Origin of Masses:

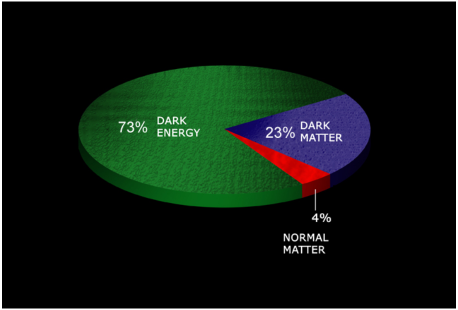
Higgs and Beyond

罗民兴
浙江大学浙江近代物理中心

中国科技大学交叉学科理论研究中心

2012年12月21日

Normal matter $\sim$ 4%



we don't know much about dark matter or dark energy
we will only focus on normal matter, $\sim$ 4% of universe energy

Mass: a fundamental concept in physics

- intrinsic property of matter (m, e, s)
- inertial mass

$$\vec{F} = m\vec{a}$$

$$i\frac{\partial}{\partial t}\psi = \left[-\frac{\hbar^2}{2m}\nabla^2 + V\right]\psi$$

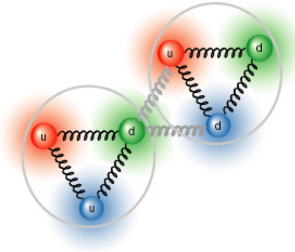
- gravitational mass

$$F = G\frac{m_1 m_2}{r^2}$$

- special relativity $E = mc^2$, $E^2 = \vec{p}^2c^2 + m^2c^4$
- general relativity, equivalence principle: inertial mass $\sim$ gravitational mass

QCD accounts for masses of most normal matter
(instead of the Higgs boson)

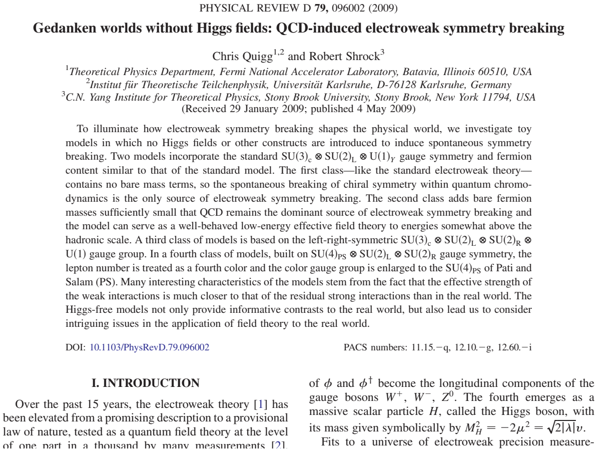
QCD dynamics dominates the proton mass.



proton (uud) mass: $m_p = 938.27$ MeV
but $m_u \sim 2.3$ MeV, $m_d \sim 4.8$ MeV

hadron masses cannot be calculated analytically (yet or ever)
perhaps string theory can help? AdS/QCD? lattice, of course

But why do we need Higgs?
arXiv:0901.3958



PHYSICAL REVIEW D **79,** 096002 (2009)

Gedanken worlds without Higgs fields: QCD-induced electroweak symmetry breaking

Chris Quigg[1,2] and Robert Shrock[3]
[1]*Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[2]*Institut für Theoretische Teilchenphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany*
[3]*C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA*

(Received 29 January 2009; published 4 May 2009)

To illuminate how electroweak symmetry breaking shapes the physical world, we investigate toy models in which no Higgs fields or other constructs are introduced to induce spontaneous symmetry breaking. Two models incorporate the standard $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ gauge symmetry and fermion content similar to that of the standard model. The first class—like the standard electroweak theory—contains no bare mass terms, so the spontaneous breaking of chiral symmetry within quantum chromodynamics is the only source of electroweak symmetry breaking. The second class adds bare fermion masses sufficiently small that QCD remains the dominant source of electroweak symmetry breaking and the model can serve as a well-behaved low-energy effective field theory to energies somewhat above the hadronic scale. A third class of models is based on the left-right-symmetric $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)$ gauge group. In a fourth class of models, built on $\mathrm{SU}(4)_{\mathrm{PS}} \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$ gauge symmetry, the lepton number is treated as a fourth color and the color gauge group is enlarged to the $\mathrm{SU}(4)_{\mathrm{PS}}$ of Pati and Salam (PS). Many interesting characteristics of the models stem from the fact that the effective strength of the weak interactions is much closer to that of the residual strong interactions than in the real world. The Higgs-free models not only provide informative contrasts to the real world, but also lead us to consider intriguing issues in the application of field theory to the real world.

