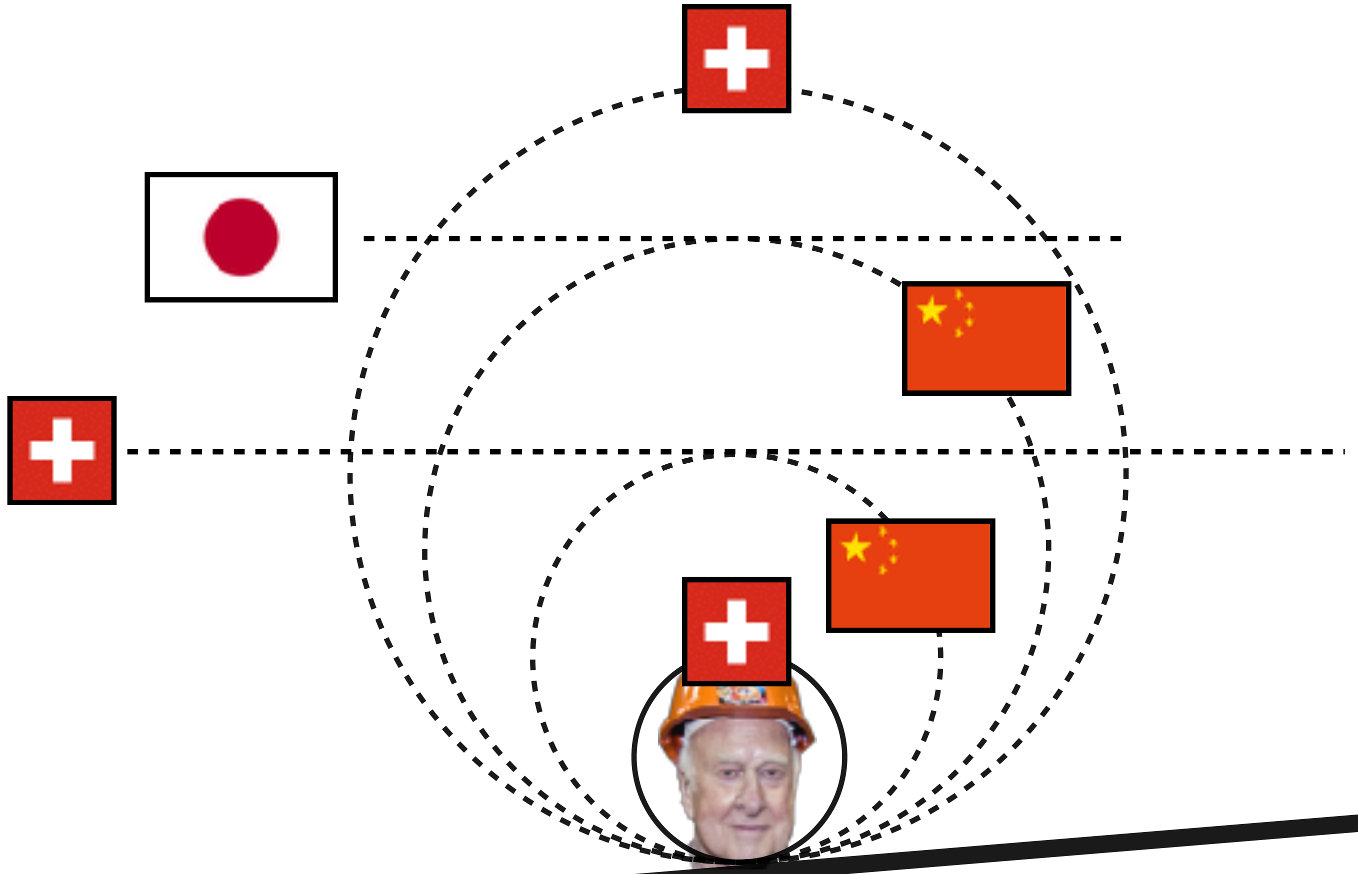
Future Physics (2/3)

SM to BSM: LHC legacy and future collider prospects

Swiss Institute for Particle Physics Winter School

Engelberg, Jan. 23-24, 2019



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Guaranteed deliverables
Legacy measurements

The importance of precise measurements

FCC-ee physics potential

Material from A. Blondel, P. Janot et al.

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements
-- ~20-50 *(stat 400…)* fold improved precision on many EW quantities (eq. x 5-7 in mass)
$m_{Z,}$ m_W, m_{top} , $\sin^2\theta_w^{eff}$, R_b , α_{QED} (m_z) α_s $(m_z\, m_W\, m_\tau)$, top quark couplings

~ Model-independent Higgs width and couplings measurements at percent-permil level.
~3σ, possibly 5 discovery of effect of Higgs self-coupling from Vertex corrections
possible investigation of Hee coupling at $\sqrt{s} = m_H$

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
-- ex FCNC ($Z \to \mu\tau$, $e\tau$) in $5\ 10^{12}$ Z decays and τ BR in $2\ 10^{11}$ $Z \to \tau\tau$
+ flavour physics (10^{12} bb events) ($B \to s\tau\tau$ etc..)

DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loopholes)

DIRECT DISCOVERY of very weakly coupled particle in 5-100 GeV energy scale
such as: Right-Handed neutrinos, Dark Photons etc…

+ and many opportunities in – e.g. QCD ($H \to gg$) etc….

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Guaranteed deliverables

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10-5

-- ex FCNC (Z --> $\mu\tau$, eτ) in 5 10^{12} Z decays and τ BR in 2 10^{11} Z→ τ τ

+ flavour physics (10^{12} bb events) (B→s τ τ etc..)

DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loop… …es)

Exploration potential

DIRECT DISCOVERY of very weakly coupled particle in 5-100 GeV energy scale

such as: Right-Handed neutrinos, Dark Photons etc…

+ and many opportunities in – e.g. QCD (H→ gg) etc….

FCC-ee EW measurement potential

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1 *	QED / EW
R_l	Peak	20.767 ± 0.025	0.001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \to bb$
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\sin^2\theta_W^{eff}$	$A_{FB}^{\mu\mu}$ (peak)	0.23148 ± 0.00016	0.000003	<0.000005 *	Beam energy
$1/\alpha_{QED}(m_Z)$	$A_{FB}^{\mu\mu}$ (off-peak)	128.952 ± 0.014	0.004	< 0.004	QED / EW
$\alpha_s(m_Z)$	R_l	0.1196 ± 0.0030	0.00001	<0.0002	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.6	< 0.6	EW Corr.
Γ_W (MeV)	Threshold scan	2085 ± 42	1.5	<1.5	EW Corr.
N_ν	$e^+e^- \to \gamma Z$, $Z \to \nu\nu$, ll	2.92 ± 0.05	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	173340 ± 760 ± 500	20	<40	QCD corr.
Γ_{top} (MeV)	Threshold scan	?	40	<40	QCD corr.
λ_{top}	Threshold scan	μ = 1.2 ± 0.3	0.08	< 0.05	QCD corr.
ttZ couplings	$\sqrt{s}$ = 365 GeV	~30%	~2%	<2%	QCD corr

To exploit this exquisite exp. precision
some serious theory work has to be achieved

Proceeding of FCC-ee 2018 WS

arXiv.org > hep-ph > arXiv:1809.01830

High Energy Physics – Phenomenology

Standard Model Theory for the FCC-ee: The Tera-Z

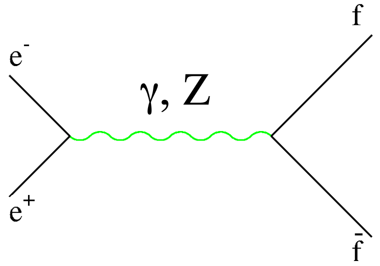
A. Blondel, J. Gluza, S. Jadach, P. Janot, T. Riemann, A. Akhundov, A. Arbuzov, R. Boels, S. Bondarenko, S. Borowka, C.M. Carloni Calame, I. Dubovyk, Y. Dydyshka, W. Flieger, A. Freitas, K. Grzanka, T. Hahn, T. Huber, L. Kalinovskaya, R. Lee, P. Marquard, G. Montagna, O. Nicrosini, C. G. Papadopoulos, F. Piccinini, R. Pittau, W. Placzek, M. Prausa, S. Riemann, G. Rodrigo, R. Sadykov, M. Skrzypek, D. Stockinger, J. Usovitsch, B.F.L. Ward, S. Weinzierl, G. Yang, S.A. Yost

(Submitted on 6 Sep 2018 (v1), last revised 22 Sep 2018 (this version, v2))

Stress test of SM

10^{12} Z

measure $\sigma(e^+e^- \to \mu^+\mu^-)$ and $A_{FB}^{\mu\mu}$ at (a) judicious $\sqrt{s}$



The γ exchange term is proportional to $\alpha^2_{QED}(\sqrt{s})$

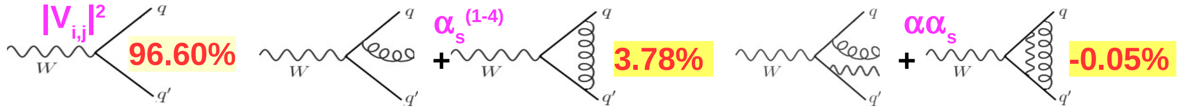
The Z exchange term is proportional to G^2_F, hence independent of α_{QED}

The γZ interference is proportional to $\alpha_{QED}(\sqrt{s}) \times G_F$

10^8 W

$$\Gamma_{\mathrm{W,had}} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks i,j}} |V_{\mathrm{i,j}}|^2 \left[1 + \sum_{k=1}^{4} \left(\frac{\alpha_s}{\pi}\right)^k + \delta_{\text{electroweak}}(\alpha) + \delta_{\text{mixed}}(\alpha\alpha_s)\right]$$

[EWK: -0.35%]

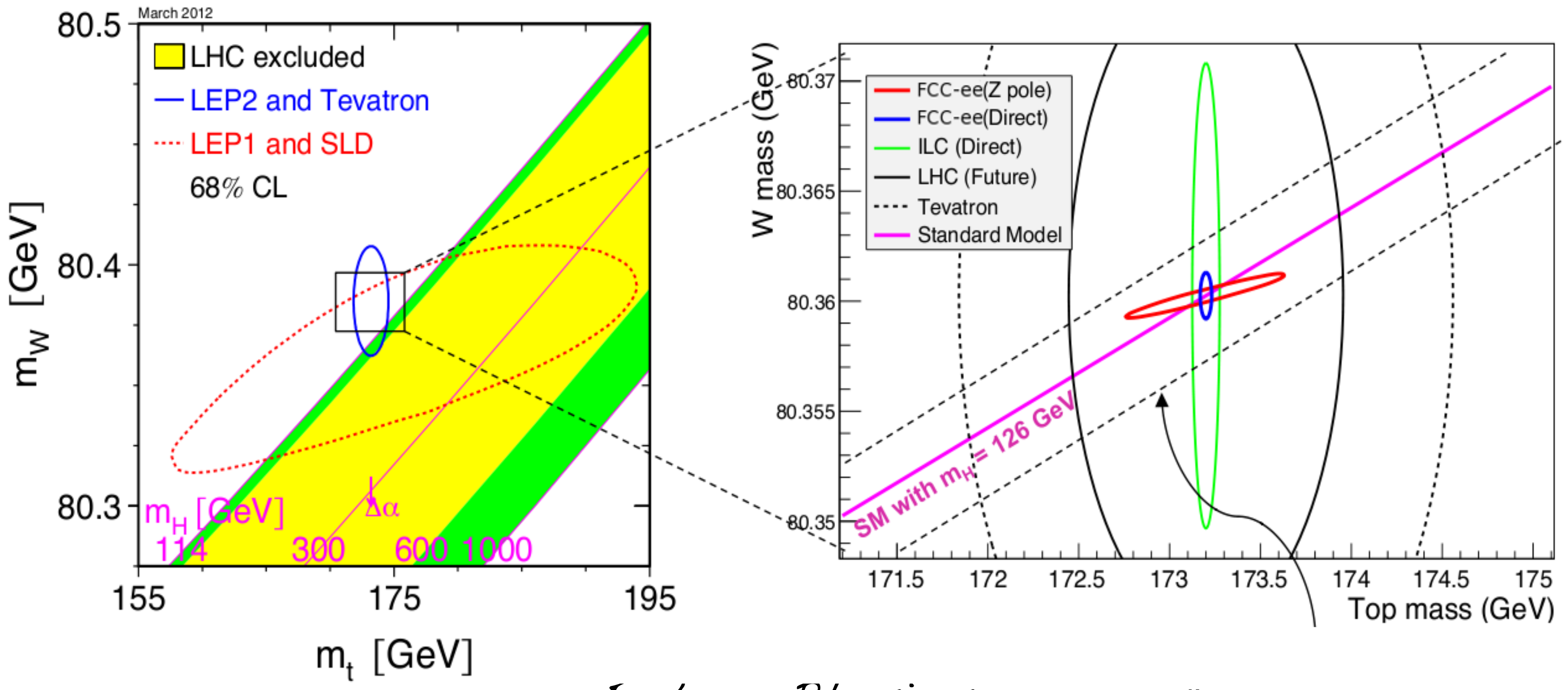


$\alpha_{QED}(m_Z)$ 10^{-5} $\alpha_{QCD}(m_Z)$ 10^{-3}

Material from P. Janot

Material from D. d'Enterria

best test of QM beyond QED (and indirect probe of new physics up to ~40TeV)

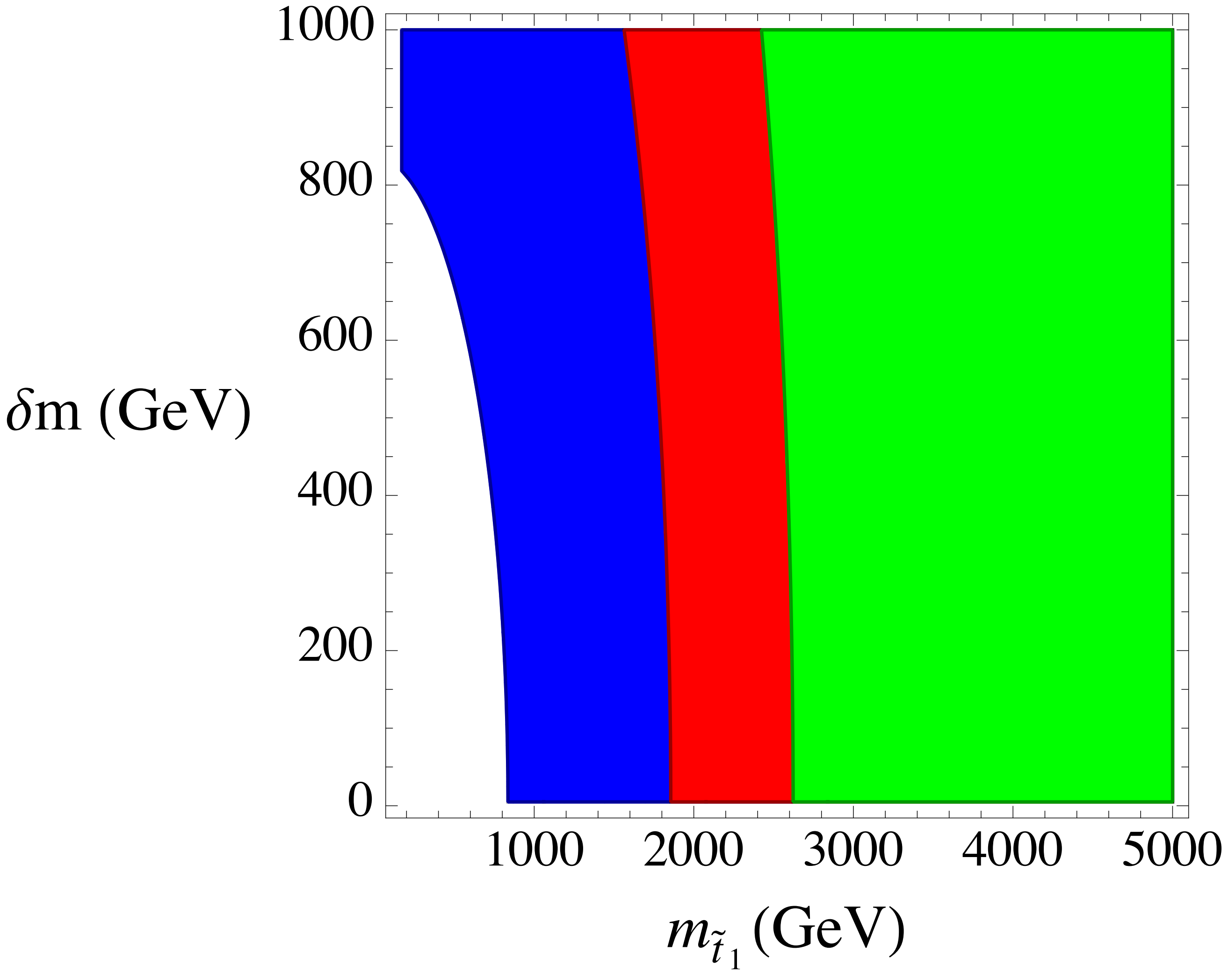


Implications for New Physics

In the SM, W mass is "predicted" in terms of Z mass, G_F, α_{em}...

