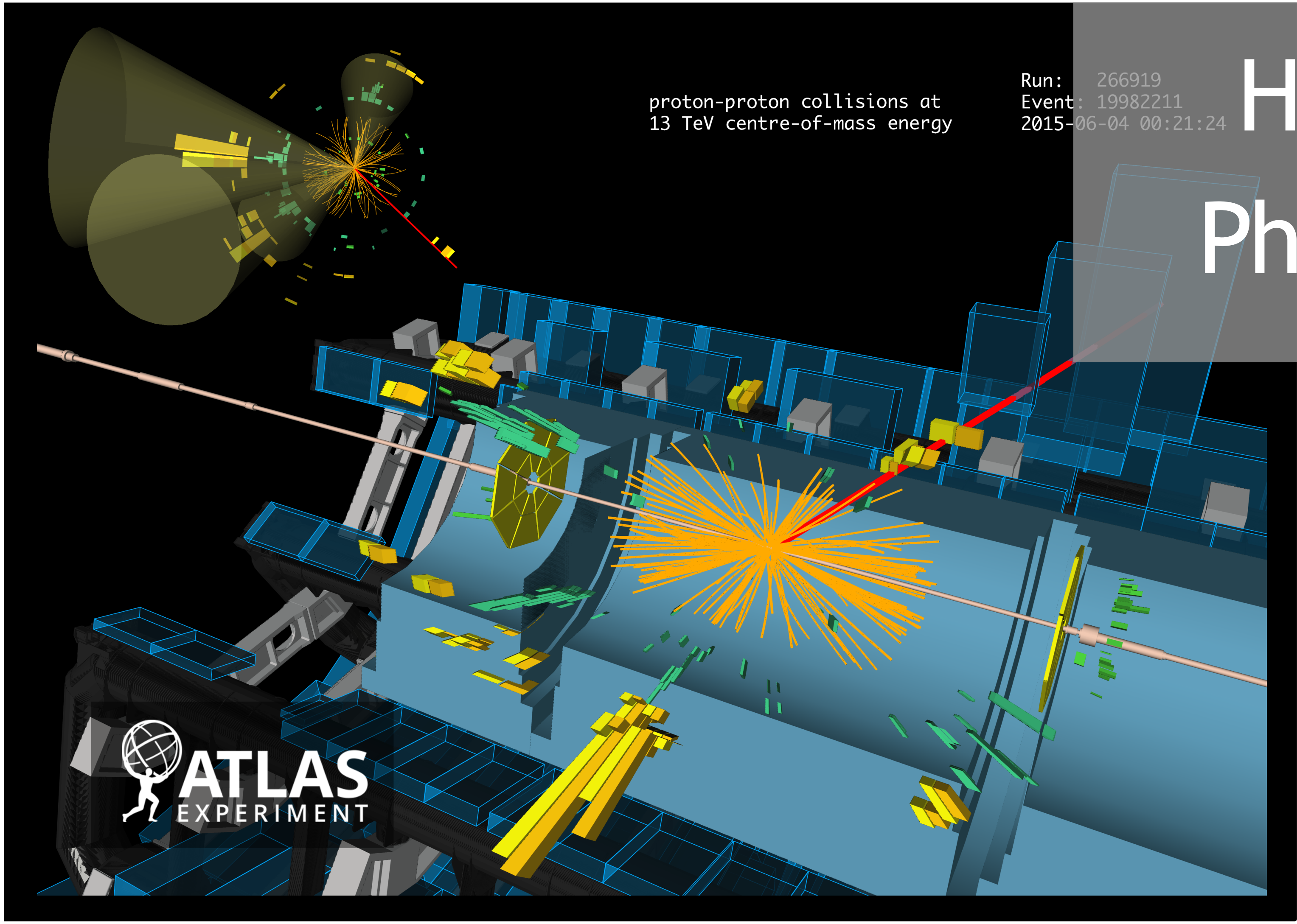

Higgs Physics

HCP 2015

Lecture III

Implications, Additional Higgs states and What next?

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Outline

Lecture I

- Introduction : Elements of history
- Elements of SM Higgs theory
- Precision EW tests
- The discovery of the Higgs boson
- An (early) experimental profile of the Higgs boson: The discovery channels

Lecture II

- An (early) experimental profile of the Higgs boson: All Final States (Fermion modes)
- The Higgs width
- Rare decay modes
- Rare production modes
- Combined measurements

Lecture III

- Implications of the discovered state
- Search for BSM Higgs and extended sectors
- New trends
- Future Higgs programs

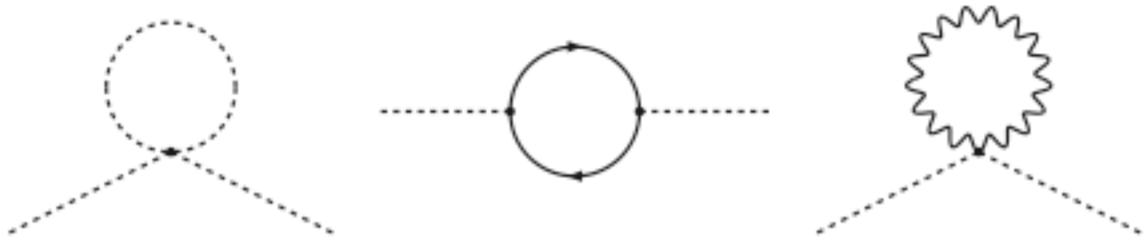
Hierarchy, Fine Tuning and Naturalness

How the Higgs boson does not only SOLVE problems

The Hierarchy Problem the Usual Picture

The Higgs potential is fully renormalizable, but…

Loop corrections to the Higgs boson mass…



…are quadratically divergent : $$\Delta m^2 \propto \int^{\Lambda} \frac{d^4k}{(2\pi)^4}\frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi^2}$$

If the scale at which the standard model breaks down is large, the Higgs natural mass should be of the order of the cut-off. e.g. the Planck scale

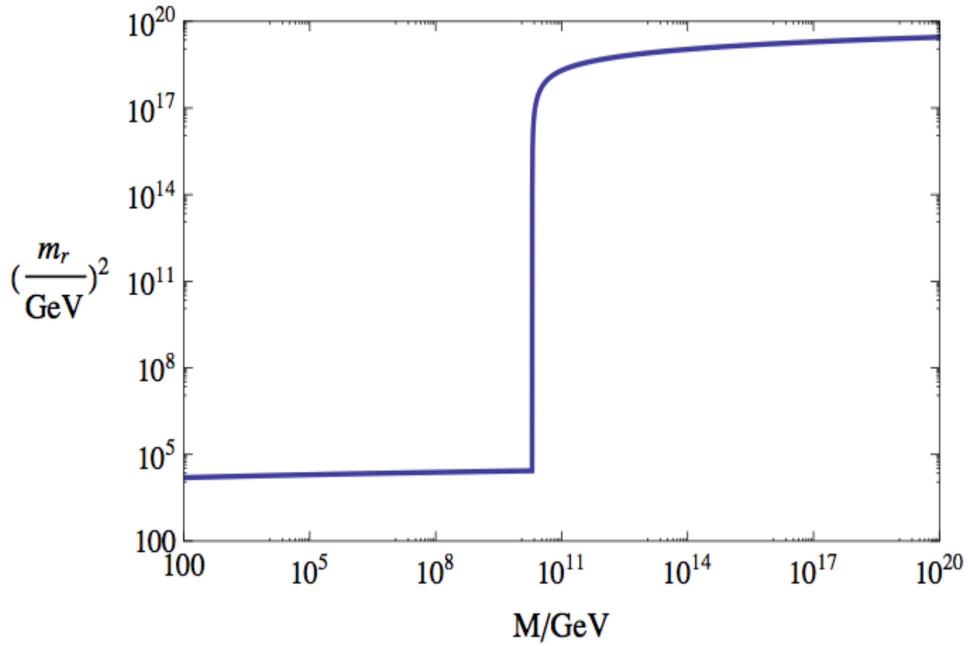
$$m_H = m_0 + \Delta m + \ldots$$ *Higher orders*

…but the Higgs boson has a low mass!

