A primer to (selected) winter conference'14 highlights in High Energy Physics

Outline:

SM

EWK precision tests, Higgs, Top

Flavor & BSM

Heavy Flavors

Neutrinos & Cosmology

Outlook

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Acronyms

SM: Standard Model of Particle Physics

BSM: Beyond the SM

EWK: Electroweak (electromagnetic and weak forces)

QFT: Quantum Field Theory

FCNC: Flavor Changing Neutral Current

GIM: Glashow-Iliopoulos-Maiani mechanism to suppress FCNCs by degeneracy

LHC: Large Hadron Collider

CKM: Cabibbo-Kobayashi-Maskawa quark mixing matrix

BEH: Brout-Englert-Higgs mechanism of spontaneous breaking of EWK symmetry

The Standard Model of Particle Physics

renormalizable QFT in 3+1 Minkowski space w. local symmetry

$$\underbrace{SU(3)_C}_{strong\, interaction} \times \underbrace{SU(2)_L \times U(1)_Y}_{EWK\, interaction}$$

fundamental degrees of freedom:

ψ: fermions (quarks and leptons)

$F_{\mu\nu}$: gauge bosons $g^a, a = 1, ..8$ plus 4 EWK ones

$$\mathcal{L}_{\mathcal{SM}} = -\frac{1}{4}F^2 + \bar{\psi} i \not{D} \psi$$

3 coupling constants

Known fundamental matter comes in generations $\psi \rightarrow \psi_i$, $i = 1, 2, 3$, subject to identical gauge transformations, e.g. for e^-, μ^-, τ^-.

The fundamental degrees of freedom are massless in this model.

The Standard Model of Particle Physics

renormalizable QFT in 3+1 Minkowski space w. local symmetry which spontaneously gets broken to QCD $\times$ QED

$$SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$$

$$\mathcal{L}_{\mathcal{SM}} = -\tfrac{1}{4}F^2 + \bar{\psi} i \not{D} \psi + \underbrace{\frac{1}{2}(D\Phi)^2 - \underbrace{\bar{\psi} Y \Phi \psi}_{Flavor\,physics} + \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2}_{Higgs\,physics}$$

ψ: fermions (quarks and leptons)

$F_{\mu\nu}$: gauge bosons $g^a, \gamma, Z^0, W^\pm$

Φ: Higgs doublet (observation of h 2012 at LHC consistent with SM)

$$\Phi(x) = 1/\sqrt{2} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

The Standard Model of Particle Physics

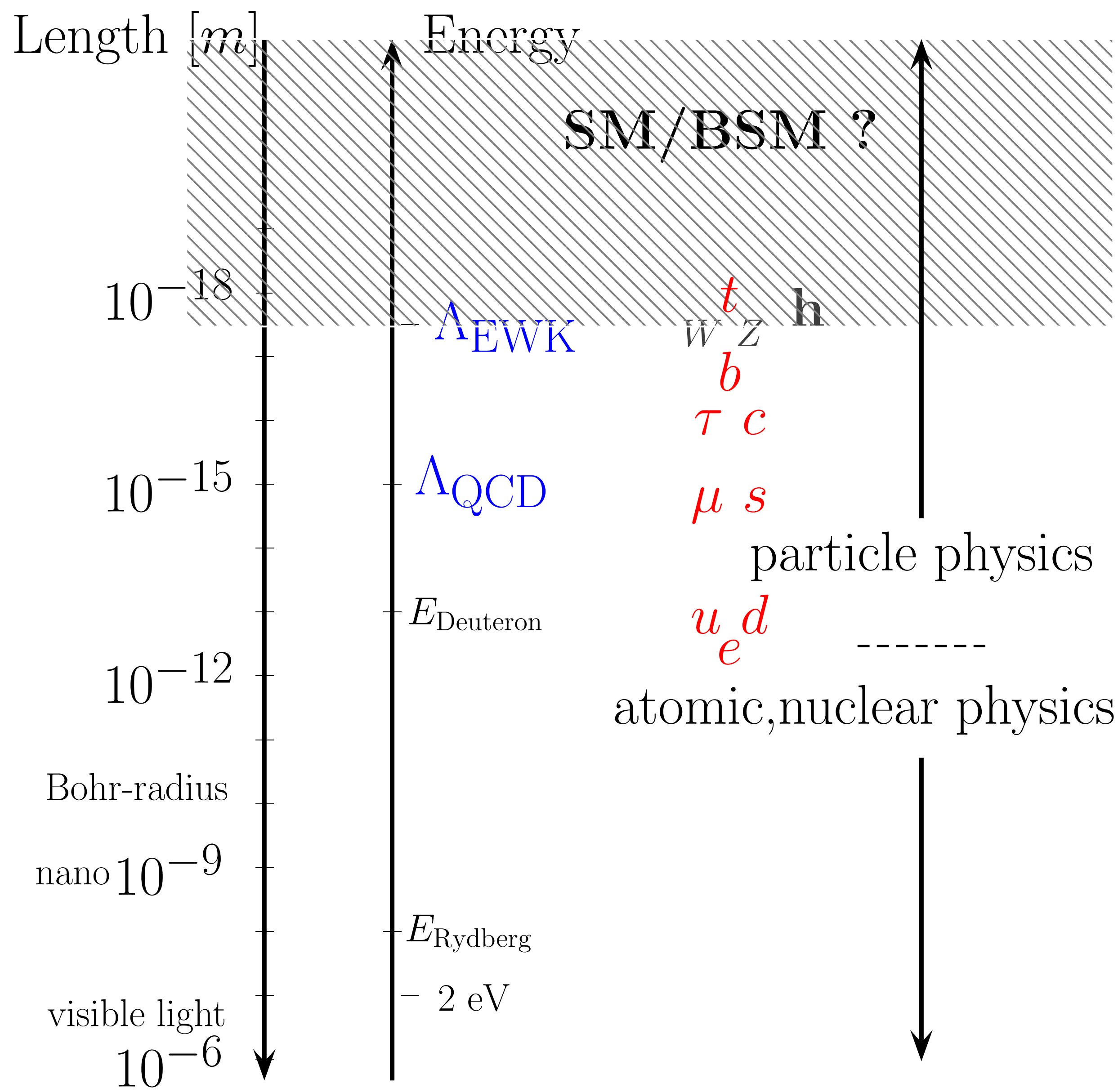
renormalizable QFT in 3+1 Minkowski space w. local symmetry which spontaneously gets broken to QCD $\times$ QED

$$SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$$

$$\mathcal{L}_{\mathcal{SM}} = -\frac{1}{4}F^2 + \bar{\psi} i \not{D} \psi + \frac{1}{2}(D\Phi)^2 - \bar{\psi} Y \Phi \psi + \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2$$

A fundamental description of microscopic processes based on 3 coupling constants, $\alpha_s, \alpha_e, \sin^2\vartheta_W$, $m_W = 80.4$ GeV, $m_h = 125$ GeV and $O(10)$ masses and mixings from the flavor sector (generational structure $\psi \to \psi_i$, $i = 1, 2, 3$).

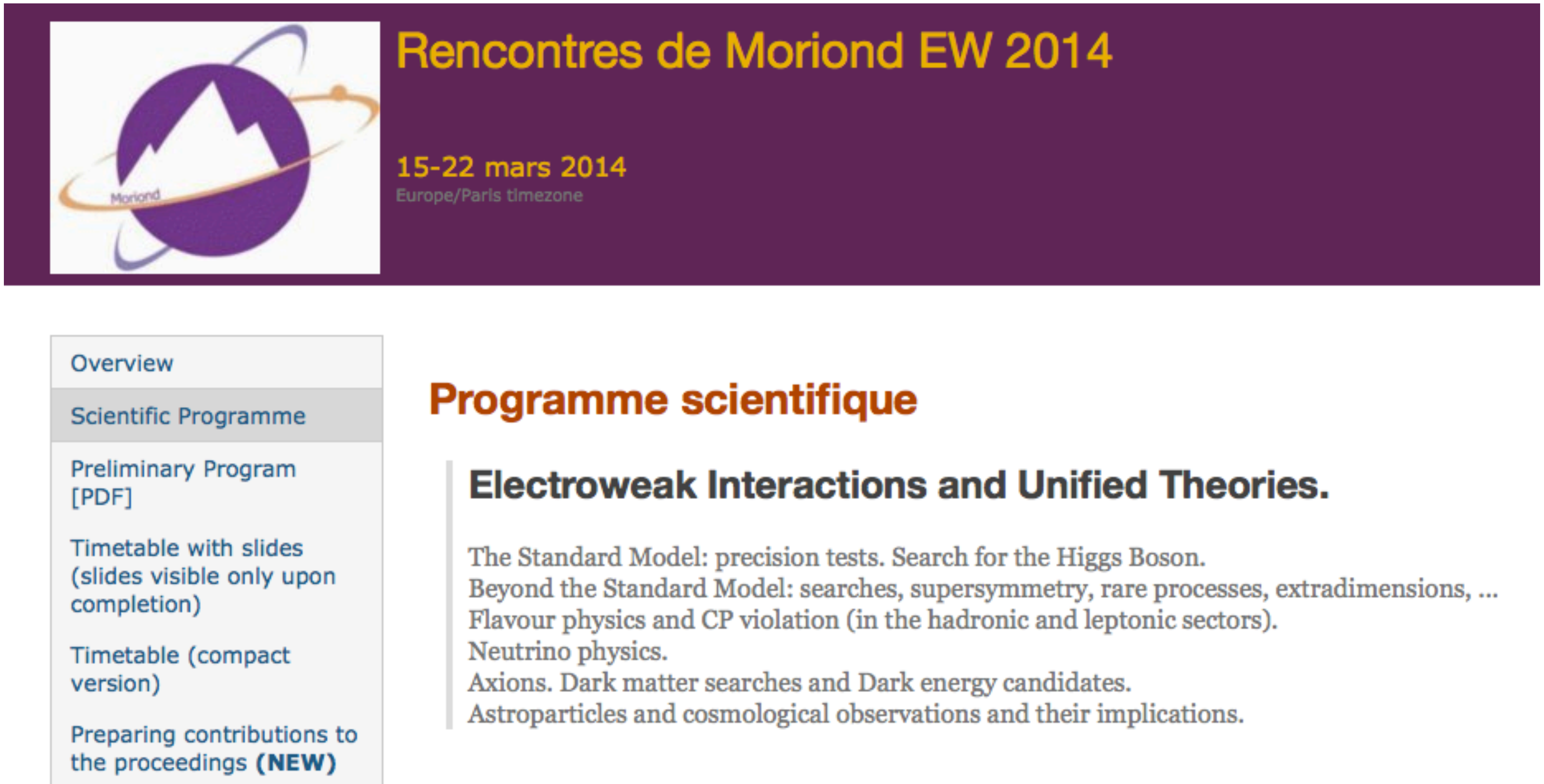
1. Experimental support of SM
2. Given the short-comings of the SM, whats next?


Length [m]
Energy
SM/BSM ?
10^{-18}
$\Lambda_{\rm EWK}$
t
W Z
h
b
τ c
10^{-15}
$\Lambda_{\rm QCD}$
μ s
particle physics
$E_{\rm Deuteron}$
u d
e

10^{-12}
atomic,nuclear physics
Bohr-radius
nano 10^{-9}
$E_{\rm Rydberg}$
2 eV
visible light
10^{-6}

The Moriond Conference: counting experiment - P1

- Let’s have an overview on the Conference contents.



Rencontres de Moriond EW 2014

15-22 mars 2014

Europe/Paris timezone

- Overview
- Scientific Programme
- Preliminary Program [PDF]
- Timetable with slides (slides visible only upon completion)
- Timetable (compact version)
- Preparing contributions to the proceedings **(NEW)**

Programme scientifique

Electroweak Interactions and Unified Theories.

The Standard Model: precision tests. Search for the Higgs Boson.
Beyond the Standard Model: searches, supersymmetry, rare processes, extradimensions, ...
Flavour physics and CP violation (in the hadronic and leptonic sectors).
Neutrino physics.
Axions. Dark matter searches and Dark energy candidates.
Astroparticles and cosmological observations and their implications.

