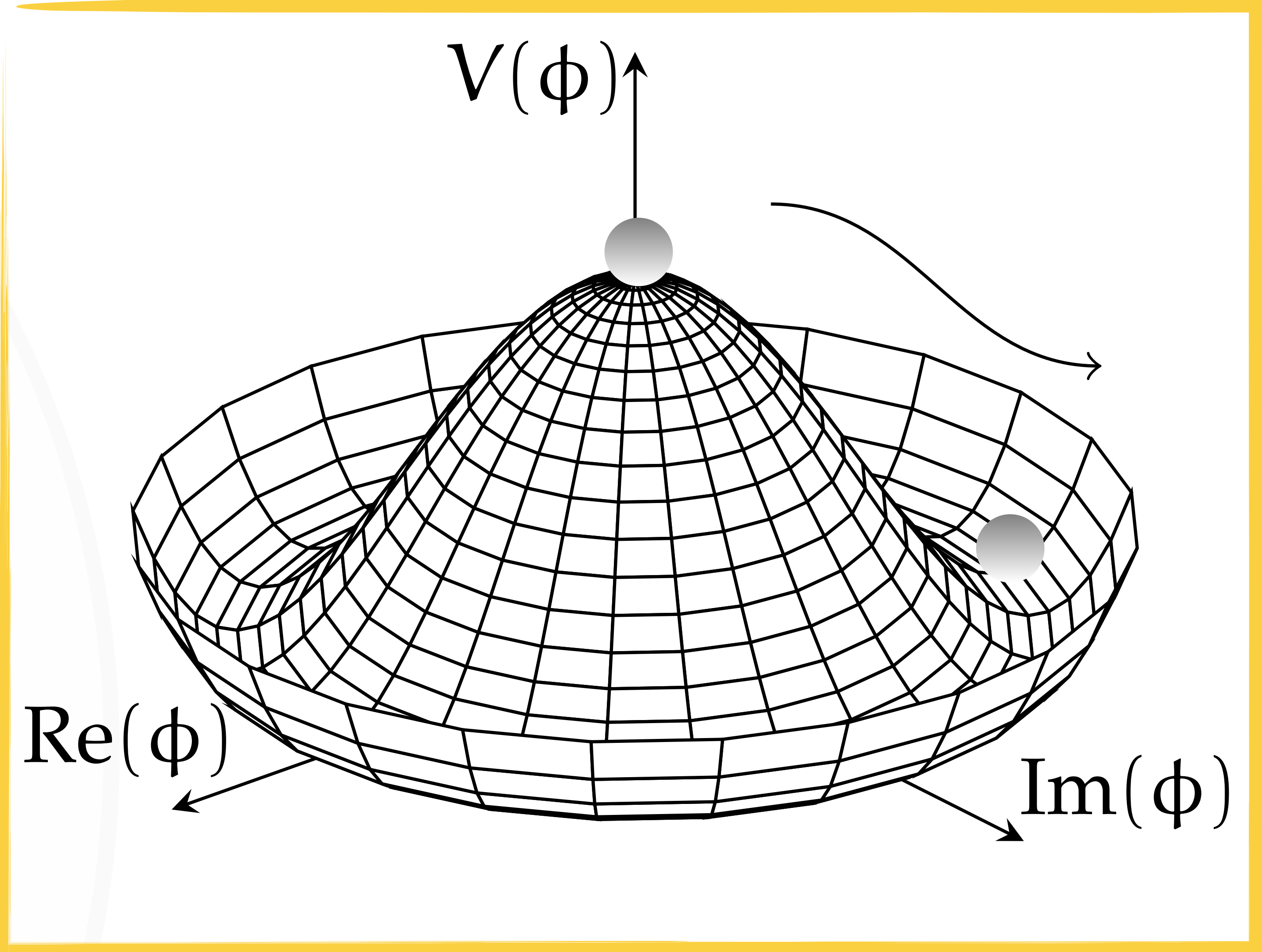
$$+ i\overline{\psi}^{\dagger}D\psi$$

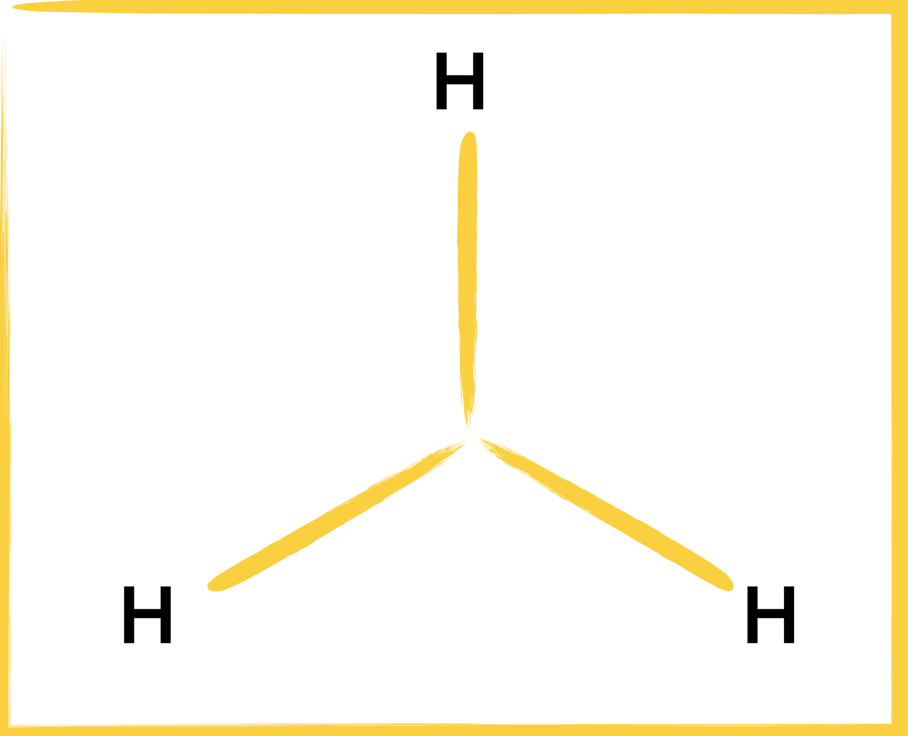
Yukawa Interaction

$$+ y_{ij}\psi_i\phi\psi_j + h.c.$$

BEH Mechanism

$$+ |D_\mu\phi|^2 - \mu^2(\phi^\dagger\phi) - \lambda(\phi^\dagger\phi)^2$$

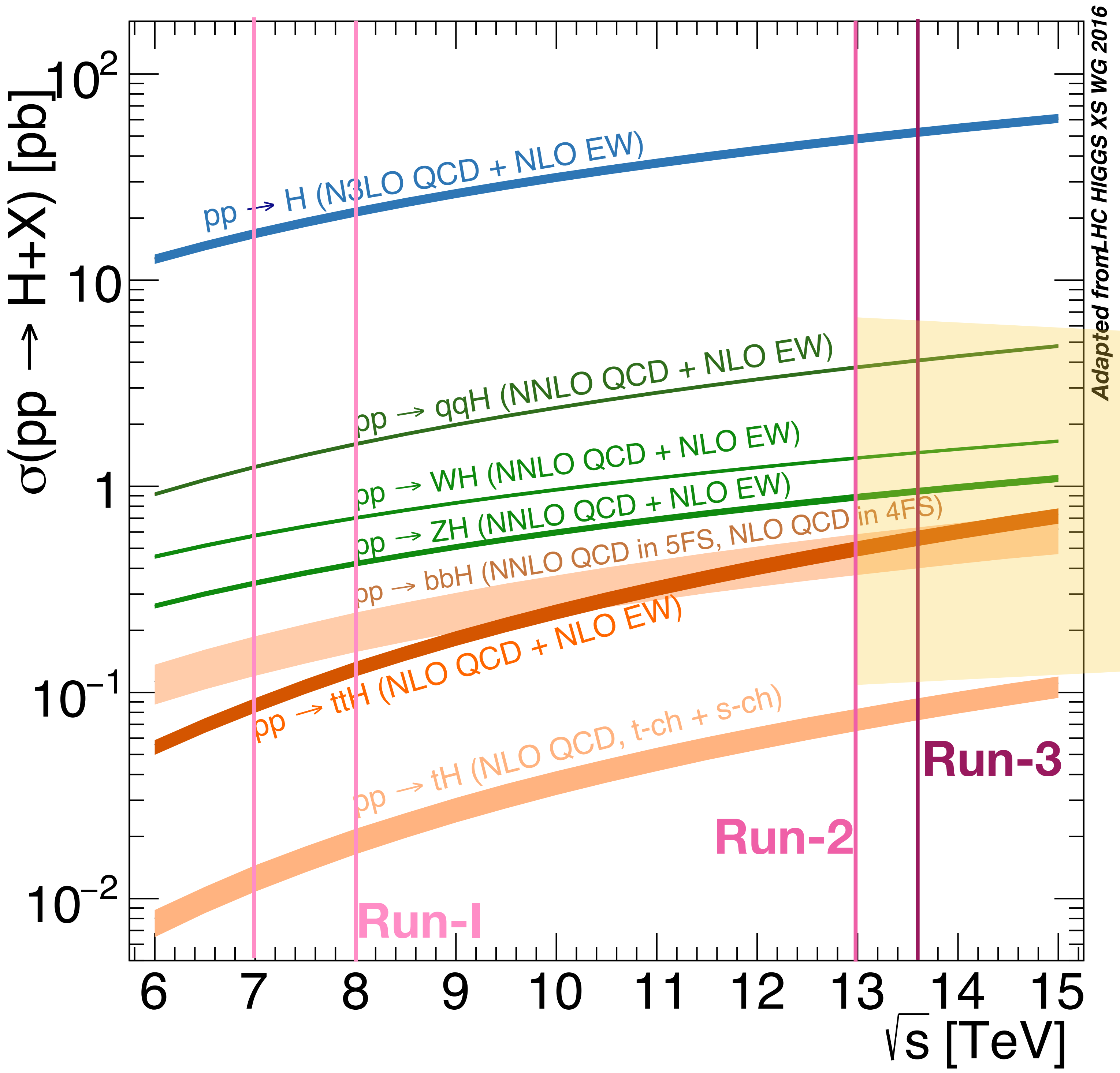


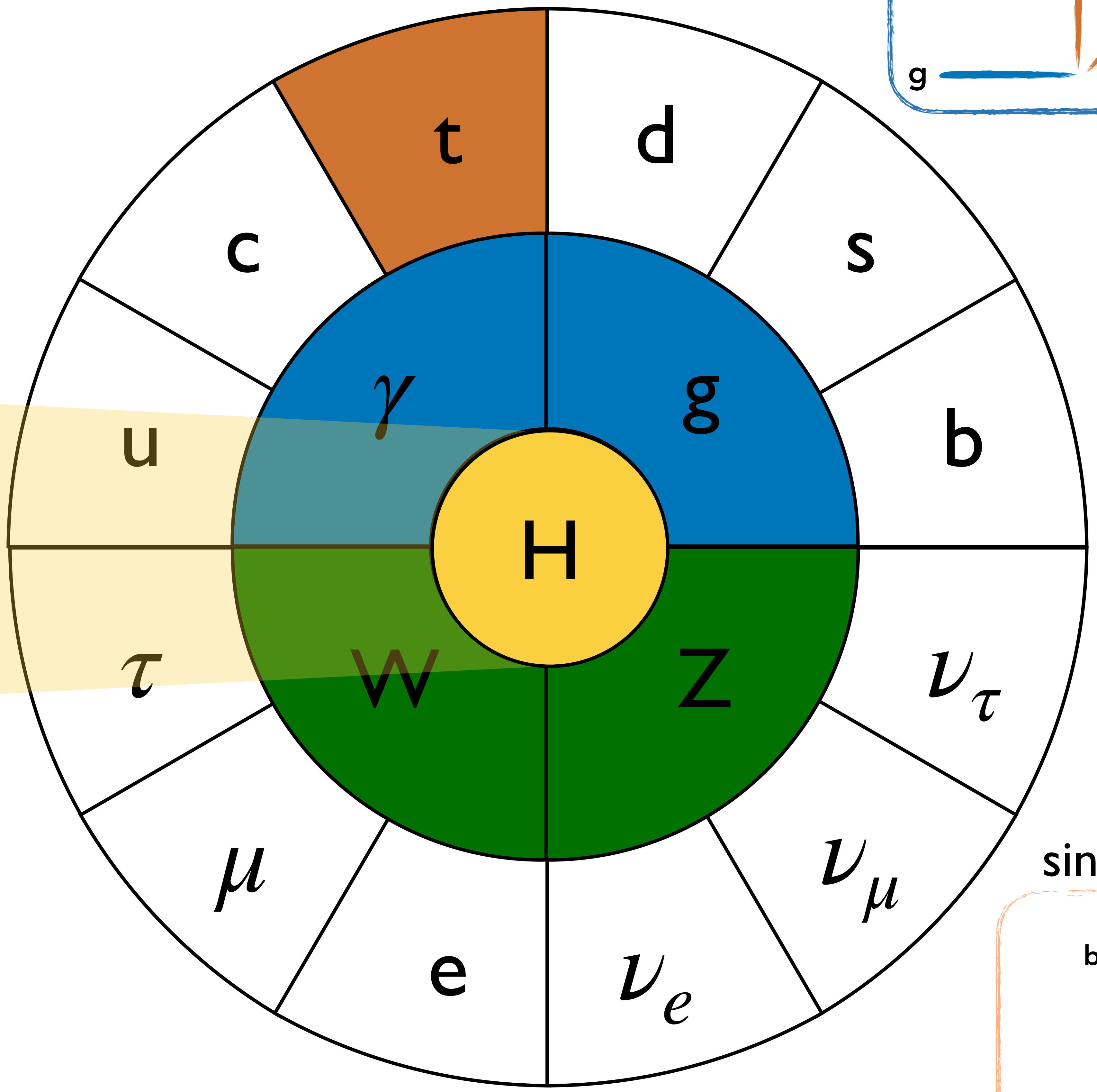


Interacts directly with all massive particles of the SM (and indirectly with γ, g) → ***incredibly rich phenomenology !***

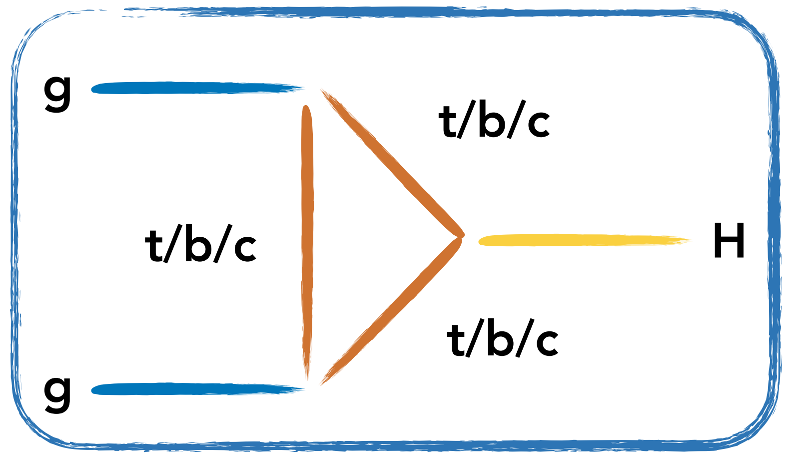
Producing Higgs bosons

Higgs boson production cross-section



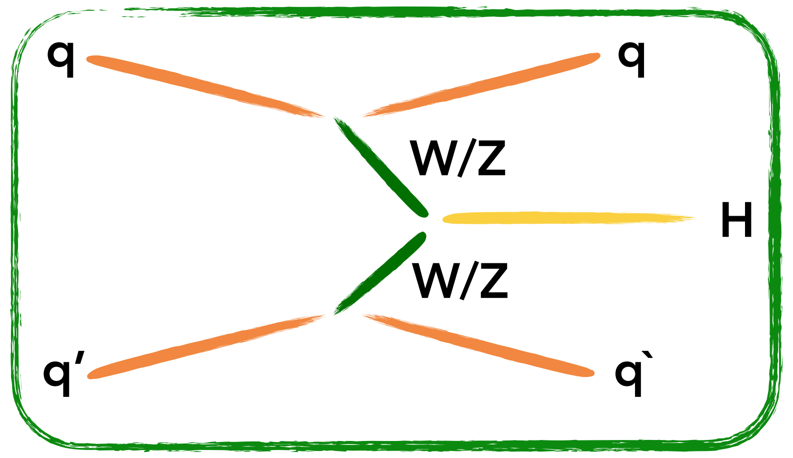


gluon-gluon fusion



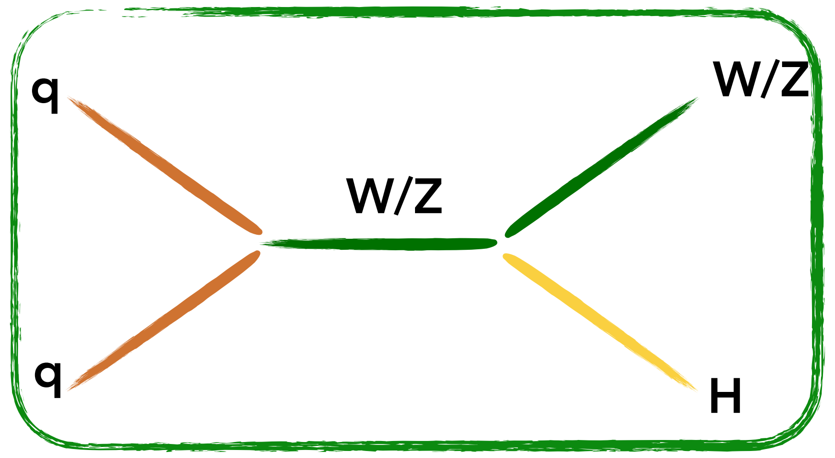
(ggF)

vector boson fusion



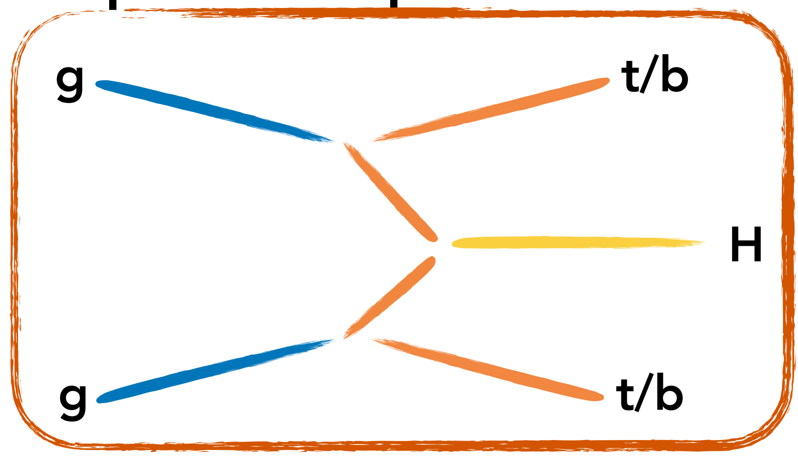
(VBF)