DOI: 10.1103/PhysRevD.79.096002 PACS numbers: 11.15.−q, 12.10.−g, 12.60.−i

I. INTRODUCTION

Over the past 15 years, the electroweak theory [1] has been elevated from a promising description to a provisional law of nature, tested as a quantum field theory at the level of one part in a thousand by many measurements [2],

of ϕ and $\phi^\dagger$ become the longitudinal components of the gauge bosons W^+, W^-, Z^0. The fourth emerges as a massive scalar particle H, called the Higgs boson, with its mass given symbolically by $M_H^2 = -2\mu^2 = \sqrt{2|\lambda|}v$.

Fits to a universe of electroweak precision measure-

Why is mass an issue?

- symmetry dictates interaction
- gauge symmetry to ensure renormalizibility
  prohibits gauge boson masses
- fermions are chiral, parity violation
  chiral symmetry prohibits fermion masses
- dynamical origins of masses for gauge bosons and chiral fermions
- scalars are different, no symmetry to prevent a mass term (except supersymmetry)
  no fundamental scalars before the Higgs boson

Chiral symmetry

$$1 = \frac{1+\gamma_5}{2} + \frac{1-\gamma_5}{2}$$

- vector interaction, in which ψ_L and ψ_R transform in the same way, has $SU(N)_L \times SU(N)_R$ chiral symmetry

$$i\bar{\psi}\not{D}\psi = i\bar{\psi}_L\not{D}\psi_L + i\bar{\psi}_R\not{D}\psi_R$$

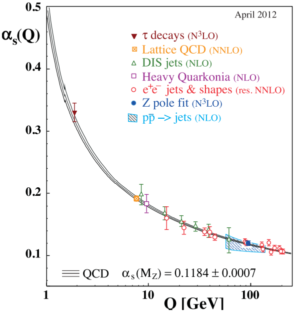
invariant under $\psi^i_L \to U^{ij}_L\psi^j_L, \;\; \psi^i_R \to U^{ij}_L\psi^j_R$

- broken by mass terms of ψ

$$\bar{\psi}\psi = \bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R$$

Chiral symmetry breaking

low energy QCD has $SU(2)_L \times SU(2)_R$ chiral symmetry



at an energy scale Λ_{QCD}, strong interactions become strong, confinement and fermion condensates $\langle \bar{q}q \rangle$ appear

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

leave with three Goldstone bosons (massless pions)

Quark condensate links left- and right-handed fermions

$$\langle \bar{q}q \rangle = \langle \bar{q}_R q_L + \bar{q}_L q_R \rangle$$

while

$$Q_L^i = \begin{pmatrix} u^i \\ d^i \end{pmatrix}_L : (3, 2, \frac{1}{3})$$

$$u_R^i : (3, 1, \frac{4}{3}); \quad d_R^i : (3, 1, -\frac{2}{3})$$

$\langle \bar{q}q \rangle$ transform as $SU(2)_L$ doublet with $\mid Y \mid = 1$
which breaks $SU(2)_L \times U(1)_Y \to U(1)_{EM}$

Weak gauge boson masses

broken generators: 3 axial currents; couplings to π: f_π
gauge interactions $SU(2)_L \times U(1)_Y$: gauge bosons couple to axial currents, acquire mass $\sim g f_\pi$, $g \sim 0.65, g' \sim 0.34$, $f_\pi = 90$ MeV, under the basis (W_1, W_2, W_3, B)

$$M^2 = \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g'^2 \end{pmatrix} \frac{f_\pi^2}{4}$$

diagnoalization results in

$$M_W = g f_\pi/2 \sim 28\,\text{MeV}, M_Z = \sqrt{g^2 + g'^2} f_\pi/2 \sim 32\,\text{MeV}, M_A = 0$$

weak Interaction strongly enhanced! fast β-decay.