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

Any deviation (if the TH uncertainty can be kept under control) tests NP



Probing MSSM stops

$\delta m_W < 5\,\mathrm{MeV} \Rightarrow m_{\tilde{t}_1} > 850\,\mathrm{GeV}$

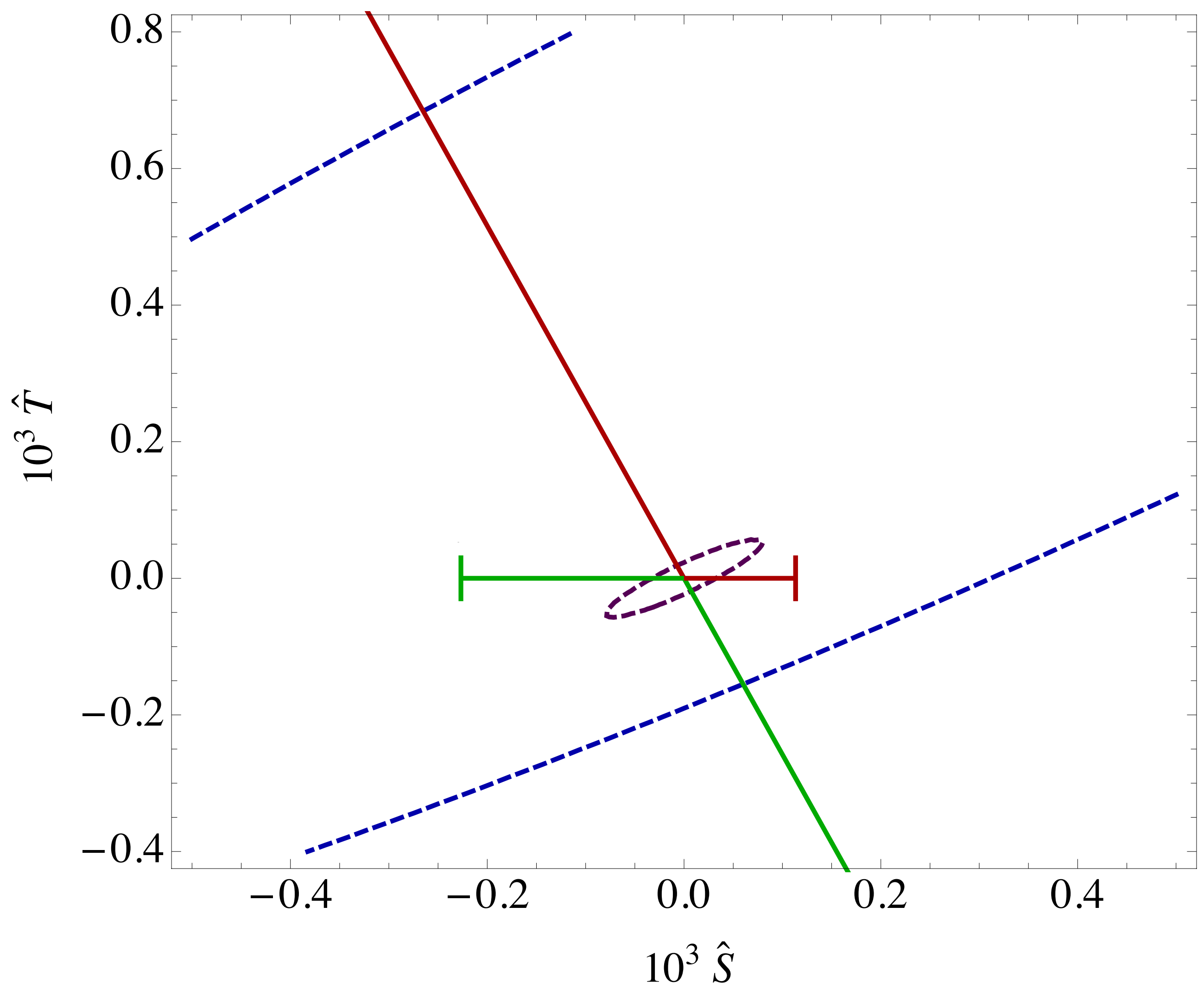
$\delta m_W < 1\,\mathrm{MeV} \Rightarrow m_{\tilde{t}_1} > 1.9\,\mathrm{TeV}$

$\delta m_W < 0.5\,\mathrm{MeV} \Rightarrow m_{\tilde{t}_1} > 2.6\,\mathrm{TeV}$

TLEP (physics case) '13

Implications for New Physics

For Universal Models, EW measurements nicely captured by oblique parameters S,T…



$$\hat{S} = \frac{m_W^2}{m_{NP}^2} \quad \Rightarrow \quad \hat{S} < 10^{-6,5,4} \Leftrightarrow m_{NP} > 80, 25, 8\,\mathrm{TeV}$$

We'll see some concrete examples in specific UV models in tomorrow lecture

Guaranteed deliverables
Legacy measurements

The case of the Higgs boson

High Energy Physics with a Higgs boson

The Higgs is a target and motivation for future colliders

ECFA
European Committee for Future Accelerators

J. D'Hondt ECFA '18

Towards new discoveries via the Higgs sector

- No clear indication where new physics is hiding, hence experimental observations will have to guide us in our exploration.
- One of the avenues is to explore as fast as possible, and as wide as possible, the Higgs sector.
  - Yukawa couplings
  - Self-couplings (HHH and HHHH)
  - Couplings to Z/W/γ/g
  - Rare SM and BSM decays (H→Meson+γ, Zγ, FCNC, μe/$\tau\mu$/τe, …)
  - CP violation in Higgs decays
  - Invisible decay
  - Mass and width
  - …
- Important progress will be made on Higgs physics with the LHC and the HL-LHC.
- To discover new physics inaccessible to the (HL-)LHC, future colliders will be complementary.

November 14th, 2018 Proposal on WG Higgs physics 13

Theoretically, we know a lot
(SM Higgs is unique, all parameters are fixed and measured)

Experimentally, the Higgs Lagrangian is far from being established

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"

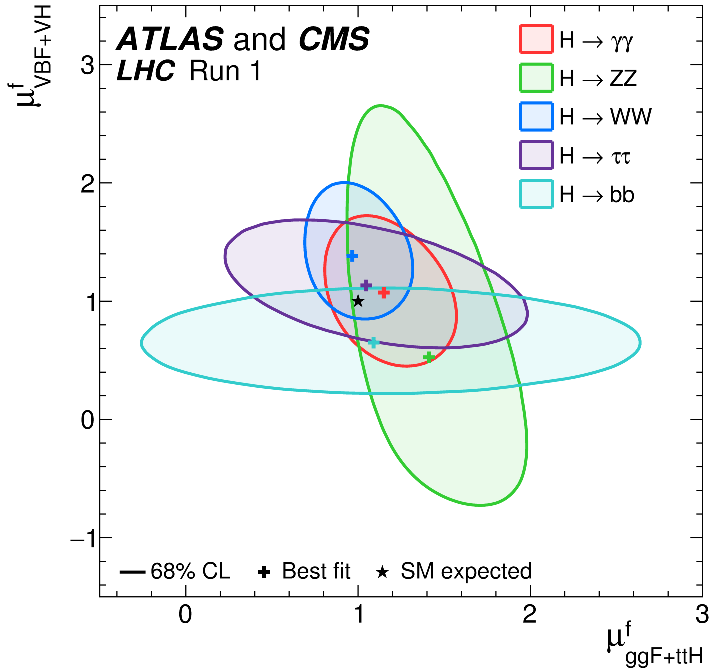
M. Zuckerberg, Harvard graduation ceremony speech, May 25, 2017

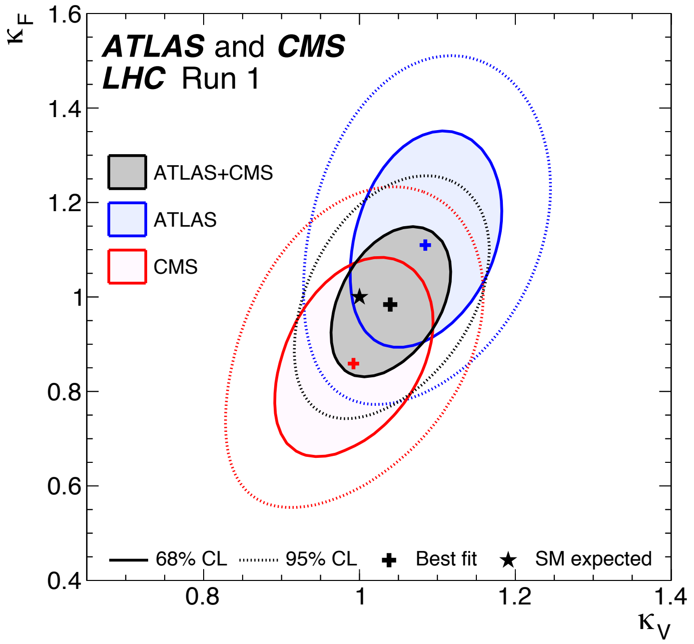
(before Cambridge analytica story)

How to report Higgs data: from κ to EFT

LHCHXSWG '12

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





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

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

How to report Higgs data: from κ to EFT

LHCHXSWG '12

Main limitations of μ and κ

1) No manifestly gauge SU(2)xU(1) invariant formalism
(vertices with different number of Higgs bosons are not related to each others)

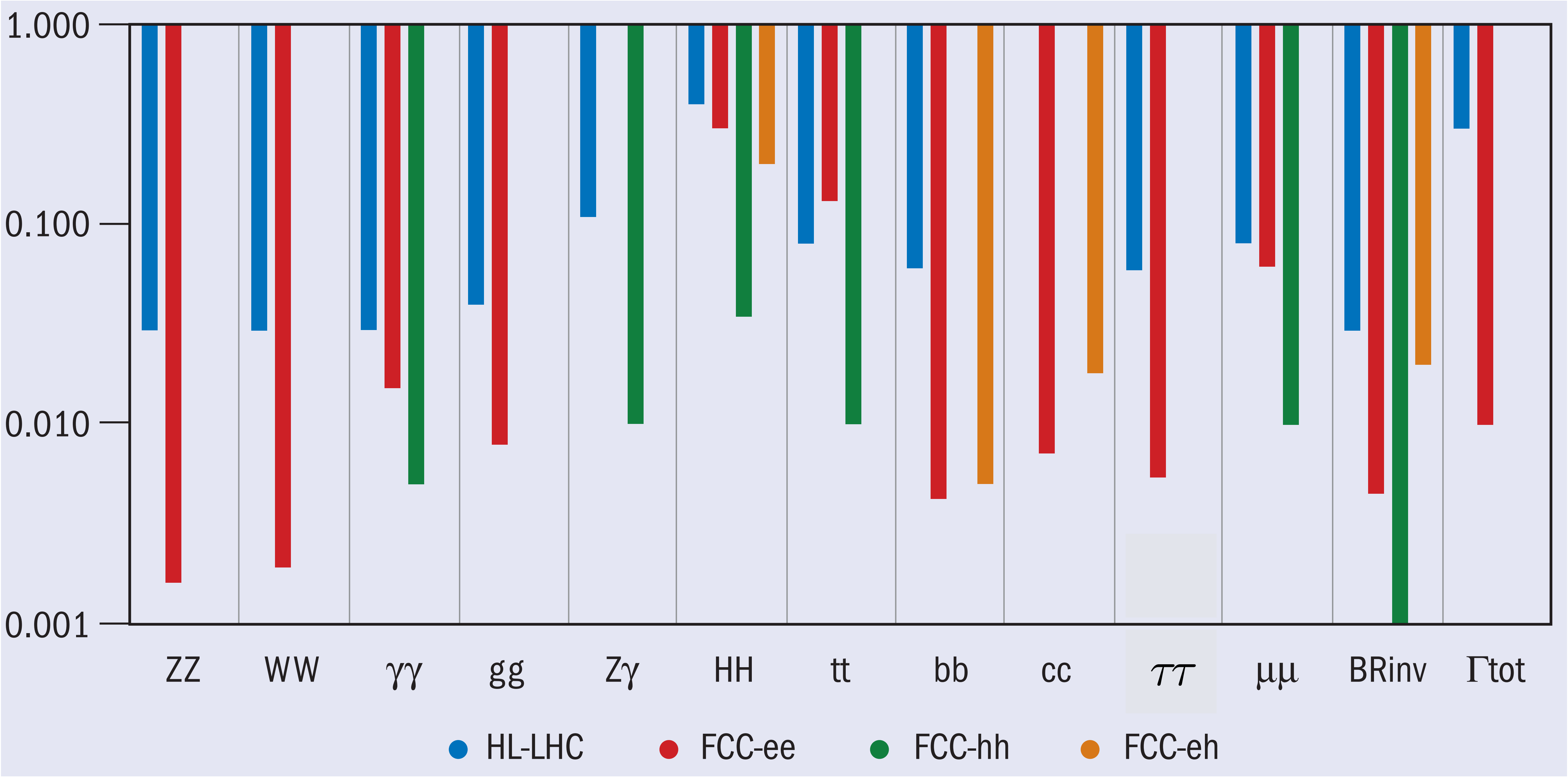
2) Missing some important symmetry properties of SM, already well constrained outside Higgs physics, e.g. in EW precision measurements

3) No general Lorentz structure (i.e. doesn't fully exploit diff. measurements)

