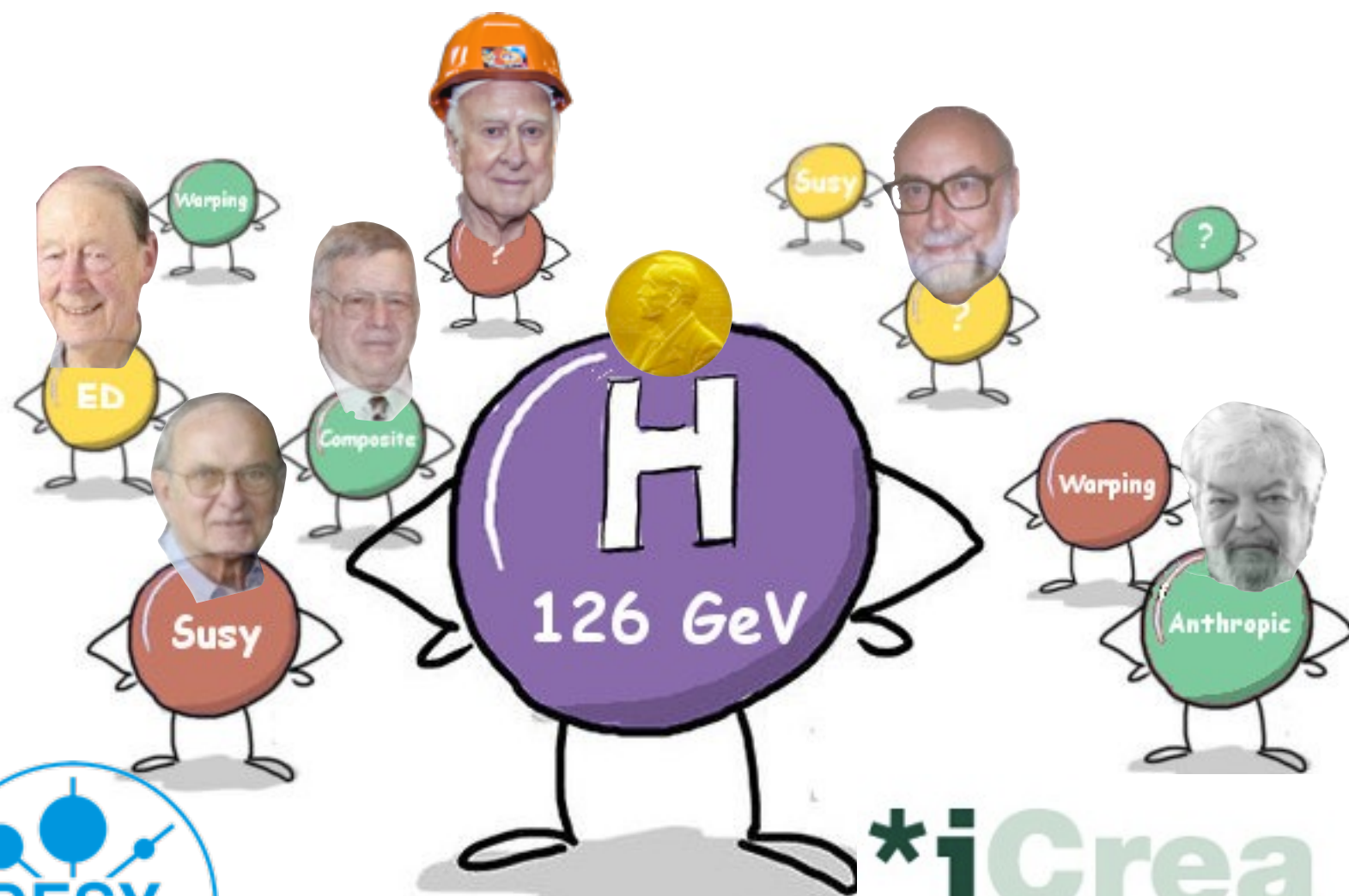


Status & Future Prospects in Higgs Physics



P. Cámara/C. Grojean

*IFIC, Valencia
May 14, 2015*

Christophe Grojean

DESY (Hamburg)
ICREA@IFAE (Barcelona)
(christophe.grojean@cern.ch)



***iCrea**
INSTITUCIÓ CATALANA DE
RECERCA I ESTUDIS AVANÇATS

HEP with a Higgs boson

"If you don't have the ball, you cannot score"

Now with the Higgs boson in their hands,
particle physicists can... play as well as Germans against Brazilians



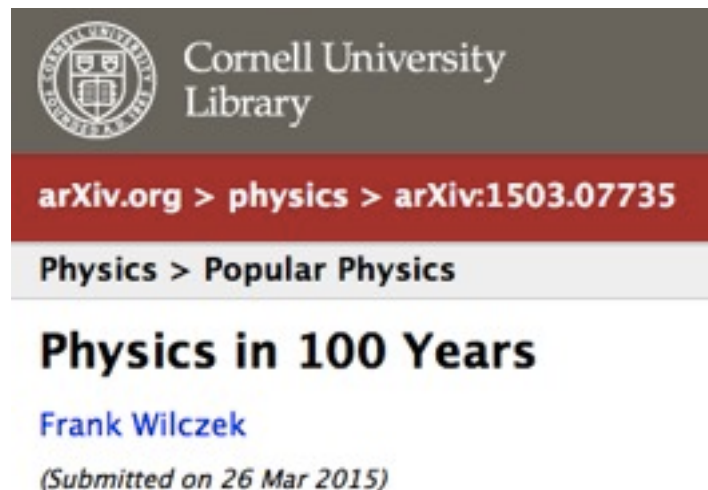
Profound change in paradigm:

missing SM particle $\Rightarrow$ tool to explore SM and venture into physics landscape beyond

A unique moment in the history of physics

The Higgs discovery is the triumph of XXth 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} ?)



*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:

- 1) Only a description of EW symmetry breaking, not an explanation
furthermore Higgs field requires a delicate cancelation of large radiative corrections
- 2) No place for the particle(s) that make up the cosmic DM
- 3) Does not explain the asymmetry matter-antimatter

A unique moment in the history of physics

The Higgs discovery is the triumph of XXth 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} ?)

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

The SM is not free of inadequacies:

- 1) Only a description of EW symmetry breaking, not an explanation
furthermore Higgs field requires a delicate cancelation of large radiative corrections
- 2) No place for the particle(s) that make up the cosmic DM
- 3) Does not explain the asymmetry matter-antimatter

HEP with a Higgs boson

The successes have been breathtaking:

- ▶ in $O(2)$ years, the Higgs mass has been measured to 0.2% (vs 1% for the 20-year old top)
- ▶ some of its couplings, e.g. κ_γ , have been measured with LEP accuracy (10^{-3})

Higgs agenda for the LHC-II, HL-LHC, ILC/CLIC, FCC, 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, naturalness, etc)

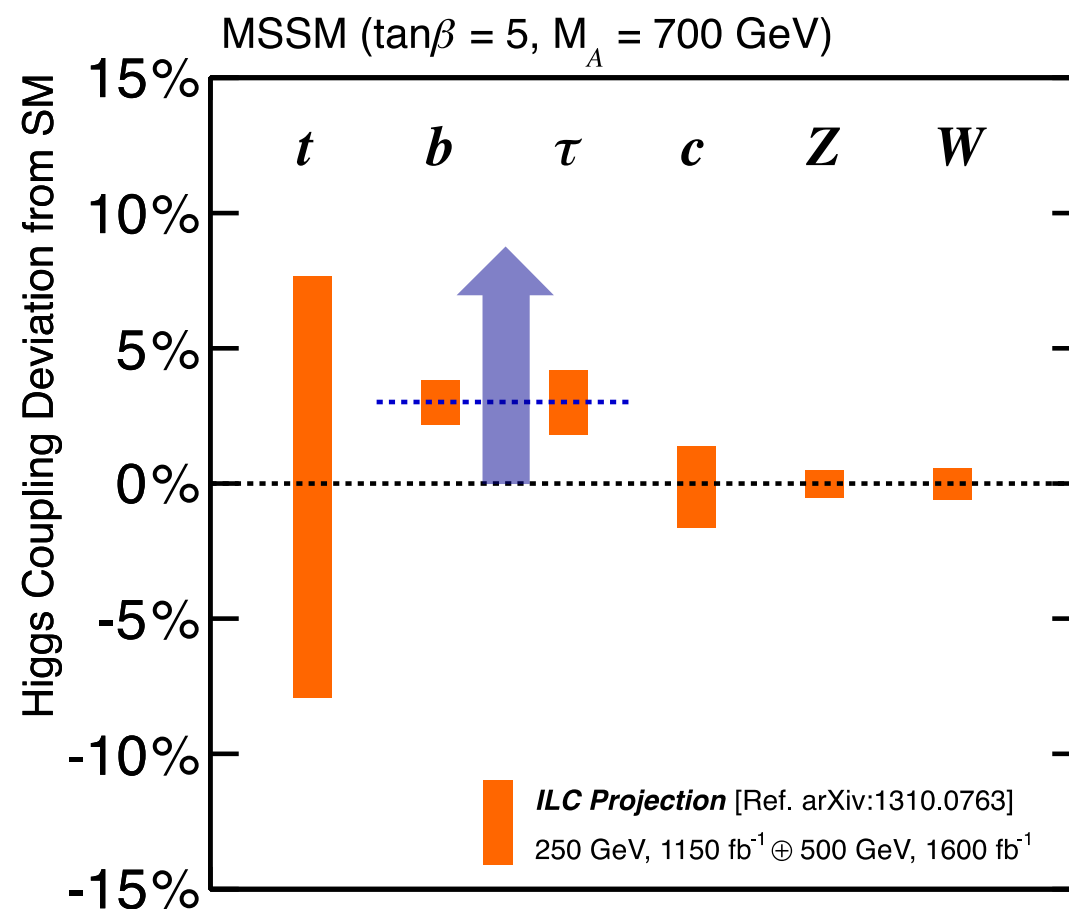
M.L. Mangano, Washington '15

- ▶ rare Higgs decays: $h \rightarrow \mu\mu$, $h \rightarrow \gamma Z$
- ▶ Higgs flavor violating couplings: $h \rightarrow \mu\tau$ and $t \rightarrow hc$
- ▶ Higgs CP violating couplings
- ▶ exclusive Higgs decays (e.g. $h \rightarrow J/\Psi + \gamma$) and measurement of couplings to light quarks
- ▶ exotic Higgs decay channels:
 - $h \rightarrow \cancel{E}_T$, $h \rightarrow 4b$, $h \rightarrow 2b2\mu$, $h \rightarrow 4\tau$, $2\tau2\mu$, $h \rightarrow 4j$, $h \rightarrow 2\gamma2j$, $h \rightarrow 4\gamma$, $h \rightarrow \gamma/2\gamma + \cancel{E}_T$,
 - $h \rightarrow \text{isolated leptons} + \cancel{E}_T$, $h \rightarrow 2l + \cancel{E}_T$, $h \rightarrow \text{one/two lepton-jet(s)} + X$, $h \rightarrow b\bar{b} + \cancel{E}_T$, $h \rightarrow \tau\tau + \cancel{E}_T \dots$
- ▶ searches for extended Higgs sectors (H , A , $H^\pm$, $H^{\pm\pm} \dots$)
- ▶ Higgs self-coupling(s)
- ▶ Higgs width
- ▶ Higgs/axion coupling?

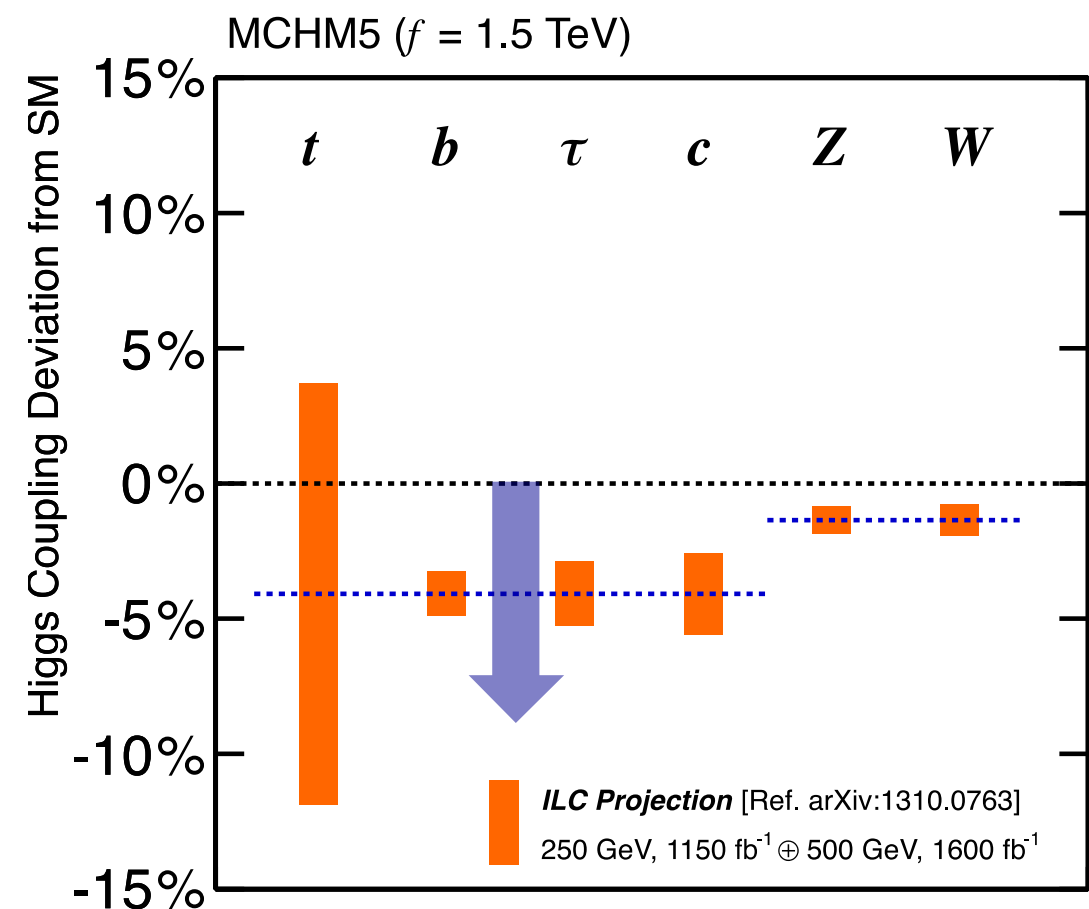
Higgs couplings and model discriminations

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

Supersymmetry (MSSM)



Composite Higgs (MCHM5)



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	$h\gamma\gamma$	$h\gamma Z$	hGG	h^3
MSSM	✓		✓	✓	✓	
NMSSM	✓	✓	✓	✓	✓	
PGB Composite	✓	✓		✓		✓
SUSY Composite	✓	✓	✓	✓	✓	✓
SUSY partly-composite			✓	✓	✓	✓
“Bosonic TC”						✓
Higgs as a dilaton			✓	✓	✓	✓

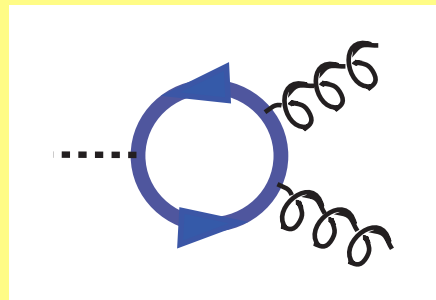
A. Pomarol, Naturalness '15

Higgs couplings and tests of naturalness

$$\delta m_H^2 = \overset{p=0}{\text{---}} \text{SM} \overset{p=0}{\text{---}} + \overset{p=0}{\text{---}} \text{New} \overset{p=0}{\text{---}} \sim m_H^2$$

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

charged particles *generically* neutral particles

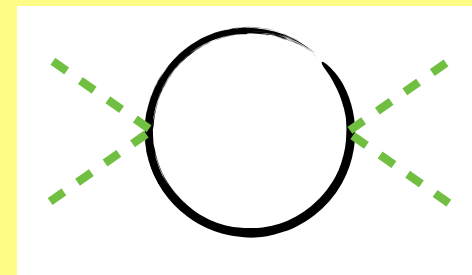


$$\frac{g_s^2 g_*^2}{16\pi^2} \frac{1}{m_*^2} |H|^2 G_{\mu\nu}^2 \quad \frac{e^2 g_*^2}{16\pi^2} \frac{1}{m_*^2} |H|^2 F_{\mu\nu}^2$$

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

Colorful naturalness probed @ LHC

Neutral naturalness (invisible?) @ LHC



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

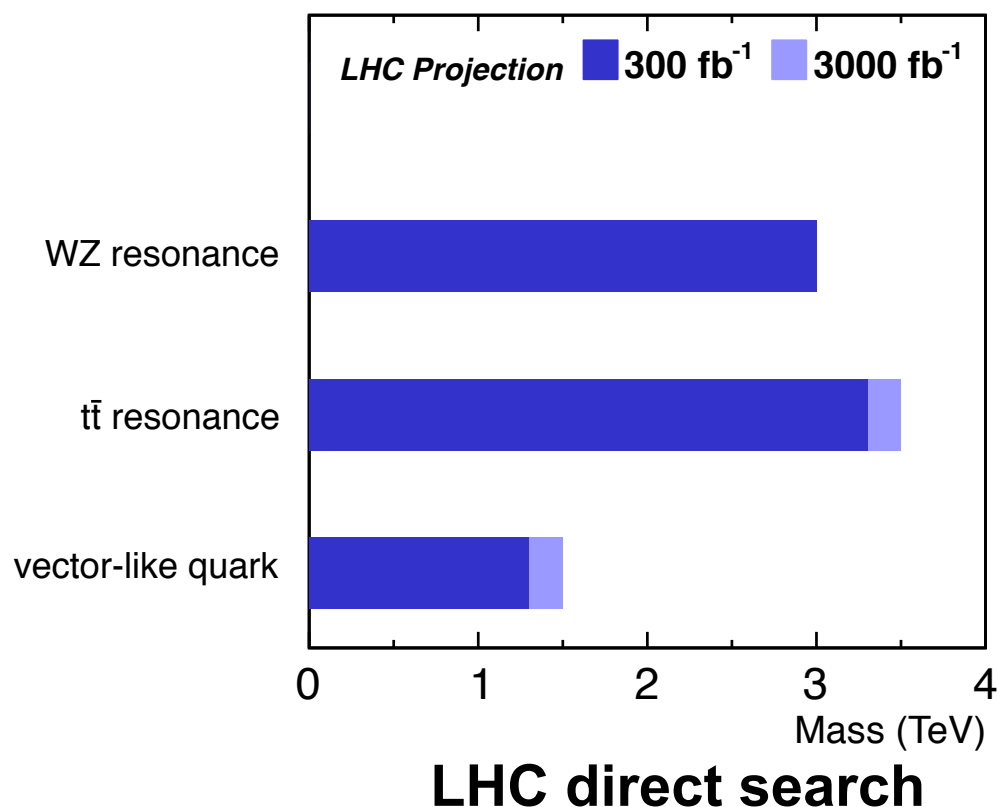
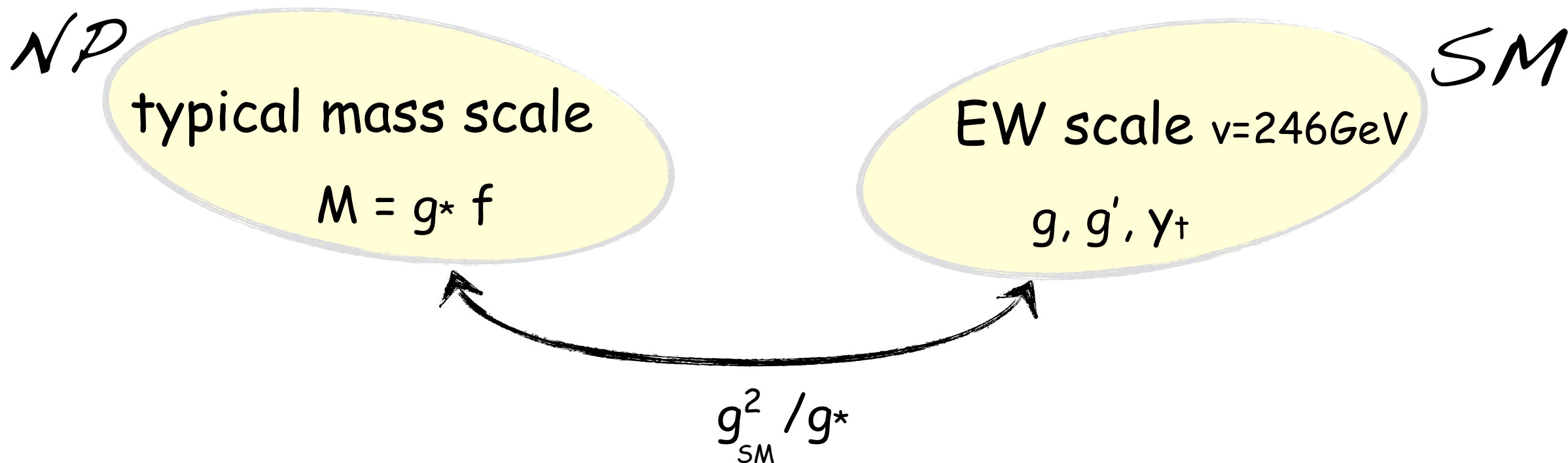
$$BR(h \rightarrow ii) = BR_{\text{SM}} \quad \Gamma = \left(1 - \frac{g_*^2 v^2}{16\pi^2 m_*^2} \right) \Gamma_{\text{SM}}$$

