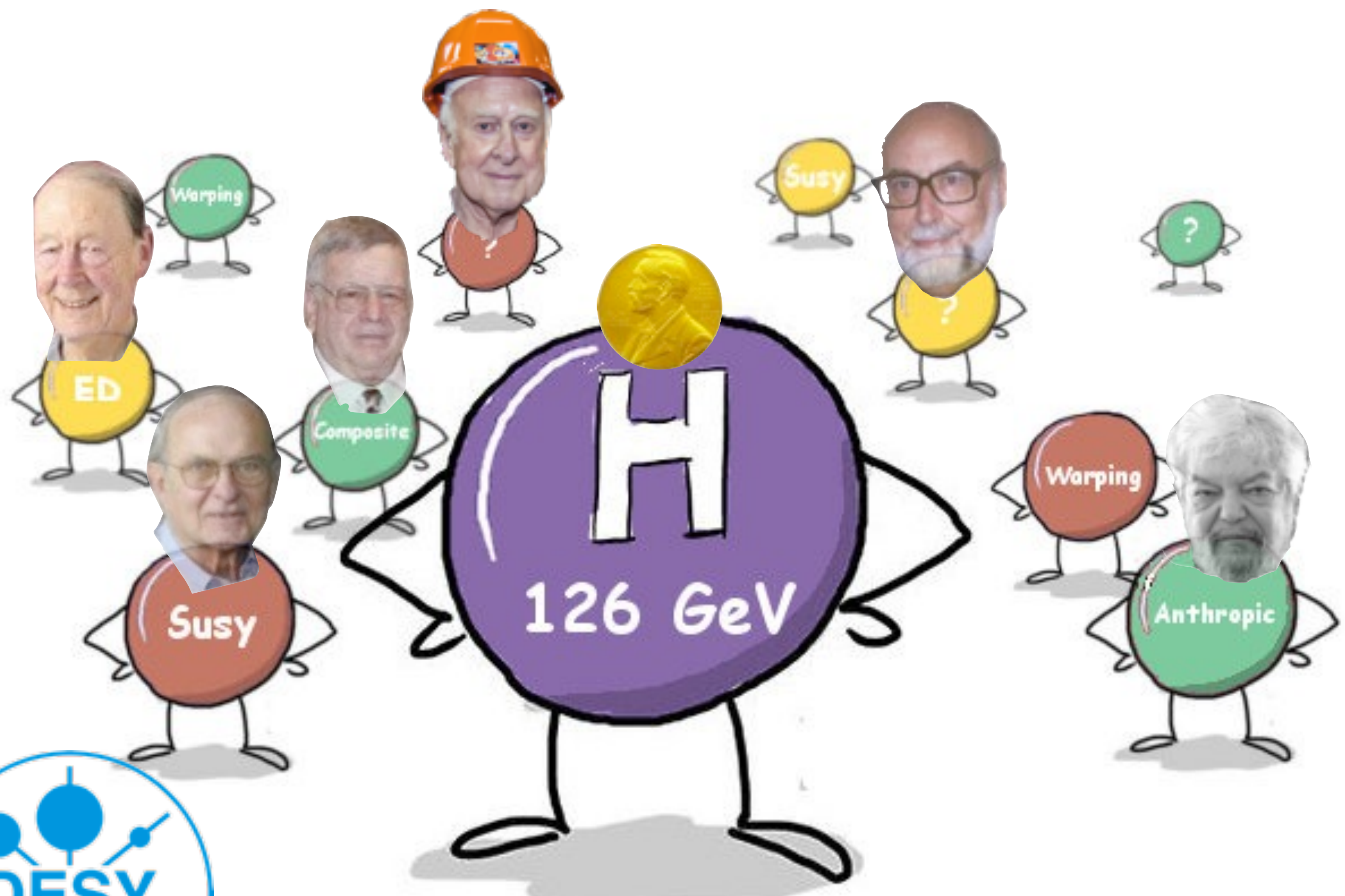
Higgs Physics Landscape

DESY Theory Workshop

"Physics at the LHC and Beyond"

DESY, Hamburg, September 29 - October 2, 2015



P. Cámara/C. Grojean adapted from phdcomics.com

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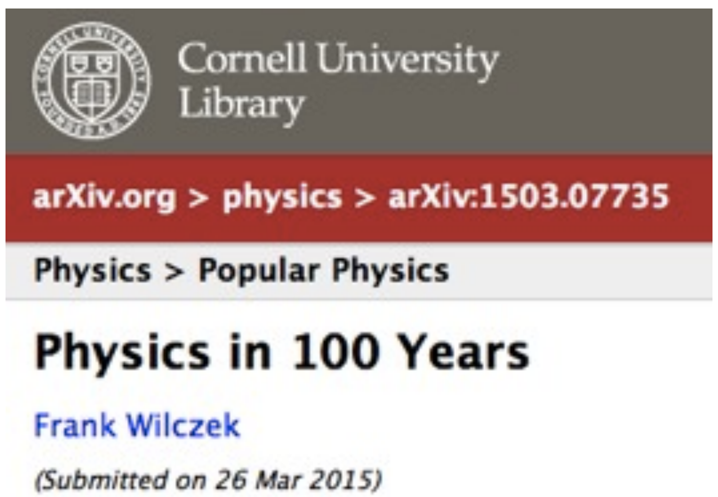
A unique moment in the history of physics

The Higgs discovery is the triumph of XX^{th} century physics
combination of Quantum Mechanism + Special Relativity

For the first time in the history of physics,
we have a *consistent* description of the fundamental constituents of matter and their interactions and this description can be extrapolated to very high energy (up M_{Planck}?)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Physics in 100 Years
Frank Wilczek
(Submitted on 26 Mar 2015)

The equations of the [SM] have been tested with far greater accuracy, and under far more extreme conditions, than are required for applications in chemistry, biology, engineering, or astrophysics. While there certainly are many things we don't understand, we do understand the Matter we're made from, and that we encounter in normal life - even if we're chemists, engineers, or astrophysicists (sic: DM!)

The SM is not free of inadequacies: (without forgetting flavor and neutrinos)

1) Only a description of EW symmetry breaking, not an explanation
➠ What separates the EW scale from the Planck scale?

2) No place for the particle(s) that make up the cosmic DM
➠ What are the DM particles?

3) Does not explain the asymmetry matter-antimatter
➠ Are the conditions realized to allow for EW baryogenesis?

we do not understand the Matter the Universe is made from

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Where and how does the SM break down?
Which machine(s) will reveal (best) this breakdown?

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we do not understand the Matter the Universe is made from

Now what? aka What's Next?

"The experiment worked better than expected and the analysis uncovered a very difficult to find signal"

the words of a string theorist

Great success...

...but the experimentalists haven't found what the BSM theorists told them they will find in addition to the Higgs boson: no susy, no BH, no extra dimensions, nothing ...

Have the theorists been lying for so many years?

Have the EXP's been too naive to believe the TH's?

HEP future

exploration/discovery era or consolidation/measurement era?

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1

Higgs Portrait

HEP with a Higgs boson

The successes have been breathtaking

- in O(3) 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 LEP accuracy (10^{-3})

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

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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)

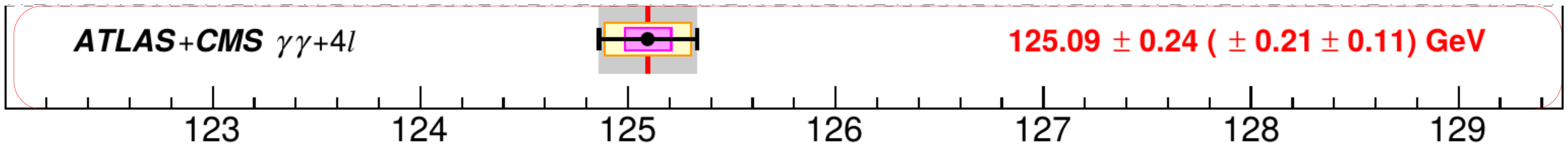
M.L. Mangano, Washington '15

- 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:

  $h\to \not{E}_T$, $h\to 4b$, $h\to 2b2\mu$, $h\to 4\tau, 2\tau 2\mu$, $h\to 4j$, $h\to 2\gamma 2j$, $h\to 4\gamma$, $h\to\gamma/2\gamma+\not{E}_T$,

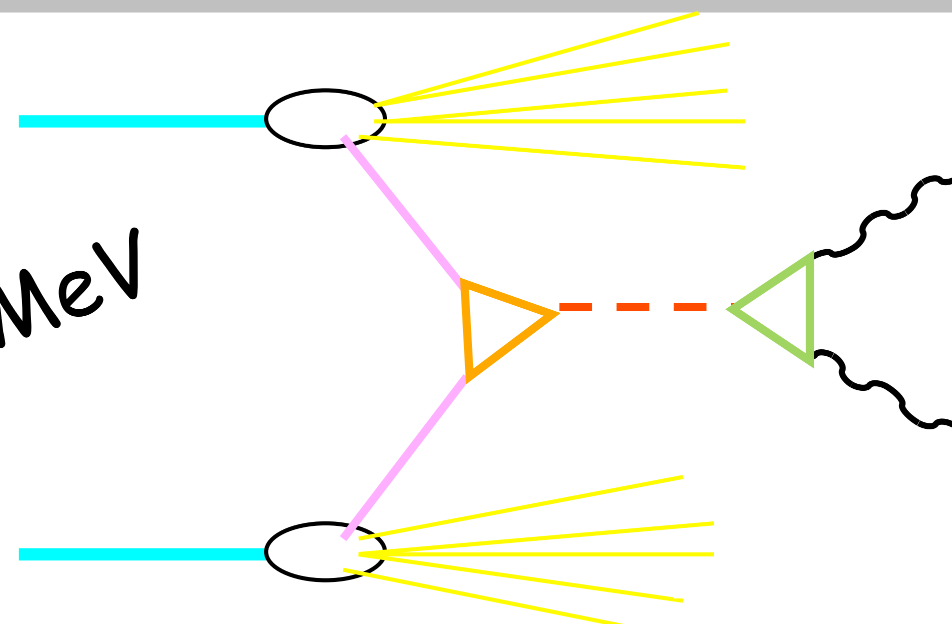
  $h\to$isolated leptons$+\not{E}_T$, $h\to 2l+\not{E}_T$, $h\to$one/two lepton-jet(s)+X, $h\to bb+\not{E}_T$, $h\to\tau\tau+\not{E}_T$ ...
- searches for extended Higgs sectors (H, A, $H^\pm$,$H^{\pm\pm}$...)
- Higgs self-coupling(s)
- Higgs width
- Higgs/axion coupling?
- ...

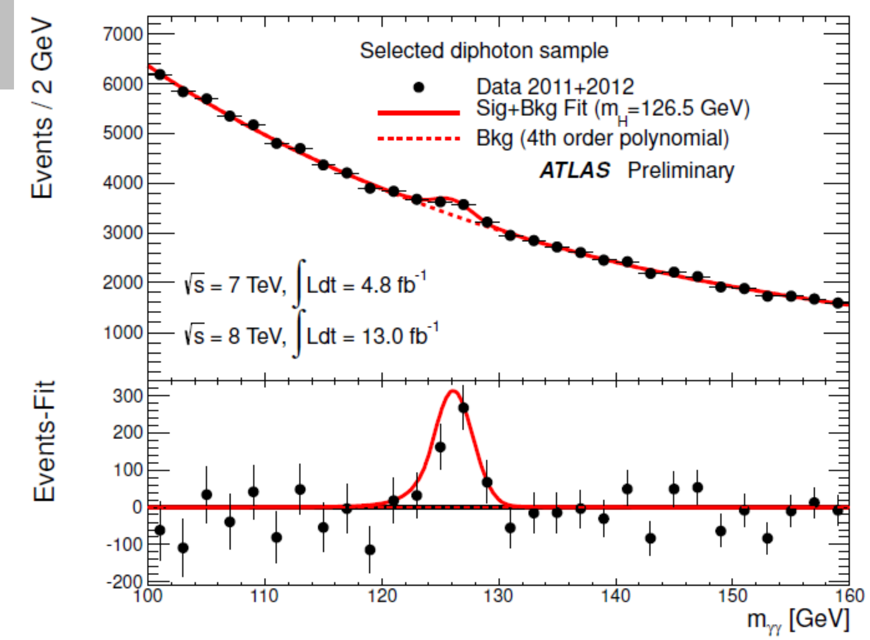
Higgs mass



see G. Quast's talk

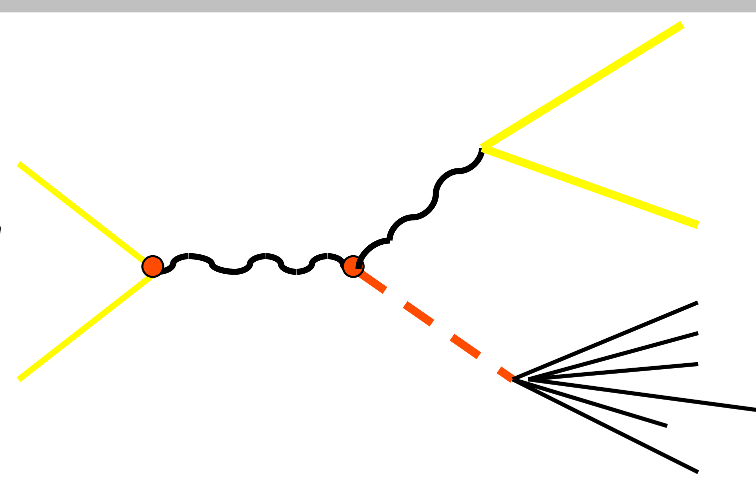
LHC H→γγ Invariant mass of γγ

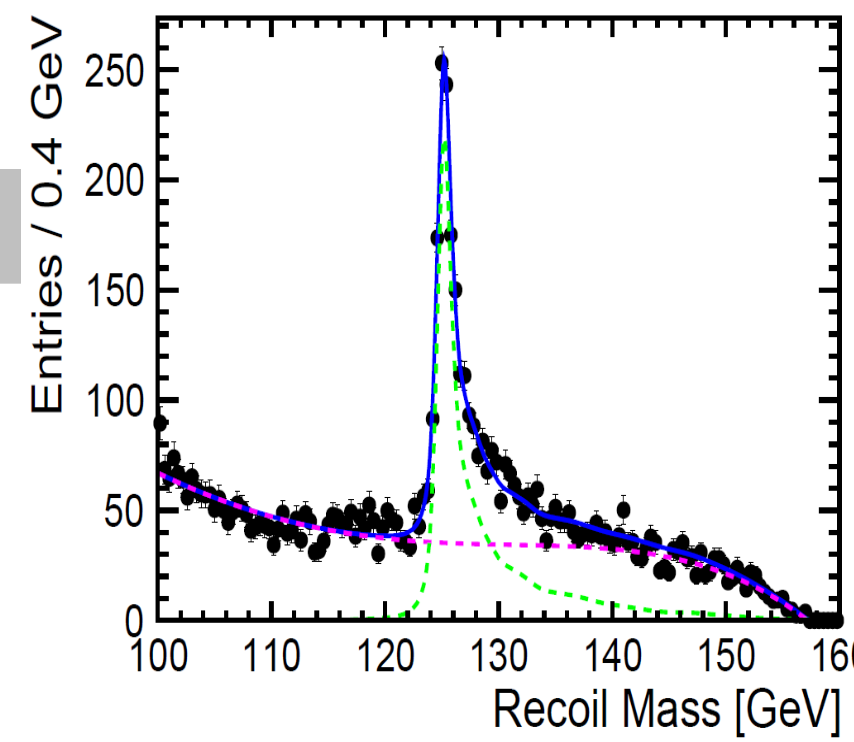




Δm_H~200 MeV

ILC Recoil mass of Z($\mu^+\mu^-$)





Δm_H~30 MeV

Higgs & SM: a paradoxical triumph

The Higgs is related to some of the deepest problems of HEP

$$\mathcal{L}_{\rm Higgs} = V_0 - \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \left(y_{ij}\bar\psi_{Li}\psi_{Rj} H + h.c.\right)$$

vacuum energy
cosmological constant
$V_0 \approx (2\times 10^{-3}\ {\rm eV})^4 \ll M_{\rm PL}^4$

hierarchy problem
$m_H \approx 100\ {\rm GeV} \ll M_{\rm Pl}$

triviality/stability
of EW vacuum

mass and mixing
hierarchy

flavour & CP

~~ Higgs interactions ~~

many different couplings not set by any gauge symmetry
(are fundamental interactions all linked to gauge symmetry?)
but they obey 3 basic structures

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

➠ test of the Higgs as unitarizing agent

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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The Higgs is related to some of the deepest problems of HEP

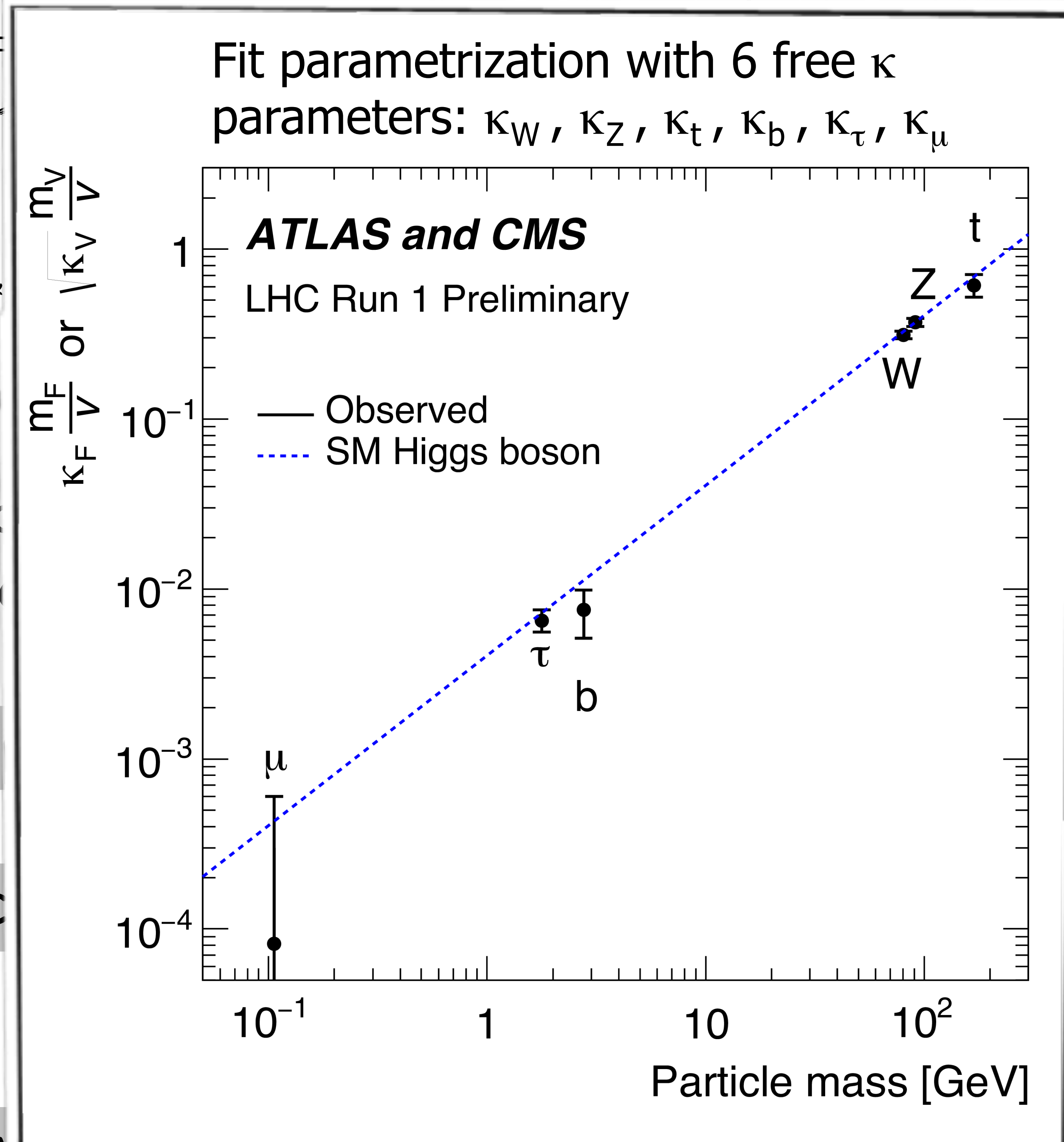
$\mathcal{L}_{\text{Higgs}} =$ ... $_{Rj} H + h.c.)$

vacuum energy
cosmological constant

$V_0 \approx (2 \times 10^{-3}\ \text{eV})^4 \ll M_{PL}^4$

...mixing
...hy

flavour & CP



many ... ...nmetry
(are fun... ...nmetry?)

1) pro... ...gent

2) fac...

...rs

3) flav...

