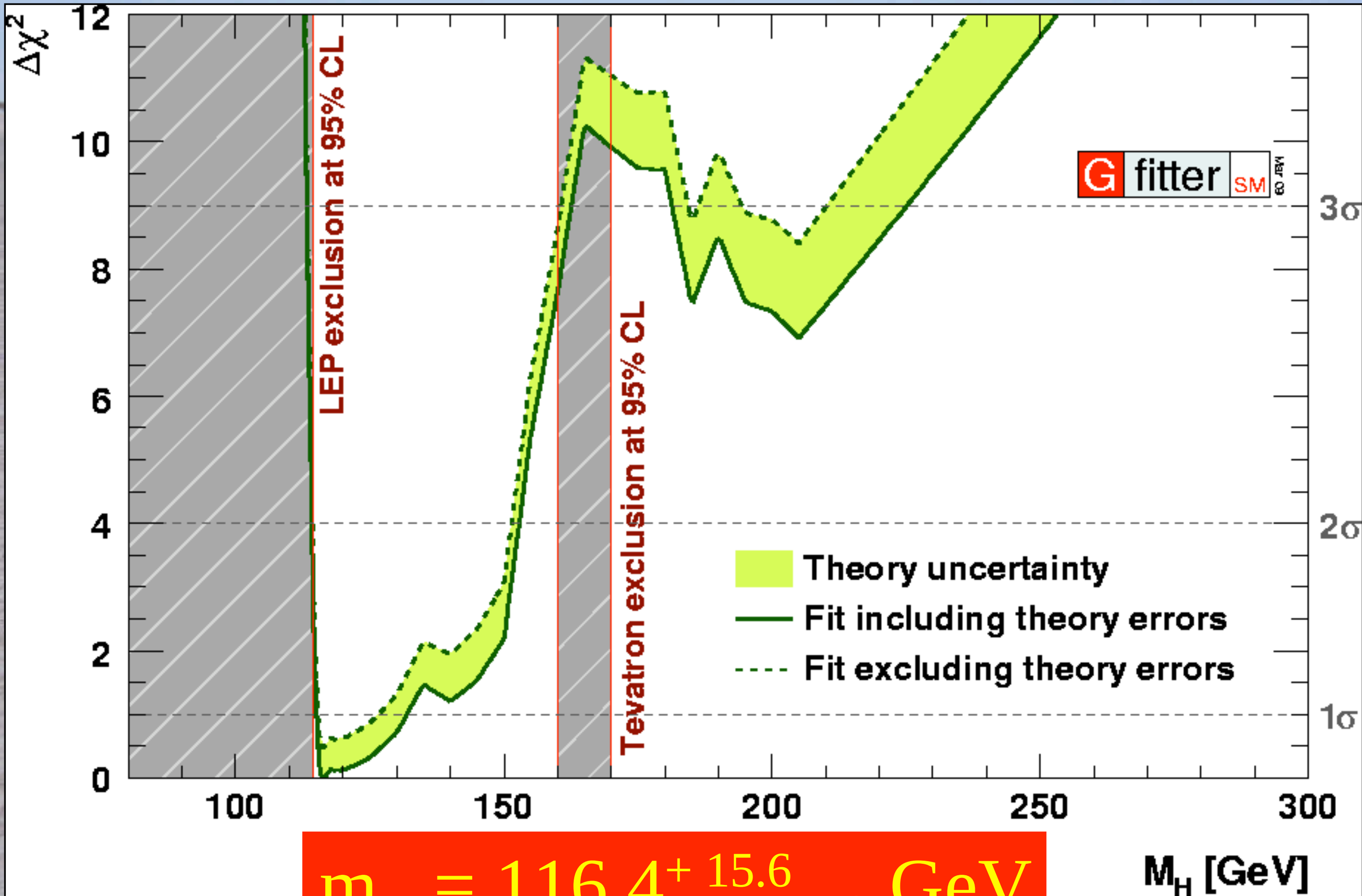
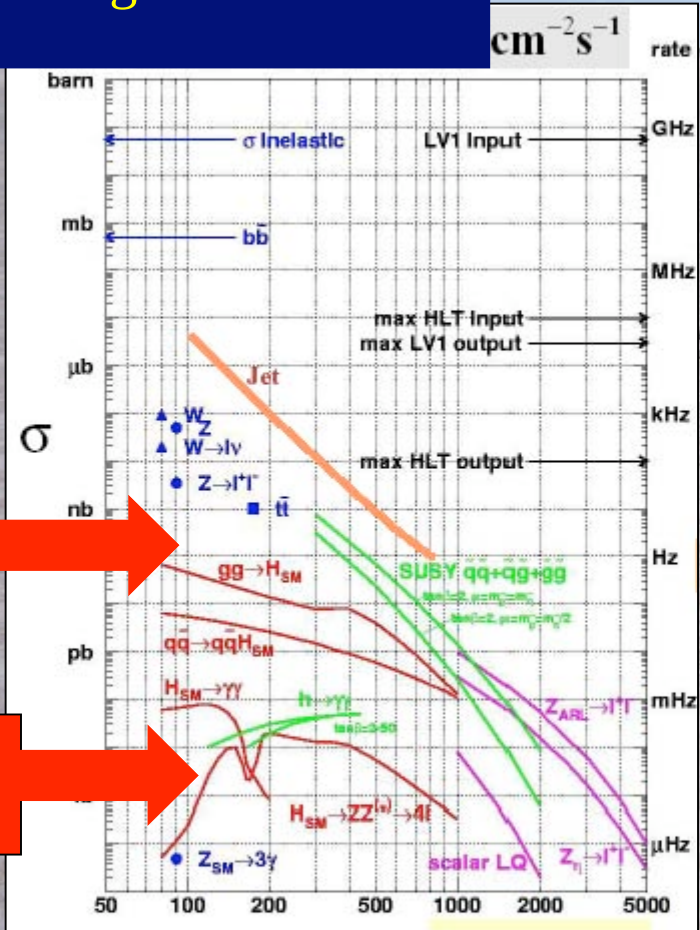
Combining the Higgs Information



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

The LHC Physics Haystack(s)

Interesting cross sections



Susy

Higgs

- Cross sections for heavy particles

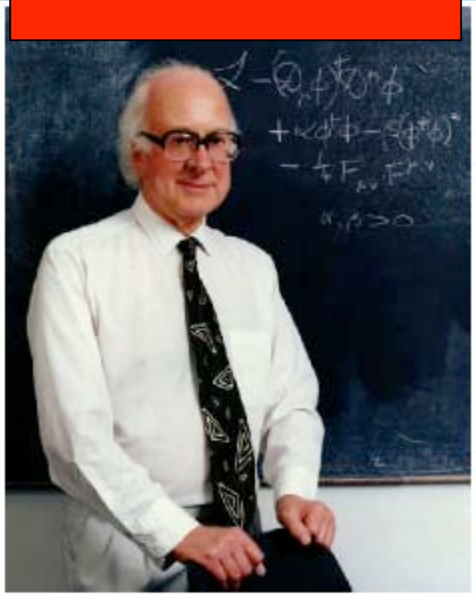
  ~ 1 /(1 TeV)^2
- Most have small couplings ~ α^2
- Compare with total cross section

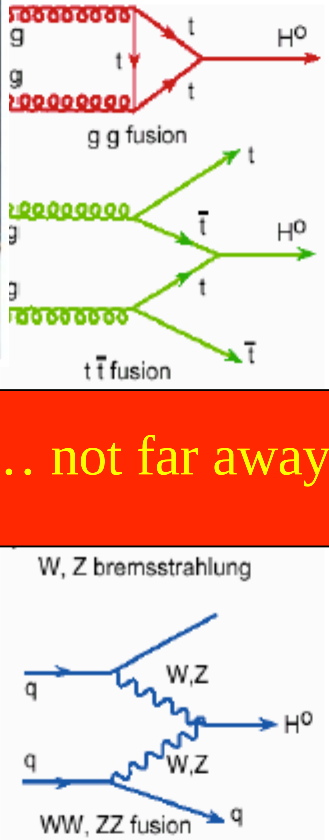
  ~ 1/(100 MeV)^2
- Fraction ~ 1/1,000,000,000,000
- Need ~ 1,000 events for signal
- Compare needle

