EP/TH Faculty Meeting, 1 June 2018

Measurement of Higgs properties: sensitivity of present and future facilities

G.F. Giudice

- Traditionally, Faculty Meetings were reserved to Senior Staff
- Series of Faculty Meetings dedicated to topics of interest for the European Strategy for Particle Physics Update
- We need to look into the future, and the future belongs to the youth
- Measurements of Higgs properties are benchmarks for any future collider project

- Why do we want to measure precisely the Higgs couplings?

- What is the best parametrisation of new-physics effects in Higgs couplings?

- Why do we want to measure precisely the Higgs couplings?

If you don’t know, return your CERN access card immediately!

Nature at the fundamental level:

Gauge $\int d^4x\sqrt{-g}\left(\frac{M_P^2}{2}\mathcal{R} - \frac{1}{4}G^{\mu\nu}G_{\mu\nu} + i\bar{\psi}\gamma^\mu D_\mu\psi\right)$ $\Rightarrow$ 4 fundamental forces

Higgs interactions $\left(y\,\bar{\psi}_L H\psi_R + \mathrm{h.c.}\right) + V(H)$ $\Rightarrow$ 14 new fundamental forces!
and new theoretical problems
(naturalness, flavour, vacuum stability, …)

Exploring the "obscure" sector of the SM through Higgs couplings is a program of high scientific priority with possible great rewards
(dynamics of EW breaking, nature of the Higgs boson, fate of naturalness, origin of fermion masses, dynamics of the EW phase transition, baryogenesis, dark matter,…)

Nature of the Higgs boson:

Is the Higgs elementary or composite?

unnaturalness?
supersymmetry?

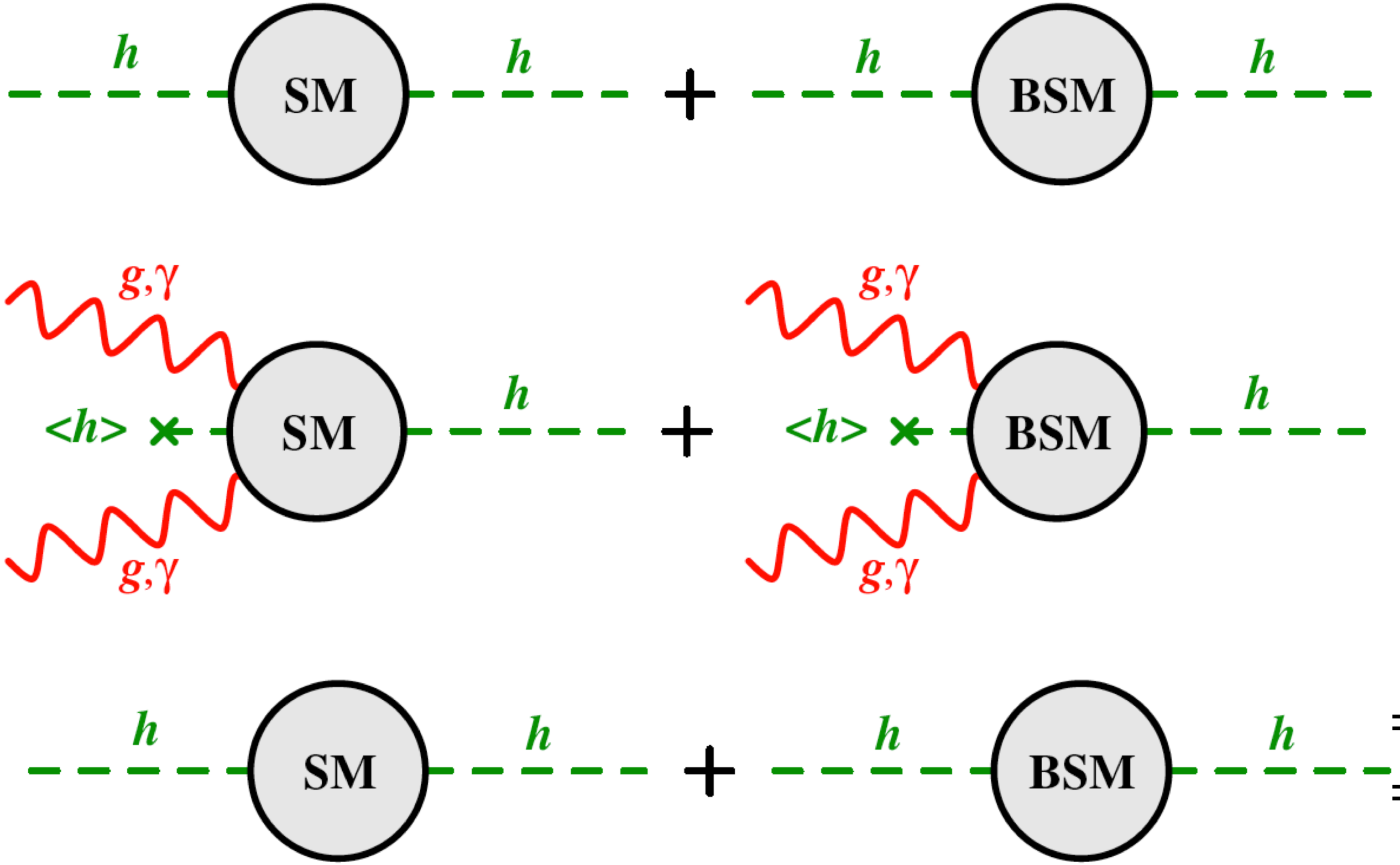
Goldstone symmetry?
gauge principle strikes back?

