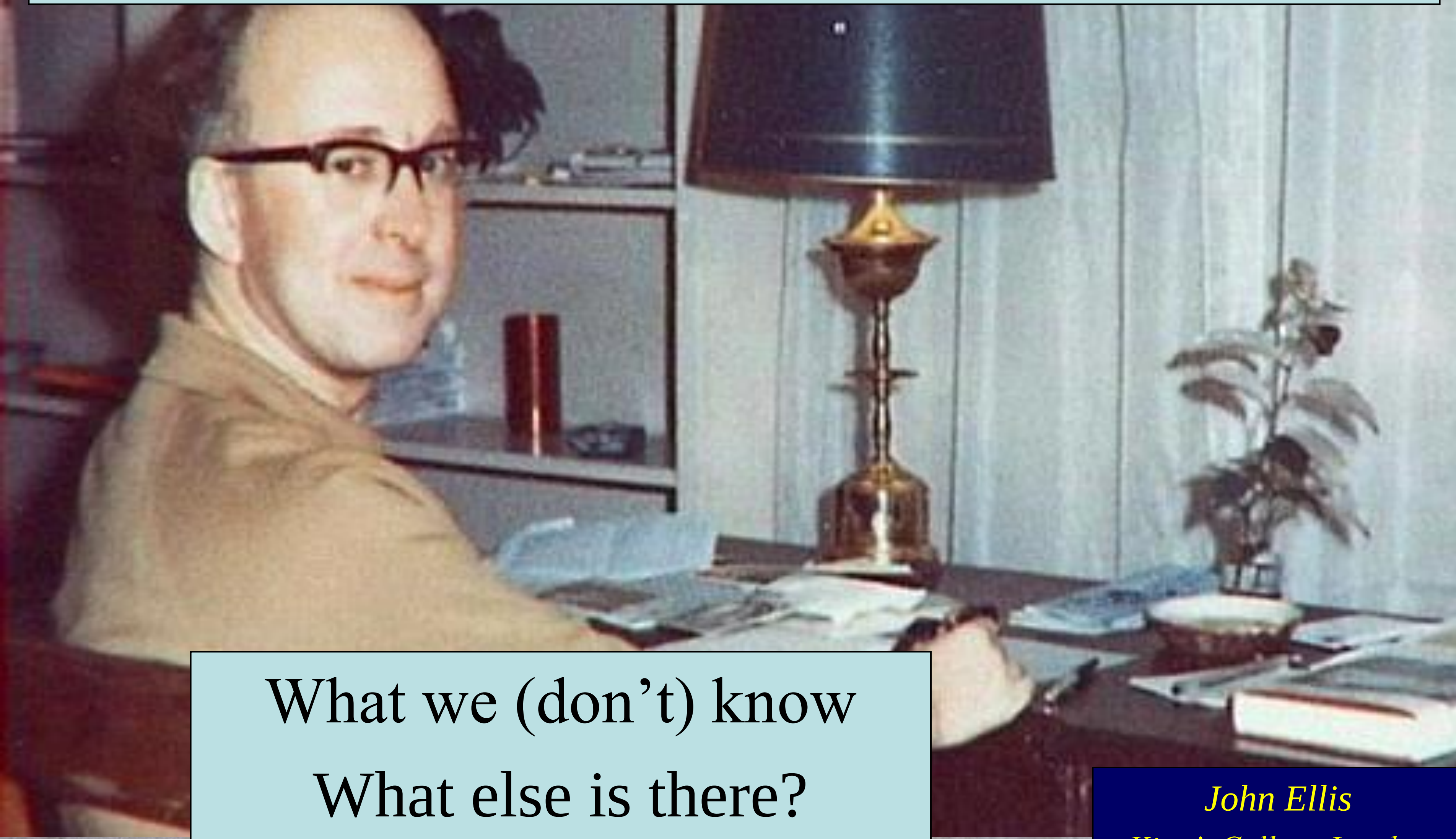
# The Higgs Boson



What we (don’t) know

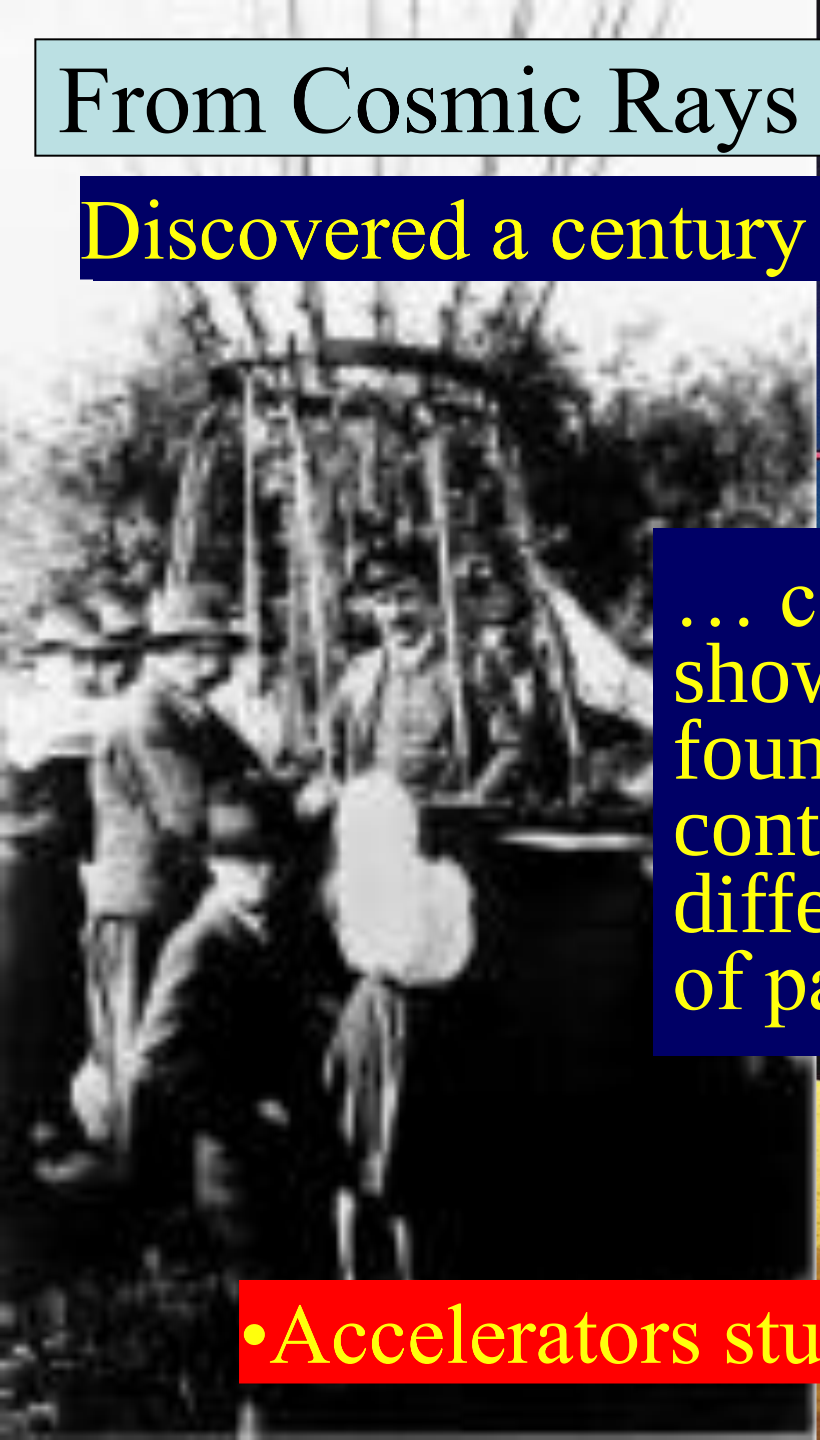
What else is there?