→ test for flavor models, origin of fermion masses

Higgs & SM: a paradoxical triumph

The Higgs is related to some of the deepest problems of HEP

$\mathcal{L}_{\text{Higgs}} =$ ... $_{Rj} H + h.c.)$

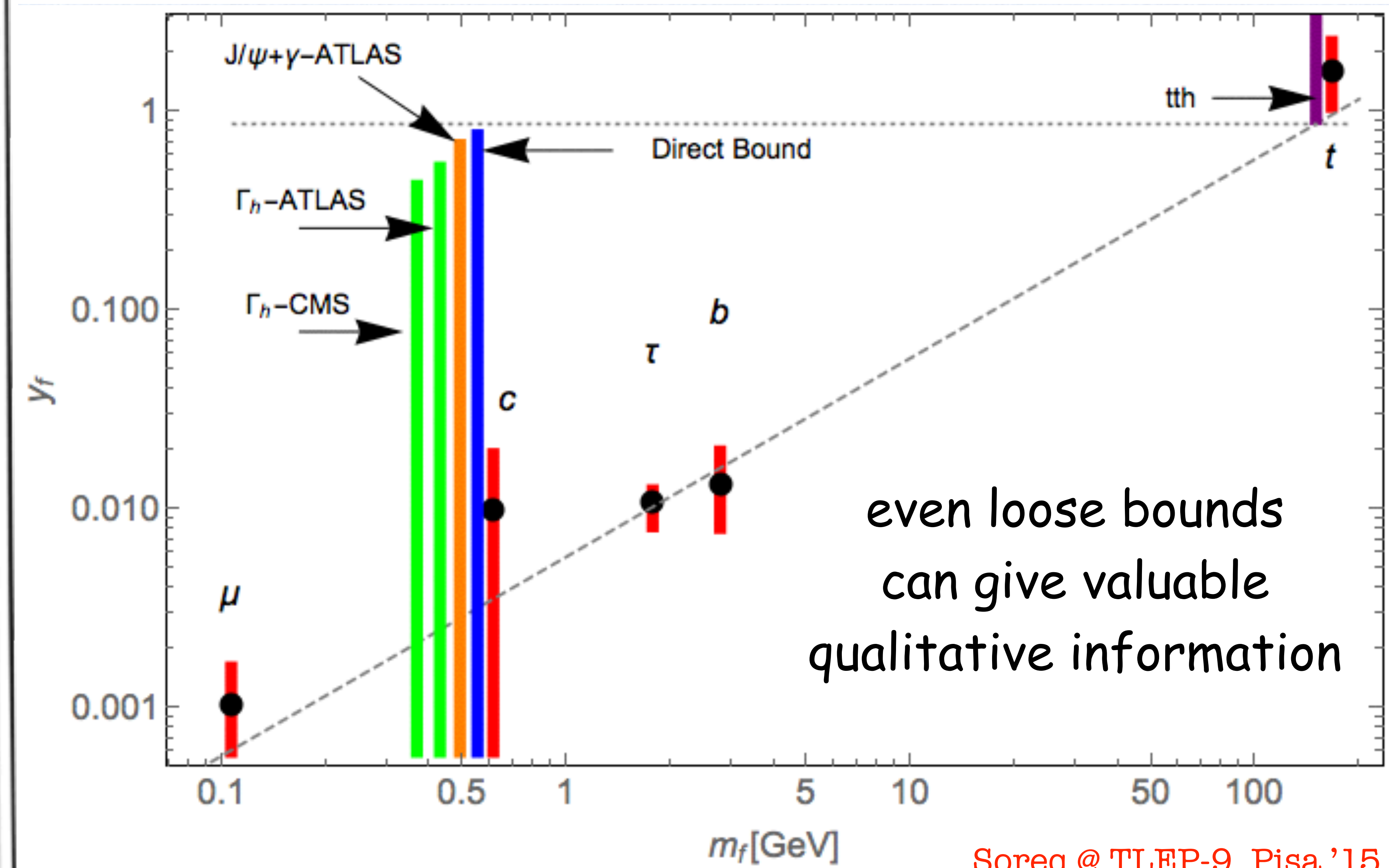
vacuum

cosmological

$V_0 \approx (2 \times 10^{-3}$ e

flavour & CP

Fit parametrization with 6 free κ



even loose bounds can give valuable qualitative information

Soreq @ TLEP-9, Pisa '15

3) flav...

➠ test for flavor models, origin of fermion masses

Flavor alignment

In SM, the Yukawa interactions are the only source of the fermion masses

$$y_{ij} \bar{f}_{L_i} H f_{R_j} = \underbrace{\frac{y_{ij} v}{\sqrt{2}} \bar{f}_{L_i} f_{R_j}}_{\text{mass}} + \underbrace{\frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}}_{\text{higgs-fermion interactions}}$$

both matrices are simultaneously diagonalizable

⇓ ⇓ ⇓

no tree-level Flavor Changing Current induced by the Higgs

Not true anymore if the SM fermions mix with vector-like partners[(*)] or for non-SM Yukawa

$$y_{ij} \left(1 + c_{ij} \frac{|H|^2}{f^2}\right) \bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}} \left(1 + c_{ij} \frac{v^2}{2f^2}\right) \bar{f}_{L_i} f_{R_j} + \left(1 + 3c_{ij} \frac{v^2}{2f^2}\right) \frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

Look for SM forbidden Flavor Violating decays $h \to \mu\tau$ and $t \to hc$

- weak indirect constrained by flavor data (e.g. $\mu \to e\gamma$): BR<10%
- ATLAS and CMS have the sensitivity to set bounds O(1%)
- ILC/CLIC/FCC-ee can certainly do much better

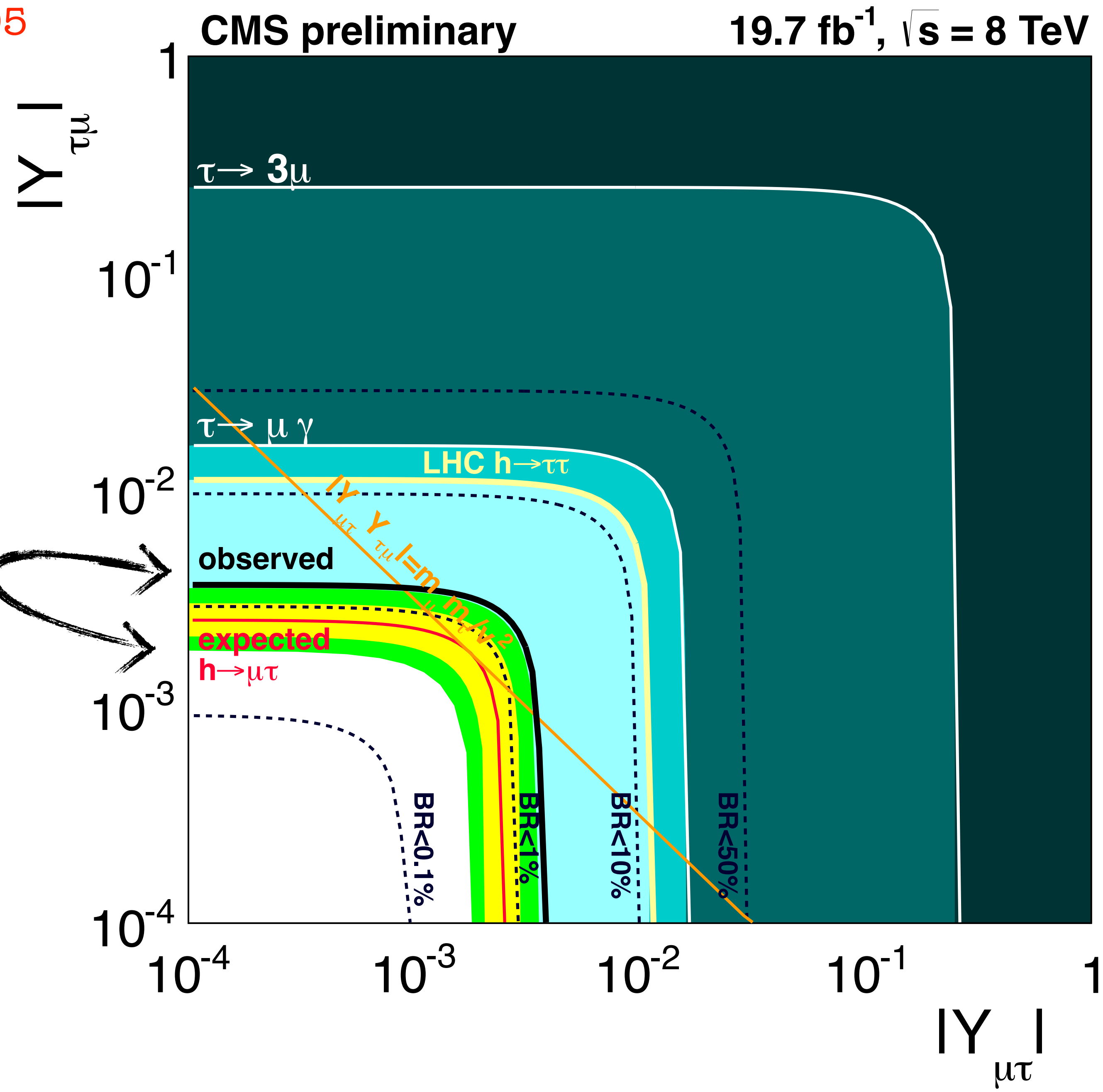
Blankenburg, Ellis, Isidori '12

Harnik et al '12
Davidson, Verdier '12
CMS-PAS-HIG-2014-005

(*) e.g. Buras, Grojean, Pokorski, Ziegler '11

Flavor alignment

CMS-PAS-HIG-2014-005



by the way: 2.3σ excess!

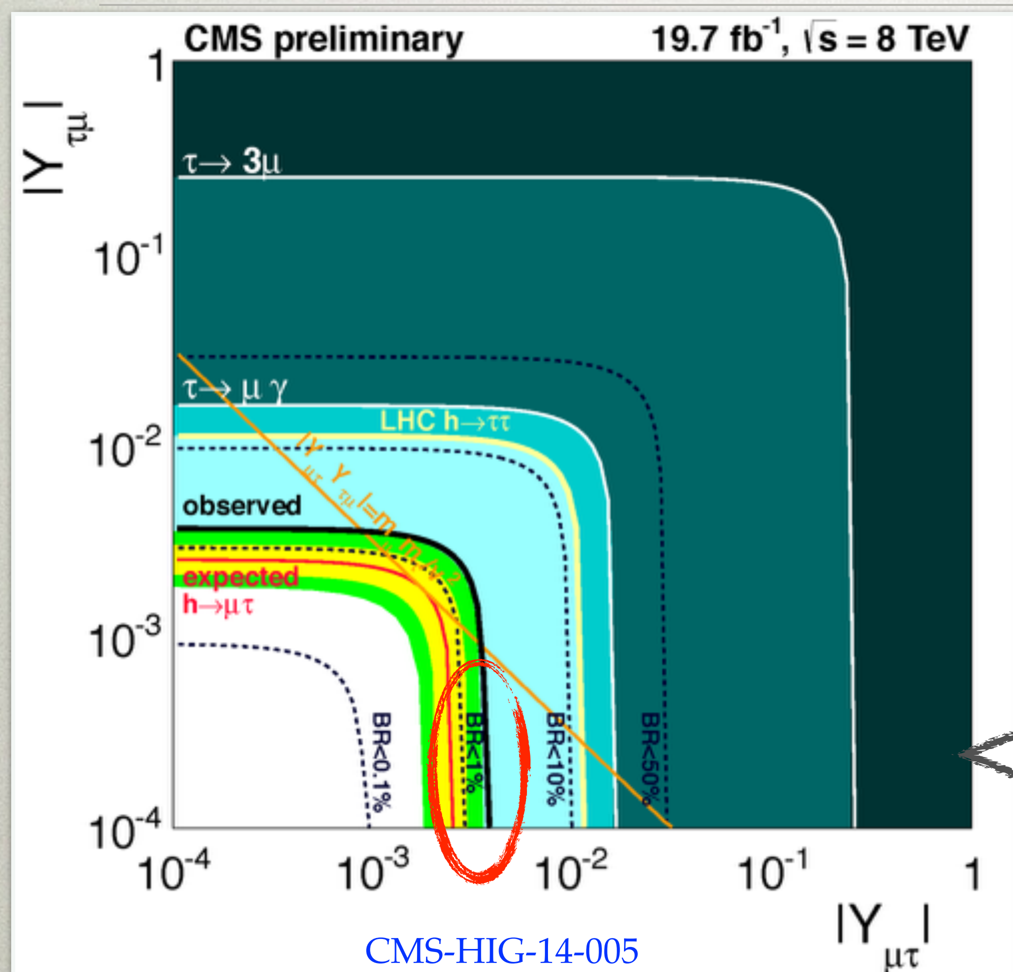
Off-diagonal Higgs couplings can reveal the origin of flavor

Importance of efficient flavor tagging!

Interesting complementarity with $t \to hq$

Flavor alignment @ FCC

$h \to \tau\mu$



- right now: 2j channel statistics limited, 0j+1j not
- how about with $\sim 10^9$ h? **LHC8 $\Rightarrow$ 100 TeV 3 ab^{-1}**
- assume same scaling for signal and bckg
  - $Br \sim 10^{-2} \Rightarrow Br \sim 10^{-4}$
  - $\Lambda \sim 0.2$ TeV $\Rightarrow \Lambda \sim 2$TeV
- if bckg free
  - $Br \sim 10^{-2} \Rightarrow Br \sim 10^{-6}$
  - $\Lambda \sim 0.2$ TeV $\Rightarrow \Lambda \sim 20$TeV ($Y_{\mu\tau} Y_{\tau\mu} = m_\mu m_\tau / \Lambda^2$)

J. Zupan, FCC@Washington '15

sensitivity in $h \to \mu e$ channel not competitive with flavor measurements

2

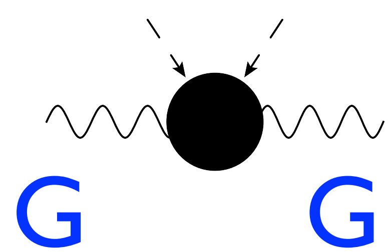
Higgs Couplings

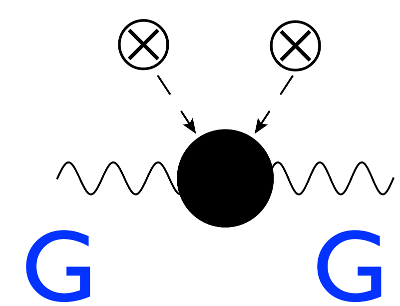
Higgs Primary Couplings

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

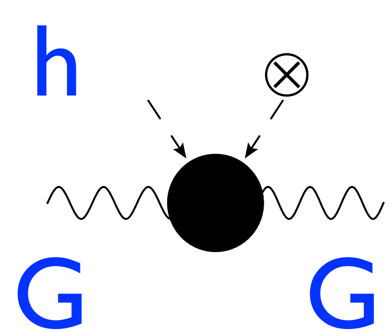
e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2}+\frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$

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





But can affect h physics:



affects GG →h!

(courtesy of A. Pomarol@HiggsHunting2014)

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)

(courtesy of A. Pomarol@HiggsHunting2014)

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' — $\boxed{|H|^2 W^a_{\mu\nu} W^{\mu\nu\, a} \rightarrow \text{hZγ coupling}}$

m_W — $|H|^2 |D_\mu H|^2$ → **hVV* (custodial invariant)**

m_h — $\boxed{|H|^6 \rightarrow h^3 \text{ coupling}}$

yet to be measured at the LHC

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

the 6 others have been measured (~15%)

Higgs/BSM Primaries

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Elias-Miro et al '13

Gupta, Pomarol, Riva '14

As many as parameters

(courtesy of A. Pomarol@HiggsHunting2014)

g_s $|H|^2 G^A_{\mu\nu} G^{A\mu\nu}$ $\longrightarrow$ G

g $|H|^2 B_{\mu\nu} B^{\mu\nu}$ $\longrightarrow$ hγ

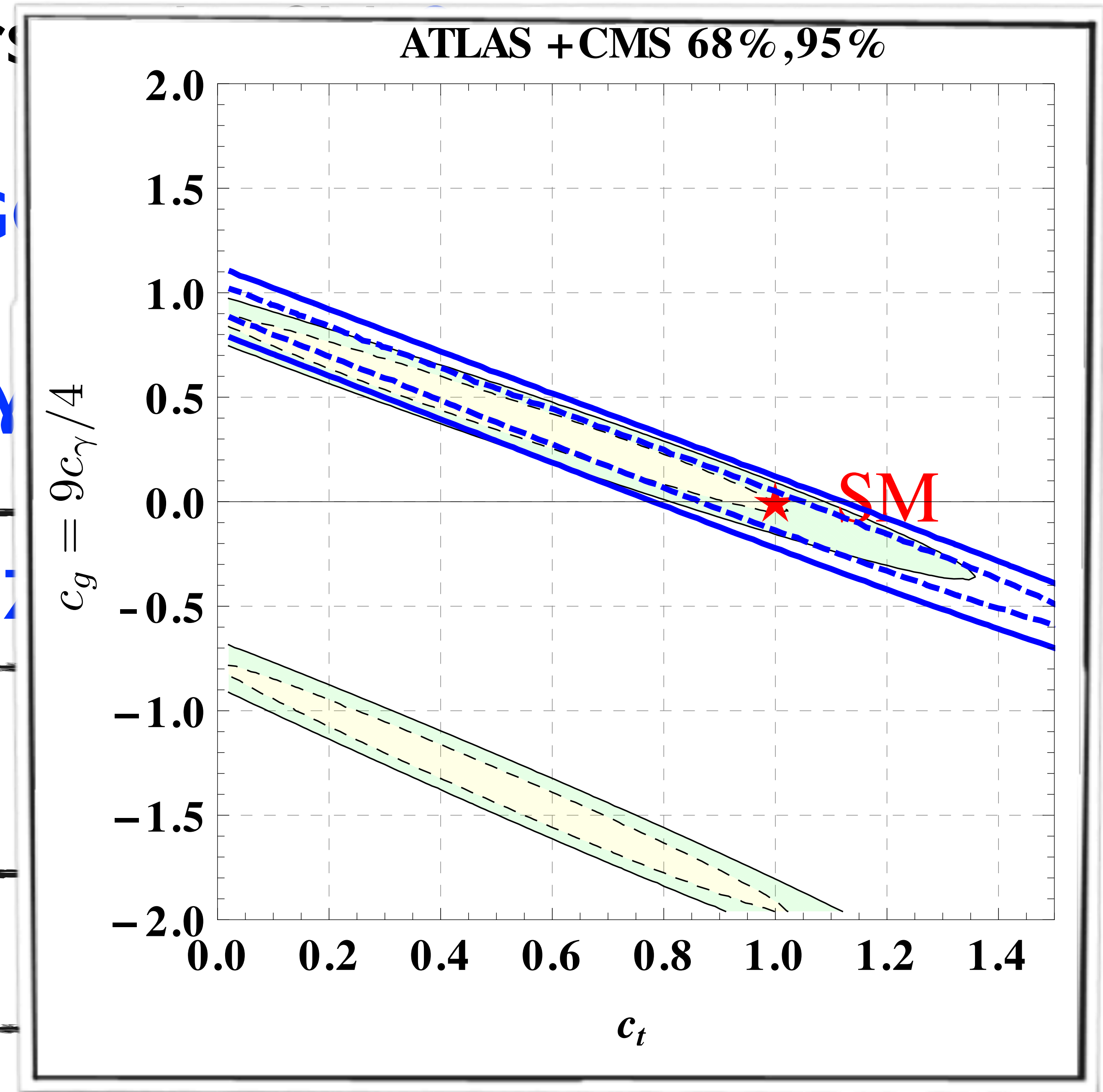
g' $|H|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$ $\longrightarrow$ h

m_W $|H|^2 |D_\mu H|^2$ $\longrightarrow$

m_h $|H|^6$ $\longrightarrow$ h^3

m_f $|H|^2 \bar{f}_L H f_R + h.c.$

(f=t,b,τ)



Azatov '15

up to a flat direction between between the top/gluon/photon couplings (to be resolved by tth or other channels)

Higgs/BSM Primaries

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(courtesy of A. Pomarol@HiggsHunting2014)

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

see G. Quast's talk

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

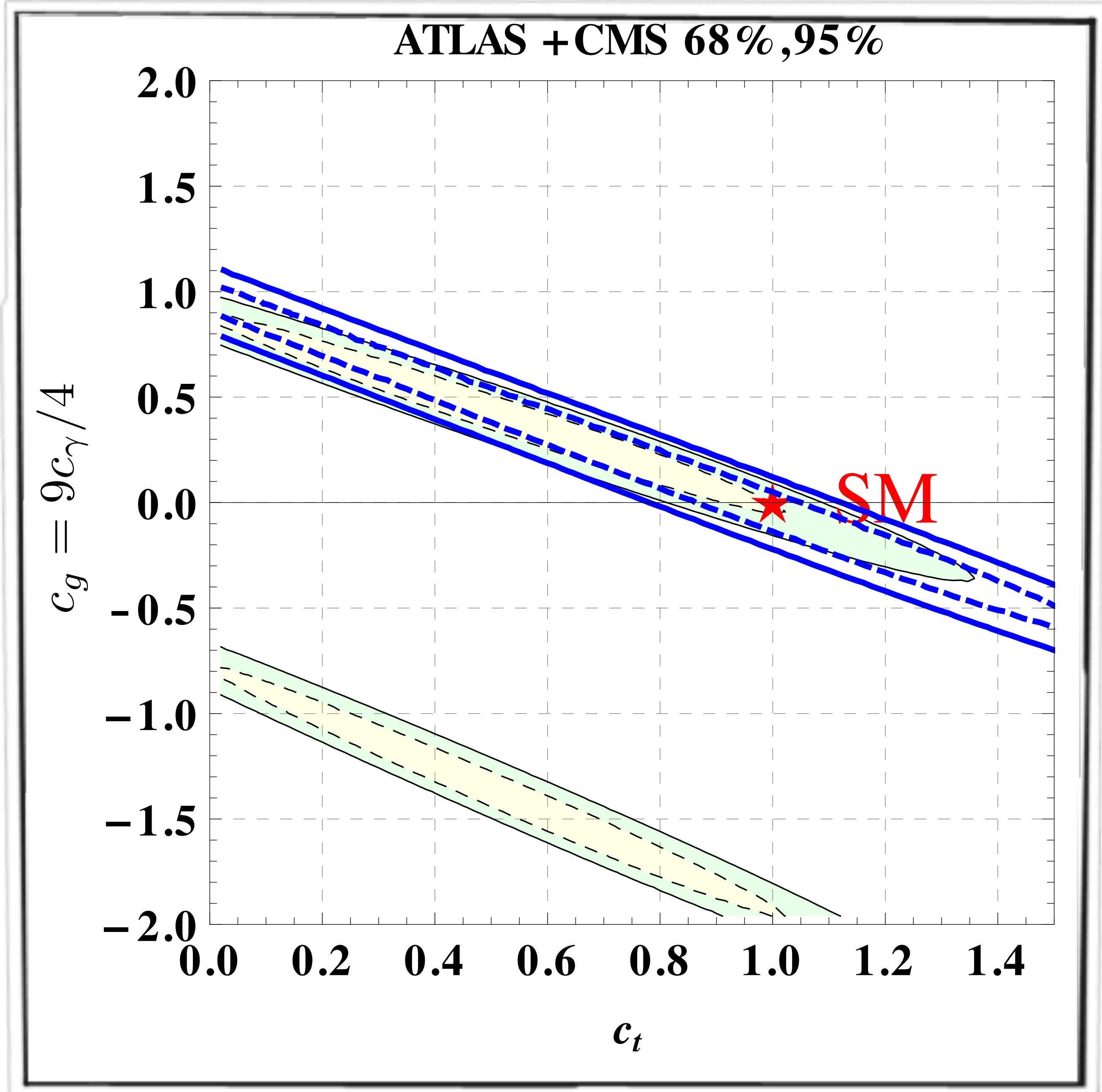
Atlas projection

With some important differences:

1) width hypothesis built-in

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

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



Azatov '15

up to a flat direction between between the top/gluon/photon couplings
(to be resolved by tth or other channels)

CP violation in Higgs physics?