Higgs coupling measurements address this question

$$\Delta = \frac{v^2}{f^2} \quad \Rightarrow \quad \text{compositeness scale} \;\; 4\pi f \approx \sqrt{\frac{\%}{\Delta}}\; 30 \text{ TeV}$$

Fate of naturalness

Modifications of Higgs couplings are an unescapable consequence of naturalness and are correlated with the degree of fine tuning



⇒ Higgs naturalness

⇒ modified g_{hgg} and $g_{h\gamma\gamma}$

⇒ modified Higgs wave function

⇒ overall rescaling of Higgs couplings

Craig, Englert, McCullough, arXiv:1305.5251

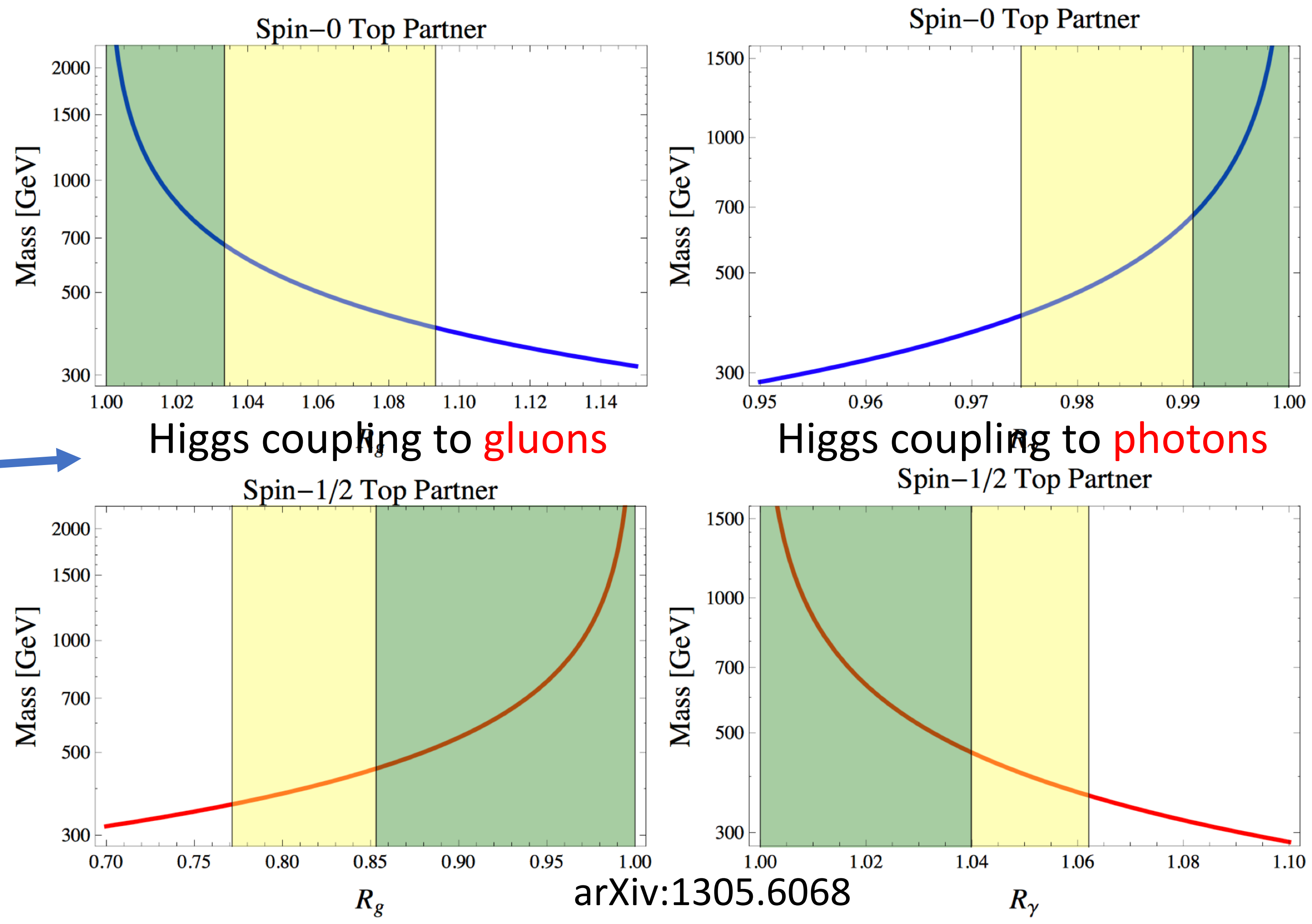
Are direct searches more effective in testing naturalness?