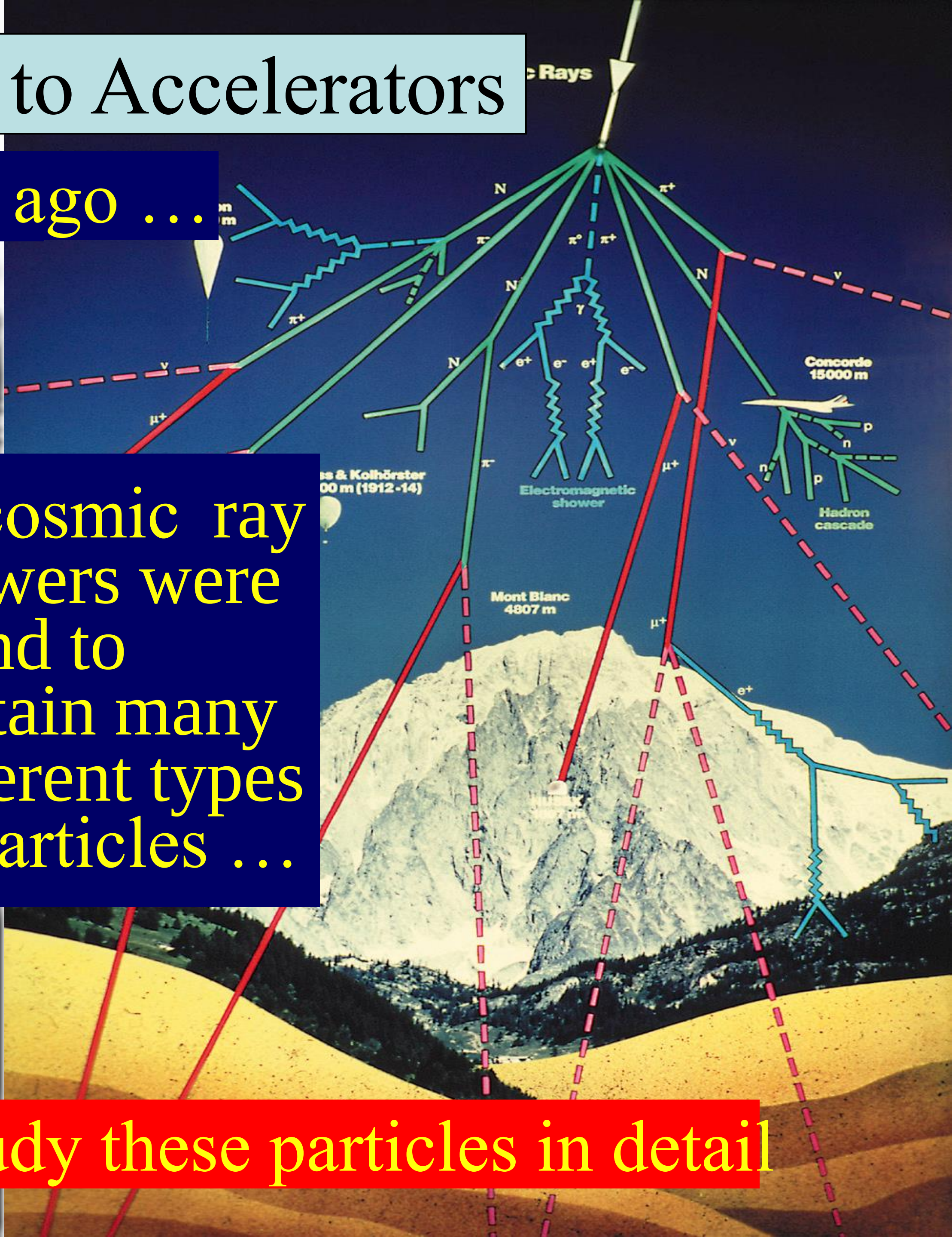
How to discover it?