Higgstrahlung



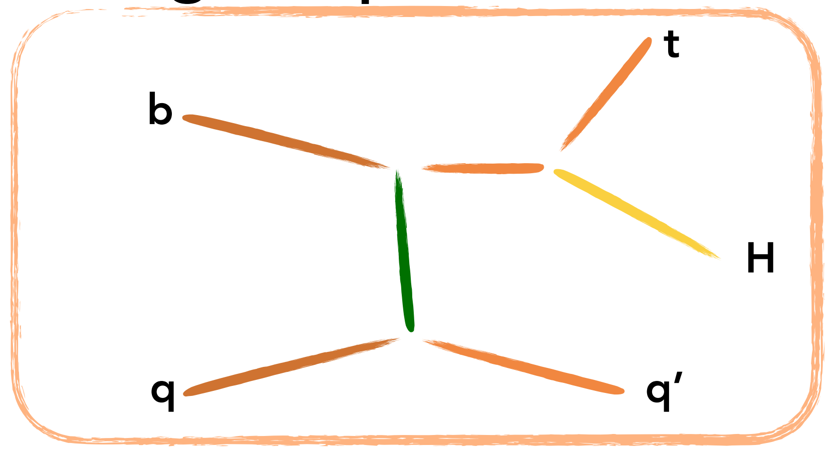
(VH,V=W,Z)

top-anti-top associated



(ttH)

single-top associated



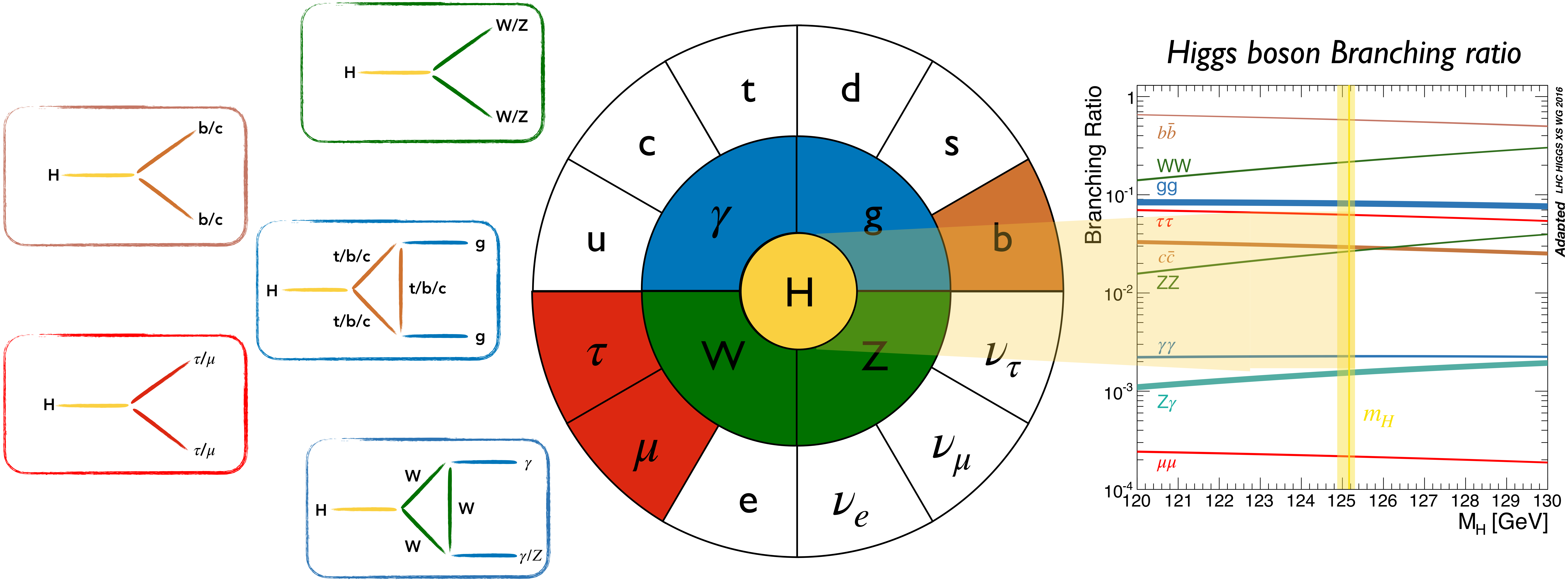
(tH)

Cross-section of different modes, varies across 3-orders of magnitude !

Kinematic features of the processes allows to pin-down the production

Large Hadron Collider (LHC)

Observing Higgs bosons



Higgs boson has a narrow width (4.07 MeV) and **decays instantaneously** ! (~10^{-22} sec)

Decays to all particles except the top quark → multiple channels to study Higgs boson


ATLAS
CMS
ALICE
LHCb

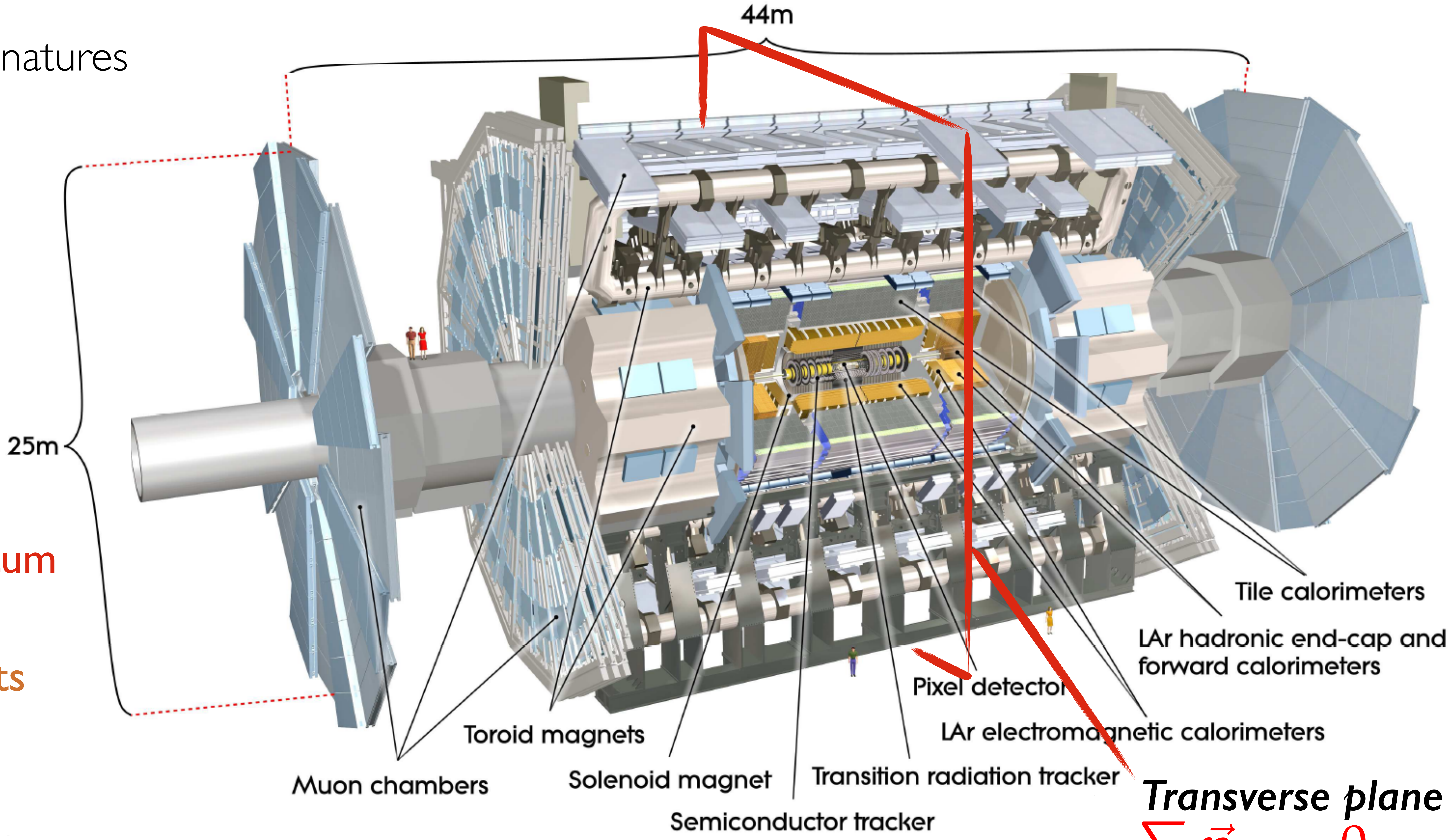
ATLAS - **A** **T**oroidal **LHC** **A**pparatus

- Layered detectors surrounding interacting point : tracker) solenoid) calorimeters) muon spectrometer)

- Fast triggering on interesting signatures

- Precise reconstruction of :
  - collision vertices
  - photons & electrons
  - muons
  - taus
  - jets
  - missing transverse momentum

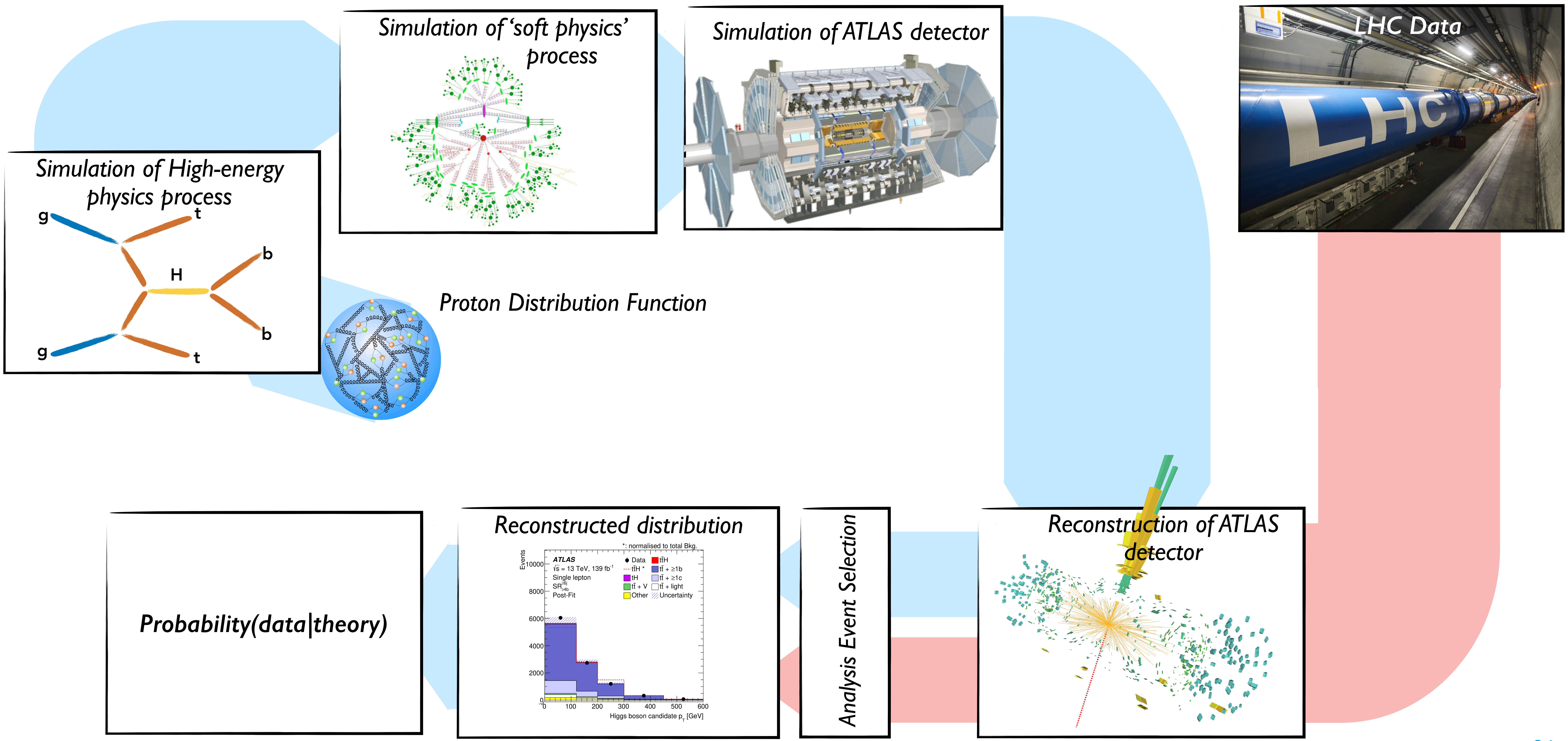
- Identification of heavy-flavor jets



Transverse plane

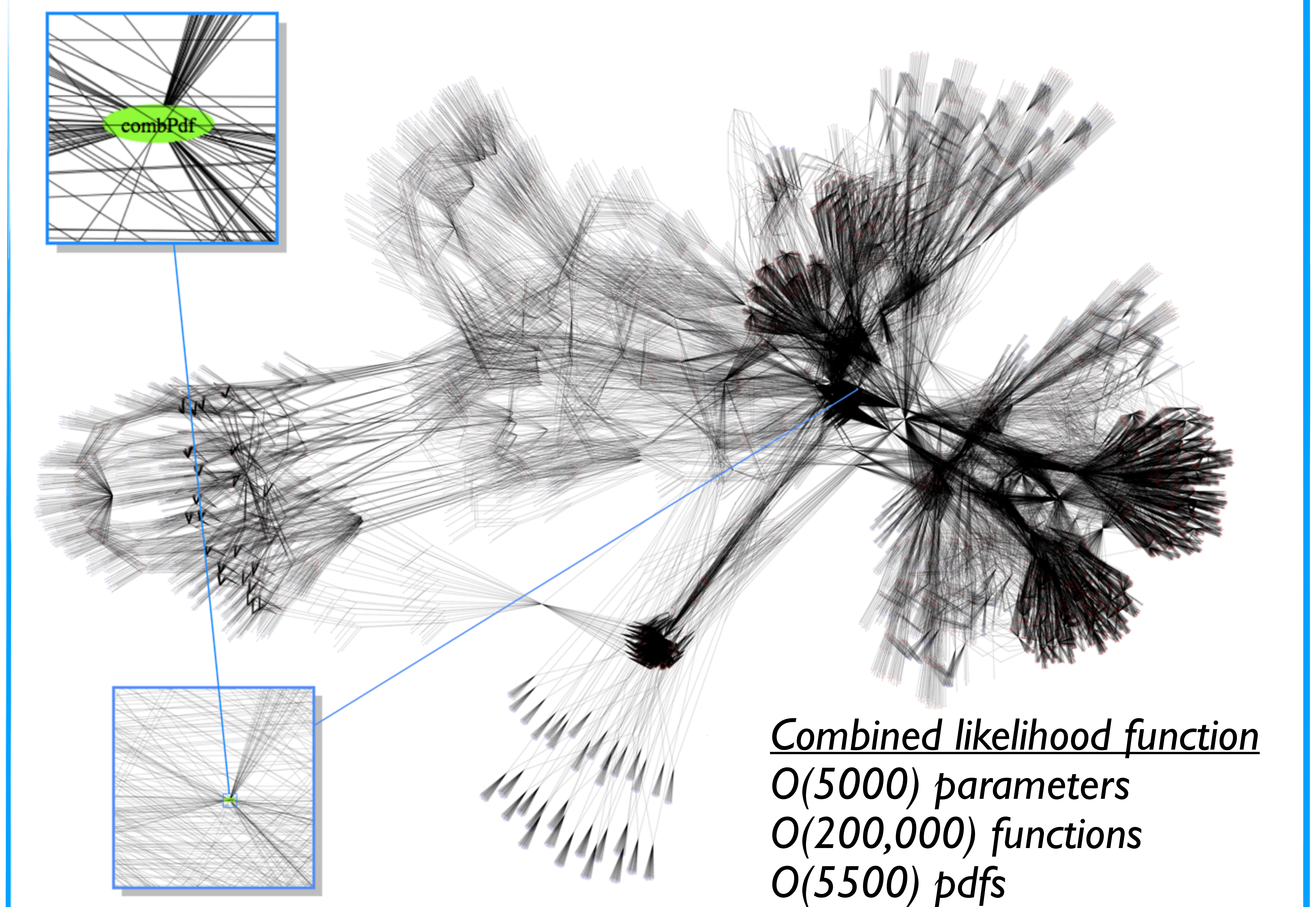
$$\sum \vec{p}_T = 0$$

ATLAS workflow : testing physics theories with data



testing physics theories with data : Likelihood function

Likelihood function, L(data|theory), is used to perform statistical inference on physics parameters



Combined likelihood function
O(5000) parameters
O(200,000) functions
O(5500) pdfs

likelihood function captures,

i. Behaviour of theory model parameters on observables *For ex. :* ***Higgs couplings*** — *Parameters of interest*

ii. Systematic uncertainties from experimental sources
For ex. : ***Calibration of Jet energy scale***