Coloured top partners

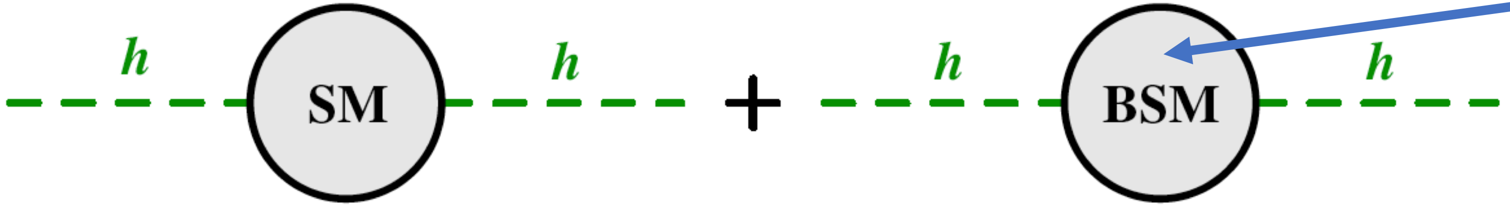
Neutral naturalness
(no coloured top partners)

Higgs coupling to gluons

Higgs coupling to photons



arXiv:1305.6068



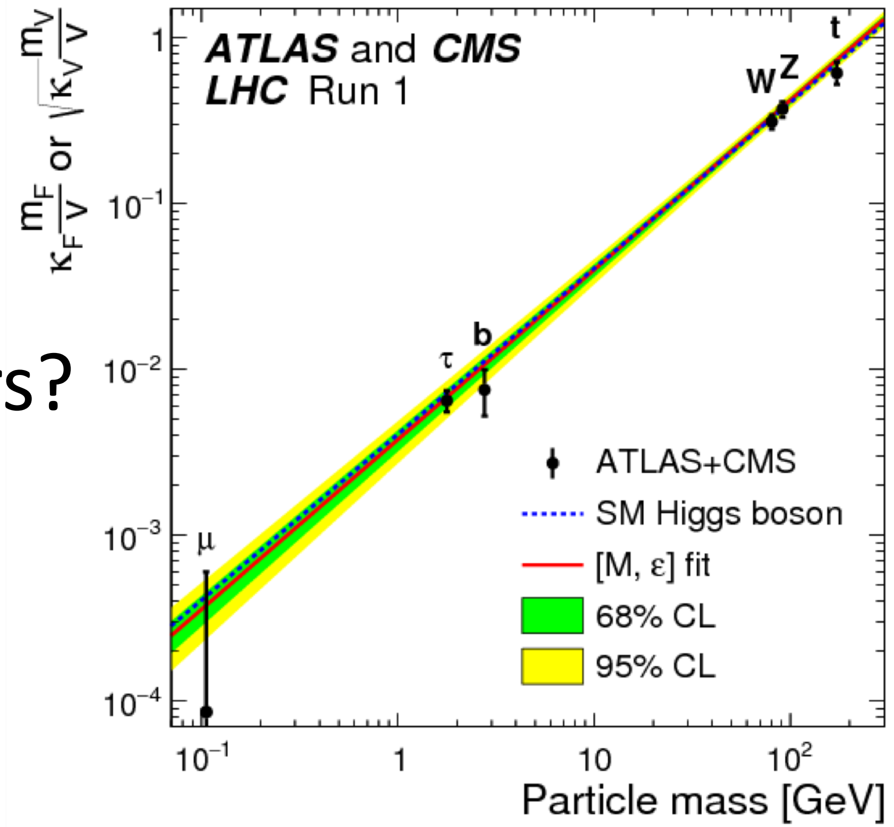
states charged under twin gauge group

Origin of quark and lepton masses