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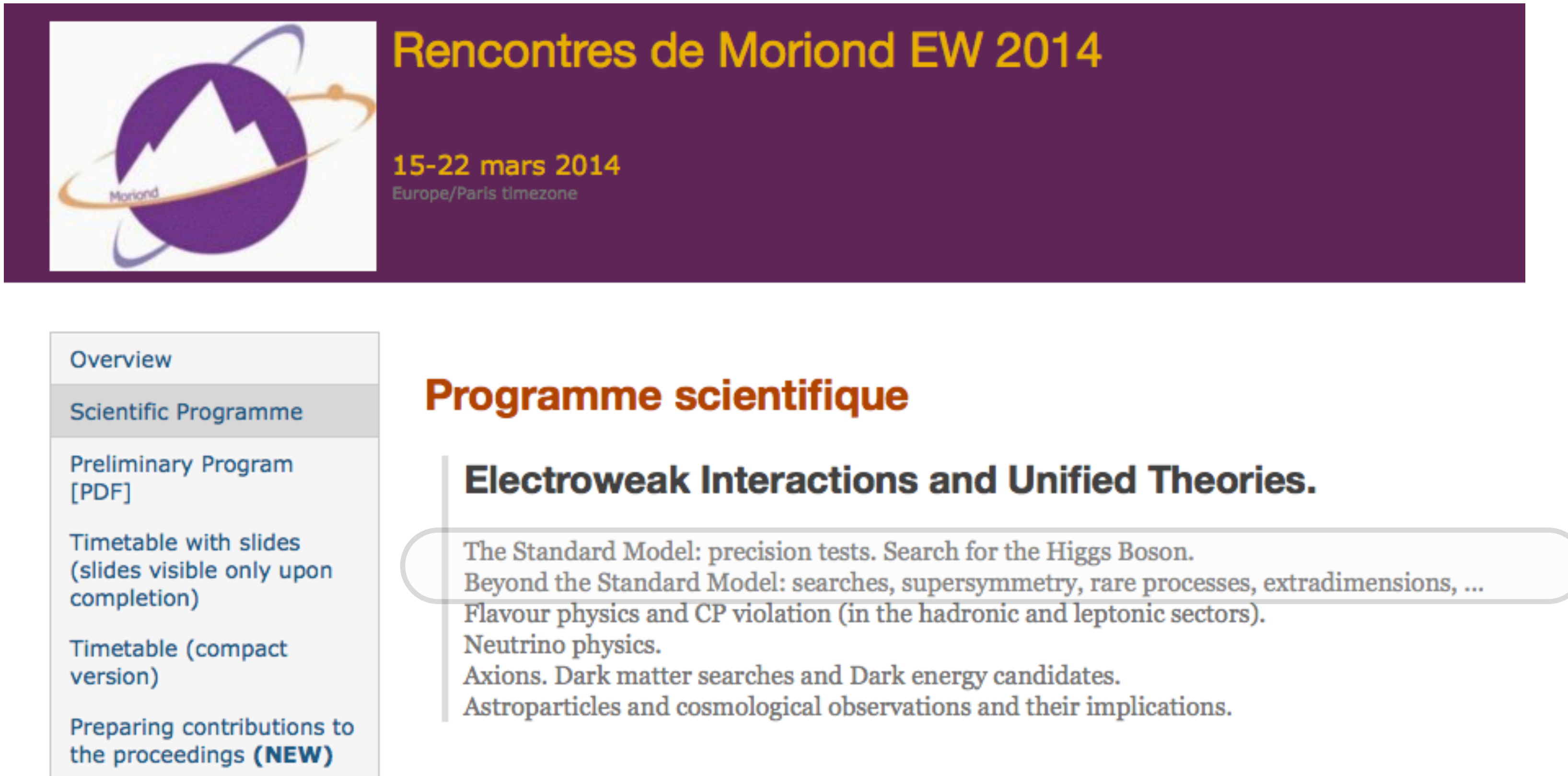

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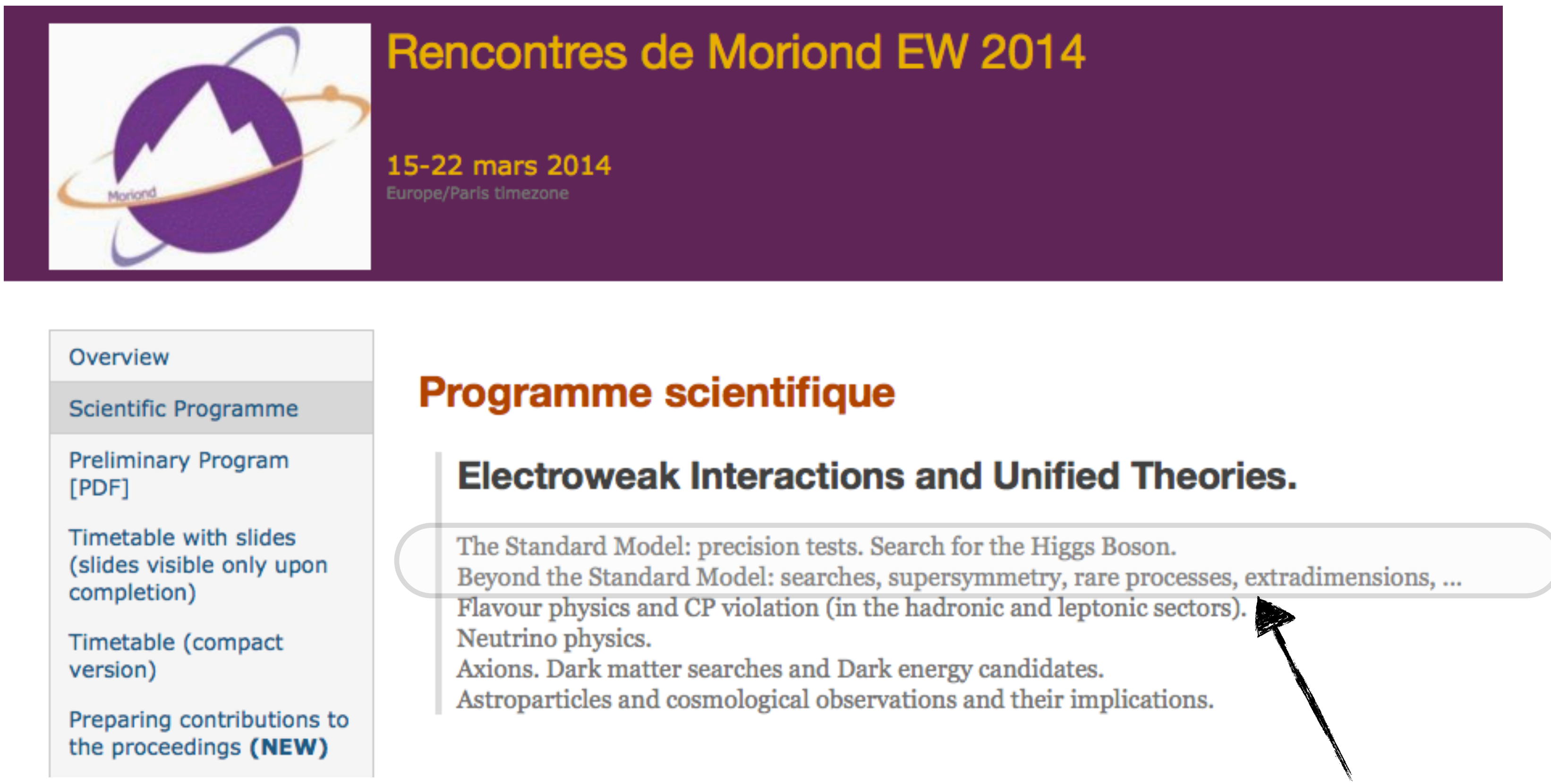


Part I

The detailed outline

1. Gauge bosons, Standard Model (SM) tests and beyond:
   Shaking the first pillar of the SM.

   - Introduction to the LHC Physics Case from previous machines.
   - The top quark properties.
   - The 126 GeV boson particle and its properties.
   - The searches for New Physics.

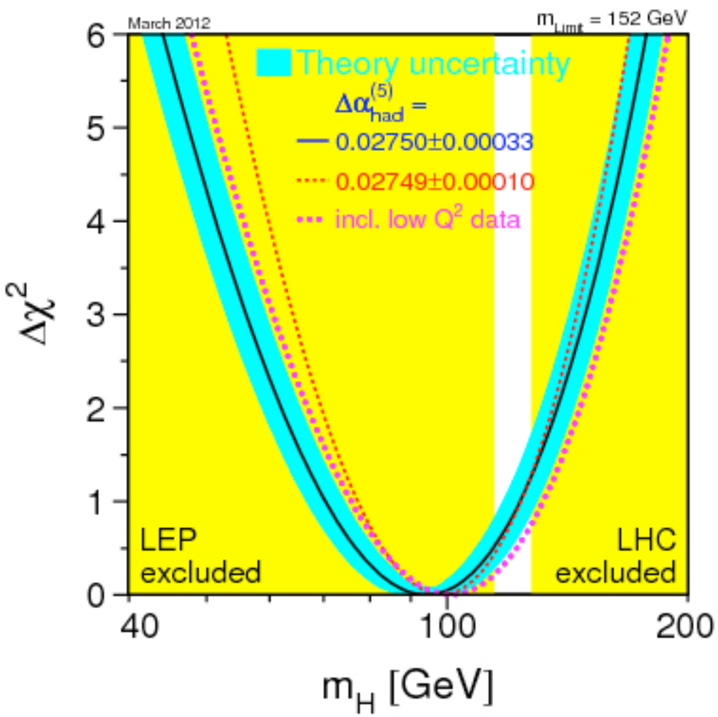
2. Quark Flavour Physics:
   Shaking the second pillar of the SM.

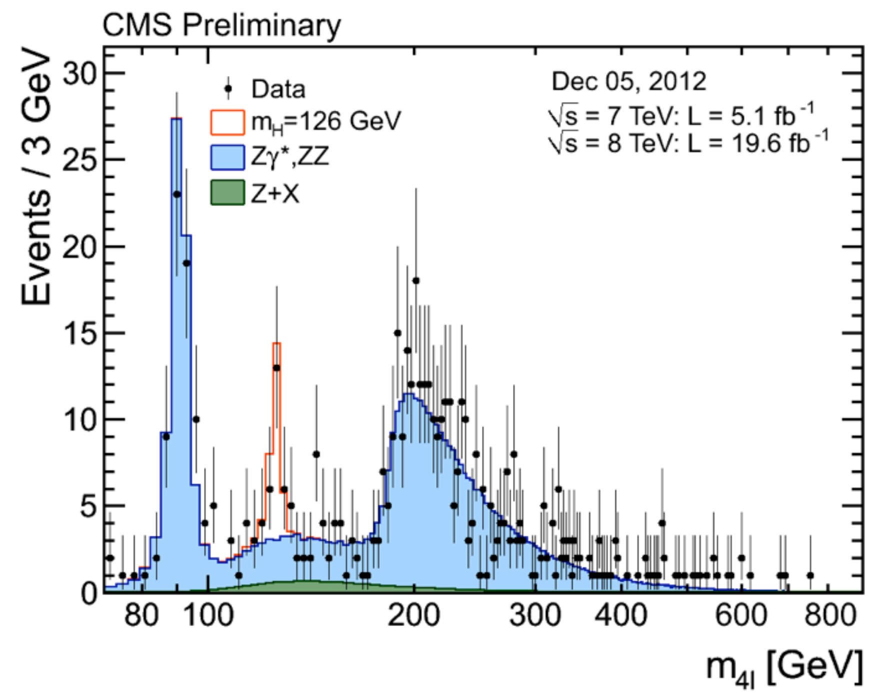
   - State of the art of the CKM matrix consistency checks.
   - Searches for rare and less rare processes.

3. The other frontiers: neutrinos, cosmology etc...
   What if the quake comes from them?

Motivation for Part I

- Any HEP physics summary talk contains the following figures:





- We'll try to undress these plots.

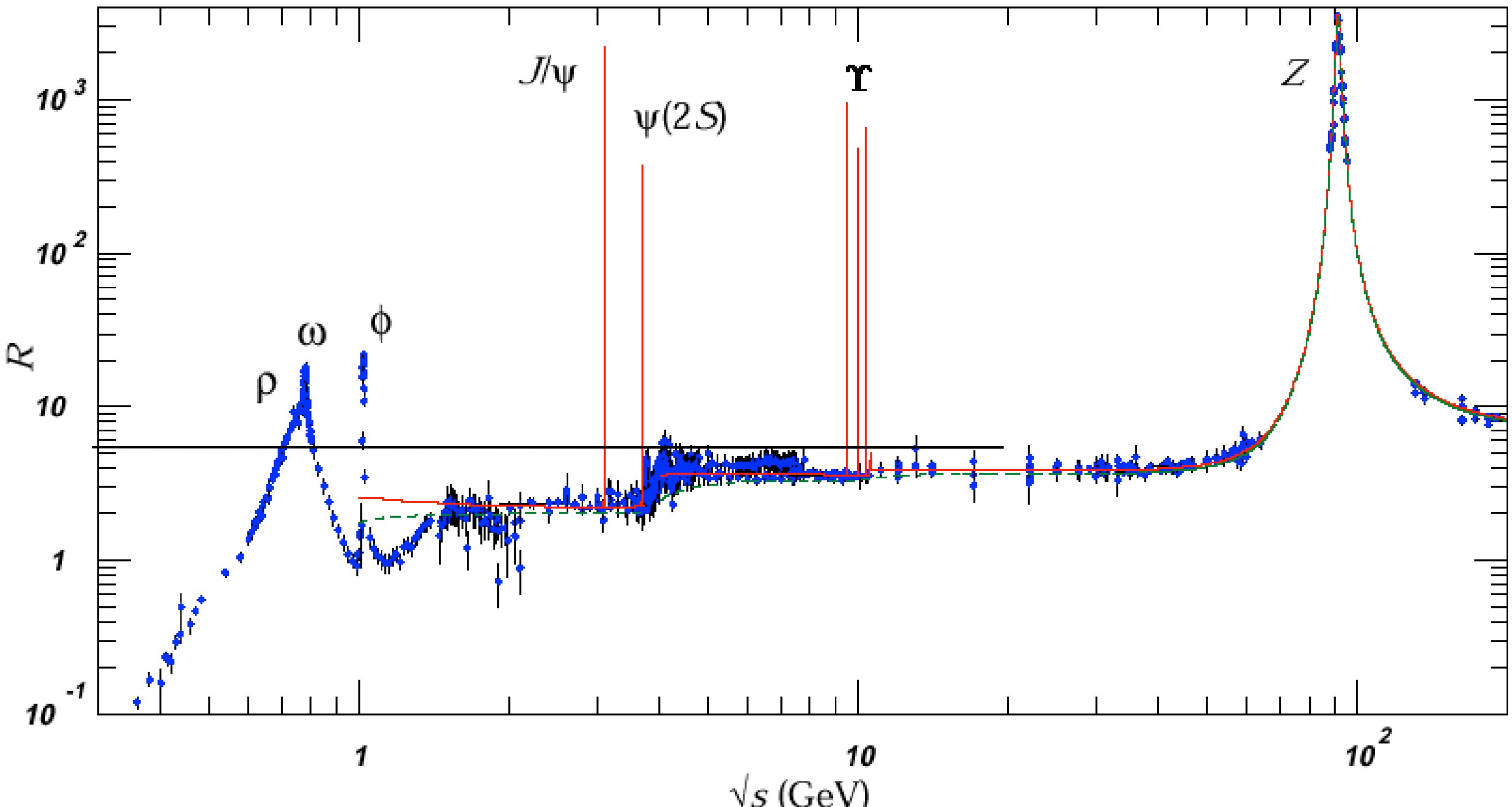
Introductory words on machines and experiments

• The former main machines in question here are the TeVatron (Fermilab, US, 2011), SLC (SLAC, US, 1998) and LEP (CERN, EU, 2001), the B-factories KEKB (KEK, JP, 2011) and PEPII (SLAC, US, 2008), and the experiments are ALEPH, DELPHI, L3 and OPAL (LEP), SLD (SLC), CDF, D0 (TeVatron) and BaBar and Belle (B-factories). The results of this continuum of experiments drive the LHC (CERN, EU) Physics Case, explored by the experiments LHCb, ATLAS and CMS. This machine is currently unique (Very)HEP machine to be operated world-wide.

