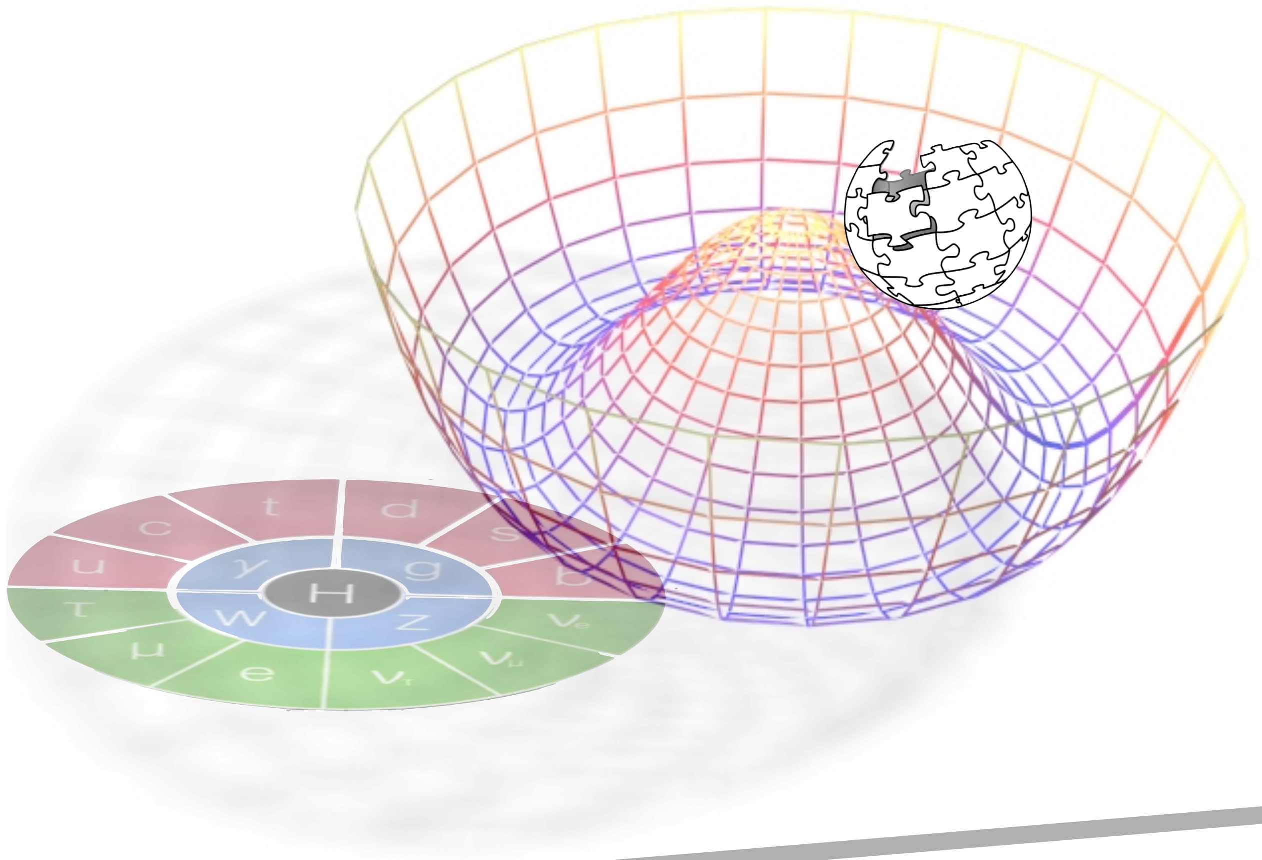
How cubic is the Higgs (self-coupling)?

LLR seminar, March 5, 2018



Christophe Grojean
DESY (Hamburg)
Humboldt University (Berlin)
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Which Higgs?

Which Higgs?

UnHiggs?

Private Higgs?

Gaugephobic Higgs?

Little Higgs?

Littlest Higgs?

Buried Higgs?

Intermediate Higgs?

Higgsless?

Slim Higgs?

Composite Higgs?

Fat Higgs?

Portal Higgs?

Gauge-Higgs?

Lone Higgs?

Twin Higgs?

Phantom Higgs?

Simplest Higgs?

Which Higgs?


UnHiggs?
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High Energy Physics with a Higgs boson

The successes have been breathtaking

- in 6 years, the Higgs mass has been measured to 0.2% (vs 0.5% for the 20-year old top)
- some of its couplings, e.g. κ_γ, have been measured with 1-loop sensitivity (as EW physics at LEP)

High Energy Physics with a Higgs boson

The meaning of the Higgs

Particle physics is not so much about particles but more about fundamental principles

- About 10^{-10}s after the Big Bang, the Universe filled with the Higgs substance because it saved energy by doing so:

"the vacuum is not empty"

(even when $\hbar \to 0$, not a Casimir effect)

- The masses are **emergent** quantities due to a non-trivial **vacuum** structure
- There are only a **finite number** of particles (the SM ones) that acquire their mass via the Higgs vev
- There exists a **new type** (non-gauged) of fundamental **forces**: matter-dependent forces ($e \neq \mu$), e.g. familon, relaxion, Higgs portals...

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Higgs agenda for the LHC-II, HL-LHC, ILC/CLIC, FCC, CepC, SppC, SHiP

multiple independent, synergetic and complementary approaches to achieve **precision** (couplings), **sensitivity** (rare and forbidden decays) and **perspective** (role of Higgs dynamics in broad issues like EWSB and vacuum stability, baryogenesis, inflation, naturalness, etc)

M.L. Mangano, Washington '15

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- rare Higgs decays: $h\to\mu\mu$, $h\to\gamma Z$
- Higgs flavor violating couplings: $h\to\mu\tau$ and $t\to hc$
- Higgs CP violating couplings
- exclusive Higgs decays (e.g. $h\to J/\Psi+\gamma$) and measurement of couplings to light quarks
- exotic Higgs decay channels:

  $h\to \not{E}_T$, $h\to 4b$, $h\to 2b2\mu$, $h\to 4\tau, 2\tau 2\mu$, $h\to 4j$, $h\to 2\gamma 2j$, $h\to 4\gamma$, $h\to \gamma/2\gamma + \not{E}_T$,
  $h\to$isolated leptons+ $\not{E}_T$, $h\to 2l+ \not{E}_T$, $h\to$one/two lepton-jet(s)+X, $h\to bb+ \not{E}_T$, $h\to \tau\tau+ \not{E}_T$ ...
- searches for extended Higgs sectors (H, A, $H^\pm$, $H^{\pm\pm}$...)
- Higgs self-coupling(s)
- Higgs width
- Higgs/axion coupling?
- ...

M.L. Mangano, Washington '15

High Energy Physics with a Higgs boson

The Higgs discovery has been an important milestone for HEP
but it hasn't taught us much about **BSM** yet

typical Higgs coupling deformation: $$\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_*^2\, v^2}{\Lambda_{\rm BSM}^2}$$

current (and future) LHC sensitivity
O(10-20)% ⇔ Λ_{BSM} > 500(g_*/g_{SM}) GeV

not doing better than direct searches unless in the case of strongly coupled new physics
(notable exceptions: when New Physics breaks some structural features of the SM
e.g. flavor number violation as in $h\to\mu\tau$)

Higgs precision program is very much wanted
to probe BSM physics

How to report Higgs data: from κ to EFT

LHCHXSWG '12

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

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

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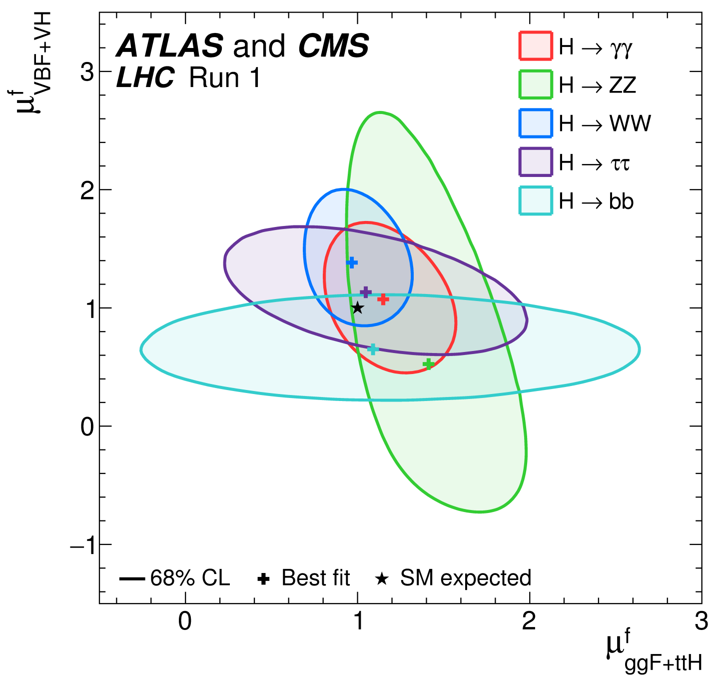
$$\mu_i = \frac{\sigma[i \to h]}{(\sigma[i \to h])_{\rm SM}}$$

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



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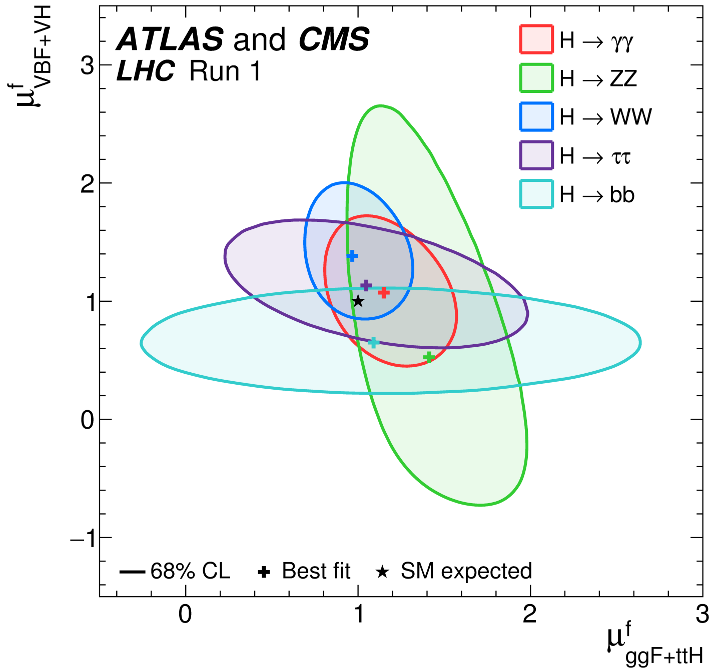

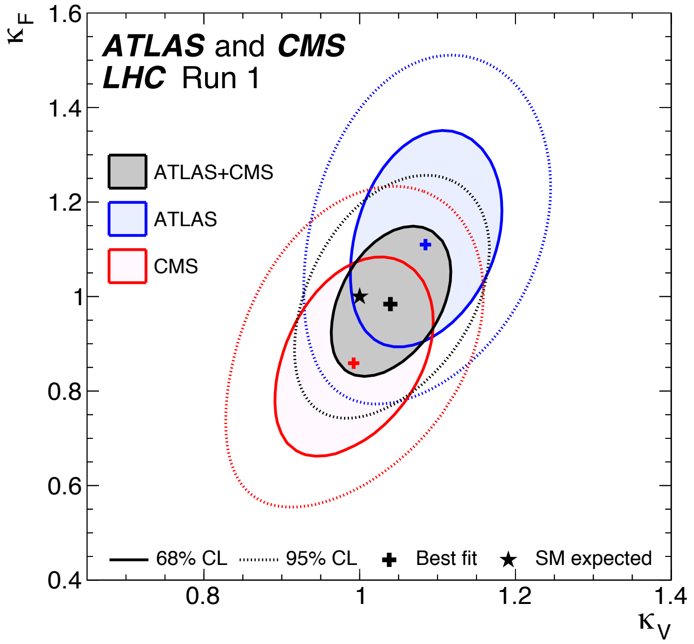

$$(\sigma \cdot {\rm BR})\,(gg \to H \to \gamma\gamma) \;=\; \sigma_{\rm SM}(gg \to H) \cdot {\rm BR}_{\rm SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

individual coupling rescaling factors

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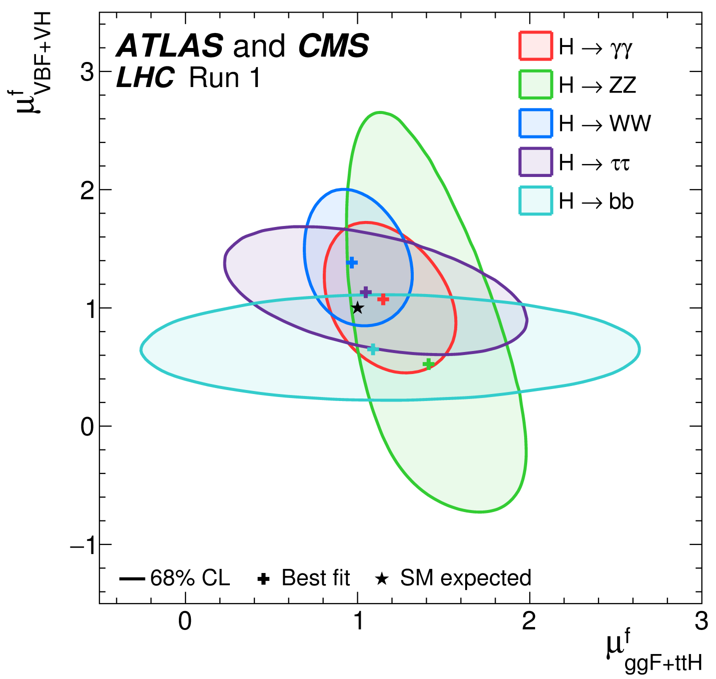

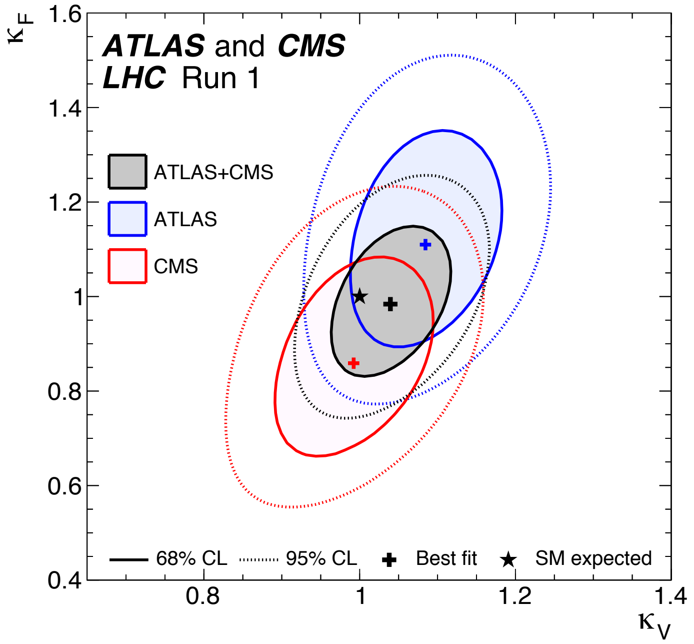

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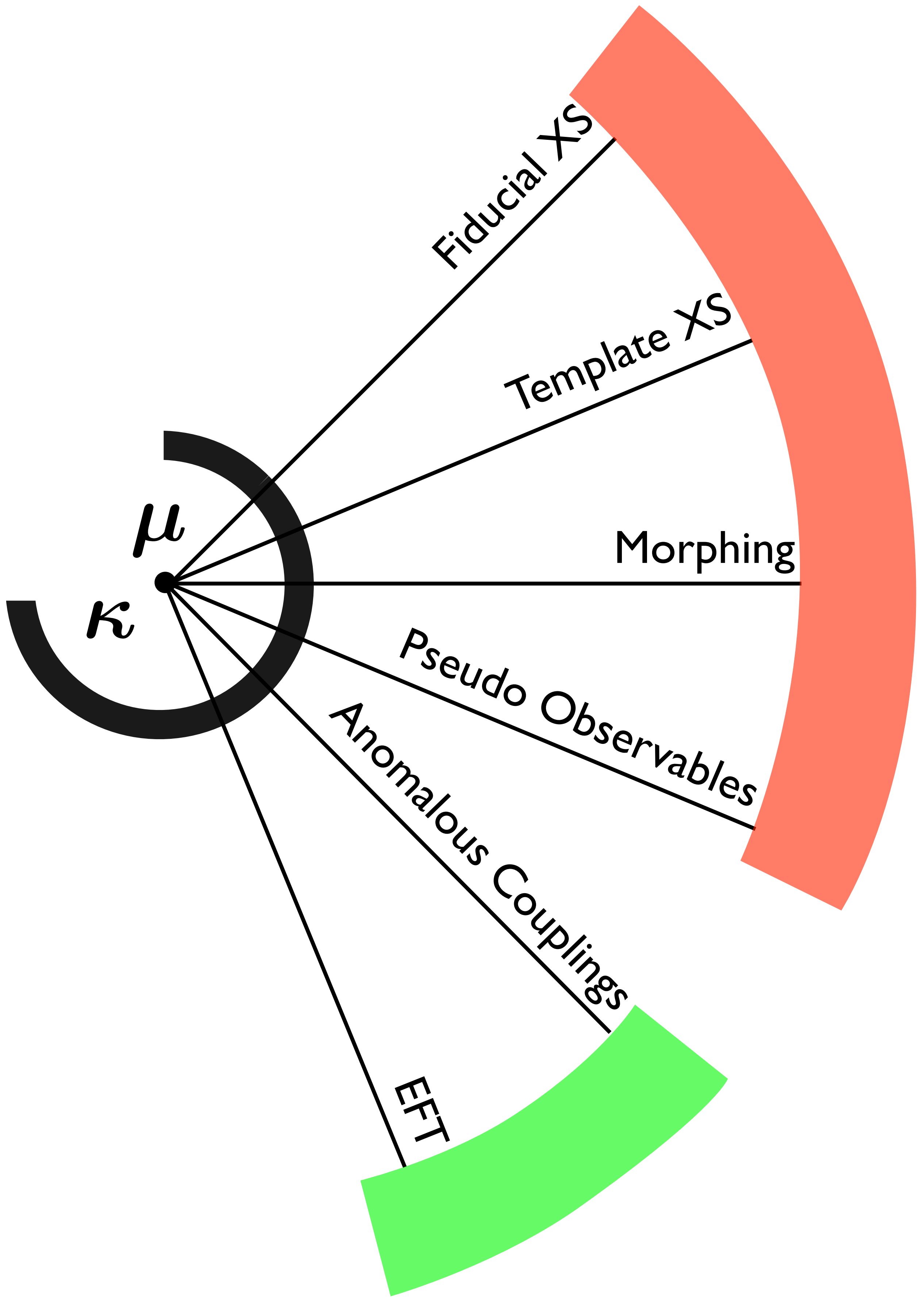
individual coupling rescaling factors

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



EFT

Not unique!
Useful tools to probe
broad classes of dynamics
and to report experimental results
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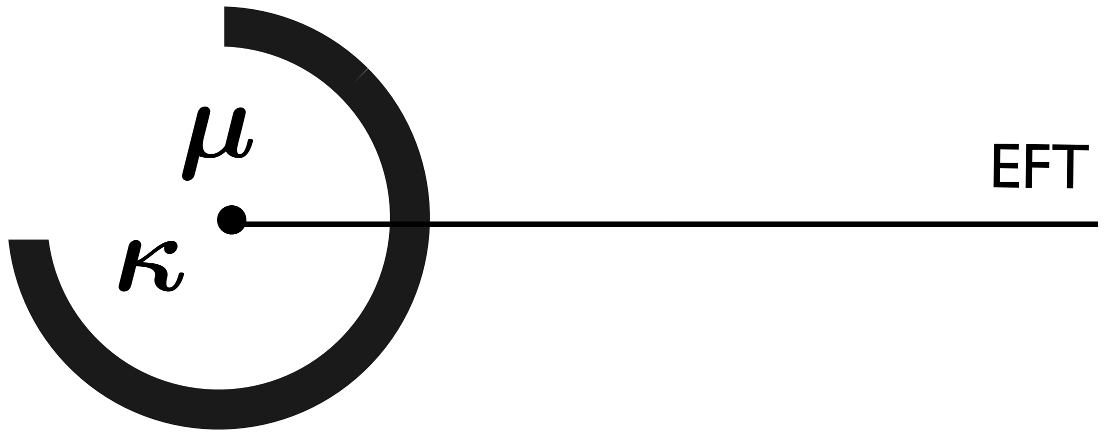

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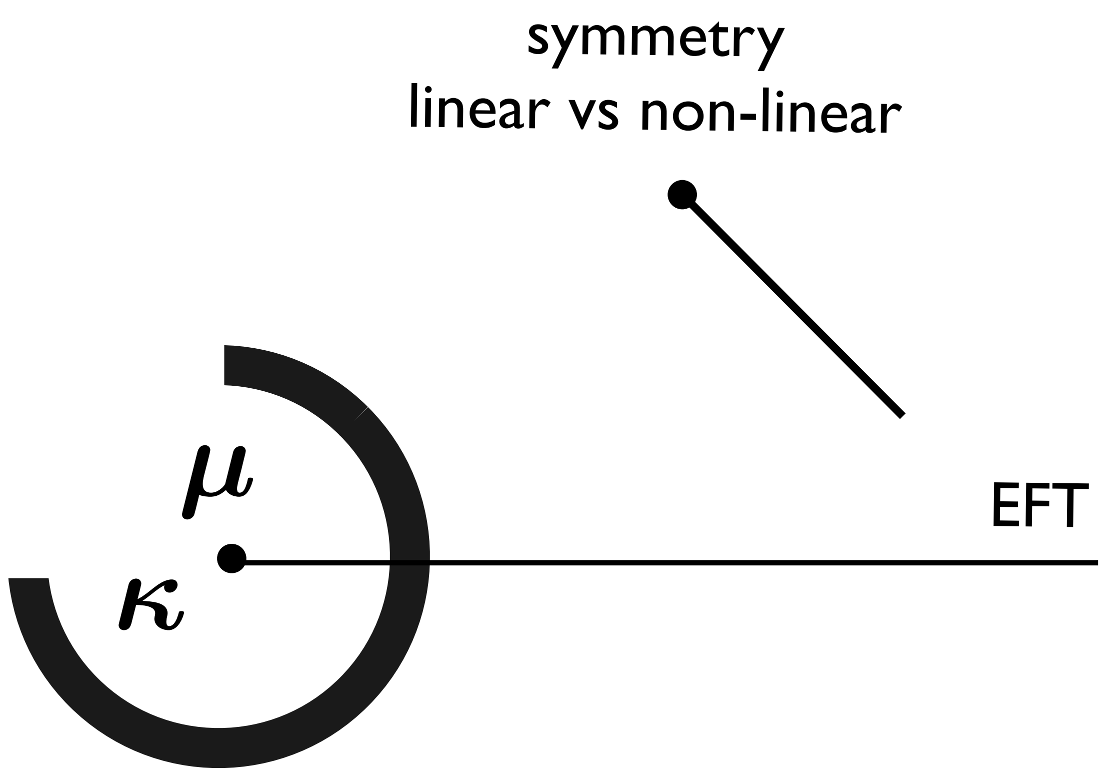