*John Ellis*
*King’s College London*
*(& CERN)*

# From Cosmic Rays to Accelerators

Discovered a century ago …



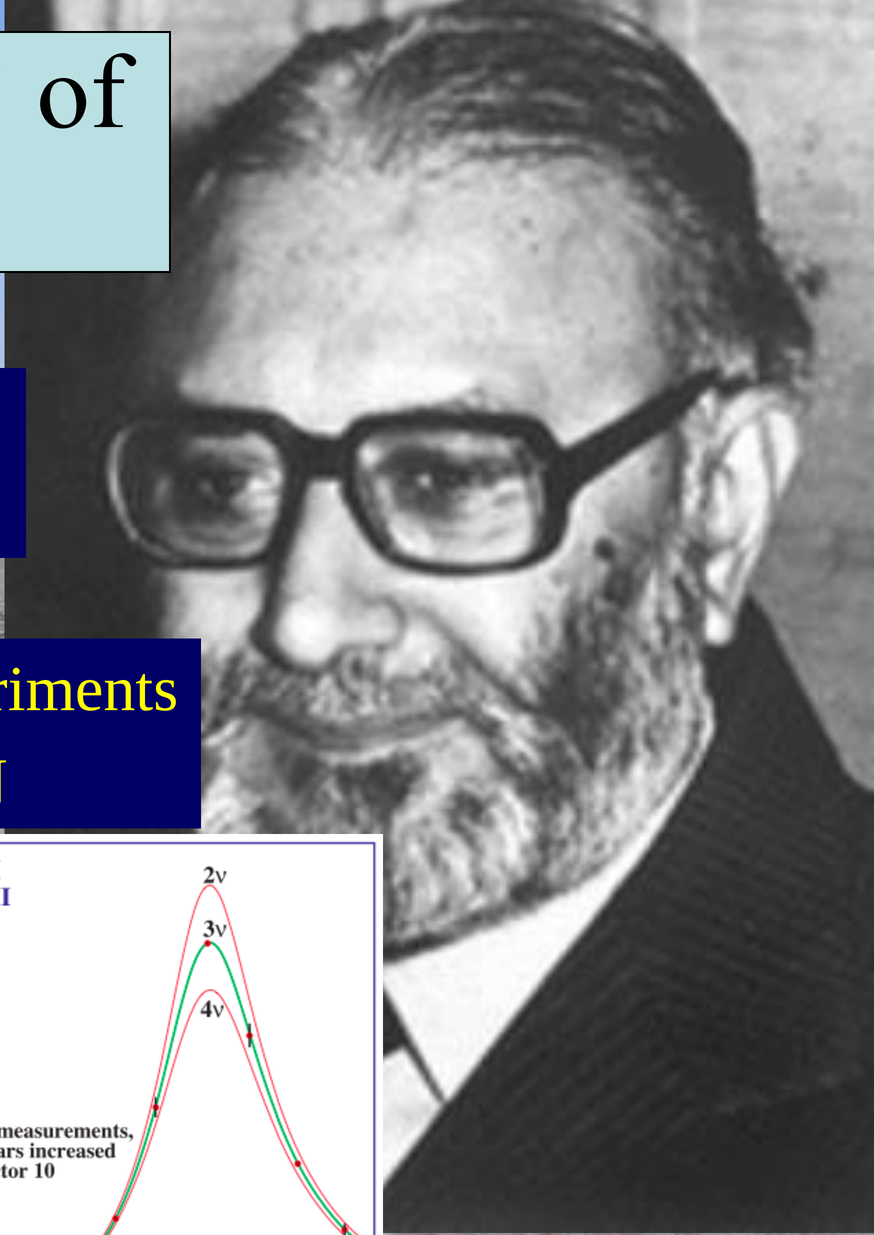



… cosmic ray showers were found to contain many different types of particles …

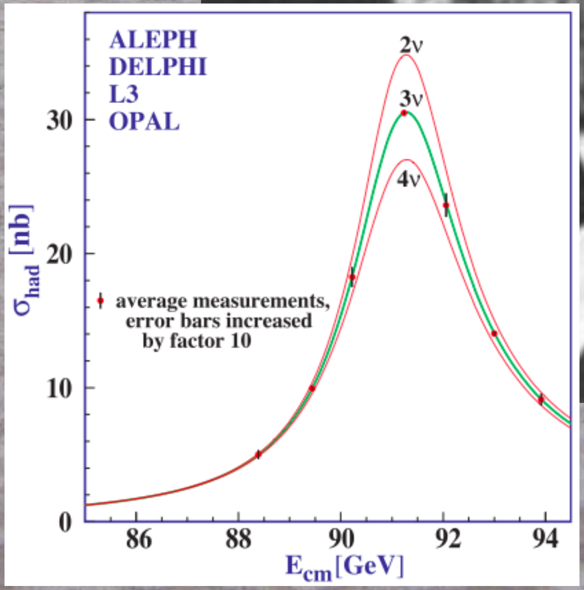
- Accelerators study these particles in detail

# The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow and Weinberg



Tested by experiments at CERN




Perfect agreement between theory and experiments in all laboratories

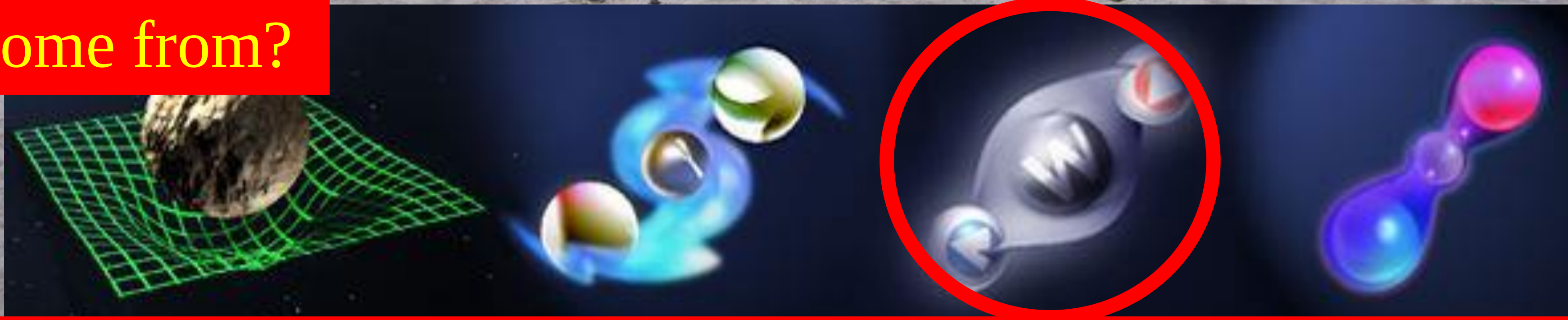
# The ‘Standard Model’

= Cosmic DNA

## The matter particles


Where does mass come from?