- KEKB: e^-/e^+ asymmetric circular collider at ~10 GeV. 2 rings yet.
- PEPII: e^-/e^+ asymmetric circular collider at ~10 GeV. 2 rings yet.
- SLC: e^-/e^+ linear collider at ~ 90 GeV.
- LEP: e^-/e^+ circular collider at 90-210 GeV.
- TeVatron: p^+/p^- circular collider at a center-of-mass energy of 2 TeV.
- LHC: - p/p circular collider at ~7-8 TeV.
  - To be upgraded to 13 TeV in 2015.
  - Two rings.
  - A high luminosity program is considered at the horizon of 2022.

Introductory words on machines and experiments

- If you want to introduce color to your friends, pick up this plot:



$$R = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c \sum_i q_i^2 = N_c(q_u^2 + q_d^2 + q_s^2 + q_c^2 + q_b^2) = N_c \frac{11}{9}$$

The free parameters of the Standard Model (SM):

- $SU(2)_L \otimes U(1)_Y$ unification: the coupling constants $\boldsymbol{G_F / g_W}$ **and** α_{EM}.

- Spontaneous breaking of the symmetry: fermions masses $\boldsymbol{m_f}$, electroweak gauge bosons $\boldsymbol{m_Z}$ **and** $\boldsymbol{m_W}$ (also $\boldsymbol{\theta_W}$), and the scalar sector parameters, $\boldsymbol{v}$ **(the v.e.v) and** $\boldsymbol{m_H}$.

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

- CKM matrix elements: 3x3 complex and unitary matrix, **4 independent parameters.** As fermion masses, decoupled from the rest of the theory.

- If you like QCD in (and you do), just add α_S (and θ_S^{CP}).

- Neutrino oscillations are implying neutrinos to be massive and to mix → 7 more parameters [This is SM as far as they are Dirac neutrinos].

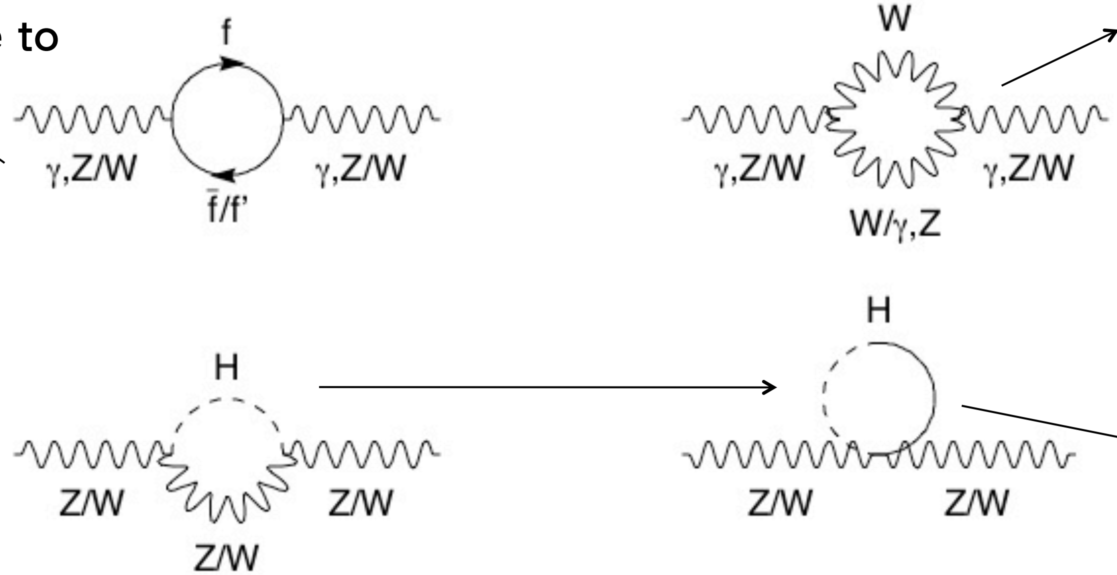
- The number of parameters amounts to 20 (28 w/ neutrinos and strong CP). Not all of them are independent though... How do we know what we know then? At the *Z* energy the non-decoupled free parameters can be seen through loop processes.

The EWK SM Consistency Check

Universal corrections to propagators (self energy)

Top dominates.
Mostly sensitive to m^2_t

Non abelian structure of the EW theory. TGC.



Scalar sector.
Contains Higgs mass info.

The form of the self-energy correction, when m_H (>)> m_W :

$$\Delta\rho_{\rm se} = \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{m_W^2} - \frac{\sin^2\theta_W}{\cos^2\theta_W}\left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right)\right] + \dots\,,$$

The EWK SM Consistency Check

2.1 universal corrections to propagators (self energy) :

- They do not depend on the final state. But sensitivity depends upon observables.
- Basically all *Z* pole observables are sensitive to these self-energy corrections. Parity-violating observables at first.
- Yet, they are suppressed in ratio of widths such as:

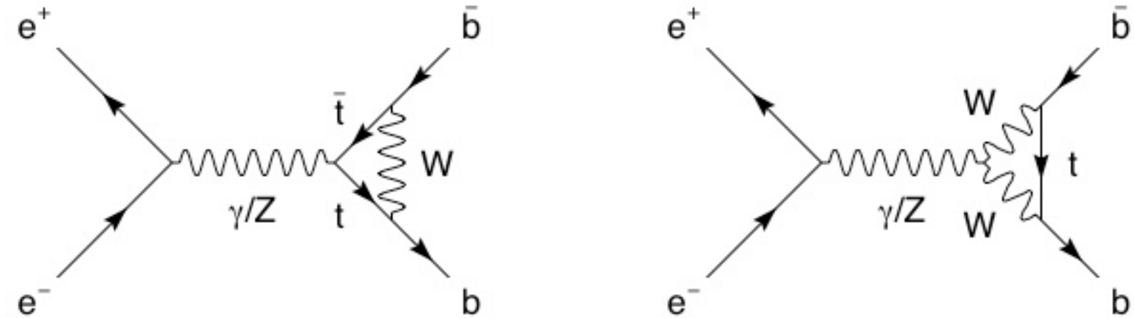
$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \mathrm{had})} \qquad \sigma^0_{\mathrm{had}} = \frac{12\pi\Gamma_{e^+e^-}\Gamma_{\mathrm{had}}}{m_Z^2\Gamma_Z^2}$$

- The mass of the W boson is a good laboratory too.
- Homework 1: Draw the one loop self-energy of the W boson.

The EWK SM Consistency Check

2.2 Corrections at the Z vertex (flavour dependent).

Again top quark dominates.Mostly sensitive to m^2_t



- In the SM, these corrections are proportional to the CKM matrix elements V_{tq}.

- The current experimental determination of these elements presents the following hierarchy (within the SM):

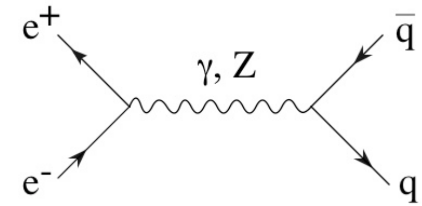
$$|V_{tb}| \approx 1 \gg |V_{ts}| \approx 0.04 \gg |V_{td}| \approx 0.008$$

- Vertex corrections are only relevant for b quarks: $\Delta\kappa_b = \frac{G_F m_t^2}{4\sqrt{2}\pi^2} + \ldots$

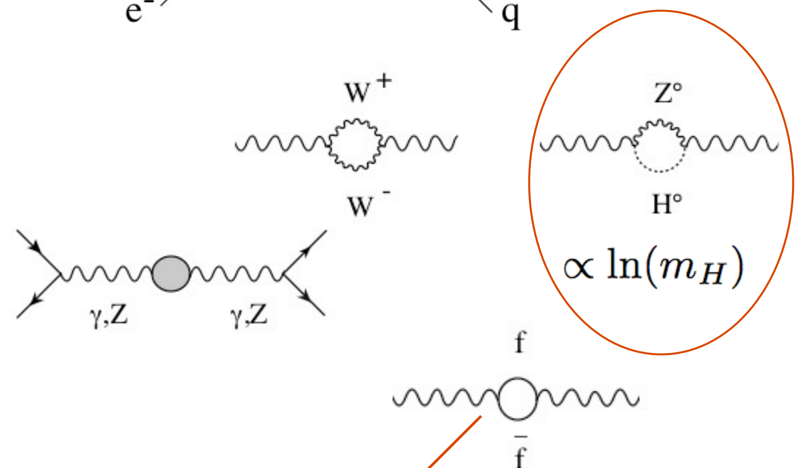
- A unique observable of interest there: R_b .

2.5 Summary for the radiative corrections at Z energy :

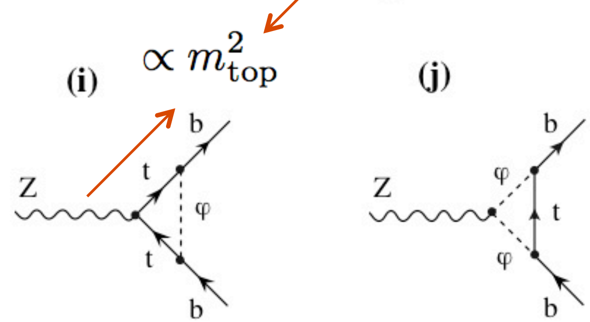
- In addition to the tree-level process:



- And beyond the standard QED and QCD radiative corrections, one must consider the electroweak radiative correction to the Z propagator:



- And last but not least the electroweak radiative corrections at the *Zbb* vertex:

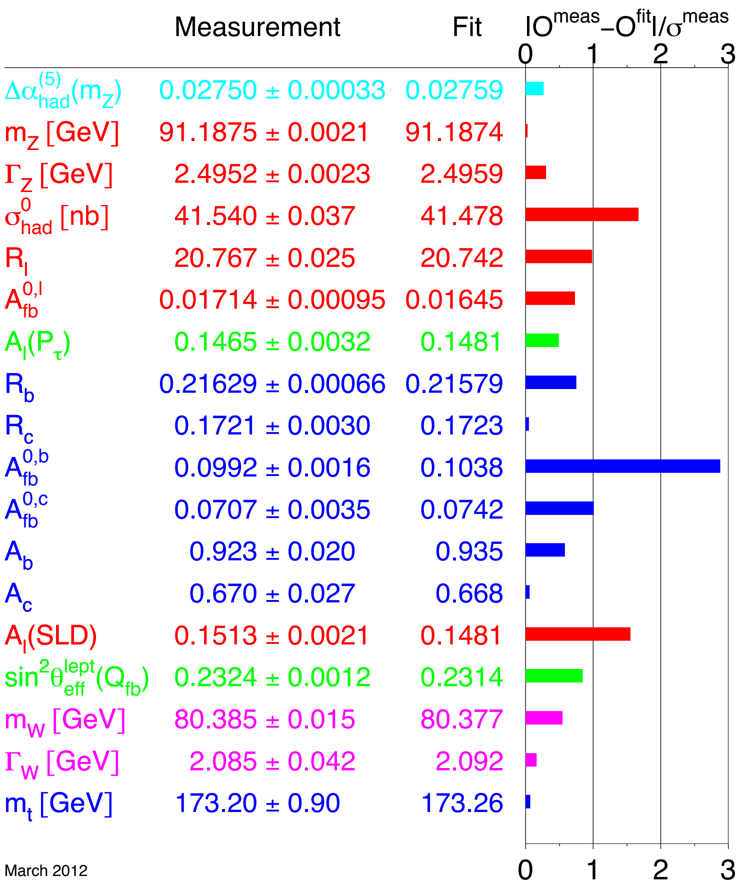


The EWK SM Consistency Check

2.5 Summary for the radiative corrections with LEP/SLC at Z energy :

- The different games we can play:
  - $R_b \rightarrow$ testing the vertex corrections.
  - $R_l \rightarrow$ testing lepton universality.
  - All Z pole observables treated globally. If the agreement is good, perform the metrology of the free parameters:
    - The ρ parameter to measure genuine weak corrections
    - Predicting m_{top}
    - Predicting m_W
  - Add up the direct measurements: m_{top} (TeVatron) and m_W (LEP/TeVatron) $\rightarrow$ Predict the Higgs mass.

