On the Future of High Energy Physics

C.E.M. Wagner, PilcherFest, September 22, 2012

Historical Perspective

- In order to reflect on the future, it is useful to look at the lessons of the past.
- I will give a few interesting examples, and then speculate on the future.
- I will start with the Higgs Boson (thanks to E. Gross)

A Phenomenological Profile of the Higgs Boson

1976

Nuclear Physics B106 (1976) 292–340

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

The situation with regard to Higgs bosons is unsatisfactory. First it should be stressed that they may well not exist. Higgs bosons are introduced to give intermediate vector bosons masses through spontaneous symmetry breaking. However, this symmetry breaking could be achieved dynamically [10] without elementary Higgs bosons. Thus the confirmation or exclusion of their existence would be an important constraint on gauge theory model building. Unfortunately, no way is known to calculate the mass of a Higgs boson, at least in the context of the popular Weinberg-Salam [11]

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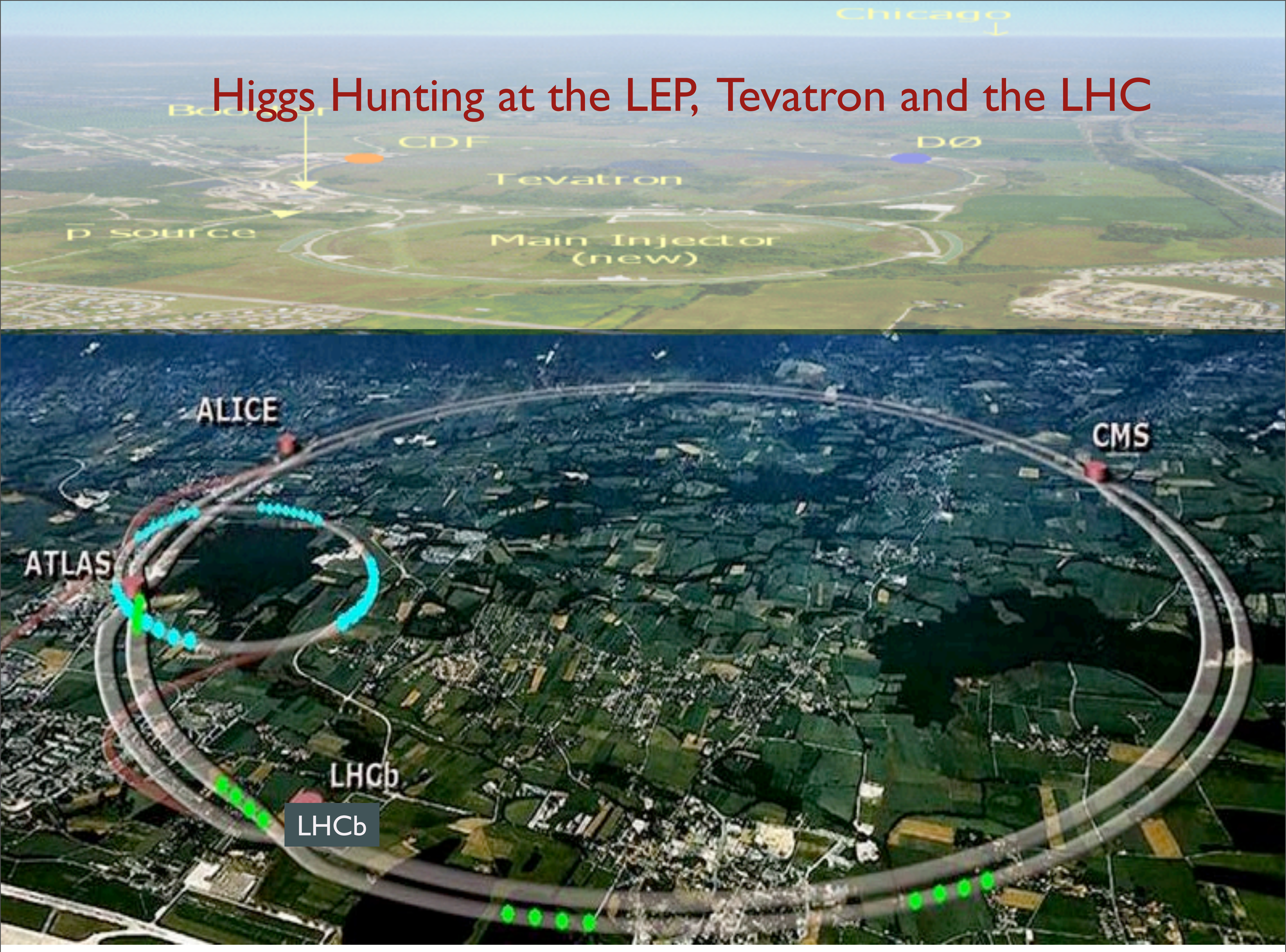
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

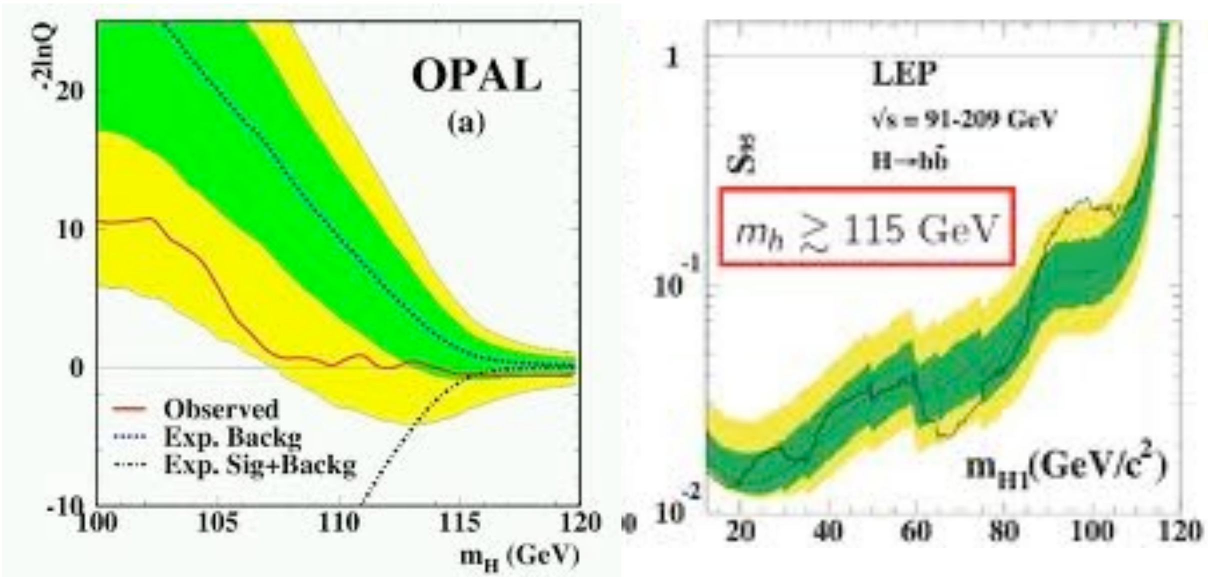
But the Higgs is not weakly coupled to all fundamental particles !

- It is relatively strongly coupled to those particles which had not been discovered at that time
- Indeed, the W mass, the Z mass and the top quark masses are all of the order of 100 times the proton mass
- Some of the authors soon realized that these could be used to produce Higgs bosons
- It is in processes mediated by these particles that we have searched for, and eventually found the Higgs boson !