## The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

# Why do Things Weigh?

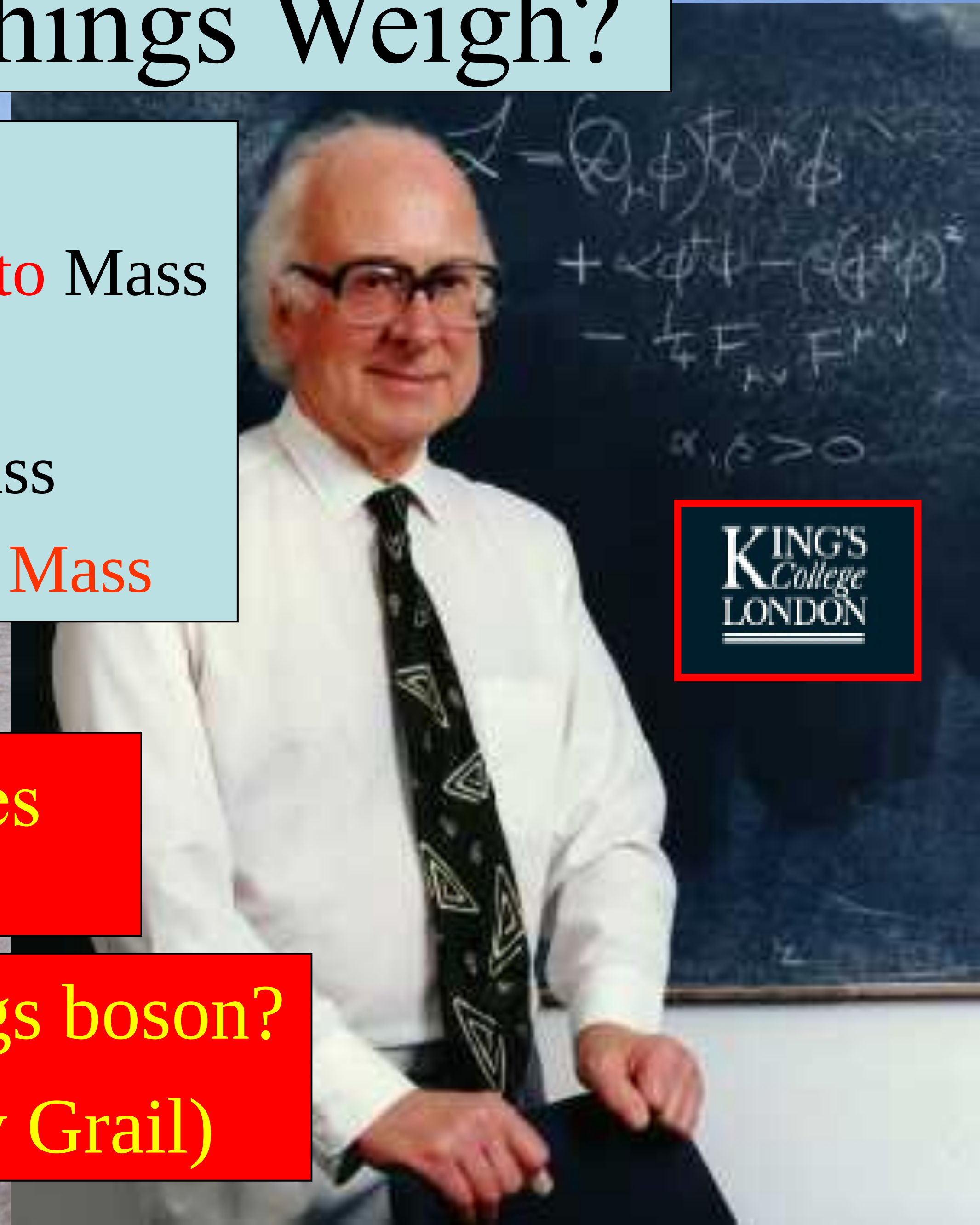
Newton:

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)

# The (NG)AEB**H**GHKMP Mechanism

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 LETTE

BROKEN SYMMETRIES AND THE MASSES OF GA

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

The only one who mentioned a massive scalar boson

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)