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

nice to be able to measure Zh & Γ

Higgs & New Physics

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



○ Precision Higgs study: $\xi \equiv \frac{\delta g}{g} = \frac{v^2}{f^2}$

○ Direct searches for resonances: $m_\rho \approx g_* f$

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

Higgs & New Physics

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

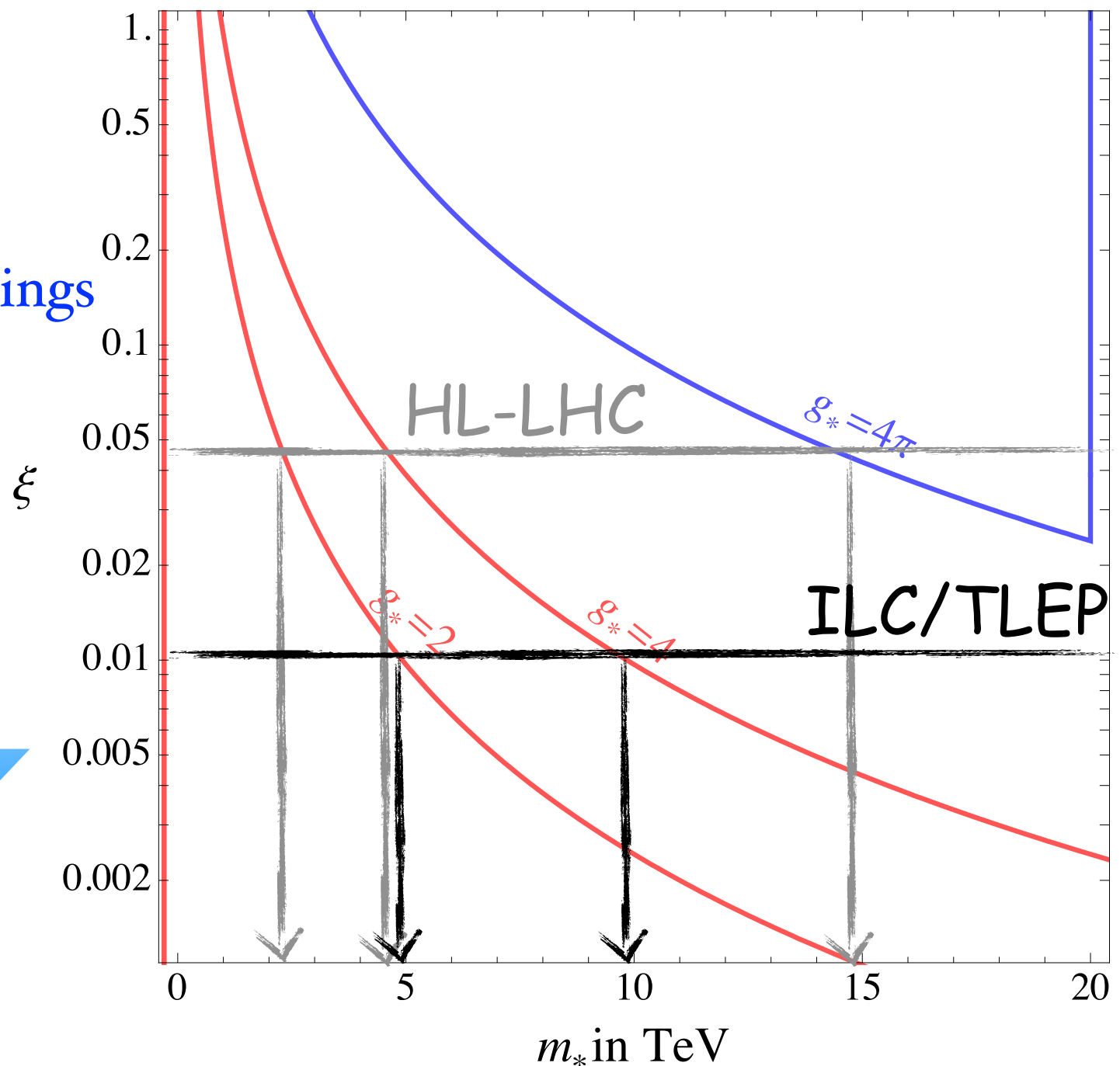
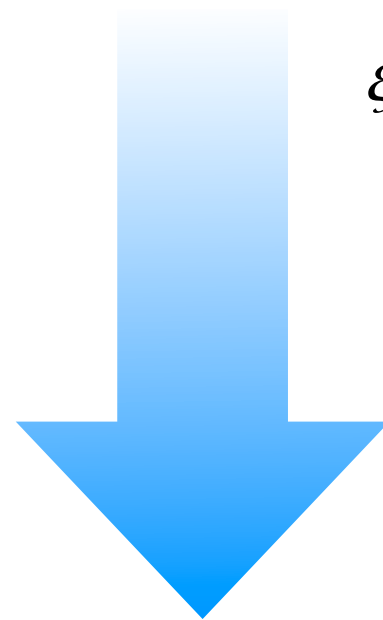
see also A. Kotwal's talk

Mass reach:

ee machines are best
to test strongly
coupled NP

pp machines are best
to test weakly
coupled NP

Higgs couplings



direct searches



Rattazzi, BSM@100TeV, CERN '14

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}

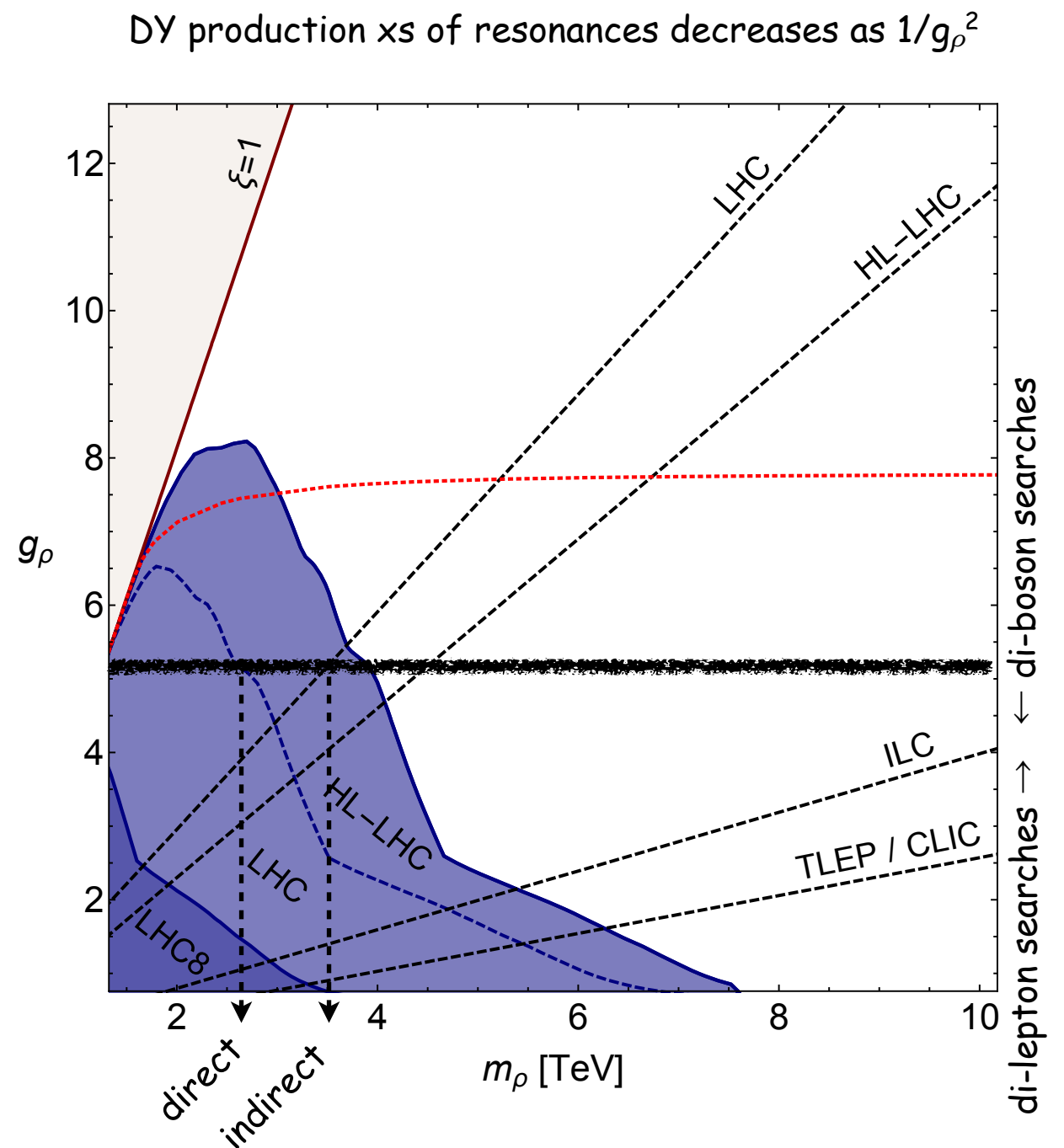
► **complementarity:**

- ▶ 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 $g > 2$



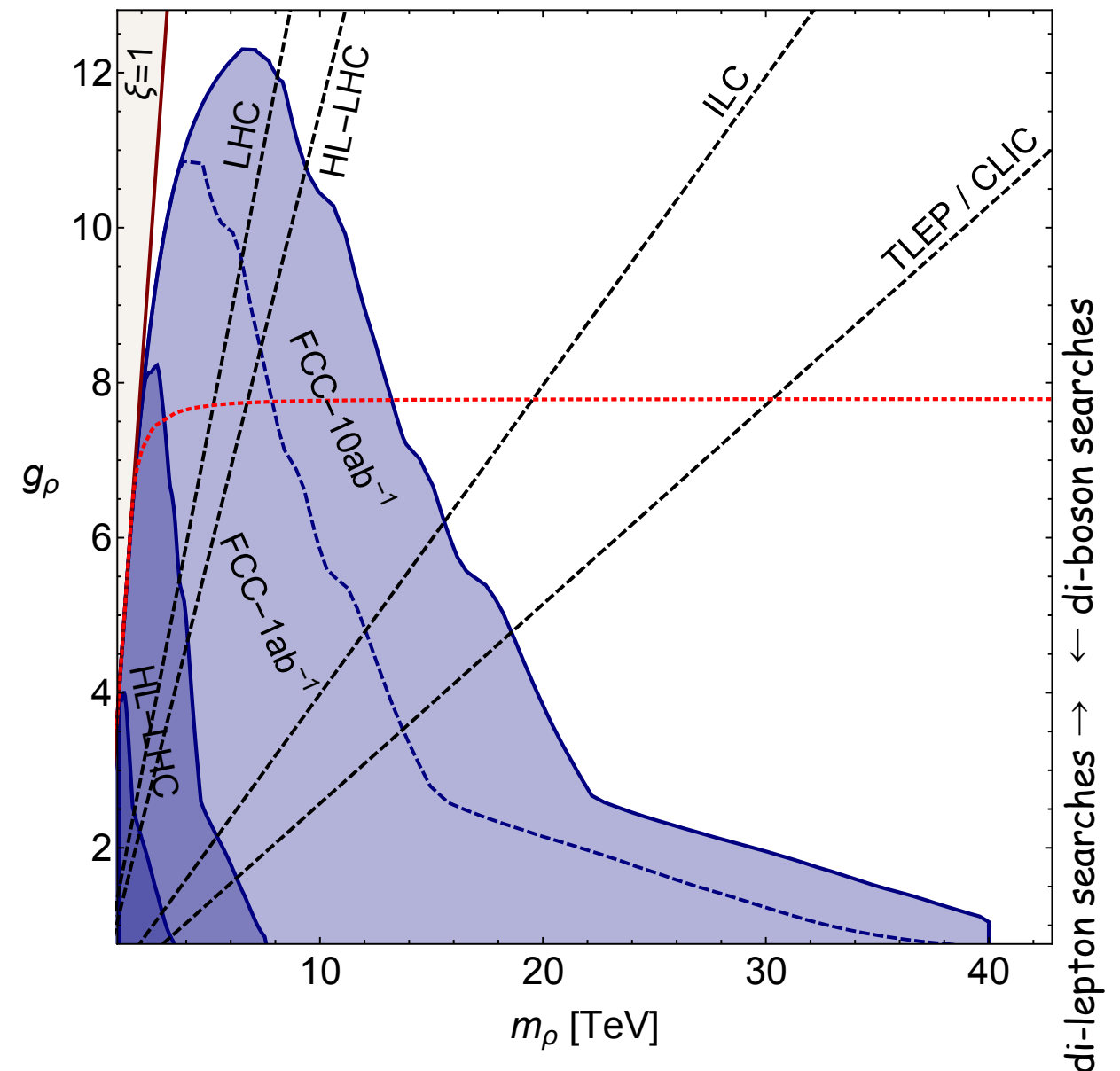
Higgs & New Physics

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

Torre, Thamm, Wulzer '15

Collider	Energy	Luminosity	$\xi [1\sigma]$
LHC	14 TeV	300 fb^{-1}	$6.6 - 11.4 \times 10^{-2}$
LHC	14 TeV	3 ab^{-1}	$4 - 10 \times 10^{-2}$
ILC	250 GeV + 500 GeV	250 fb^{-1} 500 fb^{-1}	$4.8-7.8 \times 10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	500 fb^{-1} 1.5 ab^{-1} 2 ab^{-1}	2.2×10^{-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 $g > 6$



Precision program in single Higgs processes

(assuming a mass gap between weak scale w/. Higgs doublet and new physics scale)

What is the Higgs the name of? I. Unitarity

The SM Higgs couplings are fixed to restore unitarity with mass

$$\Sigma = e^{i\sigma^a \pi^a / v} \quad \text{Goldstone of } SU(2)_L \times SU(2)_R / SU(2)_V \quad D_\mu \Sigma = g V_\mu$$

$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4} \text{Tr} (D_\mu \Sigma^\dagger D_\mu \Sigma) \left(1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} \right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c \frac{h}{v} \right)$$

'a', 'b' and 'c' are arbitrary free couplings

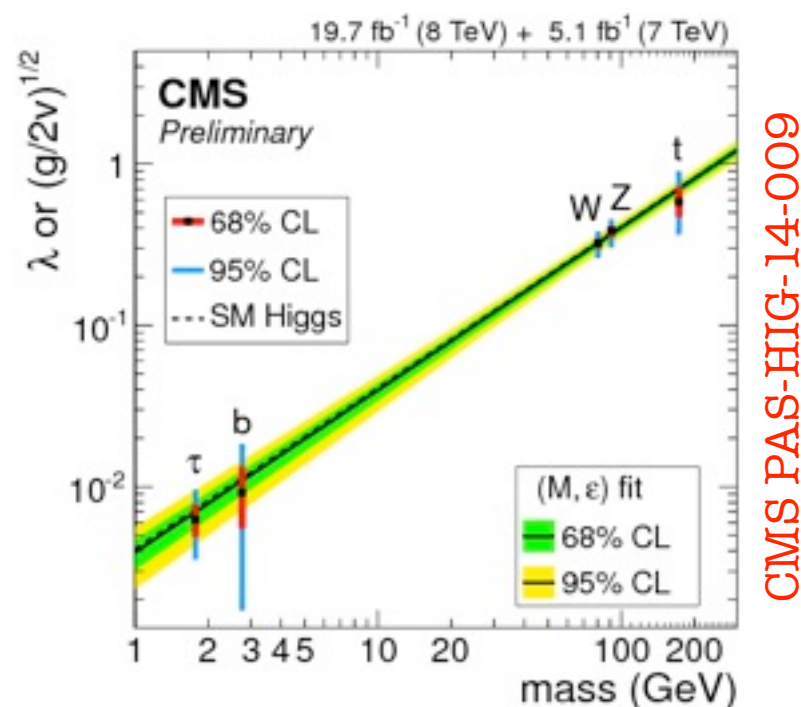
For a=1: perturbative unitarity in elastic channels $WW \rightarrow WW$

For b=a²: perturbative unitarity in inelastic channels $WW \rightarrow hh$

For ac=1: perturbative unitarity in inelastic $WW \rightarrow \psi \psi$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10



Higgs couplings
are proportional
to the masses of the particles

$$\lambda_\psi \propto \frac{m_\psi}{v}, \quad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