$U(3)^5$ global symmetry of fermions broken only by Yukawas

$$y\,\bar{\psi}_L H \psi_R$$

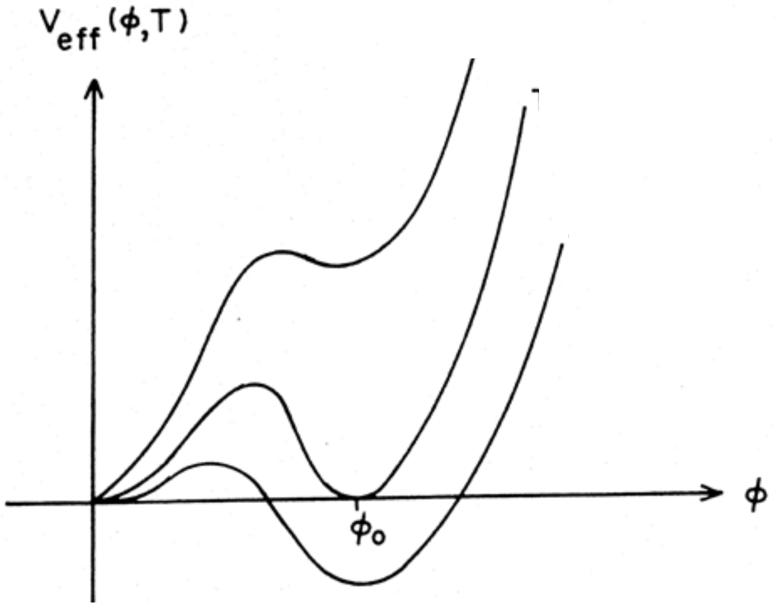
Are they just numbers?



If LHCb anomalies are confirmed,

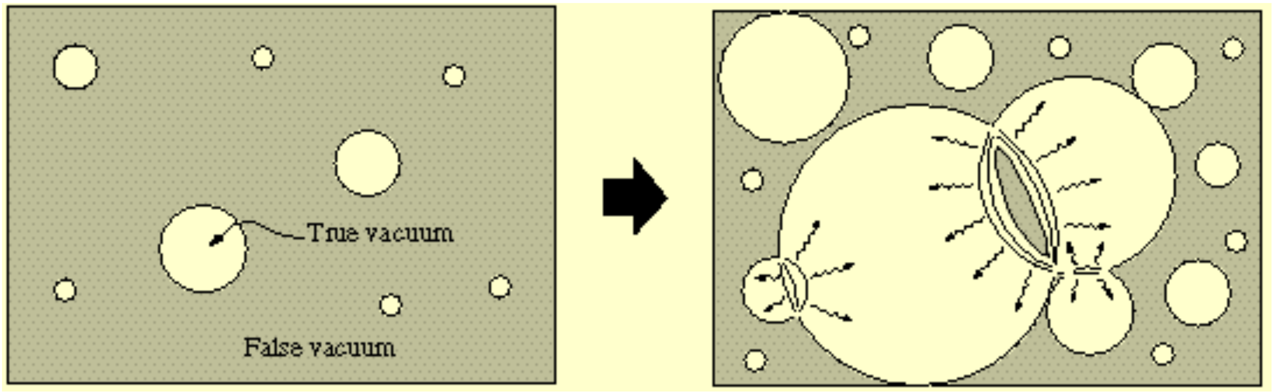
$h \to \tau\mu$, τe , μe become especially important