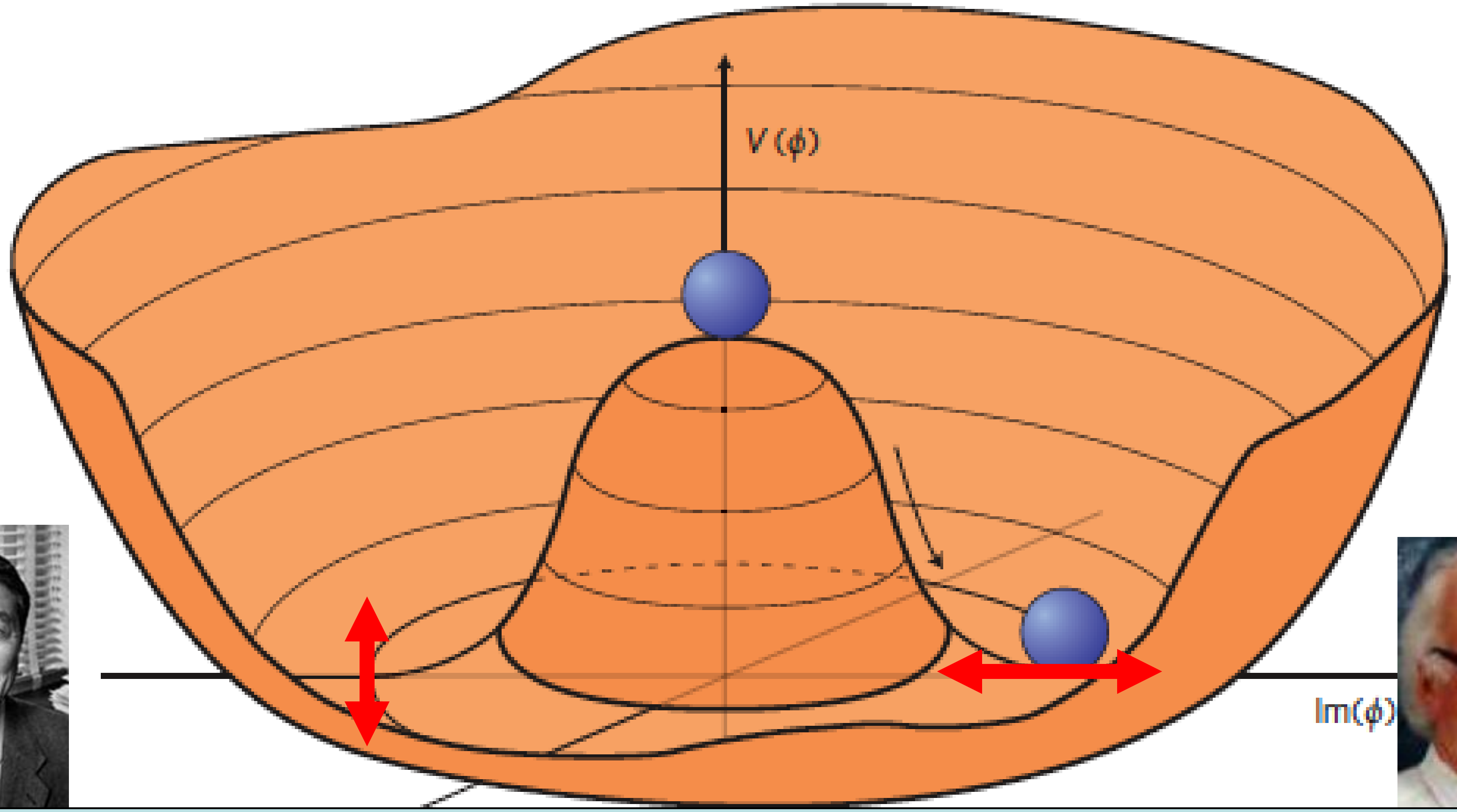
*SPONTANEOUS BREAKDOWN OF STRONG INTERACTION SYMMETRY AND THE ABSENCE OF MASSLESS PARTICLES*

A. A. MIGDAL

Submitted to JETP editor November 30, 1965; resubmitted February 16, 1966
J. Exptl.

The occurrence of massless particles in the presence of spontaneous symmetry breakdown is discussed. By summing all Feynman diagrams, one obtains for the difference of the mass

# Nambu **EB, H, GHK** **and Higgs**

Spontaneous symmetry breaking: massless Nambu-Goldstone boson **'eaten' by massless gauge boson**

