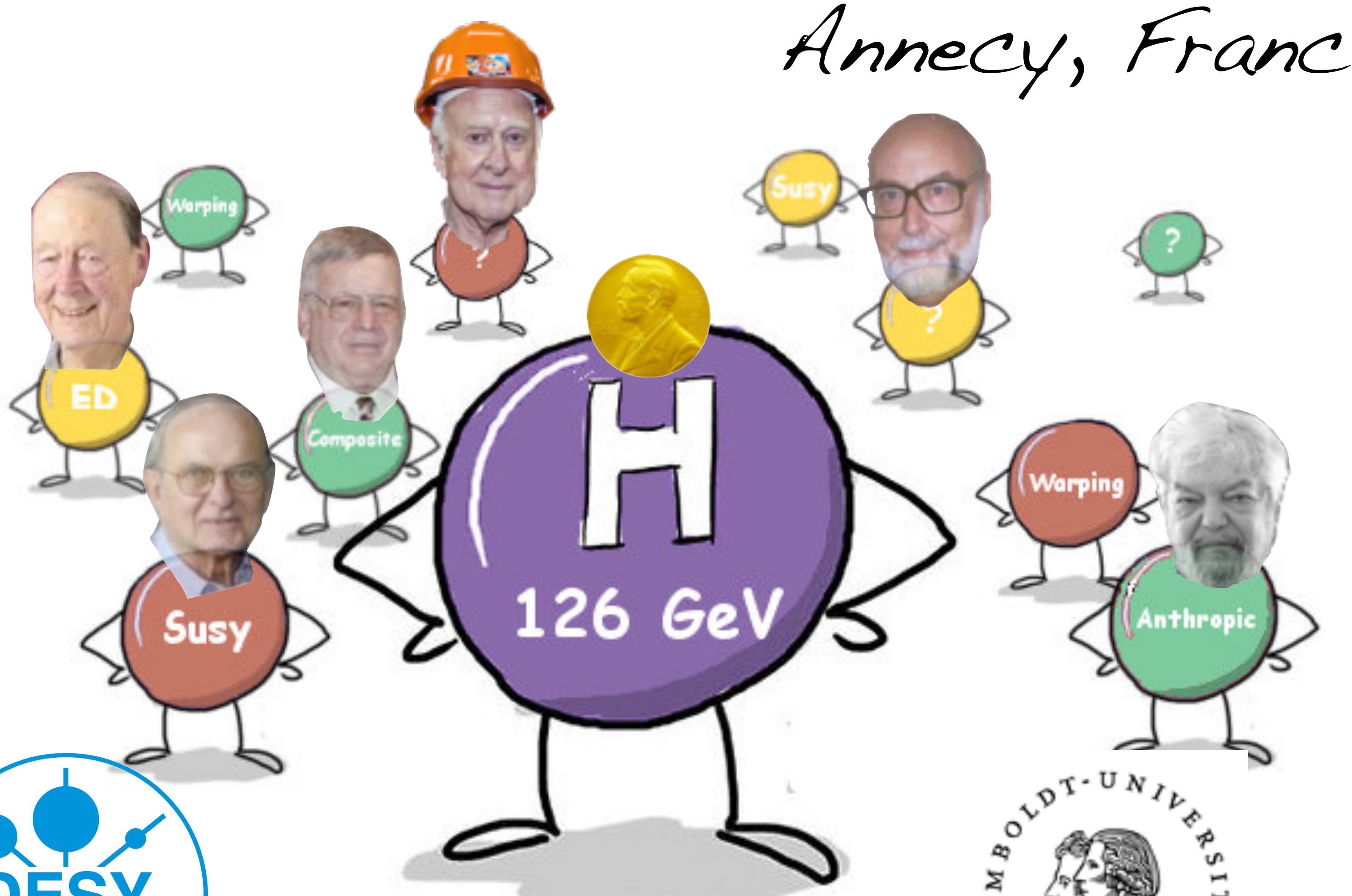
Prospectives
&
Future Accélérateurs

Ecole de Gif 2023

Annecy, France

Lecture 1/2



Christophe Grojean
DESY (Hamburg)
Humboldt University (Berlin)
(christophe.grojean@desy.de)

Outline

☐ Lecture #1: A few theoretical considerations on EFTs

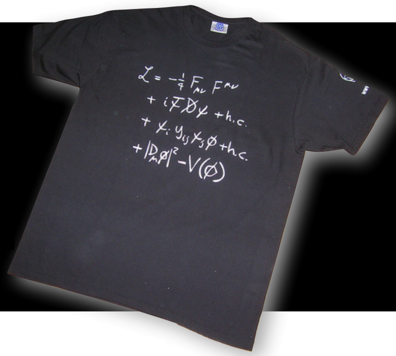
- Importance of selection rules/symmetries
- Swampland vs landscape of EFTs
- EFTs for Higgs data
- Beyond inclusive analyses
- Higgs self-couplings
- EFTs for composite Higgs models
- CP violation in (SM)EFT
- EFT validity discussion

☐ Lecture #2: Physics at future colliders

- Higgs factories
- FCC-ee: a great Higgs factory, and so much more
- FCC-hh: the energy-frontier collider with the broadest exploration potential

What is the SM?

SM =



?

SM is consistent

(i.e. closed under radiative corrections and no pathology, except maybe hypercharge Landau pole).

We certainly know that the SM is not *complete*
and it should be considered as a low energy EFT,
therefore there is no reason to stop at dim-4 operators.

— SM = SMEFT —

(i.e. particle content and gauge symmetries define SM)

— But this new view on the SM poses new questions —

❶ All SM_4 couplings known, infinite interactions of the SMEFT totally unknown.
Which organising principles?

❷ Which symmetry? B and L accidental or true symmetries
(quantum gravity forbids exact continuous global symmetry).

❸ Similarly, other structures of SM_4 now calls for further explanations
(custodial protection/GIM-FCNC…)

On the importance of selection rules

Dimensional Analysis

$[S]_m = 0$ ➡ $[\mathcal{L}]_m = 4$

$$S = \int d^4x \, \mathcal{L}$$

Scalar field $\mathcal{L} = \partial_\mu \phi \partial^\mu \phi + \ldots$ ➡ $[\phi]_m = 1$

Spin-1/2 field $\mathcal{L} = \psi^\dagger \gamma^0 \gamma^\mu \partial_\mu \psi$ ➡ $[\psi]_m = 3/2$

Spin-1 field $\mathcal{L} = F_{\mu\nu} F^{\mu\nu} + \ldots \text{ with } F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + \ldots$ ➡ $[A_\mu]_m = 1$

Particle lifetime of a (decaying) particle: $[\tau]_m = -1$ Width: $[\Gamma = 1/\tau]_m = 1$

Cross-section (“area” of the target): $[\sigma]_m = -2$

Lifetime "Computations"

muon and neutron are unstable particles

$$\mu \to e\nu_\mu\bar{\nu}_e$$

$$n \to p\,e\,\bar{\nu}_e$$

The interactions responsible for the decay of muon and neutron are effectively of the form:

$$\underset{\nearrow\,[\mathrm{mass}]^4}{\mathcal{L}} = \underset{\uparrow\,[\mathrm{mass}]^{-2}}{G_F}\,\underset{\nwarrow\,[\mathrm{mass}]^{3/2\times 4}}{\psi^4} \quad \Rightarrow \quad \Gamma \underset{\uparrow\,[\mathrm{mass}]}{\propto} G_F^2 m^5$$

G$_F$ = Fermi constant: $G_F \sim \dfrac{10^{-5}}{m_{\text{proton}}} \sim 10^{-5}\,\mathrm{GeV}^{-2}$

For the **muon**, the relevant mass scale is the muon mass m_μ=105MeV:

$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3} \sim 10^{-19}\,\mathrm{GeV} \quad \text{i.e.} \quad \tau_\mu \sim 10^{-6}\,\mathrm{s}$$

For the **neutron**, the relevant mass scale is (m_n-m_p)≈1.29MeV:

$$\Gamma_n = \mathcal{O}(1)\frac{G_F^2 \Delta m^5}{\pi^3} \sim 10^{-28}\,\mathrm{GeV} \quad \text{i.e.} \quad \tau_{\mathrm{n}} \sim 10^3\,\mathrm{s}$$

$1 = \hbar c \sim 200\,\mathrm{MeV}\cdot\mathrm{fm}$

E	**T**	**L**
1eV	10^{-16}s	10^{-7}m

Universality of Weak Interactions

$$\mu \to e \nu_\mu \bar{\nu}_e \qquad\qquad n \to p\, e\, \bar{\nu}_e$$

$\tau_\mu \approx 10^{-6}$s $\tau_n \approx 900$s

$$\mathcal{L} = G_F\, \psi^4$$

$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3} \sim 1/10^{-6\prime\prime} \qquad\qquad \Gamma_n = \frac{G_F^2 \Delta m^5}{192\pi^3} \sim 1/15'$$

[factor 192 not exactly correct
because n and p are not elementary particles:
form factors are involved]

$$\mathcal{L} \overset{?}{=} G_F\ (\bar{n} p \bar{e} \nu_e + \bar{\mu} \nu_\mu \bar{e} \nu_e)$$

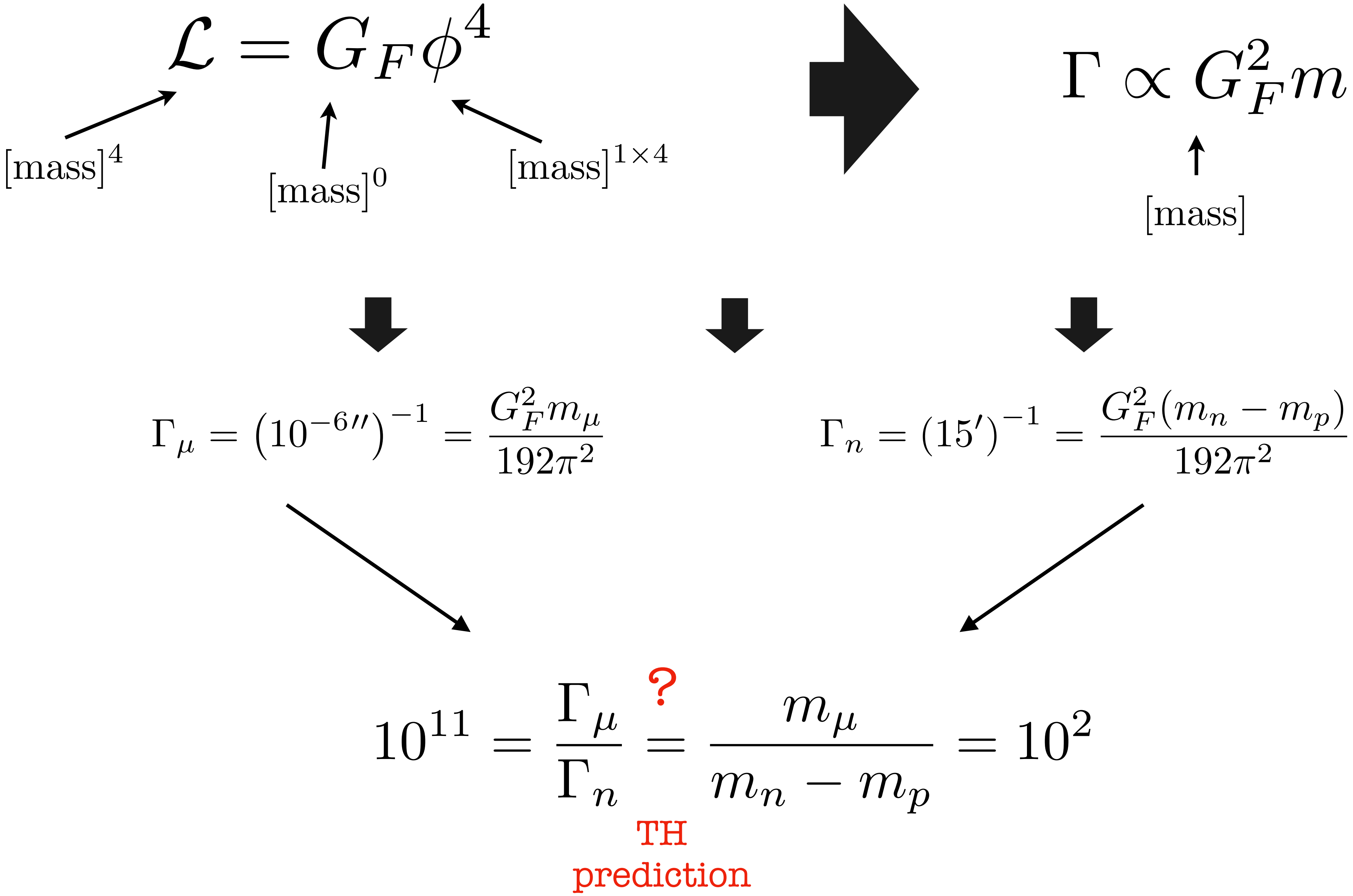
By analogy with electromagnetism, one can see the Fermi force as a current-current interaction (vector-vector interaction instead of scalar-scalar interaction)

$$\mathcal{L} = G_F\, J_\mu^* J^\mu \qquad \text{with} \qquad J^\mu \overset{?}{=} (\bar{n}\gamma^\mu p) + (\bar{e}\gamma^\mu \nu_e) + (\bar{\mu}\gamma^\mu \nu_\mu) + \ldots$$

it can be shown (thanks to the transformation law of spin-1/2 field given before) that this Lagrangian is invariant under Lorentz transformation

The cross-terms generate both neutron decay and muon decay.
The life-times of the neutron and muon tell us that the relative factor between the e and the μ in the current is of order one: the weak force has the **same strength for e and μ**.

What if particles were spin-0?



$$\underset{\overset{\nearrow}{[\text{mass}]^4}}{\mathcal{L}} = \underset{\overset{\uparrow}{[\text{mass}]^0}}{G_F}\,\underset{\overset{\nwarrow}{[\text{mass}]^{1\times 4}}}{\phi^4} \quad \Rightarrow \quad \Gamma \propto \underset{\overset{\uparrow}{[\text{mass}]}}{G_F^2}\, m$$

$$\Downarrow \qquad \Downarrow \qquad \Downarrow$$

$$\Gamma_\mu = \left(10^{-6\prime\prime}\right)^{-1} = \frac{G_F^2 m_\mu}{192\pi^2} \qquad \Gamma_n = (15^\prime)^{-1} = \frac{G_F^2(m_n - m_p)}{192\pi^2}$$

$$\searrow \qquad \swarrow$$

$$10^{11} = \frac{\Gamma_\mu}{\Gamma_n} \underset{\text{TH prediction}}{\overset{?}{=}} \frac{m_\mu}{m_n - m_p} = 10^2$$

It could still have been true but we would need to give up universality of the Fermi interactions.
Remember theorists like to connect phenomena that are seemingly different.
Even more true when they follow from simple assumptions.

Pion decay(s)

What about $\pi^{\pm}$ decay $\tau_{\pi} \approx 10^{-8}$s?

$$\pi^- \to \mu \bar{\nu}_\mu \qquad\qquad \pi^- \to e^- \bar{\nu}_e$$

experimentally the pions decay dominantly into muons and not electrons.

Why $\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} \underset{\text{EXP}}{\sim} 10^{-4}$? And not $\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} \sim \frac{(m_\pi - m_e)^5}{(m_\pi - m_\mu)^5} \underset{\text{TH}}{\sim} 500$?

Does it mean that our way to compute decay rate is wrong?
Is pion decay mediated by another interaction?
The pion is a composite particle: does is mean that the form factors drastically change our estimates?
Is the weak interaction non universal, i.e. is the value of G_F processus dependent?

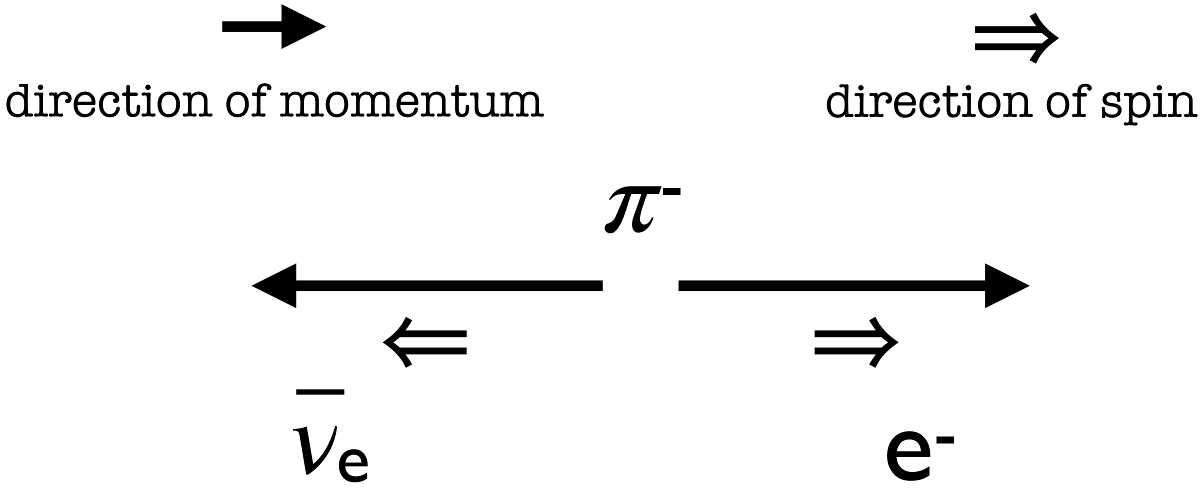
SM is a Chiral Theory

Weak interactions maximally violates P

$^{60}_{27}\mathrm{Co} \to {}^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e$ only left-handed (LH) e^- produced

Weak interactions act only on LH particles (and RH anti-particles)

this property has an important consequence (aka selection rule) for pion decay



Conservation of momentum and spin imposes to have a RH e^-

Weak decays proceed only w/ LH e^-
So the amplitude is prop. to m_e

$$\mathcal{L}_{\text{Dirac}} = \bar{\psi}_L \gamma^\mu \partial_\mu \psi_L + \bar{\psi}_R \gamma^\mu \partial_\mu \psi_R + m\left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L\right)$$

Lorentz structure
of fermion mass

$$\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} \propto \frac{m_e^2}{m_\mu^2} \sim 2 \times 10^{-5} \underset{\uparrow}{\sim} 10^{-4}_{\text{obs}}$$

Extra phase-space factor

Selection rules are important to get the right estimates

Pathology at High Energy

What about weak scattering process, e.g . $e\nu_e \to e\nu_e$?

$$\mathcal{L} = G_F\, J^*_\mu J^\mu \qquad \text{with} \qquad J^\mu = (\bar{n}\gamma^\mu p) + (\bar{e}\gamma^\mu \nu_e) + (\bar{\mu}\gamma^\mu \nu_\mu) + \ldots$$

The same Fermi Lagrangian will thus also contain a term

$$G_F\, (\bar{e}\gamma^\mu \nu_e)(\bar{\nu}_e\gamma^\mu e)$$

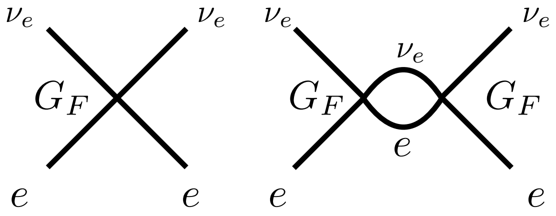
that will generate e-ν_e scattering whose cross-section can be guessed by dimensional arguments

$$\underbrace{\sigma}_{[\text{mass}]^{-2}} \propto \underbrace{G_F^2}_{[\text{mass}]^{-2\times 2}} \underbrace{E^2}_{[\text{mass}]^2}$$

⇒

non conservation of probability
(non-unitary theory)
inconsistent at high energy

It means that, at high-energy, the quantum corrections to the classical contribution can be sizeable:



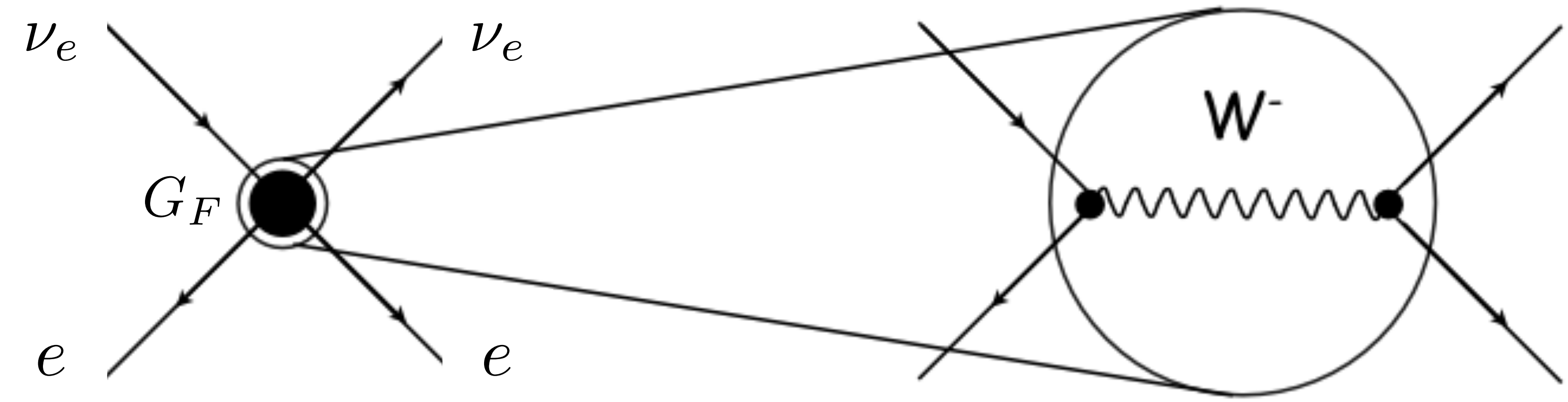
$$\sigma \propto G_F^2 E^2 + \frac{1}{16\pi^2} G_F^4 E^6 + \ldots$$

The theory becomes non-perturbative at an energy $E_{\max} = \dfrac{2\sqrt{\pi}}{\sqrt{G_F}} \sim 100\,\text{GeV–}1\,\text{TeV}$

unless new degrees of freedom appear before to change the behaviour of the scattering

Electroweak Interactions

Low energy **High energy**



$$\sigma \propto G_F^2 E^2$$

$$\sigma \propto g^4 \frac{E^2}{m_W^2\,(E^2+m_W^2)}$$

— matching —

$$G_F \propto \frac{g^2}{m_W^2}$$

The Fermi interaction is not a fundamental interaction of Nature.
It is a low energy effective interaction.

From Gauge Theory to Fermi Theory

We can derive the Fermi current-current contact interactions by "integrating out" the gauge bosons, i.e., by replacing in the Lagrangian the W's by their equation of motion. Here is a simple derivation:
(a better one should take taking into account the gauge kinetic term and the proper form of the fermionic current that we'll figure out tomorrow, for the moment, take it as a heuristic derivation)

$$\mathcal{L} = -m_W^2 W_\mu^+ W_\nu^- \eta^{\mu\nu} + g W_\mu^+ J_\nu^- \eta^{\mu\nu} + g W_\nu^- J_\nu^+ \eta^{\mu\nu}$$

$$J^{+\mu} = \bar{n}\gamma^\mu p + \bar{e}\gamma^\mu \nu_e + \bar{\mu}\gamma^\mu \nu_\mu + \dots \qquad \text{and} \qquad J^{-\mu} = \left(J^{+\mu}\right)^*$$

The equation of motion for the gauge fields: $\dfrac{\partial \mathcal{L}}{\partial W_\mu^+} = 0 \quad \Rightarrow \quad W_\mu^- = \dfrac{g}{m_W^2} J_\mu^-$

Plugging back in the original Lagrangian, we obtain an *effective Lagrangian* (valid below the mass of the gauge bosons):

$$\boxed{\mathcal{L} = \frac{g^2}{m_W^2} J_\mu^+ J_\nu^- \eta^{\mu\nu}}$$

which is the Fermi current-current interaction. The Fermi constant is given by
(the correct expression involves a different normalisation factor)

$$\boxed{G_F = \frac{g^2}{m_W^2}}$$

But what is the origin of the W mass?
By the way, it is not invariant under SU(2) gauge transformation…
That's what the Higgs mechanism will take care of!

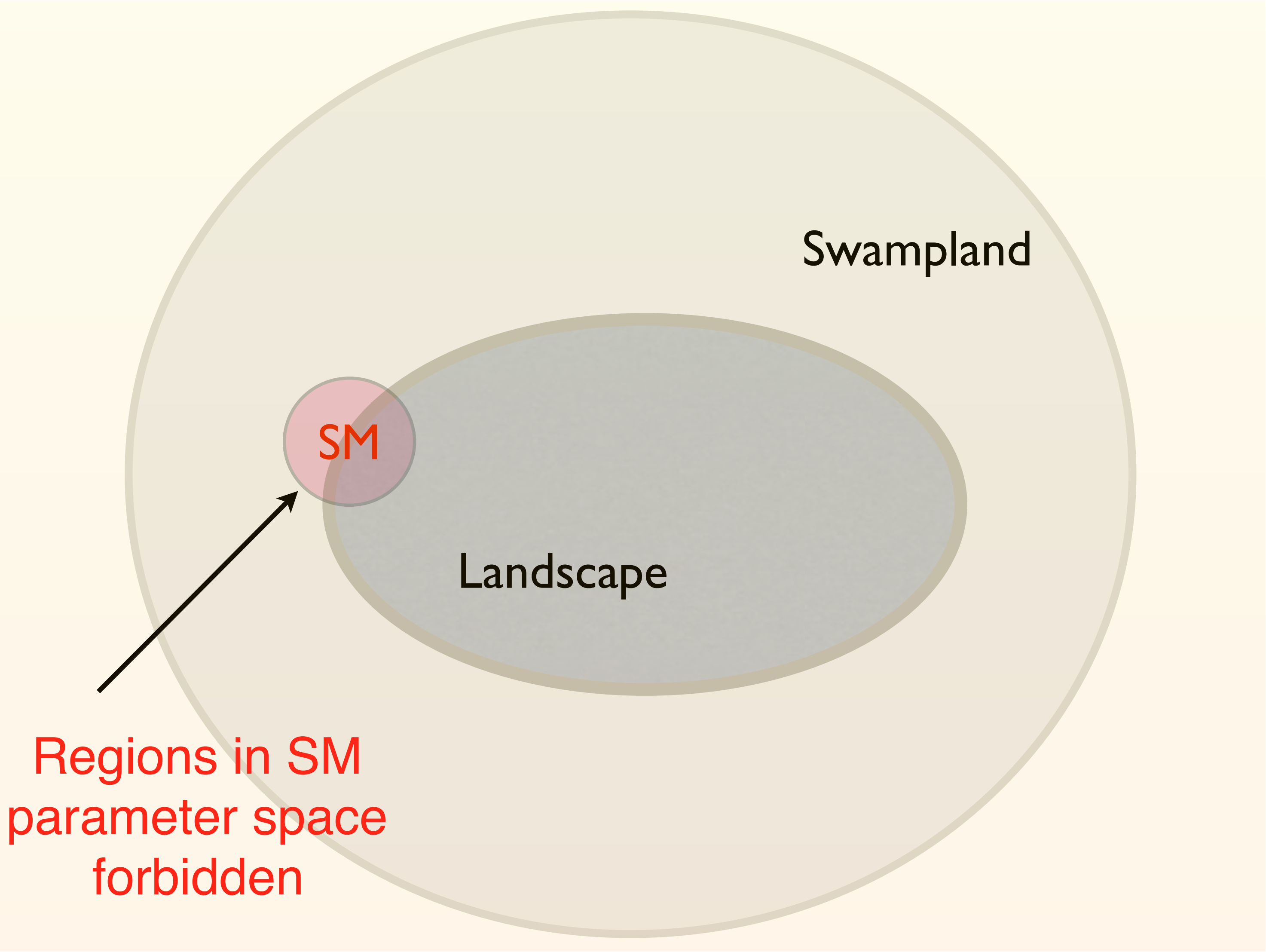
Swampland: UV/IR mixing

Particle Physics & Quantum Gravity

Can the SM be embedded in a theory of quantum gravity at the Planck scale?
Can QG be really decoupled at low energy?

Would certainly be true if any QFT can be consistently coupled to QG

Instead Vafa conjectured in 2005 that there exists a **swampland**



Ibanez @ SUSY'18

This conjecture has potentially far-reaching implications for phenomenology.

Landscape/Swampland Conjectures

0) No exact global symmetry

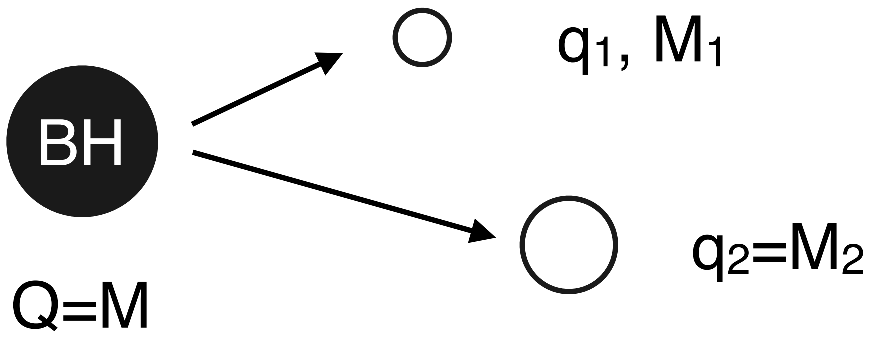
For a review, see Banks, Seiberg '10

1) Gravity is the weakest force

Arkani-Hamed, Motl, Nicolis, Vafa '06

In any UV complete U(1) gauge theory there must exist at least one charged particle with mass M such that: $M/M_P < g \, . \, q$

Why? otherwise extremal charged BH cannot decay!



BH can decay iff $M_1+M_2<M$, i.e. $M_1<M-M_2=Q-q_2=q_1$

Landscape/Swampland Conjectures

2) non-susy AdS vacua (Vmin<0) are unstable

Ooguri, Vafa '16

Consider the SM (with cc) compactified on a circle of radius R

Ibanez, Martin-Lozano, Valenzuela '17

$$V(R) \simeq \underbrace{\frac{2\pi r^3\Lambda_4}{R^2}}_{From\ 4D\ c.c.} - 4\underbrace{\left(\frac{r^3}{720\pi R^6}\right)}_{\gamma,\, g_{\mu\nu}} + \underbrace{\sum_i (2\pi R)(-1)^{s_i} n_i \rho_i(R)}_{\nu_i}$$

$$\rho(R) = \mp \sum_{n=1}^{\infty} \frac{2m^4}{(2\pi)^2} \frac{K_2(2\pi R m n)}{(2\pi R m n)^2}$$

Ibanez @ SUSY'18

Heavier particles have exponentially small contribution

Majorana neutrinos leads to an AdS vacuum ⇒ in swampland

Dirac neutrinos avoid AdS vacuum iif $m_\nu^4 < \Lambda_4$

$\langle H \rangle < 1.6 \frac{\Lambda_4^{1/4}}{Y_\nu}$ ⇒ Large quantum corrections end up in swampland (for fixed Λ_4 and Y_ν)

SM with 3 families but without Higgs also develops AdS vacuum ⇒ in swampland

Swampland Conjectures

3) $M_P \parallel \vec{\nabla}_{\phi_i} V(\phi_i) \parallel > c\,V(\phi_i)$ with c is O(1) for any field configuration

Obied, Ooguri, Spodyneiko, Vafa ’18

- Pure positive cosmological constant, i.e. vacuum energy, (dS vacuum) is forbidden
- Quintessence:

Agrawal, Obied, Steinhart, Rafa ‘18

$$V(\phi) = \Lambda^4 e^{-\kappa\phi/M_P}$$

$$0.6 > \kappa > c$$

Planck data

swampland conjecture

- Quintessence + Higgs:

Denef, Hebecker, Wrase ‘18

$$V(H,\phi) = \Lambda^4 e^{-\kappa\phi/M_P} + \lambda(|H|^2 - v^2)^2 + V_0$$

$$\frac{M_P \parallel \vec{\nabla}_{\phi_i} V(\phi_i) \parallel}{V(\phi_i)} = \begin{cases} \dfrac{\kappa\Lambda^4}{\Lambda^4 + \lambda v^4 + V_0} & @(H=0,\phi=0) \\ \dfrac{\kappa\Lambda^4}{\Lambda^4 + V_0} & @(H=v,\phi=0) \end{cases}$$

at least one of them is as small as

$$\mathcal{O}\left(\frac{\text{cc}}{\text{EW}^4}\right) \sim \frac{(10^{-3}\,\text{eV})^4}{(100\,\text{GeV})^4} \sim 10^{-56}$$

- Quintessence + axion:

Murayama, Yamazaki, Yanagida ‘18

$$V(\theta,\phi) = \Lambda^4 e^{-\kappa\phi/M_P} + \Lambda_{QCD}^4(1-\cos(\theta/f)) + V_0$$

$$\frac{M_P \parallel \vec{\nabla}_{\phi_i} V(\phi_i) \parallel}{V(\phi_i)} = \begin{cases} \dfrac{\kappa\Lambda^4}{\Lambda^4 + V_0} & @(\theta=0,\phi=0) \\ \dfrac{\kappa\Lambda^4}{\Lambda^4 + \Lambda_{QCD}^4 + V_0} & @(\theta=\pi f,\phi=0) \end{cases}$$

at least one of them is as small as

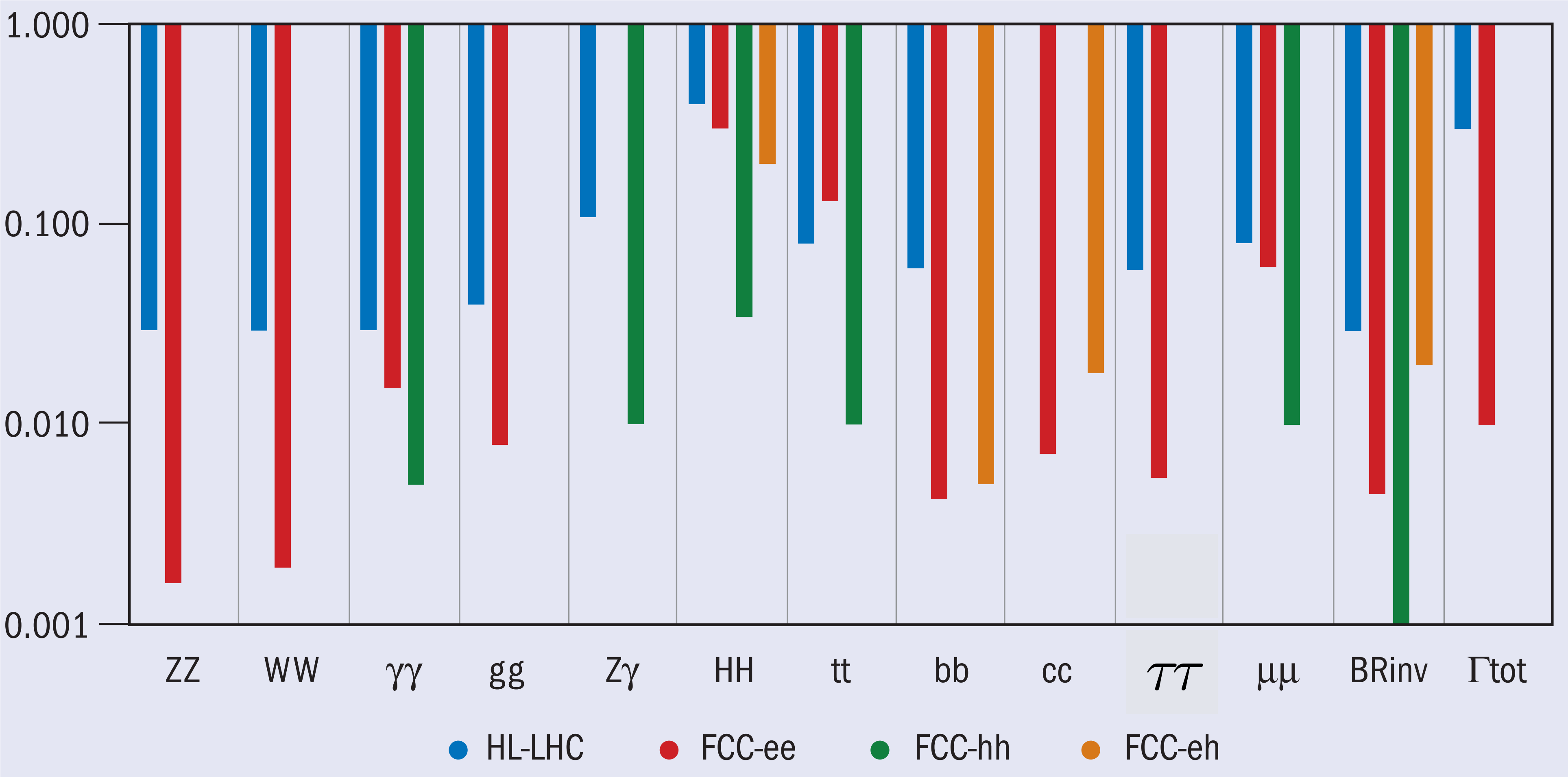
$$\mathcal{O}\left(\frac{\text{cc}}{\text{QCD}^4}\right) \sim \frac{(10^{-3}\,\text{eV})^4}{(200\,\text{MeV})^4} \sim 10^{-44}$$

Swampland Conjectures

It is not that String Theory rules out the SM as we know it.
But non-trivial interactions among seemingly decoupled sectors must exist:
UV enforces interactions among IR degrees of freedom,
like anomaly conditions enforce constraints on IR physics.