Is CP a good symmetry of Nature? 2 CP-violating couplings in the SM:

V_{CKM} (large, O(1)), but screened by small quark masses) and θ_{QCD} (small, O(10^{-10}))

Can the 0^+ SM Higgs boson have CP violating couplings?

Among the 59 irrelevant directions, 6 ~~C~~P Higgs/BSM primaries

$$
\begin{aligned}
\Delta\mathcal{L}_{\rm BSM} = & \; i\delta\tilde{g}_{hff}\, h\bar{f}_L f_R + h.c. \\
& + \tilde{\kappa}_{GG}\frac{h}{v} G^{\mu\nu}\tilde{G}_{\mu\nu} \\
& + \tilde{\kappa}_{\gamma\gamma}\frac{h}{v} F^{\gamma\,\mu\nu}\tilde{F}^{\gamma}_{\mu\nu} \\
& + \tilde{\kappa}_{\gamma Z}\frac{h}{v} F^{\gamma\,\mu\nu}\tilde{F}^{Z}_{\mu\nu}
\end{aligned}
$$

(f=b, τ, t)

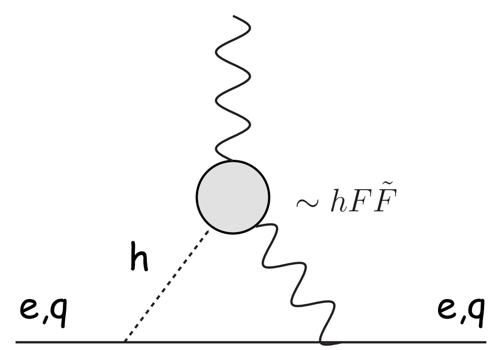
($\tilde{F}_{\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$)

CP violation in Higgs physics?

Among the 59 irrelevant directions, 6 $\cancel{CP}$ Higgs/BSM primaries

$$\begin{aligned}\Delta\mathcal{L}_{\rm BSM} = & \; i\delta\tilde{g}_{hff}\, h\bar{f}_L f_R + h.c. \qquad \text{(f=b, } \tau\text{, t)}\\ & +\tilde{\kappa}_{GG}\frac{h}{v}G^{\mu\nu}\tilde{G}_{\mu\nu} \qquad (\,\tilde{F}_{\mu\nu}\equiv \epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}\,)\\ & +\tilde{\kappa}_{\gamma\gamma}\frac{h}{v}F^{\gamma\,\mu\nu}\tilde{F}^{\gamma}_{\mu\nu}\\ & +\tilde{\kappa}_{\gamma Z}\frac{h}{v}F^{\gamma\,\mu\nu}\tilde{F}^{Z}_{\mu\nu}\end{aligned}$$

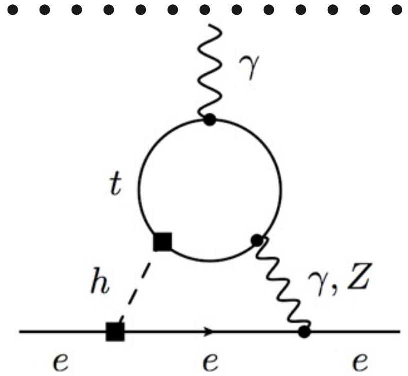
operators with γ:
already severely constrained
by e and q EDMs
McKeen, Pospelov, Ritz '12



$$\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \leq 10^{-4}$$

$\Lambda_{\cancel{CP}}$ > 25 TeV

operators with top:
already severely constrained
by e and q EDMs
Brod, Haisch, Zupan '13



$$\delta\tilde{g}_{htt} \leq 0.01$$

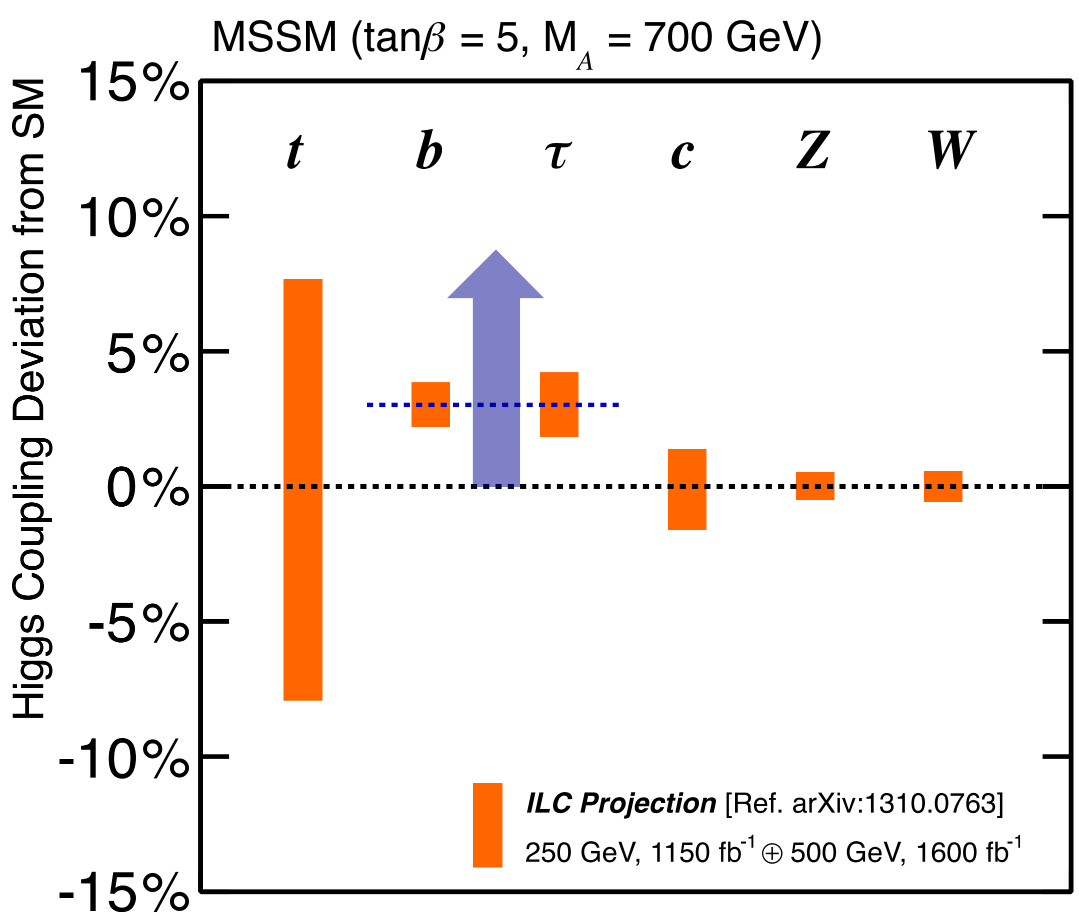
$\Lambda_{\cancel{CP}}$ > 2.5 TeV

Caveats: h couplings to light particles can be significantly reduced

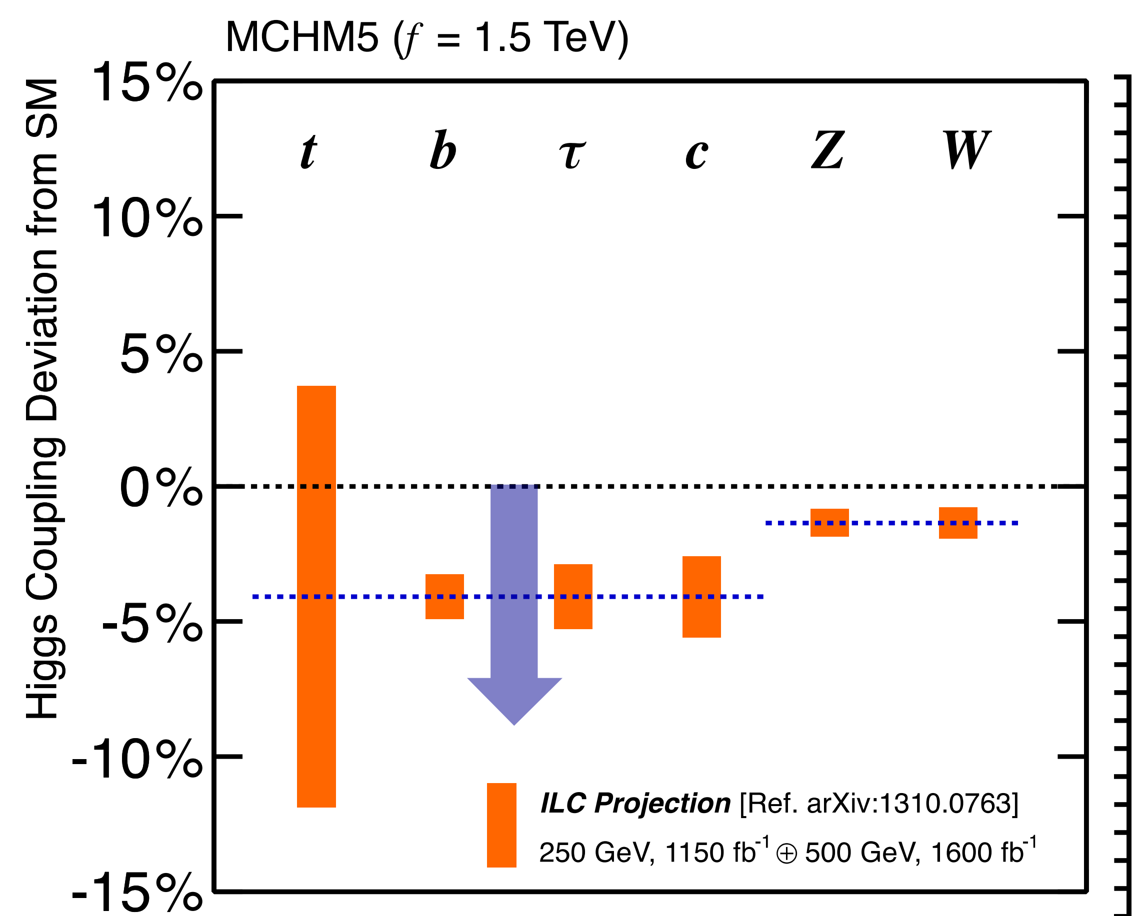
Higgs couplings and model discriminations

The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model

Supersymmetry
(MSSM)



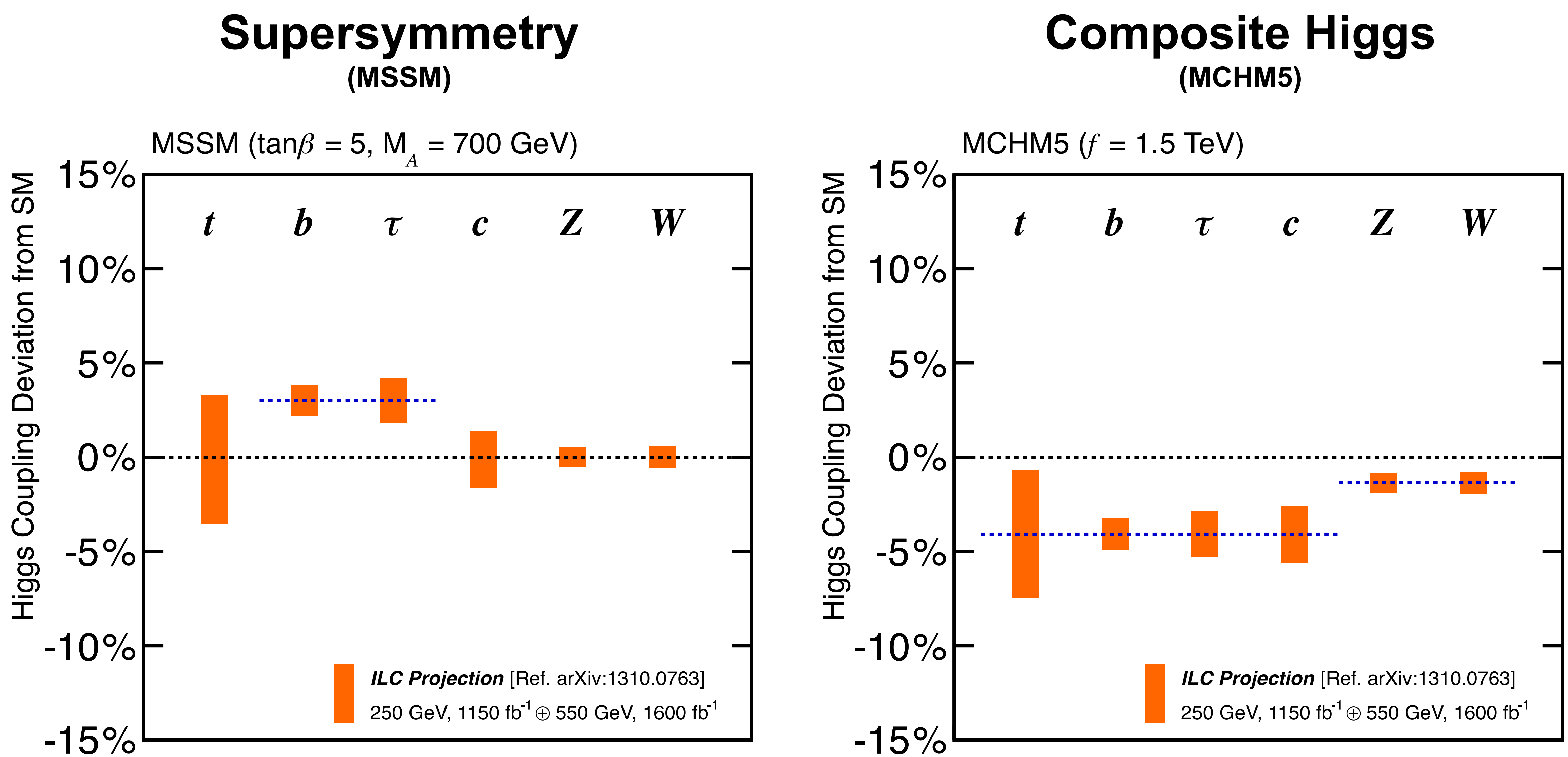
Composite Higgs
(MCHM5)



ILC Physics WG, '15

Higgs couplings and model discriminations

The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model



ILC 250+550 LumiUp

ILC Physics WG, '15

Higgs couplings and model discriminations

The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model

~~ expected largest relative deviations ~~

	hff	hVV	hγγ	hγZ	hGG	h^3
MSSM	√		√	√	√	
NMSSM	√	√	√	√	√	
PGB Composite	√	√		√		√
SUSY Composite	√	√	√	√	√	√
SUSY partly-composite			√	√	√	√
“Bosonic TC”						√
Higgs as a dilaton			√	√	√	√

A. Pomarol, Naturalness ’15

Higgs couplings and model discriminations

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	hff	hVV	hγγ	hγZ	hGG	h^3
MSSM	√		√	√	√	
NMSSM	√	√	√		√	
PGB Composite						√
					√	√
SUS			√	√	√	√
						√
Higgs as a dilaton			√	√	√	√

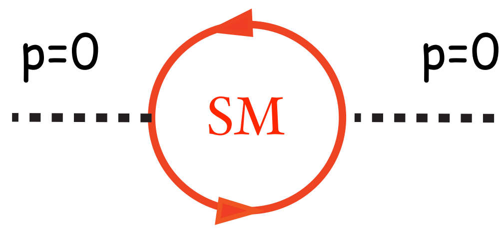
There exist some physics scenarios where high energy thresholds are important and complementary to physics near Higgs threshold (HH & ttH productions)

A. Pomarol, Naturalness '15

Higgs couplings as a test of naturalness

$-(125\text{ GeV})^2\left(\frac{\Lambda}{600\text{ GeV}}\right)^2$ $\qquad\qquad$ $\frac{g_*^2}{16\pi^2}\Lambda^2$

$\delta m_H^2 =$



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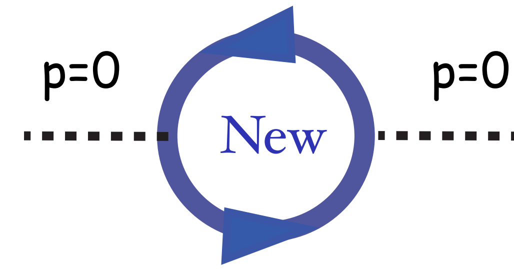
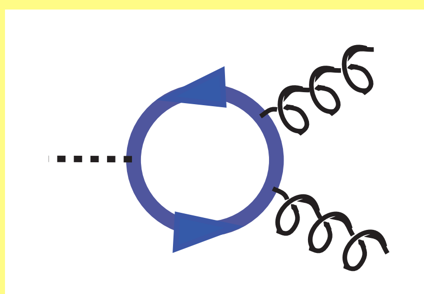