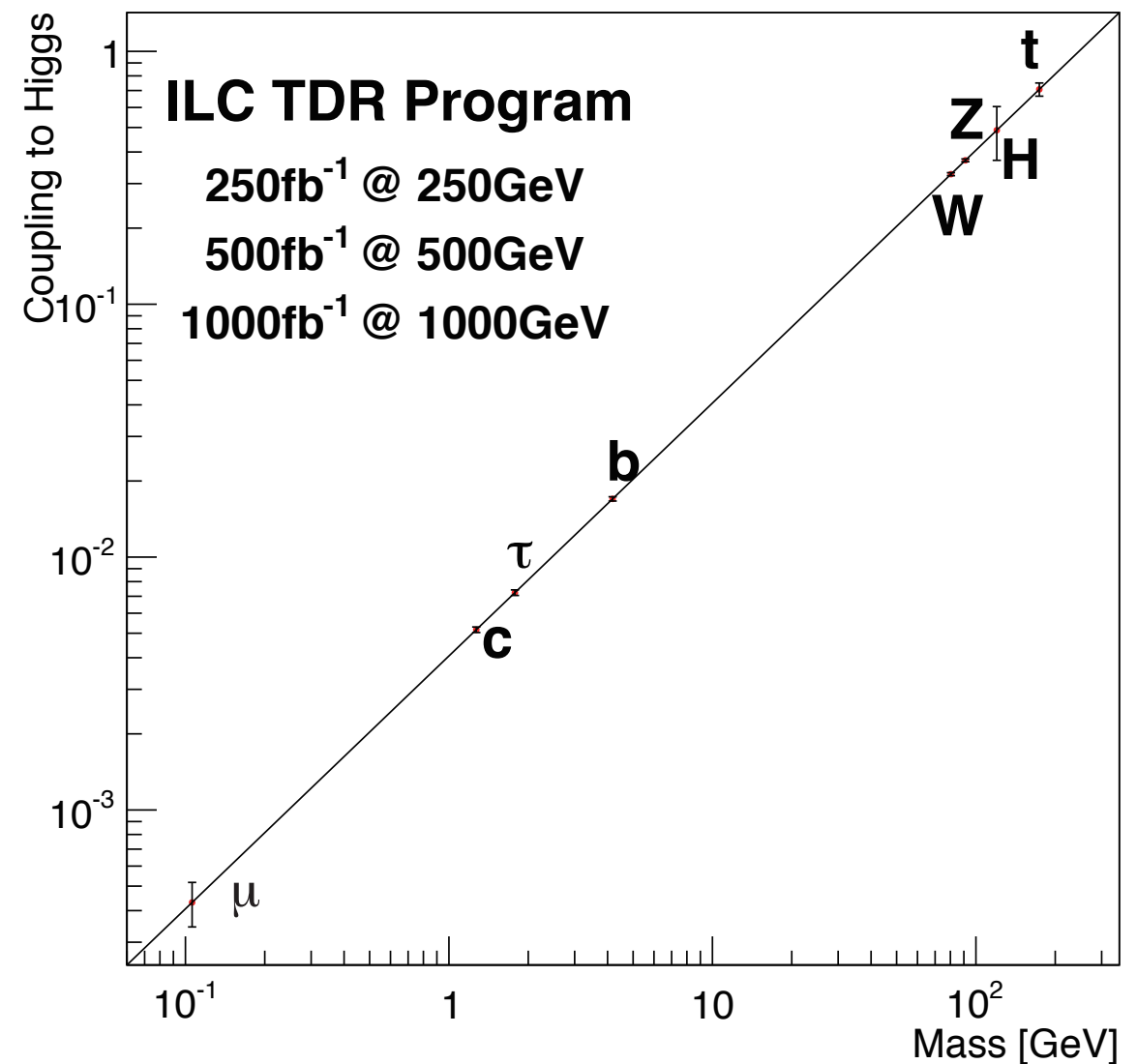
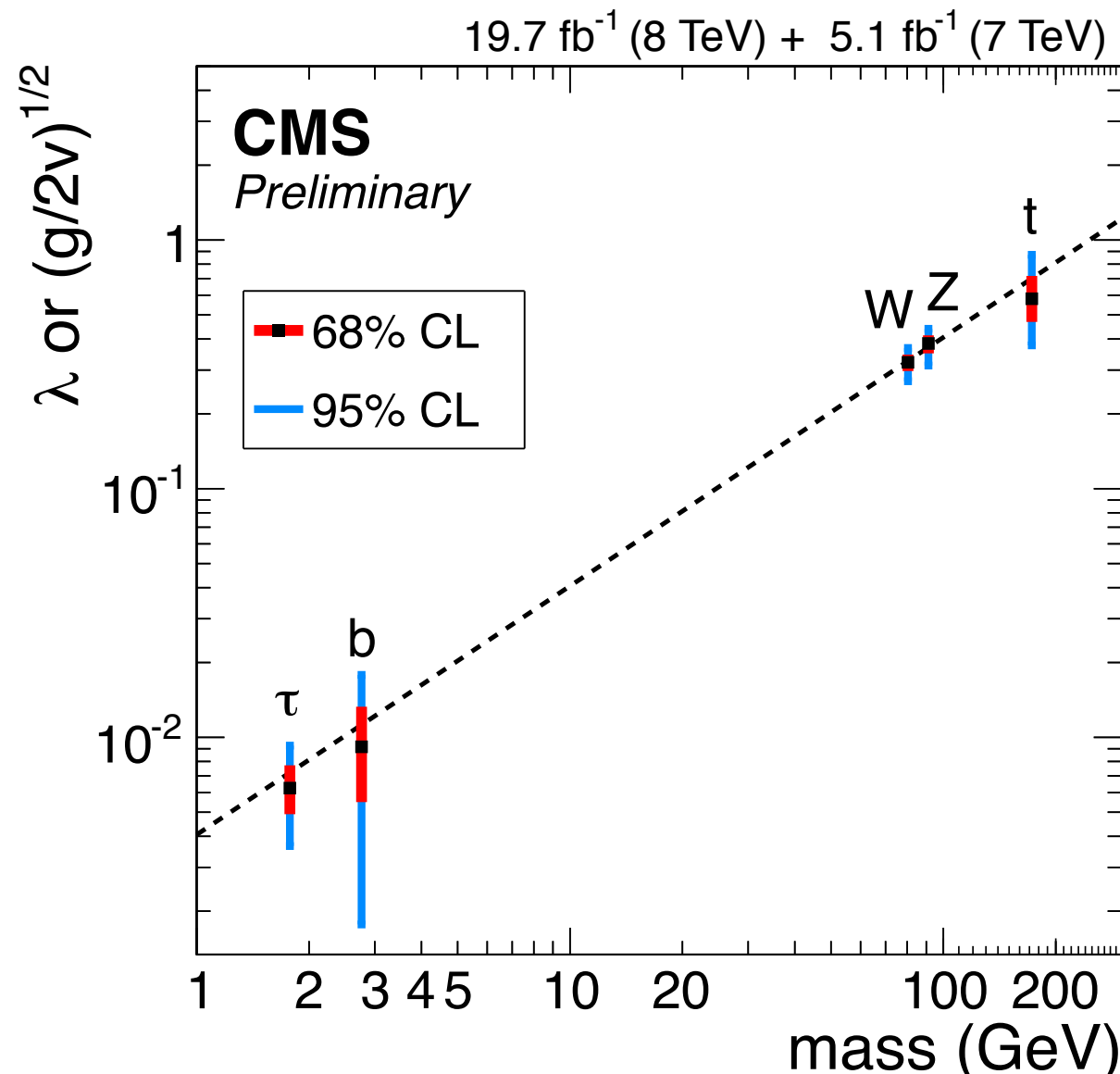
What is the Higgs the name of? I. Unitarity

The SM Higgs couplings are fixed to restore unitarity with mass

$$\Sigma = e^{i\sigma^a \pi^a / v}$$

Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$

$$D_\mu \Sigma = g V_\mu$$



The LHC cannot fully confirm this picture

(no model-independent measurements of the couplings, no access to the couplings to light particles...)

Higgs/BSM Primaries

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

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

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



But can affect h physics:



Higgs/BSM Primaries

How many of these effects can we have?

Pomarol, Riva '13

Elias-Miro et al '13

Gupta, Pomarol, Riva '14

As many as parameters in the SM: **8** for one family
(assuming CP-conservation)

g_s

$$|H|^2 G_{\mu\nu}^A G^{A\mu\nu}$$

→ **GGh coupling**

g

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

→ **h $\gamma\gamma$ coupling**

g'

$$|H|^2 W_{\mu\nu}^a W^{a\mu\nu}$$

→ **hZ γ coupling**

m_W

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

→ **hVV* (custodial invariant)**

m_h

$$|H|^6$$

→ **h³ coupling**

m_f

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

→ **htt, hbb, h $\tau\tau$**

(f=t,b, τ)

the 6 others have been measured (~15%)

yet to be measured
at the LHC

(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

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

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

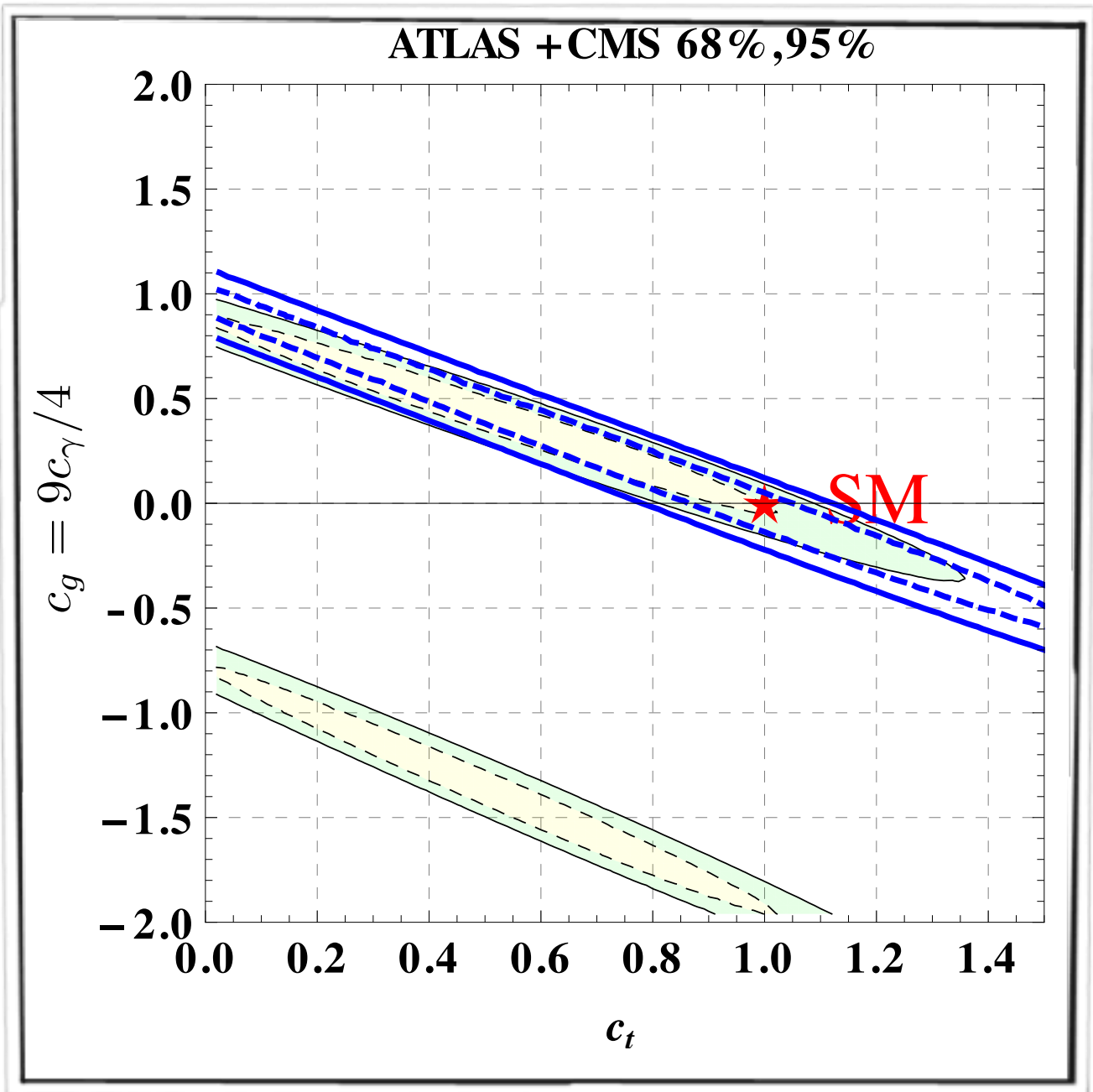
Atlas projection

With some important differences:

1) width hypothesis built-in

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

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



Azatov '15

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

CP violation in Higgs physics?

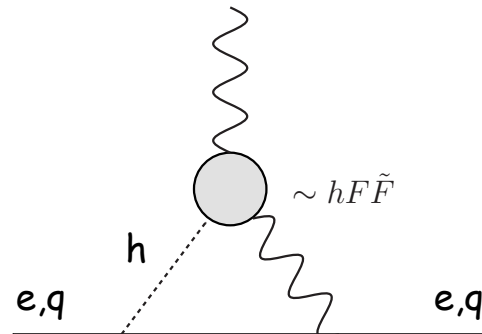
Among the 59 irrelevant directions, 6 ~~CP~~ Higgs/BSM primaries

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

operators with γ :

already severely constrained
by e and q EDMs

McKeen, Pospelov, Ritz '12



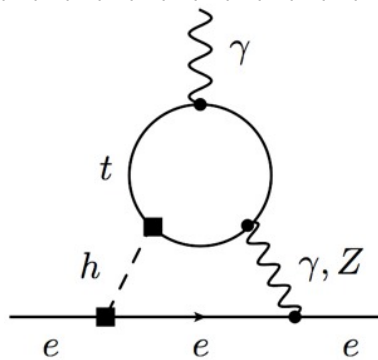
$$\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \leq 10^{-4}$$

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

operators with top:

already severely constrained
by e and q EDMs

Brod, Haisch, Zupan '13



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

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

Caveats: h couplings to light particles can be significantly reduced

What is the Higgs the name of? II. Flavor

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

$$y_{ij} \bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}} \bar{f}_{L_i} f_{R_j} + \frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

mass 

 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

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

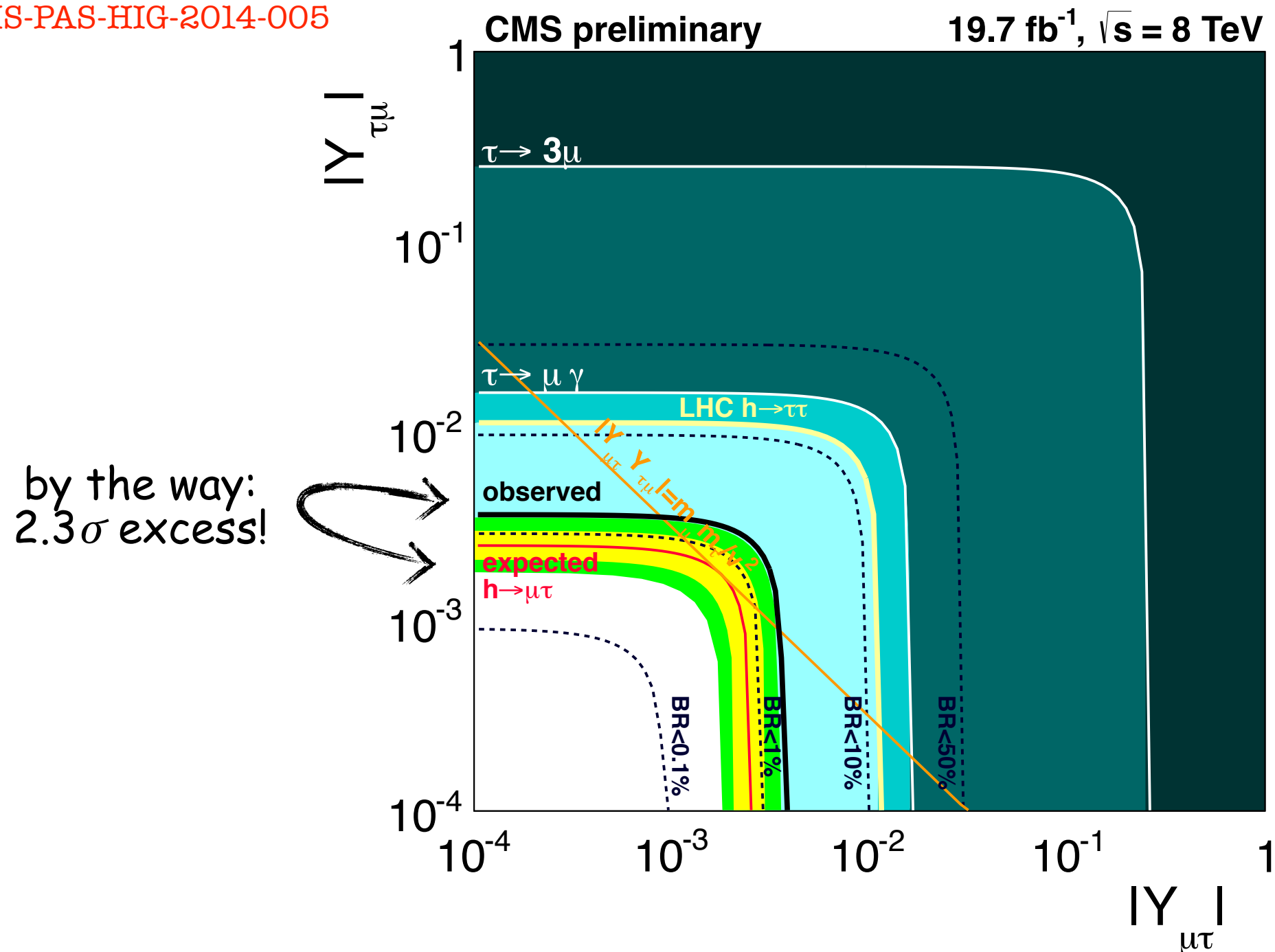
Look for SM forbidden Flavor Violating decays $h \rightarrow \mu\tau$ and $t \rightarrow hc$

- weak indirect constrained by flavor data (e.g. $\mu \rightarrow e\gamma$): BR < 10% Blankenburg, Ellis, Isidori '12
- ATLAS and CMS have the sensitivity to set bounds O(1%) Harnik et al '12
- ILC/CLIC/FCC-ee can certainly do much better Davidson, Verdier '12
CMS-PAS-HIG-2014-005

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

What is the Higgs the name of? II. Flavor

CMS-PAS-HIG-2014-005



Off-diagonal Higgs couplings can reveal the origin of flavor

We need to know the prospects to measure them at lepton colliders!

And enjoy the benefits of efficient tagging!

