New Revelations from Particle Colliders
Past, Present and Future
A Theoretical Perspective

IMPACT

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Understanding the Higgs, Torino 28 November 2012

IMPACT impact (*although CSP should improve public relations*)

September 26, 2012

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NLO Inspired Effective Lagrangians for Higgs Physics*

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Either late autumn this year or latest early next year LHC should have results with 2—3 times the current data which migth give first clues on the couplings of the light narrow resonance. A strategy for measuring deviations from the Standard Model can be based on using the "full" Standard Model, including all available QCD and electroweak higher-order corrections, and supplement it with $d = 6$ local operators. Their Wilson coefficients are assumed to be small enough that they can be treated at leading order. Examples of the connection of local operators with BSM Lagrangians are presented as well as a discussion of Lagrangians with/without decoupling of heavy degrees of freedom. The whole strategy is critically reviewed in the light of internal consistency.

Keywords: Feynman diagrams, loop calculations, radiative corrections, effective Lagrangian, Higgs physics
PACS: 11.15.Bt, 12.38.Bx, 13.85.Lg, 14.80.Bn, 14.80.Cp

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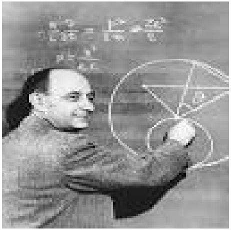
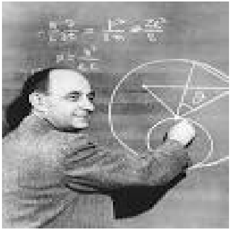
85.Lg, 14.80.Bn, 14.80.Cp

d by Compagnia di San Paolo under contract ORTO11TPXK.



Welcome on board!

Tour starting now



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Prolegomena

The other Pauli principle:

fermions are discovered in the US, while bosons are discovered in Europe

has been spectacularly confirmed

In summary:

- **Higgs hunting is over,** *the catch is now being skinned and prepared for grilling*
- **Collider physics** has achieved the most spectacular success in its history.
- *At the same time, it came dangerously close to realizing Kelvin's nightmare, of science reduced to striving for the next decimal places of accuracy.*

WELL, 100 YEARS AGO WE AVOIDED THAT FATE, MAY BE THE HISTORY WILL REPEAT ITSELF?

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Higgs outreach

It's a particle that some scientists have been looking for. Because they knew that without it the universe would be impossible. Because without it, the other particles in the universe wouldn't have mass. Because they would all continue to travel at the speed of light, just like photons do. Because I just said they would, and if you ask 'Why?' one more time we're not stopping at Burger King.

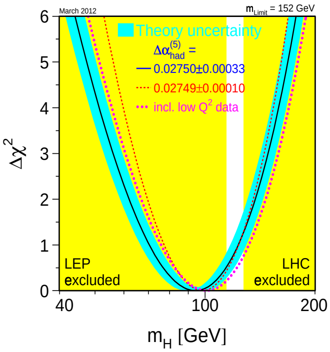
The Past

故

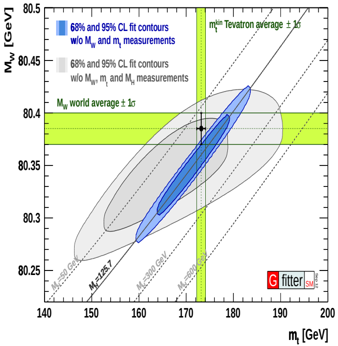
The role of EW corrections in Higgs physics

- EW corrections $\rightarrow$ sensitivity to $M_{\rm H}$ in SM fit !