3) very difficult to go beyond LO

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

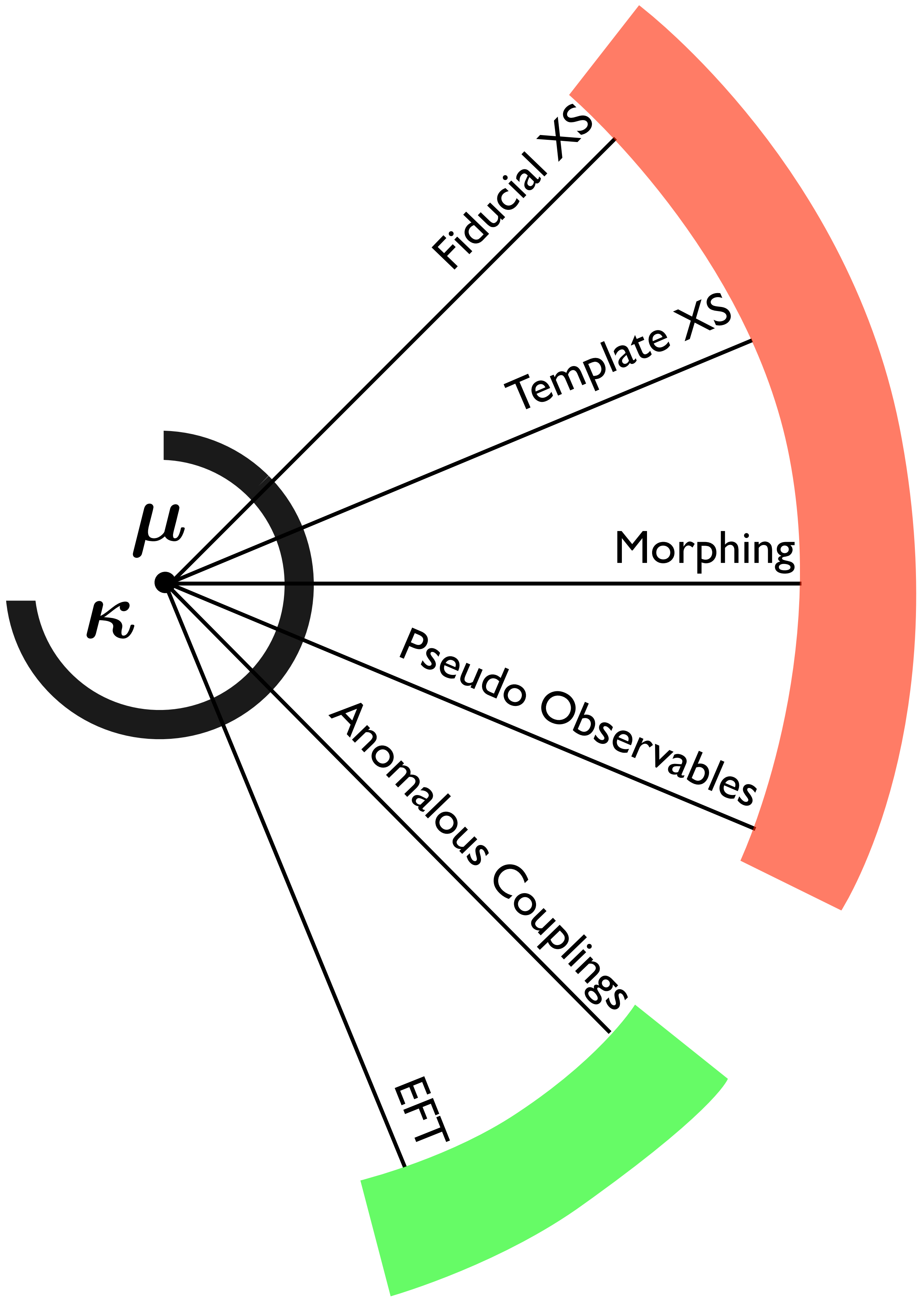
How to report Higgs data: from κ to EFT



Oversimplified PR plot

1) not a unique coupling to each particle

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



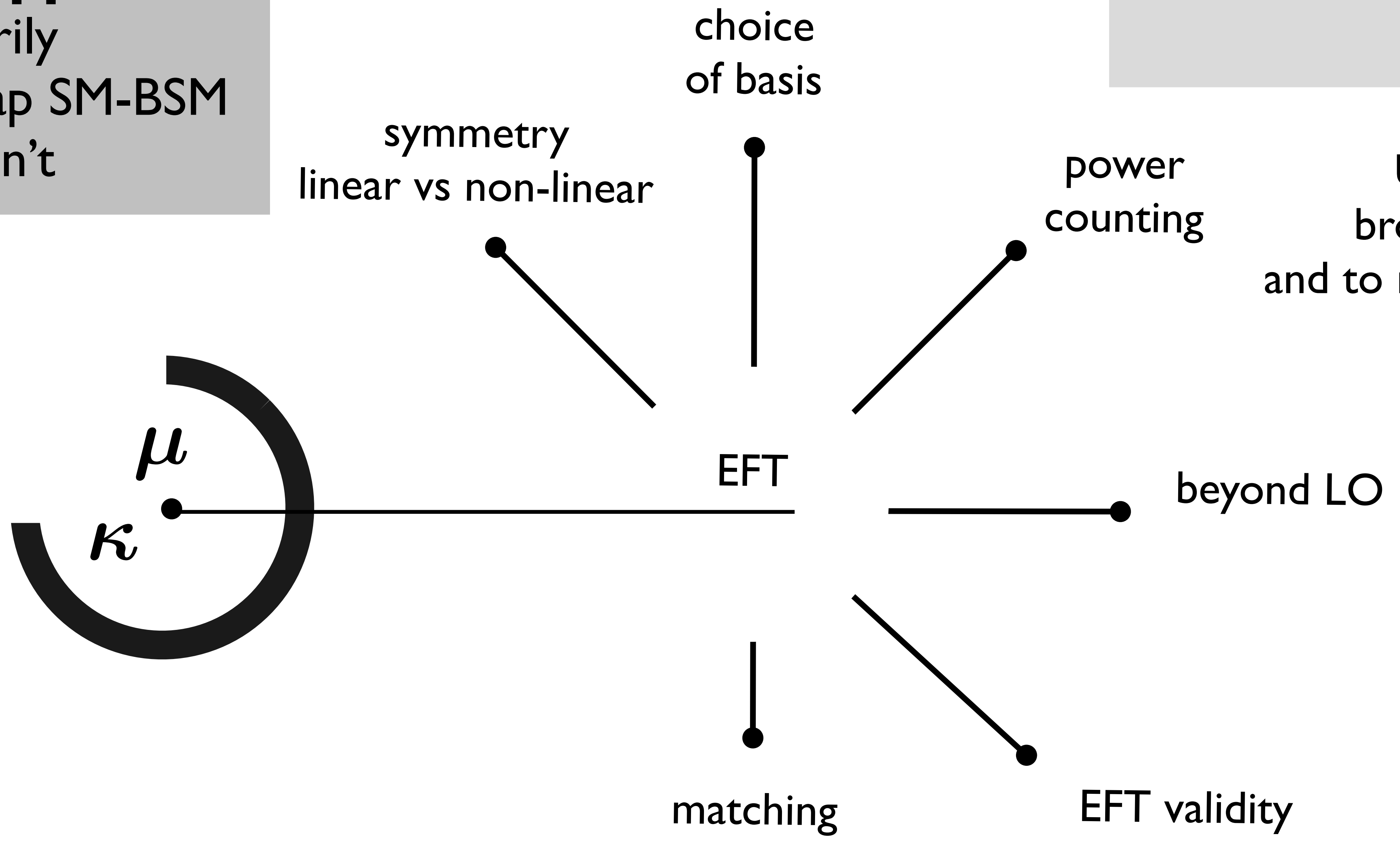
EFT

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

Better than kappa's?
Not necessarily
EFT assumes mass gap SM-BSM
Kappa's doesn't

EFT

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



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

HEP 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)% ⇔ $\Lambda_{\rm BSM}$ > 500(g_*/g_{SM}) GeV

not doing better than direct searches unless in the case of strongly coupled new physics
(notable exceptions: 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

HEP with a Higgs boson

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

Measuring Higgs couplings to 1%

=

Probing Higgs structure to 1/10th of its Compton wave-length

i.e. learning if the Higgs is an elementary particle!

e.g. flavor number violation as in h→$\mu\tau$)

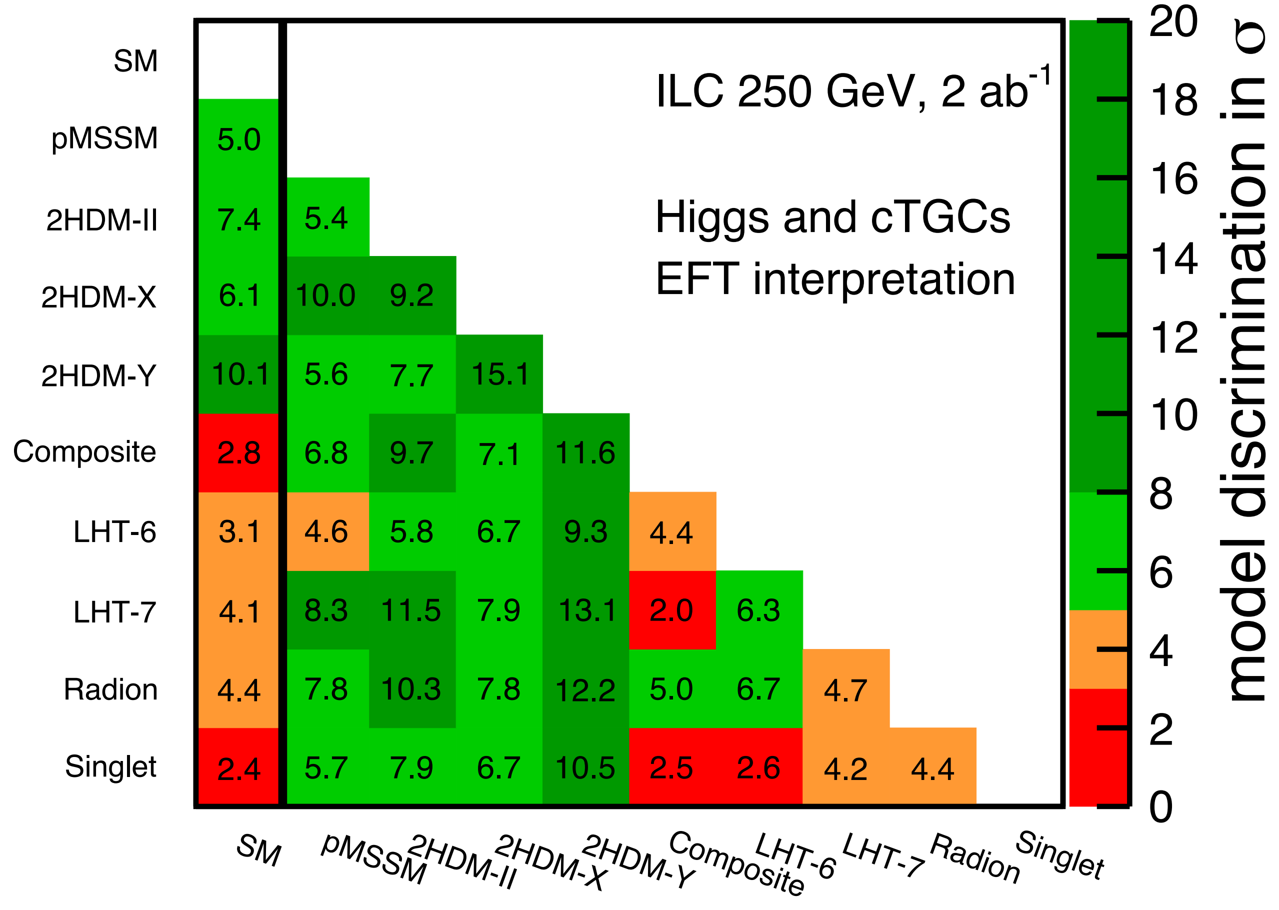
Higgs precision program is very much wanted
to probe BSM physics

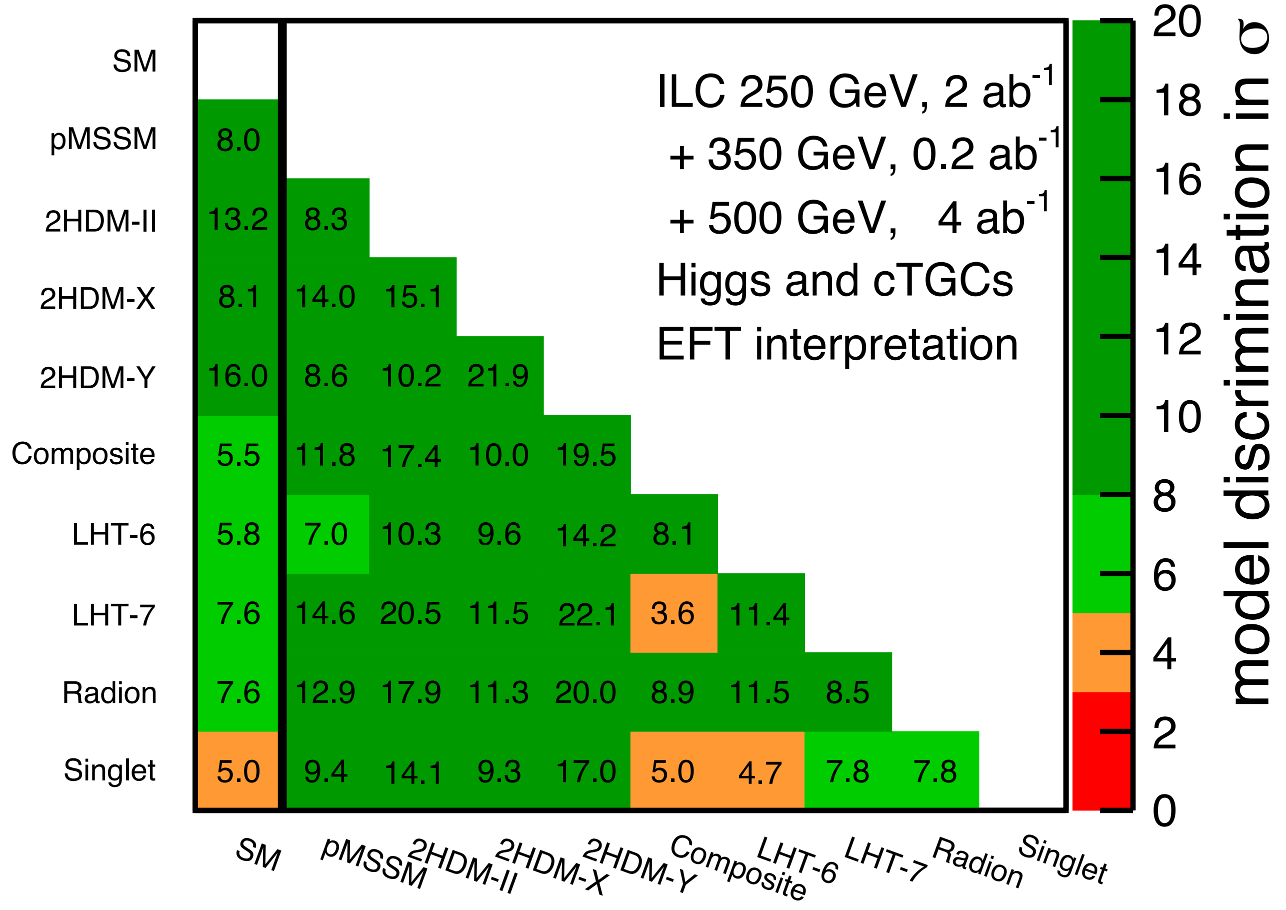
HEP with a Higgs boson

Higgs can not only reveal but also identify BSM

BSM separation power

Models that cannot be distinguished from SM at the LHC are resolved with ILC





LCC Physics WG '17

Higgs: ee colliders vs LHC

~~ significant steps in precision study of Higgs properties ~~

(1) Higgs kinematic parameters: m_H and Γ_H

↠ reduce parametric uncertainties in xs and BR

↠ control the fate of EW vacuum within the SM

↠ constrain new physics models (e.g. MSSM)

(2) Precise and model-independent access to Higgs couplings

↠ 1% level

↠ identification of correlation patterns among deviations

↠ indirect test of extended Higgs sectors/composite nature

↠ ultimate test of naturalness

(3) Access to decays modes that are background dominated @ LHC

↠ bb/cc/gg

↠ exotic decay modes (↳ portal models of Dark Matter)

