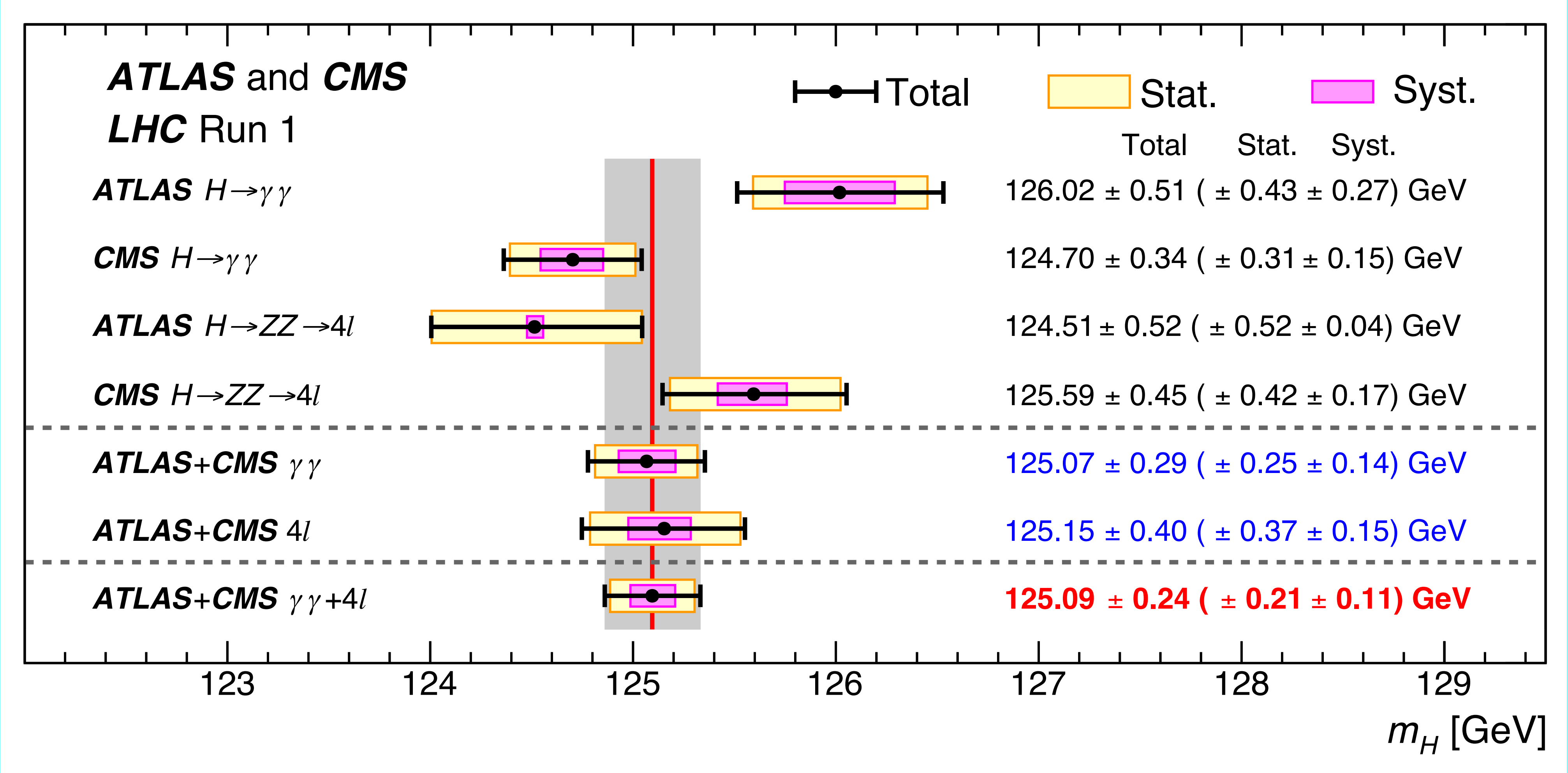
What Next? Mid Term

1-2 April 2015, LNF INFN Frascati, Italy



Higgs Physics

(is it worth the effort ?)

follow-up of La Biodola discussion…

Barbara Mele

INFN
Istituto Nazionale di Fisica Nucleare
Sezione di Roma

LNF, 2 April 2015

Outline

- where we stand today
- Higgs boson is there !
- SM Higgs sector ➜ Criticalities :
  - Naturalness
  - Flavor
  - Self-coupling
- Higgs sector ➜ Opportunities :
  - Higgs portal
  - Non-decoupling
  - ……
- Higgs boson as a "source" of Dark Photons
- Higgs self-coupling
- Outlook

no way to show here even a tiny fraction of the huge amount of beautiful LHC Higgs results, collected in the last 3 years !

where we stand today

(in one slide)

pp collisions: where we stand today

- LHC run at 7-8 TeV completed [$\int L \sim 5 + 20\ fb^{-1}$/ exp] (just initial LHC phase !)
  amazing performance → results well above expectations...
- SM tested at high accuracy in a new $\sqrt{s}$ range :
  QCD (many regimes), top physics, EW processes, flavor
- "direct" exploration of SM EWSB sector started up with observation of a (quite light) Higgs resonance !!!
- still a lot of room for a non-SM EWSB sector
- bounds on new heavy states predicted by many BSM models widely extended wrt pre-LHC era
- no real hint of BSM physics !
- SM Hierarchy-Problem solution getting harder...

SM-Lagrangian : basics

SM gauge group :

$SU(3)_{QCD} \times SU(2)_L \times U(1)_B$

spontaneusly broken via Higgs mechanism

$\rightarrow SU(3)_{QCD} \times U(1)_{em}$

Higgs Lagrangian :

$$\mathcal{L}_{\rm Higgs} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi^\dagger \phi) - \bar{\psi}_L \Gamma \psi_R \phi - \bar{\psi}_R \Gamma^\dagger \psi_L \phi^\dagger$$

$$V(\phi^\dagger \phi) = -\mu^2 \phi^\dagger \phi + \frac{1}{2}\lambda(\phi^\dagger \phi)^2$$