EFTs for Higgs data

How to report Higgs data: from *κ* to EFT



Oversimplified PR plot

1) not a unique coupling to each particle

2) powerful complementarity/synergy with non-Higgs measurements not visible (e.g. EW, diboson, top)

How to report Higgs data: from *κ* to EFT

M. Zuckerberg created FaceMash before Facebook

J.K. Rowling got rejected 12 times by editors before she published Harry Potter

Beyonce wrote hundreds of songs before ‘Halo’

... Physicists used signal strengths to report Higgs data before ...

one doesn’t have to succeed on the first try

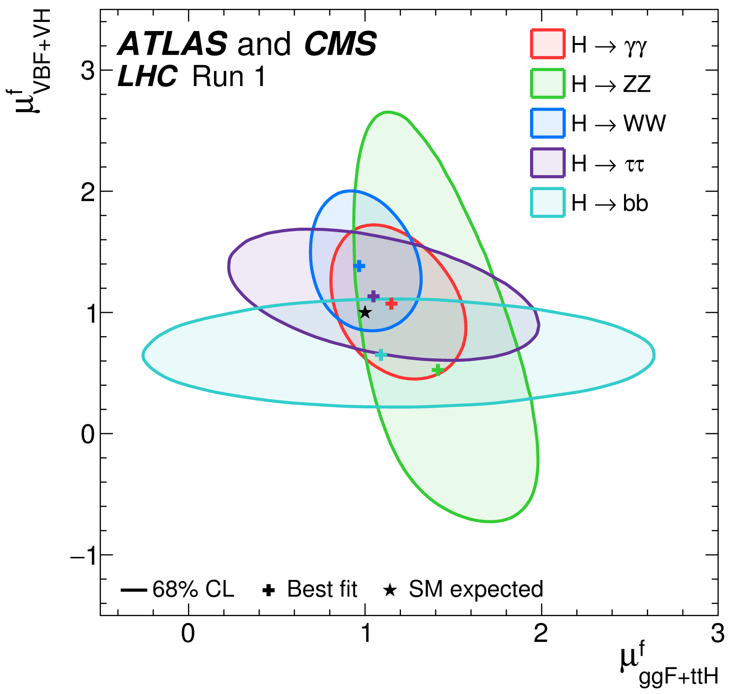
“the success comes from the freedom to fail”

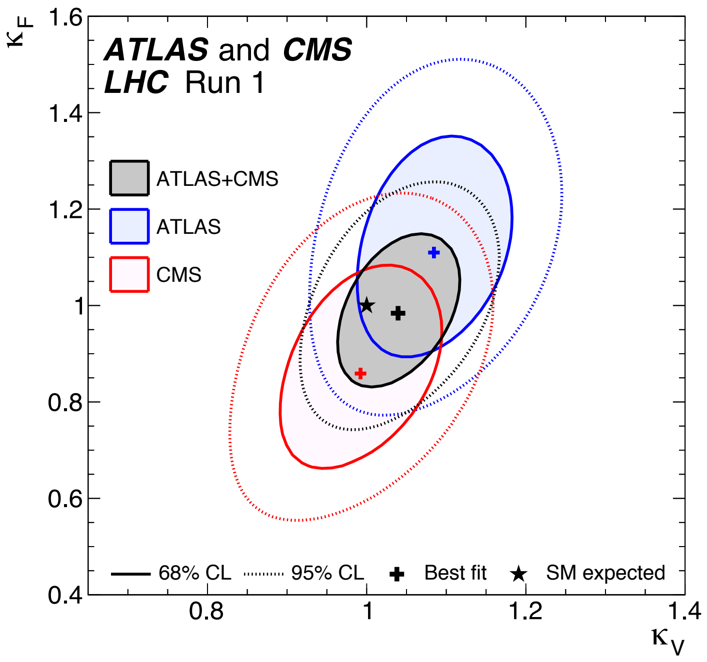
M. Zuckerberg, Harvard graduation ceremony speech, May 25, 2017

How to report Higgs data: from κ to EFT

LHCHXSWG ’12

$$\mu_i = \frac{\sigma[i \to h]}{(\sigma[i \to h])_{\rm SM}} \qquad \mu_f = \frac{{\rm BR}[h \to f]}{({\rm BR}[h \to f])_{\rm SM}}$$





$$(\sigma \cdot {\rm BR})\,(gg \to {\rm H} \to \gamma\gamma) \;=\; \sigma_{\rm SM}(gg \to {\rm H}) \cdot {\rm BR}_{\rm SM}({\rm H} \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_{\rm H}^2}$$

individual coupling rescaling factors

Well suited parametrization for inclusive measurements
but doesn’t do justice to full possible SM deformations & rich diff. information

How to report Higgs data: from *κ* to EFT

LHCHXSWG '12

Main drawbacks of μ and κ

1) No SU(2)xU(1) gauge invariant formalism

2) Missing some important symmetry properties of SM, already well constrained e.g. in EW precision measurements

3) very difficult to go beyond LO

Well suited parametrization for inclusive measurements
but doesn't do justice to full possible SM deformations & rich diff. information

Higgs Couplings: Kappa vs EFT

Complementarity between the two approaches

Kappa:

- Close connection to exp. measurements
- Widely used
- Exploration tool (very much like epsilons for LEP)
- Doesn’t require BSM theoretical computations
- Could still valid even with light new physics, i.e. exotic decays
- Captures leading effects of UV motivated scenarios (SUSY, composite)
- Main drawbacks: focused on inclusive quantities, not general

$$g_{hXX} = \kappa_X \, g_{hXX}^{\mathrm{SM}}$$

HEFT

(SM)EFT:

- Allows to put Higgs measurements in perspective with other measurements (EW, diboson, flavour…)
- Connects measurements at different scales (particularly relevant for high-energy colliders CLIC, FCC-hh)
- Fully exploits more exclusive observables (polarisation, angular distributions…)
- Can accommodate subleading effects (loops, dim-8…)
- Fully QFT consistent framework
- Assumptions about symmetries more transparent
- Valid only if heavy new physics
- Main drawbacks: assume mass gap with New Physics, not general (no new particle with a Higgs-generated mass)

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{d,i} \frac{c_i \, \mathcal{O}_d^i}{\Lambda^{d-4}}$$

Higgs Couplings: Kappa vs EFT

Complementarity between the two approaches

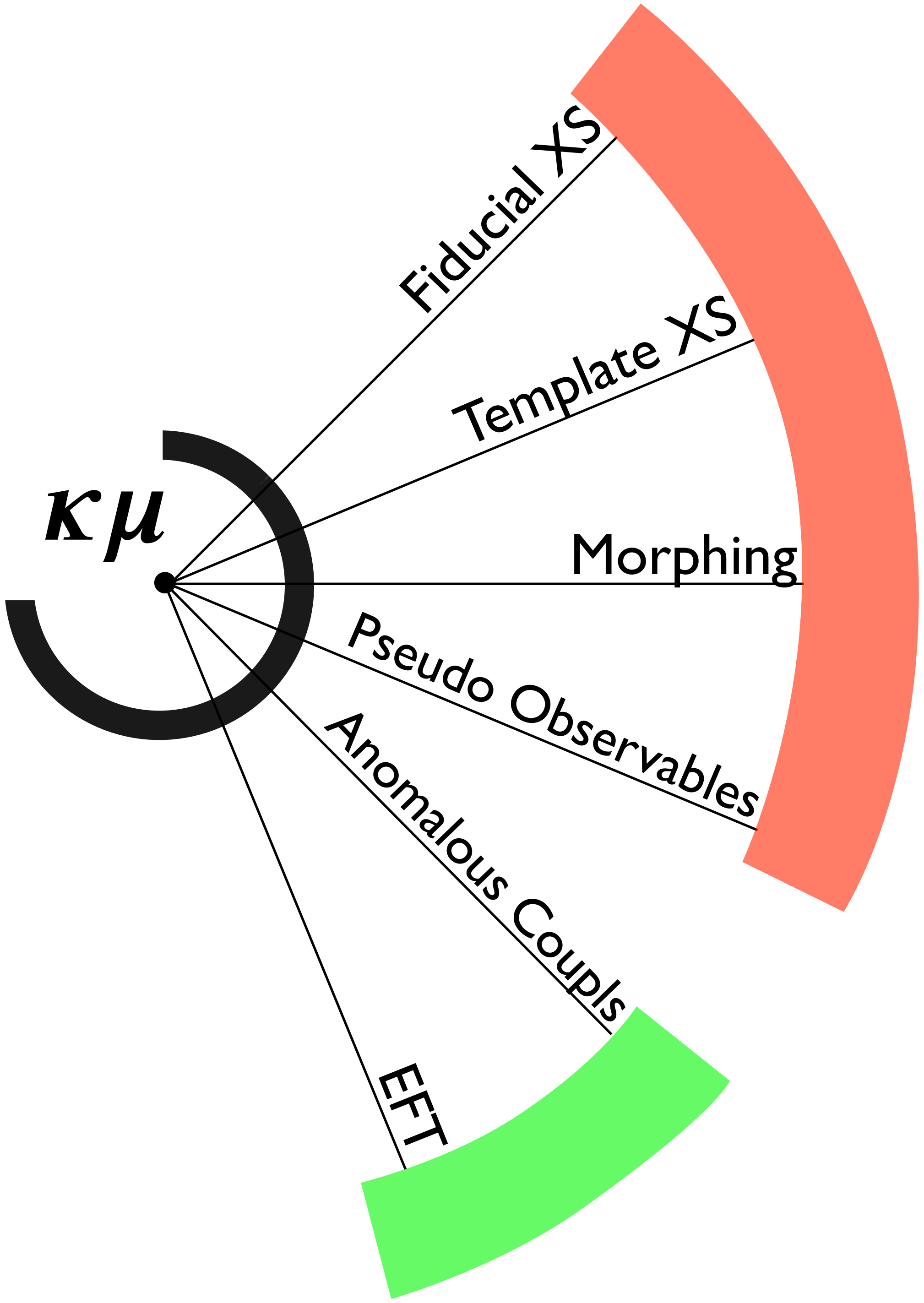
Kappa:

- Close connection to exp. measurements
- Widely used
- Exploration tool (very much like epsilons for LEP)

Why performing a **κ-fit** is always a good idea?
it can be more easily compared to the fits often performed by the various collaborations
➙ validation of the procedure/code (in particular the treatment of uncertainties and correlations and the combination of ATLAS-CMS data/projections)

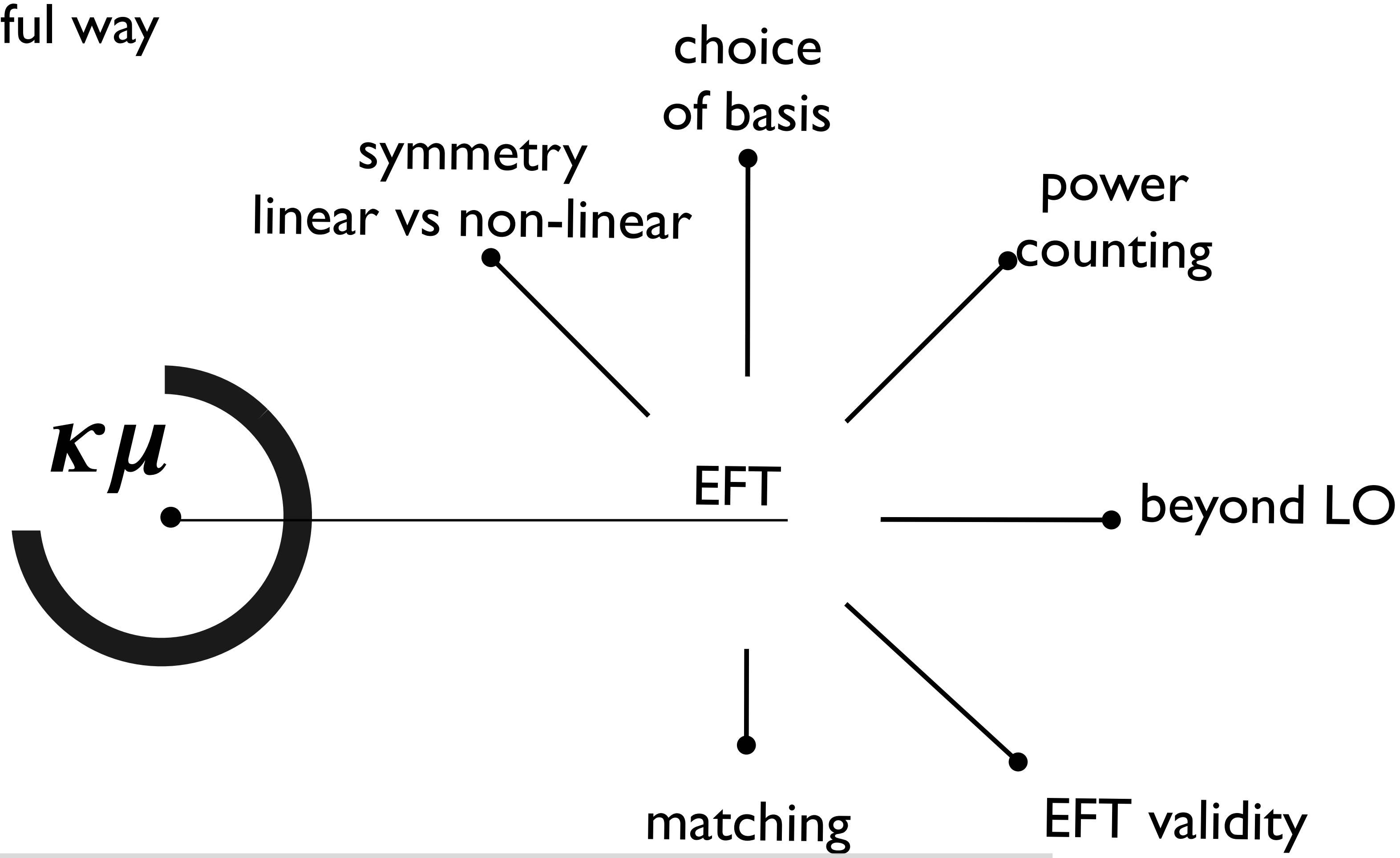
- Assumptions about symmetries more transparent
- Valid only if heavy new physics
- Main drawbacks: assume mass gap with New Physics, not general (no new particle with a Higgs-generated mass)

EFT


$\kappa\mu$
Fiducial XS
Template XS
Morphing
Pseudo Observables
Anomalous Coupls
EFT

EFT

Not unique!
Useful tools to probe
broad classes of dynamics
and to report experimental results
in a meaningful way



$\kappa\mu$

EFT

symmetry
linear vs non-linear

choice
of basis

power
counting

beyond LO

EFT validity

matching

Pros:

- correlations between different channels/observables
- combination of measurements at different energies
  e.g. EW precision data and Higgs measurements
- test of self-consistency

unique to EFT

allow to focus on channels yet
unconstrained and more likely to offer
new discovery opportunities

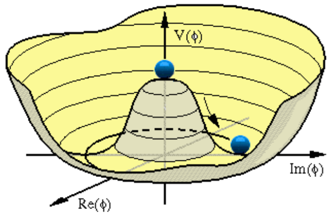
Higgs physics vs BSM

Several deformations
away from the SM
affecting Higgs properties
are already probed in the vacuum

(assuming EW symmetry linearly realized
and that new physics is heavy)

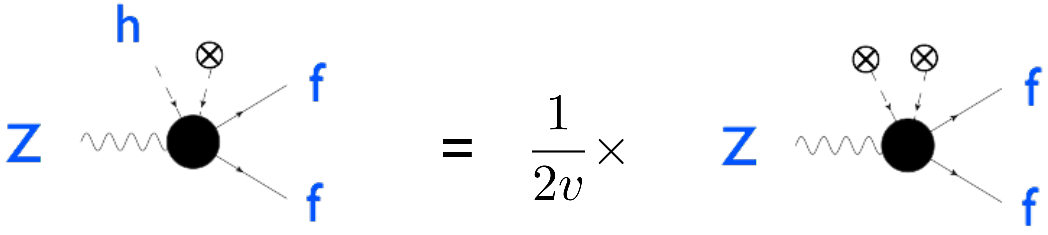
ϕ = v+h

vacuum



Potentially new BSM-effects in h physics
could have been already tested in the vacuum

e.g.



$= \frac{1}{2v}\times$

$H^\dagger D_\mu H \bar{f}\gamma^\mu f$

(assuming that the Higgs boson is part of a doublet)

Modifications in h→Zff related to Z→ff

consistency check
not discovery mode

One can use h→ZZ→4l to probe this deformation
but hard time to compete with LEP bounds

(courtesy of A. Pomarol@Moriond2014)

Higgs/BSM Primaries

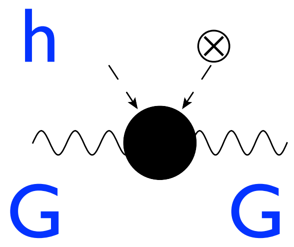
There are others deformations away from the SM
that are harmless in the vacuum
and need a Higgs field to be probed

(courtesy of A. Pomarol@HiggsHunting2014)

e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2+\frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2\to\left(\frac{1}{g_s^2}+\frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$

operator
not visible in the vacuum
(redefinition of input parameter)

But can affect h physics:



affects GG →h!

operator
visible in Higgs physics

this BSM operator is visible only in Higgs physics!

Higgs/BSM Primaries

Pomarol, Riva '13
Elias-Miro et al '13
Gupta, Pomarol, Riva '14

How many of these effects can we have?

As many as parameters in the SM: **8** for one family

(assuming CP-conservation)

g_s	$\|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\longrightarrow$ **GGh coupling**
g	$\|H\|^2 B_{\mu\nu} B^{\mu\nu}$	$\longrightarrow$ **hγγ coupling**
g'	$\|H\|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$	$\longrightarrow$ **hZγ coupling**
m_W	$\|H\|^2 \|D_\mu H\|^2$	$\longrightarrow$ hVV* (custodial invariant)
m_h	$\|H\|^6$	$\longrightarrow$ **h^3 coupling**
m_f (f=t,b,τ)	$\|H\|^2 \bar{f}_L H f_R + h.c.$	$\longrightarrow$ **htt, hbb, h$\tau\tau$**

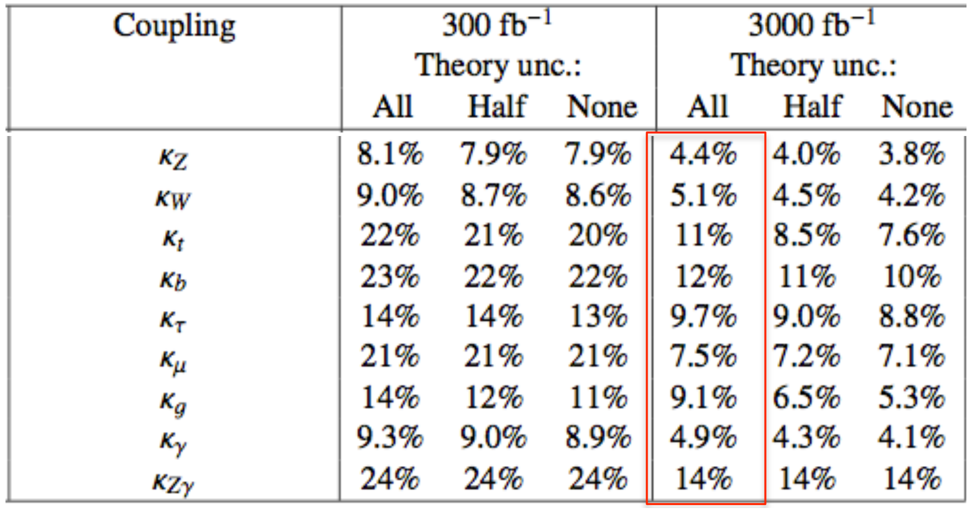
yet to be measured
at the LHC

the 6 others have been measured (~15%)

Higgs/BSM Primaries

Pomarol, Riva ’13
Elias-Miro et al ’13
Gupta, Pomarol, Riva ’14

Almost a 1-to-1 correspondence



Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
κ_t	22%	21%	20%	11%	8.5%	7.6%
κ_b	23%	22%	22%	12%	11%	10%
κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
κ_g	14%	12%	11%	9.1%	6.5%	5.3%
κ_γ	9.3%	9.0%	8.9%	4.9%	4.3%	4.1%
$\kappa_{Z\gamma}$	24%	24%	24%	14%	14%	14%

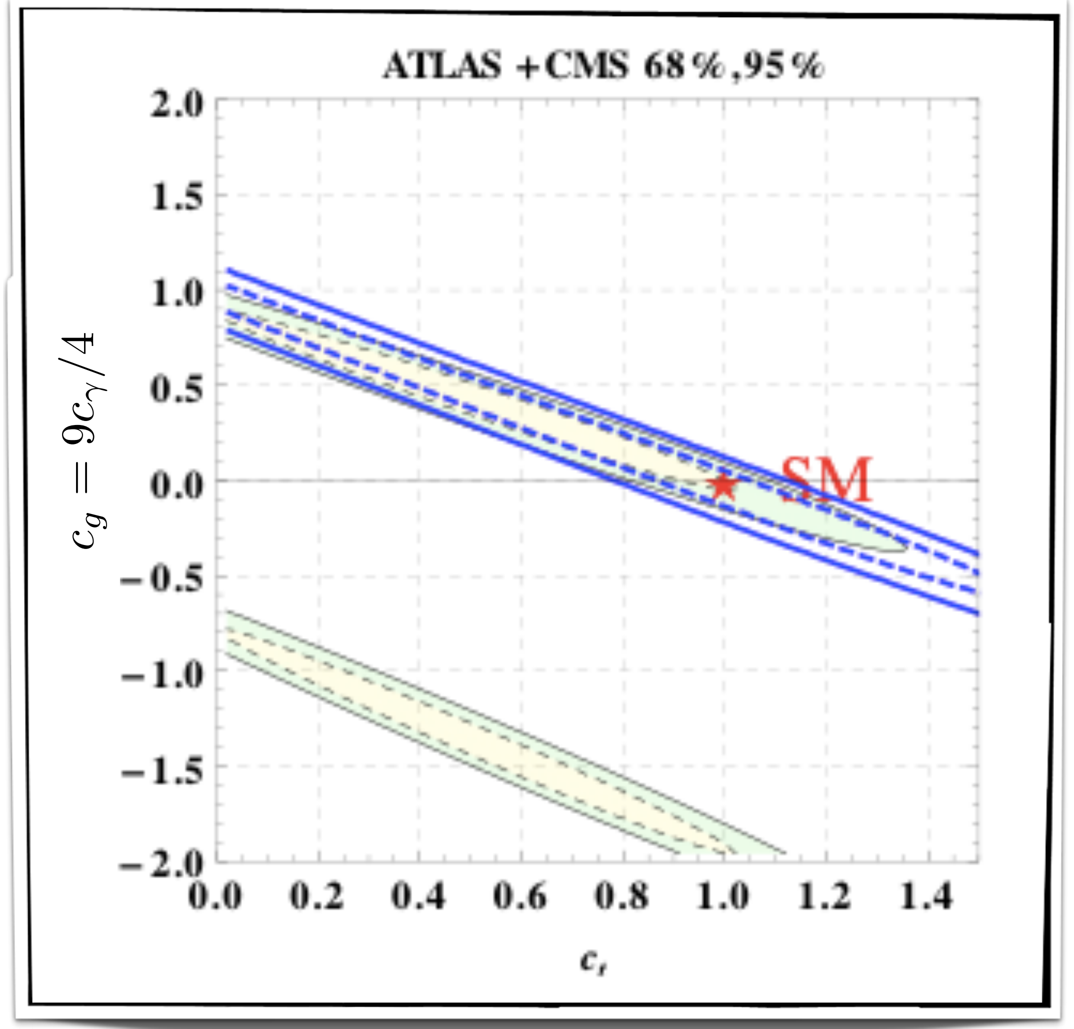
Atlas projection

With some important differences

1) width hypothesis built-in

2) κ_W/κ_Z is not a primary (constrained by $\Delta\rho$ and TGC)

3) κ_g, κ_γ, $\kappa_{Z\gamma}$ do not separate UV and IR contributions



Azatov ’15

the 6 others have been measured (~15%)

up to a flat direction between between the top/gluon/photon couplings

The LHC Scalar Harvest

(8M Brout-Englert-Higgs bosons produced so far)

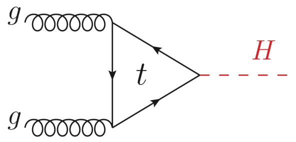
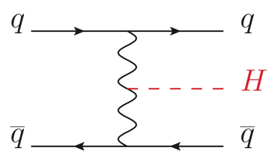
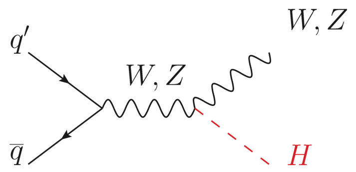
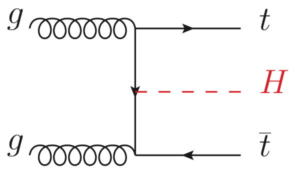
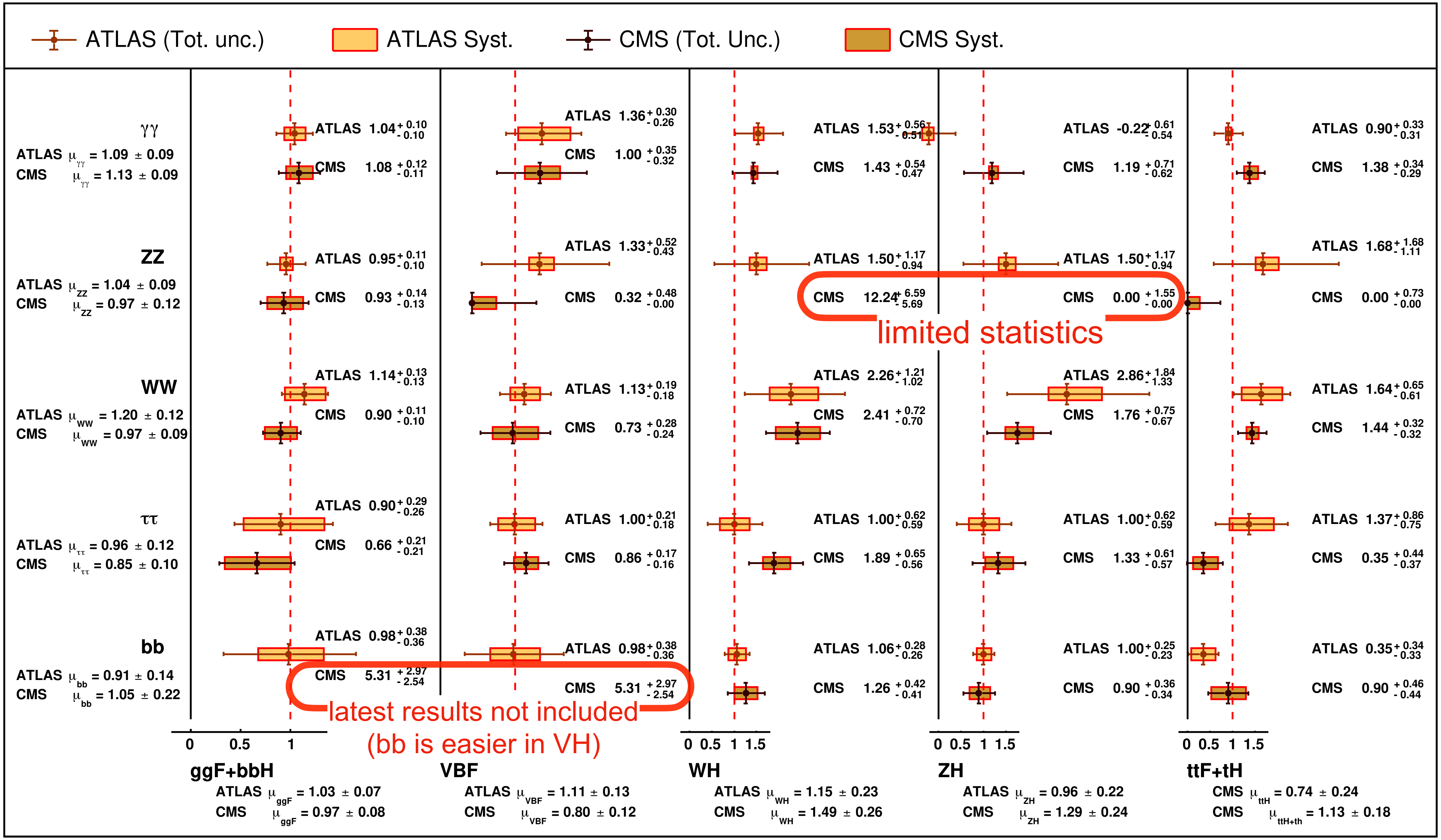
	Channel categories	Br	ggF	VBF	VH	ttH
			 ~8 M evts produced	 ~600 k evts produced	 ~400 k evts produced	 ~80 k evts produced
	Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
Observed modes	γγ	0.2 %	✓	✓	✓	✓
	ZZ	3%	✓	✓	✓	✓
	WW	22%	✓	✓	✓	✓
	ττ	6.3 %	✓	✓	✓	✓
	bb	55%	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	0.2 %	✓	✓	✓	✓
	μμ	0.02 %	✓	✓	✓	✓
Limits	Invisible	0.1 %	✓ (monojet)	✓	✓	✓

Table courtesy to M. Kado

The Higgs Rates

PDG'2024 (to appear)

Measured production and decay rates (normalised to SM)



limited statistics

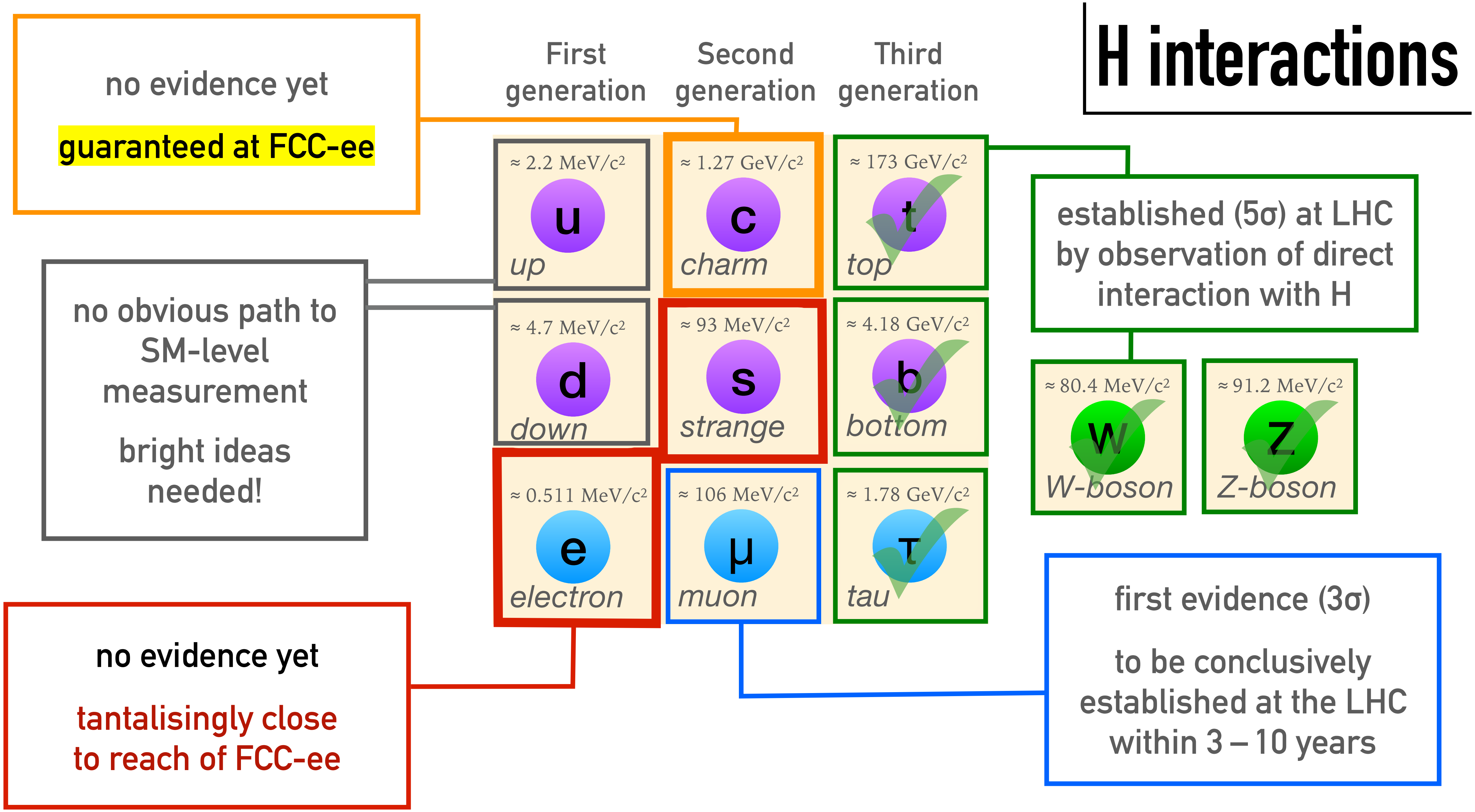
latest results not included
(bb is easier in VH)