LEPEWWG '12

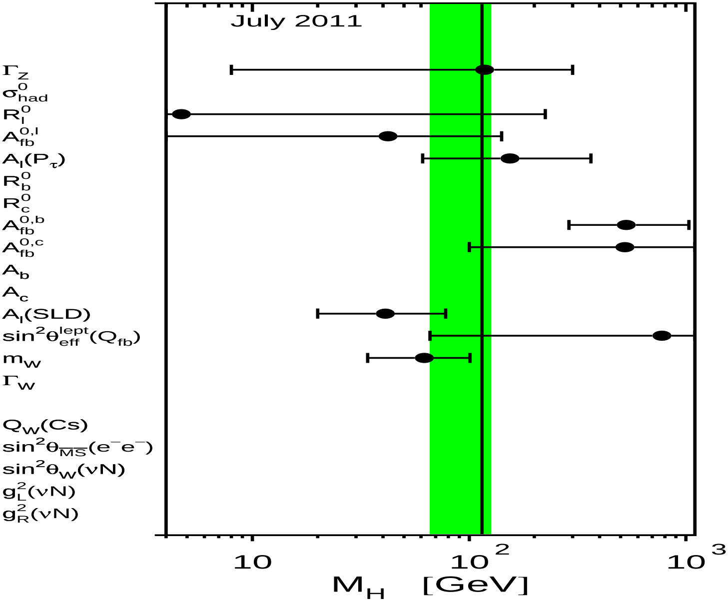


Gfitter '12



- Relevance in predictions for Higgs production and decay

  $\hookrightarrow$ to be discussed in this talk


July 2011
Γ_Z
σ^0_{had}
R^0_l
$A^{0,l}_{fb}$
$A_l(P_\tau)$
R^0_b
R^0_c
$A^{0,b}_{fb}$
$A^{0,c}_{fb}$
A_b
A_c
A_l(SLD)
$\sin^2\theta^{lept}_{eff}(Q_{fb})$
m_W
Γ_W
Q_W(Cs)
$\sin^2\theta_{\overline{MS}}(e^-e^-)$
$\sin^2\theta_W(\nu N)$
$g^2_L(\nu N)$
$g^2_R(\nu N)$
10
10^2
10^3
M_H [GeV]

The Present

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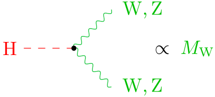
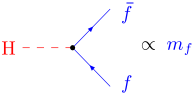
Tools

Higgs production and decay at the LHC

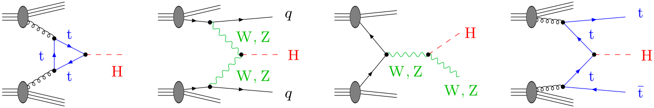
Higgs bosons couple proportional to particle masses:



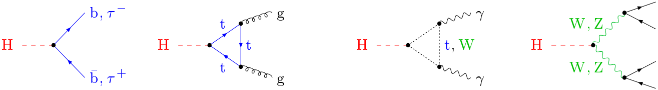


$\Rightarrow$ Higgs production via couplings to W/Z bosons or top-quarks

Production at hadron colliders ($\mathrm{p\bar{p}/pp}$):

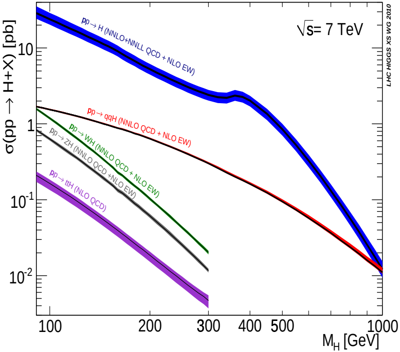


Decay channels for Higgs bosons of moderate mass ($M_{\mathrm{H}} \lesssim 300\,\mathrm{GeV}$):



Predictions

SM Higgs XS predictions
for the LHC at $\sqrt{s} = 7\,\mathrm{TeV}$
LHC Higgs XS WG 2010



Rough numbers:

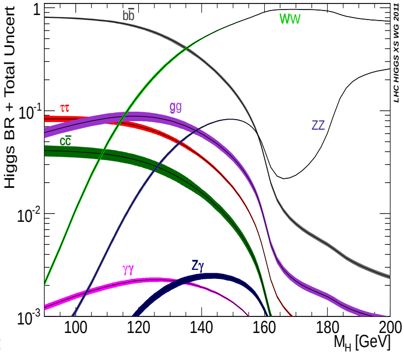
	M_{H}	Uncertainties scale	PDF4LHC	NLO/NNLO/NNLO+ QCD	EW
ggF	$< 500\,\mathrm{GeV}$	$6-10\%$	$8-10\%$	$>100\%$	5%
VBF	$< 500\,\mathrm{GeV}$	1%	$2-7\%$	5%	5%
WH	$< 200\,\mathrm{GeV}$	1%	$3-4\%$	30%	$5-10\%$
ZH	$< 200\,\mathrm{GeV}$	$1-2\%$	$3-4\%$	40%	5%
ttH	$< 200\,\mathrm{GeV}$	10%	9%	5%	?

EW corrections
$\sim \mathcal{O}$(uncertainties)

Predictions

BRs of the SM Higgs boson

LHC Higgs XS WG 2011



Parametric + theoretical uncertainty:

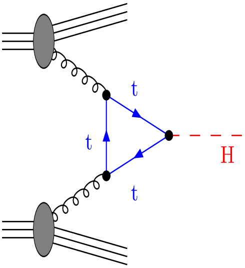
$M_{\rm H}$[GeV]	$\rm H \to$	$\rm b\bar{b}$	$\tau^+\tau^-$	$\rm c\bar{c}$	gg	$\gamma\gamma$	WW	ZZ
120		3%	6%	12%	10%	5%	5%	5%
150		4%	3%	10%	8%	2%	1%	1%
200		5%	3%	10%	8%	2%	$< 0.1\%$	$< 0.1\%$

$\leftarrow$ driven by $\delta m_{\rm b}$ via $\Gamma_{\rm H \to b\bar{b}}$

EW corrections significant in predictions for $\Gamma_{{\rm H}\to X}$ and $\rm BR_{{\rm H}\to X}$

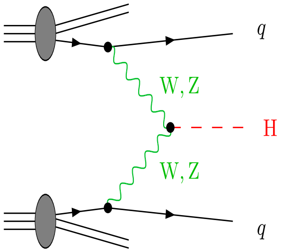
Production

Higgs production via gluon fusion



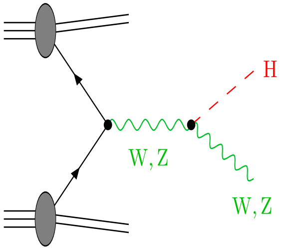
Production

Higgs production via vector-boson fusion



Production

Production via Higgs-strahlung



Where are we? What's next?

we are living a privileged moment in the history of HEP

A NEW PARTICLE HAS BEEN DISCOVERED

the discovery came at half the LHC designed luminosity that was originally judged necessary

▷ Higgs is the most exotic particle in the SM ◁

its discovery has profound implications

- Spin 0? *Against naturalness: small mass only if protected by symmetry*
- Couplings not dictated by gauge symmetry? *Against gauge principle (elegance, predictivity, robustness) which used to rule the world (gravity, QCD, QED, EW)*
- Symmetry breaking? *ground state doesn't share the full symmetry of interactions*

1950 Ginzburg-Landau (*Meissner-Ochsenfeld effect → London penetration length*)
1959 Nambu
1960 Goldstone
1961 Schwinger
1962 Anderson
1964 Brout, Englert, Higgs, Guralnik,Hagen,Kibble
1967 Weinberg, Salam Faddeev,Popov
1970 Glashow, Iliopoulos,
Maiani, 't H

1983 Rubbia, van
1984

1989 constructio
beginning c

1992 LOI of 'la
1994 TP of ATL
1995 *discovery c*
1996 approval c
1998
1999 approval c
ATLAS Pl

2006 CMS Phys
2008 ATLAS *Expected Performa*
2010 start-up at 3.5 + 3.5 TeV
2012 4th July discovery of boson

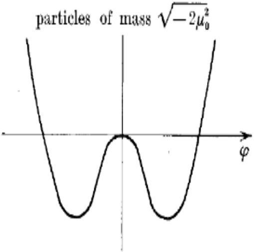


Fig. 7.

