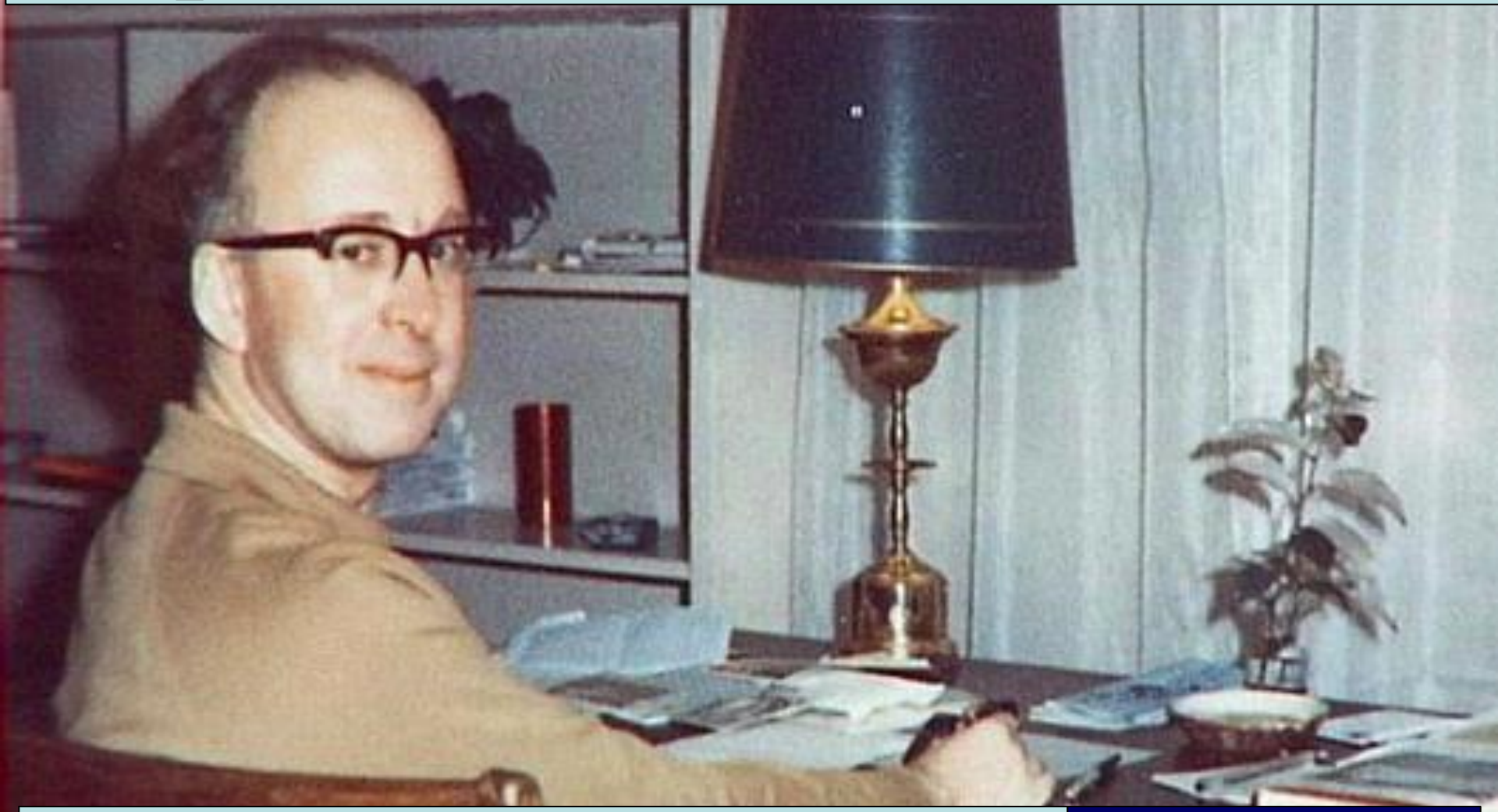
Implications of LHC Results



To Higgs or not to Higgs?

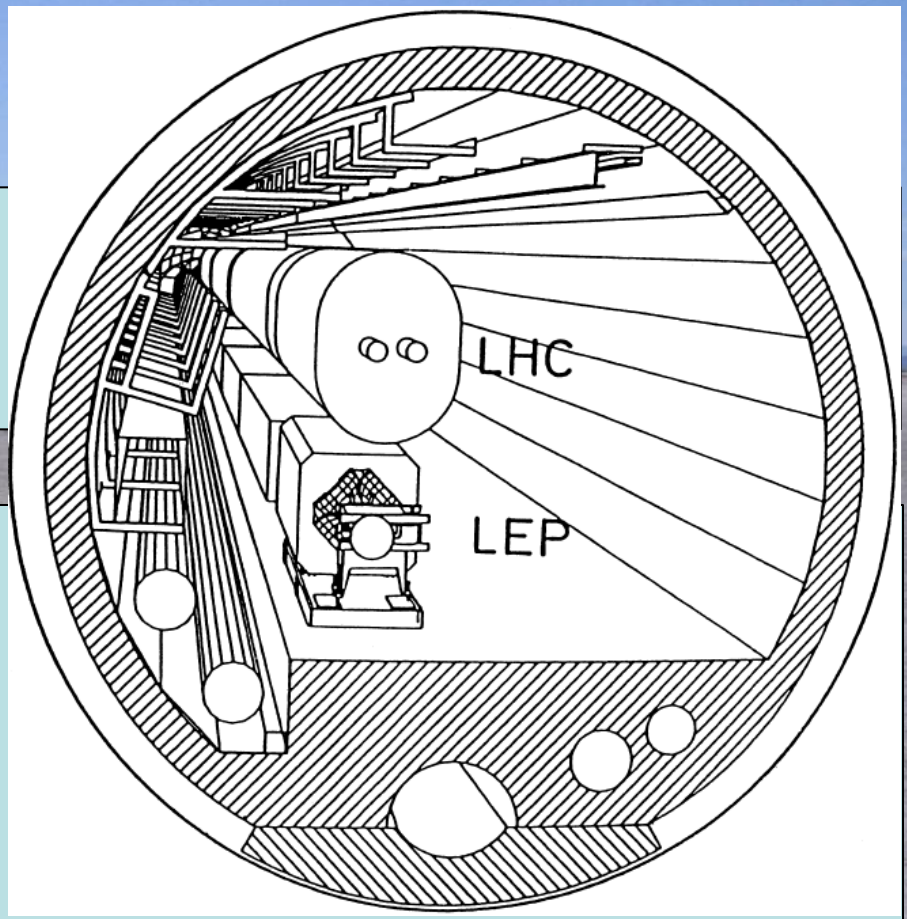
This is just one of the questions being studied at the LHC

John Ellis
King's College London
(& CERN)

Open Questions beyond the Standard Model

- What is the origin of particle masses? LHC
  due to a Higgs boson?
- Why so many types of matter particles? LHC
- What is the dark matter in the Universe? LHC
- Unification of fundamental forces? LHC
- Quantum theory of gravity? LHC

Plus ça change …



- 1984: ECFA-CERN Workshop at Lausanne & CERN

CHAPTER I: THE PHYSICS CASE

Physics with a multi-TeV hadron collider, *C.H. Llewellyn Smith*

CHAPTER XII: NEW PARTICLES AND THEIR EXPERIMENTAL SIGNATURES, *J. Ellis et al.*

The Seminal Papers

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

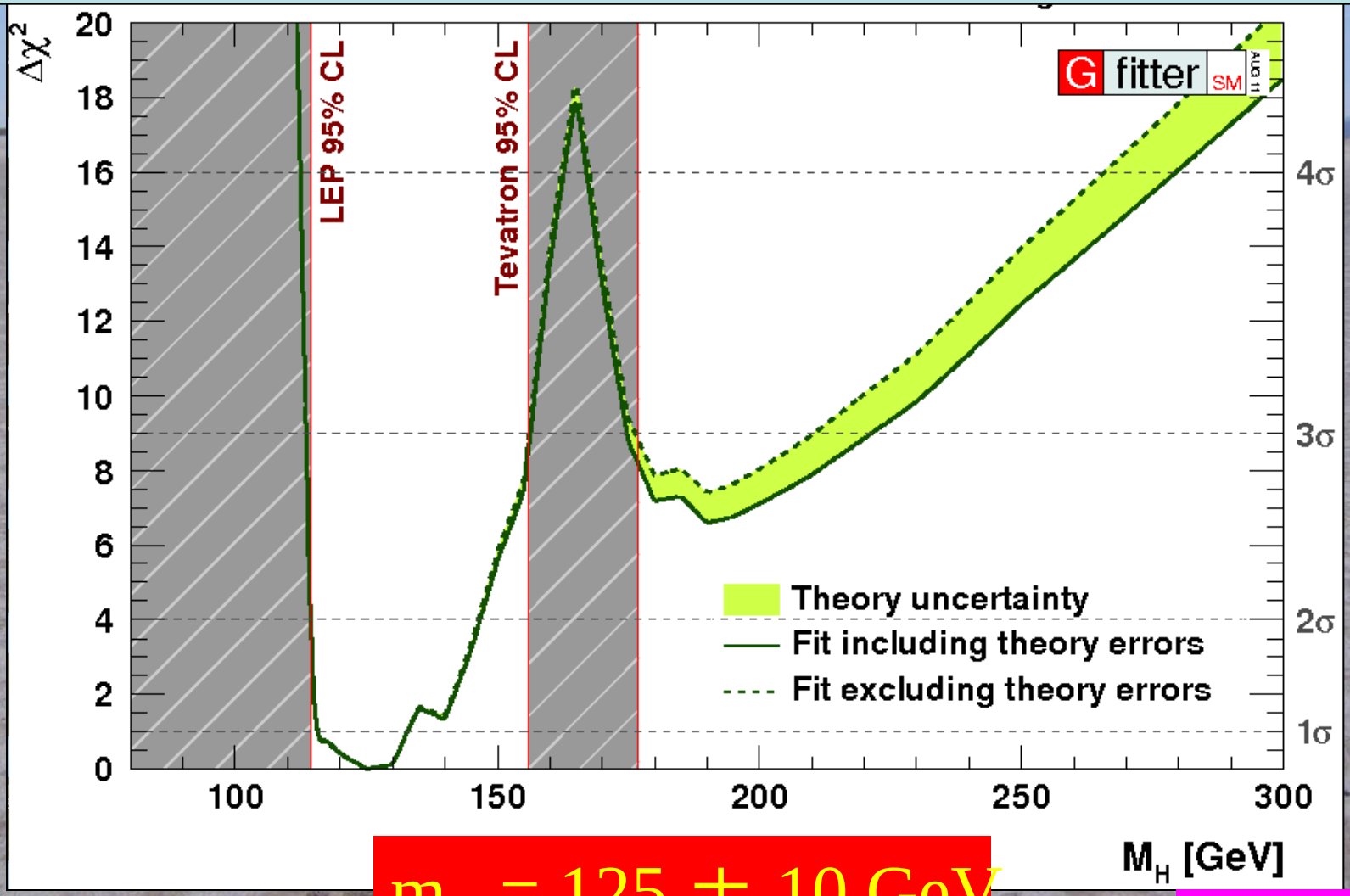
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

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.

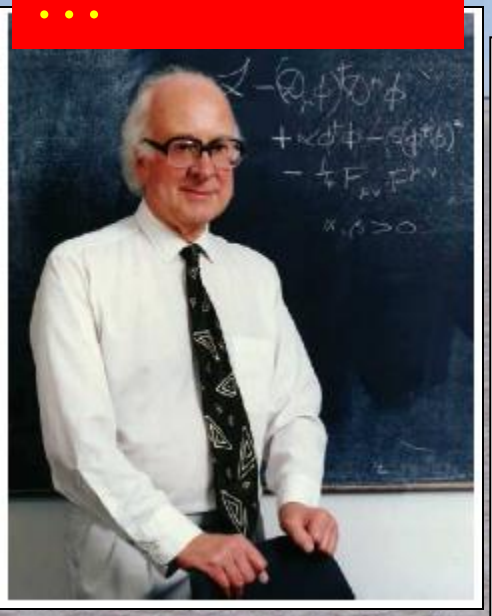
2011: Combining Information from Previous Direct Searches and Indirect Data