  ~ 1/100,000,000 m^3
- Haystack ~ 100 m^3
- Must look in ~ 100,000 haystacks

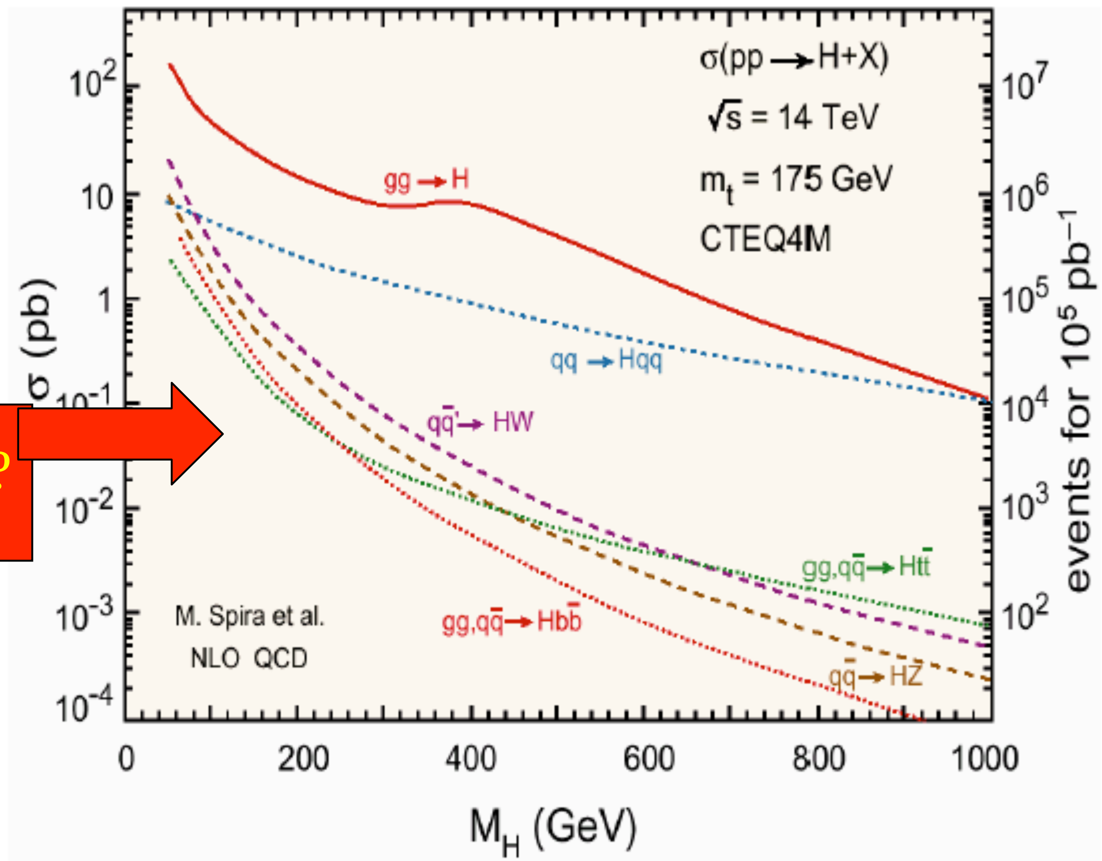
A la recherche du Higgs perdu …

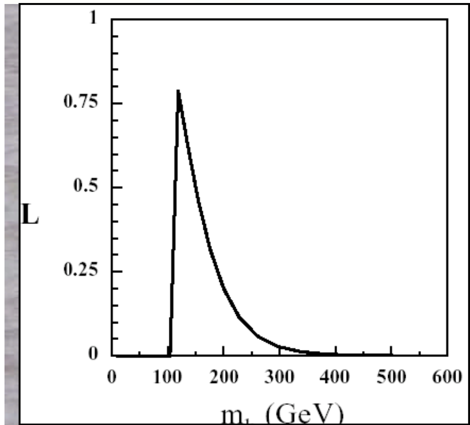
Higgs Production at the LHC





… not far away?

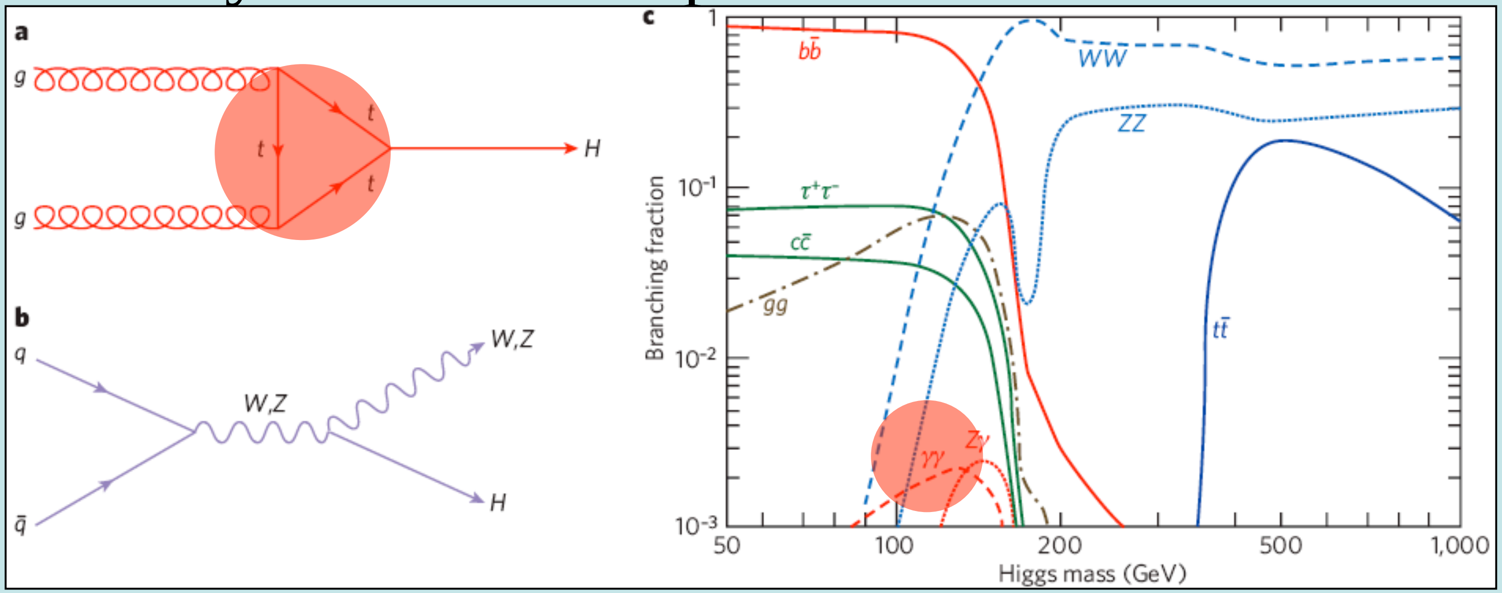




Combining direct,
Indirect information

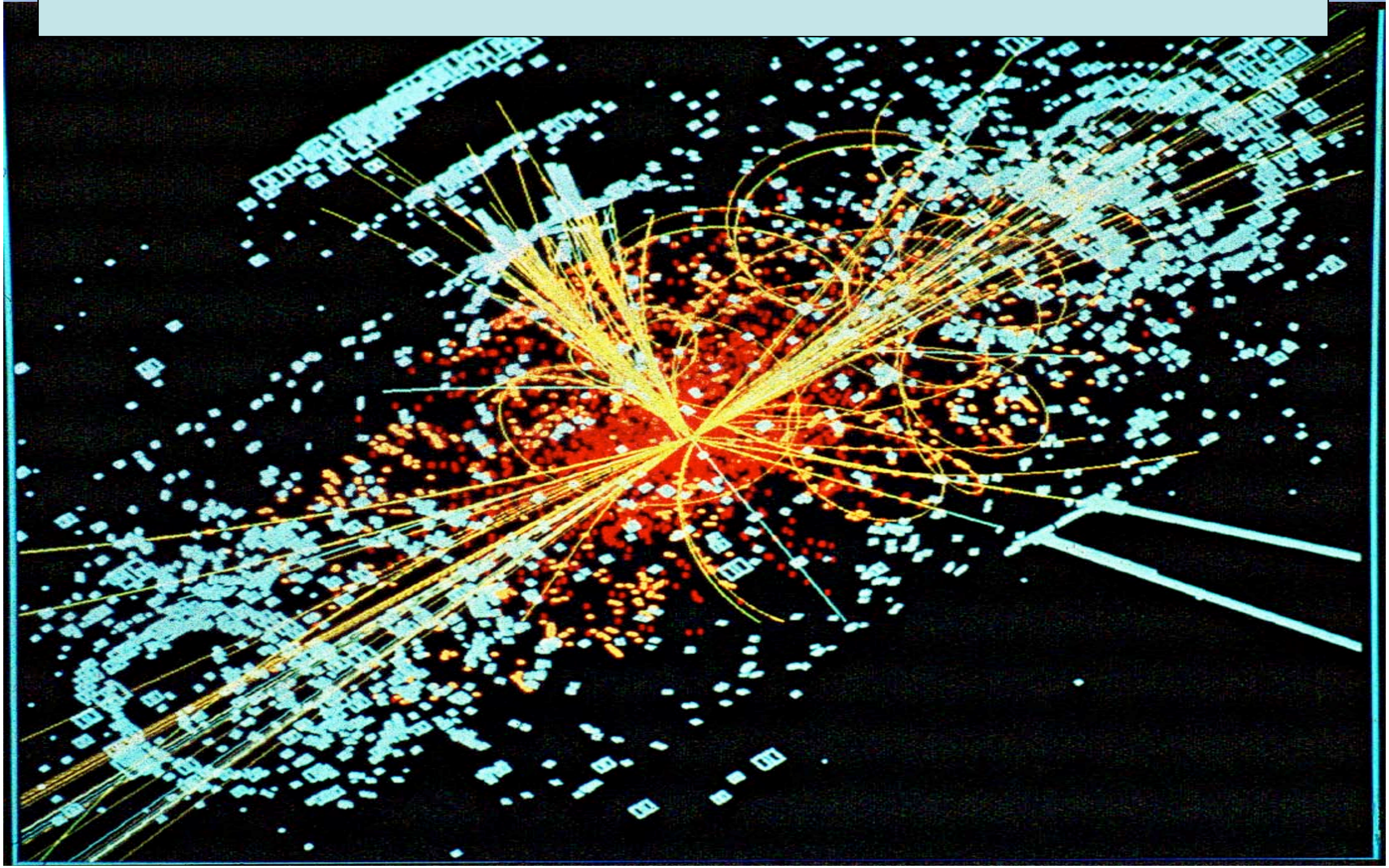
Higgs Decay Branching Ratios

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



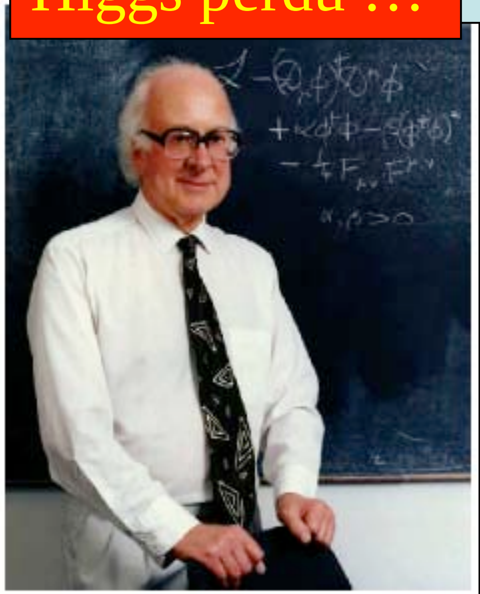
- But: important couplings through loops:
  - gluon + gluon → Higgs → γγ