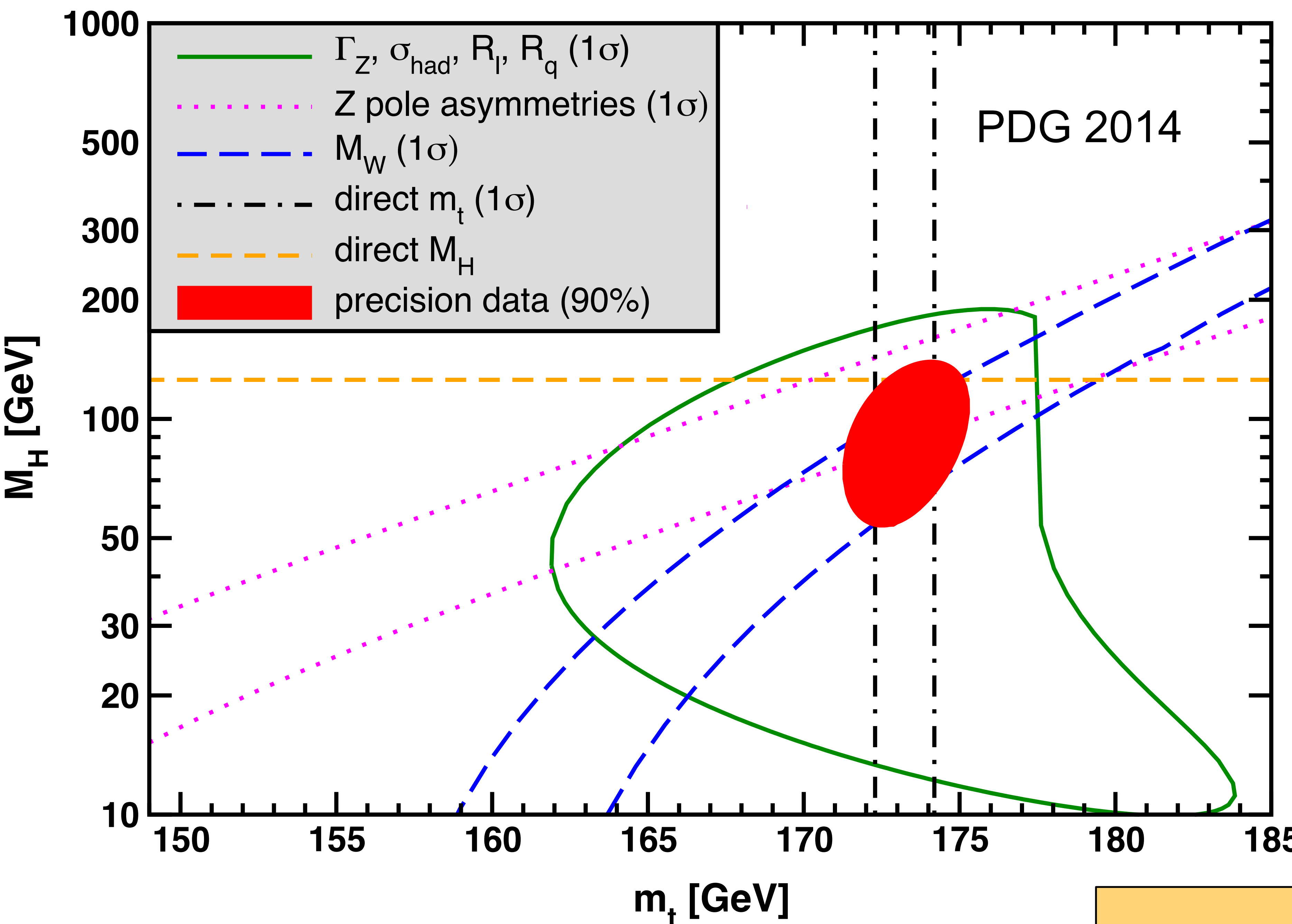
$$m_H^2 = 2\mu^2 = 2\lambda v^2$$

masses fix all Higgs interactions

built up just by imposing

- gauge invariance (L_{SM} singlet of SM group)
- renormalizability [D ≤4 operators]

Higgs observation → triumph of SM (and LHC !)



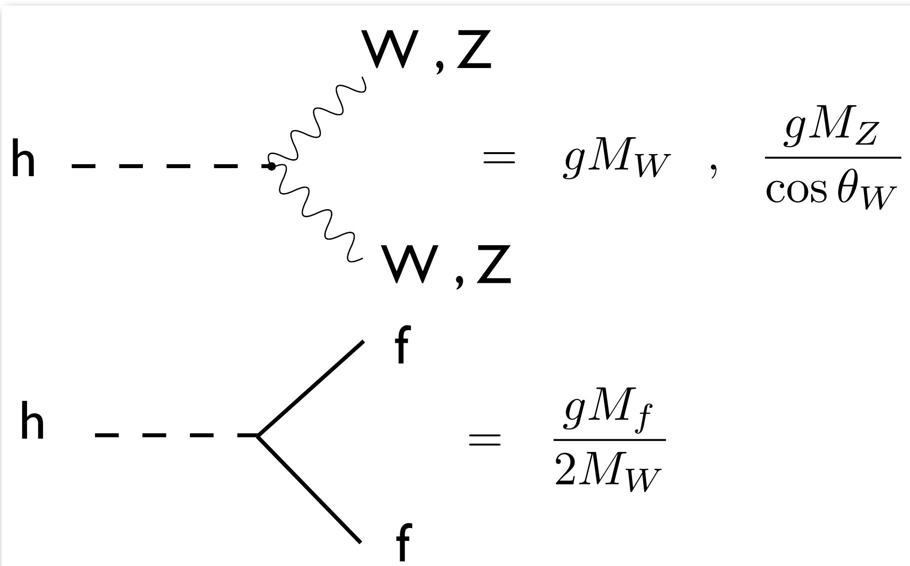
"invisible" width !
(m_H error band)

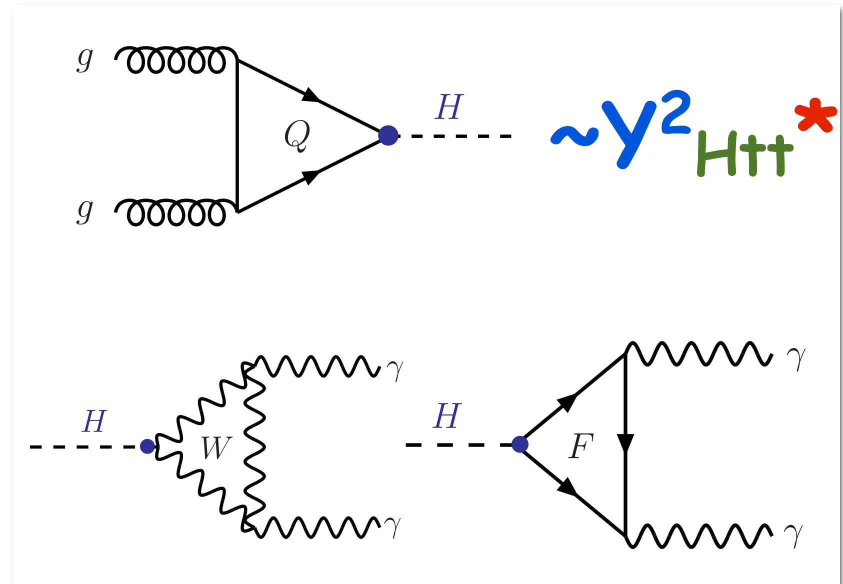
red area is 90% CL
prediction from EWPTs

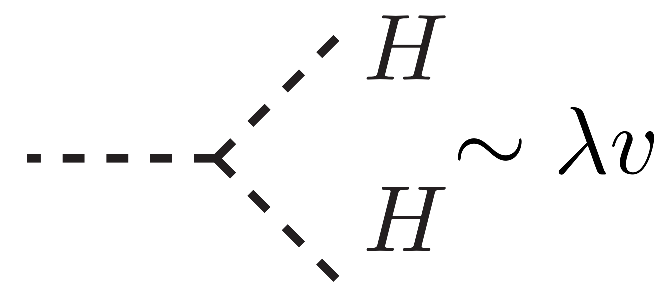
last missing
SM state !

is LHC signal really a SM Higgs ?

- test g_{HXX} (magnitude and structure) to vector bosons (EWSB), to fermions and self-couplings