$$\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{24}\varphi^4$$

ery of W and Z at CERN
Lausanne

ALICE)

4

Fayard reminded us that we can see far because we are sitting on the shoulder of giants !and profit from extraordinary collective effort from the LHC experimental collaborations

Higgs = “raison d’être” of LHC

- ! 500 physics papers over the last 5 years have an introduction starting like `“the (main) goal of the LHC is discover the Higgs boson”`

- ! 11’000 papers in Spires contain “Higgs” in their title
- ! ~~3~~x10^6 references in google (10^7 as of today ! 1% of M. Jackson)
- ... no Nobel prize (so far)

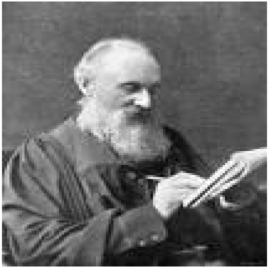
Reasons of a success

- last missing piece of the SM?
- at the origin of the masses of elementary particles?
- unitarization of WW scattering amplitudes
- screening of gauge boson self-energies

“Higgs = emergency tire of the SM”

Altarelli @ Blois’

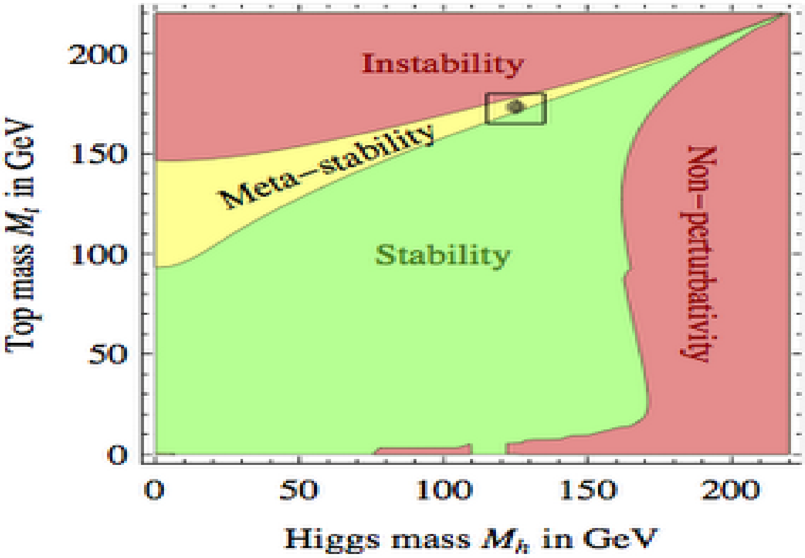
The legacy of LHC?



WE LIVE ON THE SHOULDERS OF GIANTS BUT · · ·

- *All that remains to do in physics is to look into the sixth decimal place* (Albert Michelson 1984)
- *There is nothing new to be discovered in physics now. All that remains is more and more precise measurements* (Lord Kelvin 1900)

Let us help history to repeat!

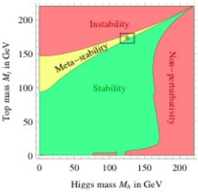

Instability
Meta−stability
Stability
Non−perturbativity
Top mass M_t in GeV
Higgs mass M_h in GeV
0
50
100
150
200
0
50
100
150
200

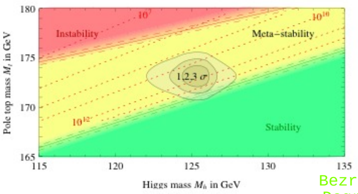
The fate of the EW vacuum

Many of my theory colleagues also started wild speculations/extrapolations

`the SM vacuum is stable/metastable`

`and the validity of the SM can be extended up to the Planc`





Bezrukov et al '1
Degrassi et al ':