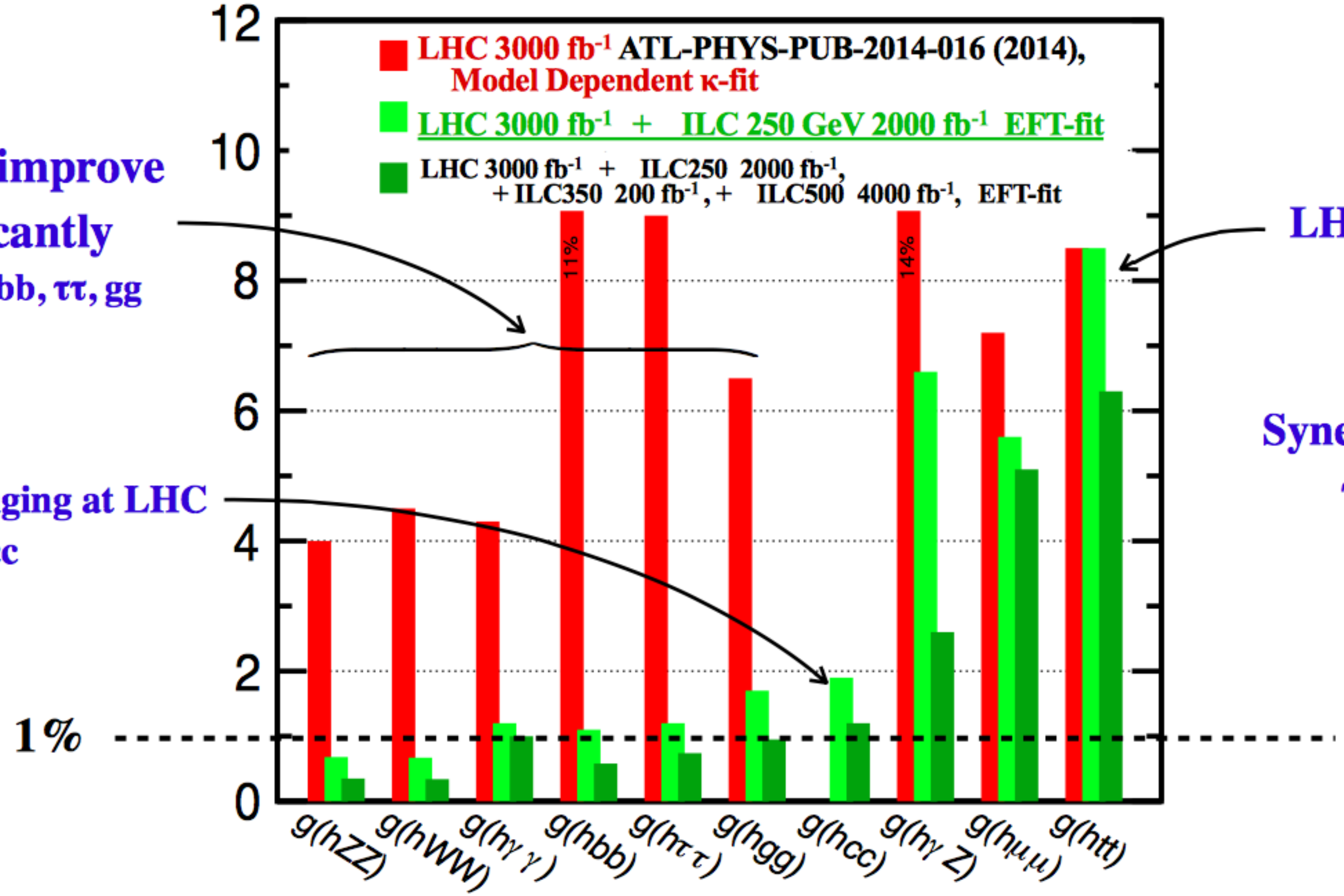
(4) Constraints on Higgs flavor violating couplings

↠ shed light on the origin of fermion masses and flavours

Higgs: synergy ee + LHC

ILC can improve significantly
ZZ, WW, bb, ττ, gg

Very challenging at LHC
cc



LHC is necessary
tt

Synergy with LHC
γγ, γZ, μμ

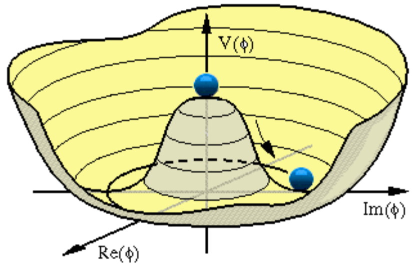
Higgs physics vs BSM

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

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

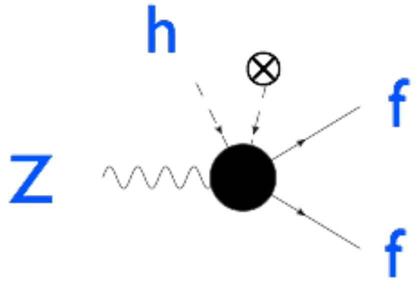
ϕ = v+h

vacuum

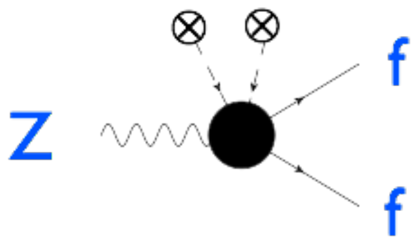


Potentially new BSM-effects in h physics
could have been already tested in the vacuum

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

consistency check
not discovery mode

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

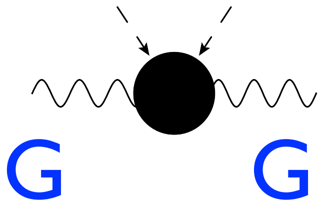
(courtesy of A. Pomarol@Moriond2014)

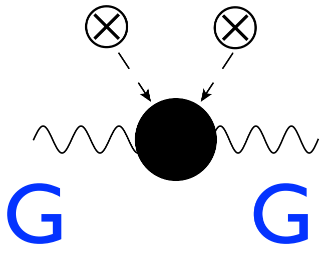
Higgs/BSM Primaries

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)

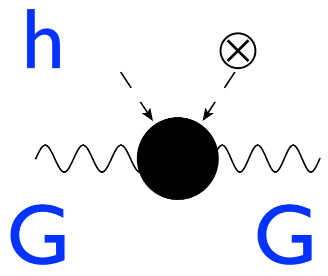
e.g. $$\frac{1}{g_s^2} G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2} G_{\mu\nu}^2 \rightarrow \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right) G_{\mu\nu}^2$$





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$\tau\tau$

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 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%

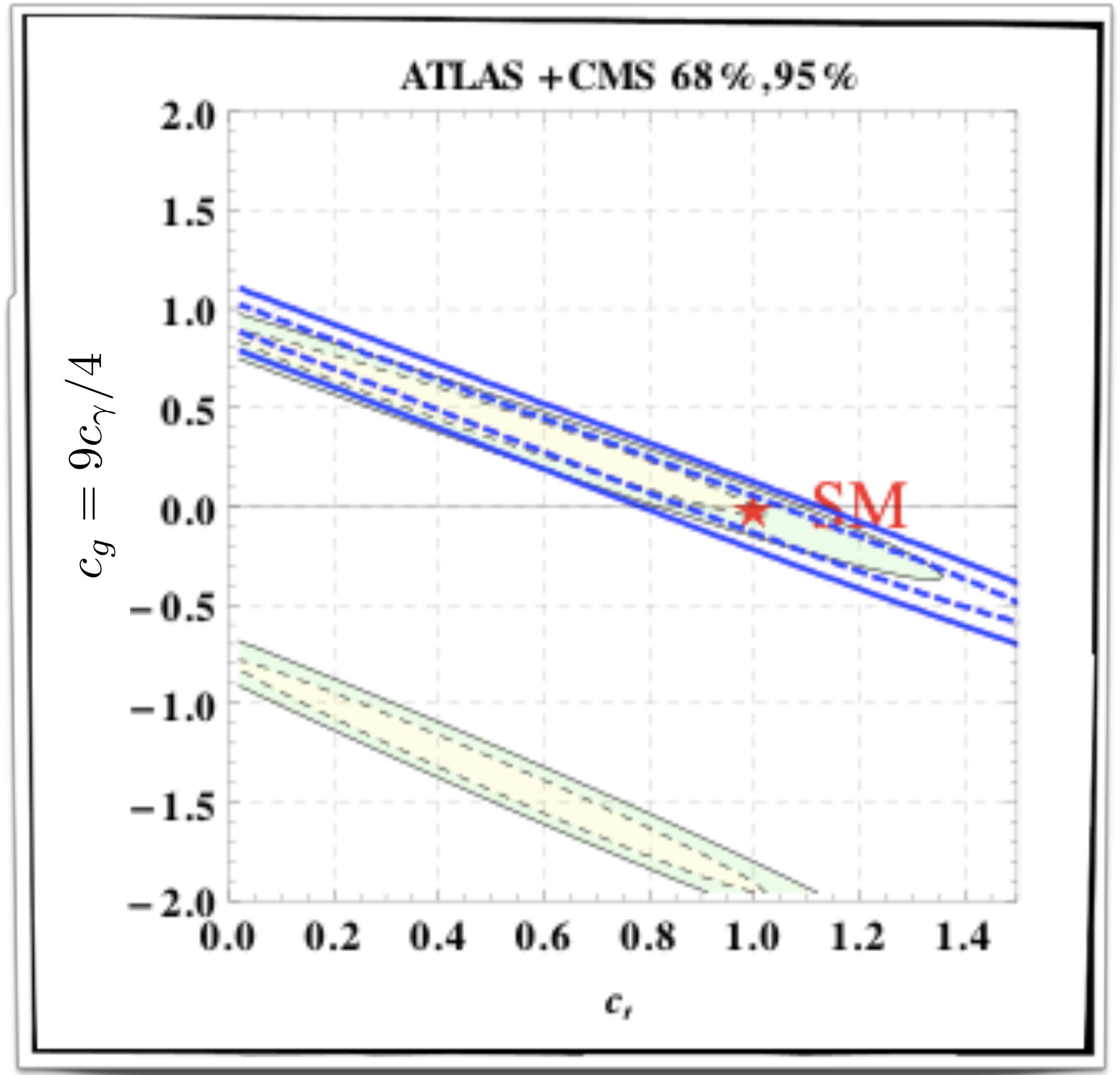
Atlas projection '2014

With some important differences:

1) width hypothesis built-in

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

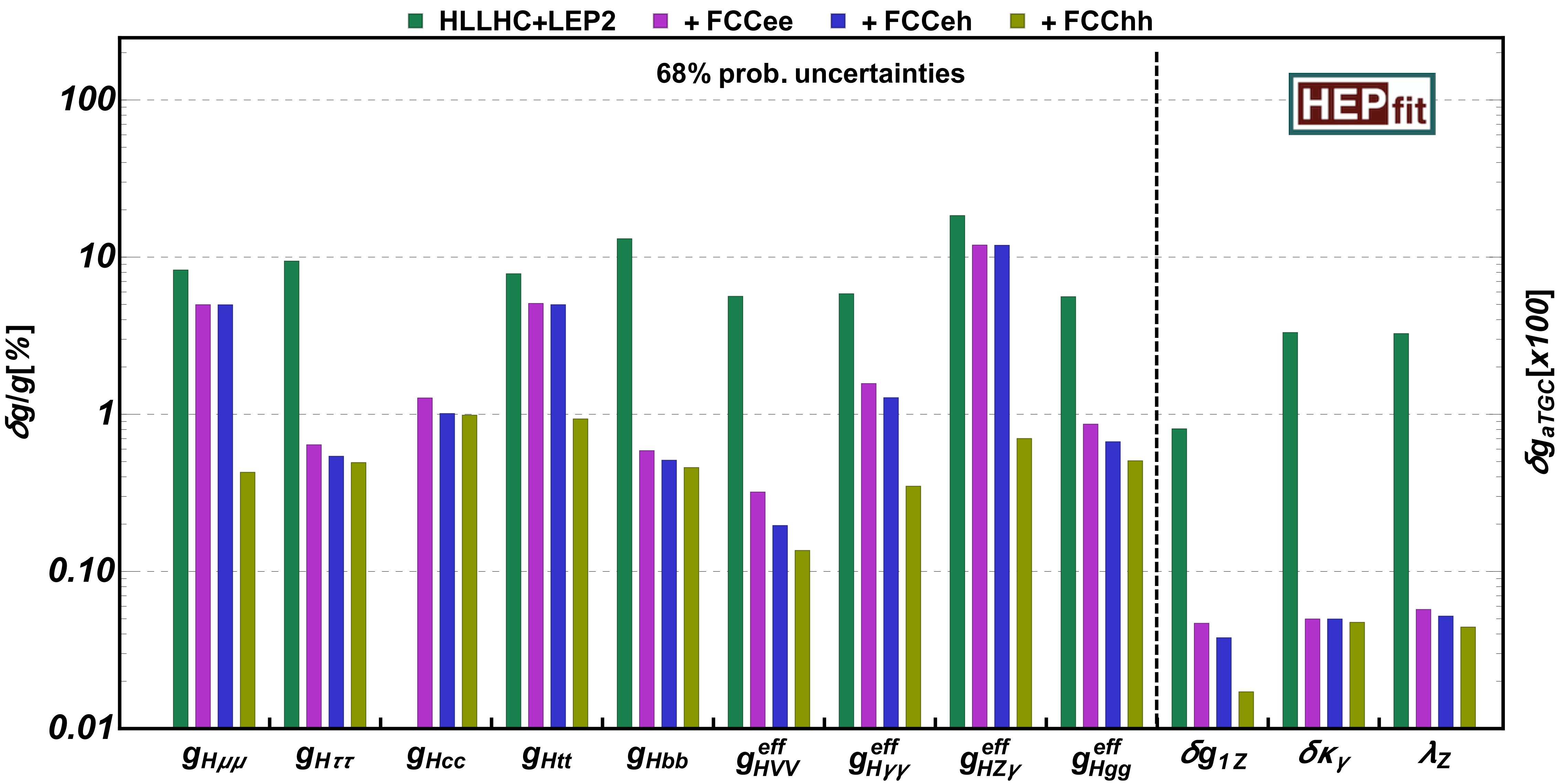
3) κ_g, κ_γ, $\kappa_{Z\gamma}$ do not separate UV and IR contributions