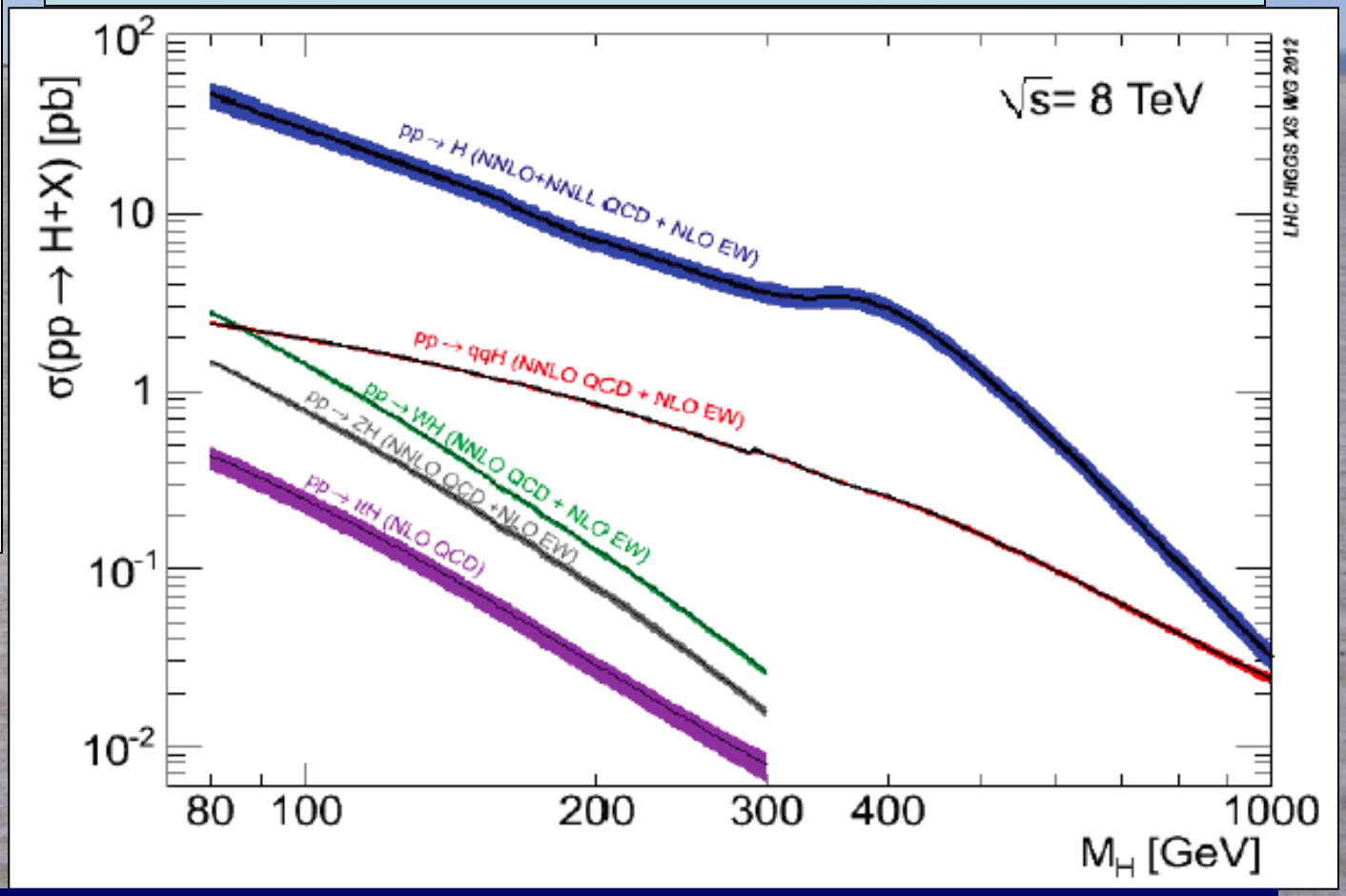
$m_H = 125 \pm 10$ GeV

Gfitter collaboration

A la recherche du Higgs perdu …



Higgs Production at the LHC

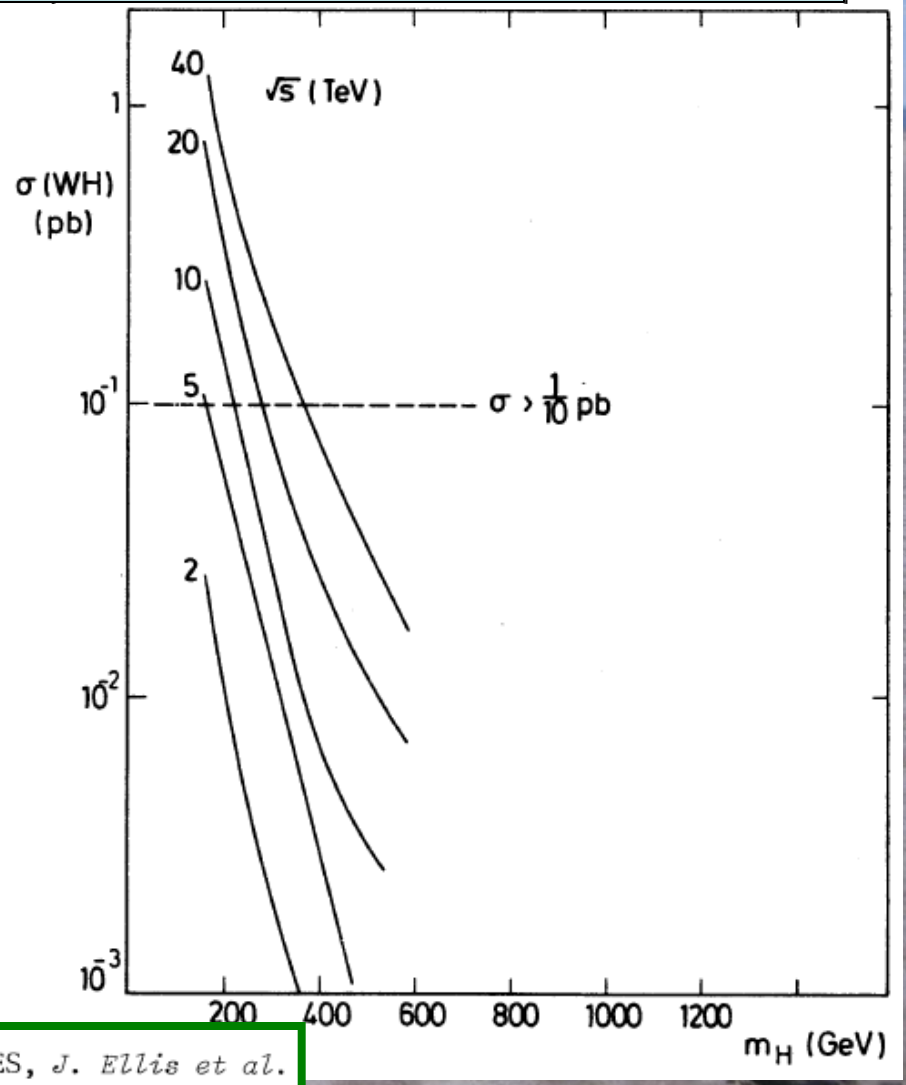


Many production modes measurable if M_h ~ 125 GeV

Higgs Production at the LHC

Fig. 21

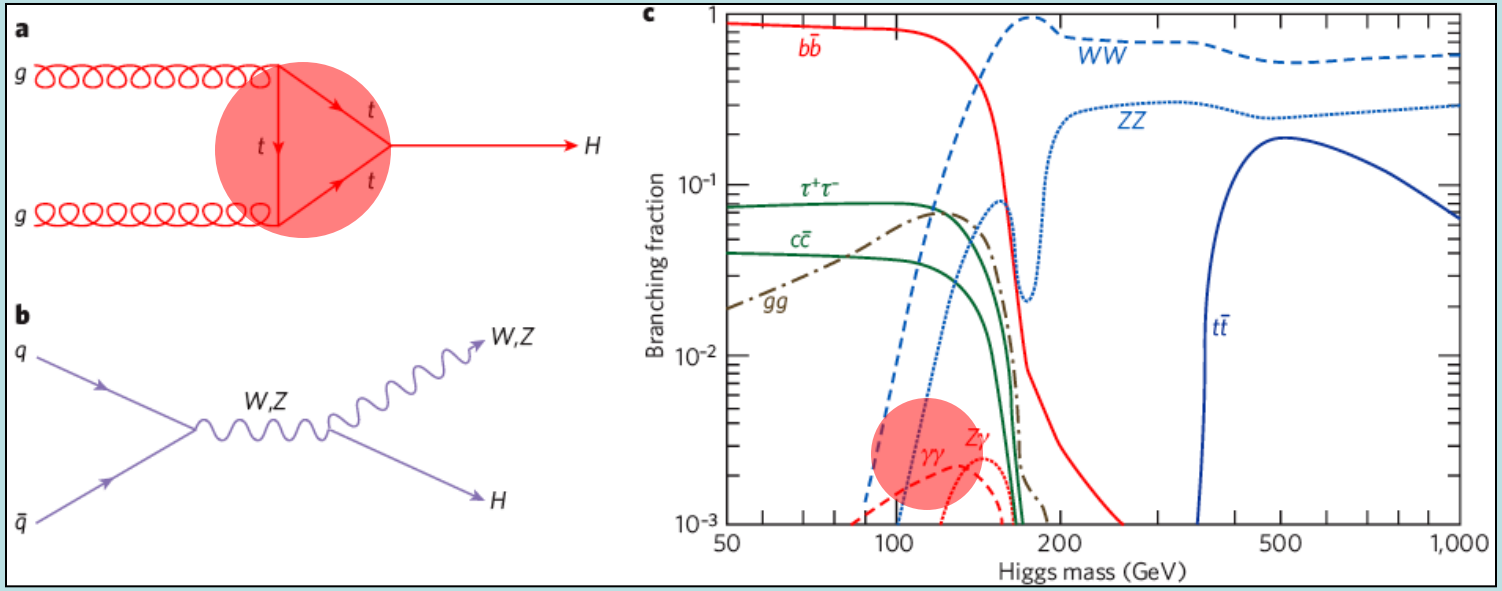
Plus ça change …



CHAPTER XII: NEW PARTICLES AND THEIR EXPERIMENTAL SIGNATURES, *J. Ellis et al.*

Higgs Decay Branching Ratios

- Couplings proportional to masses (?)



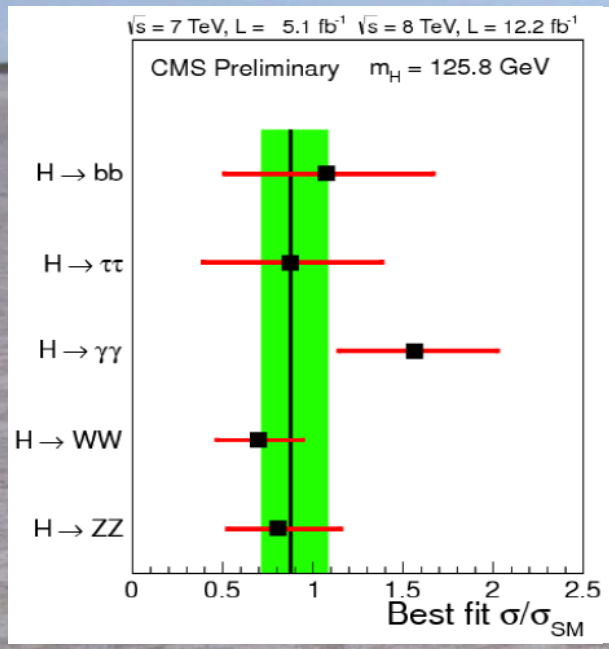
- Important couplings through loops:
  - gluon + gluon → Higgs → γγ

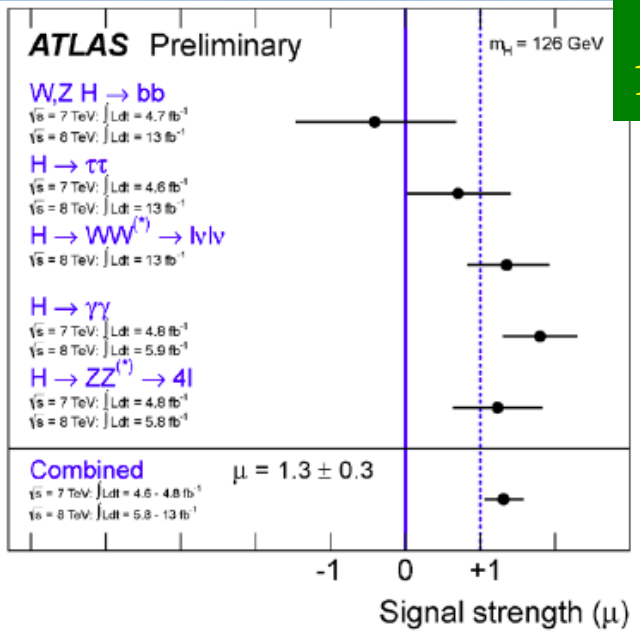
Many decay modes measurable if M_h ~ 125 GeV

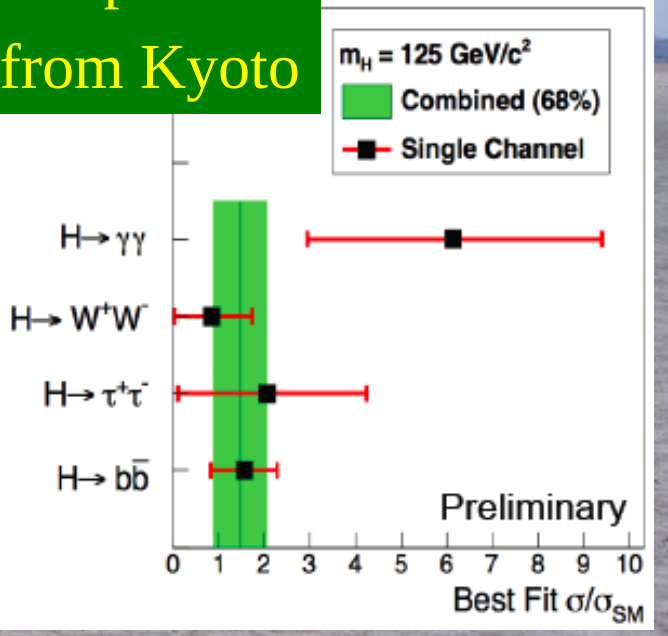
Higgsdependence Day!

