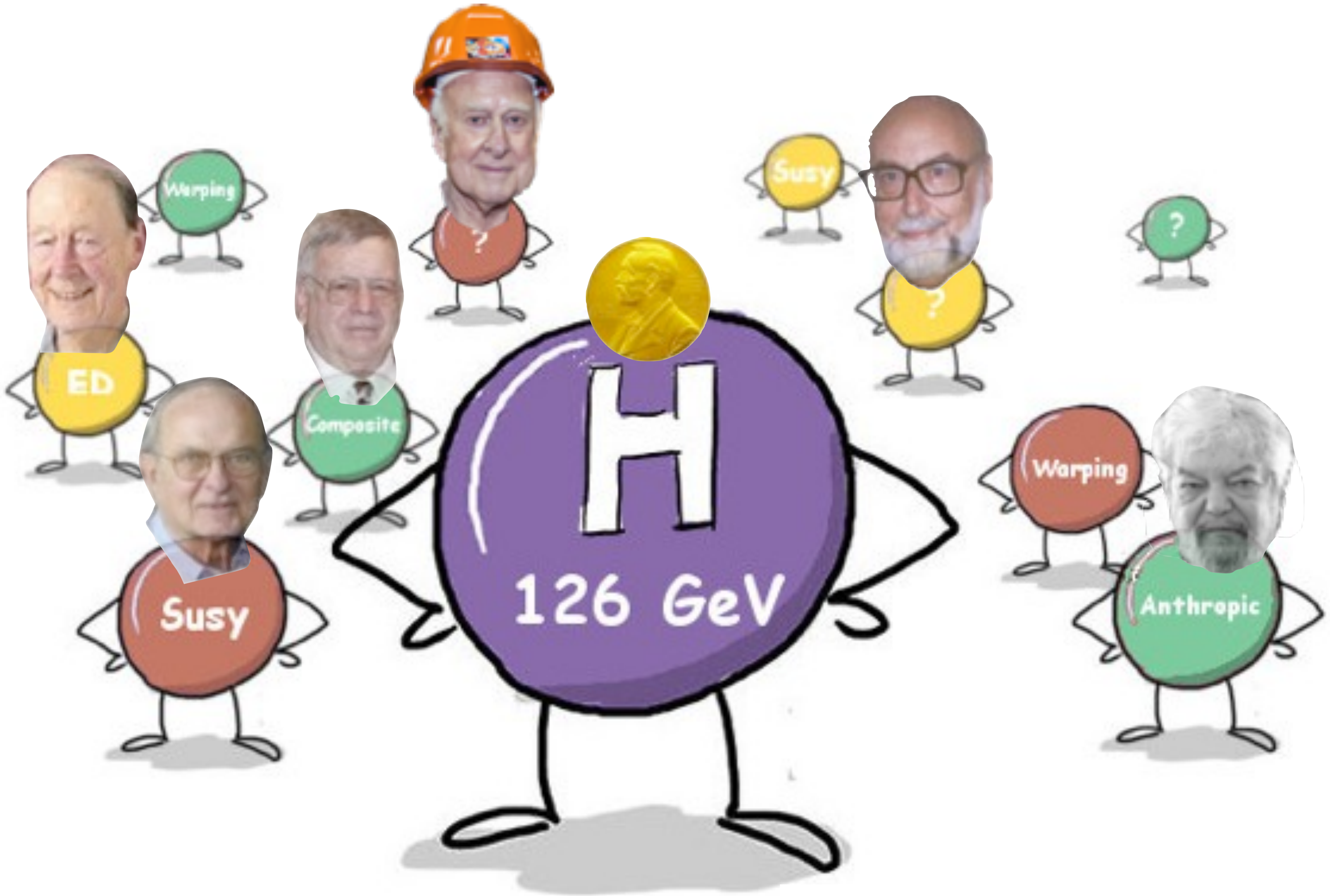
EFT-4-Higgs

Experimental challenges for LHC run II

KITP, Santa Barbara, April 18, 2015



Christophe Grojean

DESY (Hamburg)

(christophe.grojean@desy.de)

What is the Higgs the name of?

~~ Higgs interactions ~~

gauge symmetry is the organizing principle for interactions in the gauge sector not in the Higgs sector ⇛ many free parameters!

but they obey 3 basic structures to unitarize the amplitudes

(1) proportionality: $g_{hff} \propto m_f$ $g_{hVV} \propto m_V^2$

➠ test for extended Higgs sectors

(2) factor of proportionality: $g_{hff}/m_f = \sqrt{2}/v$

➠ test for extended Higgs sectors

➠ test for Higgs compositeness

(3) flavor alignment: $g_{hf_if_j} \propto \delta_{ij}$

➠ test for flavor models, origin of fermion masses

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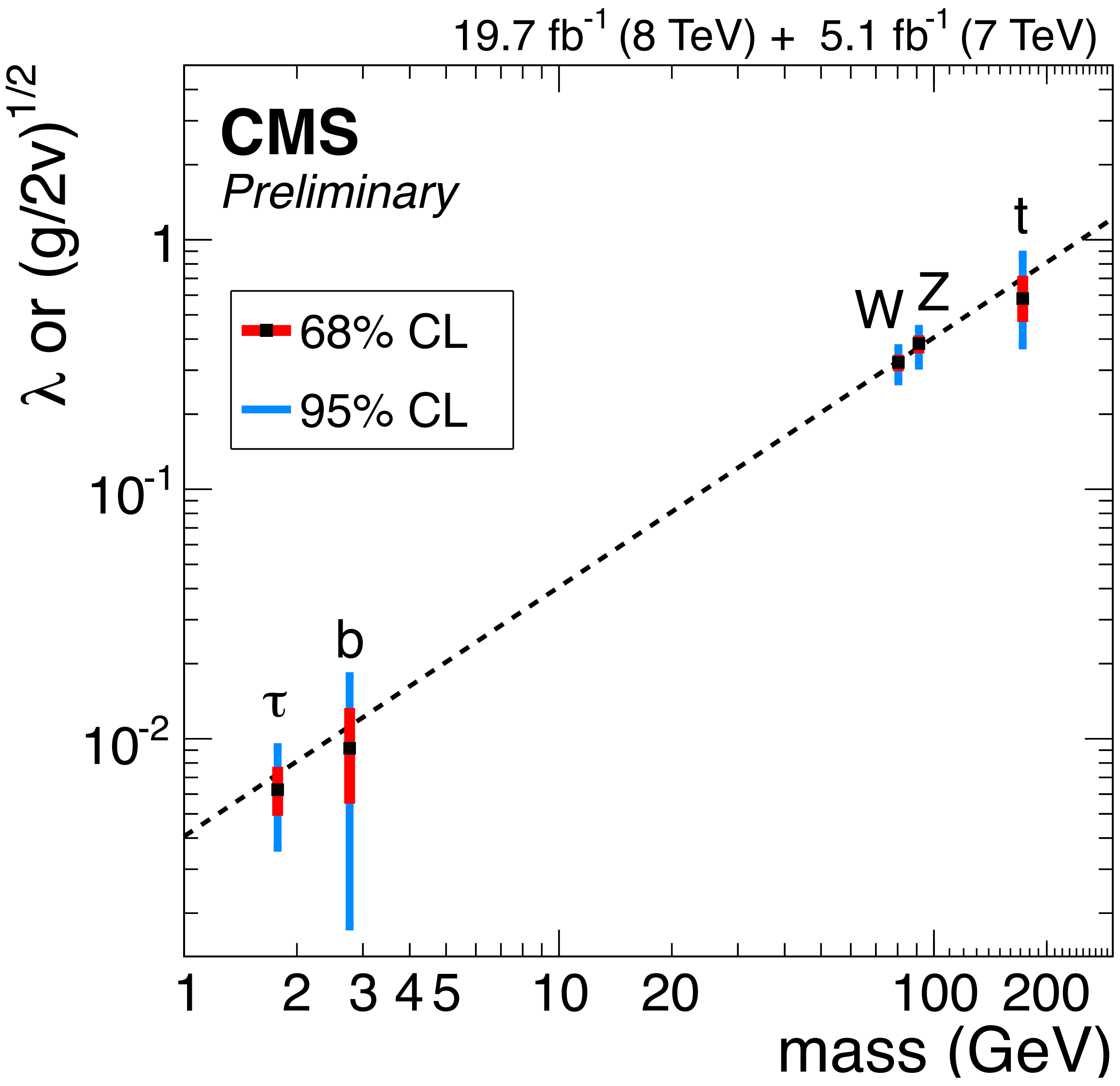

Higgs group @ Snowmass '13

Facility	LHC	HL-LHC
$\sqrt{s}$ (GeV)	14,000	14,000
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_ℓ	$6-8\%$	$2-5\%$
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$

~ Is this fit theoretically consistent? ~

can you generate a 500% deviations

in the bottom coupling without generating other coupling

structures not taken into account in the fit?

