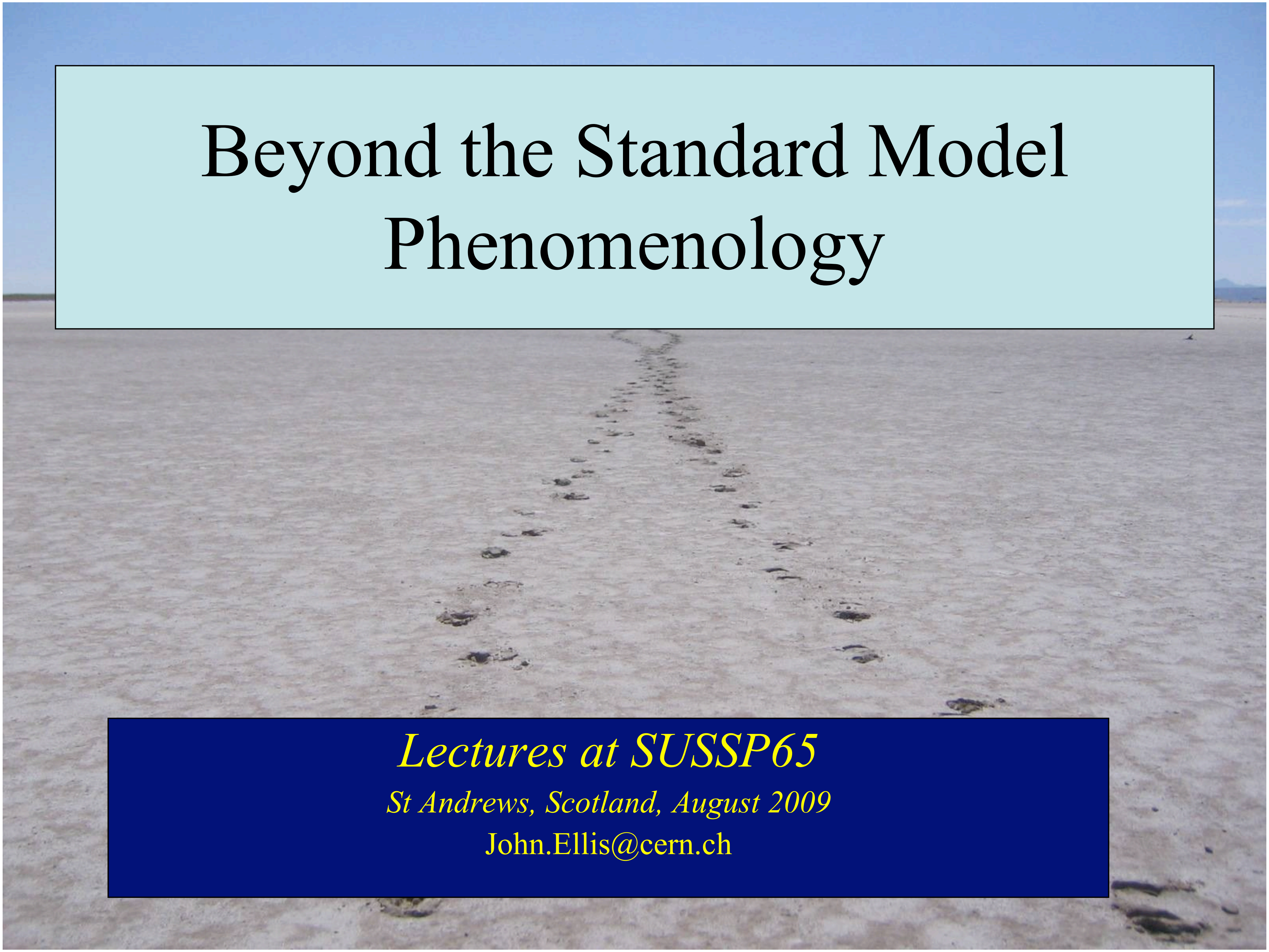
Beyond the Standard Model Phenomenology



Lectures at SUSSP65

St Andrews, Scotland, August 2009

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Plan of the Lectures

- The Standard Model and issues beyond it
- Origin of particle masses: Higgs boson(s)?
- Supersymmetry
- Searches for supersymmetry
- Neutrinos and Grand Unification
- Extra dimensions and string theory

Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

L_L	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	$(\mathbf{1},\mathbf{2},\text{-}1)$
E_R	$e^-_R\ ,\ \mu^-_R\ ,\ \tau^-_R$	$(\mathbf{1},\mathbf{1},\text{-}2)$
Q_L	$\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$	$(\mathbf{3},\mathbf{2},+1/3)$
U_R	$u_R\ ,\ c_R\ ,\ t_R$	$(\mathbf{3},\mathbf{1},+4/3)$
D_R	$d_R\ ,\ s_R\ ,\ b_R$	$(\mathbf{3},\mathbf{1},\text{-}2/3)$

- Lagrangian:

$$\begin{aligned} \mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\ \mu\nu} && \text{gauge interactions} \\ &+ i\bar{\psi}\ \not{D}\psi + h.c. && \text{matter fermions} \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. && \text{Yukawa interactions} \\ &+ |D_\mu \phi|^2 - V(\phi) && \text{Higgs potential} \end{aligned}$$

Gauge Interactions of the Standard Model

- Three separate gauge group factors:
  - SU(3) × SU(2) × U(1)
  - Strong × electroweak
- Three different gauge couplings:
  - g_3, g_2, g'
- Mixing between the SU(2) and U(1) factors:

$$\begin{pmatrix} Z^\mu \\ A^\mu \end{pmatrix} = \begin{pmatrix} \cos(\theta_W) & \sin(\theta_W) \\ -\sin(\theta_W) & \cos(\theta_W) \end{pmatrix} \begin{pmatrix} W_3^\mu \\ B^\mu \end{pmatrix}$$

$$\sin^2(\theta_W) = \frac{g'^2}{g'^2 + g^2}$$

- Experimental value: $\sin^2\theta_W = 0.23120 \pm 0.00015$

Important clue for Grand Unification

Weak Interactions

- Interactions of lepton doublets: $L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$
- Charged-current interactions:

$$\mathcal{L}_{cc} = \frac{-g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \nu_{L_\alpha} \gamma_\mu l_{L_\alpha} W^\mu \ + \ h.c.$$

- Neutral-current interactions:

$$\mathcal{L}_{nc} = \frac{-g}{2\cos\theta_W} \sum_{\alpha=e,\mu,\tau} \nu_{L_\alpha} \gamma_\mu l_{L_\alpha} Z^\mu \ + \ h.c$$

- Mixing between quark flavours:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

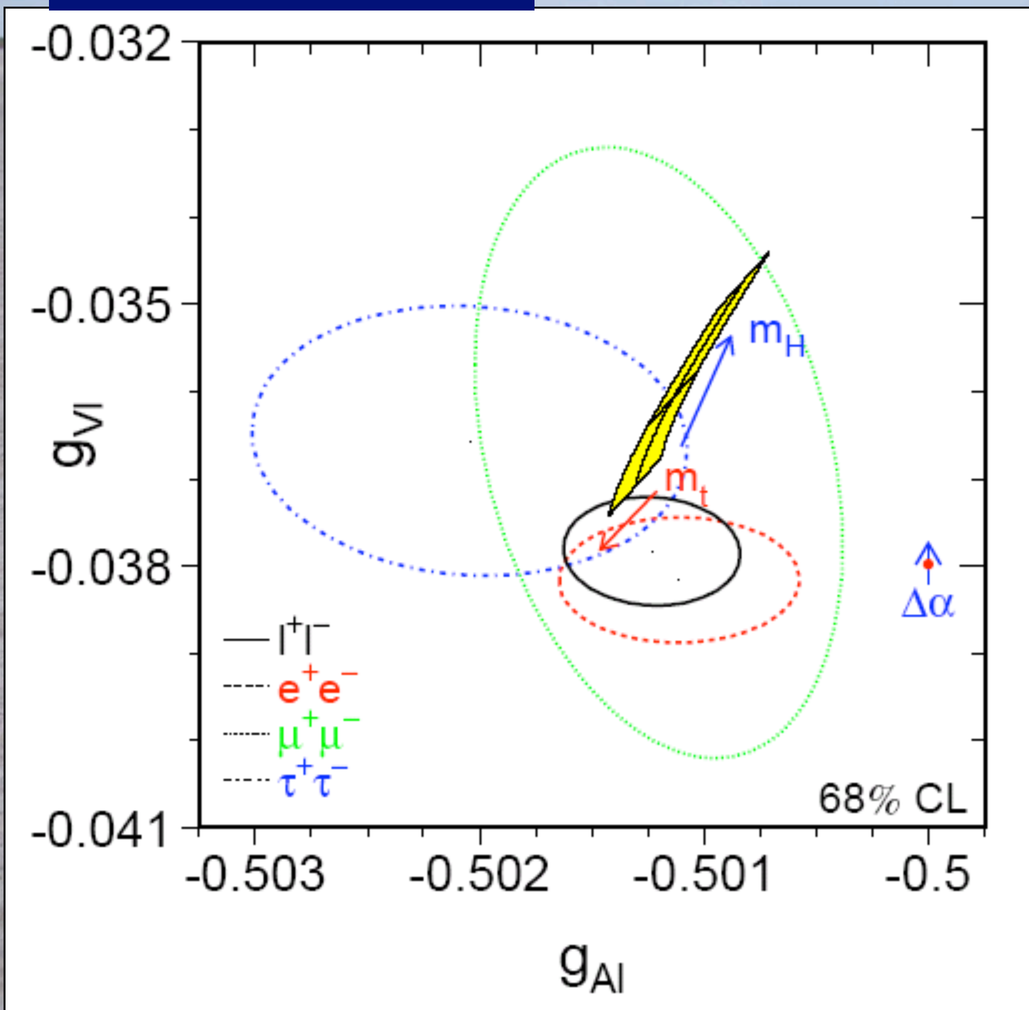
Status of the Standard Model

- Perfect agreement with all *confirmed* accelerator data
- Consistency with precision electroweak data (LEP et al) *only if there is a Higgs boson*
- Agreement seems to require *a relatively light Higgs boson* weighing < ~ 180 GeV
- Raises many unanswered questions:

mass? flavour? unification?