Summary of the Story so far

Update from Kyoto

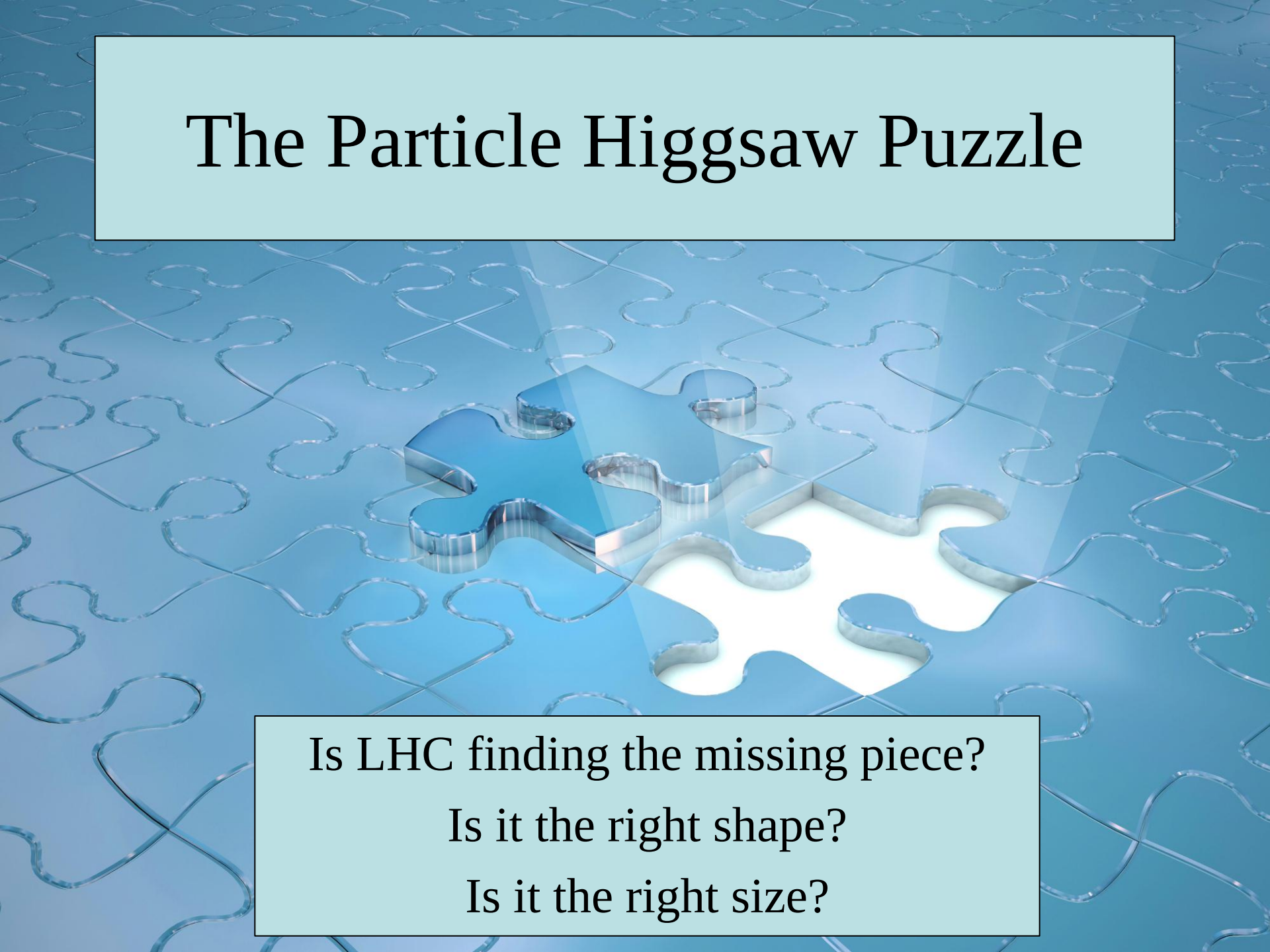






Signals compatible (so far) with the Standard Model

The Particle Higgsaw Puzzle



Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

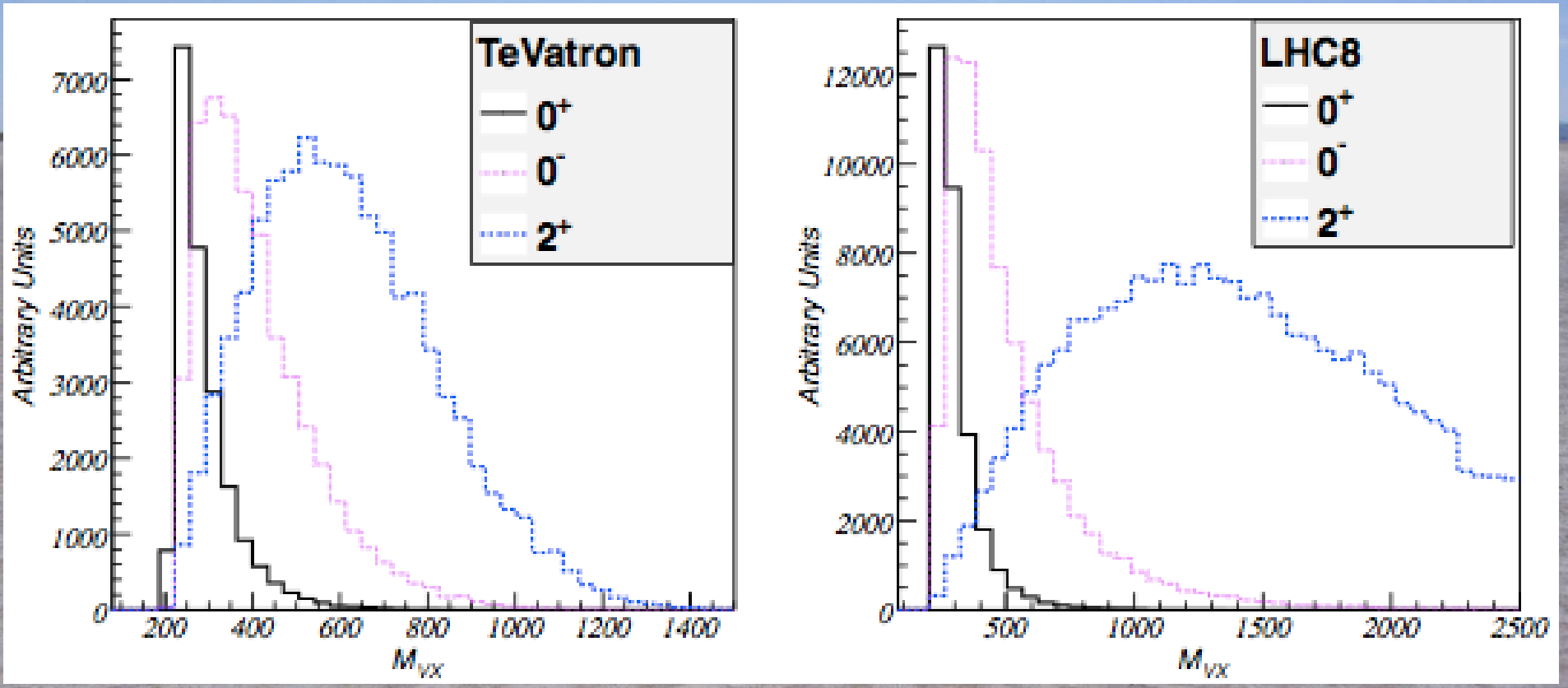
What is it ?

- Does it have spin 0 or 2?
- Is it scalar or pseudoscalar?
- Is it elementary or composite?
- Does it couple to particle masses?
- Quantum (loop) corrections?
- What are its self-couplings?

What is the Spin of the ‘Higgs’?

- Decays into $\gamma\gamma$, so cannot have spin 1
- **Spin 0 or 2?**
- Selections of WW and ZZ events are based on spin 0 hypothesis
- Can diagnose spin via
  - angular distribution of $\gamma\gamma$
  - angular correlations of leptons in WW, ZZ decays
  - Production in association with W or Z

Does the ‘Higgs’ have Spin Two ?

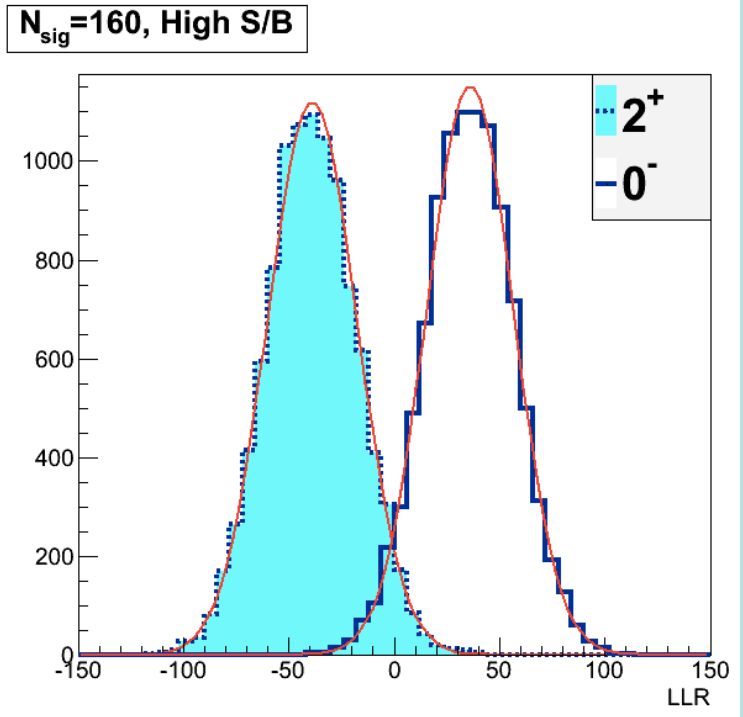


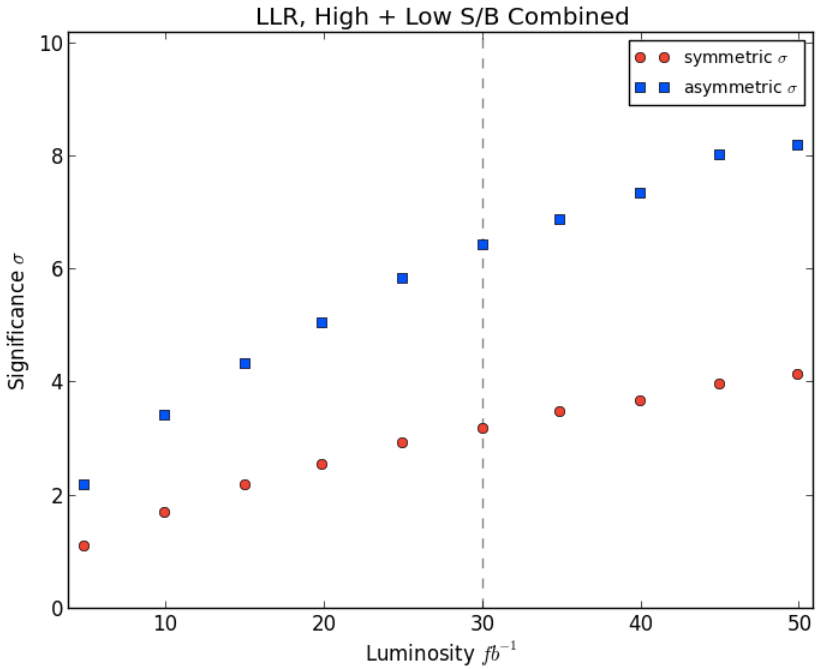
Vector boson + ‘Higgs’ combined invariant mass very different for spins 0 and 2

JE, Hwang. Sanz & You: arXiv:1208.6002

Does the ‘Higgs’ have Spin Two ?

- Discrimination spin 2 vs spin 0 via angular distribution of decays into γγ





JE, Fok, Hwang, Sanz & You: arXiv:1210.5229

What is it ?

