Concluding talk

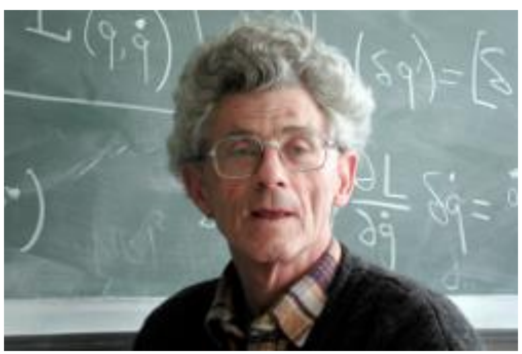
Fabio Zwirner
CERN PH-TH
University and INFN Padua
ERC Advanced Grant DaMeSyFla

Higgs Hunting 2015
LAL-Orsay, 1 August 2015

This 6th Higgs Hunting workshop is dedicated to the memory of

Yoichiro Nambu (1921-2015)

who introduced spontaneous symmetry breaking in particle physics



Raymond Stora (1930-2015)

a pioneer of quantization of gauge theories and teacher of many french physicists

and wise advisor of theorists of all seniorities worldwide

PLAN

- Preamble
- H(125) results
- SM theory & MC tools
- Higgs EFT and applications
- SM-like H(125) vs. BSM
- BSM Higgs results
- Higgs and cosmology
- Future prospects

Partly a summary, partly a set of organised comments

Apologies for: all the interesting results left out or mentioned too briefly because of time; giving references only to talks rather than original work

• PREAMBLE

We have just entered the 4th year after the (Brout-Englert-)Higgs boson discovery

Today's picture of the "fundamental forces":

- Spin-2: graviton
- Spin-1: photon, weak bosons, gluons
- Spin-0: Higgs boson

Implausible as the final picture
(even disregarding the matter sector)
a more unified description some day?
additions/modifications not excluded
but could survive for a long time …

Higgs interactions in the SM

Very special (tree-level) couplings:

$g_{Hff} \sim m_f \quad g_{(H)HVV} \sim m_V^2 \quad g_{(H)HHH} \sim m_H^2$

(normalized by the appropriate power of v)

non-universal but flavour-conserving

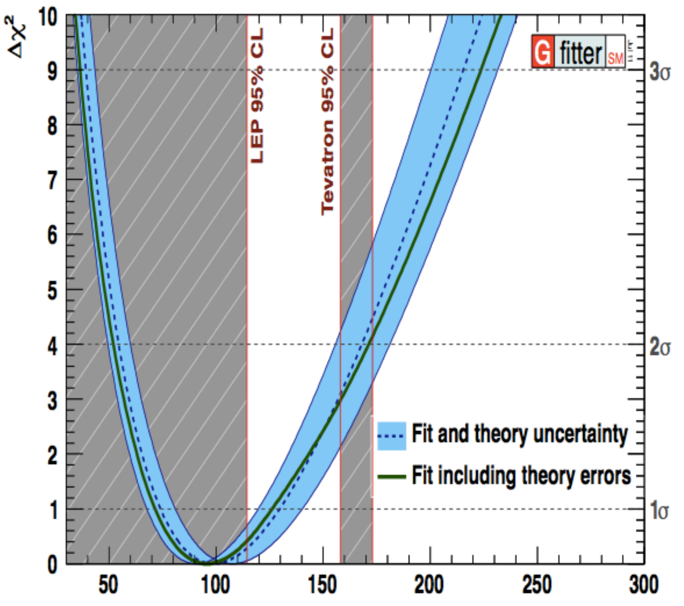
Strong indirect evidence before discovery
(electroweak and flavour precision tests)

Now accessible to direct tests

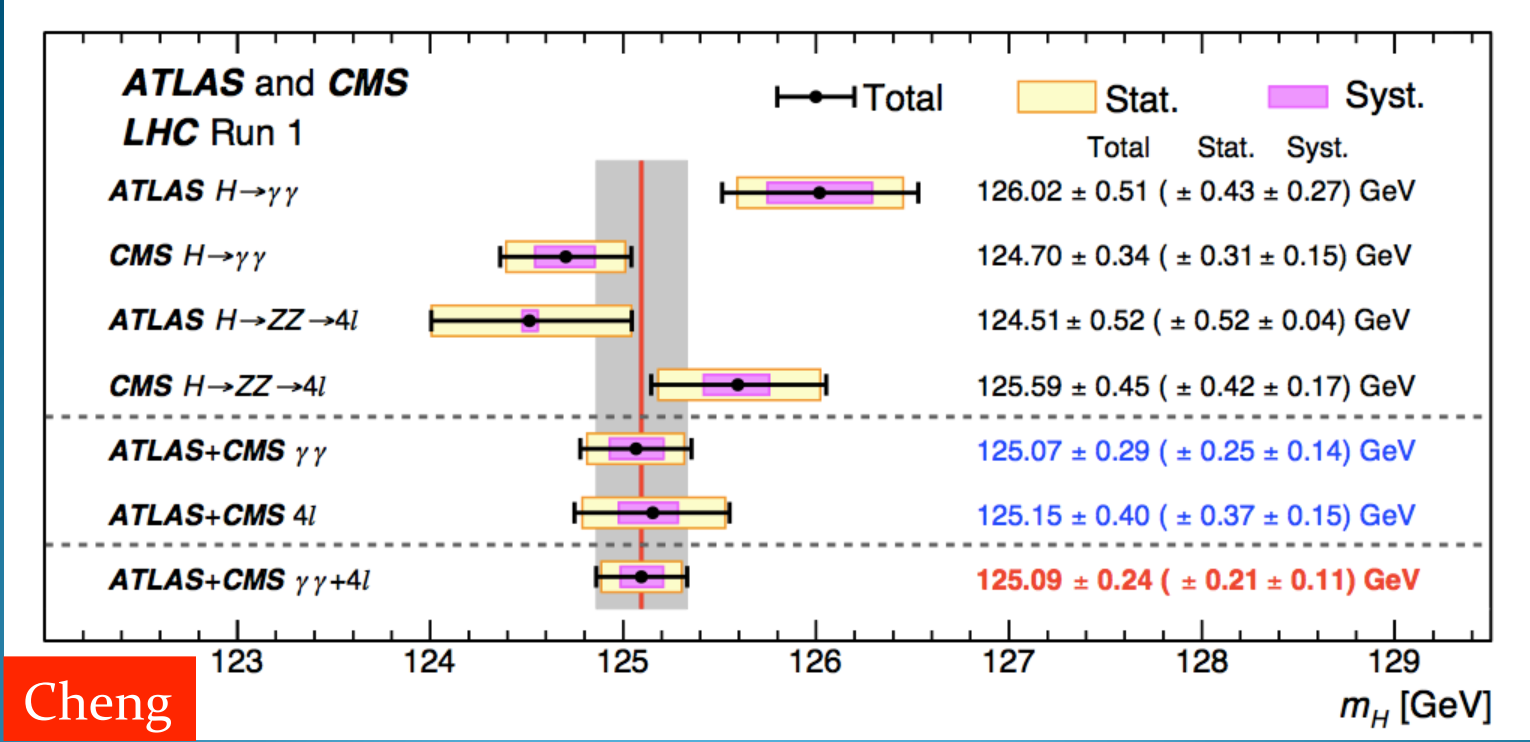
A challenging and essential program
will take several decades to complete
significant results already from Run 1