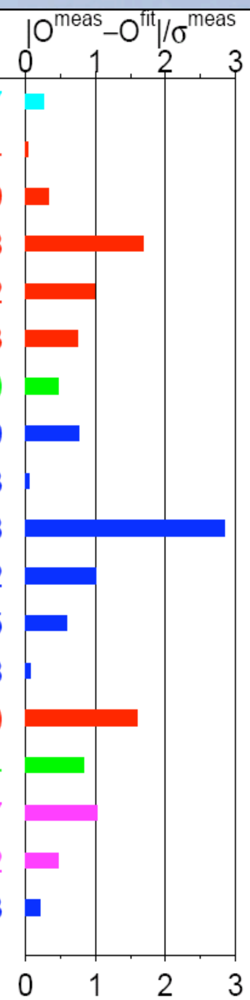
Precision Tests of the Standard Model

Lepton couplings



Pulls in global fit

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.410 ± 0.032	80.377
Γ_W [GeV]	2.123 ± 0.067	2.092
m_t [GeV]	172.7 ± 2.9	173.3



Parameters of the Standard Model

- Gauge sector:
  - 3 gauge couplings: g_3, g_2, g'
  - 1 strong CP-violating phase
- Yukawa interactions:
  - 3 charge-lepton masses
  - 6 quark masses
  - 4 CKM angles and phase
- Higgs sector:
  - 2 parameters: μ, λ
- **Total: 19 parameters**

Unification?

Flavour?

Mass?

Open Questions beyond the Standard Model

- What is the origin of particle masses?

  due to a Higgs boson? + other physics?

  solution at energy < 1 TeV (1000 GeV)

  Susy

- Why so many types of matter particles?

  matter-antimatter difference?

- Unification of the fundamental forces?

  at very high energy ~ 10^{16} GeV?

  probe directly via neutrino physics, indirectly via masses, couplings

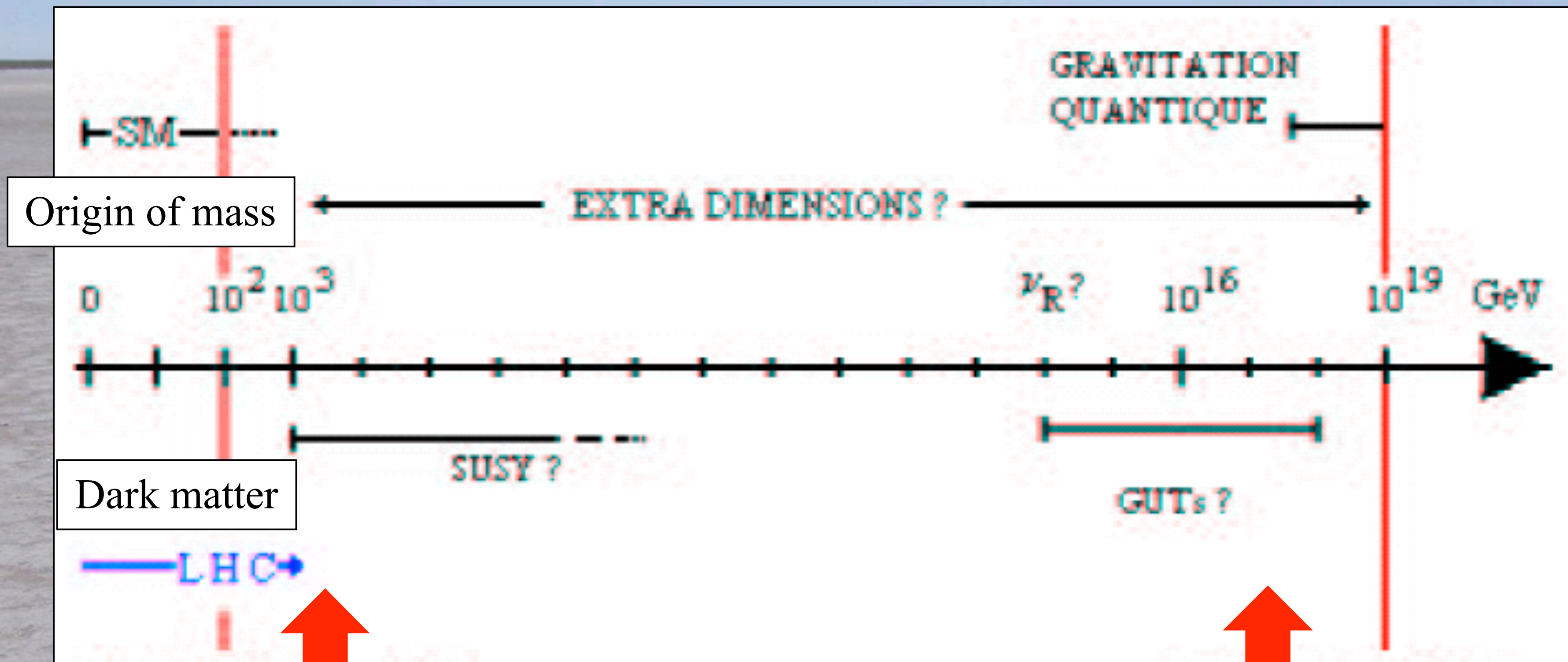
  Susy

- Quantum theory of gravity?

  (super)string theory: extra space-time dimensions?

  Susy

At what Energy is the New Physics?



A lot accessible to the LHC

Some accessible only indirectly: Astrophysics & cosmology?

Why do Things Weigh?

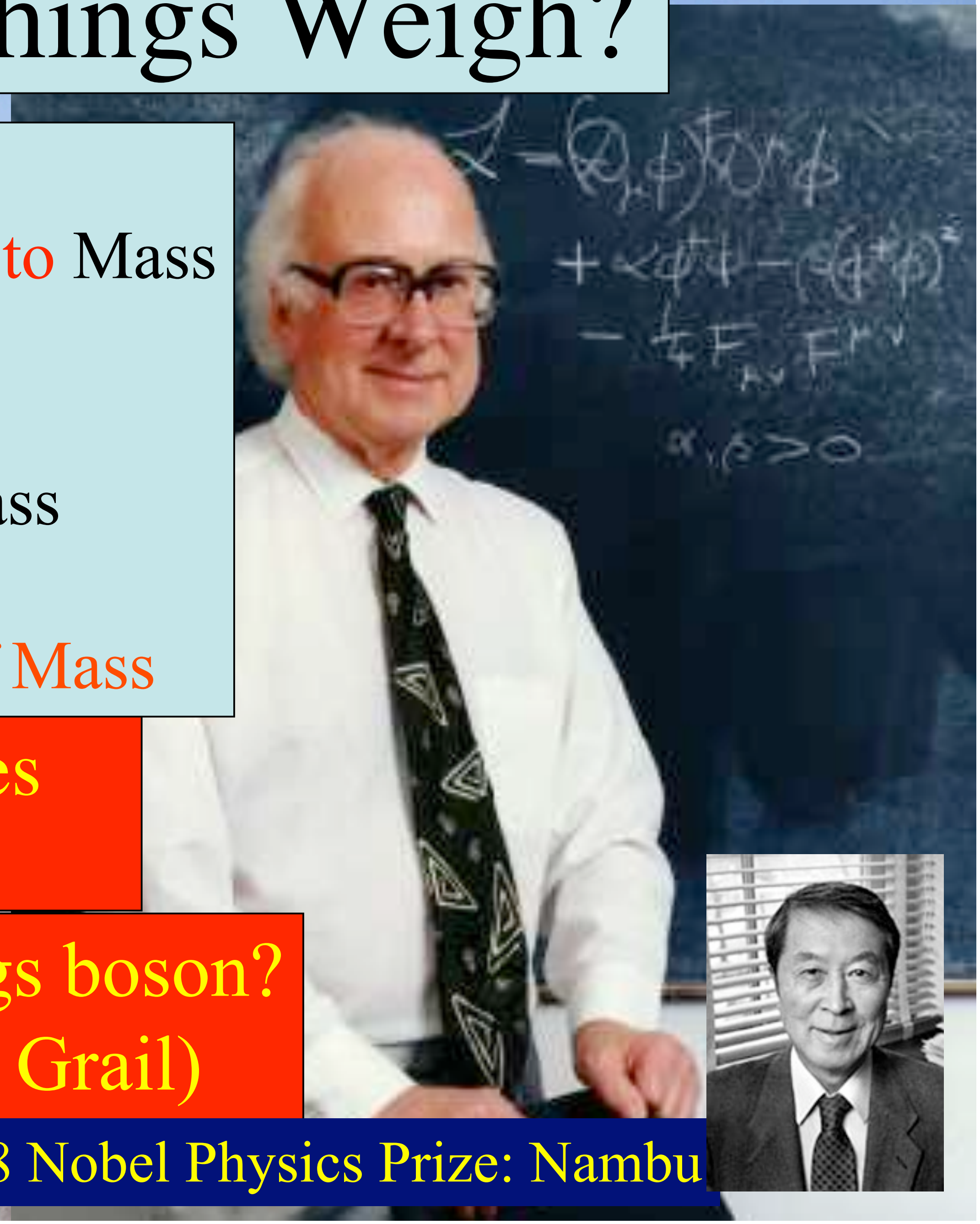
Newton:

Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass

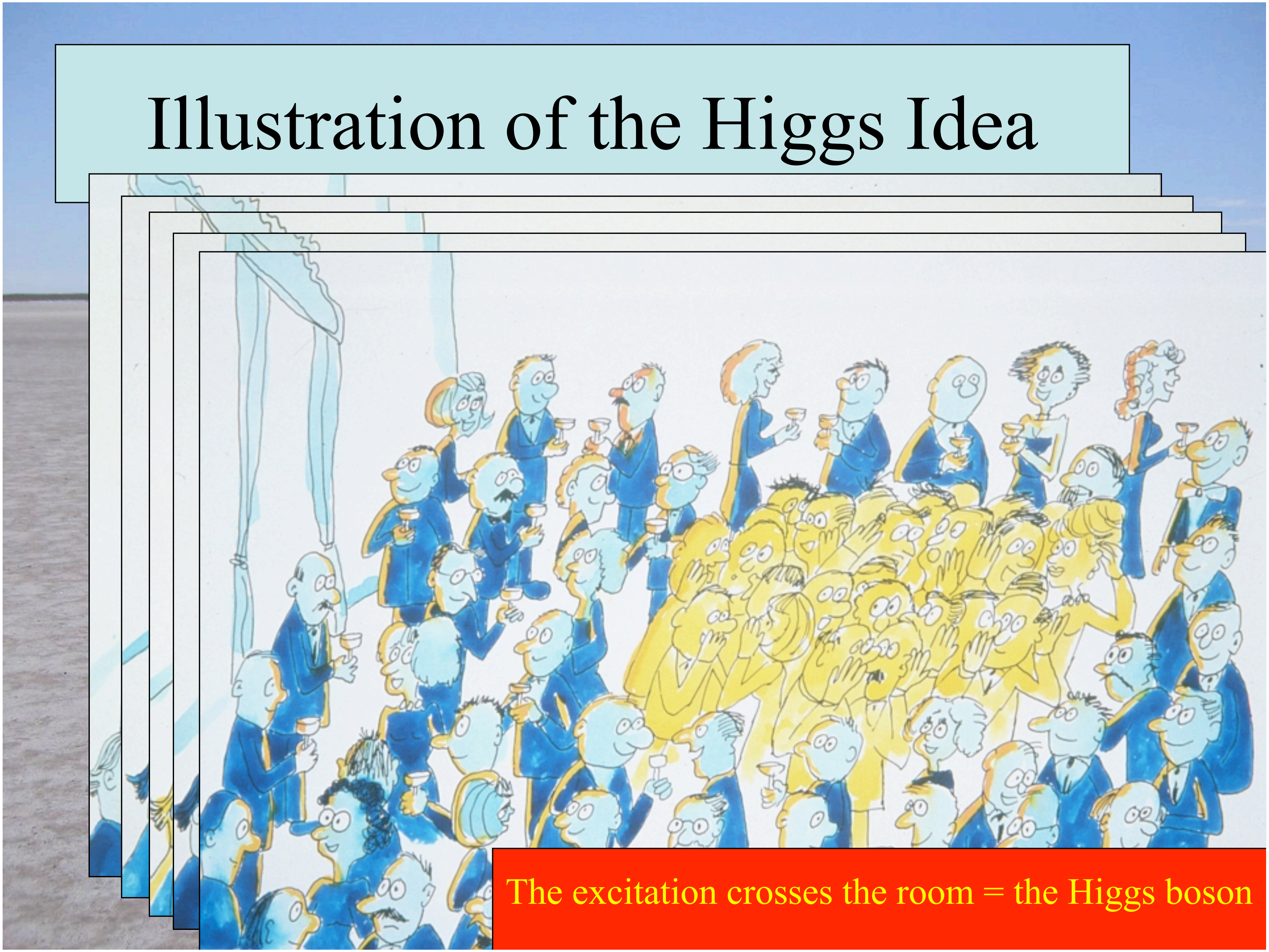


Where do the masses come from?

Are masses due to Higgs boson?
(the physicists' Holy Grail)

2008 Nobel Physics Prize: Nambu

Illustration of the Higgs Idea



The excitation crosses the room = the Higgs boson

Think of a Snowfield

Skier moves fast:
Like particle without mass
e.g., photon = particle of light

Snowshoer sinks into snow,
moves slower:
Like particle with mass
e.g., electron

The LHC will look for the snowflake: The Higgs Boson

Hiker sinks deep,
moves very slowly:
Particle with large mass

The Higgs Mechanism

- Postulated effective Higgs potential:

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

- Minimum energy at non-zero value:

$$\phi_0 =< 0|\phi|0 >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ +v \end{pmatrix} \quad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

- Non-zero masses: $M_f = y_f \frac{v}{\sqrt{2}} \quad M_W = \frac{g\,v}{2}$
- Components of Higgs field: $\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma(x))e^{i\pi(x)}$
- π massless, σ massive: $m_H^2 = 2\mu^2 = 2\lambda v$

Masses for Gauge Bosons

- Kinetic terms for SU(2) and U(1) gauge bosons:

$$\mathcal{L} = -\frac{1}{4}\, G^i_{\mu\nu} G^{i\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

where $G^i_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + i g \epsilon_{ijk} W^j_\mu W^k_\nu$ $F_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu$

- Kinetic term for Higgs field:

$$\mathcal{L}_\phi = -|D_\mu \phi|^2 \quad D_\mu \equiv \partial_\mu - i\, g\, \sigma_i\, W^i_\mu - i\, g'\, Y\, B_\mu$$

- Expanding around vacuum: $\phi =< 0|\phi|0 > + \hat{\phi}$

$$\mathcal{L}_\phi \ni -\frac{g^2 v^2}{2}\; W^+_\mu\, W^{\mu -} - g'^2\, \frac{v^2}{2}\, B_\mu\, B^\mu + g\, g' v^2\, B_\mu\, W^{\mu 3} - g^2\, \frac{v^2}{2}\, W^3_\mu\, W^{\mu 3}$$

- Boson masses:

$$m_{W^\pm} = \frac{g v}{2}$$

$$Z_\mu = \frac{g W^3_\mu - g' B_\mu}{\sqrt{g^2 + g'^2}} \;:\; m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v \;;\quad A_\mu = \frac{g' W^3_\mu + g B_\mu}{\sqrt{g^2 + g'^2}} \;:\; m_A = 0$$

Constraints on Higgs Mass

- Electroweak observables sensitive via quantum loop corrections:

$$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}\mathrm{G}_F}(1+\Delta r)$$

- Sensitivity to top, Higgs masses:

$$\frac{3\mathrm{G}_F}{8\pi^2\sqrt{2}}m_t^2 \qquad \frac{\sqrt{2}\mathrm{G}_F}{16\pi^2}m_W^2\left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2}+\ldots\right),\ M_H >> m_W$$

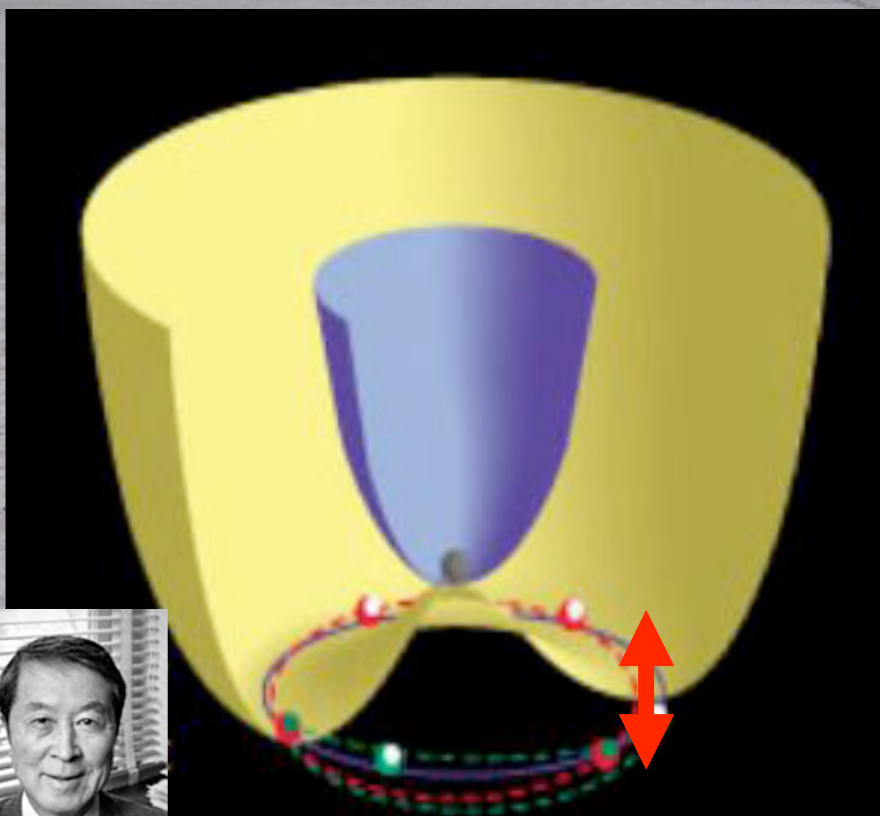
- Preferred Higgs mass: **$m_H \sim 80 \pm 30$ GeV**
- Compare with lower limit from direct searches:

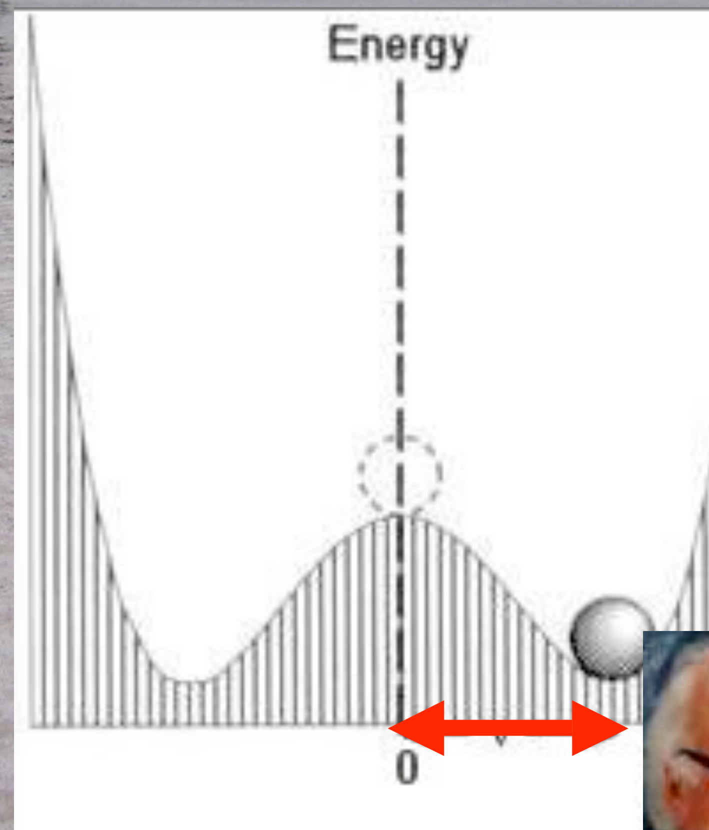
$m_H > 114$ GeV

- No conflict!