- Does it have spin 0 or 2?
  - **Spin 2 seems unlikely, but needs experimental checks**
- Is it scalar or pseudoscalar?
- Is it elementary or composite?
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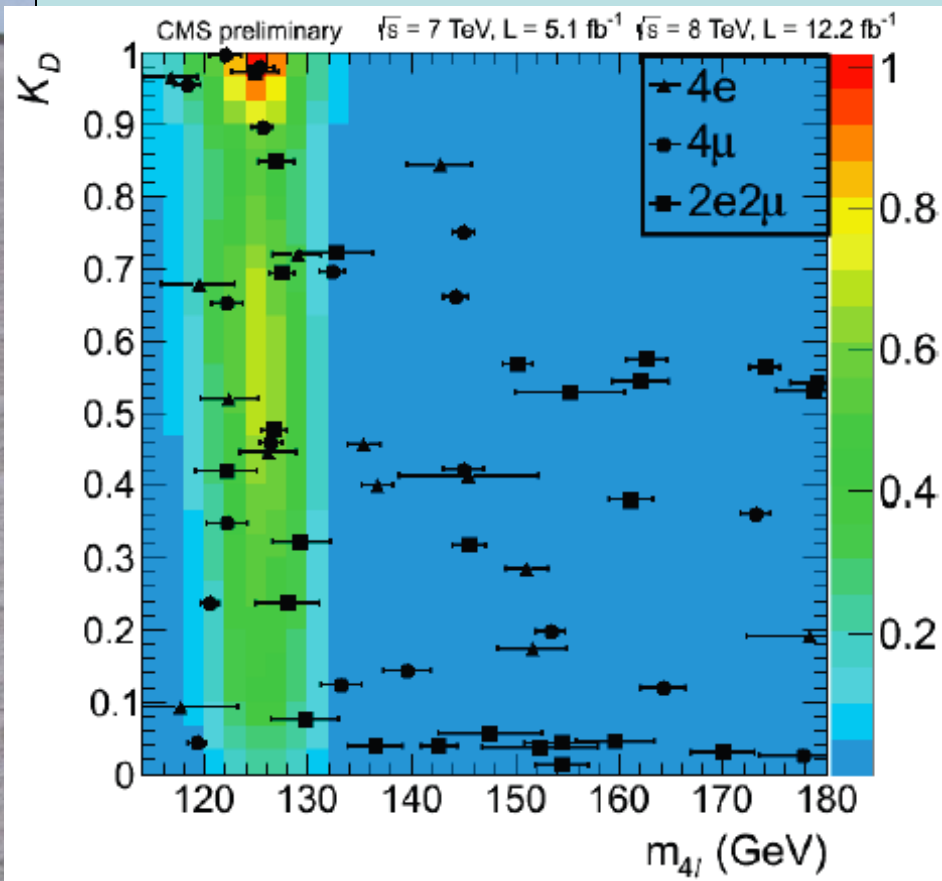
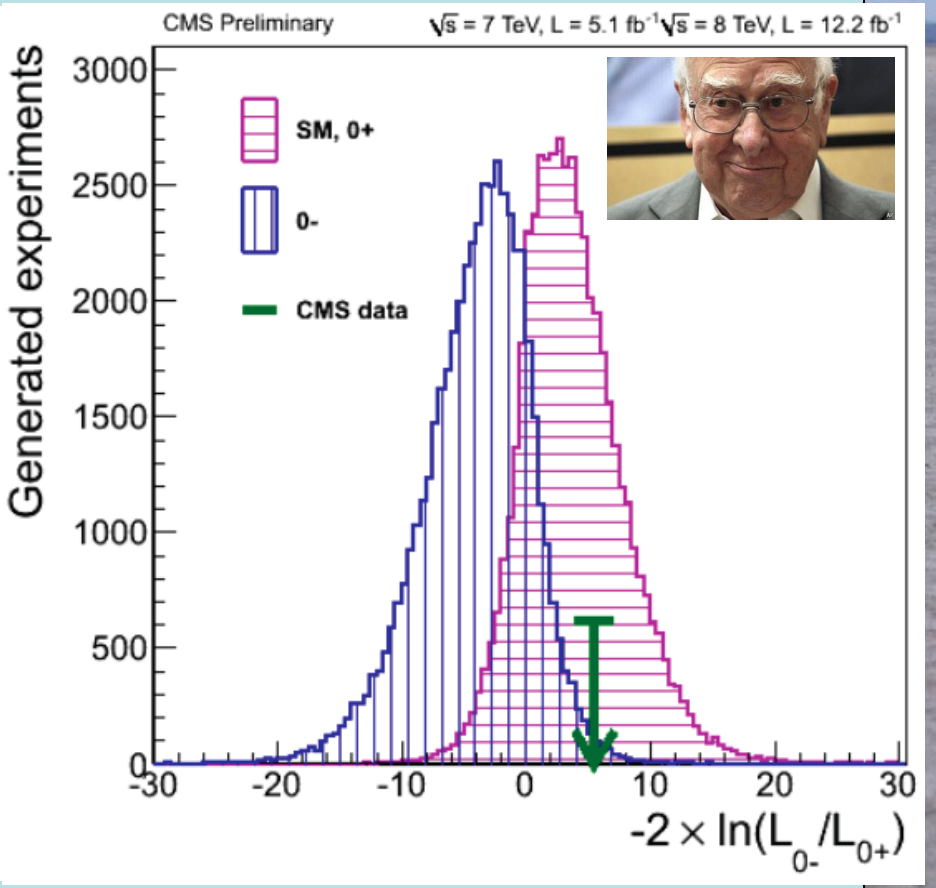
- What are its self-couplings?

Does the ‘Higgs’ have Parity +?

Update from Kyoto

- Kinematic distribution of ZZ* final state





- Favours 0^+ over 0^- by ~ 2 σ

What is it ?

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  - **Spin 2 seems unlikely, but needs experimental checks**
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  - **Pseudoscalar disfavoured by experiment**
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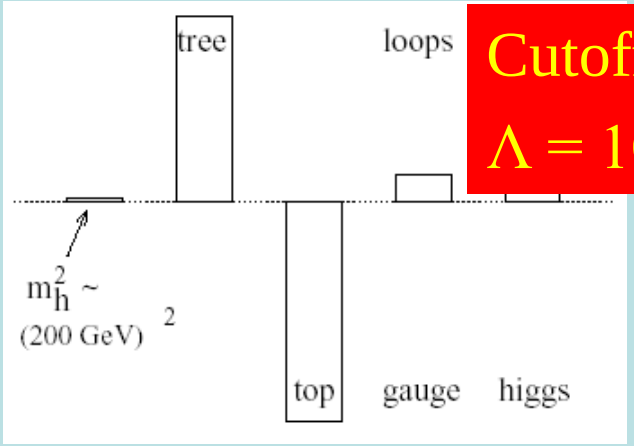
- Does it couple to particle masses?
- Quantum (loop) corrections?
- What are its self-couplings?

Elementary Higgs or Composite?

- Higgs field:

  $\langle 0|H|0\rangle \neq 0$

- Quantum loop problems



Cutoff

Λ = 10 TeV

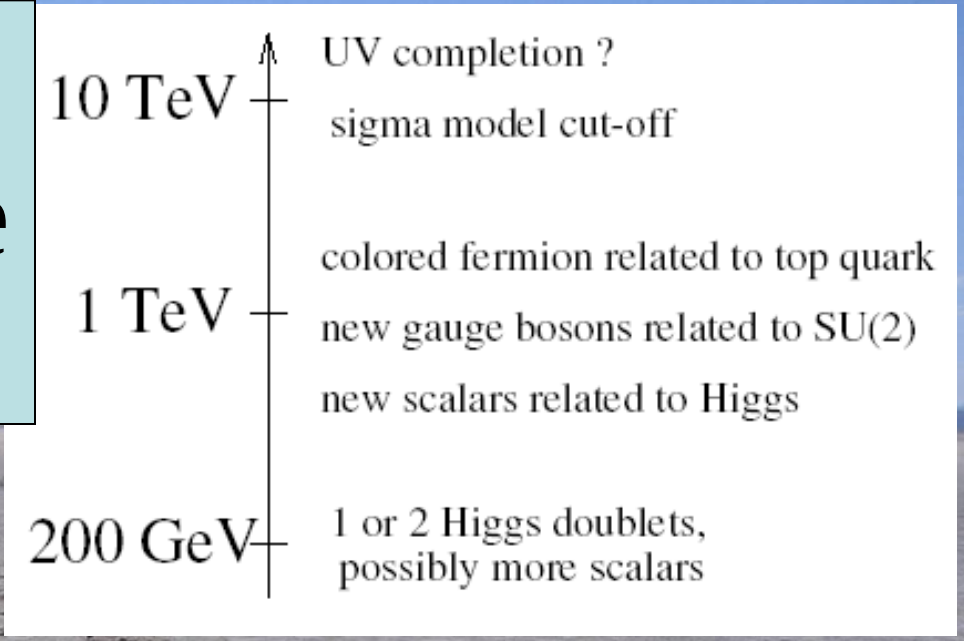
Cut-off $\Lambda \sim 1$ TeV with Supersymmetry?

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

New technicolour force?

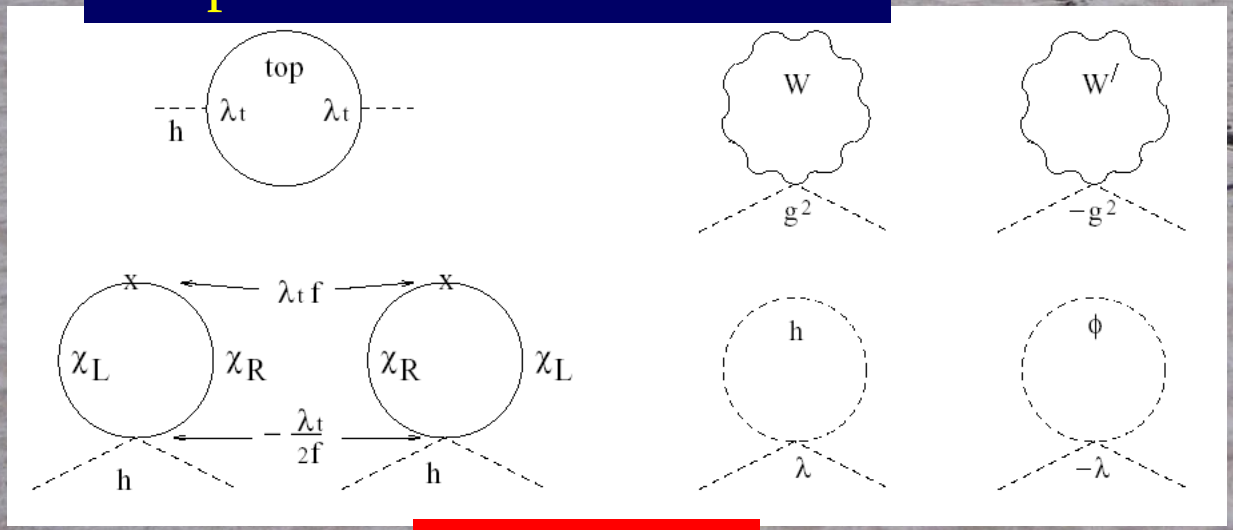
- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

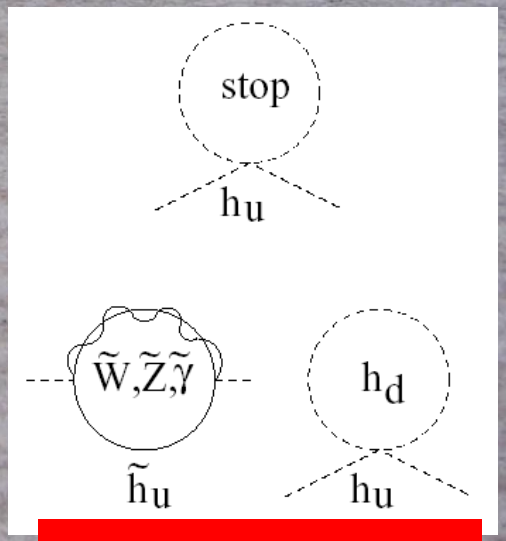
Higgs as a Pseudo-Goldstone Boson



‘Little Higgs’ models
(breakdown of larger symmetry)

Loop cancellation mechanism





Little Higgs

Supersymmetry

General Analysis of 'unHiggs' Models

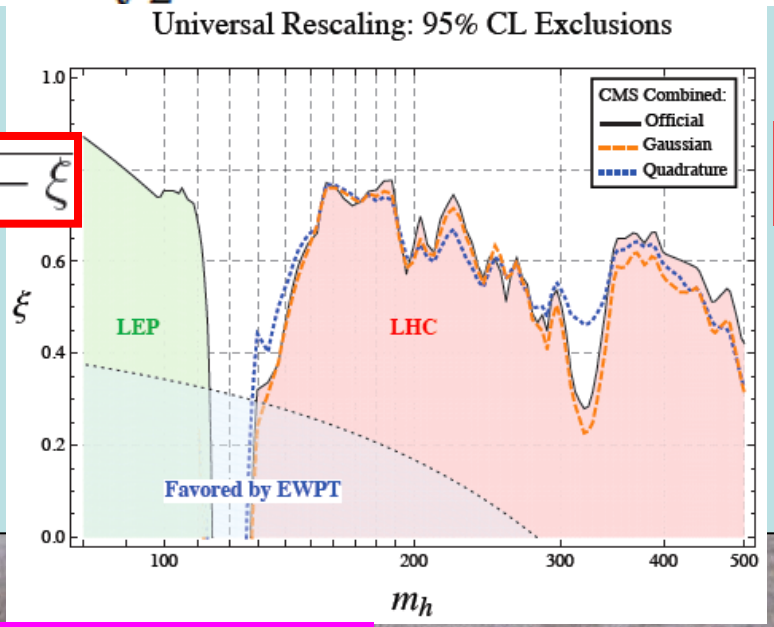
- Parametrization of effective Lagrangian:

$$\mathcal{L}^{(2)} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$

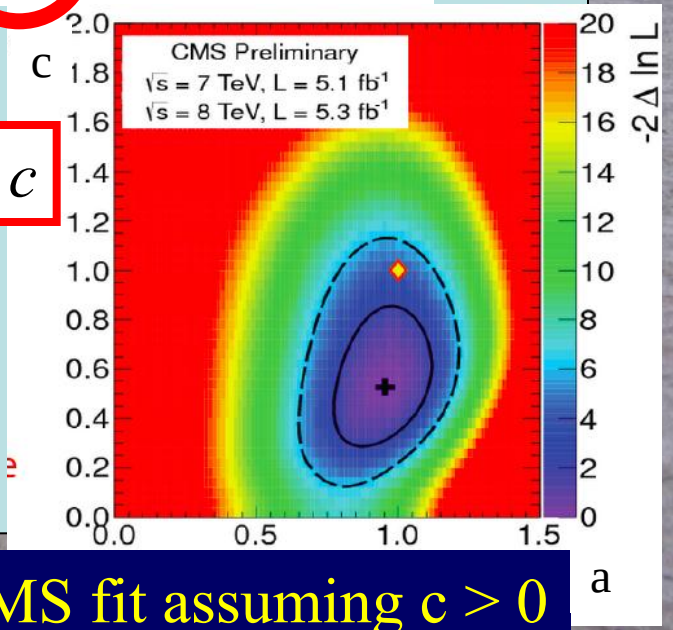
$$- \frac{v}{\sqrt{2}}\lambda^u_{ij}\left(\bar{u}^{(i)}_L, \bar{d}^{(i)}_L\right)\Sigma\left(u^{(i)}_R, 0\right)^T\left(1 + c_u\frac{h}{v} + c_{2u}\frac{h^2}{v^2} + \cdots\right)$$