This can be achieved by fine tuning our theory… Inelegant…

(note that technicolor models are not concerned by this problem)

Running of the Higgs boson Mass



R. Barbieri
Nobel Coloquium

- Impact of a new particle with typical gauge couplings
- Large step in the running mass, larger the larger the scale of new physics.
- How can the microscopic Higgs mass know how to choose its value so that the EW scale mass is so low (125 GeV) ??
- Of course no Hierarchy problem if… no new physics
- Or if the new physics is nearby !!!

Supersymmetry

The Hierarchy problem is not only a problem of esthetics : If the difference is imposed at tree level, the radiative corrections will still mix the scales and destabilize the theory.

One may note that :

$$\Delta m_H^2 \sim \frac{|\lambda_f|^2}{16\pi^2}(-2\Lambda^2 + 6m_f^2 \ln\frac{\Lambda}{m_f} + ...)$$ → Contribution of fermions

$$\Delta m_H^2 \sim \frac{\lambda_s}{16\pi^2}(\Lambda^2 + 2m_f^2 \ln\frac{\Lambda}{m_s} + ...)$$ → Contribution of scalars

Therefore in a theory where for each fermion there are two scalar fields with

$$\lambda_s = |\lambda_f|^2$$

(which is fulfilled if the scalars have the same couplings as the fermions) quadratic divergencies will cancel

The field content of the standard model is not sufficient to fulfill this condition

A solution is given by supersymmetry where each fermionic degree of freedom has a symmetrical bosonic correspondence

In supersymmetry the quadratic divergences naturally disappear but…

Immediately a problem occurs : Supersymmetry imposes $m_{boson} = m_{fermion}$

Supersymmetry must be broken!

But in the case of SUSY a SSB mechanism is far more complex than for the EWSB and no satisfactory SSB solution exists at this time…

…However an explicit breaking "by hand" is possible provided that it is softly done in order to preserves the SUSY good UV behavior…

$$\Delta m_H^2 \propto m_{soft}^2 (\ln \frac{\Lambda}{m_{soft}} + ...)$$

Interestingly similar relation to that of the general fine tuning one

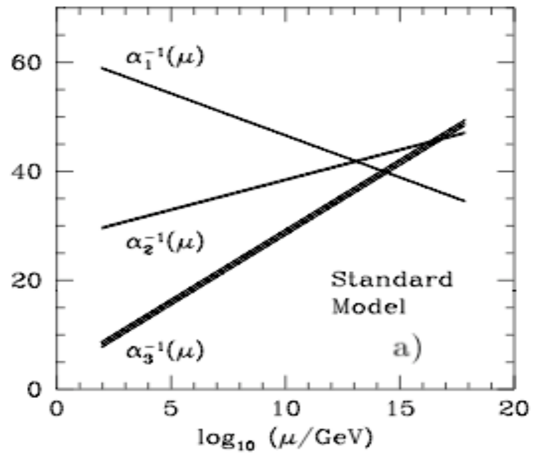
Implies that the m_{soft} should not exceed a few TeV

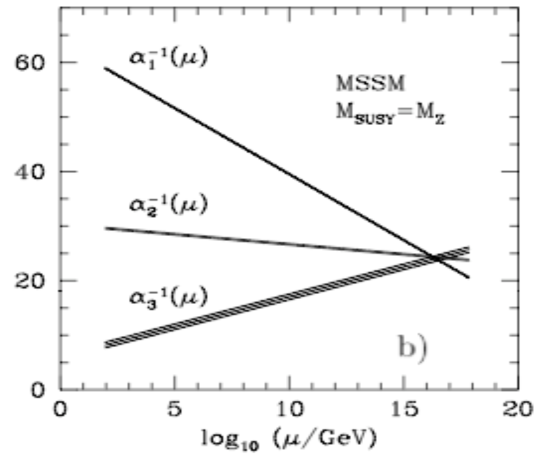
The Minimal Supersymmetric Standard Model's Higgs Sector

In a tiny nut shell

Additional motivations for supersymmetry :

- Allows the unification of couplings
- Local SUSY: spin 3/2 gravitino (essential ingredient in strings)
- Natural candidate for Dark Matter





The Higgs Sector : Two doubets with opposite hypercharges are needed to cancel anomalies (and to give masses independently to different isospin fermions)

- MSSM : 5 Higgs bosons
- Lightest mass < m_Z at tree level and smaller than ~130 GeV/c^2 w/ rad. Corr.

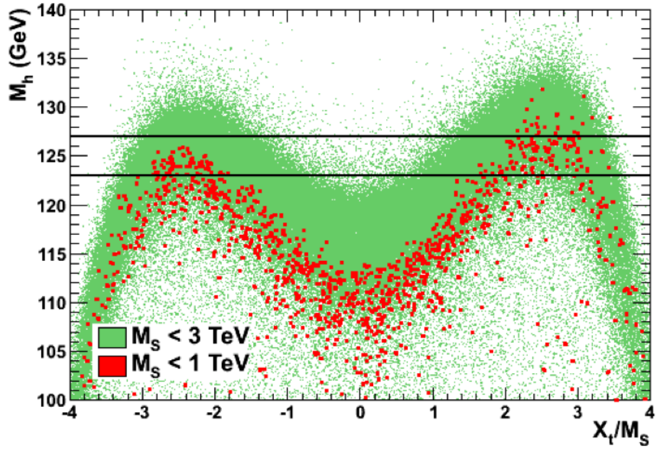
Extented Higgs Sectors

1.- Additional doublets (2 HDMs) ?

SUSY: Two doubets with opposite hypercharges are needed to cancel anomalies (and to give masses independently to different isospin fermions)

Only 2 Higgs doublets?

Parameter space in
MSSM growing thin



2.- Why should it be minimal?

3.- Additional singlets ?

μ parameter (of the superpotential) problem in SUSY, can be solved by the introduction of a singlet field in the NMSSM

4.- Additional triplet(s) ?

In order to generate Majorana mass terms for neutrinos

Consequence of Knowng the Higgs boson mass…

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

The Quartic Coupling is also fixed (if SM potential!)

$$\lambda = 0.126$$

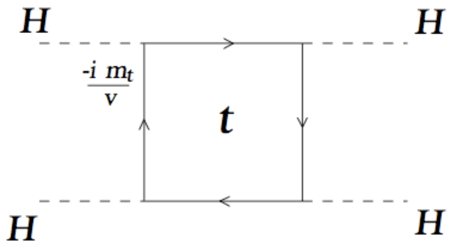
What can we learn from its RGE evolution?

Running Quartic Coupling : Vacuum stability

Looking closer into the limit where the Higgs boson mass is small :

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - \boxed{24y_t^4} + \cdots$$

The last term of the equation is dominant and due to diagrams such as :

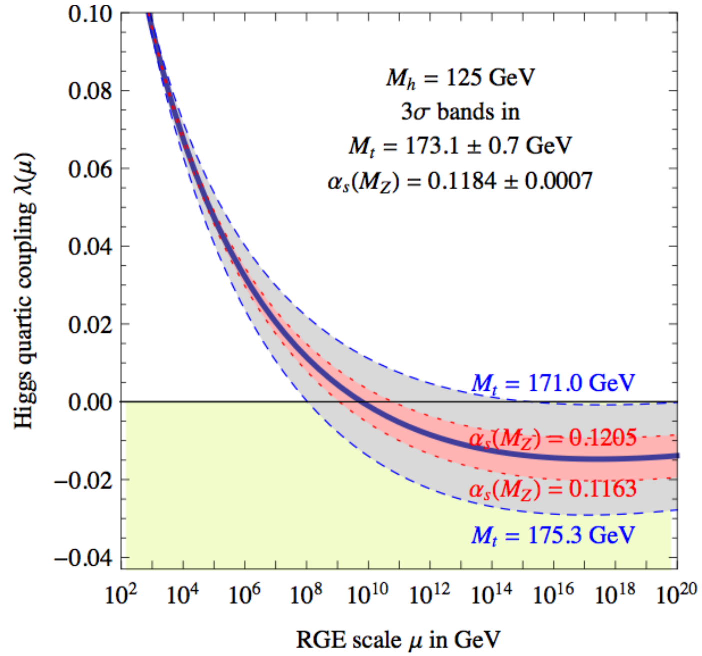


$$\sim \frac{m_t^4}{v^4}$$

The equation is then very simply solved :

$$\lambda(\Lambda) = \lambda(v) - \frac{3}{4\pi^2} y_t^2 \log\left(\frac{\Lambda^2}{v^2}\right)$$