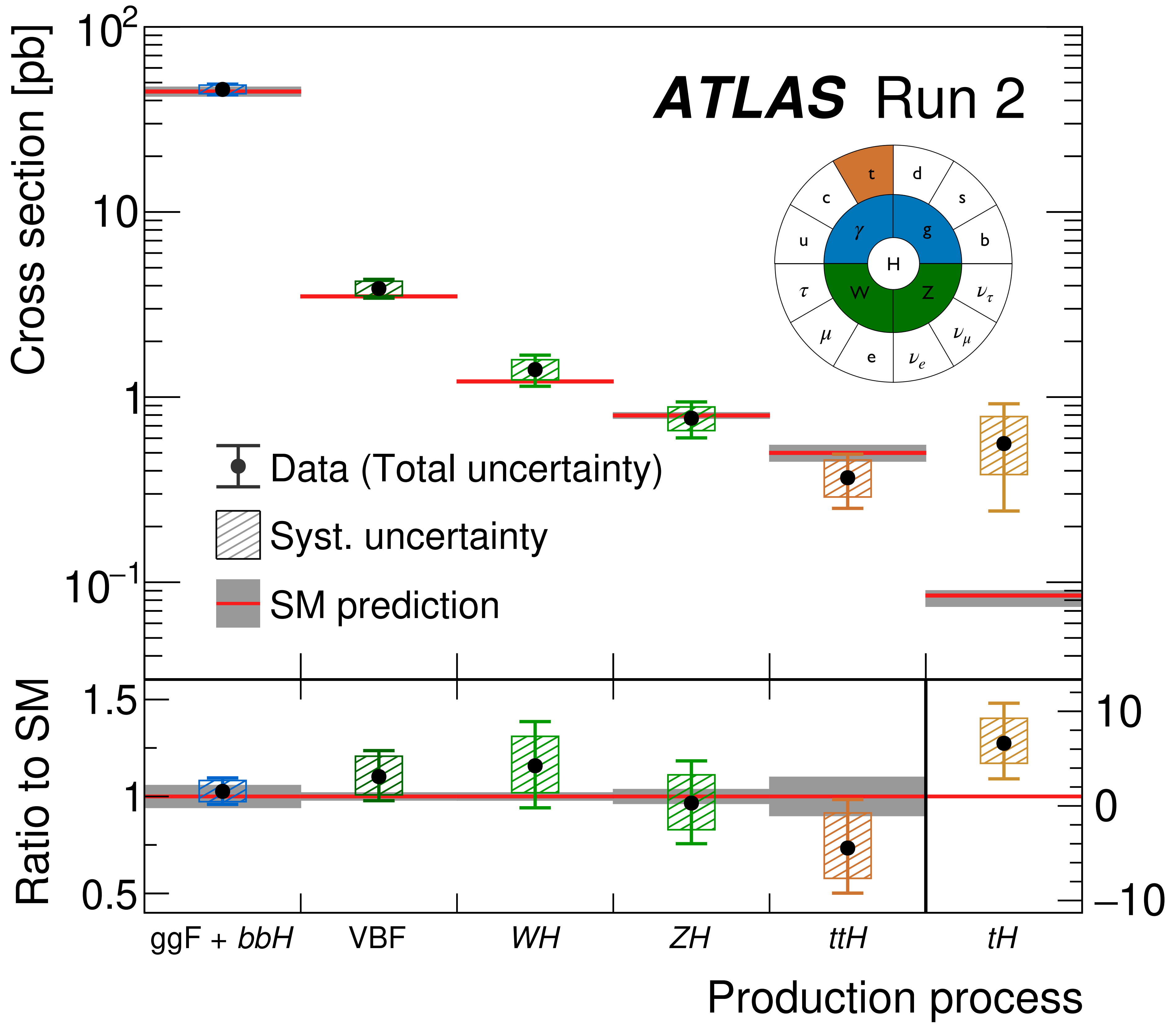
iii. Theoretical uncertainties on model
For ex. : ***PDF scale and factorisation uncertainty***

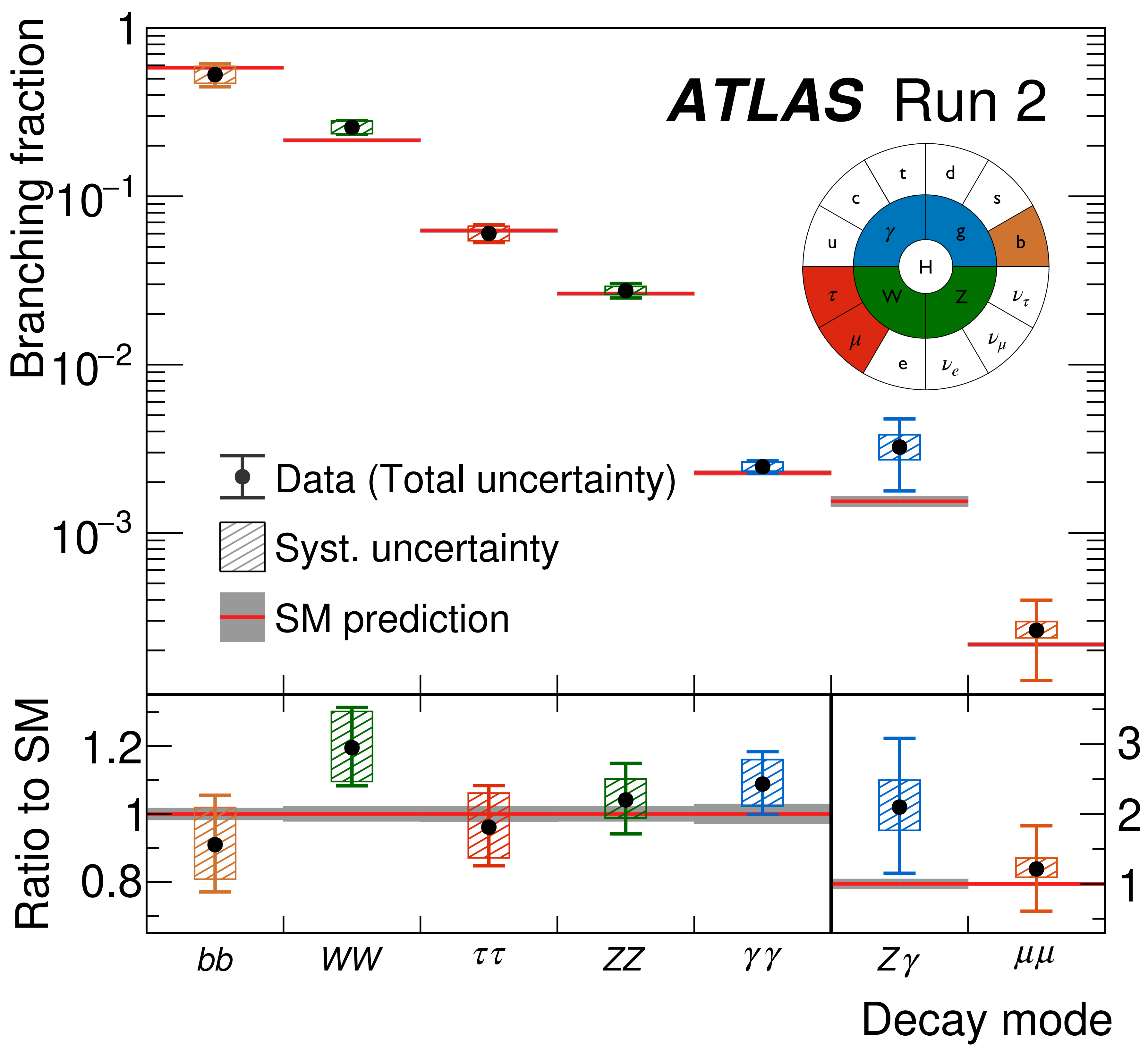
(ii–iii: *Nuisance Parameters*)

iv. Consistent signal & background modelling across different analyses
Avoid overlapping kinematic regions to extract information

Higgs inclusive measurements at ATLAS

Run-2 **30x as many Higgs** wrt Run-1, allows for precise measurements of cross-sections & couplings





All major production modes have 5σ observation and **for tH** 95% obs. (exp) upper limit of **15 (7) x SM**

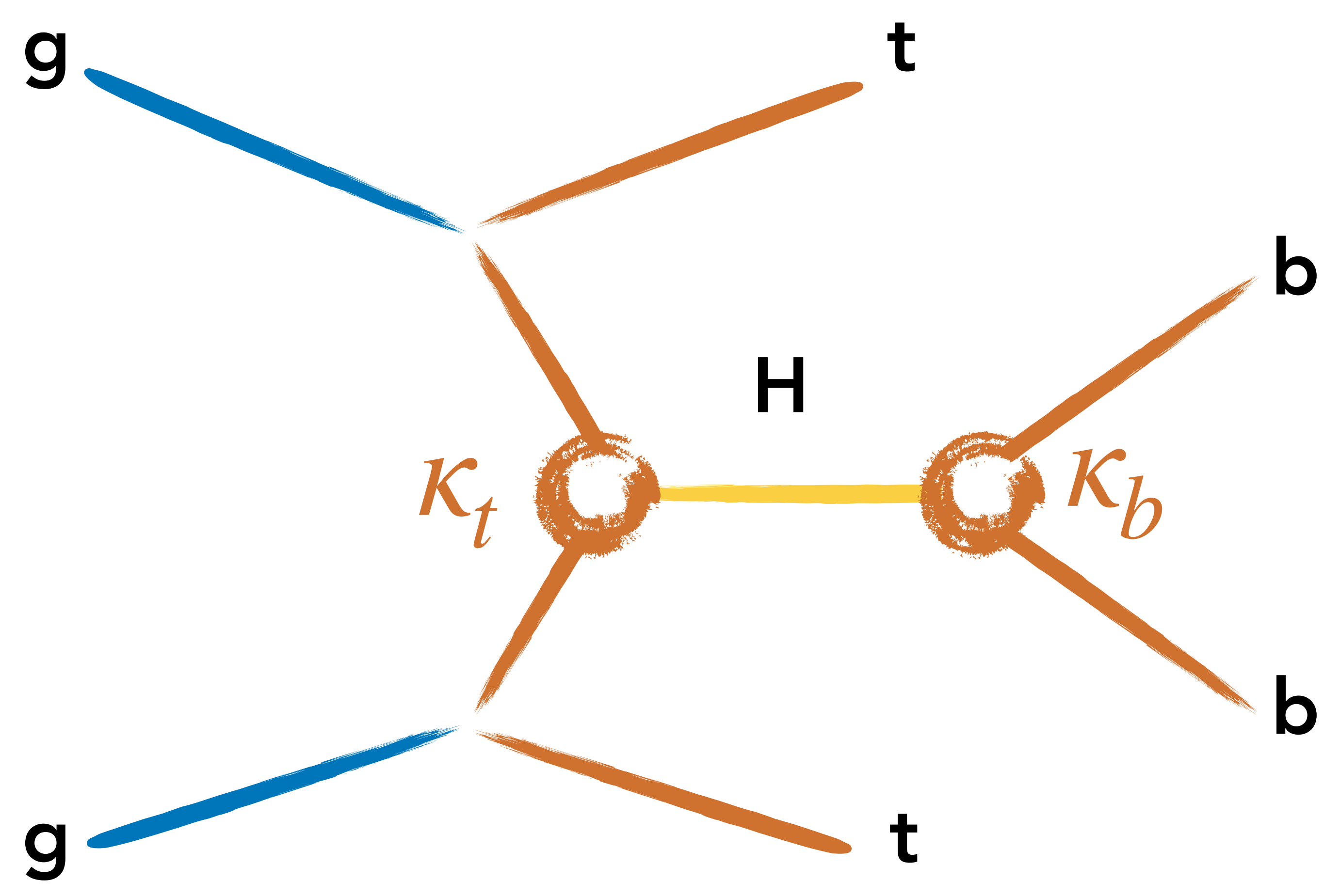
Strong indications for **rare Higgs decays** : obs. (exp) significance of 2.0σ (1.7σ) for $H \to \mu^+\mu^-$

and 2.3σ (1.1σ) for $H \to Z\gamma$

Higgs couplings to particles

Experimentally motivated couplings (κ) framework designed in Run-1 to check compatibility of inclusive measurements w.r.t SM

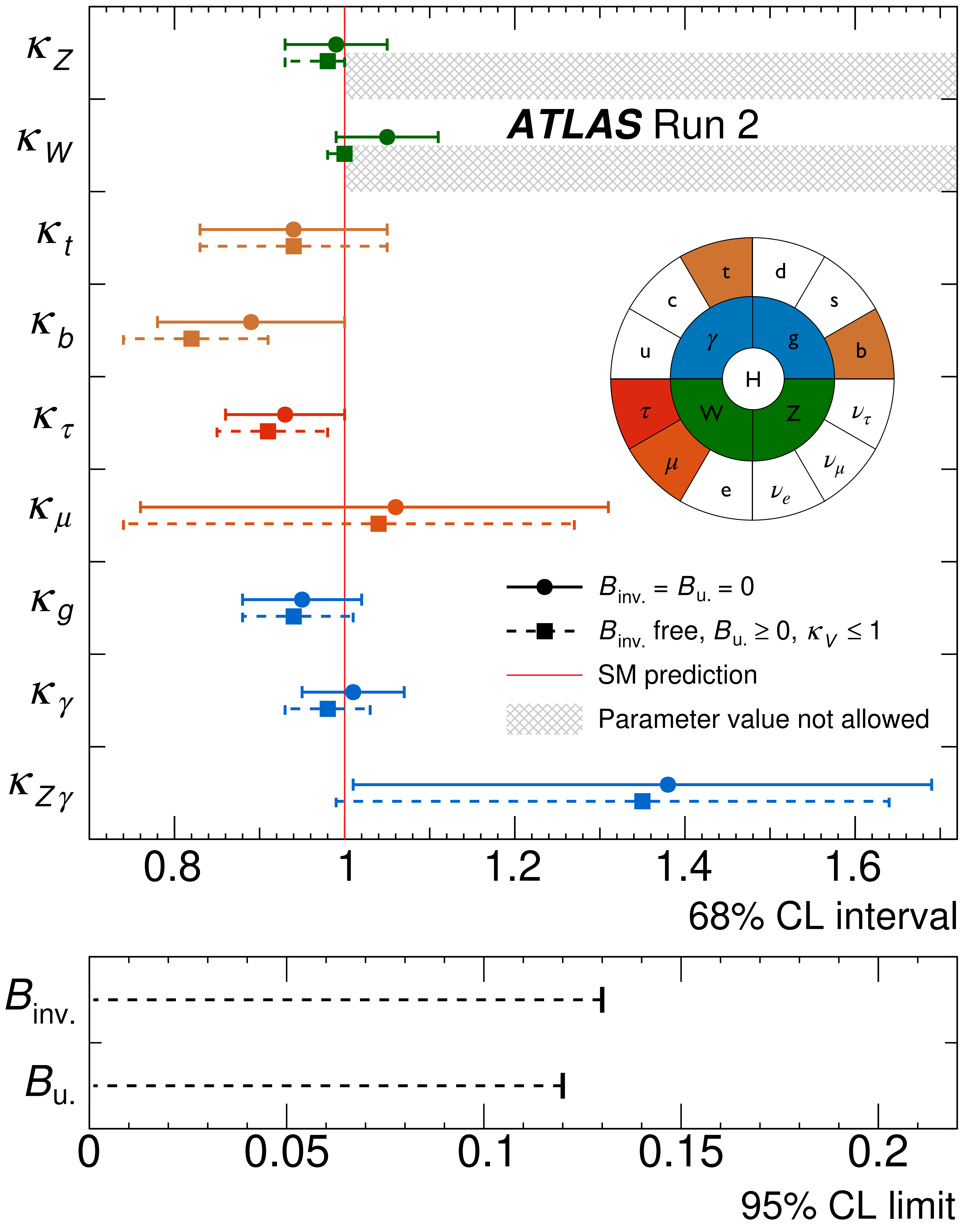
For instance, **ttH, H→$\mathbf{b\bar{b}}$,**



$$\sigma(ttH, H \to b\bar{b}) = \sigma(ttH) \times \frac{\Gamma(H \to b\bar{b})}{\Gamma(H)}$$

$$= \frac{k_t^2 k_b^2}{k_H^2} \sigma_{SM}(ttH) \times \frac{\Gamma_{SM}(H \to b\bar{b})}{\Gamma_{SM}(H)}$$

Higgs boson generic couplings to SM particles



Framework is designed for rates, **not sensitive to kinematic distributions**

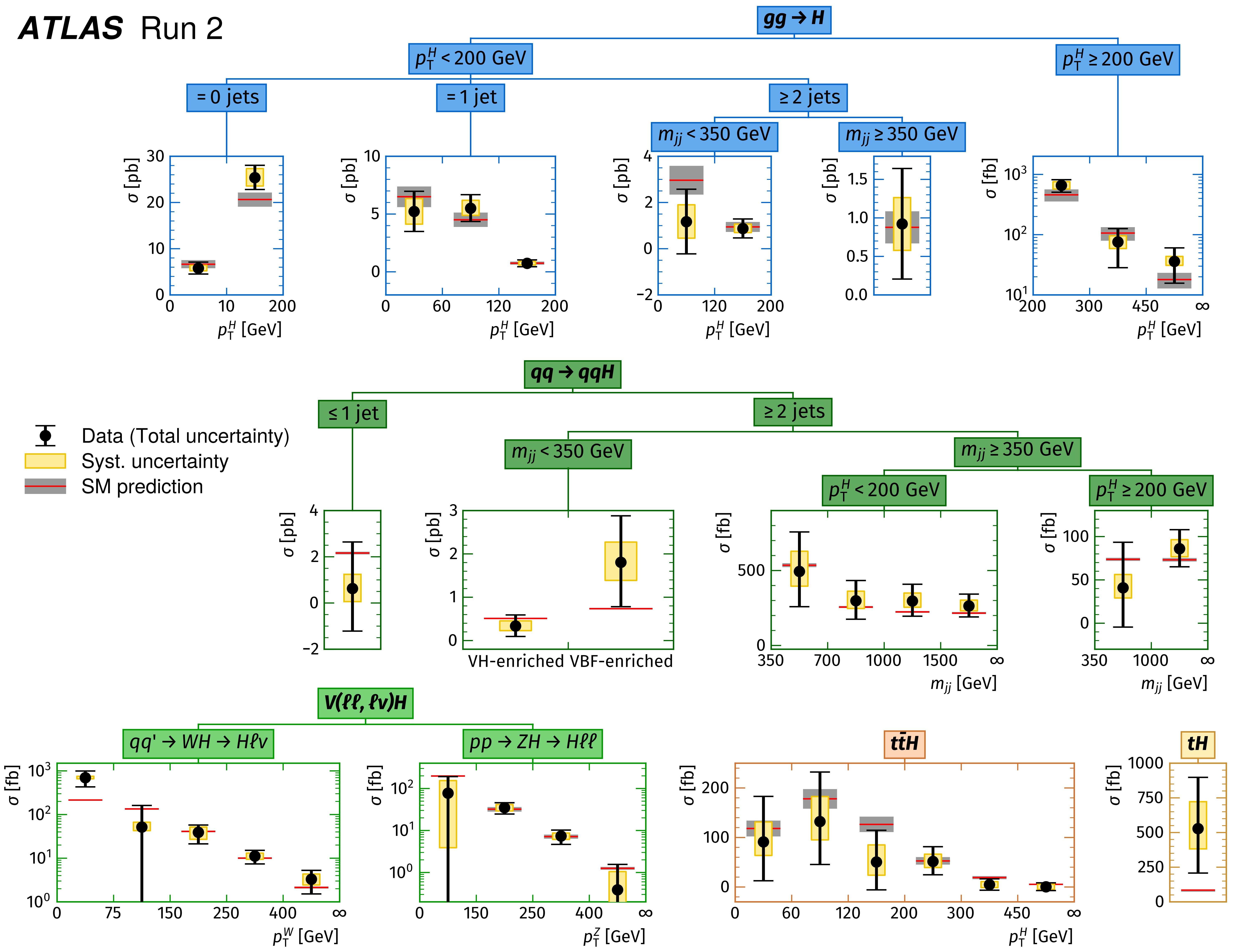
Is a LO - order framework and **not a QFT** that extends the SM