A Simulated Higgs Event in CMS

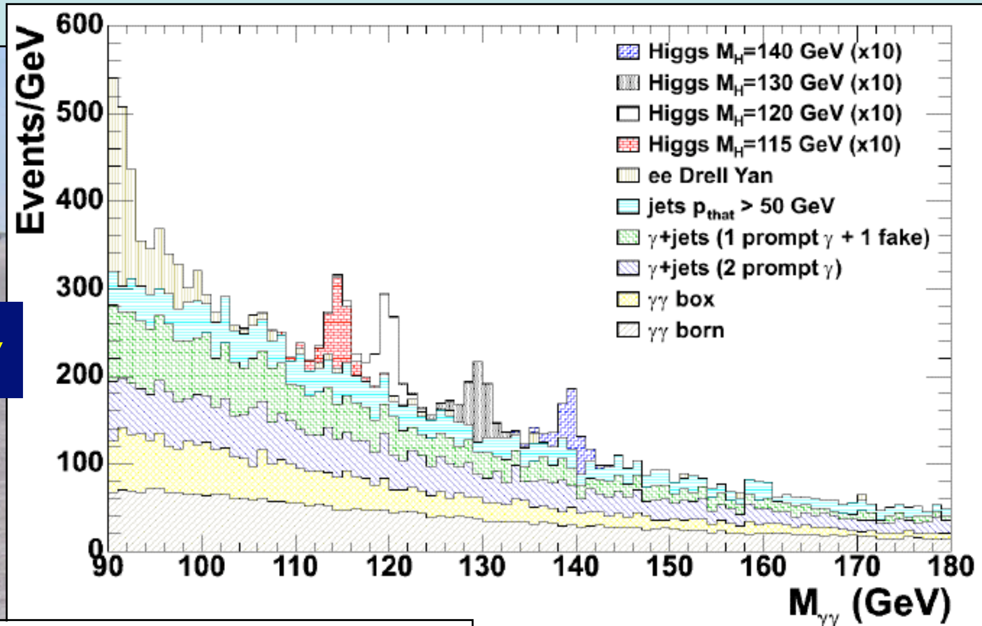


A la recherche du
Higgs perdu …

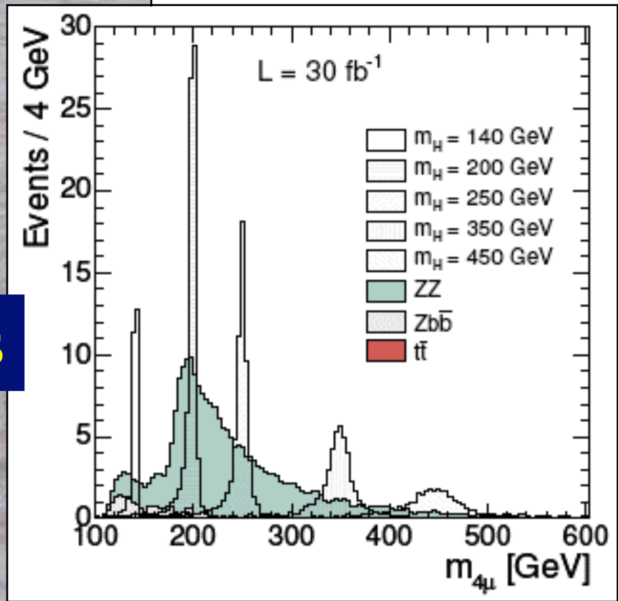
Some Sample Higgs Signals



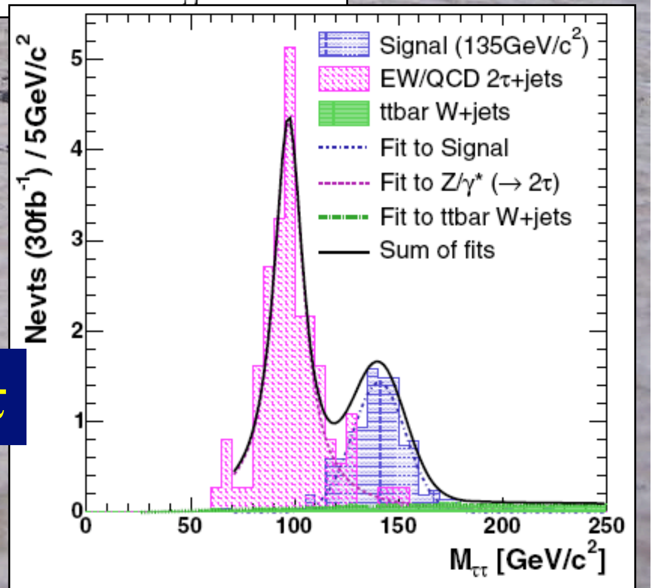
γγ



ZZ* -> 4 leptons



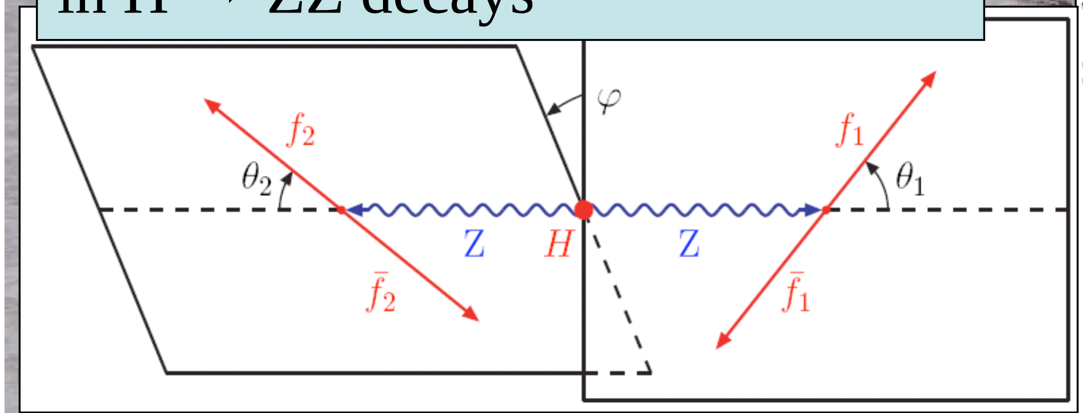
ττ

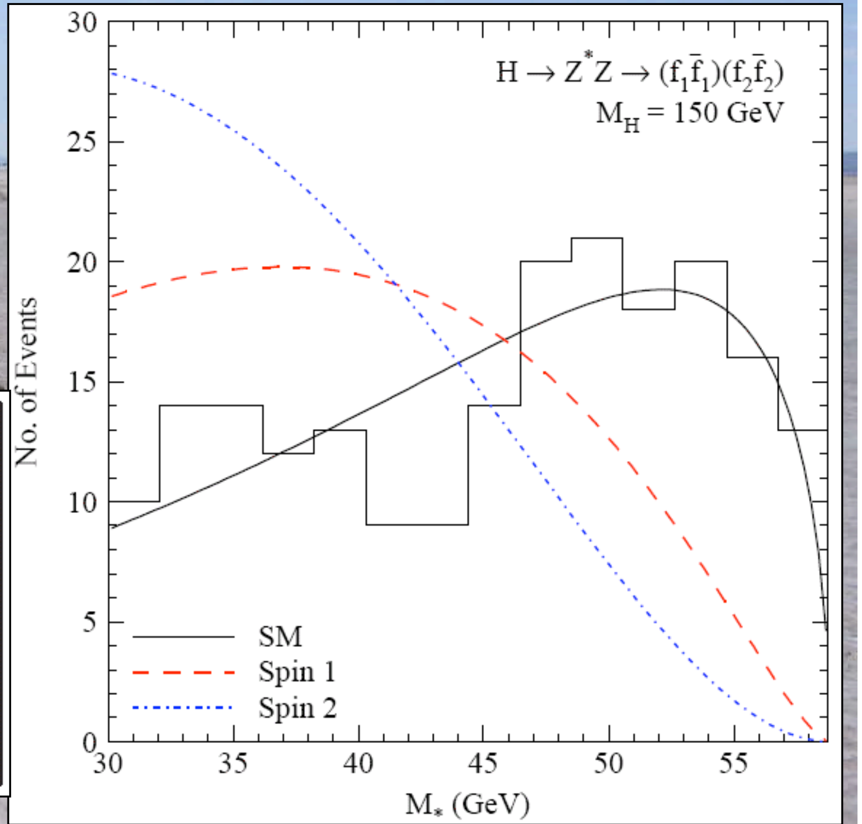


The Spin of the Higgs Boson @ LHC

Low mass: if H →γγ,
It cannot have spin 1

Higher mass: angular correlations
in H → ZZ decays



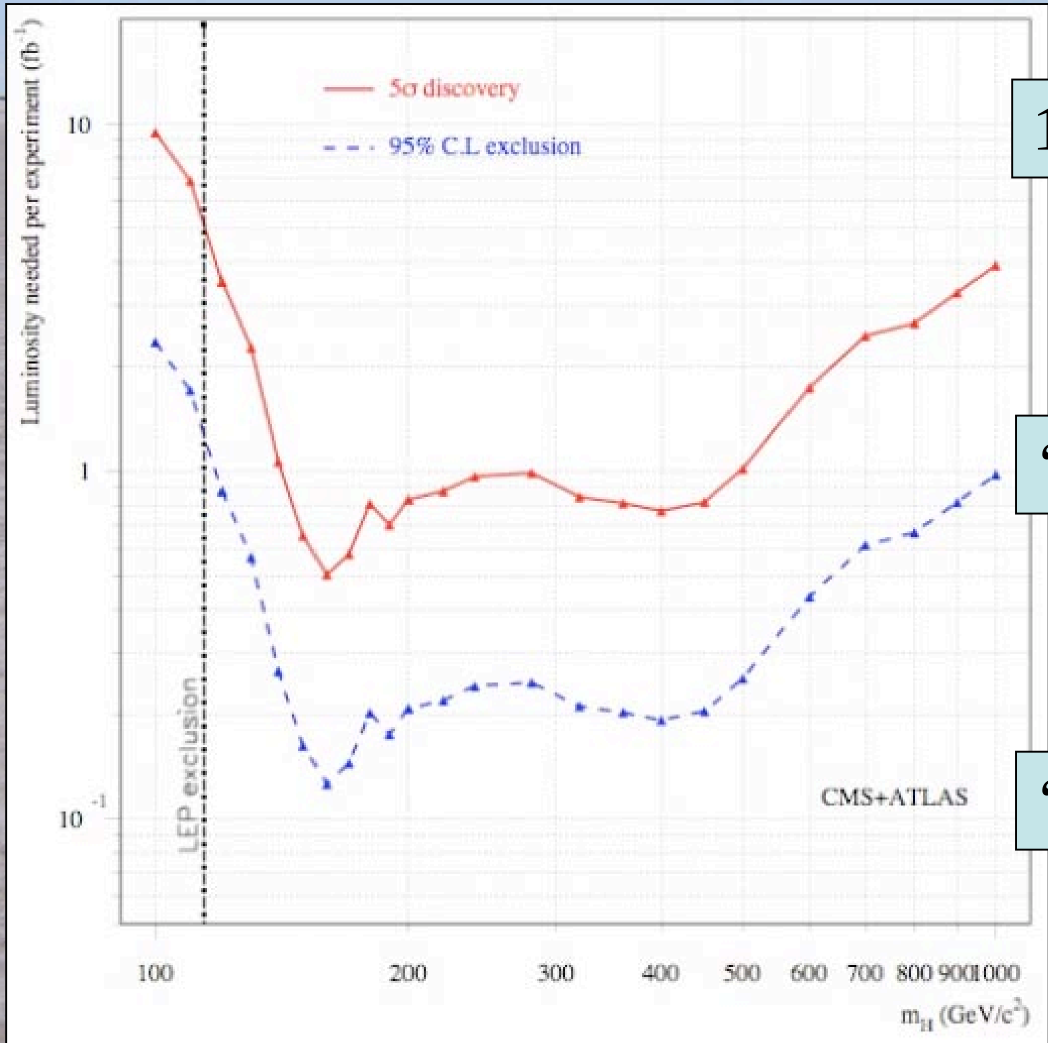


Significance for exclusion of
other J^{CP} states than 0^+

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