$\sim m_H^2$

charged particles

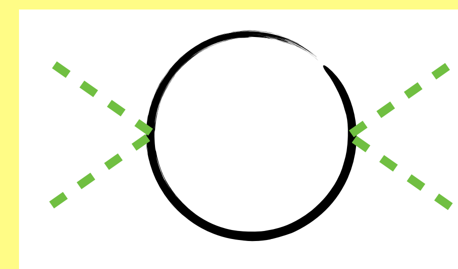
generically

neutral particles



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\text{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$



$$\frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

$$BR(h\to ii) = BR_{\text{SM}} \qquad \Gamma = \left(1-\frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

$$\delta\sigma_{Zh} = -\frac{g_\star^2}{8\pi^2}\frac{v^2}{m_\star^2}$$

nice to be able to measure Zh & Γ

Colorful naturalness probed @ LHC

Neutral naturalness (invisible?) @ LHC

Higgs couplings measurement projections

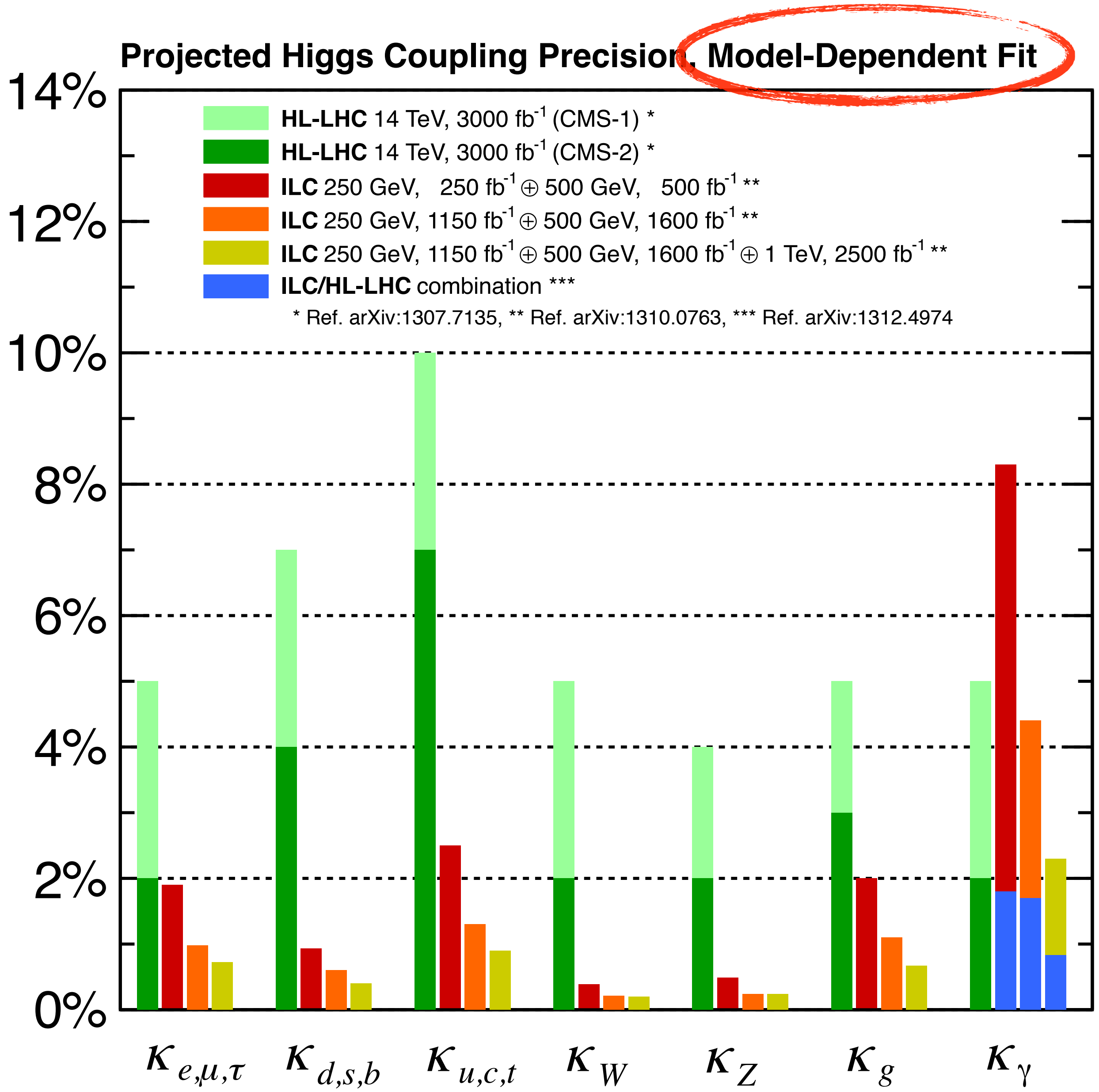
Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	$3.5/1.4/<1.3\%$	0.51%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

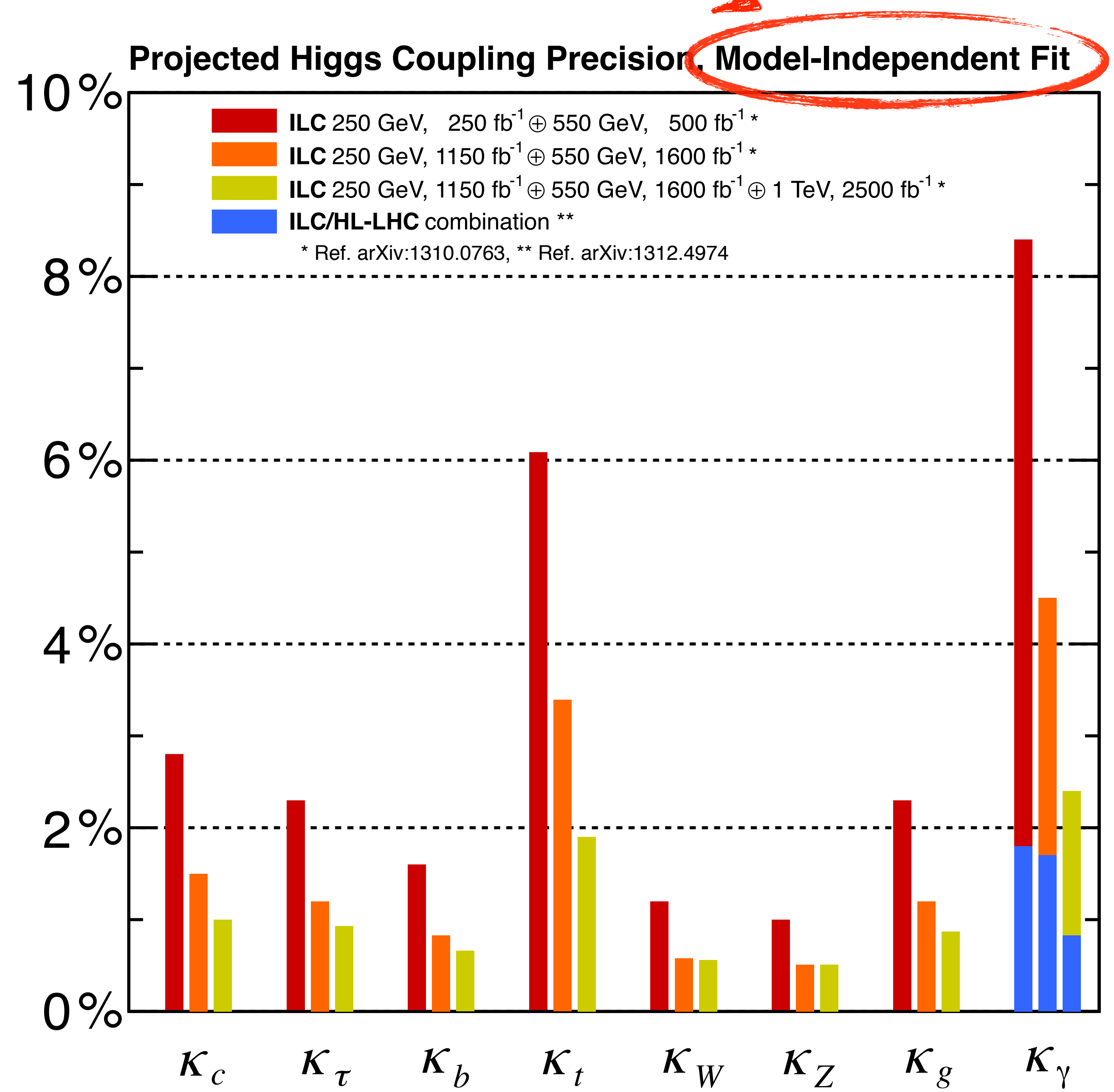
Rich experimental program of (sub)percent precision

Higgs couplings measurement projections

assumption about Higgs width



no assumption about Higgs width



Rich experimental program of (sub)percent precision

Nice synergy/complementarity LHC-ILC ($h\gamma\gamma$)

use BR ratios from hh with absolute precise BR from ee

to export ee precision to Higgs decays that are limited by statistics in ee

Higgs couplings measurement projections

g_{HXY}	FCC-ee	FCC-hh
ZZ	0.16%	
WW	0.85%	
$\gamma\gamma$	1.7%	<1% ?
$Z\gamma$		1% ?
tt		1% ?
bb	0.88%	
$\tau\tau$	0.94%	
cc	1.0%	
ss	$H\to V\gamma$, in progr.	
$\mu\mu$	6.4%	2% ?
uu,dd	$H\to V\gamma$, in progr.	
ee	$e^+e^-\to H$, in progr.	
HH		5% ?
BR_{exo}	0.48%	$< 10^{-6}$?

# of Higgses in 3 ab^{-1}

100 TeV > 2 billion

33 TeV > 500 million

14 TeV > 150 million

In comparison, O(million) Higgs at Higgs factories

@ 100 TeV

	σ	N / $10ab^{-1}$
$gg\to H$	740 pb	7.4 G
VBF	82 pb	0.8 G
WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
$gg\to HH$	1.4 pb	14 M

M. Mangano, HXSWG '15

the Higgses produced are not the Higgses reconstructed but fantastic playground for rare/exotic decays

Rare Higgs decays

Rare associated-production processes

Are they good for something? Reduced systematics? Complementary information?

Process	$\sigma_{\rm NLO}$(8 TeV) [fb]	$\sigma_{\rm NLO}$(100 TeV) [fb]	ρ
$pp \to H\ (m_t, m_b)$	$1.44 \cdot 10^4\ ^{+20\%}_{-16\%}\ ^{+1\%}_{-2\%}$	$5.46 \cdot 10^5\ ^{+28\%}_{-27\%}\ ^{+2\%}_{-2\%}$	38
$pp \to Hjj$ (VBF)	$1.61 \cdot 10^3\ ^{+1\%}_{-0\%}\ ^{+2\%}_{-2\%}$	$7.40 \cdot 10^4\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-1\%}$	46
$pp \to Ht\bar{t}$	$1.21 \cdot 10^2\ ^{+5\%}_{-9\%}\ ^{+3\%}_{-3\%}$	$3.25 \cdot 10^4\ ^{+7\%}_{-8\%}\ ^{+1\%}_{-1\%}$	269
$pp \to Hb\bar{b}$ (4FS)	$2.37 \cdot 10^2\ ^{+9\%}_{-9\%}\ ^{+2\%}_{-2\%}$	$1.21 \cdot 10^4\ ^{+2\%}_{-10\%}\ ^{+2\%}_{-2\%}$	51
$pp \to Htj$	$2.07 \cdot 10^1\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$5.21 \cdot 10^3\ ^{+3\%}_{-5\%}\ ^{+1\%}_{-1\%}$	252
$pp \to HW^\pm$	$7.31 \cdot 10^2\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$1.54 \cdot 10^4\ ^{+5\%}_{-8\%}\ ^{+2\%}_{-2\%}$	21
$pp \to HZ$	$3.87 \cdot 10^2\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$8.82 \cdot 10^3\ ^{+4\%}_{-8\%}\ ^{+2\%}_{-2\%}$	23
$pp \to HW^+W^-$ (4FS)	$4.62 \cdot 10^0\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$1.68 \cdot 10^2\ ^{+5\%}_{-6\%}\ ^{+2\%}_{-1\%}$	36
$pp \to HZW^\pm$	$2.17 \cdot 10^0\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-2\%}$	$9.94 \cdot 10^1\ ^{+6\%}_{-7\%}\ ^{+2\%}_{-1\%}$	46
$pp \to HW^\pm\gamma$	$2.36 \cdot 10^0\ ^{+3\%}_{-3\%}\ ^{+2\%}_{-2\%}$	$7.75 \cdot 10^1\ ^{+7\%}_{-8\%}\ ^{+2\%}_{-1\%}$	33
$pp \to HZ\gamma$	$1.54 \cdot 10^0\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.29 \cdot 10^1\ ^{+5\%}_{-7\%}\ ^{+2\%}_{-2\%}$	28
$pp \to HZZ$	$1.10 \cdot 10^0\ ^{+2\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.20 \cdot 10^1\ ^{+4\%}_{-6\%}\ ^{+2\%}_{-1\%}$	38
$pp \to HW^\pm j$	$3.18 \cdot 10^2\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-1\%}$	$1.07 \cdot 10^4\ ^{+2\%}_{-7\%}\ ^{+2\%}_{-1\%}$	34
$pp \to HW^\pm jj$	$6.06 \cdot 10^1\ ^{+6\%}_{-8\%}\ ^{+1\%}_{-1\%}$	$4.90 \cdot 10^3\ ^{+2\%}_{-6\%}\ ^{+1\%}_{-1\%}$	81
$pp \to HZj$	$1.71 \cdot 10^2\ ^{+4\%}_{-4\%}\ ^{+1\%}_{-1\%}$	$6.31 \cdot 10^3\ ^{+2\%}_{-7\%}\ ^{+2\%}_{-1\%}$	37
$pp \to HZjj$	$3.50 \cdot 10^1\ ^{+7\%}_{-10\%}\ ^{+1\%}_{-1\%}$	$2.81 \cdot 10^3\ ^{+2\%}_{-5\%}\ ^{+1\%}_{-1\%}$	80

Table 1: Production of a single Higgs boson at the LHC and at a 100 TeV FCC-hh. The rightmost column reports the ratio ρ of the FCC-hh to the LHC cross sections. Theoretical uncertainties are due to scale and PDF variations, respectively. Monte-Carlo-integration error is always smaller than theoretical uncertainties, and is not shown. For $pp \to HVjj$, on top of the transverse-momentum cut of section 2, I require $m(j_1, j_2) > 100$ GeV, j_1 and j_2 being the hardest and next-to-hardest jets, respectively. Processes $pp \to Htj$ and $pp \to Hjj$ (VBF) do not feature jet cuts.

P.Torrielli, arXiv:1407.1623

3

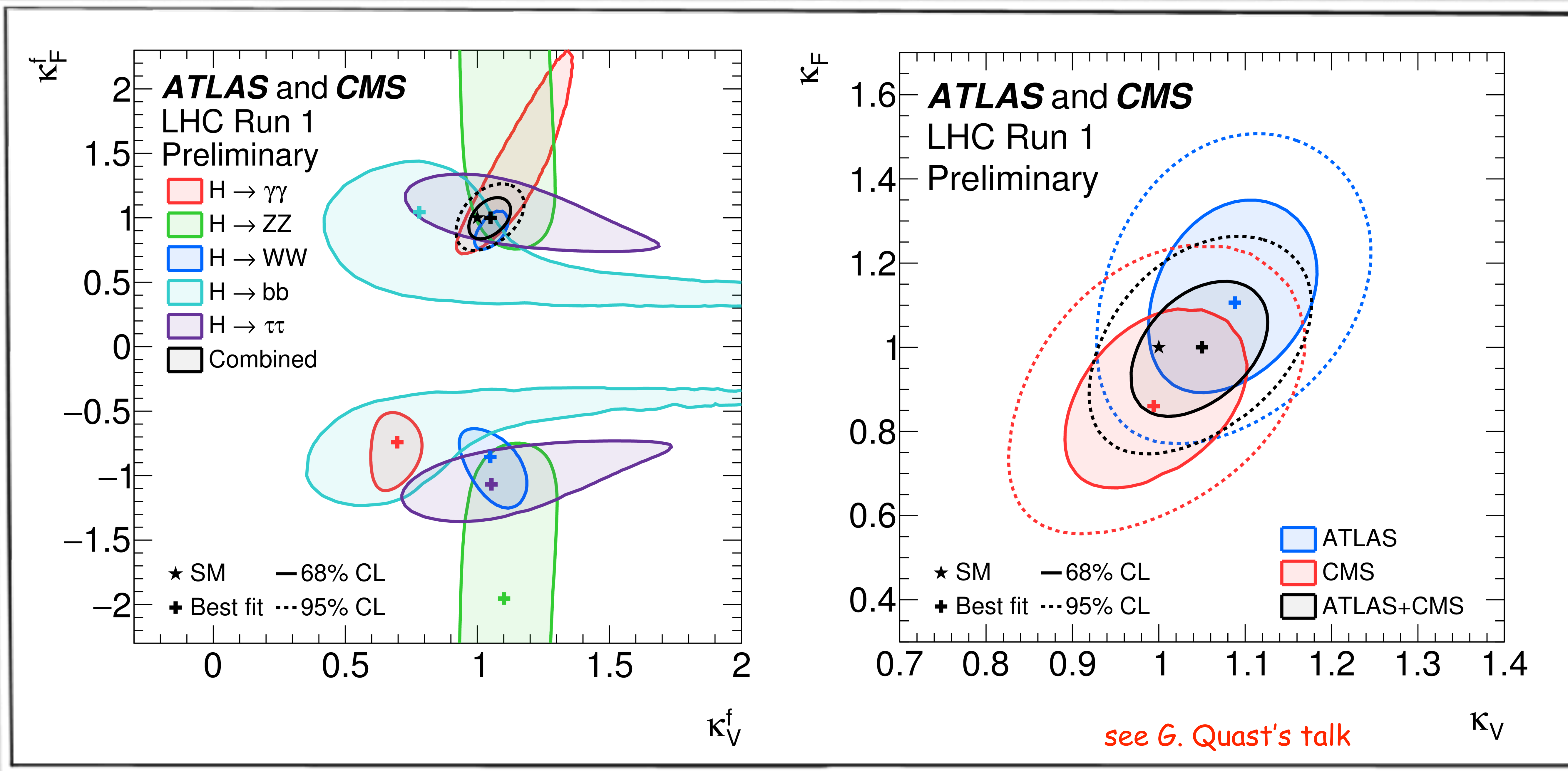
Beyond Higgs Inclusive Measurements

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



see G. Quast's talk

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)

Probing new corrections to the SM Lagrangian?

on-shell Z @ LEP1

constraints on
S and T oblique corrections

off-shell Z @ LEP2
constraints on
W and Y oblique corrections
(same order as S and T but cannot be probed @ LEP1)

But... off-shell Higgs data do not probe new corrections
that cannot be constrained by on-shell data

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

e.g. Grazzini, Sargsyan '13

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

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

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

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

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

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

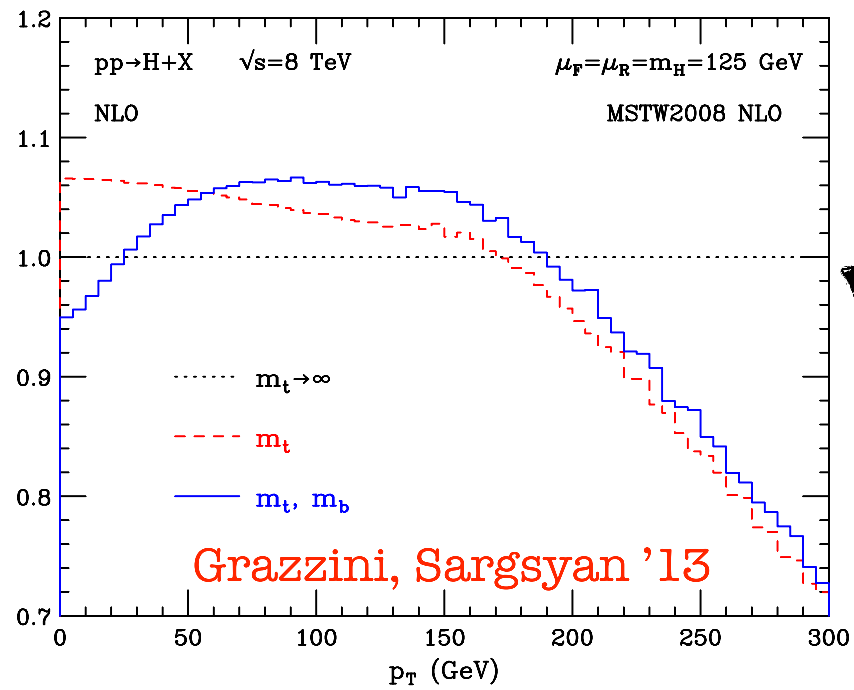
having access to $ht\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-$\mathrm{ILC}^{1000}_{1000}$