Azatov '15

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

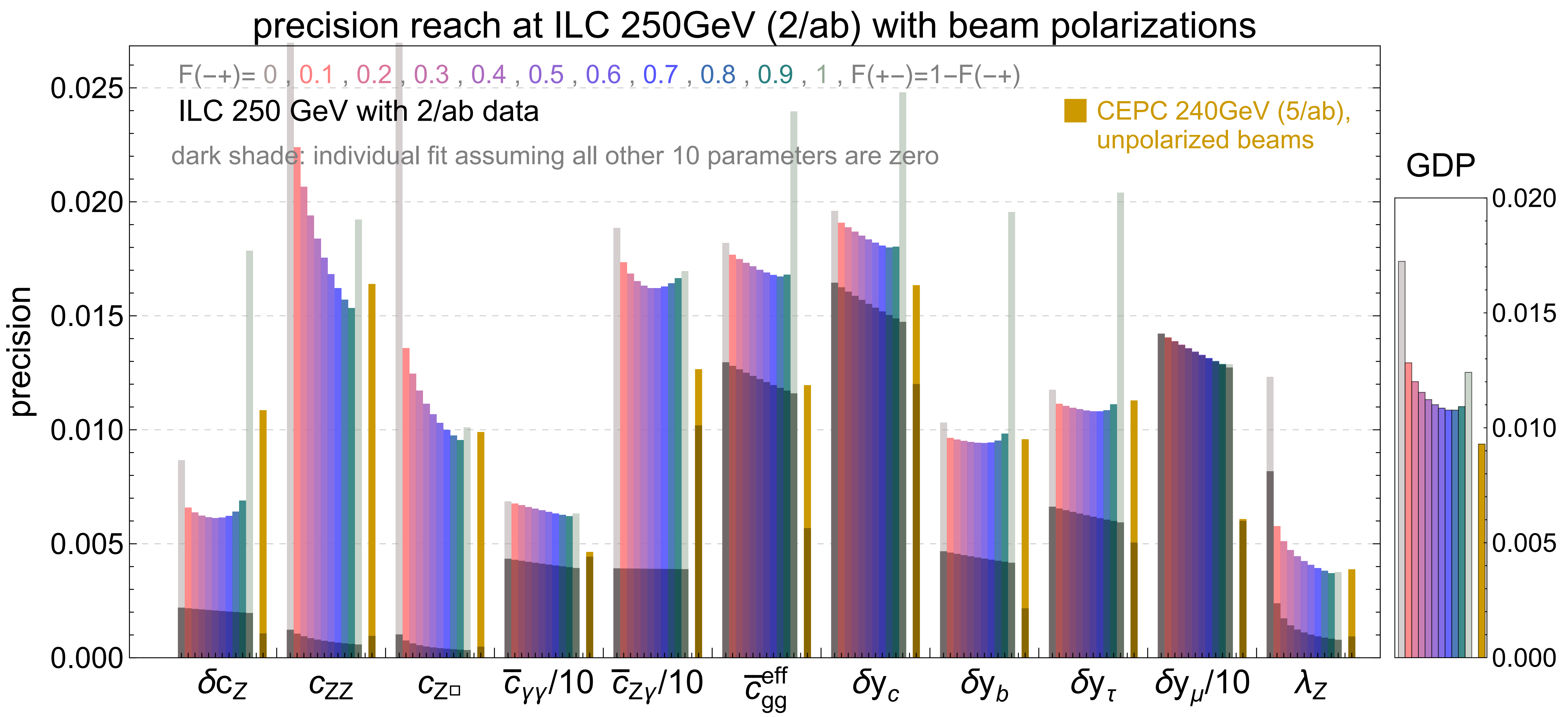
Higgs coupling sensitivities



Synergy and complementarity between colliders

- ee breaks model dependence (Γ_H, g_{HZZ}) – and measures precisely top EW couplings
  - Turns σ(ttH) measurement @ HL-LHC to an absolute ttH coupling precision of 3%
  - First 3-4σ observation or 5σ discovery of the Higgs self coupling, without a 500 GeV upgrade
- pp measures ratios-of-BR and gives huge statistics of ttZ, ttH, and HH events
  - Bring top Yukawa and Higgs self coupling precisions to the per-cent level, in particular

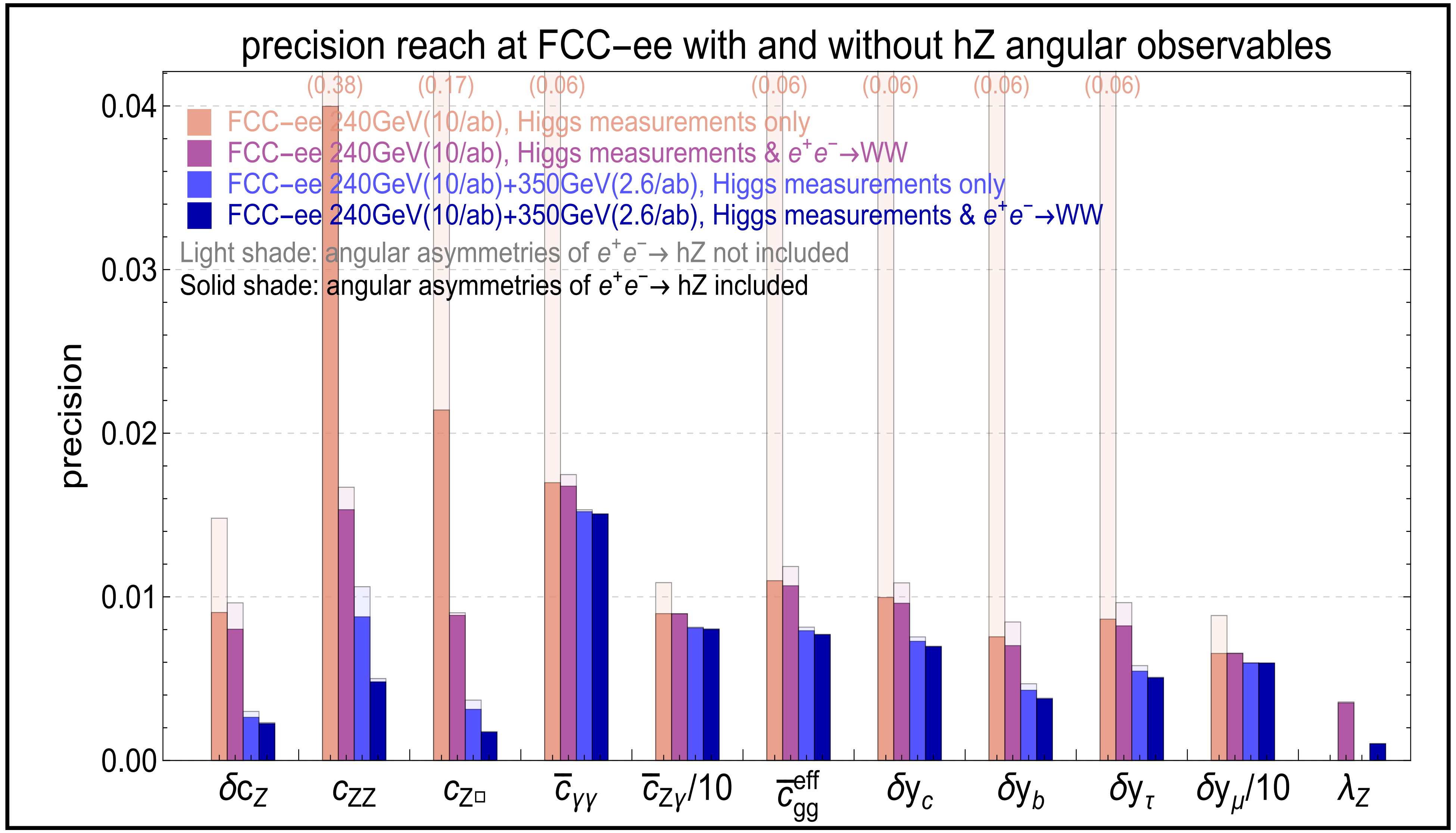
Impact of beam polarisation



Which measurements are needed?

Higgs coupling measurement is not relying on Higgs data alone
Need a machine that is complete and efficient at different energies

Durieux, Grojean, Gu, Wang '17

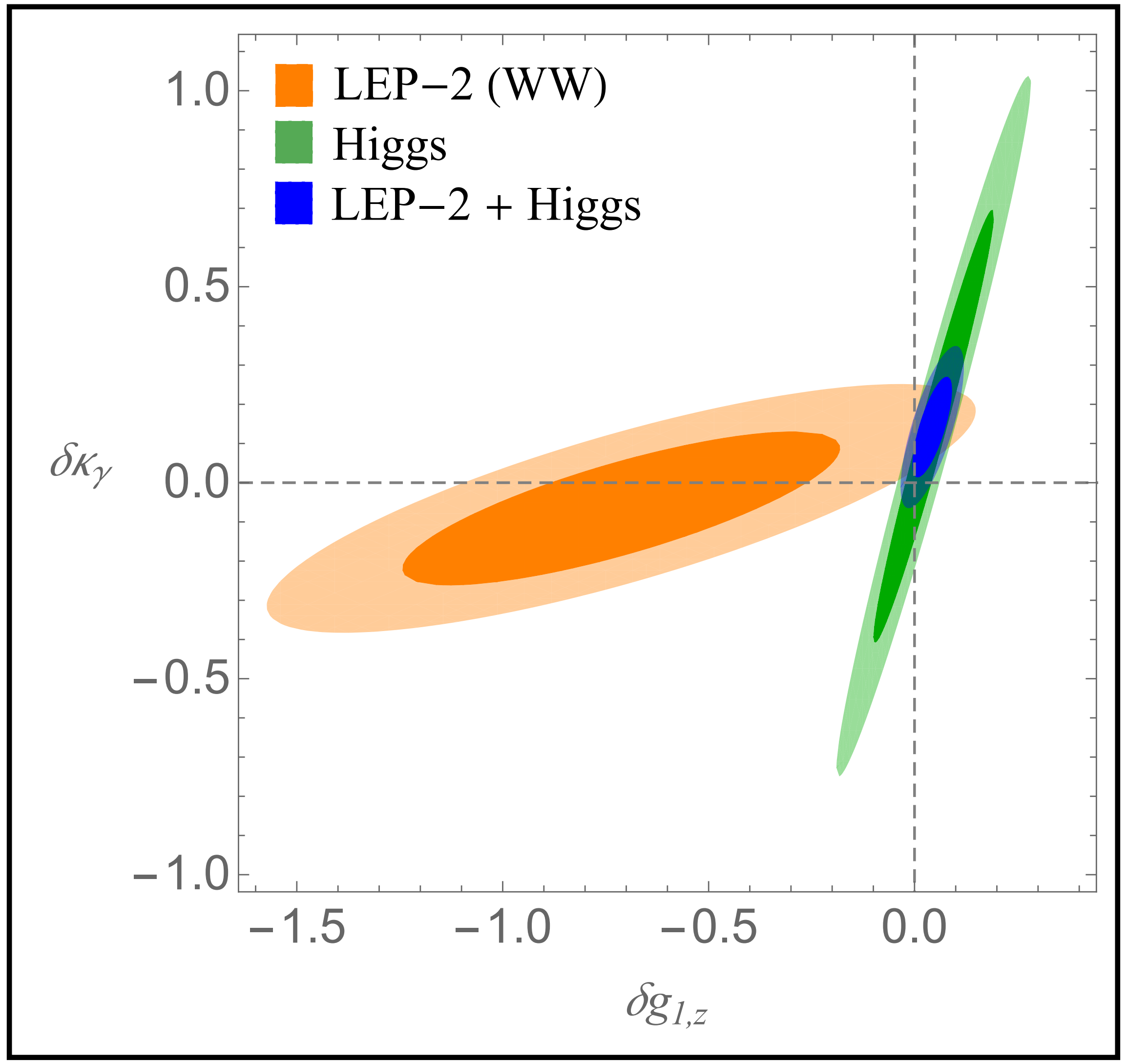


1) with a run at 240/250 GeV alone, crucial to have access to angular distributions to break degeneracies

2) with a second run at higher energy makes it less important to look at distributions

Synergy Higgs and diboson

Falkowski et al '15



(TGC+Higgs)>(TGC)∪(Higgs)

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?

Strong correlations between 2 data sets

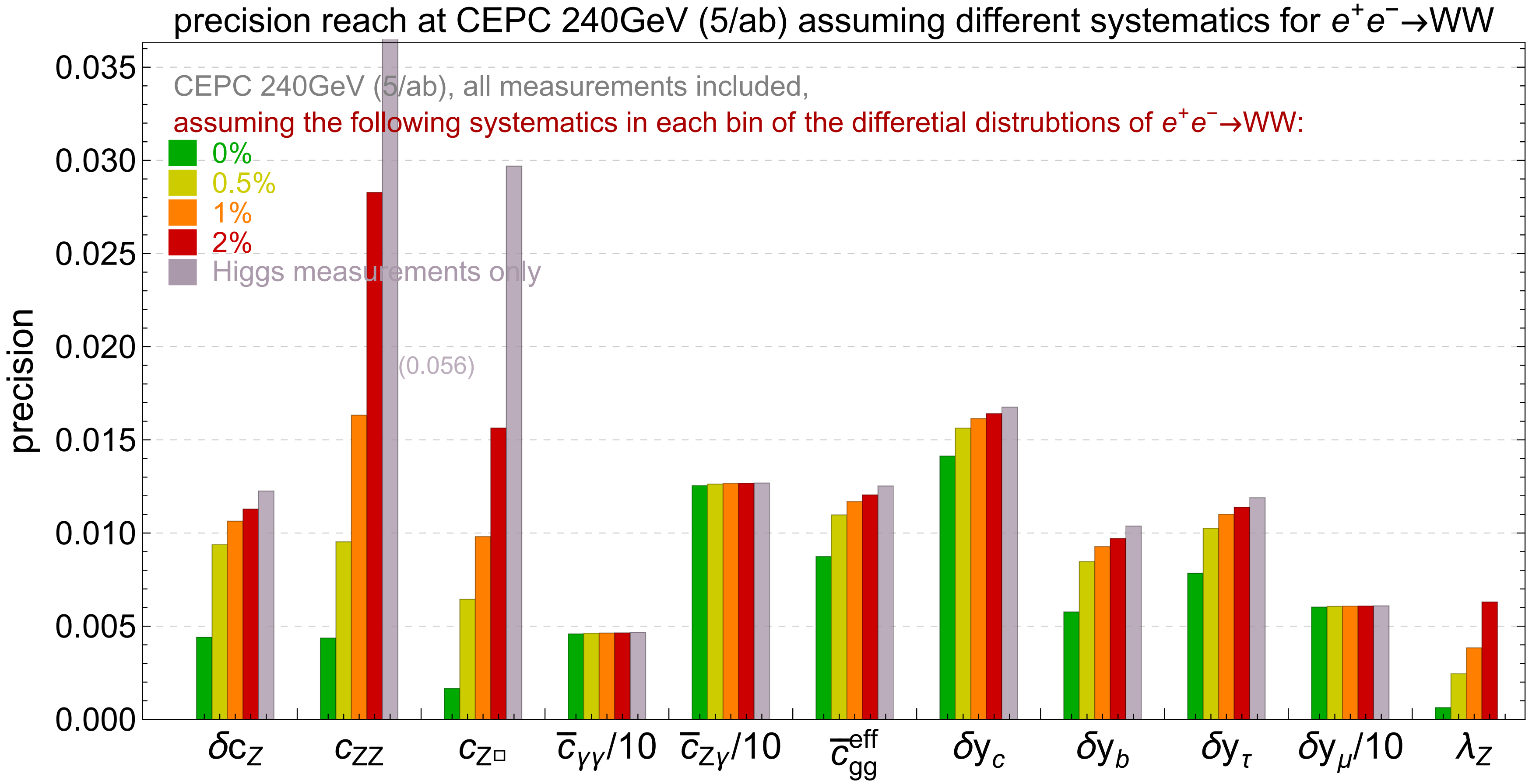
Better to do a (8+2) parameter fit!