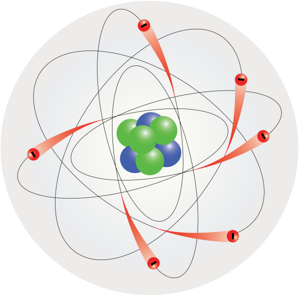
$$(M_W = 80\ \text{GeV}, M_Z = 91\ \text{GeV})$$

More important, pions exist in nature

No fermion mass: Is that a problem?

Bohr Radius

$$a_0 = \frac{\hbar}{m_e c \alpha}$$

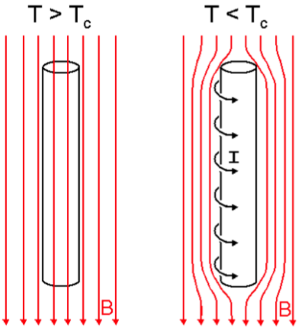


$$m_e \to 0, a_0 \to \infty$$

no atom→ no valence bonding→ no stable matter.....

extra: if $m_e \sim m_\mu$, cold fusion!

Meissner effect: condensation in condensed matter physics



- electron-phonon interaction
- Cooper-pair formed that breaks $U(1)$
- superconductivity
- $U(1)$ photon gets mass: Meissner effect

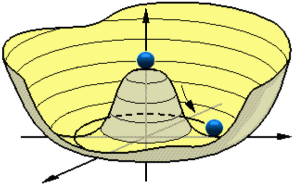
Higgs mechanism in the SM: $SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$

$$\phi = \left(\begin{array}{c} \phi^+ \\ \phi^0 \end{array} \right)_L \, : (1, 2, 1)$$

$$\mathcal{L} = (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi^\dagger \phi); \;\; V(\phi^\dagger \phi) = \mu^2 (\phi^\dagger \phi) + \mid \lambda \mid (\phi^\dagger \phi)^2$$

where

$$D_\mu = \partial_\mu + i \frac{g'}{2} Y B_\mu + i \frac{g}{2} \tau \cdot W_\mu$$



$$\langle \phi \rangle = \left(\begin{array}{c} 0 \\ v \end{array} \right)$$

Weak gauge boson masses

- if there exisits a local gauge symmetry, to each generator Q_a of the gauge group, there must be a vector field A_μ^a
- gauge boson masses violate gauge invariance
- massless A_μ has only two transverse polarizations
  longitudinal polarization $\epsilon_\mu^0 = (\frac{p}{m}, 0, 0, \frac{E}{m})$, extra $d.o.f$
- two Casimirs in Poincare group: $C_1 = p^\mu p_\mu = m^2$,
  $C_2 = W^\mu W_\mu = -m^2 s(s+1)$
  $m = 0$, $W^\mu = \lambda p^\mu$ ($\lambda = \vec{s} \cdot \hat{p}$), C_1 and C_2 are dependent
- weak gauge bosons acquire masses from $\langle\phi\rangle$
- $SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$
  three Goldstones → longitudinal $W^\pm$ and Z
  (mixing with pions)

SM fermion masses

$$-\mathcal{L} = Y_u \bar{Q}_L \bar{\phi} u_R + Y_d \bar{Q}_L \phi d_R + Y_e \bar{\ell}_L \phi e_R$$

- Y_i explicitly break $U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$
  If $Y_i = 0$, $m_f = 0$ and radiatively corrected $\Delta m_f = 0$
- SM fermion masses are consequences of both chiral and electroweak gauge symmetry breaking
- Keep in mind $m_t/m_e \sim 10^6$, $m_t/m_\nu \sim 10^{12}$

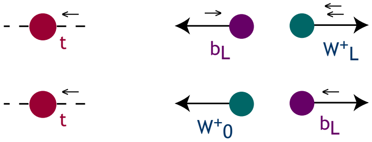
Neutrino mass may be non-trivial. Charge quantization ($U(1)_Y$ assignment) is determined by anomaly free condition of SM gauge symmetries but pure Dirac neutrino mass may result shift in it. Majorana type neutrino can ensure $Y = 0$ for right-handed neutrino.