Higgs Hunting at the LEP, Tevatron and the LHC

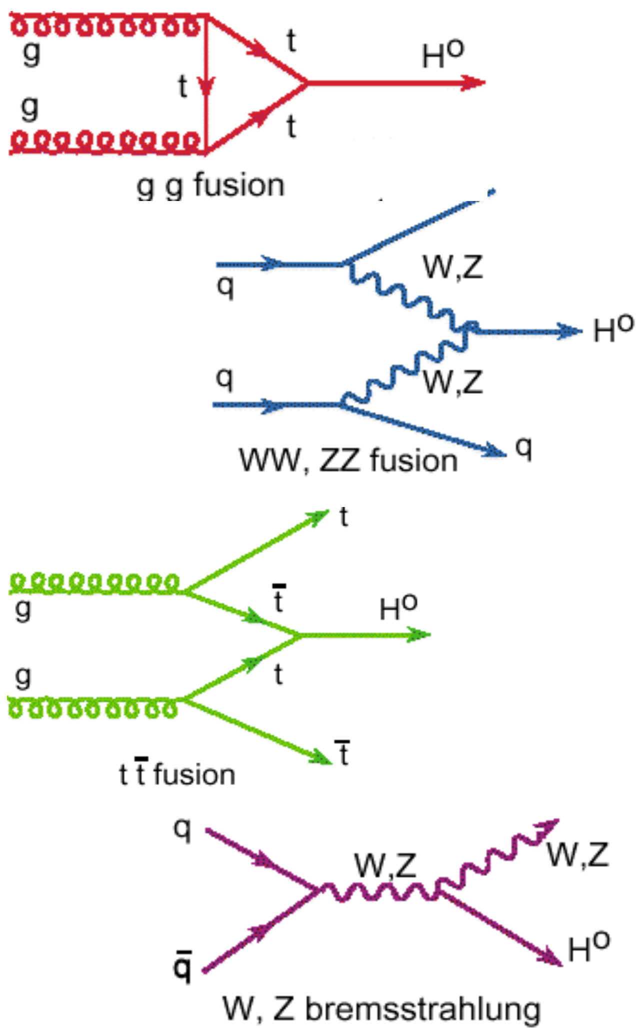


LEP almost get it !
LEP lower Higgs mass bound only 10 GeV smaller than the Higgs mass



$$e^+e^- \to Z^* \to ZH$$

Search for the Standard Model Higgs at Proton Colliders

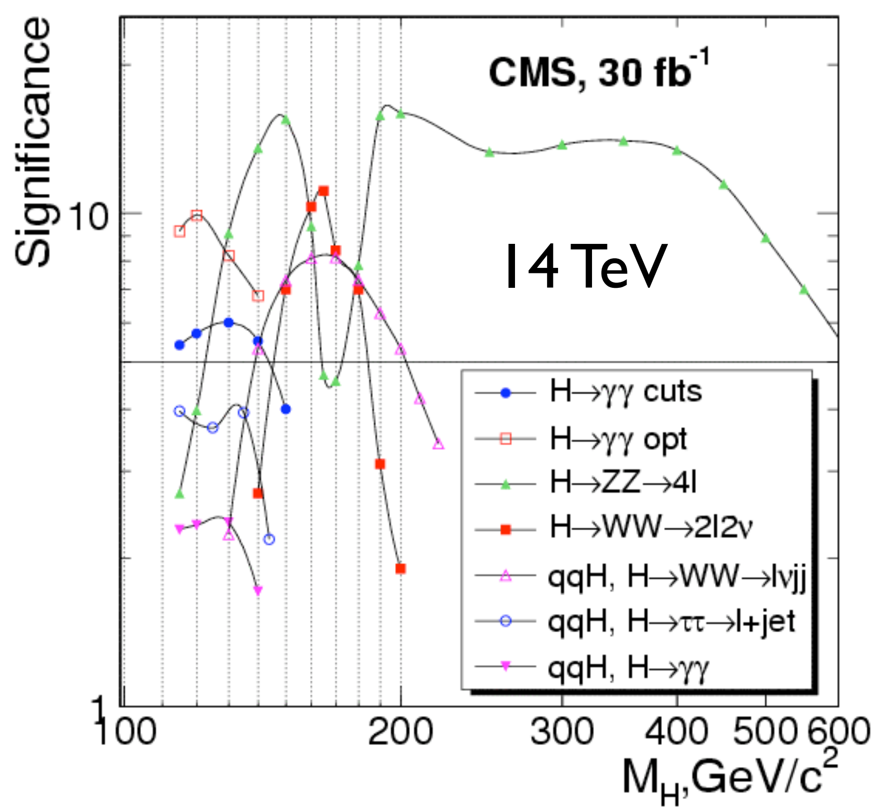


- **Low mass range** $m_{H_{SM}} < 200$ GeV

$$H \to \gamma\gamma, \tau\tau, bb, WW, ZZ$$

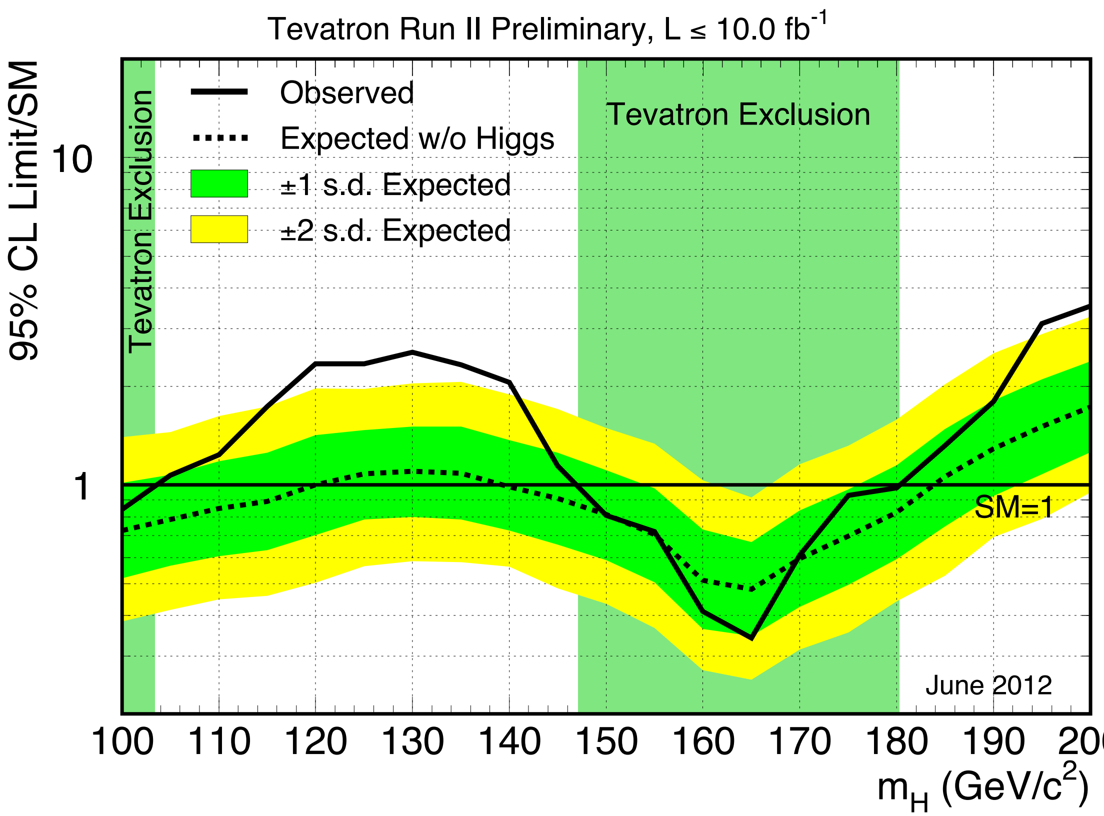
- **High mass range** $m_{H_{SM}} > 200$ GeV