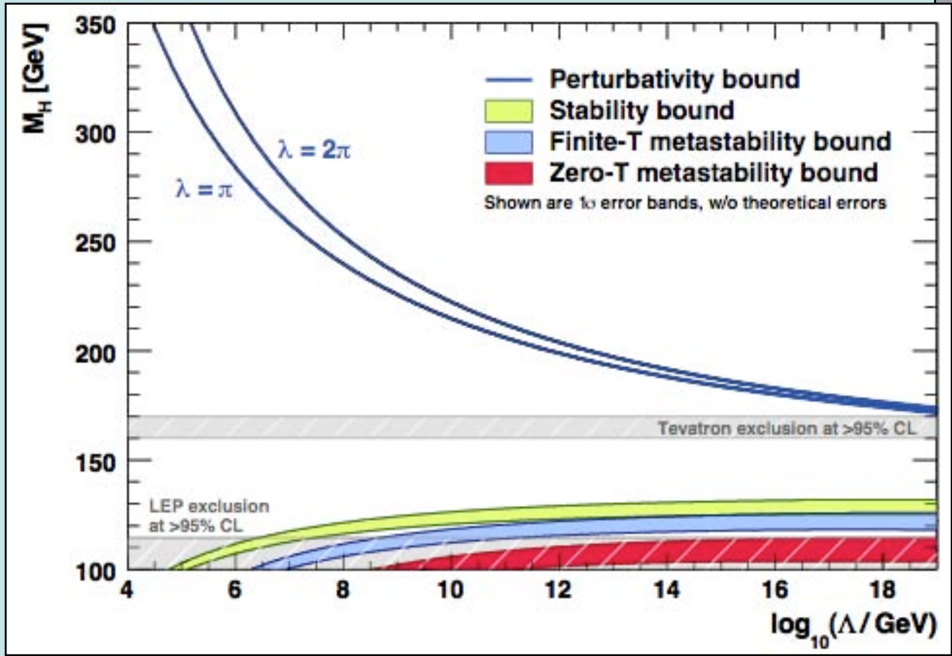
- How is gauge symmetry broken?
- Is there any elementary scalar field?
- Would have caused phase transition in the Universe when it was about 10^{-12} seconds old
- May have generated then the matter in the Universe: electroweak baryogenesis
- A related inflaton might have expanded the Universe when 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

Theoretical Constraints on Higgs Mass

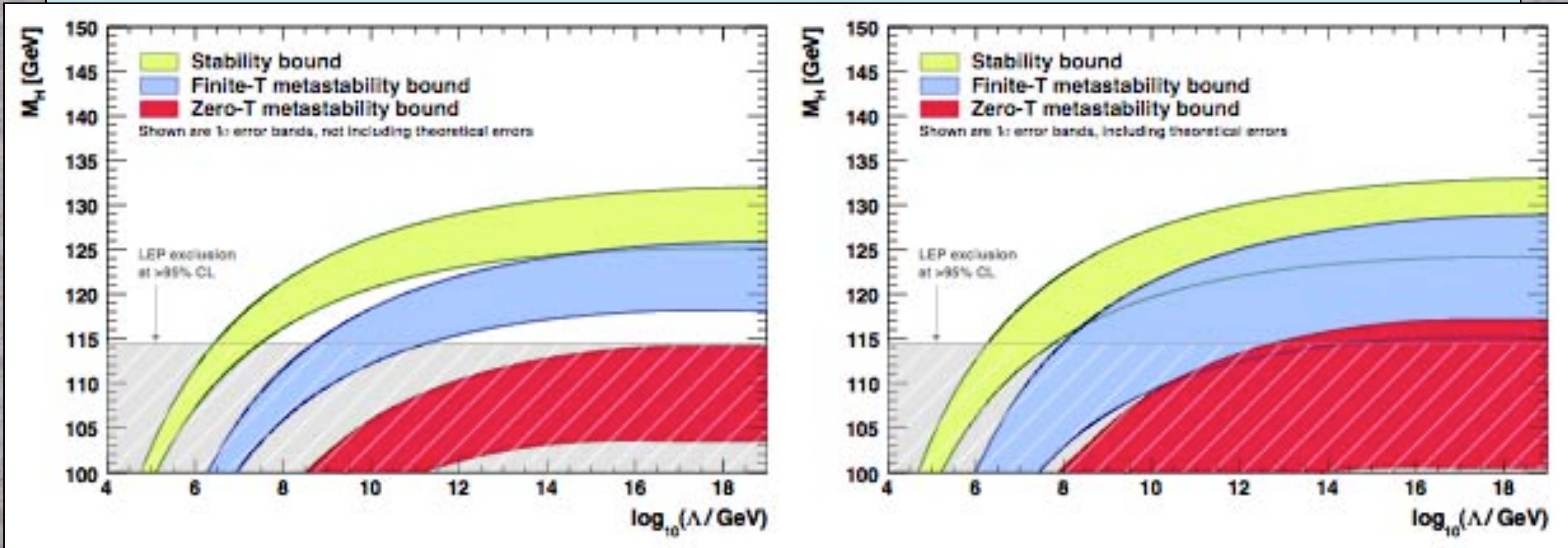
- Large → large self-coupling → blow up at low energy scale Λ due to renormalization
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable



- Bounds on Higgs mass depend on Λ

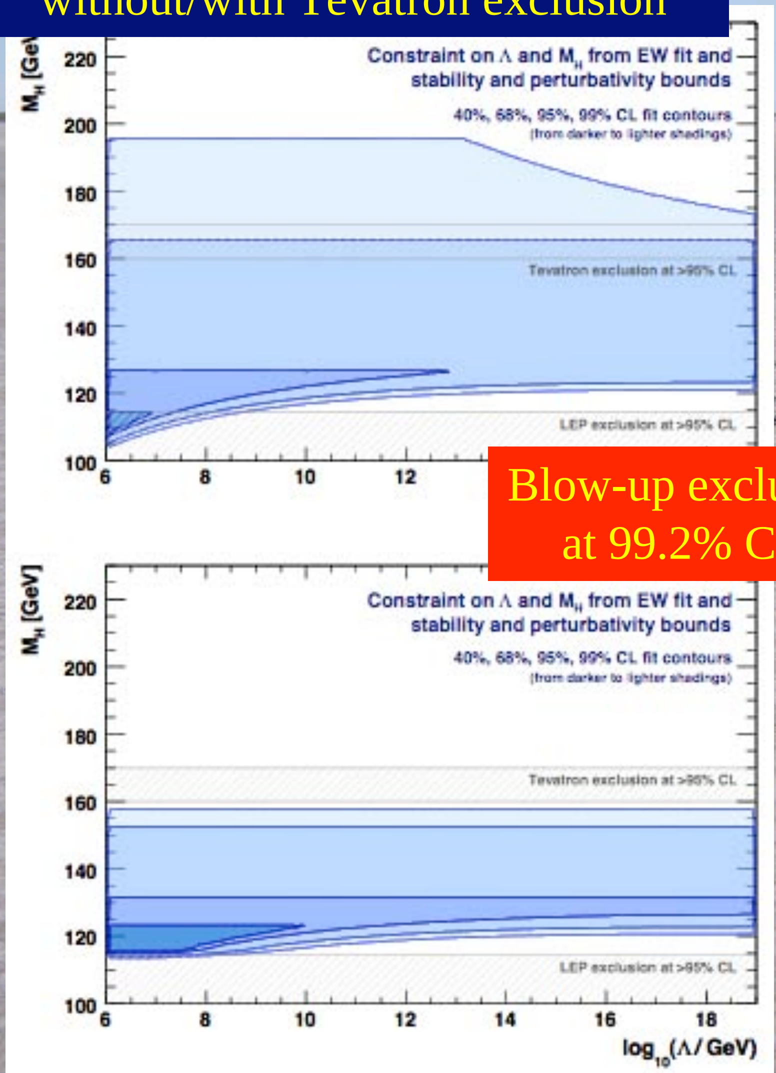
Vacuum Stability vs Metastability

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



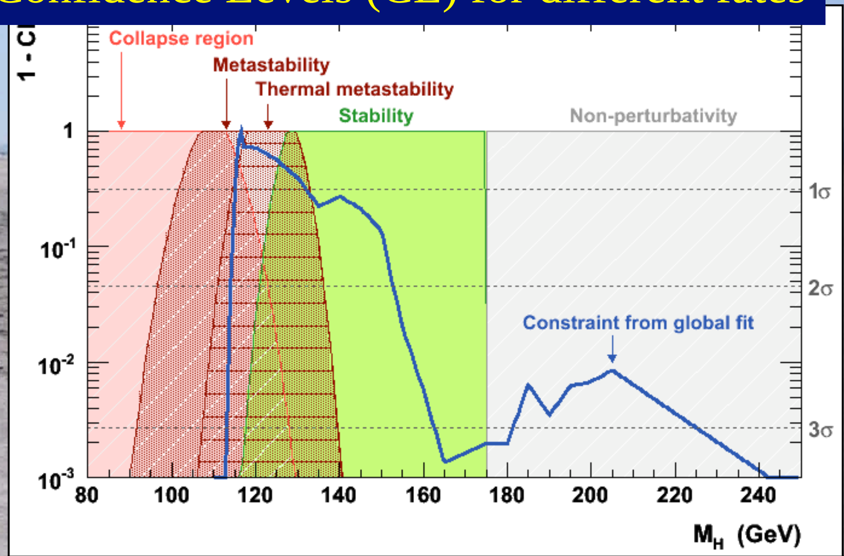
What is the probable fate of the SM?

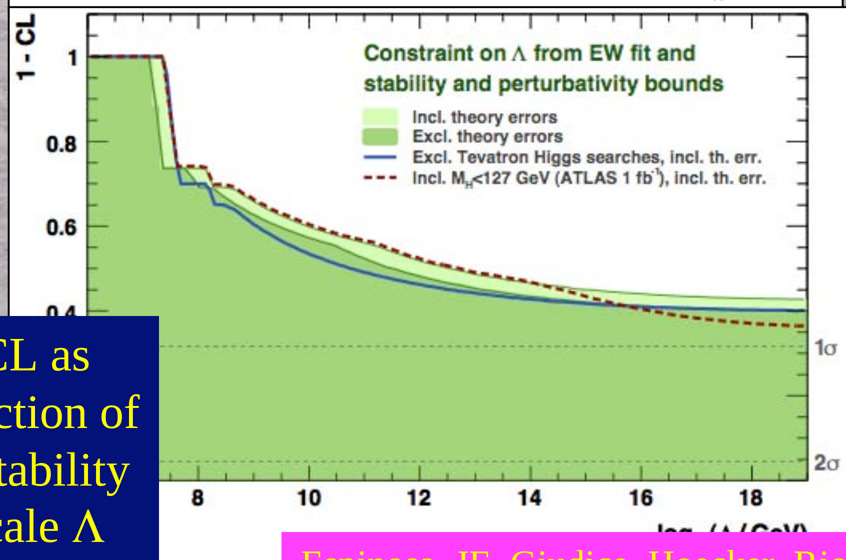
Confidence Levels (CL) without/with Tevatron exclusion



Blow-up excluded at 99.2% CL

Confidence Levels (CL) for different fates



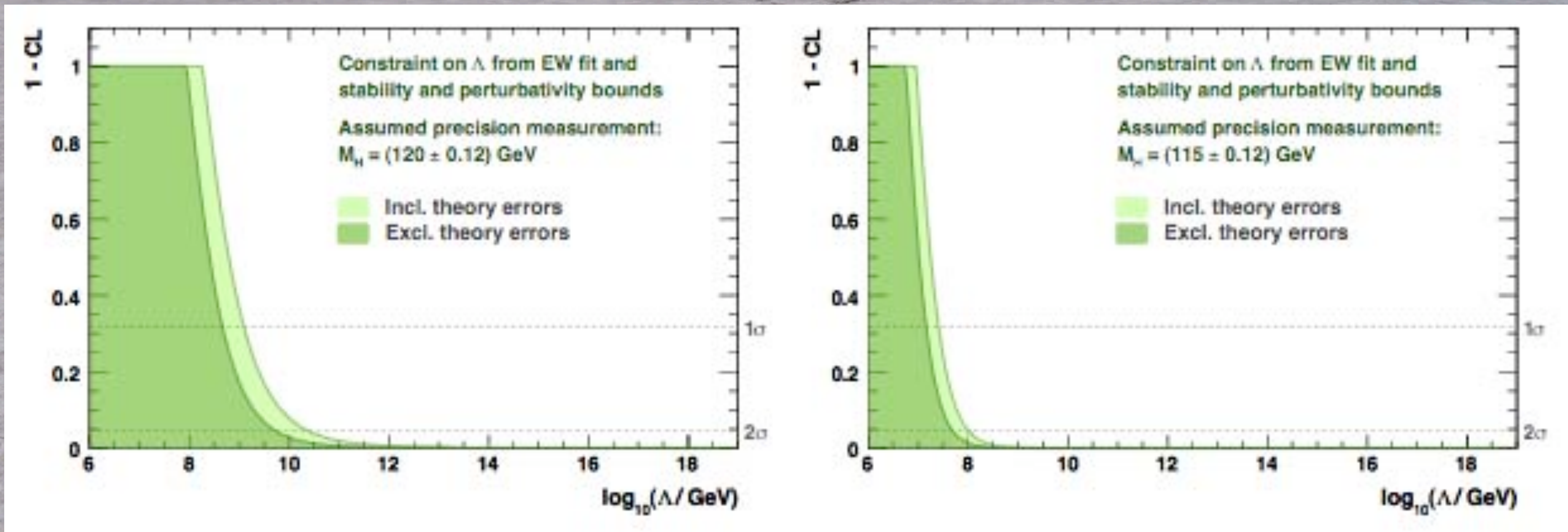


CL as function of instability scale Λ

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



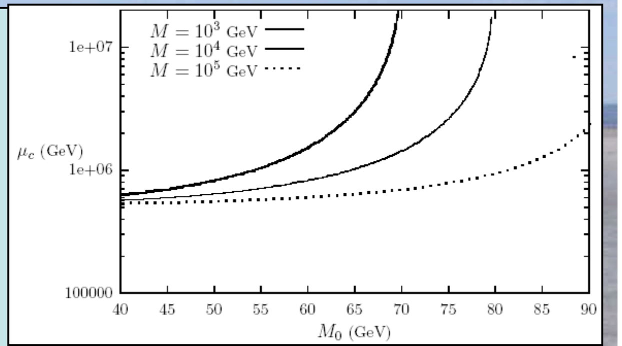
Espinosa, JE, Giudice, Hoecker, Riotto

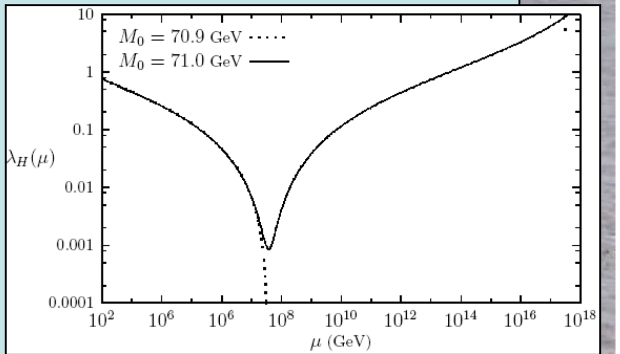
How to Stabilize a Light Higgs Boson?

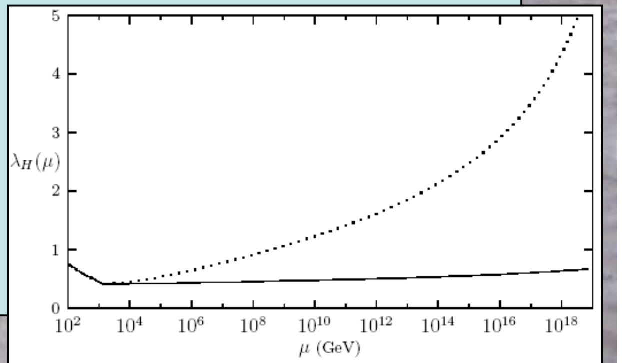
- Top quark destabilizes potential: introduce stop-like scalar:

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

- 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!**







Theorists getting Cold Feet

- Composite Higgs model?
  conflicts with precision electroweak data
- Interpretation of EW data?
  consistency of measurements? Discard some?
- Higgs + higher-dimensional operators?
  corridors to higher Higgs masses?
- Little Higgs models?
  extra `Top', gauge bosons, `Higgses'
- Higgsless models?
  strong WW scattering, extra D?

UnHiggs?

Private Higgs?

Little Higgs?

Gaugephobic Higgs?

Littlest Higgs?

Intermediate Higgs?

Slim Higgs?

Composite Higgs?

Fat Higgs?

Higgsless?

Portal Higgs?

Twin Higgs?

Lone Higgs?

Gauge-Higgs?

Phantom Higgs?

Simplest Higgs?