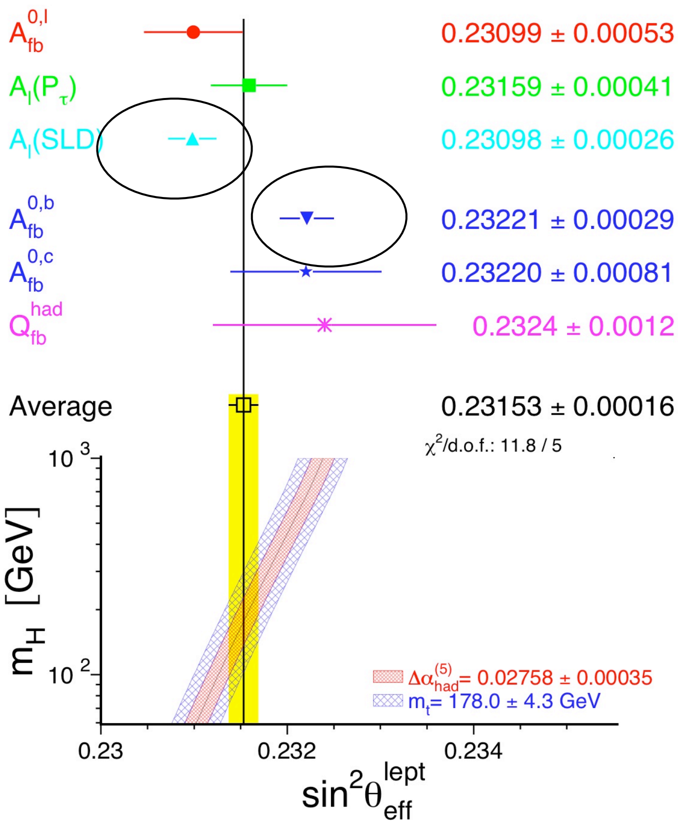
Global interpretation of the LEP/TeVatron results

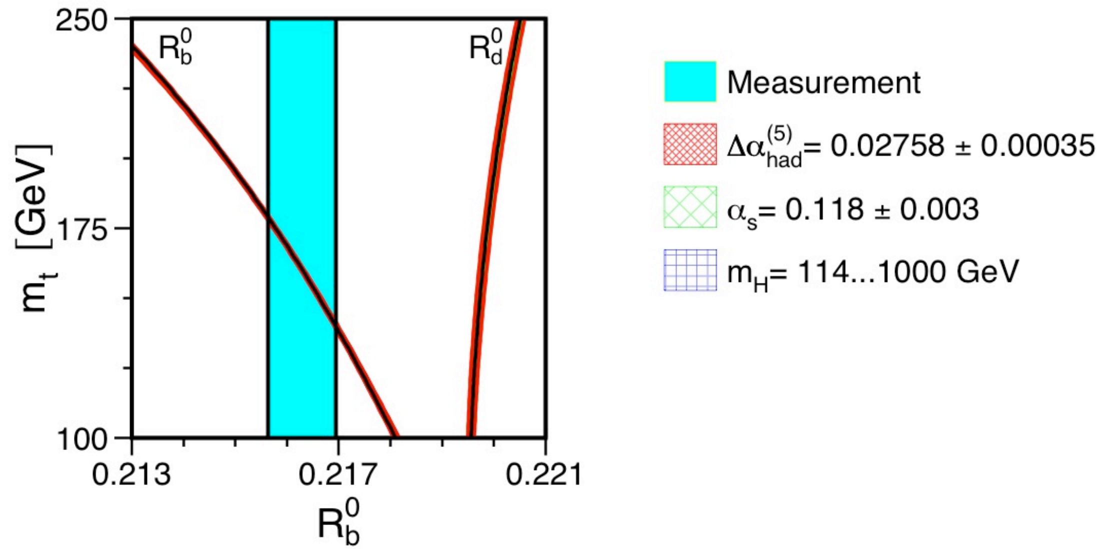


- The SM EW global fit has a remarkable χ^2_{min}/d.o.f = 1.40 (p-value=15%).
- The SM hypothesis passes the test. It does not mean that SM IS the Nature. In Science, one can usually only say NO...
- 2 observables depart « with some significance » from their prediction. It happens they are the two most important for the constraint on the Higgs boson.
- One can go one step further and make the metrology of the parameters.

Global interpretation of the LEP/TeVatron results: top

- The information on the top quark is basically brought by $\sin^2\theta_{eff}$ (A_{LR} and A_{FB} – propagator corrections), m_W (again propagator corrections) and R_b (vertex corrections).





Global interpretation of the LEP/TeVatron results: top

- The information on the top quark is basically brought by $\sin^2\theta_{\mathrm{eff}}$ (A_{LR} and A_{FB} – propagator corrections), m_W (again propagator corrections) and R_b (vertex corrections).

- Putting all these observables together (and some others) yields a top quark mass prediction of :

$$m_{\mathrm{top}} = 172.6 \,{}^{+13.3}_{-10.2}\ \mathrm{GeV}/c^2\ [(\mathrm{indirect} - \mathrm{LEP1})].$$

- basically obtained (w/ three times the current uncertainty) from 1993.

- Bottomline: if the SM is correct, there should exist an isospin partner to the *b* quark, sitting in the Nature at a mass ~ 175 times the one of the proton. The observation of a candidate at TeVatron was a tremendous success of the SM.

The top properties as of Moriond 2014.

CERN/FNAL Press Release:

A total of more than six thousand scientists from more than 50 countries participate in the four experimental collaborations. The CDF and DZero experiments discovered the top quark in 1995, and the Tevatron produced about 300,000 top quark events during its 25-year lifetime, completed in 2011. Since it started collider physics operations in 2009, the LHC has produced close to 18 million events with top quarks, making it the world's leading top quark factory.

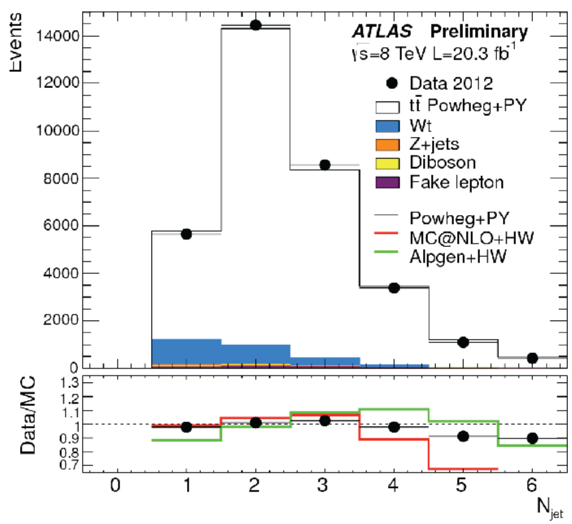
- What do we want to know about the top beyond its existence?
  - Production cross-sections.
  - Its mass: invaluable input to constrain the free parameters of the SM.
  - Single top productions.
  - And much more as a New Physics laboratory...

The top properties as of Moriond 2014.

- top pairs production cross-sections:

  - **Results for ttbar: precision cross-sections, differential distributions, ttbar+HF, ttbar+γ/W/Z.**

$\sigma_{t\bar{t}}$ = 237.7 ± 1.7 (stat) ± 7.4 (syst) ± 7.4 (lumi) ± 4.0 (beam energy) pb



World's most precise ttbar cross-section: total uncert = 4.8%

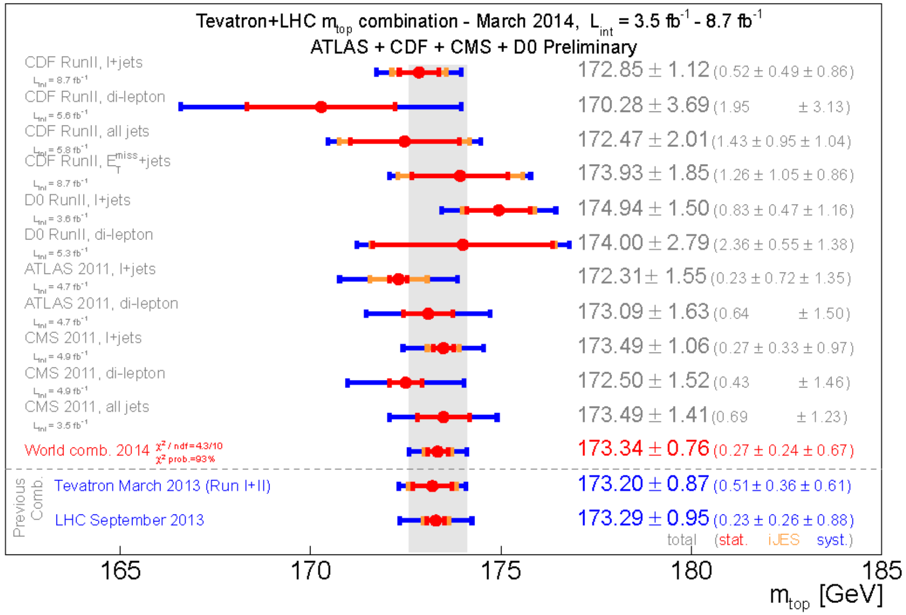
Uncertainty	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\sigma_{t\bar{t}}$ (pb)
Data statistics	0.72	1.7
$t\bar{t}$ modelling	$\boxed{1.52}$	$\boxed{3.6}$
Initial/final state radiation	$\boxed{1.23}$	$\boxed{2.9}$
Parton density functions	$\boxed{1.09}$	$\boxed{2.6}$
QCD scale choices	0.30	0.7
Single-top modelling	0.38	0.9
Single-top/$t\bar{t}$ interference	0.15	0.4
Single-top Wt cross-section	0.70	1.7
Diboson modelling	0.42	1.0
Diboson cross-sections	0.03	0.1
Z+jets extrapolation	0.05	0.1
Electron energy scale/resolution	0.48	1.1
Electron identification/isolation	$\boxed{1.42}$	$\boxed{3.4}$
Muon momentum scale/resolution	0.05	0.1
Muon identification/isolation	0.52	1.2
Lepton trigger	0.16	0.4
Jet energy scale	0.49	1.2
Jet energy resolution	0.59	1.4
Jet reconstruction/vertex fraction	0.04	0.1
b-tagging	0.42	1.0
Pileup modelling	0.28	0.7
Misidentified leptons	0.38	0.9
Total systematic	3.12	7.4
Integrated luminosity	3.11	7.4
LHC beam energy	1.70	4.0
Total uncertainty	4.77	11.3

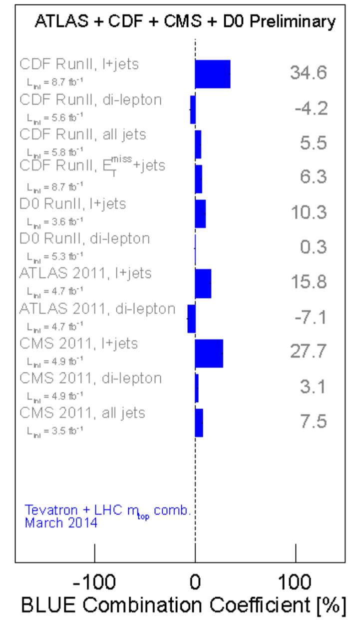
- Notes: systematics limited. SM prediction (embodied w/ the generators) is nice.

The top properties as of Moriond 2014.