A few outliers in the matrix but the row/columns combinaisons are in good agreement with SM predictions

ATLAS run-2 combination: $\mu = 1.05 \pm 0.06 = 1.05 \ \pm 0.03\ (\mathrm{stat.}) \pm 0.03\ (\mathrm{exp.})\ \pm 0.02\ (\mathrm{th.\,bkg.})\ \pm 0.04\ (\mathrm{th.\,sig.})$

CMS run-2 combination: $\mu = 1.002\ \pm 0.057.$

Higgs @ LHC and Future Higgs Factory



H interactions

no evidence yet

guaranteed at FCC-ee

no obvious path to SM-level measurement

bright ideas needed!

no evidence yet

tantalisingly close to reach of FCC-ee

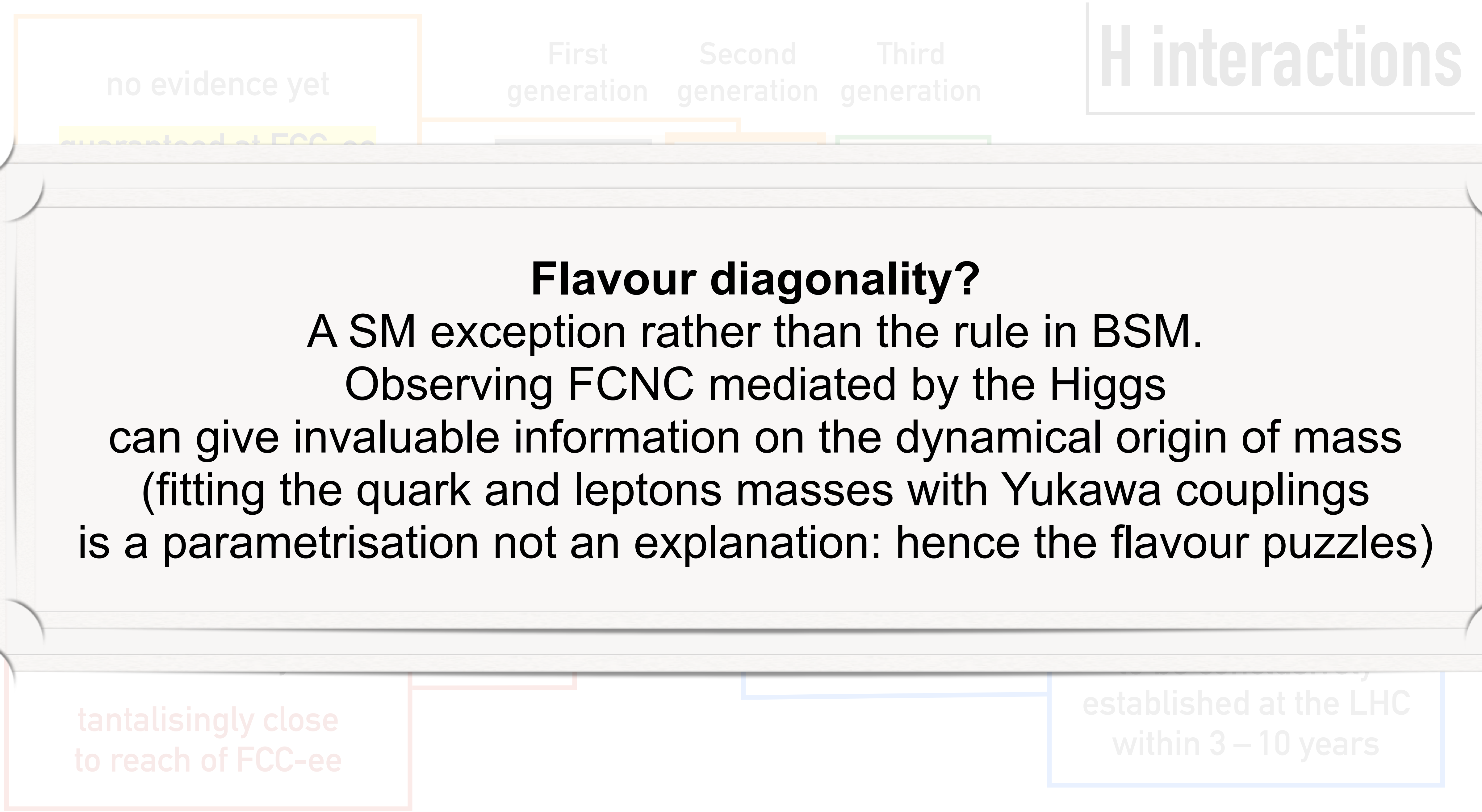
established (5σ) at LHC by observation of direct interaction with H

first evidence (3σ)

to be conclusively established at the LHC within 3 – 10 years

G. Salam @ FCC'23

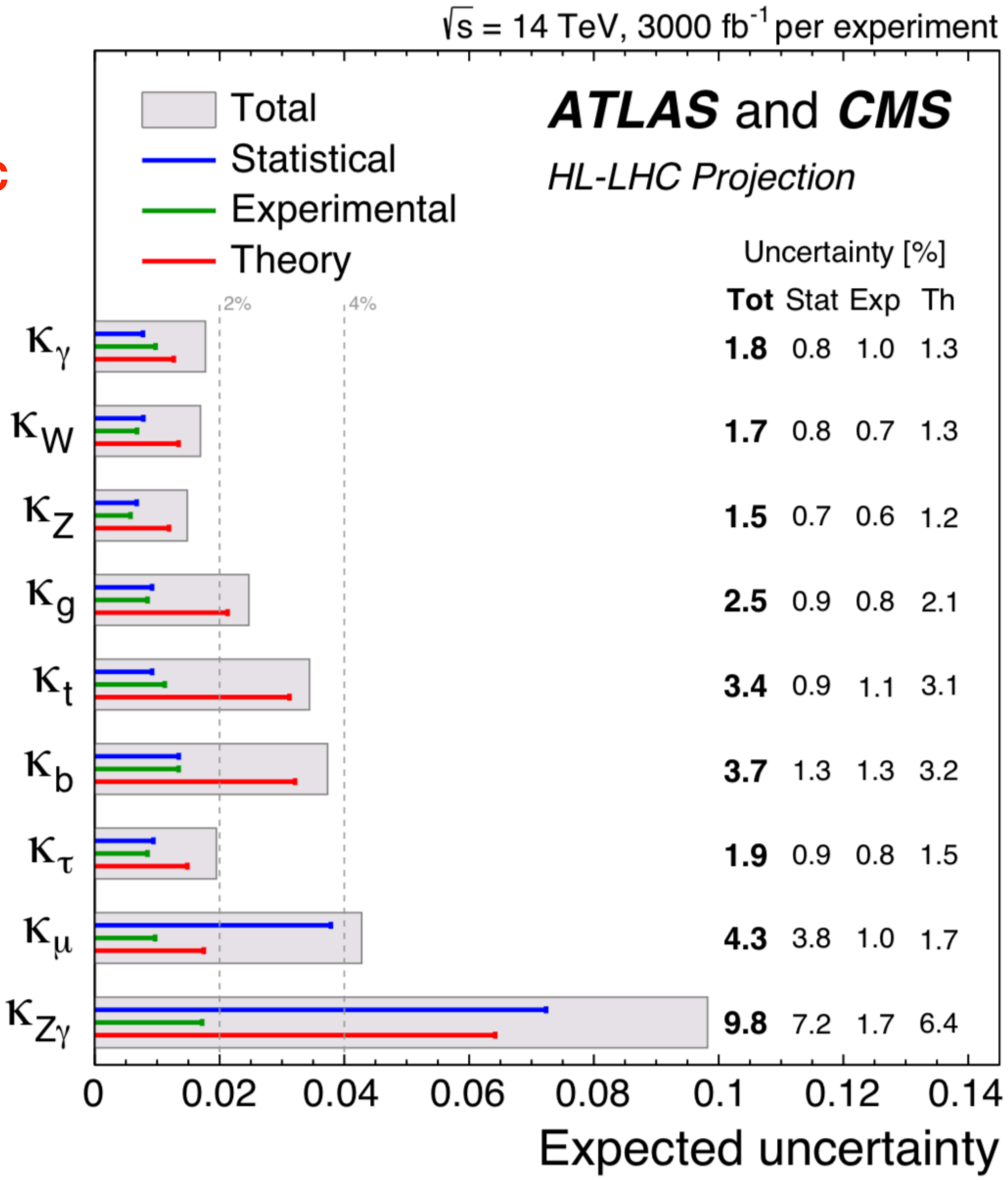
Higgs @ LHC and Future Higgs Factory



Flavour diagonality?
A SM exception rather than the rule in BSM.
Observing FCNC mediated by the Higgs
can give invaluable information on the dynamical origin of mass
(fitting the quark and leptons masses with Yukawa couplings
is a parametrisation not an explanation: hence the flavour puzzles)

Higgs @ (HL)-LHC

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision	HL-LHC
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%	1.8%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%	1.7%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%	1.5%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%	2.5%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%	3.4%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%	3.7%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%	1.9%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%	4.3%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%	9.8%
B_{inv}		$< 11\,\%$	$< 16\,\%$	11%	2.5%
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)		



Uncertainty [%]

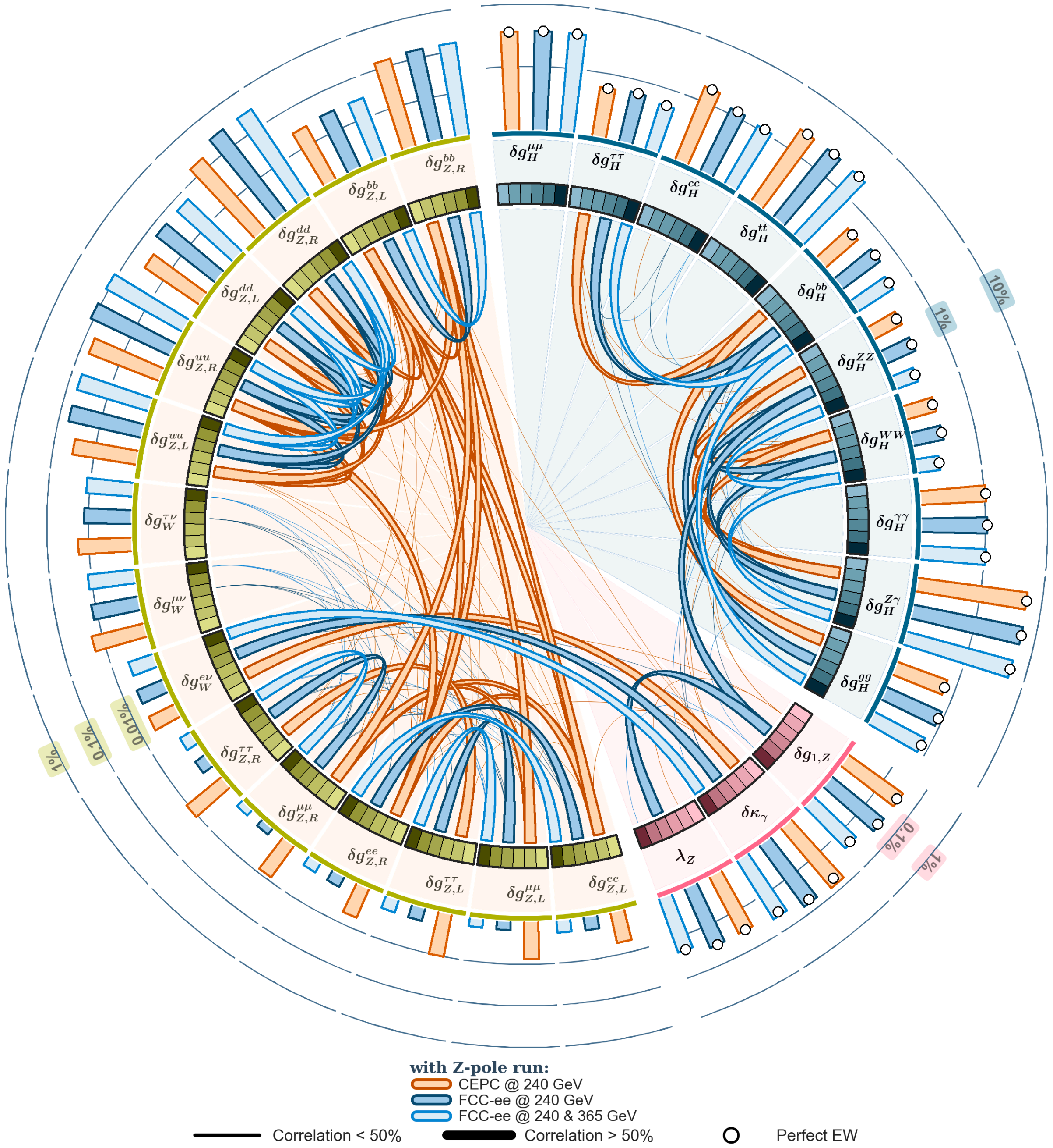
Tot	Stat	Exp	Th
1.8	0.8	1.0	1.3
1.7	0.8	0.7	1.3
1.5	0.7	0.6	1.2
2.5	0.9	0.8	2.1
3.4	0.9	1.1	3.1
3.7	1.3	1.3	3.2
1.9	0.9	0.8	1.5
4.3	3.8	1.0	1.7
9.8	7.2	1.7	6.4

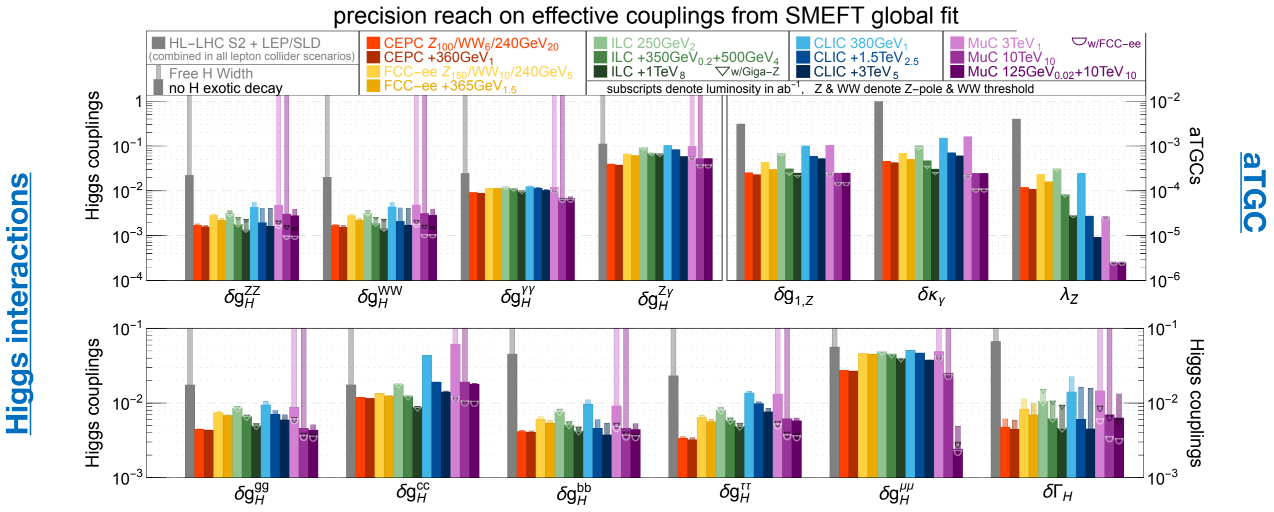
TH Uncertainties dominant
(assumed to be 1/2 of Run 2)

Higgs Global Fits

J. De Blas et al. 1907.04311

arXiv:2206.08326





ESU'20

Snowmass'22

Higgs Global Fits

J. De Blas et al. 1907.04311

arXiv:2206.08326

What's next?

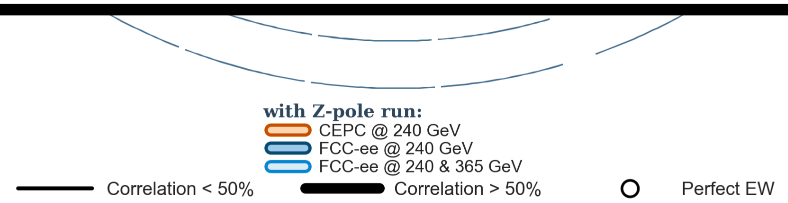
More differential measurements

More realistic
flavour scenarios

CP

Relaxed symmetry assumptions
(HEFT vs SMEFT)

Connections with models
(in particular with light dofs)



ESU'20

Snowmass'22

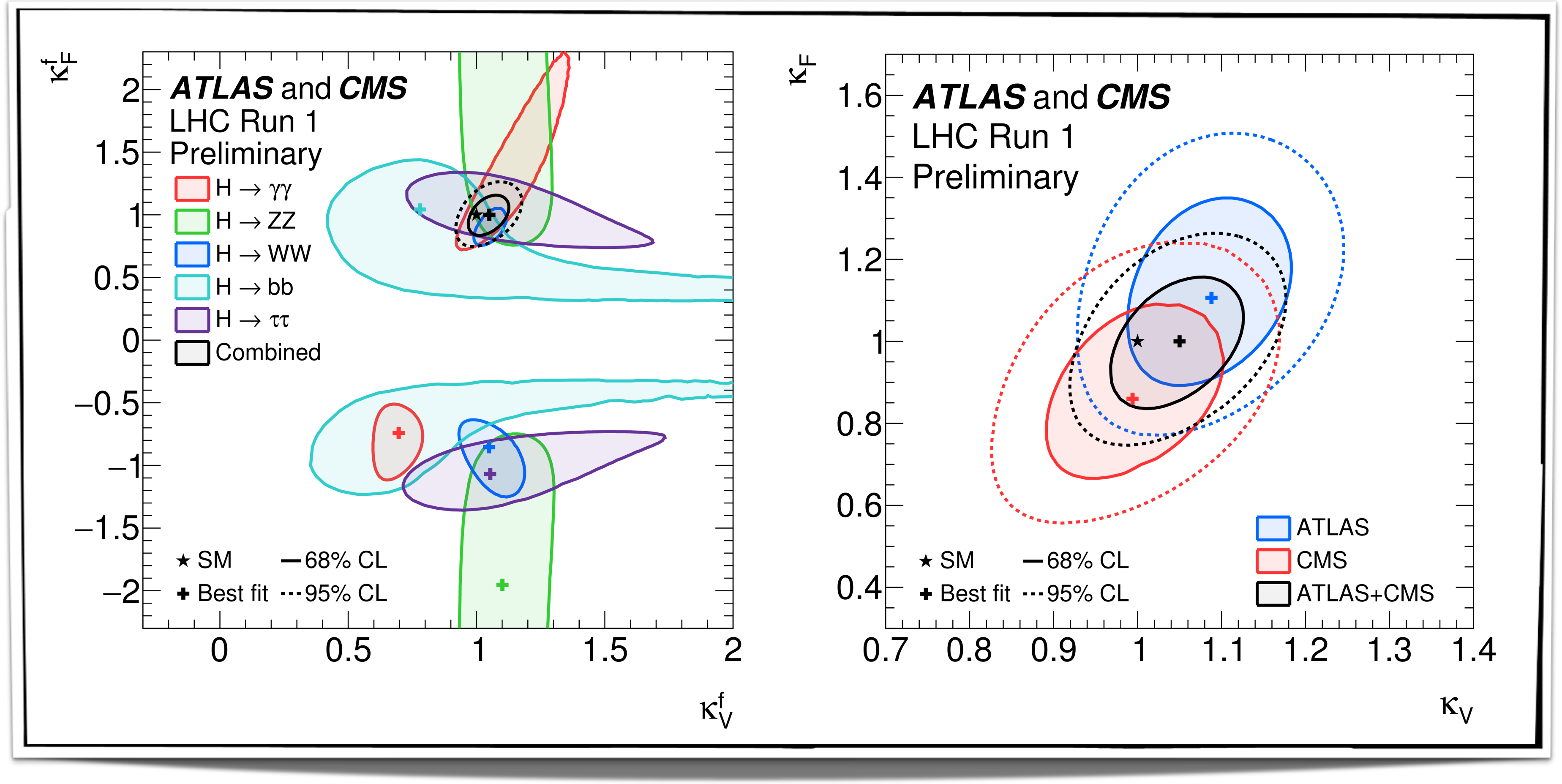
Beyond inclusive analyses

Why going beyond inclusive Higgs processes?

So far the LHC has mostly produced Higgses on-shell
in processes with a characteristic scale $\mu \approx m_H$

⇩ ⇩

access to Higgs couplings @ m_H



Why going beyond inclusive Higgs processes?

So far the LHC has mostly produced Higgses on-shell
in processes with a characteristic scale $\mu \approx m_H$

⇩ ⇩

access to Higgs couplings @ m_H

Producing a Higgs with boosted additional particle(s)
probe the Higgs couplings @ large energy
(important to check that the Higgs boson ensures perturbative unitarity)

Examples of interesting channels to explore further:

1. off-shell $gg \to h^* \to ZZ \to 4l$
2. boosted Higgs: Higgs+ high-p_T jet
3. double Higgs production

Boosted Higgs

inability to resolve the top loops

- the bearable lightness of the Higgs: rich spectroscopy w/ multiple decays channels
- the unbearable lightness: loops saturate and don't reveal the physics @ energy physics (*)

$m_H(\mathrm{GeV})$	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. Grazzini, Sargsyan '13

the inclusive rate
doesn't "see" the finite mass of the top

(*) unless it doesn't decouple
(e.g. 4th generation)

⇛ cannot disentangle
- long distance physics (modified top coupling)
- short distance physics (new particles running in the loop) ⇚

$$\mathcal{L} = \frac{\alpha_s c_g}{12\pi}|H|^2 G^{a\,2}_{\mu\nu} + \frac{\alpha c_\gamma}{2\pi}|H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2$$

$$\frac{\sigma(gg\to h)}{\mathrm{SM}} = (1+(c_g-c_t)v^2)^2 \qquad \frac{\Gamma(h\to\gamma\gamma)}{\mathrm{SM}} = (1+(c_\gamma-4c_t/9)v^2)^2$$

fermionic top-partners in composite Higgs models exactly lead to $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$

having access to $ht\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel

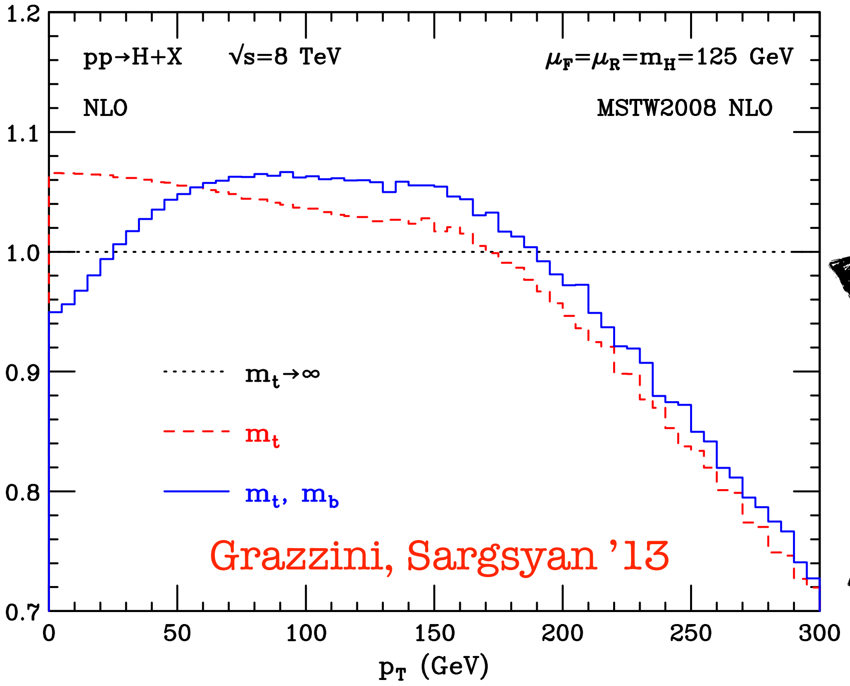
14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-$\mathrm{ILC}^{1000}_{1000}$

Resolving top loop: Boosted Higgs

cut open the top loops

high $p_T \approx$ Higgs off-shell
we “see” the details of the particles running inside the loops

Baur, Glover ’90
Langenegger, Spira, Starodumov, Trueb ’06

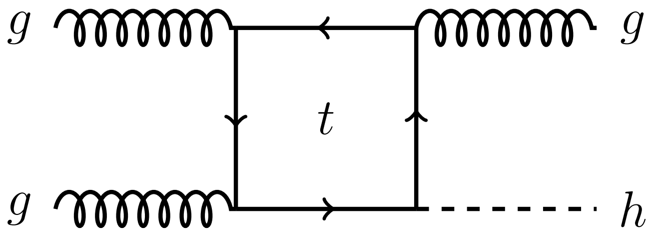


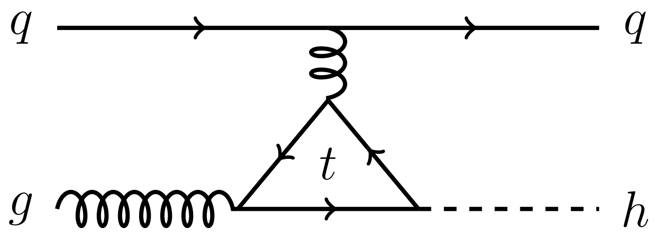
Grazzini, Sargsyan ’13

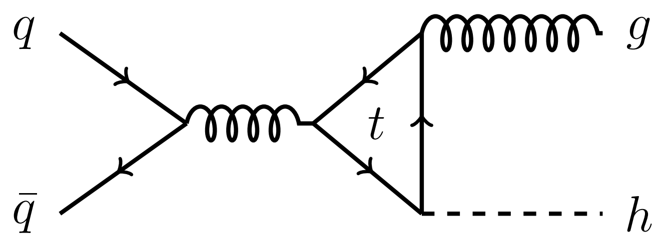
Note: LO only
NLO_{mt} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al ’12

the high p_T tail
is tens’ % sensitive
to the mass of top







the fraction gg/gq changes with p_T
@14TeV, gg/gq=67/31 for p_T >100GeV
gg/gp=42/57 for p_T >800GeV

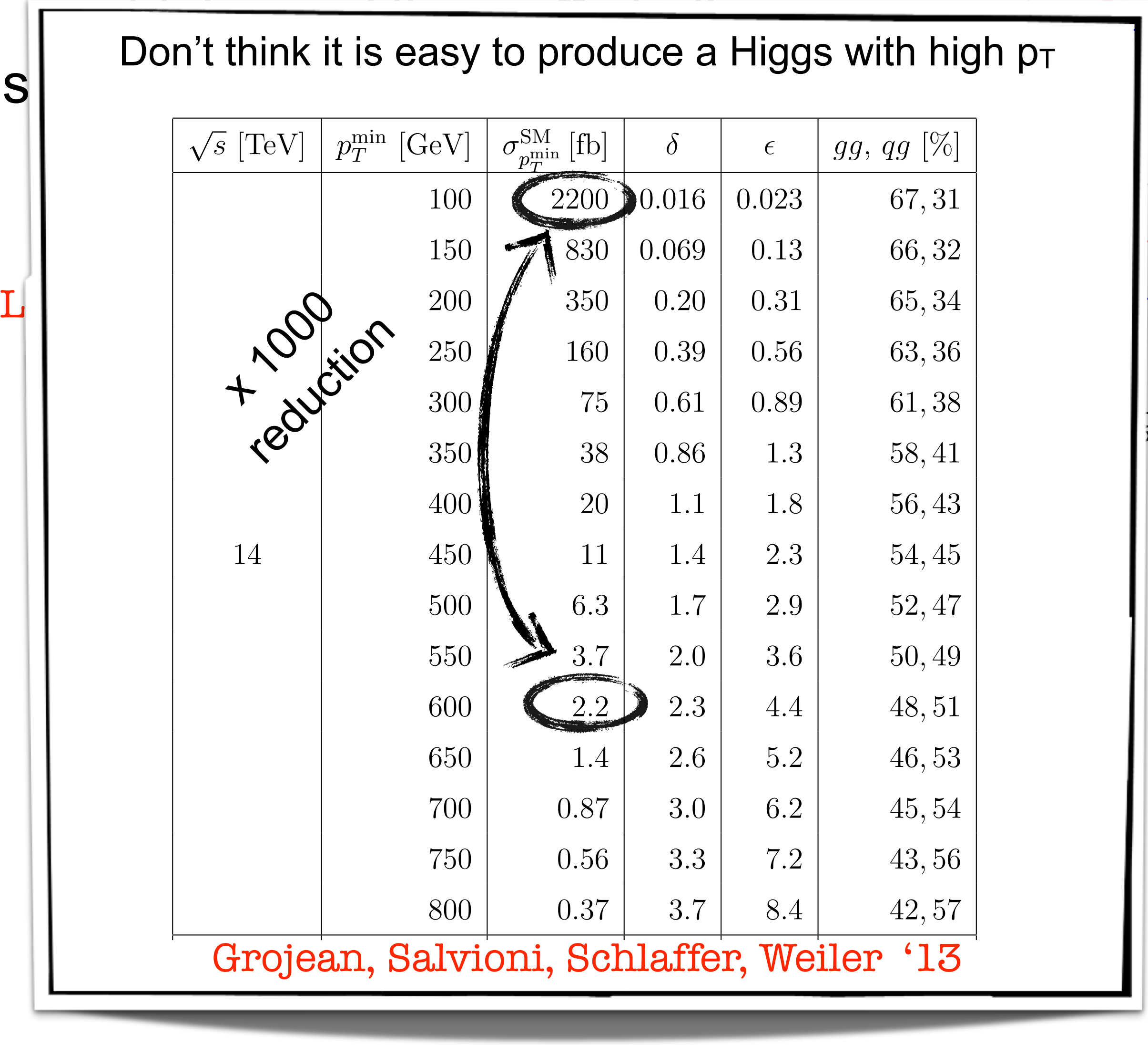
always subdominant (<2%)

Resolving top loop: Boosted Higgs

cut open the top loops

we “s

L

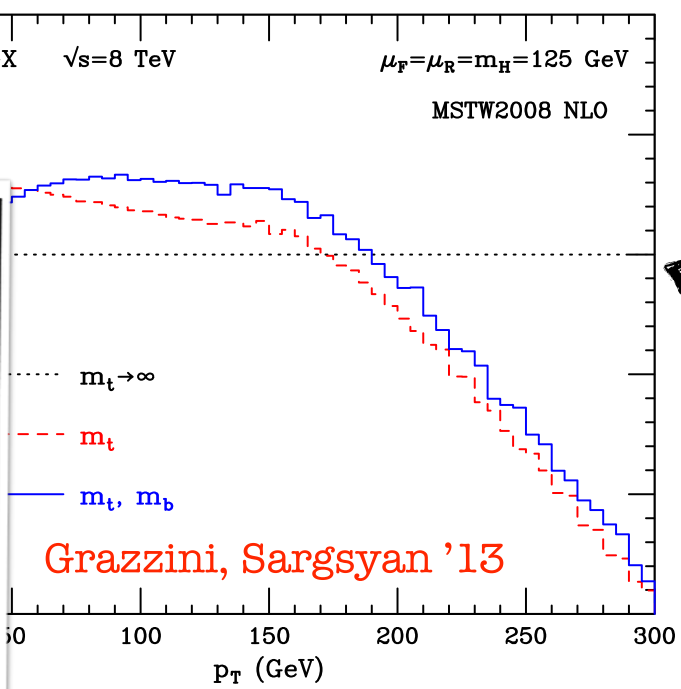


Don’t think it is easy to produce a Higgs with high p_T

$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma^{\rm SM}_{p_T^{\min}}$ [fb]	δ	ϵ	$gg,\ qg$ [%]
14	100	2200	0.016	0.023	67, 31
	150	830	0.069	0.13	66, 32
	200	350	0.20	0.31	65, 34
	250	160	0.39	0.56	63, 36
	300	75	0.61	0.89	61, 38
	350	38	0.86	1.3	58, 41
	400	20	1.1	1.8	56, 43
	450	11	1.4	2.3	54, 45
	500	6.3	1.7	2.9	52, 47
	550	3.7	2.0	3.6	50, 49
	600	2.2	2.3	4.4	48, 51
	650	1.4	2.6	5.2	46, 53
	700	0.87	3.0	6.2	45, 54
	750	0.56	3.3	7.2	43, 56
	800	0.37	3.7	8.4	42, 57

x 1000 reduction

Grojean, Salvioni, Schlaffer, Weiler ‘13



Grazzini, Sargsyan ’13

Note: LO only
NLO$_{mt}$ is not known
1/m_t corrections known O(α_s^4)
few % up to p_T~150 GeV

Harlander et al ’12

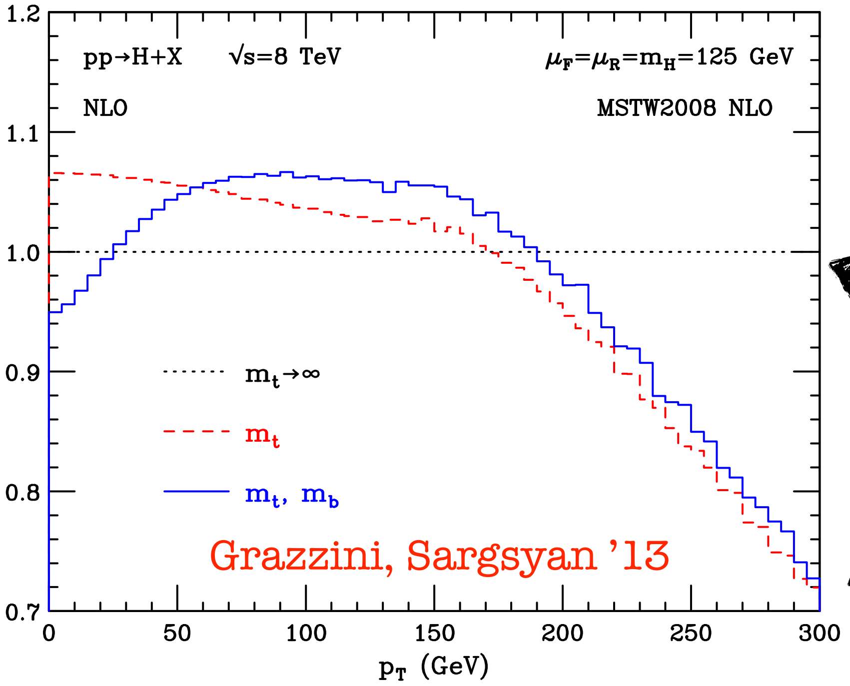
the high p_T tail
is tens’ % sensitive
to the mass of top

Resolving top loop: Boosted Higgs

cut open the top loops

high $p_T \approx$ Higgs off-shell
we “see” the details of the particles running
inside the loops

Baur, Glover ’90
Langenegger, Spira, Starodumov, Trueb ’06



Grazzini, Sargsyan ’13

Note: LO only
NLO$_{mt}$ is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al ’12