Confirmation of Higgs mechanism

large m_t couples to symmetry breaking sector strongly

Goldstone is equivalent to longitudinal polarized W

$m_b/m_t \to 0$: “massless” b is left-handed polarized



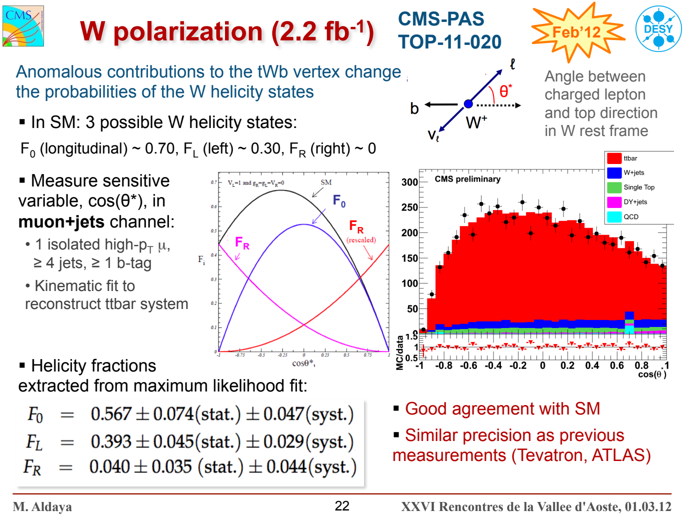
longitudinal W polarization: $\epsilon_0 \sim k_\mu/m_W$

$$\epsilon_0^* \bar{u}_{bL}\gamma_\mu u_t \simeq \frac{m_t}{m_W}\bar{u}_{bL}u_t$$

$$f_0 = \frac{\Gamma(t \to bW_0^+)}{\Gamma(t \to bW_0^+) + \Gamma(t \to bW_+^+) + \Gamma(t \to bW_-^+)} \simeq 70\%$$

$$f_- \simeq 30\%, f_+ \simeq 0$$

Confirmed by both Tevatron and LHC



W polarization (2.2 fb^{-1})

CMS-PAS TOP-11-020

Anomalous contributions to the tWb vertex change the probabilities of the W helicity states

Angle between charged lepton and top direction in W rest frame

- In SM: 3 possible W helicity states:

F_0 (longitudinal) ~ 0.70, F_L (left) ~ 0.30, F_R (right) ~ 0

- Measure sensitive variable, cos(θ*), in **muon+jets** channel:
  - 1 isolated high-p_T μ, ≥ 4 jets, ≥ 1 b-tag
  - Kinematic fit to reconstruct ttbar system

- Helicity fractions extracted from maximum likelihood fit:

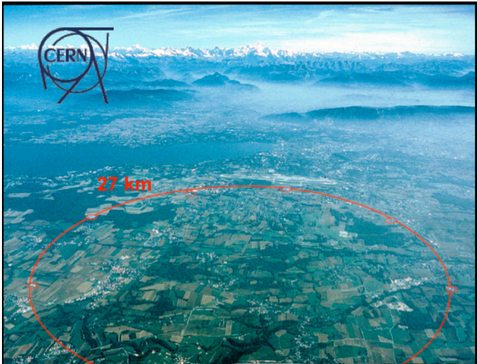
$$
\begin{aligned}
F_0 &= 0.567 \pm 0.074(\text{stat.}) \pm 0.047(\text{syst.})\\
F_L &= 0.393 \pm 0.045(\text{stat.}) \pm 0.029(\text{syst.})\\
F_R &= 0.040 \pm 0.035\ (\text{stat.}) \pm 0.044(\text{syst.})
\end{aligned}
$$

- Good agreement with SM
- Similar precision as previous measurements (Tevatron, ATLAS)

M. Aldaya 22 XXVI Rencontres de la Vallee d'Aoste, 01.03.12

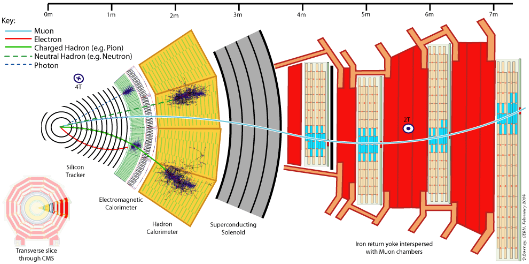
Great! but what does it tell us?
EWSB occurs but not how EWSB take place.....