- top mass

- **Top level results of the LHC/Tevatron combination: 173.34 +/- 0.76 GeV (Tevatron +/- 0.87, LHC +/- 0.95)**



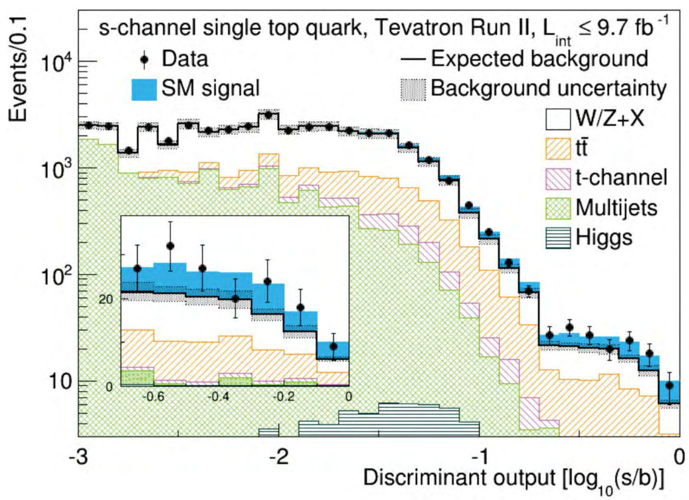


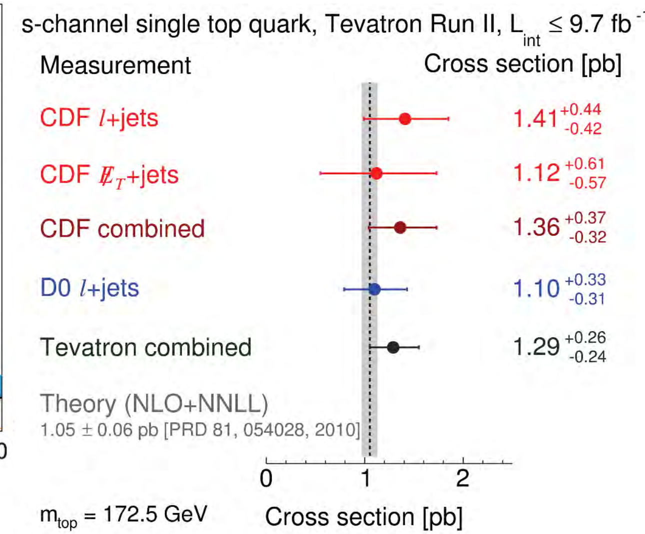
- Notes: dominated by the systematics. Very consistent among machines. A concern comes from the top mass definition. Realm of future electron machines.

$$
\begin{aligned}
m_{\rm top} &= 173.26 \pm 0.95 \ \mathrm{GeV}/c^2, \ [\text{direct} - \text{Moriond2014}] \\
m_{\rm top} &= 172.6^{+13.2}_{-10.2} \ \mathrm{GeV}/c^2, \ [\text{indirect} - \text{LEP1}]
\end{aligned}
$$

The top properties as of Moriond 2014.

- Single top production:
    - **Combined discriminant for CDF+D0, and combined result for cross-section, result 6.3σ !**
      $\sigma = 1.29 + 0.26 - 0.24$ pb^{-1}



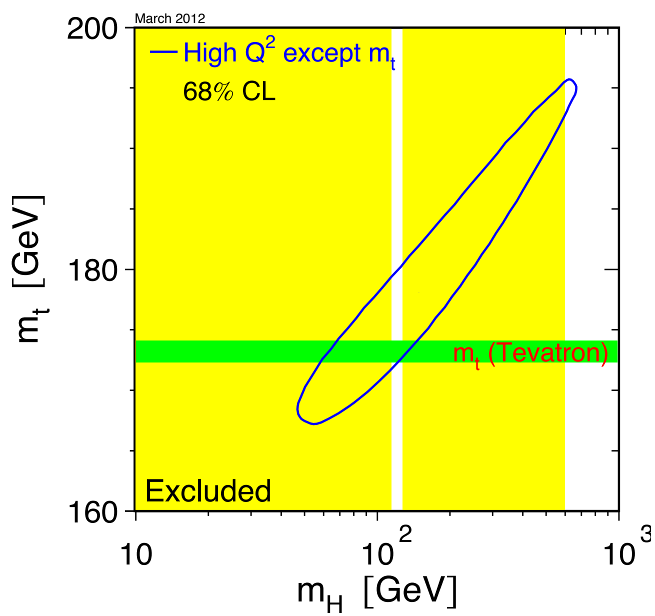


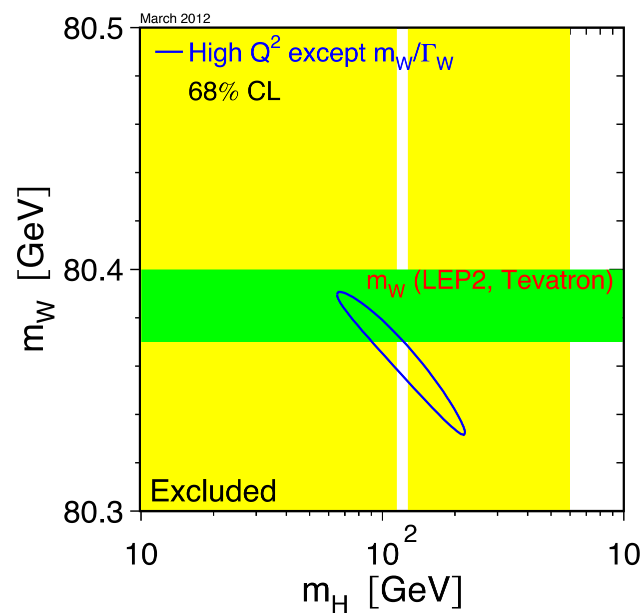
- Notes: signal established in most channels. Useful for polarization, SM tests, NP searches ...

Global interp. of the LEP/TeVatron results: the scalar

- the BEH particle is the only piece of the SM which escaped to experiments prior to LHC (Limits on direct searches are the yellow bands (Left band: LEP; Right band: TeVatron, LHC 2010))

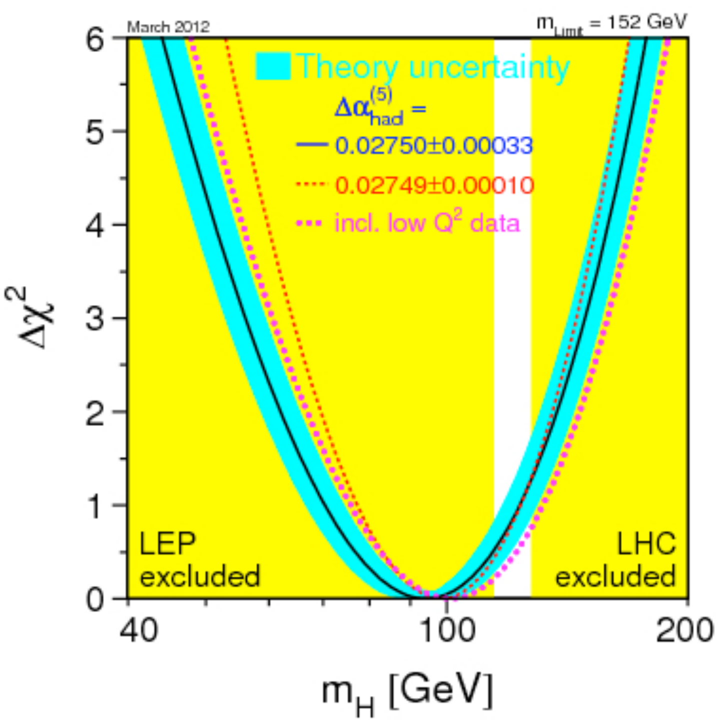
- If one adds the top and *W* mass measurements to the EW precision measurements at the *Z* pole, one is able to get information on *H* mass. Here, the main actors at the *Z* pole are $\sin^2\theta_{eff}$ (A_{LR} and A_{FB} – propagator corrections).





- We can bound the mass of the SM Brout-Englert-Higgs boson.

- A central part of the physics at the LHC is about the gauge scalar search. Was mostly driven by EW precision measurements.

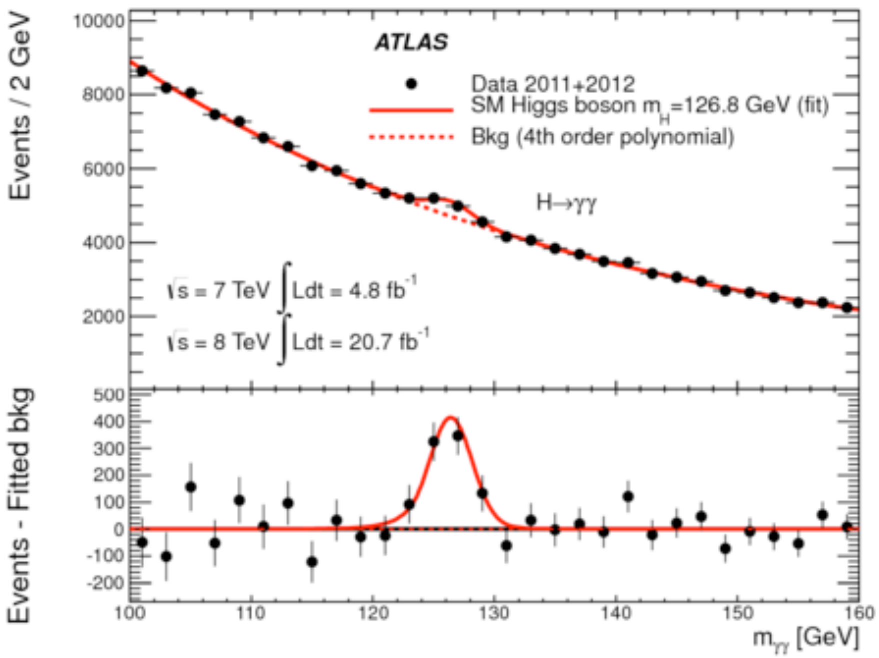


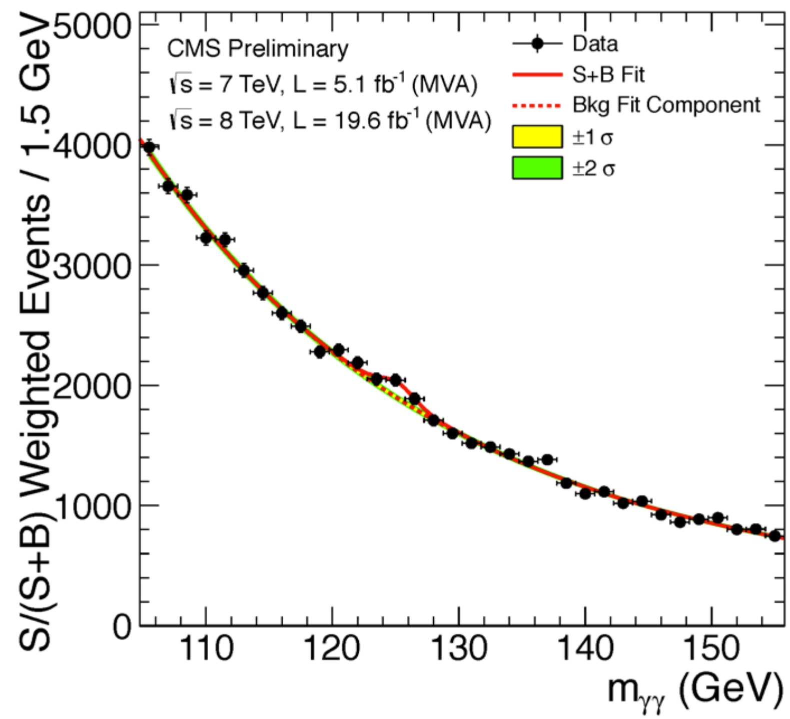
- Bottomline: if the SM is correct, there should exist an isospin partner to the *b* quark, sitting in the Nature at a mass ~ 175 times the one of the proton and a fundamental scalar boson with:

$$m_{\mathrm{BEH}} < 152\ \mathrm{GeV}/c^2 \quad 95\%\ \mathrm{CL}.$$

The fundamental (scalar?) boson observation

- There is very much something around: $H \to \gamma\gamma$

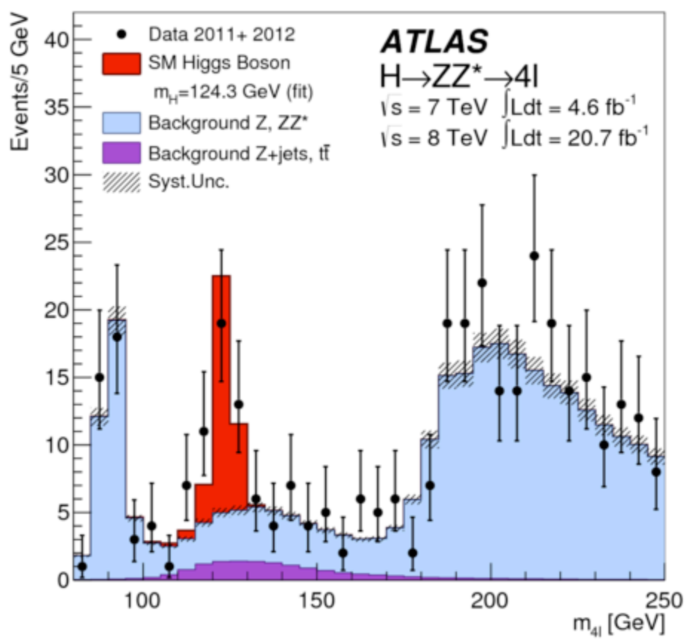


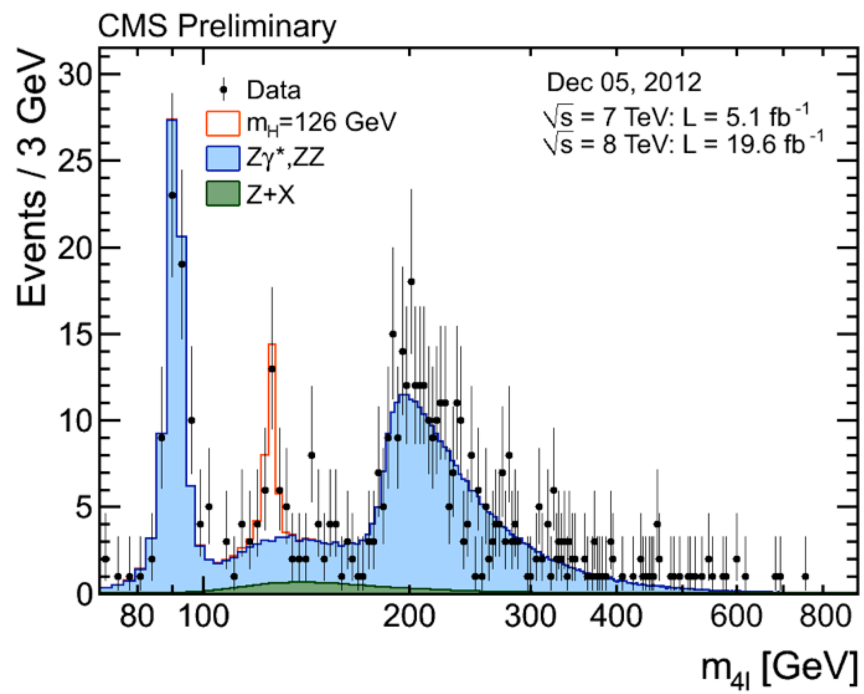


- Note: it's a boson and it's not a spin 1 (Landau theorem).