Nambu and Higgs

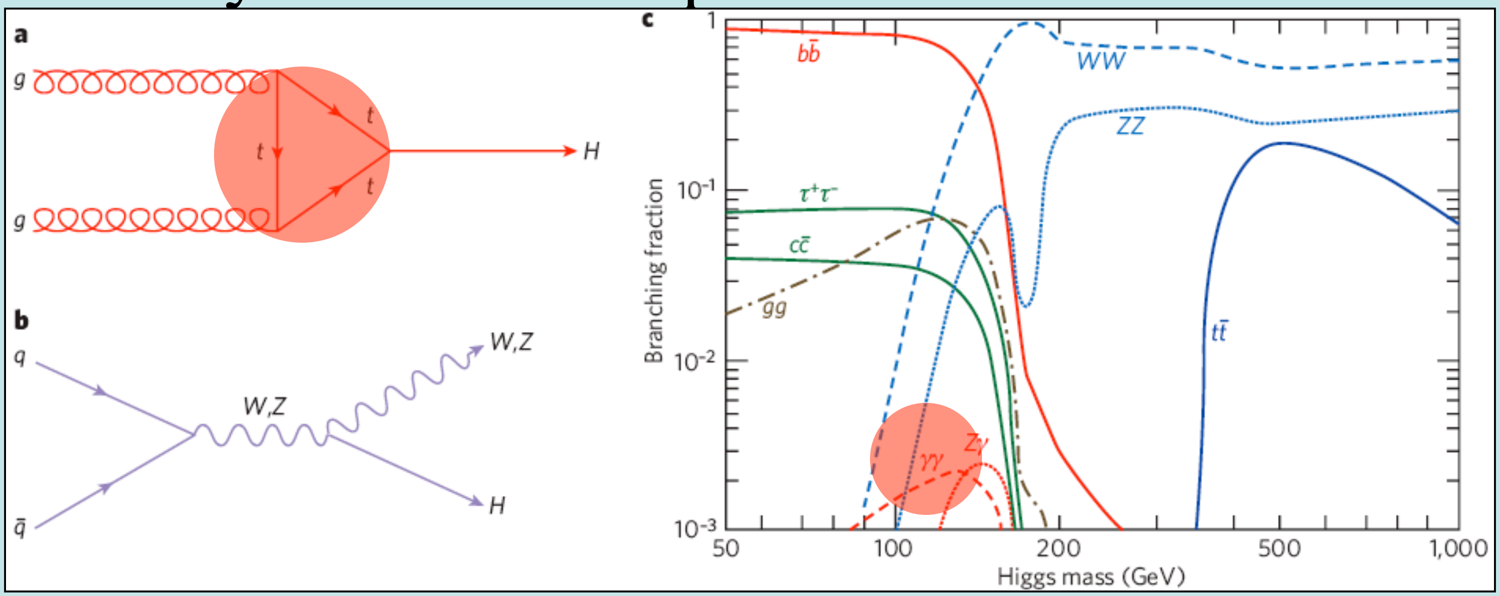
Spontaneous breaking of symmetry





Higgs Decay Branching Ratios

- Couplings proportional to mass:
  - Decays into heavier particles favoured

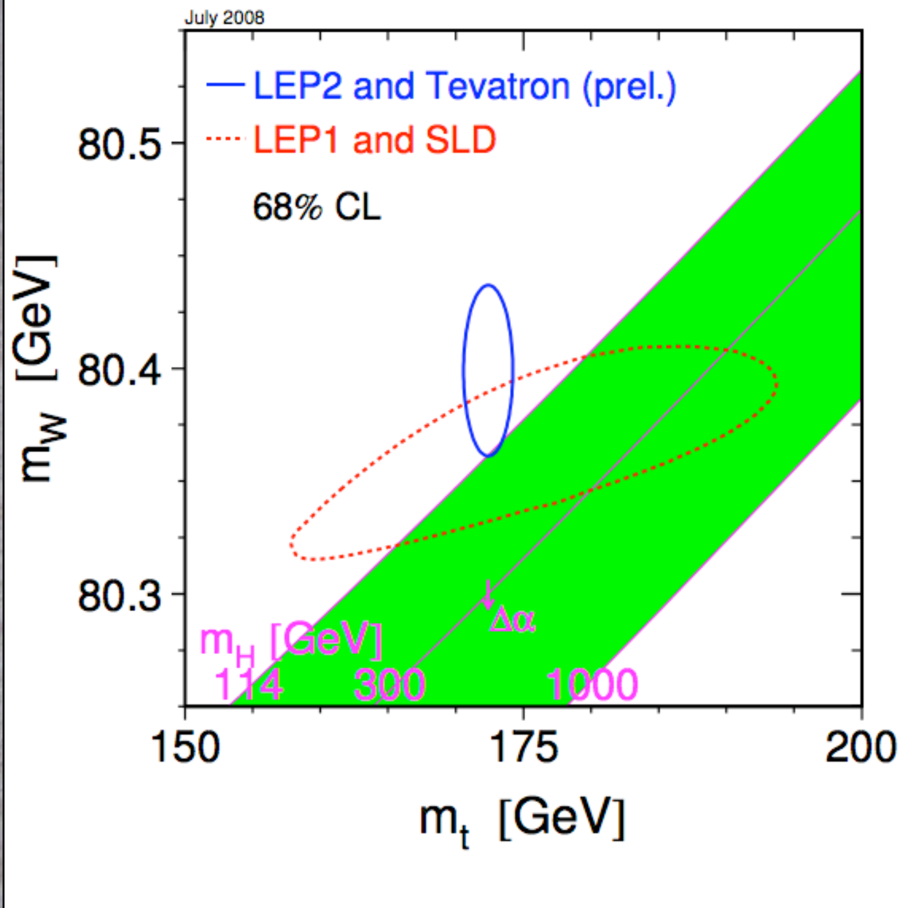


- But: important couplings through loops:
  - gluon + gluon → Higgs → γγ

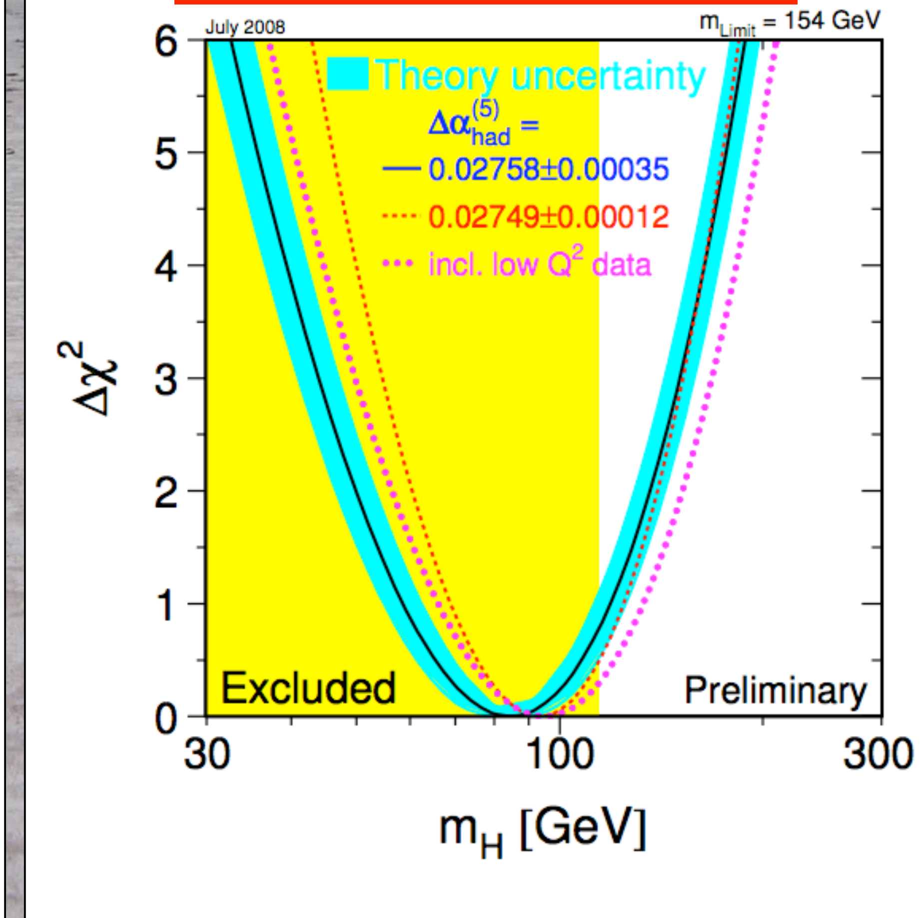
Summer 2008

Indications on the Higgs Mass

Sample observable:
W mass @ LEP & Tevatron



Combined information
on Higgs mass



The State of the Higgs: August 2009

- Direct search limit from LEP:

  $m_H > 114.4$ GeV

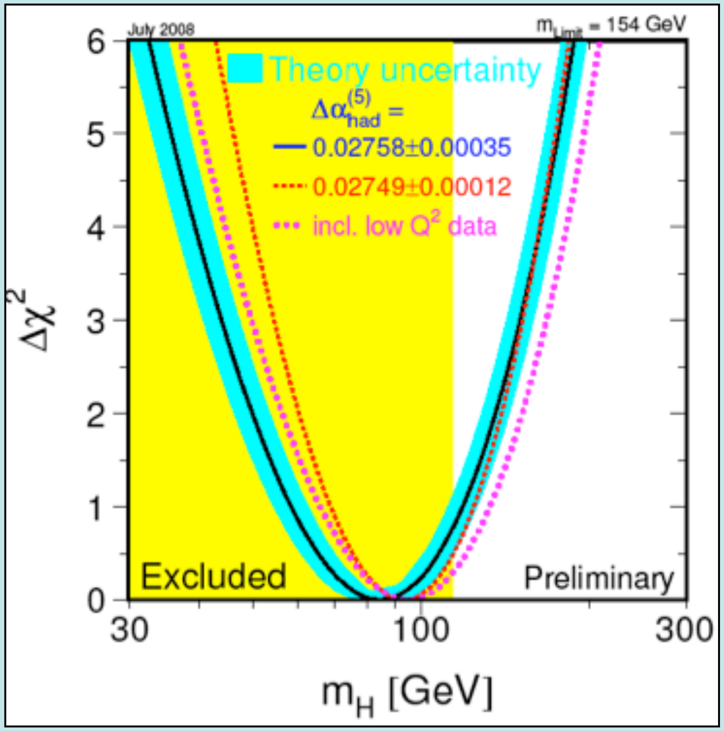
- Electroweak fit sensitive to m_t

  (Now $m_t = 173.1 \pm 1.3$ GeV)

- Best-fit value for Higgs mass:

  $m_H = 84^{+34}_{-26}$ GeV

- 95% confidence-level upper limit:

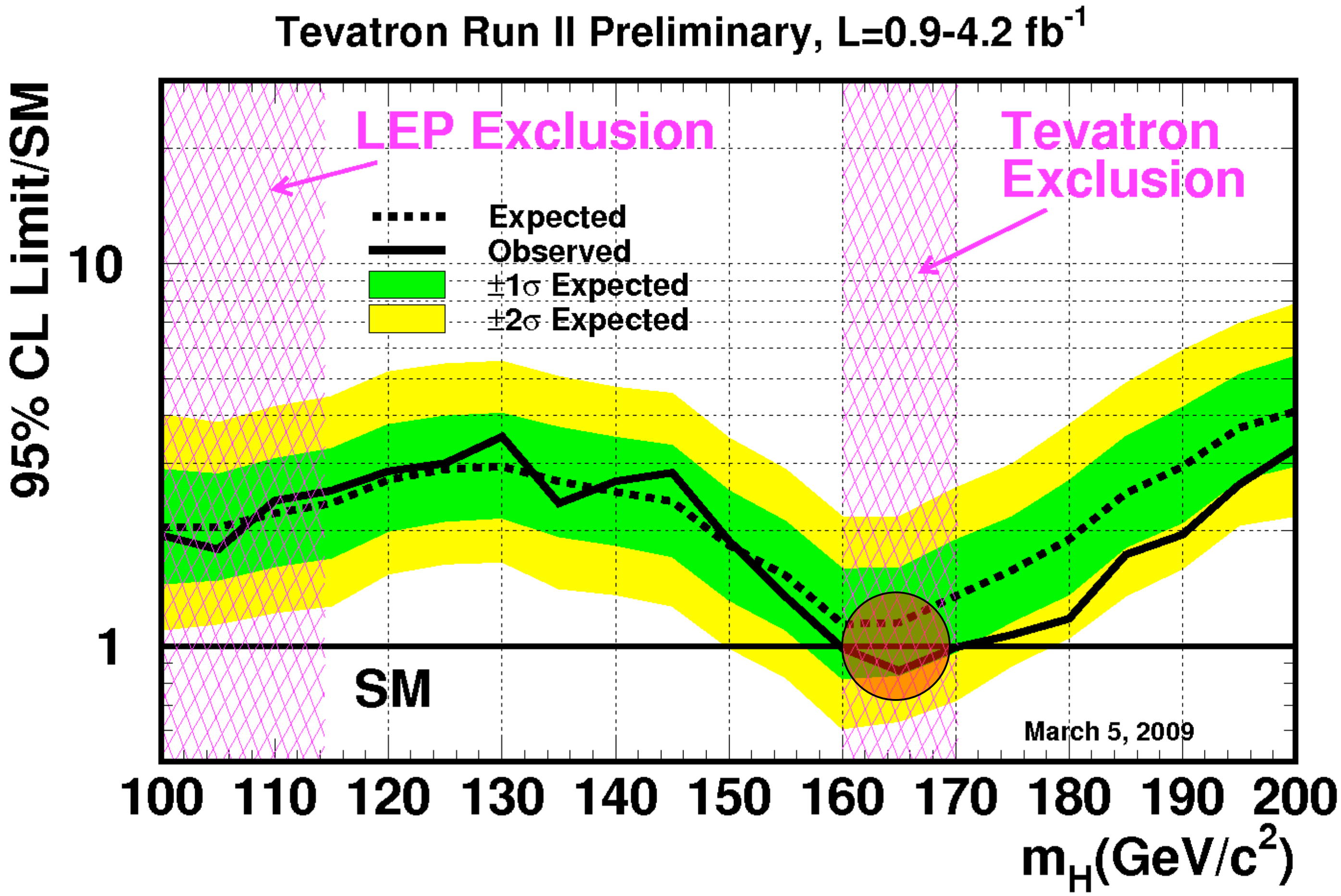


  $m_H < 154$ GeV, or 185 GeV including direct limit

- Tevatron exclusion:

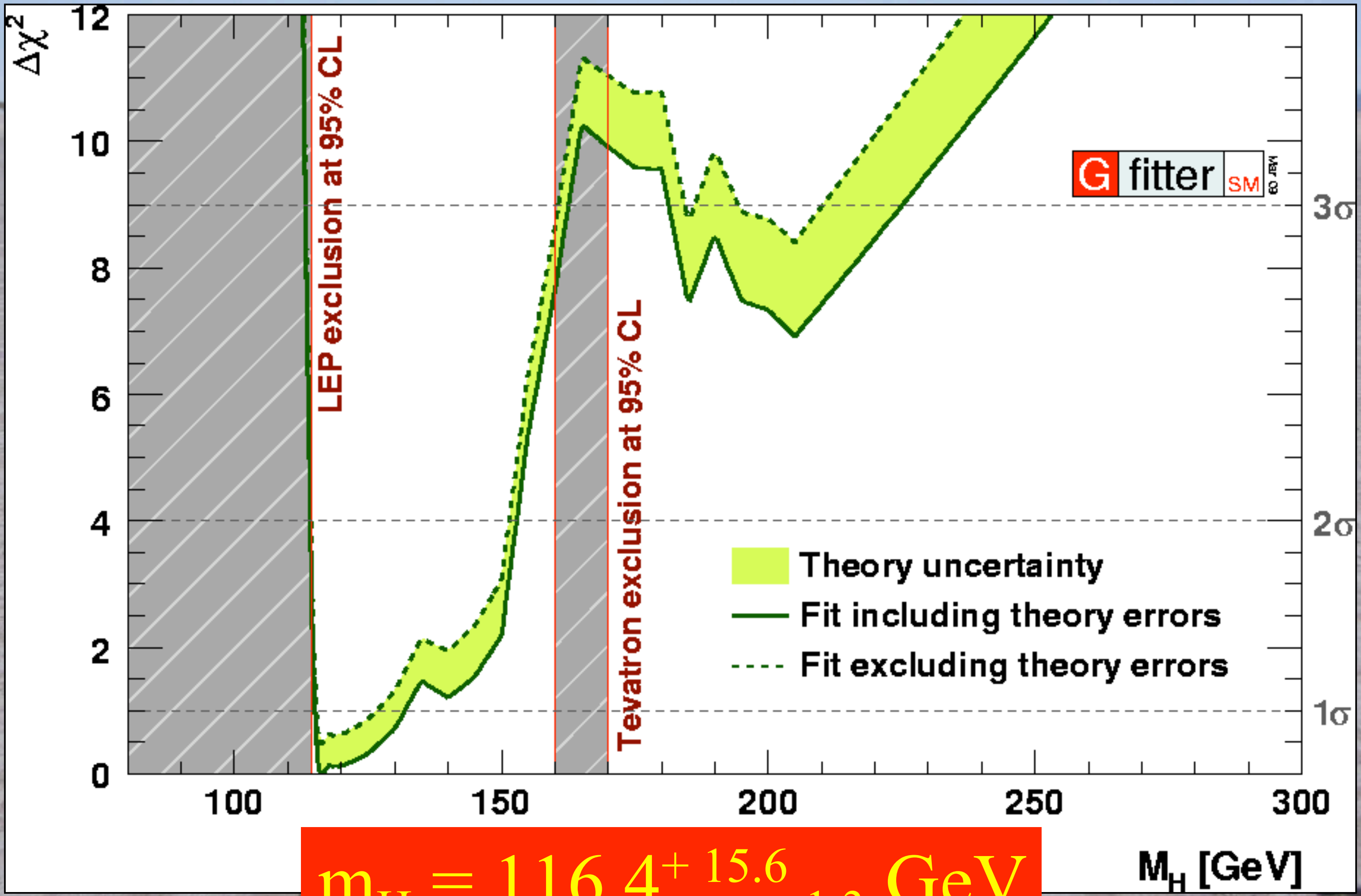
  $m_H < 160$ GeV or > 170 GeV

Higgs Search @ Tevatron



Tevatron excludes Higgs between 160 & 170 GeV

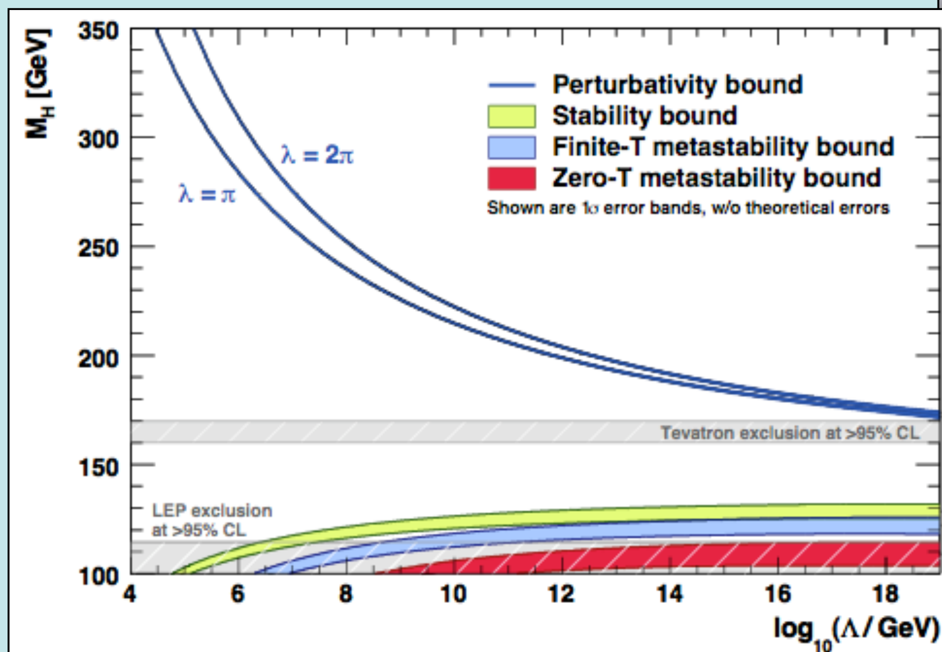
Combining the Higgs Information



$m_H = 116.4^{+15.6}_{-1.3}$ GeV

Theoretical Constraints on Higgs Mass

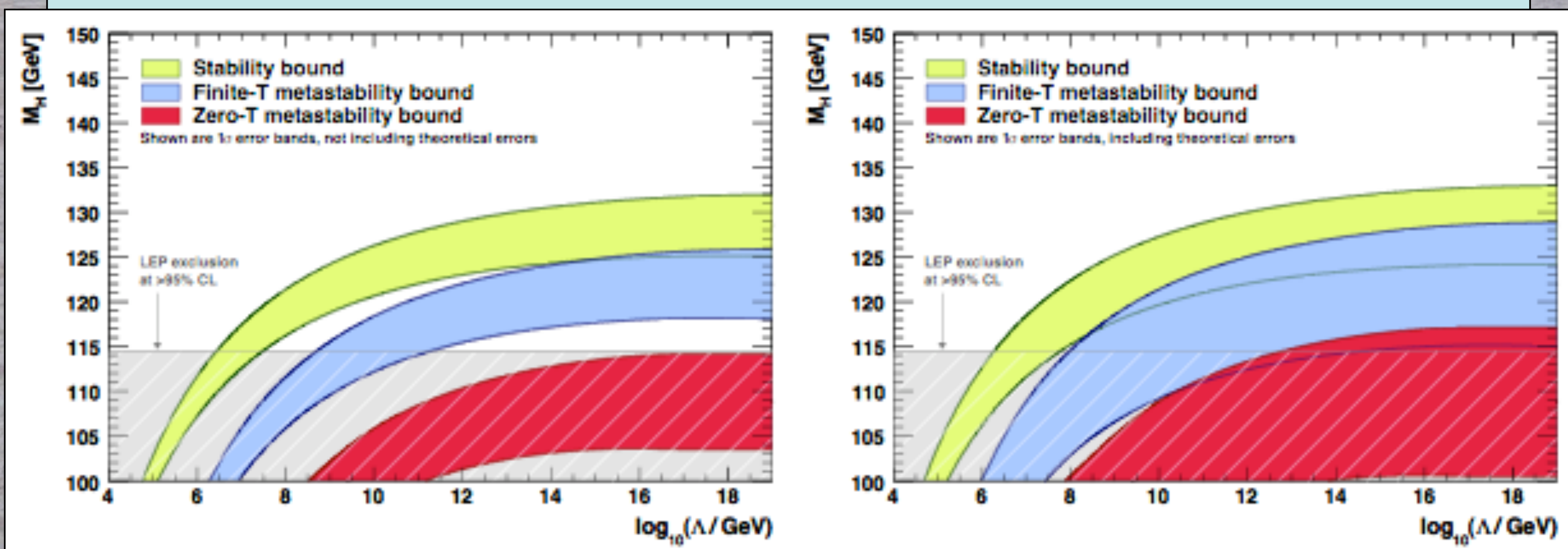
- Large → large self-coupling → blow up at low energy scale Λ due to renormalization
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable



- Bounds on Higgs mass depend on Λ

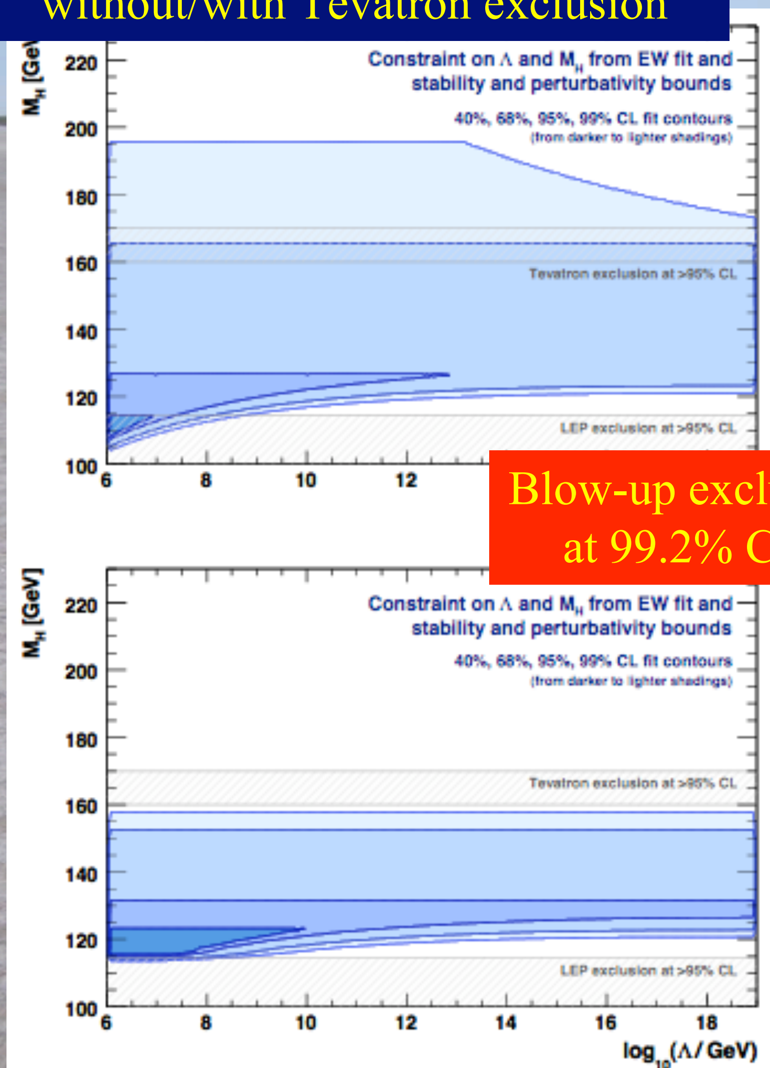
Vacuum Stability vs Metastability

- Dependence on scale up to which Standard Model remains
  - **Stable**
  - **Metastable at non-zero temperature**
  - **Metastable at zero temperature**



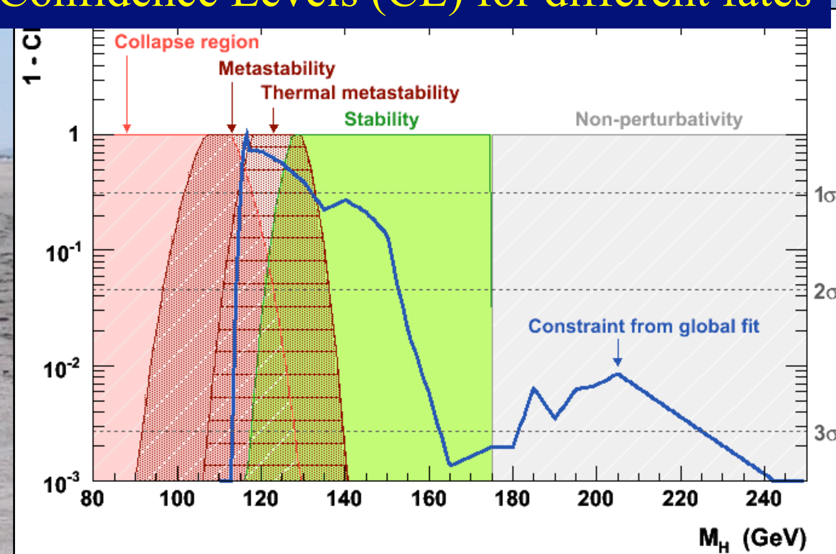
What is the probable fate of the SM?

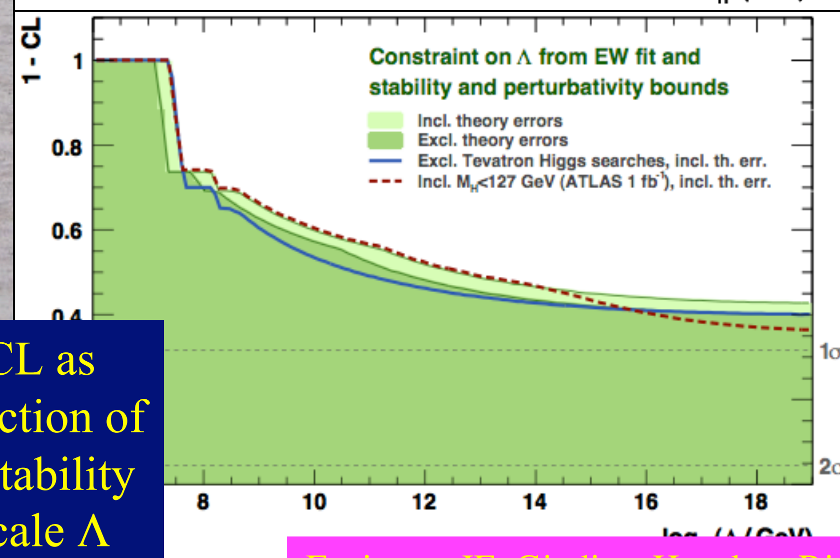
Confidence Levels (CL) without/with Tevatron exclusion