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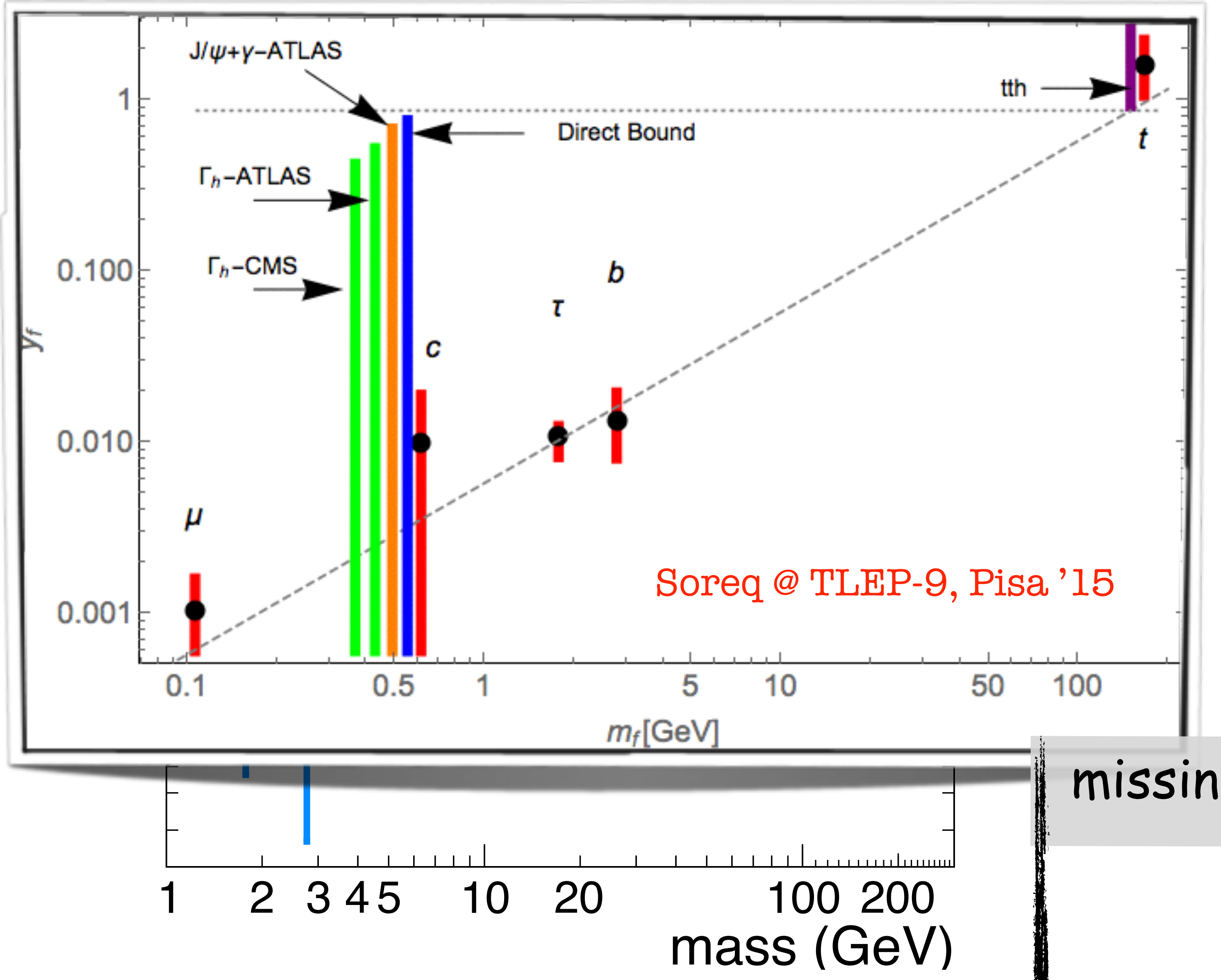
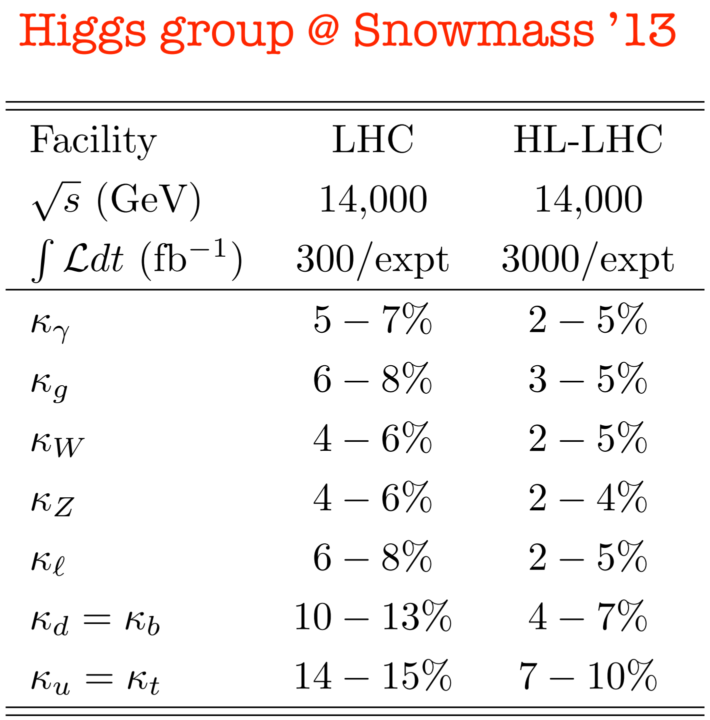


Soreq @ TLEP-9, Pisa '15

Higgs group @ Snowmass '13



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~ Is this fit theoretically consistent? ~

can you generate a 500% deviations

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missing information to complete the picture

° width measurement?

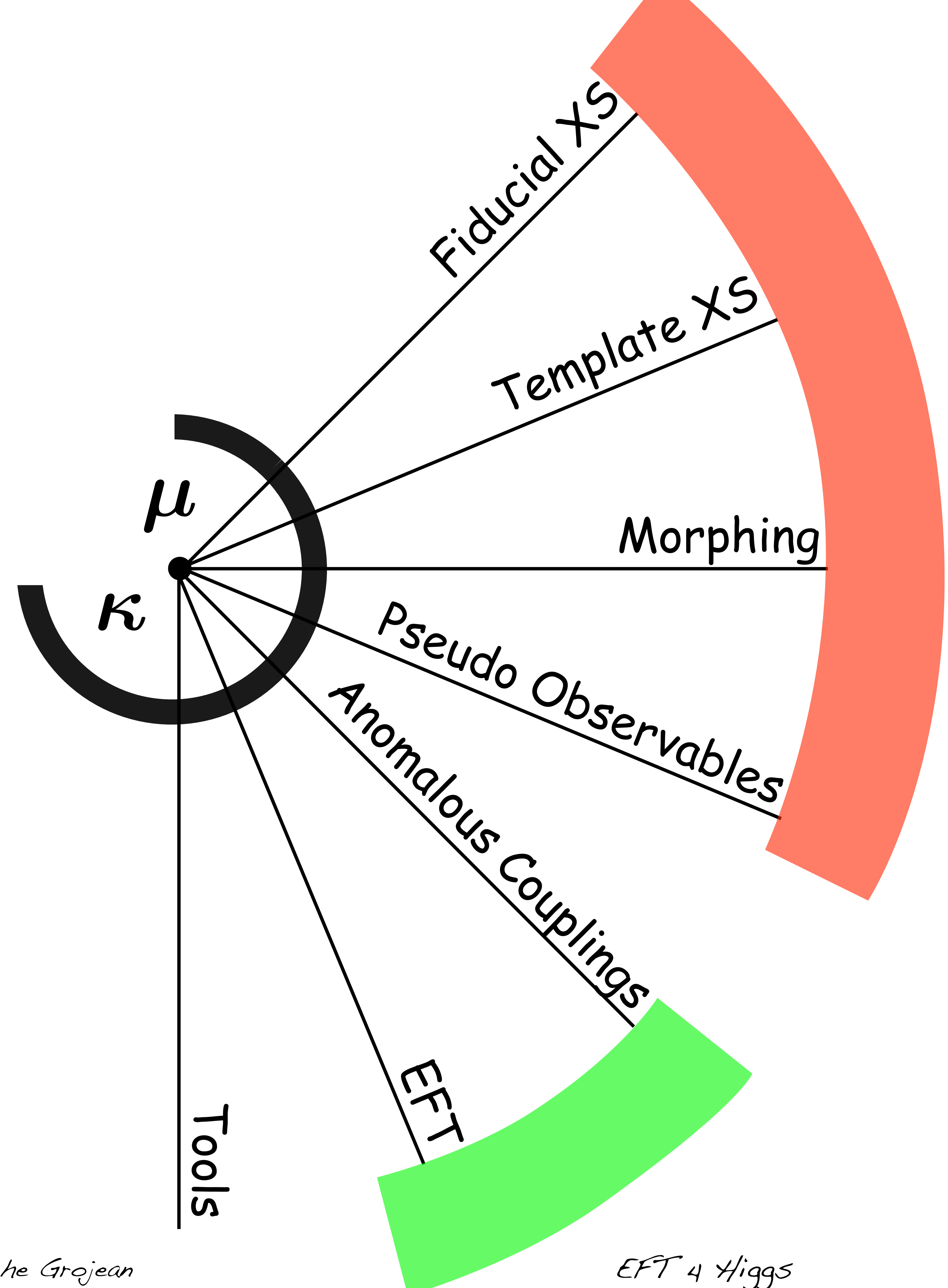
° couplings to light particles?

inclusive (e.g. c-tagging) or exclusive (h → J/Ψ+γ)

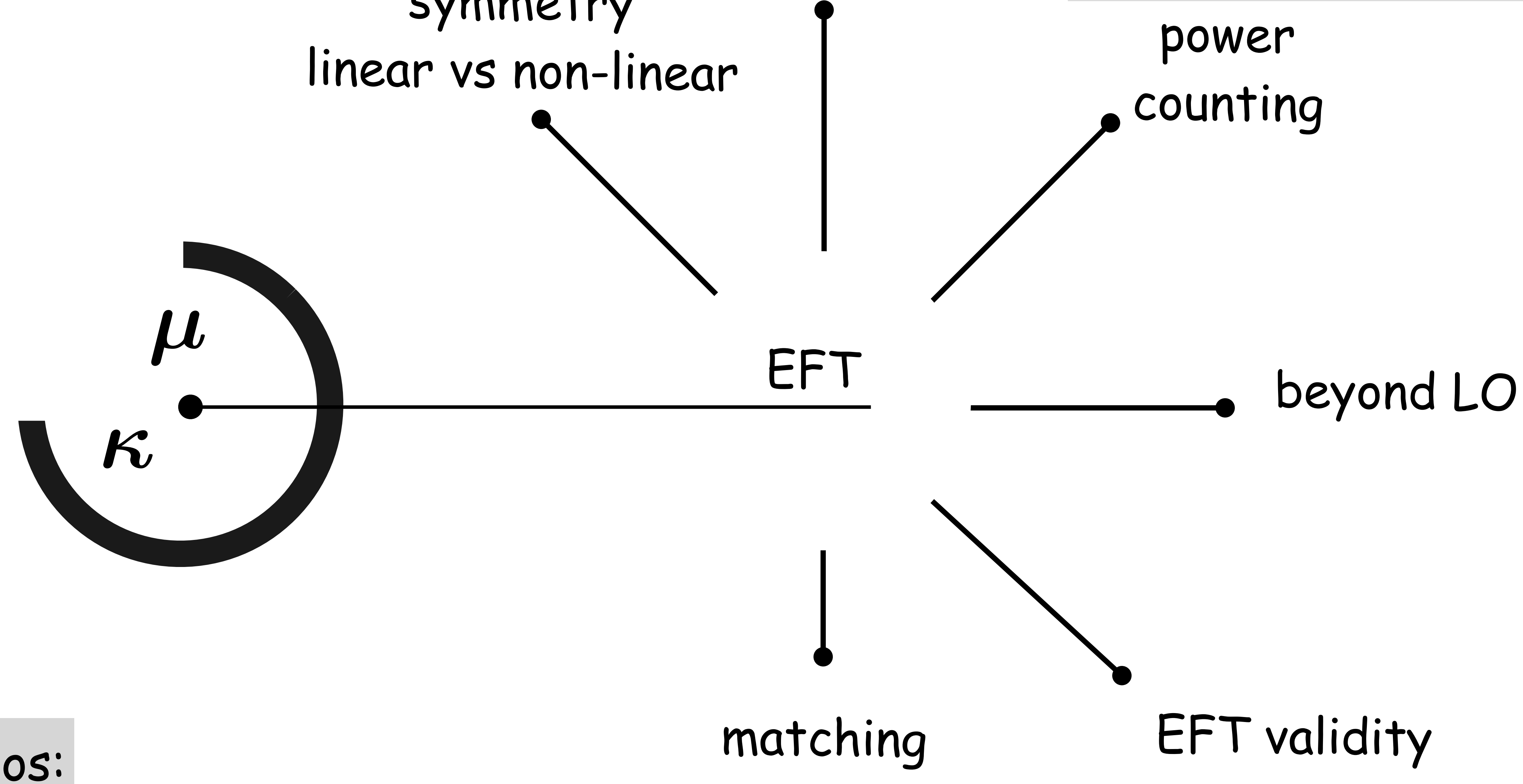
° coupling to top?