- Fits

$a = c = \sqrt{1-\xi}$



$a \neq c$

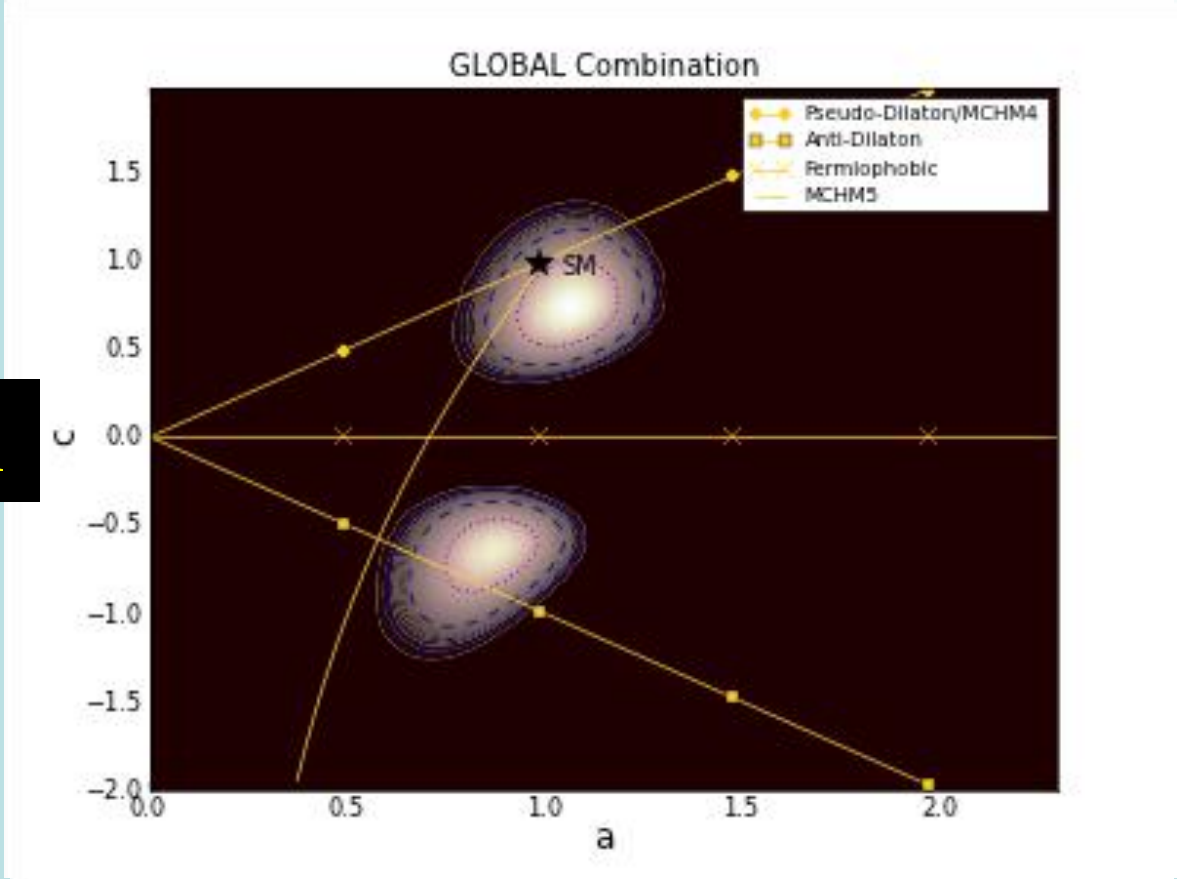


CMS fit assuming c > 0

Azatov, Contino, Galloway: arXiv:1202.3415

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by a, to fermions by c



Global

0

- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1207.1693

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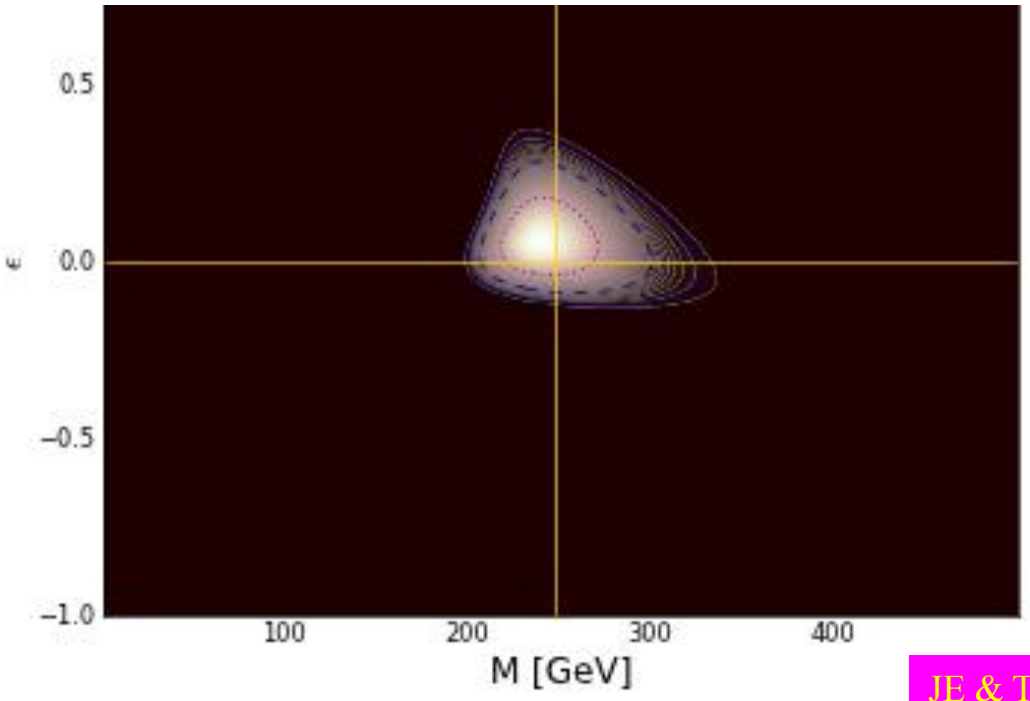
- Does it have spin 0 or 2?
  - **Spin 2 seems unlikely, but needs experimental checks**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar disfavoured by experiment**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
- Quantum (loop) corrections?
- What are its self-couplings?

It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

Global fit



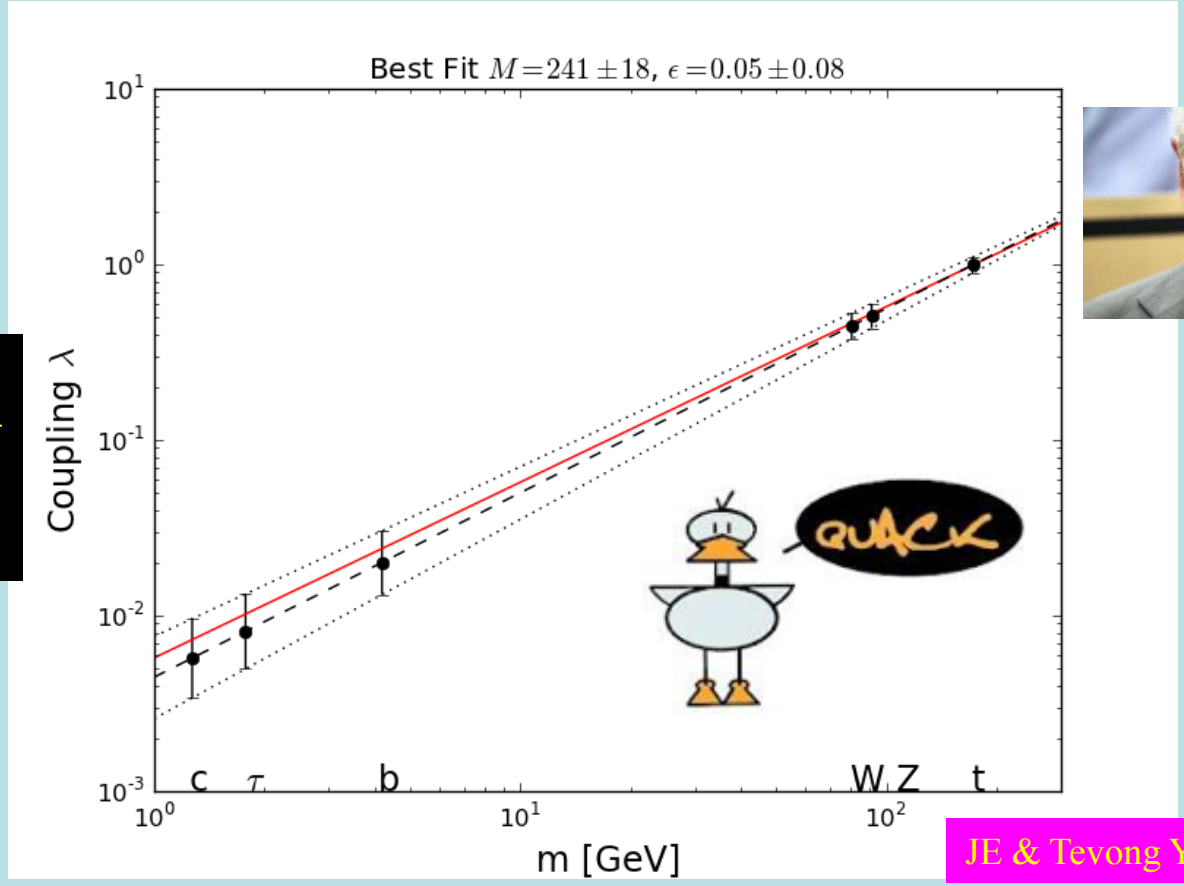
JE & Tevong You, arXiv:1207.1693

- Standard Model Higgs: $\varepsilon = 0$, $M = v$

It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

Global fit



JE & Tevong You, arXiv:1207.1693

- **Red line = SM**, dashed line = best fit

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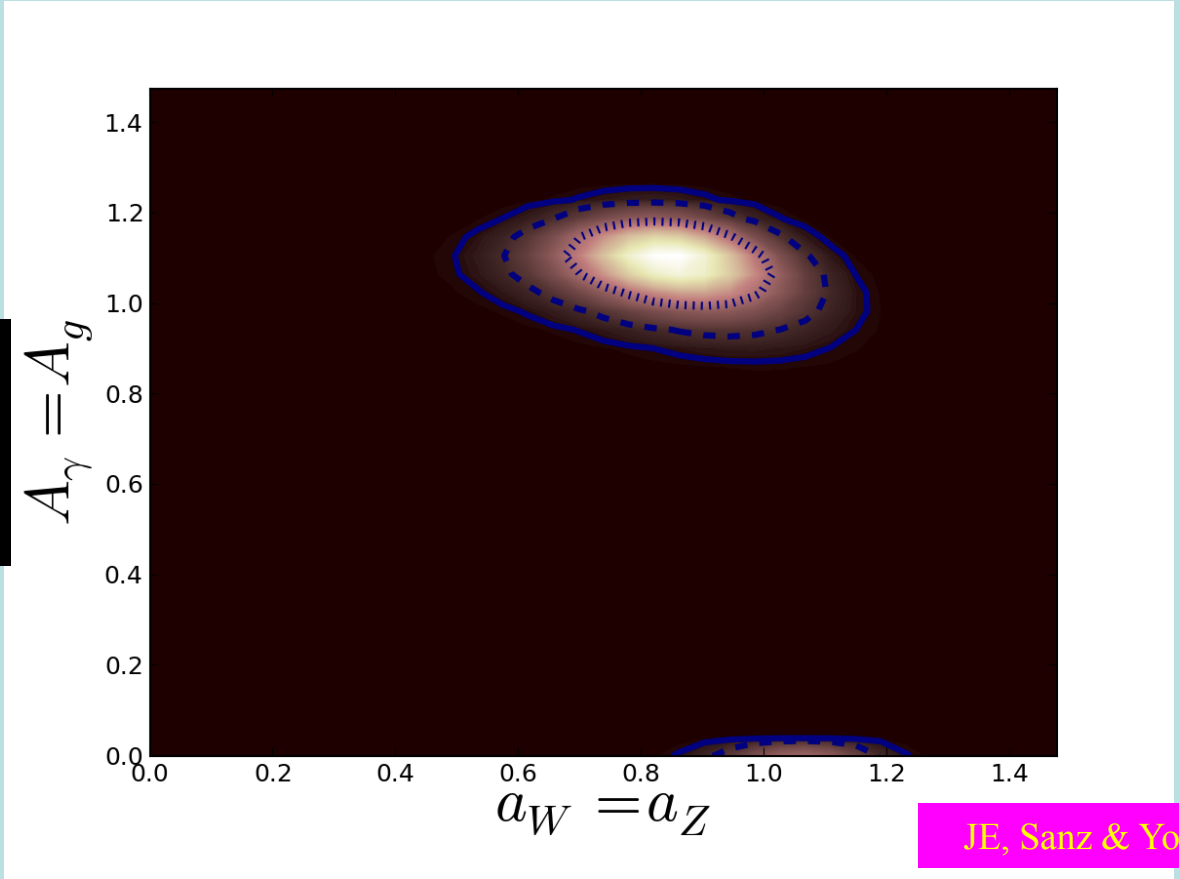
  - **Some *prima facie* evidence that it does**
- Quantum (loop) corrections?
- What are its self-couplings?