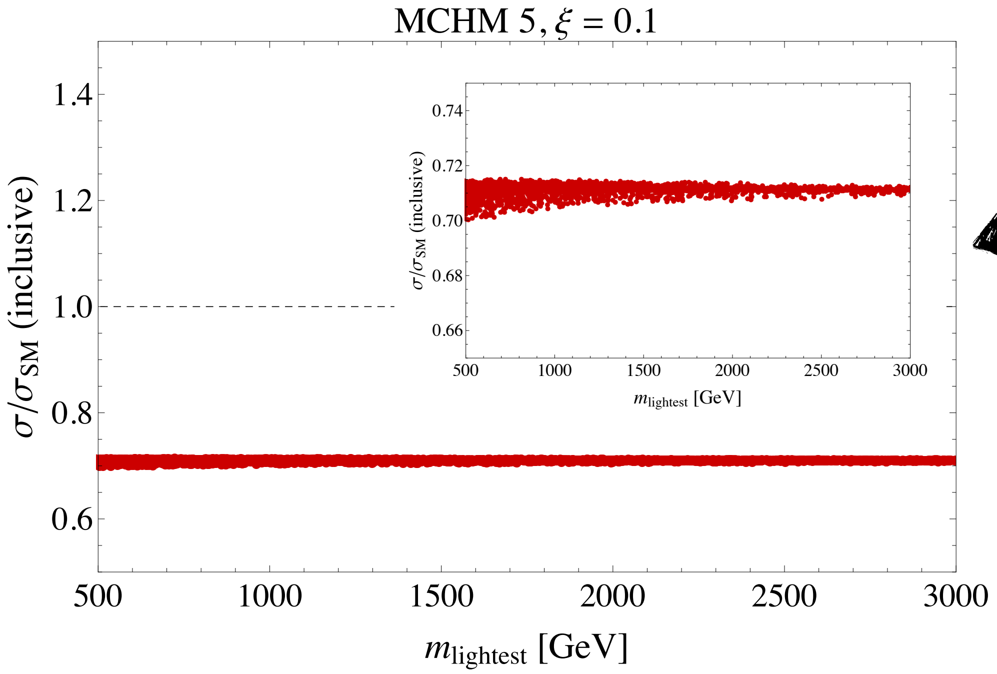
the high p_T tail
is tens’ % sensitive
to the mass of top

Composite Higgs Model

top partners contributions

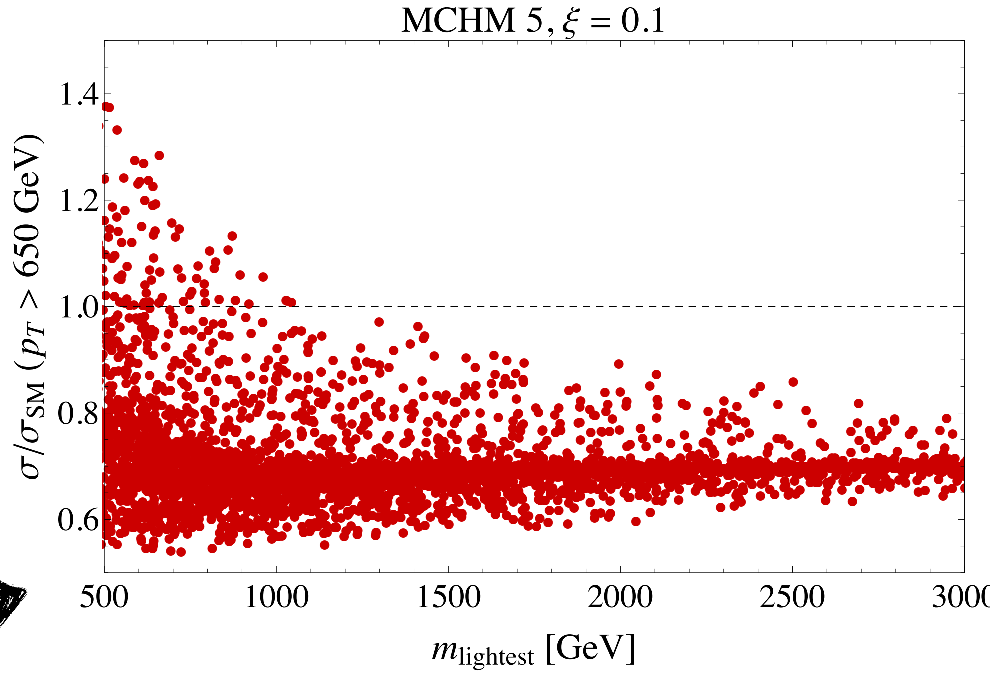
see also Banfi, Martin, Sanz ’13
see also Azatov, Paul ’13

Grojean, Salvioni, Schlaffer, Weiler ‘13



inclusive rate: O(%)

with high-p_T cut: O(x10’%)



high-p_T tail “sees” the top partners that are missed by the inclusive rate

Boosted Higgs

high p_T tail discriminates short and long distance physics contribution to gg → h

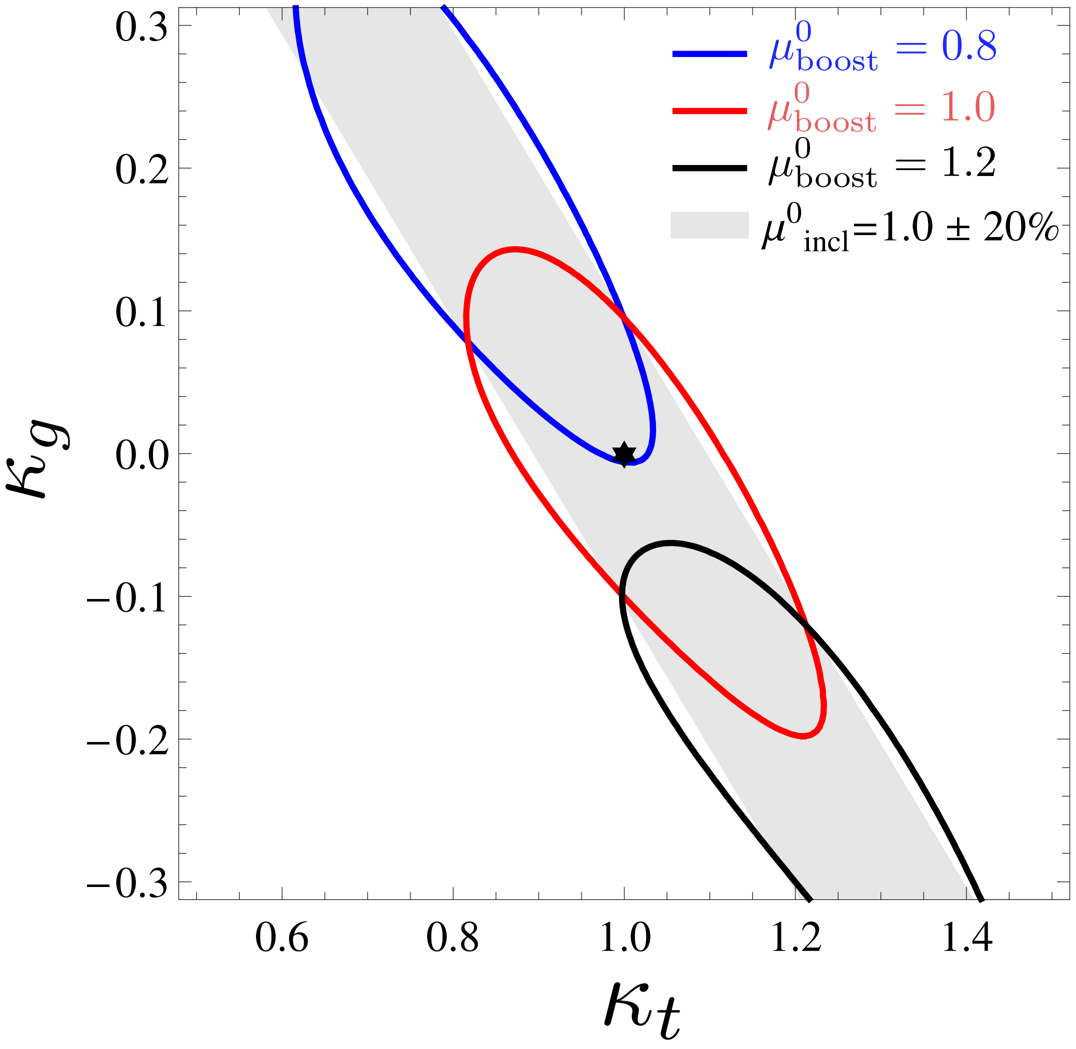
$$\sqrt{s} = 14\ \mathrm{TeV},\ \int dt\,\mathcal{L} = 3\mathrm{ab}^{-1}, p_T > 650\ \mathrm{GeV}$$

(partonic analysis in the boosted “ditau-jets” channel)

see Schlaffer et al ’14 for a more complete analysis including WW channel

see also Azatov, Paul ’13

Grojean, Salvioni, Schlaffer, Weiler ‘13



10-20% precision on κ_t

⇓ ⇓

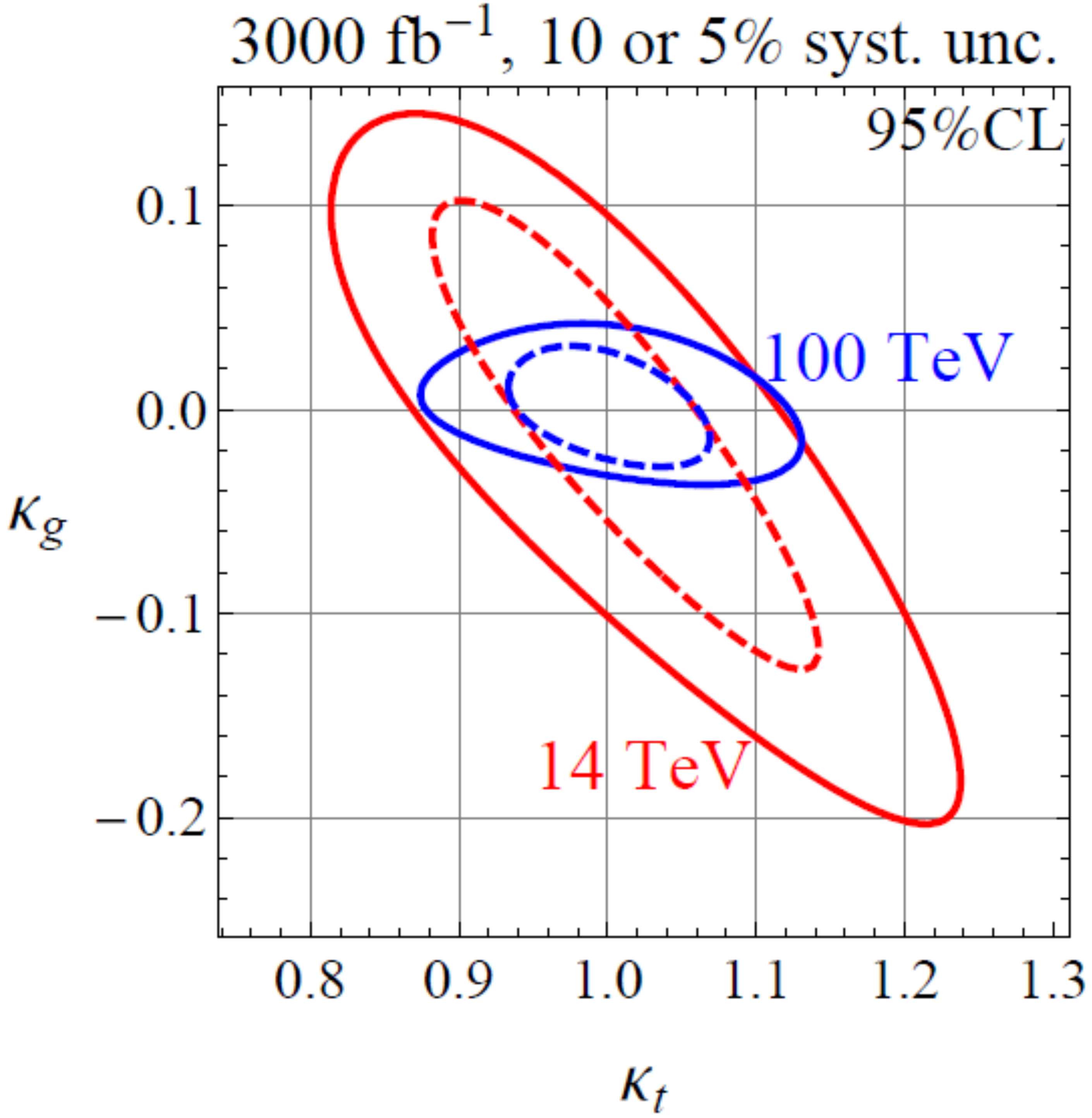
competitive/complementary to htt channel
for the measure the top-Higgs coupling

Are the $\mathrm{NLO_m}$ QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: $\mathrm{N^3LO_\infty}$ for inclusive xs or $\mathrm{NLO_{mt}}$ for pT spectrum?

Boosted Higgs

high p_T tail discriminates short and long distance physics contribution to gg ➙ h

$$\sqrt{s} = 14\ \mathrm{TeV}, \int dt\,\mathcal{L} = 3\mathrm{ab}^{-1}, p_T > 650\ \mathrm{GeV}$$



A perfect case for
a very energetic machine

tth increases by 10 from 14 to 100TeV

h+j$_{pT>600GeV}$ increases by 210

$$\mathcal{R}_{14} = \frac{\sigma(p_T > 650\,\mathrm{GeV})}{\sigma(p_T > 150\,\mathrm{GeV})}$$

$$\mathcal{R}_{100} = \frac{\sigma(p_T > 2000\,\mathrm{GeV})}{\sigma(p_T > 500\,\mathrm{GeV})}$$

Azatov, Grojean, Paul, Salvioni '16

see also Azatov, Paul '13

Grojean, Salvioni, Schlaffer, Weiler '13

Low p_T: bounding light quark Yukawa's

Bishara et al '16
[1606.09253]

Soreq et al '16
[1606.09621]

Bonner, Logan '16
[1608.04376]

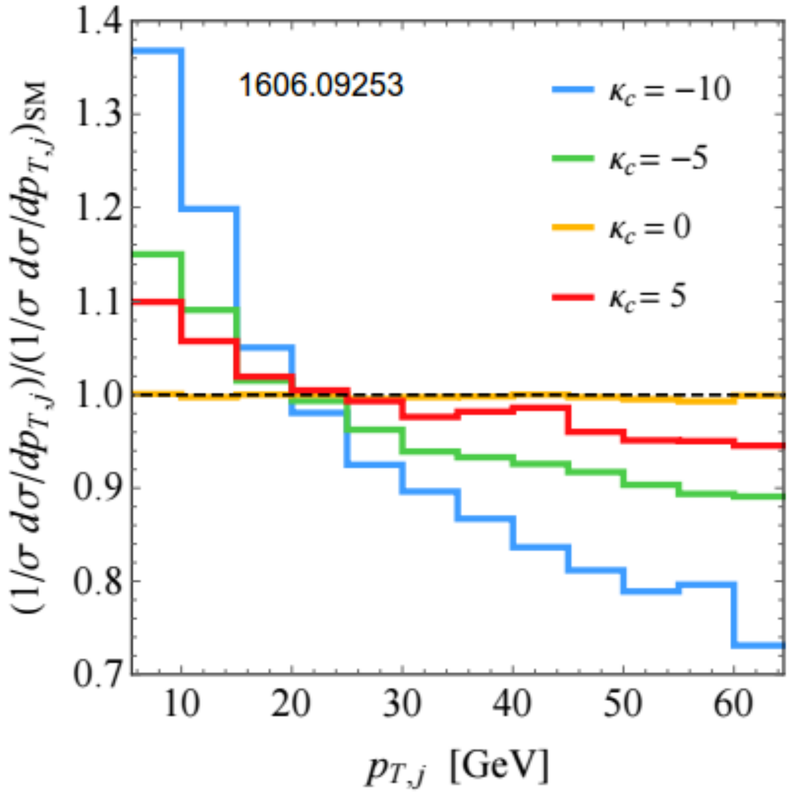
(courtesy of A. Azatov@HiggsHunting2016)

- Modifications of the light quark Yukawa couplings modify the differential distributions.
- Sudakov's dilogarithms *1606.09253* enhance the production cross-section

$$\sim k_Q \frac{m_Q^2}{m_h^2} \ln^2 \frac{p_\perp^2}{m_Q^2}$$

modifications are especially important in the region $m_Q \ll p_\perp \ll m_h$.

- The main contribution appears from the interference with the top quark loop, which scales as y_Q not y_Q^2.



Low p_T: bounding light quark Yukawa's

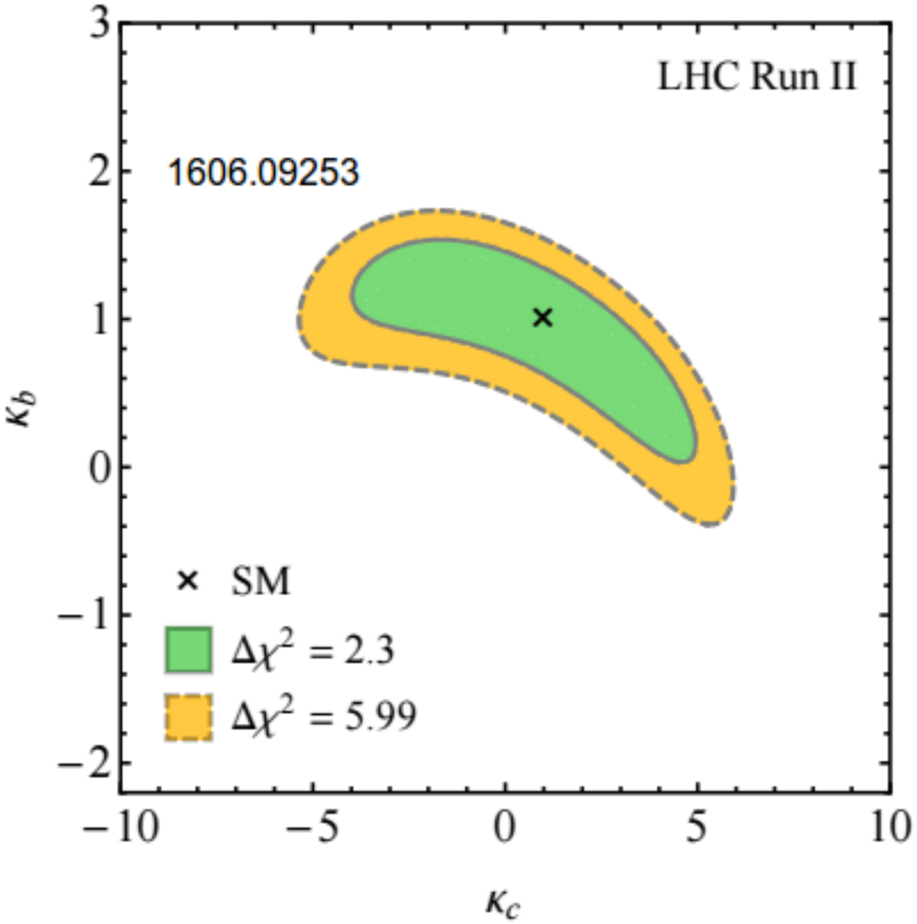
Bishara et al '16
[1606.09253]

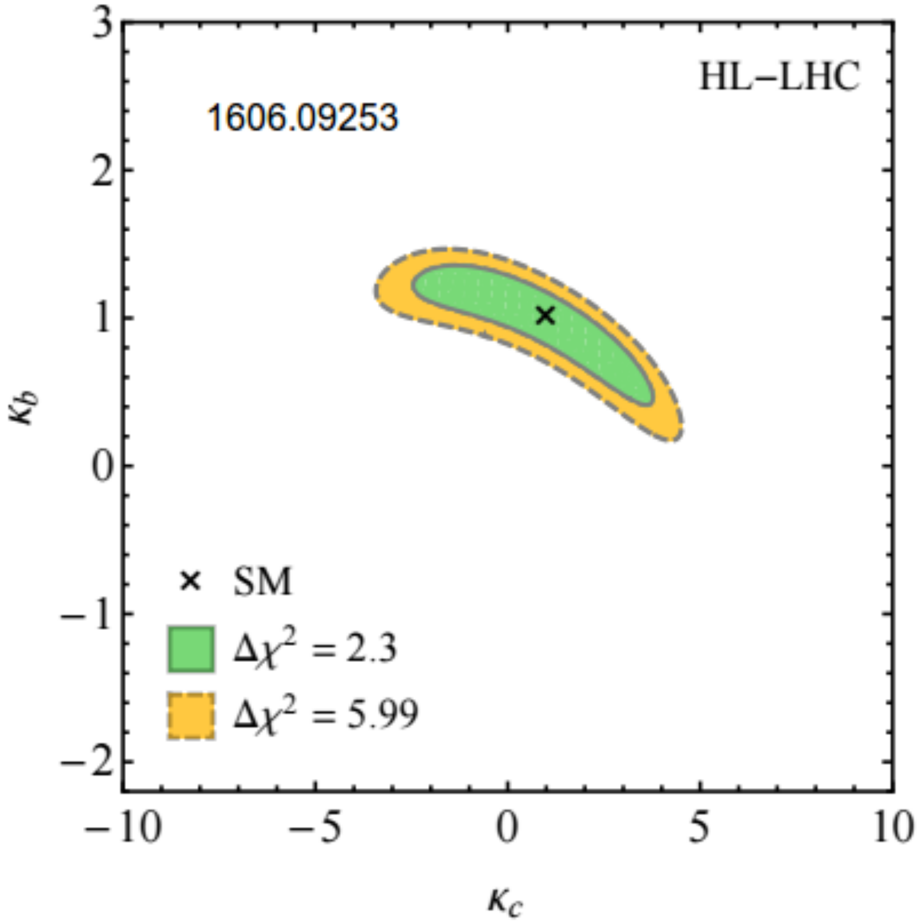
Soreq et al '16
[1606.09621]

Bonner, Logan '16
[1608.04376]

- from $h \to \gamma\gamma, ZZ, WW$ using $p_T \in [0, 70]$ GeV

(courtesy of A. Azatovl@HiggsHunting2016)





Off-shell Higgs

Off-shell Higgs effects naively small
since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a 125 GeV Higgs
but enhancement due to the particular couplings of H to V_L

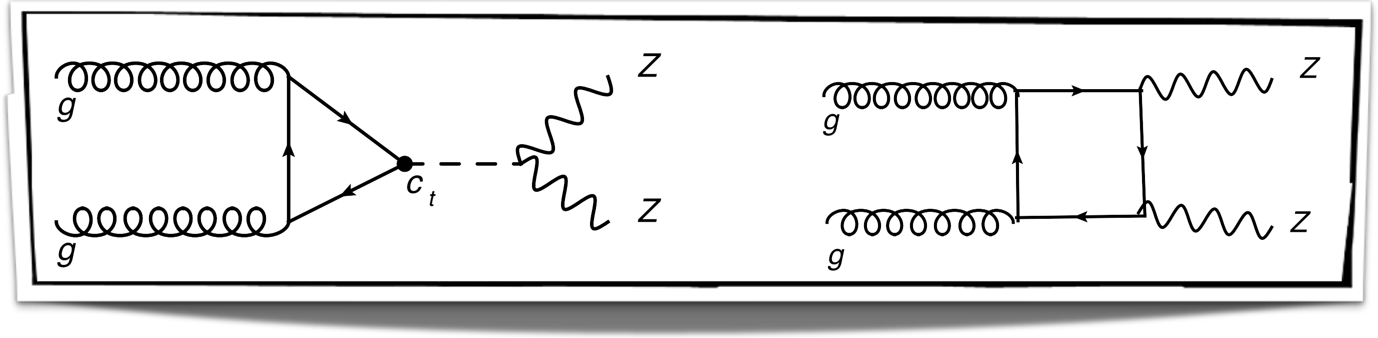
Analysis of gg→H*→ZZ→4l

CMS 2202.06923
ATLAS 2304.01532

(about 15% of the Higgs events are far off-shell with m_{4l}>300GeV)

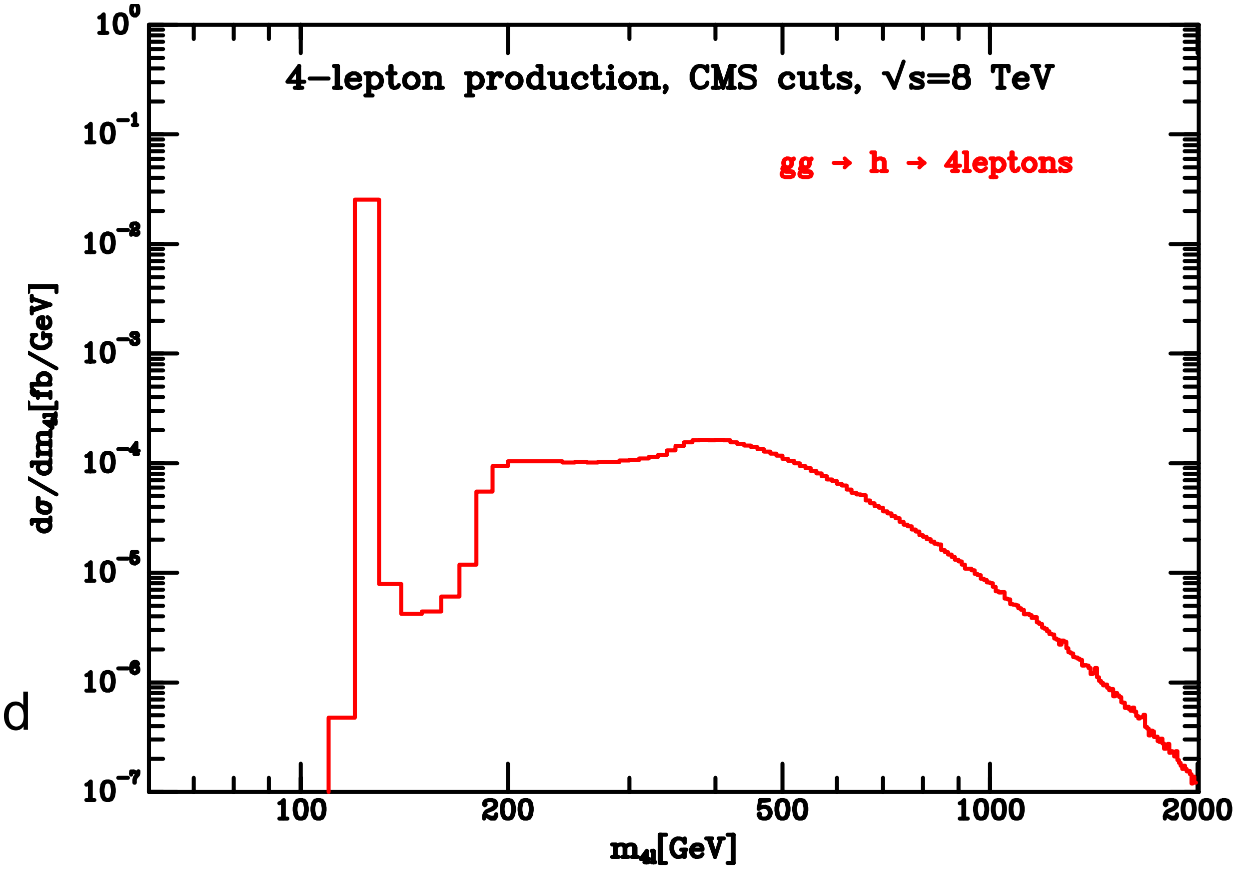
$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g_{ggH}g_{HZZ}\frac{F(m_{ZZ})}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H}$$

Glover, van der Bij '89



$$\mathcal{M}^{++00}_{\text{Higgs}} \sim \log^2\frac{\hat{s}}{m_t^2} \qquad \mathcal{M}^{++00}_{\text{box}} \sim -\log^2\frac{\hat{s}}{m_t^2}$$

SM: cancelation forced by unitarity
BSM: deviations of Higgs couplings at large $\hat{s}$ will be amplified



Off-shell Higgs

Off-shell Higgs effects naively small
since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a 125 GeV Higgs
but enhancement due to the particular couplings of H to V_L

Analysis of gg→H*→ZZ→4l

CMS 2202.06923
ATLAS 2304.01532

(about 15% of the Higgs events are far off-shell with m_{4l}>300GeV)

Access to the Higgs width @ LHC?

often said, it is impossible to measure the Higgs width at the LHC. Not quite true.
it can be done either via off-shell measurements or via the mass shift in gg→h→γγ

Narrow Width Approx.: on-shell

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}$$

ratios of κ only
no direct access to the width itself
(upper bound if $\kappa_V < 1$ is assumed)

e.g. Dobrescu, Lykken ’12

off-shell

different width dependence
Γ_H can be fitted w/o assumption

$$\sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}$$

Kauer, Passarino ’12
Caola, Melnikov ’13
Campbell et al ’13

Off-shell Higgs

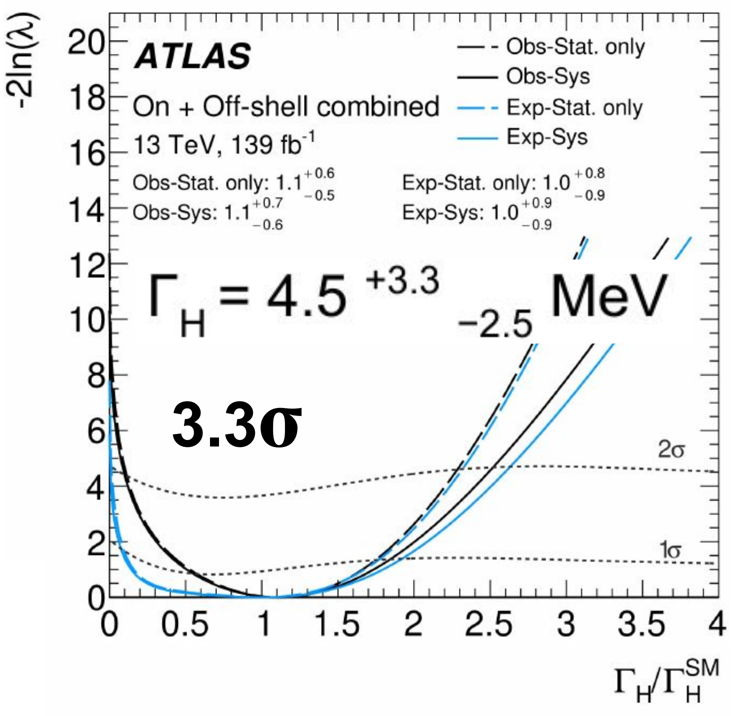
Off-shell Higgs effects naively small
since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a 125 GeV Higgs
but enhancement due to the particular couplings of H to V_L

Analysis of gg→H*→ZZ→4l

CMS 2202.06923
ATLAS 2304.01532

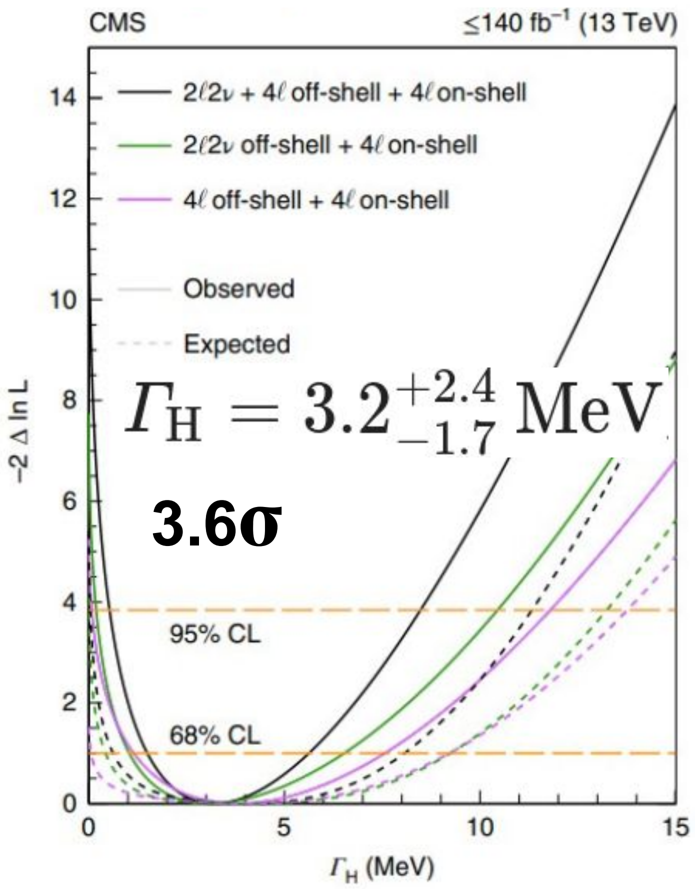
(about 15% of the Higgs events are far off-shell with m_{4l}>300GeV)

Access to the Higgs width @ LHC?



$\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

3.3σ



$\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

3.6σ

Off-shell Higgs

Off-shell Higgs effects naively small
since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a 125 GeV Higgs
but enhancement due to the particular couplings of H to V_L

Analysis of gg→H*→ZZ→4l

CMS 2202.06923
ATLAS 2304.01532

(about 15% of the Higgs events are far off-shell with m_{4l}>300GeV)

Access to the Higgs width @ LHC?

often said, it is impossible to measure the Higgs width at the LHC. Not quite true.
it can be done either via off-shell measurements or via the mass shift in gg→h→γγ

Narrow Width Approx.: on-shell

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH}g^2_{HZZ}}{\Gamma_H}$$

ratios of κ only
no direct access to the width itself
(upper bound if $\kappa_V < 1$ is assumed)

e.g. Dobrescu, Lykken '12

off-shell

different width dependence
Γ_H can be fitted w/o assumption

$$\sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH}g^2_{HZZ}$$

Kauer, Passarino '12
Caola, Melnikov '13
Campbell et al '13

What do we learn? BR_{inv} <85%?
Not competitive with global fits on $BR_{inv:}$ BR_{inv} < 20%
Model independent analysis might not be robust because of unitarity issues
($g_i(m_h)$ might be quite different than $g_i(m_{4l})$)

Englert, Spannowski '14

Off-shell Higgs

Off-shell Higgs effects naively small
since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a 125 GeV Higgs
but enhancement due to the particular couplings of H to V_L

Analysis of gg→H*→ZZ→4l

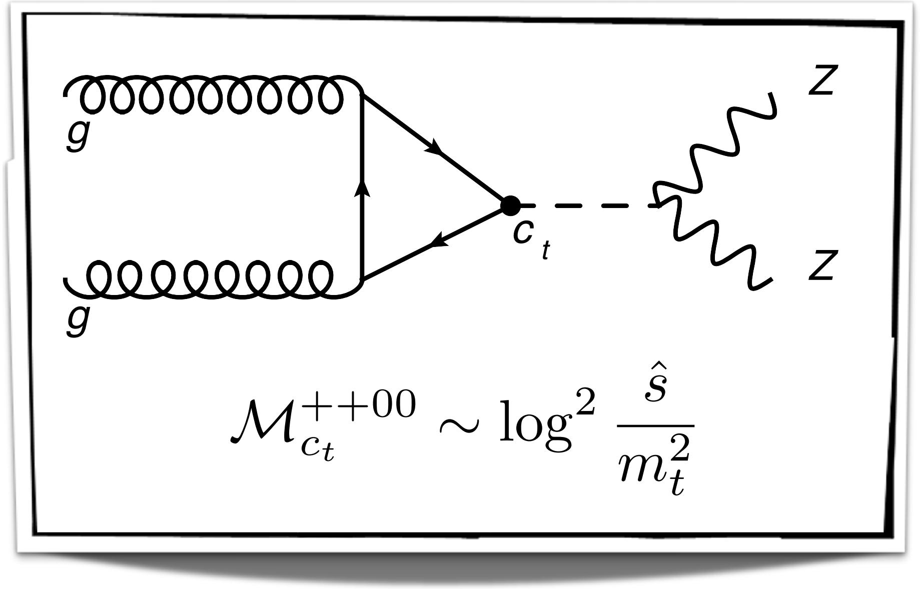
CMS 2202.06923
ATLAS 2304.01532

(about 15% of the Higgs events are far off-shell with m_{4l}>300GeV)

Access to top Yukawa coupling?