known indirectly (gg→h) or via difficult tth channel

Beyond μ & κ



EFT



choice of basis

symmetry
linear vs non-linear

power counting

μ

κ

EFT

beyond LO

matching

EFT validity

Pros:

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

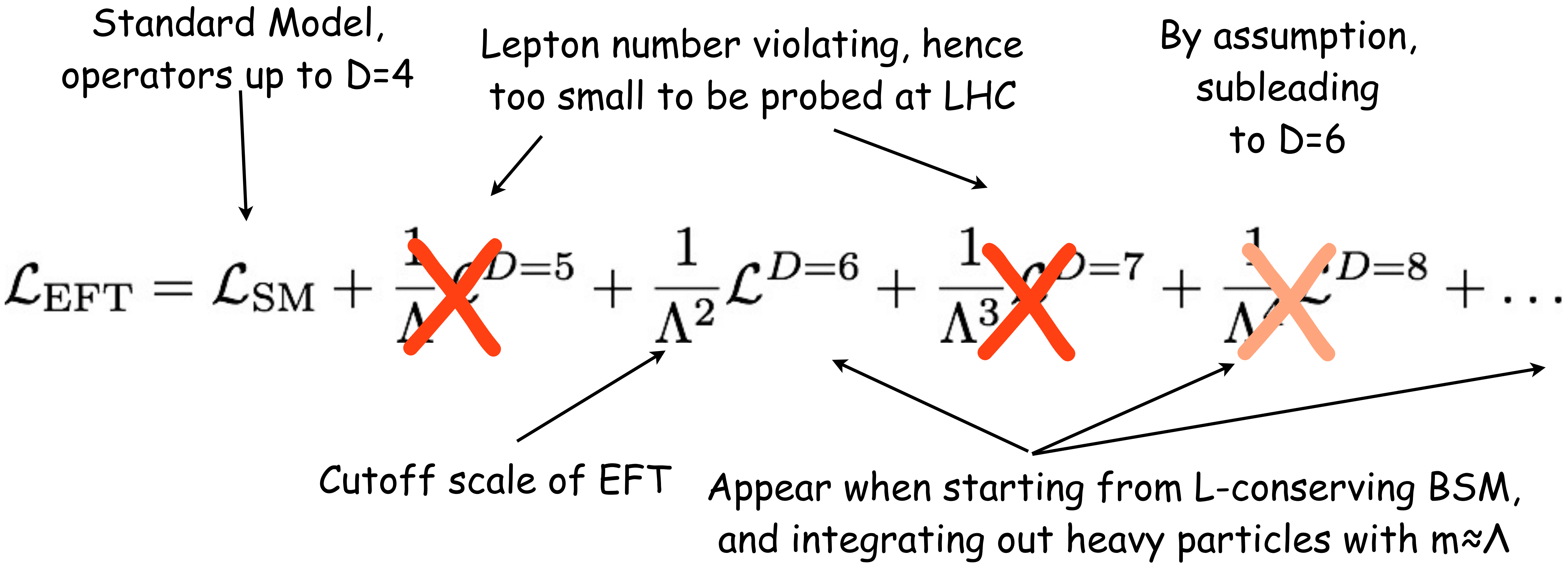
Effective Theory Approach to BSM

Basic assumptions

- New physics scale Λ separated from EW scale v, Λ >> v
- Linearly realized SU(3)xSU(2)xU(1) local symmetry spontaneously broken by VEV of Higgs doublet field

(courtesy of A. Falkowski)

EFT Lagrangian beyond the SM expanded in operators of dimension D



Standard Model, operators up to D=4

Lepton number violating, hence too small to be probed at LHC

By assumption, subleading to D=6

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \cancel{\frac{1}{\Lambda}\mathcal{L}^{D=5}} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \cancel{\frac{1}{\Lambda^3}\mathcal{L}^{D=7}} + \cancel{\frac{1}{\Lambda^4}\mathcal{L}^{D=8}} + \ldots$$

Cutoff scale of EFT

Appear when starting from L-conserving BSM, and integrating out heavy particles with m≈Λ

Effective Theory Approach to BSM

Observable effects of D=6 operators

- Corrections to SM Z and W boson couplings to fermions (so-called vertex corrections)
- Corrections to SM Higgs couplings to matter and new tensor structures of these interactions
- Corrections to triple and quartic gauge couplings and new tensor structures of these interactions
- Contact 4-fermion interactions
- ... and much more

Frontiers of knowledge

Many EFT operators, especially those involving leptons or affecting gauge boson propagators are already strongly constrained by LEP and other low-energy experiments. LHC rarely can compete on this field.

However, other operators, especially those involving Higgs bosons or quarks, are less strongly constrained, which opens opportunity for LHC to improve constraints (or discover new physics)

There are observables where new physics effects grow with energy, which gives the LHC an advantage

(courtesy of A. Falkowski)

EFT = mass scale + coupling

Too often, people think of EFT as higher dimensional operators suppressed by a cutoff scale, but there is also a coupling between new physics and SM

1) validity of EFT

2) relative size of various operators

Example: New physics characterized by one coupling and one-scale

NP

mass scale $M = g_* f$

coupling g_*

SM

EW scale $v=246\text{GeV}$

g, g', y_t

Often thought that effects of dim-6 operators have to be smaller than SM for EFT consistency. This is not true, one can find large deviations still within the validity of the truncation (dim-8<dim-6). One good example is HH production.

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	$-1/2$

tree-level 1-loop 2-loop

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

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

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

v is not simply a mass scale but also a "coupling"

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

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

Examples:

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

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

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

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

Higgs EFT - SILH basis

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 $m_\rho = g_\rho f$)

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

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

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

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

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

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

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

Goldstone sym.
(PGB Higgs)

dimensional analysis + selection rules

Other bases of operators

$1 : X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2 : H^6$	
Q_H	$(H^\dagger H)^3$

$3 : H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5 : \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4 : X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6 : \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

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

$8 : (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8 : (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8 : (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8 : (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8 : (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

many possible choices of operators bases, all equivalent via field redefinitions, equations of motion...

depending on the observable considered some bases might be more convenient than others, and calculations might be easier

N$_F$=1: 59 operators (76 real parameters)
N$_F$=3, 2499 real parameters

Buchmuller Wyler '86

Grzadkowski, Iskrzynski, Misiak,Rosiek '10

Alonso, Jenkins, Manohar, Trott '13

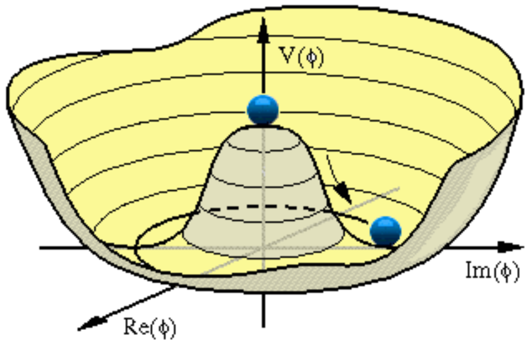
Higgs physics vs BSM

(courtesy of A. Pomarol@Moriond2014)

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

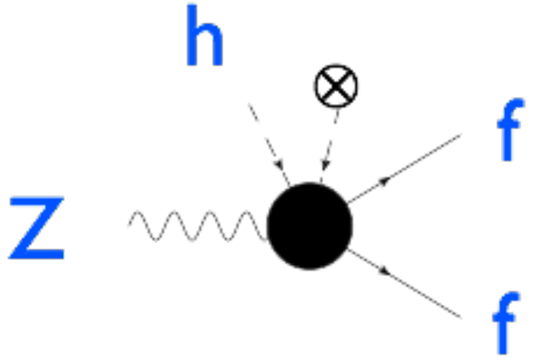
ϕ = v+h

↳ vacuum

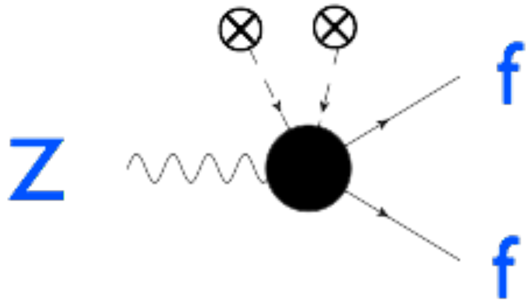


Potentially new BSM-effects in h physics
could have been already tested in the vacuum

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

Higgs/BSM Primaries

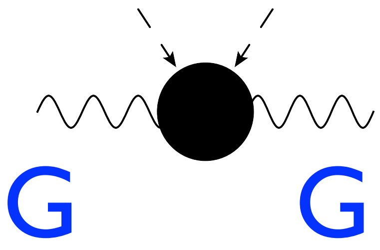
Several deformations away from the SM are harmless in the vacuum and need a Higgs field to be probed

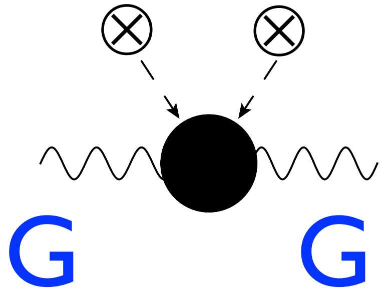
e.g.

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

operator is not visible in the vacuum

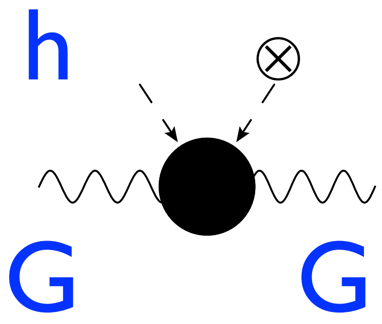
(redefinition of input parameter)





(courtesy of A. Pomarol@HiggsHunting2014)

But can affect h physics:



affects GG →h!

Higgs/BSM Primaries

How many of these effects can we have?