Loop Corrections ?

- Experimental limits on anomaly coefficients

Global fit



JE, Sanz & You, arXiv:1211.3068

- Anomalous triangle diagrams > Standard Model?

What is it ?

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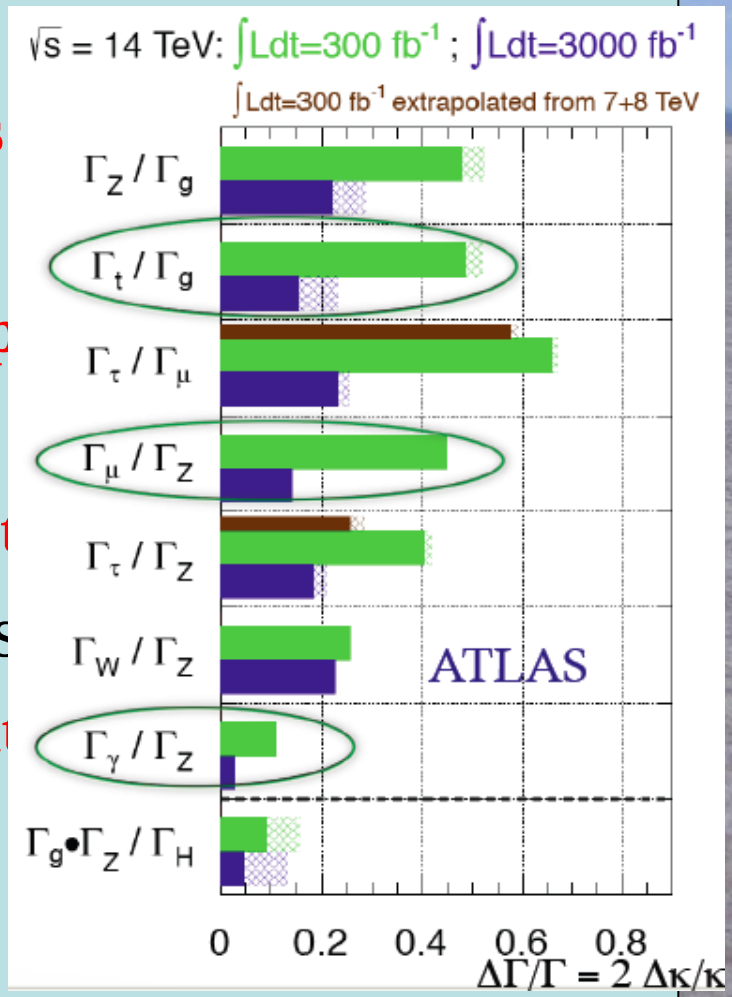
- Is it scalar or pseudoscalar?
  - **Pseudoscalar disfavoured by exp**
- Is it elementary or composite?
  - **No significant deviations from St**
- Does it couple to particle masses
  - **Some *prima facie* evidence that it**
- Quantum (loop) corrections?
  - **γγ coupling > Standard Model?**
- What are its self-couplings?



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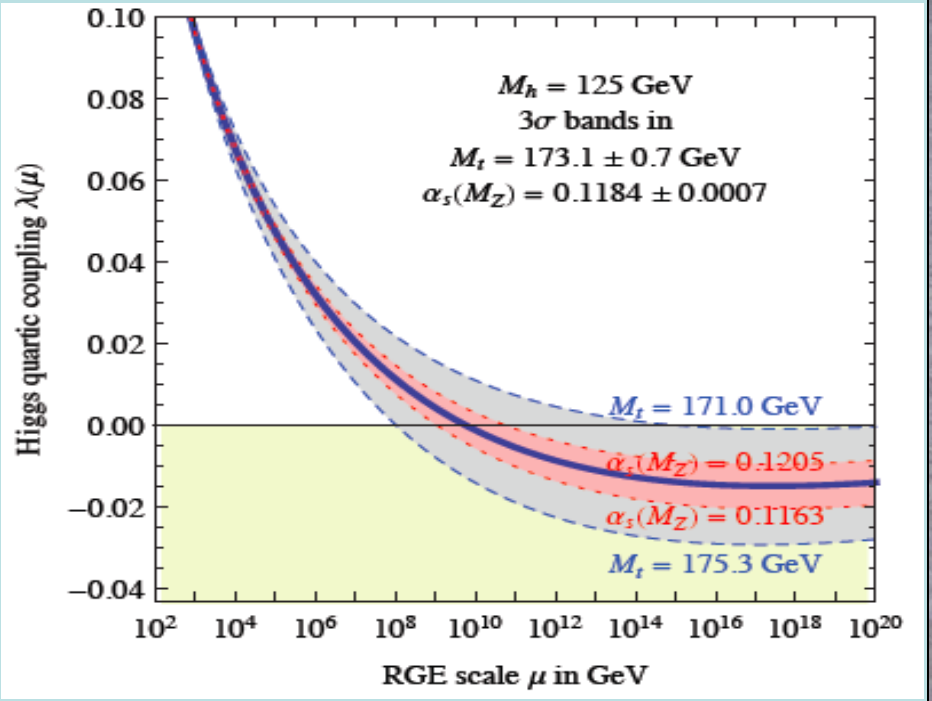
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
  - **Some *prima facie* evidence that it does**
- Quantum (loop) corrections?
  - **$\gamma\gamma$ coupling > Standard Model?**
- What are its self-couplings? **Wait for HL/E-LHC …?**

Theoretical Constraints on Higgs Mass

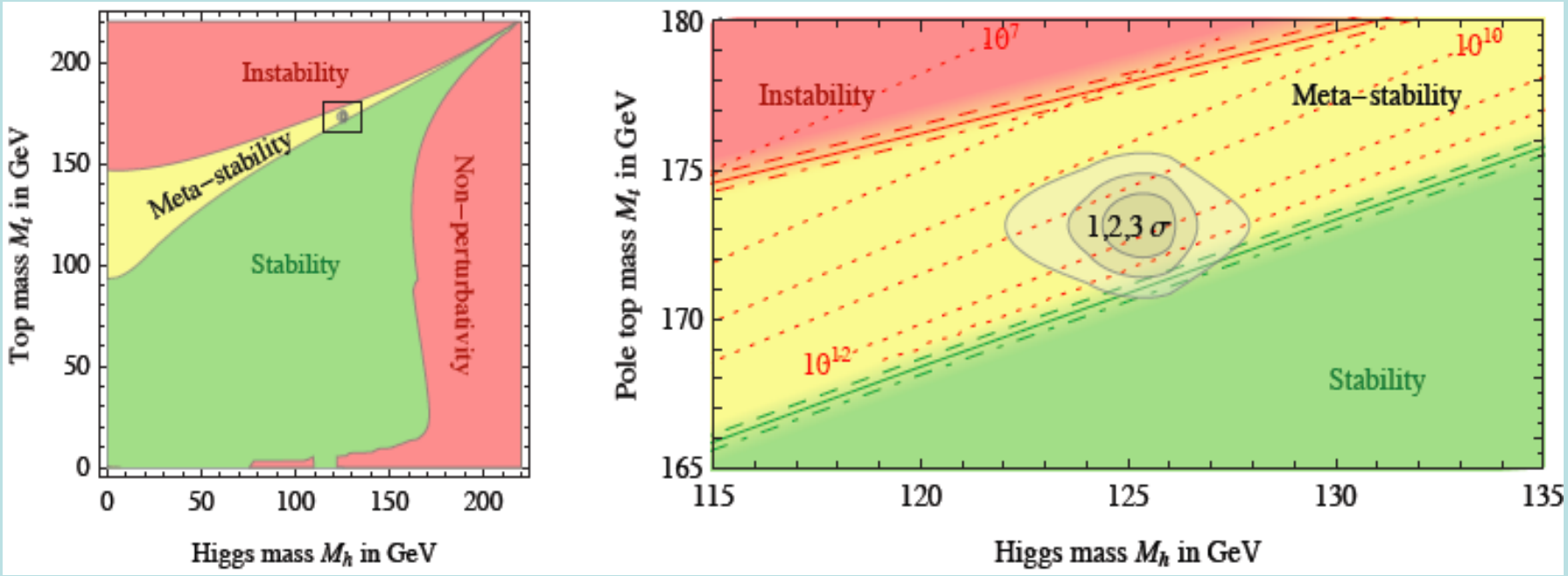
- Large M_h → large self-coupling → blow up at low-energy scale Λ due to renormalization
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable
- Vacuum could be stabilized by **Supersymmetry**



Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H



- Present vacuum probably metastable with lifetime >> age of the Universe

Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

The Stakes in the Higgs Search

- How is gauge symmetry broken?
- Is there any elementary scalar field?
- **Likely portal to new physics**
- 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!**

Supersymmetry?

- Would unify matter particles and force particles
- Related particles spinning at different rates

  0 - ½ - 1 - 3/2 - 2

  Higgs - Electron - Photon - Gravitino - Graviton

  (Every particle is a 'ballet dancer')
- Would help fix particle masses
- Would help unify forces
- Predicts light Higgs boson
- **Could provide dark matter for the astrophysicists and cosmologists**

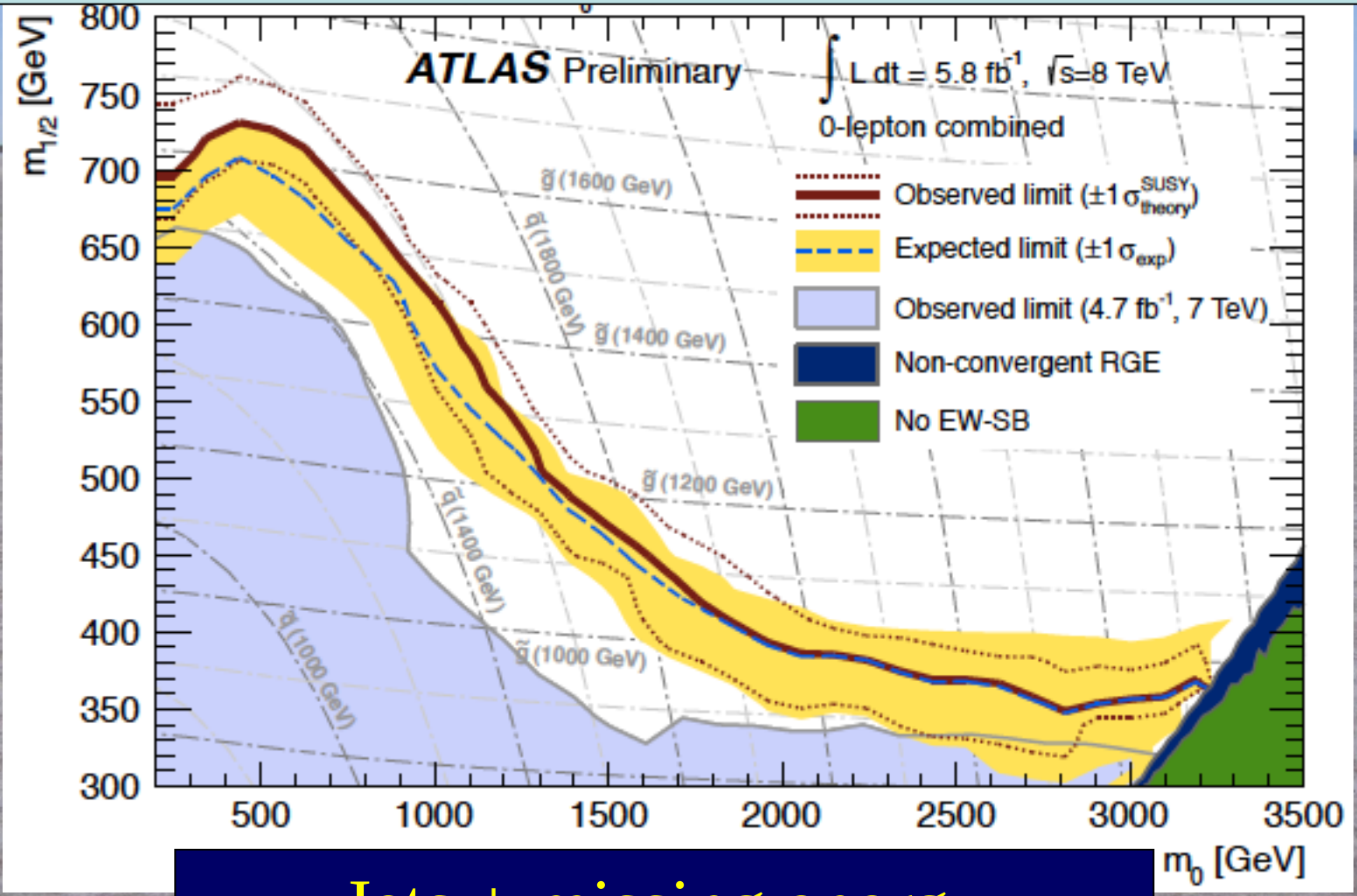
Data

- **Electroweak precision observables**
- **Flavour physics observables**
- g_μ - 2
- Higgs mass
- Dark matter
- **LHC**

MasterCode: O.Buchmueller, JE et al.