Testing EW phase transition



Is the zero-temperature Higgs SM potential modified?

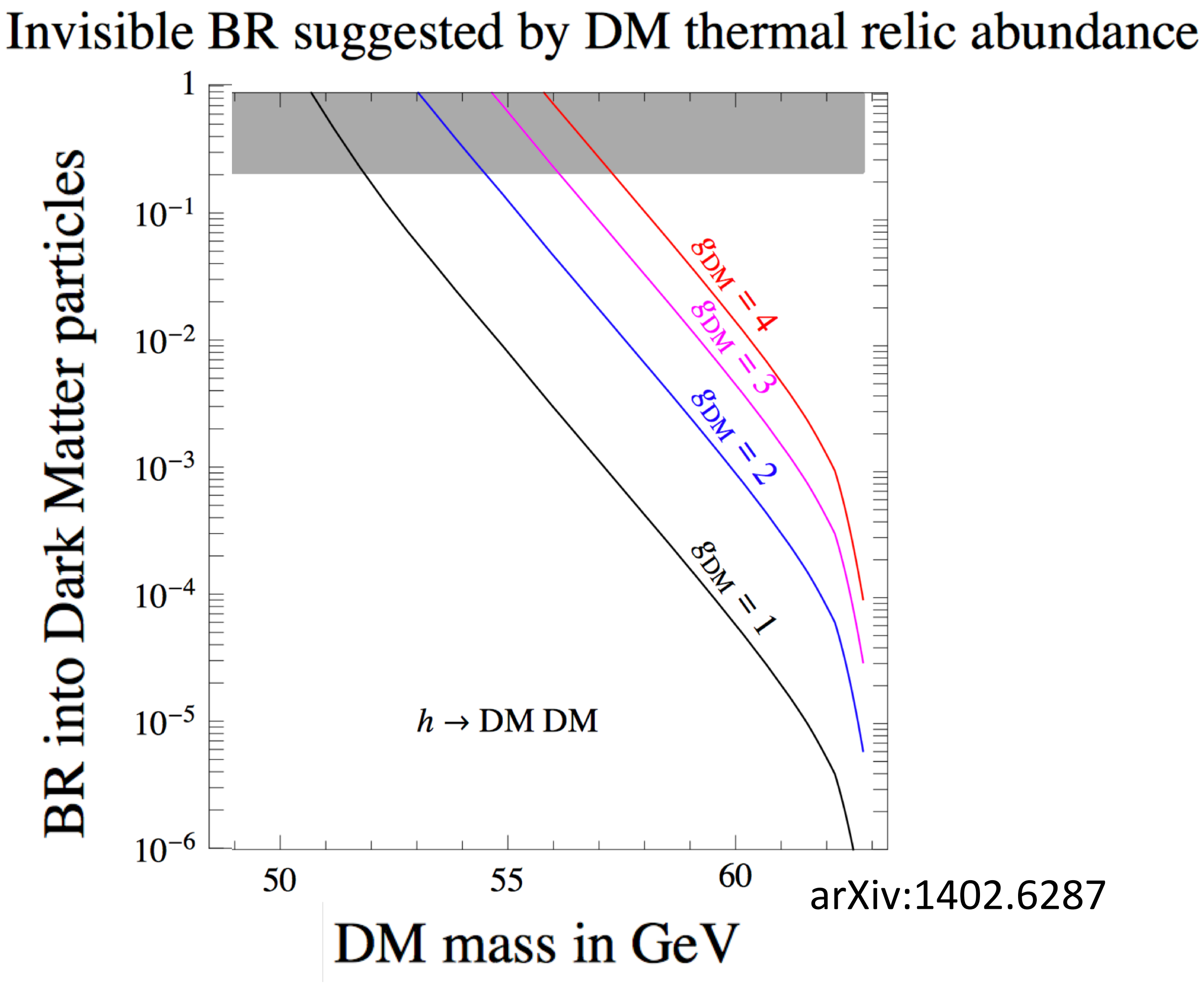
⇒ Higgs self-couplings



CP violation in Higgs decays?

Testing dark sectors

- DM coupled to the SM only via Higgs



arXiv:1402.6287

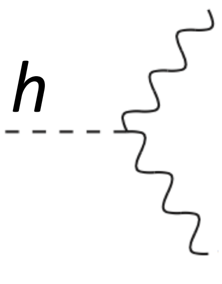
- $|H|^2$ only super-renormalizable term in SM $\Rightarrow$ invisible Higgs decay is a test of the Higgs portal to dark worlds

Higgs precision measurements offer a rich and exciting scientific program testing some of the most fundamental open questions in particle physics

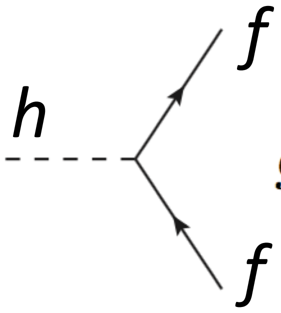
☛ see talk by Josh Ruderman

- What is the best parametrisation of new-physics effects in Higgs couplings?

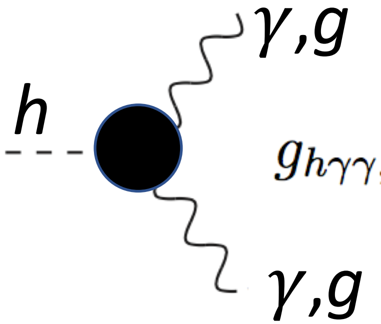
"κ-formalism"



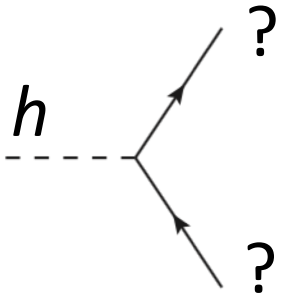