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

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

(assuming CP-conservation)

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

(courtesy of A. Pomarol@HiggsHunting2014)

Higgs/BSM Primaries

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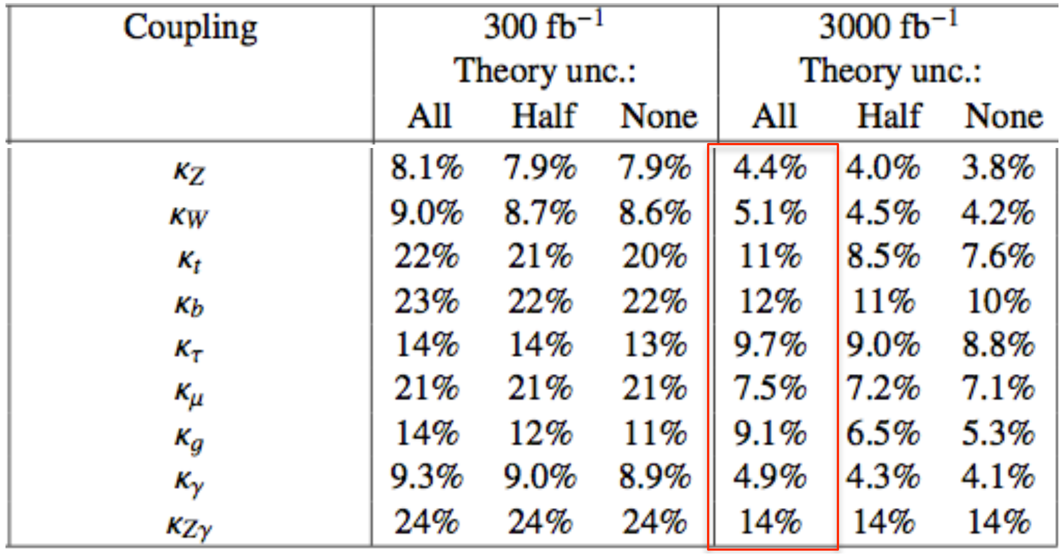
Almost a 1-to-1 correspondence with the 8 κ's in the Higgs fit



Coupling	300 fb^{-1} Theory unc.:			3000 fb^{-1} Theory unc.:		
	All	Half	None	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%

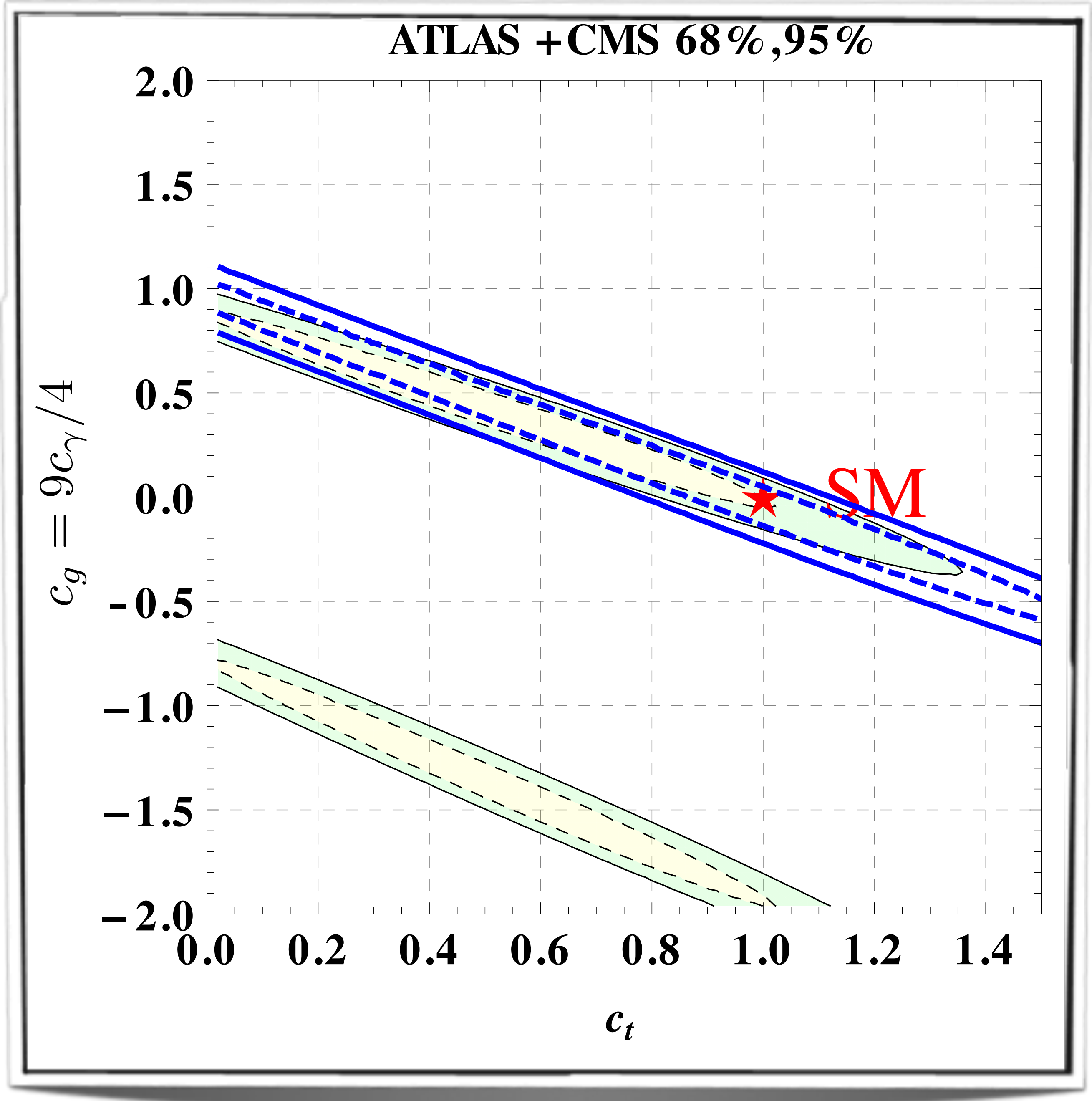
Atlas projection

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

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

Higgs Priorities

1. *Better measurements of Higgs primaries*
   - in inclusive measurements
   - in differential distributions
2. *Going beyond the κ's? What for?*
   - to compete with other (EW, TGC...) measurements?
   - to check the correlations imposed by SM structure?

     e.g. 1) doublet nature of the Higgs,

     2) accidental custodial symmetry @ dim-6 level

~ fully establishing the SM will require checking correlations among different vertices ~

0-Higgs vertices ↔ 1-Higgs vertices (with and beyond the κ's) ↔ 2-Higgs vertices

Higgs Regge's plot is a prime example
Need to look at the correlations with TGC

test of the Ginzburg-Landau's model
test of PGB nature of the Higgs

Questions not fully addressed yet:
what is the precision that you need in Higgs physics?
will the LHC reach this required sensitivity?

EFT validity

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \underset{\nearrow\ \text{Included}}{c_i^{(6)}\mathcal{O}_i^{(6)}} + \sum_j \underset{\uparrow\ \text{Ignored}}{c_j^{(8)}\mathcal{O}_j^{(8)}} + \cdots ,$$

- Under what conditions does EFT with D=6 operators adequately describe low-energy phenomenology of some BSM models?

- When D=8 operators or loop-suppressed D=6 effects are non-negligible?

- How should experiments present EFT results so as to maximize their applicability range?

Can we answer from a bottom-up approach,
i.e. by looking at experimental constraints?

EFT validity

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} + \sum_j c_j^{(8)} \mathcal{O}_j^{(8)} + \cdots ,$$

Included **Ignored**

(courtesy of F. Riva)

Expansion Validity: $E/\Lambda \ll 1$

Experimentally: better access to leading $c_i\, E^2/\Lambda^2$ and not directly to Λ

Truncation depends on $c^{(8)}_i\, E^4/\Lambda^4$

Example: Fermi theory

$$\mathcal{L}_{\text{eff}} = \frac{2}{v^2} (\bar{e}\gamma^\mu \nu_e)(\bar{\nu}_\mu \gamma_\mu \mu)$$

low energy measurements give access to GF, i.e. v, and not the true cutoff $m_W = 1/2\ g\ v$

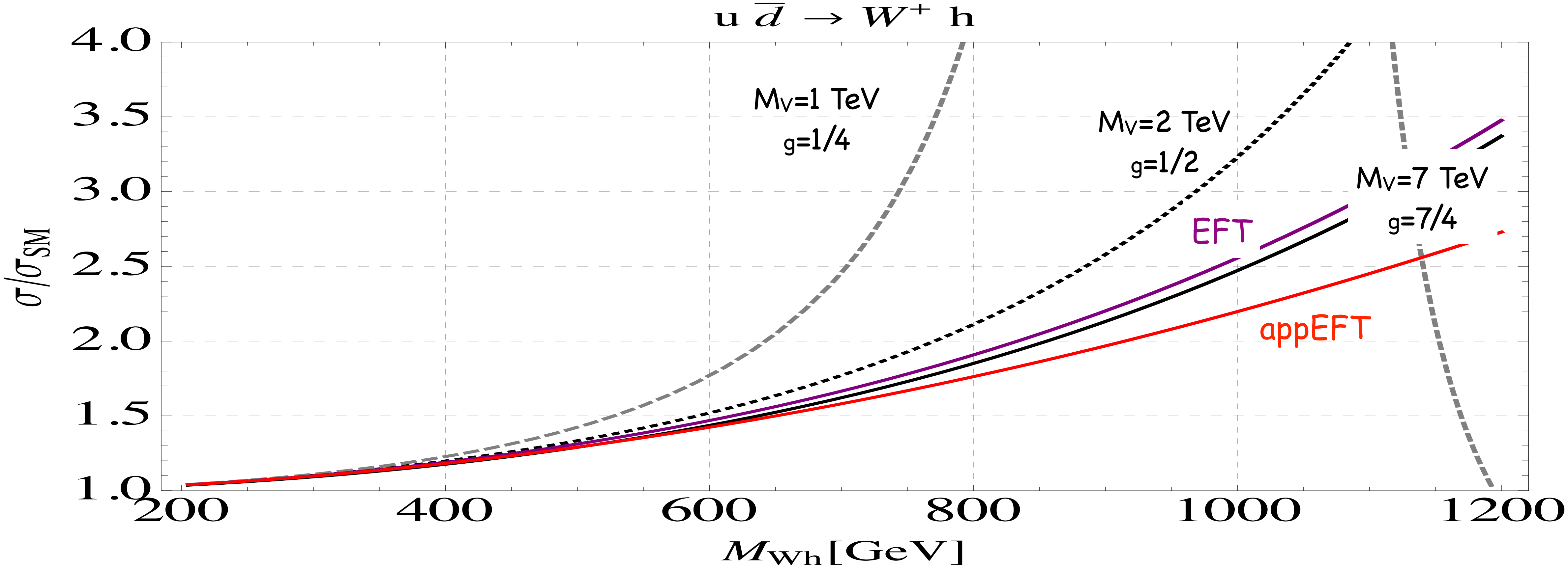
for a fixed deviation to the SM predictions:

Weak couplings reduce the validity range of the EFT (as naively expected)
Strong couplings extend it ($g=4\pi$ Fermi theory would have been valid up to E≈3 TeV)

EFT validity: illustrative example

SU(2)$_L$
heavy vector triplet

$$\mathcal{L} \supset i g_H V^i_\mu H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + g_q V^i_\mu \bar{q}_L \gamma_\mu \sigma^i q_L$$



EFT $M_W \ll M_{Wh} \ll M_V$

$$\frac{\sigma}{\sigma_{SM}} \approx \left(1 - 160\, g_H g_q \frac{v^2}{M_V^2} \frac{M_{Wh}^2}{\text{TeV}^2}\right)^2$$

validity of EFT depends on couplings

- **Strongly coupled:** $M_V = 7$ TeV, $g_H = -g_q = 7/4$
- **Moderately coupled:** $M_V = 2$ TeV, $g_H = -g_q = 1/2$
- **Weakly coupled:** $M_V = 1$ TeV, $g_H = -g_q = 1/4$