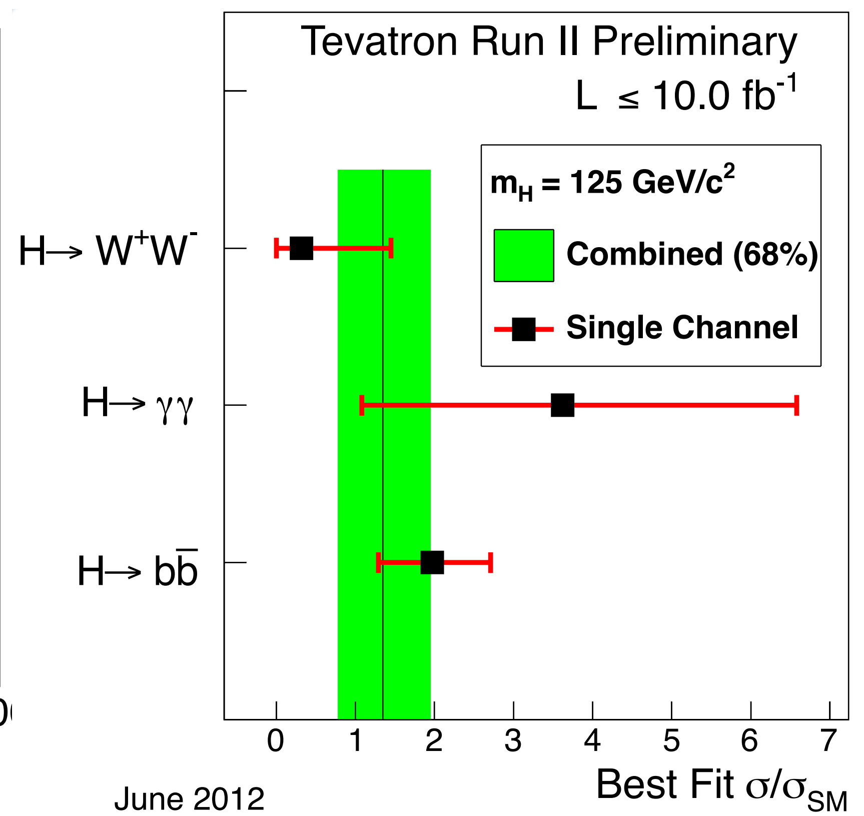
$$H \to WW,\ ZZ$$



Tevatron

Combination of searches for Higgs decaying into WW and bb shows a clear excess in the 115 GeV to 135 GeV mass region

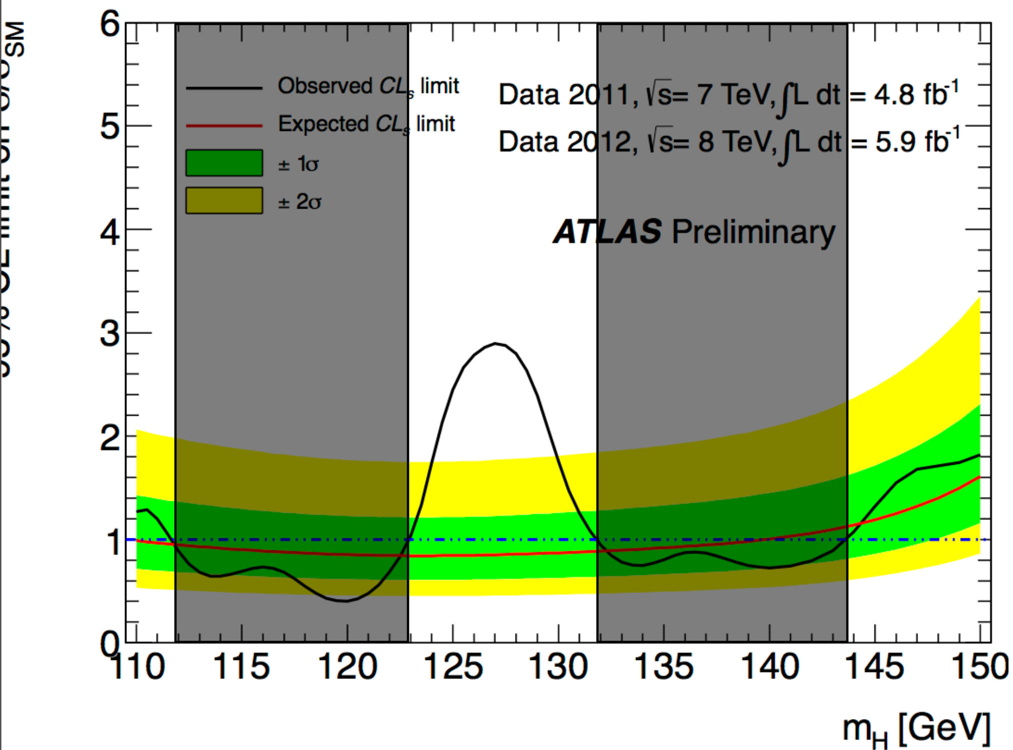


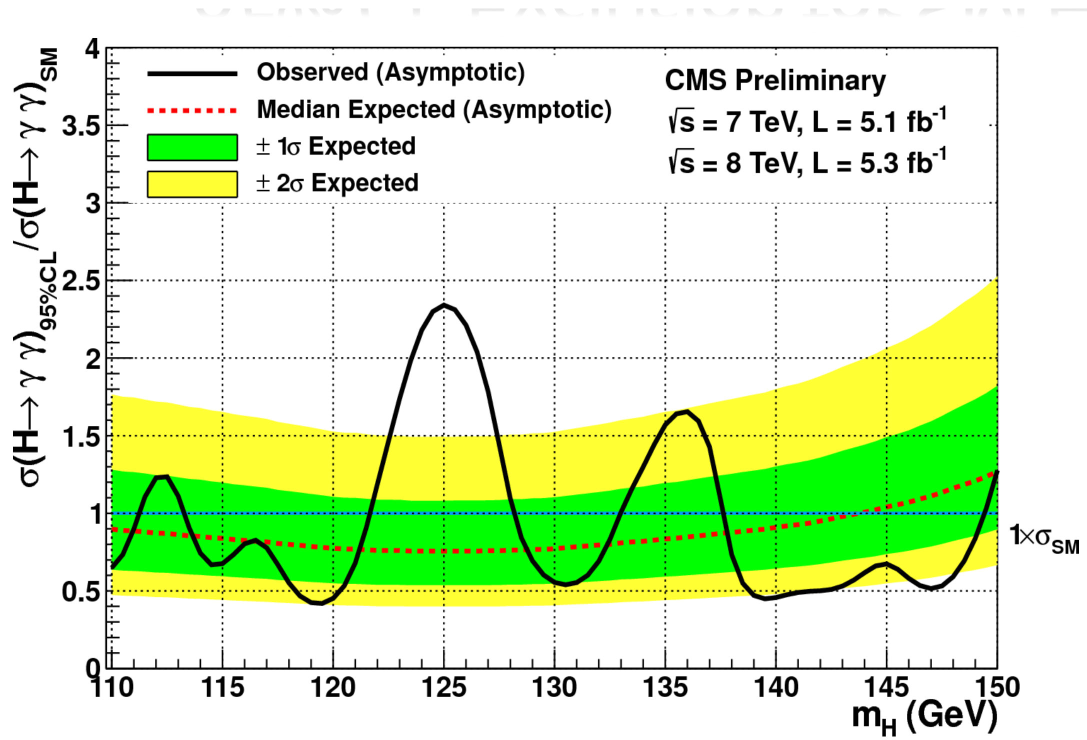


For a Higgs mass of 125 GeV, the combined production rates are consistent with the SM ones within 1 σ

LHC Got it !