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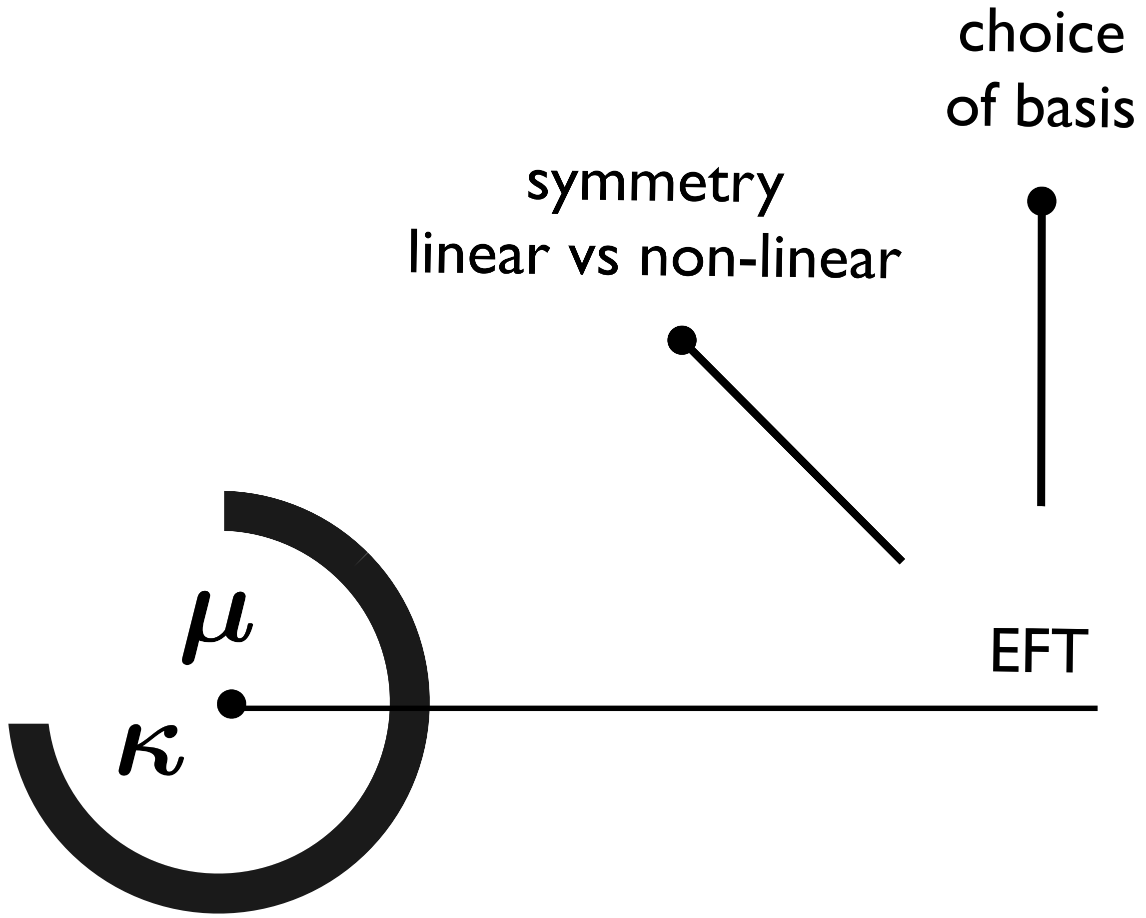

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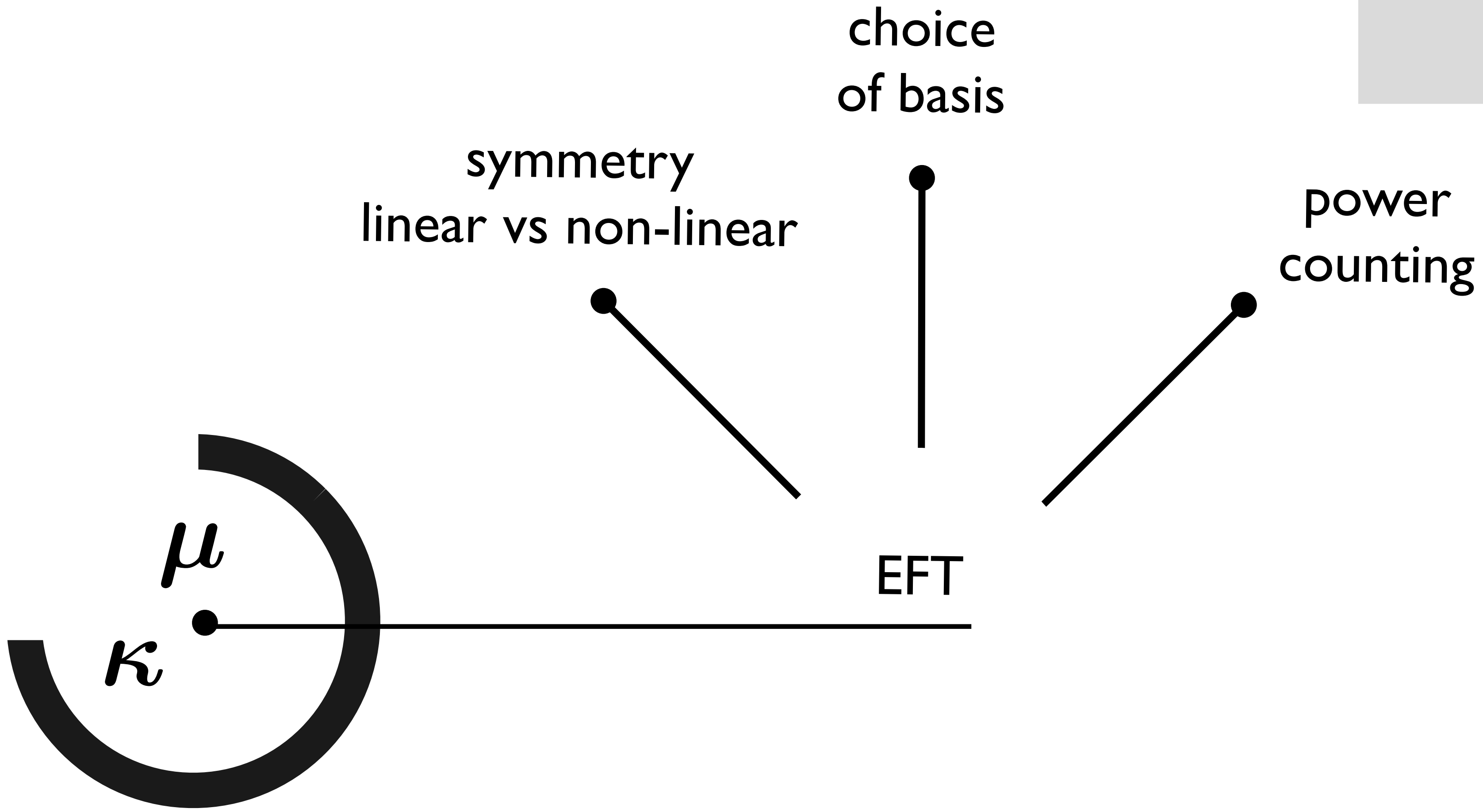

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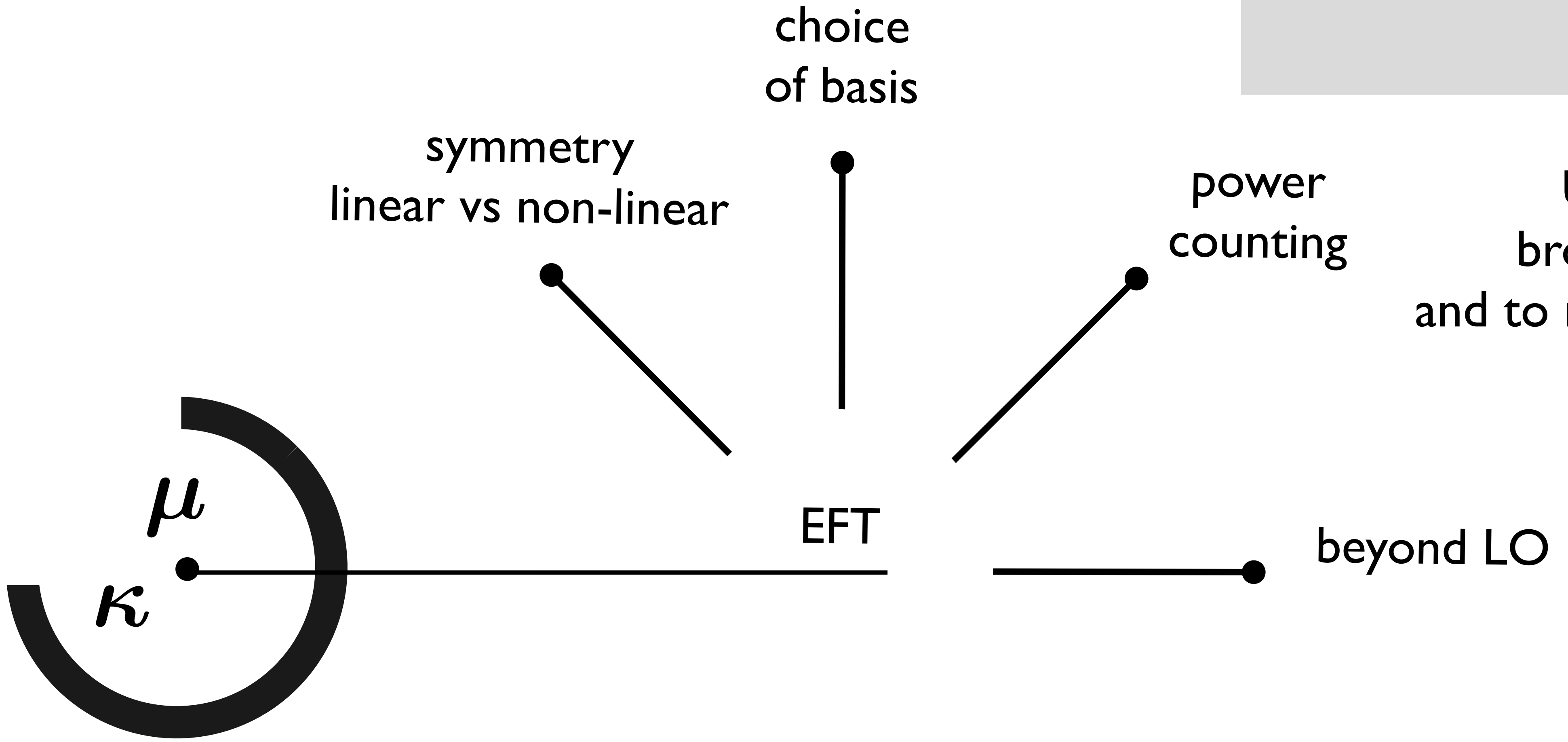

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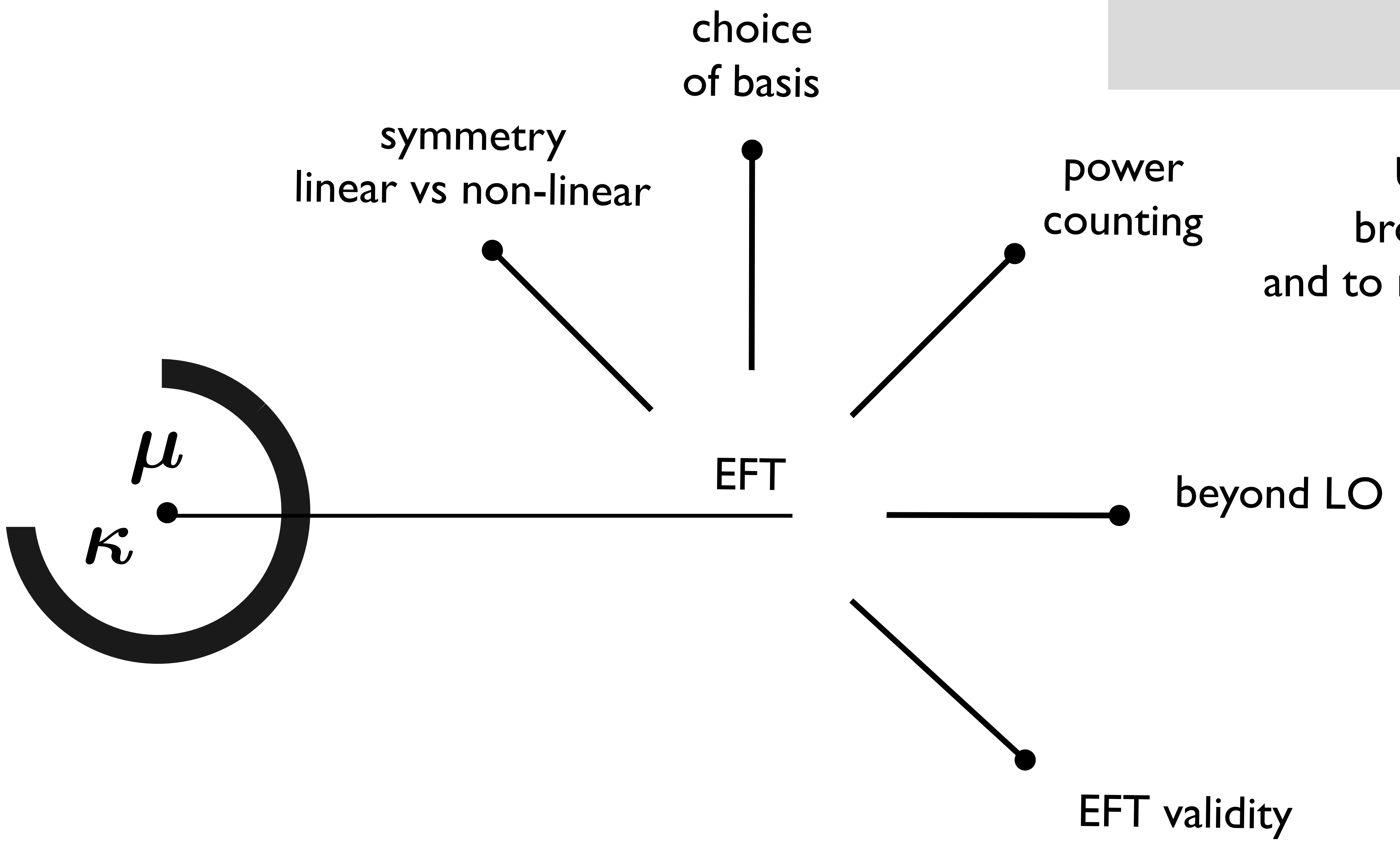

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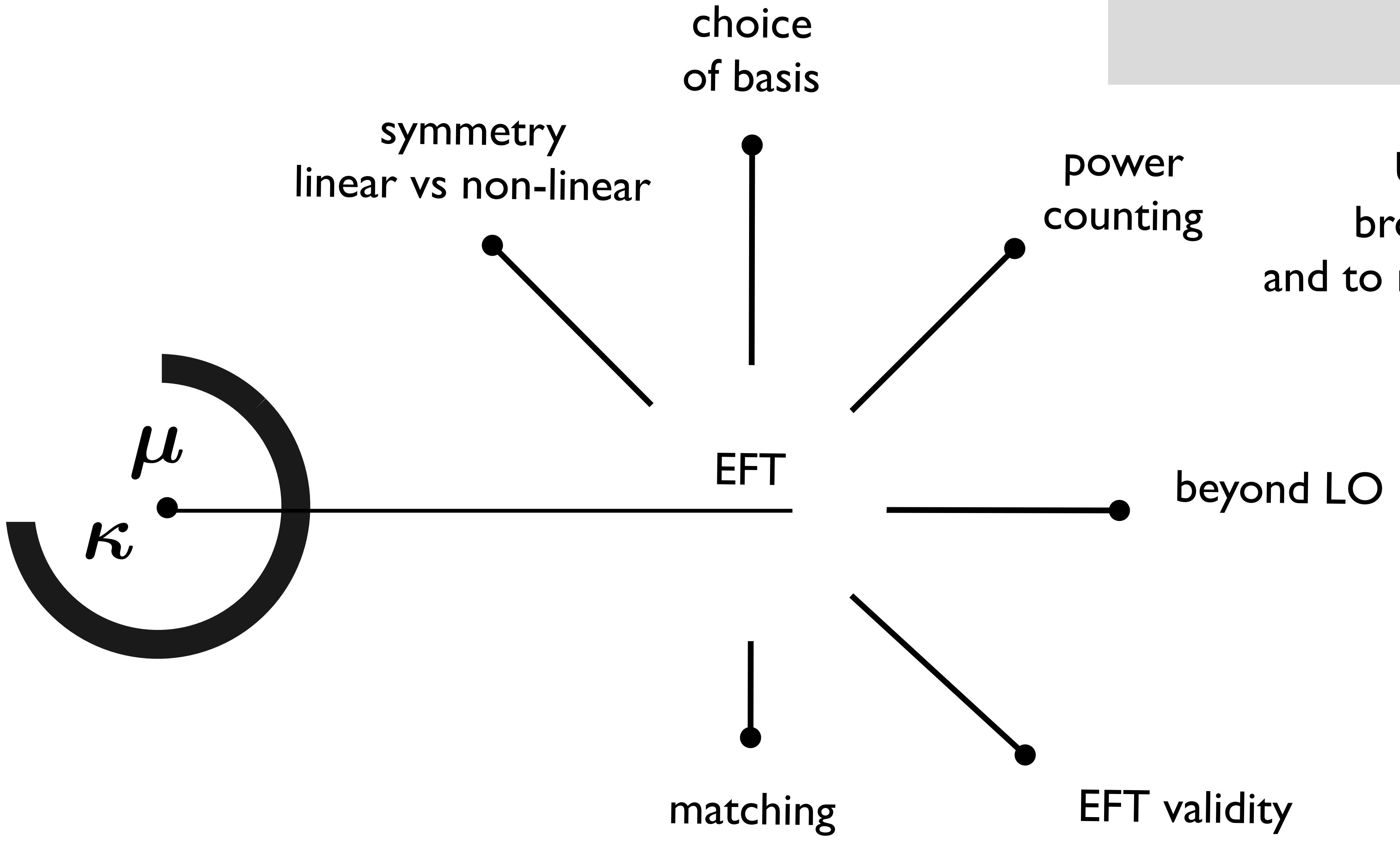

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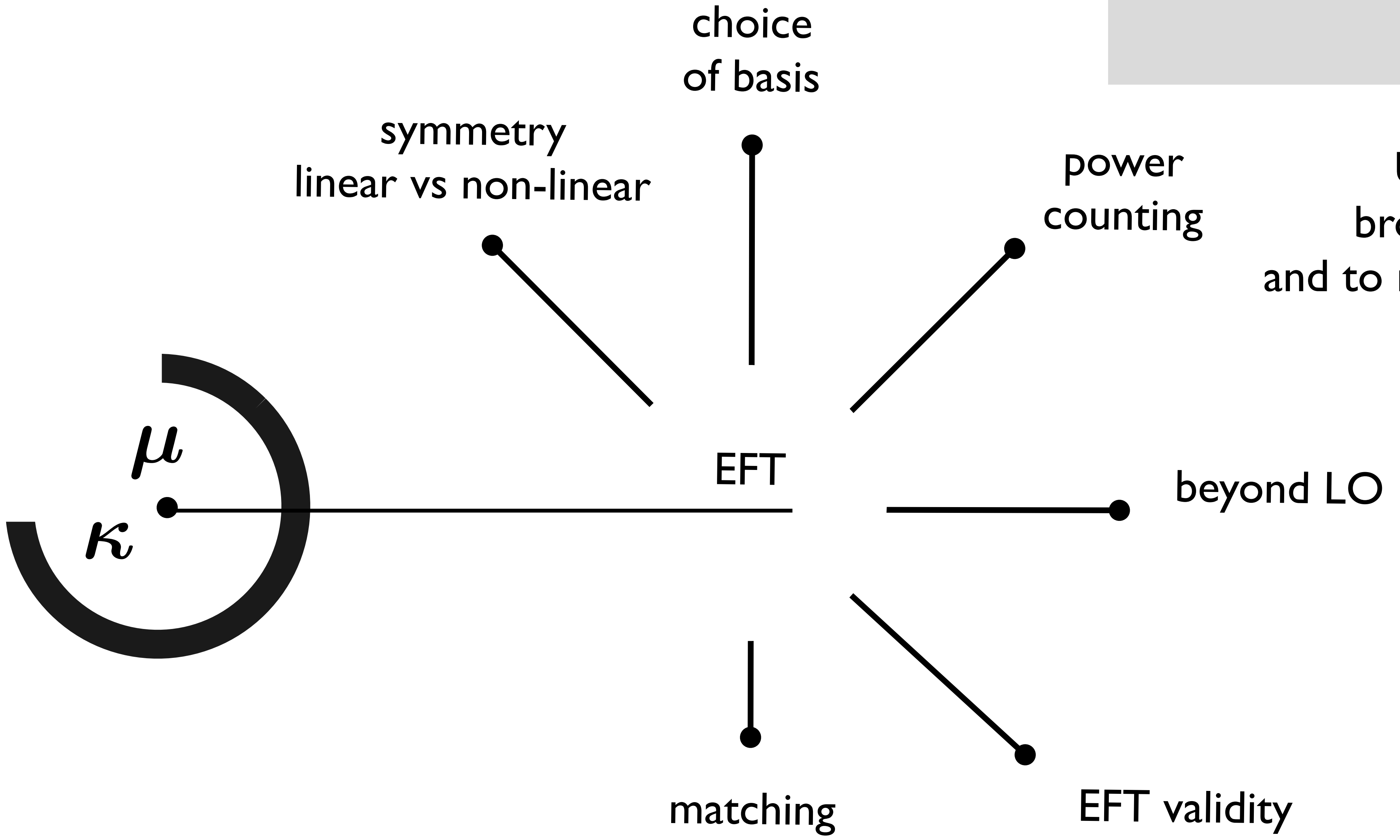

Pros:

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

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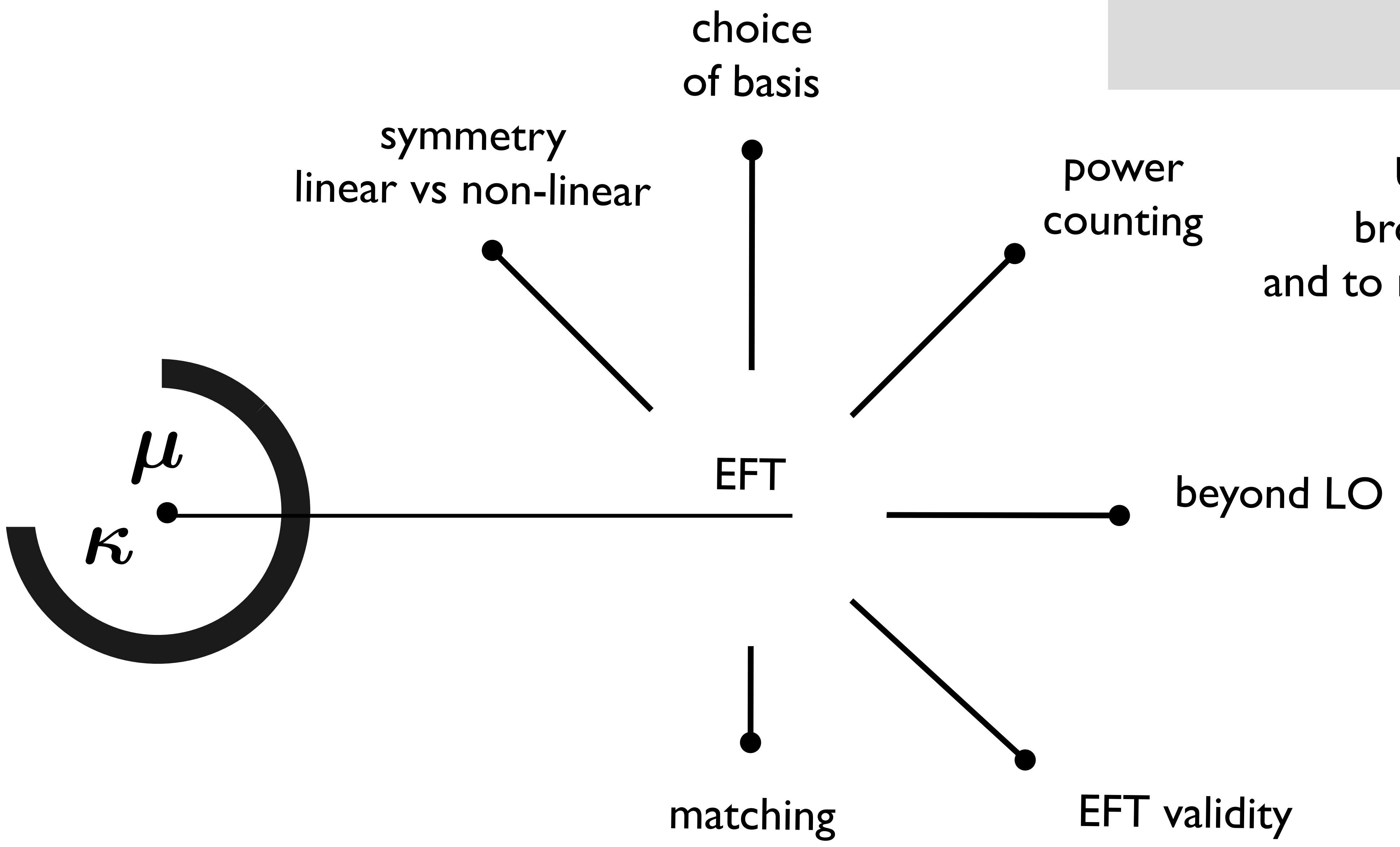