3 benchmark models with same EFT behavior

EFT validity: illustrative example

Consider mock measurement of σ(qq → Wh) at LHC at different invariant mass of final state

M_{Wh}[TeV]	0.5	1	1.5	2	2.5	3
$\frac{\sigma}{\sigma_{\rm SM}}$	1 ± 1.2	1 ± 1.0	1 ± 0.8	1 ± 1.2	1 ± 1.6	1 ± 3.0

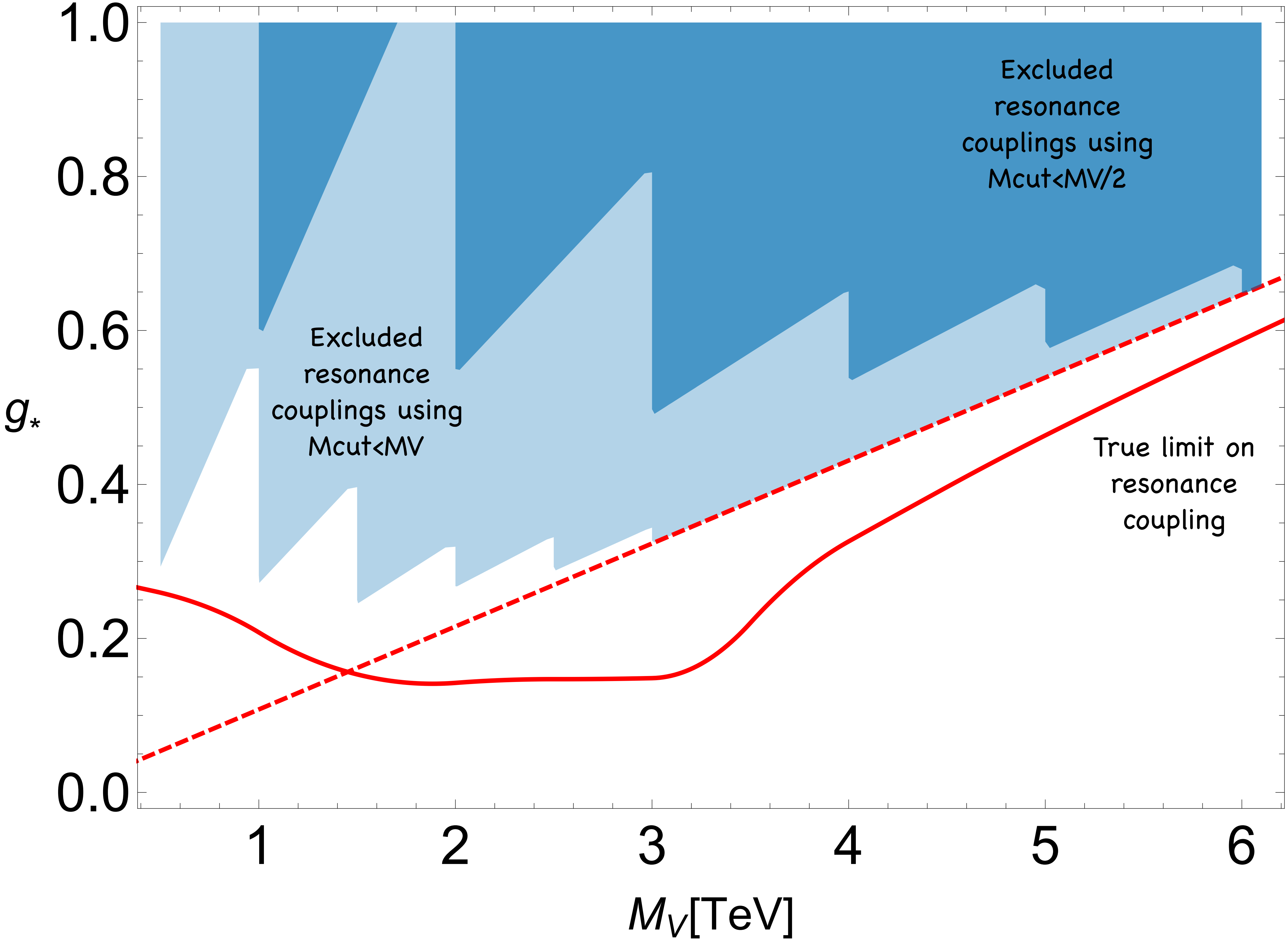
constraints on EFT parameter

$M_{\rm cut}$[TeV]	0.5	1	1.5	2	2.5	3
$-g_H\, g_q \frac{v^2}{M_V^2} [\times 10^{-3}]$	[-70, 20]	[-16,4]	[-7,1.6]	[-4.1,1.1]	[-2.7,0.8]	[-2.2,0.7]

- Different limits correspond to taking into account measurements up to different $M_{\rm cut}$
- Stronger limits on EFT are obtained for larger $M_{\rm cut}$
- However, limits with lower Mcut are also useful, to constrain parameter space of model with M_V < 3 TeV

⚠ one shouldn't include bin $M_{\rm cut} > M_V$, but exp. no access to M_V

EFT validity: illustrative example



limit on $g_*=g_H=-g_q$ include bins up to Mcut = k M_V ⇒ EFT error < k^2

Examples of Higgs EFT analyses

1. Higgs+jet
2. off-shell Higgs
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 (*)

$m_H(\text{GeV})$	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
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) ⇚

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

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

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$^{500}_{500}$-ILC$^{1000}_{1000}$

Boosted Higgs

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

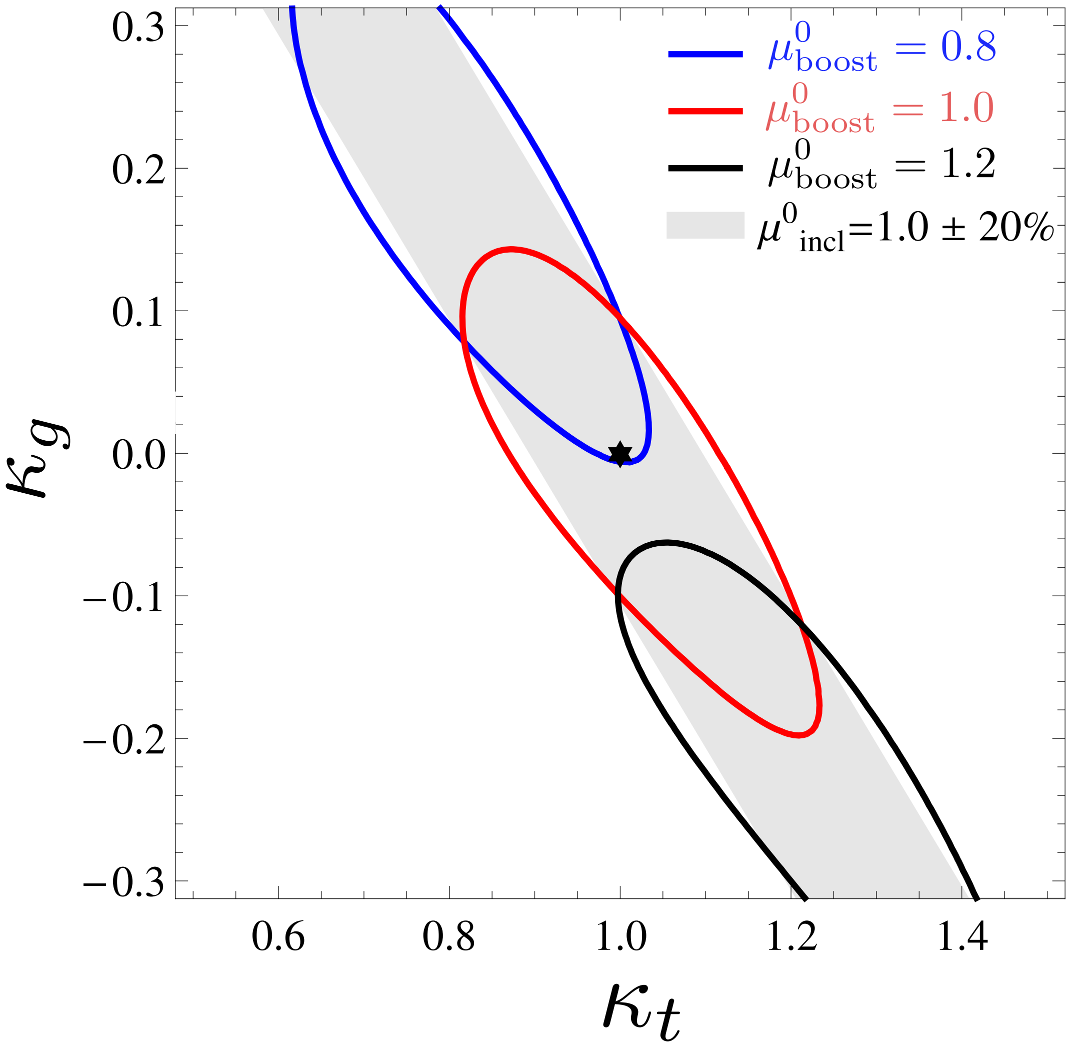
$$\sqrt{s} = 14\ \text{TeV}, \int dt\, \mathcal{L} = 3\text{ab}^{-1}, p_T > 650\ \text{GeV}$$

(partonic analysis in the boosted "ditau-jets" channel)