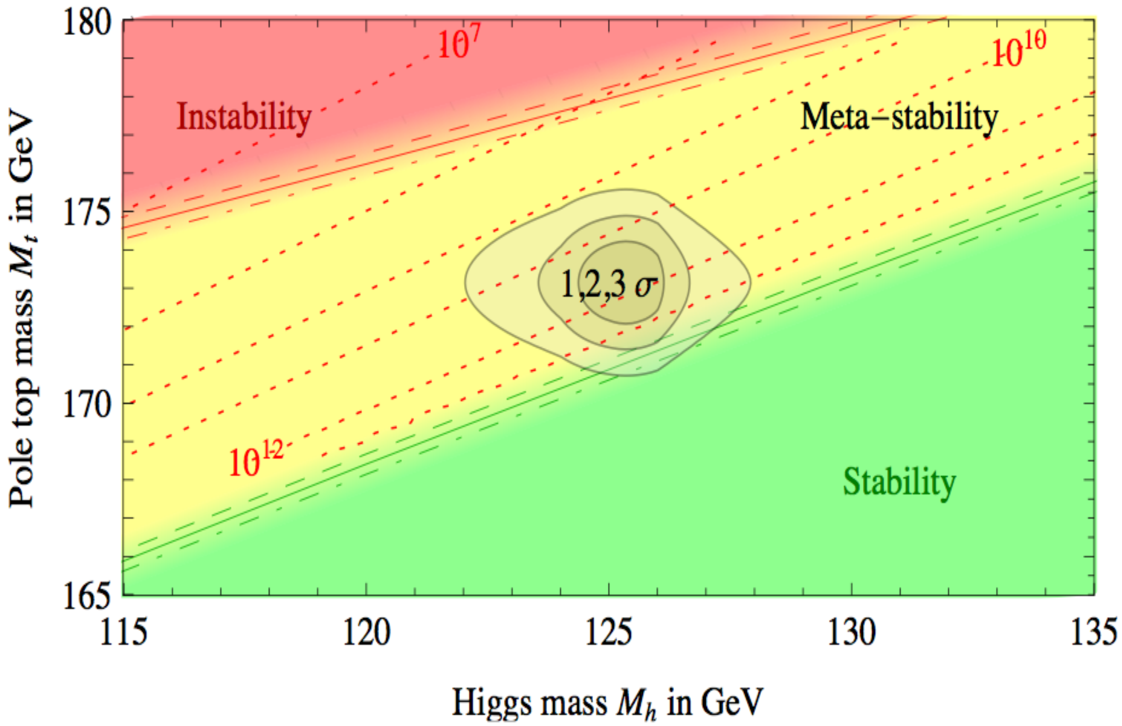
$\lambda \sim 0$
(at the high scale)



Running of the Quartic Coupling

Metastability

Guiding Principle?



Large dependence on top mass and of course Higgs boson mass

Return to the EW fit again !

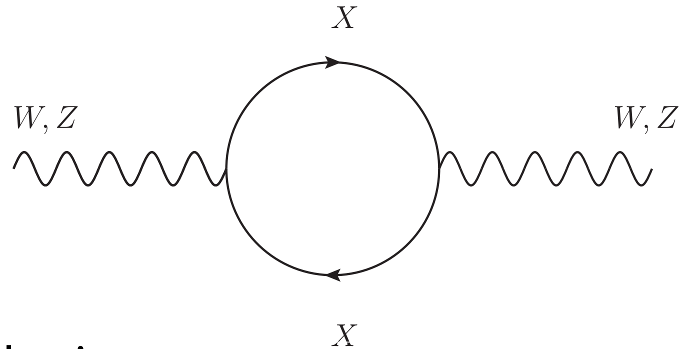
1.- We have seen how precision EW can predict the Higgs boson mass before having observed it ! This was simply using the Standard Model (with a Higgs boson) assumption.

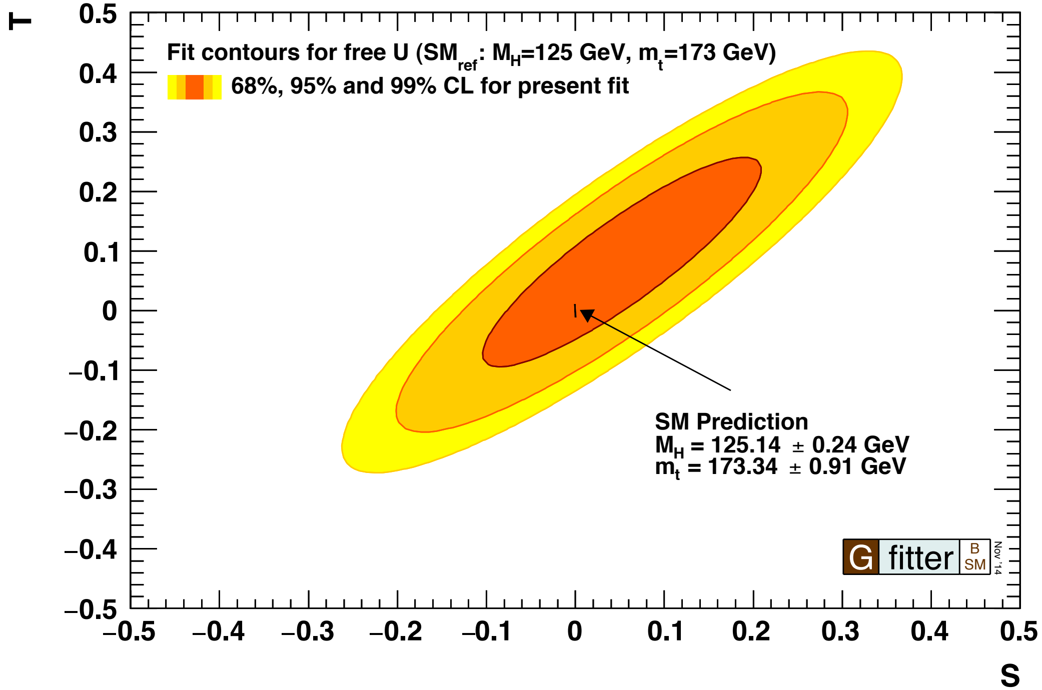
2.- We have seen the effect of knowing the Higgs boson mass on predicting key parameters such as the W and top mass.

3.- We have seen how precision EW measurements (still in this SM framework) can help us constraining the Higgs couplings.

What can it tell us about new physics beyond the SM ?

The Oblique Parameters





Parameterization of new physics contributions to EW observables :

- S : New physics contribution to neutral currents

- T : Difference between charged currents and neutral currents

- U : Mostly sensitive to the W mass and Width

Particularly useful to compare predictions of BSM new physics with EW data

e.g. allows to exclude : Compositte Higgs, extra dimensions, and many other with constraints at the level of 1-2 TeV

Global Interpretation Guidelines

Important : assumes that all new physics is at a higher scale Λ

Operators involving bosons only
$\mathcal{O}_H = 1/(2v^2)\left(\partial^\mu(\Phi^\dagger\Phi)\right)^2$
$\mathcal{O}_T = 1/(2v^2)(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)^2$
$\mathcal{O}_6 = -\lambda/(v^2)\left(\Phi^\dagger\Phi\right)^3$
$\mathcal{O}_B = (ig')/(2m_W^2)(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\partial^\nu B_{\mu\nu})$
$\mathcal{O}_W = (ig)/(2m_W^2)(\Phi^\dagger\sigma^i \overleftrightarrow{D}^\mu\Phi)(D^\nu W_{\mu\nu})^i$
$\mathcal{O}_{HB} = (ig')/m_W^2\,(D^\mu\Phi)^\dagger(D^\nu\Phi)B_{\mu\nu}$
$\mathcal{O}_{HW} = (ig)/m_W^2\,(D^\mu\Phi)^\dagger\sigma^i(D^\nu\Phi)W^i_{\mu\nu}$
$\mathcal{O}_{BB} = g'^2/m_W^2\,\Phi^\dagger\Phi\,B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{GG} = g_S^2/m_W^2\,\Phi^\dagger\Phi\,G^A_{\mu\nu}G^{A\mu\nu}$
$\mathcal{O}_{H\tilde{B}} = (ig')/m_W^2\,(D^\mu\Phi)^\dagger(D^\nu\Phi)\tilde{B}_{\mu\nu}$
$\mathcal{O}_{H\tilde{W}} = (ig)/m_W^2\,(D^\mu\Phi)^\dagger\sigma^i(D^\nu\Phi)\tilde{W}^i_{\mu\nu}$
$\mathcal{O}_{B\tilde{B}} = g'^2/m_W^2\,\Phi^\dagger\Phi\,B_{\mu\nu}\tilde{B}^{\mu\nu}$
$\mathcal{O}_{G\tilde{G}} = g_S^2/m_W^2\,\Phi^\dagger\Phi\,G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$

(H)EFT

What is the scale of new physics?