The fundamental (scalar?) boson observation

- There is very much something around: *$H \to ZZ$.*

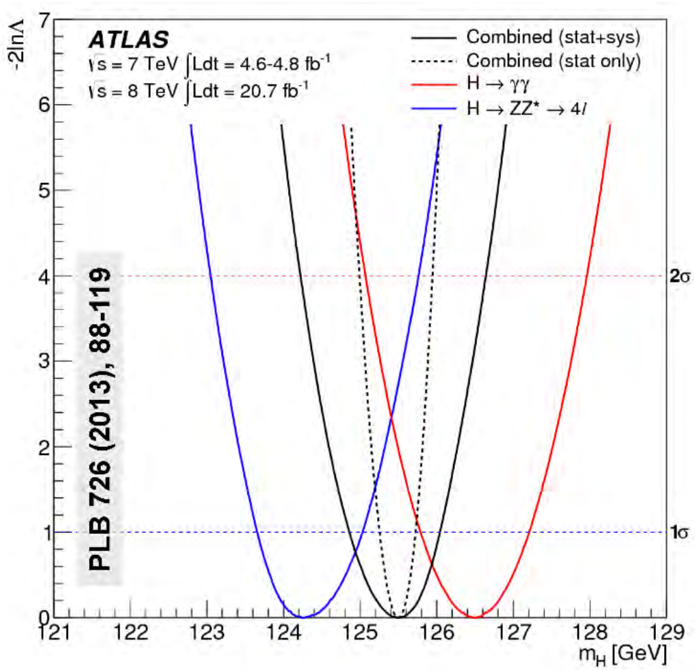


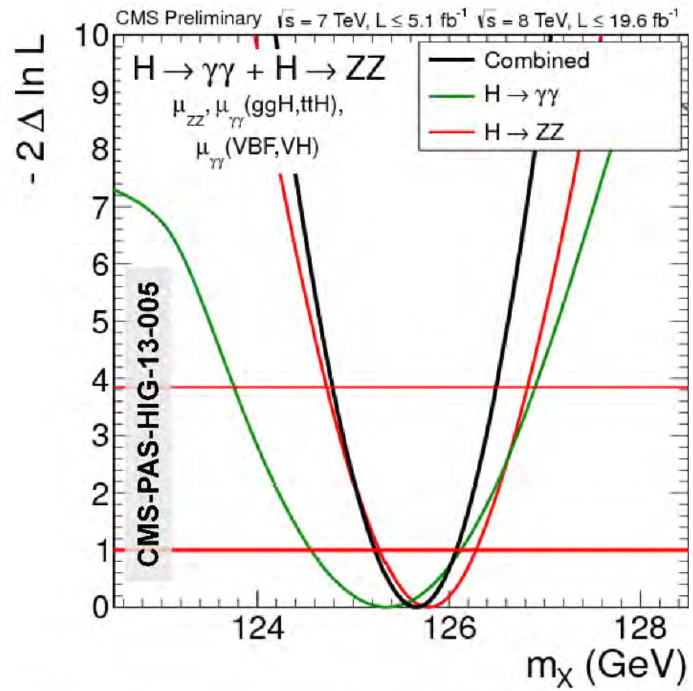


- Evidence also observed in *$H \to WW$* (gauge couplings most likely there) but also in heavy fermions *$H \to bb$, $\tau\tau$*.

The (scalar?) boson properties as of Moriond 2014

- The mass:



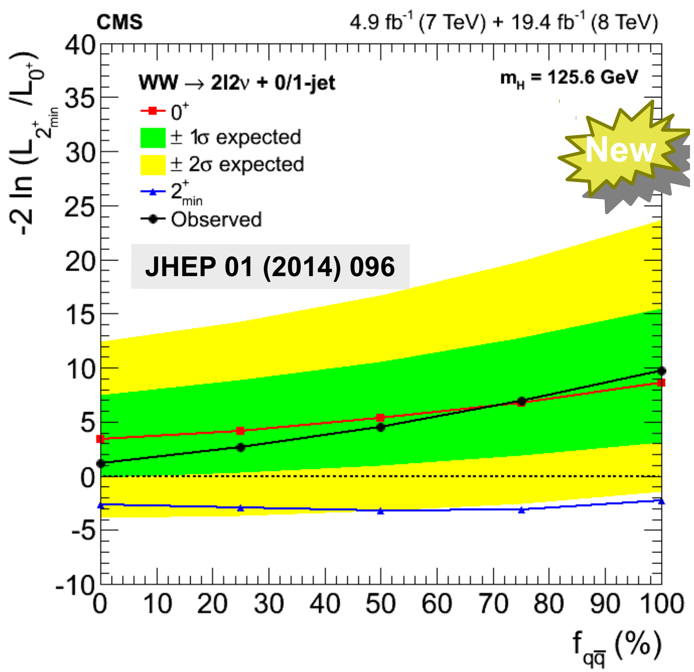


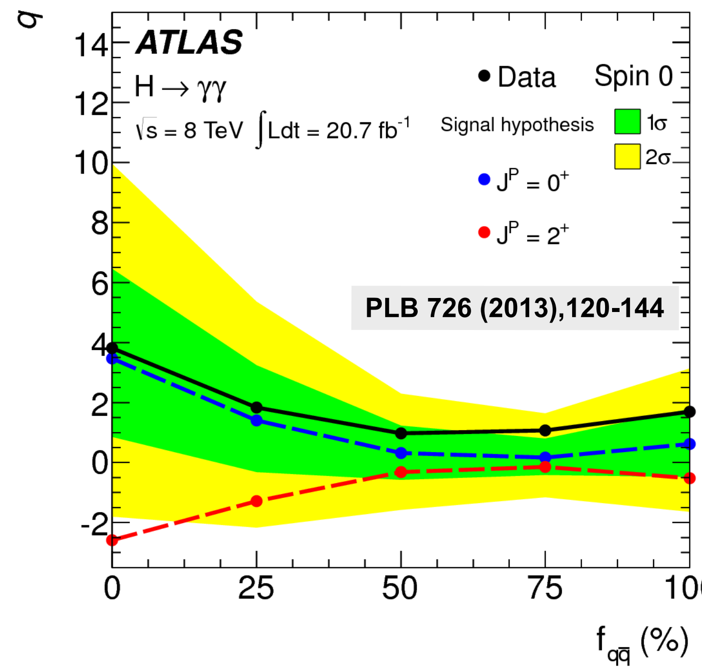
ATLAS	CMS (new ZZ(4l) not used)
125.5 +-0.2 (stat) $^{+0.5}_{-0.6}$(syst) GeV	125.7 +- 0.3(stat) +- 0.3(syst) GeV

- Notes: the two main modes for Atlas slightly discrepant. Very much OK for CMS. Likely that nothing is to be dug further there.

The (scalar?) boson properties as of Moriond 2014

- The spin-parity: out of angular distributions studies of the final state products in $H \rightarrow VV$

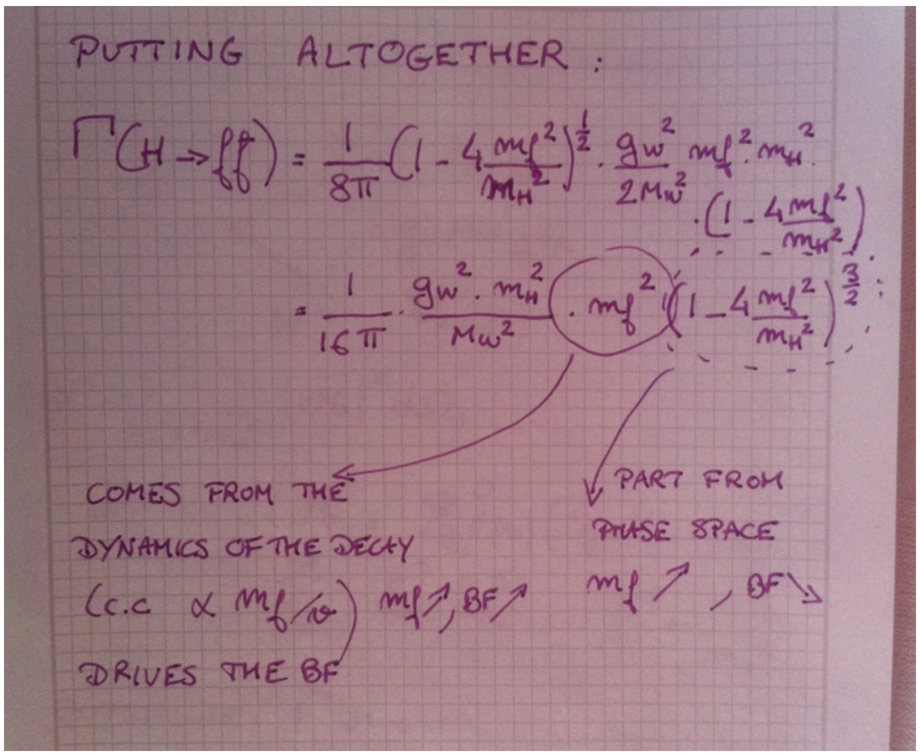




- Note: the $J^P = 0^+$ hypothesis is so far preferred by the data.

The *H* boson properties as of Moriond 2014

• The couplings: each of the SM couplings of *H* to fermions or bosons can be quit accurately calculated. Measuring all (most) of them is the next global consistency check in the field.



- top quarks dominate ...

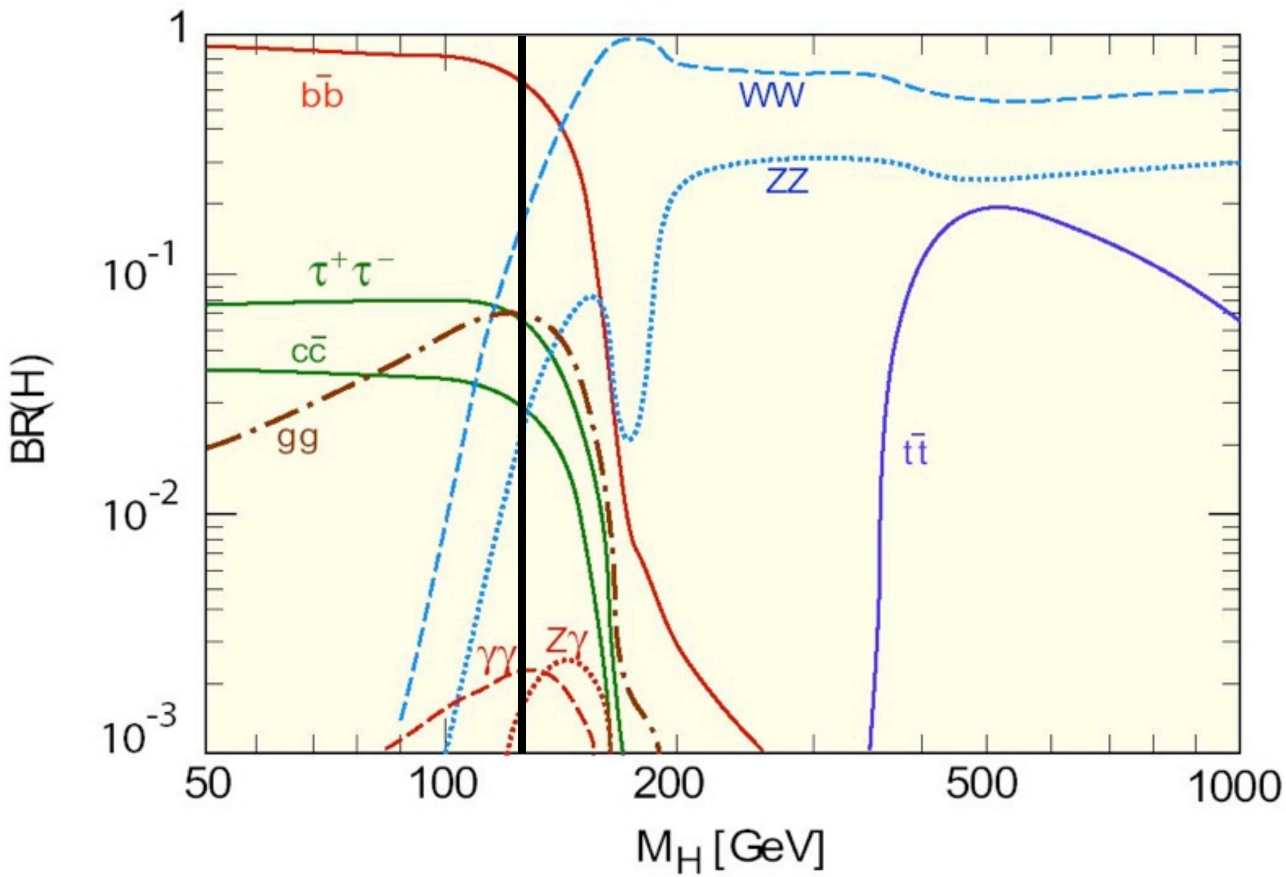
[When a guy weighing 100 kg is saying some things, the 60 kg guys do listen ... M. Audiard,]

... if you can afford twice its mass...Higgstrahlung.