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unique to EFT

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

Higgs physics vs BSM

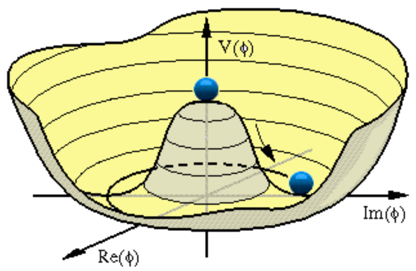
(assuming EW symmetry linearly realized and that new physics is heavy)

(courtesy of A. Pomarol@Moriond2014)

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

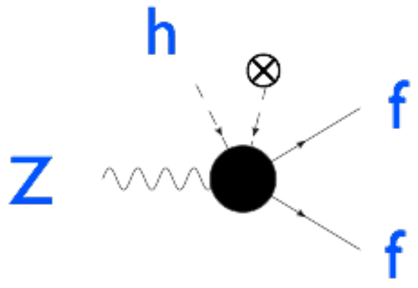
$\phi = v + h$

↳ vacuum

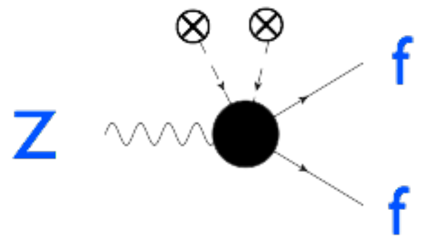


Potentially new BSM-effects in h physics
could have been already tested in the vacuum

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

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

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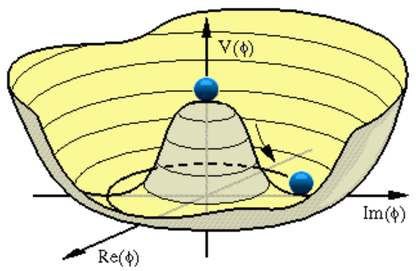

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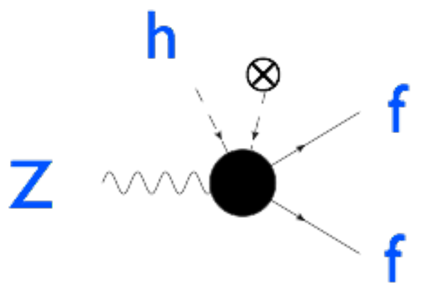

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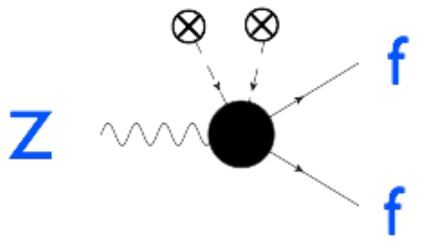

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Modifications in h→Zff related to Z→ff

consistency check
not discovery mode

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

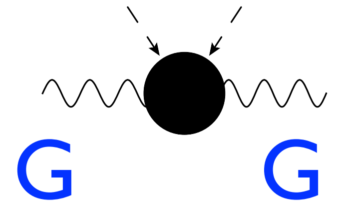
(courtesy of A. Pomarol@Moriond2014)

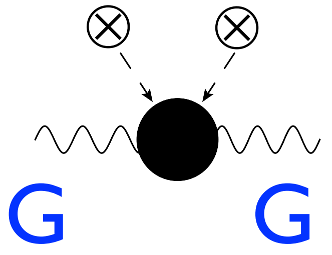
Higgs/BSM Primaries

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)

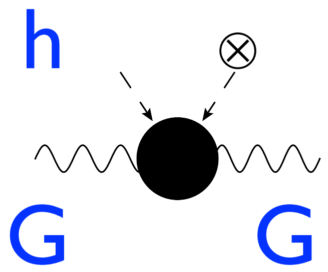
e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$





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

But can affect h physics:



affects GG →h!

operator
visible in Higgs physics

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

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m_h — $|H|^6$ → **h^3 coupling**

m_f (f=t,b,τ) — $|H|^2 \bar{f}_L H f_R + h.c.$ → **htt, hbb, h$\tau\tau$**

yet to be measured at the LHC (hZγ coupling, h^3 coupling)

the 6 others have been measured (~15%)

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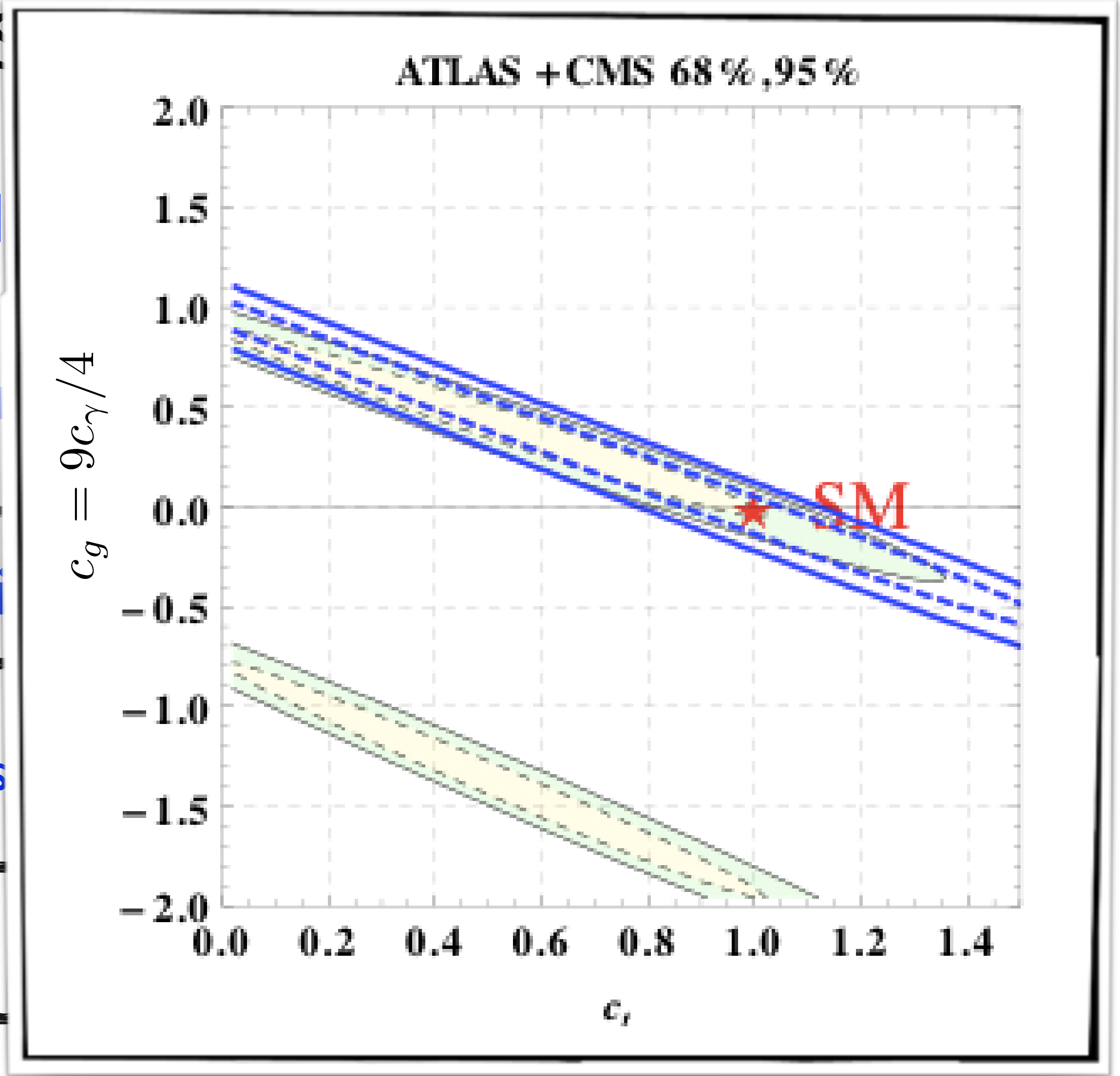

Azatov '15

the 6 others have been measured (~15%) up to a flat direction between between the top/gluon/photon couplings

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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.: 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%

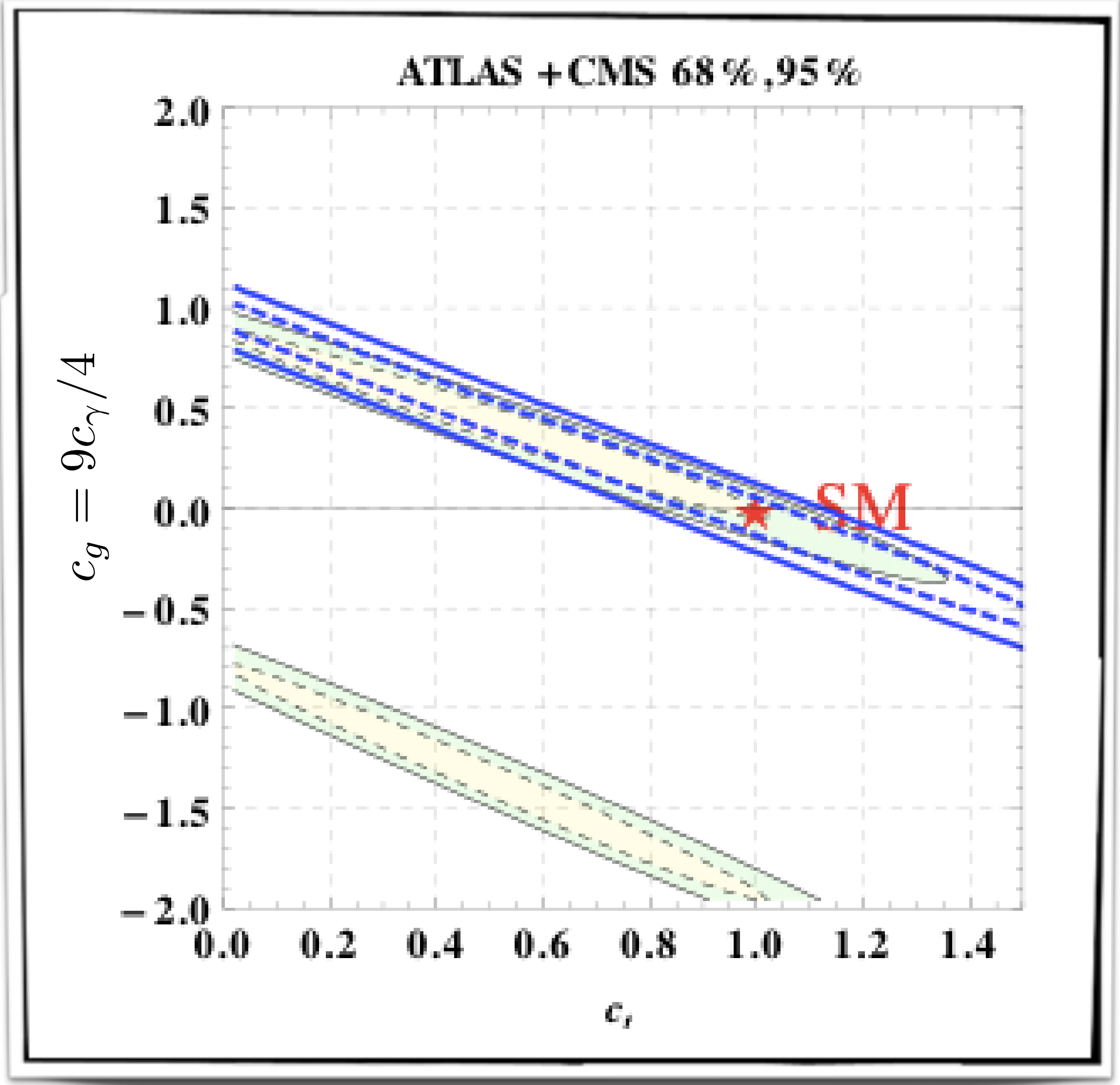
Atlas projection

With some important differences:

1) width hypothesis built-in

2) κ_W/κ_Z is not a primary (constrained by Δρ and TGC)

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



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Why going beyond inclusive Higgs processes?

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

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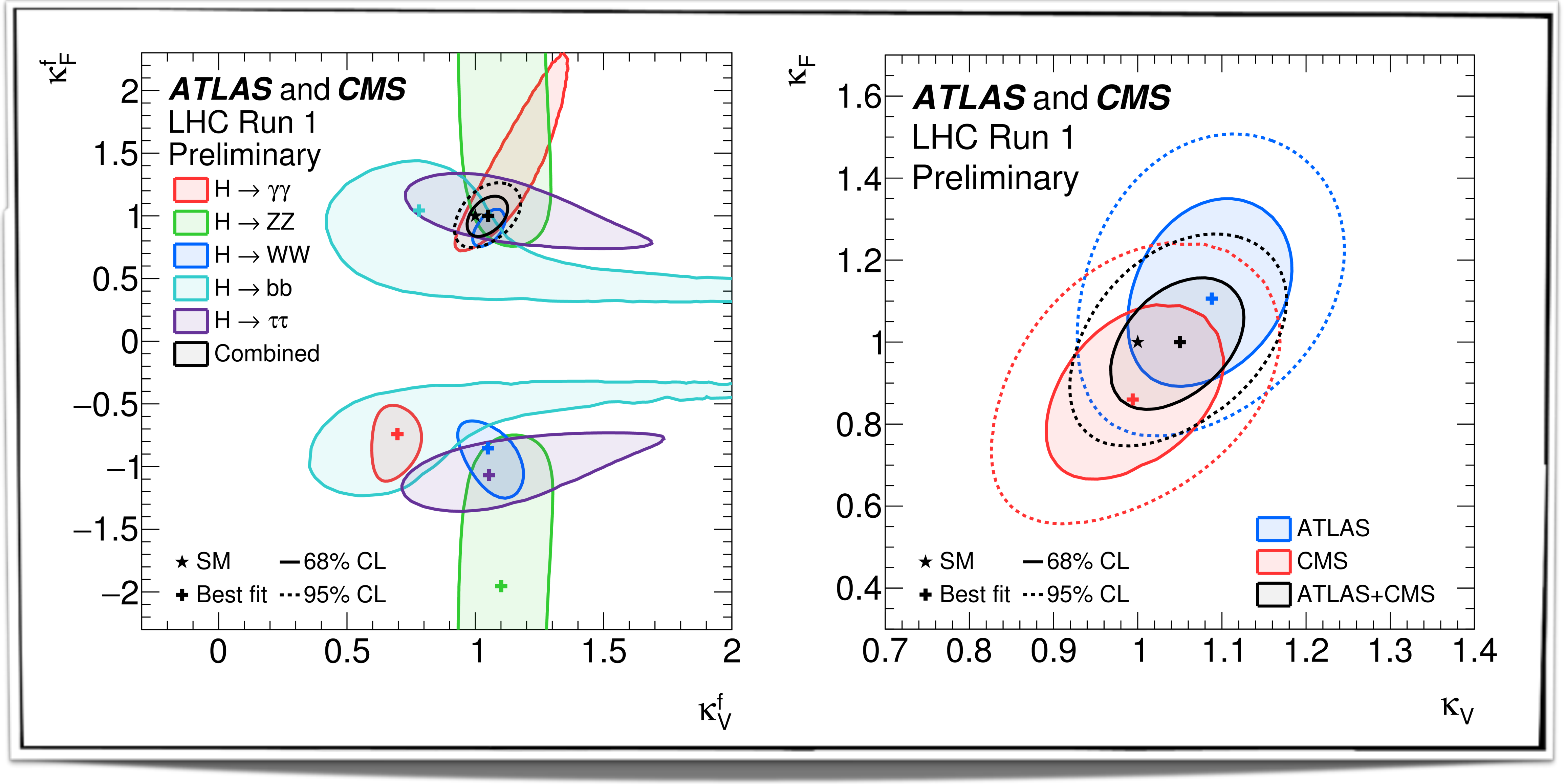

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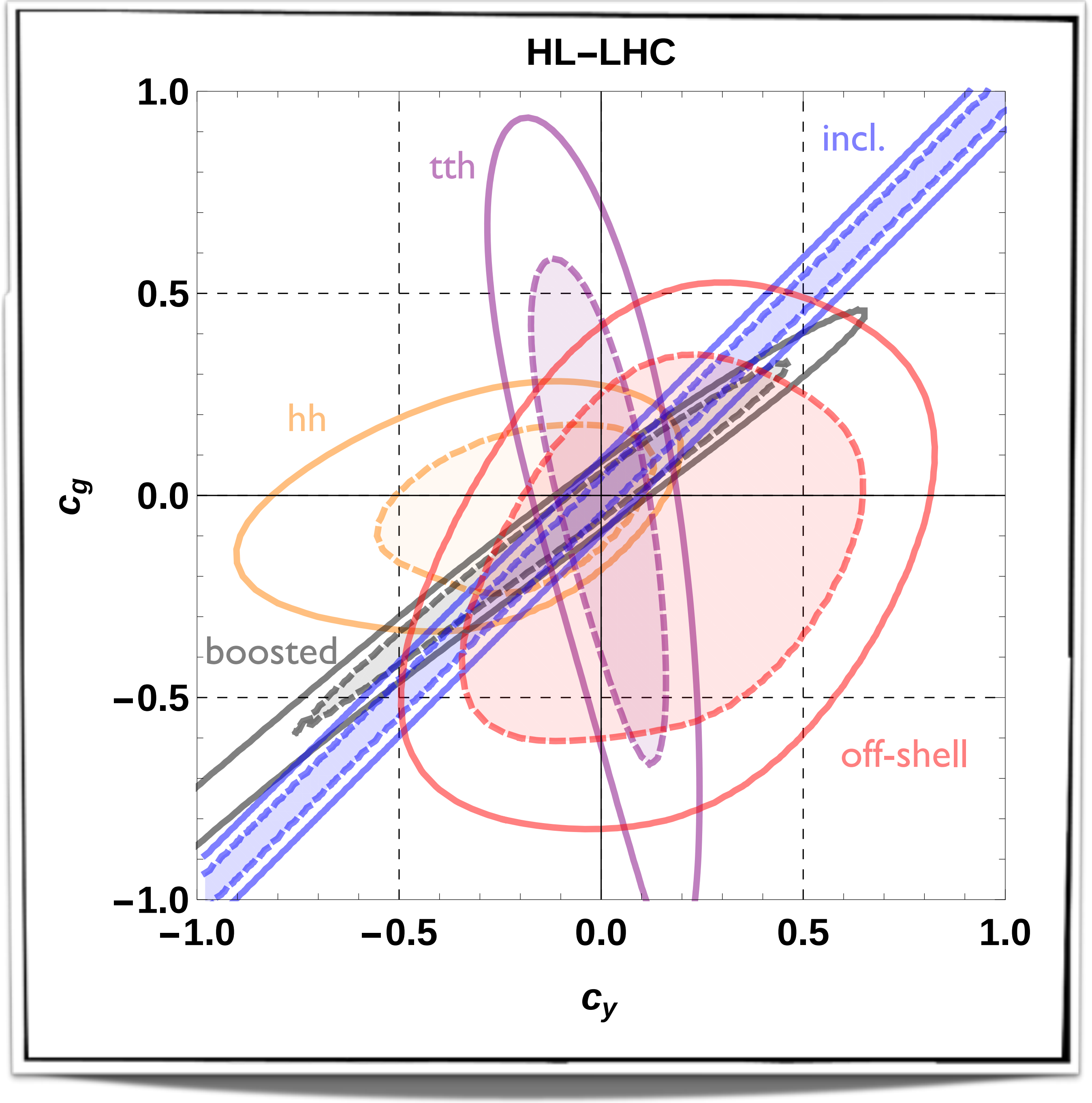
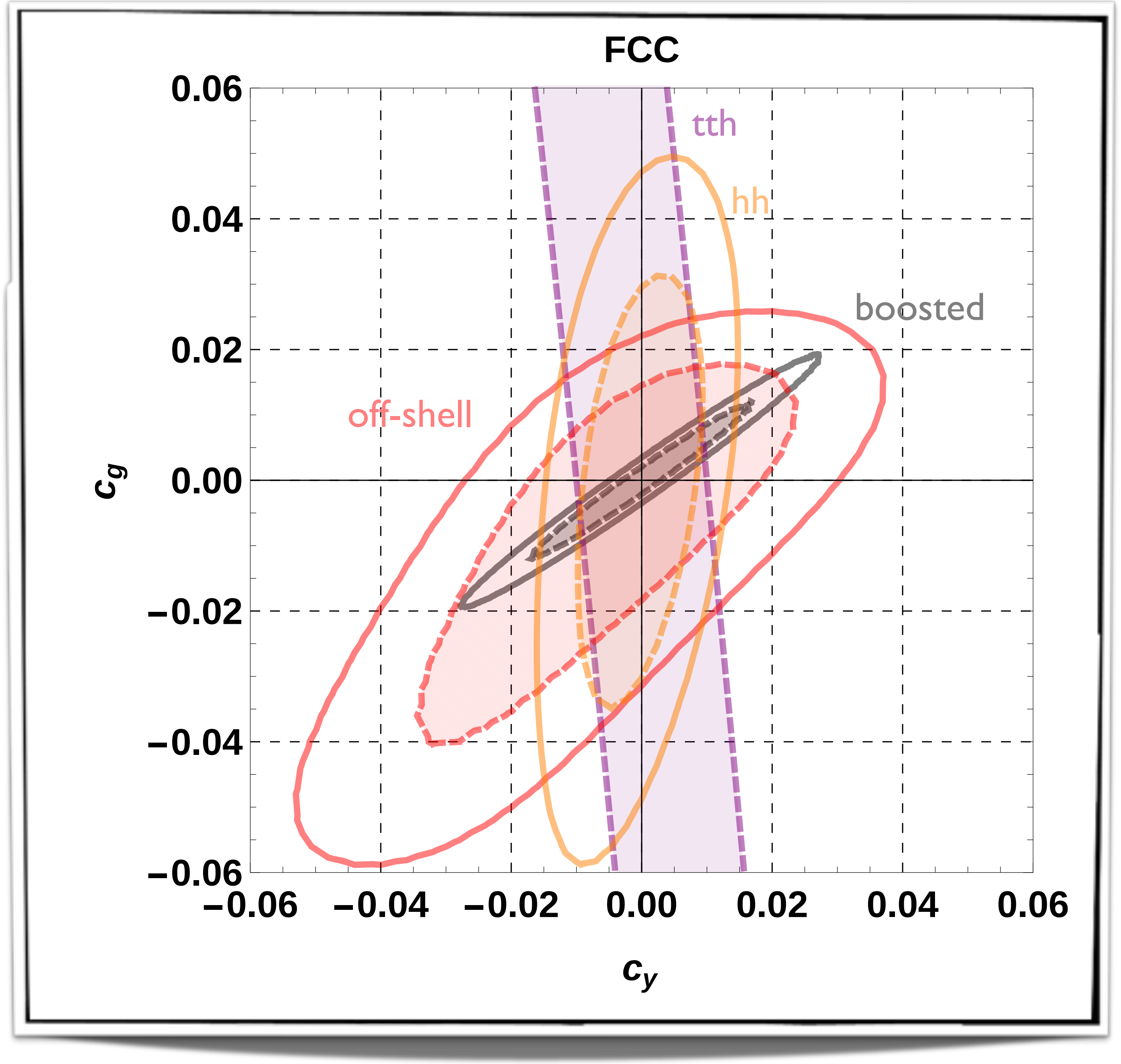
Producing a Higgs with boosted additional particle(s)
probe the Higgs couplings @ large energy
(important to check that the Higgs boson ensures perturbative unitarity)

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

Why going beyond inclusive Higgs processes?