Resolving top loop: Boosted Higgs

cut open the top loops

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

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



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

Harlander et al '12

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

Resolving top loop: Boosted Higgs

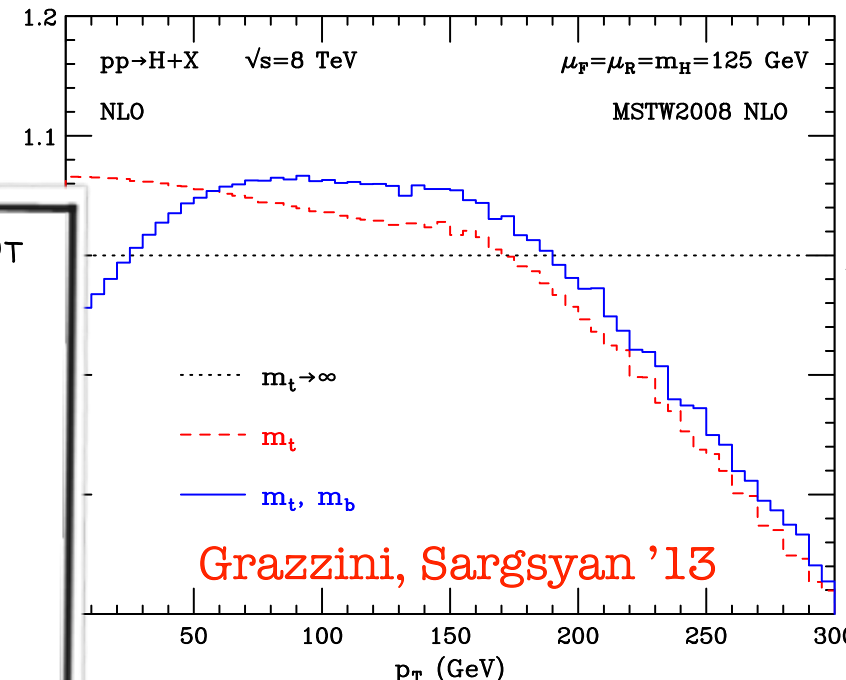
cut open the top loops

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

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

× 1000 reduction

Grojean, Salvioni, Schlaffer, Weiler '13



Grazzini, Sargsyan '13

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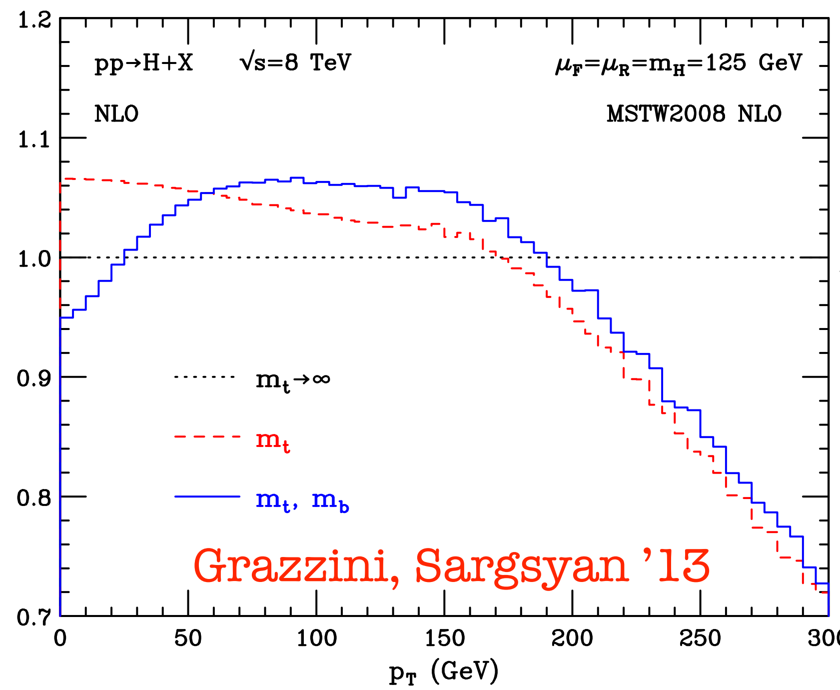

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Harlander et al '12

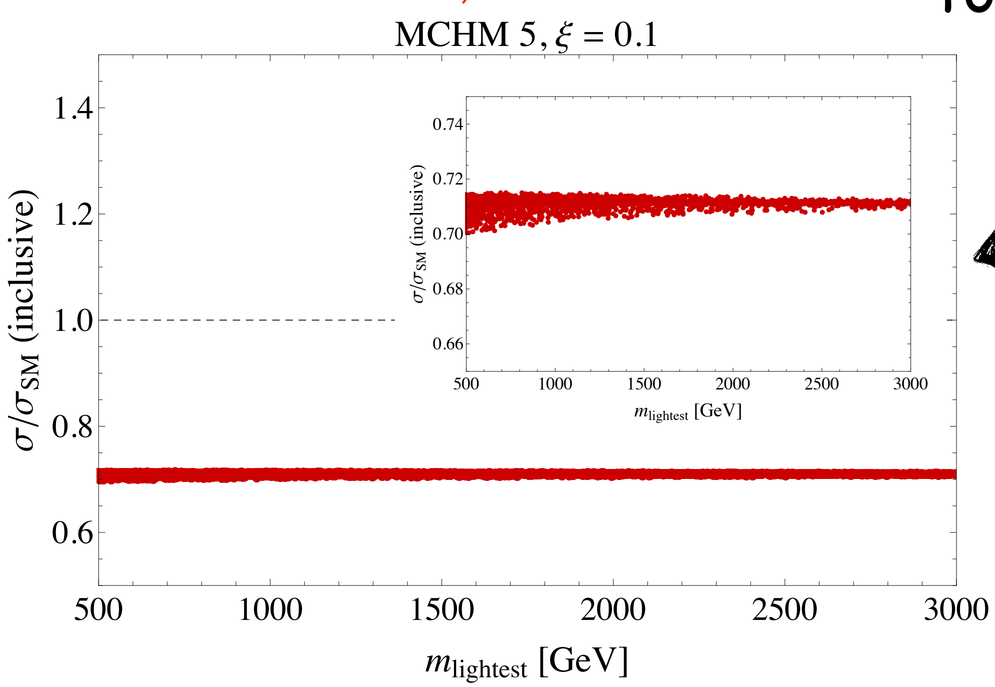
the high p_T tail
is tens' % sensitive
to the mass of top

Composite Higgs Model

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

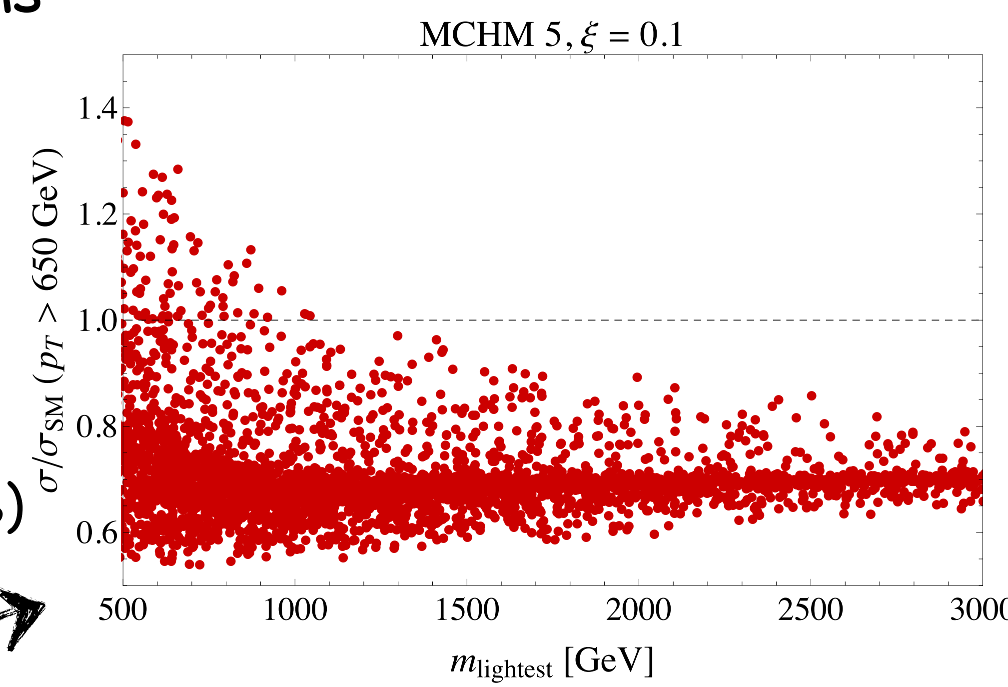
top partners contributions

Grojean, Salvioni, Schlaffer, Weiler '13



inclusive rate: O(%)

with high-p_T cut: O(x10'%)



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

Boosted Higgs

see also Azatov, Paul '13

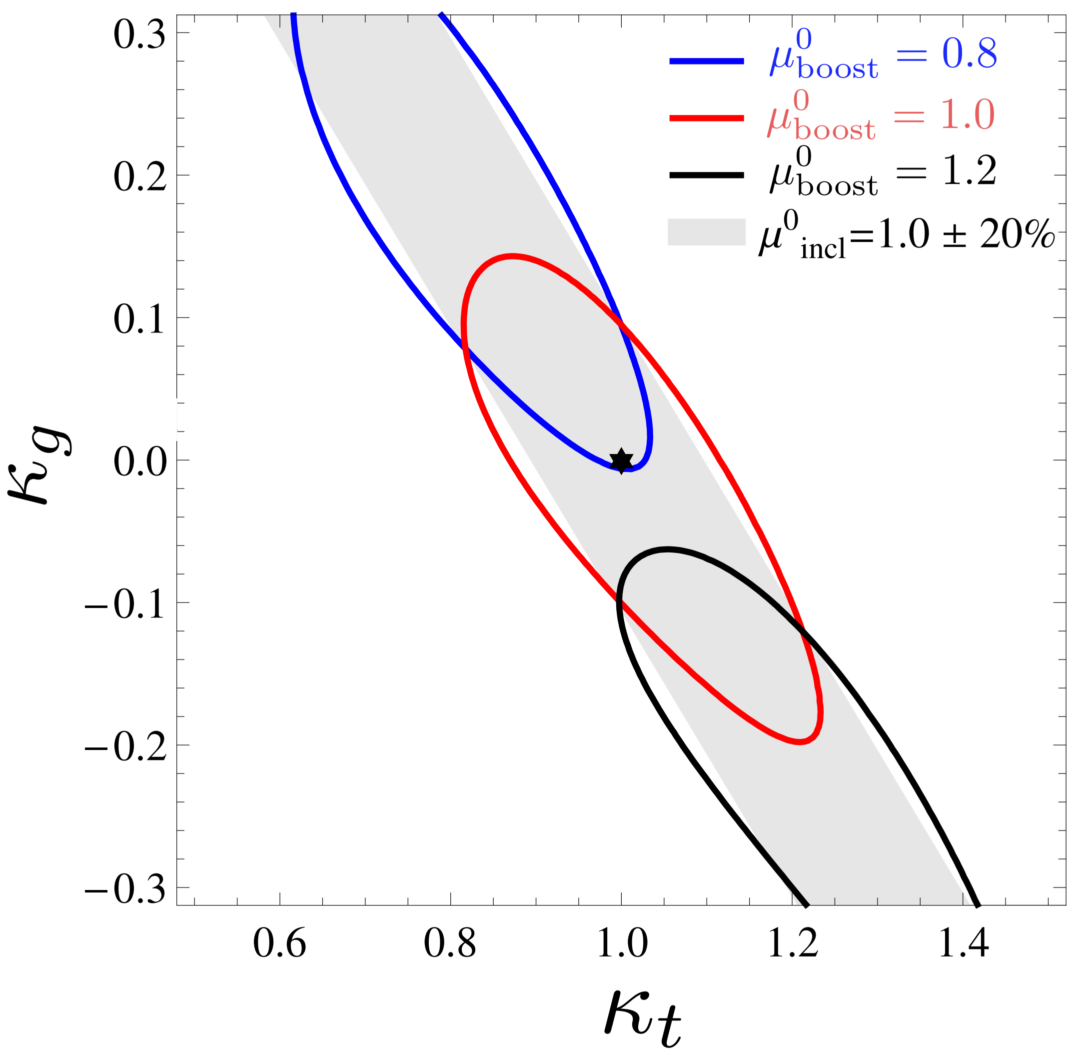
Grojean, Salvioni, Schlaffer, Weiler '13

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

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

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

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



10-20% precision on κ_t

⇓ ⇓

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

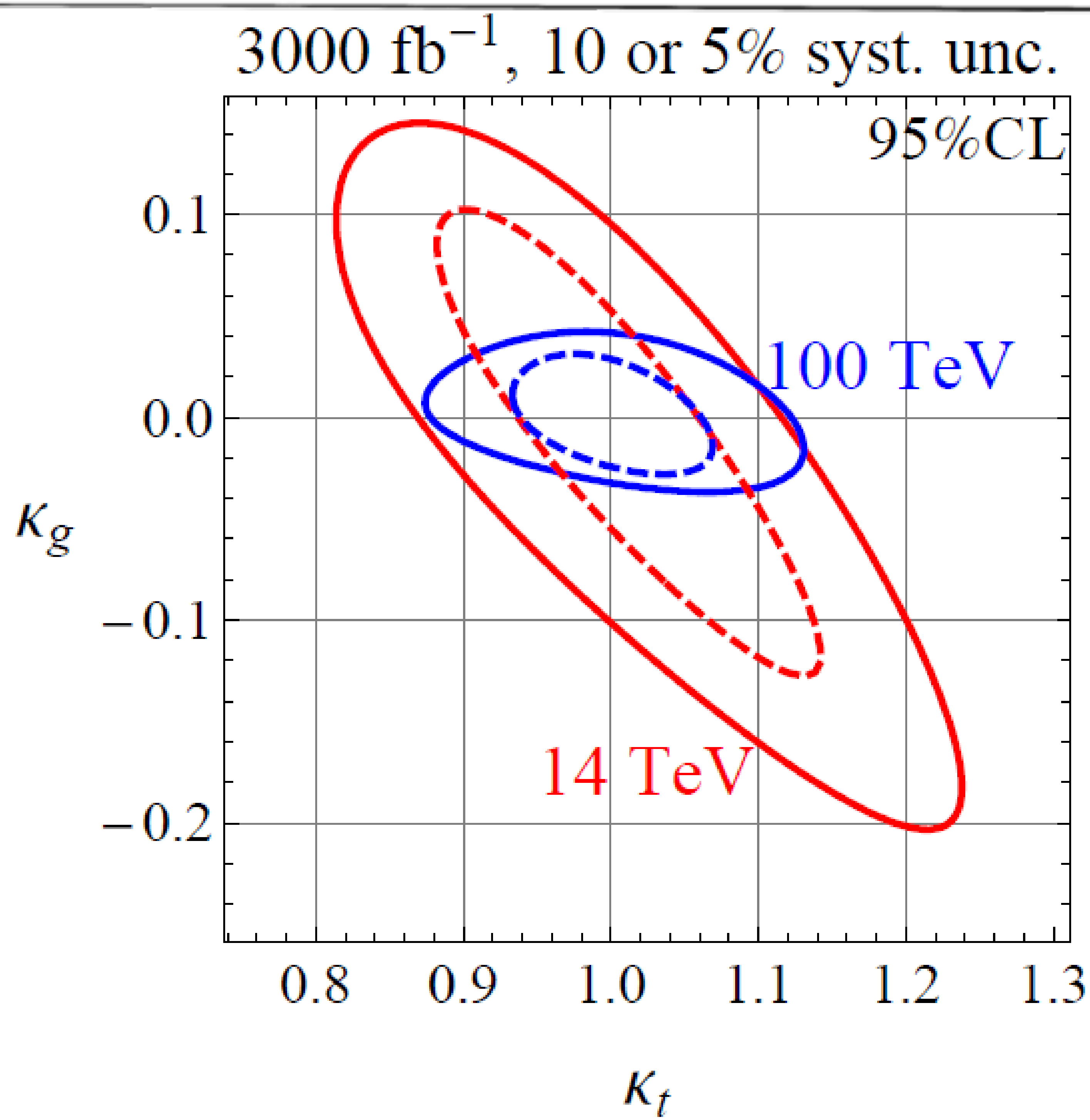
Are the NLO_m QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: N^3LO_∞ for inclusive xs or NLO_{mt} for pT spectrum?

Boosted Higgs

see also Azatov, Paul '13

Grojean, Salvioni, Schlaffer, Weiler '13

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



A perfect case for a very energetic machine

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

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

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

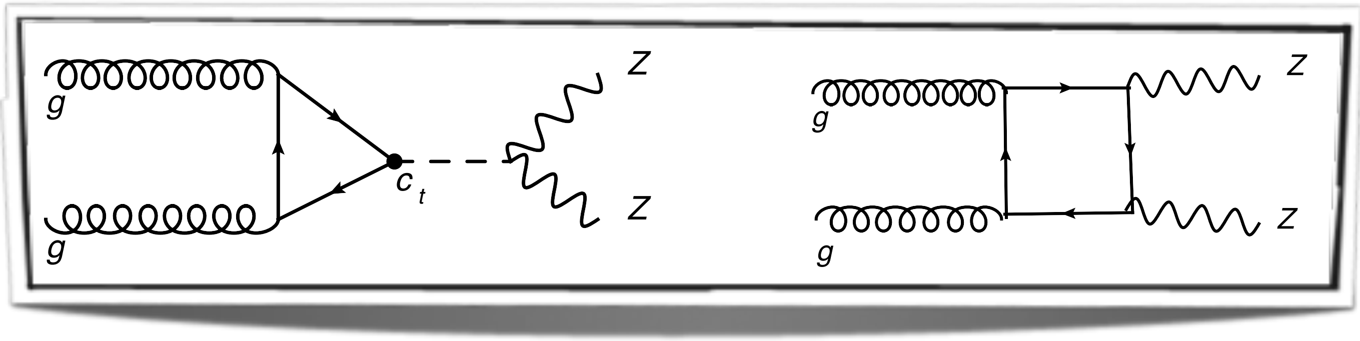
$$\mathcal{R}_{100} = \frac{\sigma(p_T > 2000\text{ GeV})}{\sigma(p_T > 500\text{ GeV})}$$

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

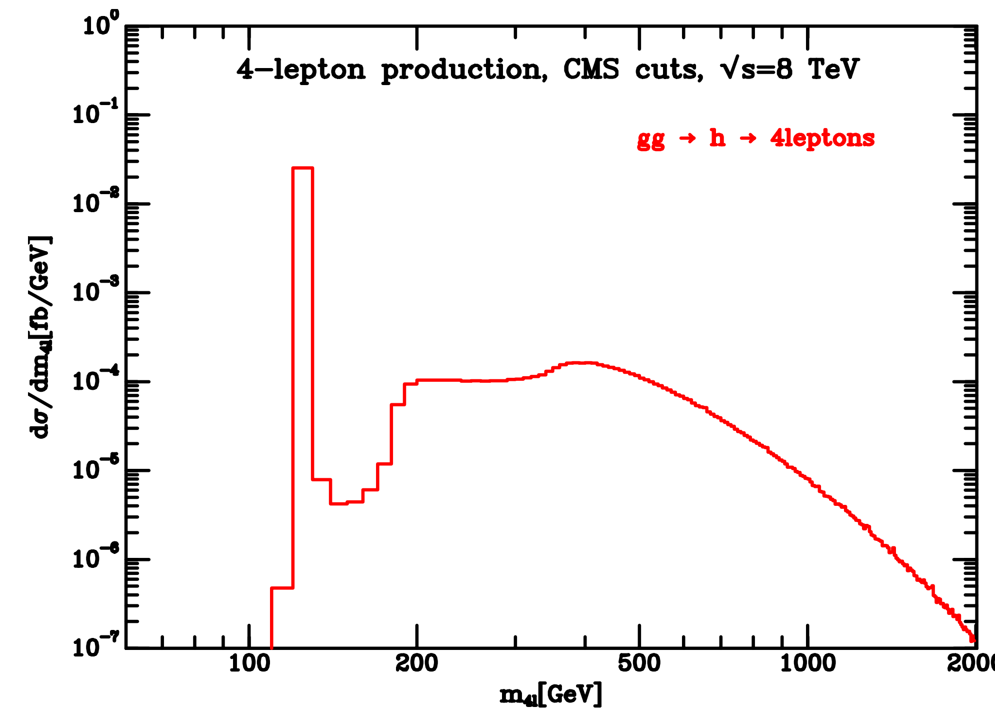
Off-shell Higgs: $gg \to h^* \to ZZ \to 4l$