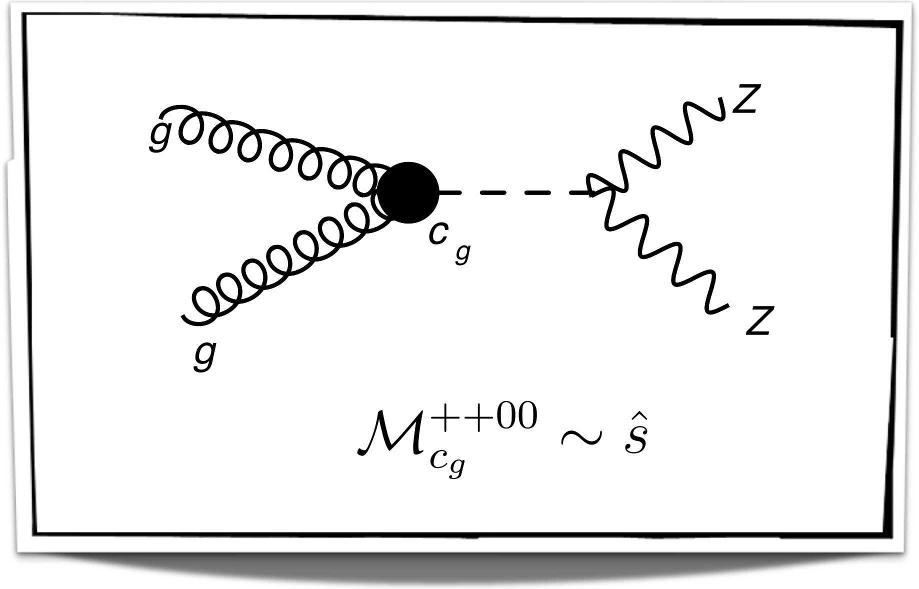
strong departure of the Higgs low energy theorem in the far off-shell region

can distinguish c_t from c_g



$$\mathcal{M}_{c_t}^{++00} \sim \log^2 \frac{\hat{s}}{m_t^2}$$

Cacciapaglia et al. ’14



$$\mathcal{M}_{c_g}^{++00} \sim \hat{s}$$

Azatov, Grojean, Paul, Salvioni ’14

Off-shell Higgs

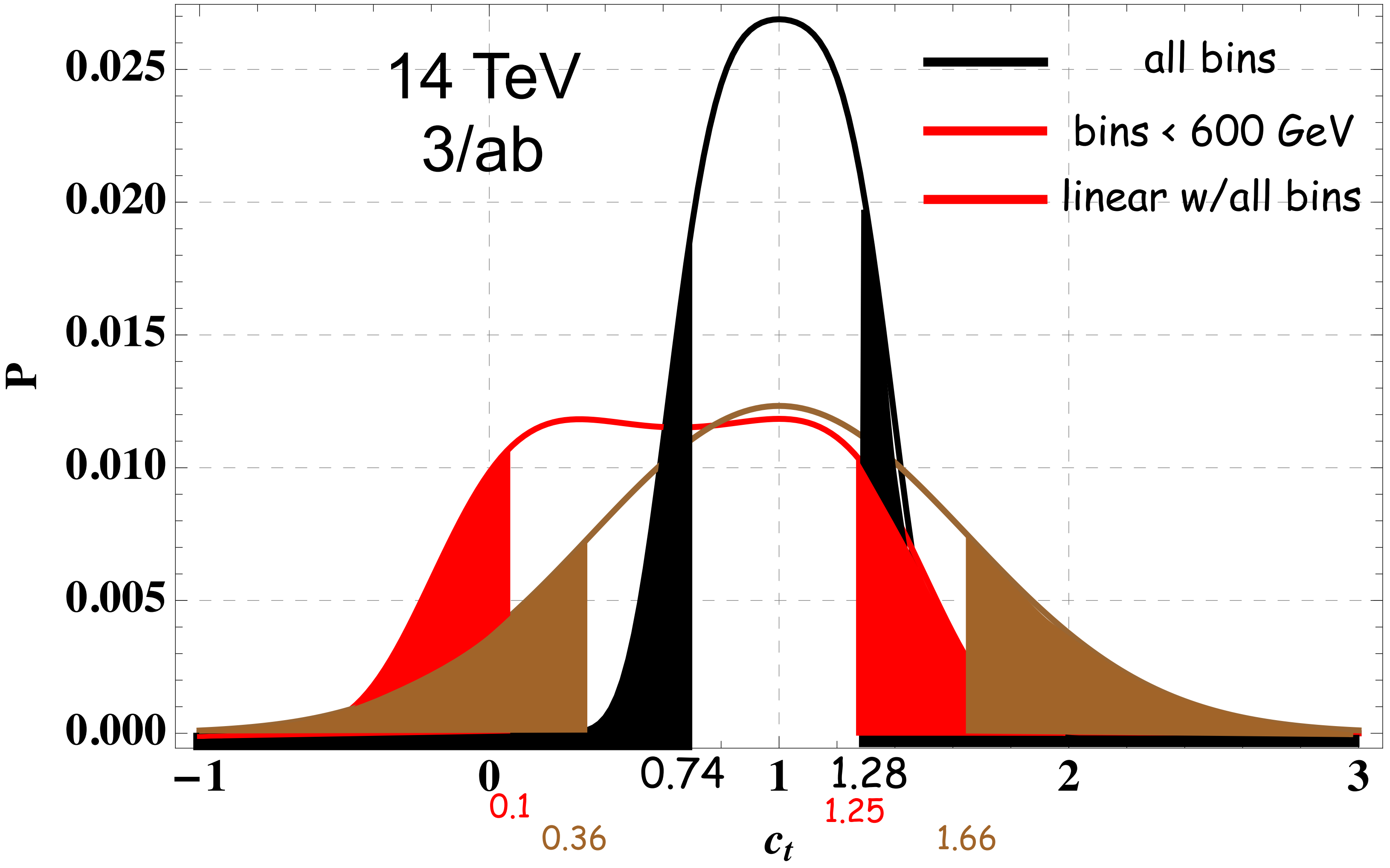
Off-shell Higgs effects naively small
since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a 125 GeV Higgs
but enhancement due to the particular couplings of H to V_L

Analysis of gg→H*→ZZ→4l

CMS 2202.06923
ATLAS 2304.01532

(about 15% of the Higgs events are far off-shell with m_{4l}>300GeV)

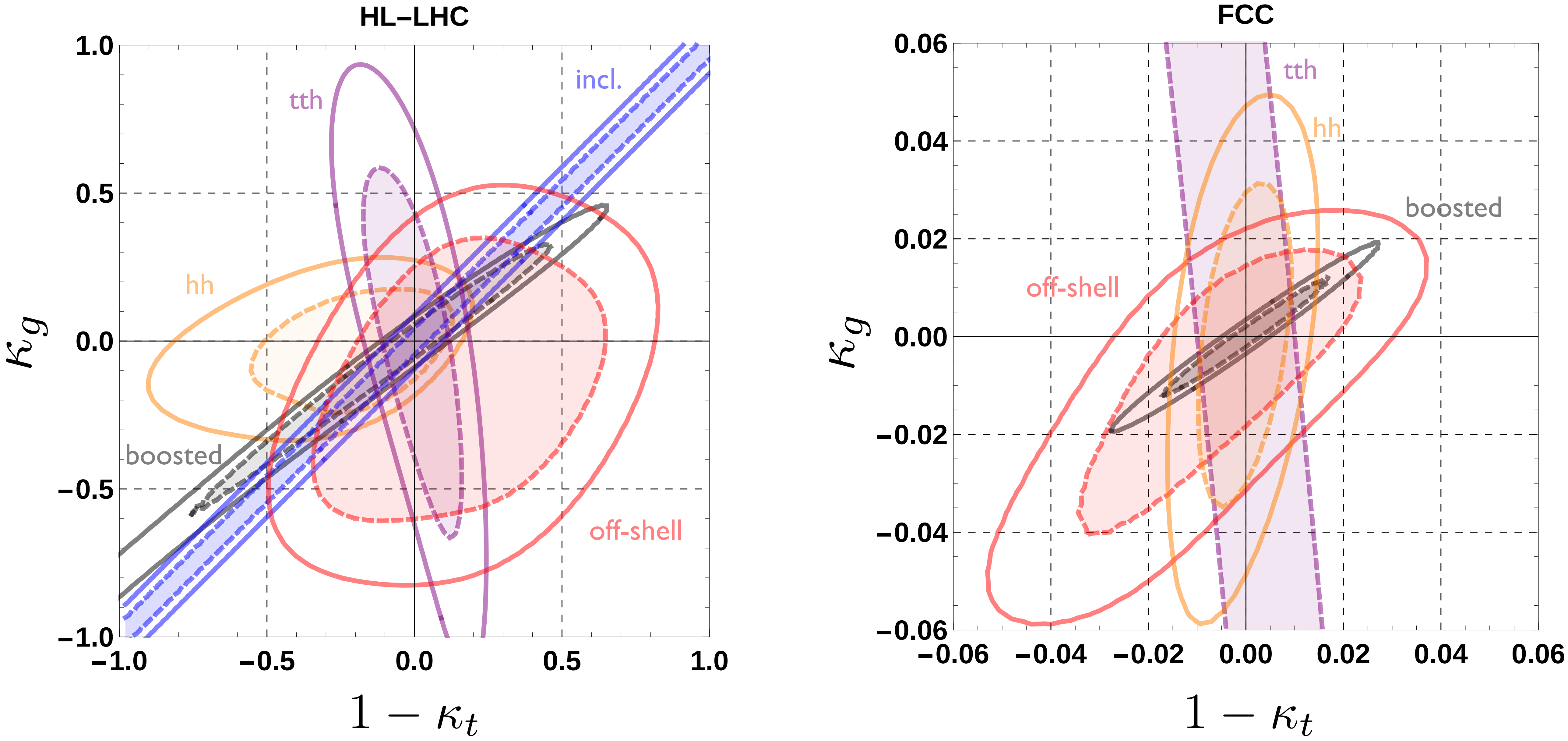
provides an alternative to ttH to measure the top Yukawa coupling



Azatov, Grojean, Paul, Salvioni '16

Prospectives: HL-LHC$_{14\text{TeV},300/\text{fb}}$ and FCC$_{100\text{TeV},20/\text{ab}}$

Azatov, Grojean, Paul, Salvioni '16



hh ~ align with tth
because hh SM amplitude is imaginary
while κ_g contribution is real
hence SM/BSM interference prop. to κ_t

See LHC H WG public note 2203.02418

How to measure the Higgs self-coupling

One missing beast: h^3

The Higgs self-couplings plays important roles

1) controls the stability of the EW vacuum

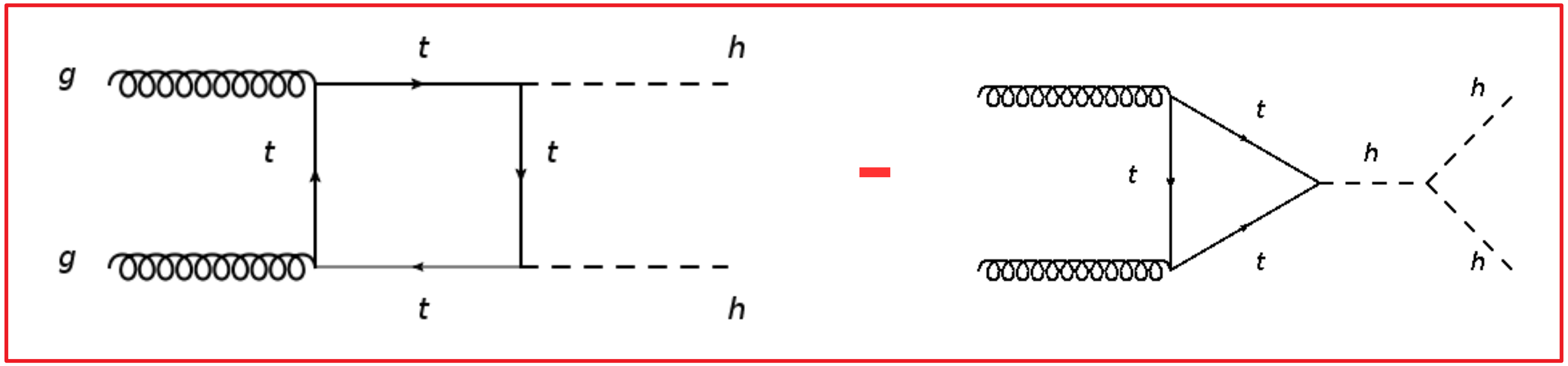
2) dictates the dynamics of EW phase transition and potentially conditions the generation of a matter-antimatter asymmetry via EW baryogenesis

Does it need to be measured with high accuracy?

difficult to design new physics scenarios that dominantly affect the Higgs self-couplings and leave the other Higgs coupling deviations undetectable

Higgs self-coupling prospects

$$\mathcal{L}_{\rm SM} \supset -m_h^2\sqrt{\frac{G_F}{2\sqrt{2}}}\; h^3$$



$$\frac{\sigma(pp\to hh)}{\sigma(pp\to h)} \sim 10^{-3}$$

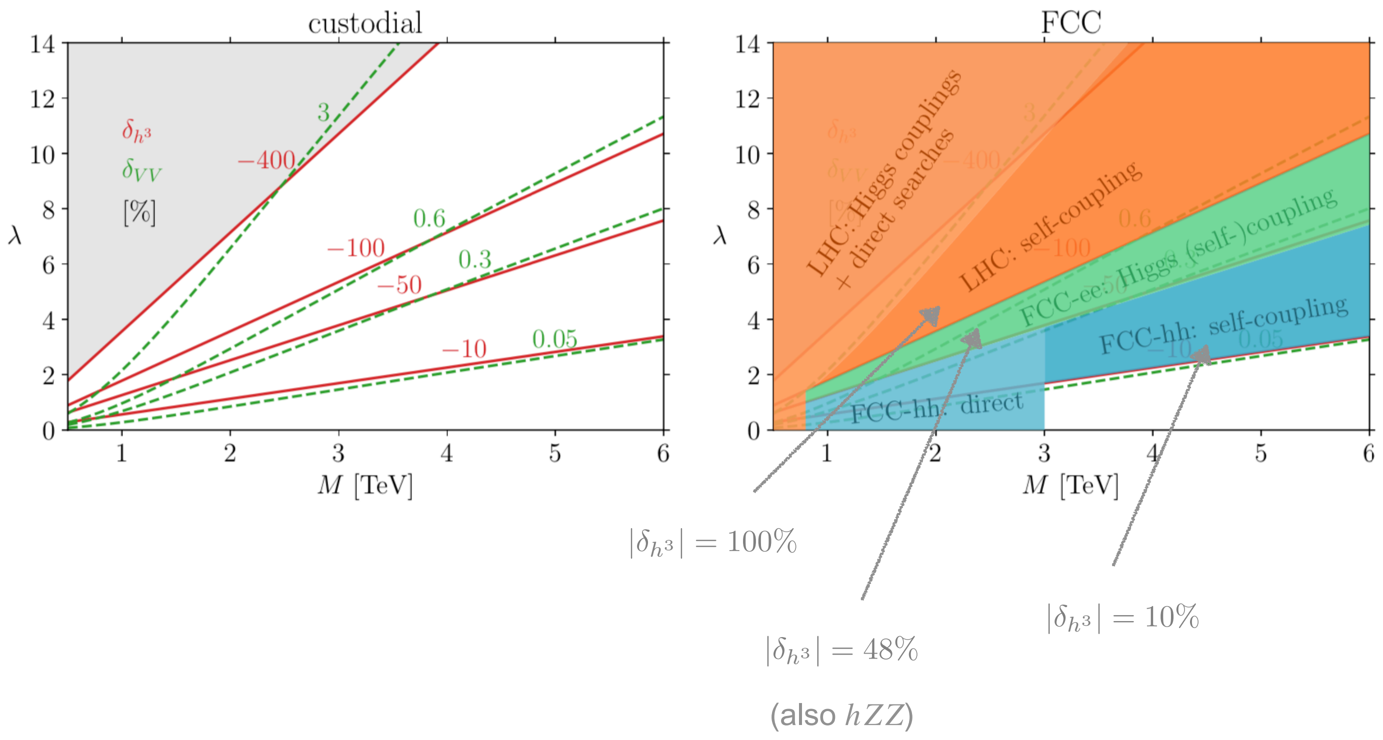
Large Higgs self-coupling Scenarios

Generically: $\left|\dfrac{\delta_{h^3}}{\delta_{\text{single }h}}\right| \sim O(1)$

Particular exceptions:

Higgs DM-portal models or custodial EW quadruplet, Gegenbauer goldstones
not for composite/susy

DiVita et al,: 1704.01953 Falkowski, Rattazzi: 1902.05936 Durieux, McCullough, Salvioni: 2209.00666

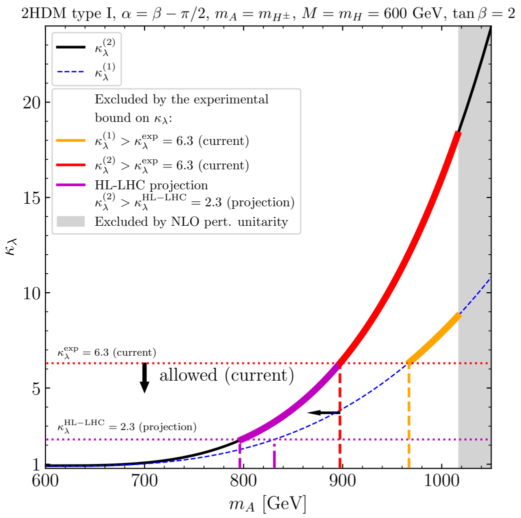


$|\delta_{h^3}| = 100\%$

$|\delta_{h^3}| = 48\%$

(also hZZ)

$|\delta_{h^3}| = 10\%$

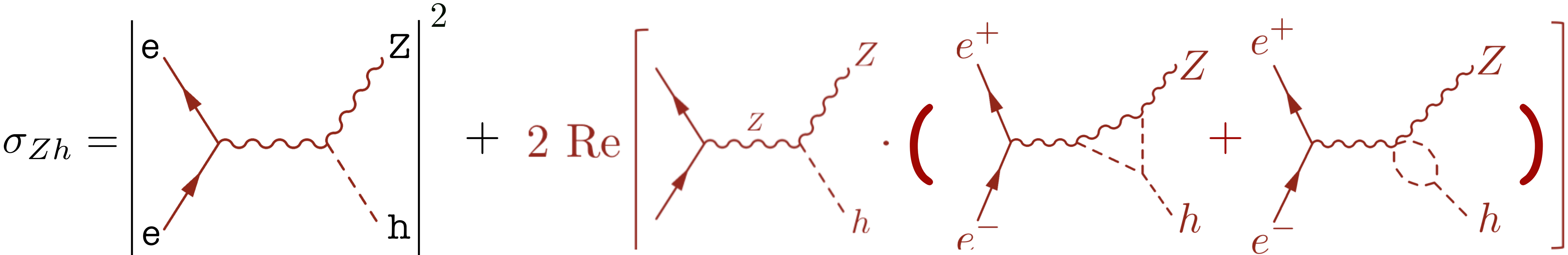


Other exceptions: non-decoupled/fine-tuned spectra

Bahl, Braathen, Weiglein: 2202.03453

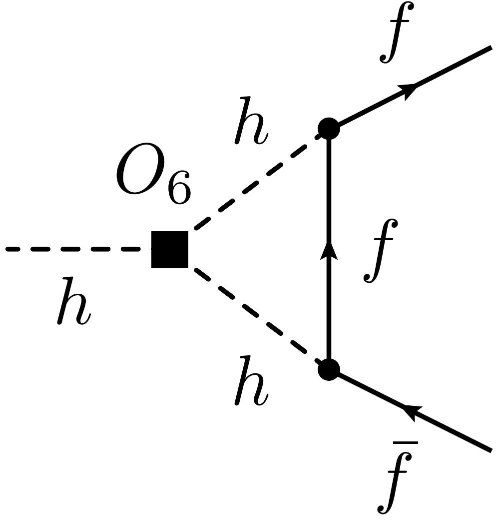
h^3 from h@NLO@LHC

M. McCullough '14

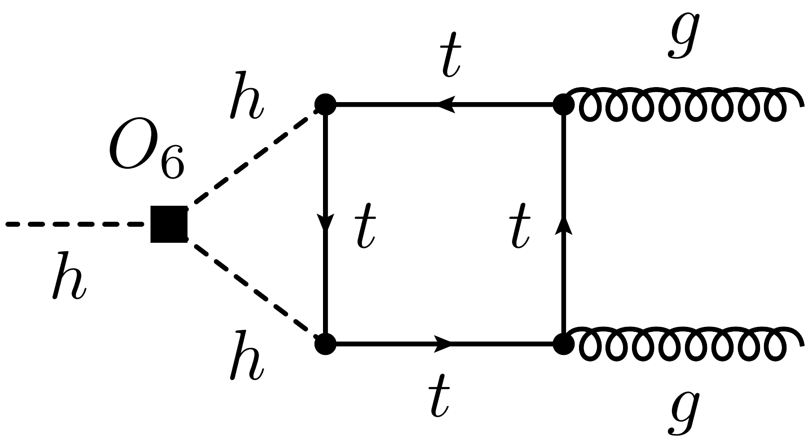


$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

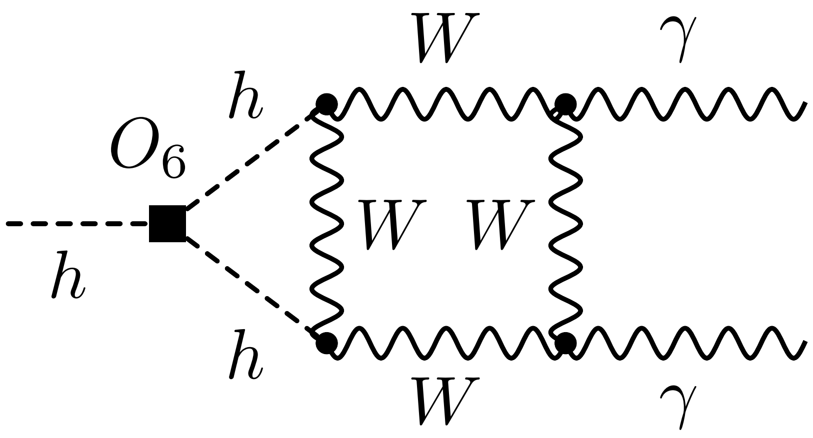
Gorbahn et al '16

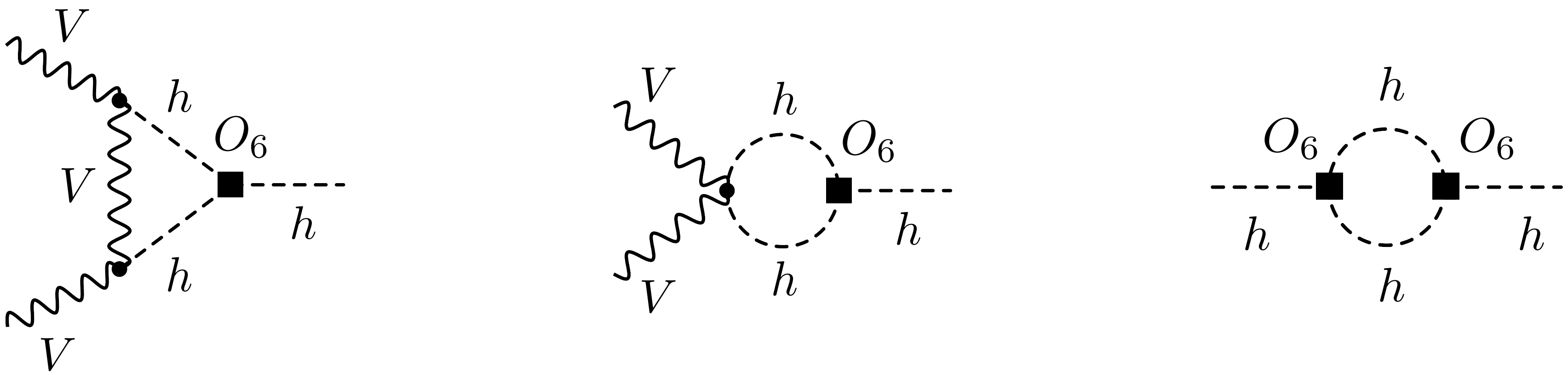


Degrassi et al '16



Bizon et al '16



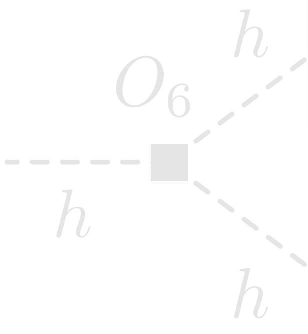


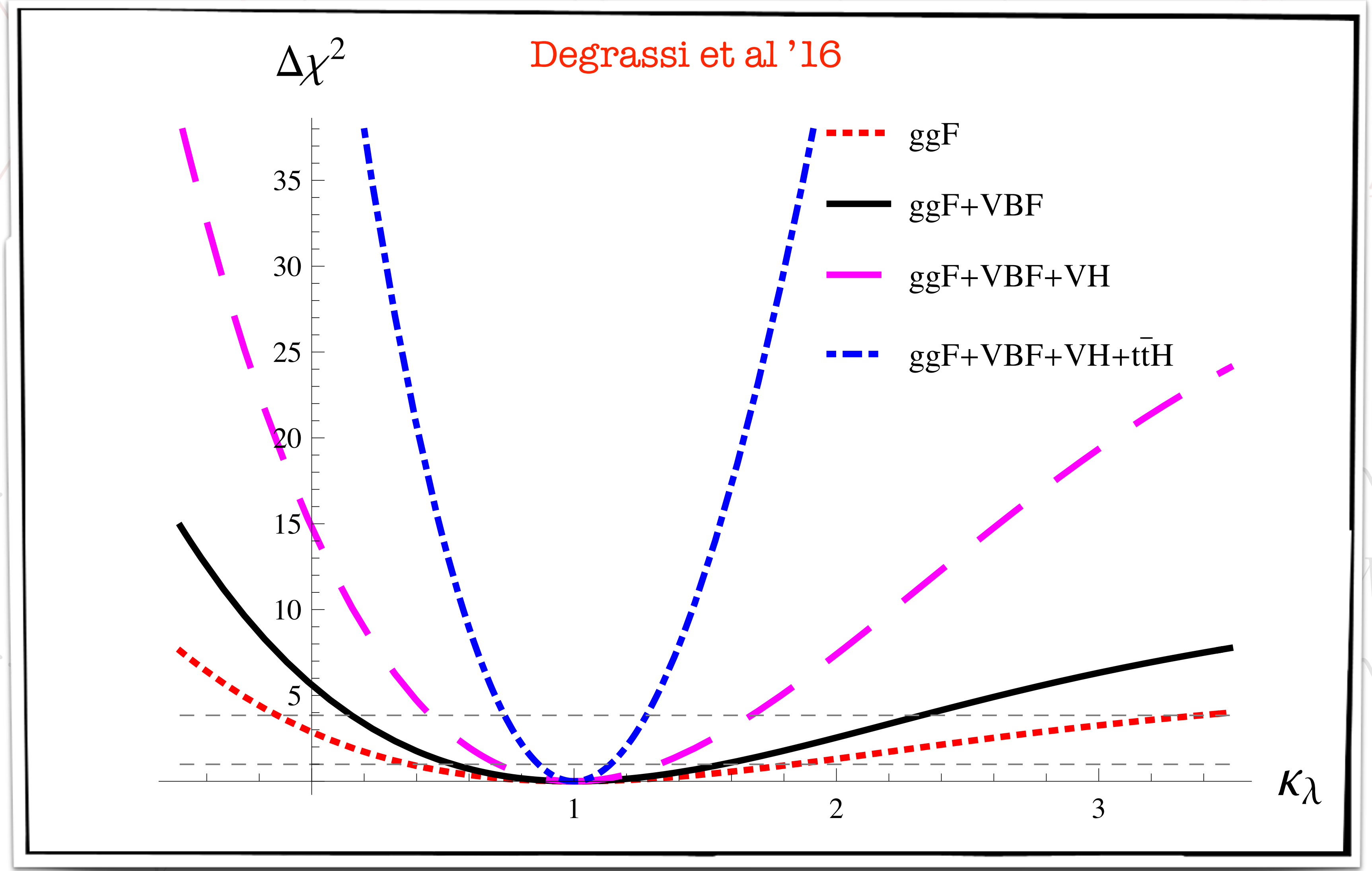
h^3 from h@NLO@LHC

M. McCullough '14

Gorbahn et al '16

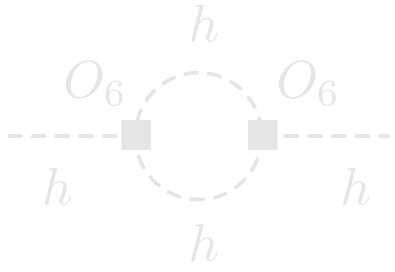
Bizon et al '16





Degrassi et al '16

$$\kappa_\lambda \in [-0.7, 4.2]$$



h^3 @NLO vs h @ LO in global fit

The fabulous 5^2 channels

5 main production modes: ggF, VBF, WH, ZH, ttH
5 main decay modes: ZZ, WW, γγ, ττ, bb

h^3 @NLO vs h @ LO in global fit

The fabulous 5^2 channels

5 main production modes: ggF, VBF, WH, ZH, ttH
5 main decay modes: ZZ, WW, γγ, ττ, bb

a priori **25** measurements
but for an on-shell particles, at most **10** physical quantities
since only products σxBR are measured
only **9** independent constraints

$$\mu_i^f = \mu_i \times \mu^f = \frac{\sigma_i}{(\sigma_i)_{\text{SM}}} \times \frac{\text{BR}[f]}{(\text{BR}[f])_{\text{SM}}}$$

$$\mu_i^f \simeq 1 + \delta\mu_i + \delta\mu^f$$

$$\mu_i \to \mu_i + \delta \qquad\qquad \mu^f \to \mu^f - \delta.$$

h^3 @NLO vs h @ LO in global fit

The fabulous 5^2 channels

5 main production modes: ggF, VBF, WH, ZH, ttH
5 main decay modes: ZZ, WW, γγ, ττ, bb

a priori **25** measurements
but for an on-shell particles, at most **10** physical quantities
since only products σxBR are measured
only **9** independent constraints

$$\mu_i^f = \mu_i \times \mu^f = \frac{\sigma_i}{(\sigma_i)_{\rm SM}} \times \frac{{\rm BR}[f]}{({\rm BR}[f])_{\rm SM}}$$

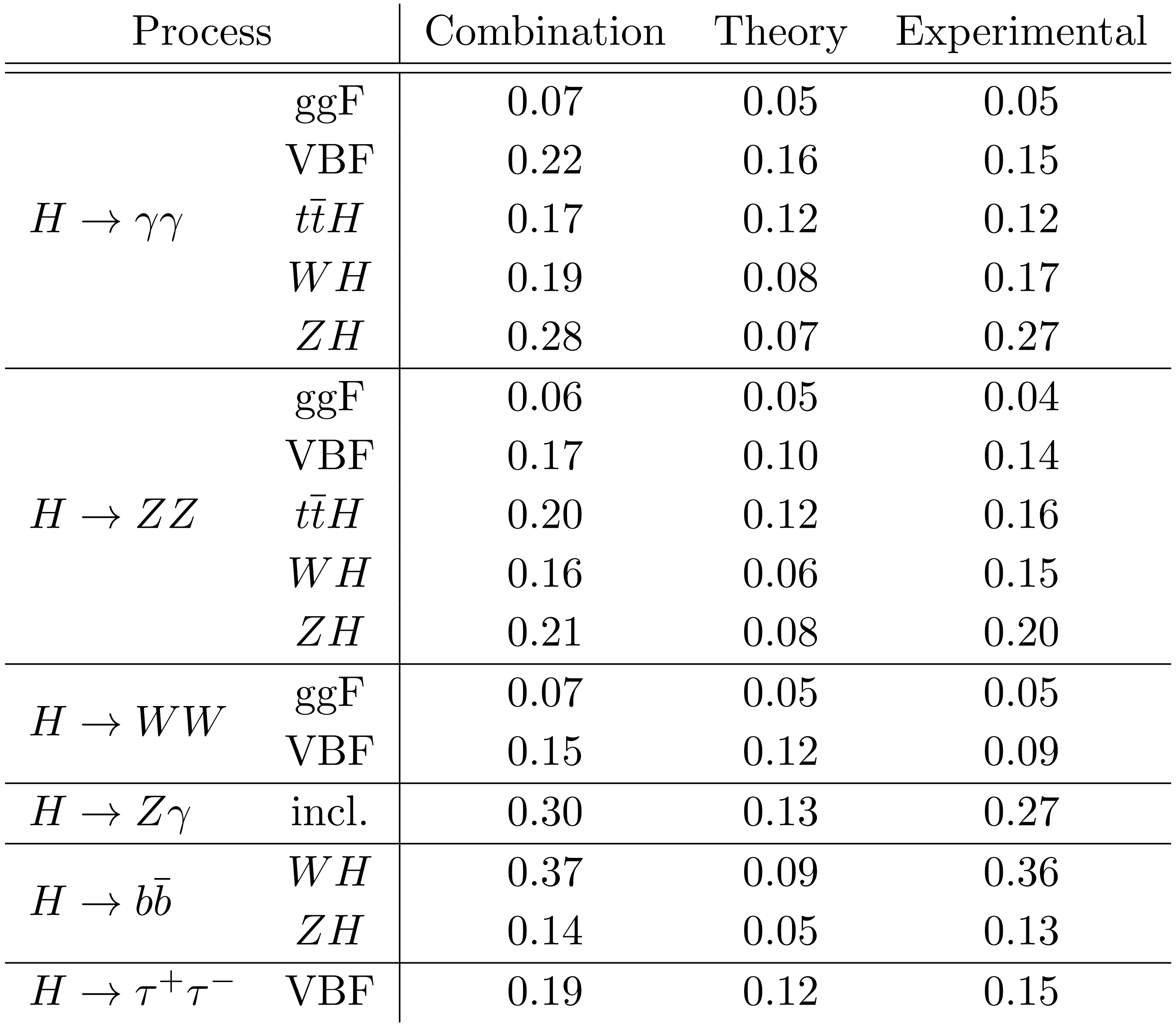
$$\mu_i^f \simeq 1 + \delta\mu_i + \delta\mu^f$$

$$\mu_i \to \mu_i + \delta \qquad\qquad \mu^f \to \mu^f - \delta.$$

cannot determine univocally 10 EFT parameters!
one flat direction is expected!