Azatov, Grojean, Paul, Salvioni '16

Synergy Higgs and diboson

In EFT$_{\text{(dim-6)}}$

8 deformations affecting Higgs physics alone

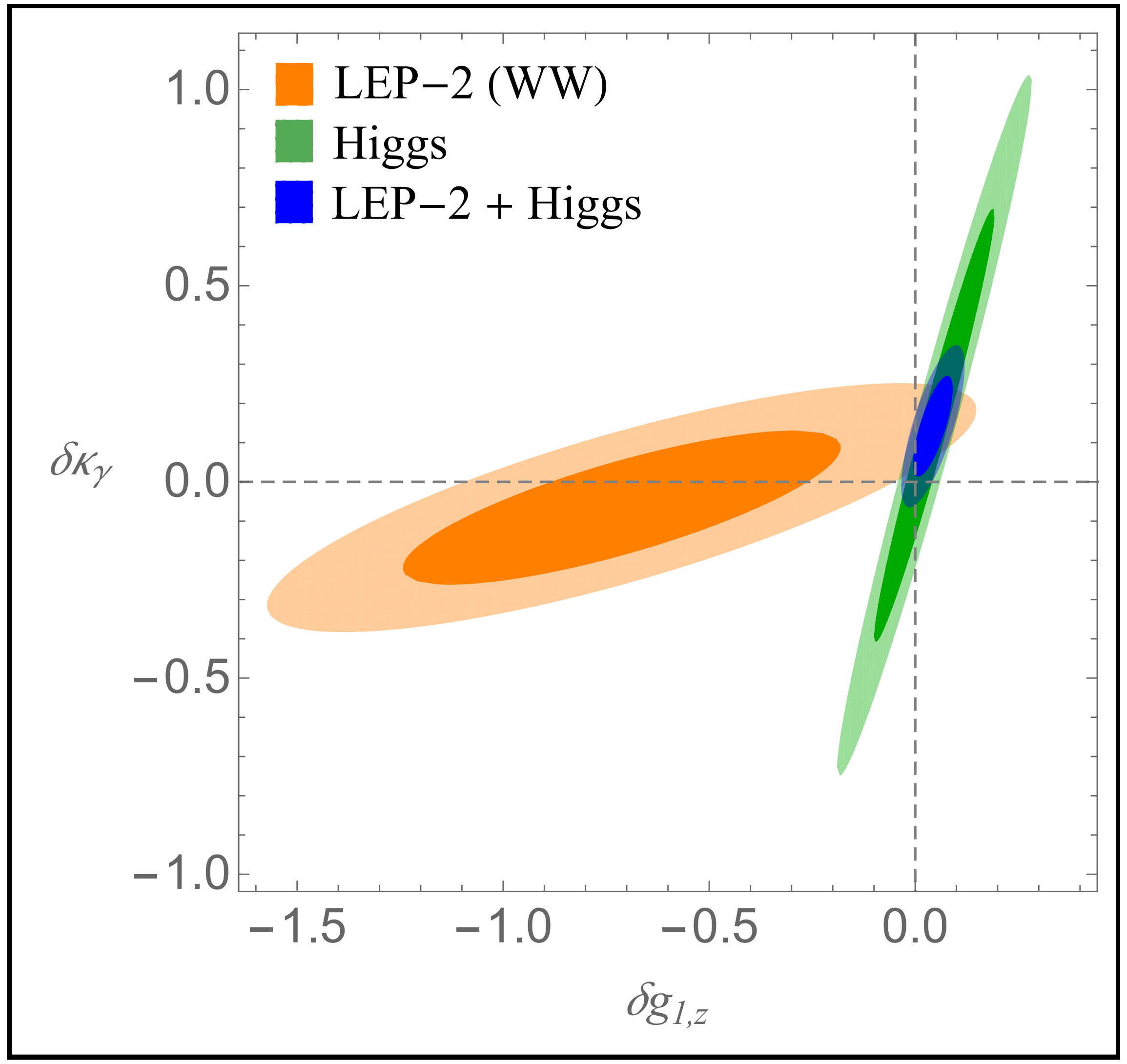
2 deformations affecting Higgs and diboson data

diboson (1%) are a priori more constraining than Higgs (10%)

Is there any value in doing a global fit?

Synergy Higgs and diboson

Falkowski et al '15



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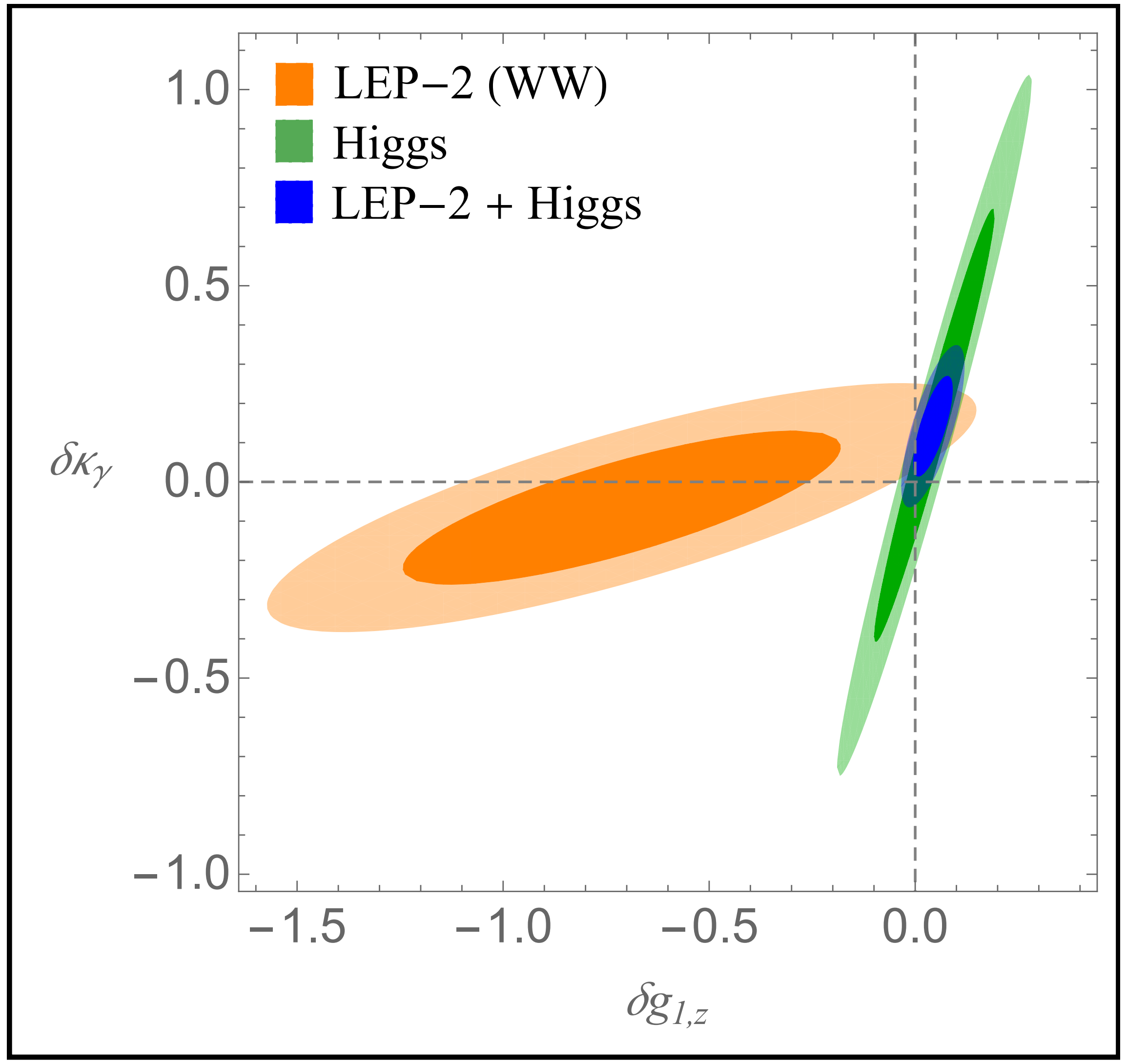

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Impact of HL-LHC WW data?

we assumed 1% syst. and also studied the impact of this assumption

One missing beast: h^3

The Higgs self-couplings plays important roles

1) linked to **naturalness/hierarchy** problem

2) controls the **stability** of the EW vacuum

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

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Does it need to be measured with high accuracy?

Not a straightforward discovery tool for new physics since difficult to design new physics scenarios that dominantly affect the Higgs self-couplings and leave the other Higgs coupling deviations undetectable.
So new physics is likely to show up in other cleaner channels

Higgs self-couplings and Naturalness

In the SM, $|H|^2$ is the only relevant operator
and it is the source of the hierarchy/naturalness/fine-tuning problem
It presence has never been tested!

Reconstructing the Higgs potential before EW symmetry breaking
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SM

$$V = -\mu^2 |H|^2 + \lambda |H|^4 \quad \Rightarrow \quad V(h) = \frac{1}{2} m_h^2 h^2 + \frac{1}{6} \frac{3 m_h^2}{v} h^3 + \dots$$

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EWSB W/O H^2

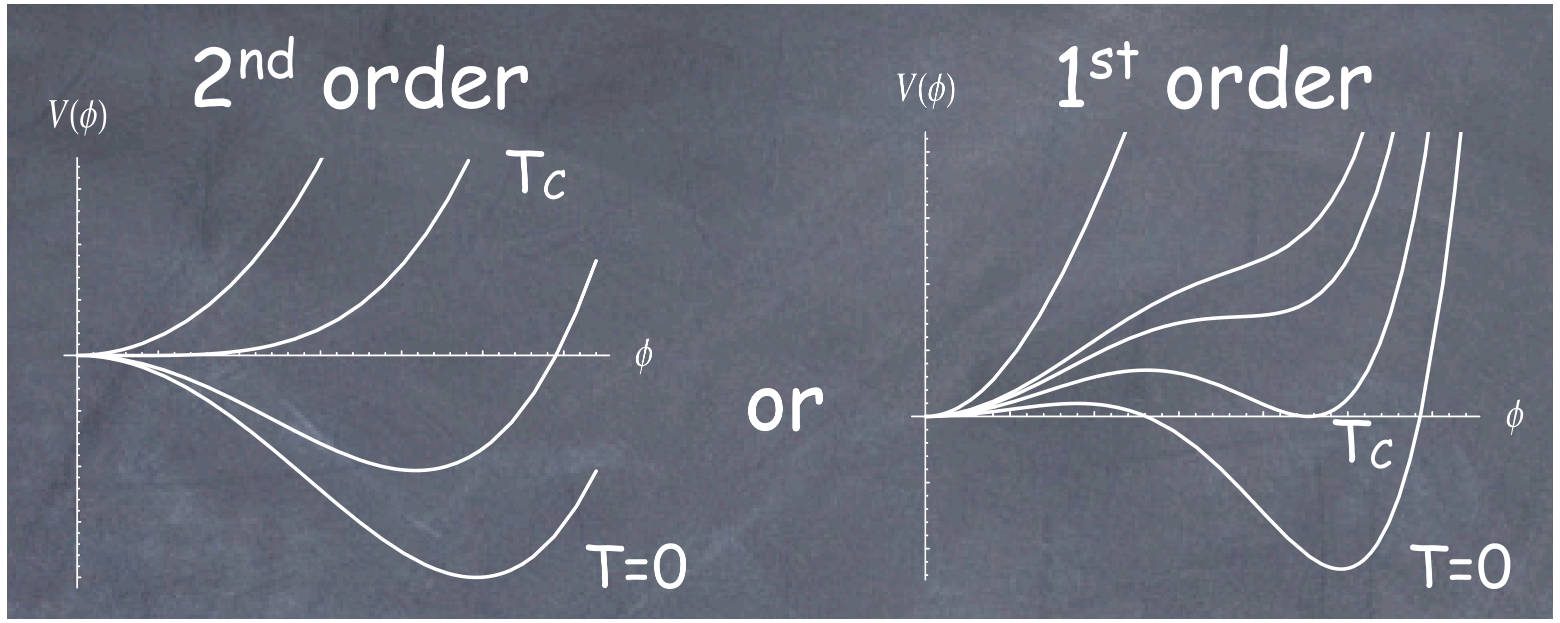
$$V = -\lambda|H|^4 + \frac{1}{\Lambda^2}|H|^6 \quad \Rightarrow \quad V(h) = \frac{1}{2}m_h^2 h^2 + \frac{1}{6}\frac{7m_h^2}{v}h^3 + \ldots$$

200% correction
to SM prediction
+
allows 1st order phase transition

Dynamics of EW phase transition

The asymmetry between matter-antimatter can be created dynamically
it requires an out-of-equilibrium phase in the cosmological history of the Universe

An appealing idea is EW baryogenesis associated to a first order EW phase transition
(not the only option but the only one that can be tested at colliders)



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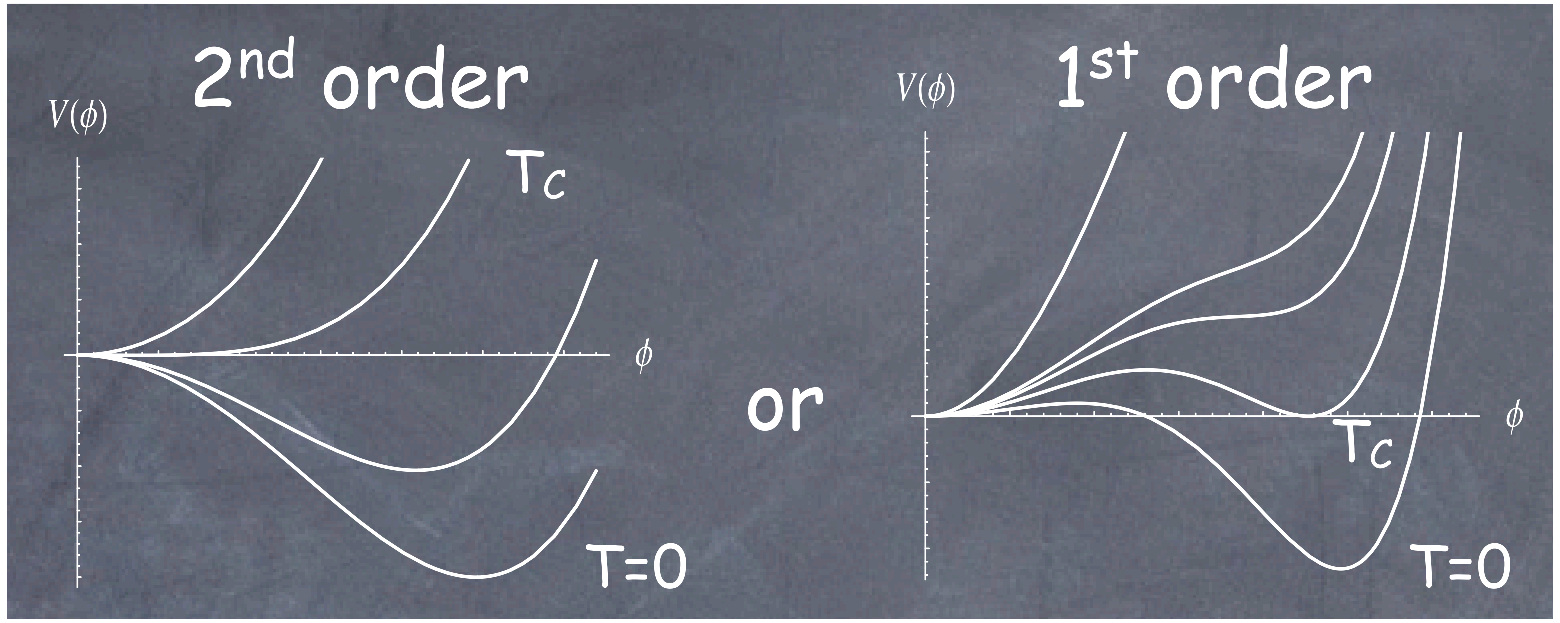

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which we have no direct access at in colliders (LHC≠Big Bang machine)

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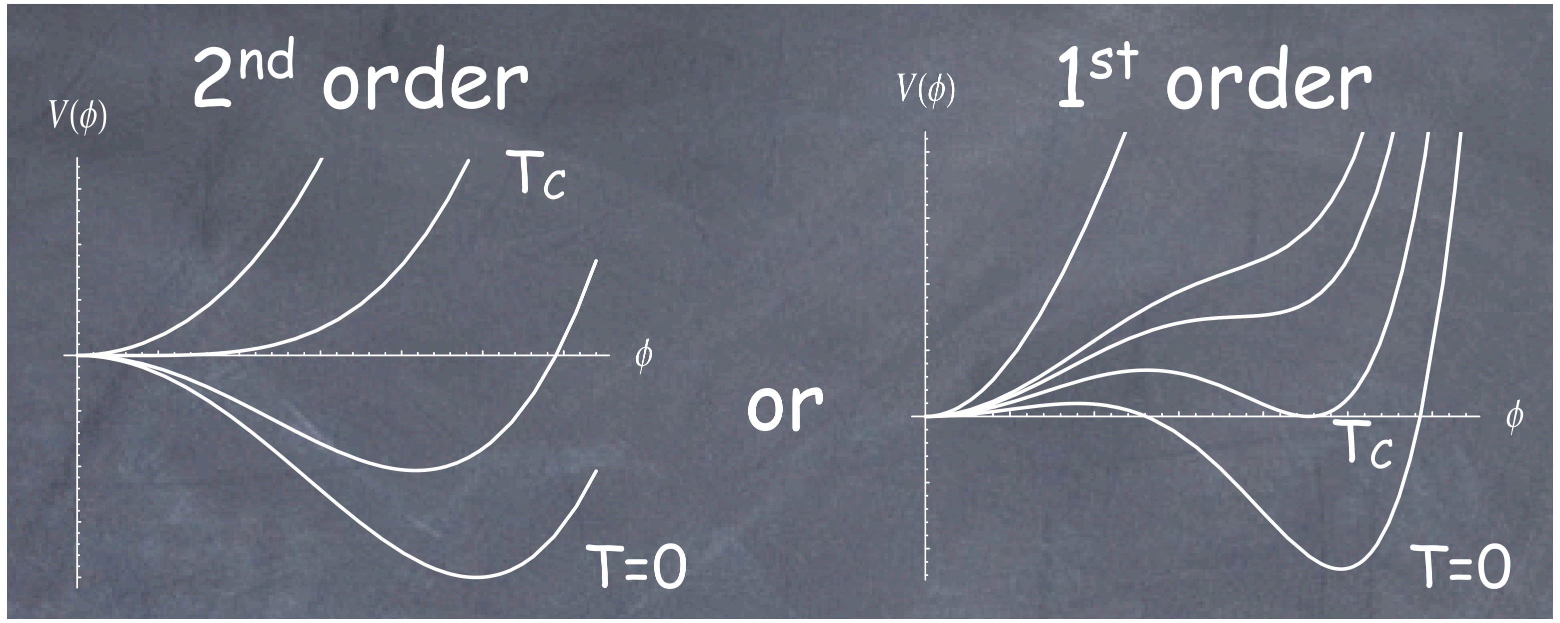

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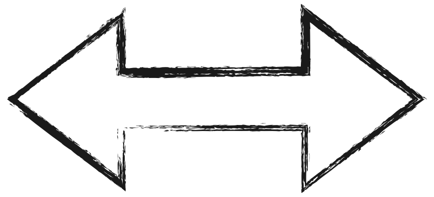
finite T
Higgs potential



Higgs couplings
at T=0

SM: first order phase transition iff mH < 47 GeV
BSM: first order phase transition needs some sizeable deviations in Higgs couplings

h^3 and GW

GW interact very weakly and are not absorbed

⇓ ⇓

direct probe of physical process of the very early universe

possible cosmological sources:

inflation, vibrations of topological defects, excitations of xdim modes, 1st order phase transitions...

ElectroWeak Phase Transition (if 1st order)

typical freq. ~ (size of the bubble)$^{-1}$ ~ (fraction of the horizon size)$^{-1}$

$$@\, T = 100 \text{ GeV}, \qquad H = \sqrt{\frac{8\pi^3}{45}\frac{T^2}{M_{Pl}}} \sim 10^{-15} \text{ GeV}$$

redshifted ⇓ freq.