What is the Higgs the name of? II. Flavor

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

Not the case in e.g. generic 2HDM

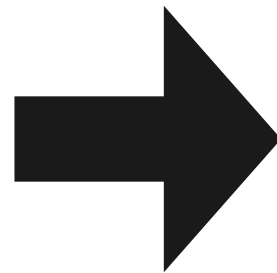
Omura, Senaha and Tobe '15

Botella and Branco 'in progress

$$y_{hij} = \frac{m_f^i}{v} s_{\beta\alpha} \delta_{ij} + \frac{\rho_f^{ij}}{\sqrt{2}} c_{\beta\alpha},$$

$$y_{Hij} = \frac{m_f^i}{v} c_{\beta\alpha} \delta_{ij} - \frac{\rho_f^{ij}}{\sqrt{2}} s_{\beta\alpha},$$

$$y_{Aij} = \begin{cases} -\frac{i\rho_f^{ij}}{\sqrt{2}}, & (f = u), \\ \frac{i\rho_f^{ij}}{\sqrt{2}}, & (f = d, e), \end{cases}$$



even small mixing ($c_{\beta\alpha} \sim 0.1$)
and moderate FCYC ($\rho \sim 0.3$)
can explain
 $\text{BR}(h \rightarrow \mu\tau) = (0.89 \pm 0.40)\%$

consequences:

► $(g-2)_\mu$

► $\tau \rightarrow \mu\gamma$

NB: Flavor Changing decays of H and A can easily dominate

explain why even light H/A hasn't been found at LHC directly

ILC should be able to probe these scenarios with an unprecedented accuracy

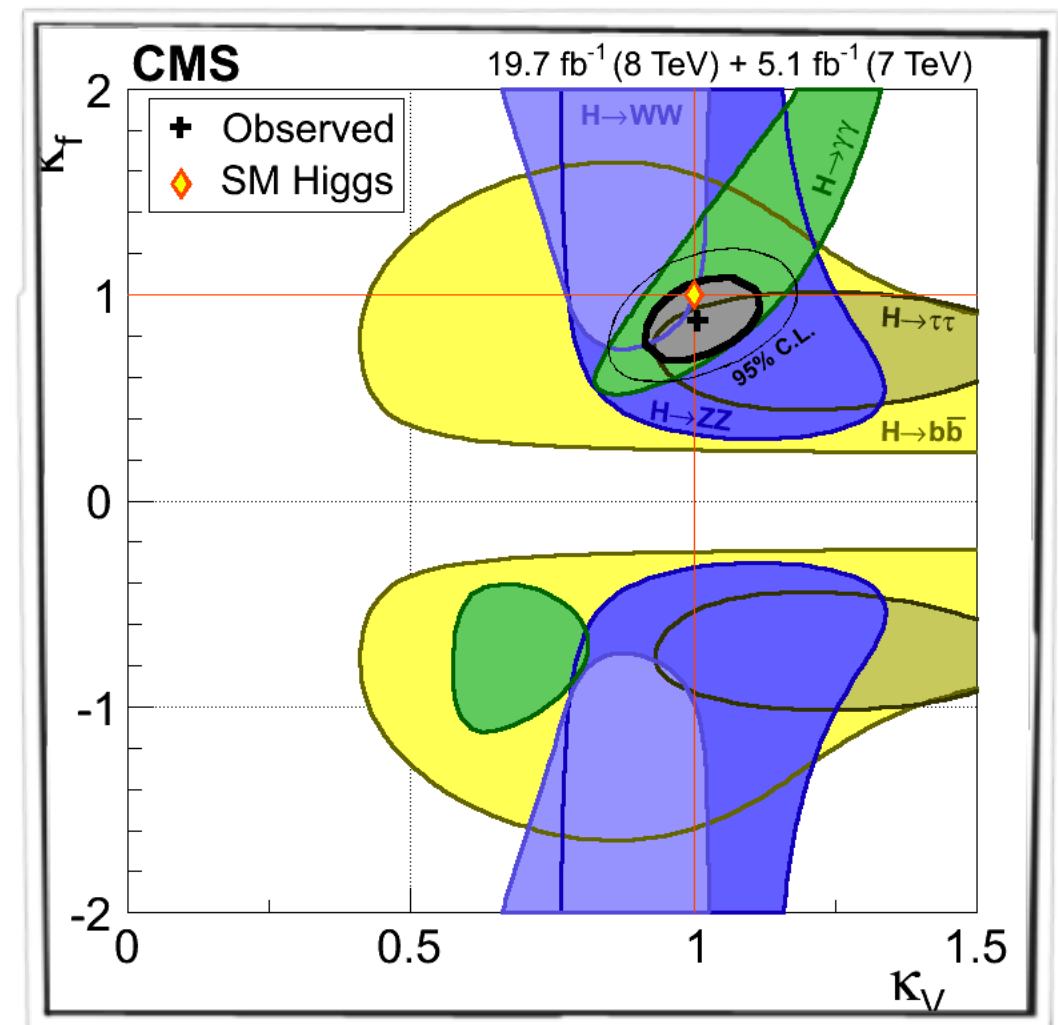
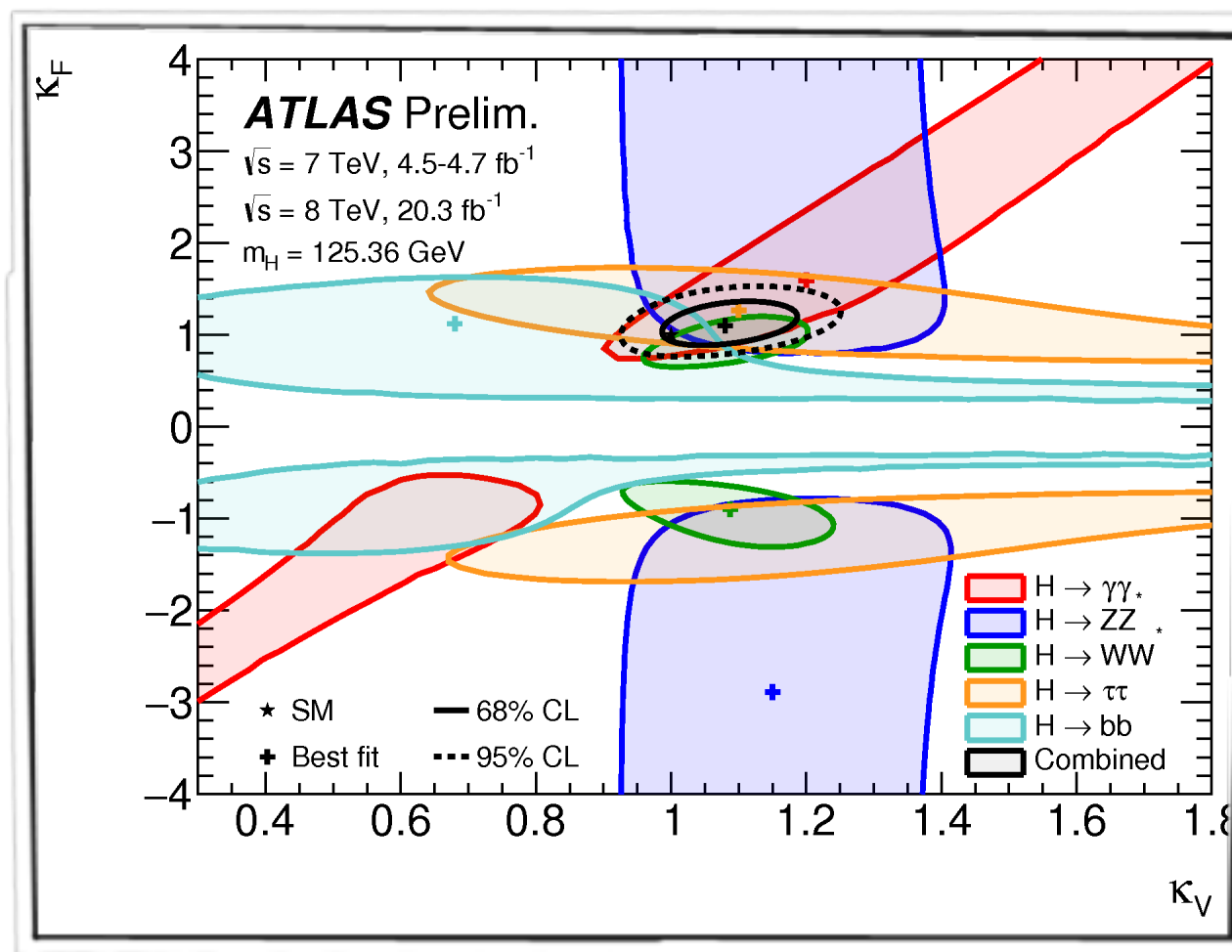


Boosted and off-shell Higgs channels

Why going beyond inclusive Higgs processes?

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

$\Downarrow$ $\Downarrow$
 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)

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 (*)

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

e.g. Grazzini, Sargsyan '13

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

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

⇒ cannot disentangle ○ long distance physics (modified top coupling)
○ short distance physics (new particles running in the loop) ⇐

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

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

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

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

14%-4% @ LHC¹⁴₃₀₀-LHC¹⁴₃₀₀₀ vs 10%-4% @ ILC⁵⁰⁰₅₀₀-ILC¹⁰⁰⁰₁₀₀₀

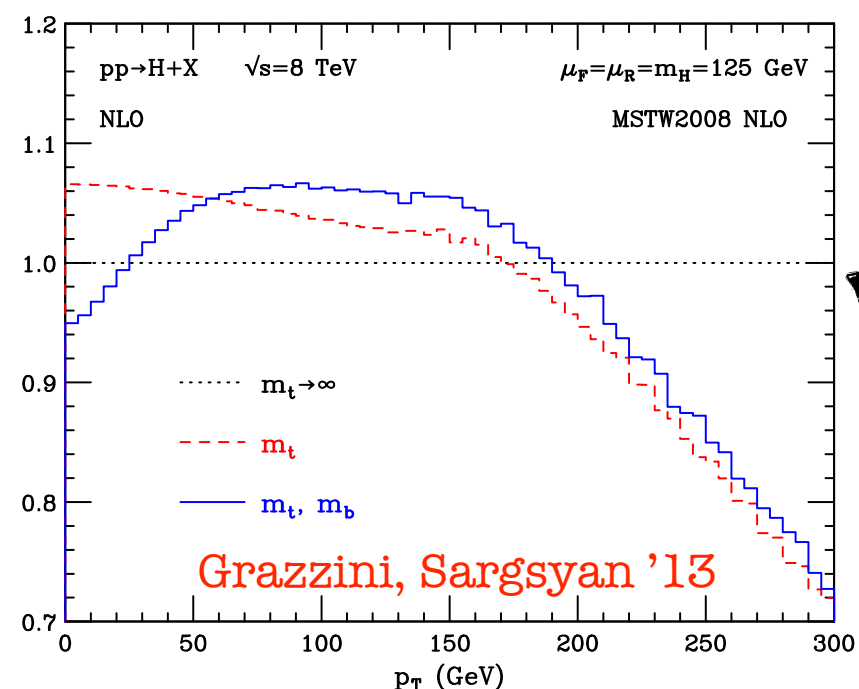
Resolving top loop: Boosted Higgs

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_{m_t} is not known

$1/m_t$ corrections known $O(\alpha_s^4)$

few % up to $p_T \sim 150$ GeV

Harlander et al '12

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

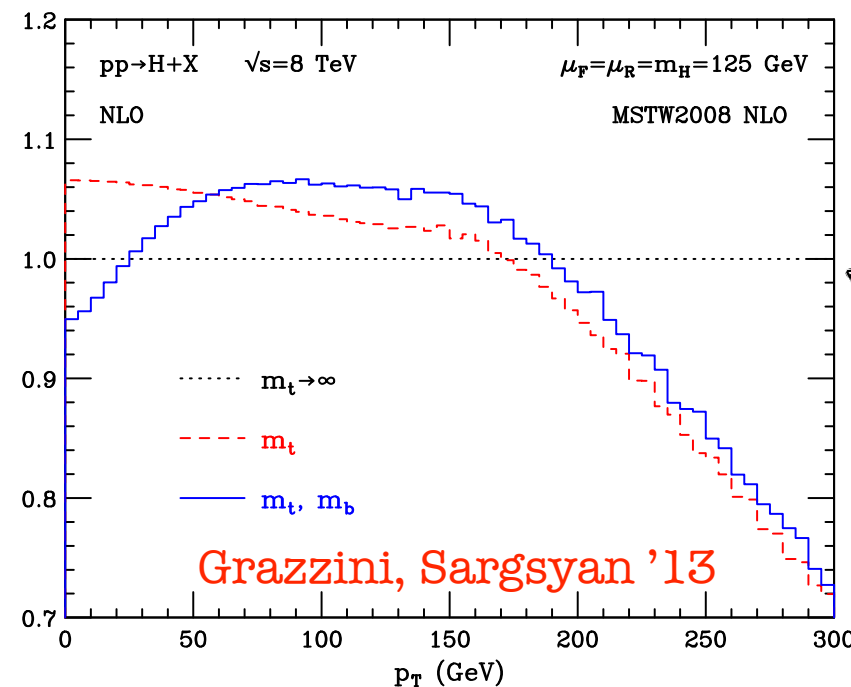
Resolving top loop: Boosted Higgs

cut open the top loops

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

Baur, Glover '90

Langenegger, Spira, Starodumov, Trueb '06



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

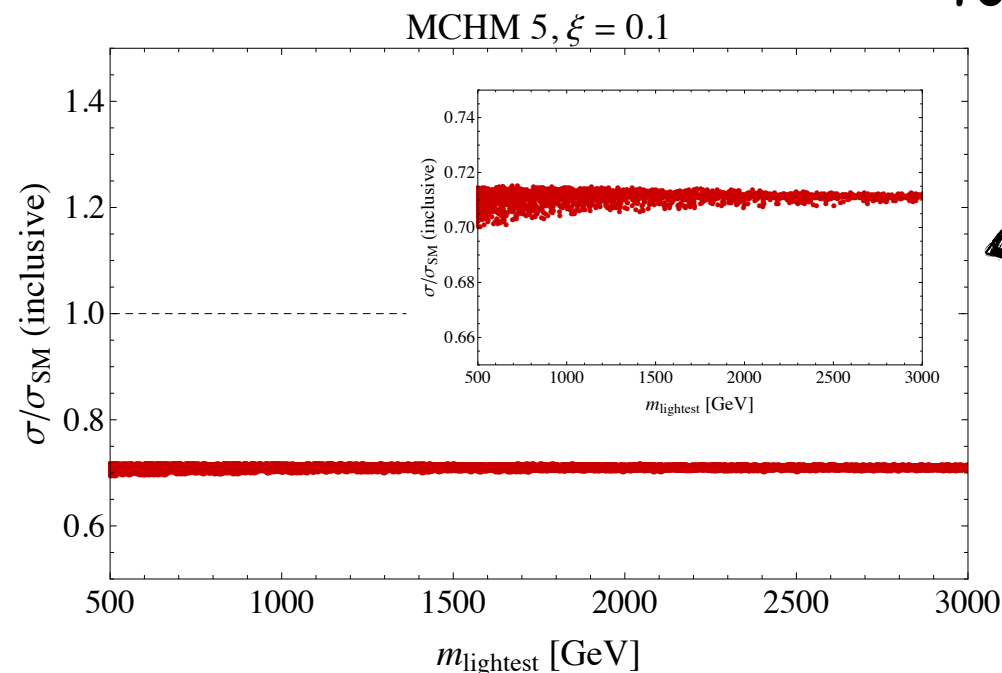
Harlander et al '12

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

Composite Higgs Model top partners contributions

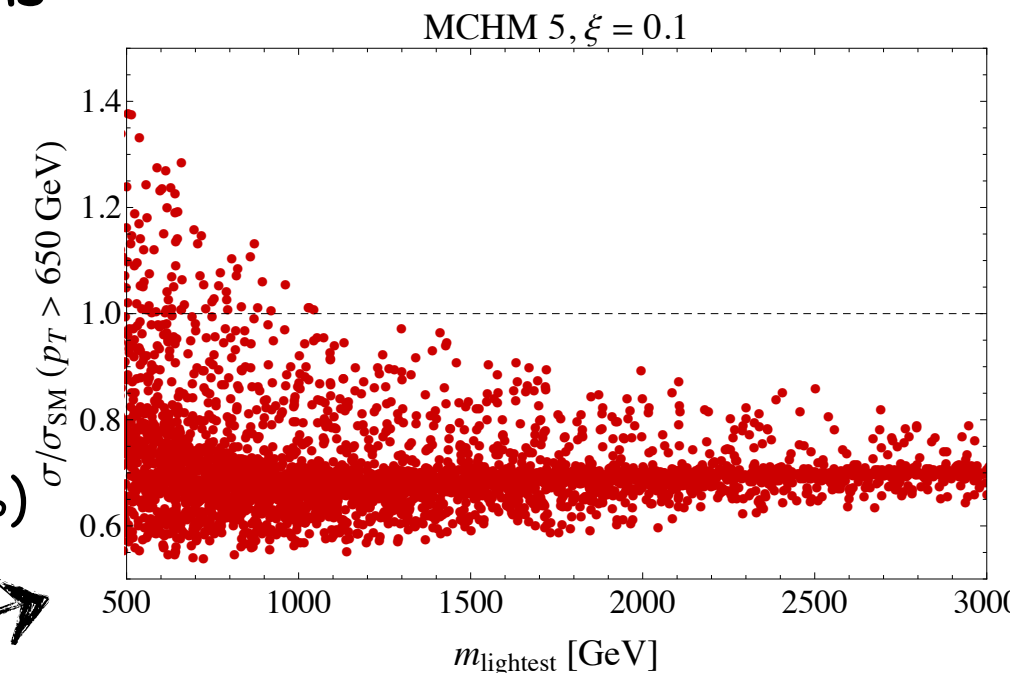
see also Banfi, Martin, Sanz '13
see also Azatov, Paul '13

Grojean, Salvioni, Schlaffer, Weiler '13



inclusive rate: $O(\%)$

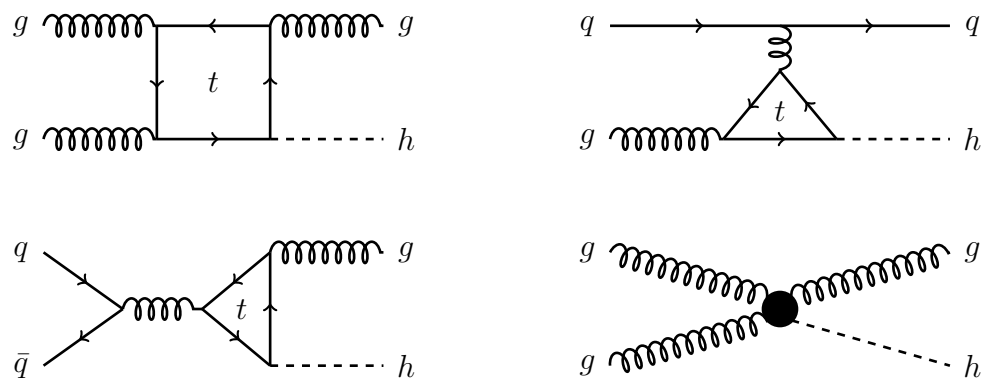
with high- p_T cut: $O(\times 10\%)$



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

Boosted Higgs

Grojean, Salvioni, Schlaffer, Weiler '13



$$\frac{\sigma_{p_T^{\min}}(\kappa_t, \kappa_g)}{\sigma_{p_T^{\min}}^{\text{SM}}} = (\kappa_t + \kappa_g)^2 + \delta \kappa_t \kappa_g + \epsilon \kappa_g^2$$

large p_T , small rates
need to focus on dominant decay modes

$$h \rightarrow b\bar{b}, WW, \tau\tau$$

non-isolated "ditau-jets"

(separation between the 2 tau's: $\Delta R \sim 2m_h/p_T \lesssim 0.5$)

$$\epsilon_{\text{tot}} = \text{BR}(h \rightarrow \tau\tau) \left(\sum_{i=\tau\ell\tau\ell, \tau\ell\tau h, \tau h\tau h} \text{BR}(\tau\tau \rightarrow i) \epsilon_i \right) \simeq 2 \times 10^{-2}$$

$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma_{p_T^{\min}}^{\text{SM}}$ [fb]	δ	ϵ	gg, qg [%]
14	100	2200	0.016	0.023	67, 31
	150	830	0.069	0.13	66, 32
	200	350	0.20	0.31	65, 34
	250	160	0.39	0.56	63, 36
	300	75	0.61	0.89	61, 38
	350	38	0.86	1.3	58, 41
	400	20	1.1	1.8	56, 43
	450	11	1.4	2.3	54, 45
	500	6.3	1.7	2.9	52, 47
	550	3.7	2.0	3.6	50, 49
	600	2.2	2.3	4.4	48, 51
	650	1.4	2.6	5.2	46, 53
	700	0.87	3.0	6.2	45, 54
	750	0.56	3.3	7.2	43, 56
	800	0.37	3.7	8.4	42, 57
100	500	970	1.8	3.1	72, 28
	2000	1.0	14	78	56, 43