Observable	Source Th./Ex.	Constraint
m_t [GeV]	[39]	173.2 ± 0.90
$\Delta\alpha^{(5)}_{\rm had}(m_Z)$	[38]	0.02749 ± 0.00010
M_Z [GeV]	[40]	91.1875 ± 0.0021
Γ_Z [GeV]	[24] / [40]	$2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$
$\sigma^0_{\rm had}$ [nb]	[24] / [40]	41.540 ± 0.037
R_l	[24] / [40]	20.767 ± 0.025
$A_{\rm fb}(\ell)$	[24] / [40]	0.01714 ± 0.00095
$A_\ell(P_\tau)$	[24] / [40]	0.1465 ± 0.0032
$R_{\rm b}$	[24] / [40]	0.21629 ± 0.00066
$R_{\rm c}$	[24] / [40]	0.1721 ± 0.0030
$A_{\rm fb}(b)$	[24] / [40]	0.0992 ± 0.0016
$A_{\rm fb}(c)$	[24] / [40]	0.0707 ± 0.0035
A_b	[24] / [40]	0.923 ± 0.020
A_c	[24] / [40]	0.670 ± 0.027
A_ℓ(SLD)	[24] / [40]	0.1513 ± 0.0021
$\sin^2\theta^\ell_{\rm w}(Q_{\rm fb})$	[24] / [40]	0.2324 ± 0.0012
M_W [GeV]	[24] / [40]	$80.399 \pm 0.023 \pm 0.010_{\rm SUSY}$
$BR^{EXP}_{b\to s\gamma}/BR^{SM}_{b\to s\gamma}$	[41] / [42]	$1.117 \pm 0.076_{\rm EXP} \pm 0.082_{\rm SM} \pm 0.050_{\rm SUSY}$
$BR(B_s \to \mu^+\mu^-)$	[27] / [37]	$(< 1.08 \pm 0.02_{\rm SUSY}) \times 10^{-8}$
$BR^{EXP}_{B\to\tau\nu}/BR^{SM}_{B\to\tau\nu}$	[27] / [42]	$1.43 \pm 0.43_{\rm EXP+TH}$
$BR(B_d \to \mu^+\mu^-)$	[27] / [42]	$< (4.6 \pm 0.01_{\rm SUSY}) \times 10^{-9}$
$BR^{EXP}_{B\to X_s\ell\ell}/BR^{SM}_{B\to X_s\ell\ell}$	[43]/ [42]	0.99 ± 0.32
$BR^{EXP}_{K\to\mu\nu}/BR^{SM}_{K\to\mu\nu}$	[27] / [44]	$1.008 \pm 0.014_{\rm EXP+TH}$
$BR^{EXP}_{K\to\pi\nu\bar\nu}/BR^{SM}_{K\to\pi\nu\bar\nu}$	[45]/ [46]	< 4.5
$\Delta M^{EXP}_{B_s}/\Delta M^{SM}_{B_s}$	[45] / [47,48]	$0.97 \pm 0.01_{\rm EXP} \pm 0.27_{\rm SM}$
$\frac{(\Delta M^{EXP}_{B_s}/\Delta M^{SM}_{B_s})}{(\Delta M^{EXP}_{B_d}/\Delta M^{SM}_{B_d})}$	[27] / [42,47,48]	$1.00 \pm 0.01_{\rm EXP} \pm 0.13_{\rm SM}$
$\Delta\epsilon^{EXP}_K/\Delta\epsilon^{SM}_K$	[45] / [47,48]	$1.08 \pm 0.14_{\rm EXP+TH}$
$a^{EXP}_\mu - a^{SM}_\mu$	[49] / [38,50]	$(30.2 \pm 8.8 \pm 2.0_{\rm SUSY}) \times 10^{-10}$
M_h [GeV]	[26] / [51,52]	$> 114.4 \pm 1.5_{\rm SUSY}$
$\Omega_{\rm CDM}h^2$	[29] / [53]	$0.1109 \pm 0.0056 \pm 0.012_{\rm SUSY}$
$\sigma^{\rm SI}_p$	[23]	$(m_{\tilde\chi^0_1}, \sigma^{\rm SI}_p)$ plane
jets $+\not{E}_T$	[16,18]	$(m_0, m_{1/2})$ plane
$H/A, H^\pm$	[19]	$(M_A, \tan\beta)$ plane

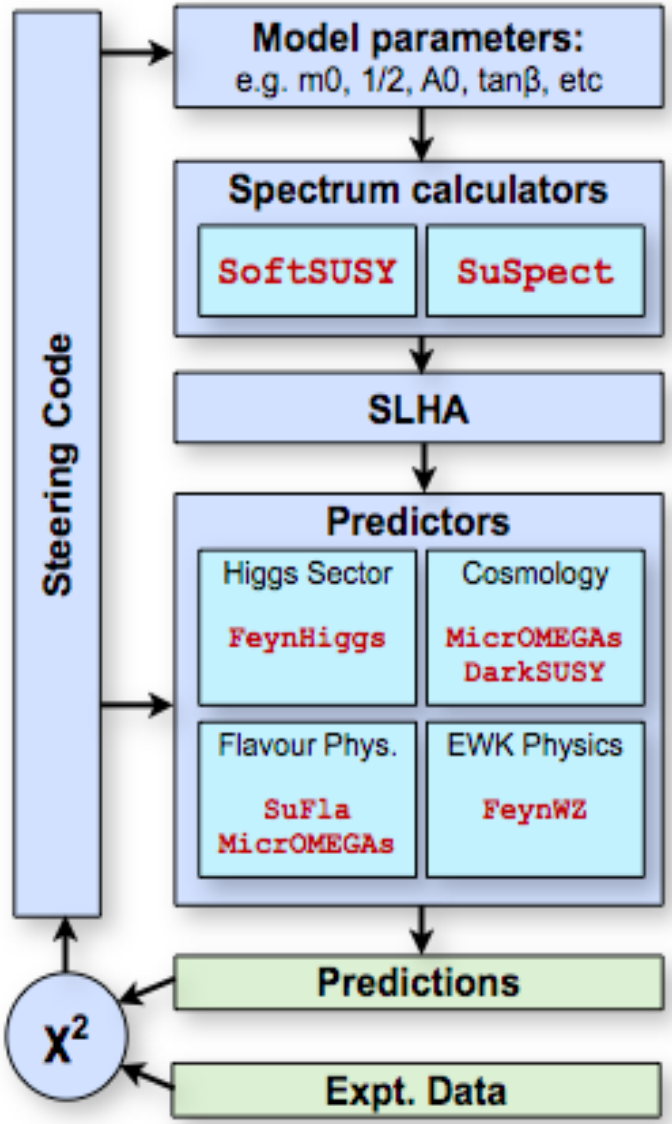
Search with ~ 5/fb @ 8 TeV



Jets + missing energy

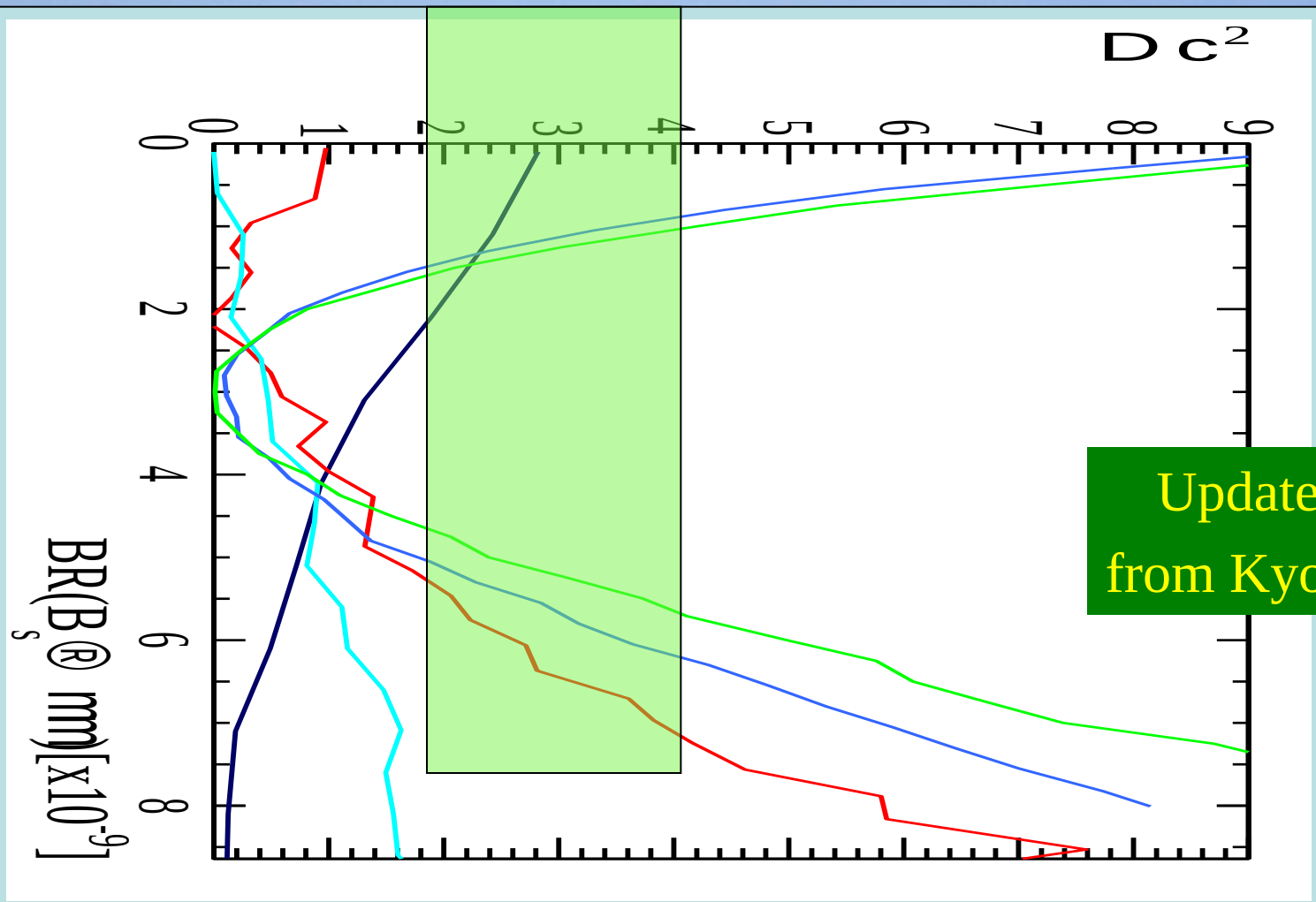
MasterCode

- **Combines diverse set of tools**
  - different codes : all state-of-the-art
    - Electroweak Precision (`FeynWZ`)
    - Flavour (`SuFla`, `micrOMEGAs`)
    - Cold Dark Matter (`DarkSUSY`, `micrOMEGAs`)
    - Other low energy (`FeynHiggs`)
    - Higgs (`FeynHiggs`)
  - different precisions (one-loop, two-loop, etc)
  - different languages (Fortran, C++, English, German, Italian, etc)
  - different people (theorists, experimentalists)
- **Compatibility is crucial! Ensured by**
  - close collaboration of tools authors
  - standard interfaces



O. Buchmueller, R. Cavanaugh, *M. Citron*, A. De Roeck, M.J. Dolan, J.E., H. Flacher, S. Heinemeyer, G. Isidori, J. Marrouche, D. Martinez Santos, *S. Nakach*, K.A. Olive, *S. Rogerson*, F.J. Ronga, *K.J. de Vries*, G. Weiglein