Mass

SM fit to EWPT in 2011 ➔



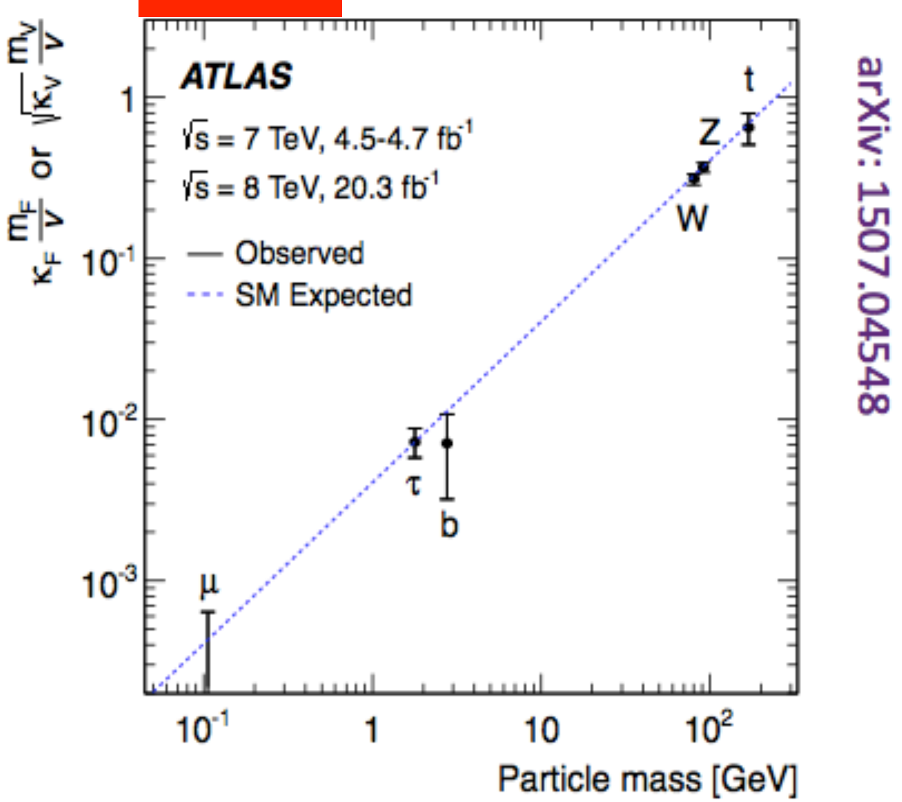
ATLAS and CMS
Run 1 combination
2 per mille accuracy!



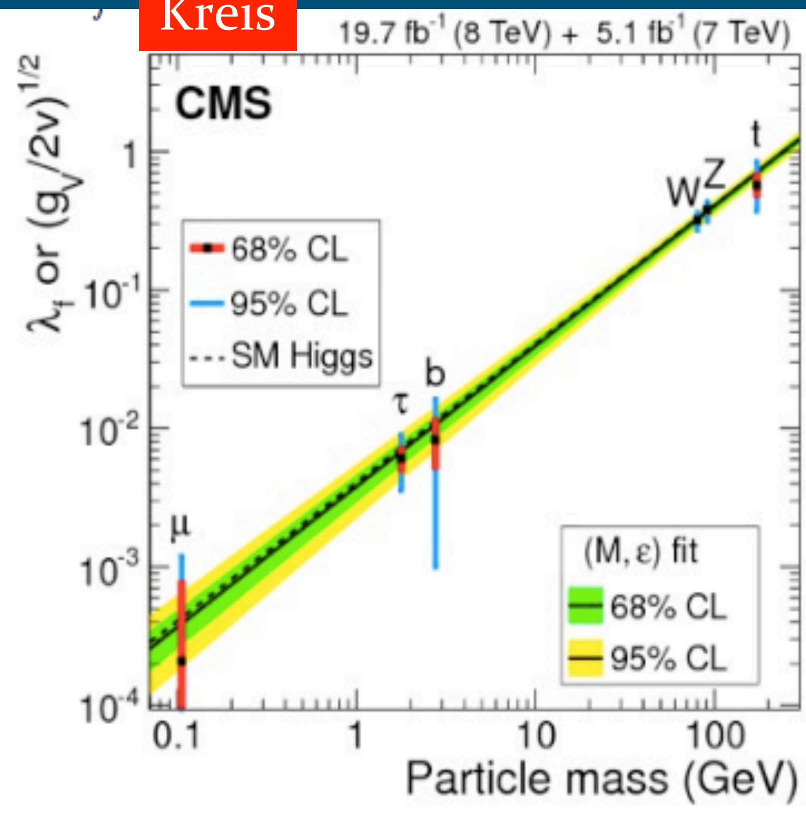
Cheng

Couplings vs. mass

Polifka



Kreis



The fitted couplings trace mass, as predicted by the SM although still with O(20% or more) uncertainities

• H(125) RESULTS

Mountricha, Sperka, Bortignon, Nakamura, Denisov, Cheng, Kreis, Polifka; Kinghorn-Taenzer, Courbon, Fink, Nakenhorst

No big surprises because of the shutdown
Legacy papers for Run-I
and some new analyses

- CMS VBF H$\rightarrow$bb [Bortignon]
- ATLAS ttH (bb, leptons) [Nakenhorst]
- CMS tH [Fink]

plus further combinations and fits of couplings

Status of H(125) signals after Run I

- $>5\sigma$ observation in WW, ZZ, $\gamma\gamma$ channels
- $Z\gamma$ channel: CMS $\mu<9$, ATLAS $\mu<11$

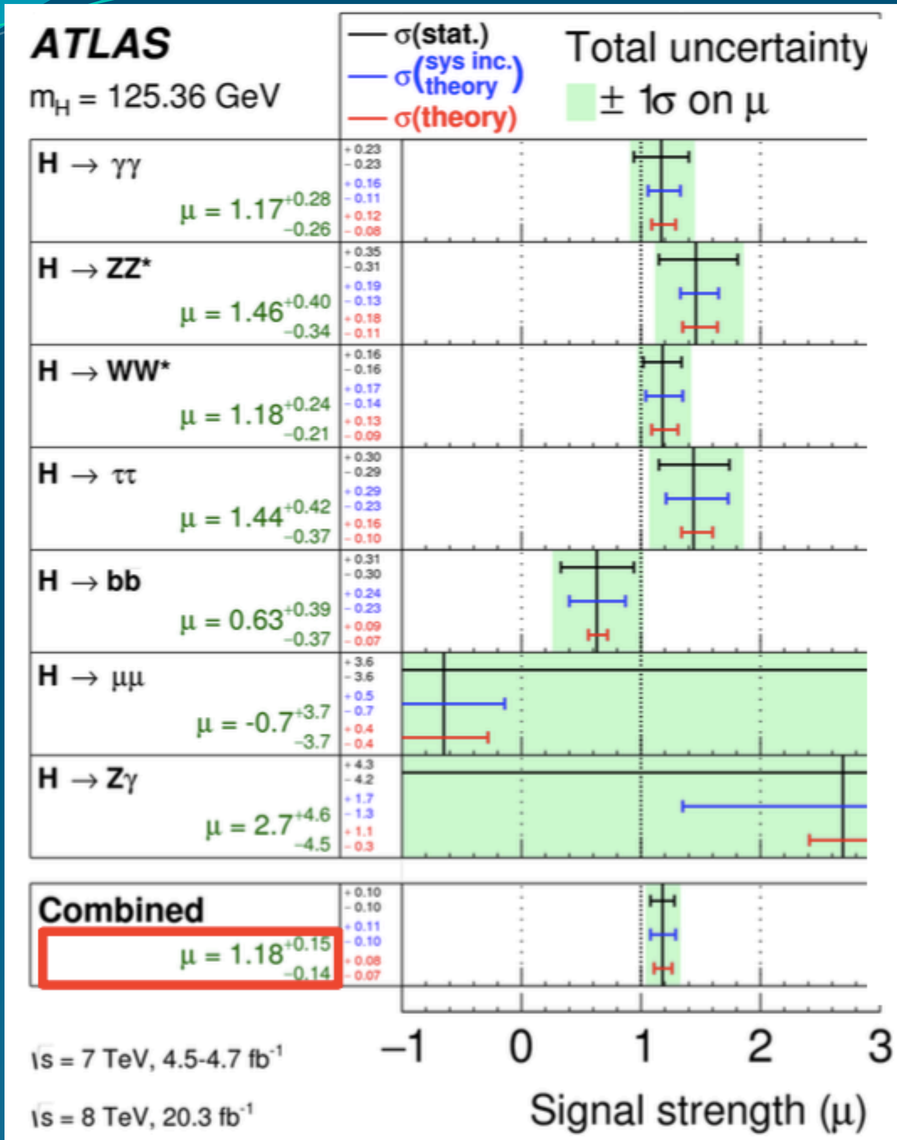
- "observation" also in $\tau\tau$ [ATLAS 4.5σ, CMS 3.2σ]
  Unofficial naïve combination [Mansoulie]: 5.5σ
- bb channel: CMS 2.6σ, Tevatron 2.2σ, ATLAS 1.8σ
  Un. n. comb. [Mansoulie]: 3.2σ wo TeV; $>4\sigma$ w TeV?