The LHC Roulette Wheel

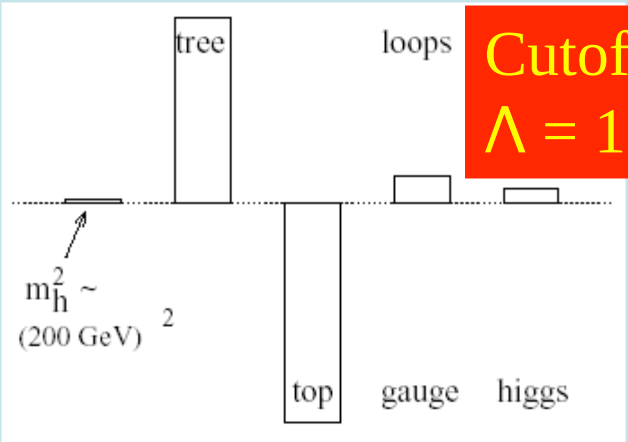
Techni colour

Elementary Higgs or Composite?

- Higgs field:

  $<0|H|0> \neq 0$

- Quantum loop problems



Cutoff
Λ = 10 TeV

- Cut-off $\Lambda \sim 1$ TeV with Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed $m_t > 200$ GeV

- New technicolour force? inconsistent with precision electroweak data?

General Parametrization of Radiative Corrections

- 'Oblique' corrections S, T

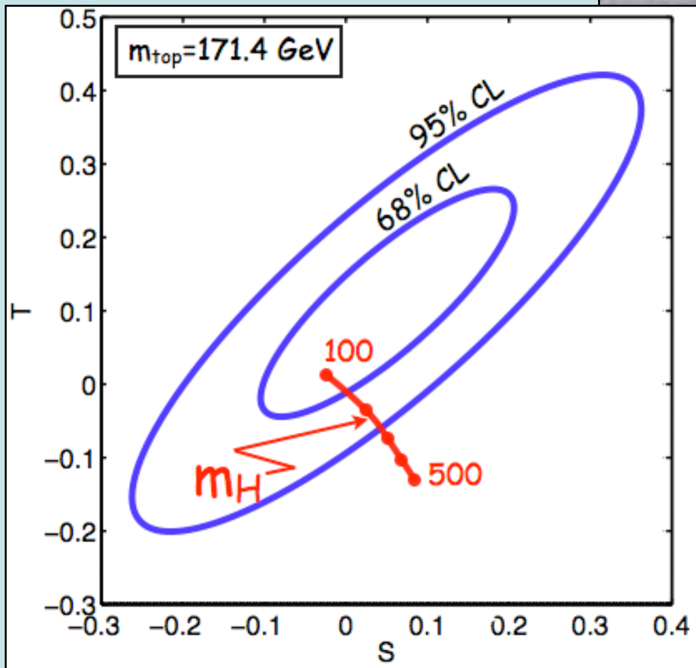
$$\rho \equiv 1 + \alpha_{em} T \qquad \rho \equiv \frac{M_W^2}{M_Z^2 c^2}$$

- Contributions from Standard Model Higgs

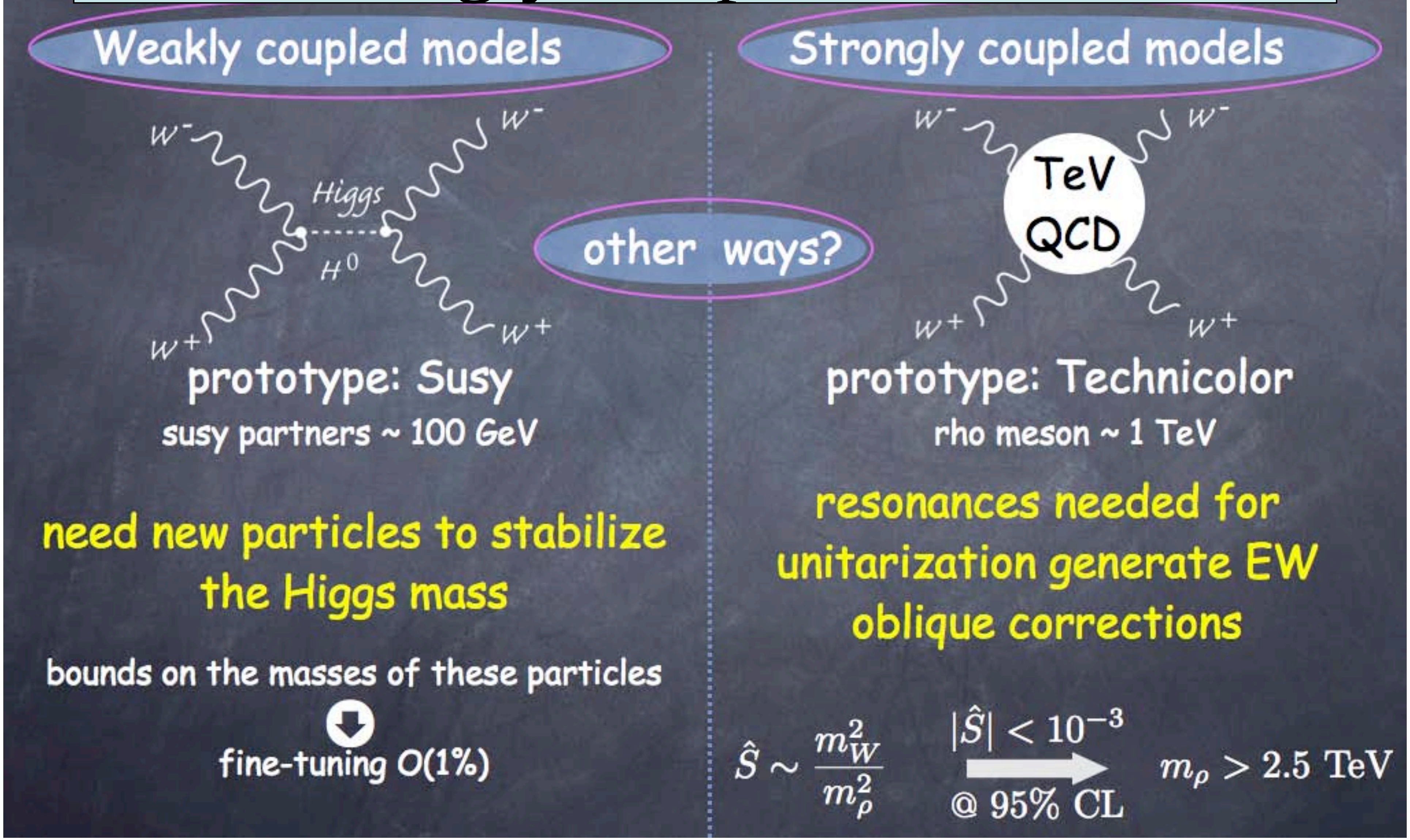
$$\delta S = \frac{1}{12\pi} \log \frac{m_h^2}{m_{h_0}^2}$$

$$\delta T = -\frac{3}{16\pi\, c^2} \log \frac{m_h^2}{m_{h_0}^2}$$

- Low m_H compatible with data
- Technicolour ↔ high m_H



Comparison between Weakly- and Strongly-coupled Models



Interpolating Models

- Combination of Higgs boson and vector ρ

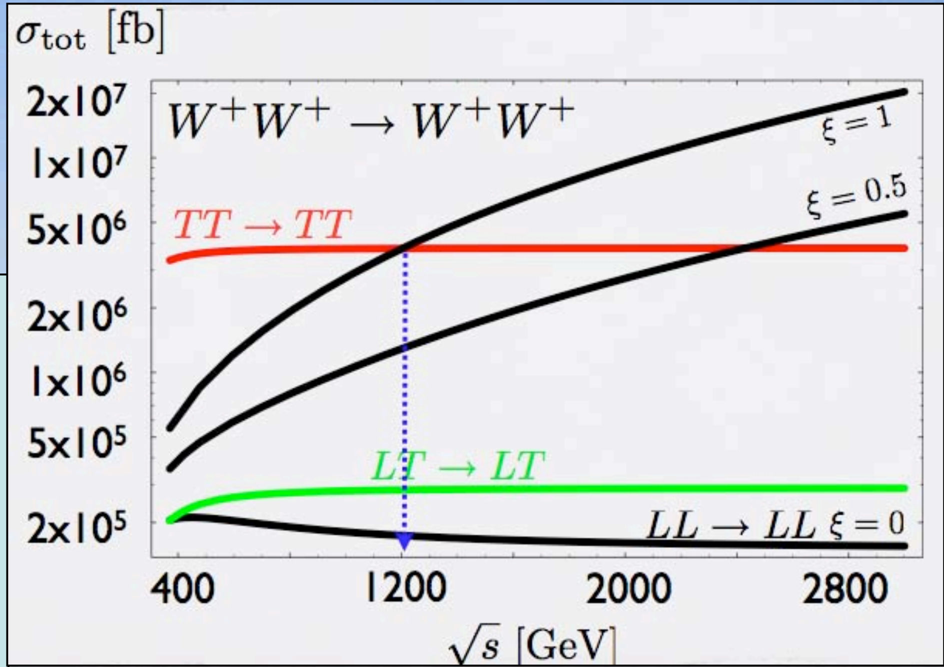
- Two main parameters: m_ρ and coupling g_ρ
- Equivalently ratio weak/strong scale:

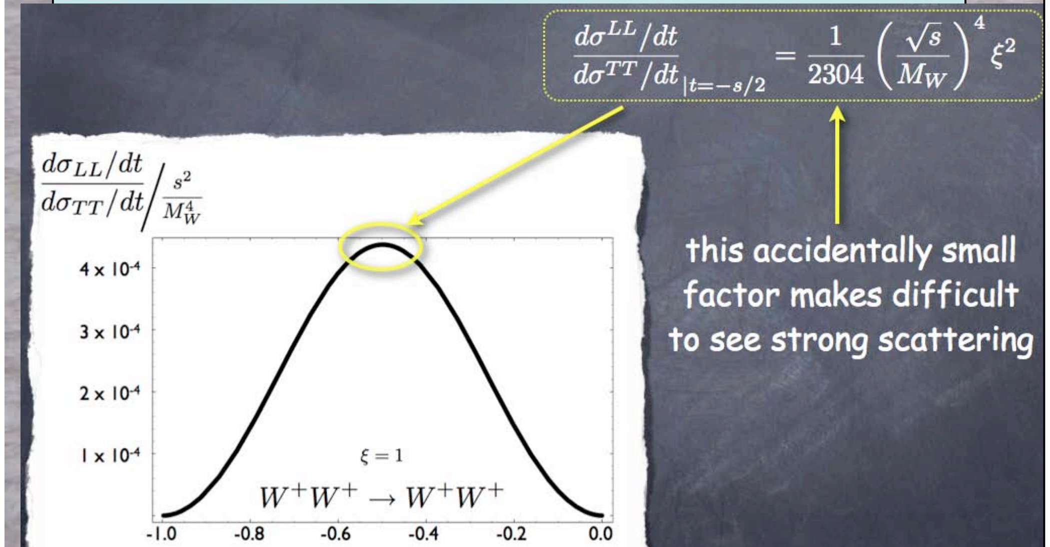
$$\xi \equiv v\, g_\rho / m_\rho$$

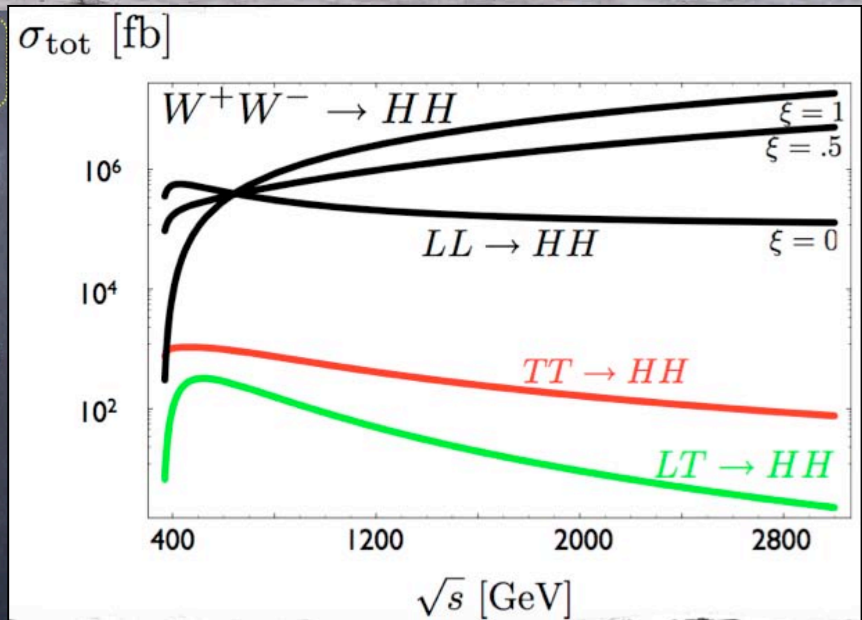
Grojean, Giudice, Pomarol, Rattazzi

Effects in WW Scattering?

- Look for effects in $W_L W_L$ scattering ($W_L \leftrightarrow H$)
- Drowned by $W_T W_T$ ($W_L \leftrightarrow V$)
- Some hope for double Higgs production?







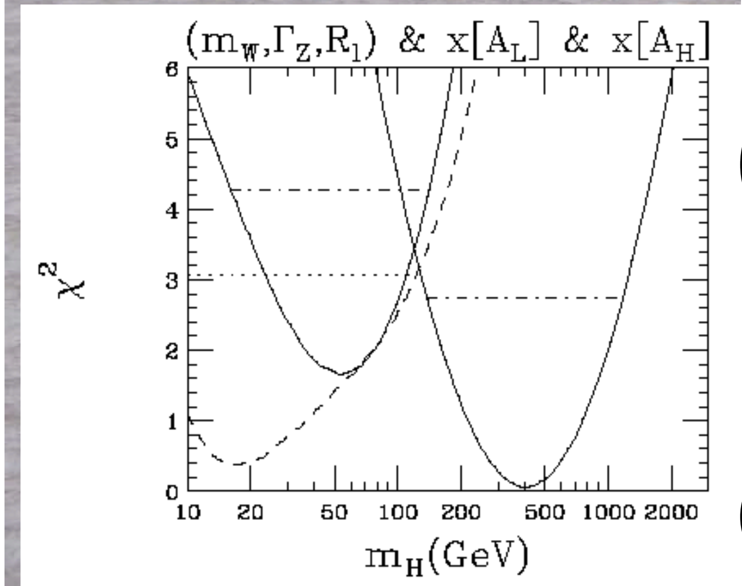
Grojean, Giudice, Pomarol, Rattazzi

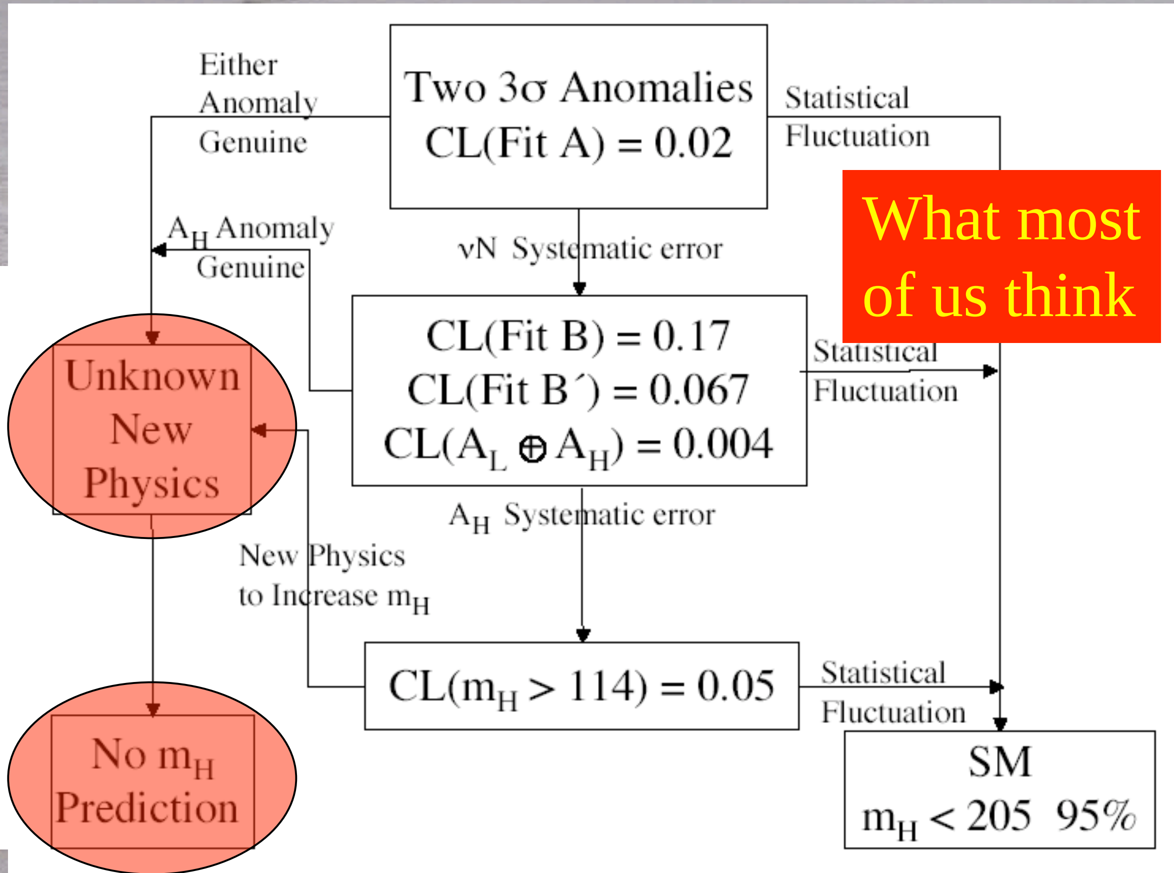
Heretical Interpretation of EW Data

What attitude towards LEP, NuTeV?

Do all the data tell the same story?