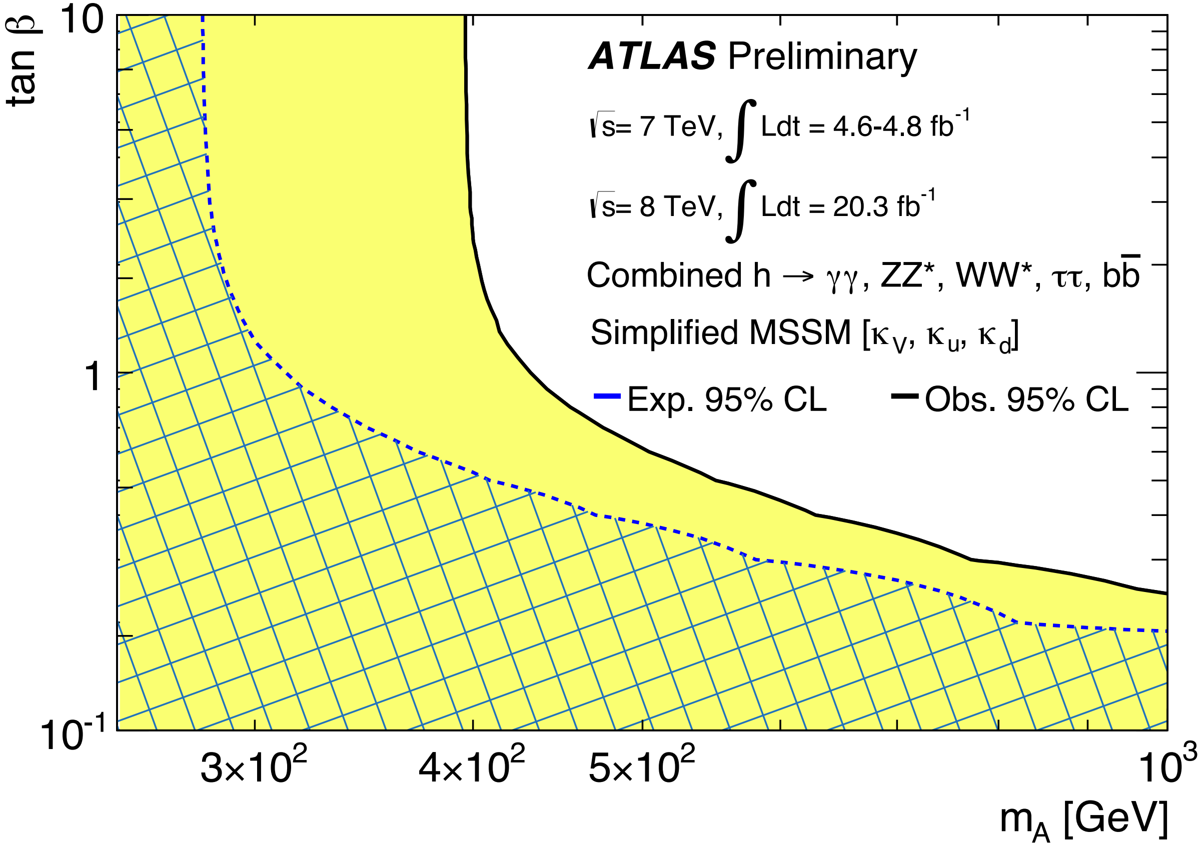
Ops. involving bosons and fermions
$\mathcal{O}_{uB} = (g'\,y_u)/m_W^2\,(\bar{q}_L\Phi^c\sigma^{\mu\nu}u_R)\,B_{\mu\nu}$
$\mathcal{O}_{uW} = (g\,y_u)/m_W^2\,(\bar{q}_L\sigma^i\Phi^c\sigma^{\mu\nu}u_R)\,W^i_{\mu\nu}$
$\mathcal{O}_{uG} = (g_S\,y_u)/m_W^2\,(\bar{q}_L\Phi^c\sigma^{\mu\nu}t^A u_R)\,G^A_{\mu\nu}R$
$\mathcal{O}_{dB} = (g'\,y_d)/m_W^2\,(\bar{q}_L\Phi\sigma^{\mu\nu}d_R)\,B_{\mu\nu}$
$\mathcal{O}_{dW} = (g\,y_d)/m_W^2\,(\bar{q}_L\sigma^i\Phi\sigma^{\mu\nu}d_R)\,W^i_{\mu\nu}$
$\mathcal{O}_{dG} = (g_S\,y_d)/m_W^2\,(\bar{q}_L\Phi\sigma^{\mu\nu}t^A d_R)\,G^A_{\mu\nu}$
$\mathcal{O}_{lB} = (g'\,y_l)/m_W^2\,(\bar{L}_L\Phi\sigma^{\mu\nu}l_R)\,B_{\mu\nu}$
$\mathcal{O}_{lW} = (g\,y_l)/m_W^2\,(\bar{L}_L\sigma^i\Phi\sigma^{\mu\nu}l_R)\,W^i_{\mu\nu}$

Ops. involving bosons and fermions
$\mathcal{O}_t = y_t/v^2\,(\Phi^\dagger\Phi)\,(\bar{q}_L\Phi^c t_R)$
$\mathcal{O}_b = y_b/v^2\,(\Phi^\dagger\Phi)\,(\bar{q}_L\Phi b_R)$
$\mathcal{O}_\tau = y_\tau/v^2\,(\Phi^\dagger\Phi)\,(\bar{L}_L\Phi\tau_R)$
$\mathcal{O}_{Hq} = i/v^2\,(\bar{q}_L\gamma^\mu q_L)\,(\Phi^\dagger\overleftrightarrow{D}_\mu\Phi)$
$\mathcal{O}^{(3)}_{Hq} = i/v^2\,(\bar{q}_L\gamma^\mu\sigma^i q_L)\,(\Phi^\dagger\sigma^i\overleftrightarrow{D}_\mu\Phi)$
$\mathcal{O}_{Hu} = i/v^2\,(\bar{u}_R\gamma^\mu u_R)\,(\Phi^\dagger\overleftrightarrow{D}_\mu\Phi)$
$\mathcal{O}_{Hd} = i/v^2\,(\bar{d}_R\gamma^\mu d_R)\,(\Phi^\dagger\overleftrightarrow{D}_\mu\Phi)$
$\mathcal{O}_{Hud} = i\,y_u y_d/v^2\,(\bar{u}_R\gamma^\mu d_R)\,(\Phi^{c\dagger}\overleftrightarrow{D}_\mu\Phi)$
$\mathcal{O}_{Hl} = i/v^2\,(\bar{l}_R\gamma^\mu l_R)\,(\Phi^\dagger\overleftrightarrow{D}_\mu\Phi)$