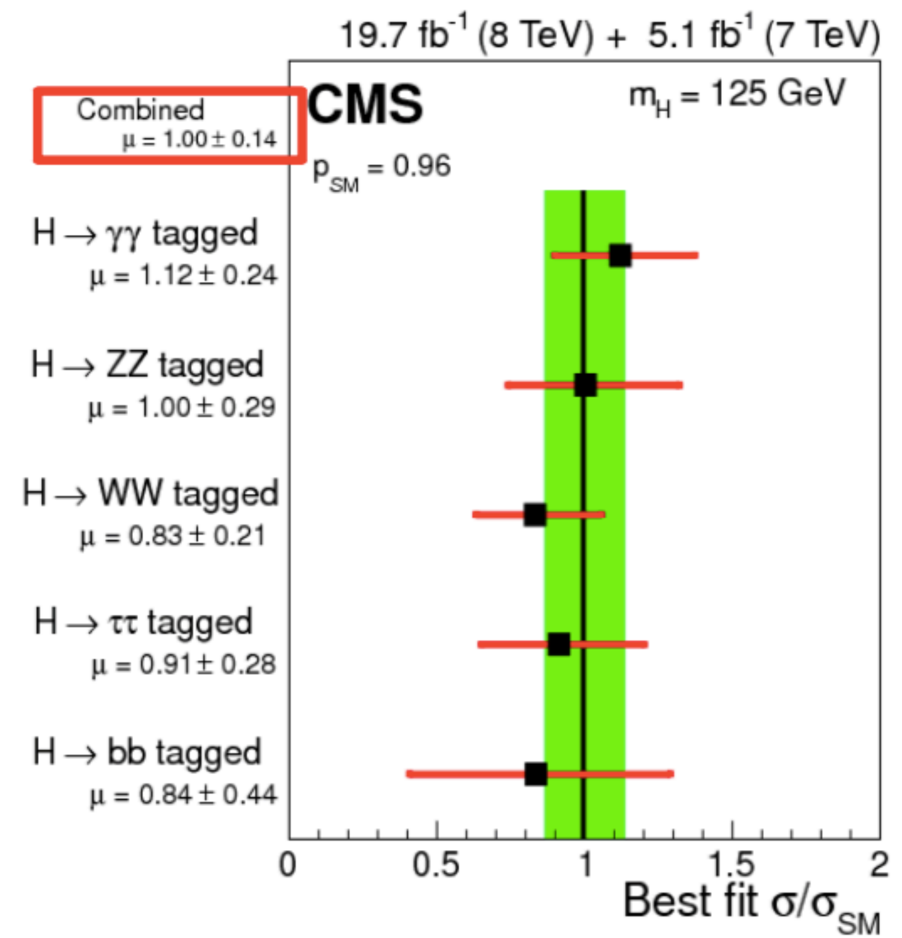
- $\mu\mu$ channel: CMS $\mu<7.4$, ATLAS $\mu<7$

- ttH: CMS $\mu=2.8\pm1.0$, ATLAS $\mu=1.8\pm0.8$
  Un. n. comb. [Mansoulie]: $\mu=2.2\pm?[0.6-1.1]$

Signal strength vs decay channel

Polifka, Kreis





$$\text{theory} = {}^{+0.08}_{-0.07}$$

Duhr

• SM THEORY AND MC TOOLS

Impressive progress in perturbative SM calculations and matching with parton-shower MC simulations

Important for the Higgs discovery

Crucial for the Higgs precision era

Duhr, Re, Passarino, Forte; Dreyer

Take generic process with hard scale Q

The corresponding cross section can be written as

Partonic cross section

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2\, f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \times \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu_R), Q^2; \mu_F^2, \mu_R^2) + \left(\frac{\Lambda}{Q}\right)^p$$

Parton distributions (PDFs)

Power suppressed terms

Accurate predictions for hadronic cross section depend on good knowledge of both $f_{i,h}(x, \mu_F^2)$ and $\hat{\sigma}_{ij}$