+150
enhancement

VHE-LHC is the machine
to decipher the $gg \rightarrow h$ process

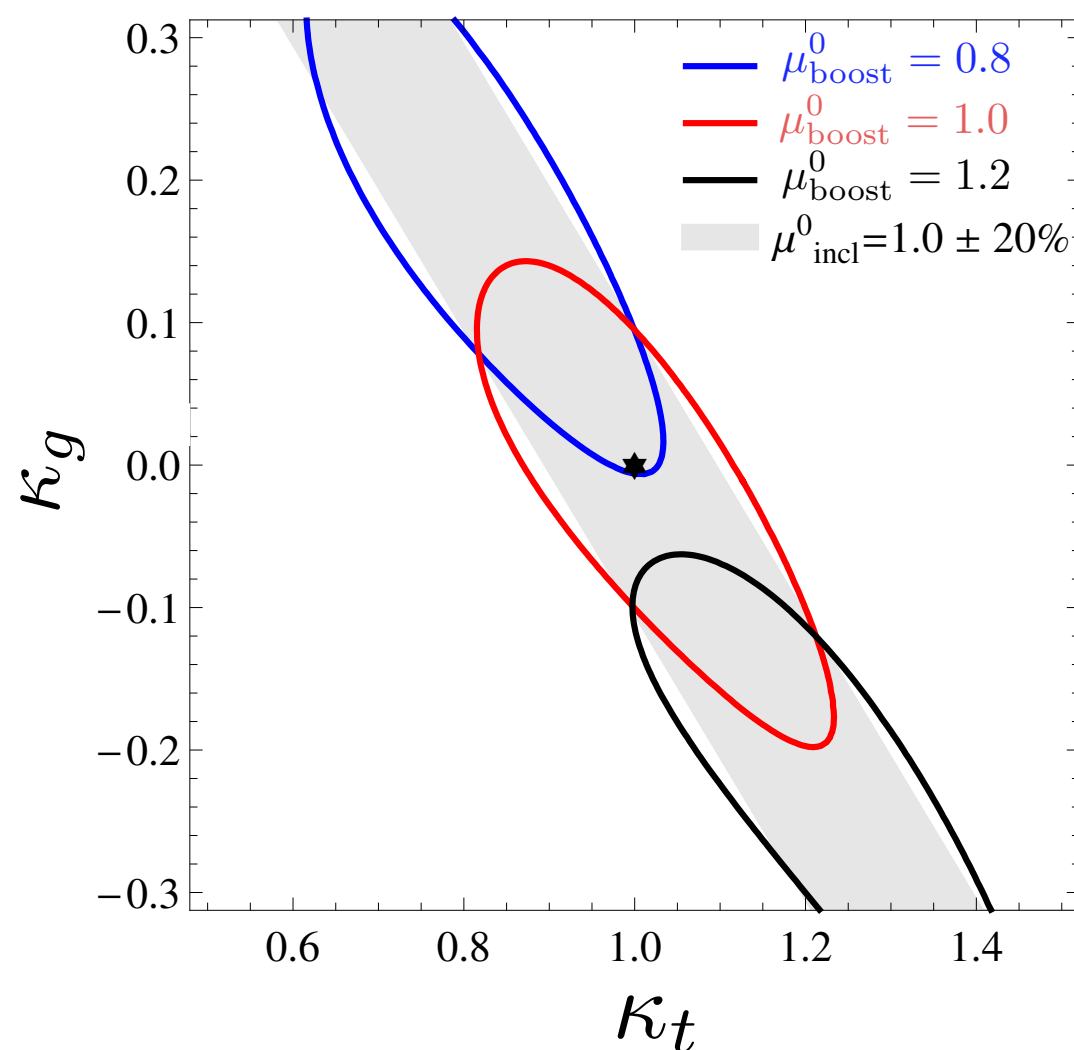
Boosted Higgs

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

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

(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



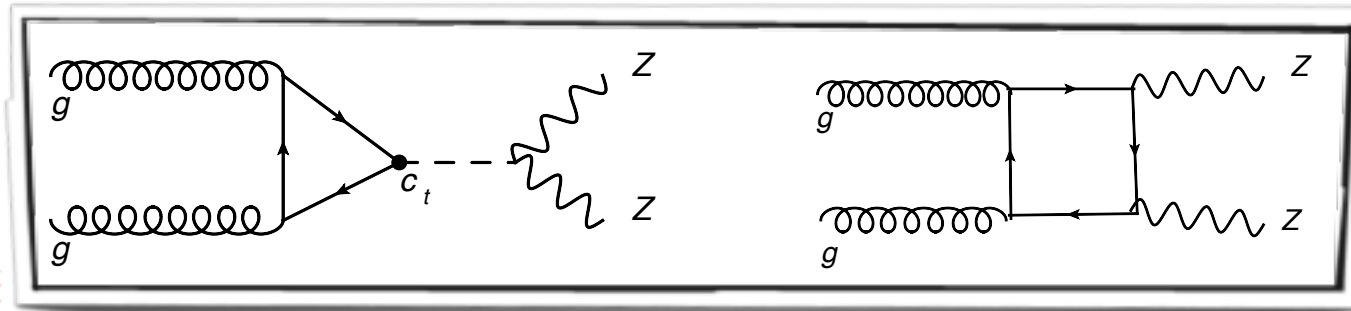
competitive/complementary to htt channel
for the measure the top-Higgs coupling

Are the NLO_m QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: N³LO_∞ for inclusive xs or NLO_{mt} for pT spectrum?

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

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

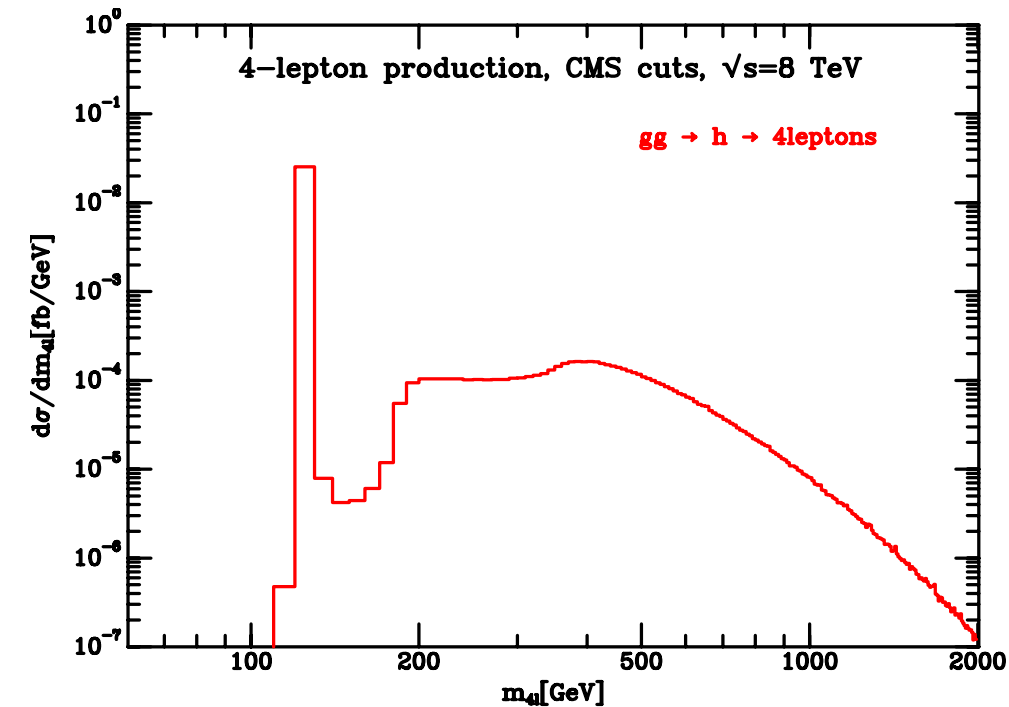
Glover, van der Bij '89



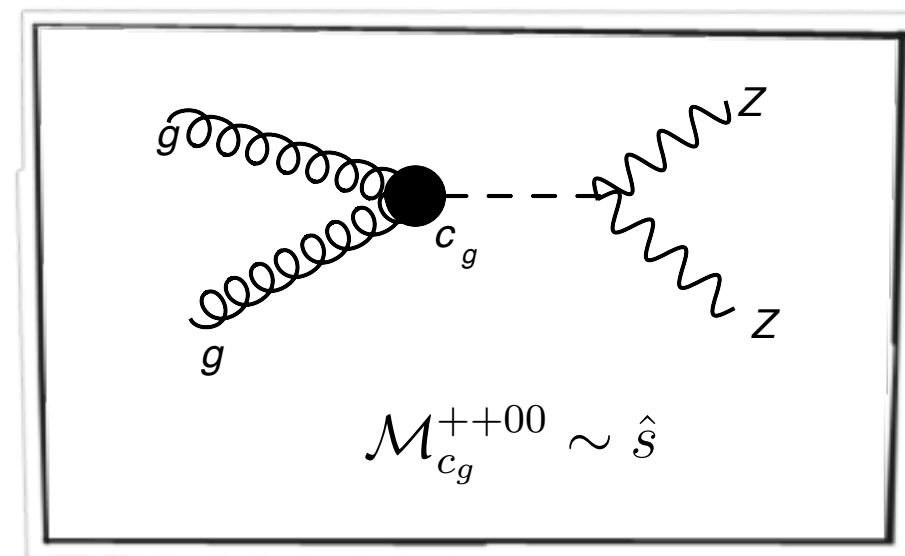
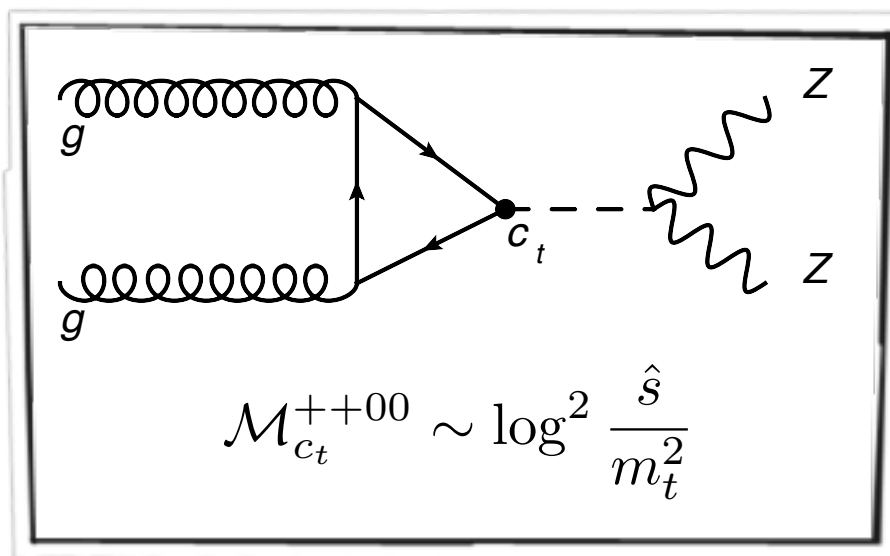
$$\mathcal{M}_{\text{Higgs}}^{++00} \sim \log^2 \frac{\hat{s}}{m_t^2} \quad \mathcal{M}_{\text{box}}^{++00} \sim -\log^2 \frac{\hat{s}}{m_t^2}$$

SM: cancelation forced by unitarity

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

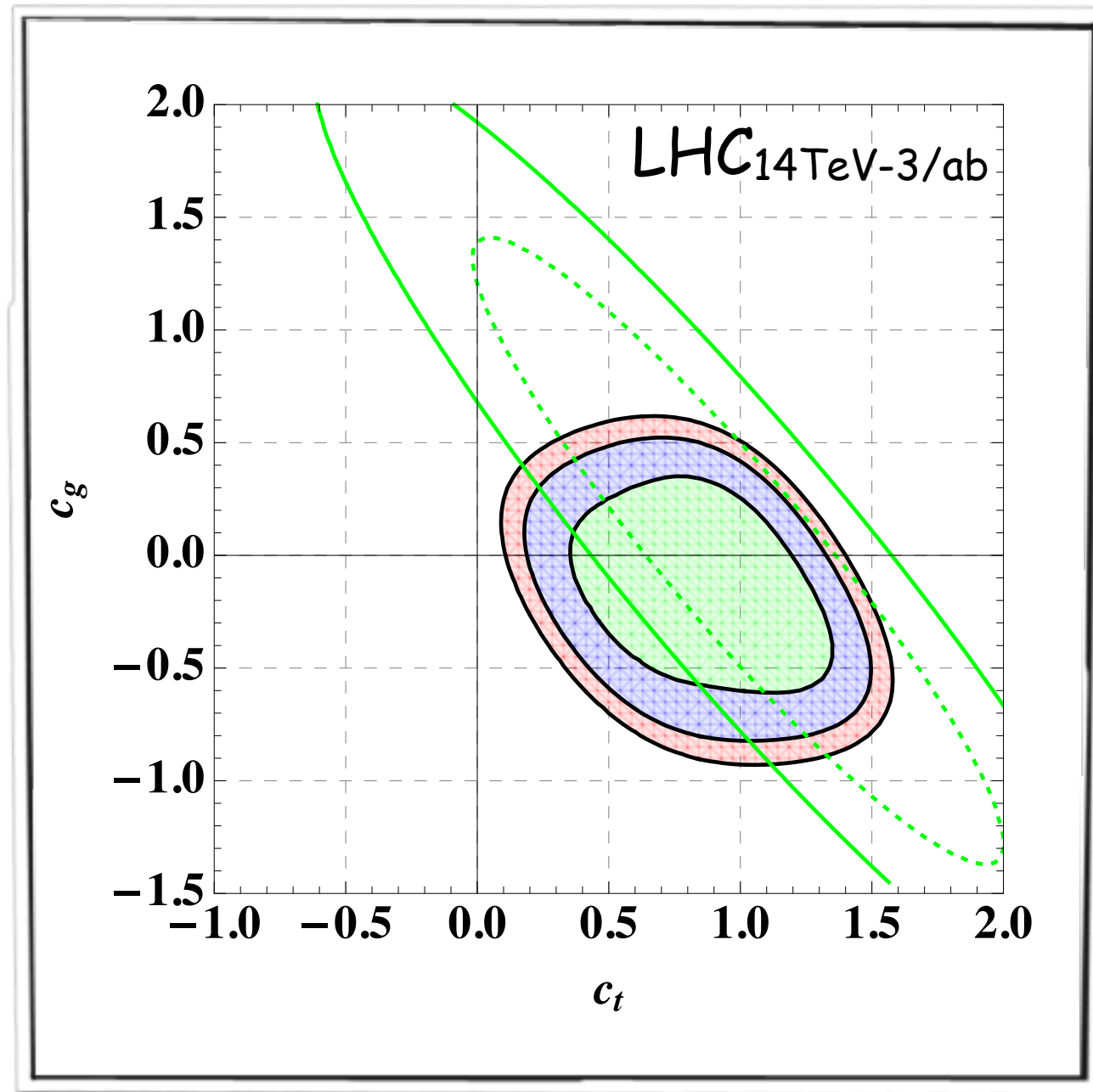
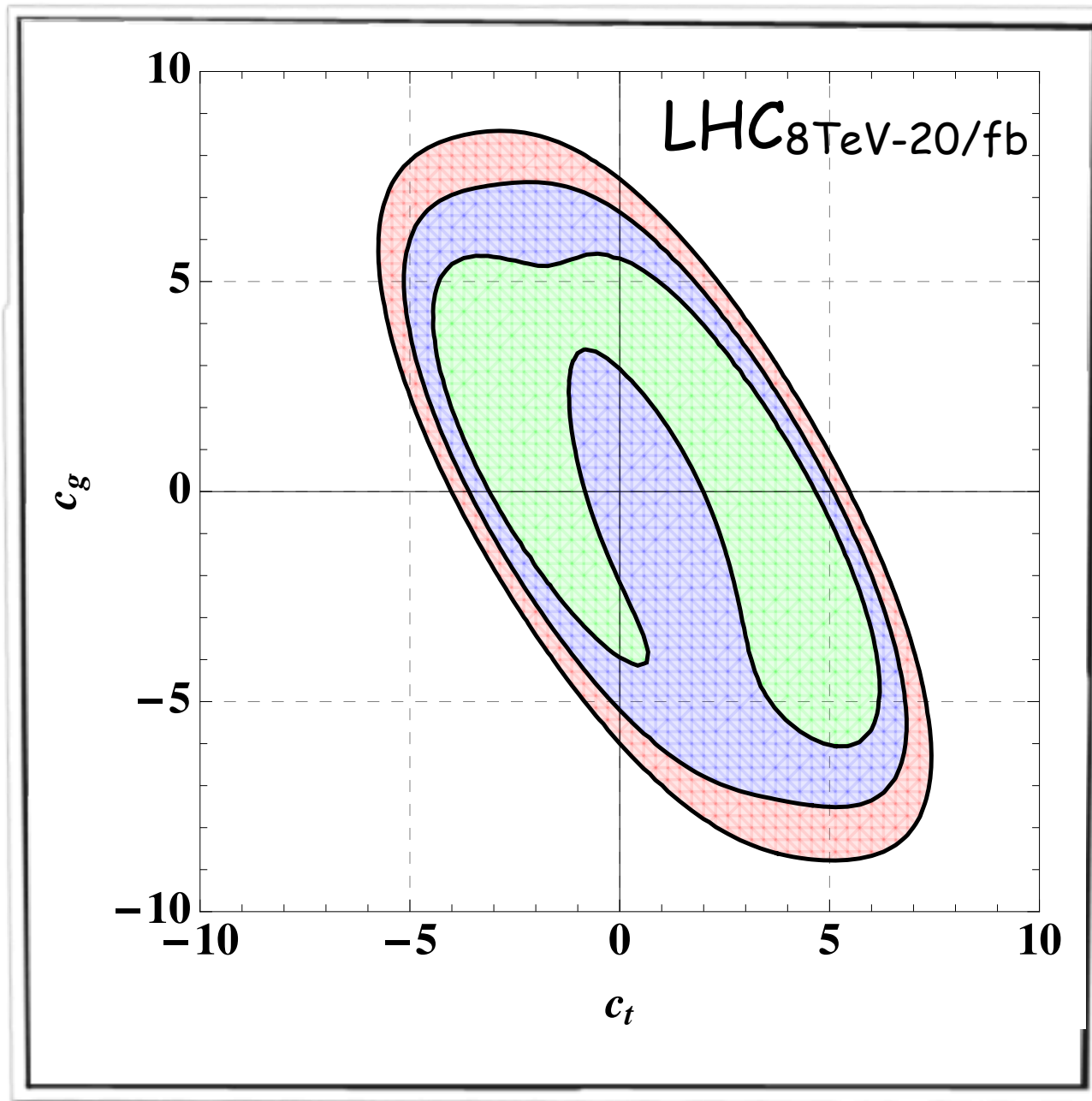


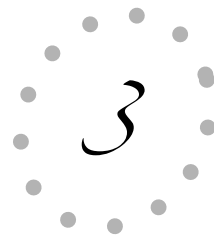
interpretations in terms of bounds of the Higgs width are limited/model-dependent
but data can be better used to measure the structure of the couplings at high $\sqrt{s}$



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

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





Double Higgs channels

Higgs self-couplings

The Higgs self-couplings plays important roles

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

Does it need to be measured with high accuracy?