Detailed kinematic picture of the Higgs boson

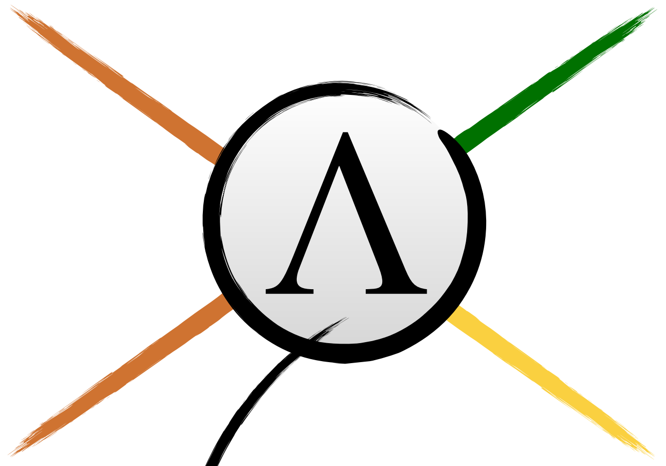
Increased dataset and modern analysis techniques give access **detailed kinematic information**

Combining measurements from different analysis allows to study Higgs production across **4 orders of magnitude in cross-section**

Detailed kinematic information requires a **consistent theoretical framework** to study deviations from the Standard Model



The Standard Model as an Effective Field Theory



$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + O\left(\frac{1}{\Lambda^{d>2}}\right)$$

$\propto \frac{1}{\Lambda^0}$

Weinberg operator
violates Baryon & Lepton no.
Λ ~ Majorana ν mass scale

2499 SMEFT operators at dimension 6 with $\Delta L, \Delta B = 0$

Wilson Coefficients *parameters of interest*

much larger than energy scales probed at LHC

Operators built from SM fields, **all possible local interactions respecting symmetries**:
Poincare, and gauge symmetry, **$SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$ -** Standard Model Effective Field Theory (**SMEFT**)

Wilson coefficients (c_i) new measurable parameters, capture deformations from large class of dedicated physics models

Additional flavour symmetry in SMEFT dictated by experimental considerations, allow to scale down the complexity of operators !

New terms in the Lagrangian at d=6

Only certain kinds of operators are allowed from symmetry considerations and dimensionality

$$[\mathrm{H}] = 1,\ [\psi] = \frac{3}{2}, [\mathrm{X}] = 2, [\mathrm{D}] = 1$$

Can be broadly classed into 7 types,

i. Boson self-coupling
ii. Higgs kinetic term
iii. Higgs-gauge
iv. Higgs-fermions
v. Dipole
vi. EW current
vii. Four-fermion

$\mathcal{L}_6^{(1)} - X^3$	
Q_G	$f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$
$Q_{\widetilde{G}}$	$f^{abc} \widetilde{G}_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$
Q_W	$\varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$
$Q_{\widetilde{W}}$	$\varepsilon^{ijk} \widetilde{W}_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$

$\mathcal{L}_6^{(2)} - H^6$	
Q_H	$(H^\dagger H)^3$

$\mathcal{L}_6^{(3)} - H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$(D^\mu H^\dagger H)\,(H^\dagger D_\mu H)$

$\mathcal{L}_6^{(4)} - X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^a_{\mu\nu} G^{a\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^{a\mu\nu}$
Q_{HW}	$H^\dagger H\, W^i_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^{i\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \sigma^i H\, W^i_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B^{\mu\nu}$

$\mathcal{L}_6^{(5)} - \psi^2 H^3$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$\mathcal{L}_6^{(6)} - \psi^2 X H$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\sigma^i H W^i_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^a u_r)\widetilde{H}\, G^a_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\sigma^i \widetilde{H}\, W^i_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^a d_r) H\, G^a_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\sigma^i H\, W^i_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$\mathcal{L}_6^{(7)} - \psi^2 H^2 D$	
$Q^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}_p \sigma^i \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_p \sigma^i \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$\mathcal{L}_6^{(8a)} - (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \sigma^i q_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$
$Q^{(1)}_{lq}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q^{(3)}_{lq}$	$(\bar{l}_p \gamma_\mu \sigma^i l_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$

$\mathcal{L}_6^{(8b)} - (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q^{(1)}_{ud}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q^{(8)}_{ud}$	$(\bar{u}_p \gamma_\mu T^a u_r)(\bar{d}_s \gamma^\mu T^a d_t)$

$\mathcal{L}_6^{(8c)} - (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^a q_r)(\bar{u}_s \gamma^\mu T^a u_t)$
$Q^{(1)}_{qd}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^a q_r)(\bar{d}_s \gamma^\mu T^a d_t)$

$\mathcal{L}_6^{(8d)} - (\bar{L}R)(\bar{R}L), (\bar{L}R)(\bar{L}R)$	
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$
$Q^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$
$Q^{(8)}_{quqd}$	$(\bar{q}^j_p T^a u_r)\varepsilon_{jk}(\bar{q}^k_s T^a d_t)$
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$

l : LH-lepton doublet, e : RH-lepton singlet, q : LH-quark doublet, u : RH-up-type quark singlet, d : RH-down-type quark singlet

10.1007/JHEP 04 (2021) 073 - Brivio

New operators → New couplings

New operators introduce modifications to existing couplings

Can also introduces new types of interactions that are not allowed in the Standard Model

Typically, the operators containing the Higgs field end up affect both the Higgs sector and the Electroweak sectors → **strong interplay between different measurements**

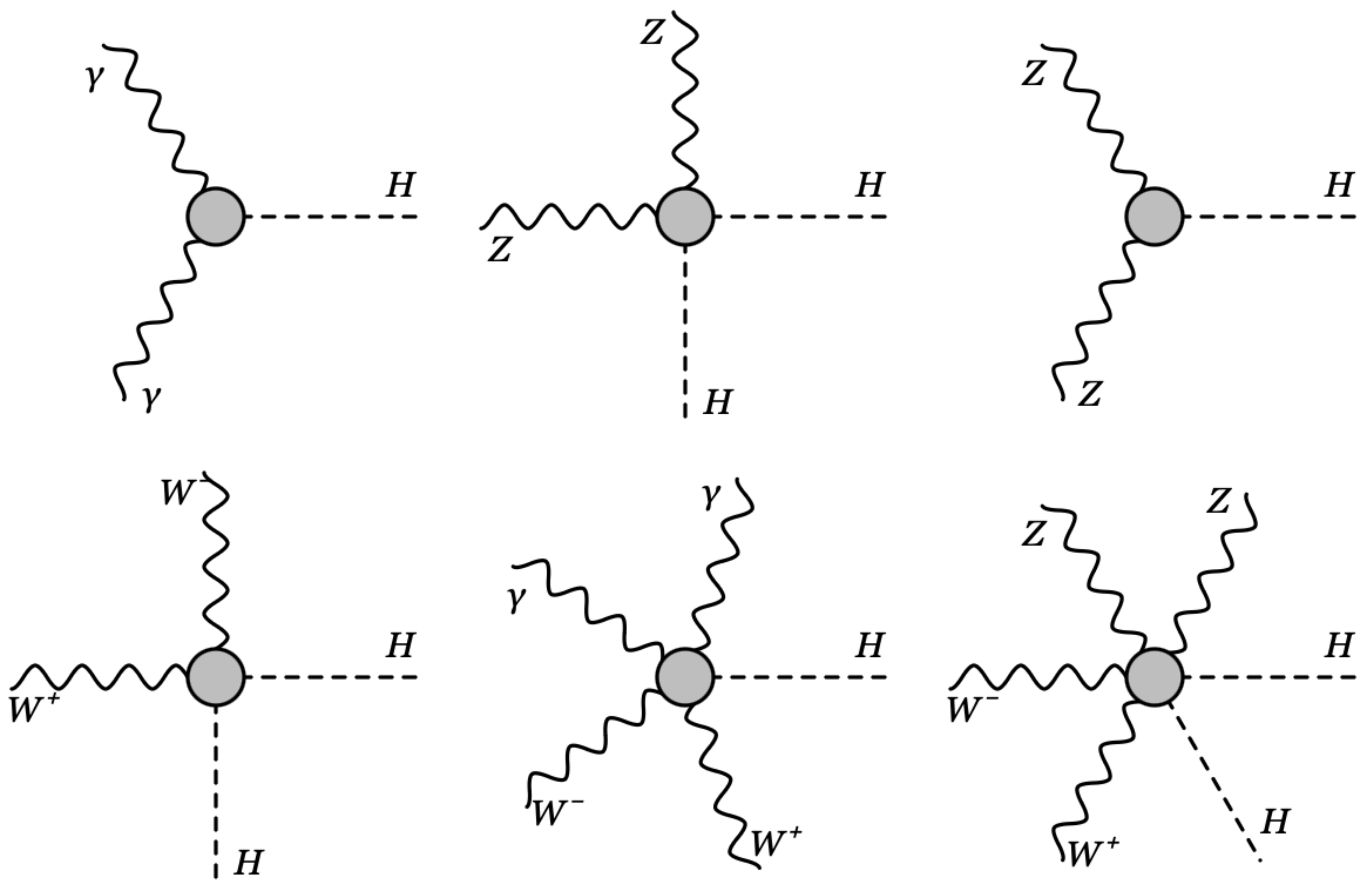
$Q_{HW} = H^\dagger H \, W^i_{\mu\nu} W^{I\mu\nu}$

Particle

Please select the particle of your choice:

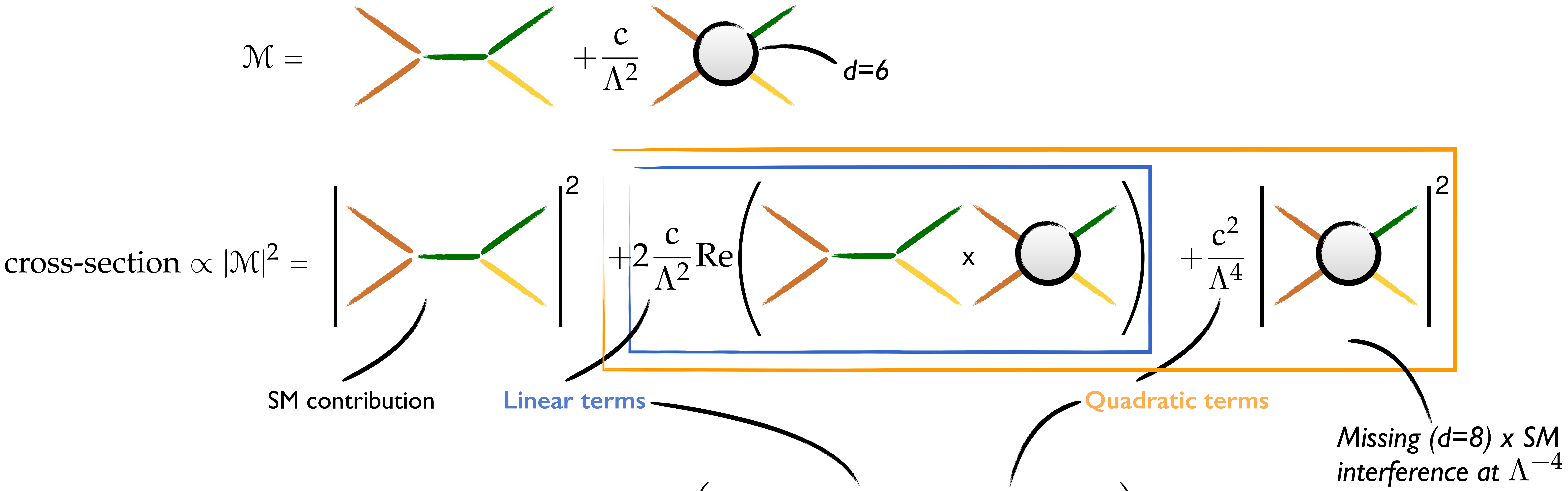
u	c	t	$\bar{u}$	$\bar{c}$	$\bar{t}$	g	H
d	s	b	$\bar{d}$	$\bar{s}$	$\bar{b}$	γ	
e^-	μ^-	τ^-	e^+	μ^+	τ^+	Z	
ν_e	ν_μ	ν_τ	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$	W^+	W^-

Result vertices



From Lagrangian to Observables

Continuous signal modelling in the likelihood function : $L(\text{data}|\vec{\mu},\vec{\theta}) \rightarrow L(\text{data}|\vec{\mu}(\vec{c}),\vec{\theta})$



$$\mathcal{M} = [\text{SM}] + \frac{c}{\Lambda^2}[\text{d=6}]$$

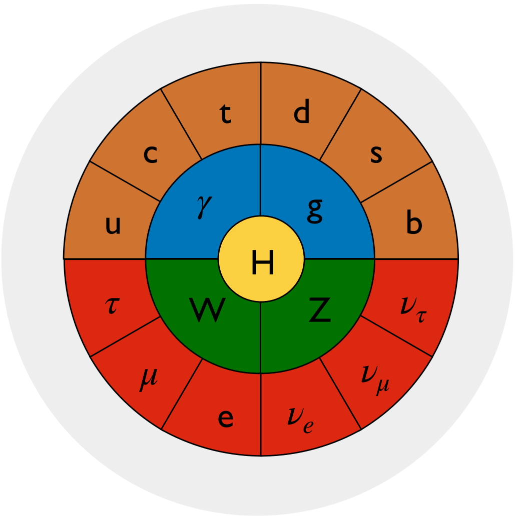
$$\text{cross-section} \propto |\mathcal{M}|^2 = |\text{SM}|^2 + 2\frac{c}{\Lambda^2}\text{Re}\left(\text{SM} \times \text{d=6}\right) + \frac{c^2}{\Lambda^4}|\text{d=6}|^2$$

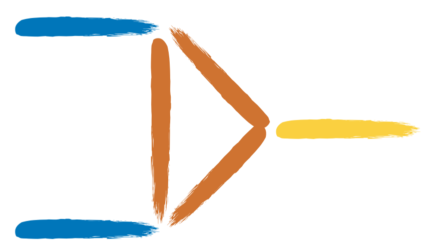
$$\sigma_{SMEFT} = \sigma_{SM}\left(1 + \sum_j A_i c_i + \sum_{ij} b_{ij} c_i c_j\right)$$

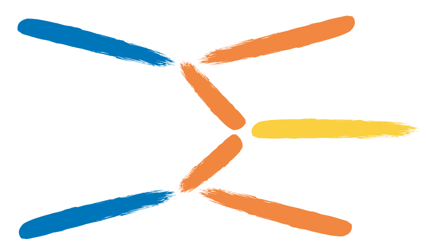
(cross-sections, decay widths)