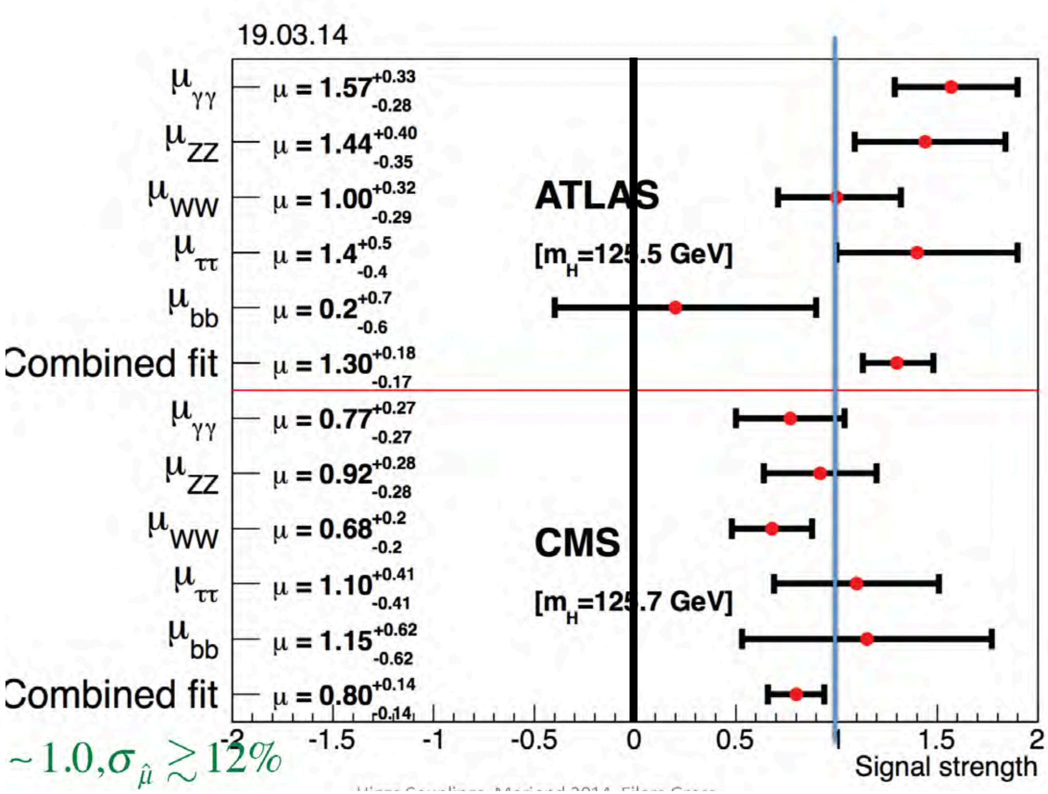
- If not, beauty quarks dominate.
- The lepton tau is very appealing ...

The *H* boson properties as of Moriond 2014

- The couplings: each of the SM couplings of *H* to fermions or bosons can be quit accurately calculated. Measuring all (most) of them is the next global consistency check in the field.

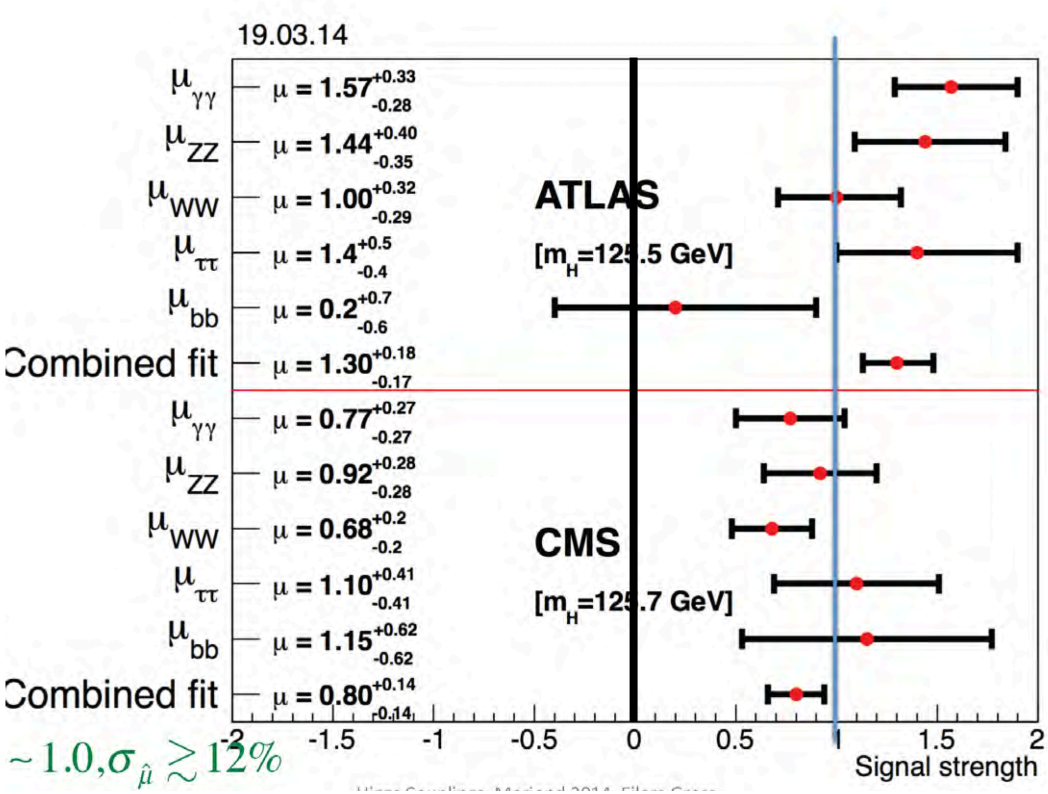


The *H* boson properties as of Moriond 2014



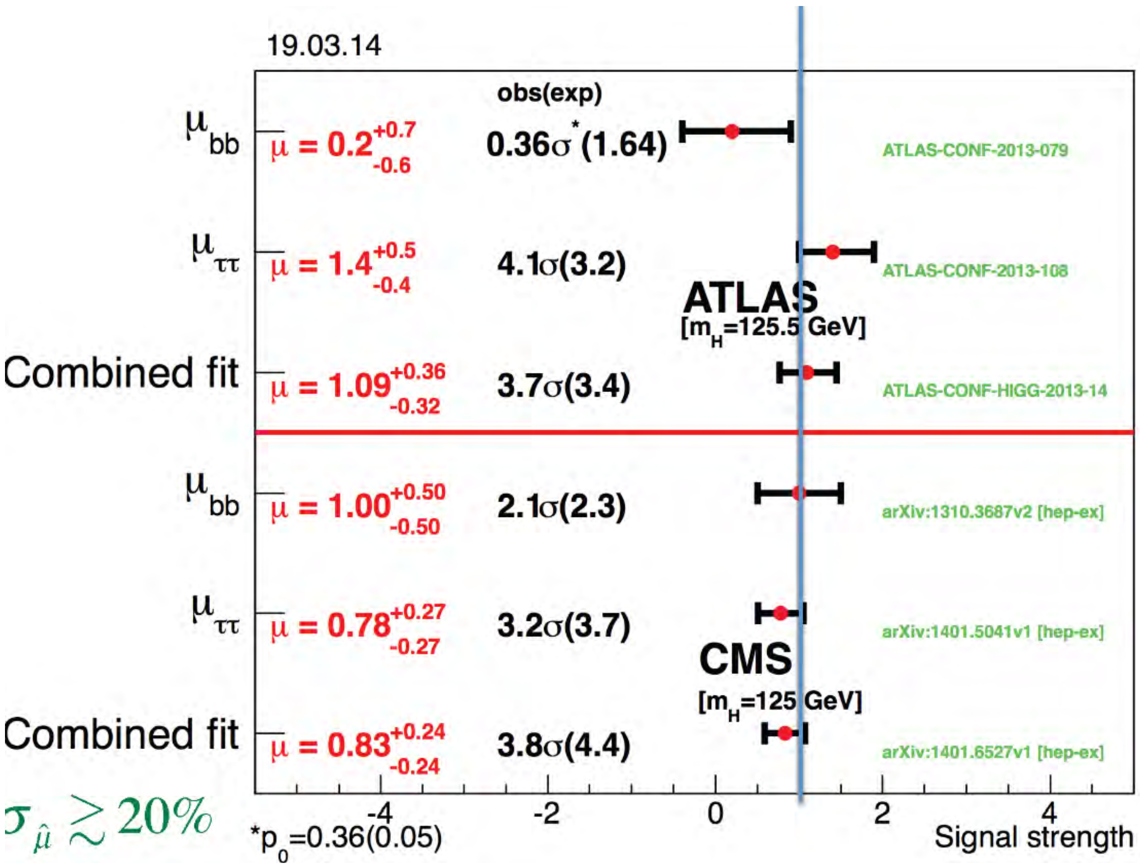
The H boson properties as of Moriond 2014

- The couplings: though LHC is at the level of evidence for most of the channels (when accessible), significant constraints can be brought. Signal strength is defeind as σ_{obs}/σ_{SM}



- Note: it's amazing that LHC brought so much with Run I.

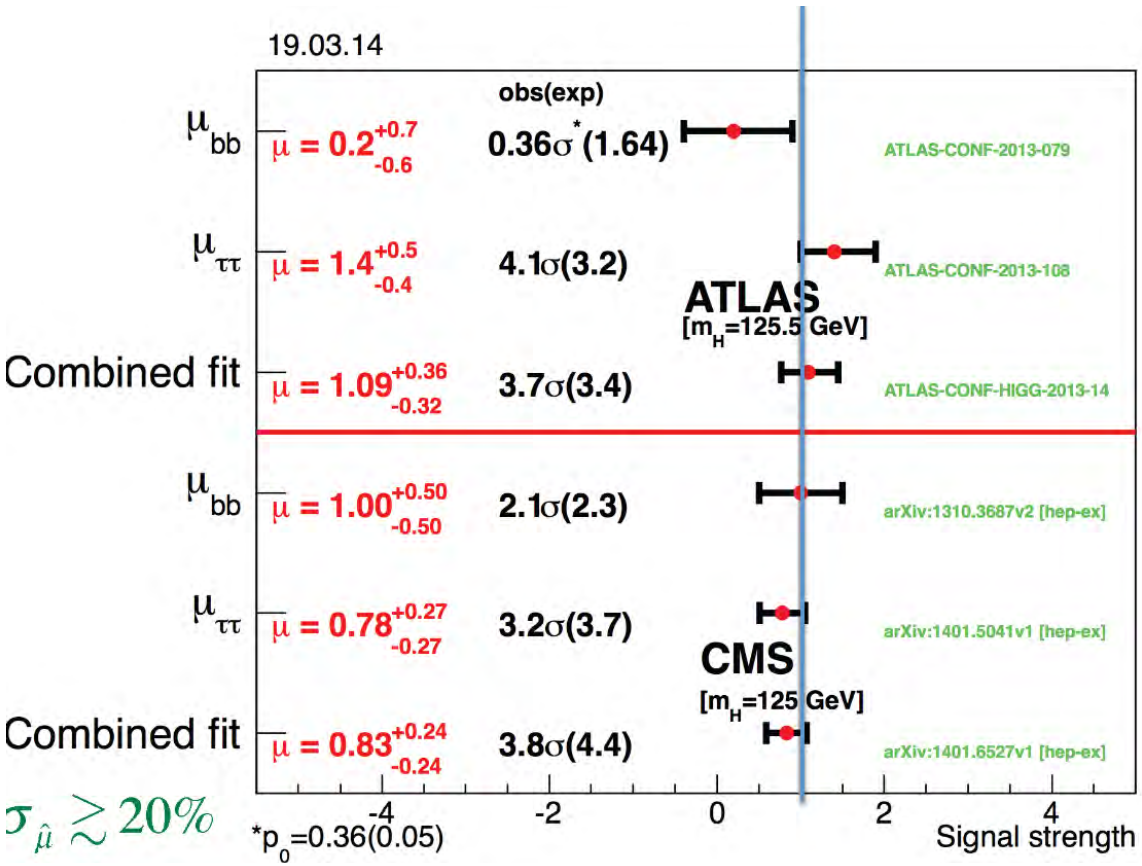
The *H* boson properties as of Moriond 2014