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

Higgs self-coupling prospects

	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 $\sim 28\%$ via VBF at 1TeV, 1/ab CLIC at 3TeV, 2/ab $\sim 12\%$ via VBF	$b\bar{b}\gamma\gamma$: golden channel. 5-10% determination might be possible with 30/ab. $\sim 3x$ 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

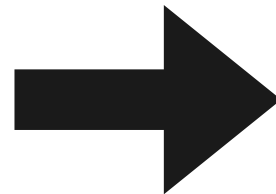
Higgs self-couplings and Naturalness

In the SM, $|H|^2$ is the only relevant operator
and it is the source of the hierarchy/naturalness/fine-tuning problem
Its 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

$$V = -\mu^2 |H|^2 + \lambda |H|^4$$

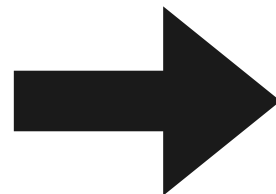


$$V(h) = \frac{1}{2} m_h^2 h^2 + \frac{1}{6} \frac{3m_h^2}{v} h^3 + \dots$$

EWSB

W/O H^2

$$V = -\lambda |H|^4 + \frac{1}{\Lambda^2} |H|^6$$



$$V(h) = \frac{1}{2} m_h^2 h^2 + \frac{1}{6} \frac{7m_h^2}{v} h^3 + \dots$$

200% correction
to SM prediction

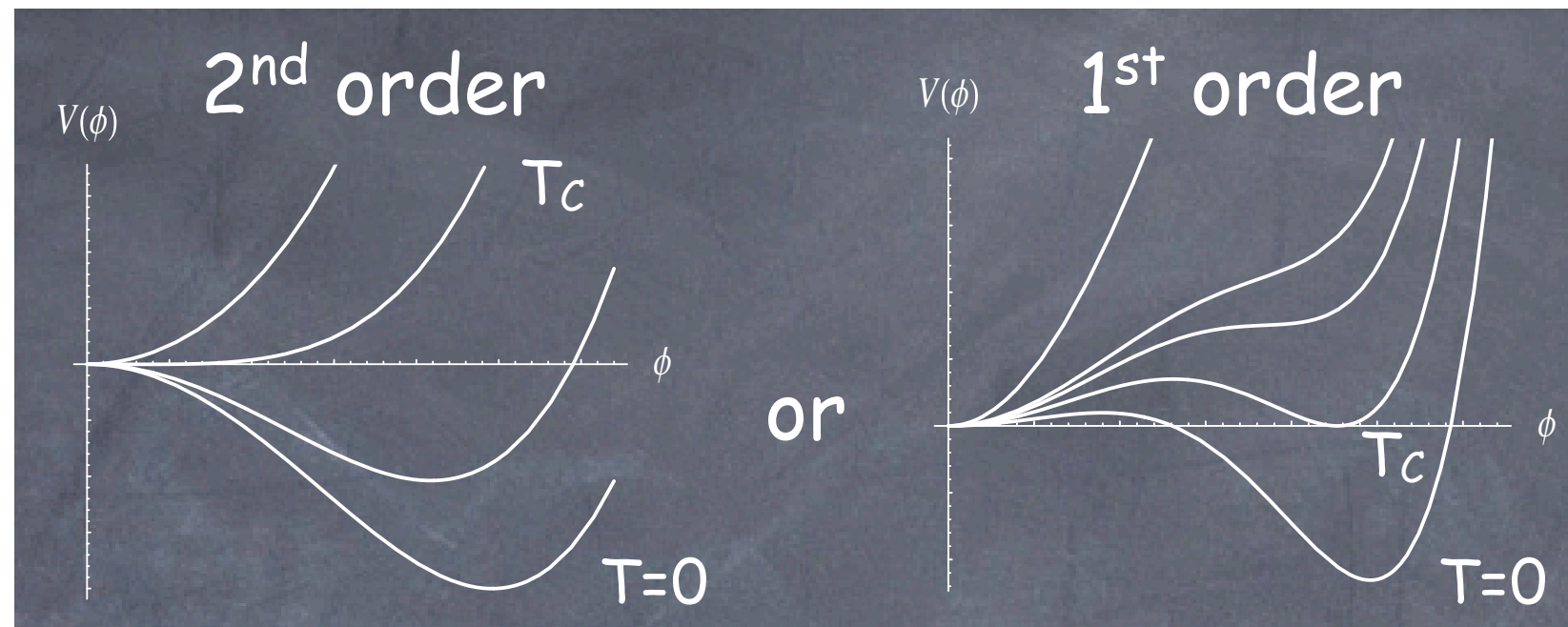
+

allows 1st phase transition

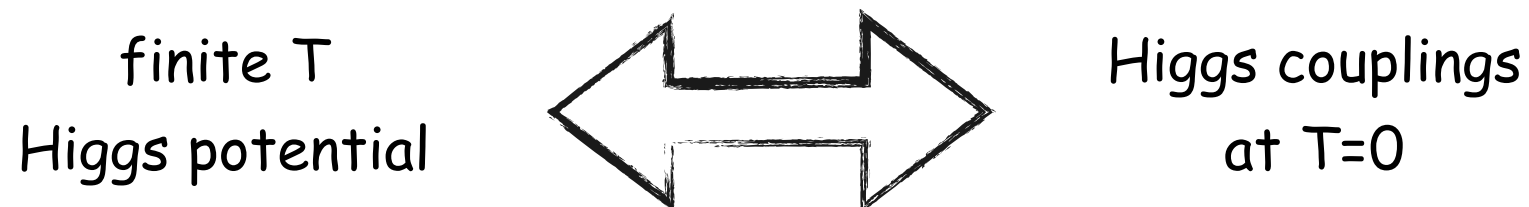
Dynamics of EW phase transition

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)



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 $\neq$ Big Bang machine)



SM: first order phase transition iff $m_H < 47 \text{ GeV}$

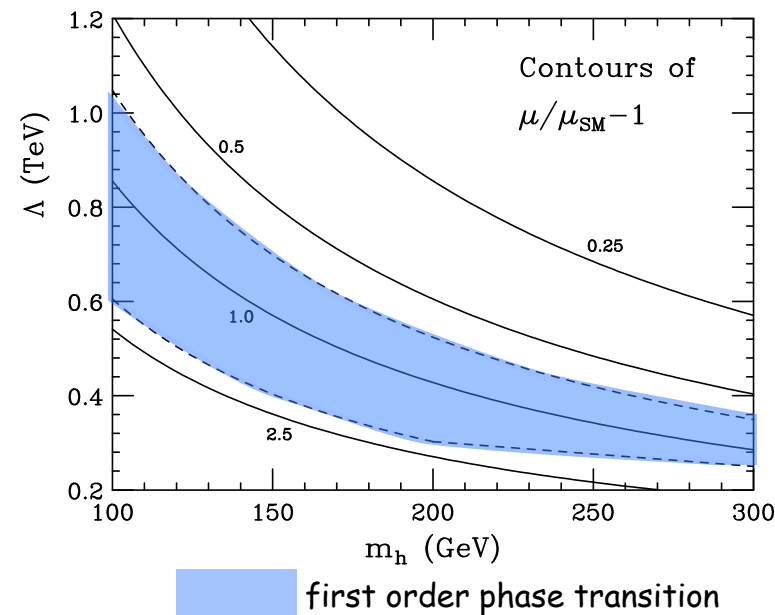
BSM: first order phase transition needs some sizeable deviations in Higgs couplings

Higgs couplings for 1st order EW phase transition

⋮ New physics @ tree-level ⋮

Grojean, Servant, Wells '04
Noble, Perelstein '07

mixing with other scalars modify the tree-level Higgs potential



$$V(\Phi) = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2 + \frac{1}{\Lambda^2} \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^3$$

1st order phase transition

comes with 80-200% deviations in Higgs self-interaction

⇓⇓ visible @ ILC/TLEP

⋮ New physics in loops ⋮

Katz, Perelstein '14

new particles, e.g. scalars, coupled to the Higgs without affecting its tree-level potential

$$V \propto \kappa |\Phi|^2 |H|^2$$

Higgs couplings for 1st order EW phase transition

⋮ New physics @ tree-level ⋮

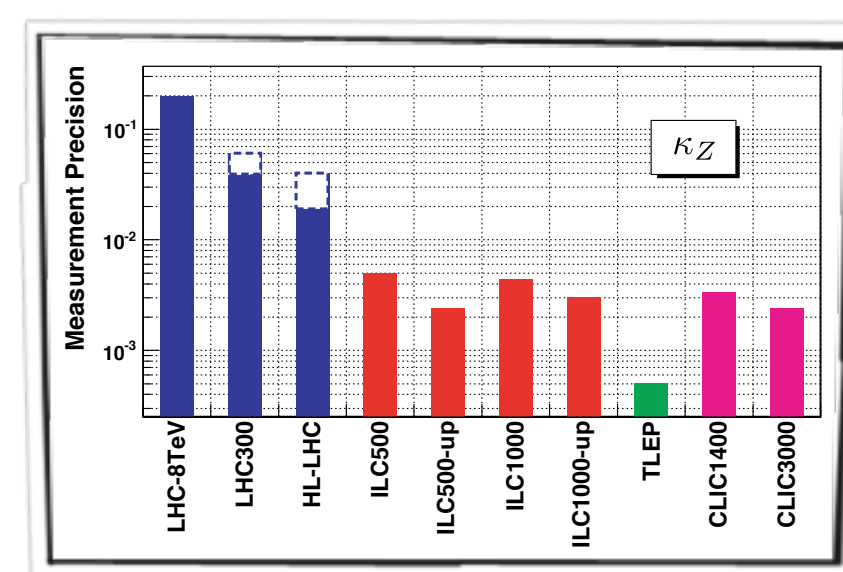
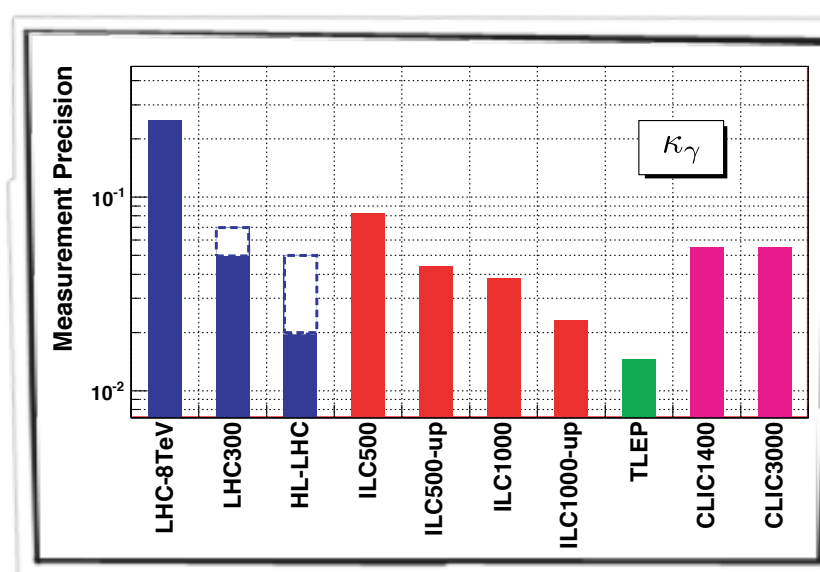
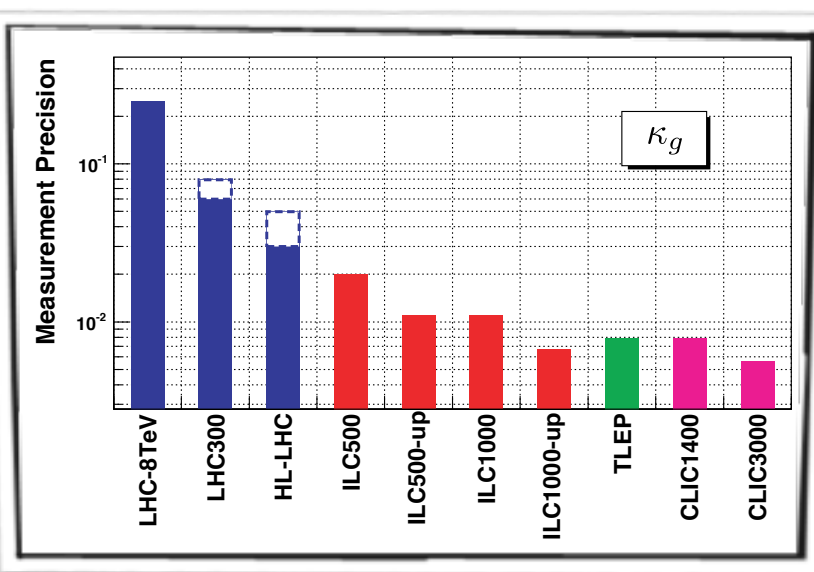
Grojean, Servant, Wells '04
Noble, Perelstein '07

⋮ New physics in loops ⋮

Katz, Perelstein '14

new particles, e.g. scalars, coupled to the Higgs without affecting its tree-level potential

$$V \propto \kappa |\Phi|^2 |H|^2$$



colored scalars



O(20%) deviation in $h \rightarrow gg$

(8%LHC₁₄, 5%HL-LHC, 1%ILC, <1%TLEP)

electrically charged scalars



O(5%) deviation in $h \rightarrow \gamma\gamma$

(5%LHC₁₄, 2%HL-LHC, 2%ILC, 1%TLEP)

SM neutral scalars



O(1%) deviation in $\sigma(ee \rightarrow Zh)$

(10%LHC₁₄, 2%HL-LHC, 0.25%ILC, 0.05%TLEP)

HH production as a probe of HE couplings

$$\sim c_t^2 \times \text{const.}$$

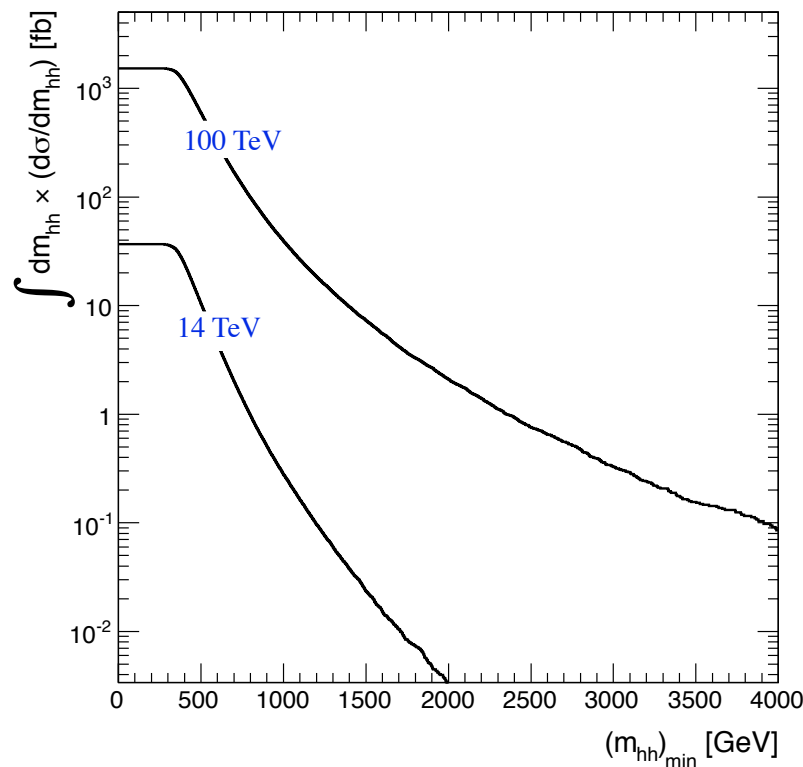
$$\sim c_t c_3 \times \frac{m_h^2}{\hat{s}} \log^2 \left(\frac{m_t^2}{\hat{s}} \right)$$

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

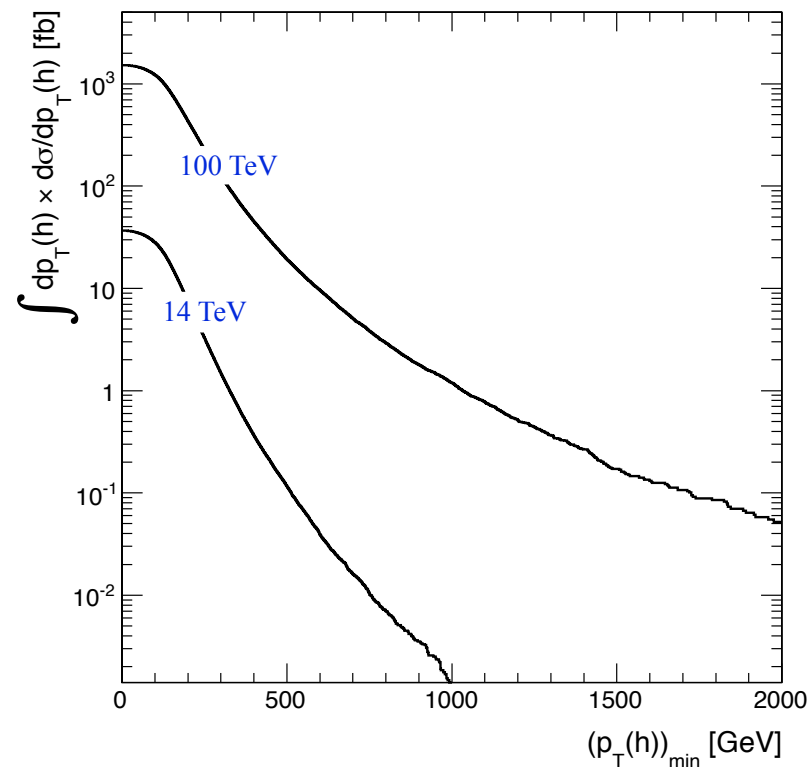
$$\sim c_g c_3 \frac{\alpha_s}{4\pi} \times \text{const.}$$

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

Signal (SM)