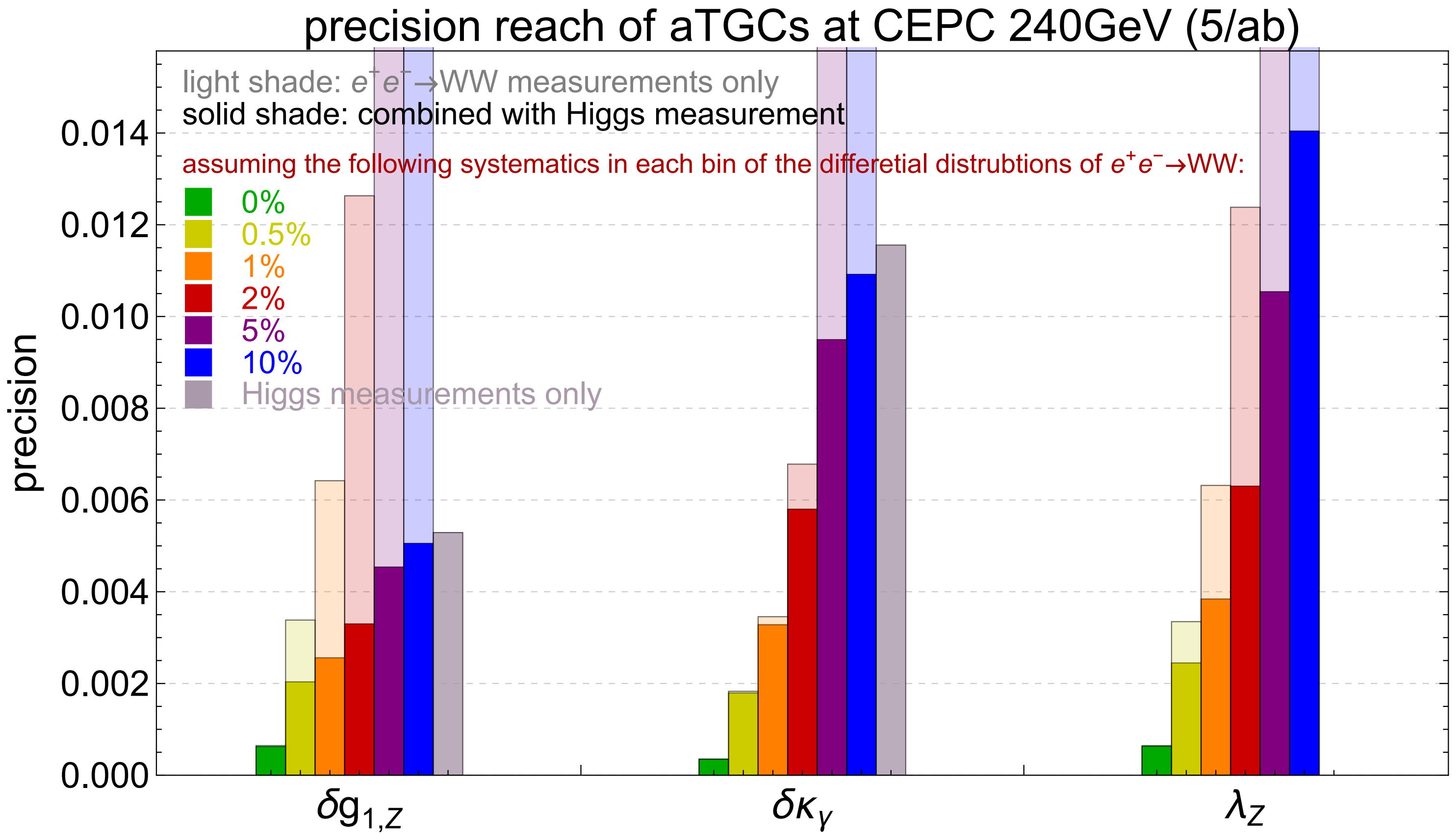
Impact of HL-LHC WW data?

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

Importance of WW run

(TGC+Higgs)>(TGC)∪(Higgs)



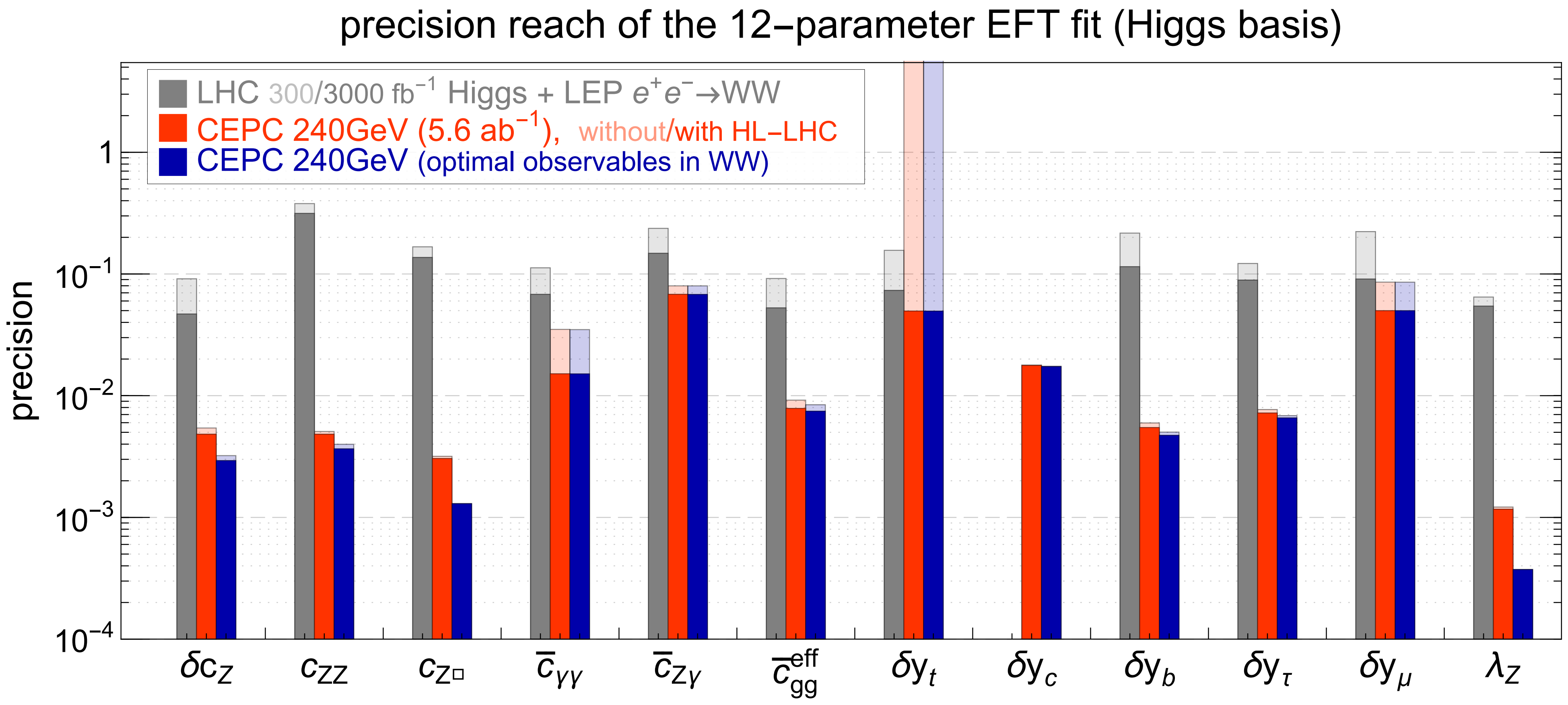


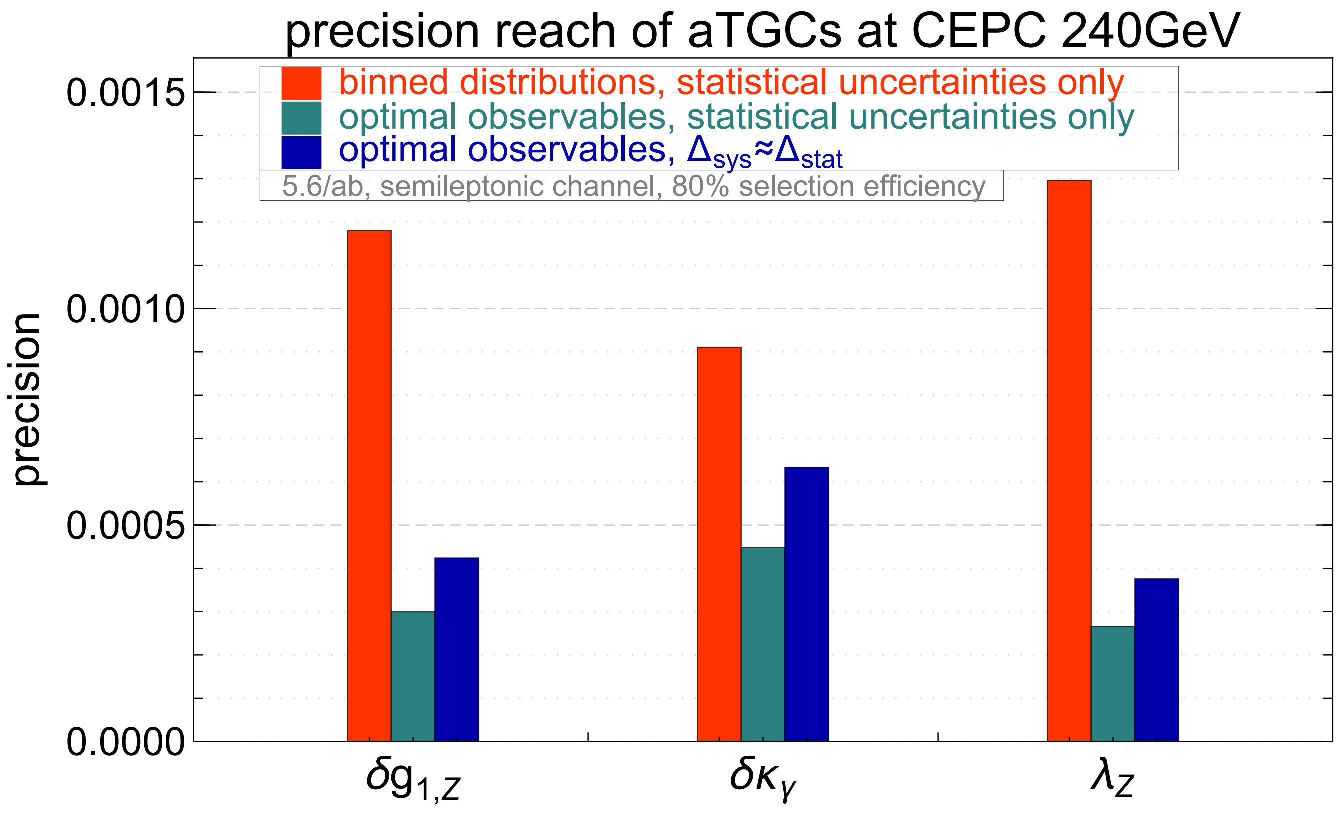
Durieux, Grojean, Gu, Wang '17

Importance of WW run

(TGC+Higgs)>(TGC)∪(Higgs)