Taking all di-photon production channels, one can exclude the presence of a low mass SM Higgs for a large region of masses

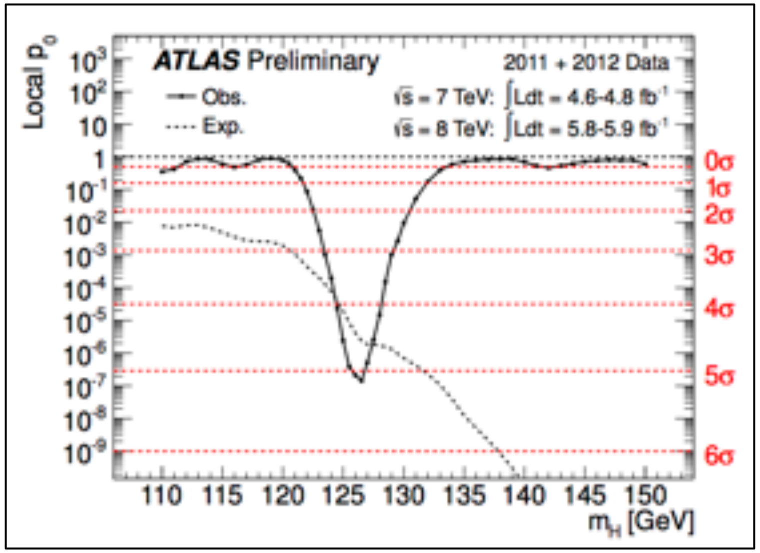


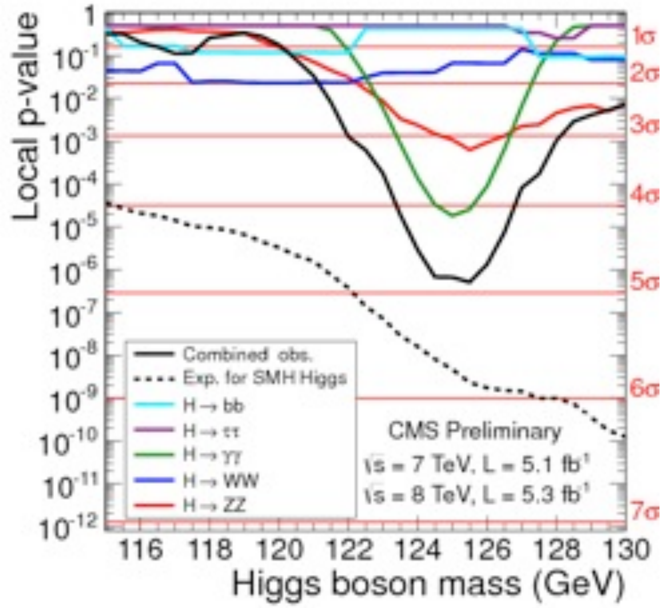


Clear Excess observed in the 124 GeV to127 GeV mass range in both experiments.

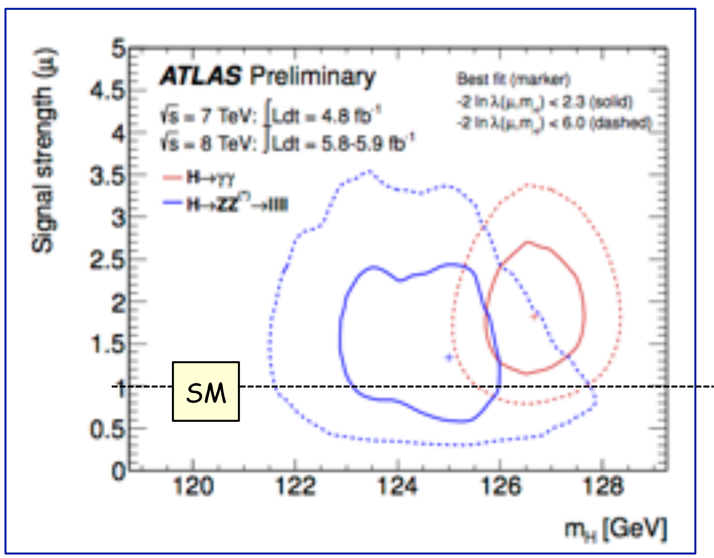
Combination of all channels.

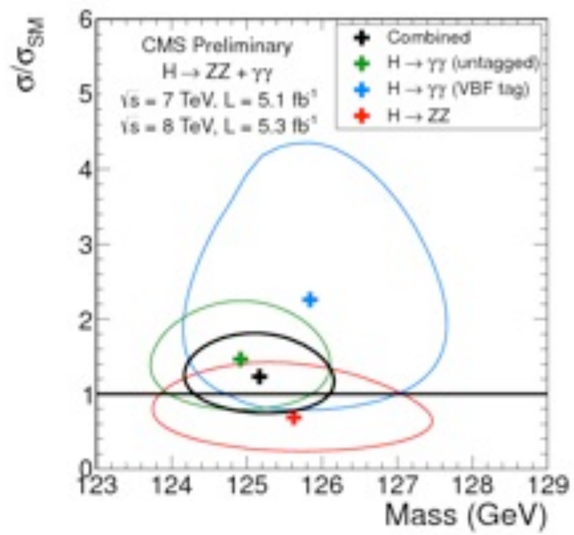
ATLAS considers 2011+2012 diphoton and ZZ channels and
all other channels with only 2011 data.
CMS based its analysis on the 2011 + 2012 results





- Comb. Sign.: 5 σ excess
- Comb. Sign.: 4.9 σ excess






Now What?

Still much work to do on the Higgs at the LHC

- Is this really the Standard Model Higgs ?
- What is the spin of the resonance ?
- What are its CP properties ?
- Are the couplings proportional to masses, as predicted by the SM ?
- By the end of the year, we probably have an understanding of the first two questions.
- The third one will take longer. LHC will provide about 20 percent precision on couplings.

Assume Resonance behaves like a SM Higgs: What are the implications for the future of High Energy Physics?

Many questions remain unanswered. Just to list some important ones :

- Why is gravity so weak or, equivalently, why is the Planck scale so high compared to the weak scale ? (hierarchy problem)
- What is the origin of the matter-antimatter asymmetry
- What is the origin of Dark Matter ?
- Are neutrinos their own antiparticle ?
- Why are there three generations of fermions ?
- What is the origin of the hierarchy of fermion masses ?
- Do forces unify ? Is the proton (ordinary matter) stable ?
- What about Dark Energy ?

LHC

- The LHC has been running since March 2011.
- Expected collision energy : 14,000 proton masses (now 8,000)
- Heaviest particle known : Top quark. Mass = 175 proton masses

LHC major goals :

- Finding the Higgs   (Achieved)
- Looking for Dark Matter particles
- Looking for particles leading to the solution of the hierarchy problem
- Searching for the Unexpected

Dark Matter : Missing Energy at Colliders

- In general, if the dark matter particle is neutral and weakly interacting, it will not be detected at current colliders.
- Just like when the neutrino was discovered, evidence of the production of such a particle will come from an apparent lack of conservation of the energy and momentum in the process.
- Missing Energy and (transverse) momentum signatures, beyond the ones expected in the Standard Model, should be sizable and will be the characteristic signatures of theories with a thermal WIMP as a Dark Matter Candidate.

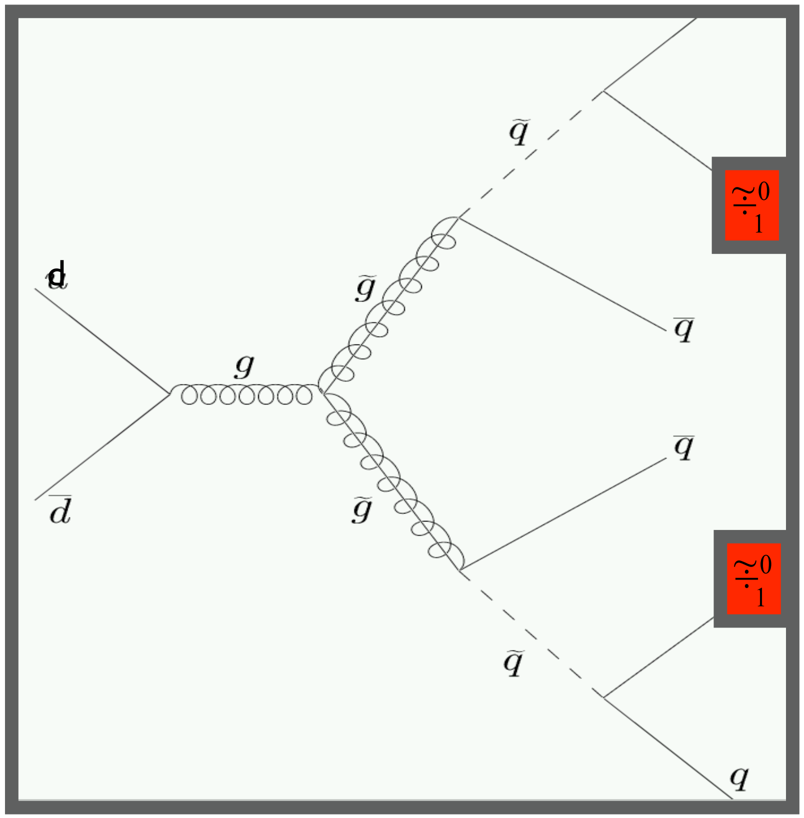
Example :

Supersymmetry at colliders

Gluino production and decay: Missing Energy Signature

Supersymmetric Particles tend to be heavier if they carry color charges.