Weights from the matrix elements

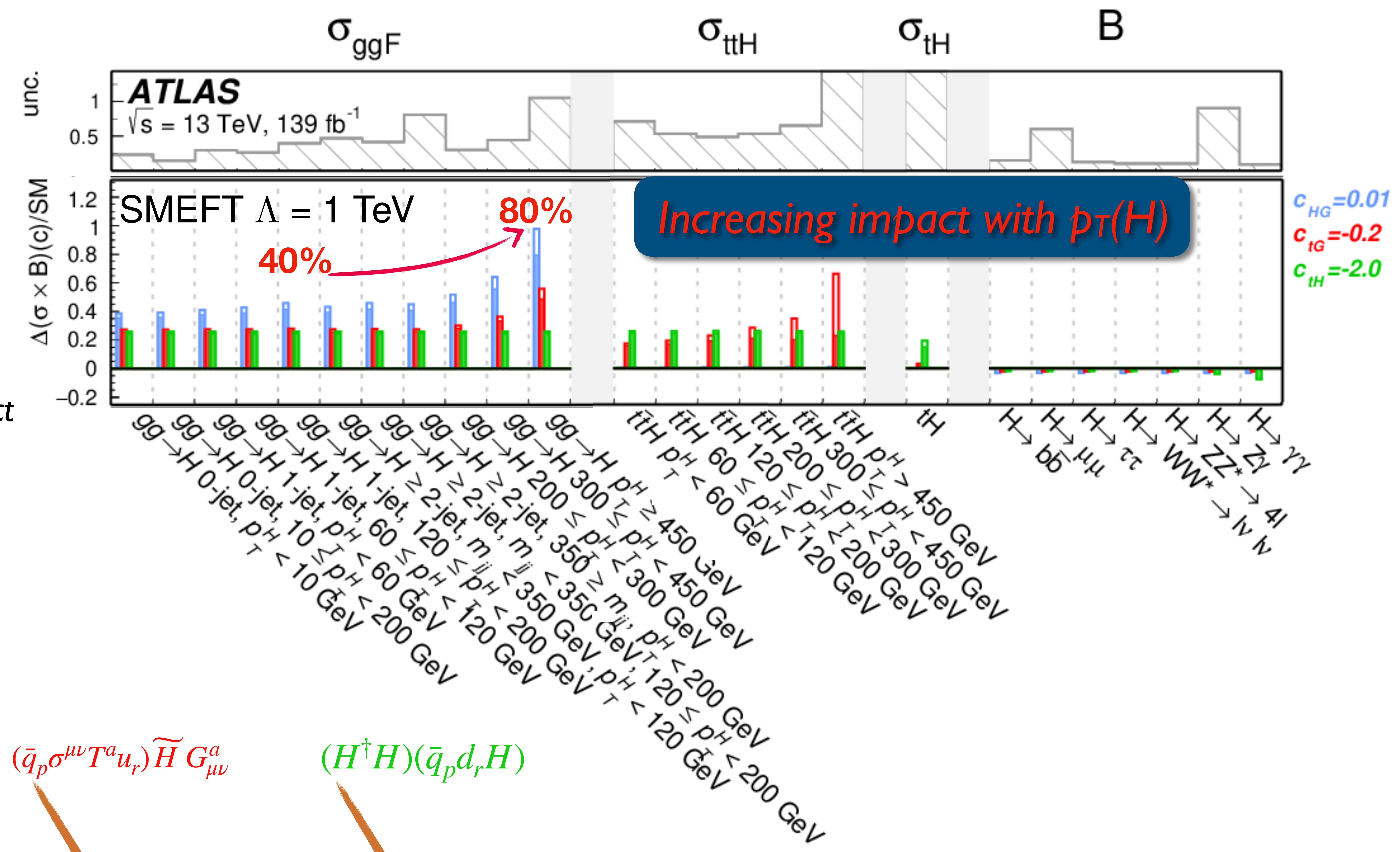
An example : Higgs-gluon & Higgs-top in SMEFT



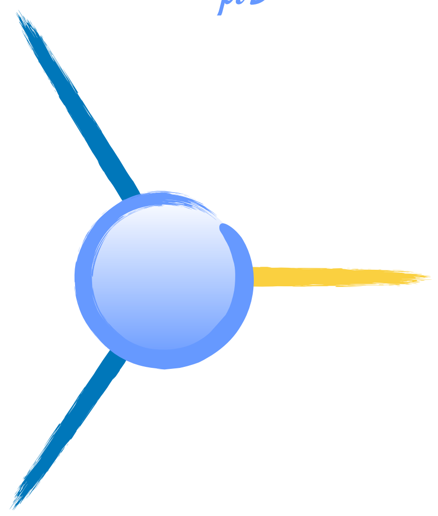




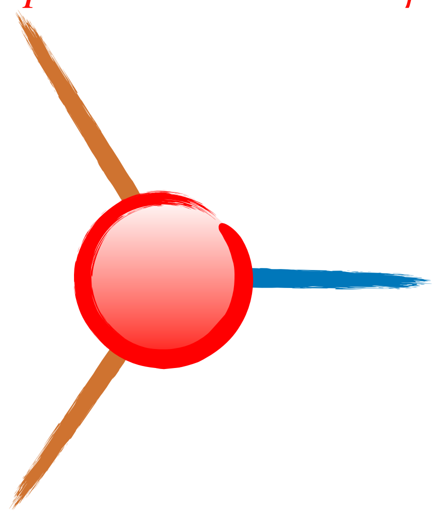
SMEFT impact w.r.t SM



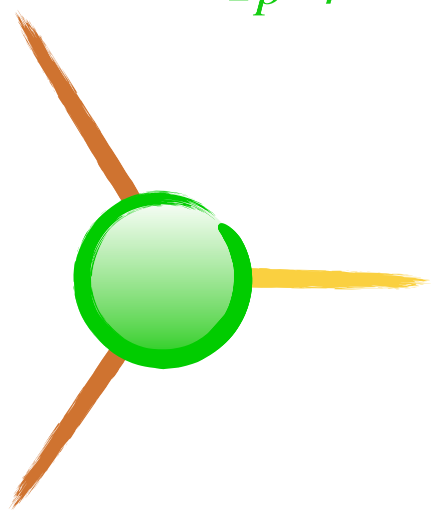
$H^\dagger H\, G^a_{\mu\nu} G^{a\mu\nu}$



$(\bar{q}_p \sigma^{\mu\nu} T^a u_r)\widetilde{H}\, G^a_{\mu\nu}$

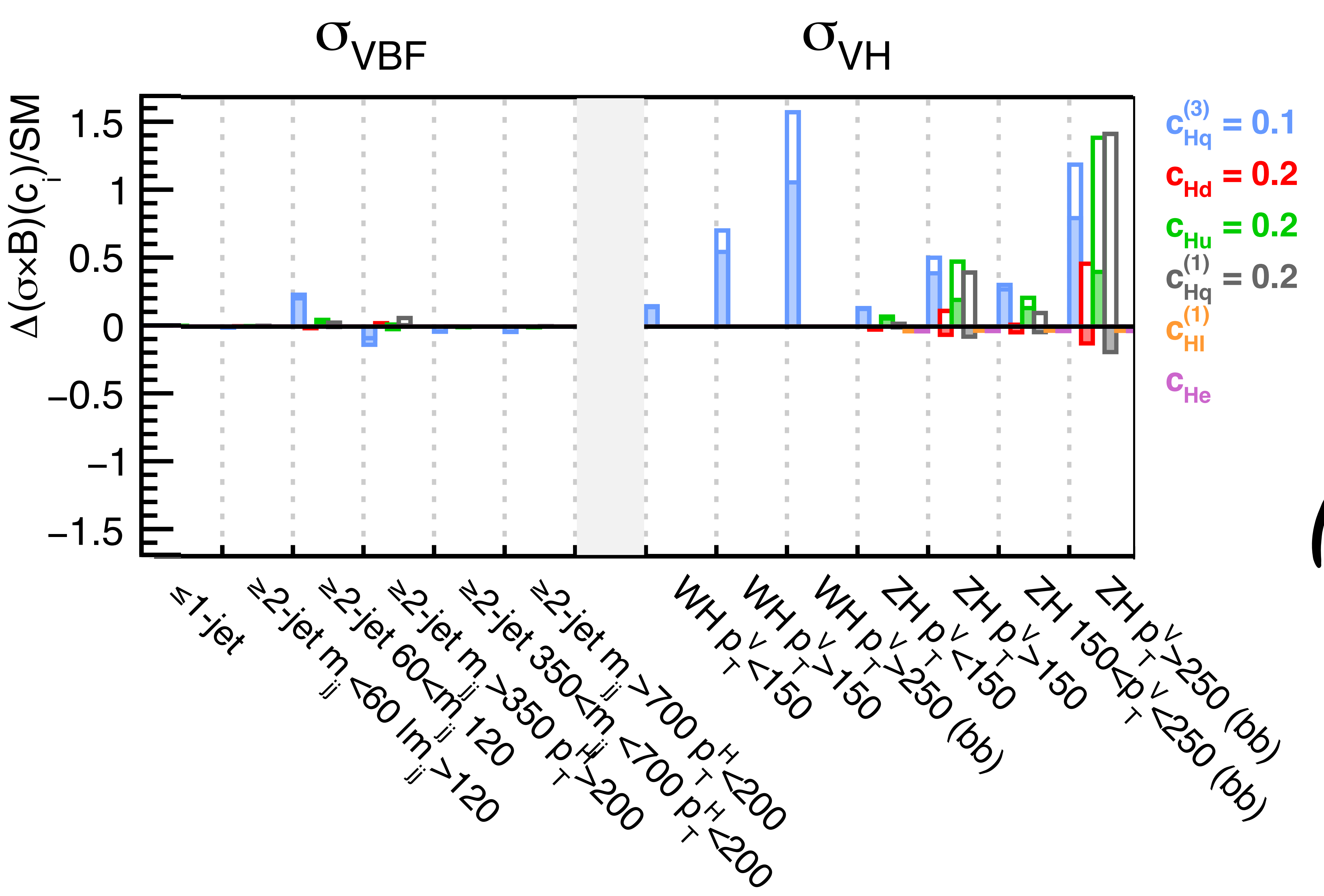


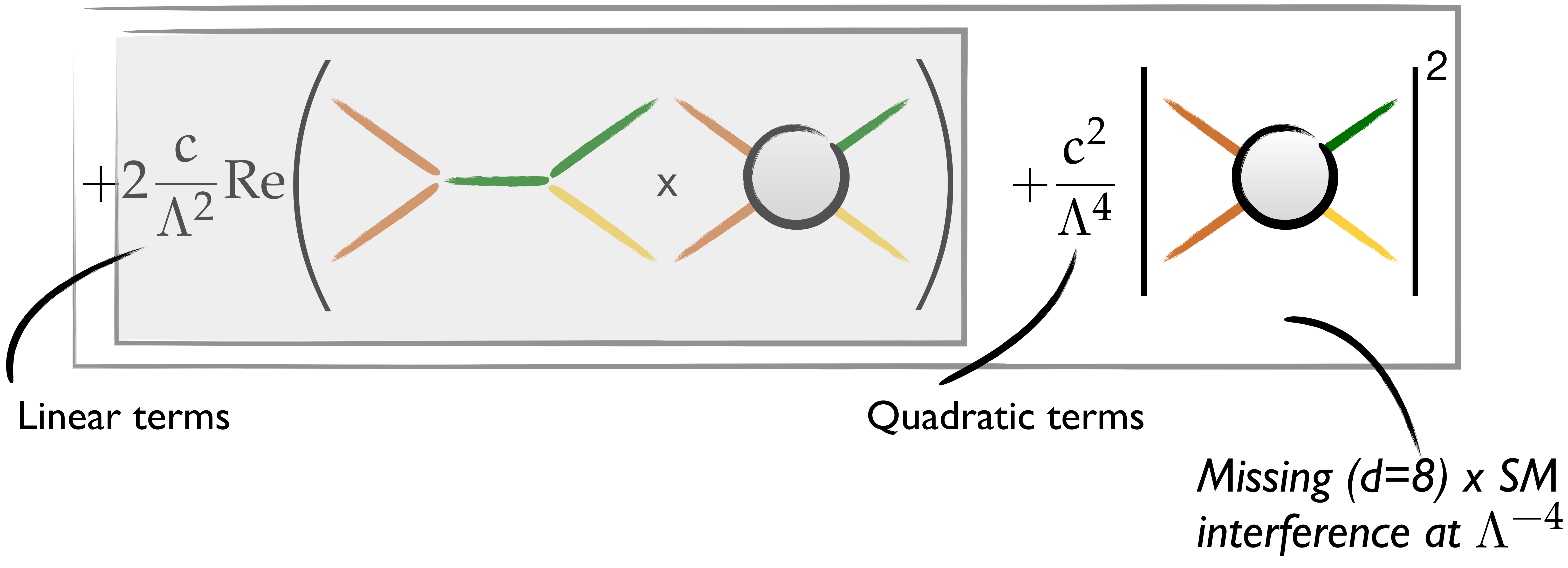
$(H^\dagger H)(\bar{q}_p d_r H)$



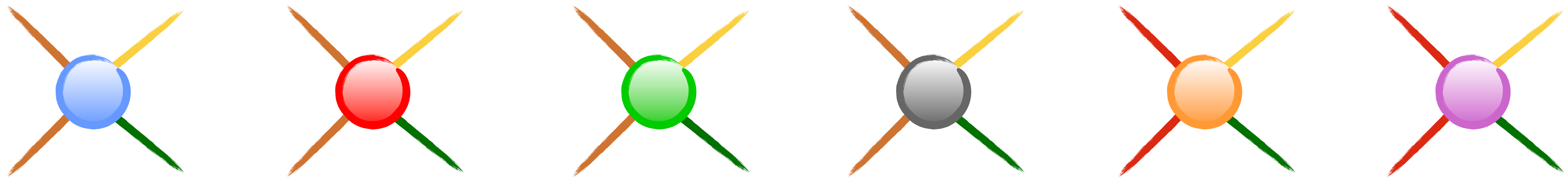
SMEFT linear terms vs linear + quad. terms

Difference due to quadratic terms qualitatively shows, impact of missing d=8 operator contributions





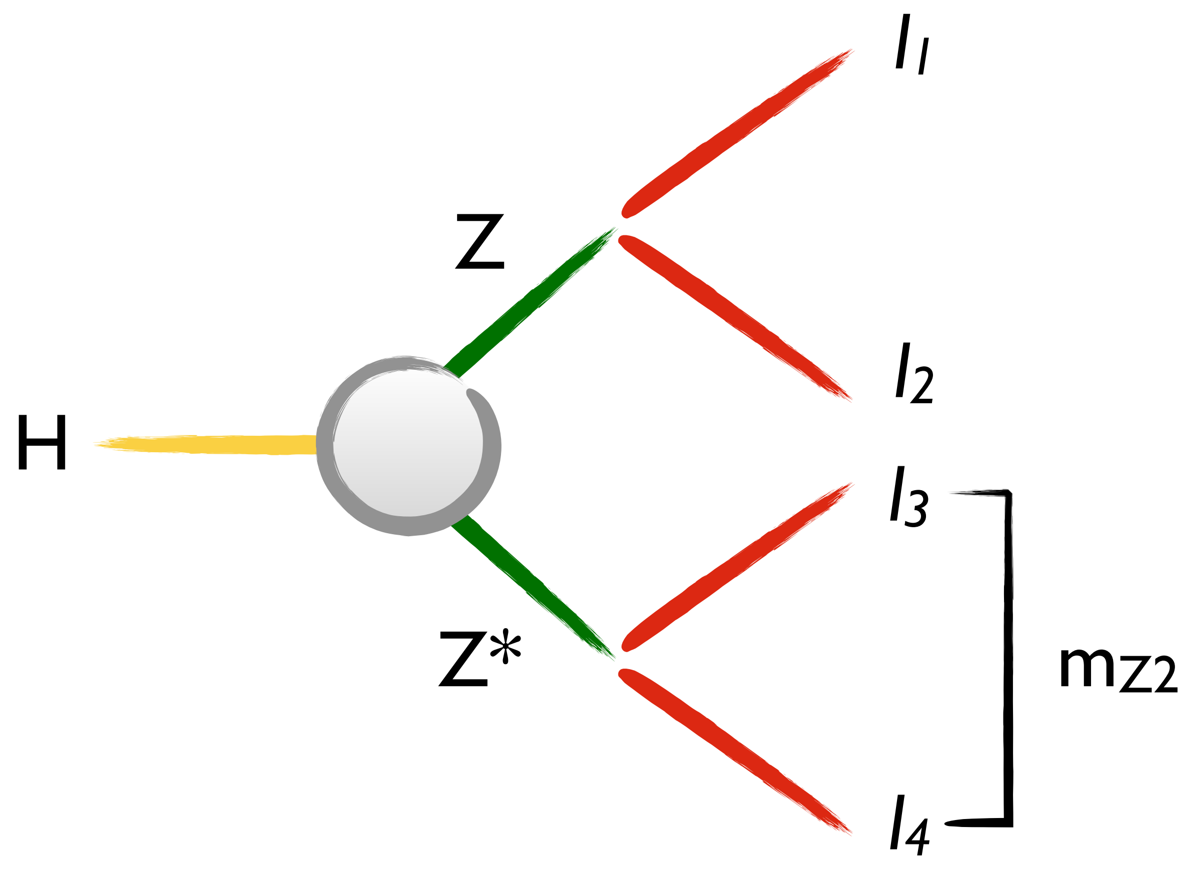
$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\overline{q}_p\sigma^i\gamma^\mu q_r)$ $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$ $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$ $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$ $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$ $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$

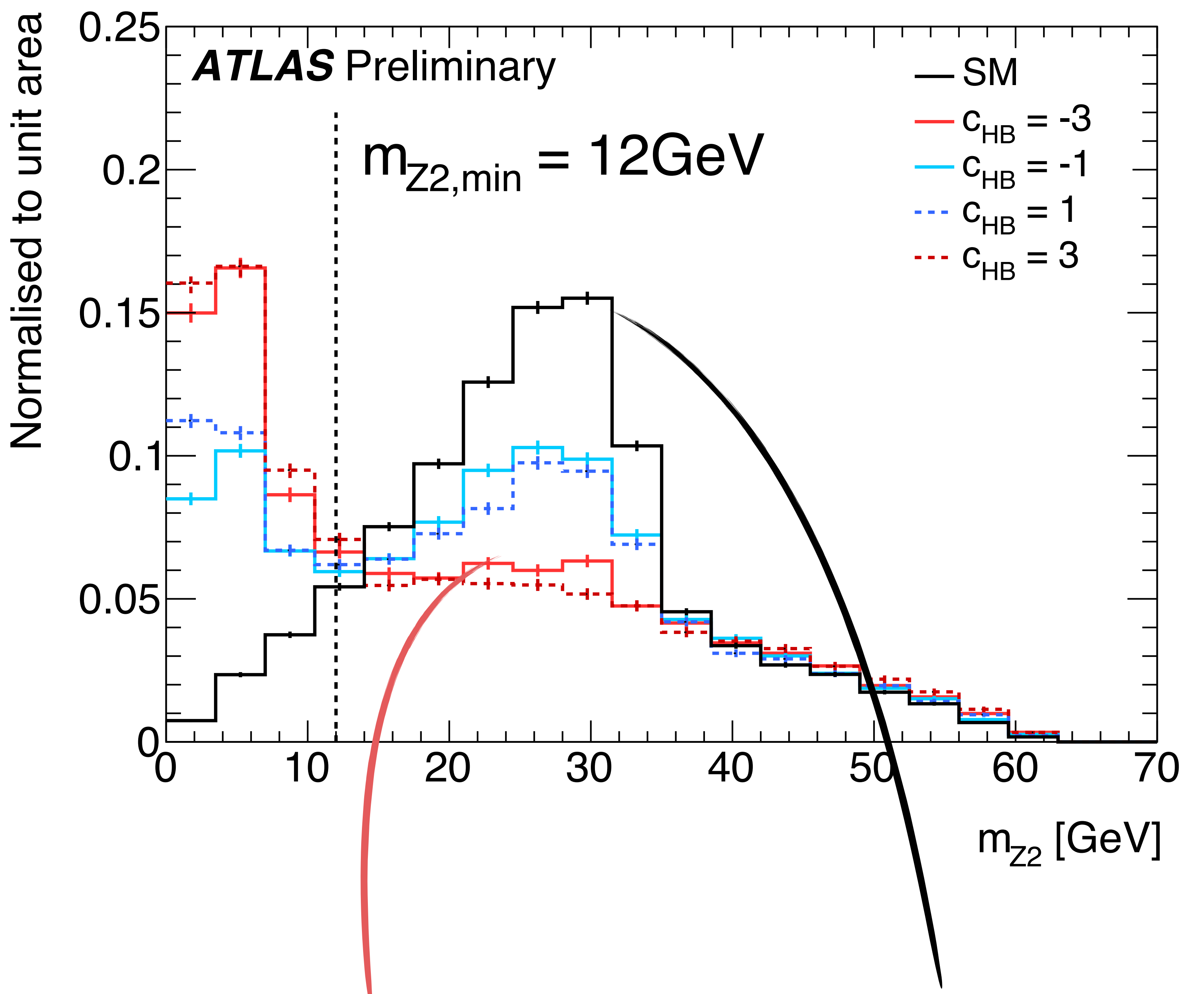


Impact of Experimental Acceptance

SMEFT parameterisation can be affected by analysis selections involved in Higgs boson reconstruction

$O_{HB} = c_{HB}\, H^{\dagger}\sigma^{i}H\, W^{i}_{\mu\nu}B^{\mu\nu}$





Two options :

i. Re-design analysis to capture low-m_{Z2} spectrum to enhance sensitivity to O_{HB}

ii. Account for SMEFT impact on parameterisation by mimicking analysis selections → *pragmatic approach*

What can we constrain ?