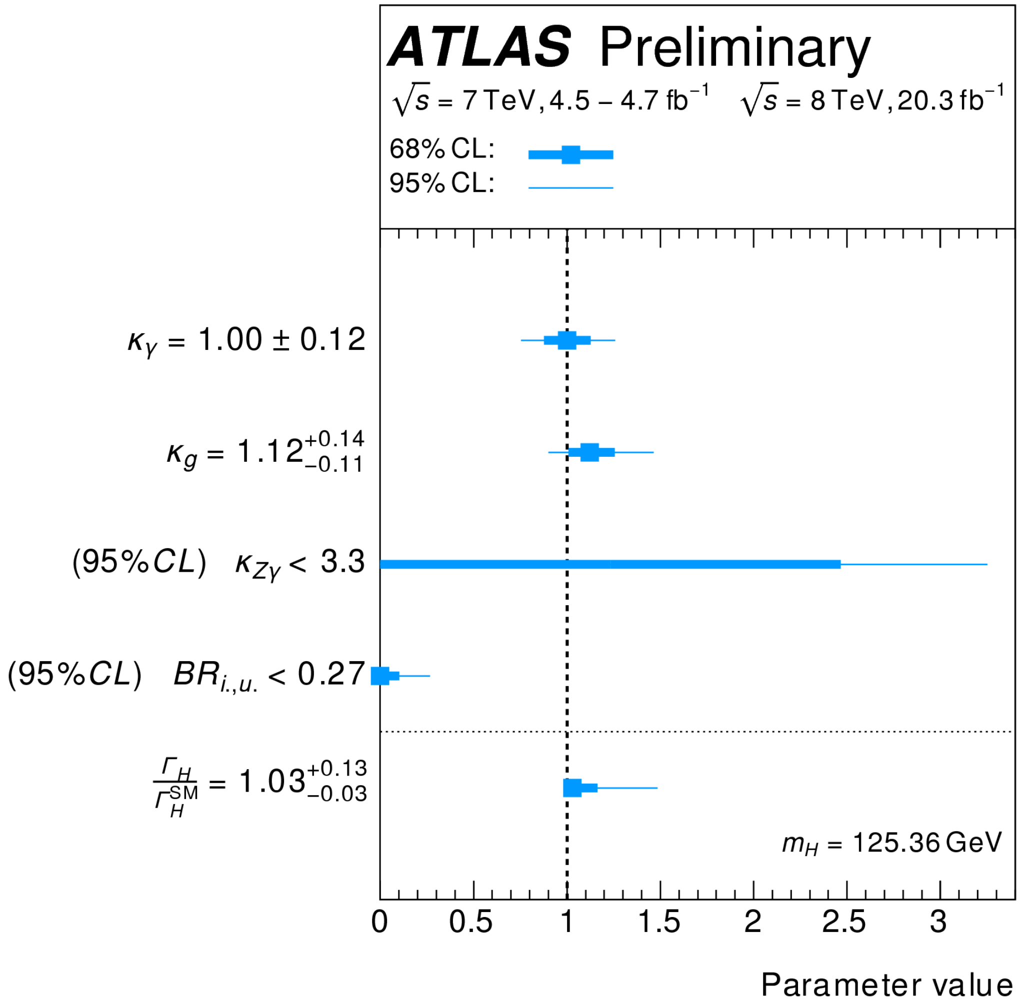
Constraining the MSSM When Probing the fermion couplings

Simplified MSSM interpretation :

- Fitting k_V, k_u and k_d
- Assuming no new particles neither in the decay nor in the loops



Constraining BSM Scenarios through Higgs Couplings Combination

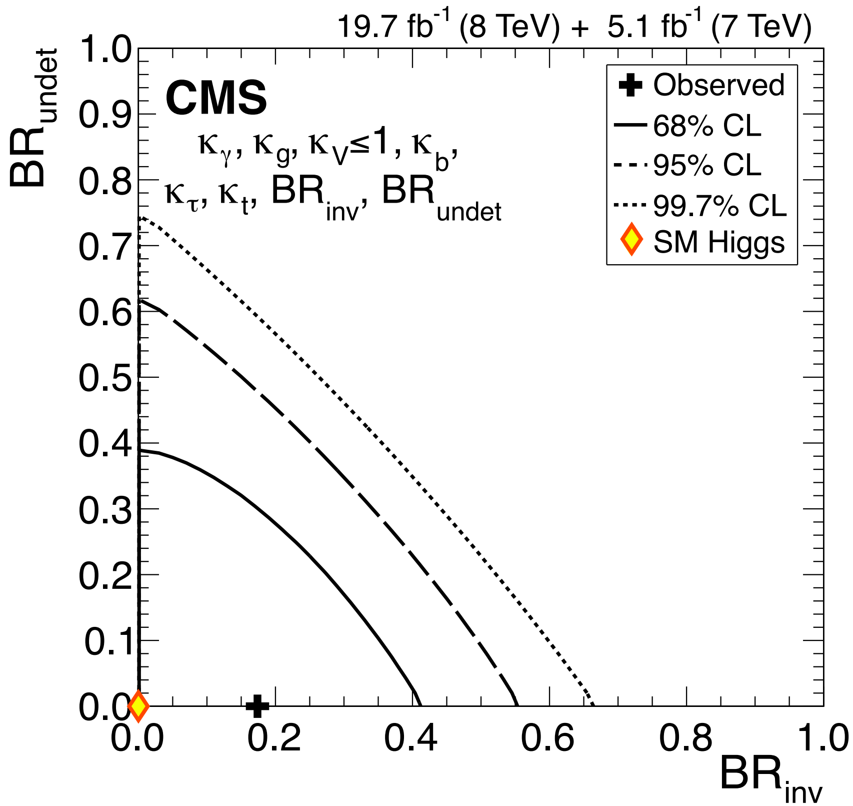


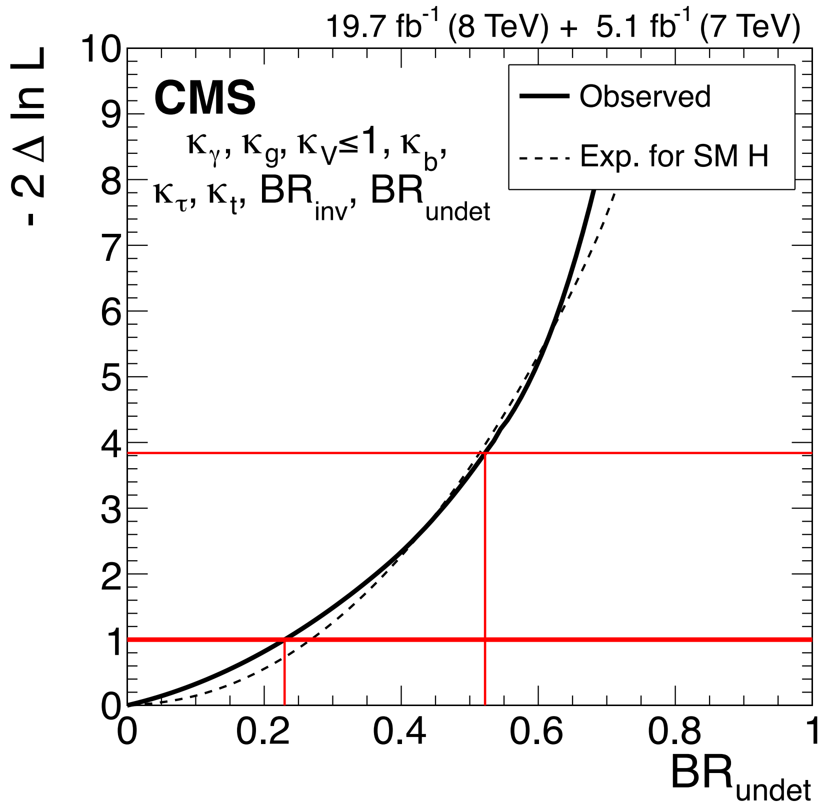
Fitting the effective coupling of the Higgs to photons k_g (charged particles) and to gluons k_g (particles with color).

- Assuming all couplings to SM particles to be SM like $k_V = k_F = 1$

- No assumption on the total width (yields a limit on the total width) – Or the invisible and undetected branching fraction.

Combining Visible and Invisible Channels





Constraining the undetected branching only (or limit on the width assuming that the undetected part is 0)

Run-2 Start Up : 13 TeV is here !