$$g_{hVV} = g_{hVV}^{\mathrm{SM}}\,\kappa_V$$



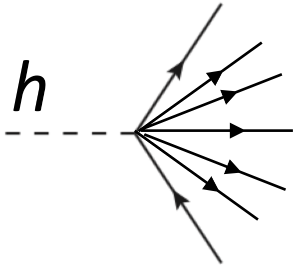
$$g_{hff} = g_{hff}^{\mathrm{SM}}\,\kappa_f$$



$$g_{h\gamma\gamma,hgg} = g_{h\gamma\gamma,hgg}^{\mathrm{SM}}\,\kappa_{\gamma,g}$$



Γ_{inv}



$\Gamma_{\mathrm{untagged}}$ $\Longleftrightarrow$

$$\Gamma_{\mathrm{tot}} = \sum_i \kappa_i^2 \Gamma_i^{\mathrm{SM}} + \Gamma_{\mathrm{inv}} + \Gamma_{\mathrm{untagged}}$$

$$BR_{\mathrm{inv}} = \frac{\Gamma_{\mathrm{inv}}}{\Gamma_{\mathrm{tot}}}$$

9 free parameters: κ_W , κ_Z , κ_t , κ_b , κ_τ , κ_g , κ_γ , Γ_{tot} , BR_{inv}

or more: κ_c , κ_μ , $\kappa_{\gamma Z}$, …

or less: $\kappa_W = \kappa_Z$, universal κ_f , $\Gamma_{\mathrm{tot}} = \Gamma^{\mathrm{SM}}$, $BR_{\mathrm{inv}} = 0$, …

κ-formalism

- Simple parametrisation
- Transparent interpretation

What's the problem?