e.g., A_L vs A_H

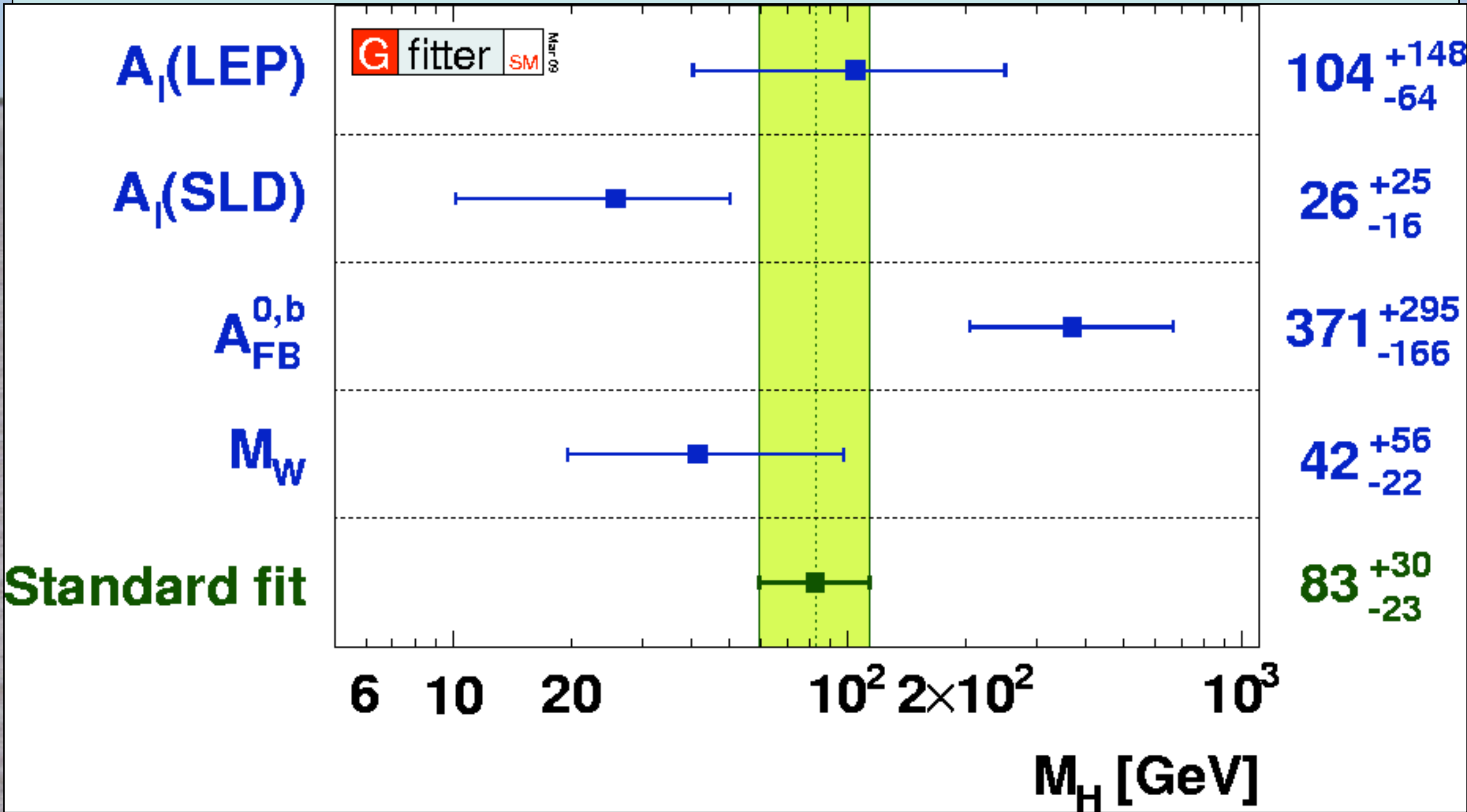




What most of us think

Chanowitz

Estimates of m_H from different Measurements



Spread looks natural: no significant disagreement

Higgs + Higher-Order Operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^p} \mathcal{O}_i^{(4+p)}$$

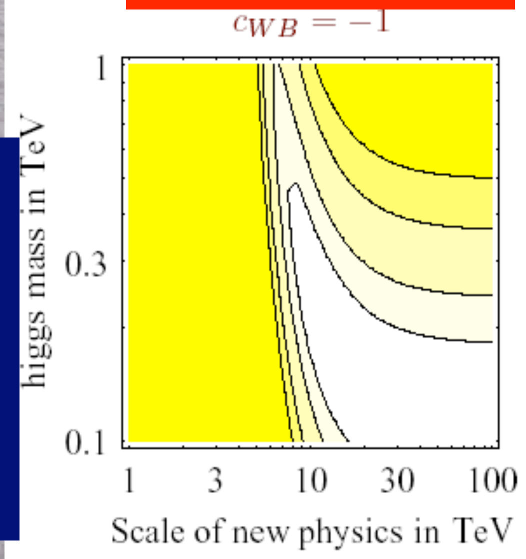
Precision EW data suggest they are small: why?

Dimension six operator	$c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB} = (H^+ \sigma^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.0	13
$\mathcal{O}_H = \lvert H^+ D_\mu H \rvert^2$	4.2	7.0
$\mathcal{O}_{LL} = \frac{1}{2}(\bar{L}\gamma_\mu \sigma^a L)^2$	8.2	8.8
$\mathcal{O}_{HL} = i(H^+ D_\mu H)(\bar{L}\gamma_\mu L)$	14	8.0

95% lower bounds on Λ/TeV

But conspiracies are possible: m_H could be large, even if believe EW data …?

Corridor to heavy Higgs?

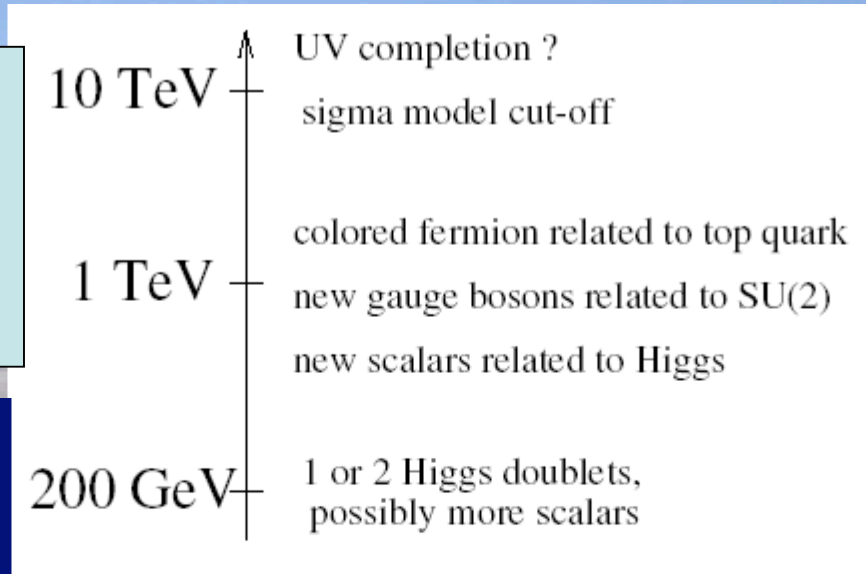


Do not discard possibility of heavy Higgs

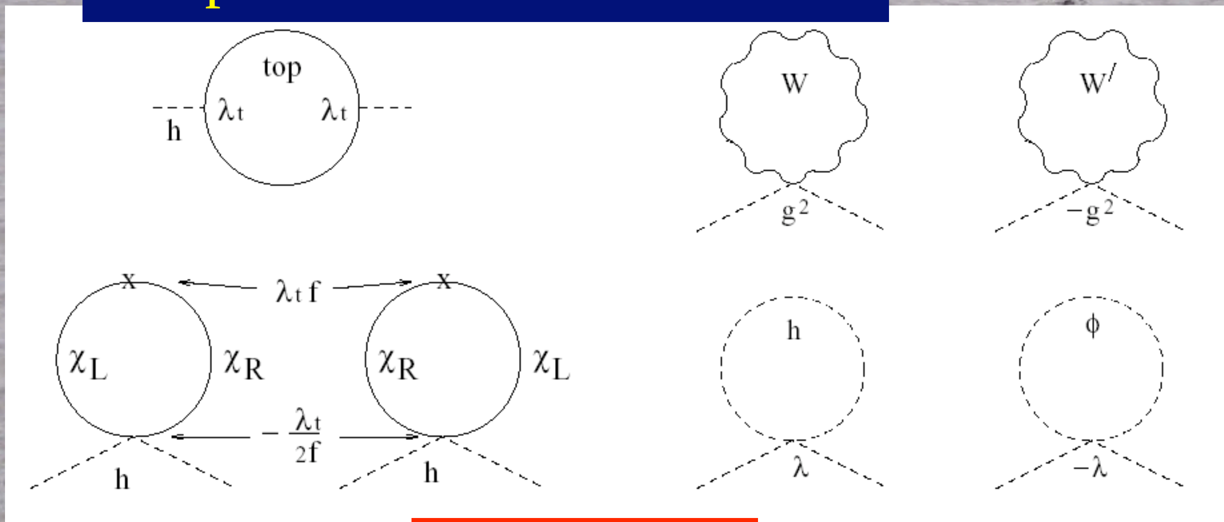
Barbieri, Strumia

Generic Little Higgs Models

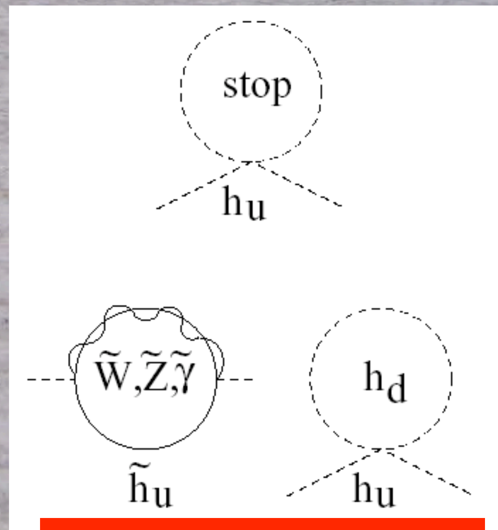
(Higgs as pseudo-Goldstone boson of larger symmetry)



Loop cancellation mechanism



Little Higgs



Supersymmetry

Little Higgs Models

- Embed SM in larger gauge group
- Higgs as pseudo-Goldstone boson
- Cancel top loop

$$\delta m^2_{H,top}(SM) \sim (115GeV)^2 (\frac{\Lambda}{400GeV})^2$$

with new heavy T quark $m_T > 2\lambda_t f \sim 2f$ $f > 1 \text{ TeV}$

$$\delta m^2_{H,top}(LH) \sim \frac{6G_F m_t^2}{\sqrt{2}\pi^2} m_T^2 log \frac{\Lambda}{m_T} \gtrsim 1.2 f^2$$

- New gauge bosons, Higgses
- Higgs light, other new physics heavy

$M_T < 2$ TeV (m_h / 200 GeV)^2
$M_{W'} < 6$ TeV (m_h / 200 GeV)^2
$M_{H++} < 10$ TeV

Not as complete as susy: more physics > 10 TeV

To Higgs or not to Higgs?

- Higgs must discriminate between different types of particles:
  - Some have masses, some do not
  - Masses of different particles are different
- In mathematical jargon, symmetry must be broken: how?
  - Break symmetry in equations?
  - **Or in solutions to symmetric equations?**
- This is the route proposed by Higgs
  - **Is there another way?**

Where to Break the Symmetry?

- Throughout all space?
  - Route proposed by Higgs
  - Universal Higgs (snow)field breaks symmetry
  - **If so, what type of field?**
- Or at the edge of space?
  - **Break symmetry at the boundary?**
- Not possible in 3-dimensional space
  - No boundaries
  - **Postulate extra dimensions of space**
- Different particles behave differently in the extra dimension(s)