Diboson analysis can still be improved, e.g., using optimised observables

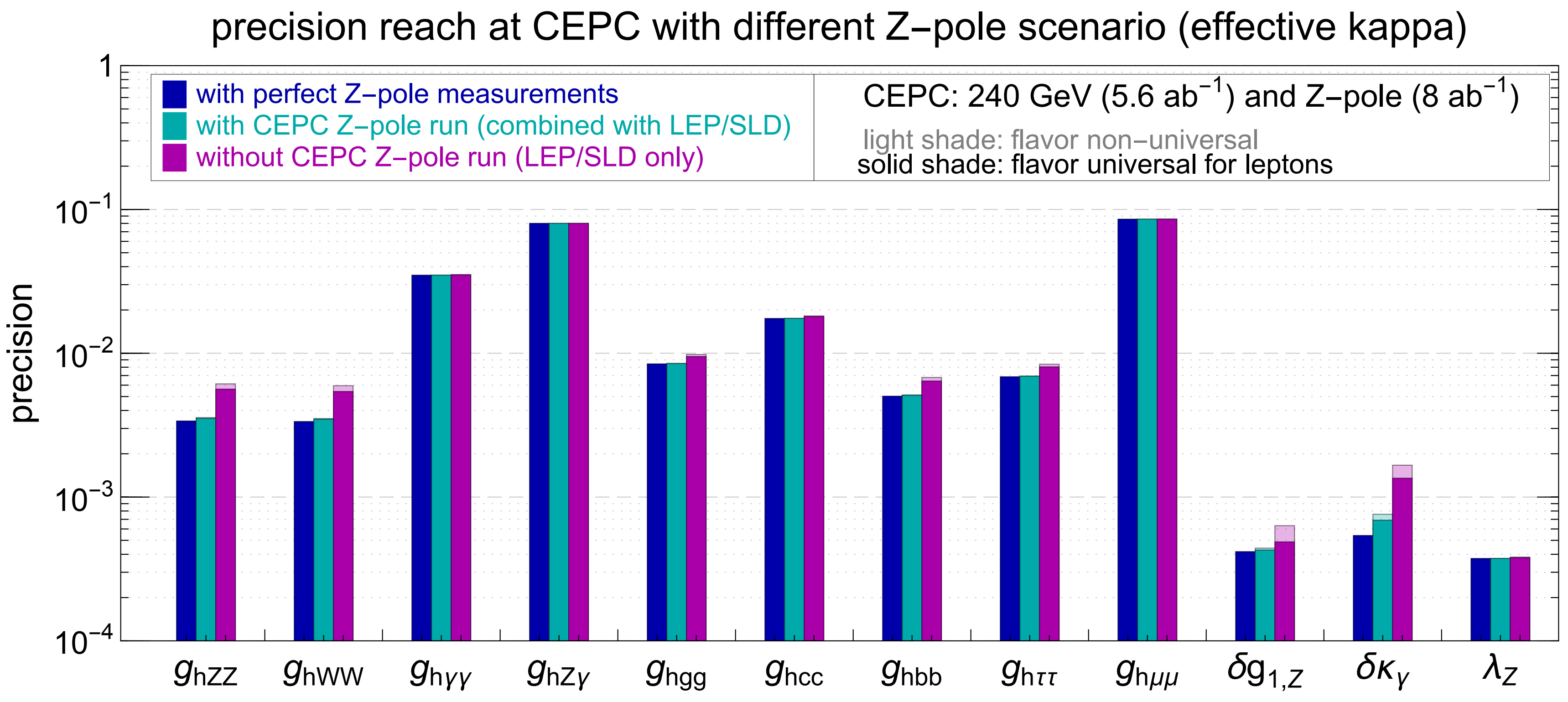


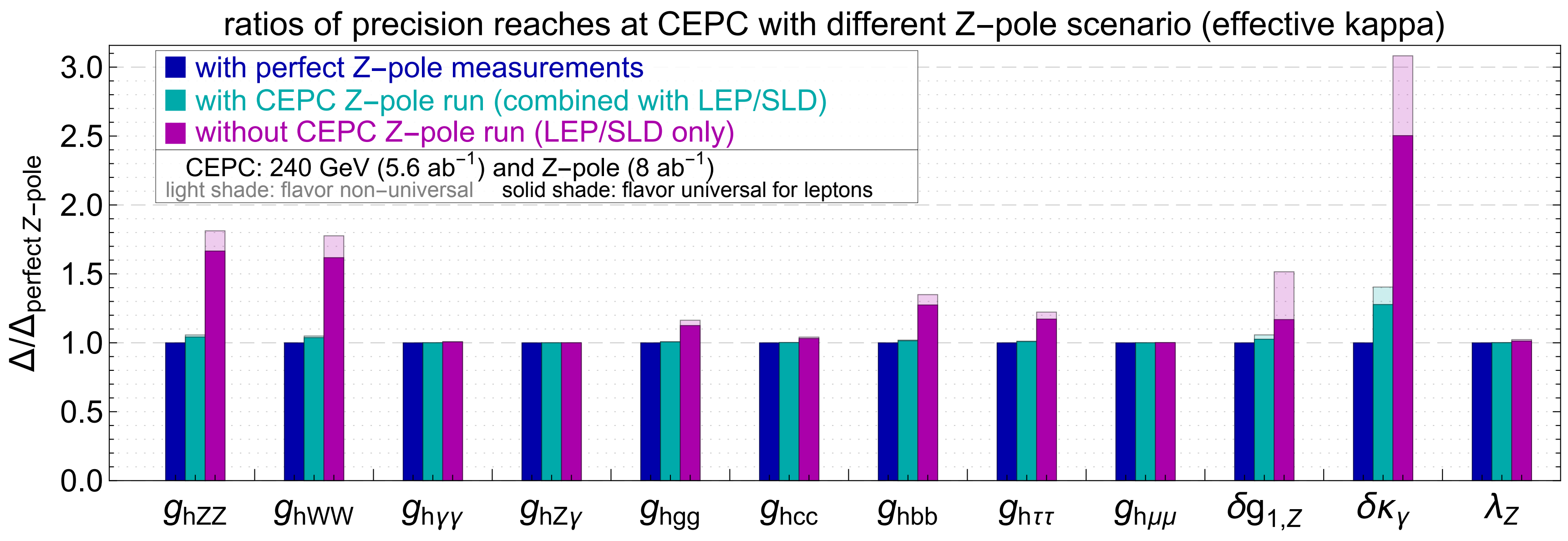


De Blas, Durieux, Grojean, Gu, Paul 'in progress

EW measurement's impact on Higgs

De Blas, Durieux, Grojean, Gu, Paul 'in progress





EFT fit translated into

postdicted Higgs couplings

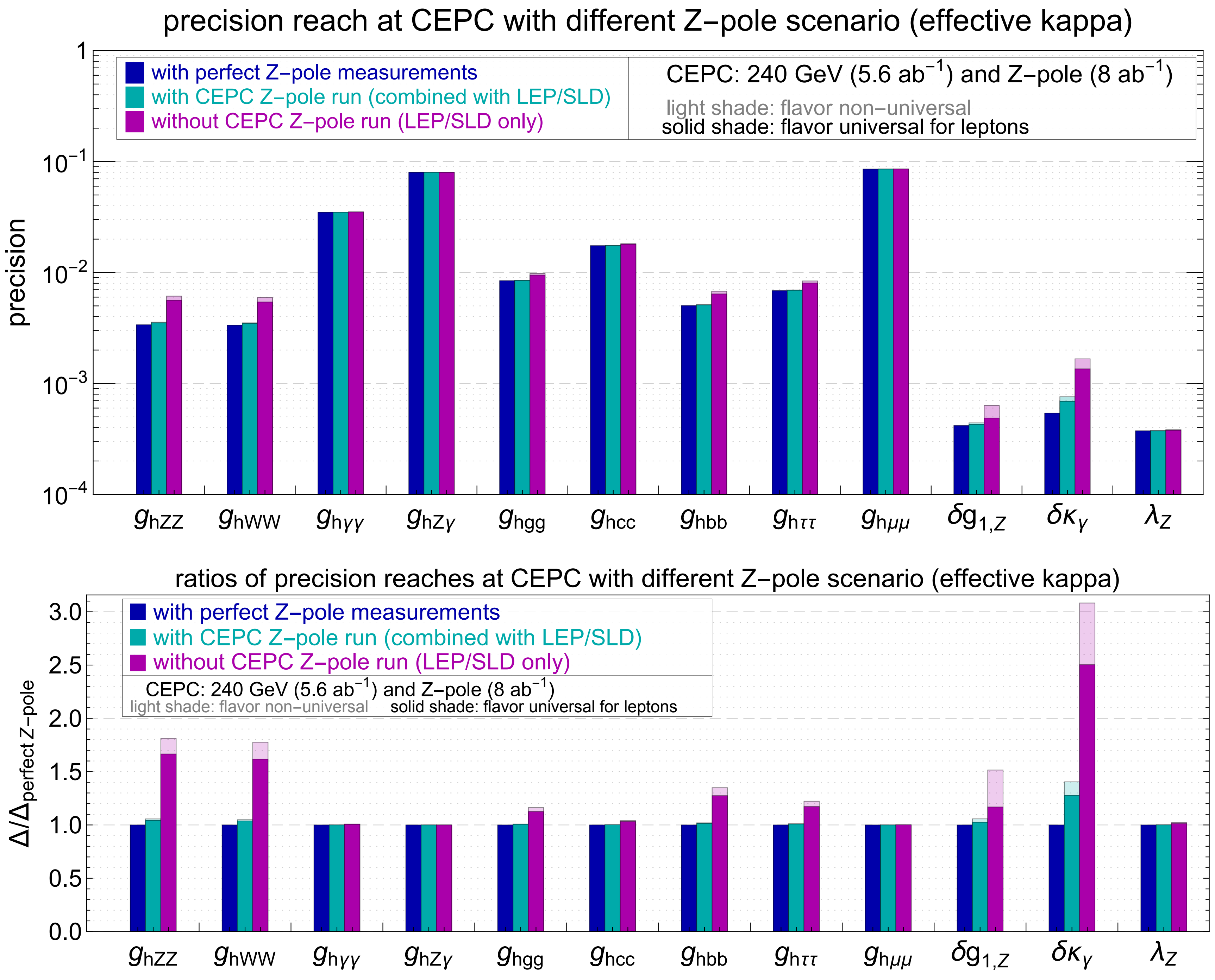
($e.g.$ $g_{hZZ} \propto \sqrt{\Gamma_{h\to ZZ}}$)

✗ CEPC alone

(combination with HL-LHC projections on its way)

EW measurement's impact on Higgs

De Blas, Durieux, Grojean, Gu, Paul 'in progress



Z-pole run needed
LEP/SLD is not enough
Issue for ILC?

Linear: L ↗ w/ E

Circular: L ↘ w/E

EFT fit translated into postdicted Higgs couplings

($e.g.$ $g_{hZZ} \propto \sqrt{\Gamma_{h\to ZZ}}$)

✗ CEPC alone

(combination with HL-LHC projections on its way)

Higgs portals and Higgs exotic decays

$|H|^2$ and HL are SM-singlet of low dimension

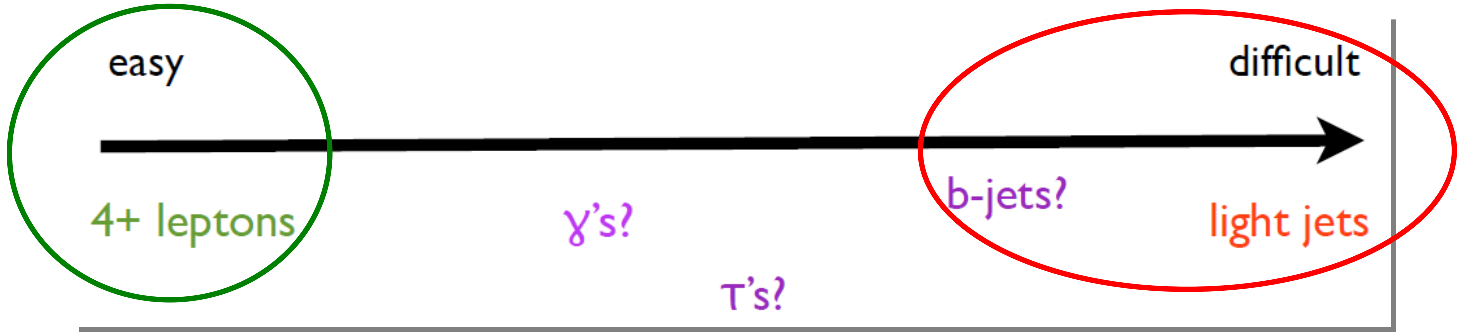
they can have large (renormalizable) couplings to hidden/dark sector that could
(i) make up the DM relic abundance
or (ii) be key agents in models of neutral naturalness

new exotic/invisible decay modes: ee sensitivity $BR_{exo}<1\%$

(if $m_{NP} > m_H/2$: possible production via off-shell Higgs but limited reach Craig et al '14)

$Z_{\mu\nu}Z_D^{\mu\nu}$	$\|H\|^2\|S\|^2$	HLN
$H \to ZZ_D$	$H \to ss$	$H \to LN$
new force	new Higgses	new matter

Gori @ LCWS'15



Example:
$h \longrightarrow ZZ_D \longrightarrow 4l$
These can be seen by the LHC pretty easily:
BRs ~ $10^{-6} - 10^{-7}$ can be probed by the HL-LHC
Curtin, Essig, SG, Shelton 1412.0018

See Liu, Potter, 1309.0021 for a ILC $h \longrightarrow 4\tau$ analysis

Example: (as in the NMSSM)
$h \longrightarrow ss \longrightarrow 4b$
Background limited at the LHC.
Theory studies show that BRs ~ 0.1 might be reached Cao et al, 1309.4939

~ Complementarity with LHC searches

~ Importance to measure Higgs width

Higgs portals and Higgs exotic decays

$|H|^2$ and HL are SM-singlet of low dimension

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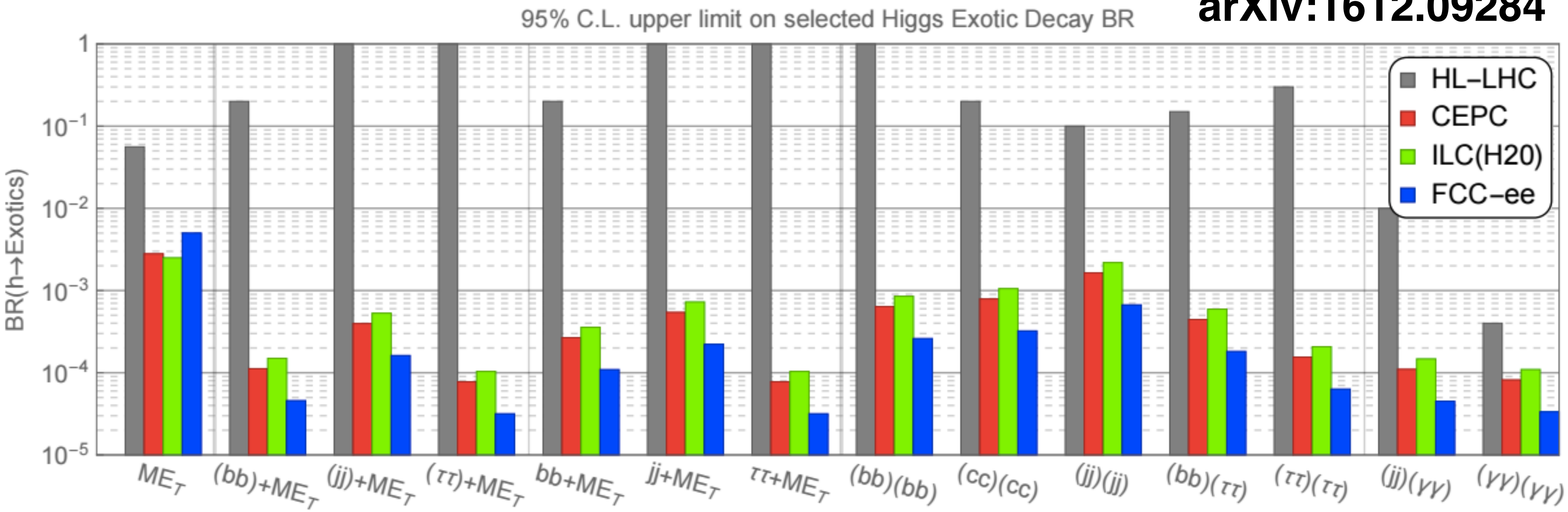
(i) make up the DM relic abundance