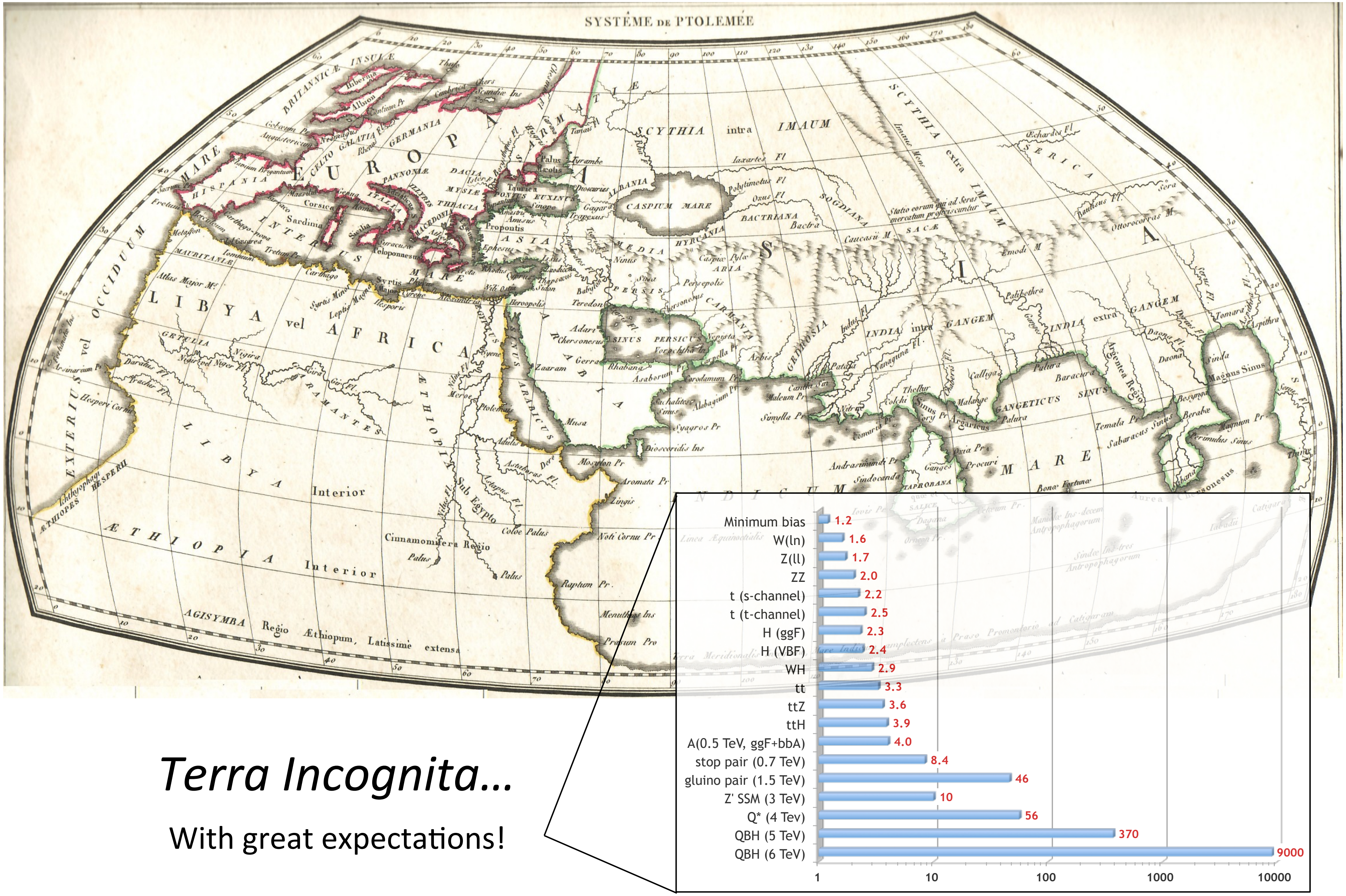
Unique opportunity for spectacular discovery
for quite some time…

… Exploration of a new territory

Need strong Motivations, we don't have a no loose theorem any more, but we have **Naturalness**

Of course we'll leave no stones unturned (also with Th guidance)

Next Steps



Terra Incognita…

With great expectations!

Nano Review of (Run 1) BSM Channels

- Charged Higgs
  - Main current analysis $H^{\pm}$ to tn
  - $H^{\pm}$ to cs
  - High mass specific $H^{\pm}$ to AW
  - High mass specific $H^{\pm}$ to tb

- MSSM h, H, and A
  - Main current analysis tt (LHCb as well)
  - Also searched for in mm
  - Also searched for in bb(b)
  - New open channel in the intermediate-high mass: hh, hZ (in many channels with subsequent decays of h and Z)

- NMSSM a
  - Direct mm
  - Exotic cascades h to aa in various channels (ttmm, 4g, 4m, etc…)
  - Radiative transitions U to g a (Babar)

- High (low) Mass CP-even Higgs
  - ZZ (llll, llqq, llvv, vvqq, qq qq channels)
  - WW (lvlv, lvqq qq qq channels)
  - Diphoton channel (allows to investigate low mass as well)
  - gg See latest CMS result and extending
    mass domain

- Doubly charged Higgs

The Higgs boson as Tool to Search for new phenomena

- In Higgs production Di-Higgs and Higgs-VB production channels (hh, hZ and hW)

- Search for BSM in the Higgs decays:
  - Invisible Higgs decays
  - Dark Z (with mass lower than the Z)
  - Hidden valley pions

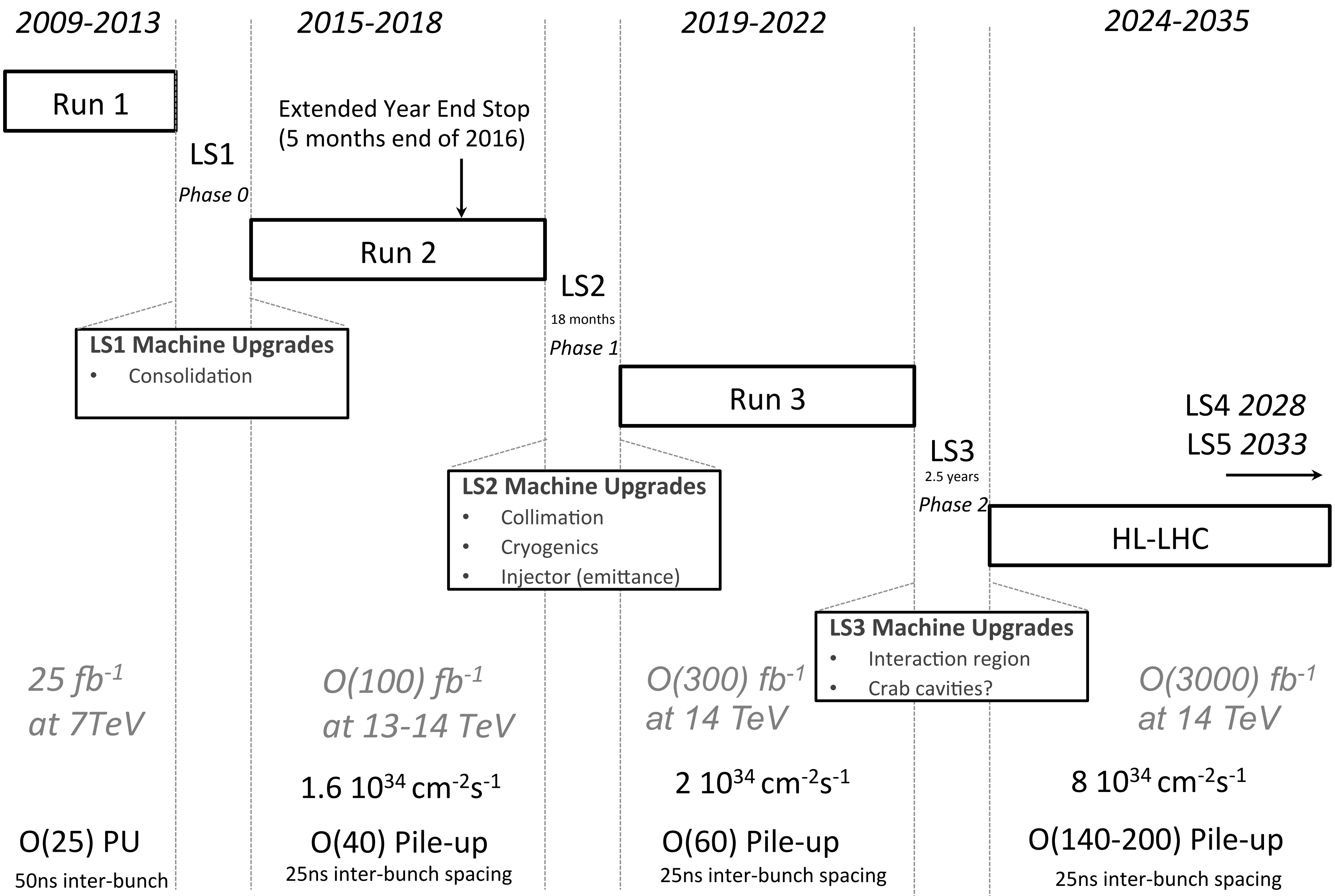
- Search for dark matter in mono Higgs production