h^3 @NLO vs h @ LO in global fit

Good sensitivity on 16 channels 2 HL-LHC



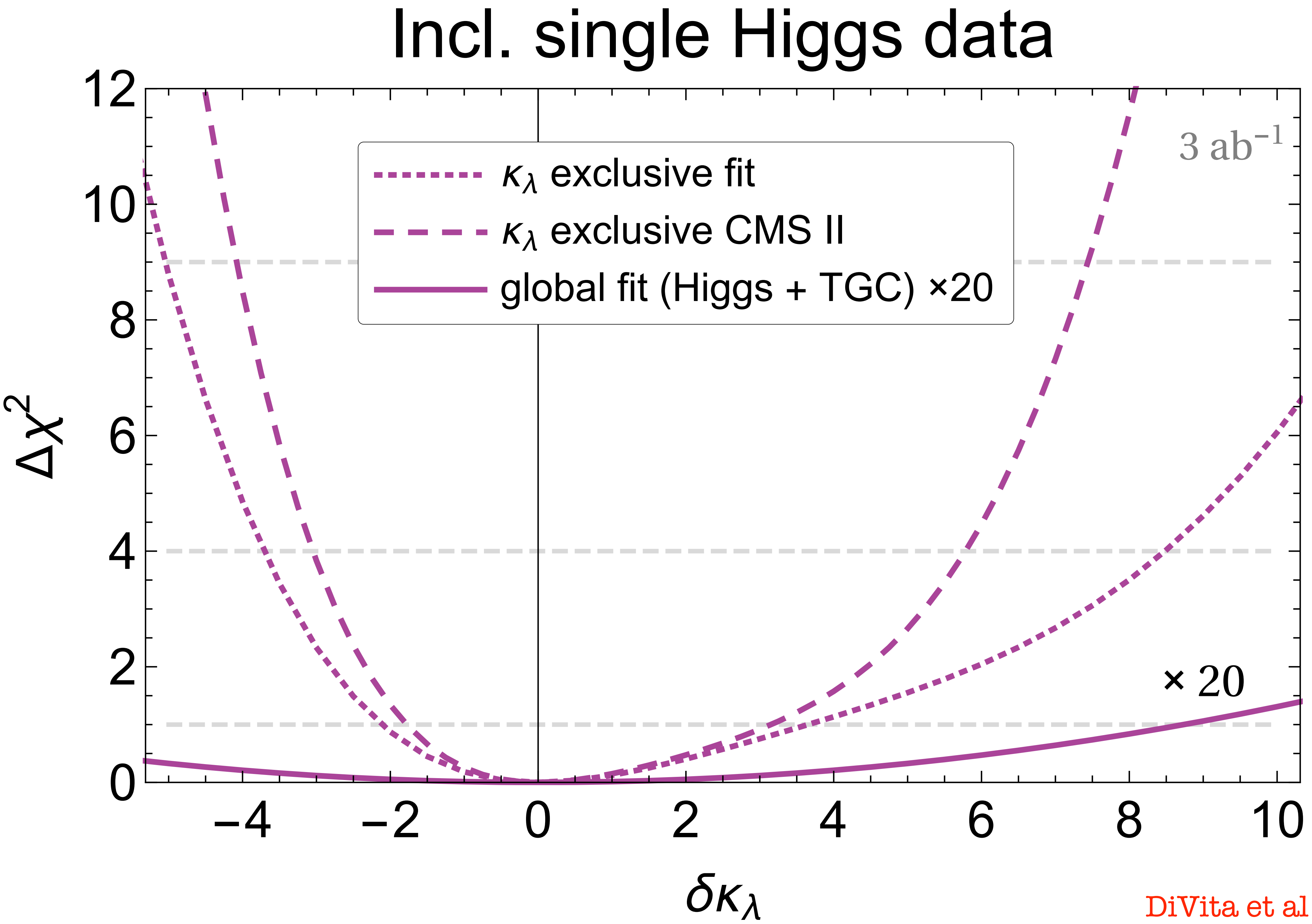
Process		Combination	Theory	Experimental
$H \to \gamma\gamma$	ggF	0.07	0.05	0.05
	VBF	0.22	0.16	0.15
	$t\bar{t}H$	0.17	0.12	0.12
	WH	0.19	0.08	0.17
	ZH	0.28	0.07	0.27
$H \to ZZ$	ggF	0.06	0.05	0.04
	VBF	0.17	0.10	0.14
	$t\bar{t}H$	0.20	0.12	0.16
	WH	0.16	0.06	0.15
	ZH	0.21	0.08	0.20
$H \to WW$	ggF	0.07	0.05	0.05
	VBF	0.15	0.12	0.09
$H \to Z\gamma$	incl.	0.30	0.13	0.27
$H \to b\bar{b}$	WH	0.37	0.09	0.36
	ZH	0.14	0.05	0.13
$H \to \tau^+\tau^-$	VBF	0.19	0.12	0.15

Estimated relative uncertainties on the determination of single-Higgs production channels at the HL-LHC(14 TeV center of mass energy, 3/ab integrated luminosity and pile-up 140 events/bunch-crossing).

ATL-PHYS-PUB-2014-016 ATL-PHYS-PUB-2016-008 ATL-PHYS-PUB-2016-018

one flat direction is expected!

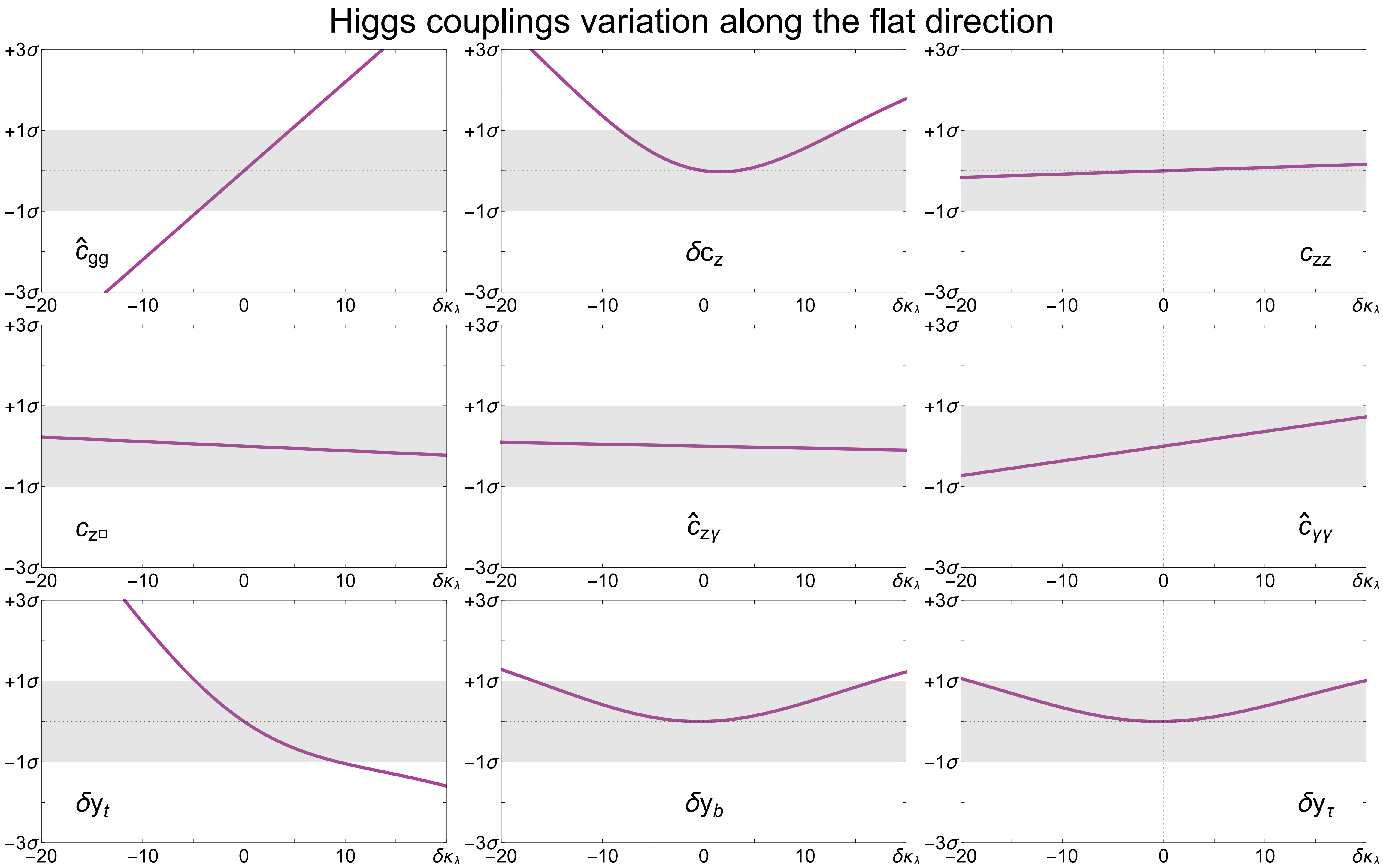
h³ @NLO vs h @ LO in global fit



DiVita et al ’17

one flat direction is expected!

h^3 @NLO vs h @ LO in global fit


Higgs couplings variation along the flat direction

DiVita et al '17

The particular direction of this flat direction

tells that adding new data on diboson or h→Zγ won't help much

one flat direction is expected!

Does h^3 modify the fit to other couplings?

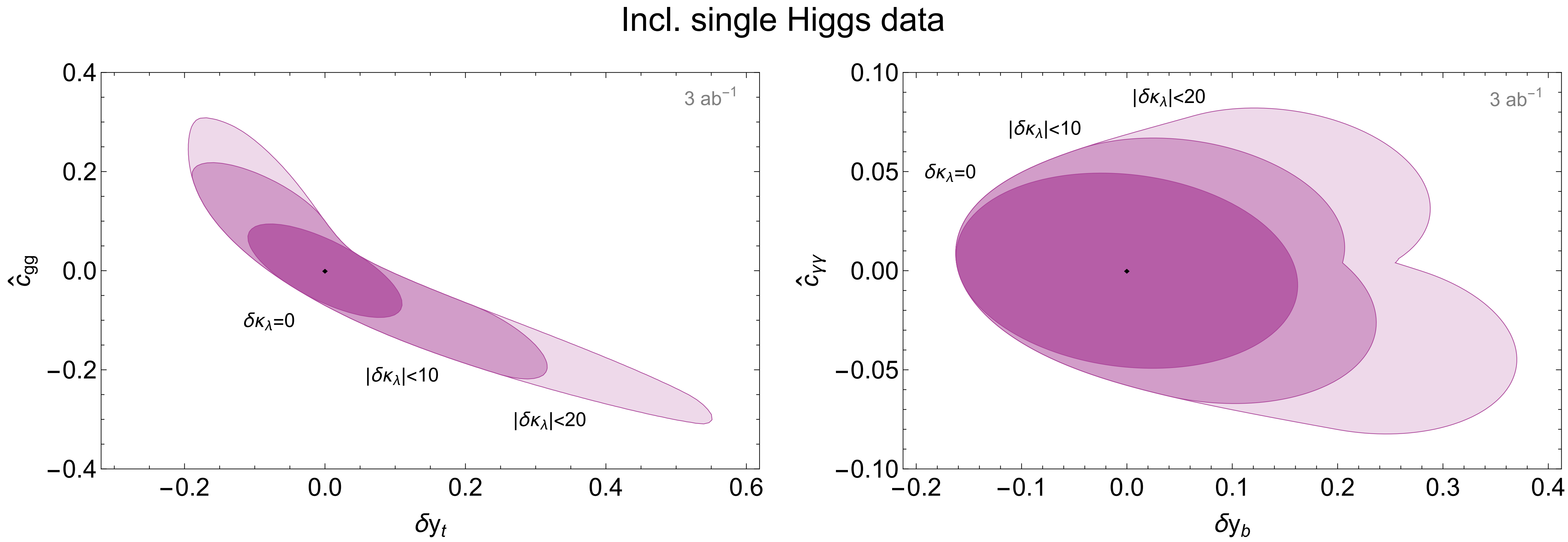


Figure 3. Constraints in the planes $(\delta y_t, \hat{c}_{gg})$ (left panel) and $(\delta y_b, \hat{c}_{\gamma\gamma})$ (right panel) obtained from a global fit on the single-Higgs processes. The darker regions are obtained by fixing the Higgs trilinear to the SM value $\kappa_\lambda = 1$, while the lighter ones are obtained through profiling by restricting $\delta\kappa_\lambda$ in the ranges $|\delta\kappa_\lambda| \leq 10$ and $|\delta\kappa_\lambda| \leq 20$ respectively. The regions correspond to 68% confidence level (defined in the Gaussian limit corresponding to $\Delta\chi^2 = 2.3$).

NLO single H vs double Higgs

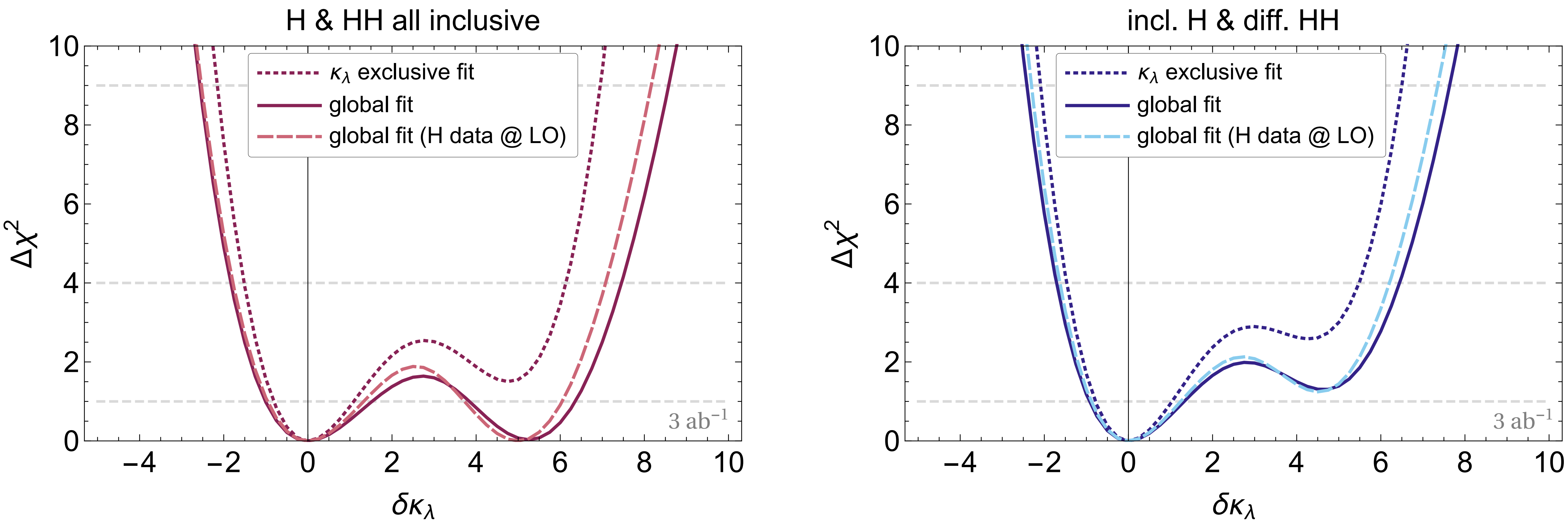


Figure 4. *Left:* The solid curve shows the global χ^2 as a function of the corrections to the Higgs trilinear self-coupling obtained from a fit exploiting inclusive single Higgs and inclusive double Higgs observables. The dashed line shows the fit obtained by neglecting the dependence on $\delta\kappa_\lambda$ in single-Higgs observables. The dotted line is obtained by exclusive fit in which all the EFT parameters, except for $\delta\kappa_\lambda$, are set to zero. *Right:* The same but using differential observables for double Higgs.

double Higgs first!

single Higgs observables at NLO plays a marginal role in determining h^3

differential double Higgs removes degenerate minima

Be careful: if non-linear EFT, more parameters are needed!

Is differential single H @ NLO a good option?

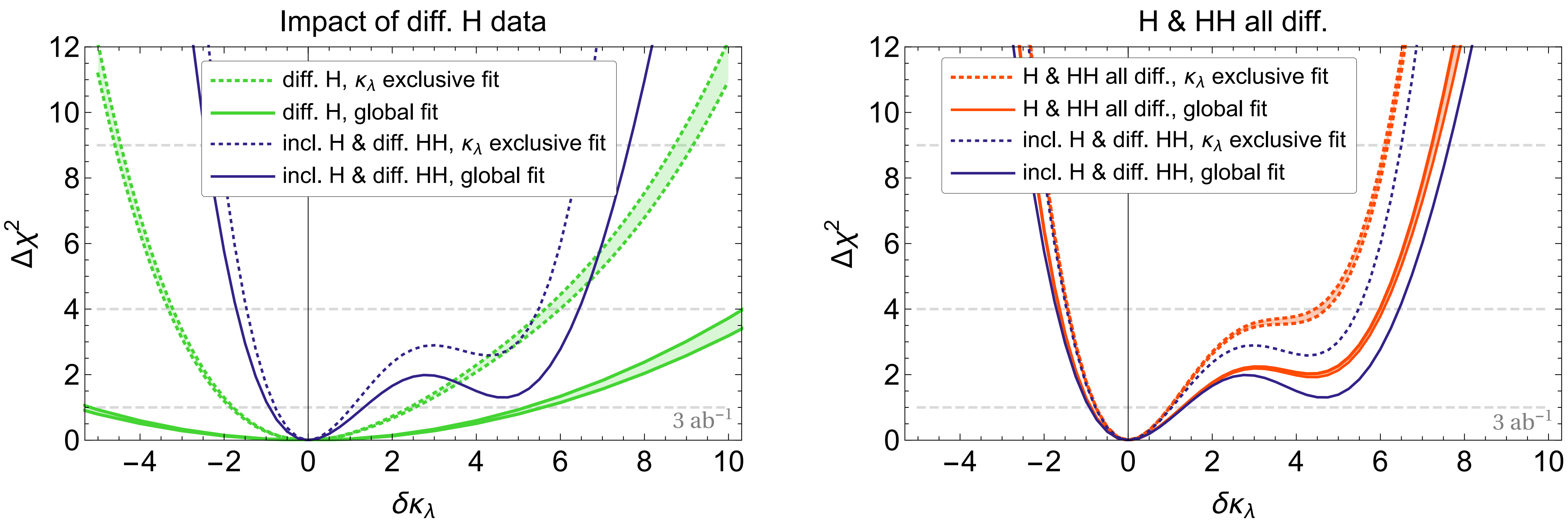
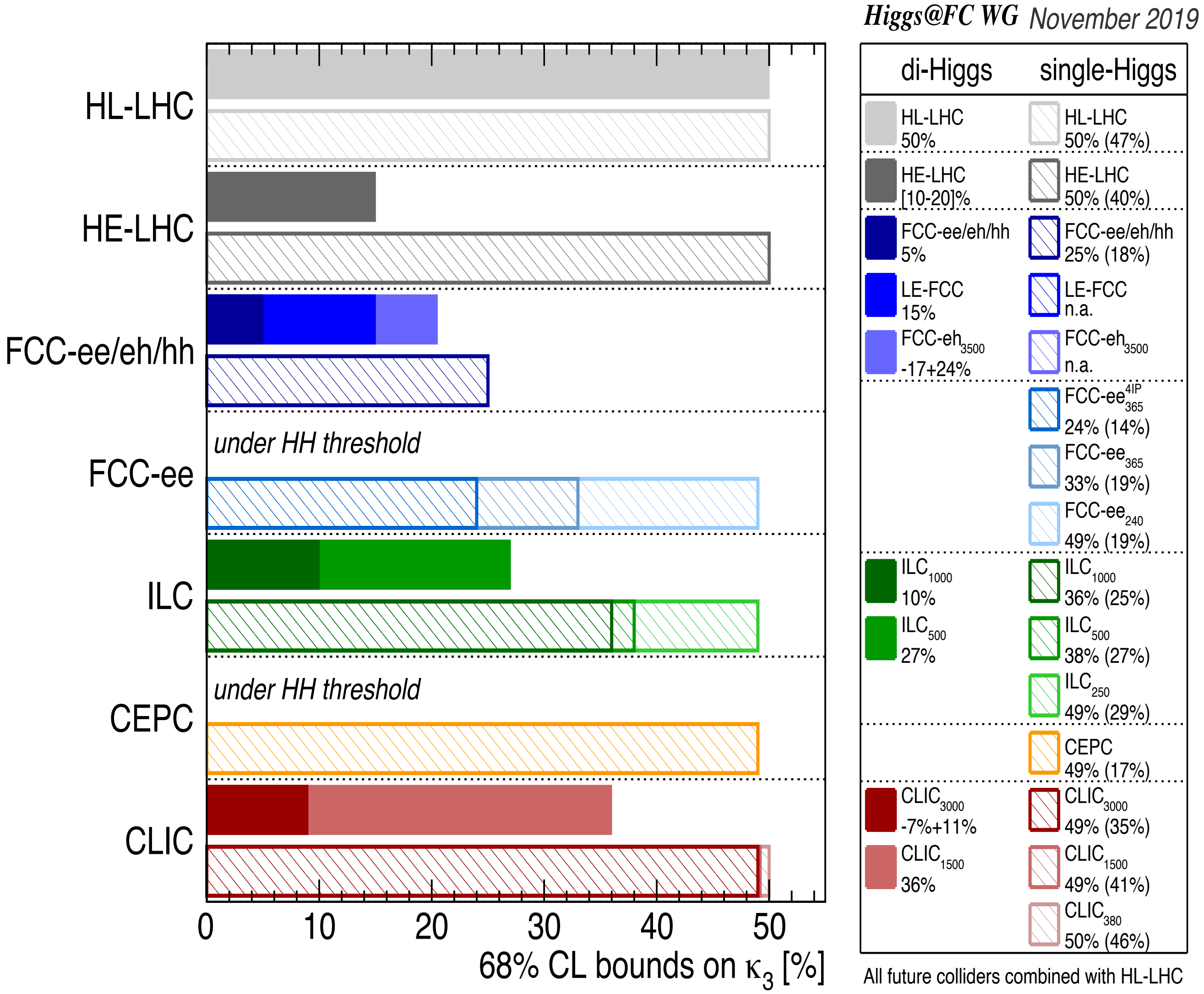


Figure 5. *Left:* χ^2 as a function of the Higgs trilinear self-coupling. The green bands are obtained from the differential analysis on single-Higgs observables and are delimited by the fits corresponding to the optimistic and pessimistic estimates of the experimental uncertainties. The dotted green curves correspond to a fit performed exclusively on $\delta\kappa_\lambda$ setting to zero all the other parameters, while the solid green lines are obtained by a global fit profiling over the single-Higgs coupling parameters. *Right:* The red lines show the fits obtained by a combination of single-Higgs and double-Higgs differential observables. In both panels the dark blue curves are obtained by considering only double-Higgs differential observables and coincide with the results shown in fig. 4.

interesting potential option
but more detailed estimates of exp. uncertainties are required
to fully asses its potential

Higgs self-coupling prospects

ECFA Higgs study group '19



1

Don't need to reach HH threshold

to have access to h^3.

Z-pole run is very important

if the HH threshold cannot be reached

2

The determination of h^3 at FCC-hh

relies on HH channel,

for which FCC-ee is of little direct help.

But the extraction of h^3

requires precise knowledge of y_t.

1% y_t ↔ 5% h^3

Precision measurement of y_t needs ee

50% sensitivity: establish that $h^3 \neq 0$ at 95%CL

20% sensitivity: 5σ discovery of the SM h^3 coupling

5% sensitivity: getting sensitive to quantum corrections to Higgs potential

EFTs for composite Higgs models

Composite Higgs Anomalous Couplings

Giudice, Grojean, Pomarol, Rattazzi ‘07

$$\mathcal{L} \supset \frac{c_H}{2f^2} \partial^\mu \left(|H|^2\right) \partial_\mu \left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

f=compositeness scale of the Higgs boson

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Longrightarrow \mathcal{L} = \frac{1}{2}\left(1 + c_H \frac{v^2}{f^2}\right) (\partial^\mu h)^2 + \dots$$

Modified
Higgs propagator

~

Higgs couplings
rescaled by

$$\frac{1}{\sqrt{1 + c_H \frac{v^2}{f^2}}} \sim 1 - c_H \frac{v^2}{2f^2} \equiv 1 - \xi/2$$

Higgs anomalous coupling: a = √1-ξ≈ 1-ξ/2

$$\xi = v^2/f^2$$

Typical resonance mass: $m_\rho = g_\rho \times f$. Strong coupling: $m_\rho \gg f$

EFT = dimensional analysis

It is important to remember that couplings are not dimensionless

		M^n	$\hbar^n$
scalar field	ϕ	1	1/2
fermion field	ψ	3/2	1/2
vector field	A_μ	1	1/2
mass	m	1	0
gauge coupling	g	0	$-1/2$
quartic coupling	λ	0	-1
Yukawa coupling	y_f	0	$-1/2$

$$\mathcal{S} = \int d^4x \left(\mathcal{L}_0 + \hbar\mathcal{L}_1 + \hbar^2\mathcal{L}_2 + \ldots\right)$$

$[\mathcal{L}_0]_\hbar = 1$ $\quad [\mathcal{L}_1]_\hbar = 0$ $\quad [\mathcal{L}_2]_\hbar = -1$

$[\mathcal{L}_0]_M = 4$ $\quad [\mathcal{L}_1]_M = 4$ $\quad [\mathcal{L}_2]_M = 4$

v is not simply a mass scale but also a “coupling”

$$[v]_\hbar = 1/2$$

$$\mathcal{A}_{W_L W_L \to W_L W_L} = \frac{s}{v^2}$$ even when gauge coupling are zero

$[\cdot]_\hbar = -1$ $\quad [\cdot]_\hbar = 2$

$$\frac{1}{M^2} g_*^2 \left(\partial^\mu |H|^2\right)^2$$

$[\cdot]_\hbar = 1$ $\quad [\cdot]_\hbar = 0$

$$\frac{ic_W}{2M^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(g\, D^\nu W_{\mu\nu}\right)^i$$

SILH Effective Lagrangian

(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi ‘07

- extra Higgs leg: H/f
- extra derivative: ∂/m_ρ

Genuine strong operators (sensitive to the scale f)

$$\frac{c_H}{2f^2}\left(\partial^\mu |H|^2\right)^2$$

$$\frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2$$

custodial breaking

$$\frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + \text{h.c.}$$

$$\frac{c_6 \lambda}{f^2}|H|^6$$

Form factor operators (sensitive to the scale m_ρ)

$$\frac{ic_W}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i$$

$$\frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$\frac{ic_{HW}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$$

$$\frac{ic_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

$$\frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

Goldstone sym.

Higgs anomalous couplings

$$\mathcal{L}_{\rm EWSB} = m_W^2 W_\mu^+ W_\mu^+ \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_\psi \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right)$$

The Higgs couplings deviates from SM ones (a=b=c=1)
and the deviations are controlled by c_H and c_y

Anomalous couplings are related to the coset symmetry and not the spectrum of resonances

Minimal composite Higgs model (MCHM): SO(5)/SO(4)

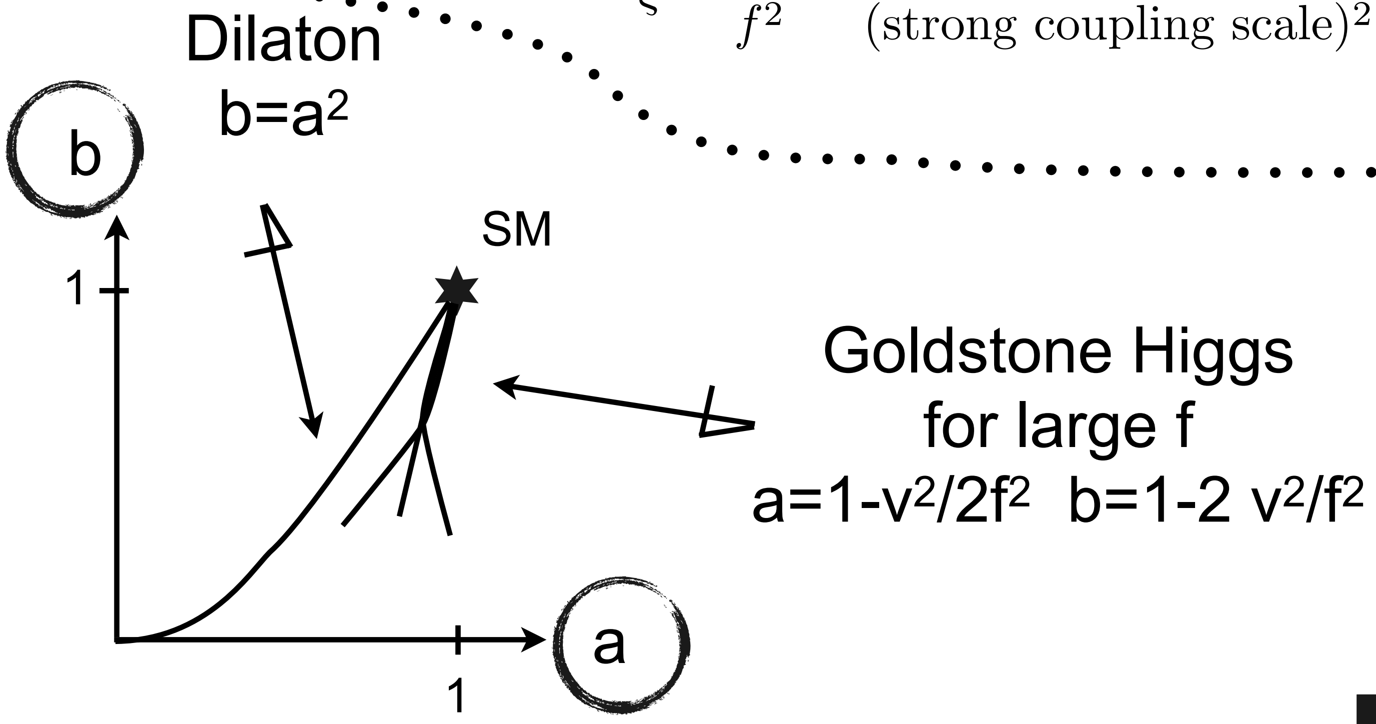
$$a = \sqrt{1-\xi} \qquad b = 1-2\xi \qquad b_3 = -\frac{4}{3}\xi\sqrt{1-\xi} \qquad c = \left(\sqrt{1-\xi}, \frac{1-2\xi}{\sqrt{1-\xi}}\right) \qquad c_2 = -(\xi, 4\xi)$$

Uniqueness of Goldstone models in the SM vicinity

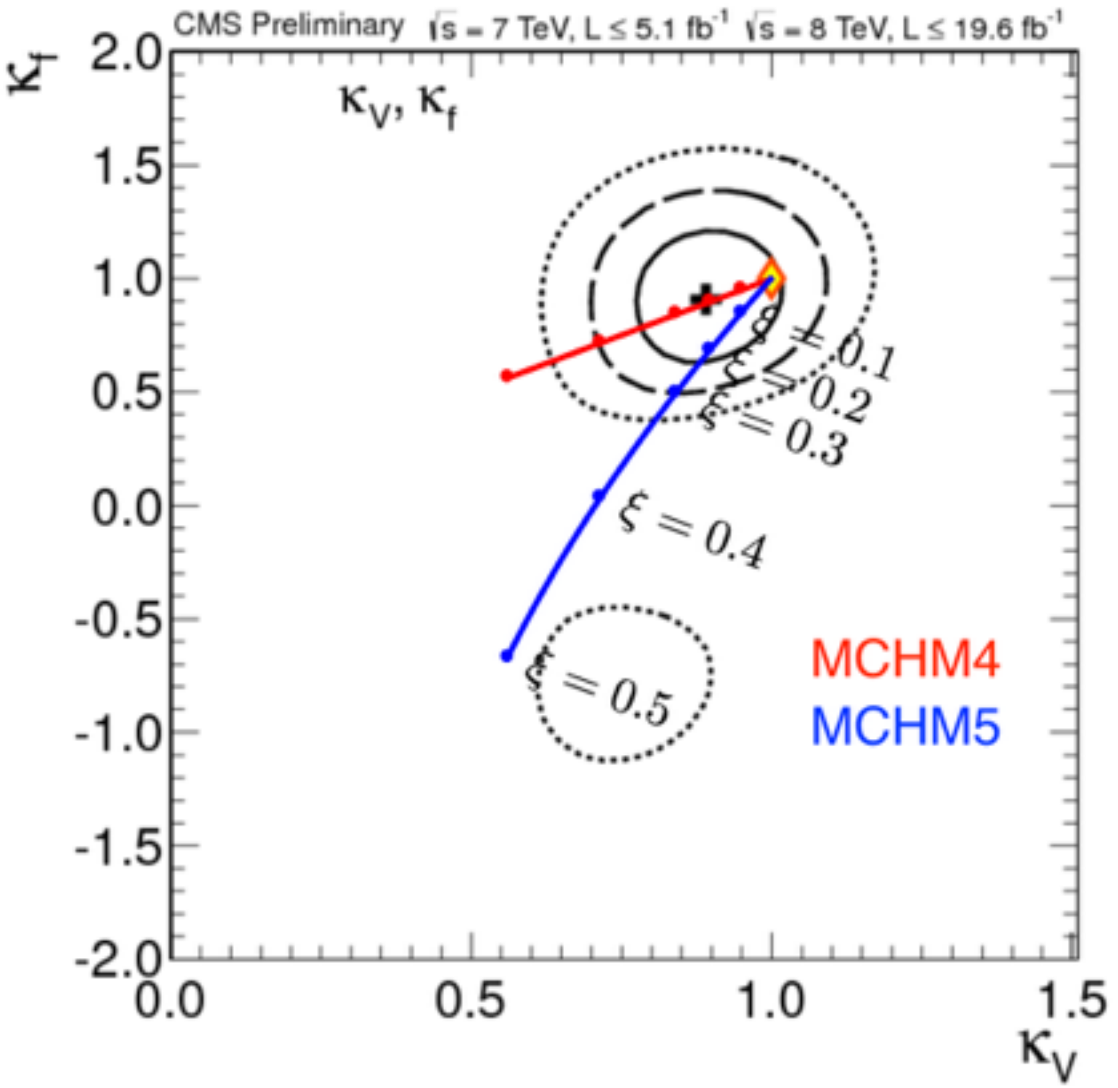
— a single operator at dimension-6 level controls the amplitudes —