$m_H \sim 125$ GeV

$\Gamma_H = 4.2$ MeV

$\lambda = (m_H / v)^2/2 = 0.131$

$H \to WW^*$ 23%*

$H \to ZZ^*$ 2.9%*

$H \to bb$ 56%*

$H \to cc$ 2.8%

$H \to \tau\tau$ 6.2%*

$H \to \mu\mu$ 0.21‰

$H \to gg$ 8.5%*

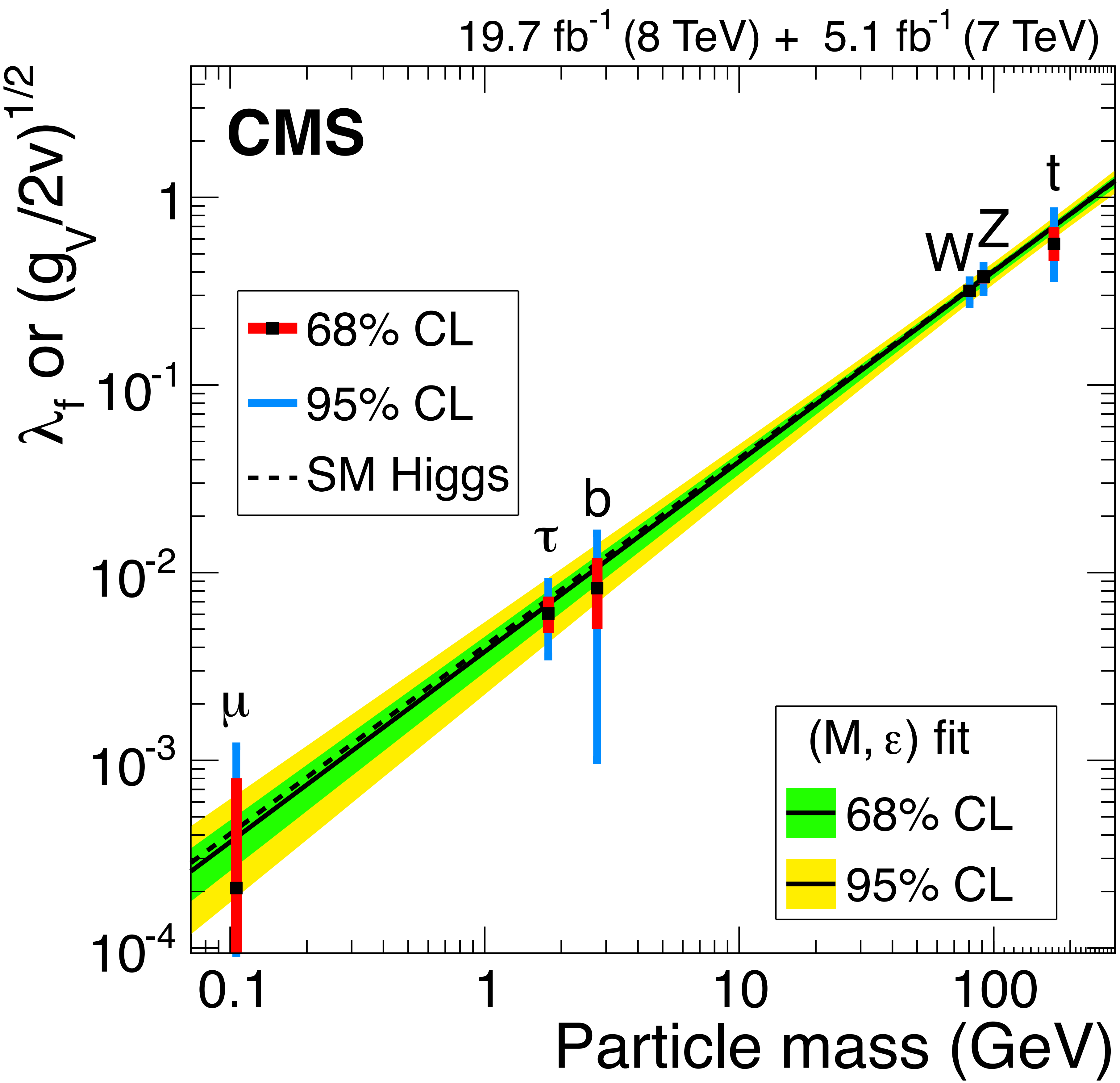
$H \to \gamma\gamma$ 2.3‰*

$H \to \gamma Z$ 1.6 ‰*

new set of reference SM parameters

most couplings accessible at LHC (*) !

a clear SM footprint is emerging : $g_{HXX} \sim m_X^{(2)}$



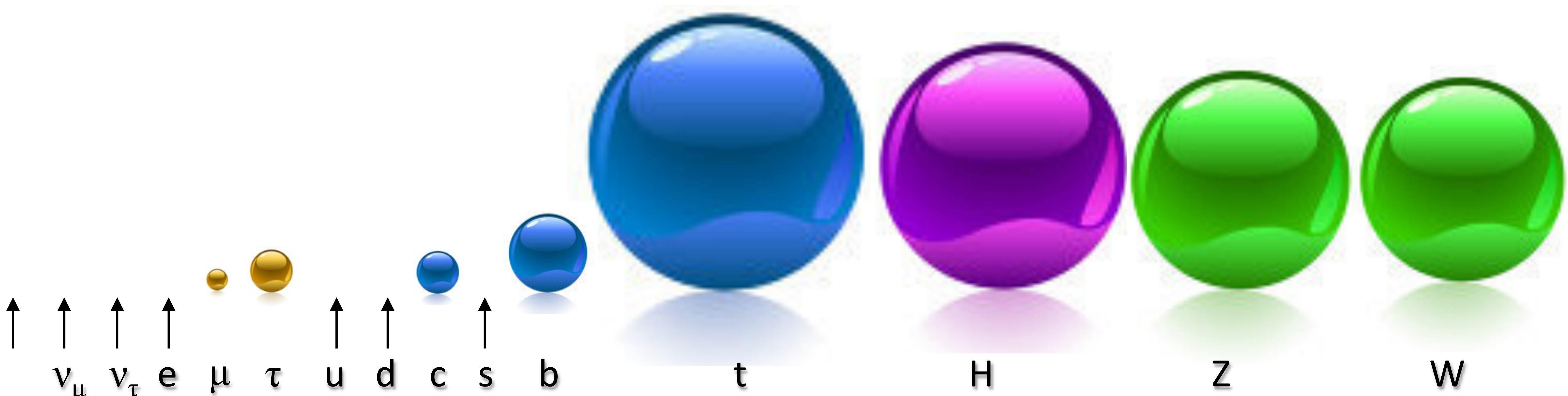
it is not a generic scalar state!

SM pattern well matched within errors !

Mystery in Hierarchy of SM Yukawa's

$$\mathcal{L}_{Y_f} \sim \frac{m_f}{v} \bar{f} f H$$

m_f's span many orders of magnitudes…



courtesy of R. Chierici

origin of Flavor Symmetry Breaking ?

$$Y_{top} = \frac{\sqrt{2}\, m_t}{v} \simeq 1 \quad (???)$$

SM is not enough !

- SM beautifully successful at E < 1 TeV, but has some "messy features" (flavour sector...), and does not explain a number of things (strong CP, neutrino sector, baryogenesis, Dark Matter...)

- crucial issue for Collider Physics (and LHC !) :

what is the expected Energy THReshold (E_{THR}) to go BSM ???

$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda' H^4$$

M_H unprotected by Symmetries !

- quadratic divergences on fundamental-scalar mass

drive M_H to the next energy threshold E_{THR} !

→ to avoid huge Fine-Tuning of parameters, one expects roughly :

$$E_{THR} \sim M_H / g_{coupling} \sim o\,(1\ \text{TeV})$$

- this was (before LHC start-up), and STILL IS (after Run 1), a ROBUST statement !!!