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

Grojean, Salvioni, Schlaffer, Weiler '13

see also Azatov, Paul '13



10-20% precision on κ_t

⇓ ⇓

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

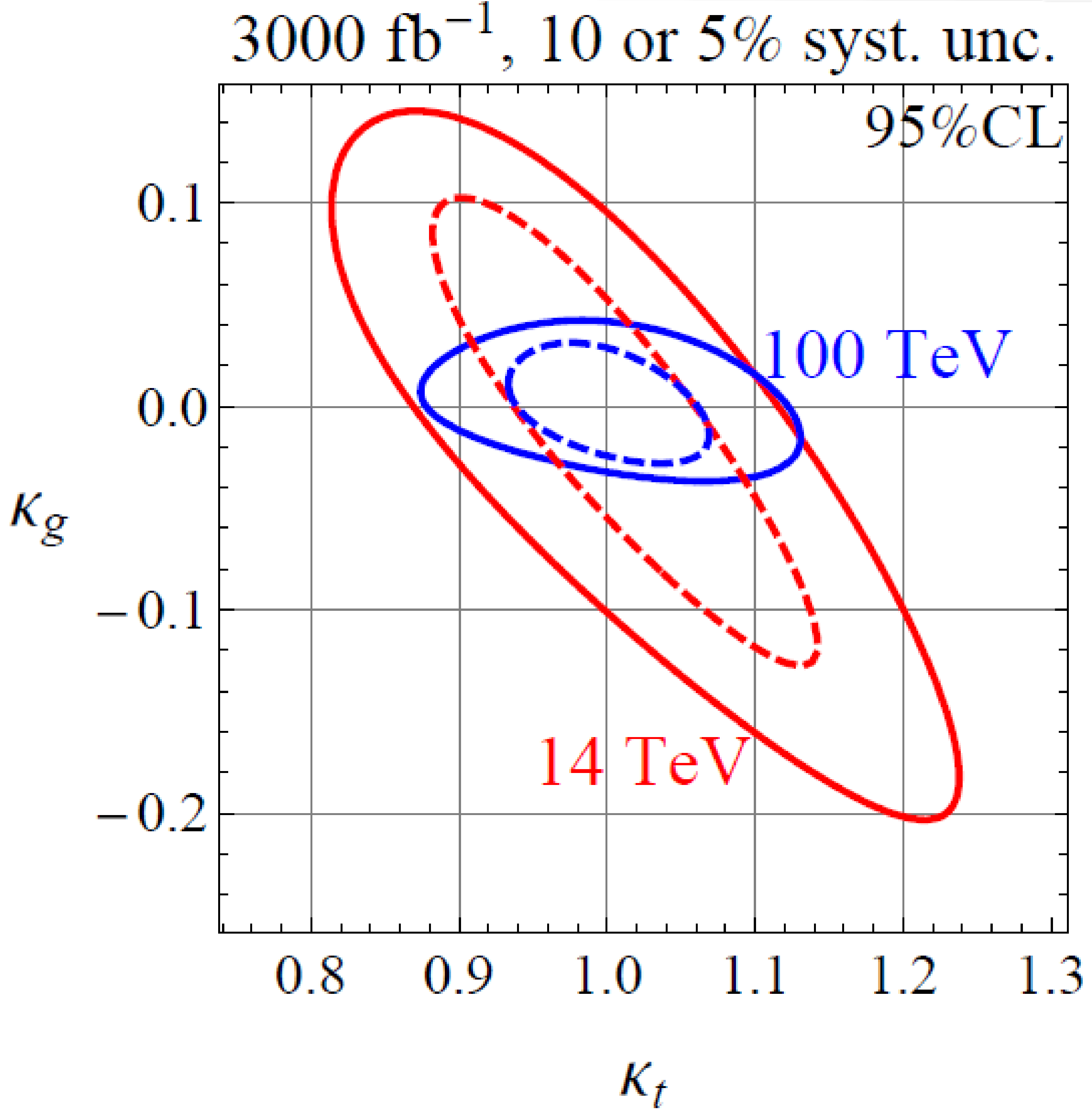
Are the NLO_m QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: $\text{N}^3\text{LO}_\infty$ for inclusive xs or NLO_{mt} for pT spectrum?

Boosted Higgs

see also Azatov, Paul '13

Grojean, Salvioni, Schlaffer, Weiler '13

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



A perfect case for a very energetic machine

$t\bar{t}h$ increases by 10 from 14 to 100TeV

$h+j_{p_T>600\mathrm{GeV}}$ increases by 210

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

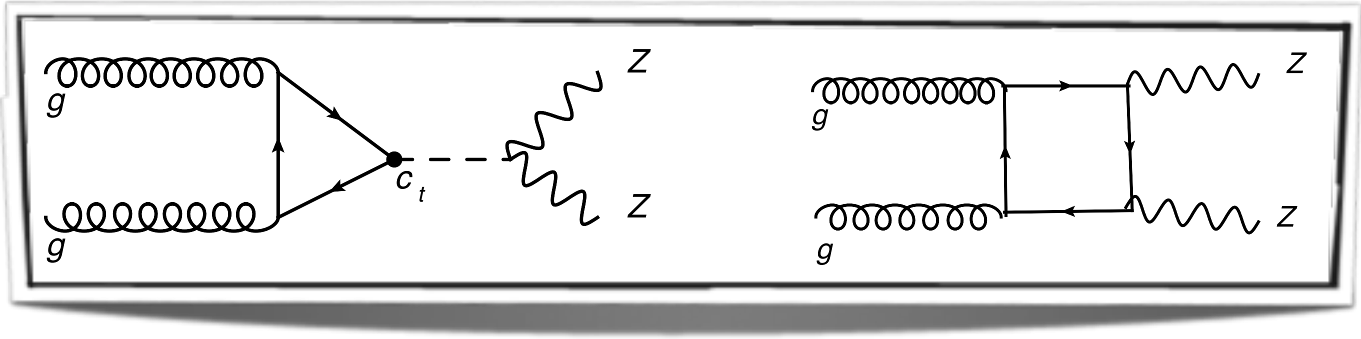
$$\mathcal{R}_{100} = \frac{\sigma(p_T > 2000\ \mathrm{GeV})}{\sigma(p_T > 500\ \mathrm{GeV})}$$

Frontier priority: $\mathrm{N^3LO}_\infty$ for inclusive xs or NLO_{mt} for pT spectrum?

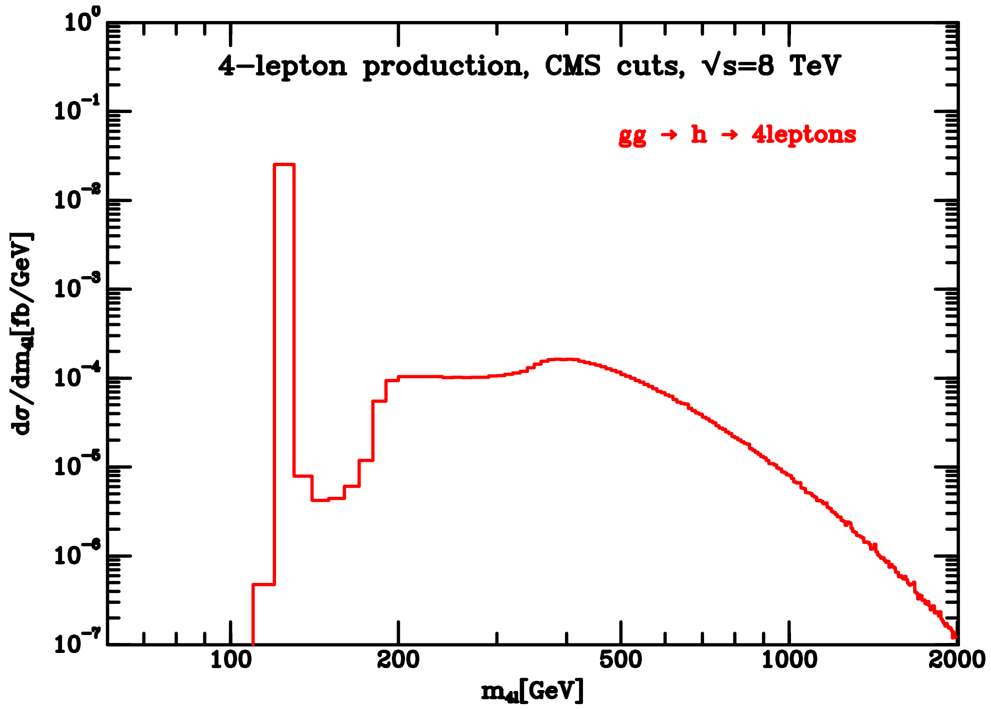
Off-shell Higgs: gg → h* → ZZ → 4l

off-shell effects enhanced by the particular couplings of H to V_L

Glover, van der Bij '89



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



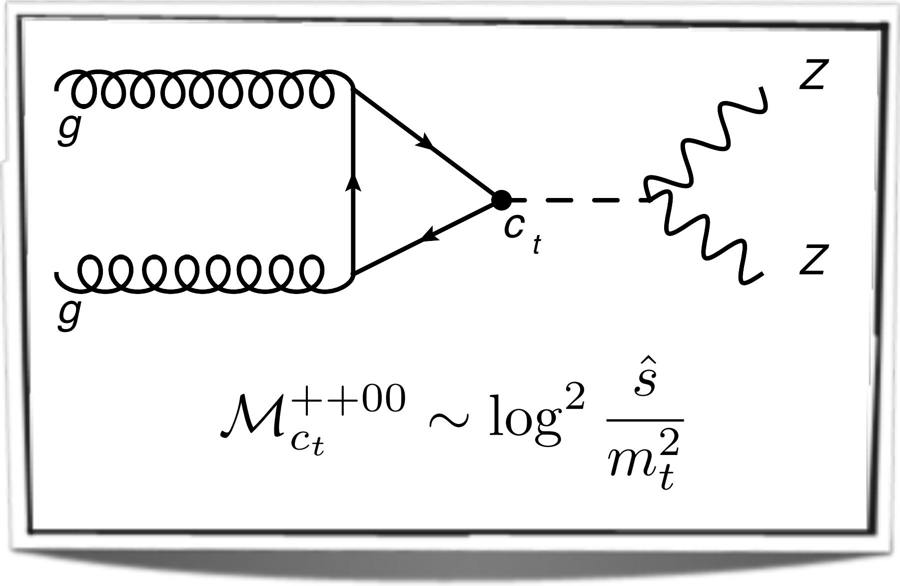
SM: cancelation forced by unitarity

BSM: deviations of Higgs couplings at large s will be amplified

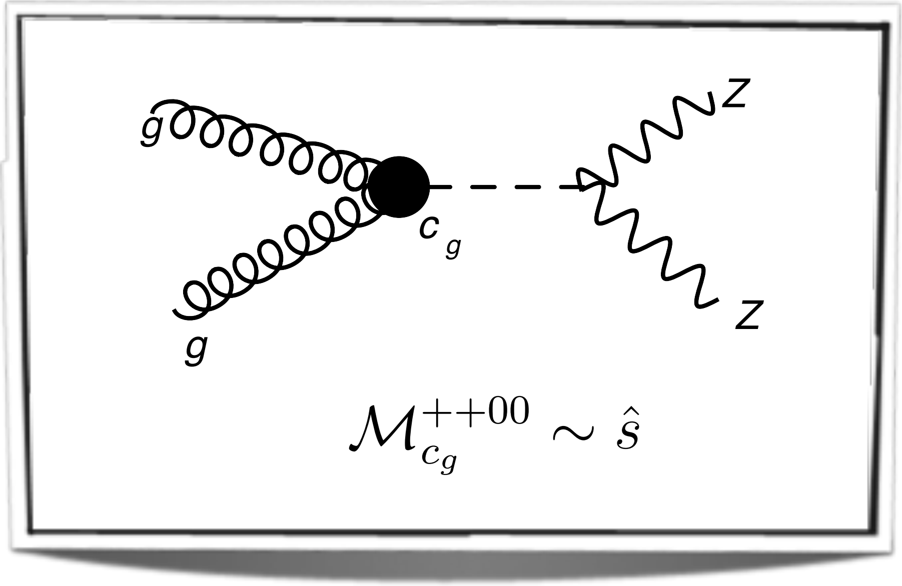
Azatov, Grojean, Paul, Salvioni '14

interpretations in terms of bounds of the Higgs width are limited/model-dependent