PDFs

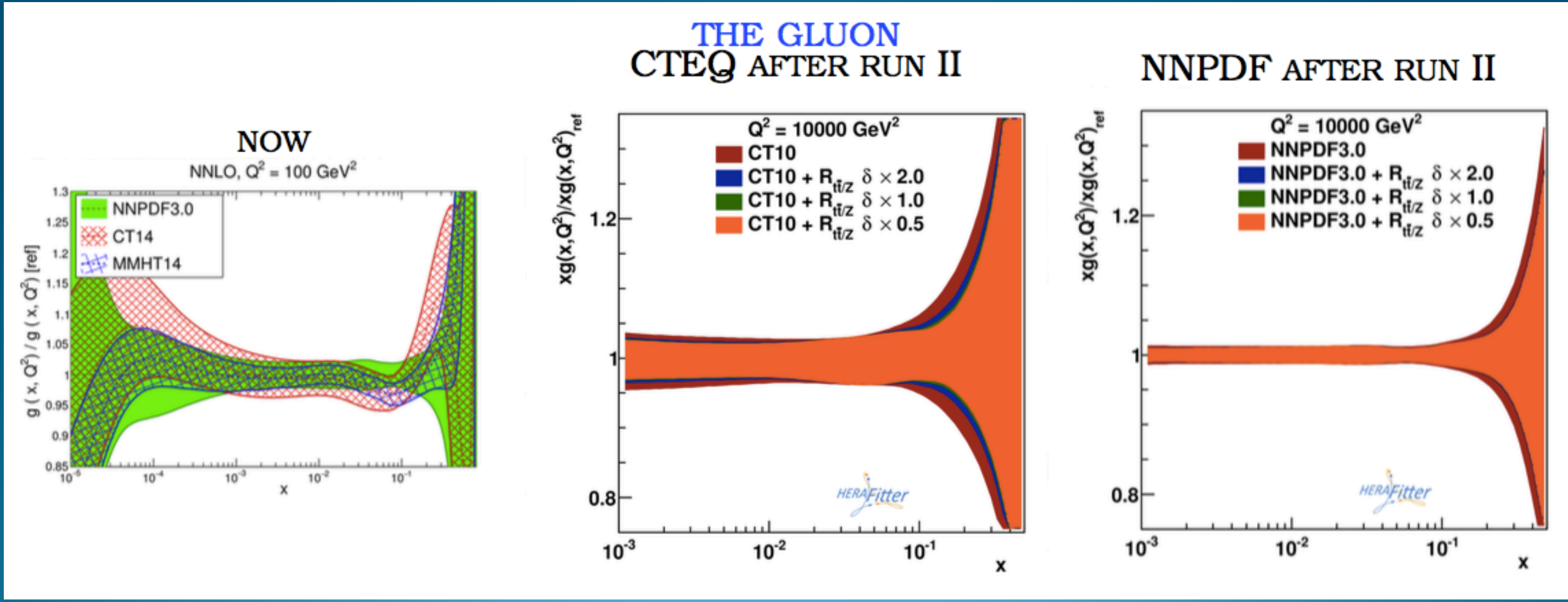
Forte

Latest gluon PDFs from global fits in good agreement

Prospects for further improvements after Run II

Good news for Higgs production and HL-LHC

Solid 3-4% should be reachable without LHeC



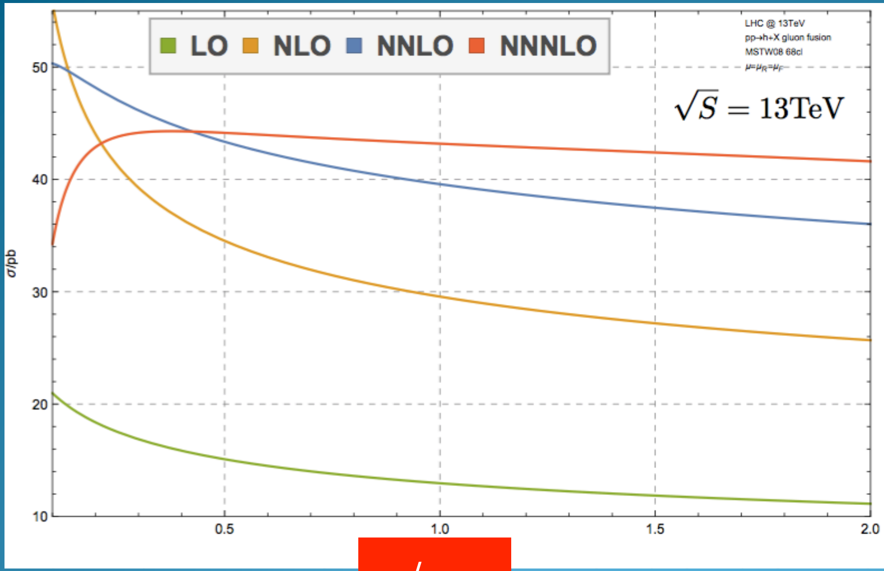
Partonic cross-sections and MC tools

Duhr, Re, Forte; Dreyer (and references therein)

(N)NNLO calculations important for Higgs production because of large NLO corrections and fut. exp. precision

- Fully differential VBF H production at NNLO [Dreyer]
- Fully differential gg →H + jet production at NNLO
- NLO+PS matching established, automation [Re]
- NLOPS multijet merging, NNLO+PS in progress [Re]

σ [pb]



μ/m_H

End of a tour-de-force: N^3LO σ for inclusive gg →H production (in the large m_t limit) [Duhr]

Nice stabilisation of scale dependence

• HIGGS EFT AND APPLICATIONS

Spannowski, Davidson, Passarino, Kreis, Polifka;
Vega-Morales, Pedersen, Bishara, Goertz, Ilnicka

Physics effectively organised in terms of scales
At each scale can write EFT with only the dof
that can be excited (heavy dof integrated out)
Such EFT must respect underlying symmetries
LHC: SM fields, Lorentz and gauge invariance

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D\,\leq\,4} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{D=6} + \ldots$$

2499 non-redundant parameters in D=6 operators!

More on Higgs EFT

Further constraints can be imposed:

- On practical grounds (exp. sensitivity, #param.)
- On the basis of consistent assumptions on dynamics/symmetries of underlying theory
- Explicit calculable UV models → predictions for/ correlations among different coefficients

EFT bounds general but looser than in specific models/scenarios: keep in mind in interpretation

Useful strategy (examples follow) for:
off-shell effects, p_T spectrum, BSM couplings, fits to EWPT, CP properties, flavour violation, …

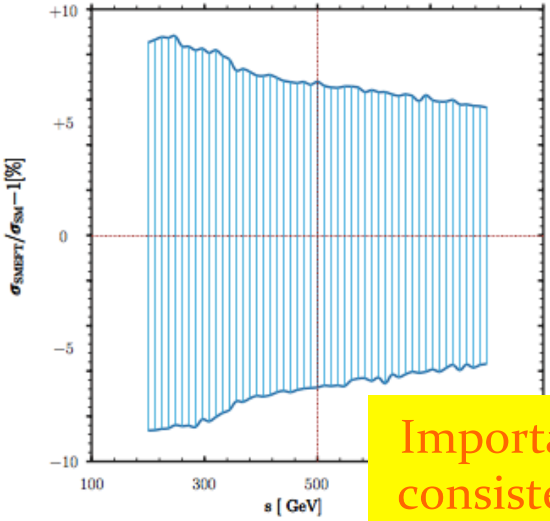
Off-shell effects

Passarino

No NP yet? Construct a consistent theory of SM-deviations:

Past: Off-shell bounding Γ_H Present: SMEFT at NLO Future: Understanding H couplings

$gg \to H$ off-shell

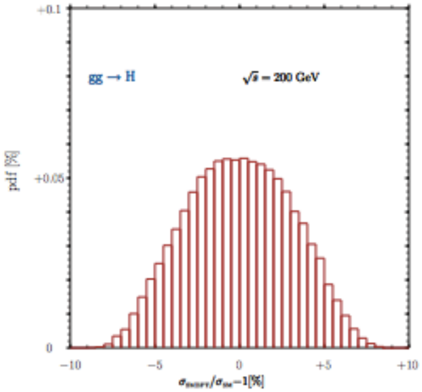


The successful search for the on-shell H did put little emphasis on the potential of the off-shell events

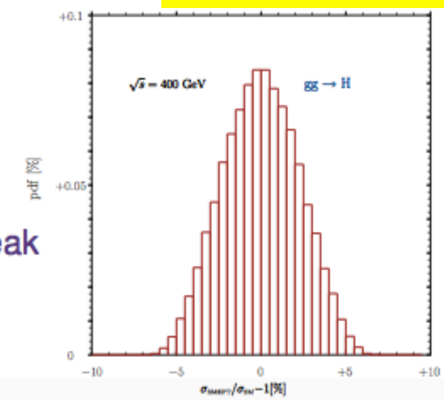
Wilson coefficients

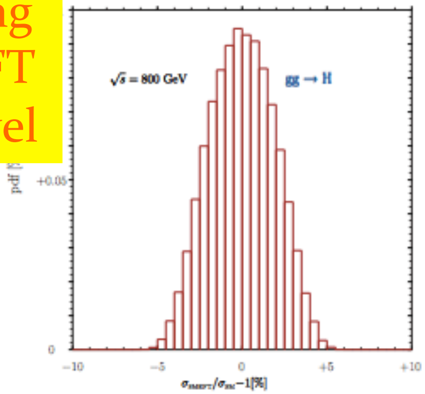
$| a_i | \in [-1, +1]$

$\Lambda = 3$ TeV



Importance of using consistently the EFT at the quantum level





Scaling couplings at the peak

is not the same thing as scaling them off-peak

On-shell studies will tell us a lot
off-shell ones will tell us (hopefully) more

Spin/CP properties

Kreis, Polifka, Denisov; Pedersen

Kinematic tests of discrete J^{CP} values in H→WW/ZZ/γγ
exclude 0^-,1^-,1^+,various spin-2 models at >99.9% CL

A consistency test that had to be done
but now is of limited interest (at least to me)

M_H known, SM 0^+ fits all data (not only in LHC Higgs physics, also EWPT and flavour) with no free parameter

The sensible thing to do now is to parametrize possible CP-violating interactions of H(125) in the EFT and look for small perturbations around predicted SM properties

Recent ATLAS/CMS studies are following this approach

From operators to Higgs couplings

59 d=6 operators, 17 involving H, 8 affecting only H physics, all the others already constrained by EWPT

8 primary Higgs couplings

for one family (assuming CP-conservation)

$$\Delta\mathcal{L}_{\rm BSM} = \delta g_{hff}\, h \bar{f}_L f_R + h.c. \quad (f=b,\tau,t)$$

$$+\, g_{hVV}\, h\left[W^{+\,\mu}W^-_\mu + \frac{1}{2\cos^2\theta_W} Z^\mu Z_\mu\right]$$

$$+\, \kappa_{GG}\frac{h}{v}G^{\mu\nu}G_{\mu\nu}$$

$$+\, \kappa_{\gamma\gamma}\frac{h}{v}F^{\gamma\,\mu\nu}F^\gamma_{\mu\nu}$$

$$+\, \kappa_{\gamma Z}\frac{h}{v}F^{\gamma\,\mu\nu}F^Z_{\mu\nu}$$

$$+\, \delta g_{3h}\, h^3$$

6 measured at the LHC

H→Zγ can still be 9 x SM

gg→HH a challenge for HL-LHC

Pomarol@Naturalness 2014
equivalent to Spannowsky here + custodial symmetry

Elias-Miro, Espinosa, Masso, AP, JHEP 1311 (2013) 066
AP, Riva, JHEP 1401 (2014) 151