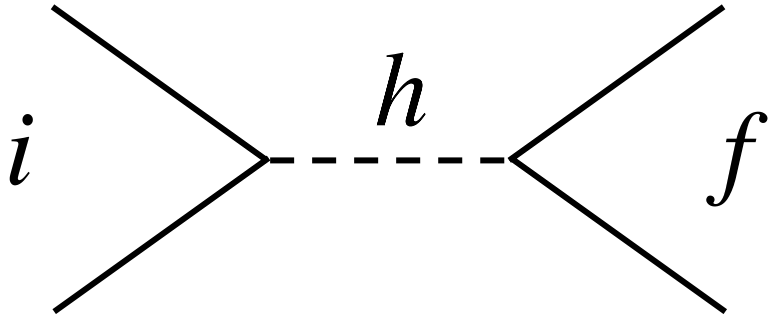
κ-formalism

- Simple parametrisation
- Transparent interpretation

What’s the problem?

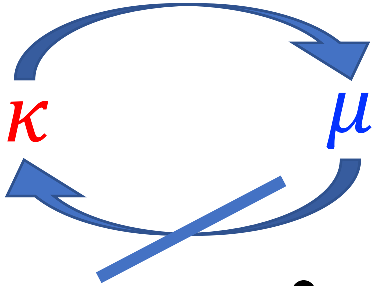
- General κ-deformation violates gauge invariance (ill-suited for higher-order calculations and UV matching)
- It misses modifications in kinematic distributions and energy dependence (generally present in BSM)
- It misses correlations among processes and with EWPD (generally present in BSM)

"Signal strength"



$$\mu_{if} = \frac{\sigma(i \to h)}{\sigma^{\rm SM}(i \to h)} \times \frac{{\rm BR}(h \to f)}{{\rm BR}^{\rm SM}(h \to f)}$$

Sometimes $\mu_{if} = \mu_i \times \mu_f$



$$\mu_{if} = \kappa_i^2\, \kappa_f^2\, \frac{\Gamma^{\rm SM}}{\Gamma_{\rm tot}}$$

- Simple and transparent
- Free from bias on theory interpretation
- Too inclusive
- Misses correlations

“EFT”

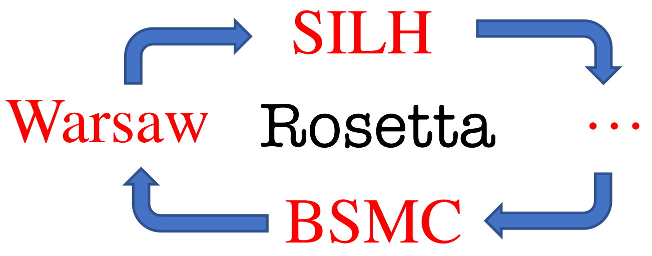
Expansion in gauge and Lorentz invariant local operators valid for

$M_{NP} >> m_h\, , E$

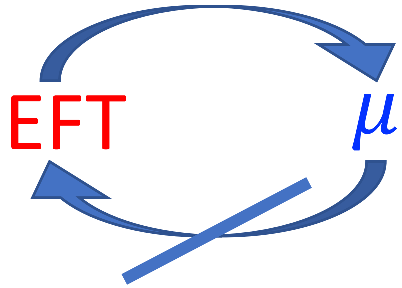
$$\mathcal{O}_{HW} = -i\, g_2\, (D^\mu H)^\dagger\, \tau^I\, (D^\nu H)\, W^I_{\mu\nu}, \qquad \mathcal{O}_{HB} = -i\, g_1\, (D^\mu H)^\dagger\, (D^\nu H)\, B_{\mu\nu},$$

$$\mathcal{O}_W = -\frac{i\, g_2}{2}\, (H^\dagger \overleftrightarrow{D}^I_\mu H)\, (D^\nu W^I_{\mu\nu}), \qquad \mathcal{O}_B = -\frac{i\, g_1}{2}\, (H^\dagger \overleftrightarrow{D}^\mu H)\, (D^\nu B_{\mu\nu}),$$

$$\mathcal{O}_T = (H^\dagger \overleftrightarrow{D}^\mu H)\, (H^\dagger \overleftrightarrow{D}^\mu H).$$



- Different Lorentz structures from SM ⇒ modified Higgs kinematics
- Extra derivatives ⇒ energy dependence
- No one-to-one relation with κ-formalism



EFT

- Consistent theoretical description (under the EFT hypothesis of scale separation)
- Easy matching with UV completions
- Describes modified kinematics and energy dependence
- Allows comparison among different processes, different kinematic configurations and EWPD

What's the problem?