UV models usually map to a selection of Wilson coefficients

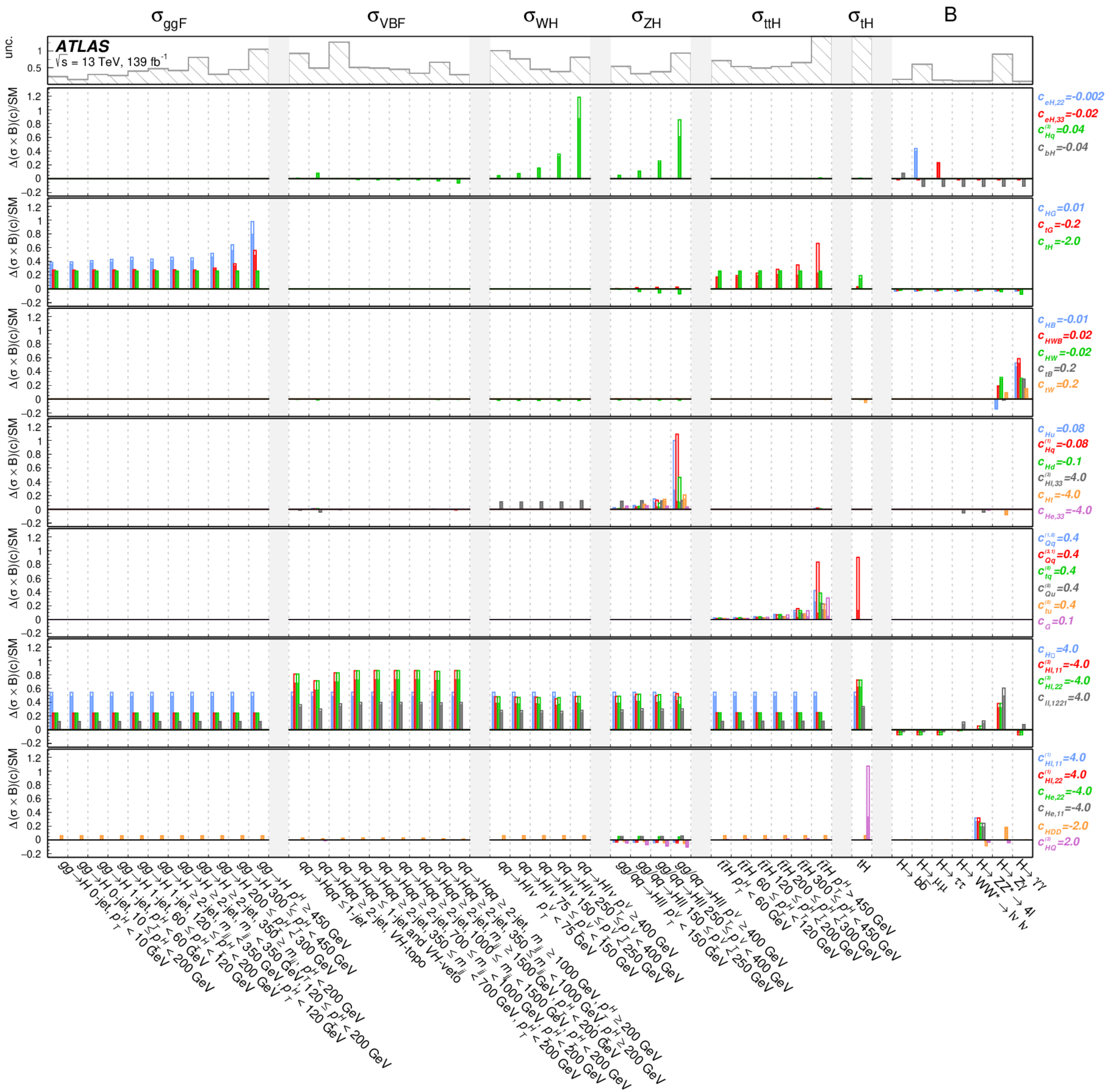
→ *Need to measure as many parameters as possible simultaneously*

However, Wilson coefficients are couplings of a general Lagrangian, not designed as a experimental framework

→ *Many parameters have similar impact, not enough information to disentangle all relevant operators*

Experimental sensitivity can be use as a guide to define and constraint SMEFT parameter space

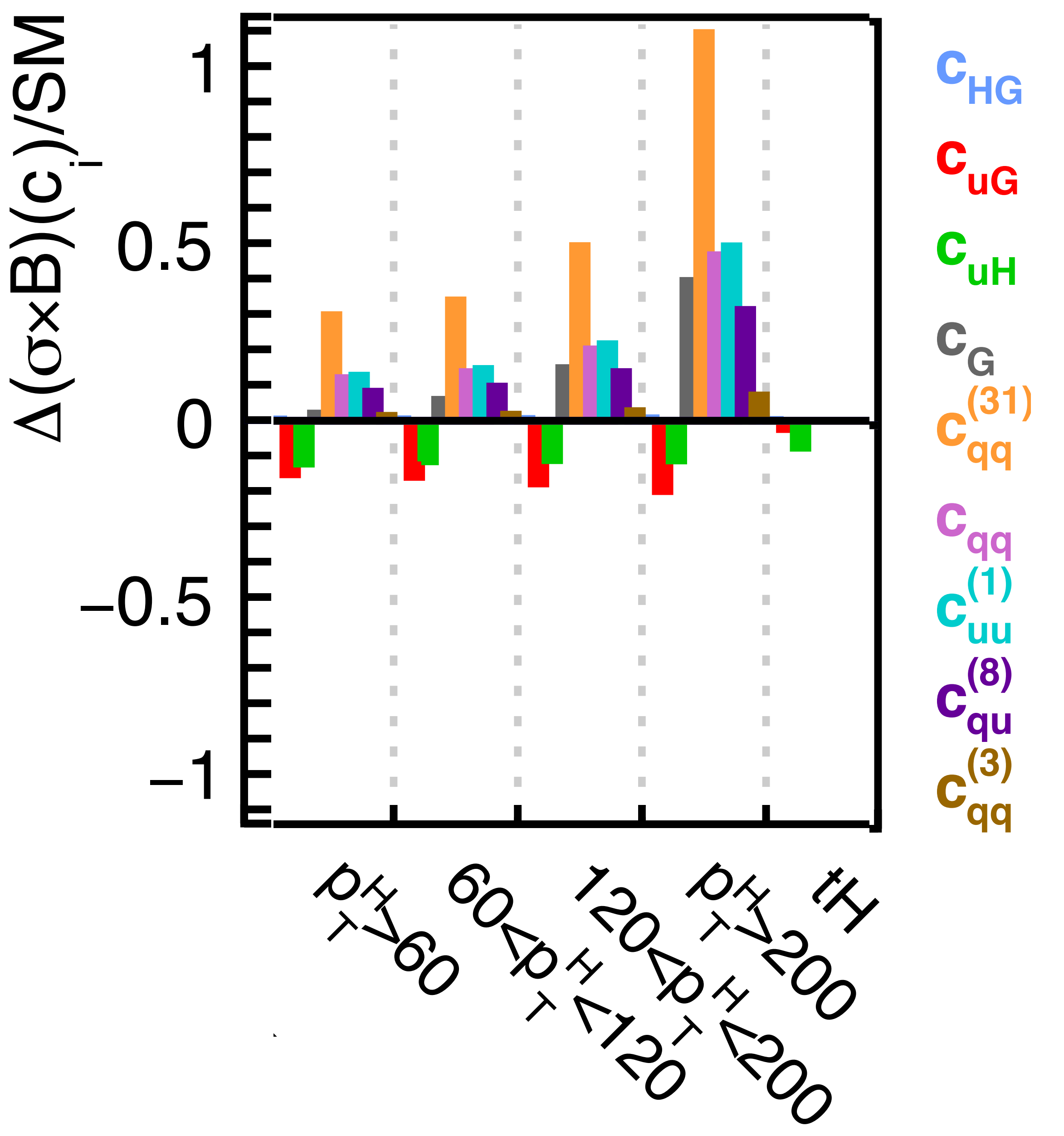
→ *Parameters have to be defined priori measurement*

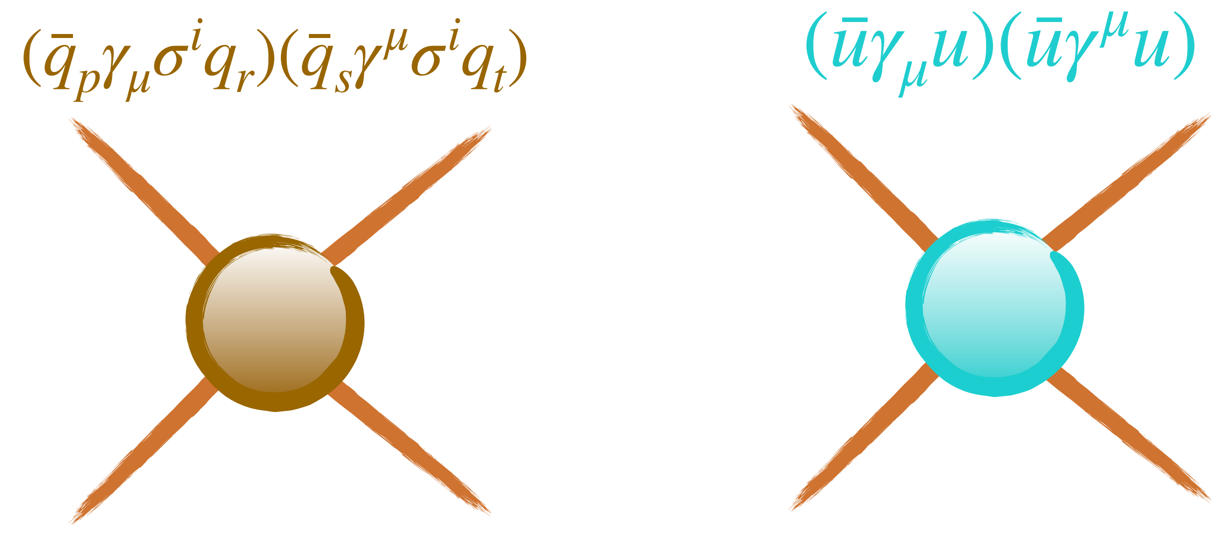


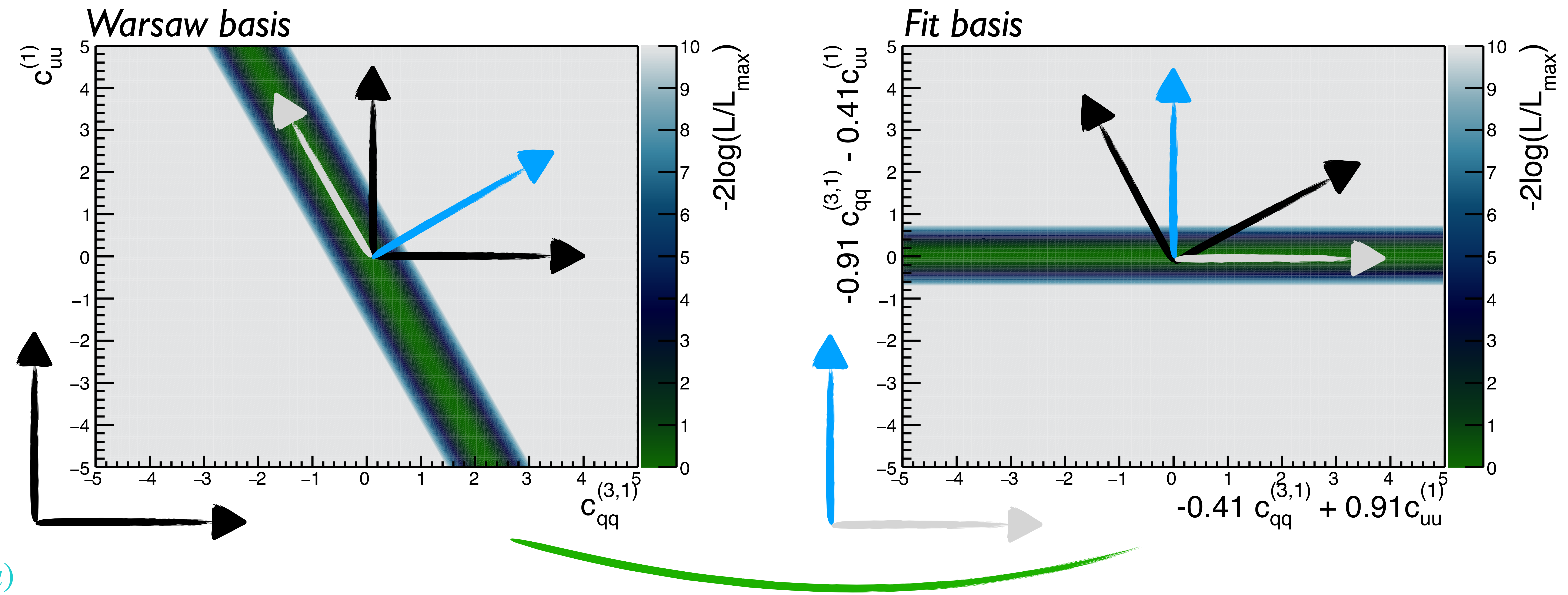
How can we constrain ?

Use Fisher information in SMEFT space to define eigen-directions within of operator group using principal component analysis (PCA)

Consider two four fermion operators from the ttH case,







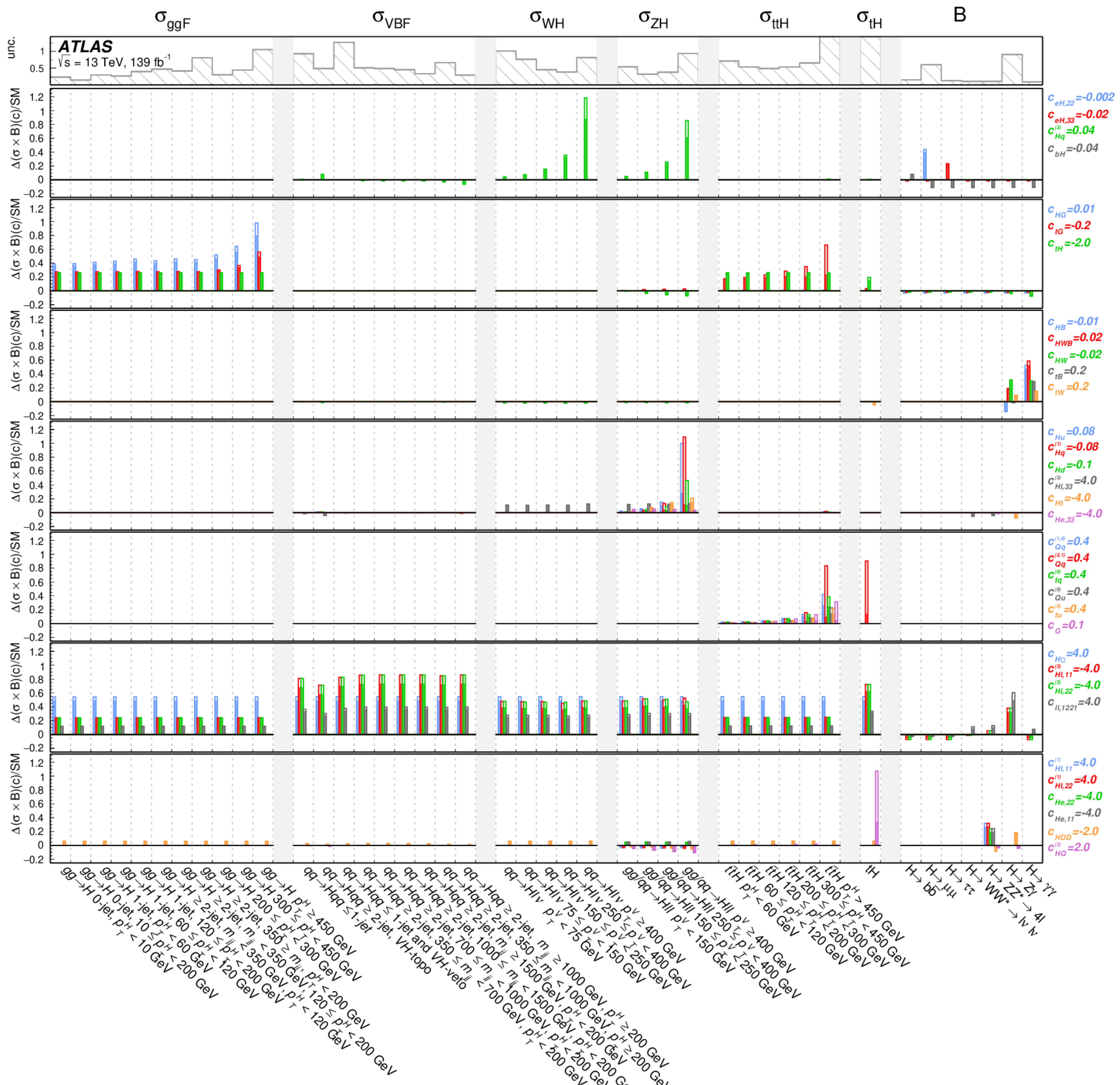
Basis rotation : identify **sensitive** and flat direction

How can we constrain ?