~ today ~

$$f \sim \# \frac{2 \cdot 10^{-4} \text{ eV}}{100 \text{ GeV}} 10^{-15} \text{ GeV} \sim \# 10^{-5} \text{ Hz}$$

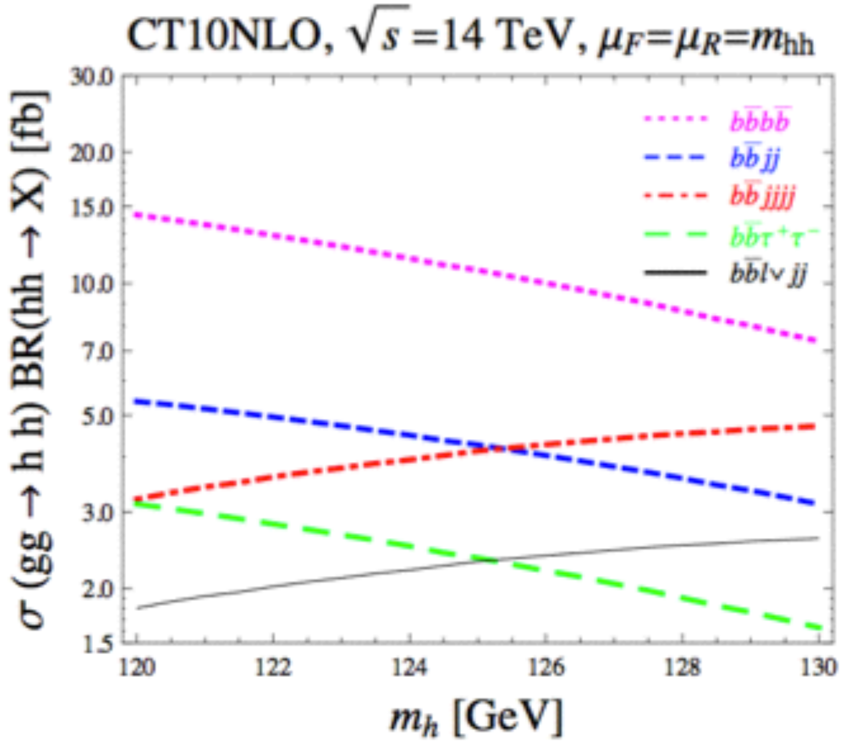
The GW spectrum from a 1st order electroweak PT is peaked around the milliHertz frequency

h^3 from hh@LHC

Measuring this small cross section in an inclusive search is very challenging at the HL-LHC: compromise between branching ratio and cleanliness of the signal

M. Spannowsky, Mainz '15

Channel	BR (%)	Events/3 ab
$bbWW$	24.7	30000
$bb\tau\tau$	7.3	9000
$WWWW$	4.3	5200
$bb\gamma\gamma$	0.27	330
$bbZZ(\to e^+e^-\mu^+\mu^-)$	0.015	19
$\gamma\gamma\gamma\gamma$	0.00052	1



Decay	Issues	Expectation 3000 ifb	References
$b\bar{b}\gamma\gamma$	• Signal small • BKG large & difficult to asses • Simple reconst.	$S/B \simeq 1/3$ $S/\sqrt{B} \simeq 2.5$	[Baur, Plehn, Rainwater] [Yao 1308.6302] [Baglio et al. JHEP 1304]
$b\bar{b}\tau^+\tau^-$	• tau rec tough • largest bkg tt • Boost+MT2 might help	**differ a lot** $S/B \simeq 1/5$ $S/\sqrt{B} \simeq 5$	[Dolan, Englert, MS] [Barr, Dolan, Englert, MS] [Baglio et al. JHEP 1304]
$b\bar{b}W^+W^-$	• looks like tt • Need semilep. W to rec. two H • Boost + BDT proposed	**differ a lot** best case: $S/B \simeq 1.5$ $S/\sqrt{B} \simeq 8.2$	[Dolan, Englert, MS] [Baglio et al. JHEP 1304] [Papaefstathiou, Yang, Zurita 1209.1489]
$b\bar{b}b\bar{b}$	• Trigger issue (high pT kill signal) • 4b background large difficult with MC • Subjets might help	$S/B \simeq 0.02$ $S/\sqrt{B} \leq 2.0$	[Dolan, Englert, MS] [Ferreira de Lima, Papaefstathiou, MS] [Wardrope et al, 1410.2794]
others	• Many taus/W not clear if 2 Higgs • Zs, photons no rate		

h^3 from hh@LHC

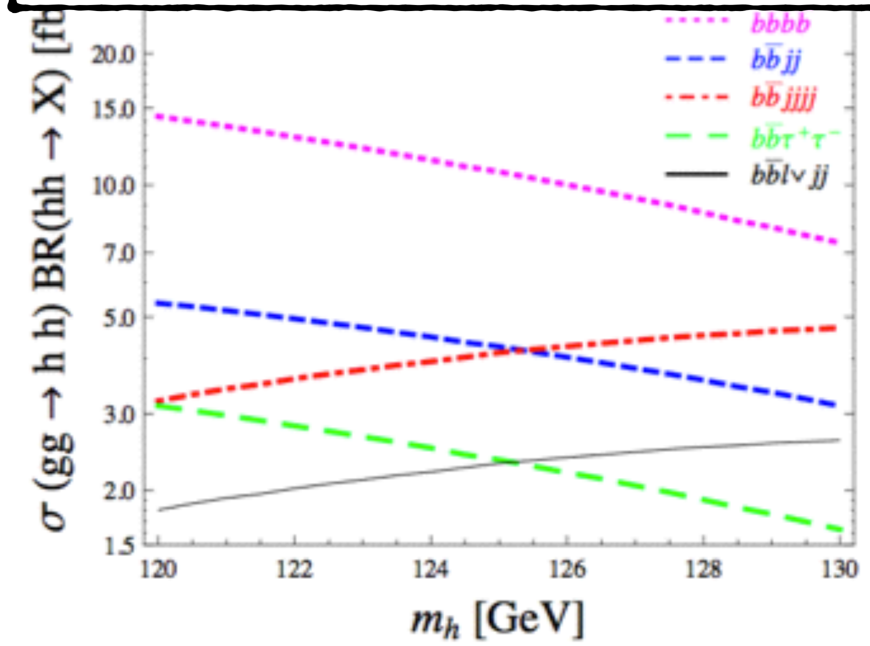
Higgs self-coupling prospects

	HL LHC 3/ab	ILC/CLIC	FCC 100TeV
Precision on λ_{HHH}	$b\bar{b}\gamma\gamma$: poor, only $\sim O(1)$ determination Other channels: needs more detailed studies	ILC • DHS alone at 500 GeV and 1TeV gives only $\sim O(1)$ determination • ~28% via VBF at 1TeV, 1/ab CLIC at 3TeV, 2/ab • ~12% via VBF	$b\bar{b}\gamma\gamma$: golden channel. 5-10% determination might be possible with 30/ab. ~3x less sensitivity with 3/ab
Comments	Combining various channels might be important	The role of VBF is important High CM energy and high luminosity are crucial	Improvements on heavy flavor tagging, fakes, mass resolution etc are crucial to achieve our goal

z '15

ILC current studies:
(4b and 2b2W modes)
29%@4/ab, 500GeV
16%@2/ab, 1TeV
10%@5/ab, 1TeV

M. Son, Washington '15



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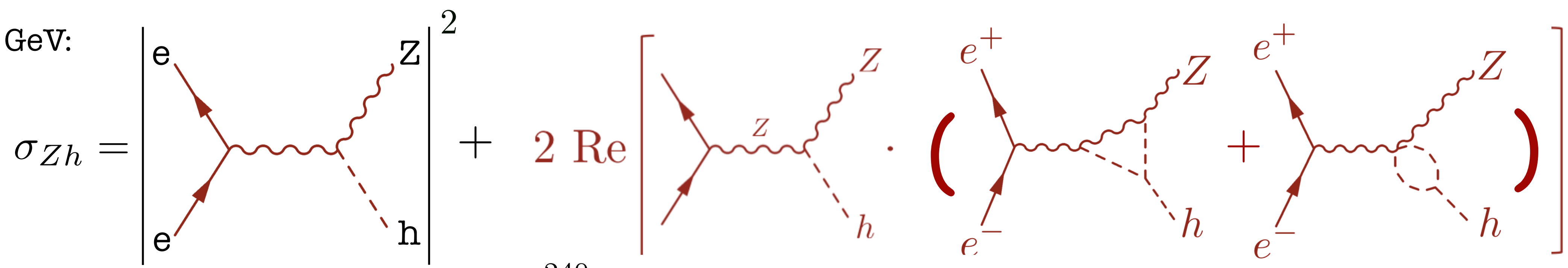
h^3 from h@NLO@LHC

M. McCullough '14

At 240 GeV:



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

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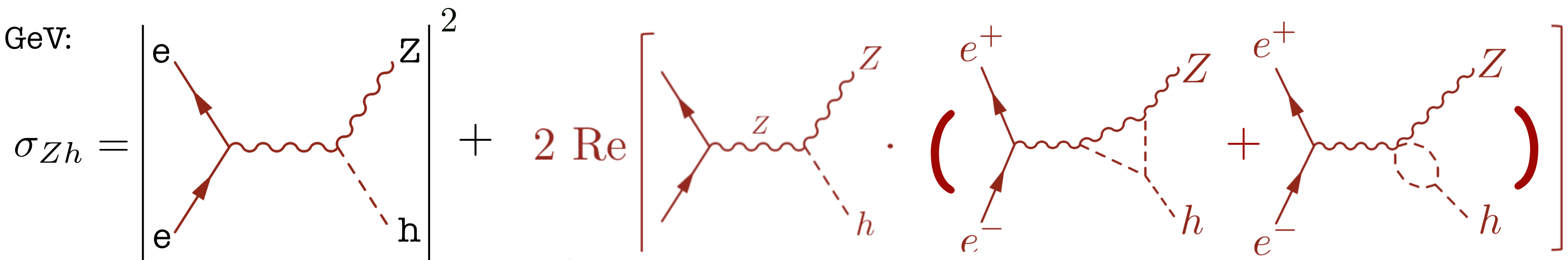

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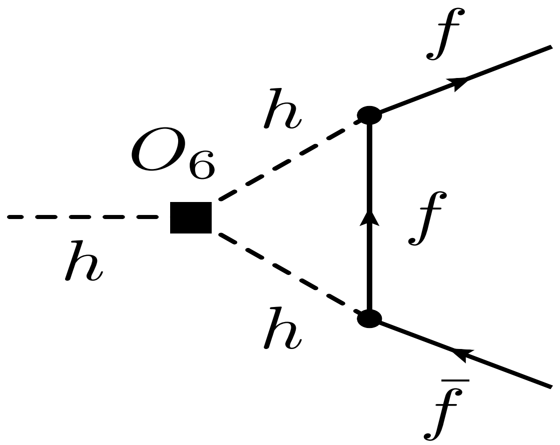
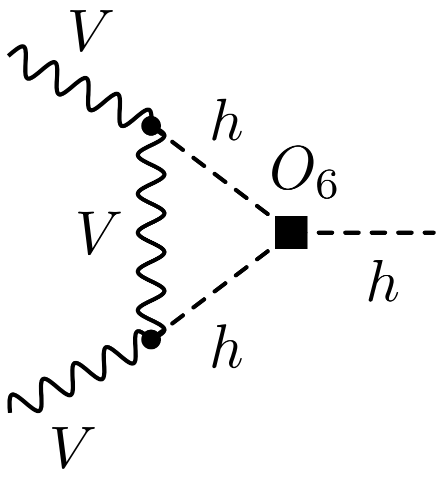
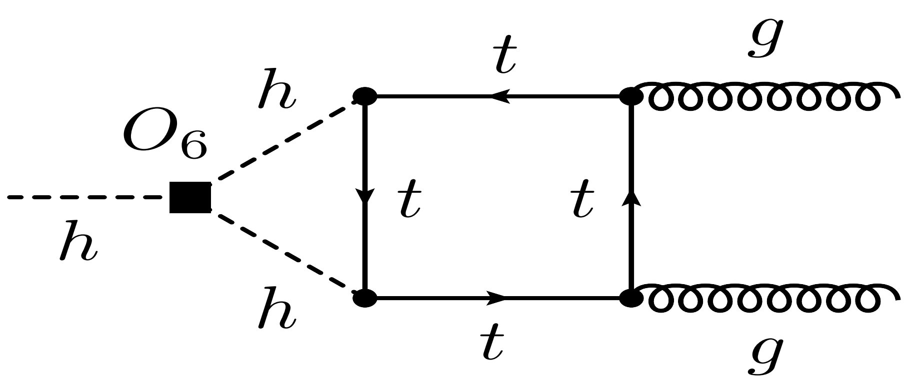
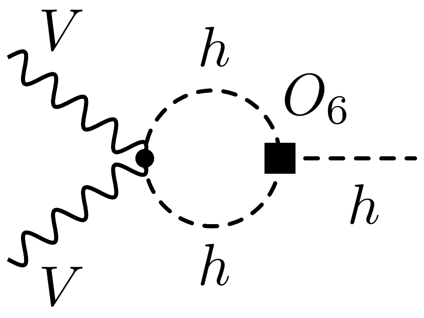
Gorbahn et al '16



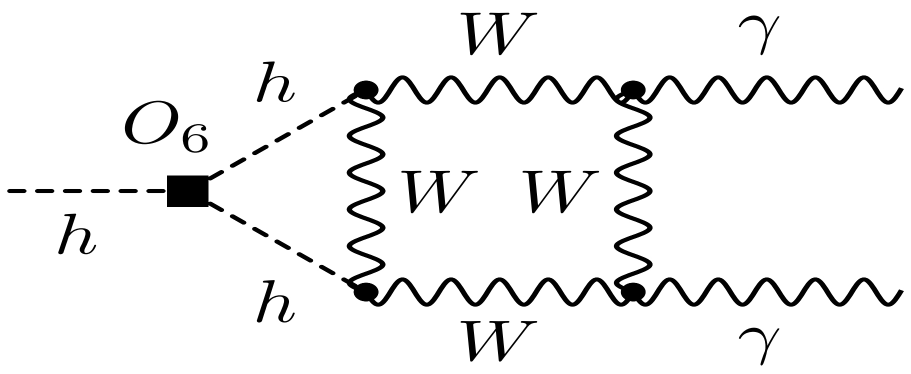


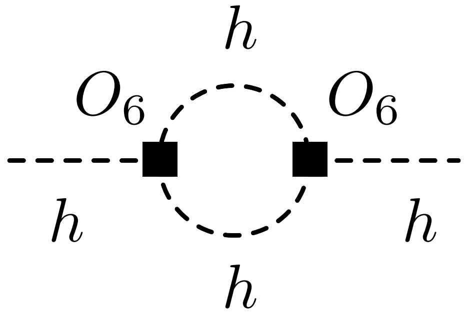
Degrassi et al '16



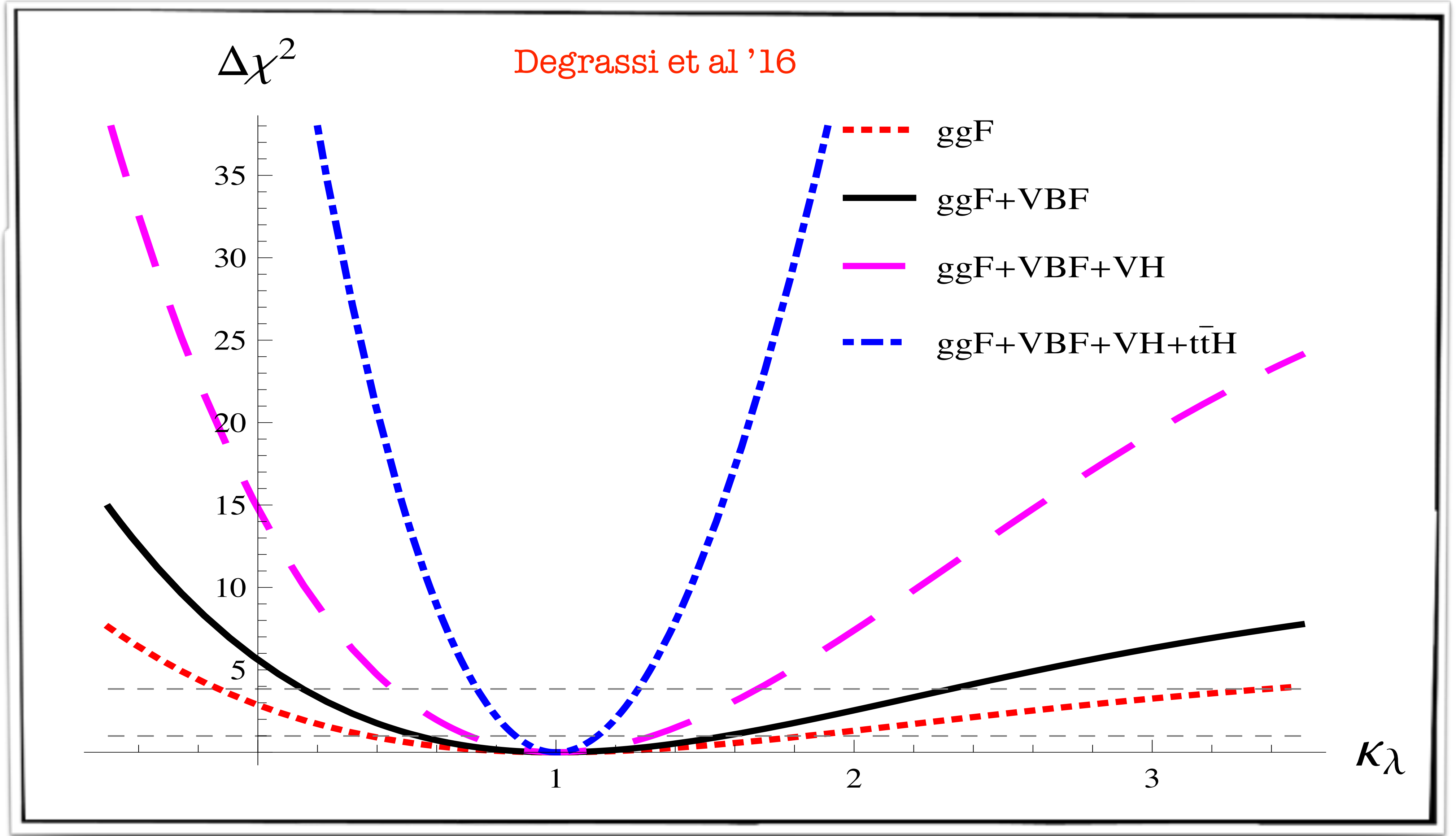


Bizon et al '16





h^3 from h@NLO@LHC



$$\kappa_\lambda = \frac{g_{h^3}}{g_{h^3}^{SM}}$$

$$\mathcal{L} \supset \frac{c_6}{\Lambda^2}|H|^6 \Longleftrightarrow \kappa_\lambda = 1 + \frac{c_6 G_F^{-2}}{m_H^2 \Lambda^2}$$

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

(a bit worse but)
in the same ballpark
as bounds obtained
from double Higgs production

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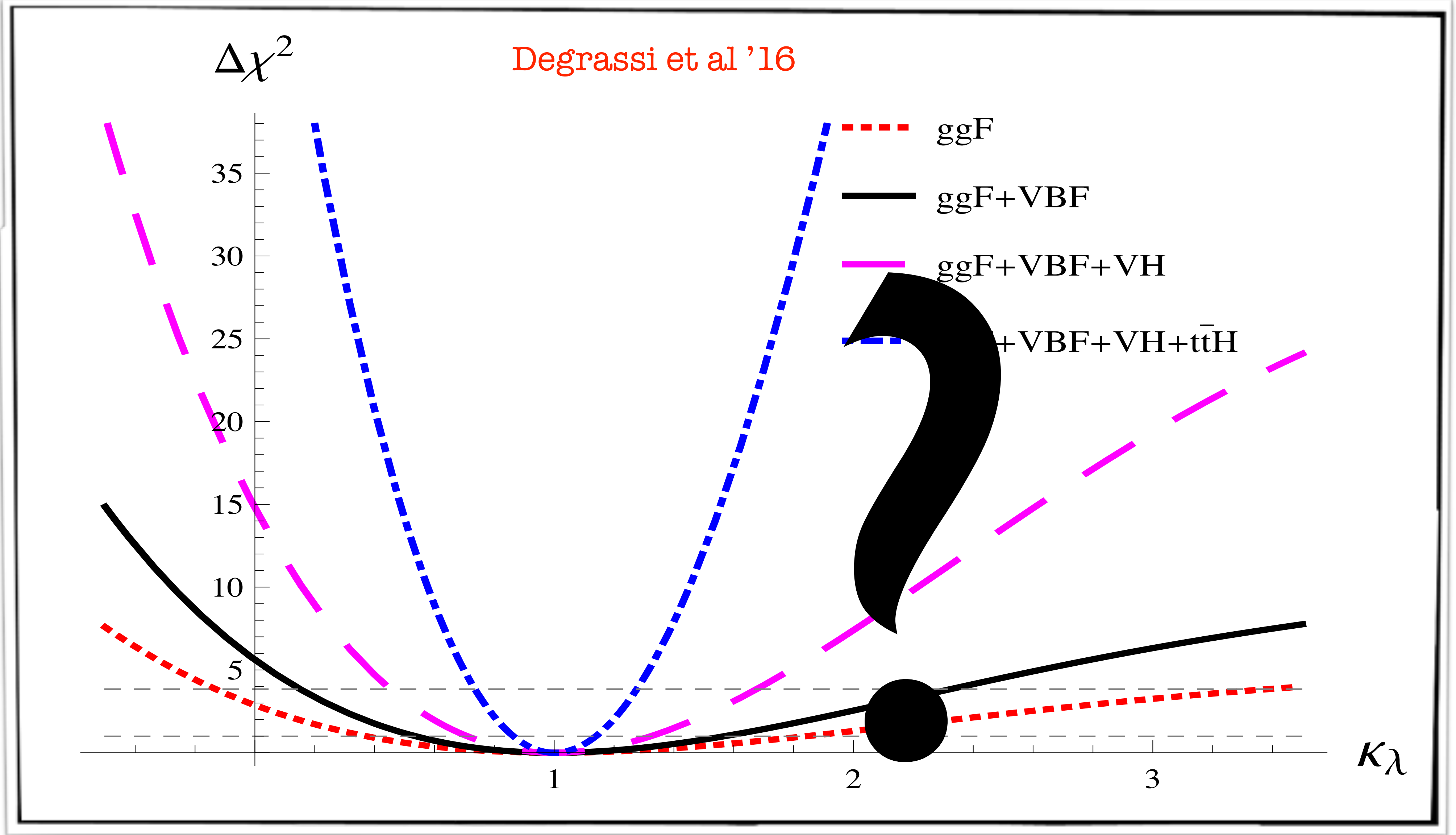

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How robust is this NLO bound?

1. Is it theoretically motivated to deform only λ_3? Which BSM dynamics is this NLO fit probing?
2. How large can λ_3 be, from the theoretical point of view? How much larger than the other deformations of Higgs couplings can $\delta\lambda_3$ be?
3. Are the bounds on λ_3 stable if other BSM deformations are allowed?
4. If λ_3 is large, does it spoil the previous single-Higgs fits?
5. Will it be enough to look at inclusive rates?
6. Can we "replace" $pp \to hh$ with other observables?
7. Can we obtain information on below the hh threshold, e.g. at a 250GeV Higgs factory?