How to search it?



LHC:

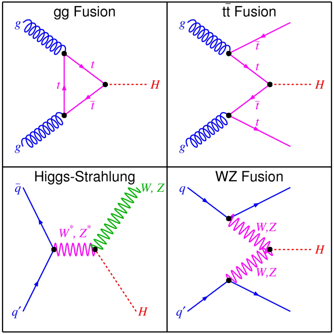
2 beams of protons collide 40 million x a second at near light speed 100m underground

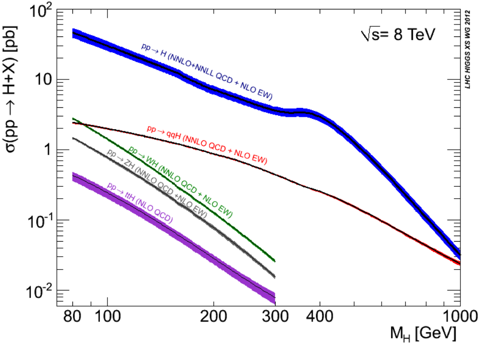


digging signal out of QCD: 1 out of 10^8

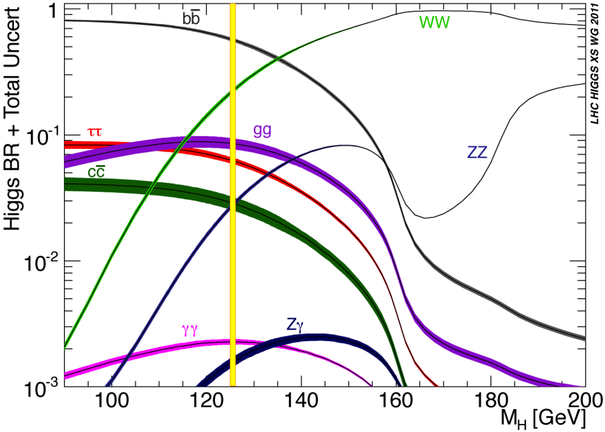
- high p_T object of $p_T > 120$ GeV: large mass difference
  Irrelevant to Higgs
- large missing transverse energy: $\not{E}_T > 40$ GeV: neutrino
- isolated hard leptons (electron or muon) or photon:
  $e^\pm, \mu^\pm, \gamma$: isolation is the key
- jet with displaced vertex: b-tagging: b is from gluon splitting
  third generation new physics

Production of SM Higgs at hadron colliders





Decay of SM Higgs



Discovery potential of $\mathcal{O}$(120 GeV) Higgs at hadron colliders

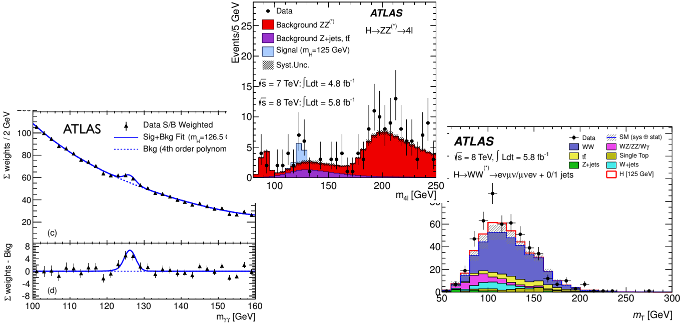
- $gg \to \phi \to b\bar{b}$ is the largest channel but suffer from huge SM background
- di-photon $gg \to \phi \to \gamma\gamma$ and four lepton $gg \to \phi \to ZZ^* \to 4\ell^\pm$ are the two most promising channels, clean and full reconstructable
- $\phi \to b\bar{b}$ can be searched via associated production $W\phi$ and $Z\phi$ (bb is large at LHC. b-jet measurement has larger uncertainty: a broad mass range)
- weak boson fusion (WBF) with $\phi \to \tau\tau$ may be useful