See lecture on BSM exotics at LHC

What Next ?

(Discuss only HL-LHC – For future accelerators see F. Zimmerman's Lectures)

The LHC Run 2 and Beyond

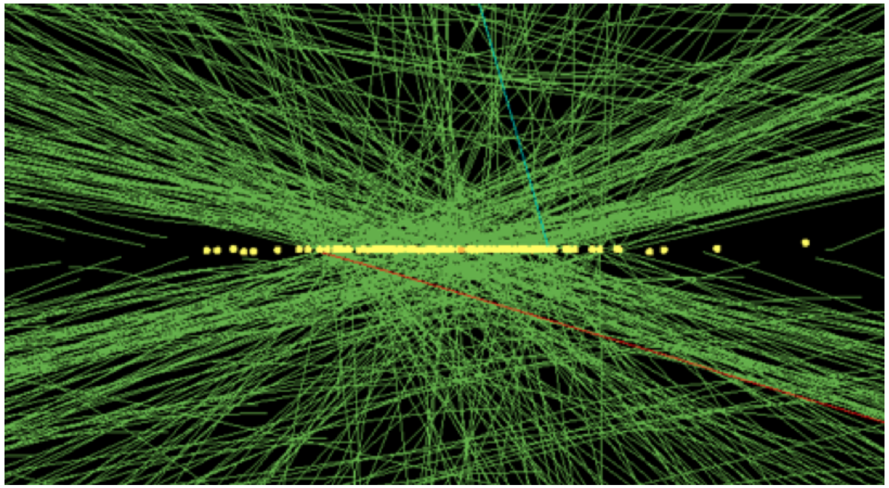


HL-LHC Beam Parameters

Two HL-LHC scenarios

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Parameter	2012	Nominal	HL-LHC (25 ns)	HL-LHC (50 ns)
C.O.M Energy	8 TeV	13-14 TeV	14 TeV	14 TeV
N_p	1.2 10^{11}	1.15 10^{11}	2.0 10^{11}	3.3 10^{11}
Bunch spacing / k	50 ns /1380	25 ns /2808	25 ns /2808	50ns /1404
ε (mm rad)	2.5	3.75	2.5	3.0
β* (m)	0.6	0.55	0.15	0.15
L ($cm^{-2}s^{-1}$)	~7x10^{33}	10^{34}	7.4 10^{34}	8.4 10^{34}
Pile up	~25	~20	~140	~260

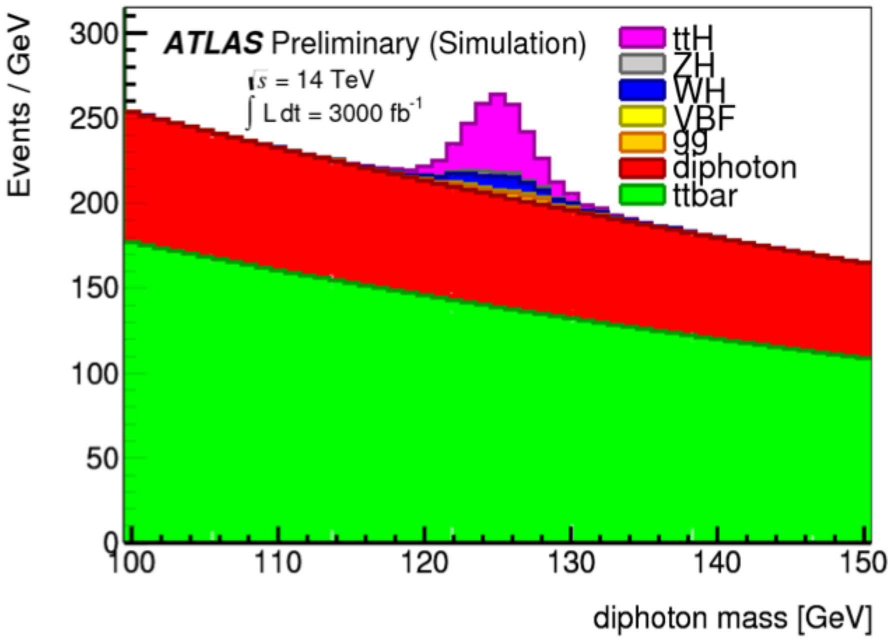


Pile up is a crucial issue!

CMS event with 78 reconstructed vertices

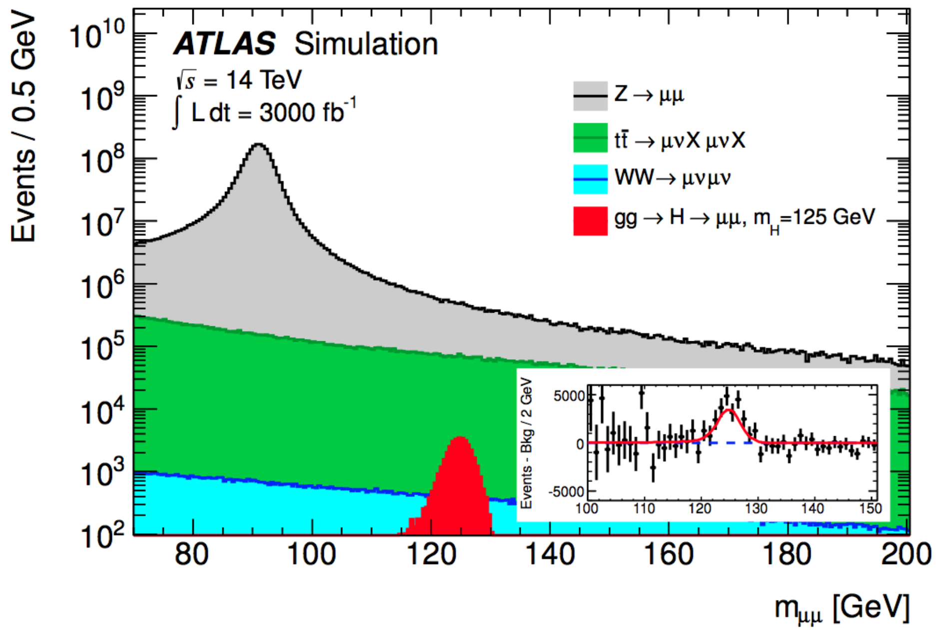
Rare and (robust) modes

Analyses not relying on more intricate decay channels (bb, ττ and WW)



- γγ channel: more than 100 Events expected with s/b~1/5
- μμ channel: approximately 30 Events expected with s/b~1