EFT

- Consistent theoretical description (under the EFT hypothesis of scale separation)
- Easy matching with UV completions
- Describes modified kinematics and energy dependence
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What's the problem?

- Most general dim-6 basis: 2499 real parameters! (Using hypotheses of MFV, CP, custodial, one can reduce the basis to 10 parameters)
- Interpretation is less transparent in terms of physical processes

Non-linear EFT

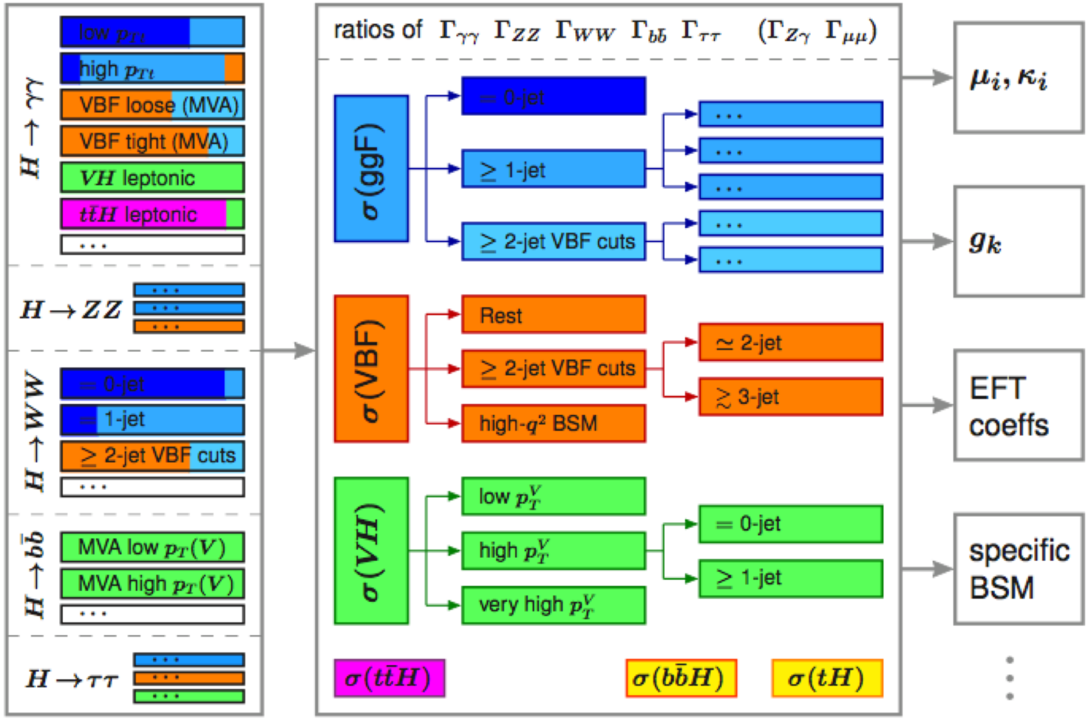
- $H = \frac{v+h}{\sqrt{2}} \exp\left(\frac{i\pi^a T^a}{v}\right)$ and chiral expansion in derivatives
- At leading order, it matches with κ-formalism

Pseudo-observables

- Start from scattering amplitude and define form-factors consistent with Lorentz-invariance
- Assuming no NP poles, expand in powers of momenta
- More general than d=6 EFT and directly related to observables: no Lagrangian description

Simplified template cross sections

- Breaking up the exp'l signal into "bins"
- Overcomes some of the limitations of signal strength
- Allows for an extraction of EFT or model-specific coefficients



- What is the best parametrisation of new-physics effects in Higgs couplings?

No single answer

(but in case of discovery, this is not a problem…)