It is almost certain (>4 σ) that $m_H > M_{\text{metastability}}$ and totally certain that $m_H < M^{h^3}_{\text{Landau}}$

(even though this certainty might by questioned by threshold effects at the Planck scale Holthausen, Lim and Lindner) '12

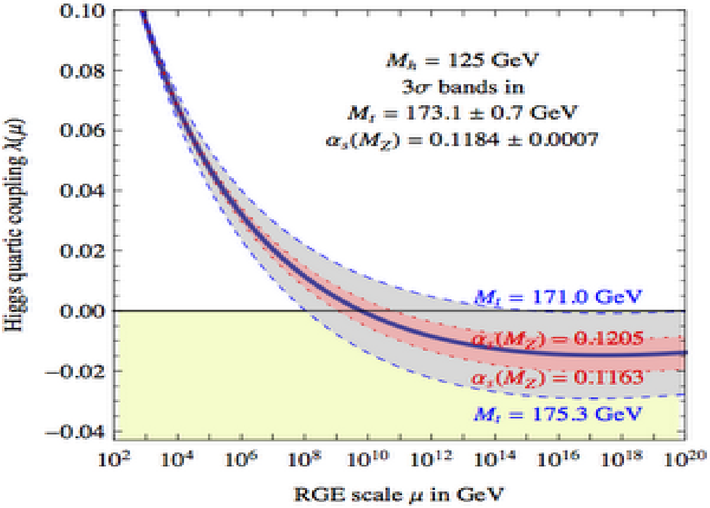
Not totally clear yet if m_H is above $M_{\text{stability}}$, but rather important question since

- ☑ if $m_H > M_{\text{stability}}$, the Higgs could serve as an inflaton
- ☑ if $m_H = M_{\text{stability}}$ the SM is asymptotically safe, ie consistent up to arbitrary high energy

Bezrukovet al '

need precise Higgs&top mass/couplings (and α_s) measurements (ILC, μ coll.)

and better understanding of pole vs MS top mass Alekhin, Djouadi, Moch '12



Is the Higgs potential vanishing at M_p? *absence of new energy scale between the Fermi and the Planck scales? EWSB determined by Planck physics?*

in a nutshell

One can assume that some unspecified physics near the Planck scale restores the boundedness of the Higgs potential

STILL, BETWEEN 10^{10} GeV AND 10^{19} GeV

▷ THE POTENTIAL IS NEGATIVE ◁

therefore it has a global minimum at large $|H|$ *that is much deeper than the vacuum we live in*

As a consequence

there is a non-zero probability of tunneling into the other vacuum

However, no "end date" of the Maya calendar

Higgs and MSSM

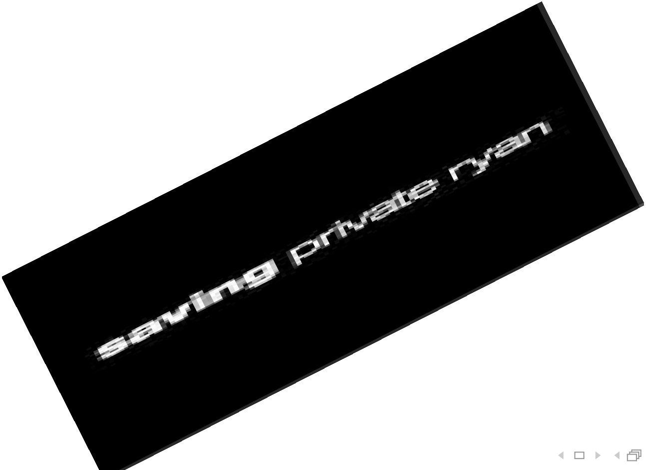
$$M_{\mathrm{H}}^2 = M_{\mathrm{Z}}^2 \cos^2 2\beta + \delta_{\mathrm{t}}^2$$