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

Glover, van der Bij '89



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



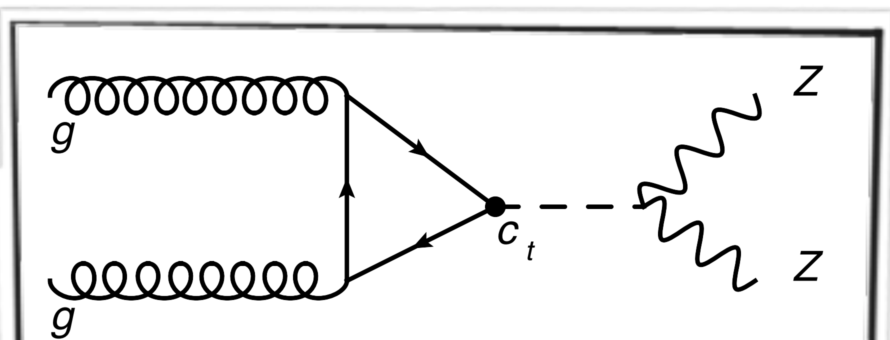
SM: cancelation forced by unitarity

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

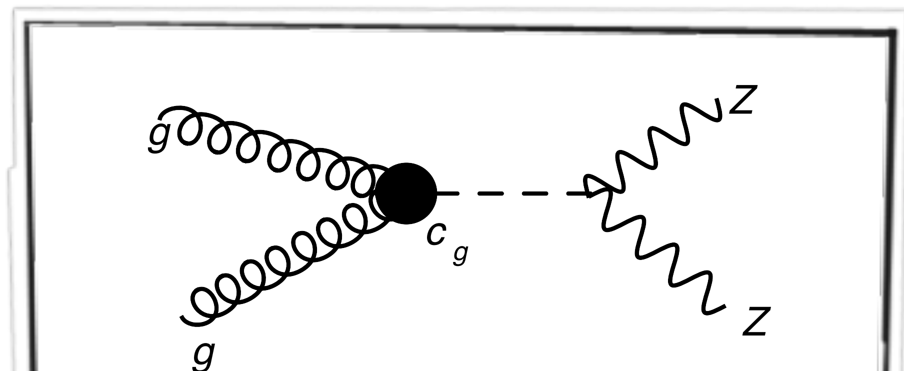
Azatov, Grojean, Paul, Salvioni '14

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 $\sqrt{s}$



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

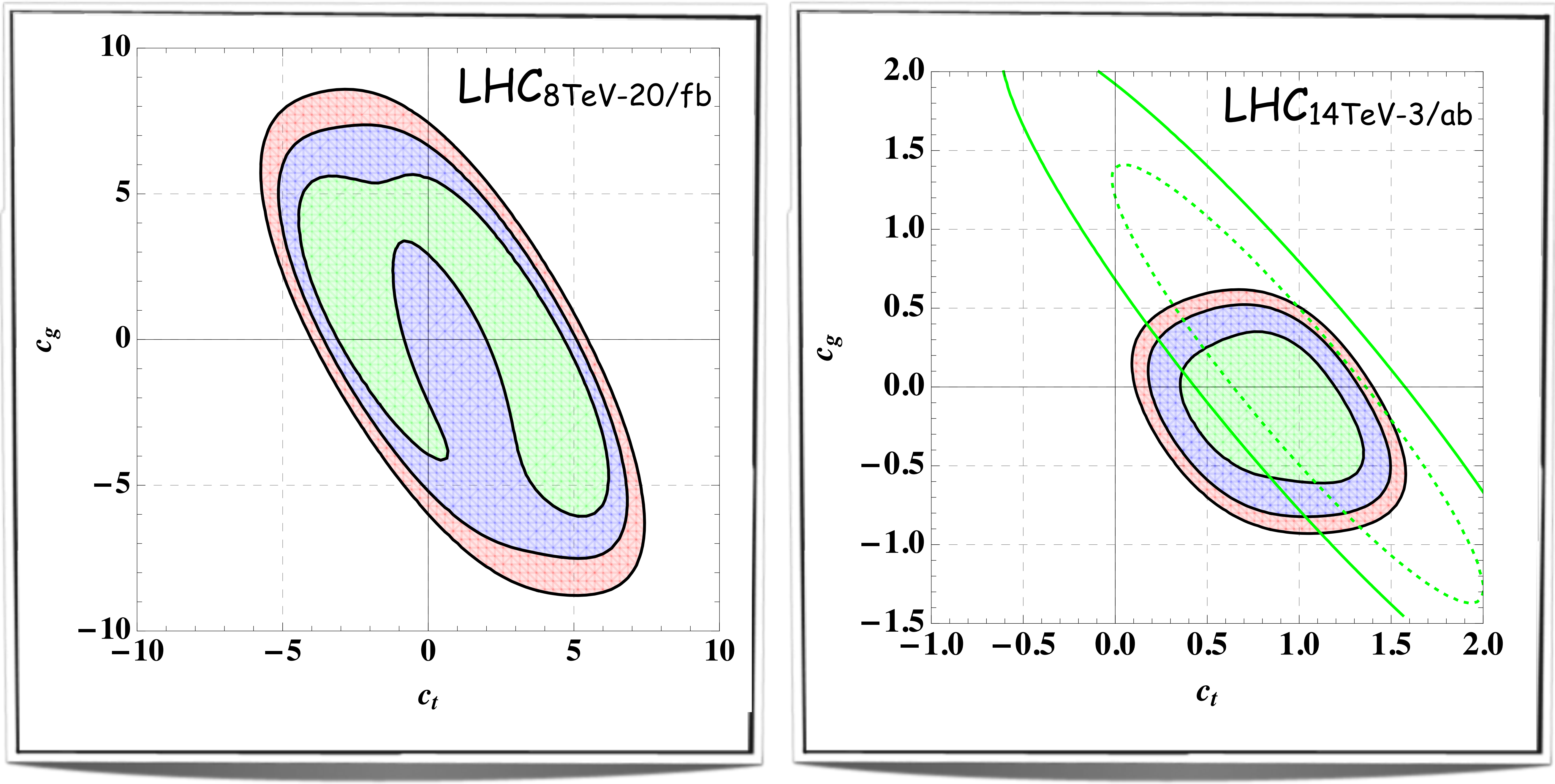


$$\mathcal{M}^{++00}_{c_g} \sim \hat{s}$$

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

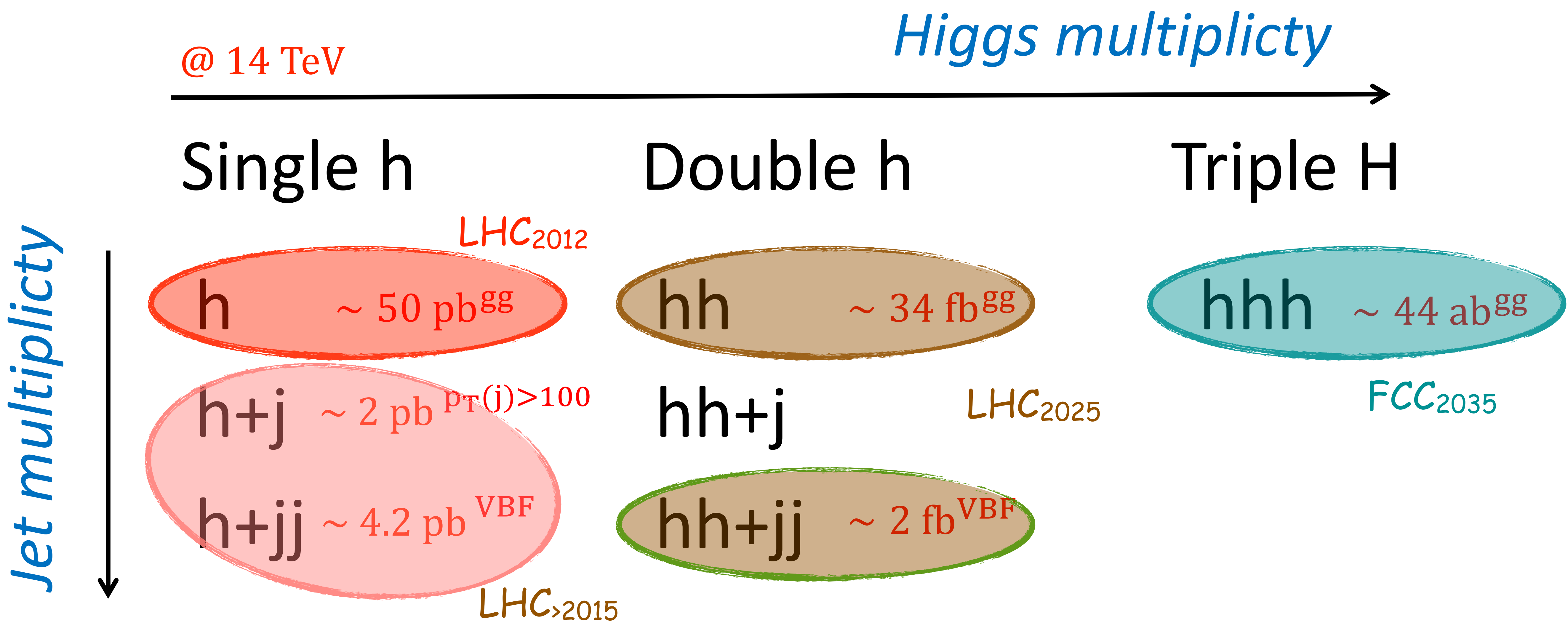
off-shell effects enhanced by the particular couplings of H to V_L

Azatov, Grojean, Paul, Salvioni '14



Beyond single Higgs processes

Producing one Higgs is good. Producing H+X is better



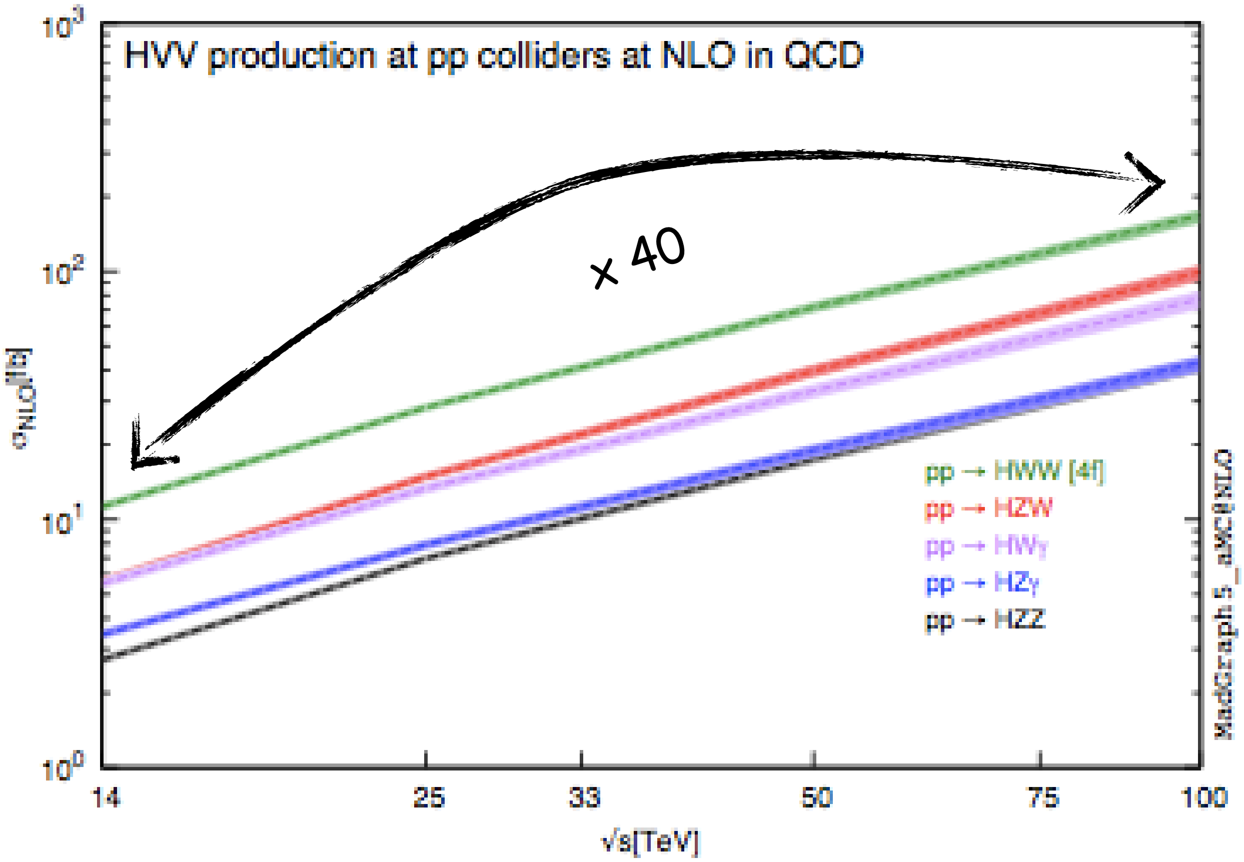
- also roughly indicates possible initial states/related kinematics
- Jet multiplicity might be replaced with V=W,Z, top, etc…

(adapted from M. Son@Planck2014)

Beyond single Higgs processes

Producing one Higgs is good. Producing H+X is better
A long term plan?

Higgs-diboson associated production

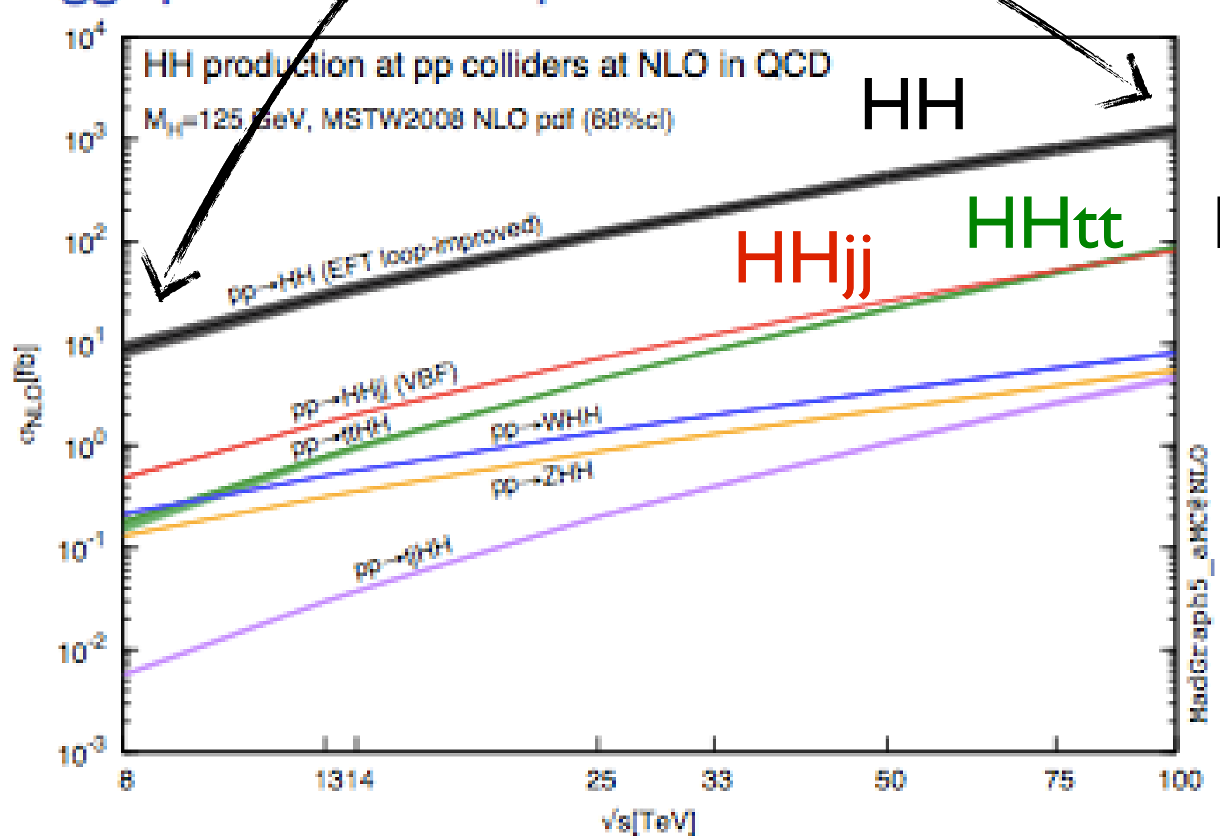


100 fb

FCC = H+X factory

× 100-1000

Higgs-pair associated production



1000 fb
100 fb

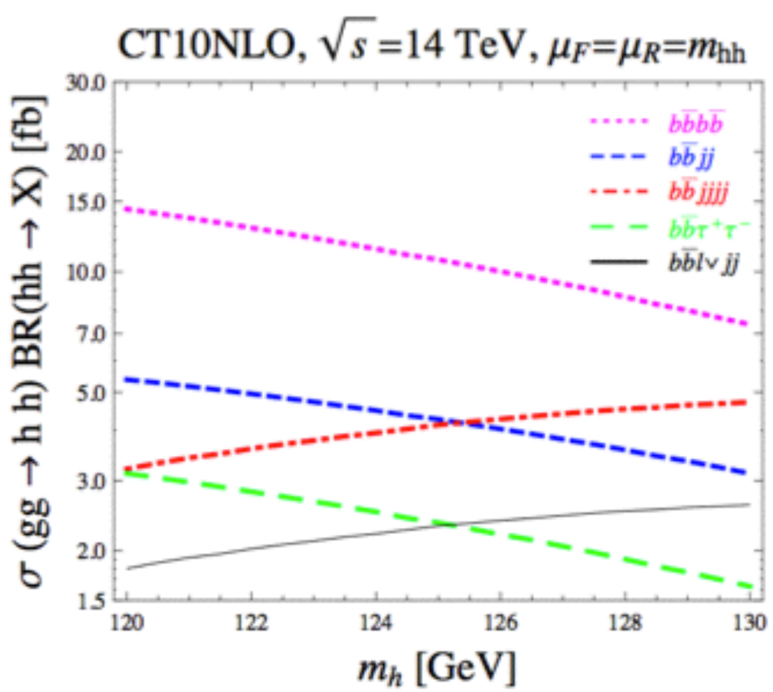
(Plots from P. Torrielli and MLM, CERN'14)

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		

Higgs self-coupling

The Higgs self-coupling plays important roles

1) controls the stability of the EW vacuum

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

Does it need to be measured with high accuracy?

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

Higgs self-coupling prospects

	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

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

M. Son, FCC@Washington '15

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

SM

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

EWSB W/O H^2

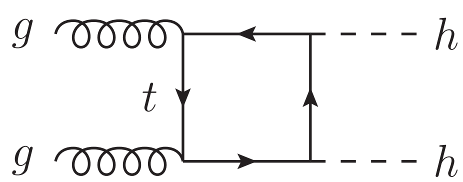
$$V = -\lambda |H|^4 + \frac{1}{\Lambda^2} |H|^6 \quad \Rightarrow \quad V(h) = \frac{1}{2} m_h^2 h^2 + \frac{1}{6} \frac{7 m_h^2}{v} h^3 + \ldots$$

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

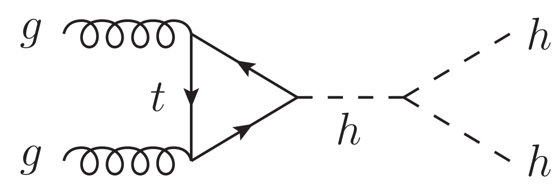
Grojean, Servant, Wells '04

Goertz '15

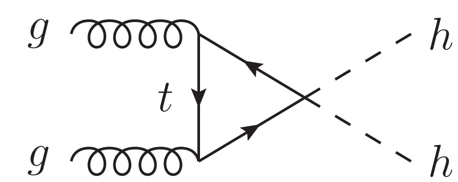
HH production as a probe of HE couplings



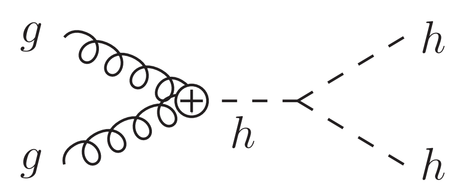
$\sim c_t^2 \times const.$



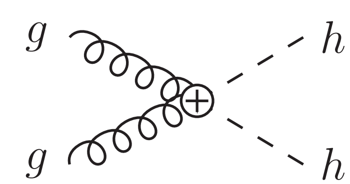
$\sim c_t c_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$



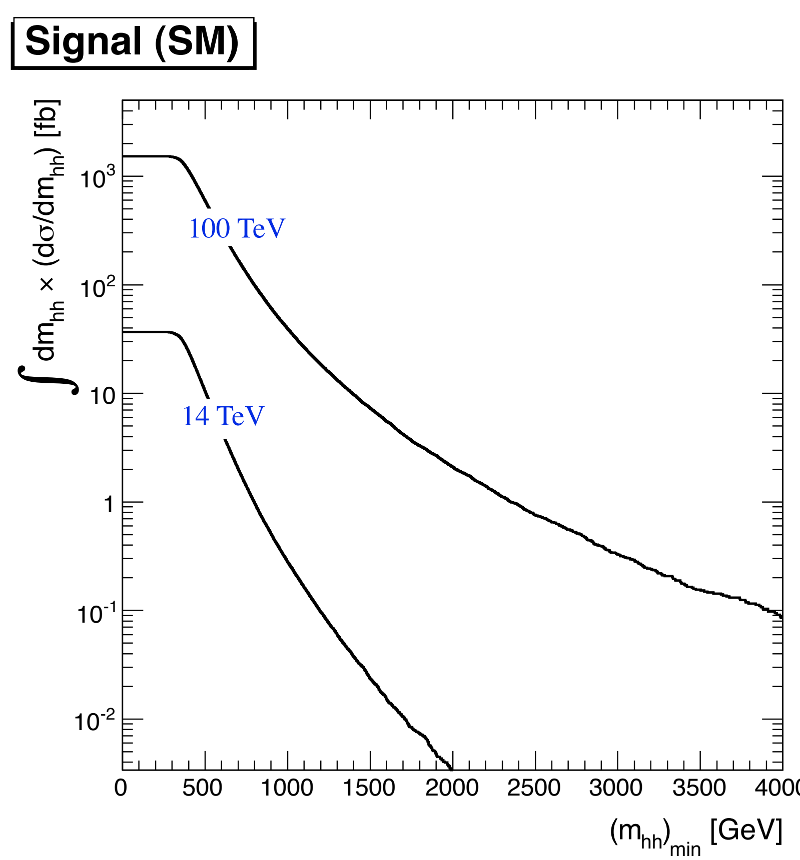
$\sim c_{2t} \times \log^2\left(\frac{m_t^2}{\hat{s}}\right)$