Charge-less particles tend to be the lightest ones.

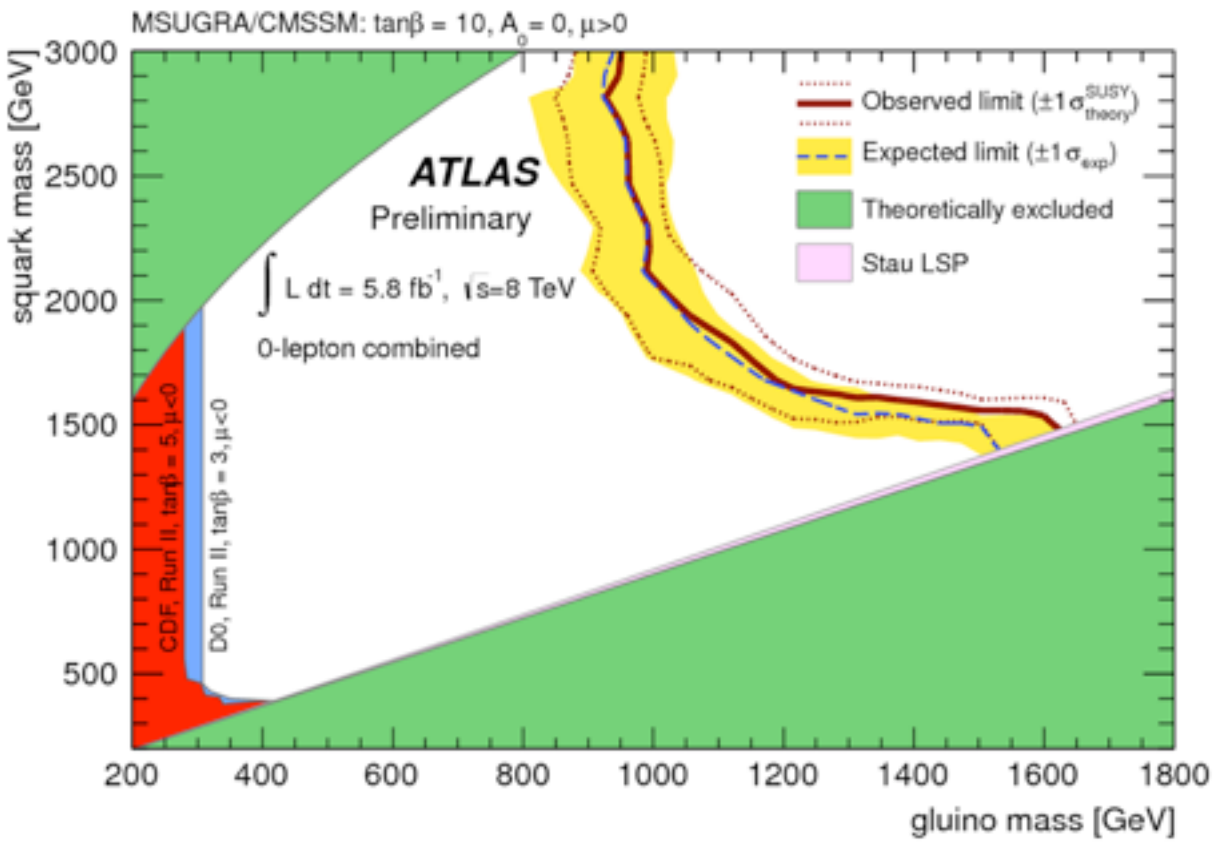


Lightest Supersymmetric Particle: Excellent cold dark matter candidate

Results of Searches for Supersymmetry at the LHC

Masses of squarks and gluinos below about 1 TeV seem to be in conflict with data in simple supersymmetry models.

But Higgs mass already pointing to masses of order 1 TeV...



So far, no evidence of new physics at the LHC.

But these bounds are strongly model dependent.

Third generation particles may be much lighter and more data coming...

Beyond the Higgs,

Are there any Hints of New Physics
at Laboratory Experiments ?

Some weak scale anomalies

Signals which are two to three standard deviations away from the expected SM predictions.

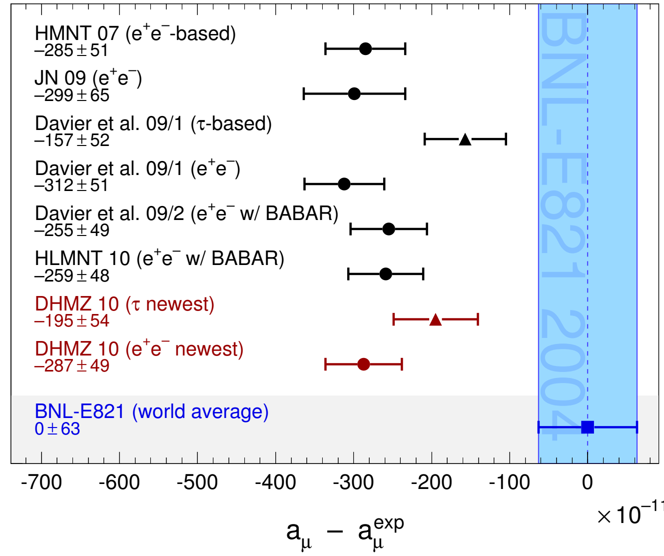
- LEP 100 GeV Higgs signal excess. Rate about one tenth of the corresponding SM Higgs one.
- DAMA/LIBRA annual modulation signal, direct DM detection searches (sodium iodide NaI scintillation crystal). COGENT experiment sees a compatible signal, disputed by XENON
- Anomalous magnetic moment of the muon.
- Forward-backward asymmetry of the bottom quark at LEP.
- Forward-backward asymmetry of the top quark at the Tevatron.
- Apparent anomalous neutrino results, in MiniBoone, LSND and reactor fluxes.
- Anomalies observed in $B \longrightarrow D \tau \nu$ transitions
- Apparent 214 MeV muon pair resonance in the decay $\Sigma \rightarrow p \, \mu^+ \mu^-$
- Anomalous W + 2 jets events with invariant mass of the 2 jets peaking at 150 GeV at CDF
- Proton radius difference measured in electron or muon hydrogen atoms ?

Muon Anomalous Magnetic Moment

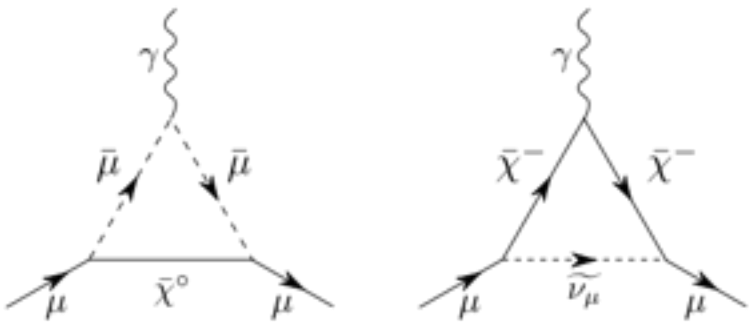
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 287\,(63)(49) \times 10^{-11}$$

3.6σ Discrepancy



New Physics at the Weak scale can fix this discrepancy. Relevant example : Supersymmetry



$$\delta a_\mu \simeq \frac{\alpha}{8\pi \sin^2\theta_W} \frac{m_\mu^2}{\tilde m^2} \tan\beta \simeq 15 \times 10^{-10} \left(\frac{100\ {\rm GeV}}{\tilde m}\right)^2 \tan\beta$$

Here $\tilde m$ represents the weakly interacting supersymmetric particle masses.