Measurements of $B_s \rightarrow \mu^+\mu^-$

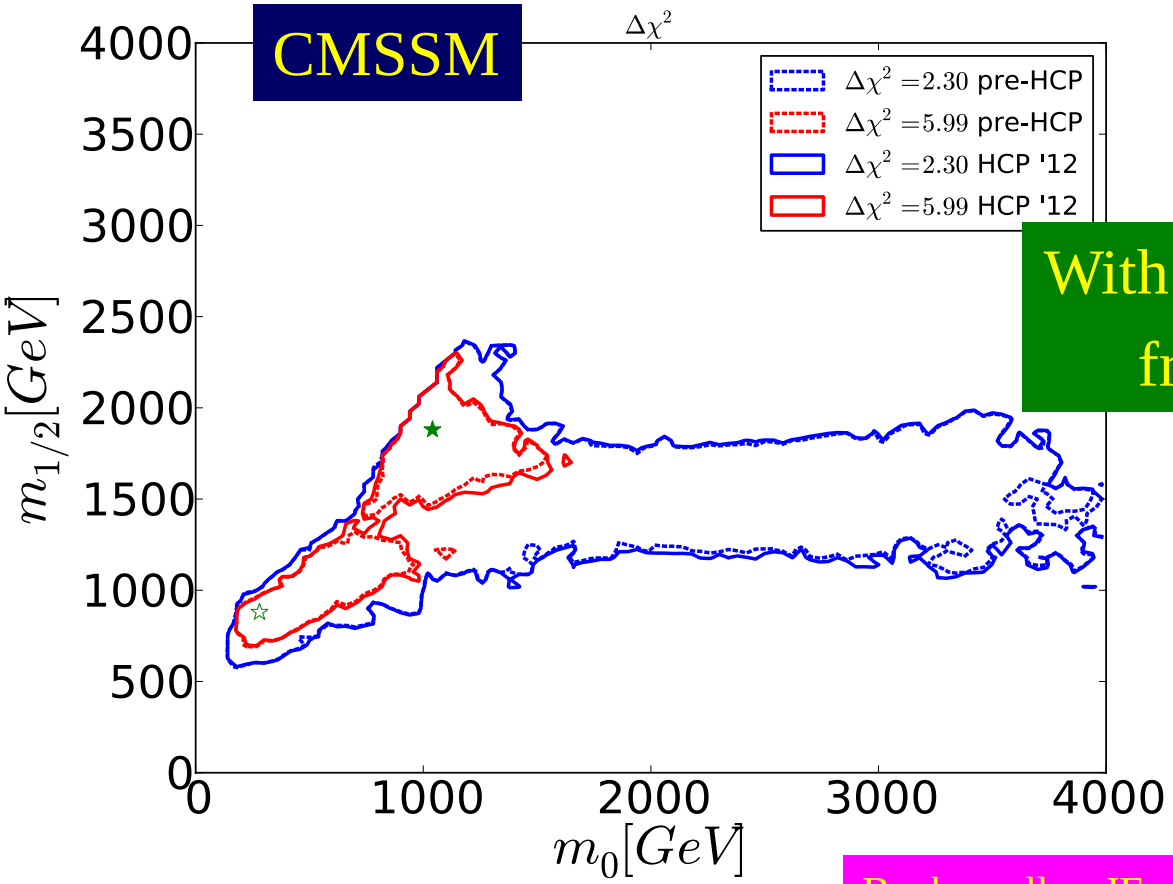


- **LHCb finds ~ (1 ± 0.3) × Standard Model**

Post-LHC, Post-XENON100

masterCode

201 2ATLAS + CMS with 5 fb^{-1} of LHC Data



With LHCb update from Kyoto

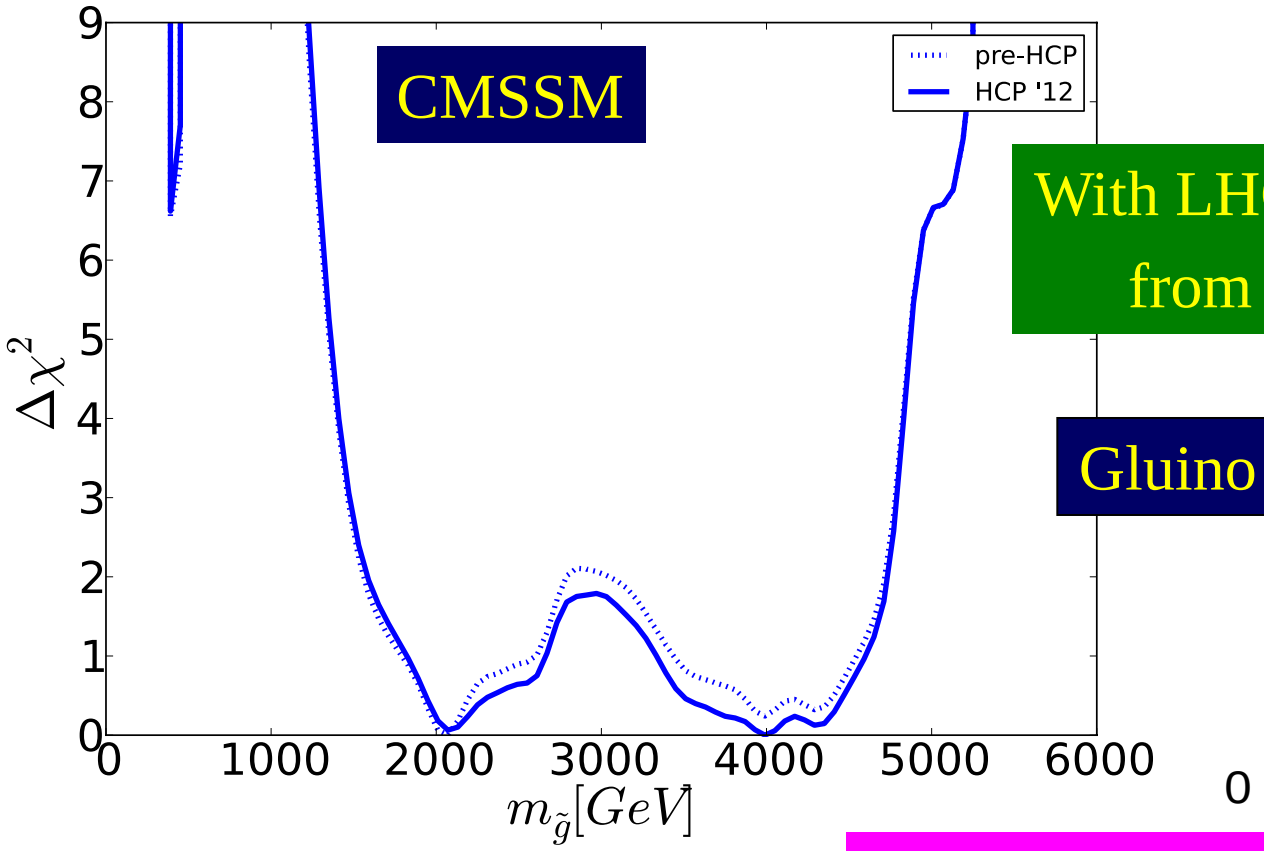
Buchmueller, JE et al: arXiv:1207.3715

Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ★

p-value of simple models < 10%

Post-LHC, Post-XENON100

201 2ATLAS + CMS with 5 fb^{-1} of LHC Data



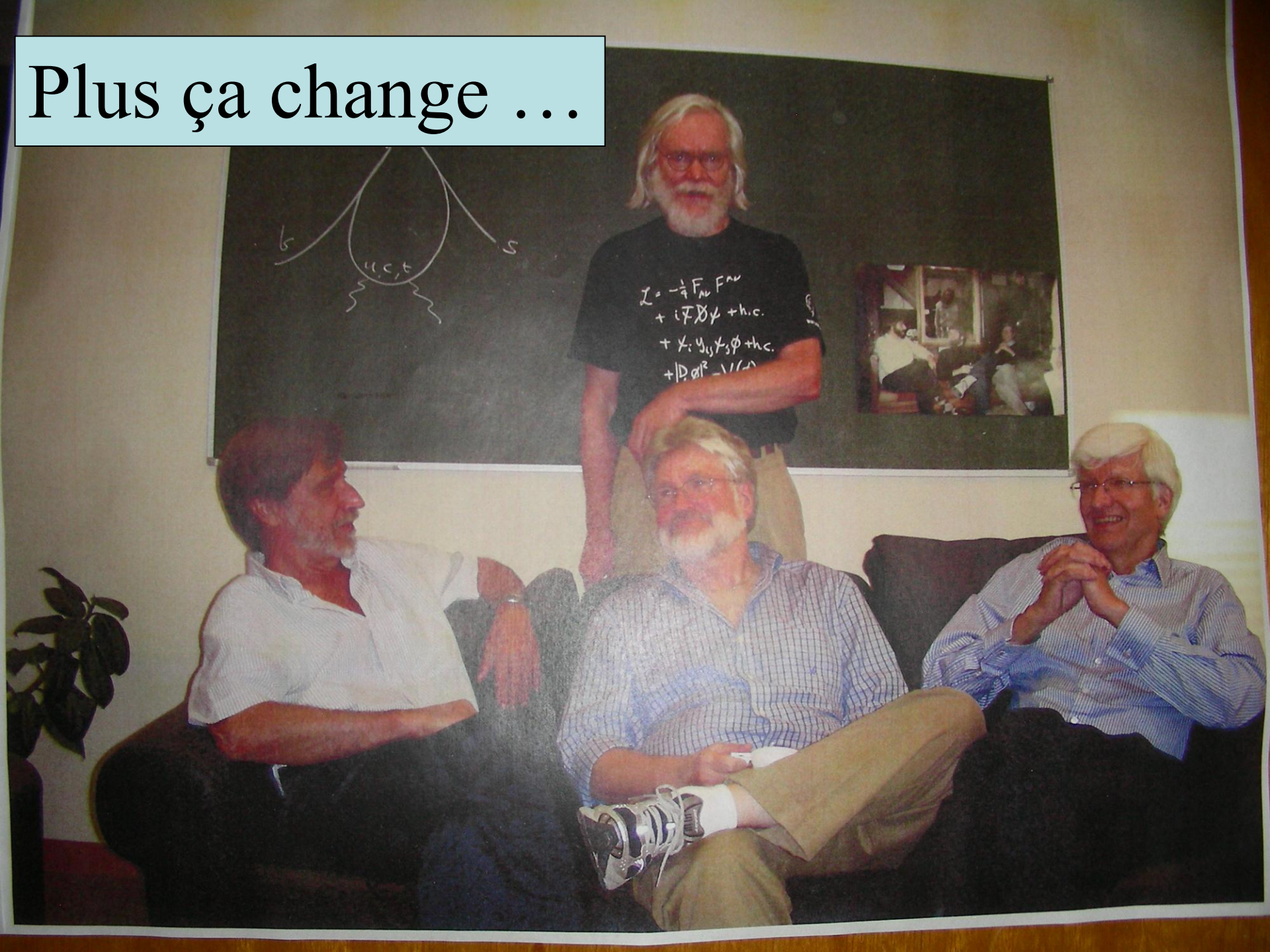
With LHCb update from Kyoto

Gluino mass

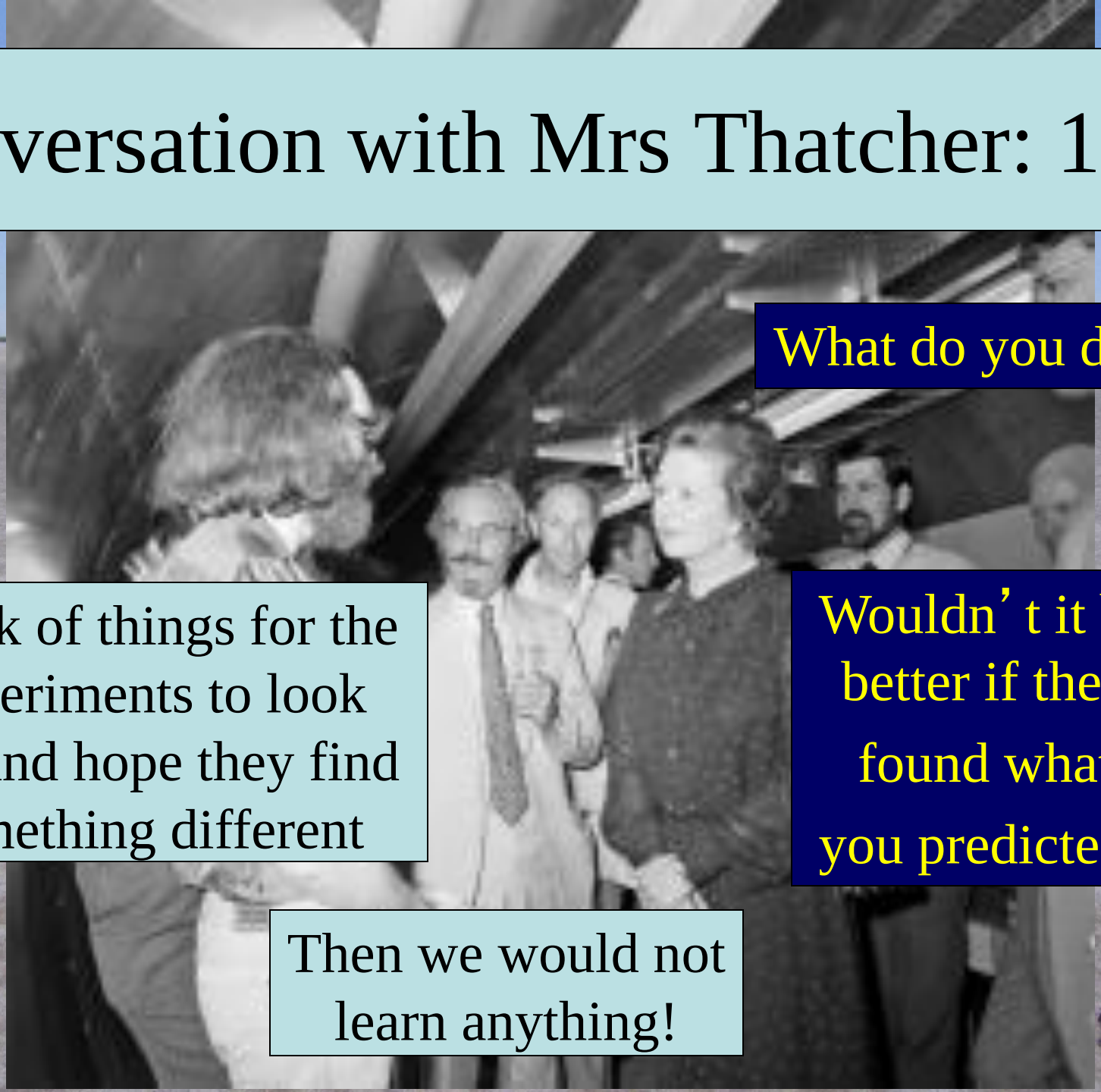
Buchmueller, JE et al: arXiv:1207.3715

Favoured values of gluino mass significantly above pre-LHC, > 1.5 TeV

Plus ça change …



Conversation with Mrs Thatcher: 1982



What do you do?

Think of things for the experiments to look for, and hope they find something different

Wouldn't it be better if they found what you predicted?

Then we would not learn anything!