but data can be better used to measure the structure of the couplings at high √s



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

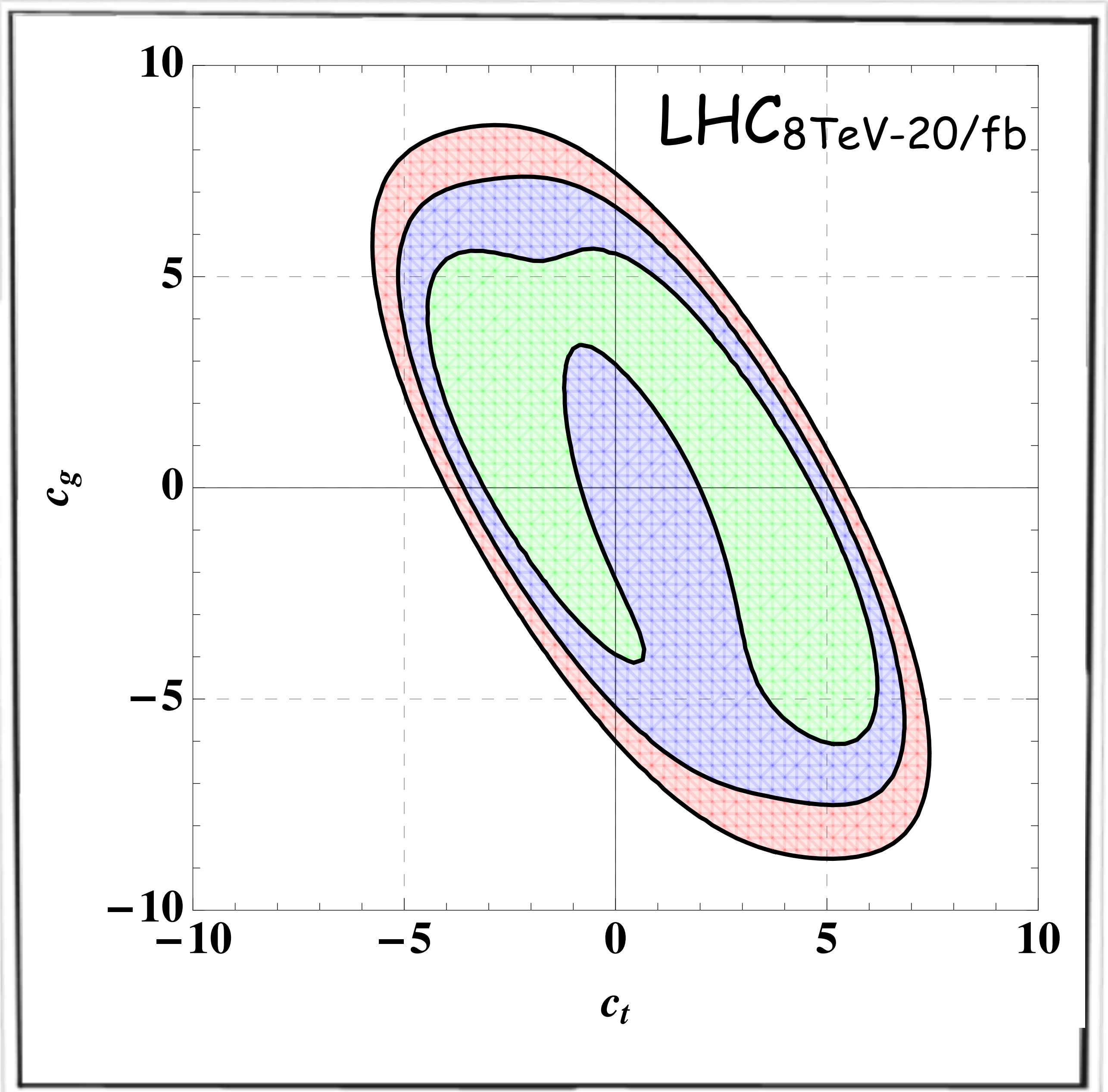


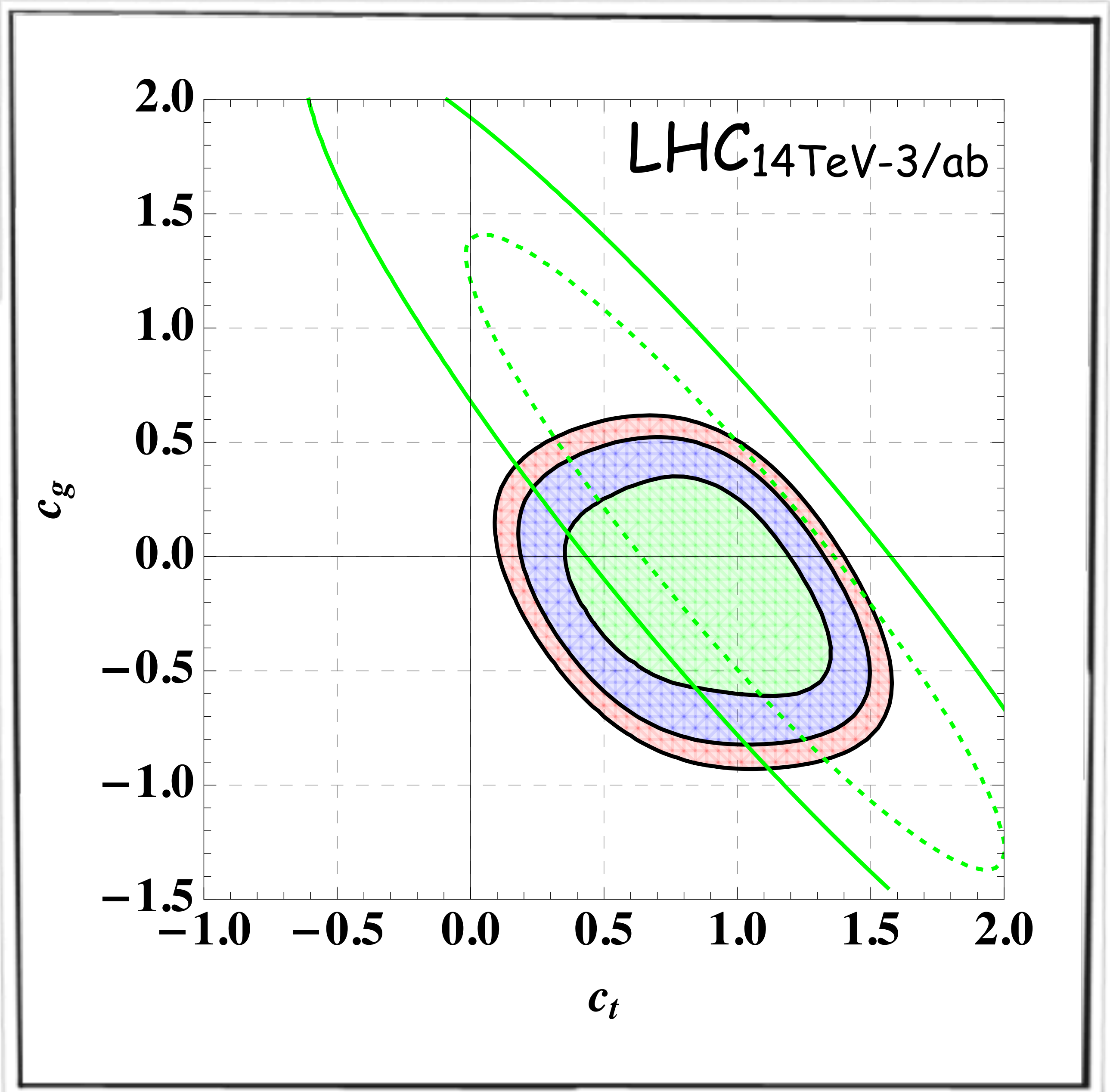
$$\mathcal{M}^{++00}_{c_g} \sim \hat{s}$$

Off-shell Higgs: $gg \to h^* \to ZZ \to 4l$

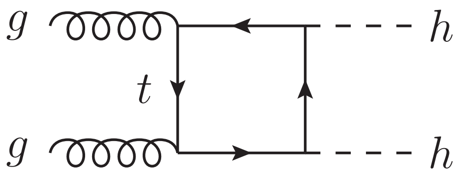
off-shell effects enhanced by the particular couplings of H to V_L

Azatov, Grojean, Paul, Salvioni '14

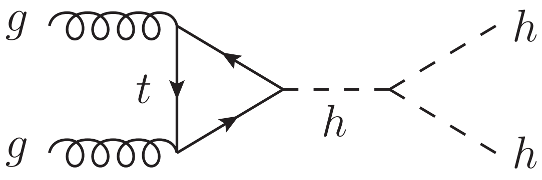




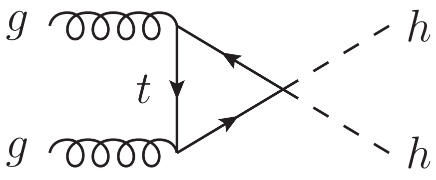
HH production



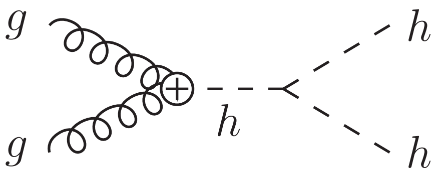
$$\sim c_t^2 \times const.$$



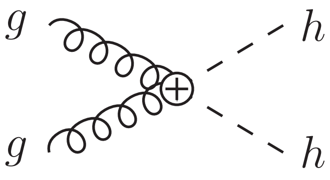
$$\sim c_t c_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$$



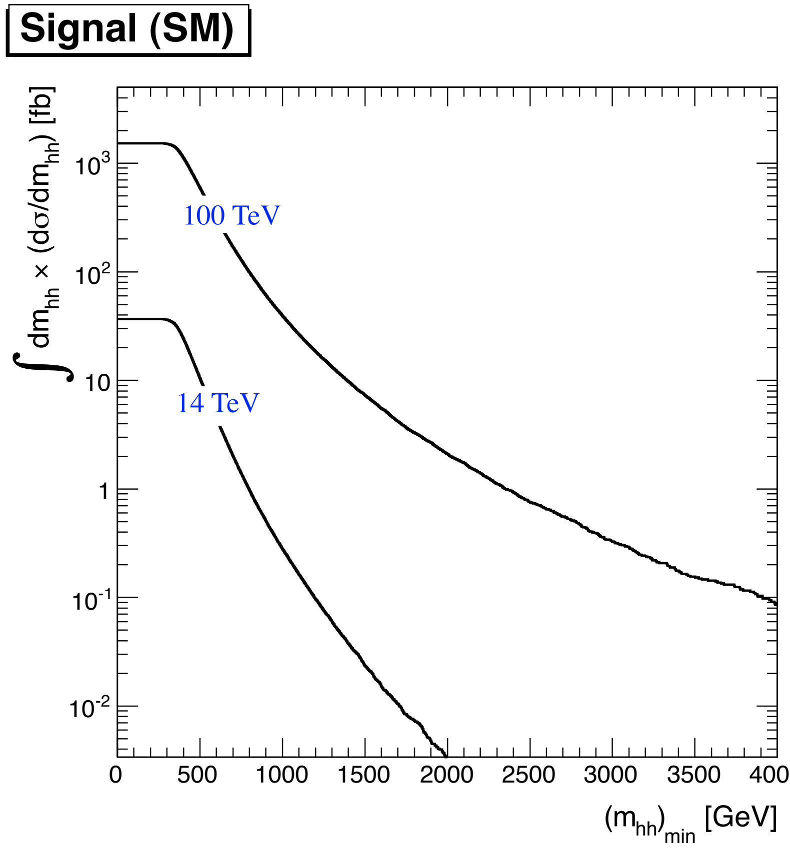
$$\sim c_{2t} \times \log^2\left(\frac{m_t^2}{\hat{s}}\right)$$