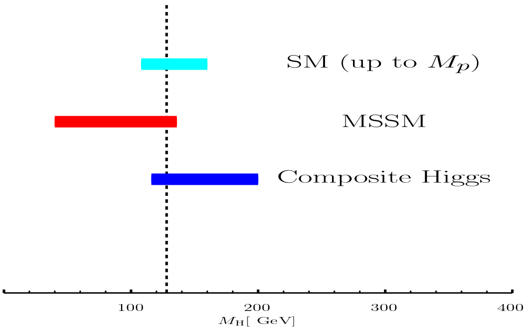
$$(125\ GeV)^2 \qquad\qquad (\geq 87\ GeV)^2$$

- substantial loop contribution from stops
- large mixings, heavy stops
- irreducible fine tuning $\sim \mathcal{O}(1\%)$

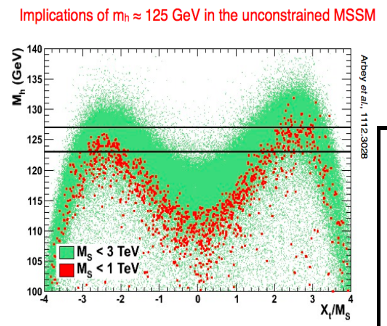
Higgs and BSM

The value of the Higgs mass together with the absence of any additional new physics so far restrict any BSM model to exotic corners of its parameter space.





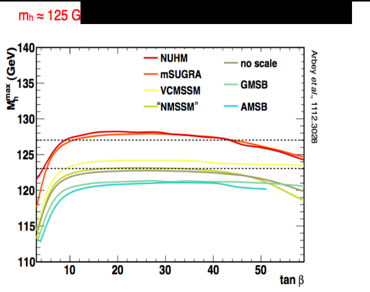
But be careful about resurrections . . . . . .



$1 \leq \tan\beta \leq 60,\ 50\text{ GeV} \leq M_A \leq 3\text{ TeV},\ -9\text{ TeV} \leq A_f \leq 9\text{ TeV},$
$50\text{ GeV} \leq m_{\tilde f_L}, m_{\tilde f_R}, M_3 \leq 3\text{ TeV},\ 50\text{ GeV} \leq M_1, M_2, |\mu| \leq 1.5\text{ TeV}.$

Large mixing scenarios surviving

Some models in trouble with MH@125

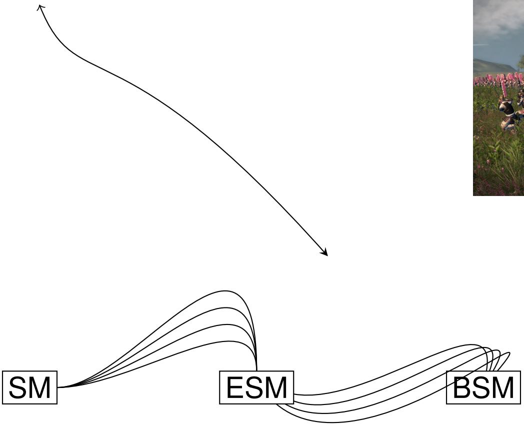


mSUGRA: $50\text{ GeV} \leq m_0 \leq 3\text{ TeV},\ 50\text{ GeV} \leq m_{1/2} \leq 3\text{ TeV},\ |A_0| \leq 9\text{ TeV};$
GMSB: $10\text{ TeV} \leq \Lambda \leq 1000\text{ TeV},\ 1 \leq M_{mess}/\Lambda \leq 10^{11},\ N_{mess} = 1;$
AMSB: $1\text{ TeV} \leq m_{3/2} \leq 100\text{ TeV},\ 50\text{ GeV} \leq m_0 \leq 3\text{ TeV}.$

- More or less SM-like Higgs couplings don't really hurt the (X)MSSM. [redacted]