Use experimental sensitivity to identify directions within group of operators

$$
\begin{array}{llll}
\boldsymbol{c} = & \{c_{eH,22}\} \cup & & \boldsymbol{c}' = \{c_{eH,22}\} \cup \\
& \{c_{eH,33}\} \cup & & \{c_{eH,33}\} \cup \\
& \{c^{(3)}_{Hq}\} \cup & & \{c^{(3)}_{Hq}\} \cup \\
& \{c_{bH}\} \cup & & \{c_{bH}\} \cup \\
& \{c_{HG}, c_{tG}, c_{tH}\} \cup & \rightarrow & \{e^{[1]}_{\mathrm{ggF}}, e^{[2]}_{\mathrm{ggF}}, e^{[3]}_{\mathrm{ggF}}\} \cup \\
& \{c_{HB}, c_{HW}, c_{HWB}, c_{tB}, c_{tW}\} \cup & \rightarrow & \{e^{[1]}_{H\gamma\gamma,Z\gamma}, e^{[2]}_{H\gamma\gamma,Z\gamma}, e^{[3]}_{H\gamma\gamma,Z\gamma}\} \cup \\
& \{c_{Hu}, c^{(1)}_{Hq}, c_{Hd}, c^{(3)}_{Hl,33}, & & \\
& \quad c_{Ht}, c_{He,33}, c^{(1)}_{Hl,33}, c_{Hb}\} \cup & \rightarrow & \{e^{[1]}_{ZH}, e^{[2]}_{ZH}, e^{[3]}_{ZH}, e^{[4]}_{ZH}\} \cup \\
& \{c_G, c^{(1,8)}_{Qq}, c^{(3,1)}_{Qq}, c^{(8)}_{tq}, c^{(8)}_{Qu}, c^{(8)}_{tu}, c^{(8)}_{td}, & & \\
& \quad c^{(8)}_{Qd}, c^{(3,8)}_{Qq}, c^{(1,1)}_{Qq}, c^{(1)}_{tu}, c^{(1)}_{tq}, c^{(1)}_{Qu}, c^{(1)}_{Qd}\} \cup & \rightarrow & \{e^{[1]}_{\mathrm{ttH}}, e^{[2]}_{\mathrm{ttH}}, e^{[3]}_{\mathrm{ttH}}\} \cup \\
& \{c_{H\Box}, c^{(3)}_{Hl,11}, c^{(3)}_{Hl,22}, c_{ll,1221}\} \cup & \rightarrow & \{e^{[1]}_{\mathrm{glob}}\} \cup \\
& \{c^{(1)}_{Hl,11}, c^{(1)}_{Hl,22}, c_{He,11}, c_{He,22}, c_{HDD}, c^{(3)}_{HQ}, c^{(1)}_{HQ}\} & \rightarrow & \{e^{[1]}_{Hllll}\}.
\end{array}
$$

Operators groups identified by similarity of physics impact !



SMEFT constraints from the Higgs sector

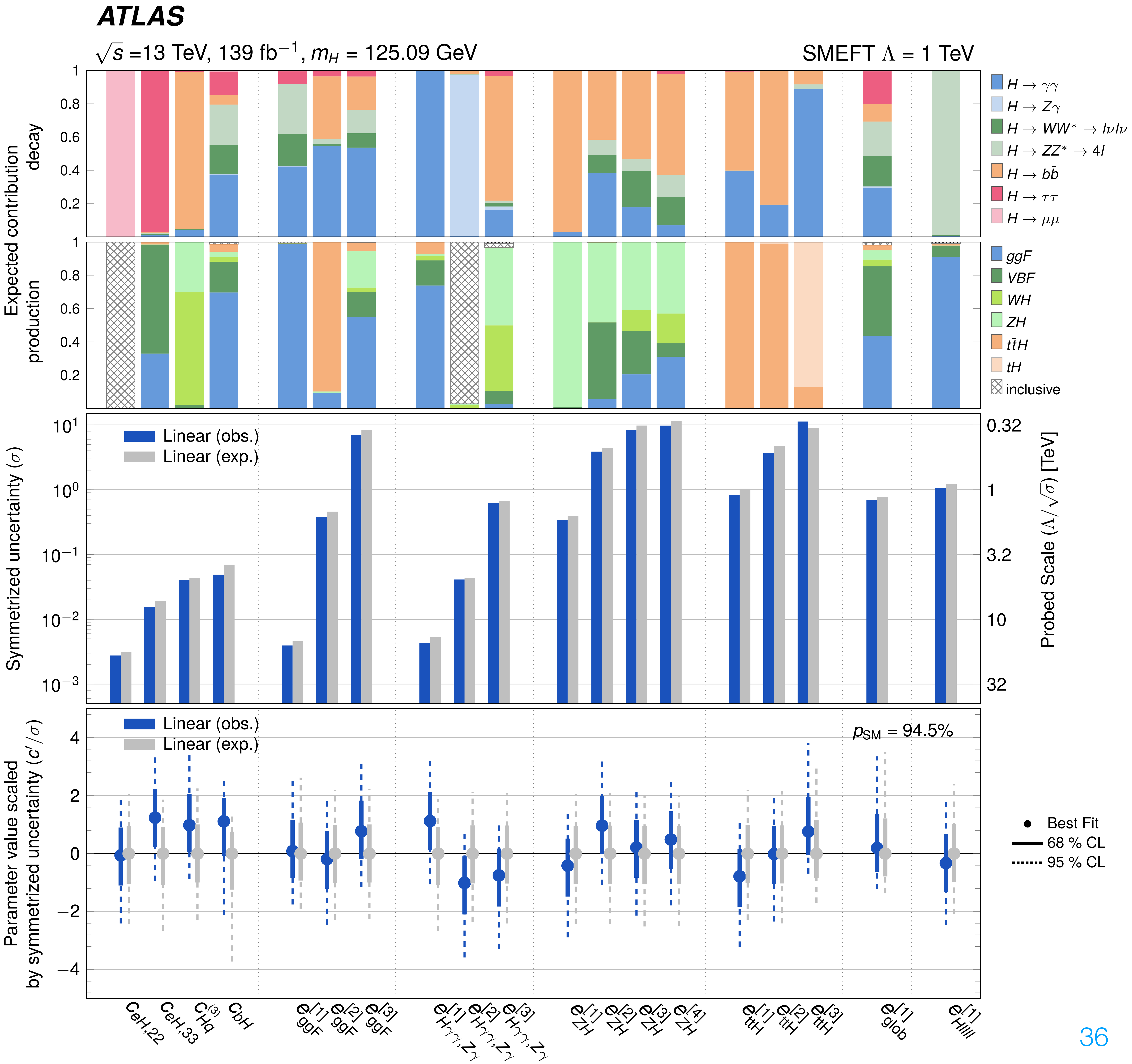
With current data, can constraint 19 parameters

First SMEFT sensitivity source analysis on Run-2 Higgs combination:

- $H \to \mu\mu$ is best-constrained operator, despite low statistics
- $H \to WW^*$ contributes only in minor ways, despite being one of the best-measured channels

High-stats regions in channels may not be the most powerful for SMEFT constraints

Operators probed energy scale of 300 GeV - 10 TeV



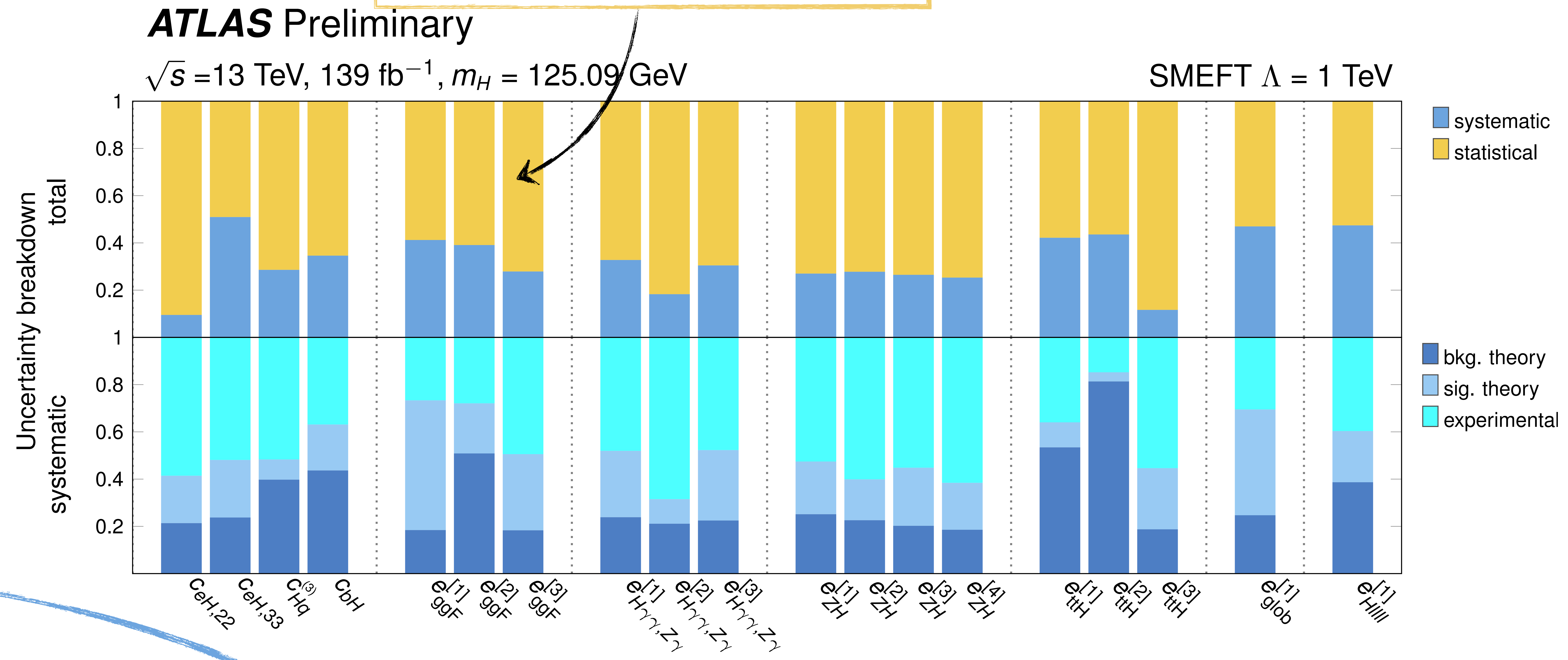
Uncertainty breakdown of SMEFT parameters

Uncertainty breakdowns inform about leading source of uncertainty and are important for guiding improvements for future results !

SMEFT parameters uncertainties mainly statistically dominated

40% systematic contribution to unc. of $e^{[1,2]}_{\mathrm{ggF}}$, $e^{[1,2]}_{\mathrm{ttH}}$

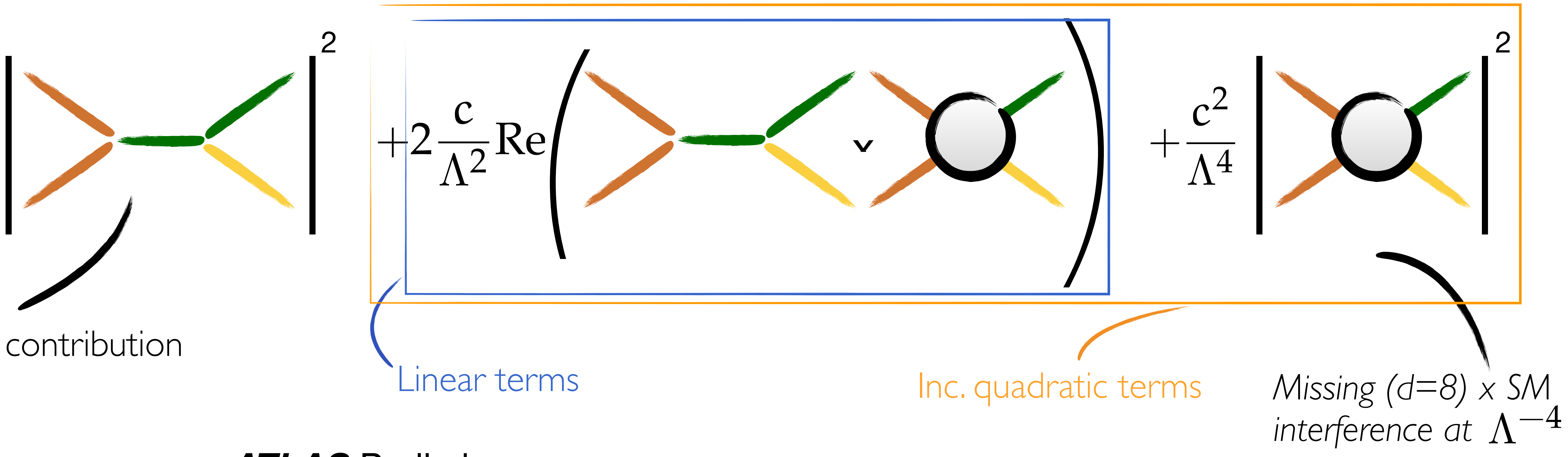
50% systematic contribution to unc. of $c_{eH,33}$, $e^{[1]}_{glob}$ and $e^{[1]}_{Hllll}$



leading source of systematic uncertainty for these parameters are signal theory ($e^{[1]}_{\mathrm{ggF}}, e^{[1]}_{\mathrm{glob}}$) , **background theory** ($e^{[2]}_{\mathrm{ggF}}, e^{[1,2]}_{\mathrm{ttH}}$)

and experimental ($c_{eH,22}, e_{Hllll}$)