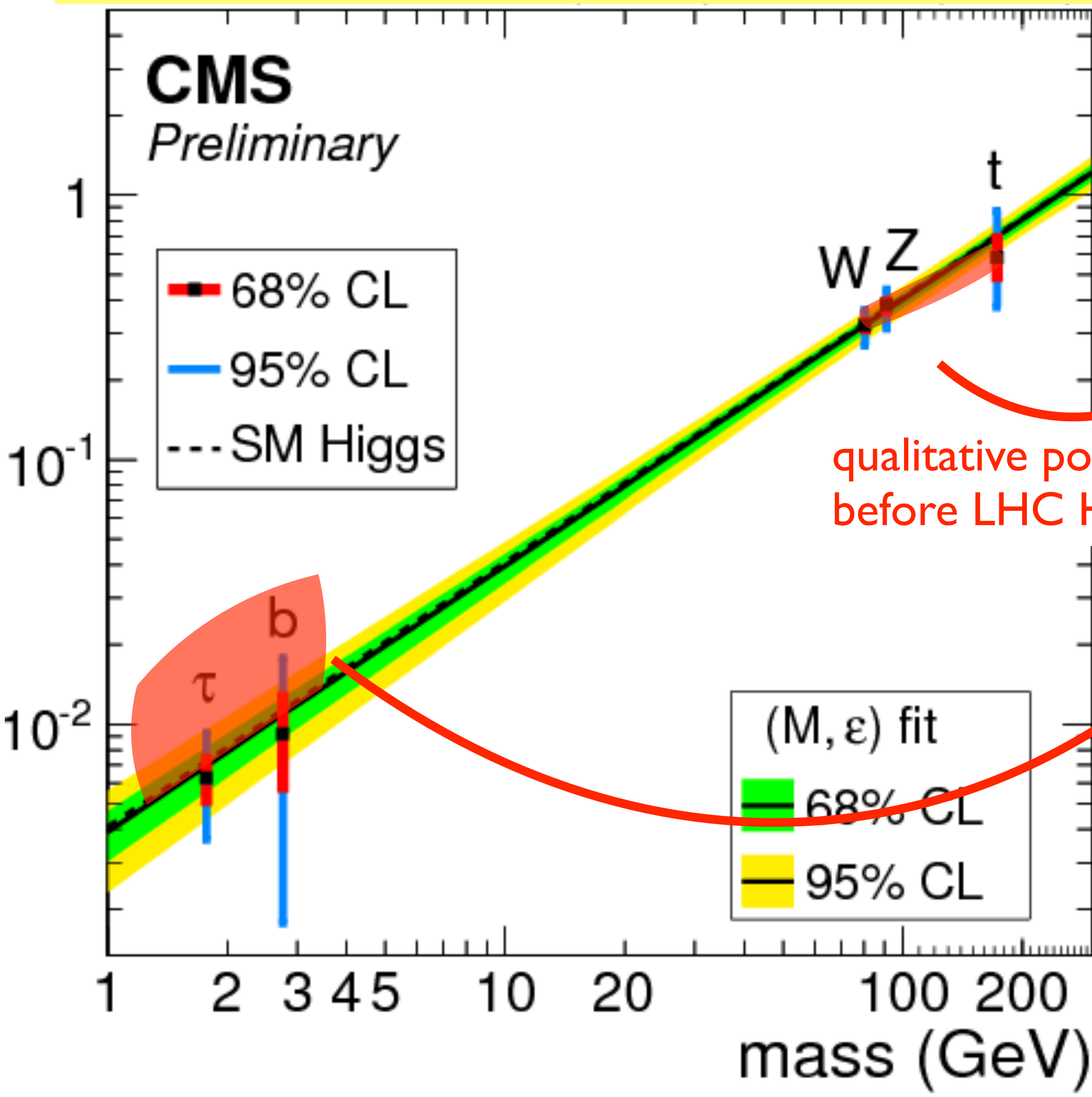
WARNING !

the exact way E_{THR} materializes (→ enters theory) depends on the actual (yet unknown !) SM extension

▷ after LHC Run I, Simplest Versions of "PROPOSED" Models look quite Fine-Tuned !

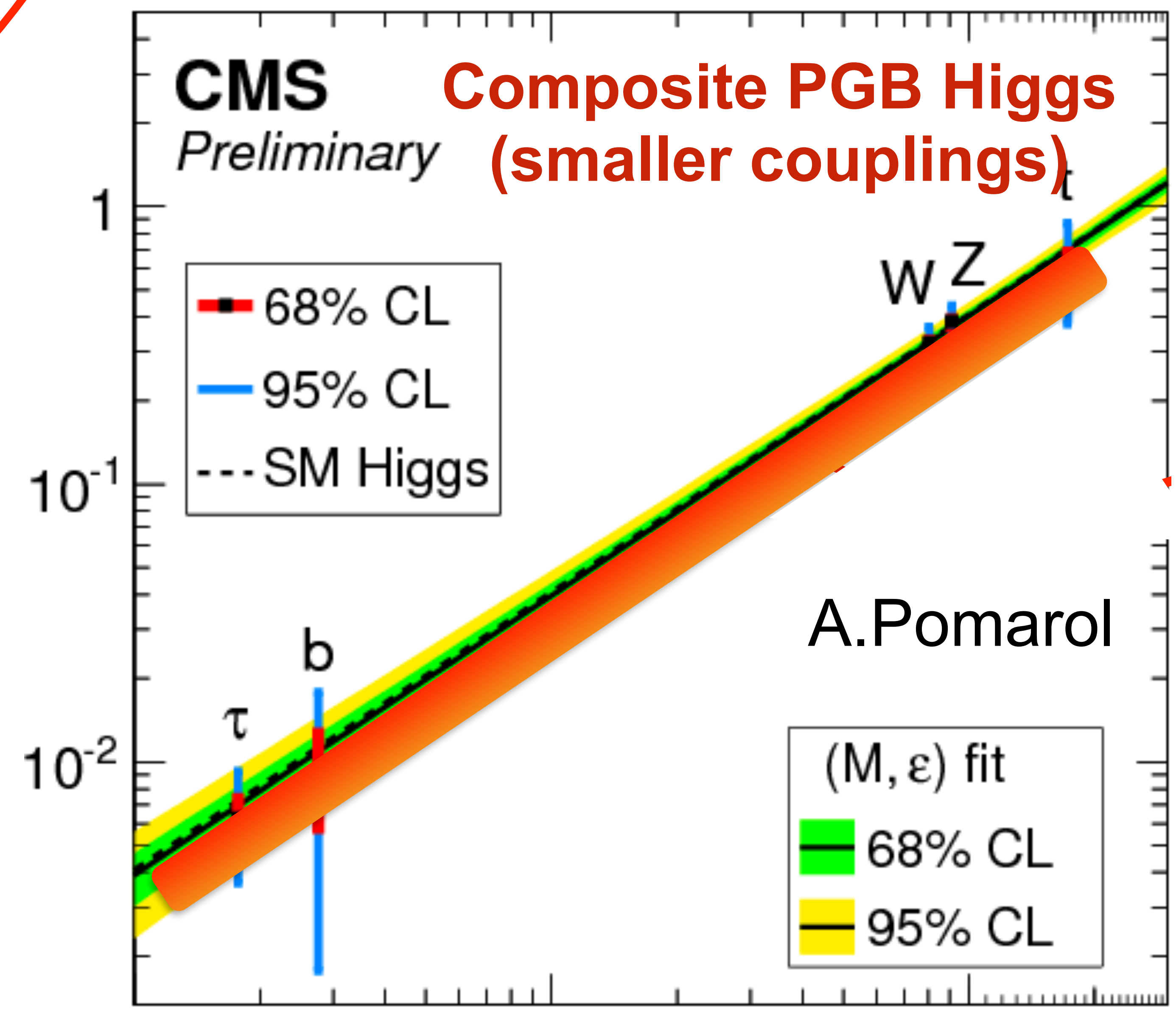
a ROBUST statement too !!!