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

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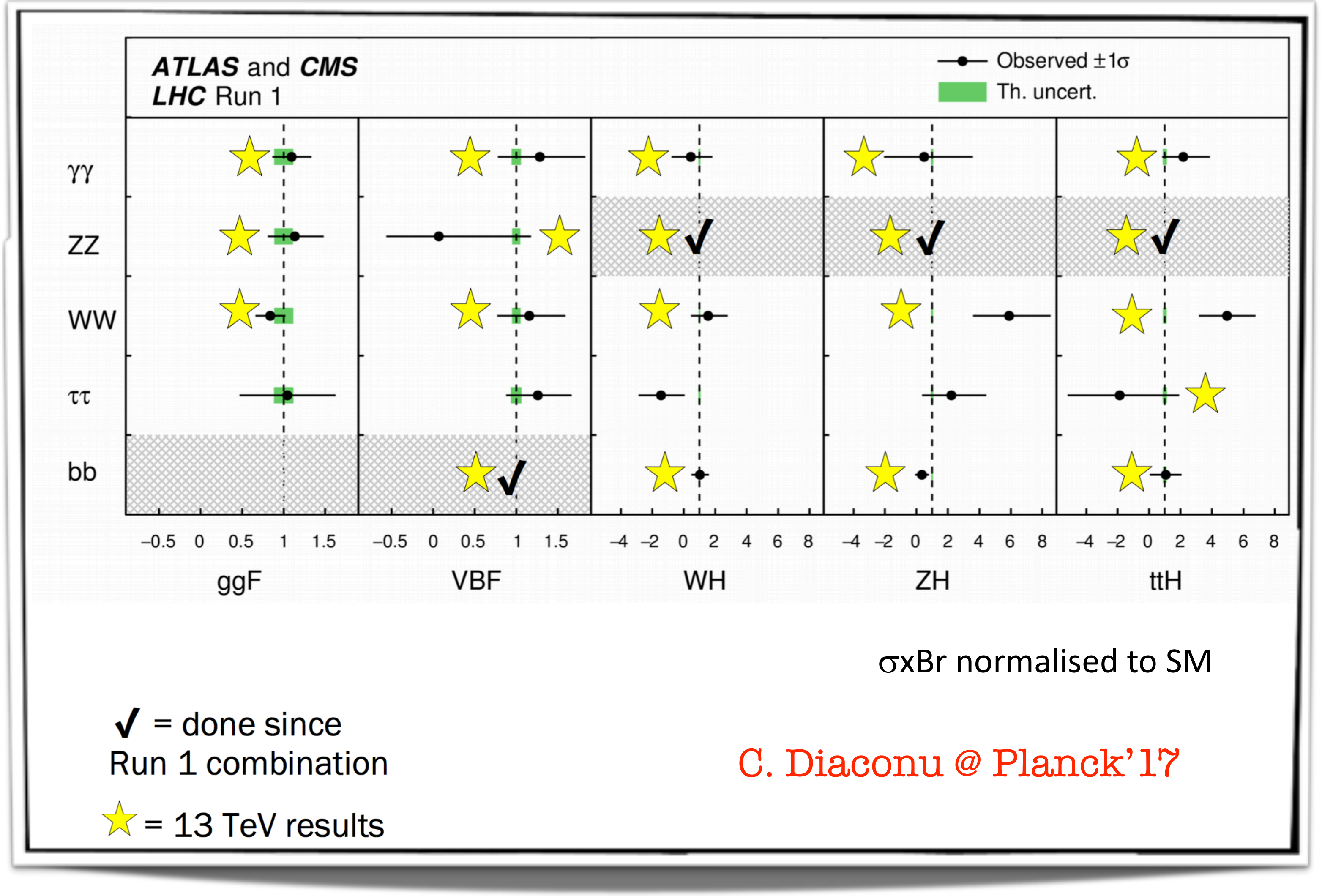

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Good sensitivity (O(5-10-20)%) on 16 channels @ **HL-LHC**

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

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

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

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

linearized BSM perturbations

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

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

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

linearized BSM perturbations

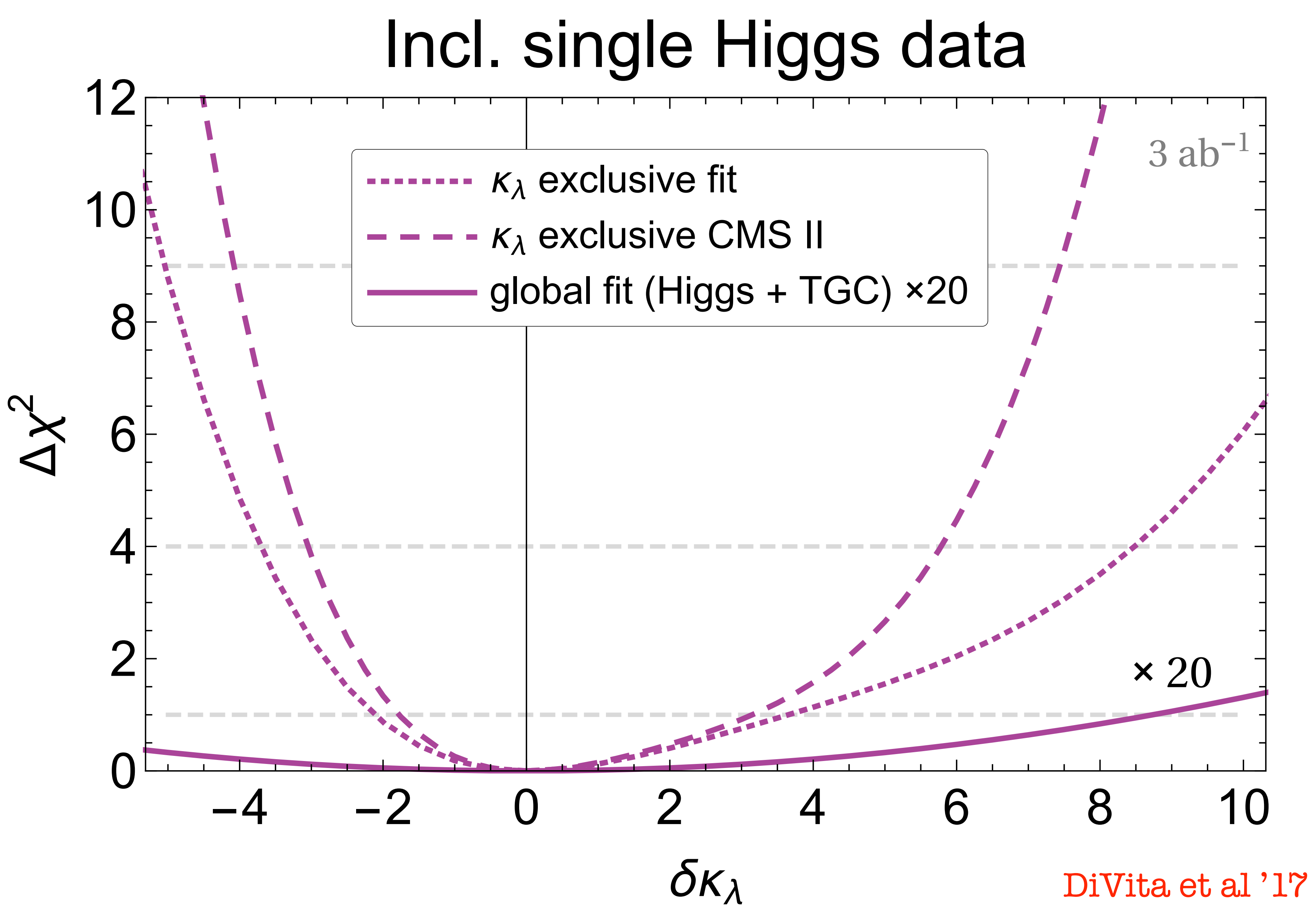
$$\mu_i \to \mu_i + \delta \qquad \mu^f \to \mu^f - \delta$$

cannot determine univocally 10 EFT parameters!

one flat direction is expected!

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

The fabulous 5^2 channels



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

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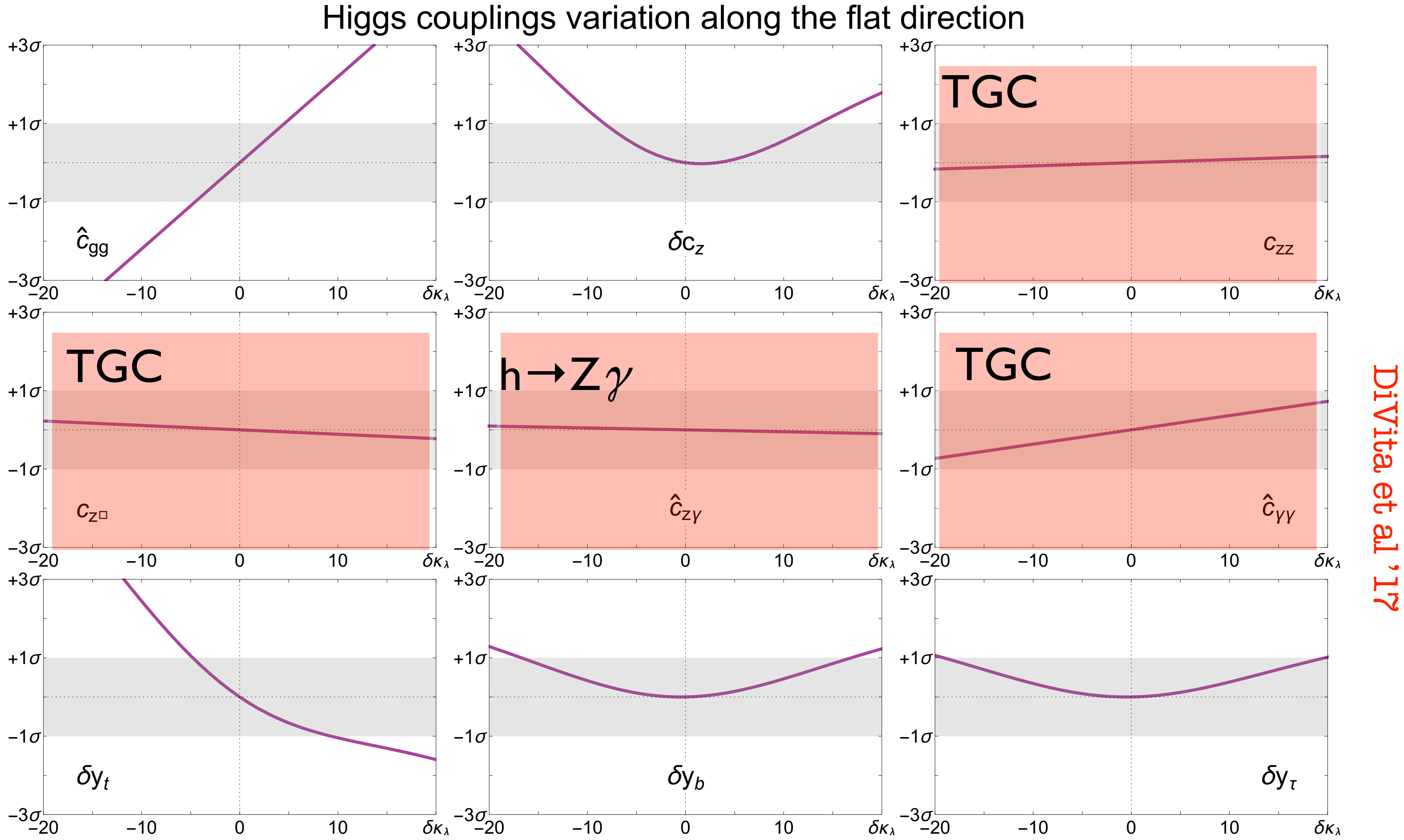

The particular structure of this flat direction tells that adding new data on diboson or h→Zγ won't help much

one flat direction is expected!

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

NLO w/ dominant h^3 ?? $>$ $=$ $<$?? LO w/ subdominant other h

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

NLO w/ dominant h^3 $\geq$?? $\leq$ LO w/ subdominant other h

Minimal Composite Higgs SILH $\xi = \frac{v^2}{f^2} \ll 1$	$\frac{1}{f^2}\left(\partial_\mu \lvert H\rvert^2\right)^2$ $\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1 + \xi$	$\frac{\lambda_4}{f^2}\lvert H\rvert^6$ $\kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1 + \xi$	NLO h^3 irrelevant
Partly Composite Higgs $\xi = \frac{v^2}{f^2} \ll 1$	$\frac{\varepsilon^4}{f^2}\left(\partial_\mu \lvert H\rvert^2\right)^2$ $\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1 + \varepsilon^4 \xi$	$\frac{\varepsilon^6}{f^2}\lvert H\rvert^6$ $\kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1 + \varepsilon^2 \frac{g_*^2 v^2}{m_h^2} \varepsilon^4 \xi$	NLO h^3 could be relevant
Bosonic Technicolor Induced EWSB $\varepsilon = \frac{f}{v} \ll 1$	$\frac{\varepsilon^4}{f^2}\left(\partial_\mu \lvert H\rvert^2\right)^2$ $\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1 + \varepsilon^2$	$\frac{\varepsilon^6}{f^2}\lvert H\rvert^6$ $\kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1 + \mathcal{O}(1)$	NLO h^3 a priori relevant

Make h³ great again: Higgs portal models

$$\mathcal{L} \supset \theta g_* m_* H^\dagger H \varphi - \frac{m_*^4}{g_*^2} V(g_* \varphi / m_*)$$

Make h³ great again: Higgs portal models

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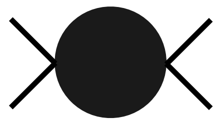
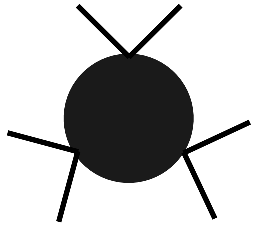
$$\varphi \sim \frac{\theta\, g_* |H|^2}{m_*}$$



$$\frac{\theta^2 g_*^2}{m_*^2} \quad \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) \quad \Rrightarrow \quad \delta c_z \sim \theta^2 g_*^2 \frac{v^2}{m_*^2}$$



$$\frac{m_*^4}{g_*^2} \frac{g_*^3}{m_*^3} \left(\frac{\theta g_*}{m_*} \right)^3 (H^\dagger H)^3 \quad \Rrightarrow \quad \delta \kappa_\lambda \sim \theta^3 g_*^4 \frac{1}{\lambda_3^{SM}} \frac{v^2}{m_*^2}$$

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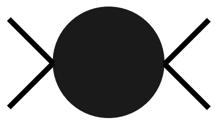

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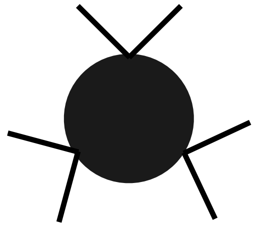


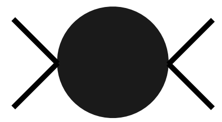
$$\frac{m_*^4}{g_*^2} \frac{g_*^3}{m_*^3} \left(\frac{\theta g_*}{m_*} \right)^3 (H^\dagger H)^3 \quad \Rrightarrow \quad \delta\kappa_\lambda \sim \theta^3 g_*^4 \frac{1}{\lambda_3^{SM}} \frac{v^2}{m_*^2}$$

parametric enhancement of h³

Make h³ great again: Higgs portal models

$$\mathcal{L} \supset \theta g_* m_* H^\dagger H \varphi - \frac{m_*^4}{g_*^2} V(g_*\varphi/m_*)$$

$$\varphi \sim \frac{\theta\, g_* |H|^2}{m_*}$$



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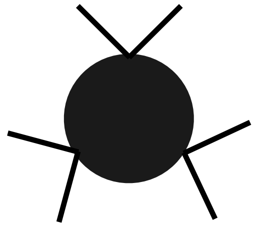

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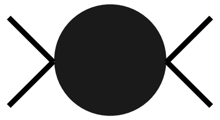
parametric enhancement of h³

but also **tuning** of Higgs quartic coupling



$$\frac{m_*^4}{g_*^2} \frac{g_*^2}{m_*^2} \left(\frac{\theta g_*}{m_*}\right)^2 |H|^4 \quad \Rrightarrow \quad \Delta \sim \frac{\theta^2 g_*^2}{\lambda_3^{SM}}$$

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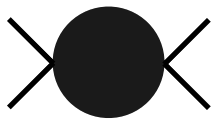

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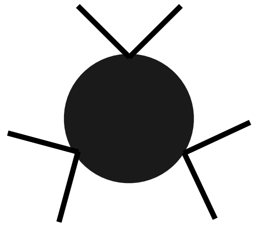

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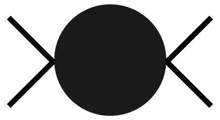

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~~ large h³ ~~
either tuning (Δ>1)
or
give-up on linear h-expansion (ε >1)

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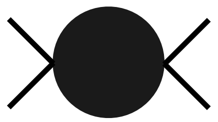

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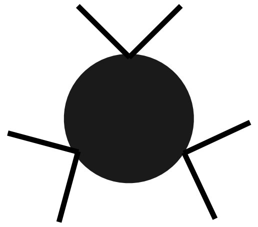

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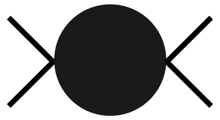

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either tuning (Δ>1)
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a possible benchmark of large h³

$\theta \simeq 1,\ g_* \simeq 3$ and $m_* \simeq 2.5$ TeV

$\varepsilon \simeq 0.1\,, \quad 1/\Delta \simeq 1.5\%\,, \quad \delta c_z \simeq 0.1\,, \quad \delta\kappa_\lambda \simeq 6$

Does h³ modify the fit to other couplings?

DiVita et al '17

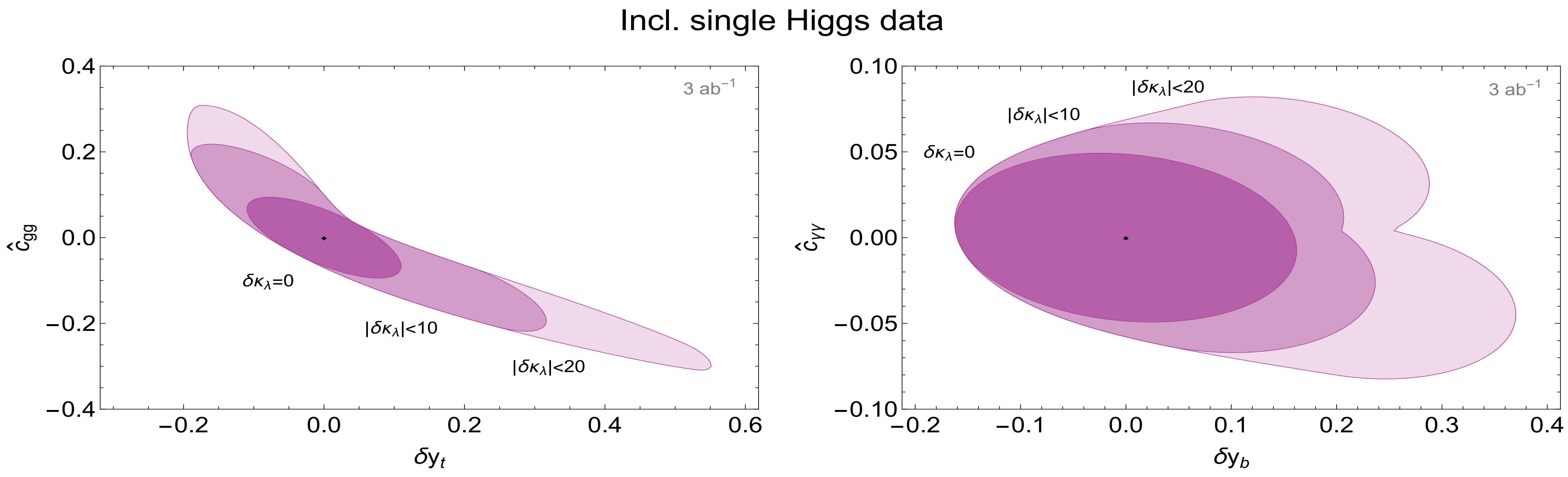

Figure 3. Constraints in the planes $(\delta y_t, \hat{c}_{gg})$ (left panel) and $(\delta y_b, \hat{c}_{\gamma\gamma})$ (right panel) obtained from a global fit on the single-Higgs processes. The darker regions are obtained by fixing the Higgs trilinear to the SM value $\kappa_\lambda = 1$, while the 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 $\Delta\chi^2 = 2.3$).

in models with parametrically large h^3

a LO fit to single Higgs couplings done omitting κ_λ could be erroneous

NLO single H vs double Higgs

DiVita et al '17

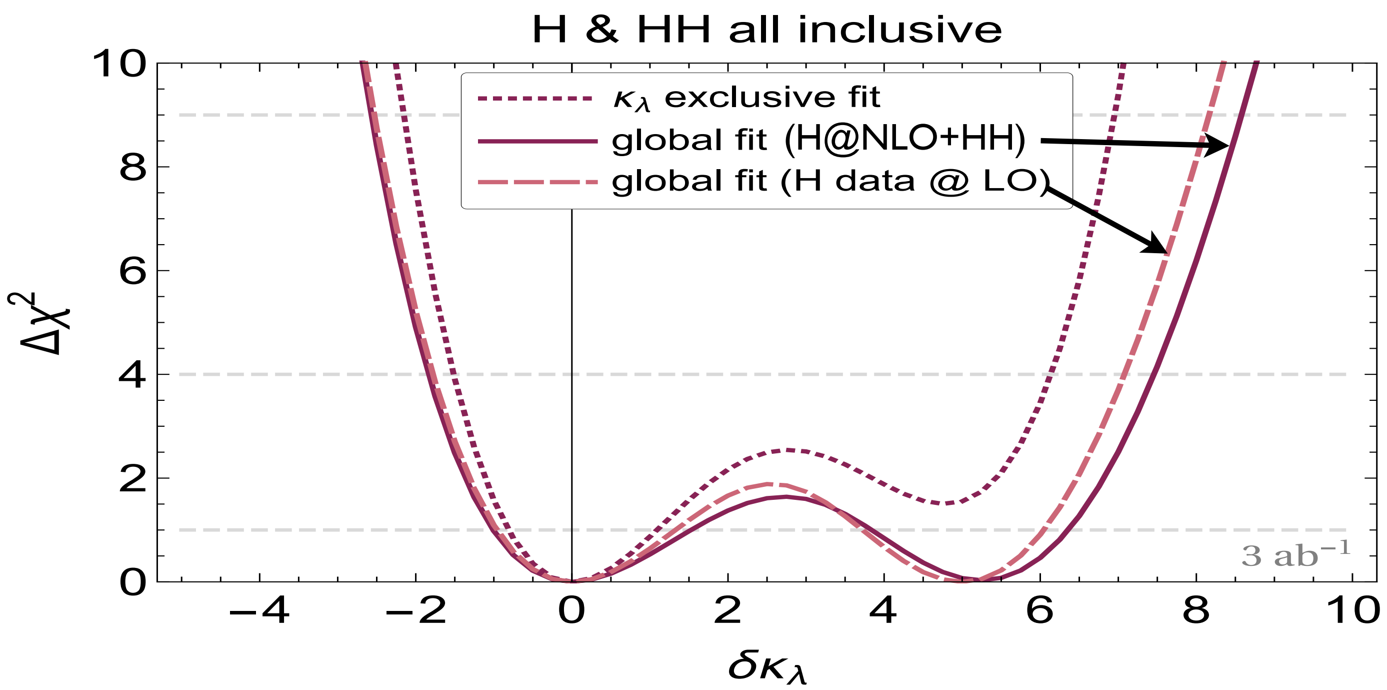

Figure 4. *Left:* The solid curve shows the global χ^2 as a function of the corrections to the Higgs trilinear self-coupling obtained from a fit exploiting inclusive single Higgs and inclusive double Higgs observables. The dashed line shows the fit obtained by neglecting the dependence on $\delta\kappa_\lambda$ 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 data first!

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

$$\kappa_\lambda \in [0.0, 2.5] \cup [4.9, 7.4]$$

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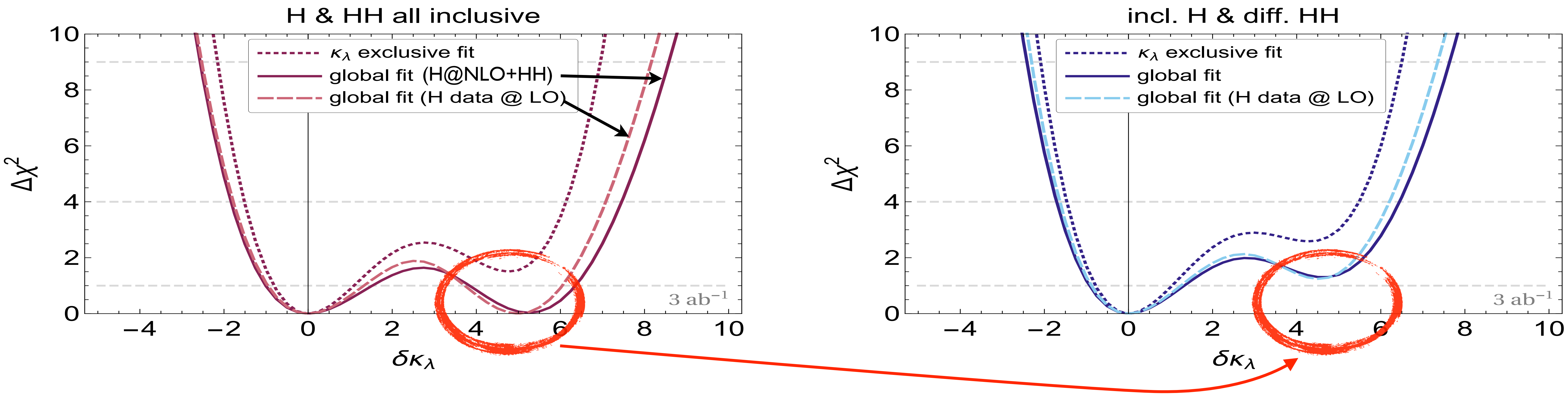
DiVita et al '17



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differential double Higgs removes degenerate minimum but doesn't improve much the bound around SM

Azatov et al '15

Is differential single H @ NLO a good option?