Higgs and flavour

Petriello, Davidson; Bishara

Increasing interest in effective Higgs couplings to light fermions: large deviations possible (in models or self-consistent EFT frameworks)

Petriello:

$H \rightarrow J/\psi\,\gamma$ theoretically clean and promising for HL-LHC

Experimental studies that will evolve with luminosity:

- CMS: $BR(h \rightarrow \tau\mu) < 1.51\%$ || $0.84 \pm 0.39\%$ || (2.4σ)
- ATLAS: $BR(h \rightarrow \tau\mu) < 1.85\%$ || $0.77 \pm 0.62\%$ || (1.3σ)

Davidson:

Compatible with bounds on LFV, e.g. $\tau \rightarrow 3\mu$, $Z \rightarrow \mu\tau$, $\tau \rightarrow \mu\gamma$

Hardly compatible with $\mu \rightarrow e\gamma$ if $e\mu/e\tau$ visible in h/Z decays

• SM-LIKE H(125) VS. BSM

Gherghetta; Thamm, Carmona, Pardo Vega, Fuchs, Goertz

No quantum SM symmetry recovered for $m_H \rightarrow 0$
Unprotected ratio m_H/M for any scale $M >> m_H$

(Subtleties if scale invariance explicitly broken only by quantum corrections and not by UV physics? [Bardeen])

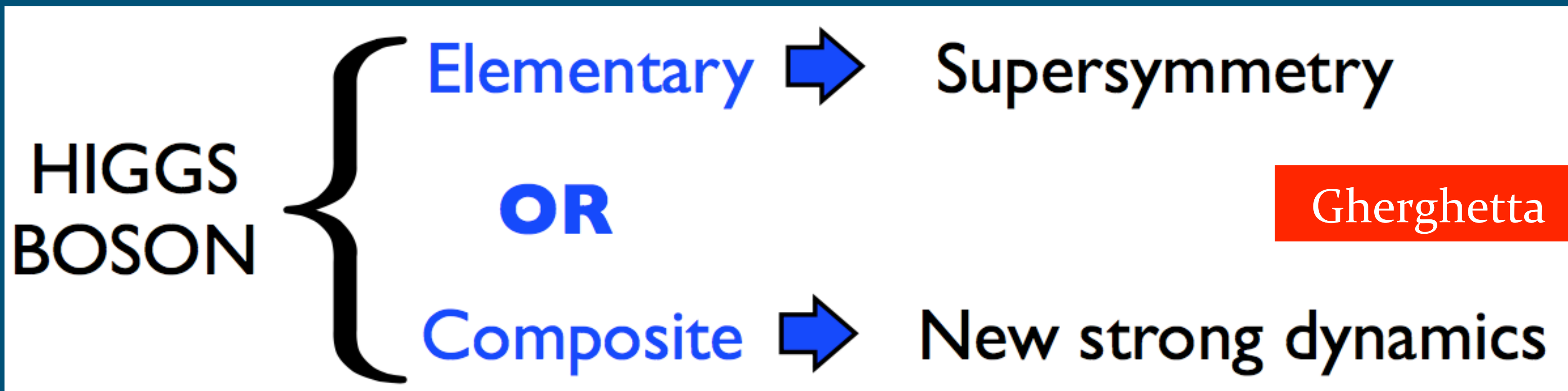
$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\,\pi^2}\Lambda^2 < O(m_H^2) \quad \rightarrow \quad \Lambda < O(500)\ \text{GeV}$$

SM unnatural unless New Physics at the TeV
but no new state found at LHC Run I

The nightmare of many theorists

stimulus for many recent theoretical efforts

Traditional natural models



Challenged by naturalness already before the LHC
Now much more severely after Run 1 of the LHC:
H(125) found with SM-like properties so far
No particles found after factor-4 increase in E

H(125) & supersymmetry

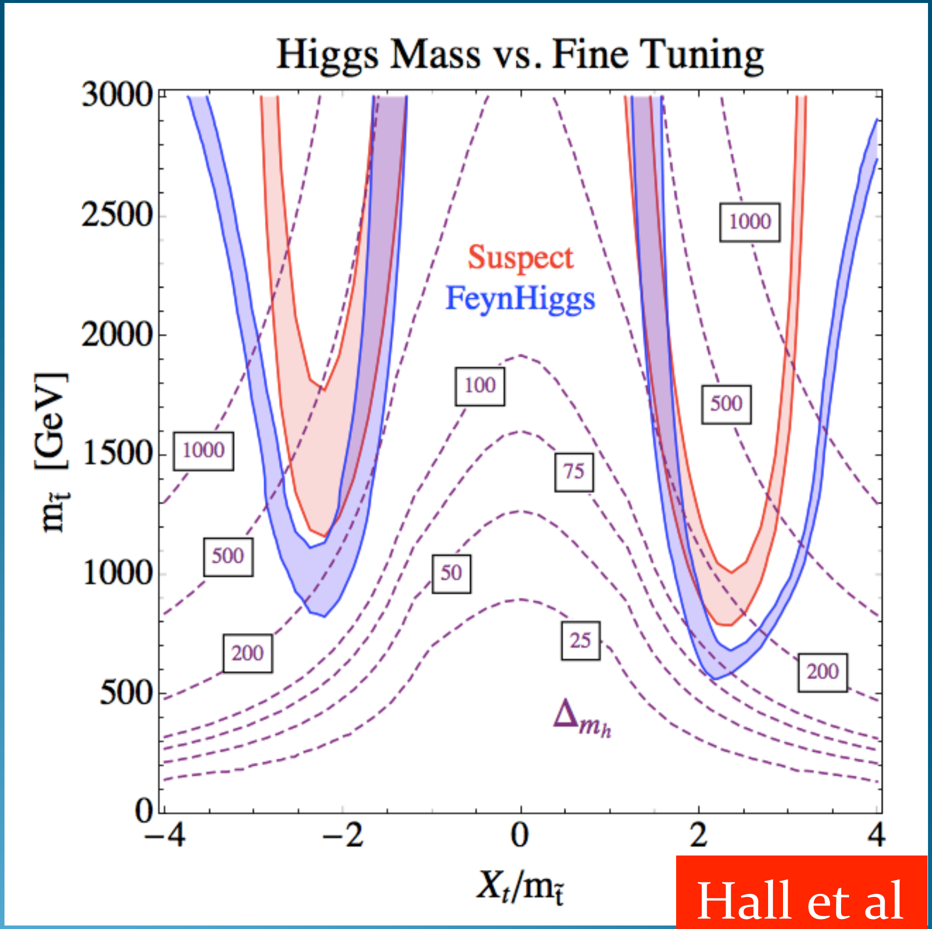
Higgs mass highly fine-tuned in MSSM (even more strongly than in figure [Pardo Vega])

Can be avoided in NMSSM with low-cut-off, but tuning of EW scale at 5% or less [Gherghetta]

Extra tree-level tuning to have H SM-like, or decoupling limit

Two options within susy:

- Look for more natural models (appear ad hoc, baroque)
- Set naturalness aside for now (split supersymmetry)



Hall et al

Less natural supersymmetry. Why?