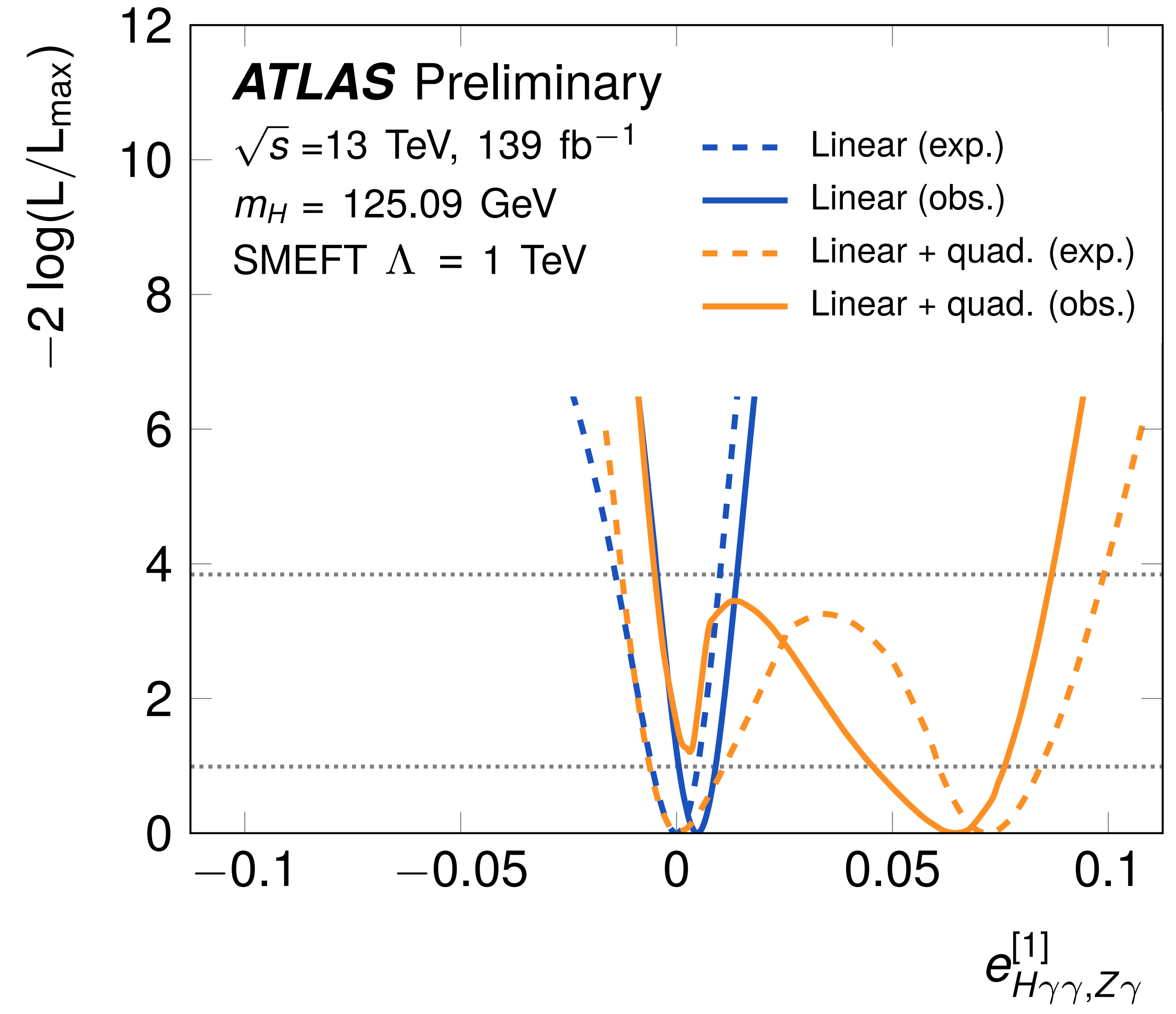
Impact of Quadratic terms

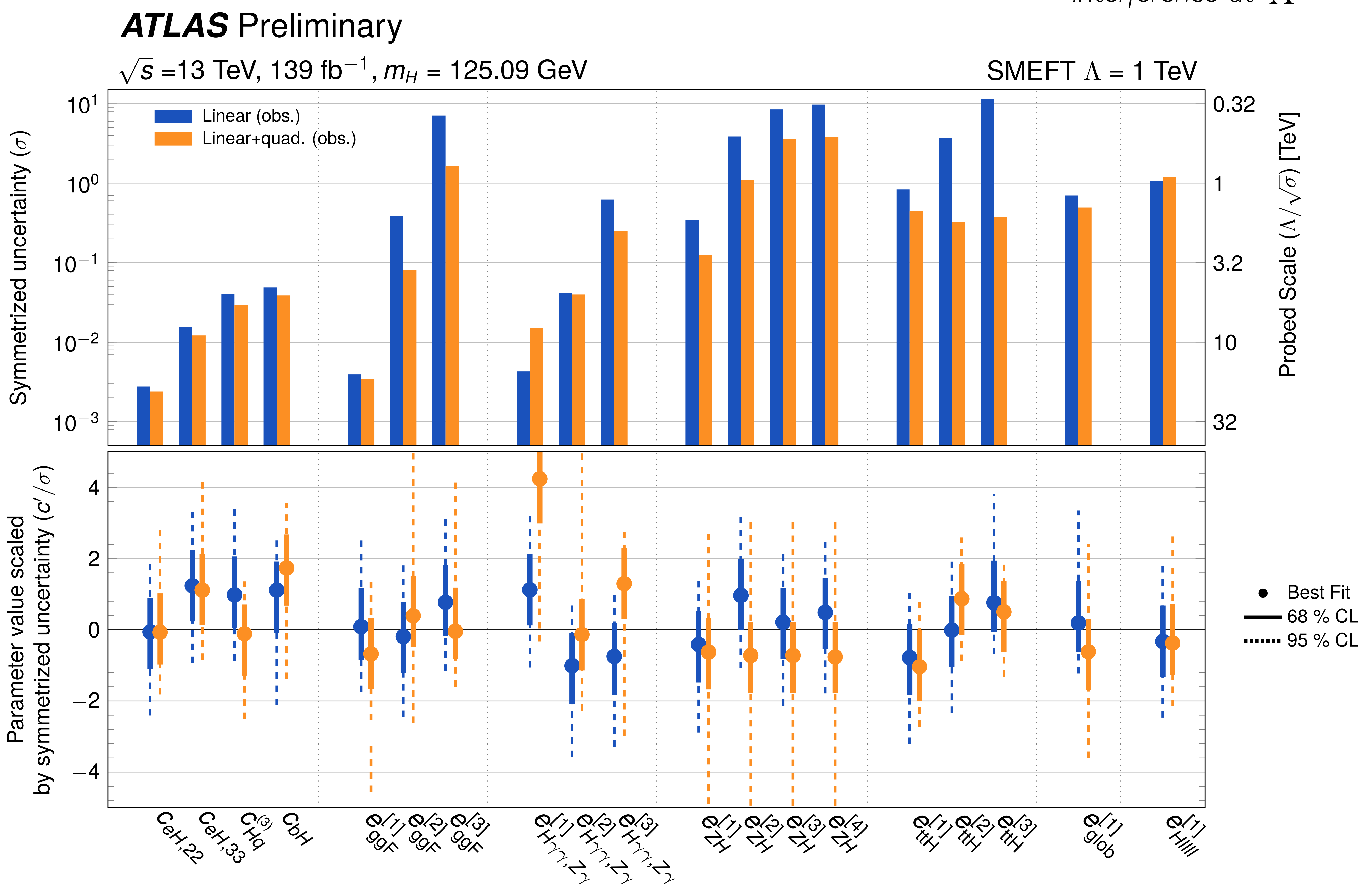


- Fit with quadratic terms allow to qualitatively describe missing d=8 x SM interference terms

- Constraints generally tighter, most notably for $e_{\mathrm{ttH}}^{[2,3]}, e_{\mathrm{ZH}}^{[1-4]}, e_{\mathrm{ggF}}^{[2,3]}$

- Quadratic terms introduce multiple minima





Matching SMEFT constraints to 2HDM

Matching relations from
10.1103/Phys. Rev. D 102, 055012 Dawson et al

<u>2-Higgs doublet model</u>: additional Higgs doublet
five Higgs boson - charged ($H^{\pm}$), CP-even (h, H), & pseudo-scalar (A)

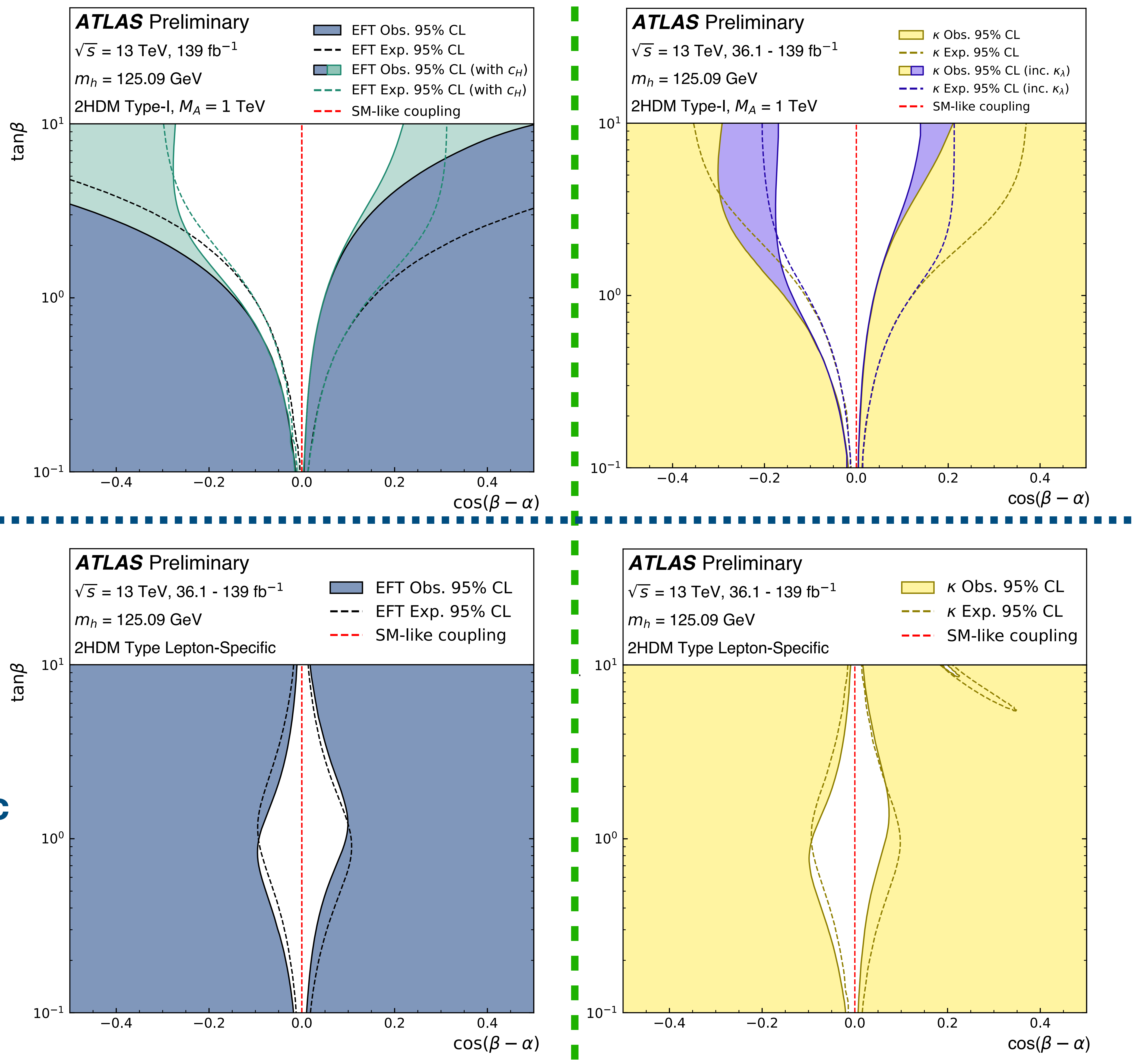
mixing of observed Higgs boson with other Higgs bosons tested
$\tan(\beta)$: ratio of vev of two doublets
$H_{SM} = h\sin(\beta - \alpha) + H\cos(\beta - \alpha)$

SMEFT matching valid in alignment limit $cos(\beta - \alpha) \rightarrow 0$, observed Higgs boson aligns with light-Higgs of 2HDM

SMEFT matching performed using d=6 linear terms only
- missing constraint from HVV coupling which enter at d=8
- No petal-like structure caused by absence of quadratic terms

Type-I

Lepton Specific



SMEFT → 2HDM **$\kappa \rightarrow$ 2HDM**

Going global with SMEFT

SMEFT allows to consistently model deformations from the SM in different physics sectors

ATLAS global SMEFT fit combines,

i. Combined measurements of Higgs boson production & decay

ii. Electroweak production of diboson and single-boson

WW, ZZ, WZ, Z+jets

iii. Electroweak precision observables from LEP & SLC

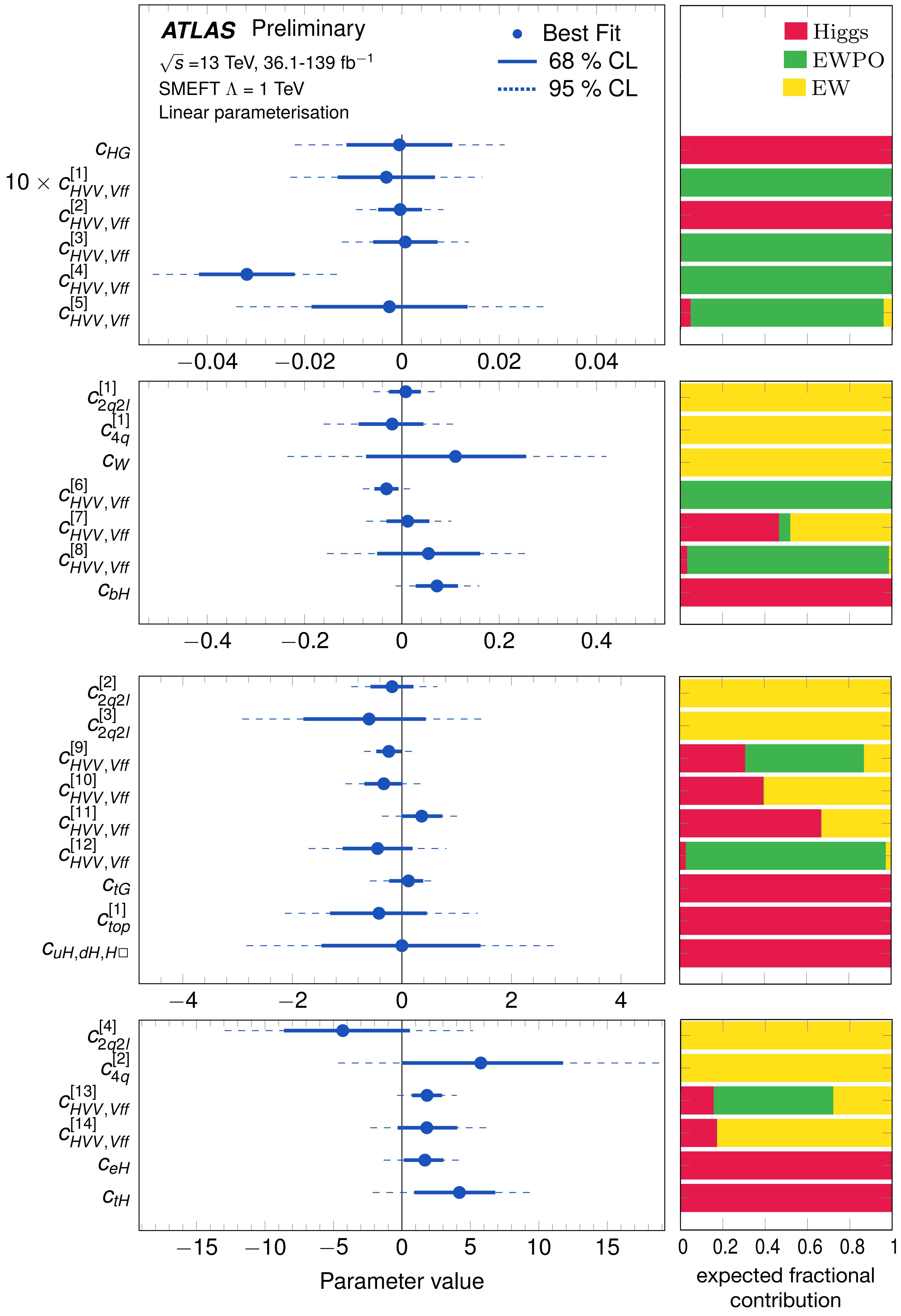
Challenging combination !

i. background in H → ZZ is signal in ZZ production

ii. WW production kinematic phase space partially overlaps with

H → WW background control region.

First global SMEFT fit within ATLAS - 28 parameters

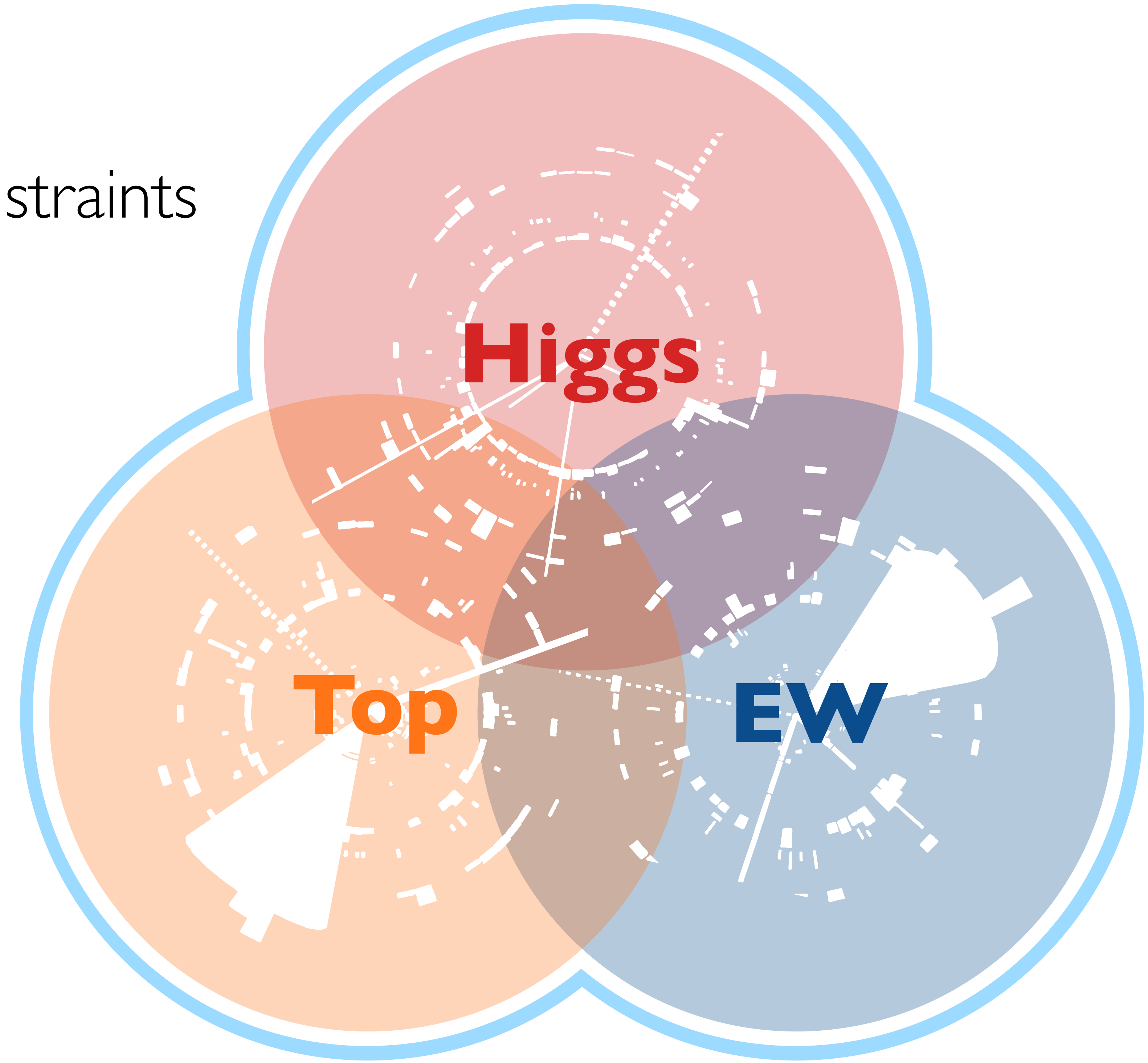


The future for SMEFT

Including more measurements will open up more parameters!

Global fits active area of development, including ATLAS top data, CMS data, LEP II constraints

→ *Joint effort within the experimental & theory community under the recently formed* LHC EFT Working Group



Many foundational topics still being developed: *uncertainties due to truncation, contribution of d=8 operators, compatibility of experimental fits with theorists,……*

Designing analysis optimised for SMEFT ?

SMEFT results are currently performed post-hoc analysis targeting measurements, no flexibility to improve SMEFT constraints

Designing analysis with considering the constraints coming in from other sectors (EWPO, for instance)

Mining SMEFT parameter space for dedicated New Physics model ?

A new physics model is expected to affect only a subset of operators, information within the SMEFT can be used in identifying potential New Physics models

A bientôt !


Annecy
Compesières
Croix-de-Rozon
Voirie-Feu-PC
Ecole du
Pré-du-Camp
Le Serpentin
Résidence
Happy Days