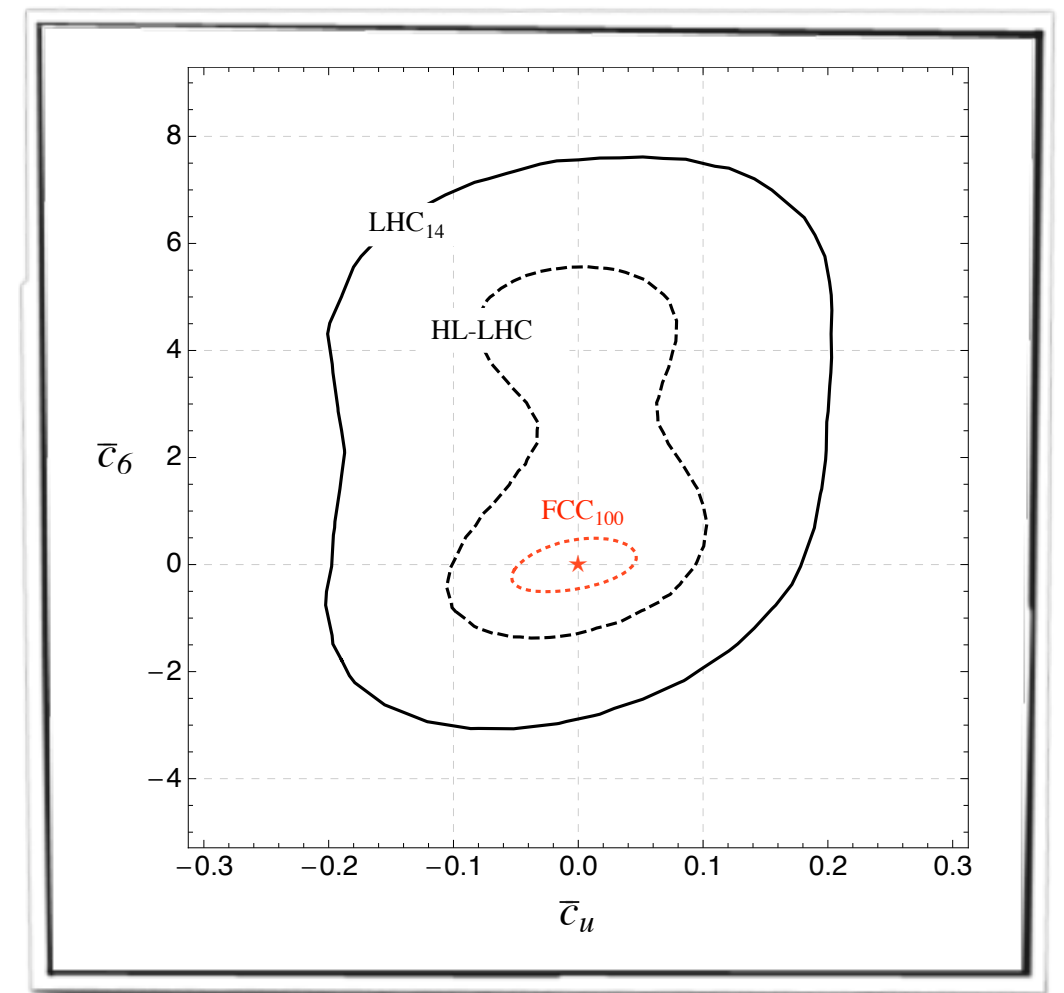
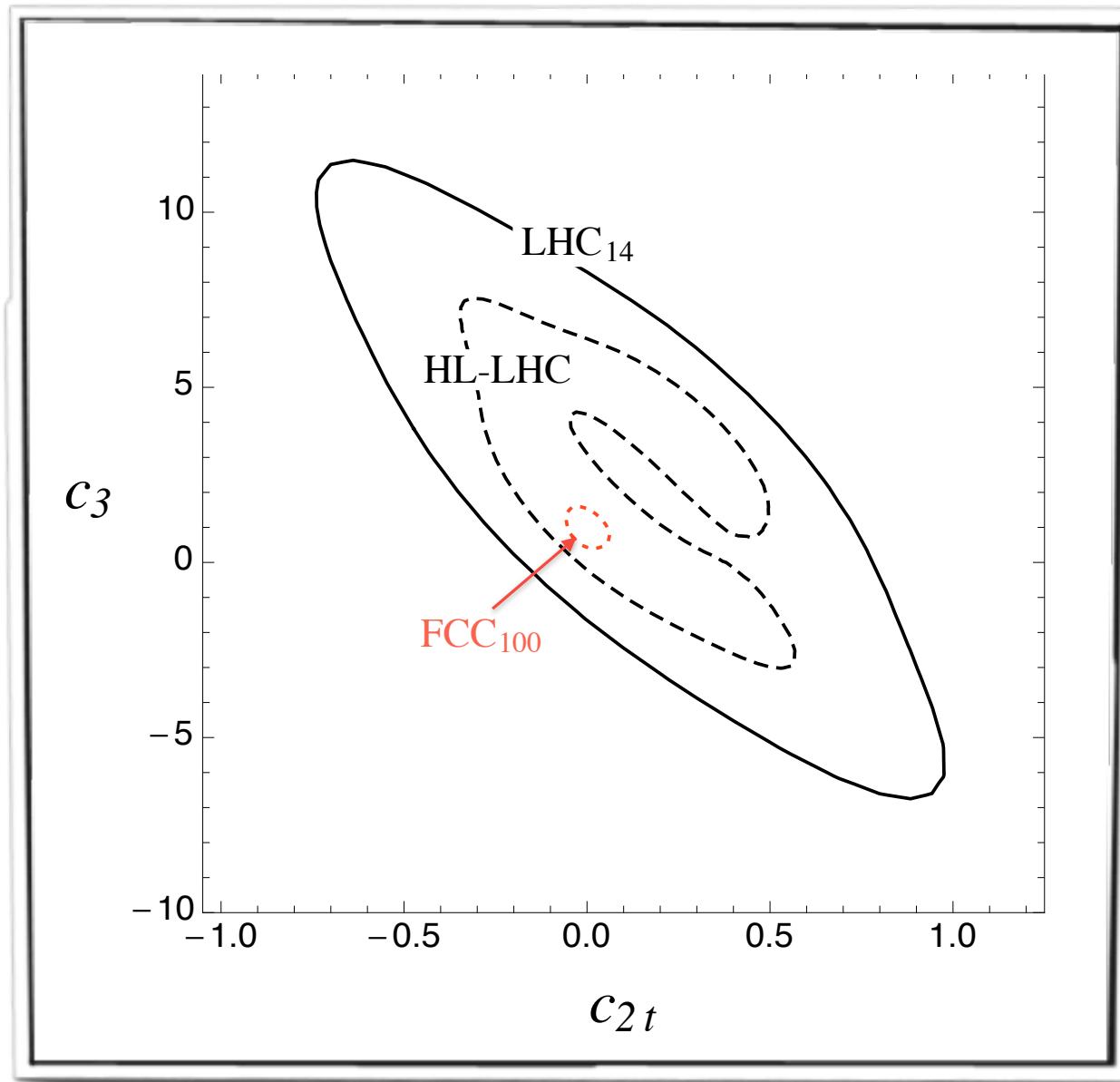


Signal (SM)



Azatov, Contino, Panico, Son '15

HH production 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

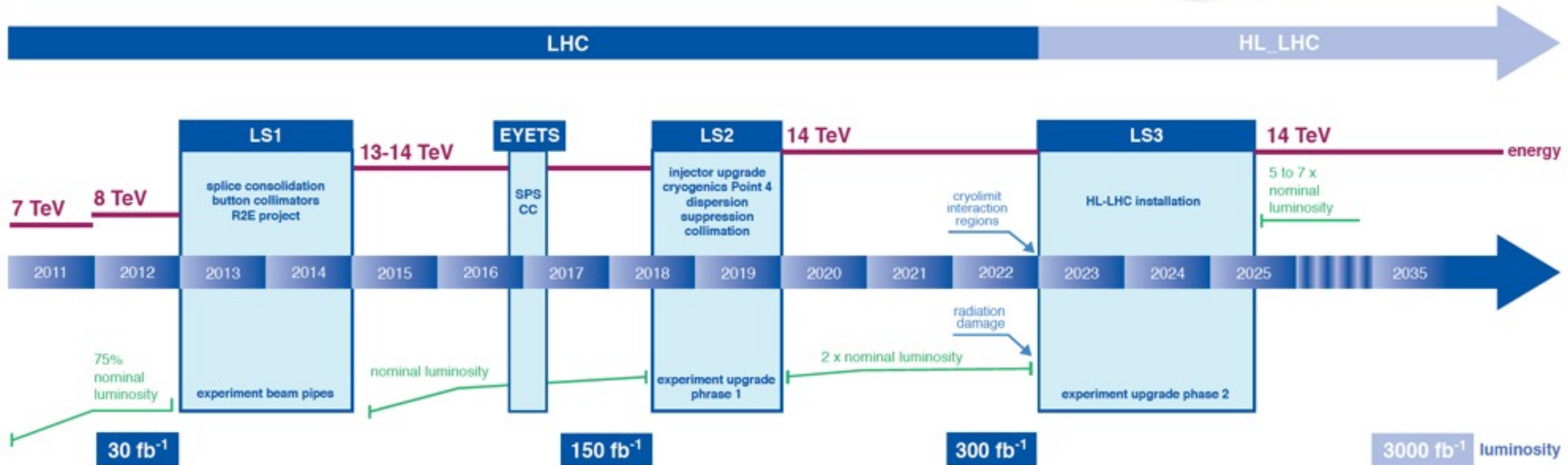


Future Colliders

HL-LHC (2023-2035)

14 TeV - 3/ab

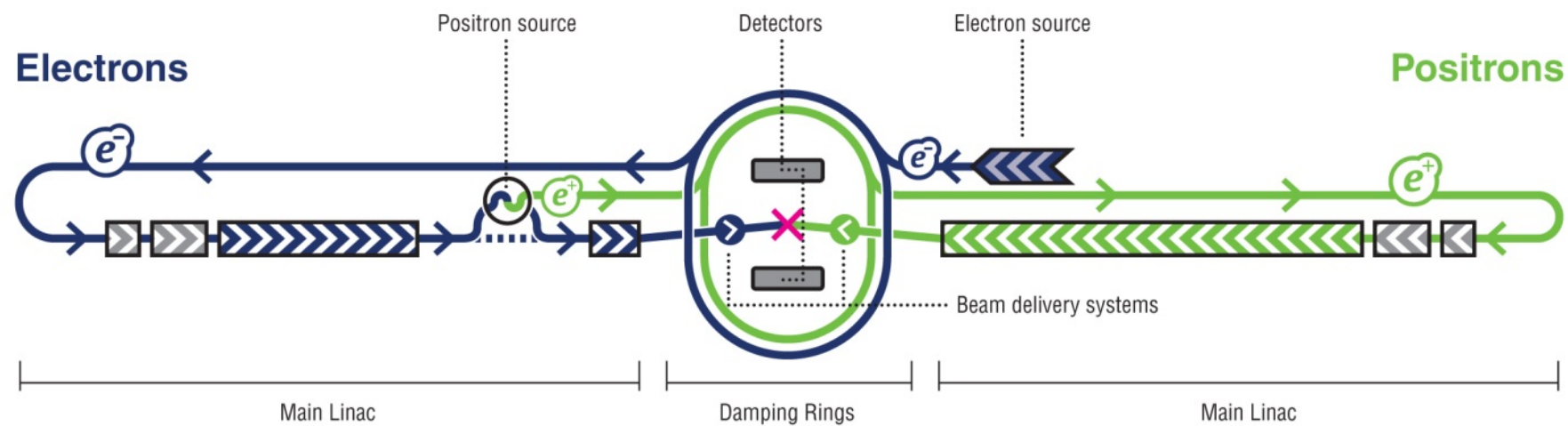
LHC / HL-LHC Plan



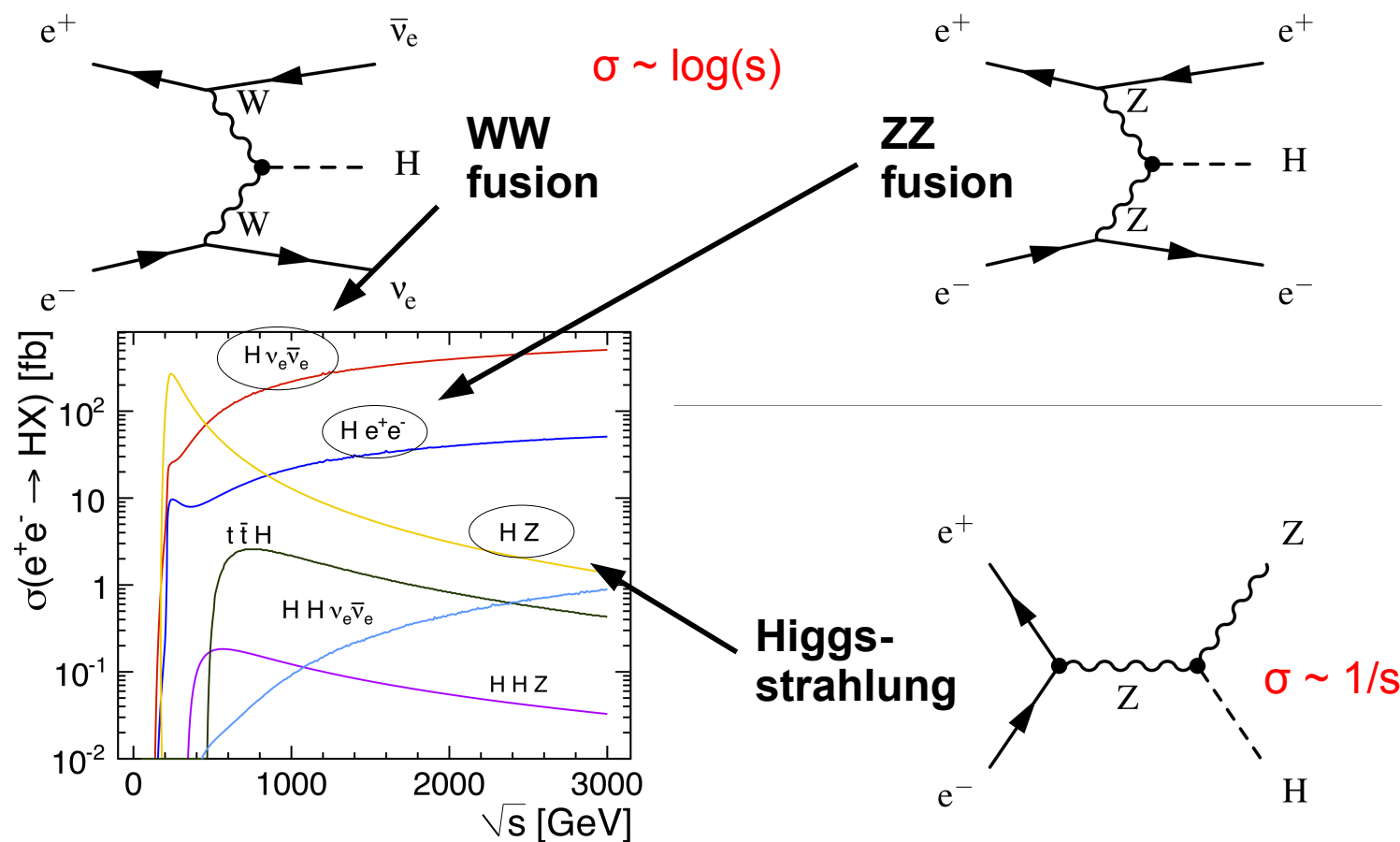
	Higgs bosons at $\sqrt{s}=14\text{TeV}$
HL-LHC, 3000fb ⁻¹	170M
VBF (all decays)	13M
ttH (all decays)	1.8M
H→Zγ	230k
H→μμ	37k
HH (all)	121k

		K_Y	K_W	K_Z	K_g	K_b	K_t	K_τ	$K_{Z\gamma}$	K_μ
300fb ⁻¹	ATLAS	[9,9]	[9,9]	[8,8]	[11,14]	[22,23]	[20,22]	[13,14]	[24,24]	[21,21]
300fb ⁻¹	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000fb ⁻¹	ATLAS	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]
3000fb ⁻¹	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