**Accompanied by massive particle**

# 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*

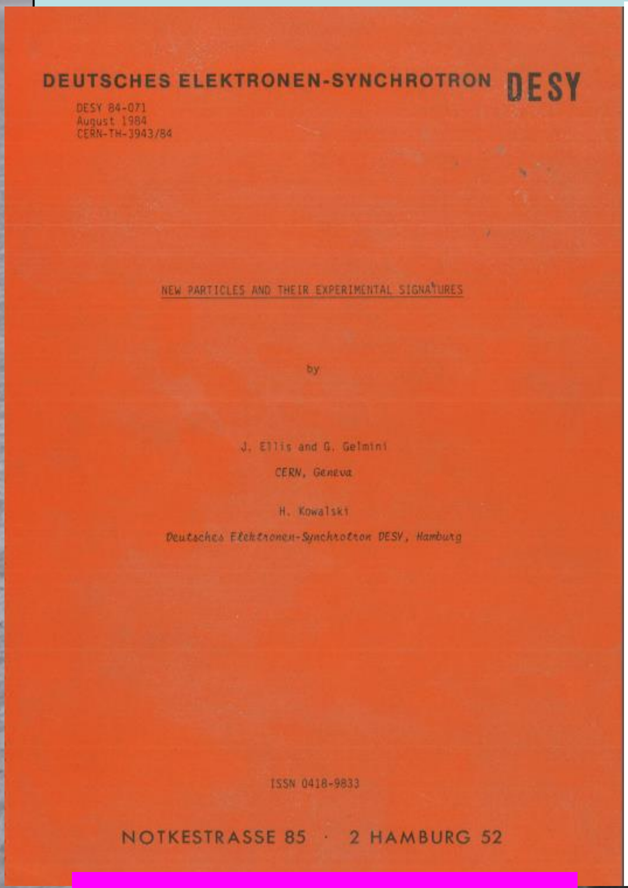
Received 7 November 1975

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.

# A Preview of the Higgs Boson @ LHC

- Prepared for LHC Lausanne workshop 1984


DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 84-071
August 1984
CERN-TH-3943/84