Higgs is an invaluable probe of BSM sectors



MSSM (light h)

qualitative possible ranges
before LHC Higgs data

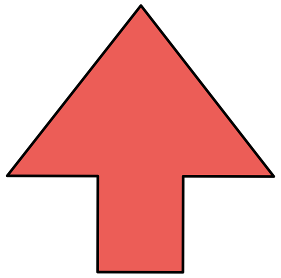


typical deviations
in H couplings in
'natural' Higgs models:
few % → 10's %

largest contributions to g_{HXX} from BSM

	g^h_{ff}	g^h_{VV}	κ_{GG}	$\kappa_{\gamma\gamma}$	$\kappa_{Z\gamma}$	g_{3h}
MSSM	✓					✓
NMSSM	✓	✓	✓	✓	✓	✓
MCHM	✓	✓			✓	✓
SUSY Composite Higgs	✓	✓				✓
Higgs as a Dilaton			✓	✓	✓	✓
Partly-Composite Higgs			✓	✓	✓	✓
Bosonic TC						✓

Pomarol, arXiv:1412.4410



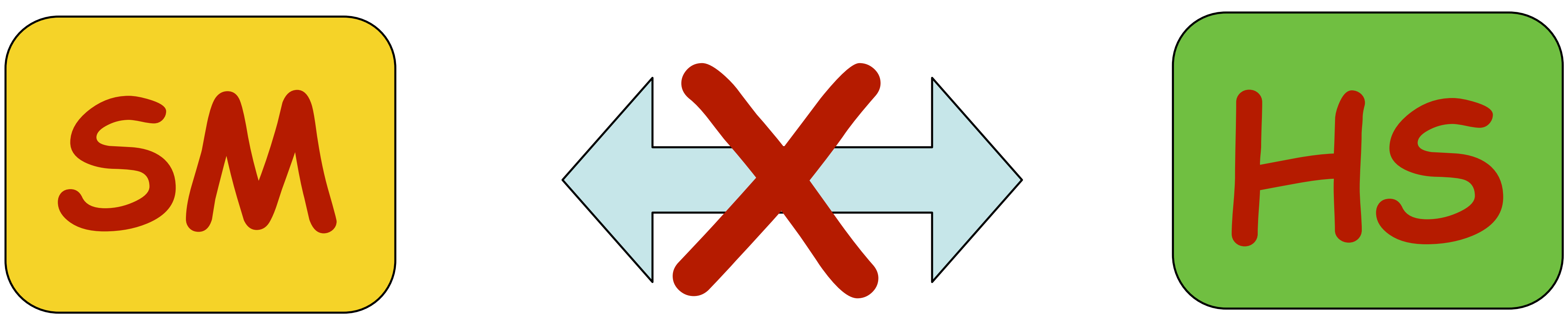
possible hint of cracks in SM could come before new heavy-states observation !

Higgs is also a privileged probe of Hidden Sectors !

Sectors UNCHARGED (= singlet) under the SM gauge group (and vice versa)”

$$L[D] \sim [SM]_{singlet} \times [HS]_{singlet} \,/\, [E]^{(D-4)}$$

in general, with D≤4 operators (→ no mediator) :



but 4D terms mixing SM and HS in the Lagrangian possible in few cases !

Higgs-portal SM ↔ HS interaction

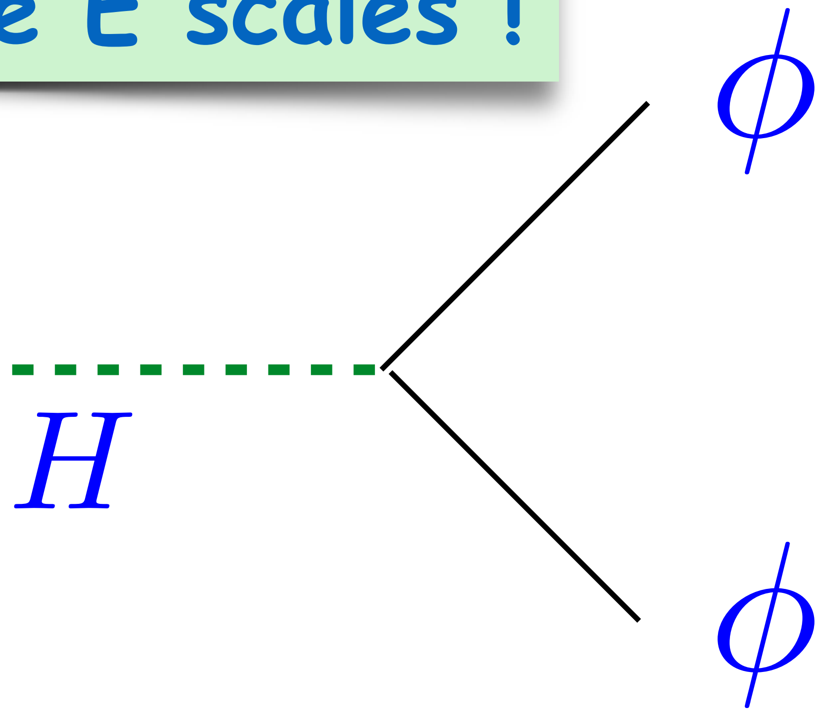
$$L \sim 1/[E]^{(D-4)} \quad [SM]_{singlet} \times [HS]_{singlet}$$

- new Hidden-Sector scalar ϕ interacting with the SM Higgs $H^\dagger H$ operator :

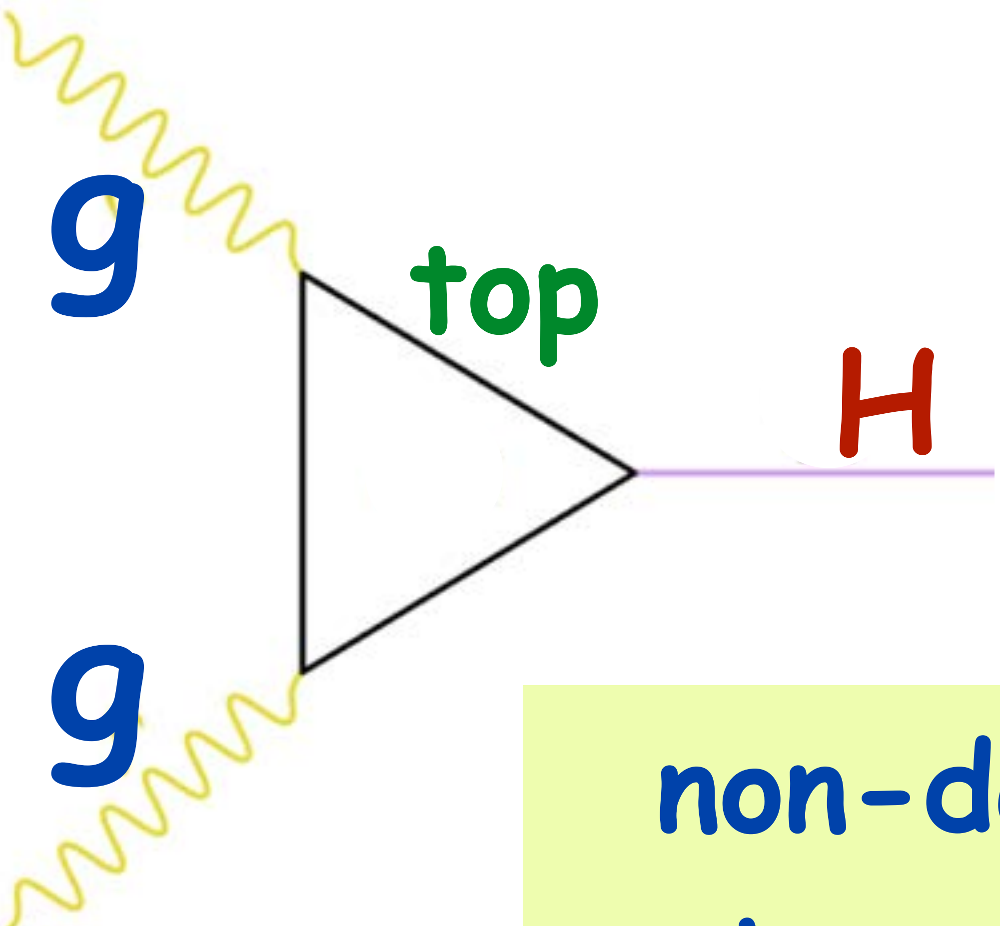
Higgs-portal : $\mathcal{L}_{D=4} \sim \phi^\dagger \phi \, H^\dagger H$ [D=4]

not suppressed by large E scales !

can contribute to H invisible width !