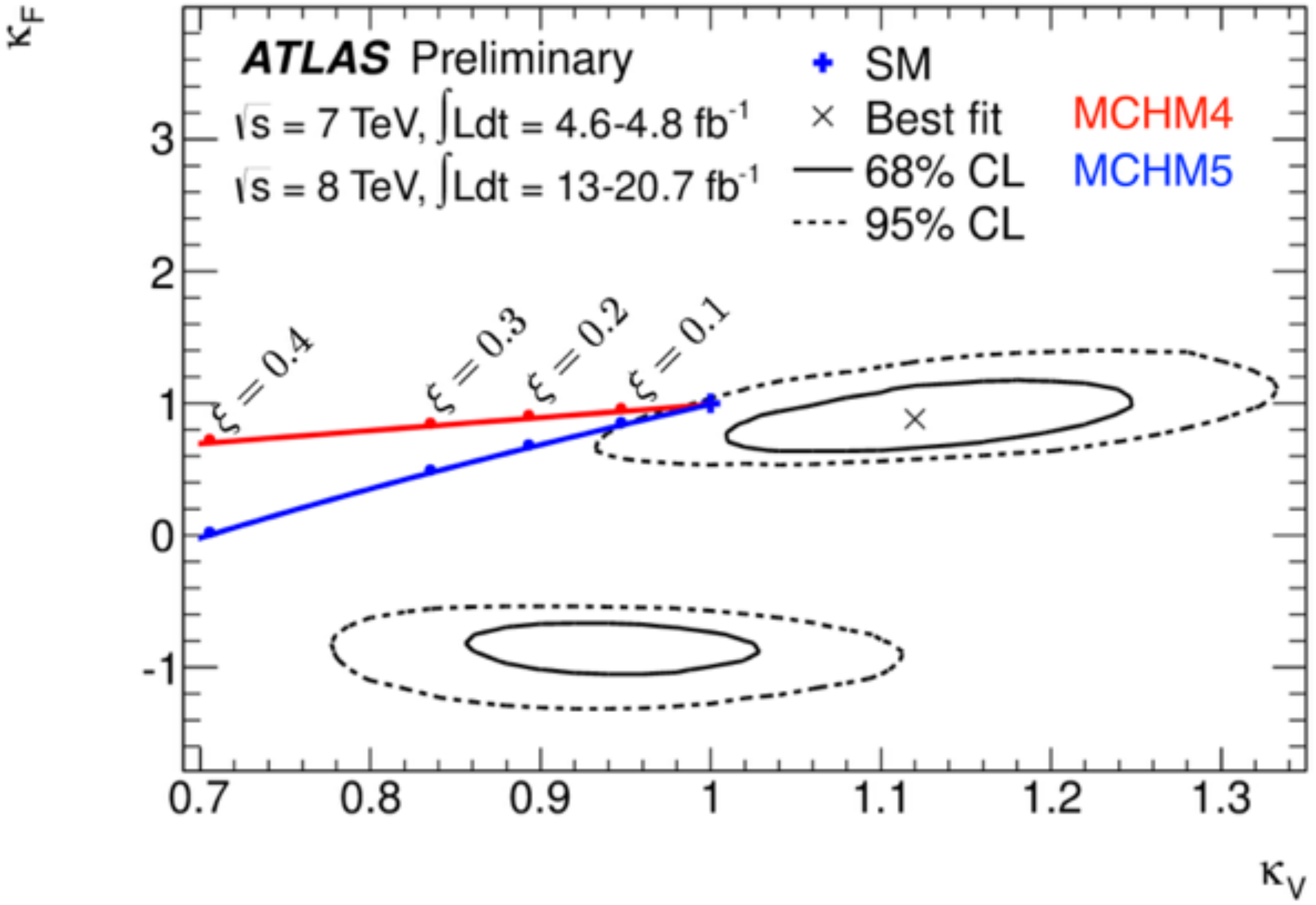
$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

Composite Higgs
vs.
SM Higgs



Higgs couplings fit





- MCHM4

$$\xi < 0.12 \quad \text{at } 95\%\text{CL}$$

- MCHM5

$$\xi < 0.10 \quad \text{at } 95\%\text{CL}$$

Indirect composite signatures

Assuming **composite** Higgs, **elementary** gauge bos.:

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* H, g_w V_\mu, \partial_\mu]$$

S-parameter @ee: [De Blas et. al.] (LEP: 10^{-3})

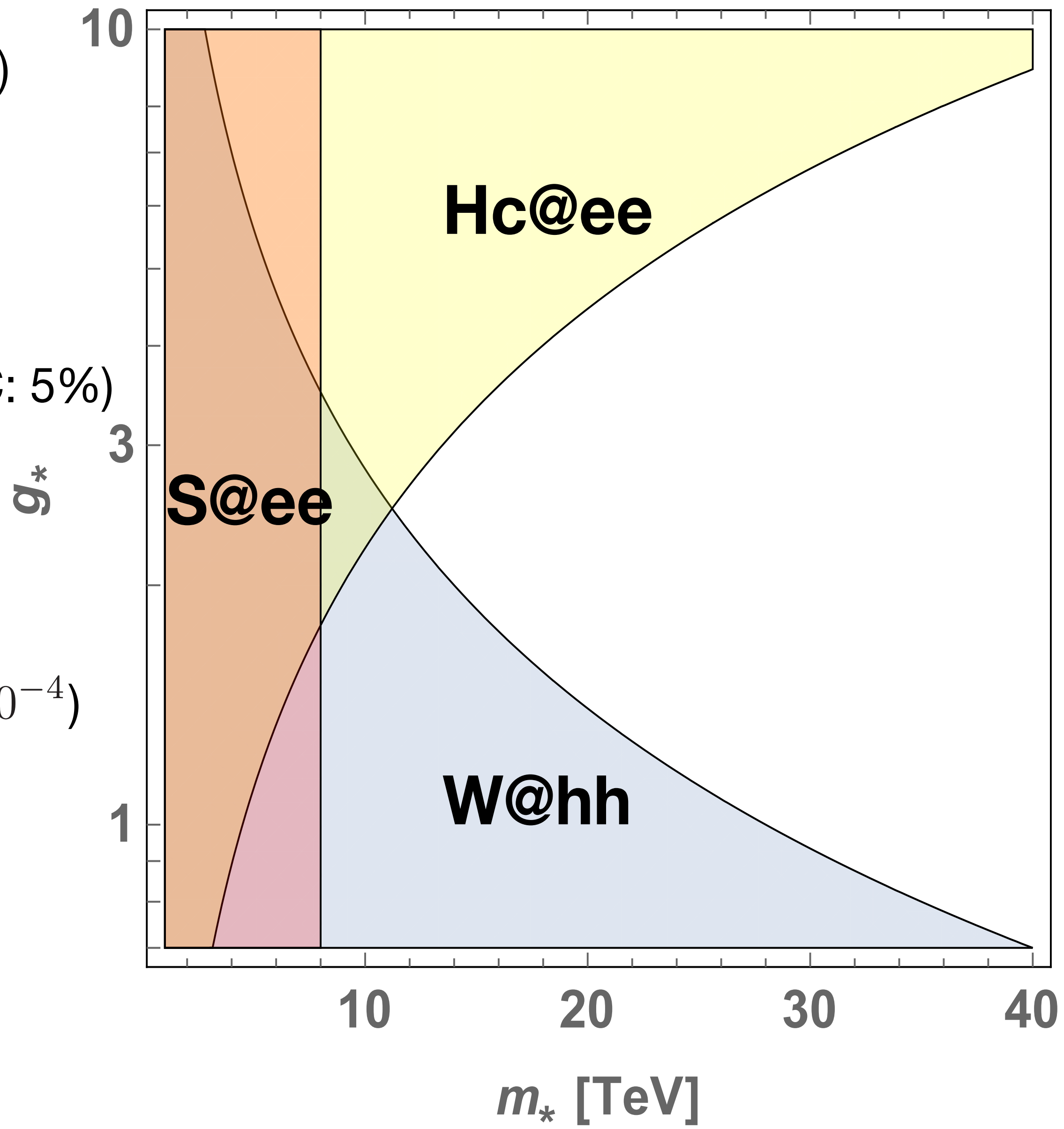
$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \Rightarrow \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$

Higgs Couplings @ee: [ee Report] (HL-LHC: 5%)

$$\frac{g_*^2}{m_*^2}\partial_\mu |H|^2 \partial^\mu |H|^2 \Rightarrow \delta\kappa_{V,F} = \frac{g_*^2 v^2}{m_*^2} < 3\,10^{-3}$$

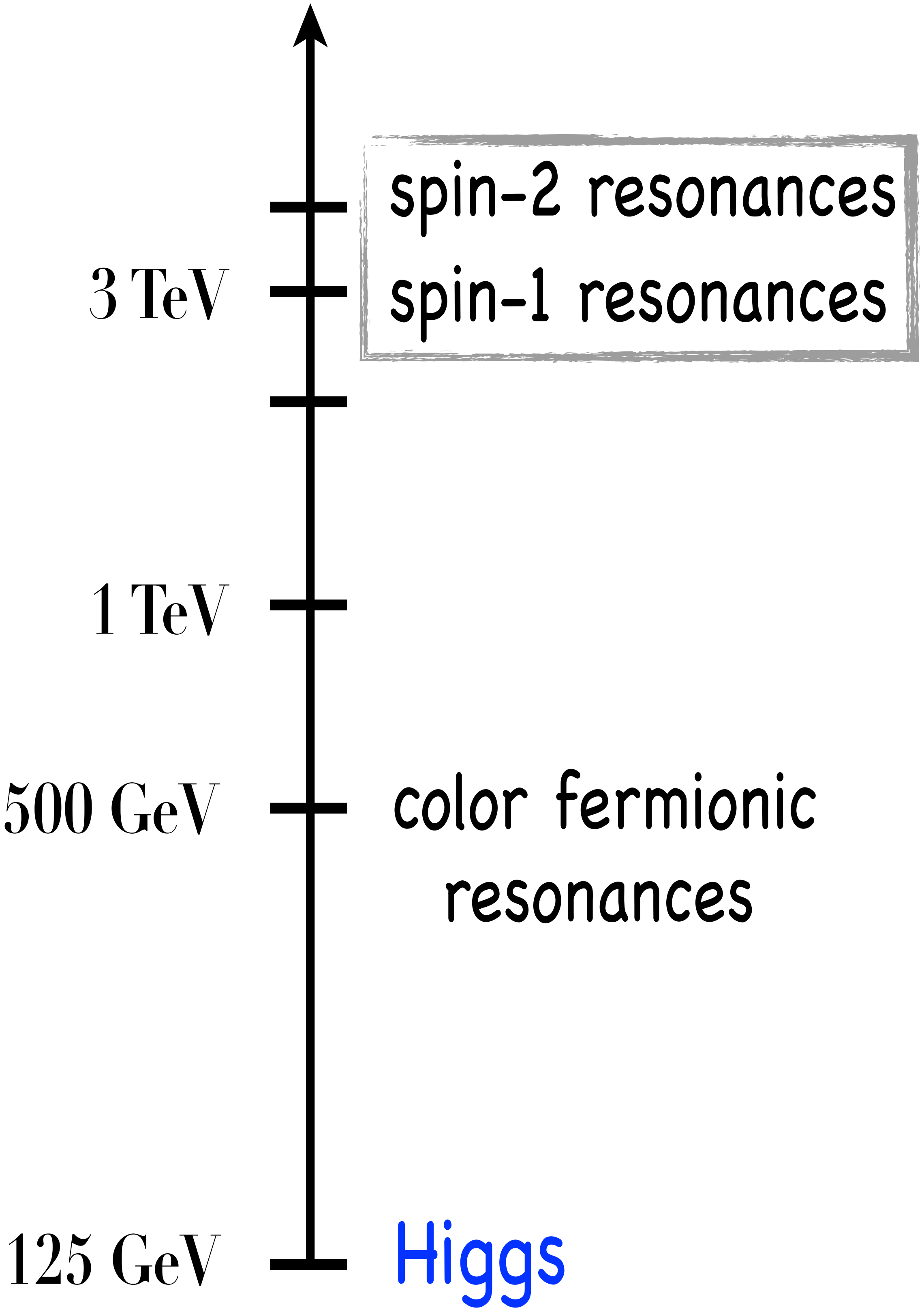
W @hh: (energy + accuracy) (HL-LHC< 10^{-4})

$$\frac{g_w^2}{g_*^2 m_*^2}(D_\mu W_{\nu\rho})^2 \Rightarrow W = \frac{g_w^2 m_w^2}{g_*^2 m_*^2} < \ 10^{-5}$$



Grojean-Wulzer @ FCC physics week '17

The other resonances



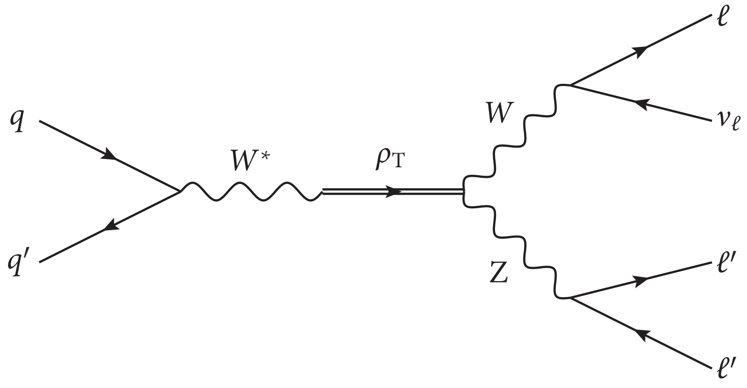
Dominant decays into longitudinal SM gauge bosons

$$\Gamma(\rho^0 \to W^+W^-) \approx \Gamma(\rho^\pm \to ZW^\pm) \approx \frac{m_\rho g_{\rho\pi\pi}^2}{48\pi} = \frac{m_\rho^5}{192\pi g_\rho^2 v^4}$$

Suppressed decays to SM quarks and leptons

$$\mathrm{Br}(\rho^\pm \to e^\pm \nu) \approx 2\mathrm{Br}(\rho^0 \to e^+e^-) \approx \frac{16 m_W^4}{m_\rho^4}$$

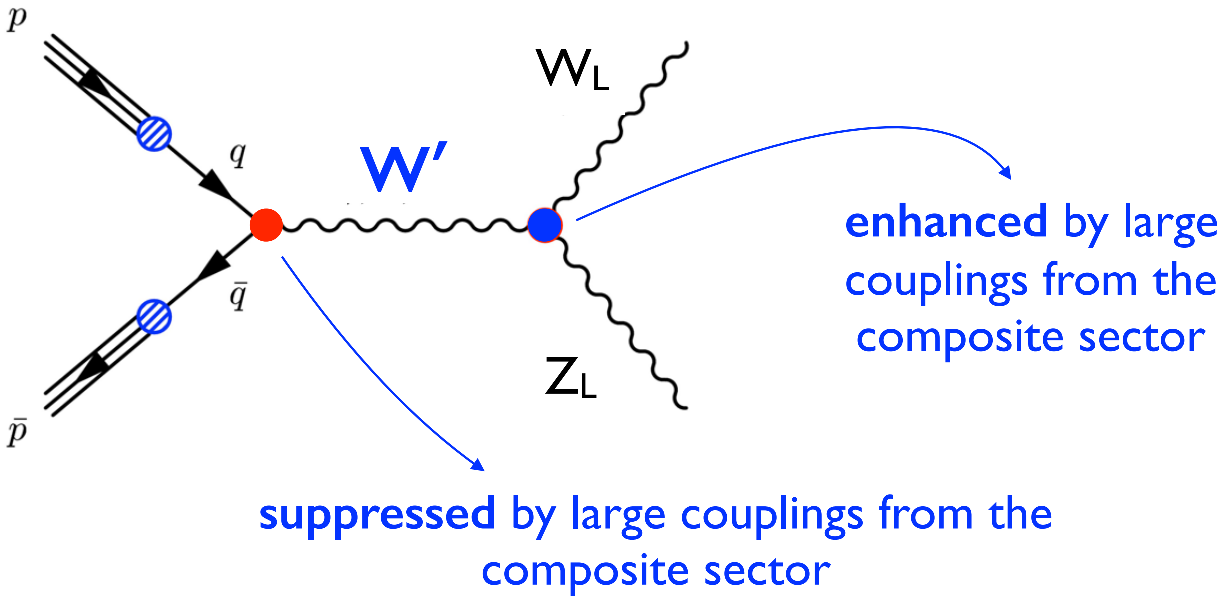
searches in WW, WZ channels in DY processes



H couplings vs searches for vector resonances

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

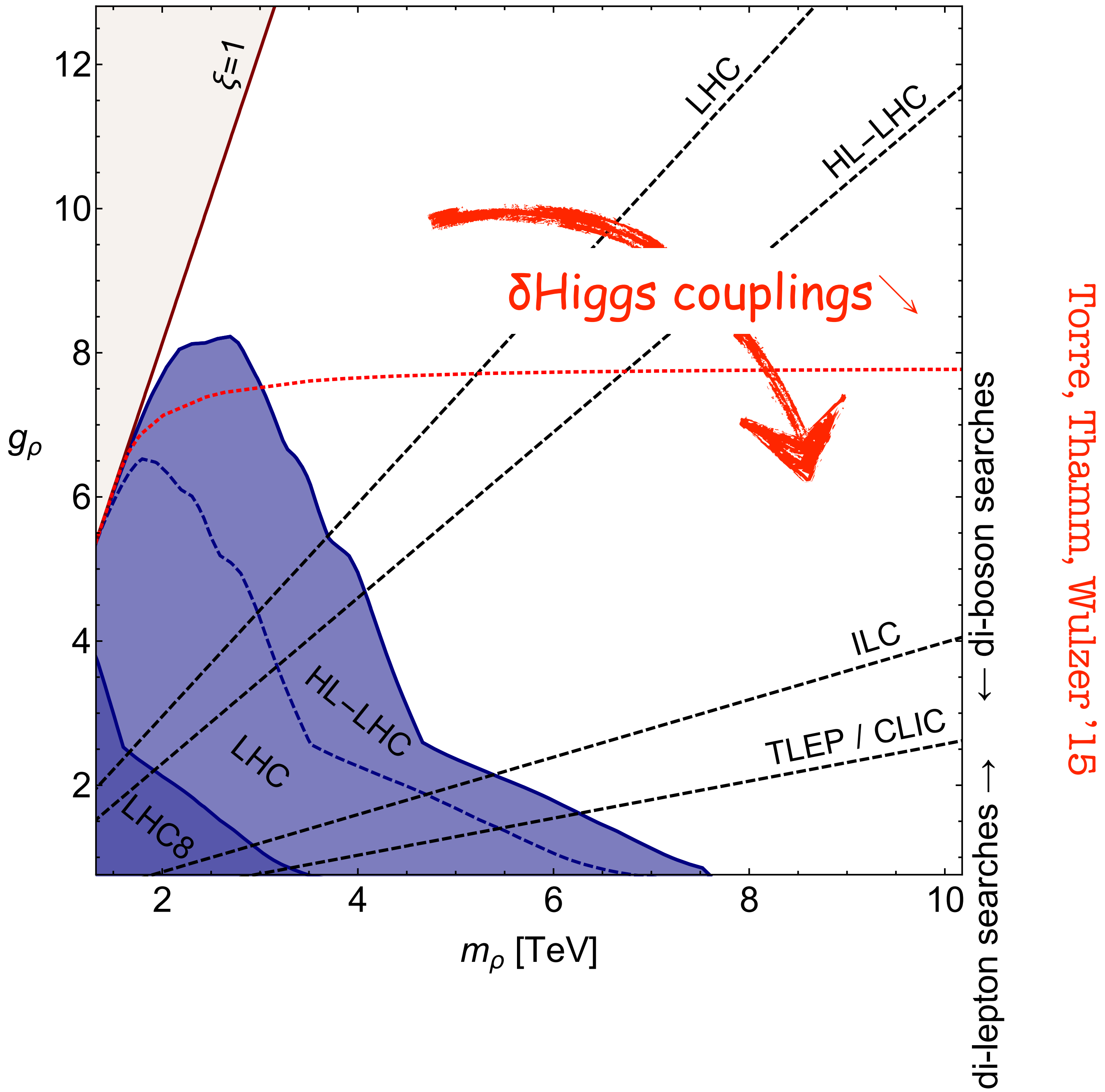
- Precision Higgs study: $\xi \equiv \frac{\delta g}{g} = \frac{v^2}{f^2}$
- Direct searches for resonances: $m_\rho \approx g_* f$



enhanced by large couplings from the composite sector

suppressed by large couplings from the composite sector

DY production xs of resonances decreases as $1/g_\rho^2$



Torre, Thamm, Wulzer '15

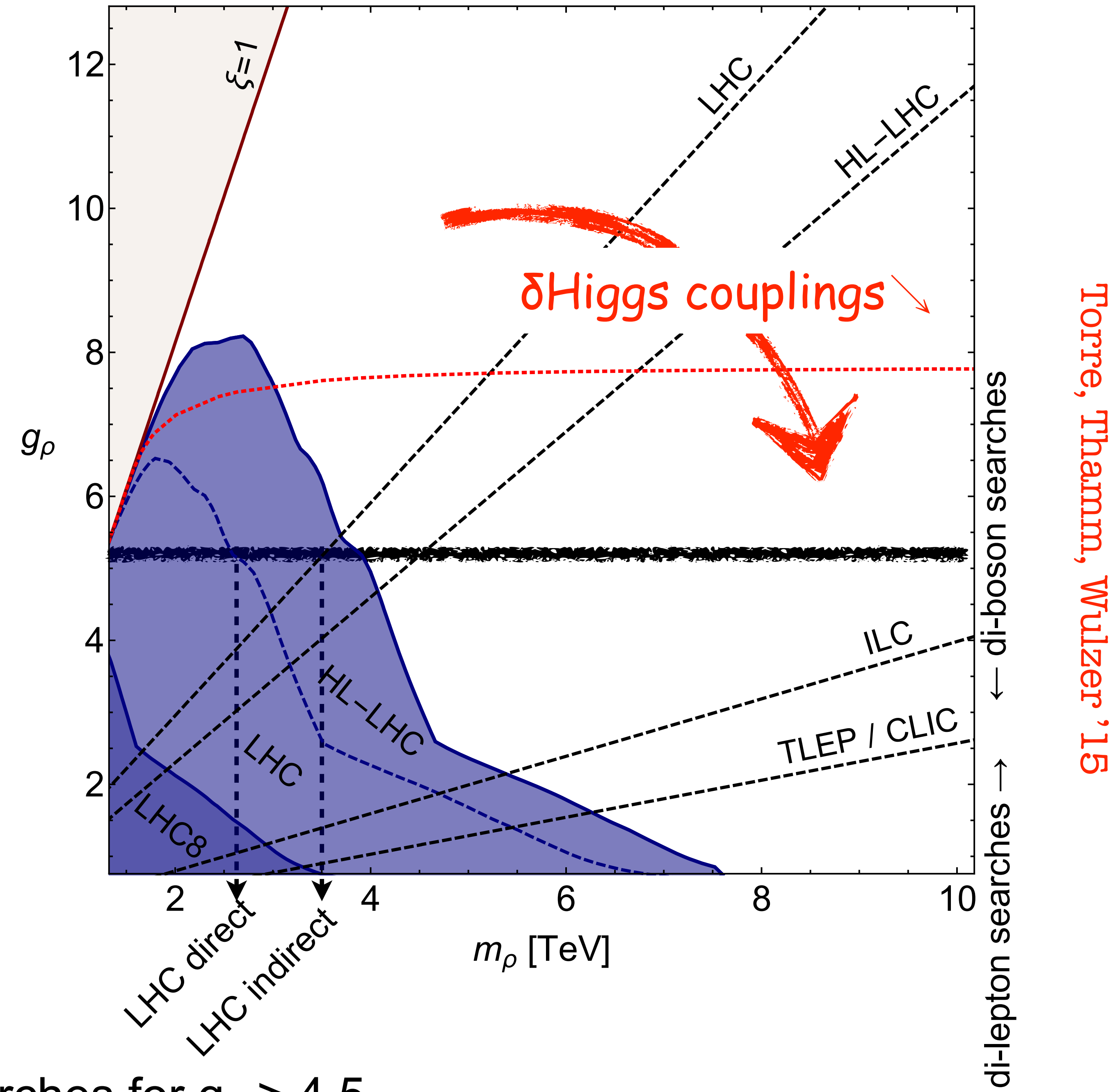
H couplings vs searches for vector resonances

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

- Precision Higgs study: $\xi \equiv \frac{\delta g}{g} = \frac{v^2}{f^2}$
- Direct searches for resonances: $m_\rho \approx g_* f$

Collider	Energy	Luminosity	ξ [1σ]
LHC	14 TeV	300 fb^{-1}	$6.6 - 11.4 \times 10^{-2}$
LHC	14 TeV	3 ab^{-1}	$4 - 10 \times 10^{-2}$
ILC	250 GeV + 500 GeV	250 fb^{-1} 500 fb^{-1}	4.8-7.8 $\times 10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	500 fb^{-1} 1.5 ab^{-1} 2 ab^{-1}	2.2 $\times 10^{-3}$
TLEP	240 GeV + 350 GeV	10 ab^{-1} 2.6 ab^{-1}	2 $\times 10^{-3}$

DY production xs of resonances decreases as $1/g_\rho^2$



Torre, Thamm, Wulzer '15

- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

e.g.

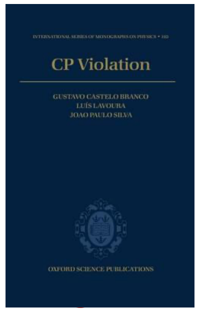
indirect searches at LHC over-perform direct searches for g_ρ > 4.5

indirect searches at ILC over-perform direct searches at HL-LHC for g_ρ > 2

CP violation in (SM)EFT

CPV in SM$_4$

CPV comes from mixing among quarks and the resulting couplings to W



See for instance, G. Branco

$$\mathcal{L}_{\rm mix} = \frac{e}{\sqrt{2}\sin\theta_w}\left[W^+_\mu \bar{u} V \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) d + W^-_\mu \bar{d} V^\dagger \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) u\right]$$

$$\Big\downarrow \text{Proper} \quad \text{CP}$$

$$\frac{e}{\sqrt{2}\sin\theta_w}\left[W^+_\mu \bar{u}\,(V^\dagger)^T \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) d + W^-_\mu \bar{d} V^T \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) u\right]$$

Phases in CKM (can) break CP!

Are Phases a Sign of CPV?

Only after exhausting all flavour symmetries!

$$V_{\text{CKM}} = \begin{pmatrix} \frac{72-21i}{325} & \frac{4}{13} & -\frac{12i}{13} \\ -\frac{12}{13} & \frac{576+168i}{1625} & \frac{49-168i}{65} \\ -\frac{96-28i}{325} & -\frac{57}{65} & -\frac{24i}{65} \end{pmatrix}$$

$$\parallel$$

$$\underbrace{\begin{pmatrix} \frac{3-4i}{5} & 0 & 0 \\ 0 & \frac{4-3i}{5} & 0 \\ 0 & 0 & \frac{3-4i}{5} \end{pmatrix}}\begin{pmatrix} \frac{3}{13} & \frac{4}{13} & \frac{12}{13} \\ -\frac{12}{13} & \frac{24}{65} & \frac{7}{65} \\ -\frac{4}{13} & -\frac{57}{65} & \frac{24}{65} \end{pmatrix}\underbrace{\begin{pmatrix} \frac{4+3i}{5} & 0 & 0 \\ 0 & \frac{3+4i}{5} & 0 \\ 0 & 0 & \frac{4-3i}{5} \end{pmatrix}}$$

phases absorbed by redefining quark fields

no complex phase after
appropriate phase shifts of quark fields

$$V_{\text{CKM}} = \begin{pmatrix} \frac{2172-5004i}{8125} & -\frac{1784+432i}{8125} & -\frac{2427+5196i}{8125} \\ -\frac{3747+3996i}{8125} & \frac{3324+912i}{8125} & \frac{4772-1164i}{8125} \\ -\frac{308+144i}{1105} & -\frac{4389+2052i}{5525} & \frac{1848+864i}{5525} \end{pmatrix}$$

$$\parallel$$

$$\begin{pmatrix} -\frac{176+468i}{625} & -\frac{9-12i}{25} & 0 \\ \frac{351-132i}{625} & \frac{16+12i}{25} & 0 \\ 0 & 0 & \frac{77+36i}{85} \end{pmatrix}\begin{pmatrix} \frac{3}{13} & \frac{4}{13} & \frac{12}{13} \\ -\frac{12}{13} & \frac{24}{65} & \frac{7}{65} \\ -\frac{4}{13} & -\frac{57}{65} & \frac{24}{65} \end{pmatrix}$$

if $m_u = m_c$,
enlarged U(2) flavour symmetry
that can be used to remove phase in CKM

CPV ~~↔ ∃ phase in Lagrangian~~ parameters

The SM$_4$ Collective CPV

The well-known KM counting

Kobayashi and Maskawa '73

	$SU(3)_Q$	$SU(3)_u$	$SU(3)_d$	$U(1)_u$	$U(1)_d$	$U(1)_B$
Y_u $(9R+9I)$	3	$\bar{3}$	1	1	0	0
Y_d $(9R+9I)$	3	1	$\bar{3}$	0	1	0
	$3R+5I$	$3R+5I$	$3R+5I$	$1I$	$1I$	$\cancel{1I}$

$$\underbrace{3R+5I \quad 3R+5I \quad 3R+5I \quad 1I \quad 1I \quad \cancel{1I}}_{9R+17I}$$

physical

$9R+1I$

- The position of this physical phase is (flavour)-basis dependent, e.g.
  - Up-basis: Y_u=diag, Y_d= V_{CKM}.diag
  - Down-basis: Y_u=$V_{CKM}^{\dagger}$.diag, Y_d=diag
  - many other choices of flavour bases

standard parametrisation
(particular choice of flavour basis)

$$V_{\text{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta_{\text{CKM}}} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta_{\text{CKM}}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\text{CKM}}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\text{CKM}}} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta_{\text{CKM}}} & c_{13}c_{23} \end{pmatrix}$$

Jarlskog Invariant

The SM CPV order

Jarlskog '85

see also Bernabeu, Branco, Gronau '86

- The lowest order flavour invariant sensitive to CPV

$$J_4 = \mathrm{ImTr}\left([Y_u Y_u^\dagger, Y_d Y_d^\dagger]^3\right)$$

- Explicitly

$$J_4 = \underbrace{6 c_{12} s_{12} c_{13}^2 s_{13} c_{23} s_{23}}_{\mathcal{O}(\lambda^6)} \underbrace{(y_c^2 - y_u^2)(y_t^2 - y_u^2)(y_t^2 - y_c^2)(y_s^2 - y_d^2)(y_b^2 - y_d^2)(y_b^2 - y_s^2)}_{\mathcal{O}(\lambda^{30})} \underbrace{\sin\delta}_{\mathcal{O}(\lambda^0)}$$

Wolfenstein parametrisation $V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$ $\quad \lambda \sim 0.22$

Wolfenstein '83

- Even if δ~O(1), large suppression effects due to collective nature of CPV
- Important property: CP is conserved iff J_4=0 (neglecting θ_{QCD} for now)

exercise 1: check that indeed J_4 vanishes on the two examples of previous slide (one need m_u=m_c for the second one!)

exercise 2: check that for N_F=2, J_4 always vanishes

BSM CPV is also a Collective Effect

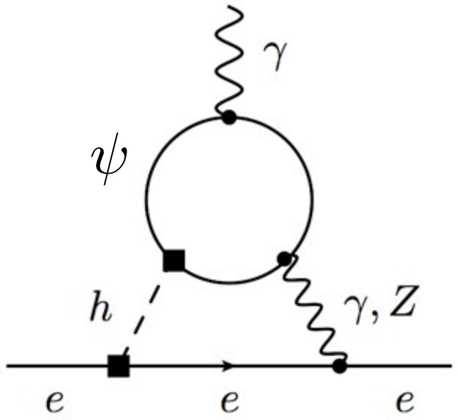
The example of electron EDM

- “Imaginary” Yukawa coupling gives rise to eEDM through Barr-Zee diagram

$$\mathcal{L} = Y_u\,\bar{Q}\tilde{H}U + C_{uH}\,|H|^2\bar{Q}\tilde{H}U$$

$$\mathcal{L} = y\,h\bar{\psi}\psi$$

$$y_u = \frac{\sqrt{2}m_u}{v}\left(1 + C_{uH}v^2/\Lambda^2\right)$$



$$\xcancel{\frac{d_e}{e} = -\frac{1}{48\pi^2}\frac{v m_e m_u}{m_h^2}\frac{\mathrm{Im}\boxed{(C_{uH})}}{\Lambda^2}F_1\left(\frac{m_u^2}{m_h^2},0\right)}$$

$$\frac{d_e}{e} = -\frac{1}{48\pi^2}\frac{v m_e}{m_h^2}\frac{\mathrm{Im}\boxed{(m_u^* C_{uH})}}{\Lambda^2}F_1\left(\frac{|m_u|^2}{m_h^2},0\right)$$

- The Yukawa can be made real by chiral rotation: $\psi \to e^{i\theta\gamma^5}\psi$
- The “phase” will appear in the mass
- The CPV effect is captured by Im (y†·m), which is invariant under chiral rotation

Trivial here, but can get complicated:

- flavour indices,
- links to UV parameters…

Dim-6 Yukawa's Contribution to EDMs

CP doesn't say Wilson coefficients are real

$$\mathcal{L} = \underbrace{Y_u}_{\substack{\text{3x3 complex}\\ \text{(9R+9I)}}} \bar{Q}\tilde{H}U + \underbrace{C_{uH}}_{\substack{\text{3x3 complex}\\ \text{(9R+9I)}}} |H|^2 \bar{Q}\tilde{H}U \quad \Rightarrow \quad \underbrace{g^{ij}_{huu}}_{Y_u^{ij} + 3v^2 C_{uH}^{ij}} h\bar{u}_i u_j$$

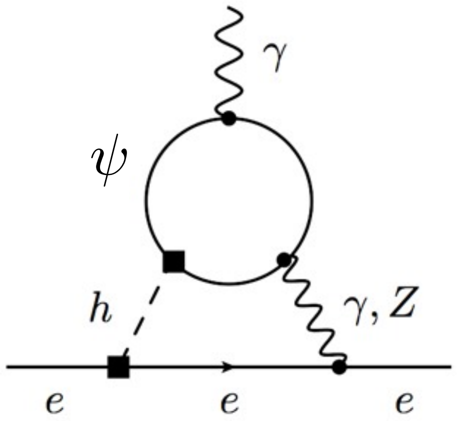
One can choose $U(3)_Q \times U(3)_U$ transformations to make C_{uH} (or g_{huu}) *real*

CPV effects $\overset{!}{\leftrightarrow}$ Im C_{uH}

Phases can be moved to mass matrices — even in mass basis, ∃ residual U(1)'s to move phase around

(flavour basis fully specified by the location of the phase in the CKM matrix)

At two loops and $1/\Lambda^2$ order, **Barr-Zee** diagrams depends only on three phases captured by **three invariants** (only diagonal phases can contribute at 2-loops because no FCNC in SM)



$$\frac{d_e}{e} \propto \frac{\alpha y_e}{16\pi^3} \left(a\, I_1 + b\, I_2 + c\, I_3\right) \qquad \text{with} \qquad I_n = \text{Im Tr}\left(Y_u^\dagger \left(Y_u Y_u^\dagger\right)^n C_{uH}\right)$$

a, b, c functions of Y_u only

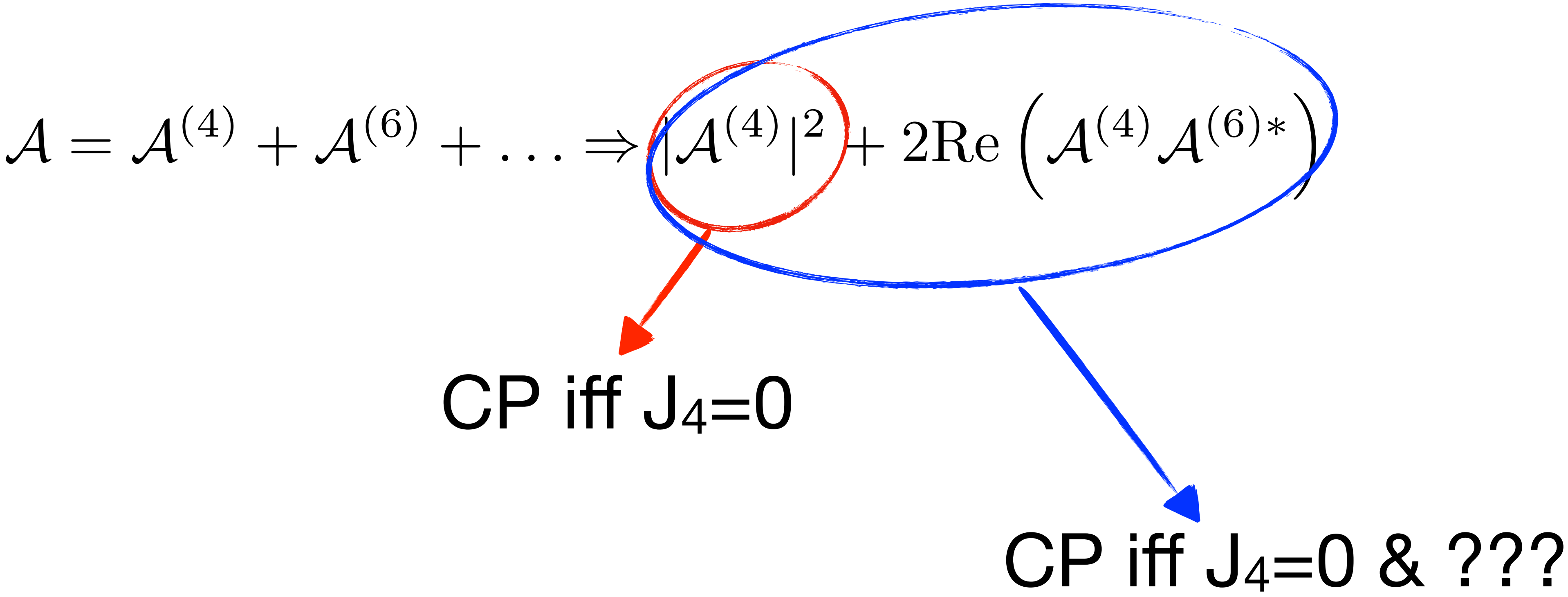
At higher loops, more phases can appear.