ILC

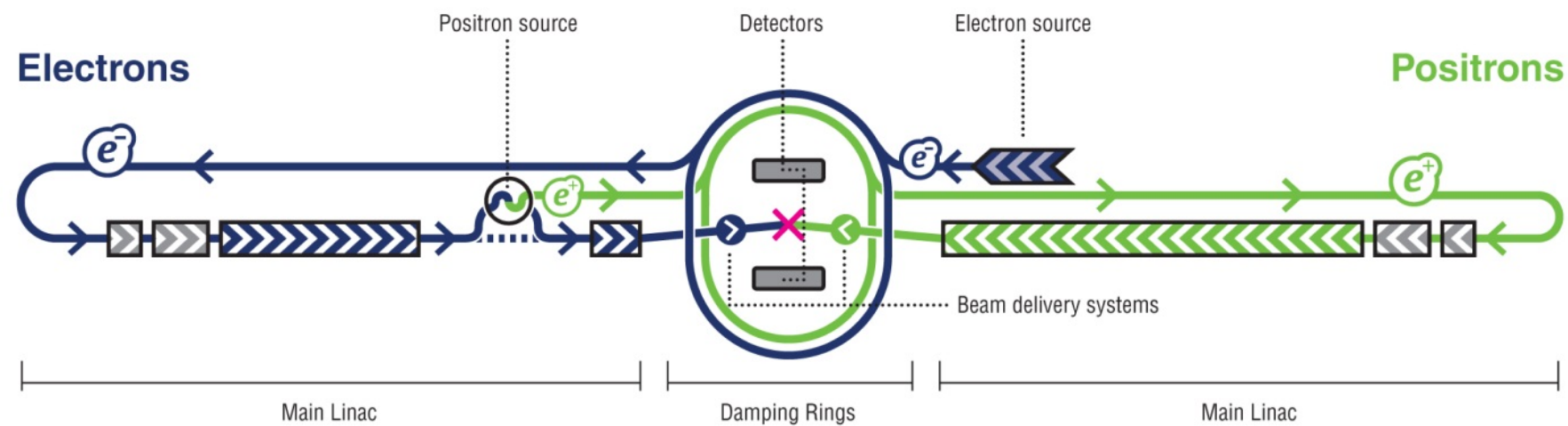


(350)/500/1000 GeV - 5/ab

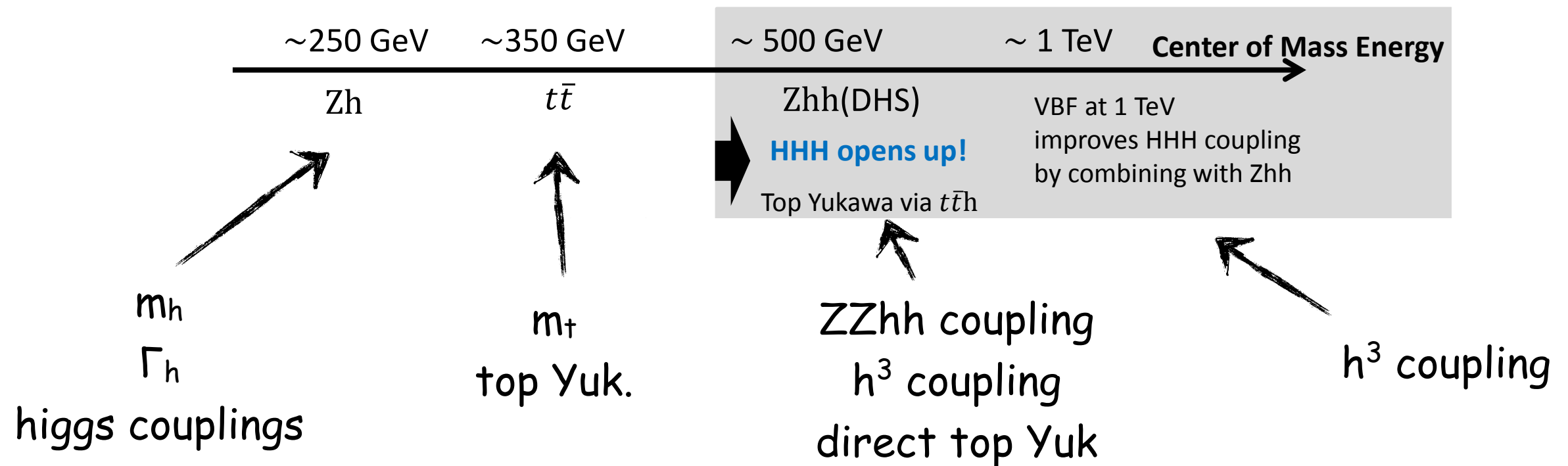


$O(10^6)$ Higgs produced and reconstructed

ILC

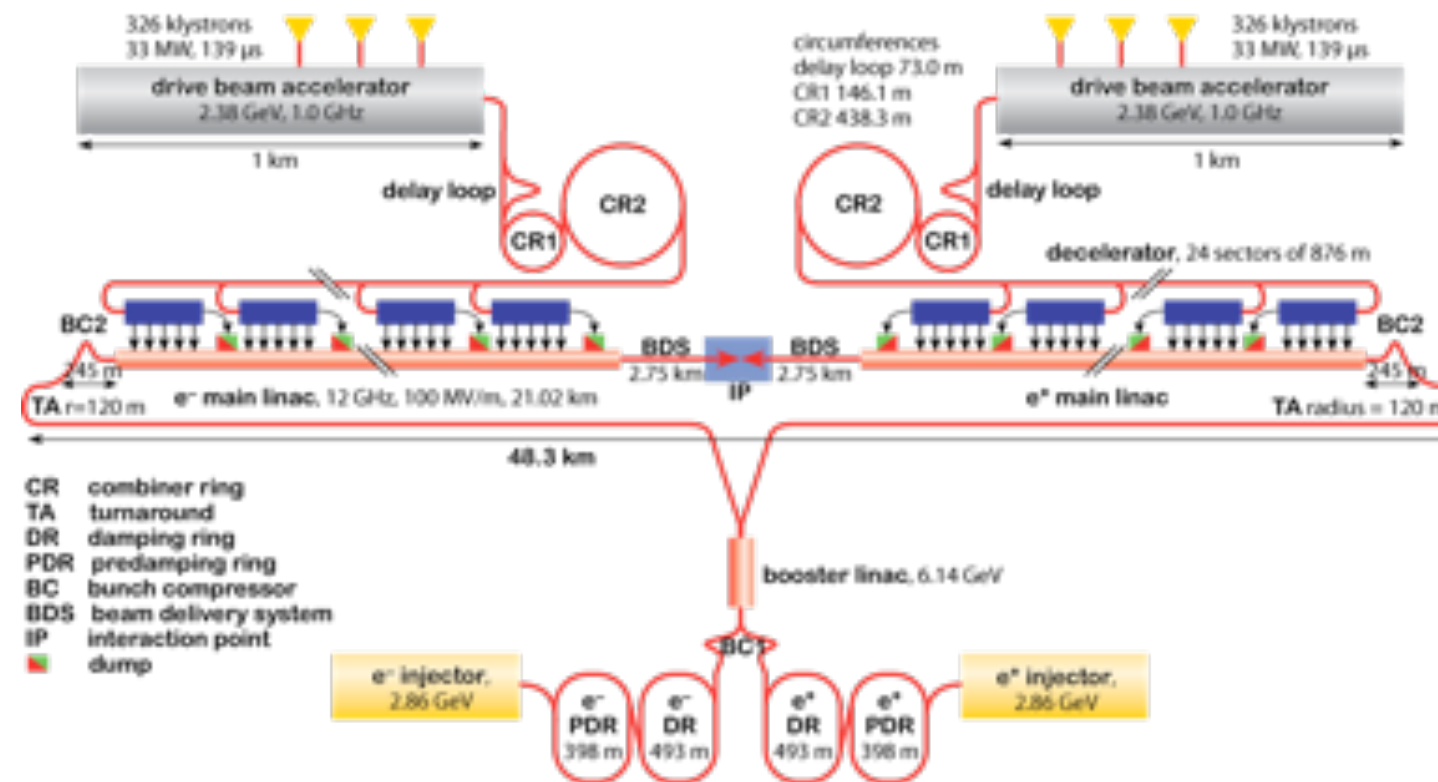


(350)/500/1000 GeV - 5/ab



$O(10^6)$ Higgs produced and reconstructed

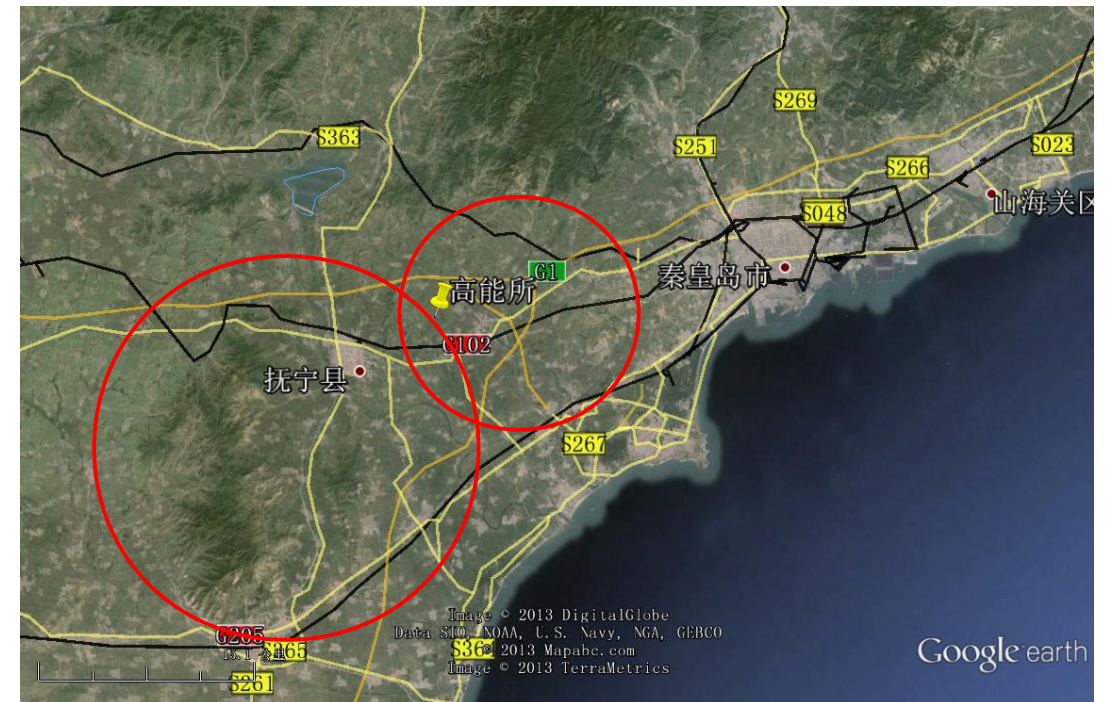
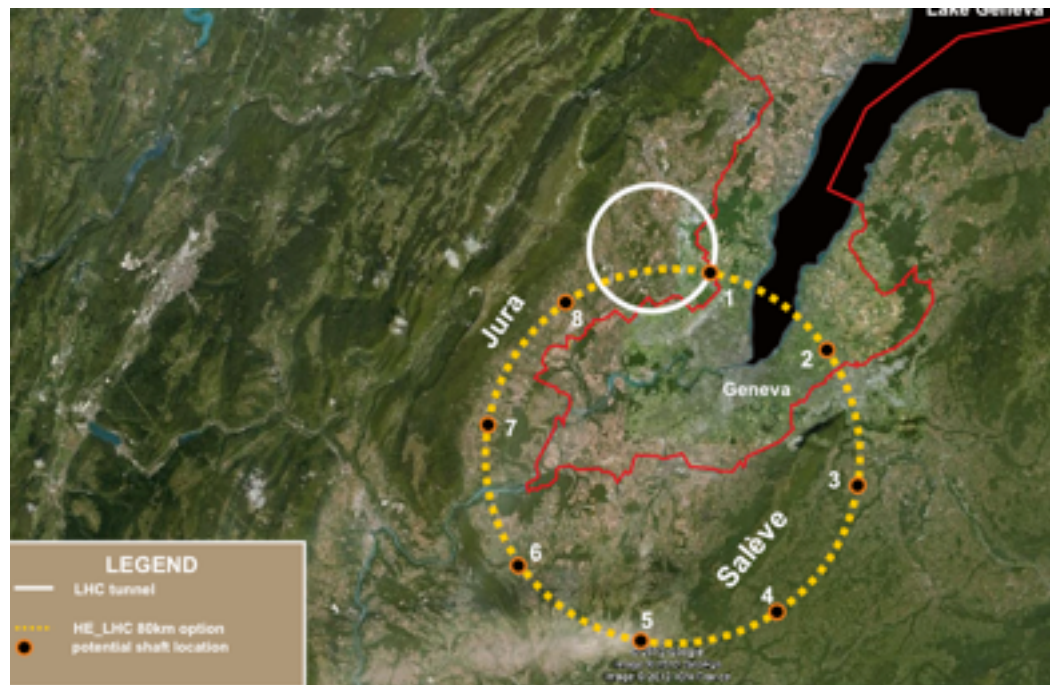
CLIC



(350)/1000/3000 GeV - 5/ab

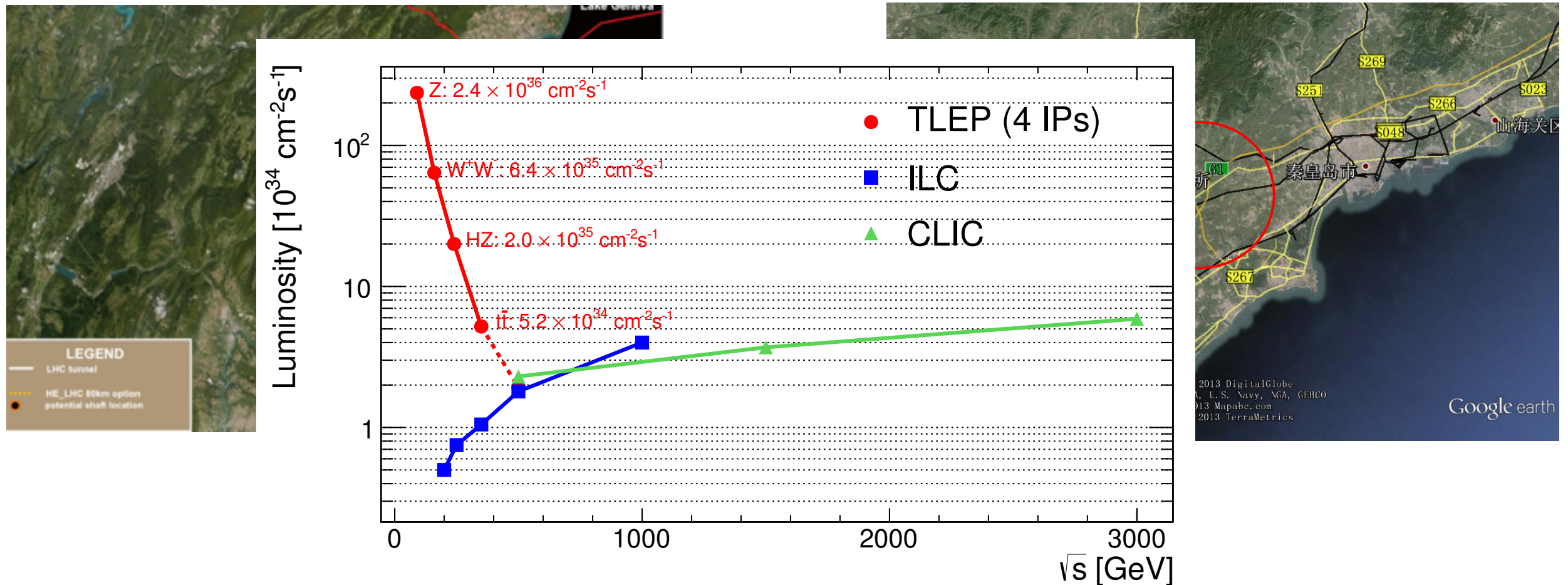
FCC-ee/CepC

240/350/(500) - 10/ab



FCC-ee/CepC

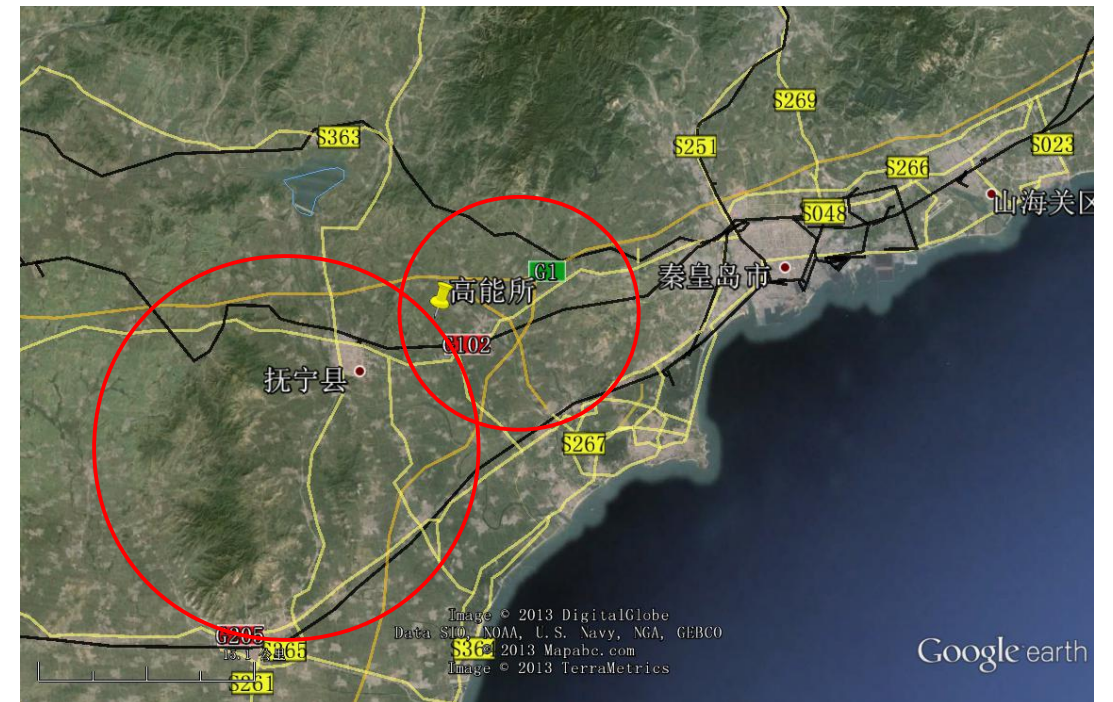
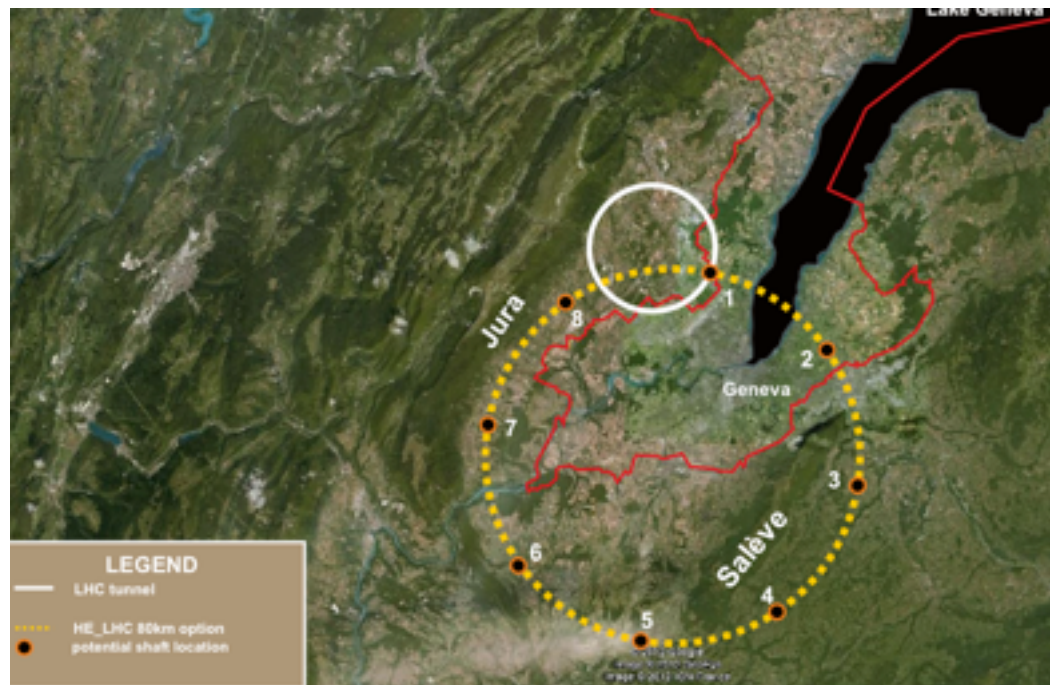
240/350/(500) - 10/ab



- 10^6 H
- 10^{12} Z (line-shape, mass & width, probe rare (FCNC) decays)
- 10^8 W (mass)
- 3×10^{10} tau/muon pairs
- 2×10^{11} b/c quarks $\Rightarrow >20'000 B_s \rightarrow \tau^+ \tau^-$
- TLEP@340/500: 10^6 top pairs (pole mass, probe FCNC decays, top Yukawa)

FCC-hh/CppC

80/100 TeV - 30/ab



SppC



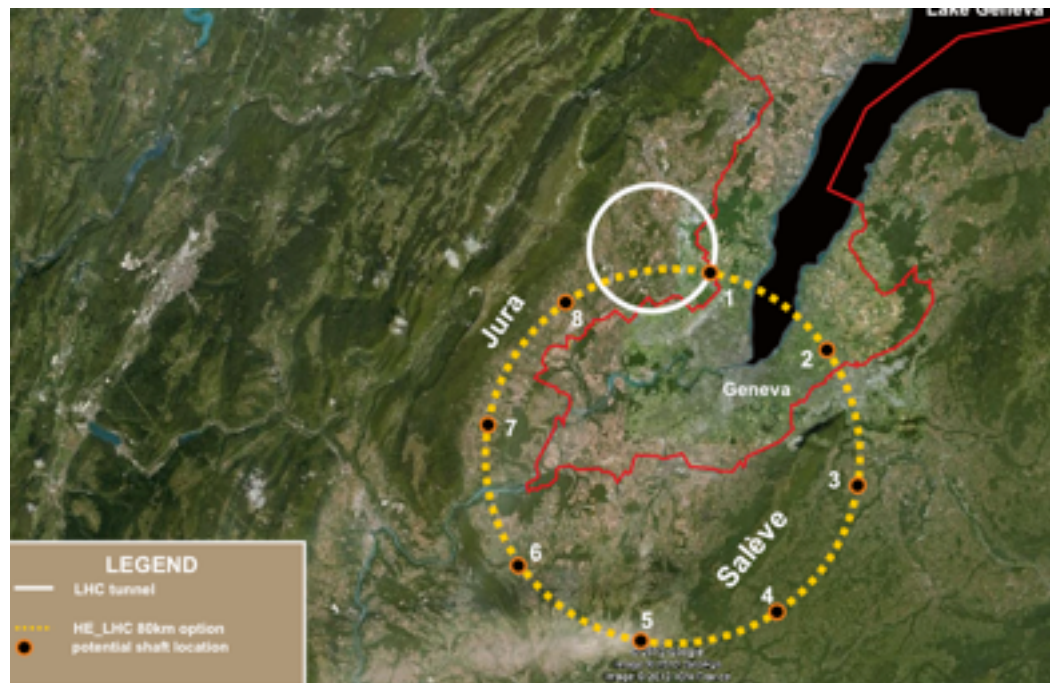
	σ	$N / 10ab^{-1}$
$gg \rightarrow H$	740 pb	7.4 G
VBF	82 pb	0.8 G
WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
$gg \rightarrow HH$	1.4 pb	14 M

10^{10} Higgs bosons $\Rightarrow 10^4 \times$ today

10^{12} top quarks $\Rightarrow 5 \times 10^4 \times$ today

FCC-hh/CppC

80/100 TeV - 30/ab



g _{HXY}	FCC-ee	FCC-hh
ZZ	0.16%	
WW	0.85%	
YY	1.7%	
Zγ		1% ?
tt		1% ?
bb	0.88%	
ττ	0.94%	
cc	1.0%	
ss	H→Vγ, in progr.	
μμ	6.4%	2% ?
uu,dd	H→Vγ, in progr.	
ee	e ⁺ e ⁻ →H, in progr.	
HH		5% ?
BR _{exo}	0.48%	< 10 ⁻⁶ ?

SppC

2020	2030
R&D (2014-2030)	Engineering Design (2030-2035)

	σ	N / 10ab ⁻¹
gg→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→HH	1.4 pb	14 M

10¹⁰ Higgs

10¹² tops

Higgs couplings measurement projections

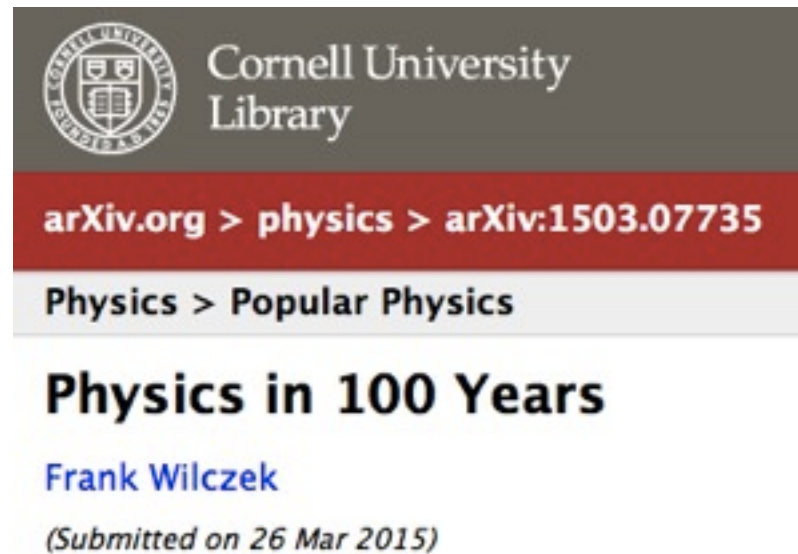
Table 1-20. Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). 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

Conclusions



- ▶ 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?

Higgs physics!

"The Higgs boson is the emergency tire of the SM"

G. Altarelli @ Blois 2010