NEW PARTICLES AND THEIR EXPERIMENTAL SIGNATURES

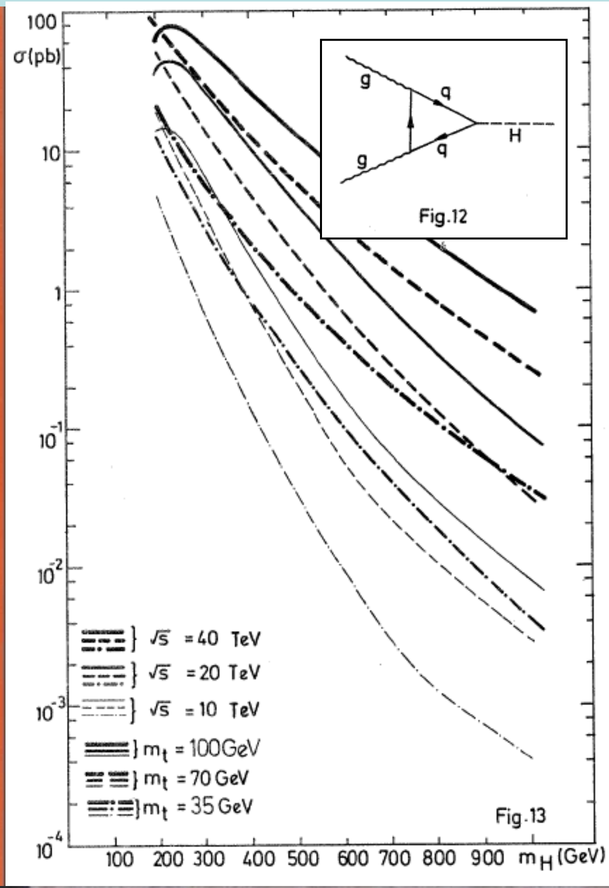
by

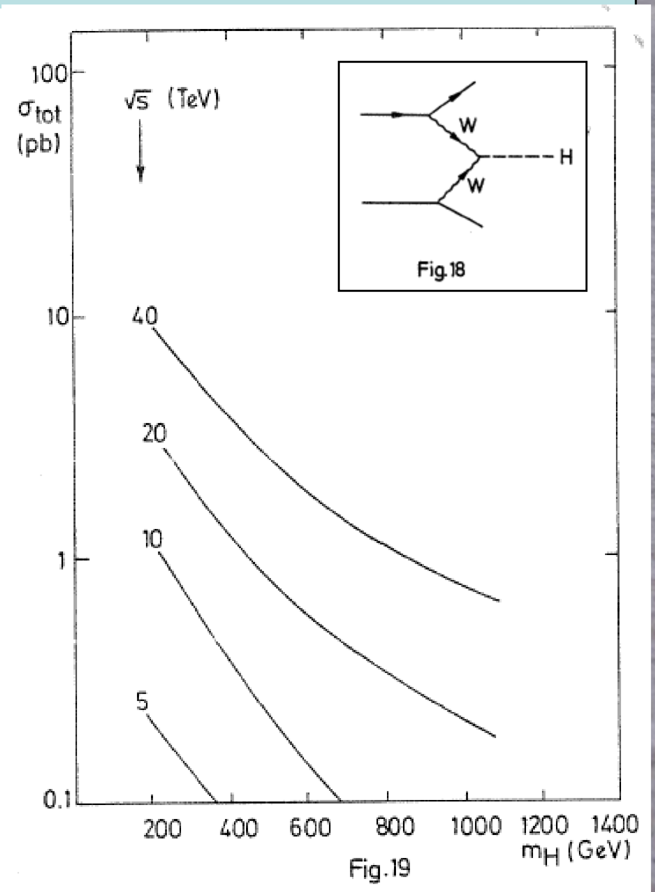
J. Ellis and G. Gelmini