or (ii) be key agents in models of neutral naturalness

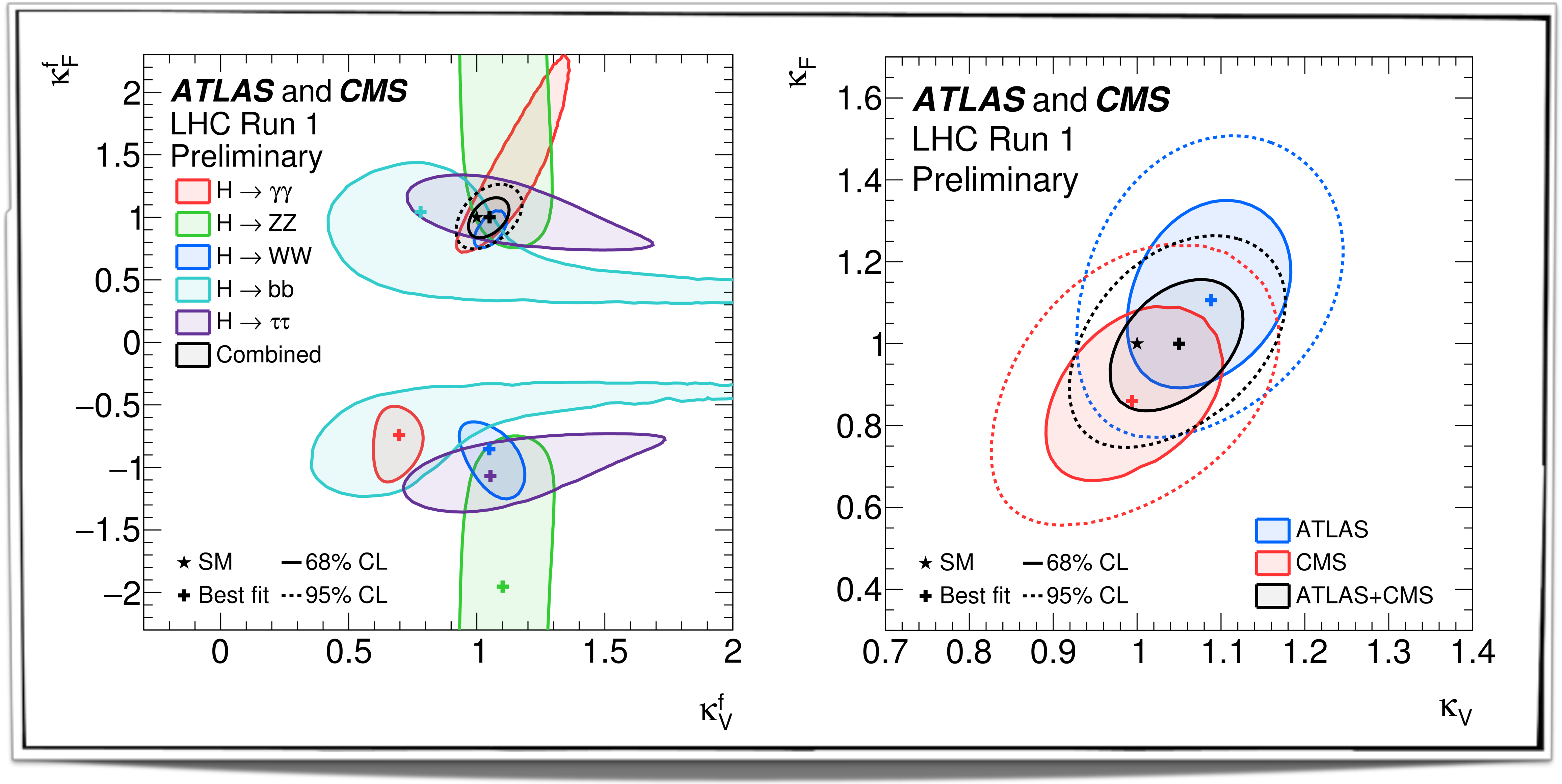
arXiv:1612.09284



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 $\mu \approx m_H$

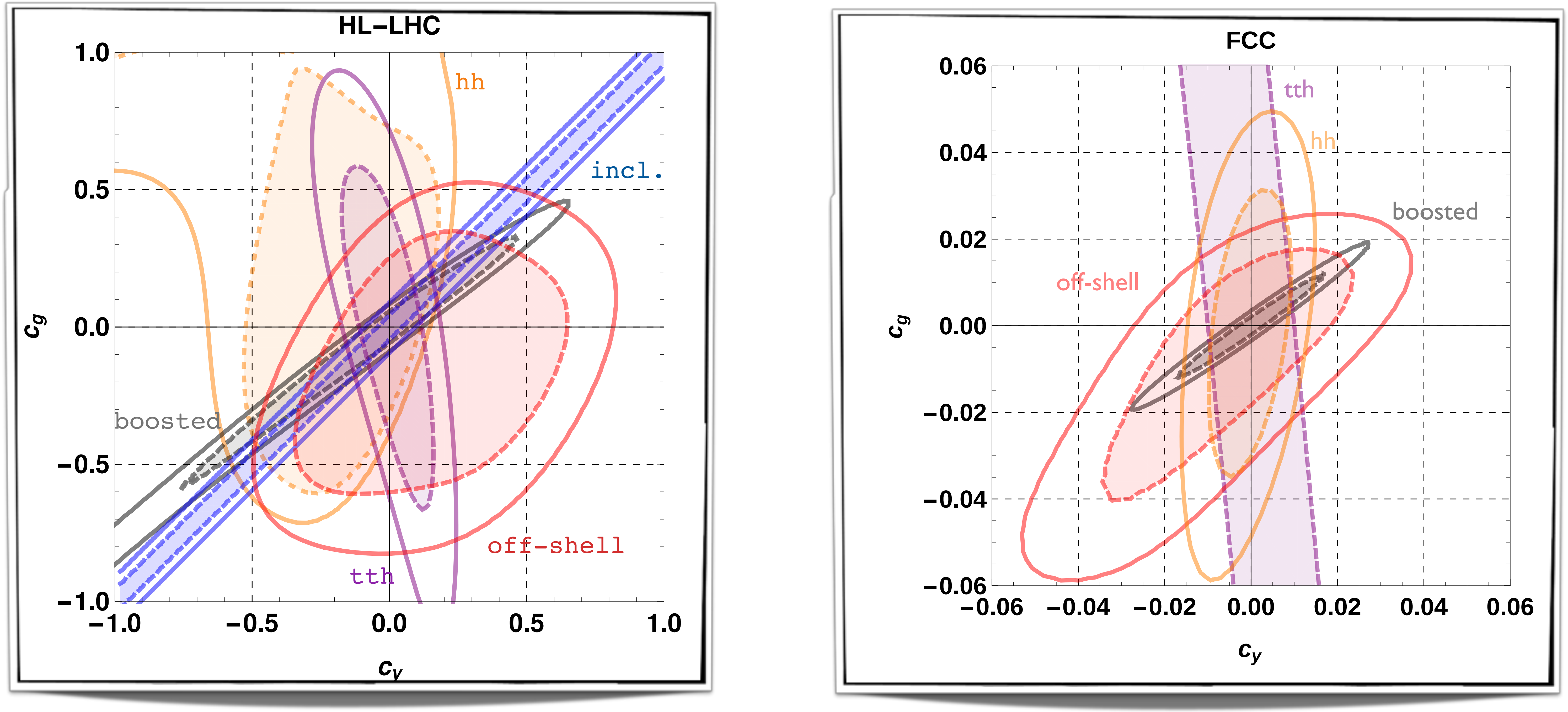
access to Higgs couplings @ m_H

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

Why going beyond inclusive Higgs processes?



Azatov, Grojean, Paul, Salvioni '16

One missing piece:
The Higgs self-coupling

Physics motivations for assessing h^3

Tomorrow, we'll see how to measure it and how well the different colliders are doing it

One missing beast: h^3

The Higgs self-coupling plays important roles

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

2) controls the **stability** of the EW vacuum (… like many other BSM parameters)

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

Does it need to be measured with high accuracy?

Only a few new physics scenarios (but they exist) that will be revealed in the measurements of h^3
But this measurement is the only way to understand the dynamics of EWSB (Cooper pair or elementary scalar?)

M. McCullough, DESY'18

What sort of precision should we aim for?

- 95% confidence it exists: Around 50% accuracy
- 5σ discovery: Around 20 % accuracy.
- Quantum structure: Around 5% accuracy.

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
from measurements around the vacuum is difficult in general
but we can easily test gross features, like the presence of the relevant operator(s)

Grojean, Servant, Wells '04

Goertz '15

SM

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

EWSB W/O H²

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

200% correction to SM prediction

Possible 1st order phase transition

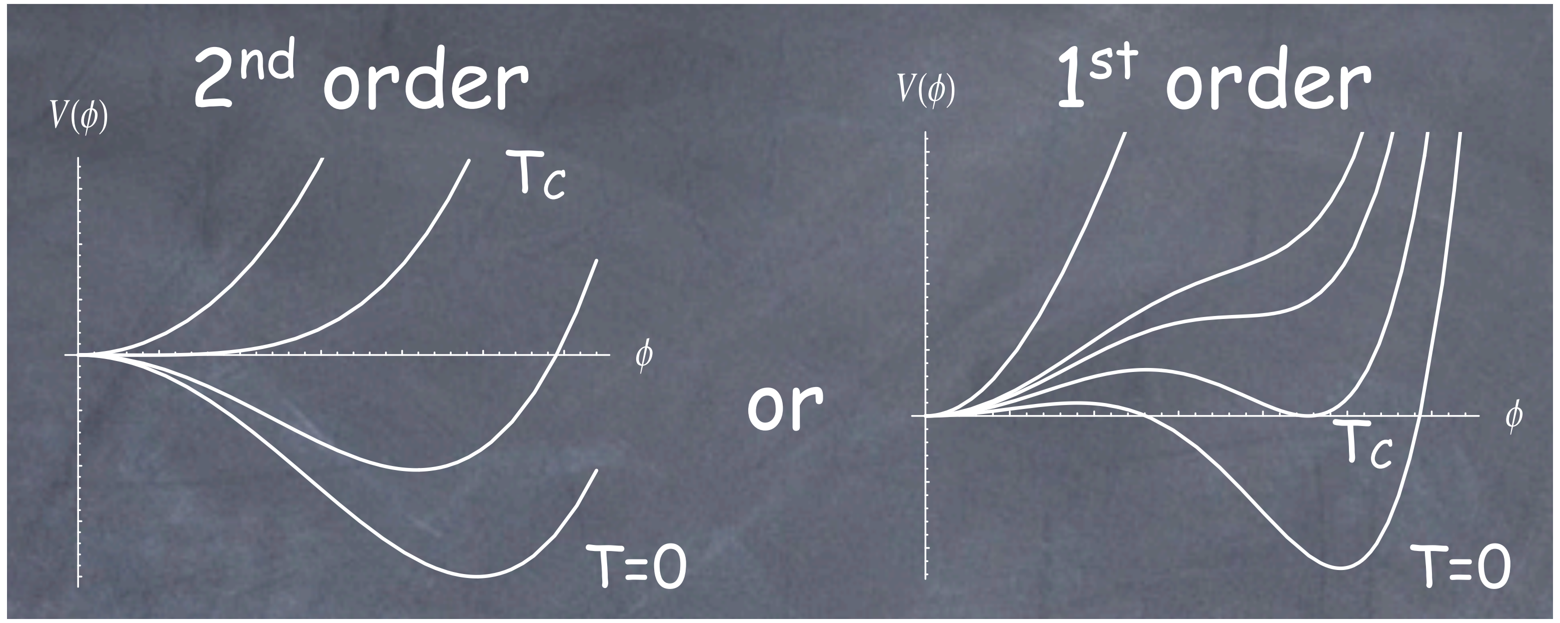
Coleman-Weinberg

$$V = C|H|^4\left(-1/8 + \log(|H|^2/v^2)\right) \quad \Rightarrow \quad V(h) = \frac{1}{2}m_h^2 h^2 + \frac{1}{6}\frac{5m_h^2}{v}h^3 + \ldots$$

Dynamics of EW phase transition

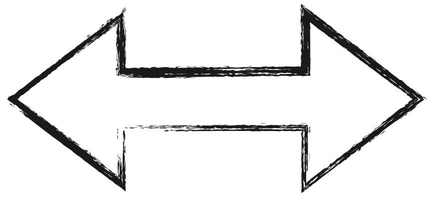
The asymmetry between matter-antimatter can be created dynamically
it requires an out-of-equilibrium phase in the cosmological history of the Universe

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)



the dynamics of the phase transition is determined by Higgs effective potential at finite T
which we have no direct access at in colliders (LHC≠Big Bang machine)

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 ~

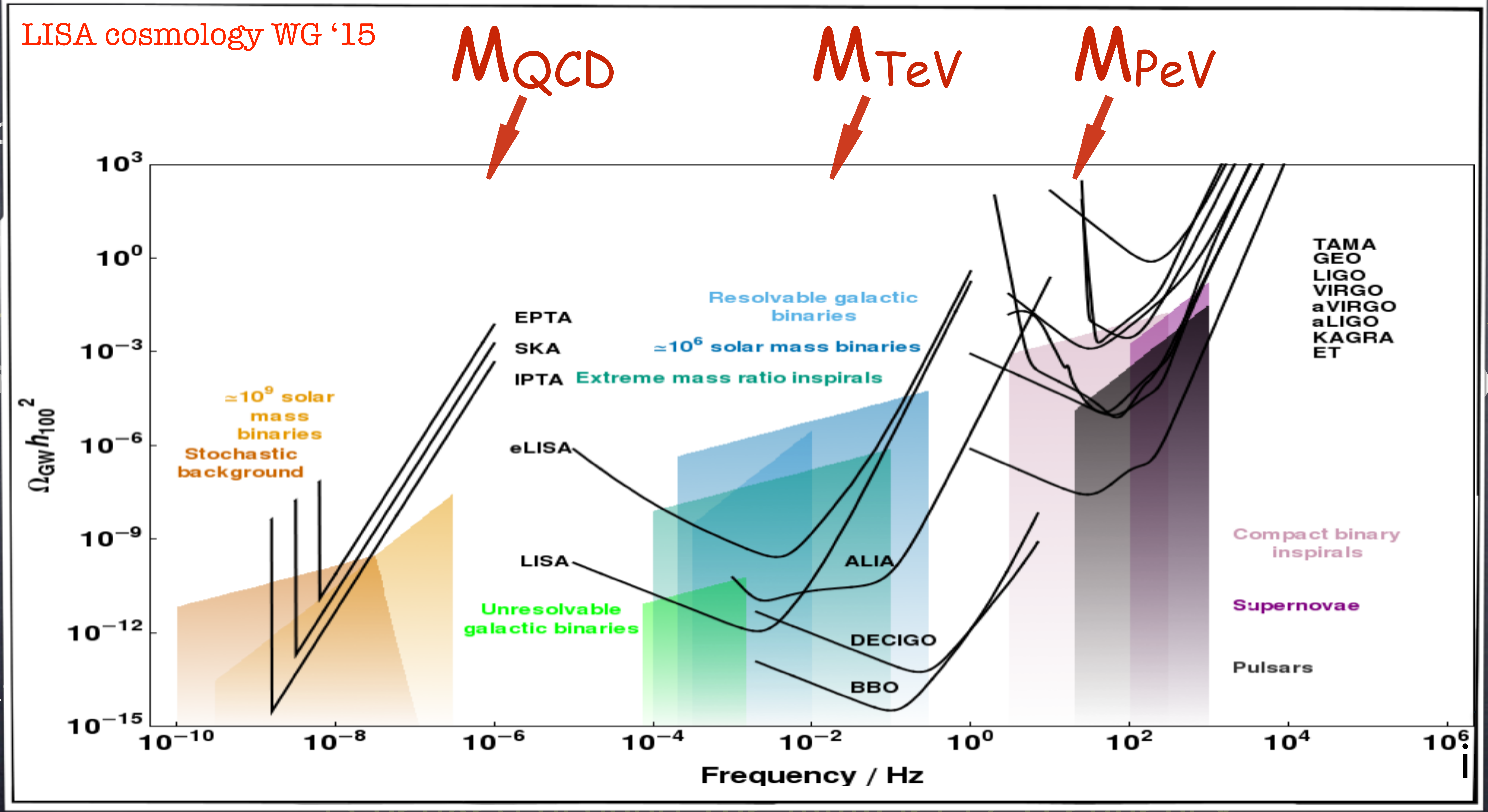
$$f \sim \# \frac{2 \cdot 10^{-4}\ \text{eV}}{100\ \text{GeV}}\, 10^{-15}\ \text{GeV} \sim \# 10^{-5}\ \text{Hz}$$

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

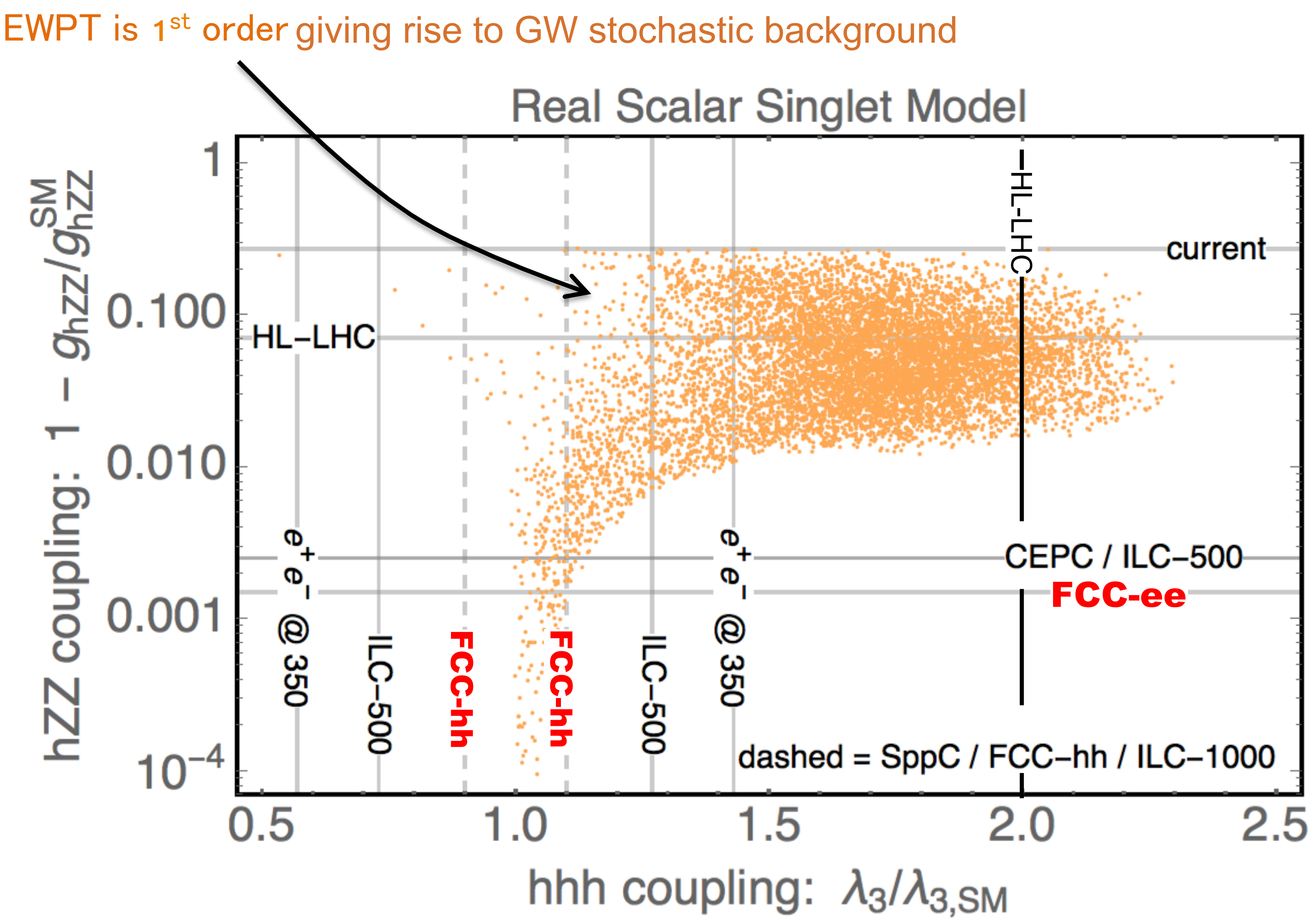
Grojean, Servant '06

h^3 and GW

Grojean, Servant '06



Window to early universe complementary GW - Colliders



Grojean, Servant, Wells ’04

Huang, Long, Wang ’16