- Can still accommodate gauge unification and DM for heavier spectra beyond the present LHC reach (lose on naturalness, improve on h~SM & flavour)
- Might need to combine SUSY and some additional ingredient to solve the SM naturalness problem, more insights may still come from a better understanding of spontaneous susy breaking
- The role of supersymmetry in QFT and string theory beyond (today's) particle phenomenology

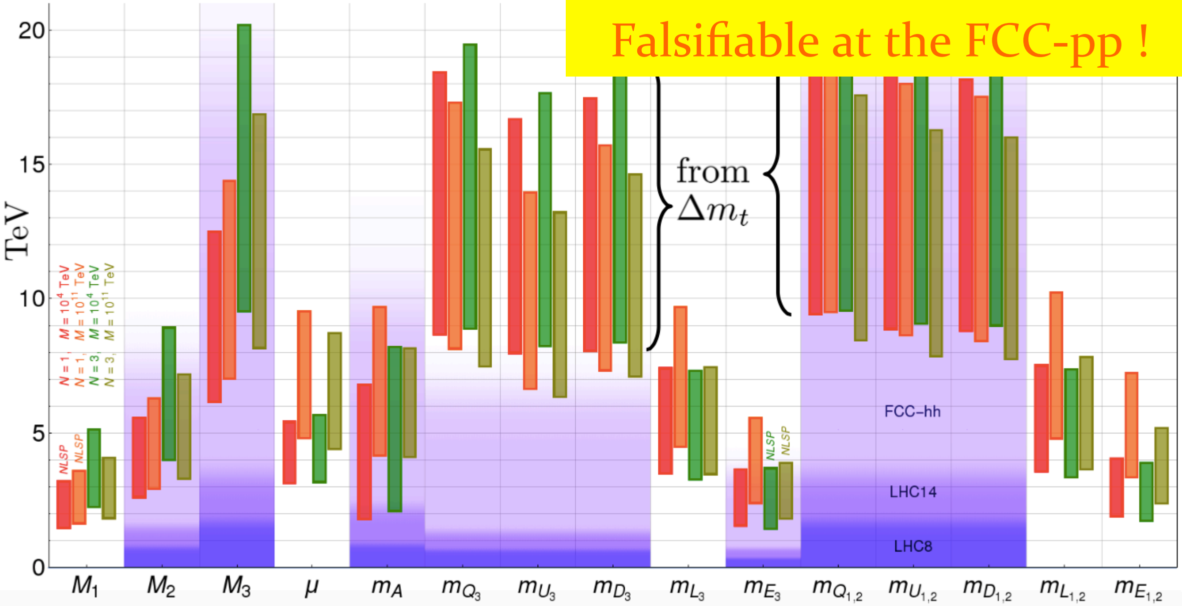
Example: Minimal Gauge Mediation

Pardo-Vega

$$\not{\mu}, \qquad \not{\Lambda = \frac{F}{M}}, \qquad M, \qquad N$$

fixed by m_Z fixed by m_h

- No FCNC
- $B\mu$, A – loop suppressed → large $\tan\beta \sim 50$
- No EDM
- Gauge coupling unification



Falsifiable at the FCC-pp !

H(125) & compositeness

Still viable composite Higgs scenario:

- H is composite state of a new strong force
- H light because pseudo-Goldstone boson
- SM fermions (e.g. top) coupled linearly to the new strongly interacting sector