- How many?
- How many constraints should we impose to ensure CP is conserved?

~~CP ↔ C_{uH} real matrix~~

Beyond Jarlskog

Necessary and sufficient conditions for CPV?



$$\mathcal{A} = \mathcal{A}^{(4)} + \mathcal{A}^{(6)} + \ldots \Rightarrow |\mathcal{A}^{(4)}|^2 + 2\mathrm{Re}\left(\mathcal{A}^{(4)}\mathcal{A}^{(6)*}\right)$$

CP iff $J_4=0$

CP iff $J_4=0$ & ???

How many conditions?

Any relation with the number of phases that can appear in L_{SM6}?

Beyond Jarlskog: Building SM$_6$ invariants

Examples of invariants from with bilinear operators

Bonnefoy+ ‘21

Bonnefoy+ ‘23

- For each operators, e.g. the dim-6 Yukawa operators, we can build a series of CP-odd invariants:

$$I_{u_1\dots d_k} = \text{Im Tr}\left(Y_u^\dagger \left(Y_u Y_u^\dagger\right)^{u_1}\left(Y_d Y_d^\dagger\right)^{d_1}\dots\left(Y_u Y_u^\dagger\right)^{u_k}\left(Y_d Y_d^\dagger\right)^{d_k} C_{uH}\right)$$

- Of course, they are not all independent:

e.g., for 3 families, $I_3 = \text{Tr}\left(Y_u Y_u^\dagger\right) I_2 + \frac{1}{2}\left(\text{Tr}\left(\left(Y_u\ Y_u^\dagger\right)^2\right) - \text{Tr}^2\left(Y_u\ Y_u^\dagger\right)\right) I_1$

- Only need to consider only a finite set of invariants:

Cayley-Hamilton: $A^3 = A^2\,\text{Tr}(A) - \frac{1}{2}A\left[\text{Tr}(A)^2 - \text{Tr}\left(A^2\right)\right] + \frac{1}{6}\left[\text{Tr}(A)^3 - 3\,\text{Tr}\left(A^2\right)\text{Tr}(A) + 2\,\text{Tr}\left(A^3\right)\right]\mathbb{I}_{3\times3}$

→ enough to consider $\text{Tr}\left(X_u^a X_d^b X_u^c X_d^d C\right)$ $X_{u/d} = Y_{u/d}\ Y_{u/d}^\dagger$

a,b,c,d=0,1,2, a≠b,c≠d

Can find a basis of invariants linearly independent from each others

Opportunistic CP violation

Opportunistic CPV = interference with CKM phase

- If $J_4=0$, we can find 699 independent invariants ⇒ **minimal** basis of invariants.

"CP is conserved iff J_4 and the invariants of the minimal basis are all vanishing"

- If $J_4\neq0$, we can actually build more invariants! Not surprising, because CP-even BSM can interfere with CP-odd SM. But what was maybe unexpected is that many of these interfering invariants can be much larger than J_4 → **maximal** basis of invariants.

dim (maximal basis) = number of physical (real and imaginary) parameters that can interfere with SM and thus can show up in observables at leading $O(1/\Lambda^2)$

Opportunistic CPV relies on interference with SM phase but it doesn't have to suffer from the same collective suppression!

How many independent invariants at a given order in Cabibbo expansion?

Taylor Rank

$$\boxed{\text{Taylor Rank}_{|\epsilon^n}(M) = \underset{N=M+\mathcal{O}(\epsilon^{n+1})}{\text{Min}} \text{Rank}\,(N)}$$

$$M = \begin{pmatrix} 1 & \epsilon \\ \epsilon & \epsilon^2 \end{pmatrix}$$

$$\text{Taylor Rank}_{|\epsilon^0} = 1 = \text{Rank}\left(M_{|\epsilon^0}\right)$$

$$\text{Taylor Rank}_{|\epsilon^1} = 1 \neq \text{Rank}\left(M_{|\epsilon^1}\right) = 2$$

Scaling of Collective CPV BSM Effects

The new invariants don't suffer from the same suppression factors

- The invariants can be evaluated in e.g. the up-flavour basis:

dim.6 up-Yukawa operator

⦿ $$I_n = \underbrace{y_u^{2n+1}}_{\mathcal{O}\left(\lambda^{16n+8}\right)}\eta_u + \underbrace{y_c^{2n+1}}_{\mathcal{O}\left(\lambda^{8n+4}\right)}\eta_c + \underbrace{y_t^{2n+1}}_{\mathcal{O}\left(\lambda^{0}\right)}\eta_t$$

$$I_n = \mathrm{Im}\ \mathrm{Tr}\left(Y_u^\dagger\left(Y_u Y_u^\dagger\right)^n C_{uH}\right)$$

⦿ $$I_{1,1} = \underbrace{c_{13}c_{23}s_{13}s_\delta}_{\mathcal{O}\left(\lambda^{3}\right)}\underbrace{\left(y_b^2 - c_{12}^2 y_d^2 - s_{12}^2 y_s^2\right) y_t\,\rho_{ut}}_{\mathcal{O}\left(\lambda^{6}\right)} + \ldots$$

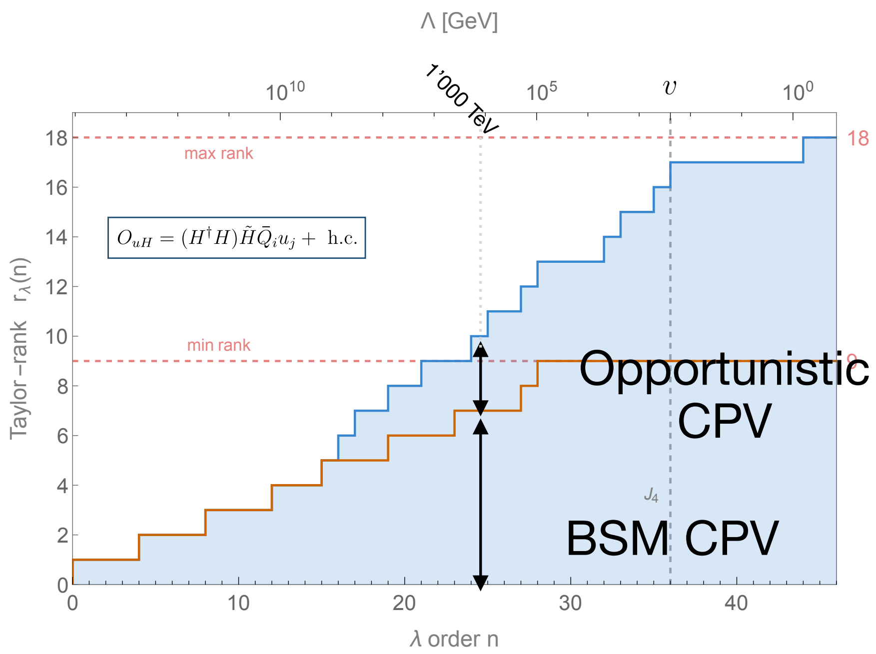
$$I_{1,1} = \mathrm{Im}\ \mathrm{Tr}\left(Y_u^\dagger\left(Y_u Y_u^\dagger\right)\left(Y_d Y_d^\dagger\right) C_{uH}\right)$$

- The BSM invariants are suppressed by scale of new physics
- but not necessarily by small Yukawa/mixing angles as J_4

$$I \sim \boxed{\lambda^n}\boxed{\frac{v^2}{\Lambda^2}} > J_4 \sim \lambda^{36} \leftrightarrow \Lambda < \lambda^{n/2-18}\ v$$

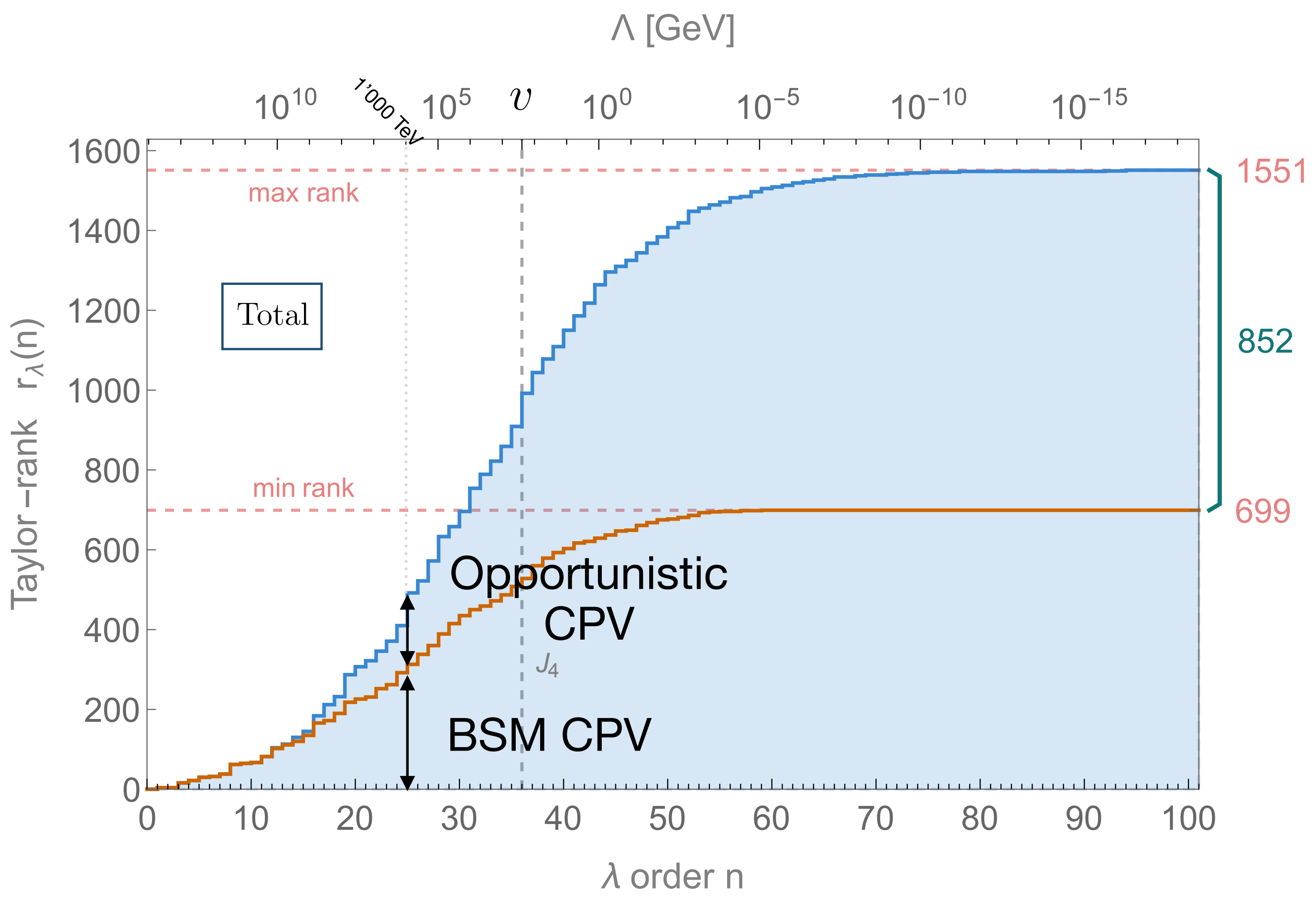
Λ~1'000 TeV → 7 BSM and 3 Opportunistic invariants larger than J_4

independent invariants at O(λⁿ)



Scaling of Collective CPV BSM Effects

independent invariants at O(λ^n) for dim-6 operators



maximal basis

(interference with CKM)

minimal basis

("new phases")

Λ~1'000 TeV → ~250 BSM and ~250 Opportunistic invariants larger than J_4

Models of Flavours

Beyond generic flavour model: MFV

- Other constraints from CP-even observables: totally flavour generic/anarchic dim-6 operators are severely constrained. How do additional flavour structure affect the orders of CPV computed above in the generic case?

- Let’s first stick to the canonical flavour “model”: Minimal Flavour Violation

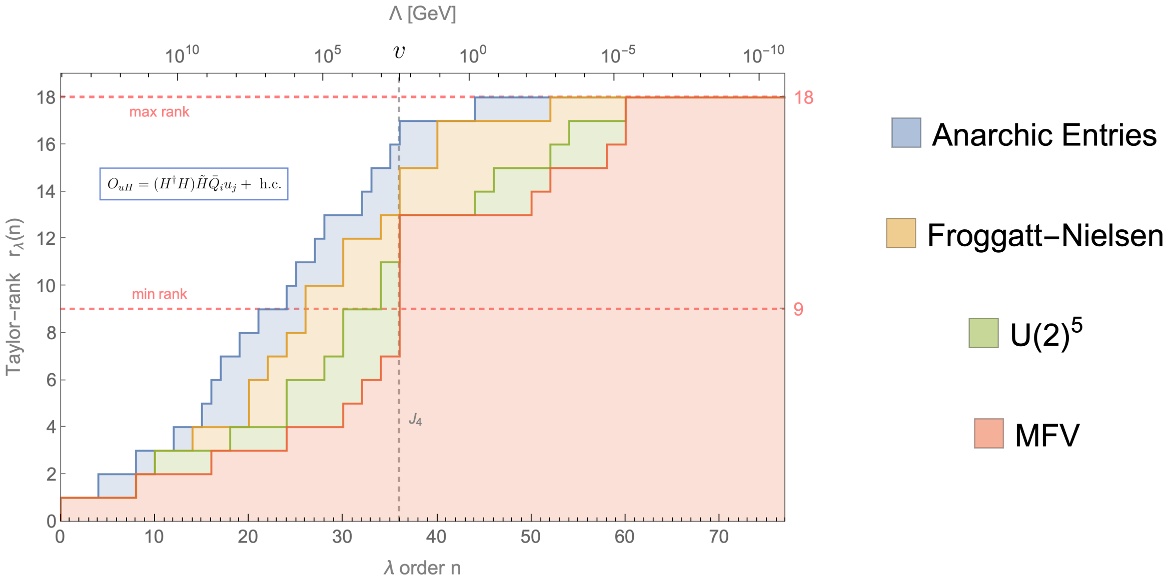
$$c_{uH} = aY_u + b\left(Y_u Y_u^\dagger\right) Y_u + c\left(Y_d Y_d^\dagger\right) Y_u + \dots$$

Generic Flavour

$\text{Rank } 1 \rightarrow \mathcal{O}\left(\lambda^0\right)$
$\text{Rank } 2 \rightarrow \mathcal{O}\left(\lambda^4\right)$
$\text{Rank } 3 \rightarrow \mathcal{O}\left(\lambda^8\right)$
$\vdots$

MFV

$\text{Rank } 1 \rightarrow \mathcal{O}\left(\lambda^0\right)$
$\text{Rank } 2 \rightarrow \mathcal{O}\left(\lambda^8\right)$
$\text{Rank } 3 \rightarrow \mathcal{O}\left(\lambda^{16}\right)$
$\vdots$

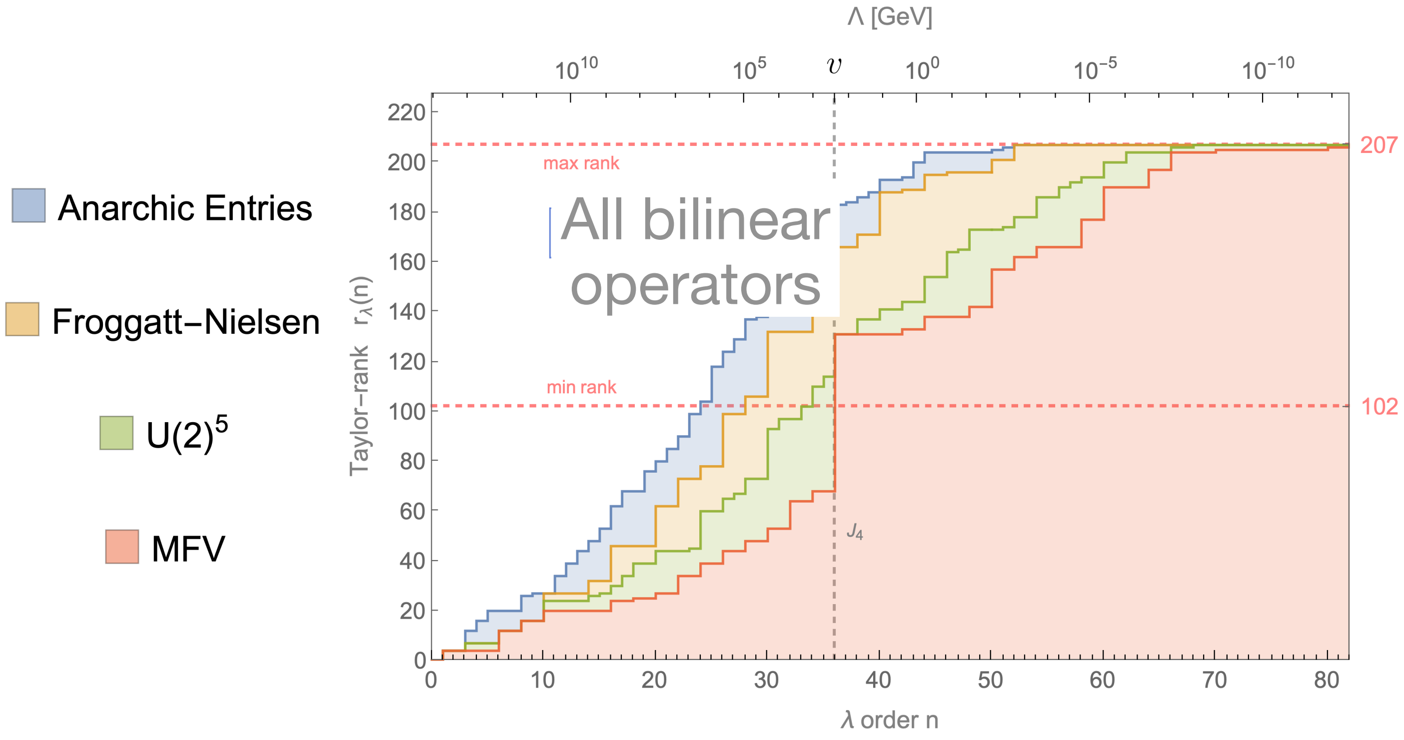


CPV Orders in Alignment Models

Froggatt-Nielsen-type & U(2)³ Flavour Structure

- Another popular flavour structure is alignment inherited e.g. from $U(1)_{FN}$ symmetry
- The U(1) charges of the quarks will imprint a particular scaling of the dim.6 WC:

$$\mathrm{Yu} = \begin{pmatrix} \lambda^8 & \lambda^5 & \lambda^3 \\ \lambda^7 & \lambda^4 & \lambda^2 \\ \lambda^5 & \lambda^2 & 1 \end{pmatrix} \qquad \mathrm{Yd} = \begin{pmatrix} \lambda^7 & \lambda^6 & \lambda^6 \\ \lambda^6 & \lambda^5 & \lambda^5 \\ \lambda^4 & \lambda^3 & \lambda^3 \end{pmatrix} \qquad C_{uH} = \mathrm{generic} = \begin{pmatrix} \lambda^8 & \lambda^5 & \lambda^3 \\ \lambda^7 & \lambda^4 & \lambda^2 \\ \lambda^5 & \lambda^2 & 1 \end{pmatrix}$$



Generic Flavour Structure

Λ >1'000 TeV ⇒ ~120 sources of CPV larger than SM

MFV Flavour Structure

Λ > 5-10 TeV ⇒ ~50 sources of CPV larger than SM

We couldn't explore effects of Flavour assumptions on 4 Fermi operators (too computational intensive)

EFT validity

Can validity of (truncated) EFT be established model-independently?

Problem: Expansion Validity: E/Λ<<1

Contino, Falkowski, Goertz, Grojean, Riva '16
F. Riva, LHCHXSWG '16

Example: Fermi theory $\frac{2}{v^2}\bar{\psi}_{\nu_\mu}\gamma^\mu\psi_\mu\bar{\psi}_{\nu_e}\gamma^\mu\psi_e$ **is it valid up to v=246 GeV?**

No, only to $E = m_W = \frac{g}{2}v \approx 81\ \mathrm{GeV}$ $c_i^6=c_i^8=g^2$

- **Weak couplings reduce the validity range of the EFT (as naively expected)**
- **Strong couplings extend it (for g=4π Fermi theory ok up to E≈3 TeV!)**

$$\mathcal{L} = \underbrace{\frac{g^2}{m_W^2}}_{C_6}\psi^4 + \underbrace{\frac{g^2}{m_W^4}}_{C_8}\partial^2\psi^4 + \dots$$

The full knowledge of the Fermi L_{EFT} could then tell us about the cutoff ($c_6/c_8 = m_W^2$) but this is **model-depend:** one needs to put in some UV assumptions to extract information on the cutoff from the EFT Lagrangian.

Can validity of (truncated) EFT be established model-independently?

Contino, Falkowski, Goertz, Grojean, Riva '16
F. Riva, LHCHXSWG '16

Message #1:
even if we have enough accuracy to reconstruct exactly L_{EFT},
we *cannot* estimate in a model-independent way
the EFT truncation errors

From Observables to L_{EFT}

The question of EFT validity is even more complicated because we don't have directly access to L_{EFT} but only to $|\mathcal{M}|^2, d\sigma \ldots$.

$$\text{observables} \longrightarrow L_{EFT}$$

can be done only from truncated L_{EFT},
and this truncation induces an error.
We need to make sure that the terms omitted in the truncation
don't affect/spoil too much the determination of the terms kept in L_{EFT}.
To answer this question, one obviously needs to make assumption
on scaling of the neglected terms as function of the terms that can be measured.

Message #2:
the estimation of the truncation errors also needs UV assumptions
and can be done only a posteriori
once the bounds on the terms kept have been obtained
(not an excuse for not getting the most precise EFT prediction, NLO etc…)

From Amplitudes to LEFT

Let’s take the simple example of a single BSM particle of mass M_* exchanged in s-channel and with a coupling g_* to the SM.

Contino, Falkowski, Goertz, Grojean, Riva ‘16
Riva, LHCHXSWG ‘16

$$\mathcal{A}(\text{SM+SM} \to \text{SM+SM}) = g_{\rm SM}^2 + \frac{g_*^2 E^2}{E^2 - M_*^2} \approx \underbrace{g_{\rm SM}^2}_{A_{\rm SM}} - \underbrace{\frac{g_*^2 E^2}{M_*^2}}_{A_6} - \underbrace{\frac{g_*^2 E^4}{M^4}}_{A_8} + \dots$$

($c_6 = g_*^2/M_*^2, c_8 = g_*^2/M_*^4$ as in the Fermi theory)

EFT benchmark for which the EFT validity/error can be estimated from the knowledge of measurements and UV imprints (g_* or M_*)

“error” (A_8 relative to A_6) is clearly controlled by the energy of the process
EXP should report c_6 as a function of characteristic energy of the measurements

LEP/flavour/early LHC: E is implicitly known
HL-LHC/Future Colliders: E should be reported explicitly

important consequence on the design of the analyses (not always that best sensitivity comes from highest bins → control of the systematics over all energy range…)

EFT Validity

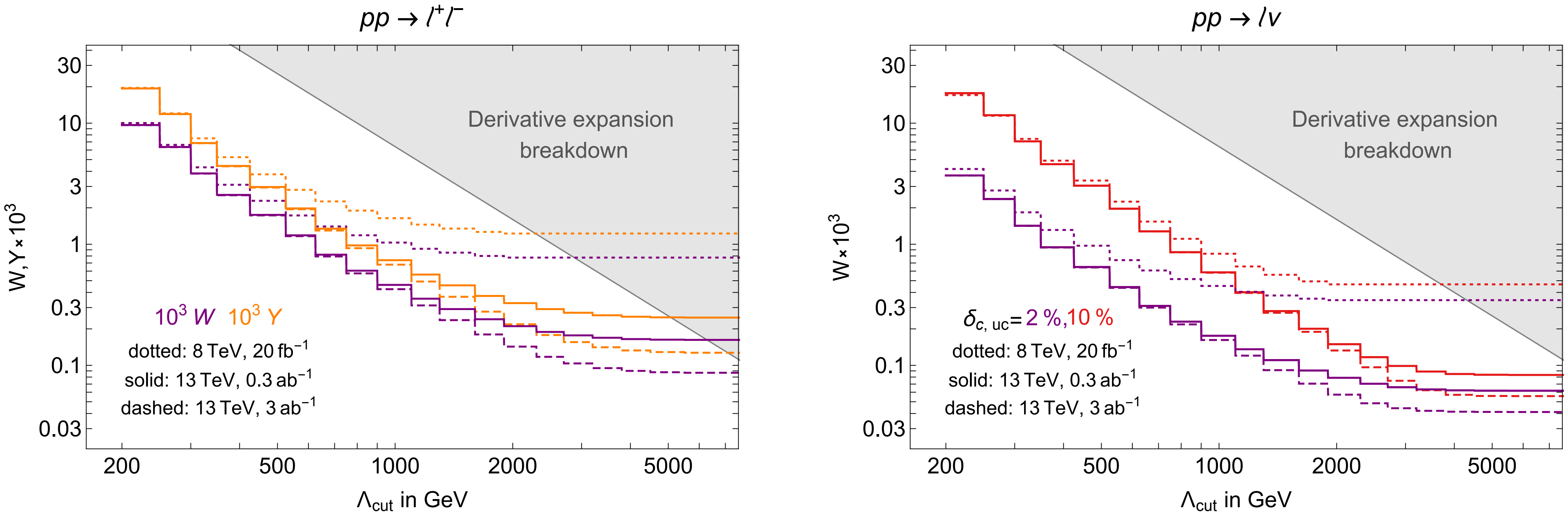
Practical simple recipe #1 in simple EFTs

report the EFT bounds as a function of sliding cut on √ŝ
(or equivalent kinematic variable)

$$G_{(6)} < \delta^{\text{exp}}(M_{\text{cut}})$$

example: Constraints on oblique corrections from Drell-Yan

Farina+ '16   Ricci+ '20



▨

regions where
the coupling of NP
would be larger than 4π
→ expansion not reliable
i.e. large uncertainty
from neglecting
higher dimensional operators

The larger the cut, the stronger the constraints.
But if it is taken too large, no consistent EFT interpretation.
One cannot exclude that, for some measurements, there is simply no possible consistent EFT interpretation.

|dim-6|² ?

Contino+ '16

Formally |dim-6|² ~ (dim4)*(dim-8) ~ 1/Λ⁴
so |dim-6|² is often, erroneously, taken as a proxy for the truncation error.

$$\mathcal{A} = g_{\rm SM}^2 + \bar{c}_6\, g_*^2 \left(\frac{E}{\Lambda}\right)^2 + \bar{c}_8\, g_*^2 \left(\frac{E}{\Lambda}\right)^4 + \dots$$

$\bar{c}_6 \sim \bar{c}_8 \sim \mathcal{O}(1)$

$$|\mathcal{A}|^2 = |\mathcal{A}|^2 \left(1 + \frac{g_*^2}{g_{\rm SM}^2}\,\bar{c}_6 \left(\frac{E}{\Lambda}\right)^2 + \left(\frac{g_*^4}{g_{\rm SM}^4}\,\bar{c}_6^2 + \frac{g_*^2}{g_{\rm SM}^2}\,\bar{c}_8\right)\left(\frac{E}{\Lambda}\right)^4 + \dots\right)$$

- $g_{\rm SM} < g_*$ ➡ $|\mathcal{A}_6|^2 > \mathcal{A}_{\rm SM} \cdot \mathcal{A}_8$
- $g_* < g_{\rm SM}$ ➡ $|\mathcal{A}_6|^2 < \mathcal{A}_{\rm SM} \cdot \mathcal{A}_8$ should we drop $|A_6|^2$ then?

Notice that: $\mathcal{A}_{\rm SM} \cdot \mathcal{A}_6 \sim \frac{g_{\rm SM}^2 g_*^2}{M_*^2} E^2 > \mathcal{A}_{\rm SM} \cdot \mathcal{A}_8$ so interference dim-8 is not dominating

so keeping $|A_6|^2$ or not has no influence on the final bound

Conclusion:
either $|A_6|^2$ is important and it shd be kept, or it is subdominant and it doesn't hurt to keep it.

|dim-6|^2 ?

Contino+ '16

Formally |dim-6|^2 ~ (dim4)*(dim-8) ~ $1/\Lambda^4$
so |dim-6|^2 is often, erroneously, taken as a proxy for the truncation error.

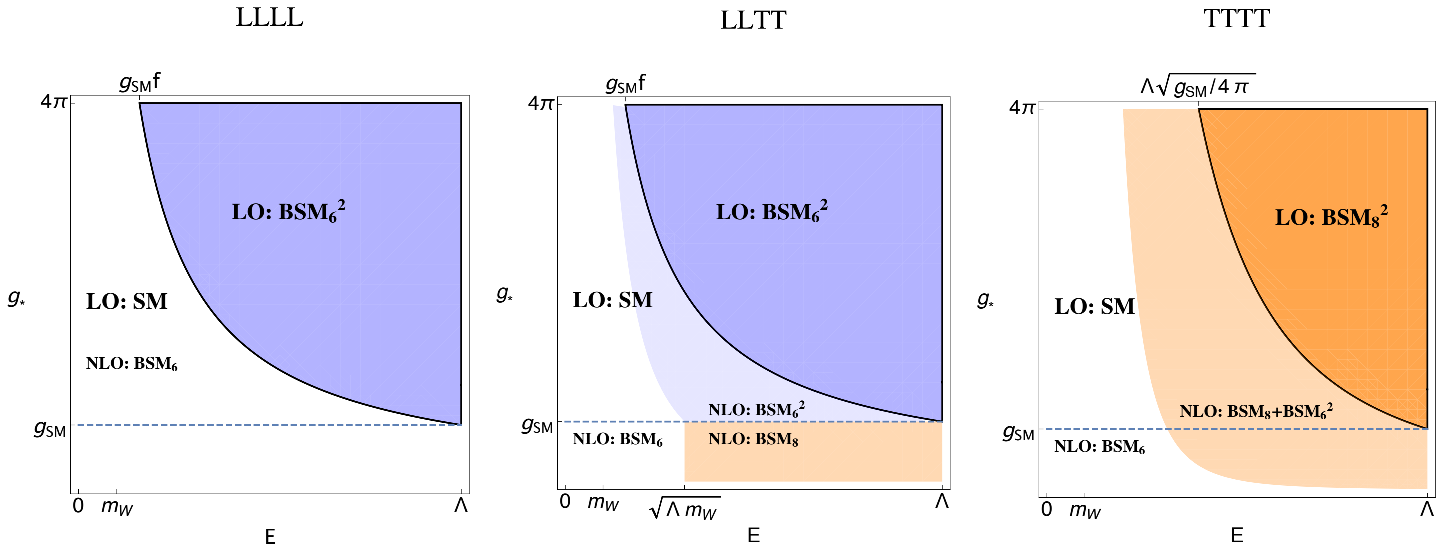
Recipe #2:
Perform a **linear and **quadratic** fits**
If the two fits differ:
either the reach is dominated by high-energy measurements
or the results are valid only in special UV scenarios
(e.g. $g_* > g_{\rm SM}\frac{M}{E}$);
more difficult to make sense of the linear fit.
— Goal of good EFT analysis —
ensure that quadratic and linear fits agree since larger interpretability

Conclusion:
either |A_6|^2 is important and it shd be kept, or it is subdominant and it doesn't hurt to keep it.

|dim-6|^2 ?

There can be (many) exception(s) to the simple general scaling rule

- Mixing with operators with weaker bounds
- SM had accidental/structural cancellation: |dim-6|^2 can dominate over SM*dim-8 even for weakly coupled UV model, e.g. flavour physics
- There is no interference between SM and dim-6 operators, e.g. non-interference theorem, or observable too inclusive (e.g. CP even observable dependence on CP-odd operators): → need to think of particular observables to "resurrect" the interference!



Azatov+ '16

FIG. 2: *A schematic representation of the relative size of different contributions to the $VVVV$ scattering cross sections, with polarization LLLL (left panel), LLTT (central panel) and TTTT (right panel). LO/NLO denote the leading/next-to-leading contributions to the cross section. In the white region the SM dominates and the leading BSM correction comes from the BSM_6-SM interference (denoted as BSM_6). BSM non-interference is responsible for the light-shaded blue and orange regions, where the BSM, although it is only a small perturbation around the SM, is dominated by terms of order E^4/Λ^4, either from $(BSM_6)^2$ or from the BSM_8-SM interference (denoted as BSM_8).*