Higgs non-decoupling !



$$A_{gg\to H} \sim \frac{Y_{top}}{m_{top}} \to \frac{1}{v}$$

$$(m_{top} \to \infty)$$

non-decoupling can also apply to new heavy chiral states !

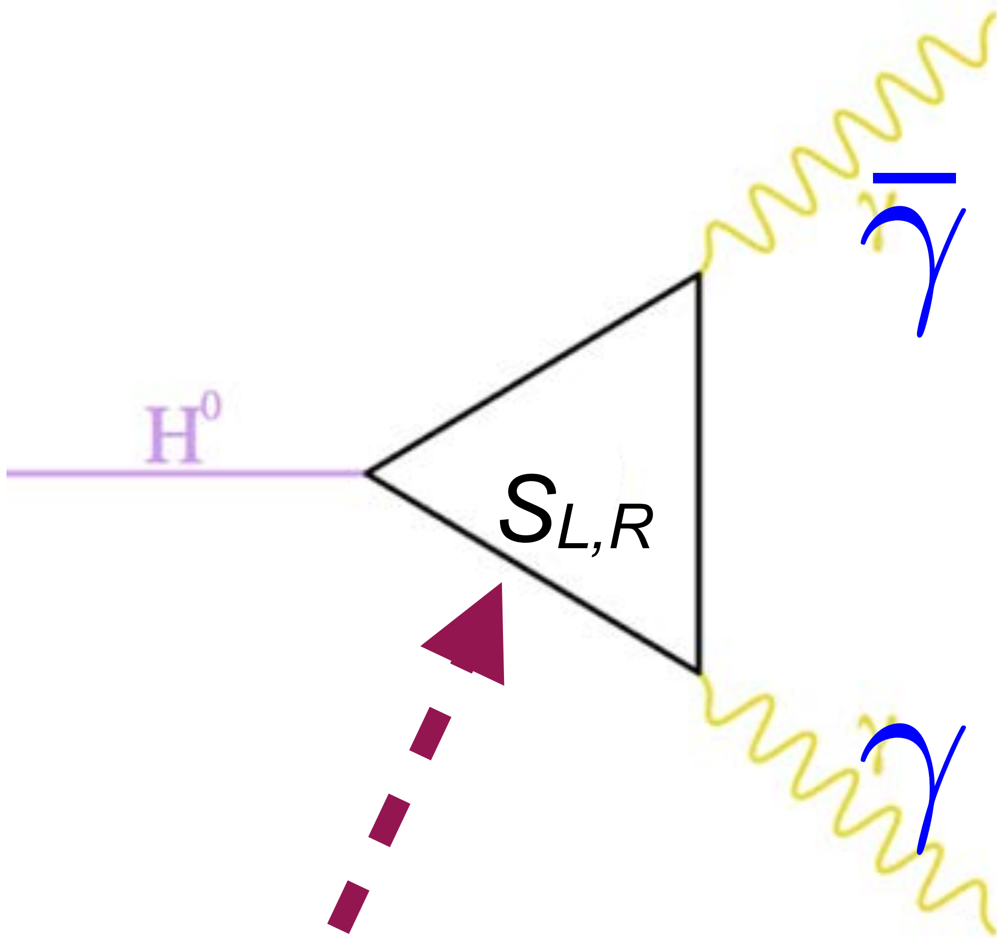
→ finite (potentially large) effects from heavy BSM states !

Higgs as a "source" of Dark Photons

Gabrielli et al, arXiv:1405.5196

$$H \to \gamma\bar{\gamma}$$

mono-photon
resonant signature



massless (invisible)
Dark Photon

(mediating long-range $U(1)_F$ force between Dark particles)

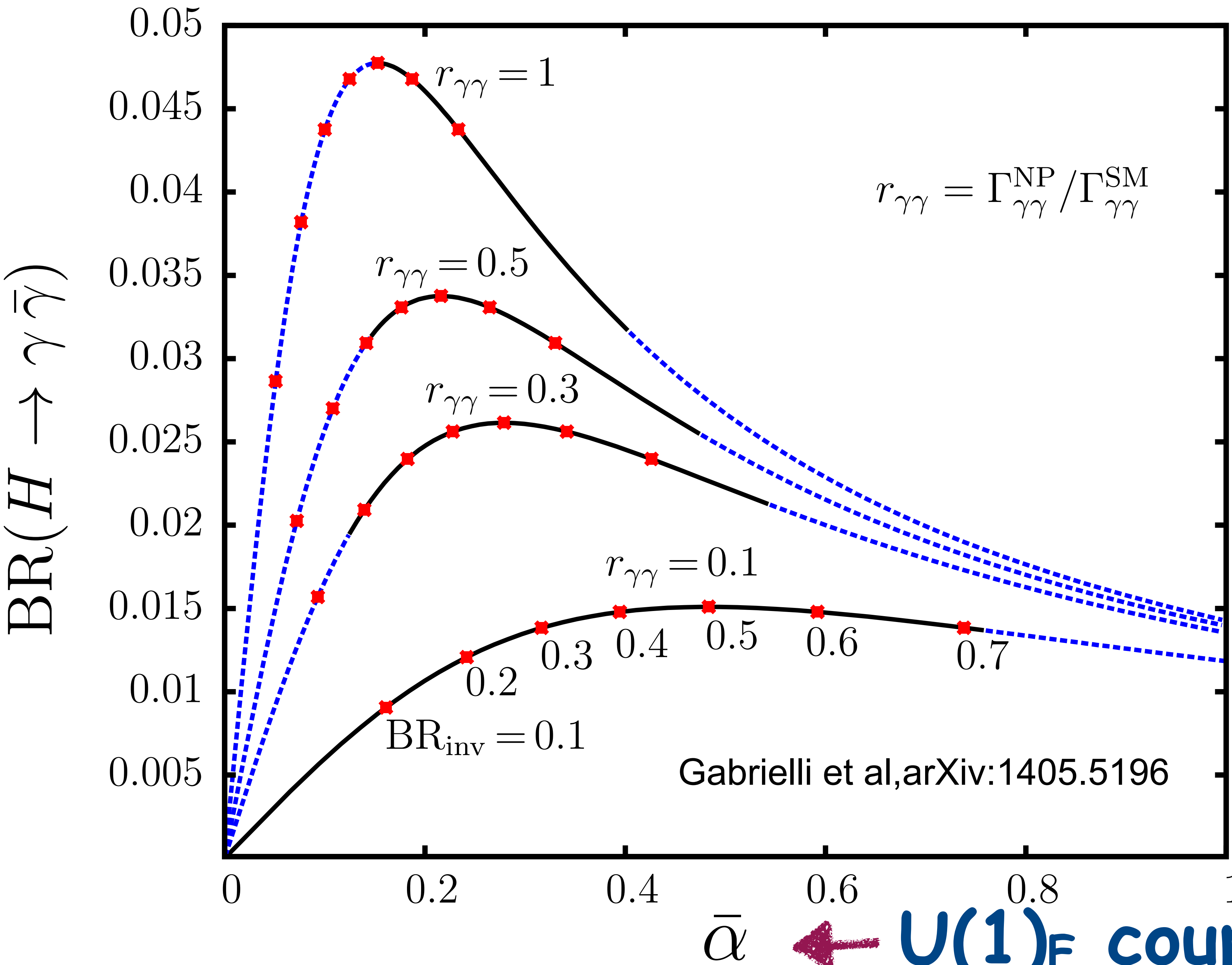
heavy scalar messengers (squark/slepton-like)

connecting SM to Dark-Fermion sector (Dark Matter?, Yukawa origin and hierarchy?)