DiVita et al '17

See also Maltoni et al 1709.08649

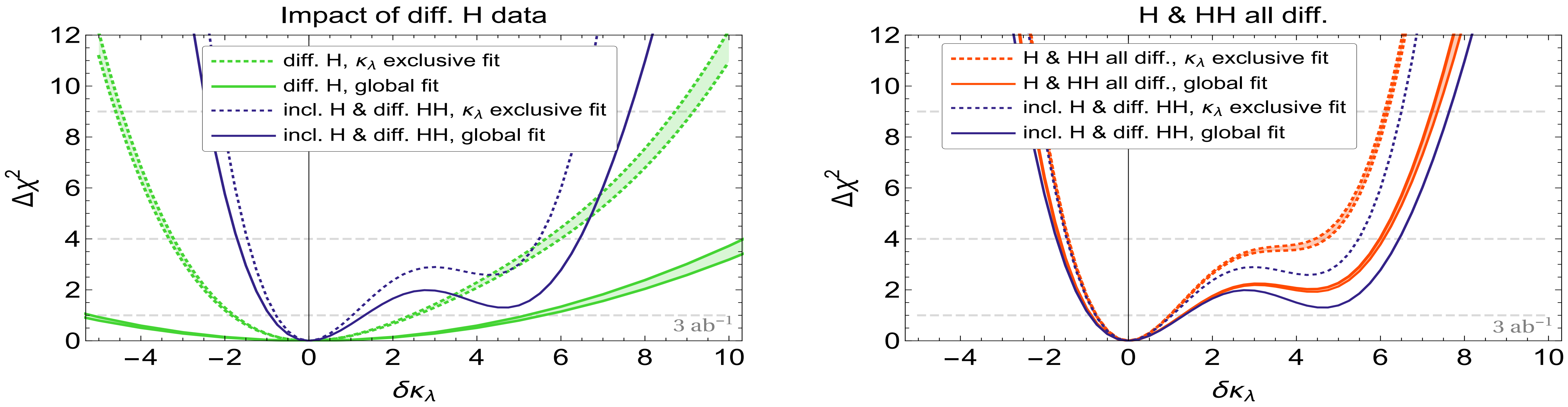


Figure 5. *Left:* χ^2 as a function of the Higgs trilinear self-coupling. The green bands are obtained from the differential analysis on single-Higgs observables and are delimited by the fits corresponding to the optimistic and pessimistic estimates of the experimental uncertainties. The dotted green 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.

diff. single Higgs observables to asses h^3 is an interesting potential option

h incl. @ NLO: flat direction

h diff. @ NLO: $\kappa_\lambda \subset [-4,7]$

w/ hh data: $\kappa_\lambda \subset [0,2.5]$

~~ synergy between diff. single Higgs and double Higgs channels ~~

more detailed estimates of exp. uncertainties are required to fully asses the potential of diff. channels

Is the fit robust against systematics?

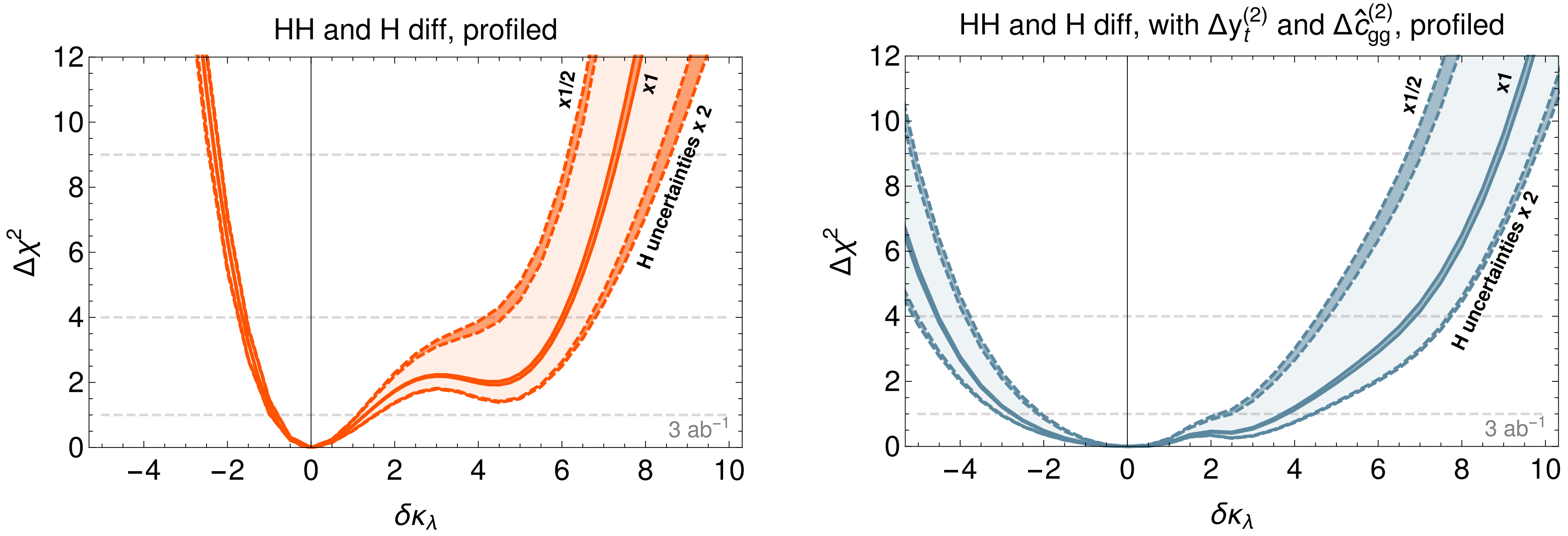
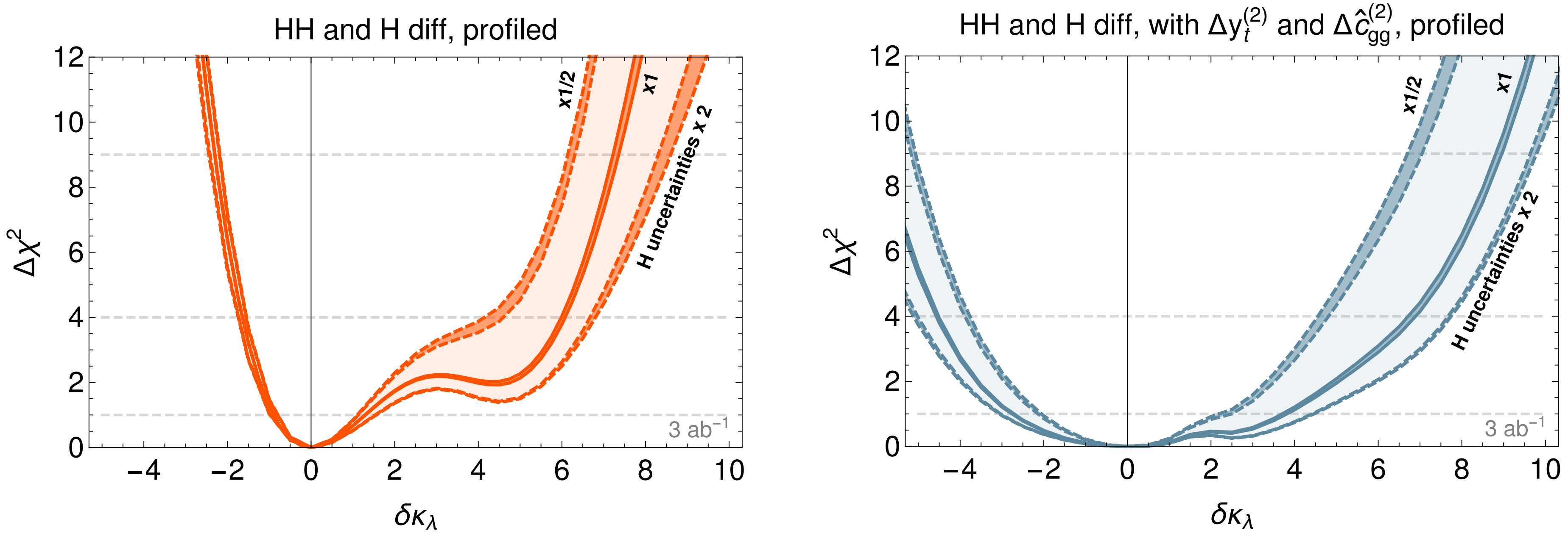


Figure 6. Band of variation of the global fit on the Higgs self-coupling obtained by rescaling the single-Higgs measurement uncertainties by a factor in the range $x \in [1/2, 2]$. The lighter shaded bands show the full variation of the fit due to the rescaling. The darker bands show how the fits corresponding to the 'optimistic' and 'pessimistic' assumptions on the systematic uncertainties (compare fig. 5) change for $x = 1/2, 1, 2$. The left panel shows the fit in the linear Lagrangian, while the right panel corresponds to the non-linear case in which $\Delta y_f^{(2)}$ and $\Delta\hat{c}_{gg}^{(2)}$ are treated as independent parameters.

DiVita et al '17

Is the fit robust against systematics?

doubling the uncertainties doesn't affect much the bounds on h^3



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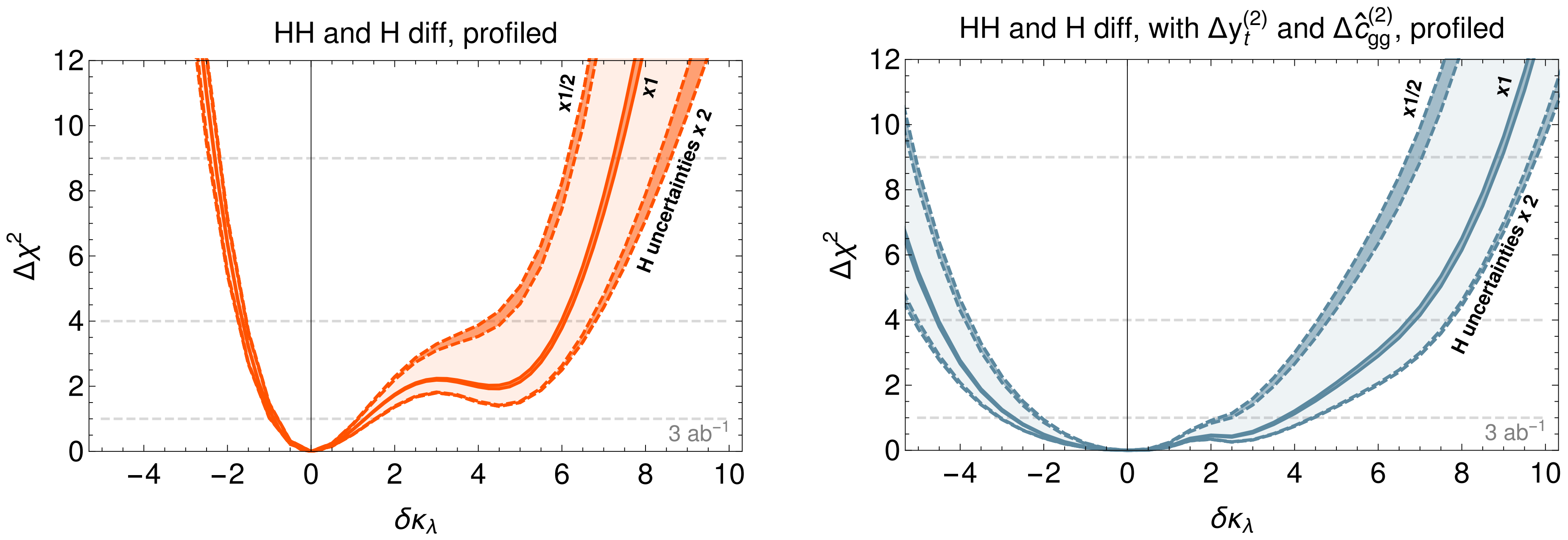

bounds on h^3 become looser in non-linear realization of SU(2)

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DiVita et al '17

in scenarios where h^3 can be naturally large,
Higgs expansion could break down & more parameters need to be fitted
(in particular due do fewer constraints from EW precision data)
no robust determination of h^3 possible yet in these scenarios

What about (low energy) e^+e^- colliders?

1 main production mode: ZH & 1 subdominant production: VBF
+ access to full angular distributions (4) and/or beam polarizations (2)
7 (+2) accessible decay modes: ZZ, WW, $\gamma\gamma$, Zγ, $\tau\tau$, bb, gg, (cc, μμ)

at least **10** solid independent constraints to fit **10** parameters

a priori no flat direction is expected!

S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. Panico, M. Riembau, T. Vantalon '17

See also F. Maltoni, D. Pagani, X. Zhao '18

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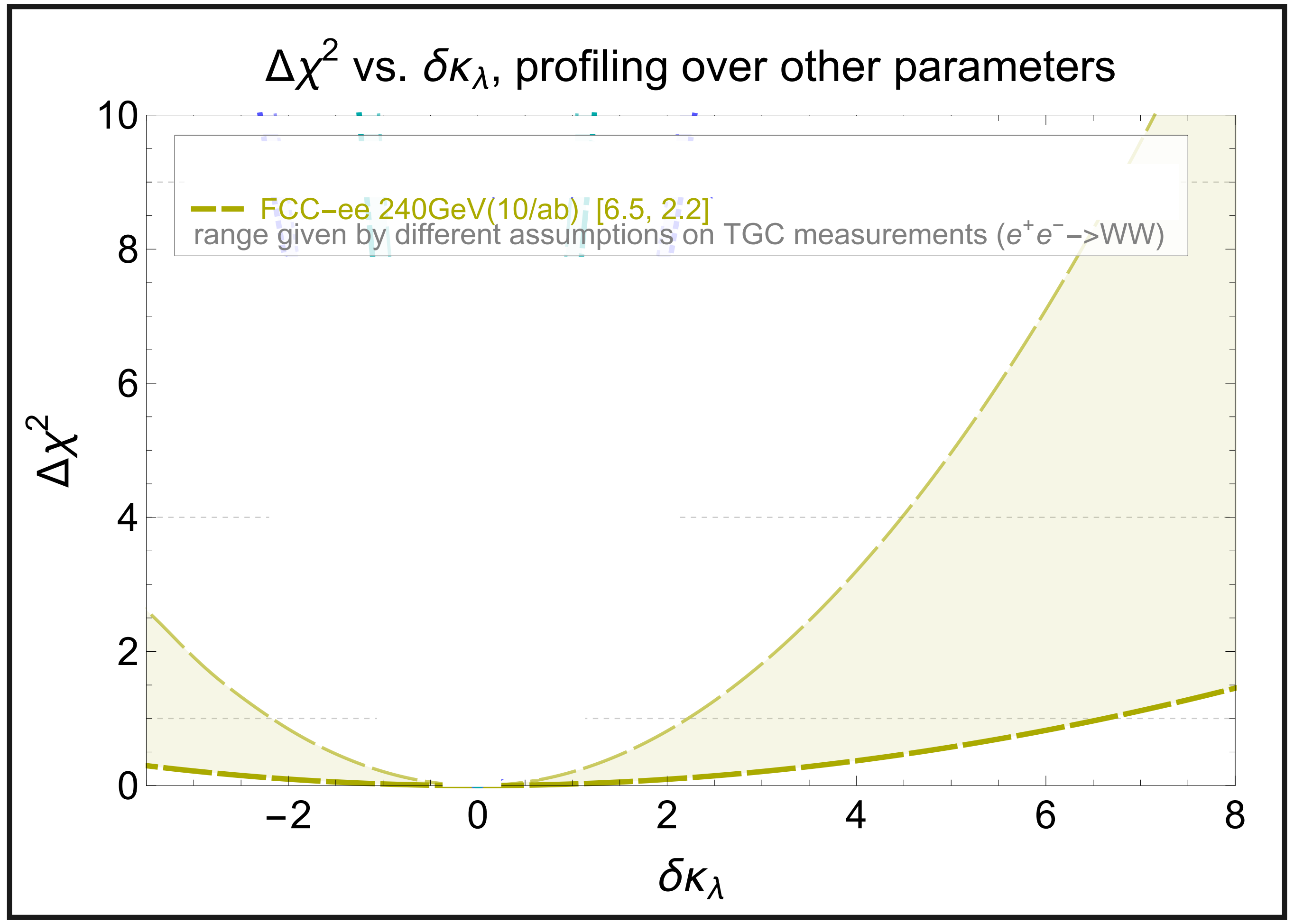

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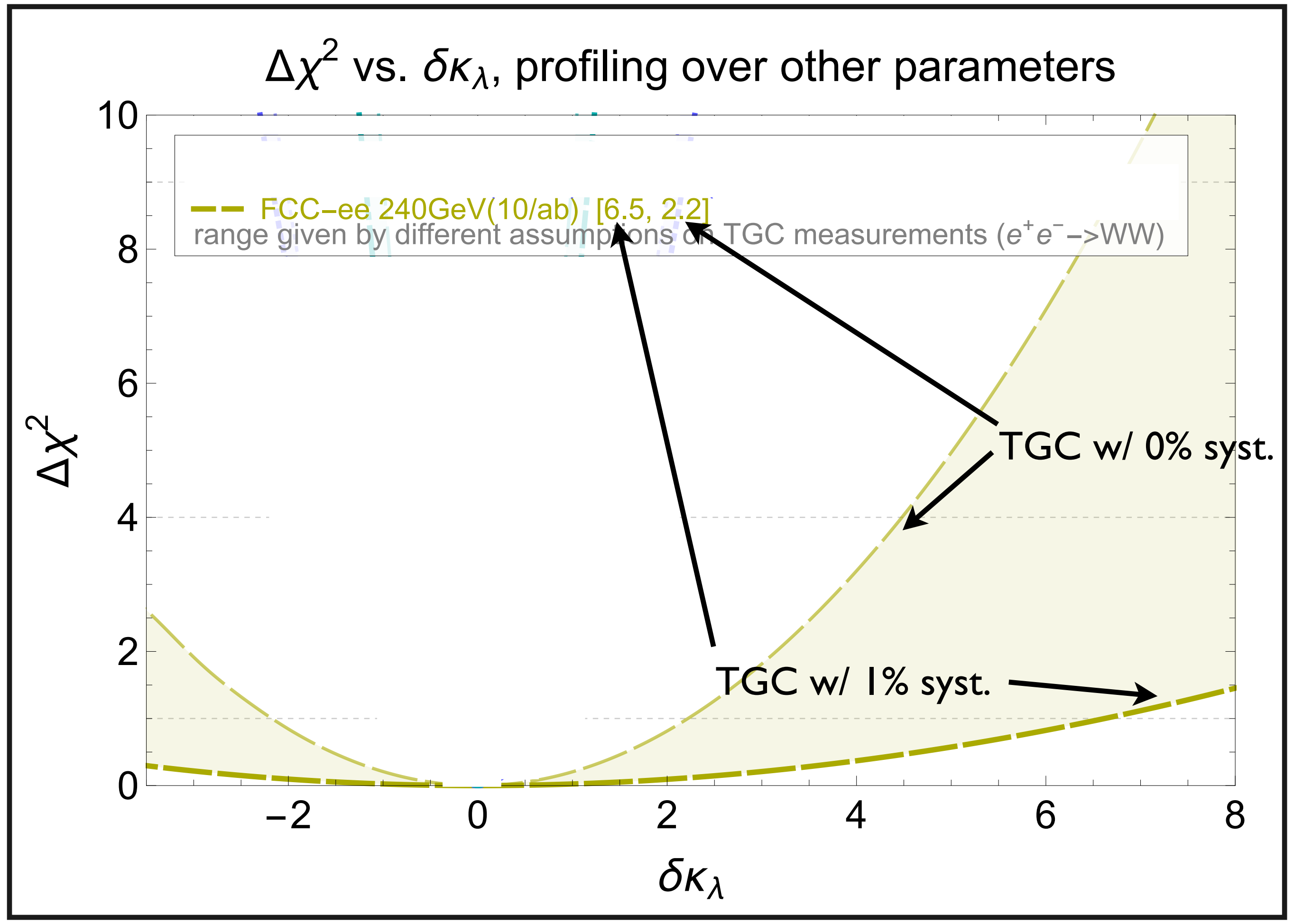

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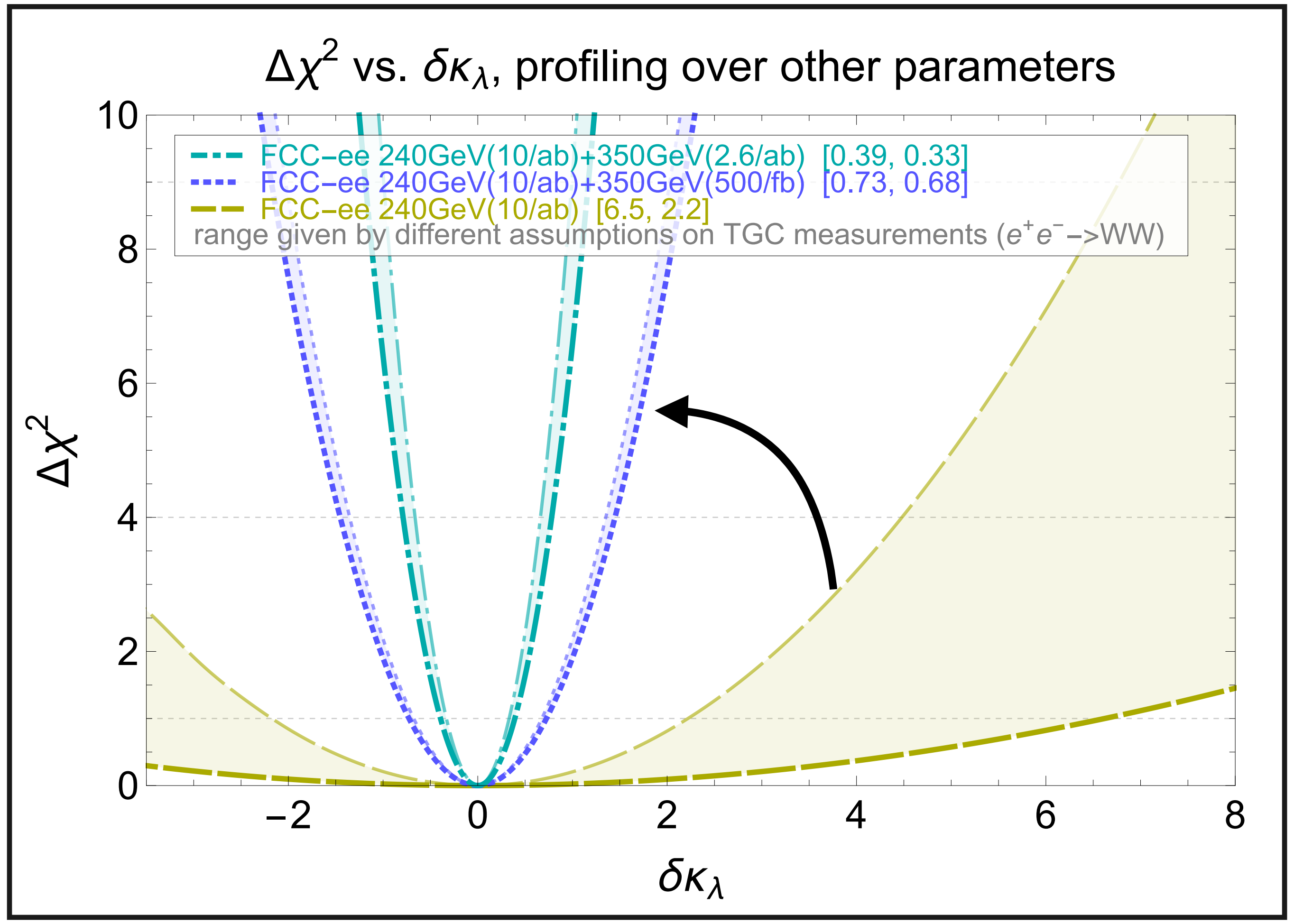