Blow-up excluded at 99.2% CL

Confidence Levels (CL) for different fates



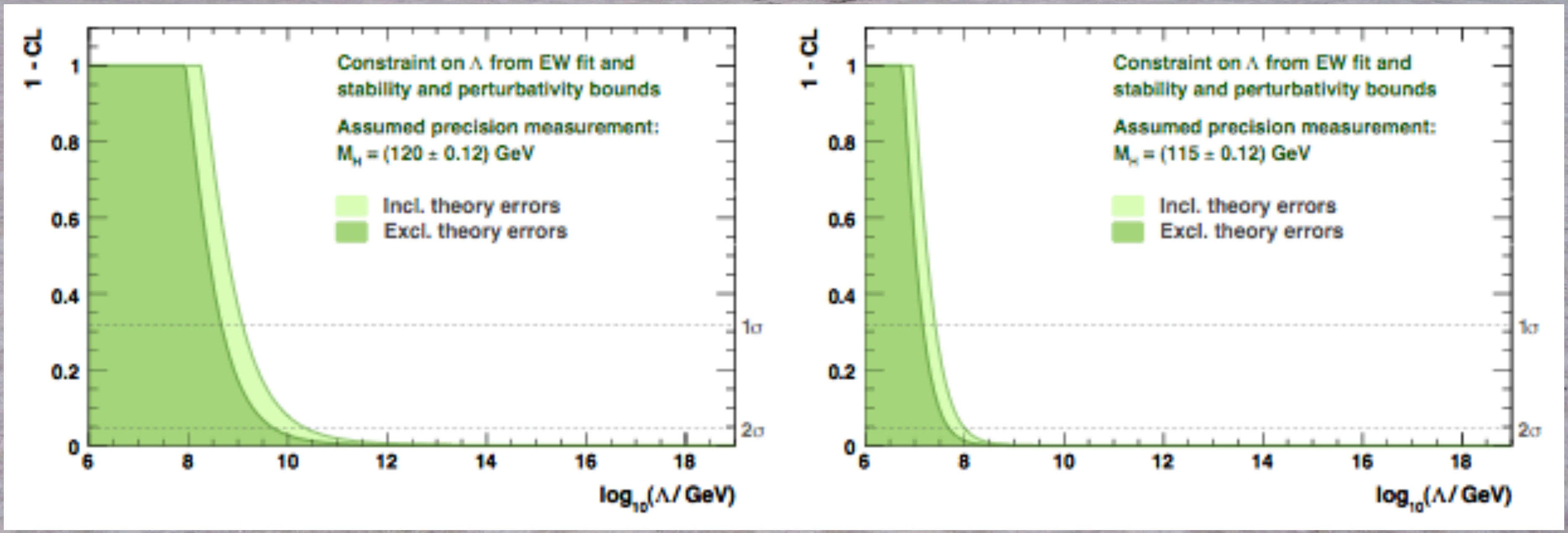


CL as function of instability scale Λ

Espinosa, JE, Giudice, Hoecker, Riotto

The LHC will Tell the Fate of the SM

Examples with LHC measurement of m_H = 120 or 115 GeV



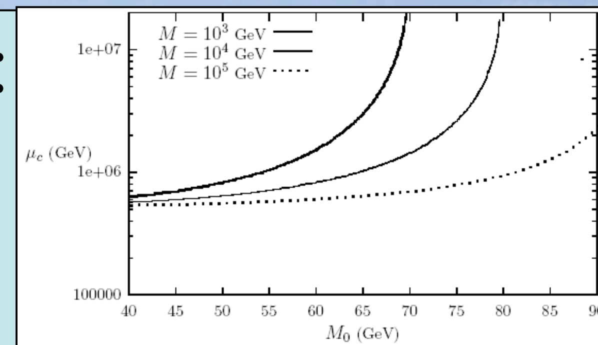
Espinosa, JE, Giudice, Hoecker, Riotto

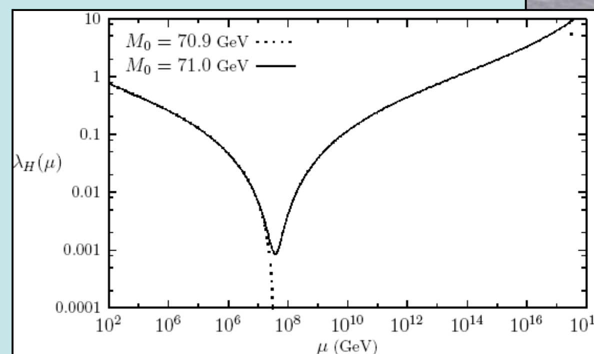
How to Stabilize a Light Higgs Boson?

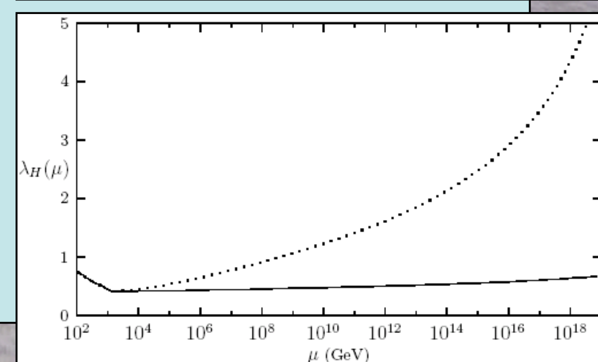
- Top quark destabilizes potential: introduce stop-like scalar:

$$\mathcal{L} \supset \; M^2|\phi|^2 + \frac{M_0}{v^2}|H|^2\,|\phi|^2$$

- Can delay collapse of potential:
- But new coupling must be fine-tuned to avoid blow-up:
- Stabilize with new fermions:
  – just like Higgsinos
- Very like **Supersymmetry!**

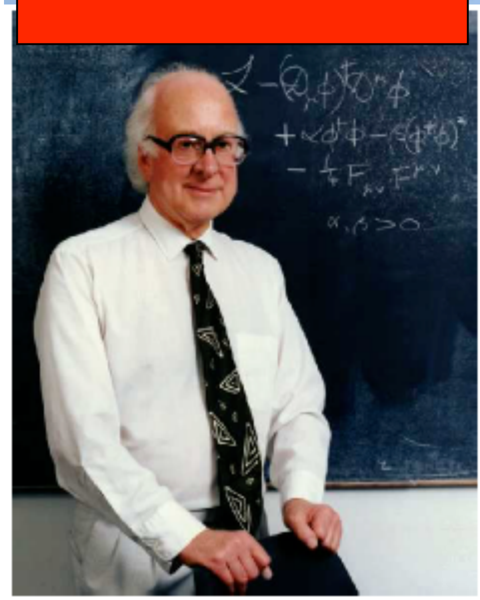




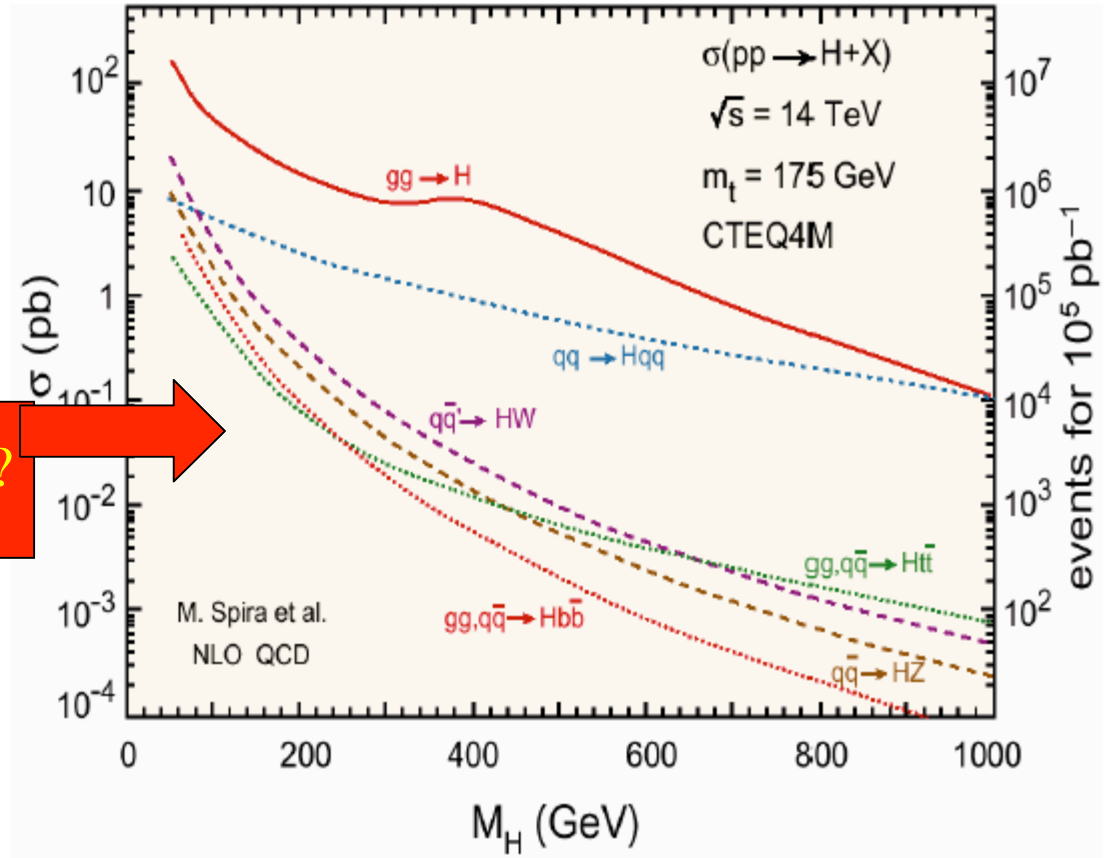


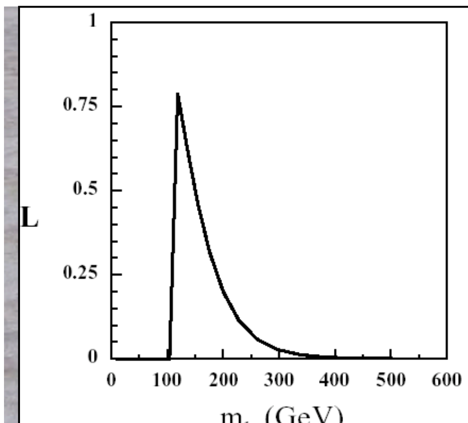
A la recherche du Higgs perdu …

Higgs Production at the LHC



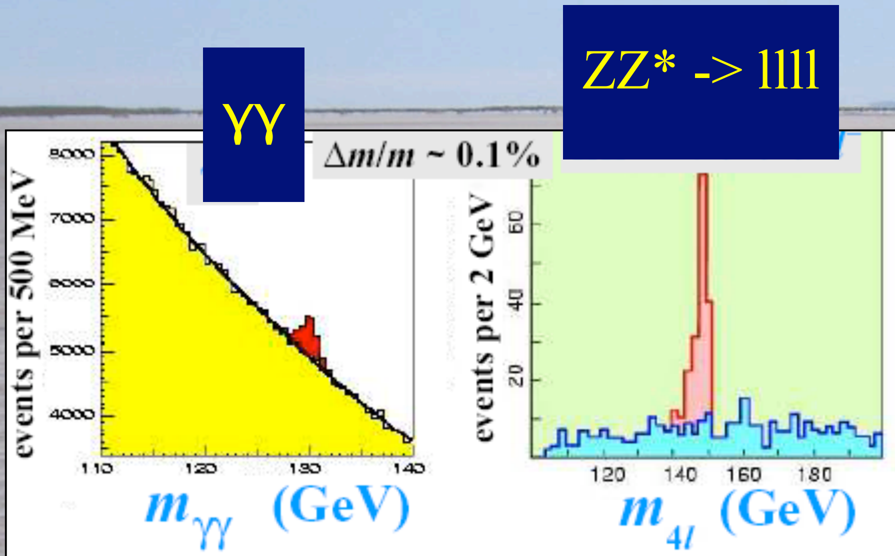
… not far away?