H non-decoupling effects (just as in SM) possible:

$$\Gamma(H \to \gamma\bar{\gamma}) \sim \frac{1}{M^2_{Heavy}} \to \frac{1}{v^2}$$

$BR_H(\bar{\gamma}\gamma)$ prediction in minimal models



← $U(1)_F$ coupling

similar loop effects contribute to :

$H \to \gamma\gamma$

$H \to \bar{\gamma}\bar{\gamma}$

affects BR_{inv}:

solid lines corresponds to :

$\mathrm{BR}^{SM}_{\gamma\gamma}/2 \leq \mathrm{BR}_{\gamma\gamma} \leq 2\ \mathrm{BR}^{SM}_{\gamma\gamma}$

$\mathrm{BR}(H \to \gamma\bar{\gamma})$
up to 5% !

resonant mono-photon signature

$$H \to \bar{\gamma}\gamma$$

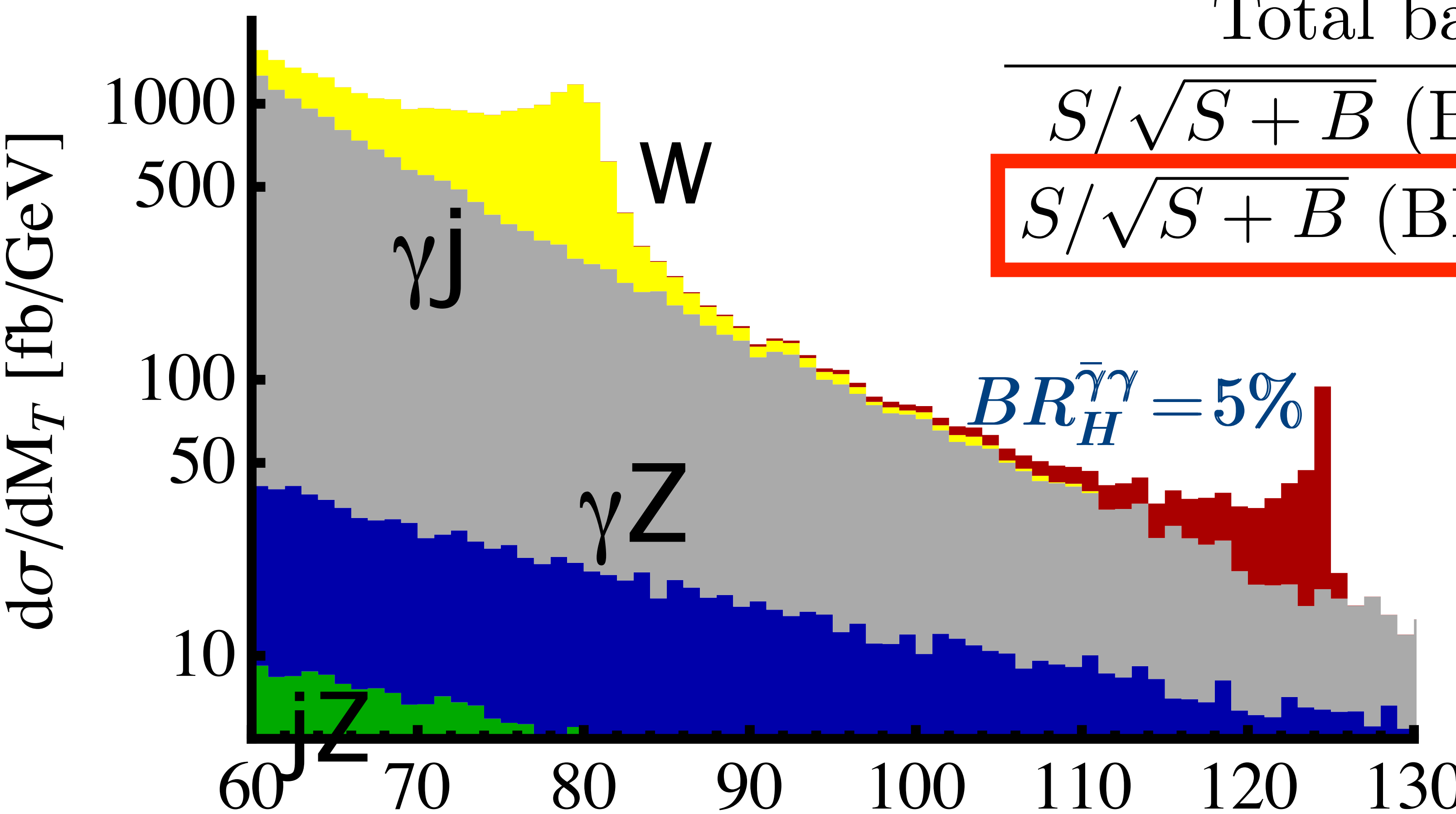
$E_{miss} \sim E_{\gamma} \sim m_H/2$

(A_1) 50 GeV $< p_T^{\gamma} <$ 63 GeV (A_2) 60 GeV $< p_T^{\gamma} <$ 63 GeV

σ (fb)	$\sigma \times A_1$	$\sigma \times A_2$
Signal $BR_{H\to\gamma\bar{\gamma}} = 1\%$	65	34
γj	715	65
$\gamma Z \to \gamma\nu\bar{\nu}$	157	27
$jZ \to j\nu\bar{\nu}$	63	11
$W \to e\nu$	22	0
Total background	957	103
$S/\sqrt{S+B}$ ($BR_{H\to\gamma\bar{\gamma}} = 1\%$)	9.1	13.0
$S/\sqrt{S+B}$ ($BR_{H\to\gamma\bar{\gamma}} = 0.5\%$)	4.6	6.9

(8TeV/20fb^{-1})

$$M_T = \sqrt{2 p_T^{\gamma} \not{E}_T (1 - \cos\Delta\phi)}$$



(parton-level analysis) M_T [GeV]

Gabrielli et al,arXiv:1405.5196

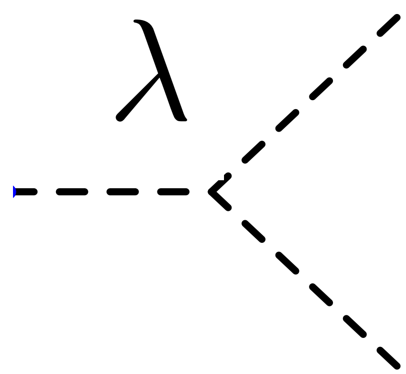
model-independent measurement of BR_{DP}!

Higgs self-couplings

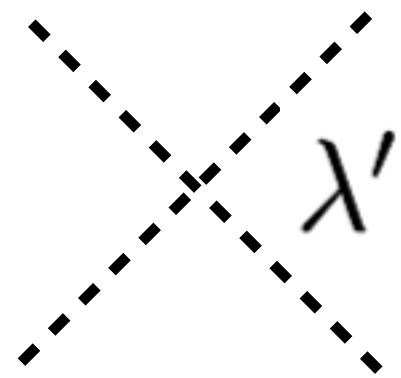
- **in the SM :** $V(H) = \frac{1}{2} M_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda' H^4$

$$\lambda = \lambda' = M_H^2/(2v^2) = 0.13$$

m_H directly related to Higgs dynamics !

- 

needs HH in final states



needs HHH

out of reach !