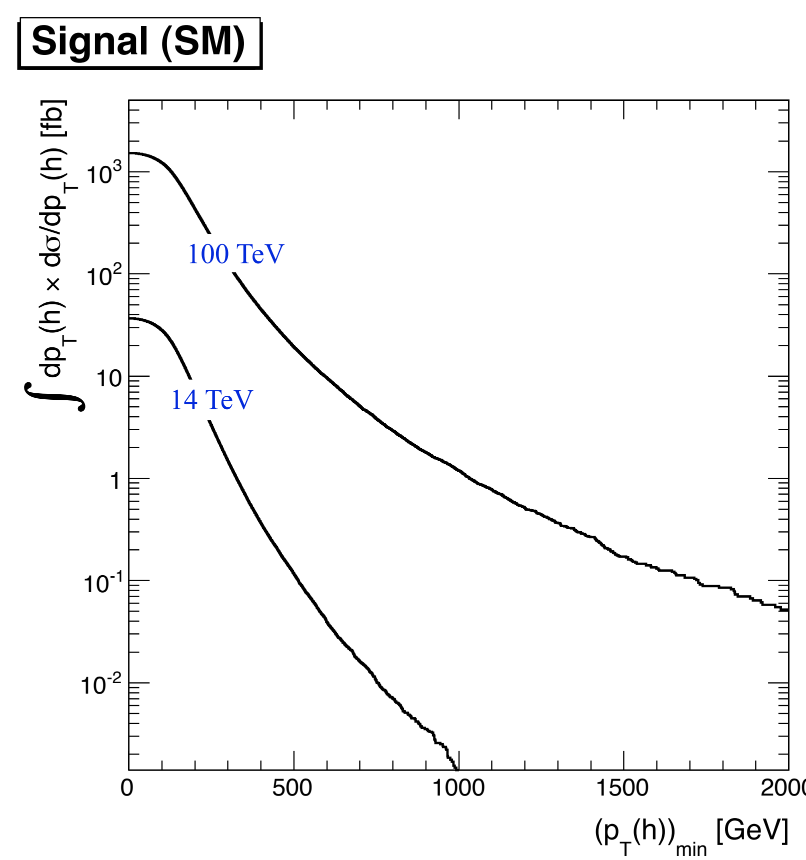


$\sim c_g c_3 \frac{\alpha_s}{4\pi} \times const.$



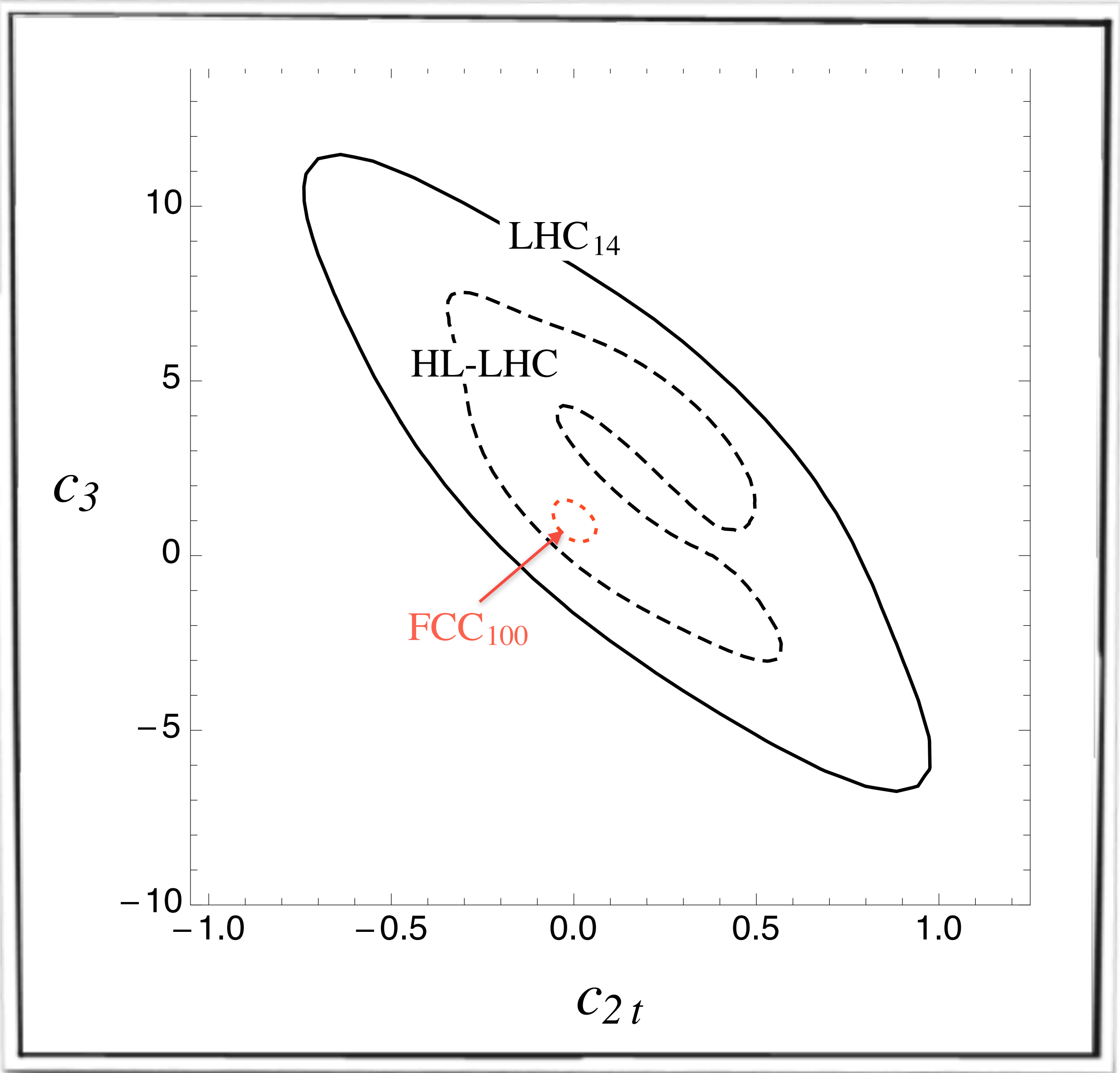
$\sim c_{2g} \frac{\alpha_s}{4\pi} \frac{\hat{s}}{v^2}$

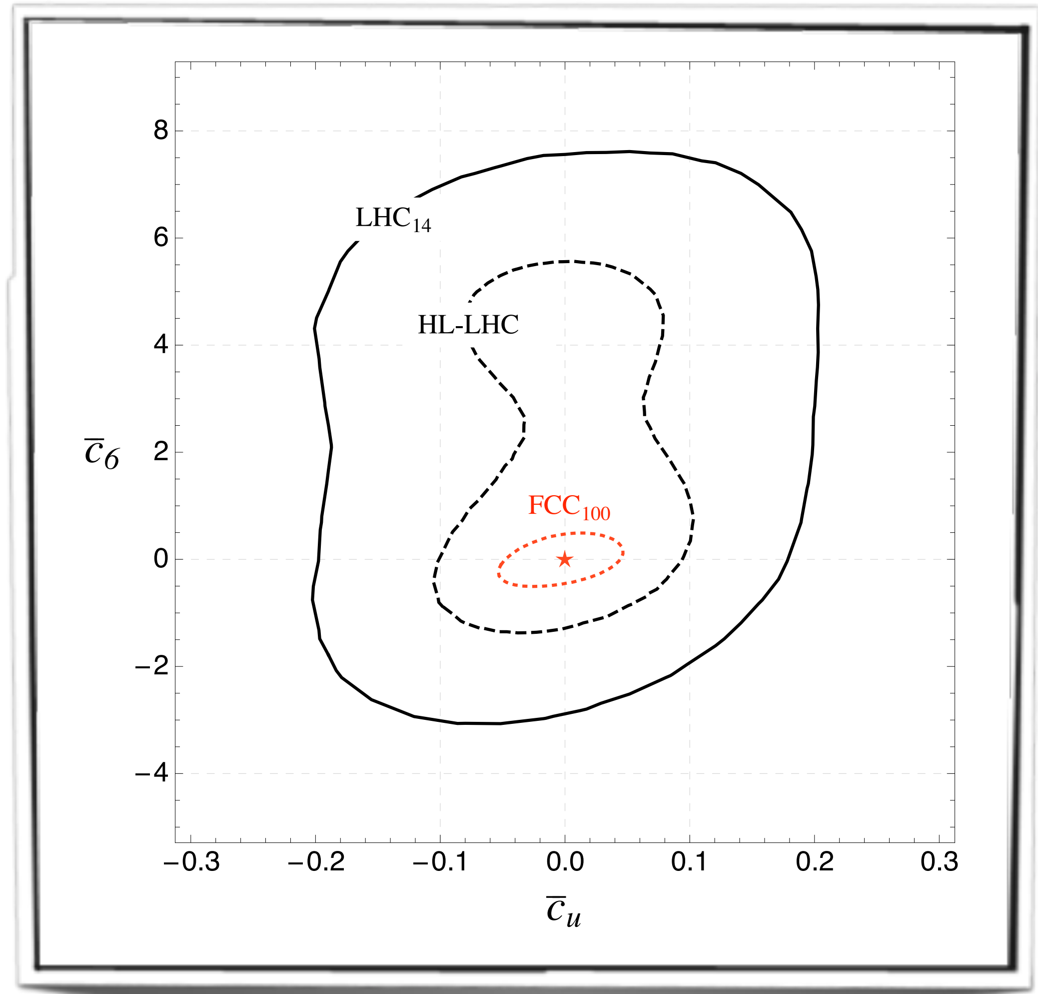




Azatov, Contino, Panico, Son '15

HH production as a probe of HE couplings





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

4

Higgs and New Physics

Higgs & New Physics

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

NP

typical mass scale

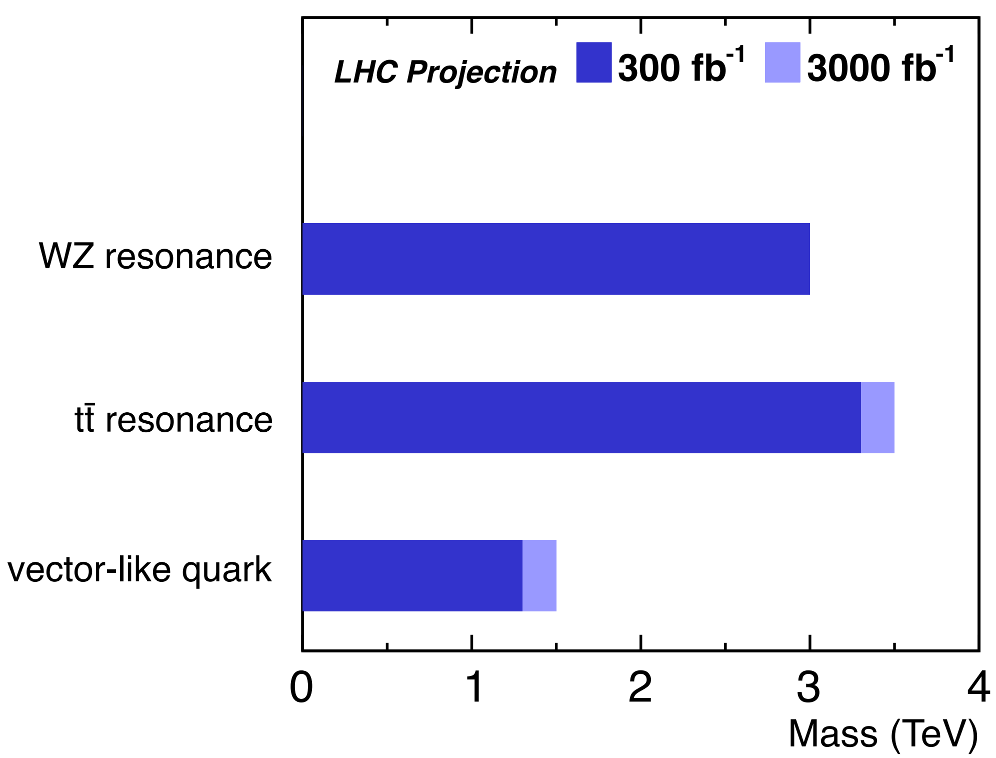
M = g_* f

SM

EW scale v=246GeV

g, g', y_t

g_{SM}^2/g_*



LHC direct search

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

Which one is doing best?
it depends on value of g_*

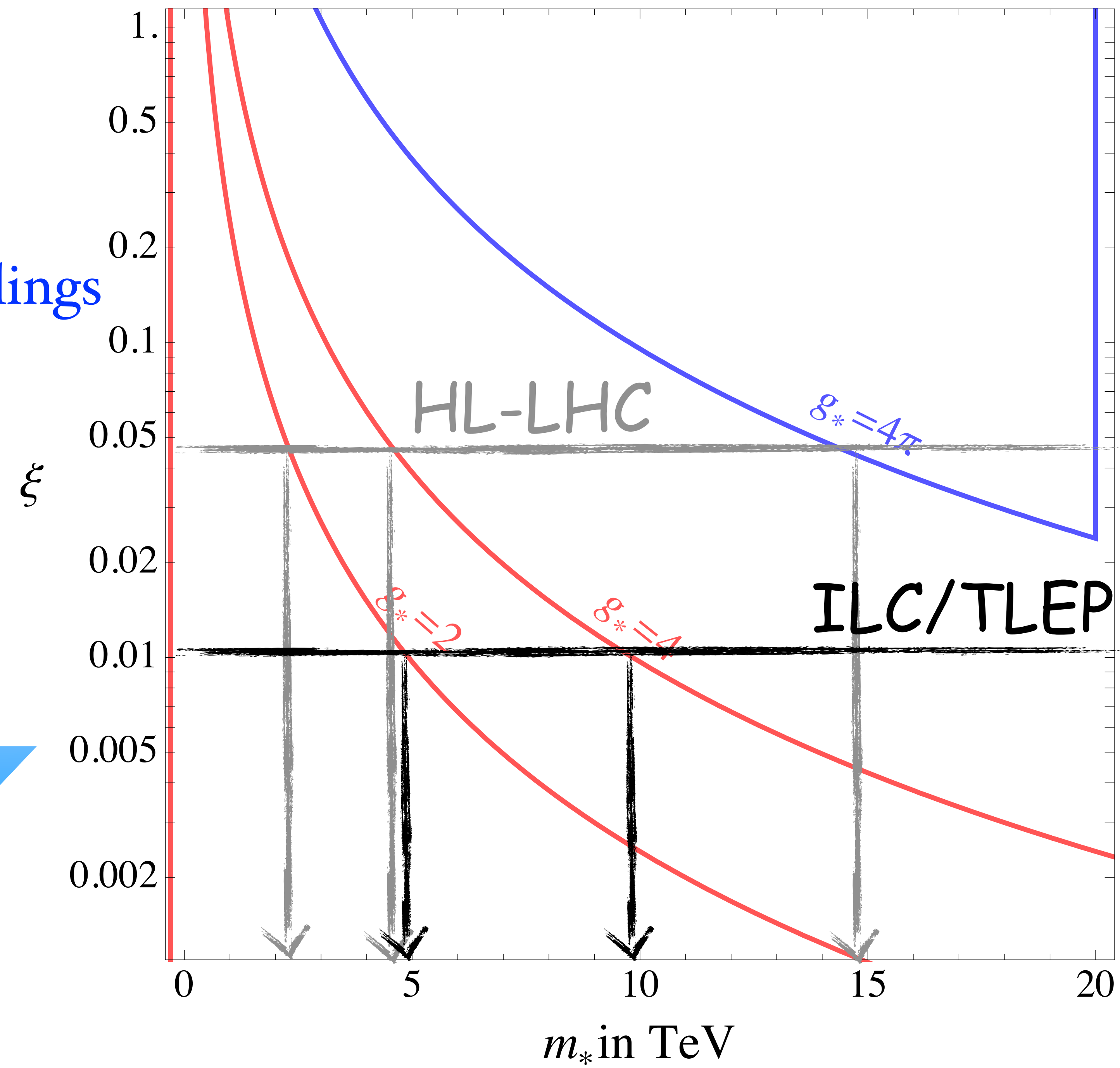
Higgs & New Physics

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

Mass reach:

a deviation in Higgs couplings also teaches us on the maximum mass scale to search for!
e.g. 10% deviation ⇛ m_V < 10TeV
i.e. resonance within the reach of FCC-hh

Higgs couplings



Rattazzi, BSM@100TeV, CERN '14

direct searches

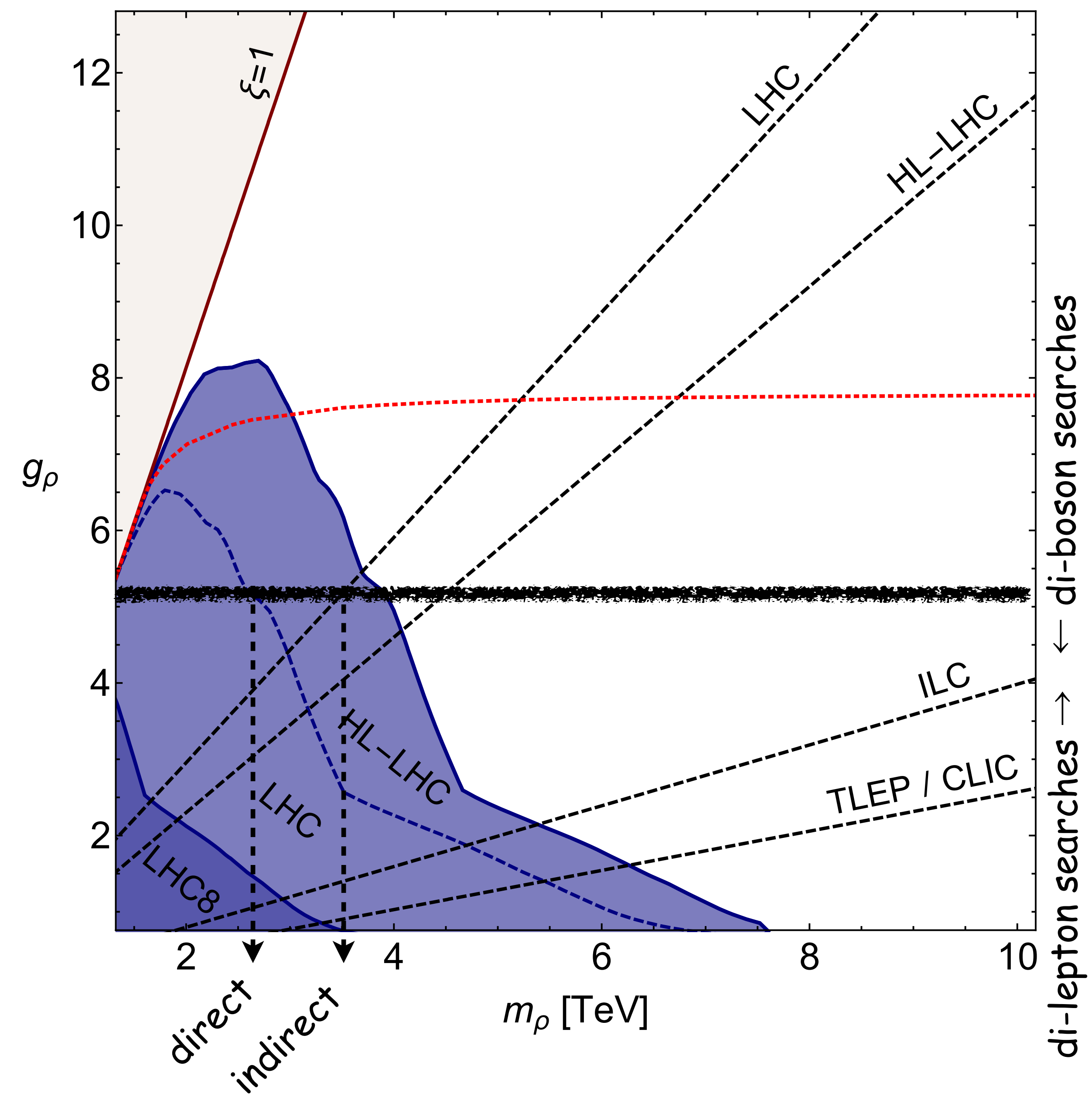
Higgs & New Physics

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

Torre, Thamm, Wulzer '15

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

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



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

e.g.
indirect searches at LHC over-perform direct searches for g > 4.5
indirect searches at ILC over-perform direct searches at HL-LHC for g > 2