Relevant parameters mass M_* and $g_* = M_*/f$

Naturalness/Tuning controlled by $\xi = v^2/f^2$

Light Higgs correlates with light top partners

Vector resonances $O(M_*)$ also expected

$$k_V = \sqrt{1-\xi}$$

Generic

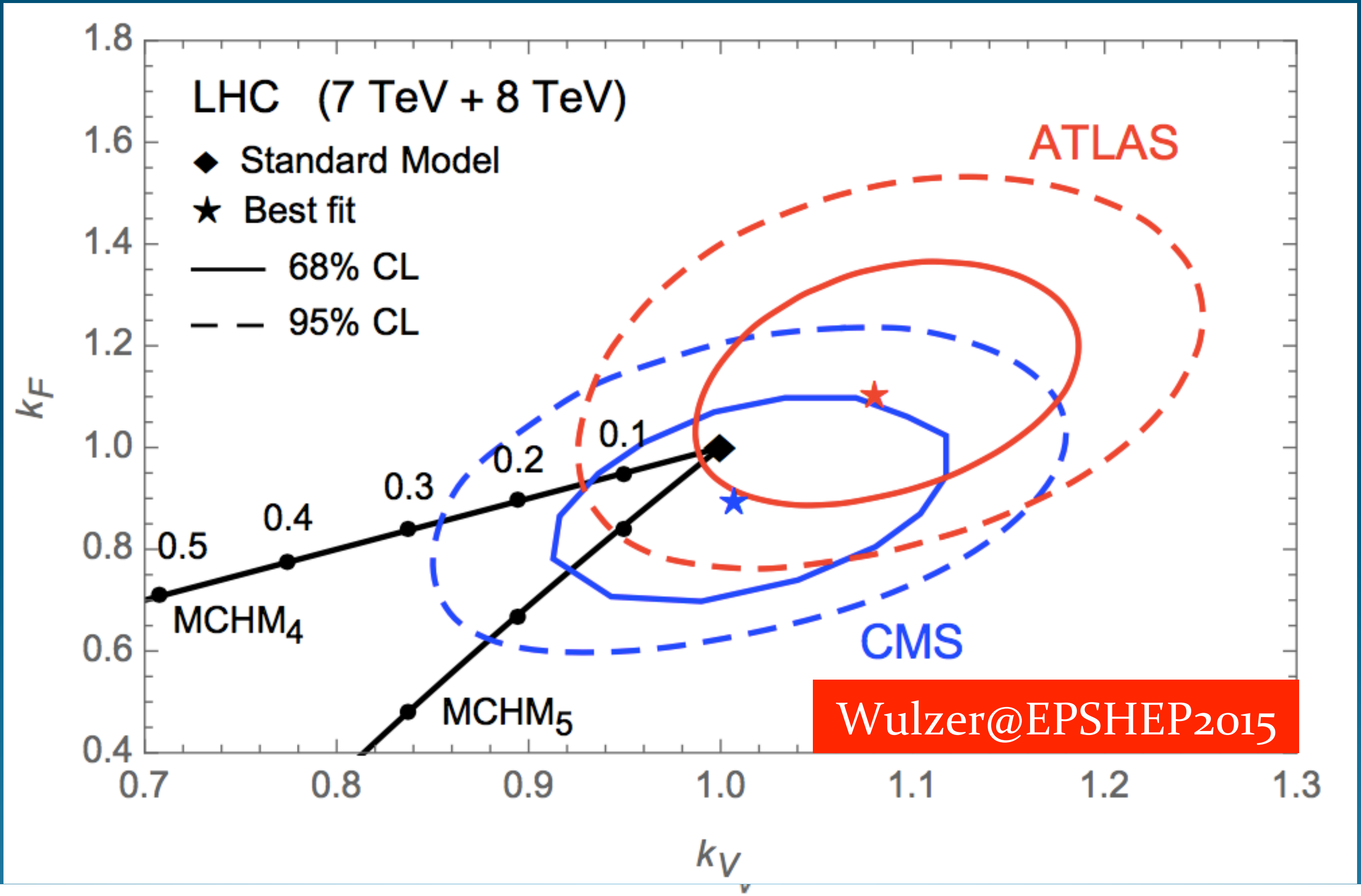
$$k_F = \sqrt{1-\xi}$$

MCHM4

$$k_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$

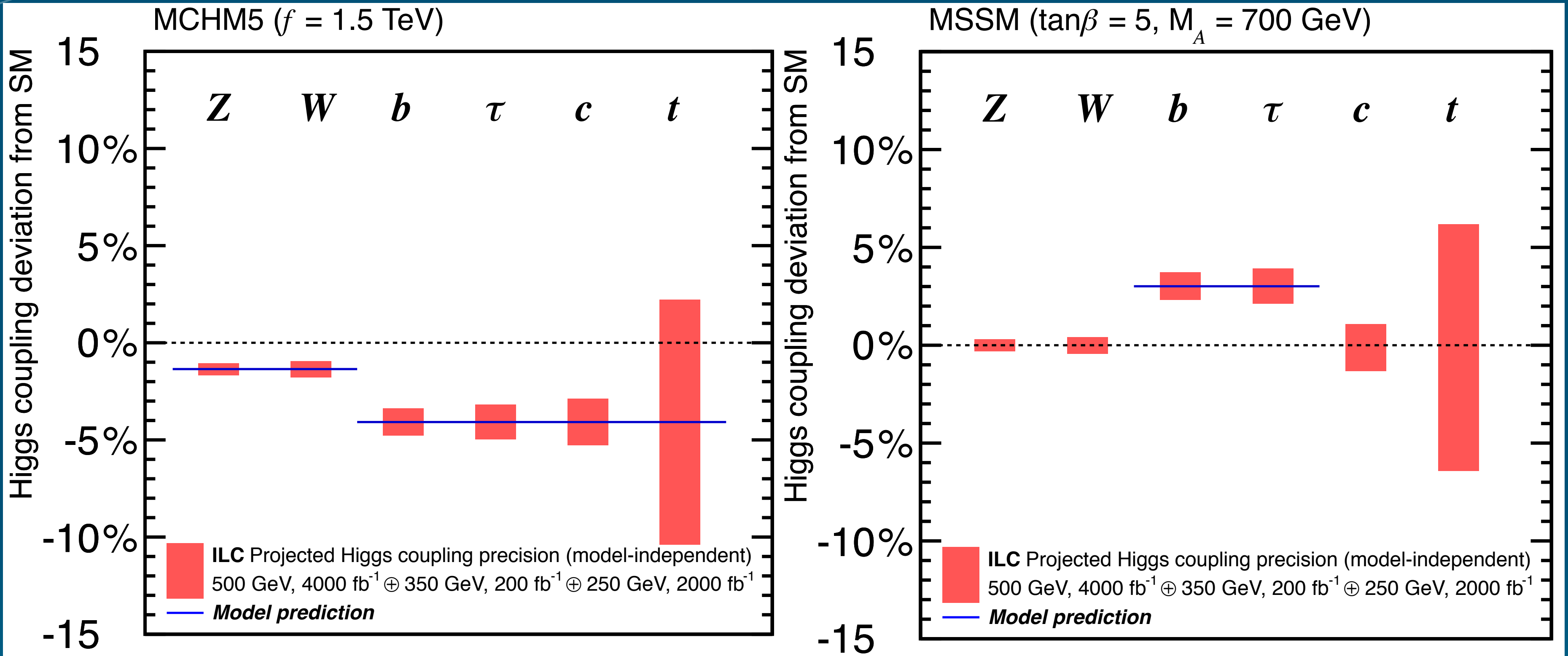
MCHM5

CH couplings



Expected LHC-300 reach (with SM central value): $\xi < 0.1$

Higgs couplings: SUSY vs CH



A side remark on CH models

Absence of an UV completion helps passing EW and flavour precision tests, thanks to the flexibility of the EFT: assumed symmetries help only in part, O(1) cancellations are required

• BSM HIGGS RESULTS

Caudron, Beckingham; Sales de Bruin, Grippo, Teixeira de Lima

Still ample room for extended Higgs sectors: more states than h(125) (MSSM, NMSSM, 2HDM, extra singlets, ...)

Several new analyses

ATLAS:
$H \to ZZ, WW, hh$; $H^{\pm} \to WZ$; NMSSM $h \to aa$; $A \to Zh \to ll\tau\tau$

CMS:
update of $\phi \to bb, \tau\tau$; $H \to hh \to bb\tau\tau$; $h \to \gamma\gamma$ low/high mass

• HIGGS AND COSMOLOGY

Binetruy, Servant

After discovery, role of Higgs in the cosmological context under more intense theoretical scrutiny

-Electroweak Vacuum stability

-Higgs Inflation

see M. Shaposhnikov's talk @ Higgs Hunting 2014 and Espinosa's talk at CERN-TH in 04-2015

Servant

-Electroweak Baryogenesis ... and the QCD axion connection

-Asymmetric Dark Matter induced by the Higgs

-Cosmological Higgs-Axion INterplay (CHAIN) ←→ RELAXION

Do we really need coloured top partners near the TeV to restore naturalness of the SM and avoid anthropics?

Hierarchy generated by the cosmological evolution?

[Graham,Kaplan,Rajendran 2015; see Abbott; Dvali and Vilenkin]

The relaxion (1/2)

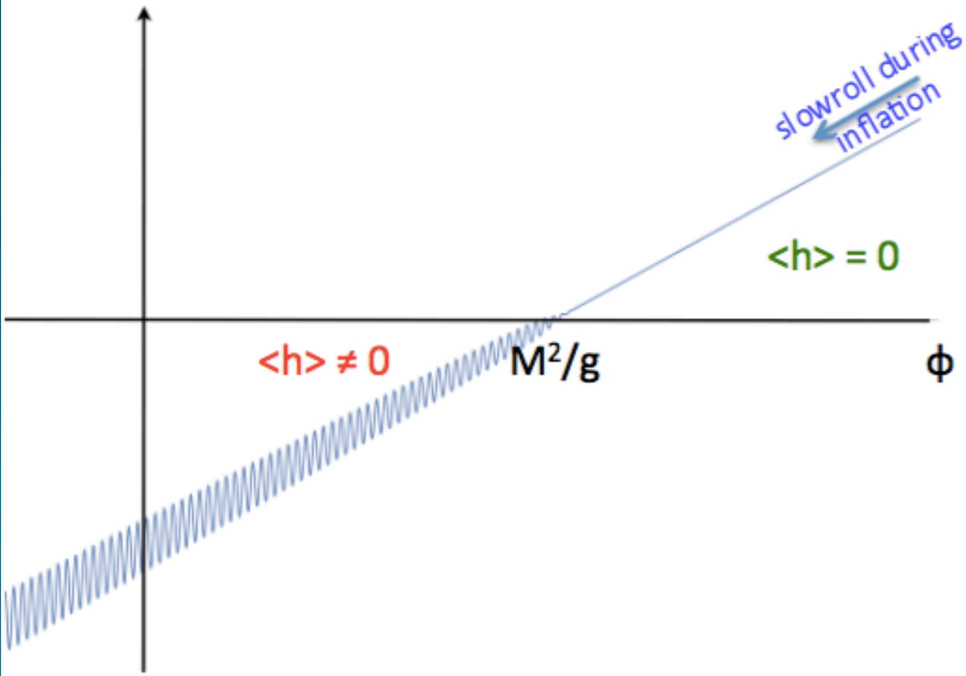
Simplest model: SM + QCD axion ϕ

large mass scale M

V(gϕ)

$\Lambda^4 \sim f_\pi m_\pi^2 \propto (\lambda_u + \lambda_d)$ <h>

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$



In the limit g → 0,
shift symmetry: $\phi \to \phi + 2\pi f$
(from continuous symmetry
(in the absence of strong interactions)
$\phi \to \phi$ + cst
g naturally small

Binetruy

The relaxion (2/2)

Minimal model with QCD axion has strong CP problem back.

Various possible fixes considered, in the GKR paper and in the subsequent one described in Servant's talk, many loose ends:

relaxion/inflaton relation

wildly trans-Planckian field excursions

a sensible UV completion?

relation with cosmological constant

My view:

Not excited by models so far proposed, but idea important as existence proof of possible solutions to naturalness problem we had not thought of, and of the connection with gravity

• FUTURE PROSPECTS

Leveque, Malcles, Forte, Di Valentino, Casasso, Stapnes, Benedikt, Wang

From the 80s on, all collider discoveries
(W/Z, t, H) strongly "guided" by theory

No-lose theorems applicable in each case,
based on general theoretical arguments
such as unitarity and/or anomaly freedom,
helped focusing the experimental strategies

We won't be again in such a condition for some time
Role of experiment more important than before
diversify now efforts to maximize chances
(until either a new experimental discovery
or a new compelling theory emerge)