- **BSM** : Max λ deviations compatible with no other BSM observation: few % to ~20%

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$

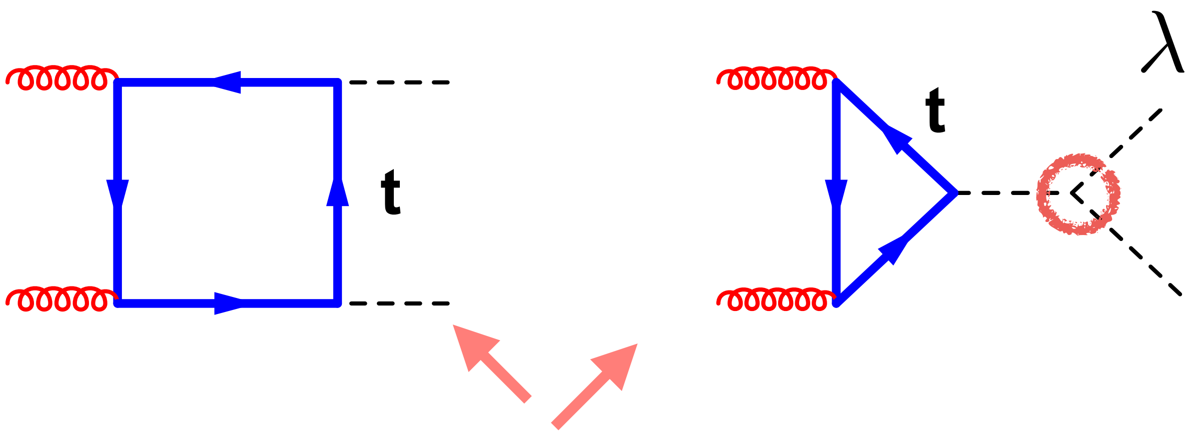
Gupta et al, arXiv:1305.6397

➜ target for both TH and EXP accuracies !

bad news ! → tiny SM HH rates !

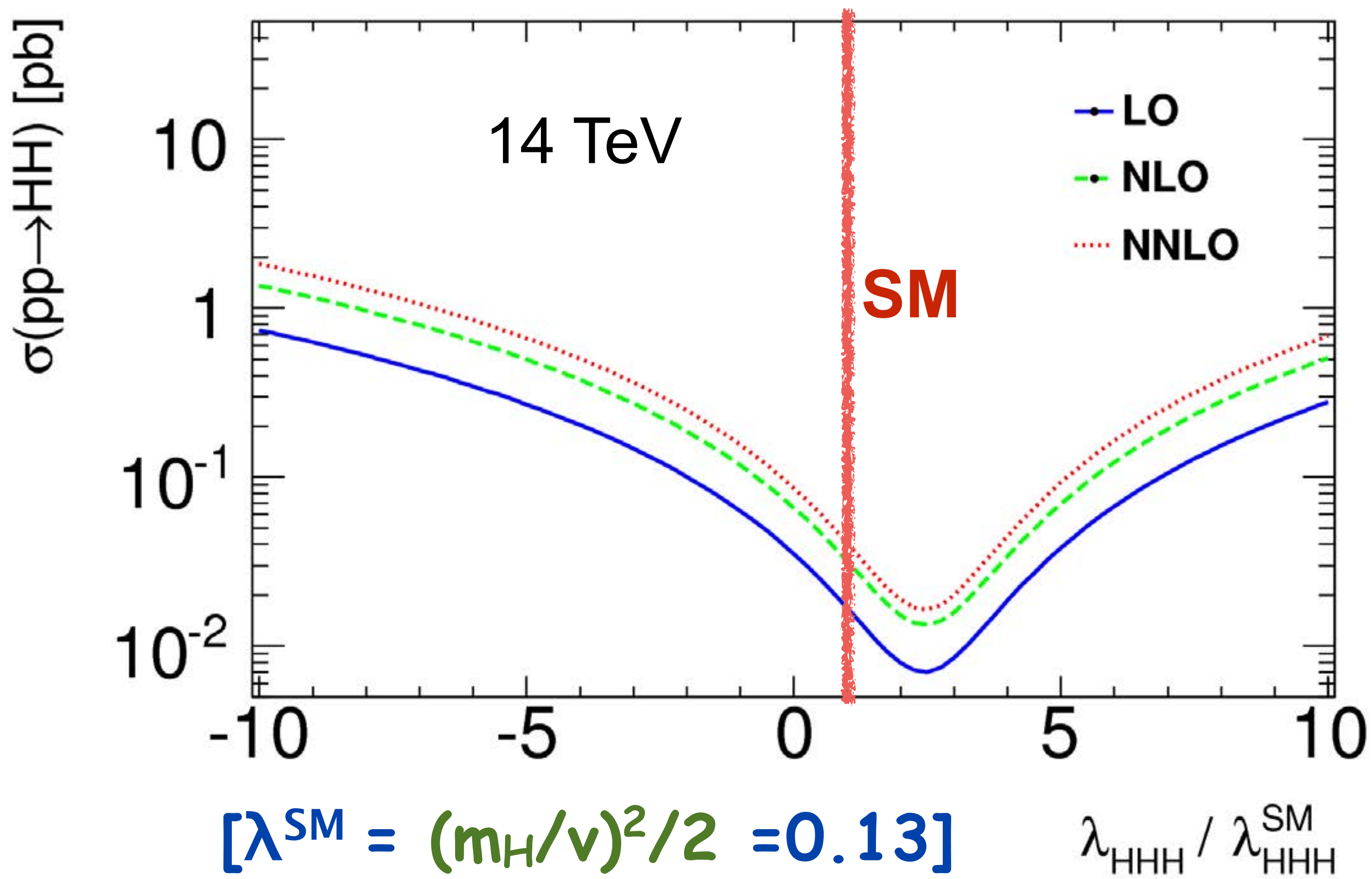
- dominant production in pp collisions :

$$gg \to HH$$



destructive interference
ruled by y_t and λ

$\sigma(HH)_{SM} \sim 10^{-3}\ \sigma(H)_{SM}$



$[\lambda^{SM} = (m_H/v)^2/2 = 0.13]$

- other production channels have σ < 1/10 $\sigma(HH)$:

$qq' \to HHqq'$ $q\bar{q}' \to ZHH/WHH$ $q\bar{q}, gg \to t\bar{t}HH$

present Δ_{TH} on $\sigma(gg \to HH)$ ~ 40% !

(SM) HH rates at HL-LHC (ev/3000fb^{-1})

Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

(40.8 fb NNLO HH)

selection of HH final states has to account for:

- final states experimentally clear and robust
- final states with large enough production rate

HH → bbWW [large rates but S(~10^3)/B(tt pairs)~10^{-4}]

HH → bbγγ [clean but small rates], (also HH → bb[ττ,bb,ZZ,μ μ])

HH → bbγγ (Snowmass studies)

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L} dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

a lot of work still needed to assess the actual HL-LHC sensitivity to λ H^3 coupling !

will likely benefit a lot from new exp strategies developed in Run 2 and knowledge of actual HL detector upgrades

(3σ significance (SM) / 3ab^{-1} doable ?)

e+e- colliders

ILC TDR + Snowmass projections

	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$	1500	+2000
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0, 0)/(-0.8, 0)$	$(0, 0)/(-0.8, 0)$
$\sigma\,(ZHH)$	42.7%		42.7%	23.7%	–	–
$\sigma\,(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%		
λ	83%	46%	21%	13%	28/21%	16/10%

based on bbbb and WWbb simulation at ILC
and bbbb at CLIC
(to be improved - ongoing simulations)

needs full luminosity program !

Outlook

- SM is not enough…
- Higgs boson is the first elementary (?) scalar field observed in nature

  → it comes together with quite a few criticalities !
- in the SM Lagrangian, the Higgs sector is the most exposed to BSM effects → measurement of Higgs properties is one of the best ways to "indirectly" discover new physics (and discriminate among different BSM's)
- possibility of exotic signatures in Higgs decays
- Higgs boson observation opened up an entire new chapter of BSM exploration
- in case of no observation of new heavy states in the next LHC run, precision Higgs physics will have a key role in paving the way for extending the SM theory…

BACK-UP

Higgs-coupling accuracy projections

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%