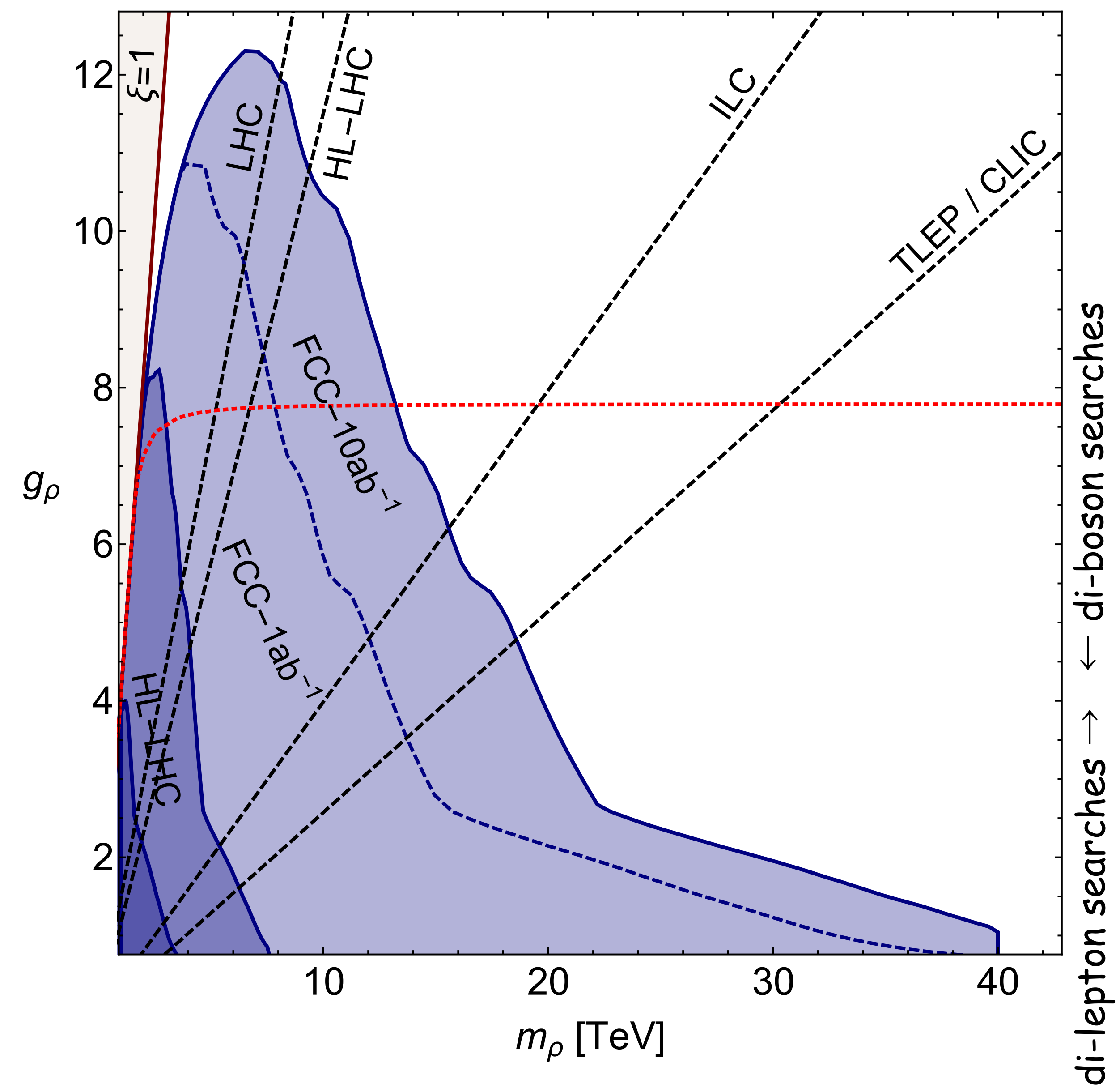
Higgs & New Physics

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

Torre, Thamm, Wulzer '15

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

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



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

e.g.

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

indirect searches at ILC over-perform direct searches at HL-FCChh for g > 6

5

What if we were wrong in expecting TeV-scale New Physics?

Naturalness & TeV scale new physics

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections
(others are not necessarily theoretically inconsistent
but they require some conspiracy at different scales)

Field	Symmetry as $m \to 0$	Implication
Spin-1/2 $m\Psi\bar{\Psi}$	$\Psi \to e^{i\theta}\Psi$ $\bar{\Psi} \to e^{-i\theta}\bar{\Psi}$ (chiral symmetry)	$\delta m \propto m$ **Natural!**
Spin-1 $m^2 A_\mu A^\mu$	$A_\mu \to A_\mu + \partial_\mu \alpha$ (gauge invariance)	$\delta m \propto m$ **Natural!**

courtesy to N. Craig @ Blois '15

The Higgs mass in the SM doesn't break any (quantum*) symmetry

* it does break classical scale invariance, as the running of the gauge couplings does too!

Naturalness principle @ work

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections
(others are not necessarily theoretically inconsistent
but they require some conspiracy at different scales)

Beautiful examples of naturalness to understand the need of "new" physics

see for instance Giudice '13 (and refs. therein) for a recent account

- the need of the positron to screen the electron self-energy: $\Lambda < m_e/\alpha_{\rm em}$
- the rho meson to cutoff the EM contribution to the charged pion mass: $\Lambda^2 < \delta m_\pi^2/\alpha_{\rm em}$
- the kaon mass difference regulated by the charm quark: $\Lambda^2 < \dfrac{\delta m_K}{m_K} \dfrac{6\pi^2}{G_F^2 f_K^2 \sin^2\theta_C}$
- the light Higgs boson to screen the EW corrections to gauge bosons self-energies
- ...
- new physics at the weak scale to cancel the UV sensitivity of the Higgs mass?

The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac:
hierarchies are induced/created by the time evolution/the age of the Universe

Graham, Kaplan, Rajendran '15

- Higgs mass-squared promoted to a field
- The field evolves in time in the early universe
- The mass-squared relaxes to a small negative value
- The electroweak symmetry breaking stops the time-dependence

Self-organized criticality

when the Higgs mass becomes negative, it
back-reacts and generates a potential barrier
that stops the evolution of the scanning field

Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics

see also Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ slowly rolling field (inflation provides friction) that scans the Higgs mass

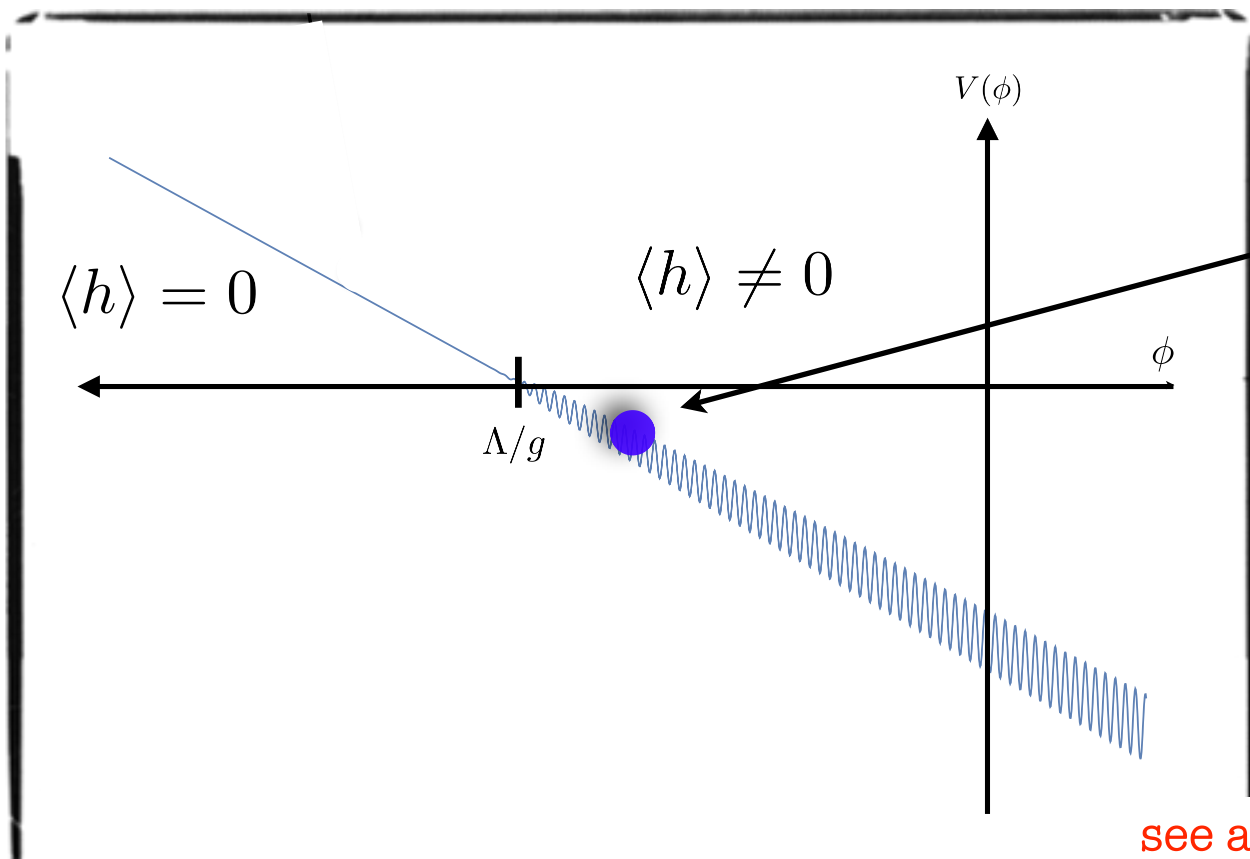
$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2+\Lambda^4 V\left(\frac{g\phi}{\Lambda}\right)+\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Higgs mass depends on ϕ

potential needed to force ϕ to roll-down in time (during inflation)

axion-like coupling that will seed the potential barrier stopping the rolling when the Higgs develops its vev

$$\Lambda^3_{\rm QCD}\, h\, \cos\frac{\phi}{f}$$



see also Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

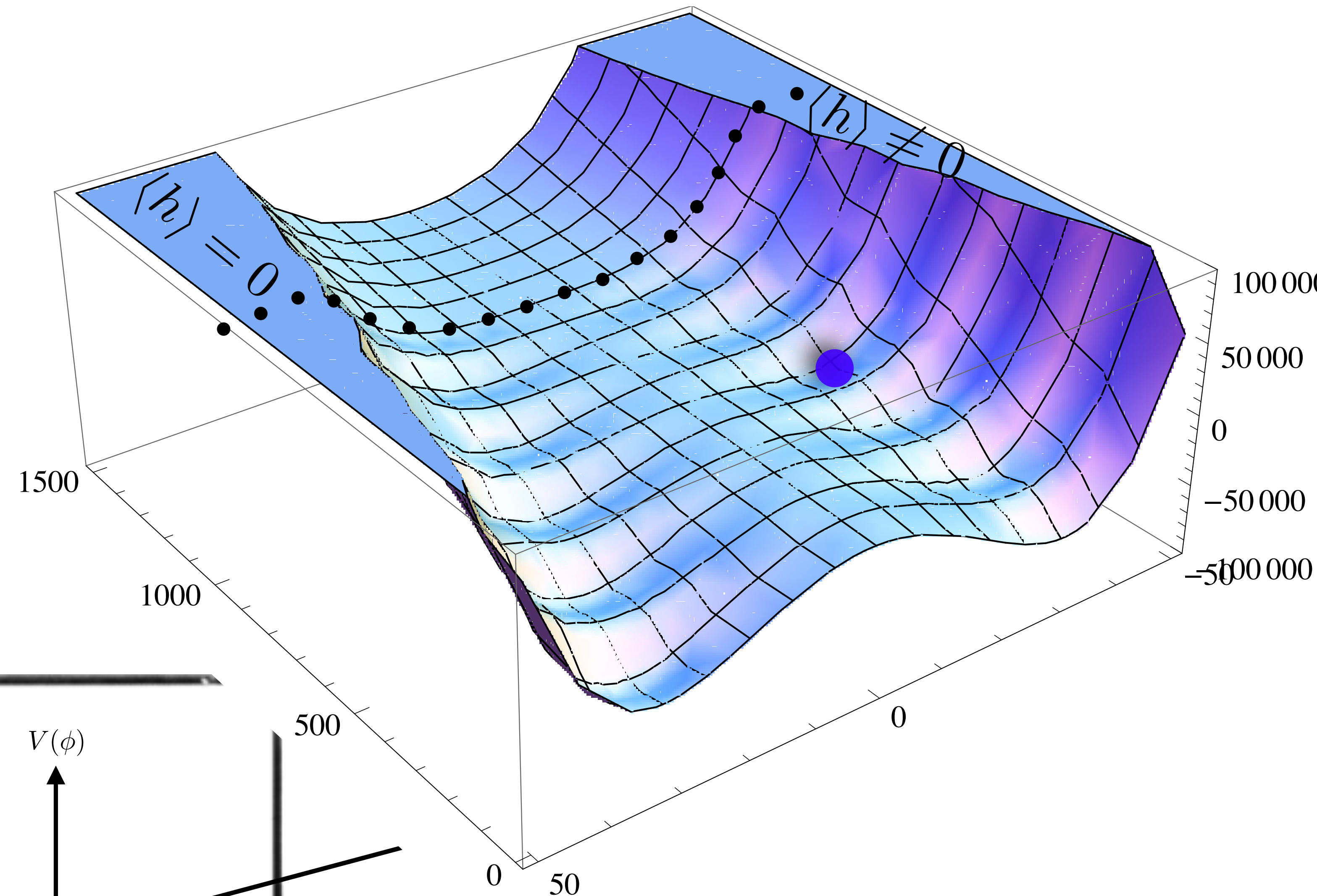
Higgs-axion cosmological relaxation

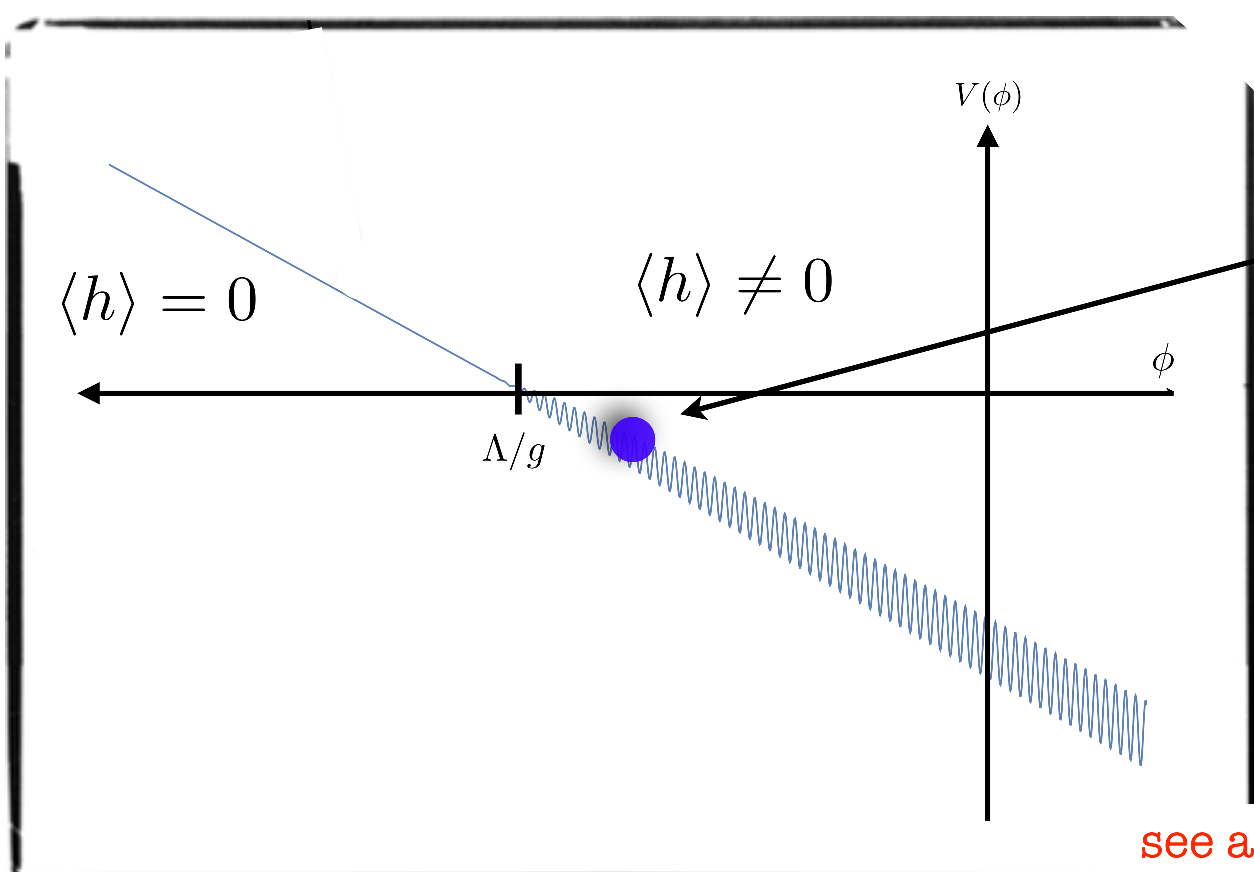
Graham, Kaplan, Rajendran '15

ϕ

$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)$$

Higgs mass depends on ϕ





If ϕ continues rolling, the Higgs vev increases, the potential barrier increases and ultimately prevents ϕ from rolling down further

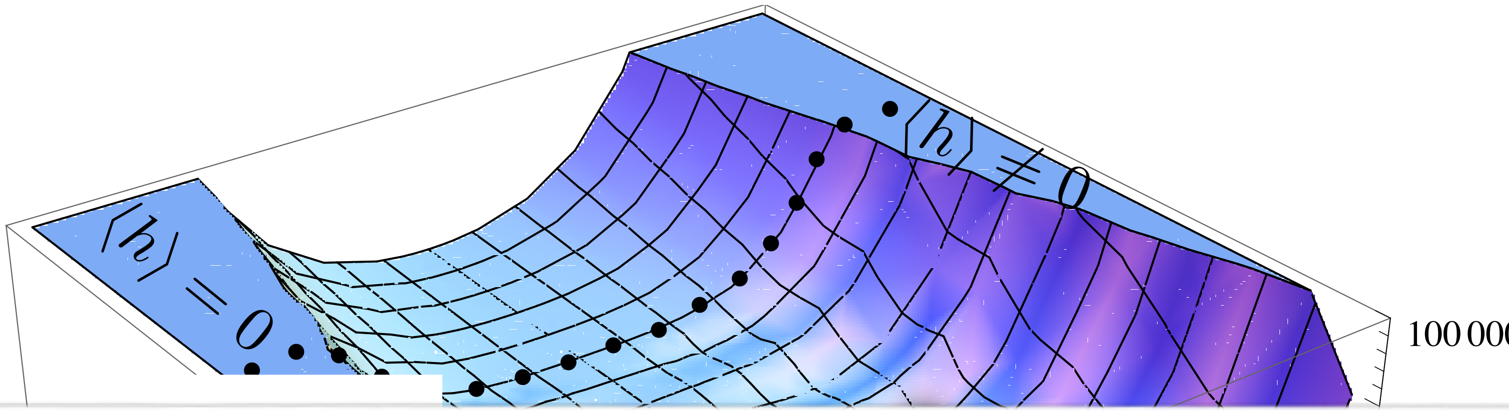
see also Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ

$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)$$



Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics

~interesting cosmology signatures~

- BBN constraints
- decaying DM signs in γ-rays background
- ALPs
- superradiance

~interesting signatures @ SHiP~

- production of light scalars by B and K decays

see also Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

Phenomenological signatures

Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

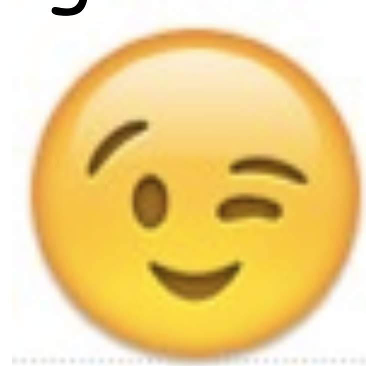
only BSM physics below Λ

two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim (10^{-20} - 10^{2})\,\mathrm{GeV}$$

$$m_\sigma \sim (10^{-45} - 10^{-2})\,\mathrm{GeV}$$

interesting signatures in cosmology



Conclusions

Cornell University Library

arXiv.org > physics > arXiv:1503.07735

Physics > Popular Physics

Physics in 100 Years

Frank Wilczek

(Submitted on 26 Mar 2015)

- *What are the weak points in our current understanding and practices?*
- *What are the growth areas in technique and capability?*
- *Where are the sweet spots where those two meet?*

More than ever: importance of the synergy and complementarity of the experimental programme

F. Gianoti EPS '15

Main questions and main approaches to address them

	High-E colliders	Dedicated high-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
H, EWSB	x	x		x	
Neutrinos	x (ν_R)		x	x	x
Dark Matter	x			x	x
Flavour, CP, matter/antimatter	x	x	x	x	x
New particles, forces, symmetries	x	x		x	
Universe acceleration					x

Combination of these complementary approaches is crucial to explore the largest range of E scales (directly and indirectly) and couplings, and properly interpret signs of new physics → hopefully build a coherent picture of the underlying theory.