Analyses (rather) robust to PU

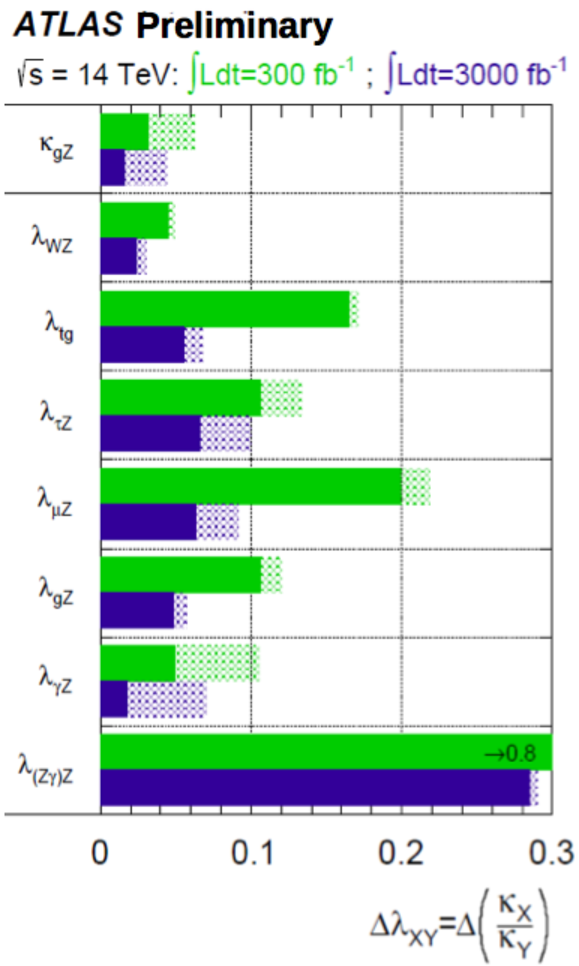


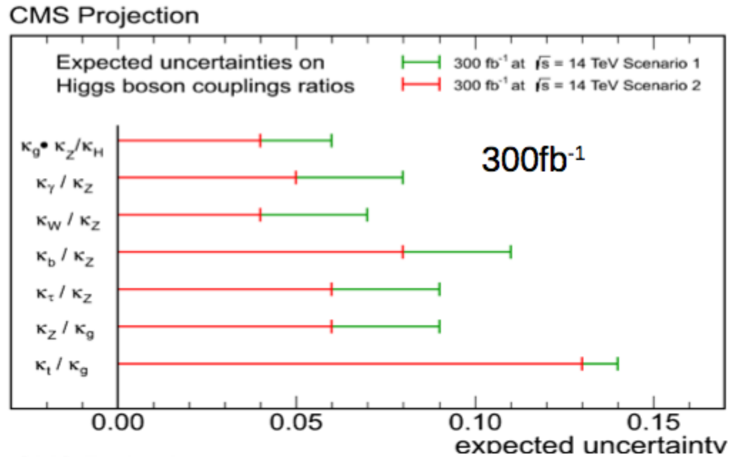
μμ decay mode should reach more than 5 standard deviation

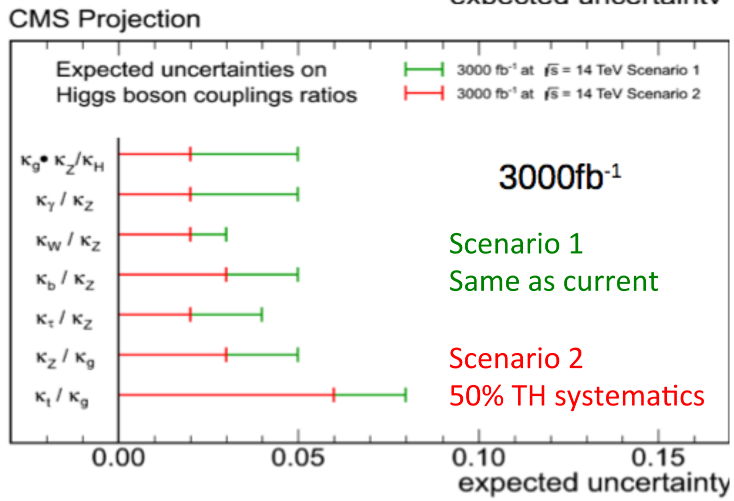
Just two examples but there are many many more!!!

LHC Higgs Physics Program: Main Couplings

Couplings Projections recently reappraised with a sample of analyses







Only indirect (however not negligible) constraint on the total width

Necessary to use assumptions or measure ratios: Precision down to ~5% level

Di-Higgs Production Self Couplings

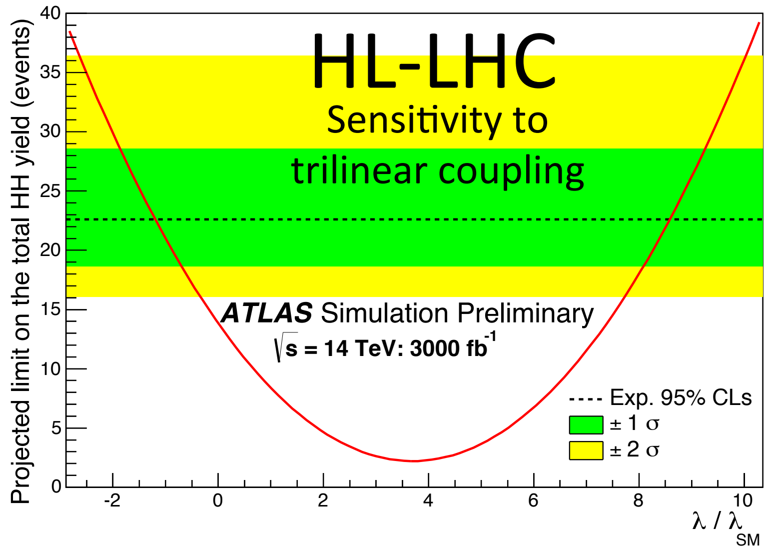
ATL-PHYS-PUB-2014-019

At HL-LHC sensitivity to SM HH

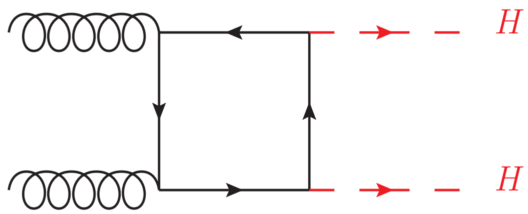
$1.3\ \sigma$

Extremely challenging!

Similarities with Off-Shell Couplings measurements



Associated production of two Higgs bosons



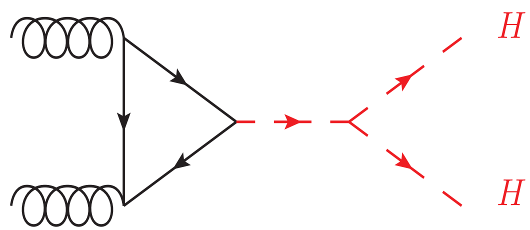
Various channels searched for (bbγγ)

Limit on non resonant cross section times branching:

$\sigma_{HH}\ Br_{bb,\ \gamma\gamma} < O(2)$ pb

Background to …

Tri-linear coupling production



λ_3 : Extremely difficult on of the main challenges for the HL-LHC

λ_4 : Incredibly difficult

Summary: Landscape Redefined

Flurry of new ideas !

Precision
- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- Off Shell couplings and width
- Interferometry

Rare decays
- $Z\gamma$, $\gamma\gamma^*$
- Muons $\mu\mu$
- LFV $\mu\tau$, $e\tau$
- $J/\Psi\gamma$, $Z\Upsilon$, WD etc…

$$H^0$$

Is the SM minimal?
- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)

…and More!
- FCNC top decays
- Di-Higgs production
- Trilinear couplings prospects
- Etc…

Conclusion and Discussion

The Higgs boson observed is compatible to a good precision with the SM Higgs boson

- Direct evidence of coupling to W and Z
- Direct evidence of coupling to taus (and therefore to fermions)
- Direct evidence for non-universal couplings
- Indirect evidence of couplings to top quark
- Evidence of the scalar nature

Establishing more precisely the properties of the Higgs boson:

- It has been and will be possible only through the developments of both TH and EXP.
- It is an essential probe of new BSM physics…
- LHC Run 1 has redefined the landscape of Higgs physics
- An entire new field has emerged with a very large number of interesting analyses (this was only part of the story and there is many more to come)

Up to you to further shape this landscape !

Run 2 and beyond offer unique opportunities for more precise measurement and exciting searches!