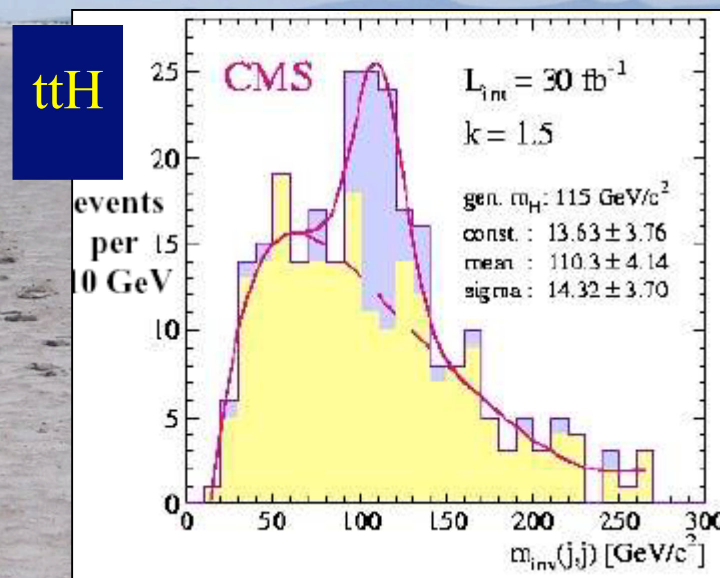


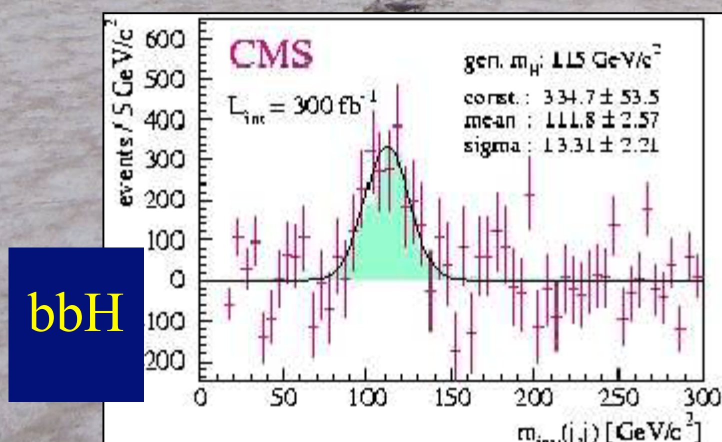


Combining direct, Indirect information

Some Sample Higgs Signals



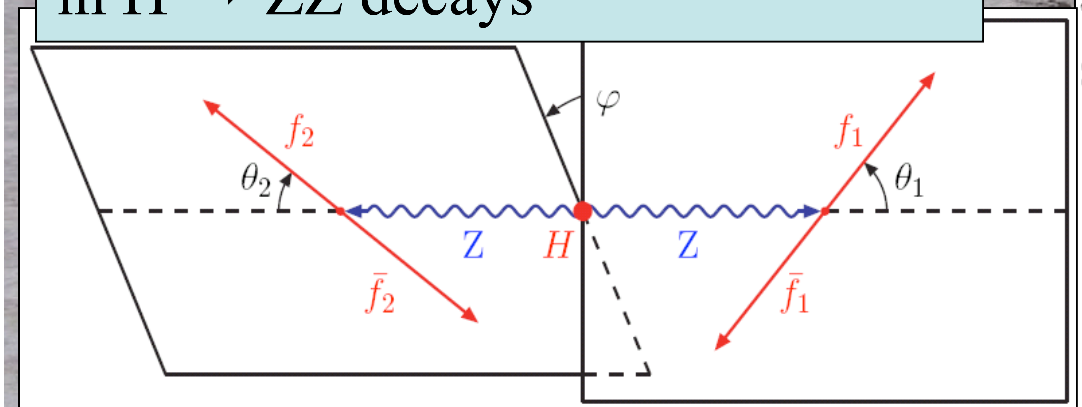


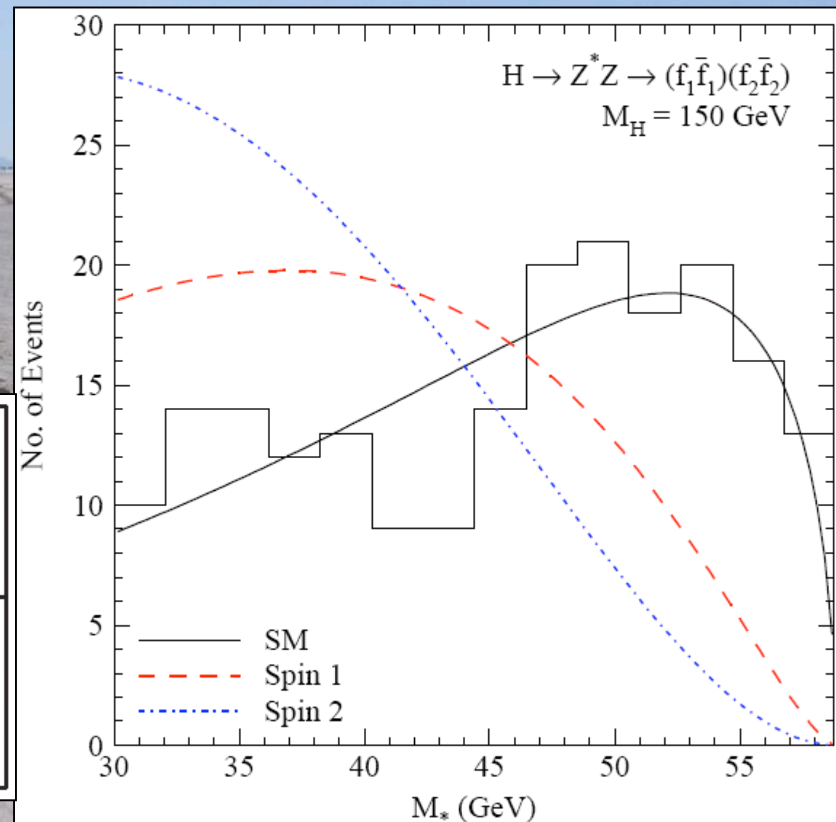


The Spin of the Higgs Boson @ LHC

Low mass: if H $\rightarrow \gamma\gamma$,
It cannot have spin 1

Higher mass: angular correlations in H $\rightarrow$ ZZ decays



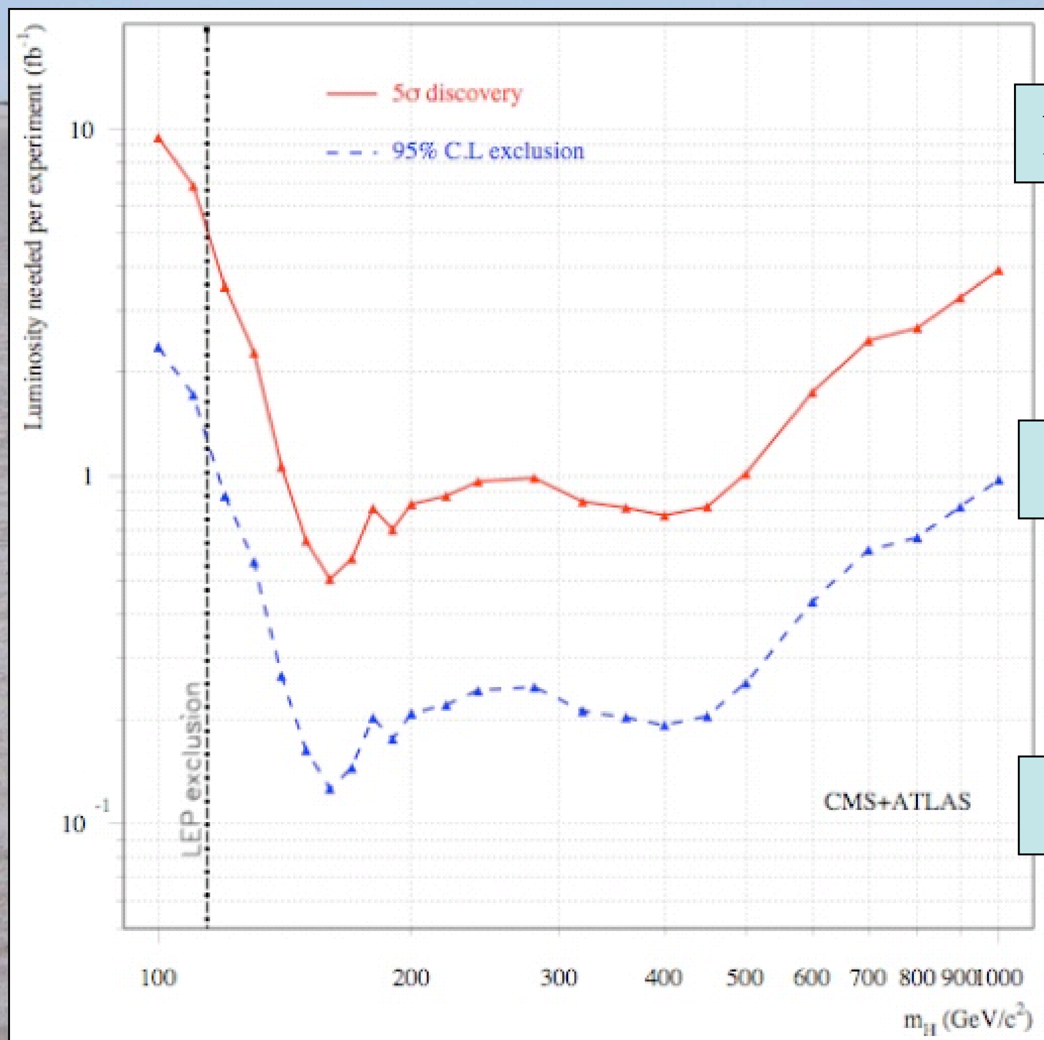


Significance for exclusion of other J^{CP} states than 0^+

ATLAS + CMS, 2 x 300 fb^{-1}

m_H (GeV)	$J^{CP} = 1^+$	$J^{CP} = 1^-$	$J^{CP}=0^-$
200	6.5 σ	4.8 σ	40 σ
250	20 σ	19 σ	80 σ
300	23 σ	22 σ	70 σ

When will the LHC discover the Higgs boson?



1 'year' @ 10^{33}

'month' @ 10^{33}

'month' @ 10^{32}

Blaising, JE et al: 2006

The Stakes in the Higgs Search

- How is gauge symmetry broken?
- Is there any elementary scalar field?
- Would have caused phase transition in the Universe when it was about 10^{-12} seconds old
- May have generated then the matter in the Universe: electroweak baryogenesis
- A related inflaton might have expanded the Universe when it was about 10^{-35} seconds old
- Contributes to today's dark energy: 10^{60} too much!

The LHC Roulette Wheel

Standard Model
Higgs boson