For $\tan\beta \simeq 10$ (50), values of $\tilde m \simeq 230$ (510) GeV would be preferred.

Masses of the order of the weak scale lead to a natural explanation of the observed anomaly !

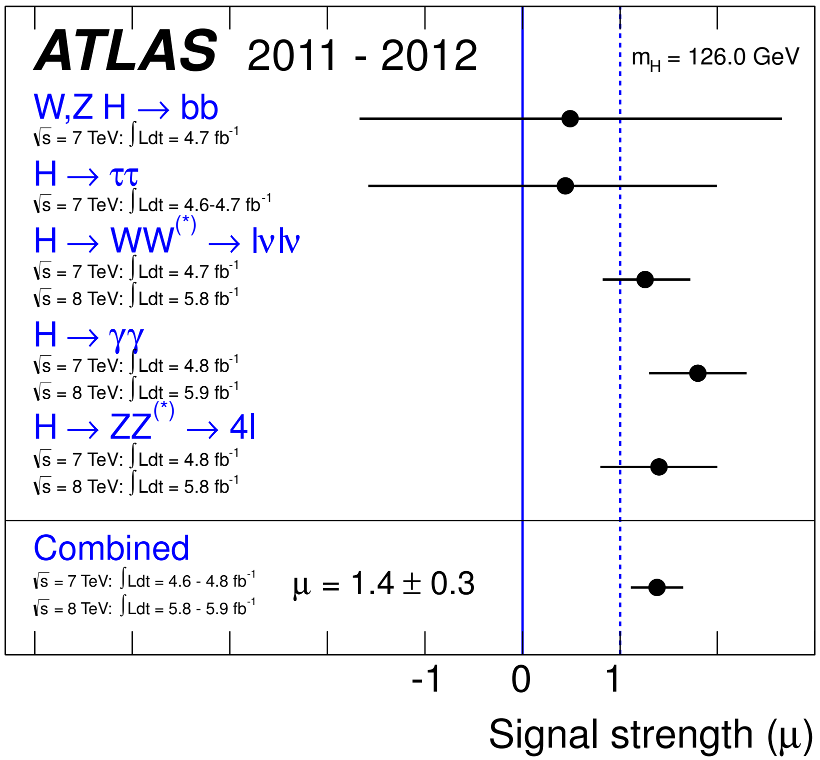
Reasons for Proposal and Later Solutions to 4 Puzzles (1932)

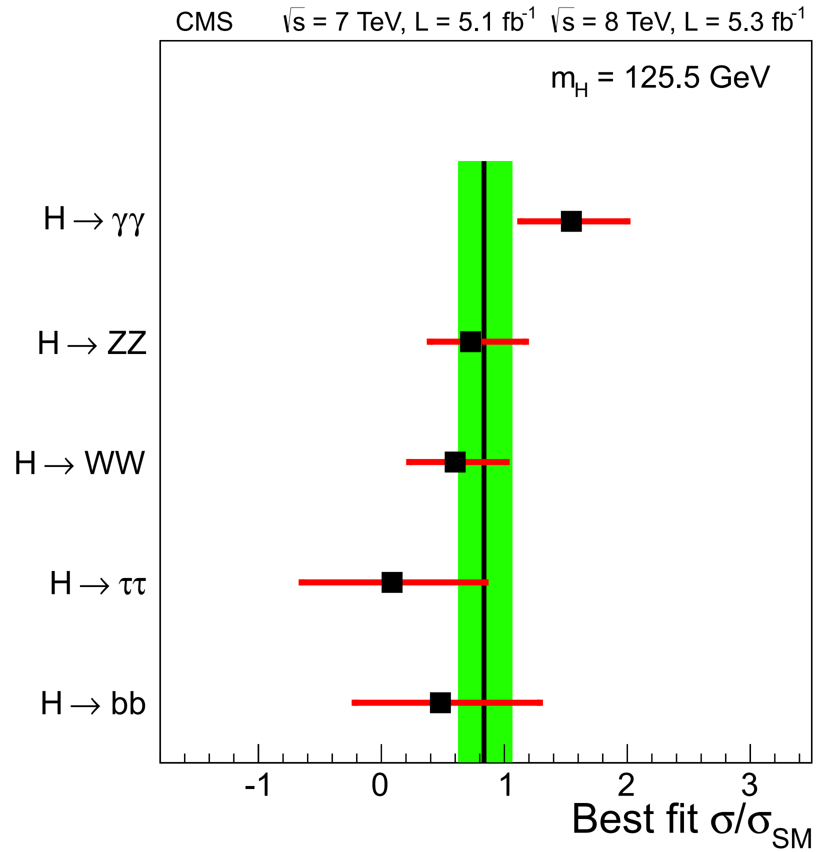
- 1) Klein Paradox --apparent violation of unitarity (solution:positron existence- pair production possible)
- 2) Wrong Statistics in Nuclei--N-14 nucleus appeared to be bosonic--(solution: neutron not a proton-electron bound state)
- 3) Beta Ray Emission-apparent Energy non conservation (solution:neutrino)
- 4) Energy Generation in Stars (solution: nuclear forces, pep chain, carbon cycle etc.----pion)

from G. Segre'10

More on the Higgs

The Signal strength may be computed in all different production and decay channels and is consistent with the SM





However

A di-photon rate enhancement is the most visible feature at both experiments.

The WW/ZZ rates are, in average, at the SM value

There is an apparent suppression of tau production in VBF.

Present experimental uncertainties allow for a wide variety of new physics alternatives.

Light, Weakly Interacting Charged Particles

- If neutral, weakly interacting particles are present (Dark Matter),
- it is probably that charged particles are there, too.
- They may contribute to the muon g-2
- They may contribute to the enhancement of the rate of the Higgs decay to diphotons !
- In SUSY, light staus may enhance the Higgs to di-photon rate. Or vector like leptons, or charginos of a strongly coupled sector...
- They are difficult to search for at the LHC
- The Linear Collider may complement the LHC efforts to study the Higgs and search for these particles

Presentation at the European Strategy Meeting

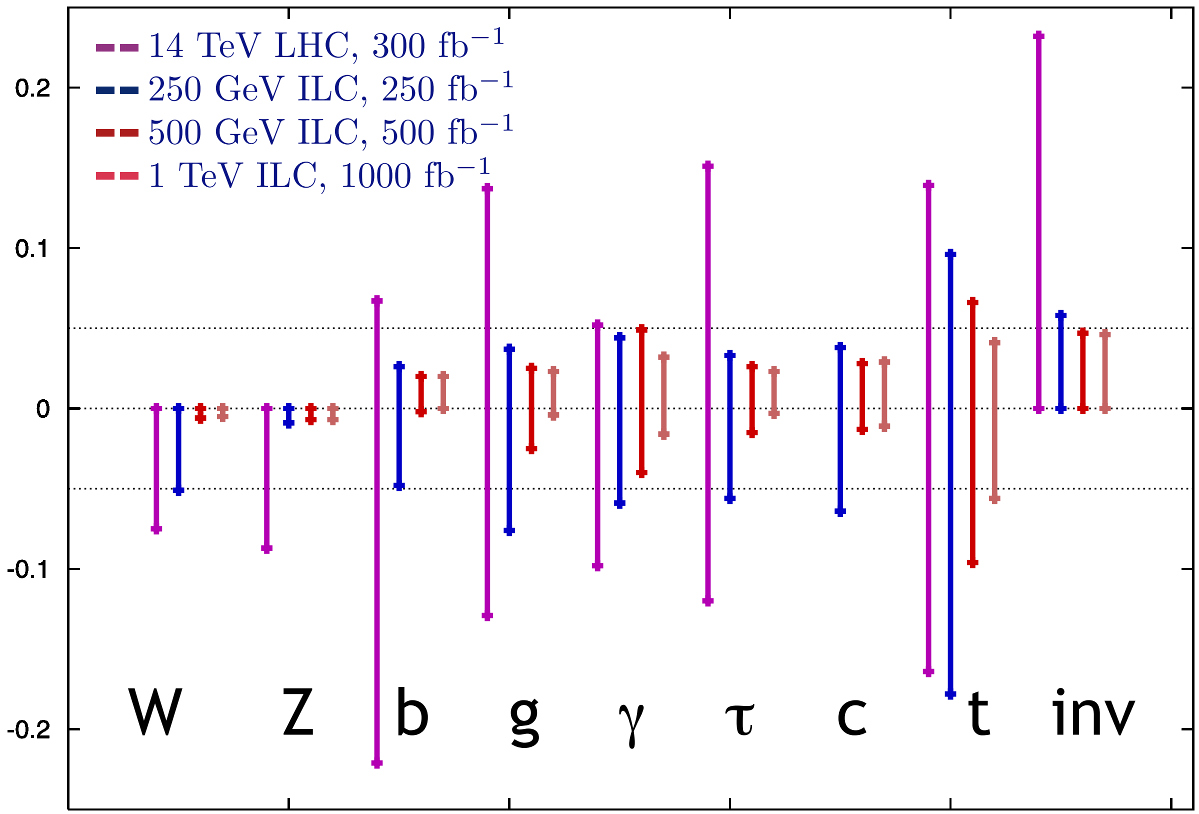
International Linear Collider in Japan ?