$\sigma_{\hat{\mu}} \gtrsim 20\%$

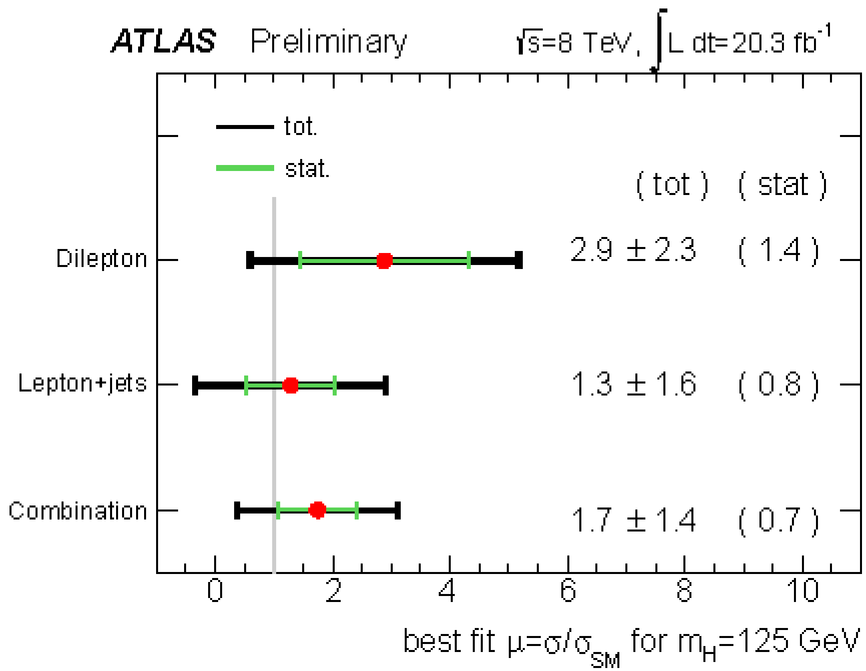
The *H* boson properties as of Moriond 2014

- The couplings: a closer look to fermions



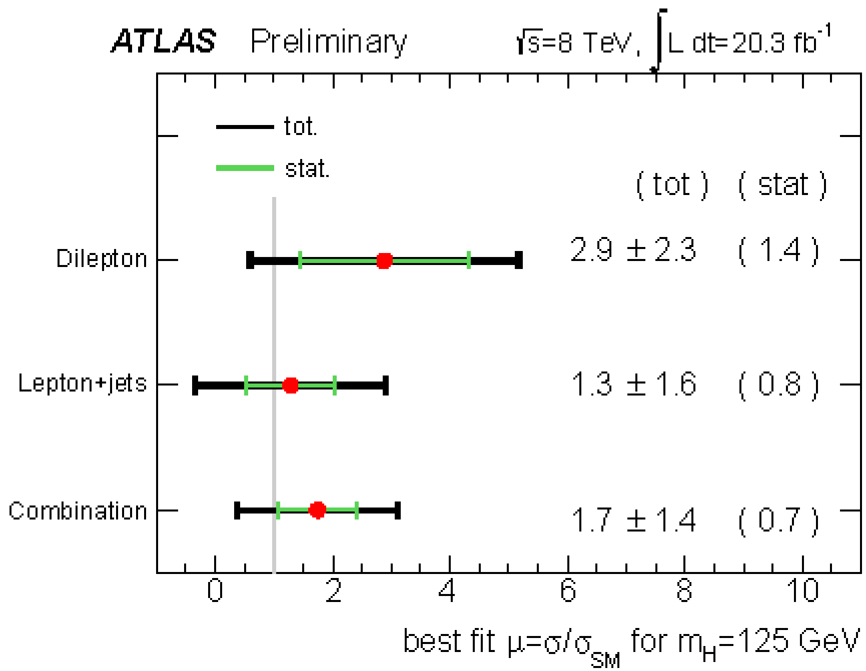
- Note: TeVatron results on bbbar still dominating.

The H boson properties as of Moriond 2014



The *H* boson properties as of Moriond 2014

- Outlook: we know so far that an overall 20% agreement w.r.t. the SM expectations is achieved. The LHC Run II will bring these studies at a mature stage. A breakthrough will come from the *ttbar* coupling, which can be accessed from top pair production with a Higgsstrahlung (remember LHC is a top factory. . Already a hint for this:



- Note: To be compared with the $H \rightarrow \gamma\gamma$ proceeding with a top loop.

A provocative transition

A provocative transition

- To my knowledge, the existence of the fundamental scalar particle sitting in the Nature at a mass below 130 GeV/c^2 is/was the uniquely testable prediction of the SuperSymmetry (well, there should as well be a Lightest Supersymmetric Particle if *R* parity is conserved...)

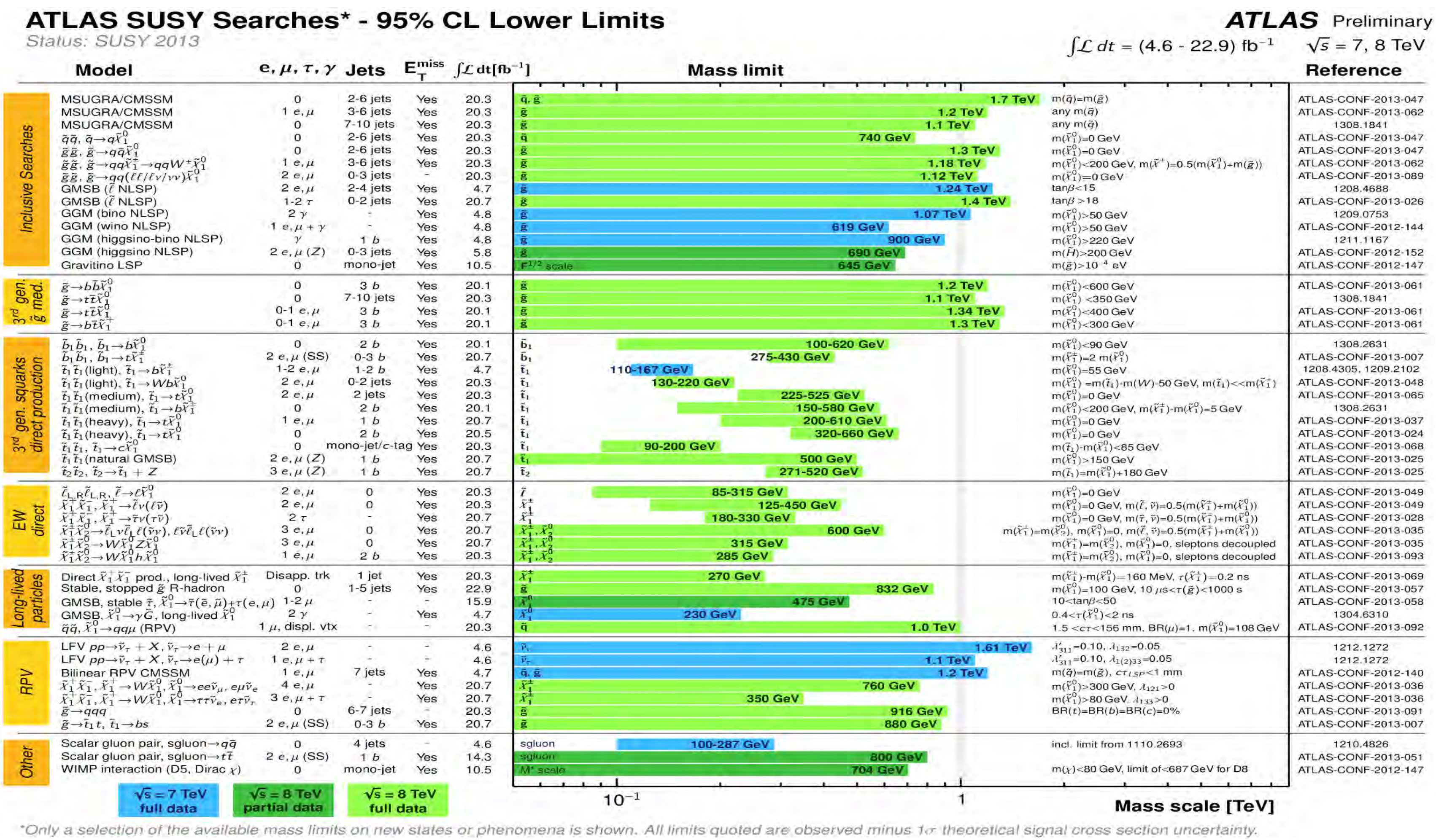
- This is met.

- The consistency with the SM couplings though might be an indication that the higher fields are strongly decoupled (hence at much higher masses).

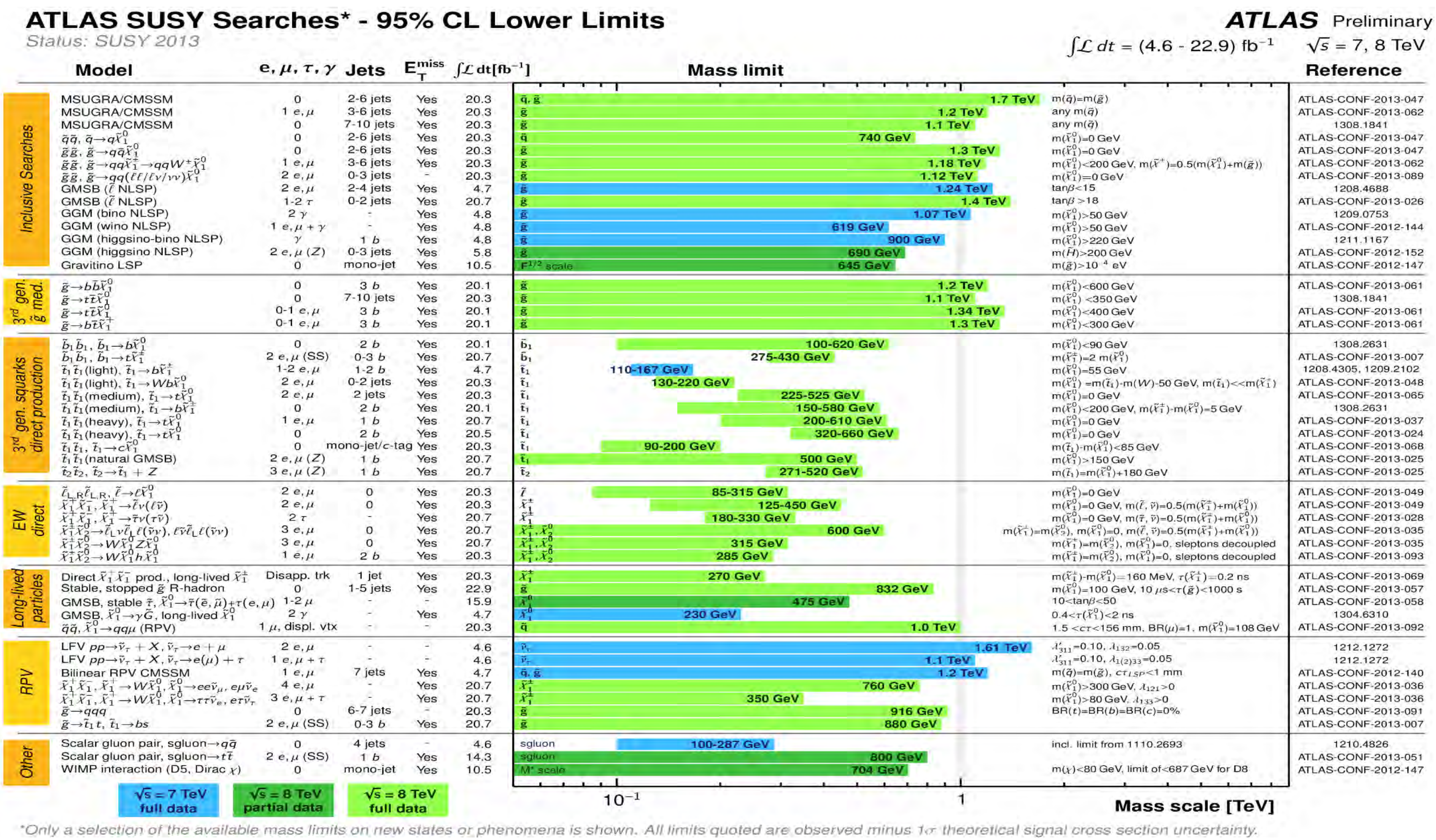
- Still, the experimentalist's honor and duty is to complete the landscape understanding. And set a/the (direct searches/ precision measurements) scale for New Physics.

- Let's examine in a glance the LHC searches.

Searches *tous azimuts* at LHC (SuSy for illustration)



Searches *tous azimuts* at LHC (SuSy for illustration)



- Note: no note.

My conclusion for Part I

My conclusion for Part I

• A continuum of ambitious and beautiful experiments in the past thirty years brought the Standard Model to the level of a theory.

• The observation of a possibly scalar particle at the LHC consecrates a daunting (collective) intellectual approach.

• You are entering the field at a time where we lost the *No-Loose theorem: Either the BEH or another source of EWK symmetry breaking below the TeV*.

• And these can be fascinating times.

• Starting by LHC Run II, approaching fast.

• Let's examine now precision physics, in the quark flavours at first.