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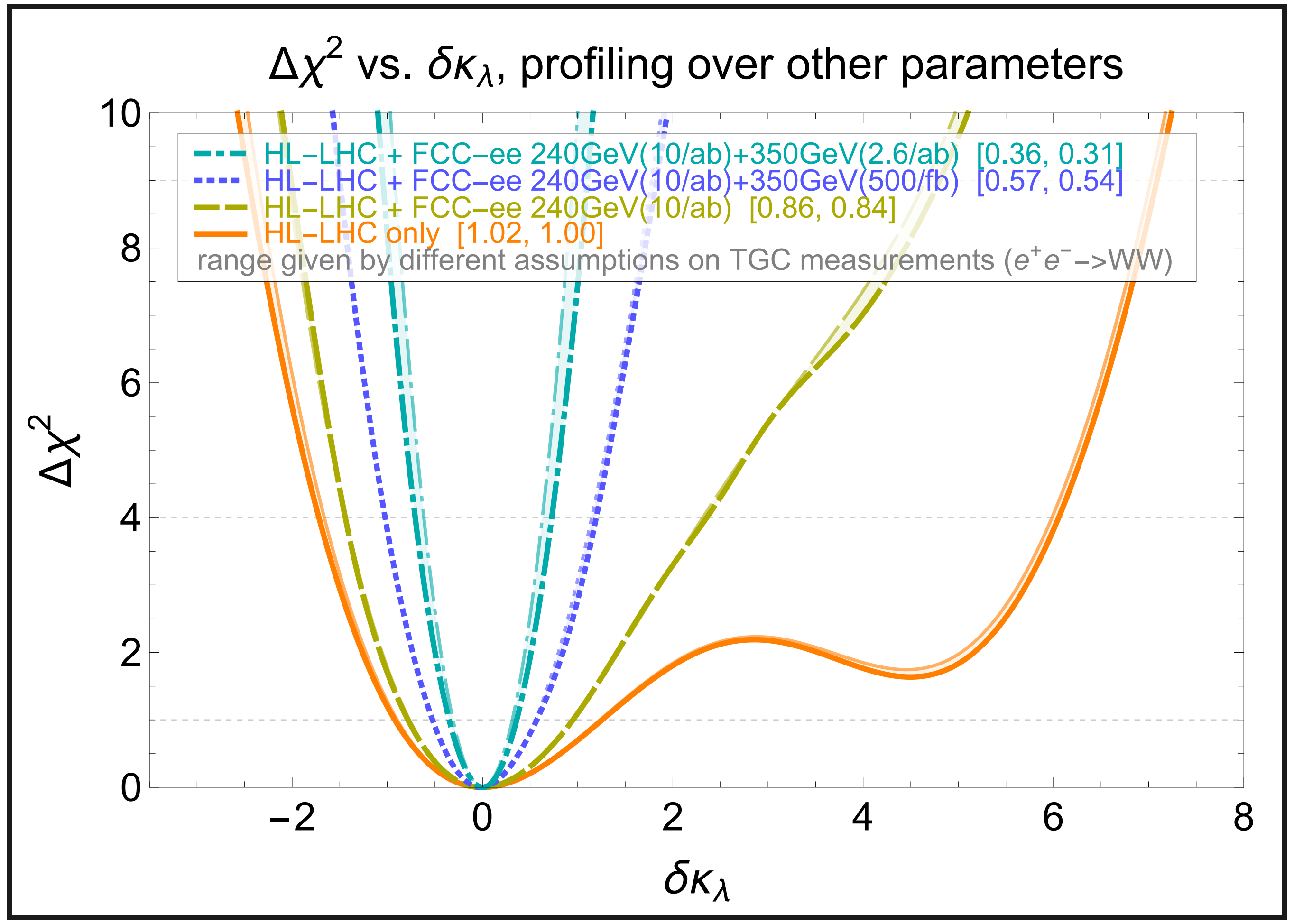

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3) combination FCC-ee and HL-LHC is very powerful (especially if cannot afford FCC-ee @ 350GeV)

S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. Panico, M. Riembau, T. Vantalon ‘17

See also F. Maltoni, D. Pagani, X. Zhao ‘18

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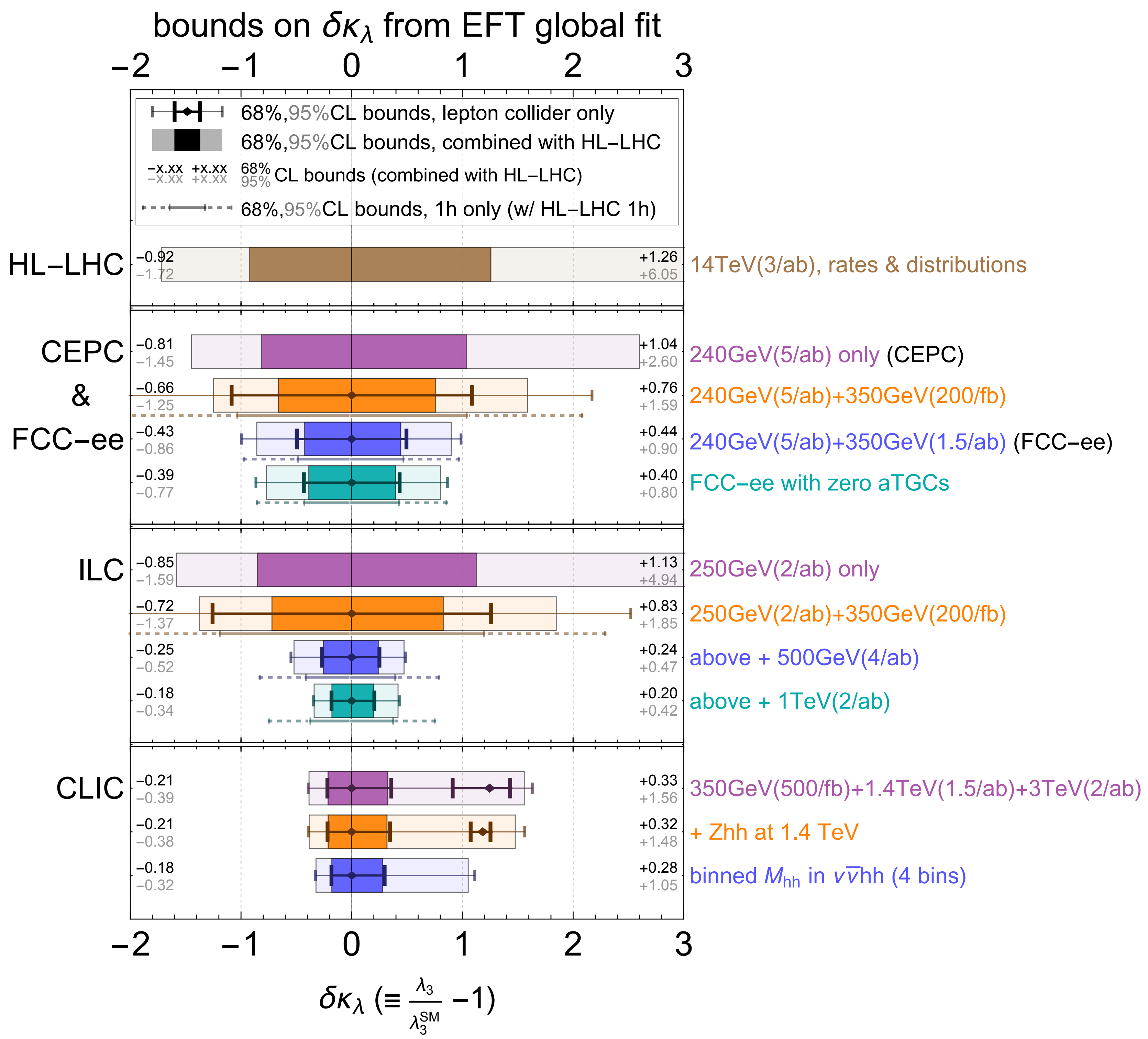

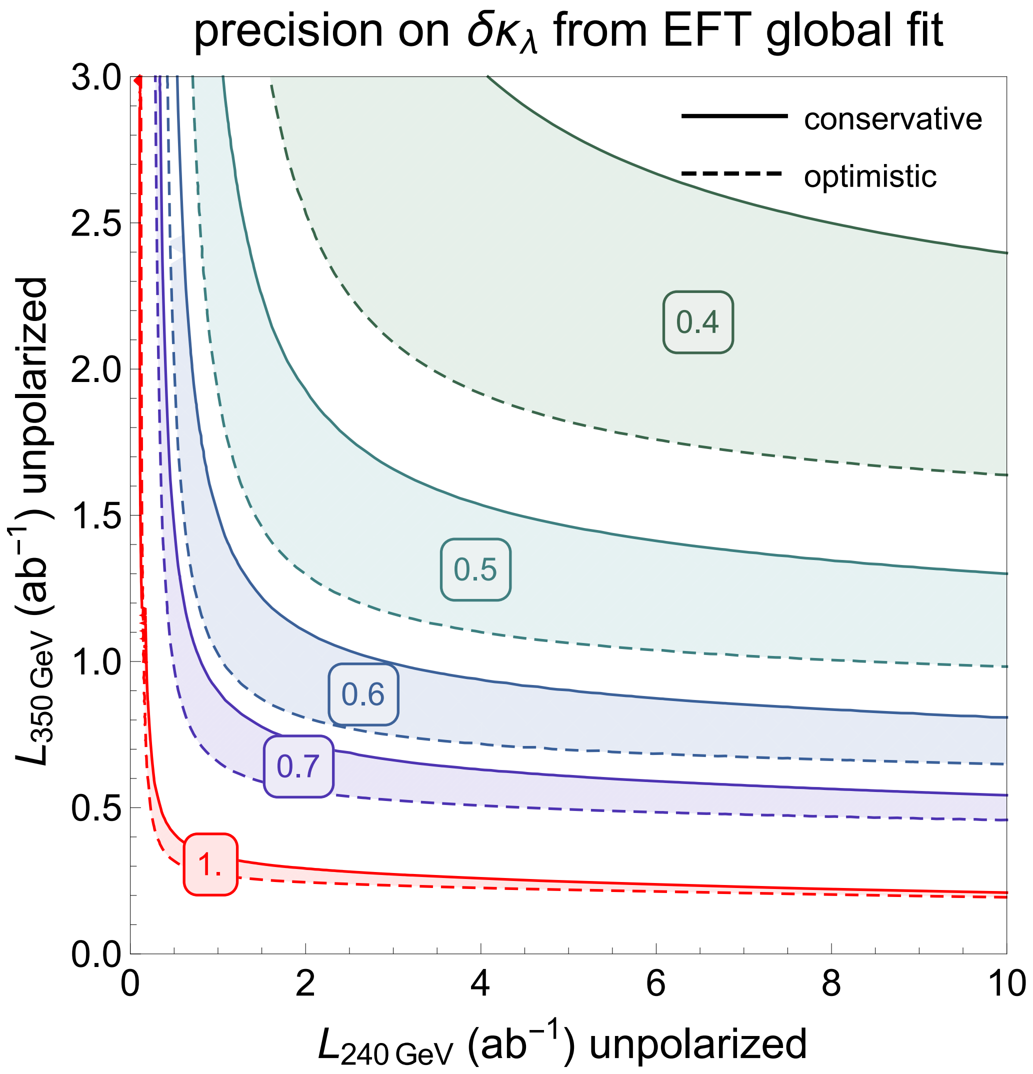

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Summary and outlook

- Keep calm and measure inclusive & differential rates. There is always value in good measurements.
- Single-Higgs could be complementary to double-Higgs (different systematics, different theoretical and parametric uncertainties).
- Training ground: use simplified frameworks with few parameters to push the combined experimental analyses and to show their limitations in such optimistic scenarios.
- Always remember the hidden assumptions and set your goal accordingly (SM measurement or BSM search?) Tautology: λ_3 can differ from SM prediction in BSM scenarios only.
- Updated HL-LHC projections for inclusive rates, and possibly for differential distributions would be welcome, in order to assess the LHC potential to constrain BSM scenarios.

Conclusions

It is often claimed that h^3 measurement is needed
1) to understand EW symmetry breaking
2) to probe new physics at the origin of EWSB

h^3 is generically *not* a precise measurement to access to new physics
but order one determination is within HL-LHC reach and it can help figure out
the thermodynamics of EW phase transition and the Higgs thermal potential
with important consequences:
1) EW baryogenesis
2) stochastic GW background

Backup

Higgs Basis

A. Falkowski '15
LHCHXSWG YR4 '16

$$\mathcal{L} \supset \frac{h}{v}\Bigg[\delta c_w \frac{g^2 v^2}{2} W^+_\mu W^{-\mu} + \delta c_z \frac{(g^2+g'^2)v^2}{4} Z_\mu Z^\mu$$

$$+ c_{ww}\frac{g^2}{2} W^+_{\mu\nu}W^{-\mu\nu} + c_{w\Box} g^2 \left(W^-_\mu \partial_\nu W^{+\mu\nu} + \text{h.c.}\right) + \hat{c}_{\gamma\gamma}\frac{e^2}{4\pi^2} A_{\mu\nu}A^{\mu\nu}$$

$$+ c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z^{\mu\nu} + \hat{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2\pi^2} Z_{\mu\nu}A^{\mu\nu} + c_{z\Box} g^2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A^{\mu\nu}\Bigg]$$

$$+ \frac{g_s^2}{48\pi^2}\left(\hat{c}_{gg}\frac{h}{v} + \hat{c}^{(2)}_{gg}\frac{h^2}{2v^2}\right) G_{\mu\nu}G^{\mu\nu} - \sum_f \left[m_f\left(\delta y_f \frac{h}{v} + \delta y^{(2)}_f \frac{h^2}{2v^2}\right)\bar{f}_R f_L + \text{h.c.}\right]$$

$$-(\kappa_\lambda - 1)\lambda_3^{SM} v h^3 \,,$$

with

$$\delta c_w = \delta c_z \,,$$

$$c_{ww} = c_{zz} + 2\frac{g'^2}{\pi^2(g^2+g'^2)}\hat{c}_{z\gamma} + \frac{g'^4}{\pi^2(g^2+g'^2)^2}\hat{c}_{\gamma\gamma} \,,$$

$$c_{w\Box} = \frac{1}{g^2-g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2\frac{g'^2}{\pi^2(g^2+g'^2)}\hat{c}_{\gamma\gamma} - (g^2-g'^2)\frac{g'^2}{\pi^2(g^2+g'^2)}\hat{c}_{z\gamma}\right],$$

$$c_{\gamma\Box} = \frac{1}{g^2-g'^2}\left[2g^2 c_{z\Box} + (g^2+g'^2)\, c_{zz} - \frac{e^2}{\pi^2}\hat{c}_{\gamma\gamma} - \frac{g^2-g'^2}{\pi^2}\hat{c}_{z\gamma}\right],$$

$$\hat{c}^{(2)}_{gg} = \hat{c}_{gg} \,,$$

$$\delta y^{(2)}_f = 3\delta y_f - \delta c_z \,.$$

10 parameters

6 deformations of Higgs couplings to gauge bosons

$$\delta c_z \,,\ c_{zz} \,,\ c_{z\Box} \,,\ \hat{c}_{z\gamma} \,,\ \hat{c}_{\gamma\gamma} \,,\ \hat{c}_{gg}$$

3 deformations of Higgs couplings to fermions

$$\delta y_t \,,\ \delta y_b \,,\ \delta y_\tau \,,$$

1 deformations of Higgs self-couplings

$$\kappa_\lambda$$

Single Higgs observables @ NLO in h³

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = 1+\delta c_z \begin{pmatrix}2.0\\2.0\\2.0\\2.0\\2.0\\2.0\end{pmatrix} + c_{z\Box}\begin{pmatrix}7.6\\7.8\\8.3\\8.4\\9.1\\10.0\end{pmatrix} + c_{zz}\begin{pmatrix}3.4\\3.4\\3.5\\3.6\\3.7\\4.0\end{pmatrix} - \hat{c}_{z\gamma}\begin{pmatrix}0.060\\0.061\\0.067\\0.068\\0.077\\0.086\end{pmatrix} - \hat{c}_{\gamma\gamma}\begin{pmatrix}0.028\\0.028\\0.030\\0.032\\0.034\\0.037\end{pmatrix}$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = 1+\delta c_z \begin{pmatrix}2.0\\2.0\\2.0\\2.0\\2.0\\2.0\end{pmatrix} + c_{z\Box}\begin{pmatrix}9.3\\9.4\\10.0\\10.1\\11.1\\12.1\end{pmatrix} + c_{zz}\begin{pmatrix}4.4\\4.4\\4.6\\4.6\\5.0\\5.3\end{pmatrix} - \hat{c}_{z\gamma}\begin{pmatrix}0.082\\0.084\\0.094\\0.095\\0.110\\0.126\end{pmatrix} - \hat{c}_{\gamma\gamma}\begin{pmatrix}0.044\\0.045\\0.048\\0.049\\0.054\\0.060\end{pmatrix}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = 1+\delta c_z \begin{pmatrix}2.0\\2.0\\2.0\\2.0\\2.0\\2.0\end{pmatrix} - c_{z\Box}\begin{pmatrix}2.2\\2.2\\2.5\\2.5\\3.0\\3.7\end{pmatrix} - c_{zz}\begin{pmatrix}0.81\\0.83\\0.89\\0.90\\1.04\\1.27\end{pmatrix} + \hat{c}_{z\gamma}\begin{pmatrix}0.029\\0.030\\0.033\\0.034\\0.041\\0.051\end{pmatrix} + \hat{c}_{\gamma\gamma}\begin{pmatrix}0.0113\\0.0117\\0.0129\\0.0131\\0.0156\\0.0193\end{pmatrix}$$

$$\frac{\sigma_{\rm ggF}}{\sigma_{\rm ggF}^{\rm SM}} = 1 + 2\hat{c}_{gg} + 2.06\delta y_t - 0.06\delta y_b$$

$$\frac{\sigma_{\rm ttH}}{\sigma_{\rm ttH}^{\rm SM}} = 1 + 2\delta y_t\,.$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\rm SM}} = 1 + 2.56\,\delta c_z + 2.15\,c_{z\Box} + 0.98\,c_{zz} - 0.066\hat{c}_{z\gamma} - 2.47\,\hat{c}_{\gamma\gamma} - 0.56\,\delta y_t\,,$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{\rm SM}} = 1 + 2.11\,\delta c_z - 3.4\,\hat{c}_{z\gamma} - 0.113\,\delta y_t\,,$$

$$\frac{\Gamma_{\rm WW}}{\Gamma_{\rm WW}^{\rm SM}} = 1 + 2.0\,\delta c_z + 0.67\,c_{z\Box} + 0.05\,c_{zz} - 0.0182\,\hat{c}_{z\gamma} - 0.0051\,\hat{c}_{\gamma\gamma}\,,$$

$$\frac{\Gamma_{\rm ZZ}}{\Gamma_{\rm ZZ}^{\rm SM}} = 1 + 2.0\,\delta c_z + 0.33\,c_{z\Box} + 0.19\,c_{zz} - 0.0081\,\hat{c}_{z\gamma} - 0.00111\,\hat{c}_{\gamma\gamma}\,,$$

$$\frac{\Gamma_{\tau\tau}}{\Gamma_{\tau\tau}^{\rm SM}} = 1 + 2.0\,\delta y_\tau\,,$$

$$\frac{\Gamma_{bb}}{\Gamma_{bb}^{\rm SM}} = 1 + 2.0\,\delta y_b\,,$$

$$\frac{\Gamma_{\rm H}}{\Gamma_{\rm H}^{\rm SM}} = 1 + 0.171\,\hat{c}_{gg} + 0.006\,c_{zz} - 0.0091\,\hat{c}_{z\gamma} + 0.15\,c_{z\Box} - 0.0061\,\hat{c}_{\gamma\gamma} + 0.48\,\delta$$
$$+ 1.15\,\delta y_b + 0.23\,\delta y_t + 0.13\,\delta y_\tau\,,$$

LHCHXSWG YR4 '16

$$\frac{\sigma}{\sigma_{\rm SM}} = 1 + (\kappa_\lambda - 1)C^\sigma + \frac{(\kappa_\lambda^2 - 1)\delta Z_H}{1 - \kappa_\lambda^2 \delta Z_H}$$

$$\frac{\Gamma}{\Gamma_{\rm SM}} = 1 + (\kappa_\lambda - 1)C^\Gamma + \frac{(\kappa_\lambda^2 - 1)\delta Z_H}{1 - \kappa_\lambda^2 \delta Z_H}\,.$$

$$\delta Z_H = -\frac{9}{16}\frac{G_\mu m_H^2}{\sqrt{2}\pi^2}\left(\frac{2\pi}{3\sqrt{3}} - 1\right) \simeq 0.0015$$

Degrassi et al '16

C^Γ [%]	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
H	0.49	0.83	0.73	0	0.66

C^σ [%]	ggF	VBF	WH	ZH	$t\bar{t}H$
7 TeV	0.66	0.65	1.06	1.23	3.87
8 TeV	0.66	0.65	1.05	1.22	3.78
13 TeV	0.66	0.64	1.03	1.19	3.51
14 TeV	0.66	0.64	1.03	1.18	3.47

TGC

$$\mathcal{L} \supset i\, g\, c_w\, \delta g_{1,z} \left(W^+_{\mu\nu} W^{\mu -} - W^-_{\mu\nu} W^{\mu +} \right) Z^\nu$$
$$+ i\, e\, \delta\kappa_\gamma\, A^{\mu\nu} W^+_\nu W^-_\nu + i\, g\, c_w\, \delta\kappa_z\, Z^{\mu\nu} W^+_\mu W^-_\nu$$
$$+ i\, \frac{e\, \lambda_\gamma}{m_w^2} W^{\mu +}{}_\nu W^{\nu -}{}_\rho A^\rho{}_\mu + \frac{g\, c_w\, \lambda_Z}{m_w^2} W^{\mu +}{}_\nu W^{\nu -}{}_\rho Z^\rho{}_\mu$$

$$\delta g_{1,z} = \frac{g'^2}{2(g^2 - g'^2)} \left[\hat{c}_{\gamma\gamma} \frac{e^2}{\pi^2} + \hat{c}_{z\gamma} \frac{g^2 - g'^2}{\pi^2} - c_{zz} \left(g^2 + g'^2 \right) - c_{z\Box} \frac{g^2}{g'^2} \left(g^2 + g'^2 \right) \right],$$

$$\delta\kappa_\gamma = -\frac{g^2}{2(g^2 + g'^2)} \left[\hat{c}_{\gamma\gamma} \frac{e^2}{\pi^2} + \hat{c}_{z\gamma} \frac{g^2 - g'^2}{\pi^2} - c_{zz}(g^2 + g'^2) \right]$$

$$\delta\kappa_z = \delta g_{1,z} - \frac{g'^2}{g^2} \delta\kappa_\gamma\,,$$

$$\lambda_\gamma = \lambda_z\,.$$