Collider physics for the years to come

1. Find out whether H is accompanied by other (heavy? light?) new particles near the TeV scale

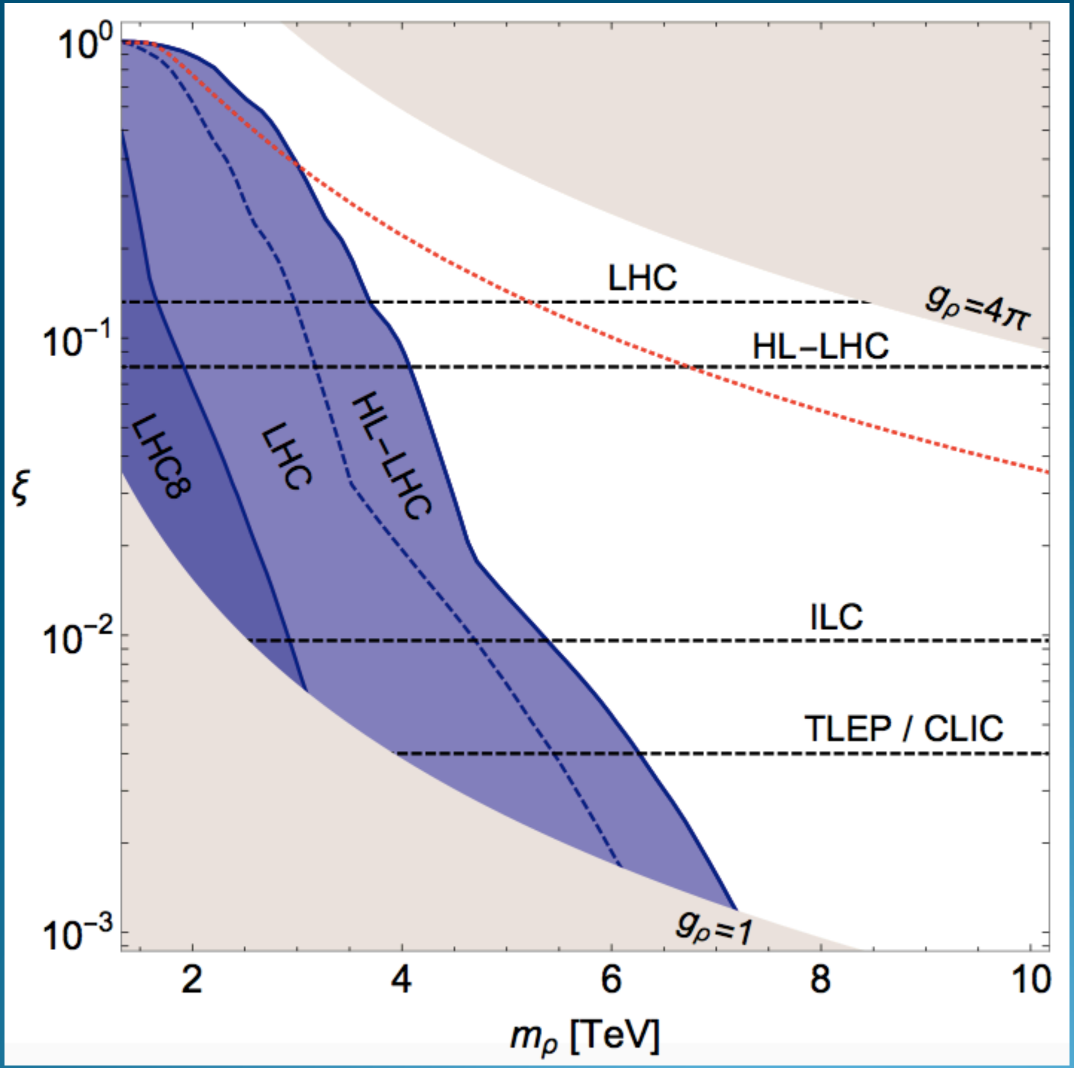
Already a great window of opportunity for Run 2!

2. Study H properties with the highest possible precision, seeking inconsistencies of the SM that would point indirectly to new physics

Complementarity of HL-LHC with future e^+e^- colliders

3. Push further precision tests of flavour physics (including Higgs flavour physics at the LHC)

Higgs couplings vs direct searches



Example from CH
[Thamm]

$$\xi = \frac{v^2}{f^2} = \frac{g_\rho^2}{m_\rho^2} v^2$$

Direct wins for small couplings and masses

Indirect wins for large couplings and masses

H(125) Highlights of Run2 and HL LHC

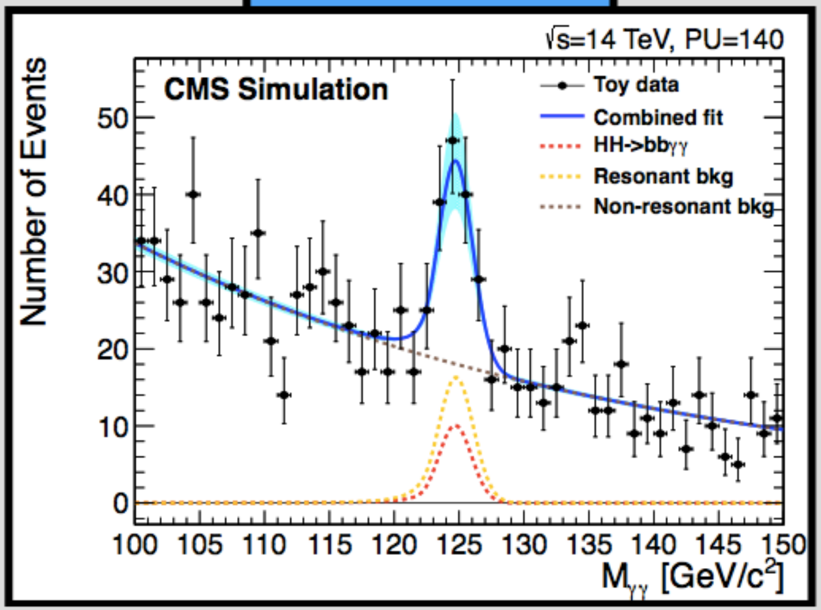
Nisati

- LHC Run2- 100 fb^{-1}:
  - observation of H→ττ, bb;
  - Evidence for ttH
  - Precision differential cross sections
- LHC Run2- 300 fb^{-1}:
  - Probably observation of ttH
  - Evidence H→μμ
  - Precision measurement of Higgs couplings at the level of 10 %
    - Need to find alternatives to the kappa-model; HEFT approach is the best candidate
- HL-LHC 3000 fb^{-1}:
  - Observation ttH
  - Observation of H→μμ and H→Zγ
  - Precision measurement of Higgs couplings at the level of few %
  - **Evidence for HH production**

A tough job for HL-LHC : HH

Di Valentino

HH → bbγγ



- Allows measurement of Higgs self-coupling λ_{HHH}
- **CMS Z_0 (3000 fb^{-1}): 1.9σ** for **bbγγ+bbττ**
  - **54%** exp. uncertainty in signal yield (for fully upgraded detector)
- **ATLAS Z_0** (λ_{HHH} / λ_{SM} = 1): **1.3σ**

Goertz

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D\,\leq\,4} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{D=6} + \ldots$$

$$-\frac{c_6}{\Lambda^2}\lambda|H|^6$$

Pure Higgs

14TeV LHC, 1σ:	$hh \to b\bar{b}\tau^+\tau^-$
model	$L = 3000\ \mathrm{fb}^{-1}$
c_6-only	$c_6 \in (-0.4, 0.4)$
full (**future**)	$c_6 \in (-0.6, 0.6)$

Correlations of c_6 with other effective couplings (c_{H}, c_t, c_{g}, ...)

NO CONCLUSIONS YET

Run2 has started, HL-LHC is on the horizon:
a guaranteed exciting physics program ahead

Experiment has currently the lead on theory
(after decades of announced SM discoveries):
No guaranteeed discovery: broad program!

Must keep exploring, directly and indirectly,
and plan seriously for post-LHC machines

We must keep pushing the high-energy frontier
(as well as the complementary frontiers)
but constraints are tough and choices difficult

Let us discuss all this again at HH2016
hopefully in the light of
new, exciting LHC Run 2 results!

The Hunting continues…

As the last speaker, many thanks, on behalf of all the participants, to:

The Organizing Committee

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G.Perrin (video), V.Brouillard (almost everything)

Speakers, session chairs, contributors to discussions

for a smoothly running and very stimulating event