- Final update on the ILC discussion in Cracow: Japan may pay 50% of a 500 GeV machine.
- The 250 GeV machine would cost about 70% of the 500 GeV machine,
- One scenario could be that Japan finances a large part of the Higgs factory
- Further upgrades to 500 GeV or 1 TeV would have to be financed by external partners.
  All subject to governmental negotiations, of course !

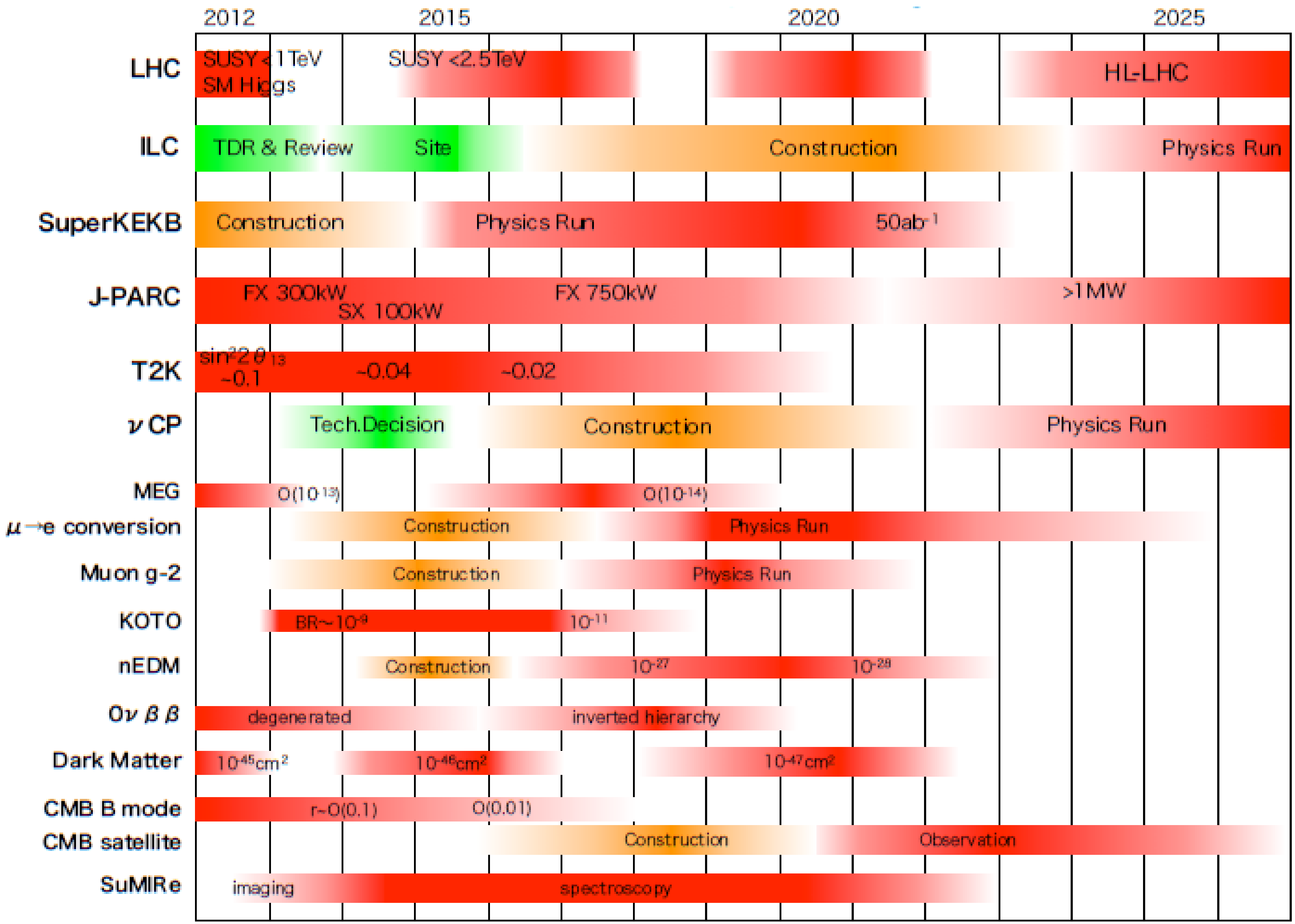
Capabilities of different colliders to determine Higgs boson couplings

M. Peskin, arXiv:1207.2516

g(hAA)/g(hAA)|$_{SM}$-1 LHC/HLC/ILC/ILCTeV



Time line of particle physics program in Japan



M. Yamauchi, European Strategy Meeting, Krakow, September 12,2012

The Near Future

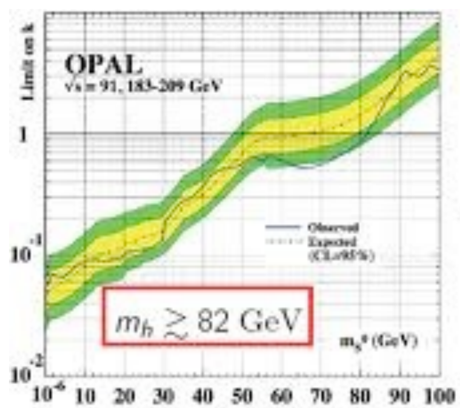
- The current decade will see the full development of the LHC program, which will provide detailed information of physics at the TeV scale.
- Origin of fermion and gauge boson masses (electroweak symmetry breaking dynamics) expected to be revealed by these experiments. Higgs Discovery is the first step.
- Missing energy signatures at the LHC may reveal one or more dark matter candidates. Direct and indirect detection experiments will reach maturity, and may lead to additional evidence of Dark Matter. Dark Energy equation of state may be determined.
- Tevatron, LHC, LHCb and super B-factories will provide accurate information on flavor physics, leading to complementary information on new physics.

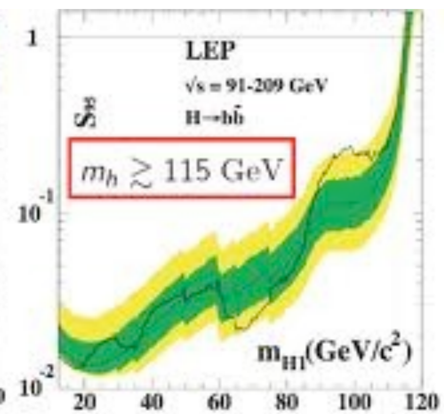
The Near Future

- Search for charged lepton number violation, g-2 of the muon and neutrino-less double beta decay experiments could shed light on the nature of neutrinos, and new dynamics at the TeV scale.
- Neutrino oscillation experiments lead to the observation of CP-violation or, indirectly, to the existence of additional sterile neutrinos.
- The Linear Collider is built, helping to do precision measurements of the Higgs properties and search for weakly interacting particles.
- Muon Collider construction may start at Fermilab.