Strategy

Let's consider the following path

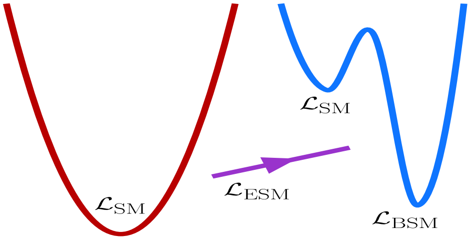


Strategy

HO TO TACKLE THE QUESTION

- Interpret the **Higgs data** in the context of the SM *until any serious tension appears*
- Interpret the **Higgs data** in the context of an **Effective Theory**: *systematically expand interactions of a Higgs-like scalar in d* $>$ 4 *operators*
- Interpret the **Higgs data** in the context of concrete models beyond the SM (*MSSM, NMSSM,* ...)

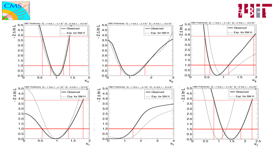
BSM Hunting



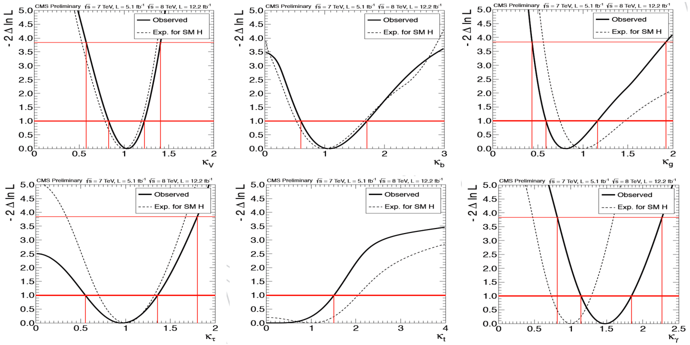
$$\mathcal{L}_{\rm ESM} = \mathcal{L}_{\rm SM} + \sum_{n>4} \sum_{i=1}^{N_n} \frac{a_i^n}{\Lambda^{n-4}} \mathcal{O}_i^{(d=n)}$$

Status HCP 2012

- Uncertainties of coupling parameters $\approx \mathbf{20 - 30\%}$
- No significant deviations from the SM couplings are observed (well within $\mathbf{2}\,\sigma$).
  N.B. 20% deviation $\equiv \Lambda \approx 5\ TeV$.
- Too early to draw any conclusion? Data-driven Theory!

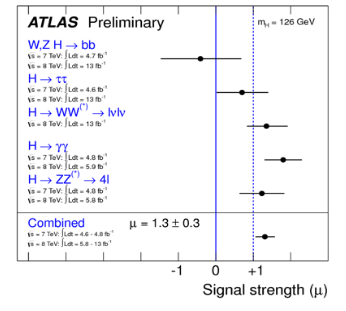


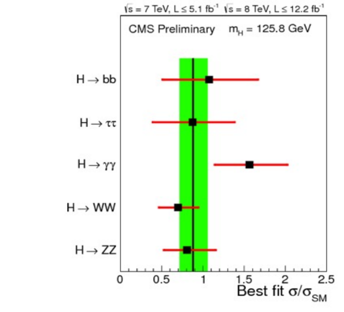
6$.


CMS Preliminary √s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 12.2 fb⁻¹
- 2 Δ ln L
Observed
Exp. for SM H
κ_V
κ_b
κ_g
κ_τ
κ_t
κ_γ

6$.

Higgs!





Interest now in Higgs properties:

- overall rate in different decay channels...