Discovery of a Higgs-like boson at the LHC

two cleanest channels $\gamma\gamma$, 4ℓ:

reconstruction masses at 125 GeV

dilepton also consistent with $ZZ^* \to 4\ell$ at 125 GeV



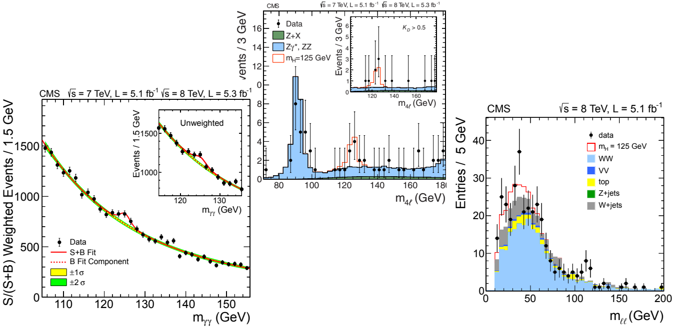
- $\gamma\gamma$: spin 0 or 2 (Landau-Yang)
- couples to weak gauge bosons (ZZ^*/WW^*)
- if it is spin-zero, production from gluon fusion

Discovery of a Higgs-like boson at the LHC

two cleanest channels $\gamma\gamma$, 4ℓ:

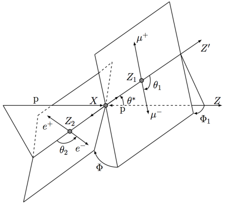
reconstruction masses at 125 GeV

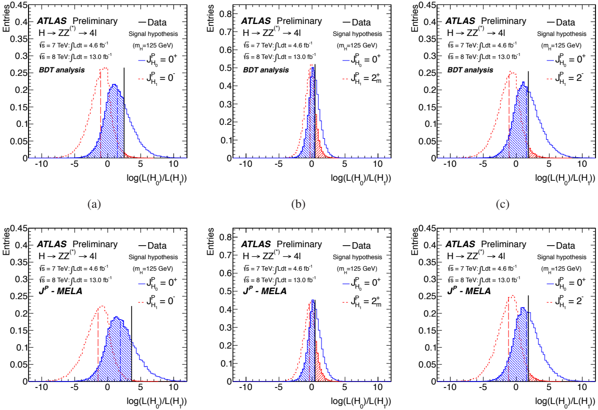
dilepton also consistent with $ZZ^* \to 4\ell$ at 125 GeV



- $\gamma\gamma$: spin 0 or 2 (Landau-Yang)
- couples to weak gauge bosons (ZZ^*/WW^*)
- if it is spin-zero, production from gluon fusion

$J^p = 0^+$ is preferred by latest data





(a) (b) (c)

(d) (e) (f)

A SM Higgs at 125 GeV?

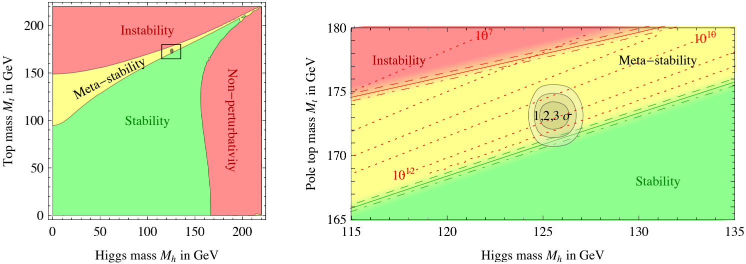
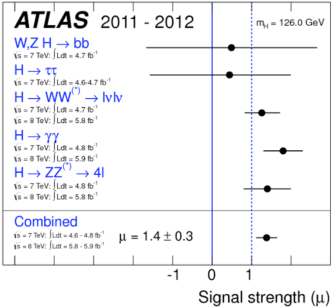


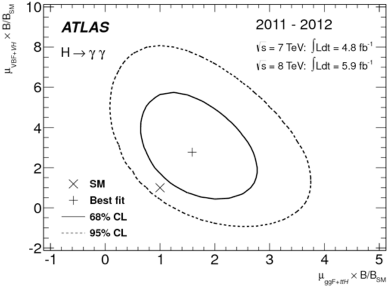
Figure 4: Regions of absolute stability, meta-stability and instability of the SM vacuum in the M_t–M_h plane

The SM Higgs? most plausible but . . .