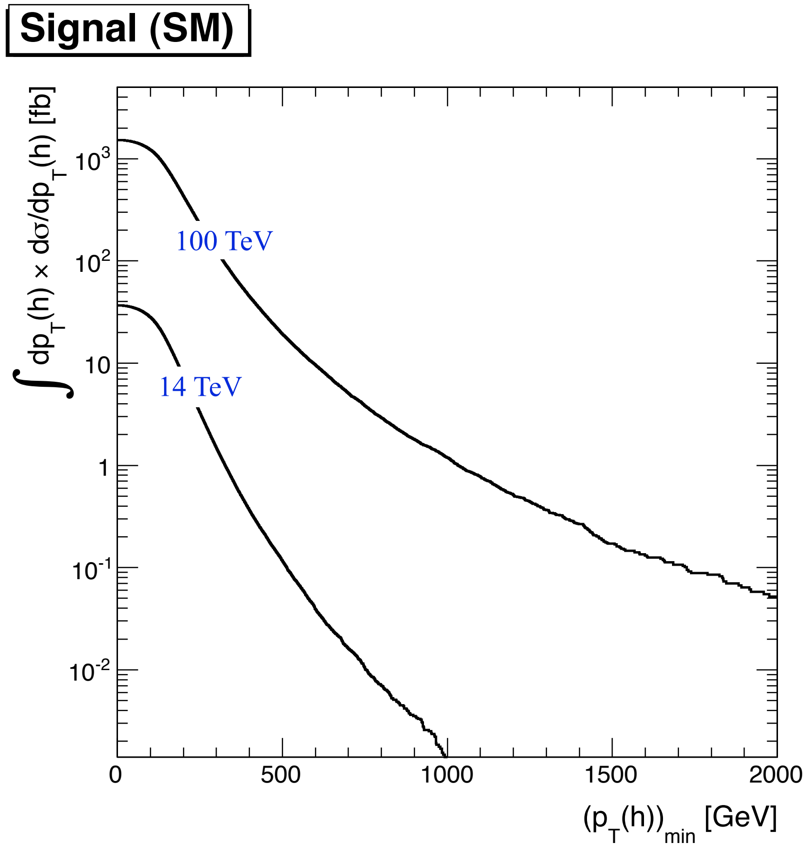
$$\sim c_g c_3 \frac{\alpha_s}{4\pi} \times const.$$



$$\sim c_{2g} \frac{\alpha_s}{4\pi} \frac{\hat{s}}{v^2}$$



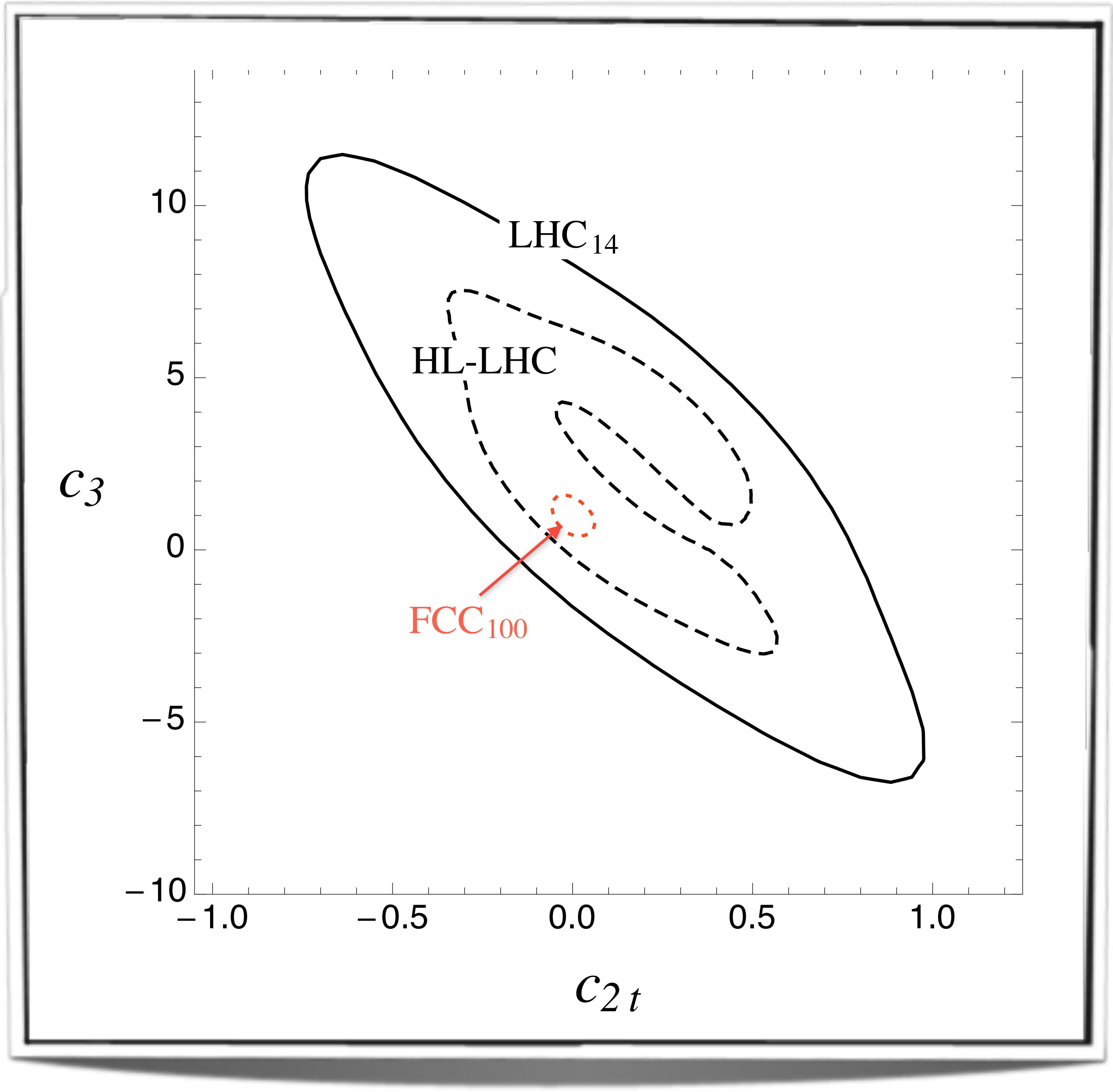
Signal (SM)

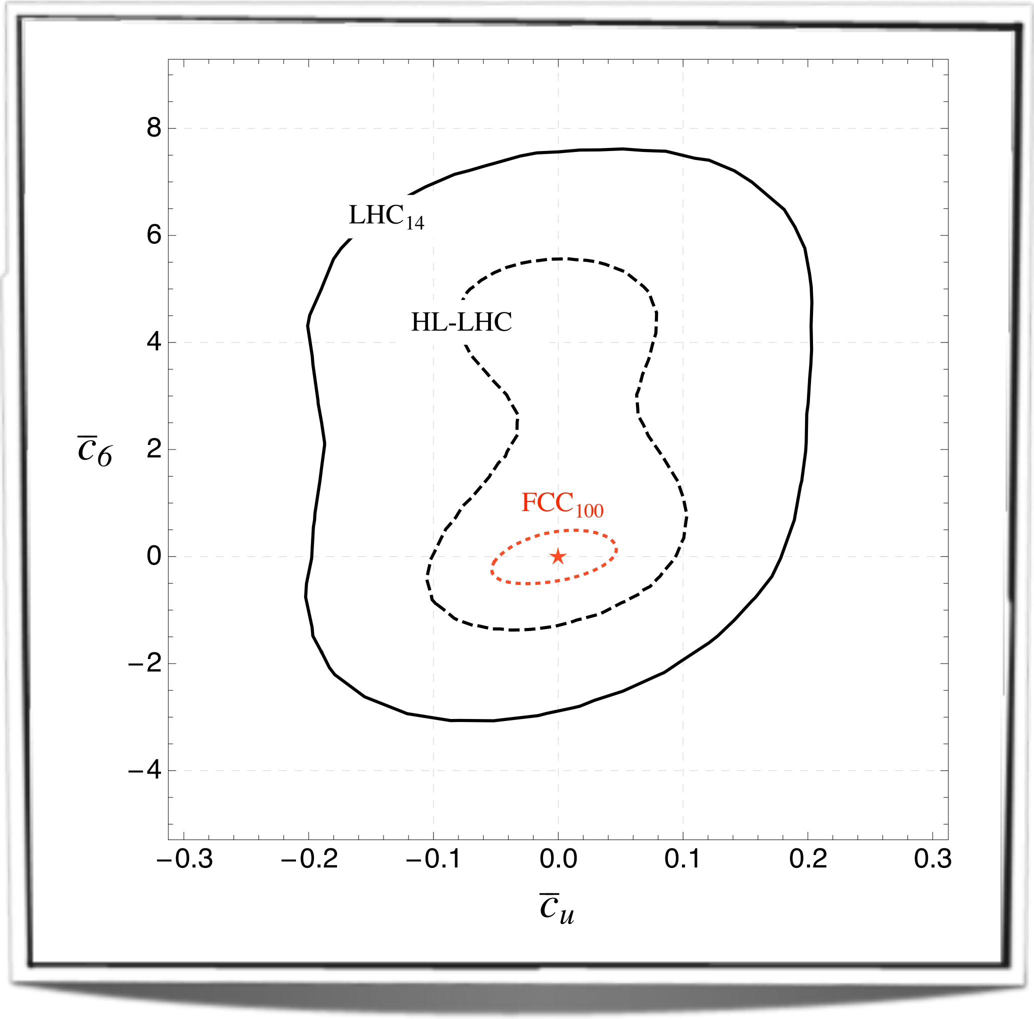


Signal (SM)

Azatov, Contino, Panico, Son ’15

HH production





Azatov, Contino, Panico, Son ’15

see also Goertz, Papaefstathiou, Yang, Zurita ’14

Remarks:

- unique access to c_3 but sensitivity is limited (within the validity of EFT?).
- statistically limited, with more luminosity

  ⇛ access to distribution

  ⇛ discriminating power c_3 vs. c_{2t} vs c_g