Key formula arXiv:1209.0040

A. David, A. Denner, M. Duehrssen, M. Grazzini, C. Grojean, G. P., M. Schumacher, M. Spira, G. Weiglein, M. Zanetti

The width of the assumed Higgs boson near 125 *GeV* is neglected ($5-10\%$ accuracy for single channels), *i.e. the zero-width approximation for this state is used.*

$$(\sigma \cdot \mathrm{BR})(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

Taking the process $\mathrm{gg} \to \mathrm{H} \to \gamma\gamma$ as an example, one would use as cross section:

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

A reason (not) to believe

This year we learned that the Higgs mass is 125.8 GeV *give or take* **1/2 GeV**

- **As a consequence,** *we learned that God plays not only dice but also russian roulette*

  In other words, that life is futile because everything we cherish and hold dear will decay. In other words, that the vacuum of the standard model could be non-stable.

- **Keep in mind the important disclaimer:** *All this discussion is valid assuming the SM is the correct theory all the way up to the Planck scale, which is unlikely.*

Perspectives

IT IS EXPENSIVE IN TIME AND MONEY TO BUILD HIGHER ENERGY COLLIDERS OUR MAIN RELIABLE TRANSPORTER INTO

▷ the high energy frontier ◁

Relatively speaking, theoretical research is inexpensive

though hundreds of theories have been born and have died. Some have died due to incompatibility of new data, but others have died under their own self-consistency problems. In that sense progress is made

When attempting to really explain, the consistency issues must be stretched to the maximum

Our hope that unsparing devotion to full consistency, both observational and mathematical will be the hallmarks of the future era

Conclusions

A lot of take-home messages

(will be expensive if you are traveling with Easyjet!)

A new particle has been discovered and it is likely to play a key role in our understanding of the fundamental laws of Nature

but we should remember that the SM doesn't "explain" the EW scale

is the EW scale "natural" or fine-tuned?

is the Dark Matter linked to the EW physics?

are neutrino masses indicating a new (high) sca

will the fundamental interactions unify?

we have to make sure that the next exp. facilities can answer these questions (and other ones) without (too much) theoretical prejudice

The Future

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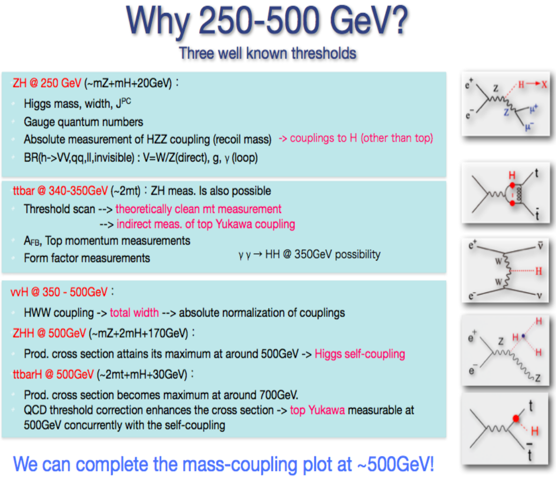
K. Fujii reminded us of the nice measurement an ILC machine reaching up to 500 GeV CM energy can do for a Higgs @ 125 GeV



Still to do

Study the $\mathrm{H}(125.8)$ landscape

▷ *Attack the list of unsolved problems* ◁

A personal wish-list

- NON-COLLIDER OBSERVATIONS *we cannot explain dark-matter and baryon asymmetry in the universe*
- LARGE HIERACHIES $\mathbf{m_t/m_e > 10^6}$
- EMBEDDING GRAVITY INTO QUANTUM MECHANICS *should bring new implications to the particle physics world*

Still to do

Study the $\mathrm{H}(125.8)$ landscape

▷ *Attack the list of unsolved problems* ◁

A personal wish-list

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- LARGE HIERACHIES $\mathbf{m}_{\mathrm{t}}/\mathbf{m}_{\mathrm{e}} > \mathbf{10^6}$
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Still to do

Study the $\mathrm{H}(125.8)$ landscape

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Conclusions?

- Higgs-landscape: asking the right questions takes as much skill as giving the right answers
- *A conclusion is the place where you got tired of thinking* (Arthur Bloch)
- *I am turned into a sort of machine for observing facts and grinding out conclusions* (Charles Darwin)
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Thanks for your attention