The next 10 to 20 years can mark the beginning of a genuine new era in physics, similar to the one that led to the successful SMs of particle physics and cosmology, which arguably started about 100 years ago.

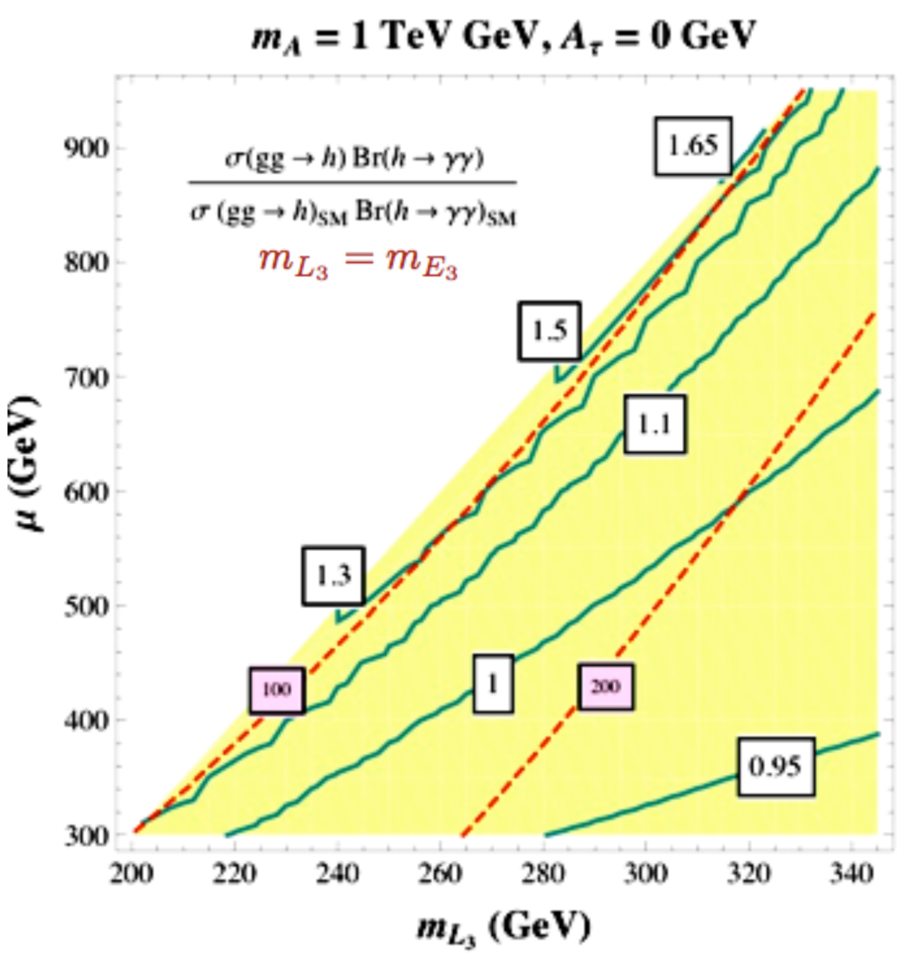

And that’s why these people are smiling !
PilcherFest, September 22, 2012


OPAL
√s = 91, 183-209 GeV
Observed
Expected
(CL=95%)
$m_h \gtrsim 82$ GeV
10 20 30 40 50 60 70 80 90 100


LEP
√s = 91-209 GeV
$H \to b\bar{b}$
$m_h \gtrsim 115$ GeV
$m_{H1}(GeV/c^2)$
20 40 60 80 100 120

Higgs Decay into two Photons in the MSSM

Charged scalar particles with no color charge can change di-photon rate without modification of the gluon production process



$$\mathcal{M}^2_{\tilde{\tau}} \simeq \begin{bmatrix} m^2_{L_3} + m^2_\tau + D_L & h_\tau v(A_\tau \cos\beta - \mu \sin\beta) \\ h_\tau v(A_\tau \cos\beta - \mu \sin\beta) & m^2_{E_3} + m^2_\tau + D_R \end{bmatrix}$$

Light staus with large mixing

[sizeable μ and tan beta]:

➔ **enhancement of the Higgs to di-photon decay rate**

Contours of constant

$$\frac{\sigma(gg\to h)Br(h\to\gamma\gamma)}{\sigma(gg\to h)_{SM}\,Br(h\to\gamma\gamma)_{SM}}$$

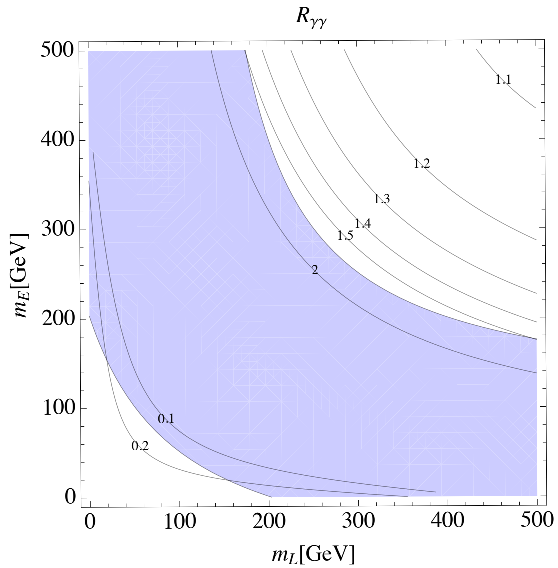
for M_h ~ 125 GeV

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336, +L.T.Wang, arXiv:1205.5842

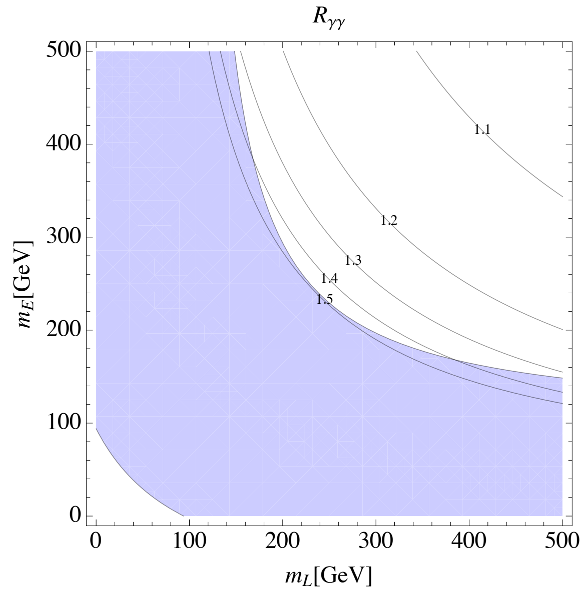
Model with a four generation leptons and their vector pairs.

Model can lead to the presence of Dark Matter and an enhanced diphoton rate

M. Carena, I. Low, C. Wagner'12;   A. Joglekar, P. Schwaller, C.W.'12



$Y'_C = Y_C" = 1$



$Y'_C = Y_C" = 0.8$

$$\mathcal{L}_{h\gamma\gamma} = \frac{\alpha}{16\pi}\frac{h}{v}\left[\sum_i b_i \frac{\partial}{\partial \log v} \log\left(\det \mathcal{M}^\dagger_{F,i}\mathcal{M}_{F,i}\right) + \sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}^2_{B,i}\right)\right] F_{\mu\nu}F^{\mu\nu}$$

Ellis, Gaillard, Nanopoulos'76,   Shifman, Vainshtein, Voloshin, Zakharov'79

$$\mathcal{M} = \begin{pmatrix} Y'_c v & m_L \\ m_E & Y'_c v \end{pmatrix}$$

$$\frac{\partial \log(\mathrm{Det} M_f)}{\partial v} \simeq -2\frac{Y'_C Y_C" v}{m_L m_E - Y'_C Y_C" v^2}$$