Signal strength of individual channels (SM: μ=1)

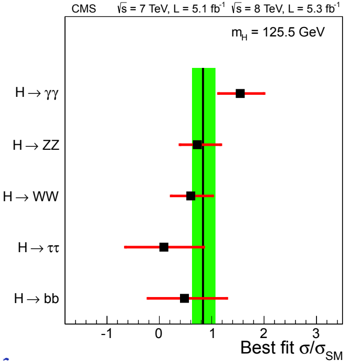


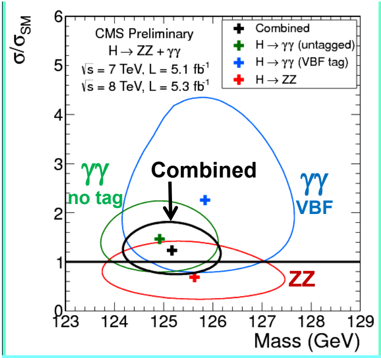
top-related production (gluon fusion + ttH) vs W/Z-related production (VBF, VH) in H→γγ



- $\sigma(gg \to h \to \gamma\gamma)/\sigma_{SM} \simeq 1.9 \pm 0.5$
- $\sigma(gg \to h \to ZZ^* \to 4\ell)/\sigma_{SM} \gtrsim 1$
- $\sigma(gg \to h \to WW^* \to 2\ell 2\nu)/\sigma_{SM} \gtrsim 1$

The SM Higgs? most plausible but . . .

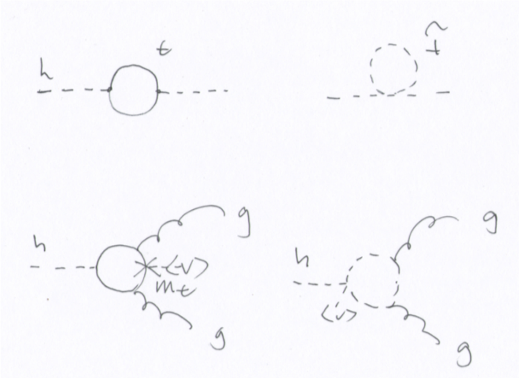




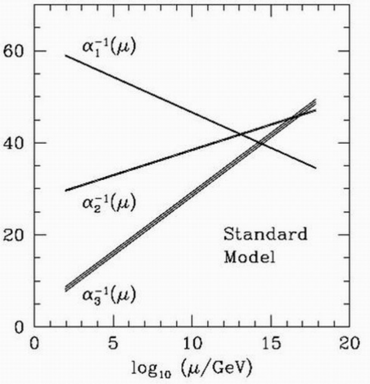
- $\sigma(gg \to h \to \gamma\gamma)/\sigma_{SM} \simeq 1.5 \pm 0.4$
- $\sigma(gg \to h \to ZZ^* \to 4\ell)/\sigma_{SM} \lesssim 1$
- $\sigma(gg \to h \to WW^* \to 2\ell 2\nu)/\sigma_{SM} \lesssim 1$

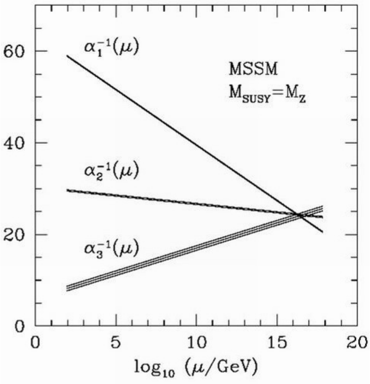
Maybe supersymmetry?

a fundamental scalar is completely arbitrary and very dangerous



Good things about SUSY





Does new data prefer SUSY?

Direct search of SUSY has excluded large parameter space of the theory, but very model dependent

Even for gluino, squarks' discovery, it requires large mass difference and right kinematics

Many SUSY models can easily evade the current searches

- light stau or light stop can explain the excess in diphoton
- reduction in $b\bar{b}$, $\tau^+\tau^-$ can be easily explained by SUSY
- large PQ- and R-symmetry breaking can induce significant radiative correction in SM fermion mass generation and reduce Yukawa couplings

Other wild beasts

- technicolor models
- little Higgs
- extra dimensions
- none of the above?

谢谢!