CERN, Geneva

H. Kowalski
Deutsches Elektronen-Synchrotron DESY, Hamburg

ISSN 0418-9833

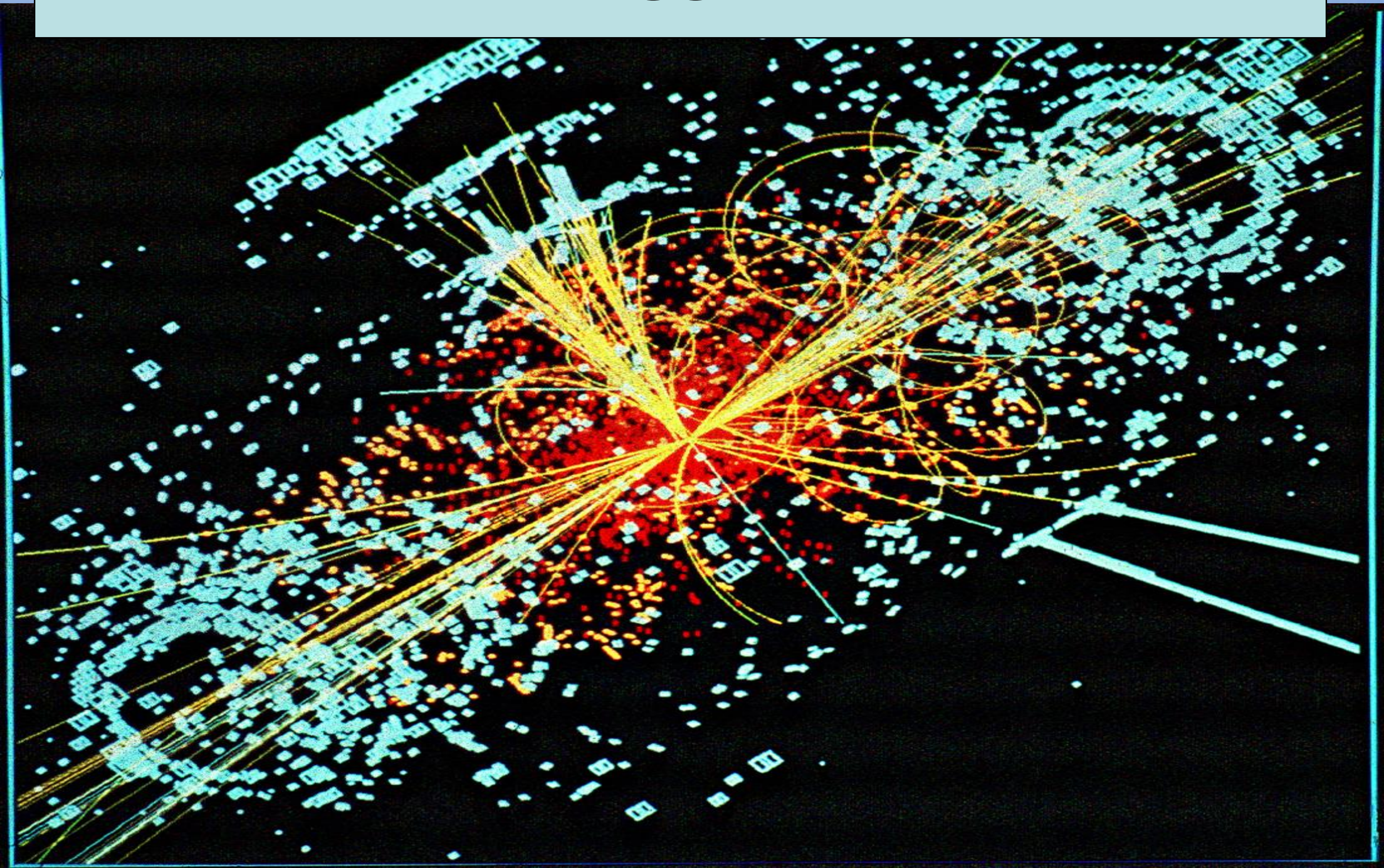
NOTKESTRASSE 85 · 2 HAMBURG 52

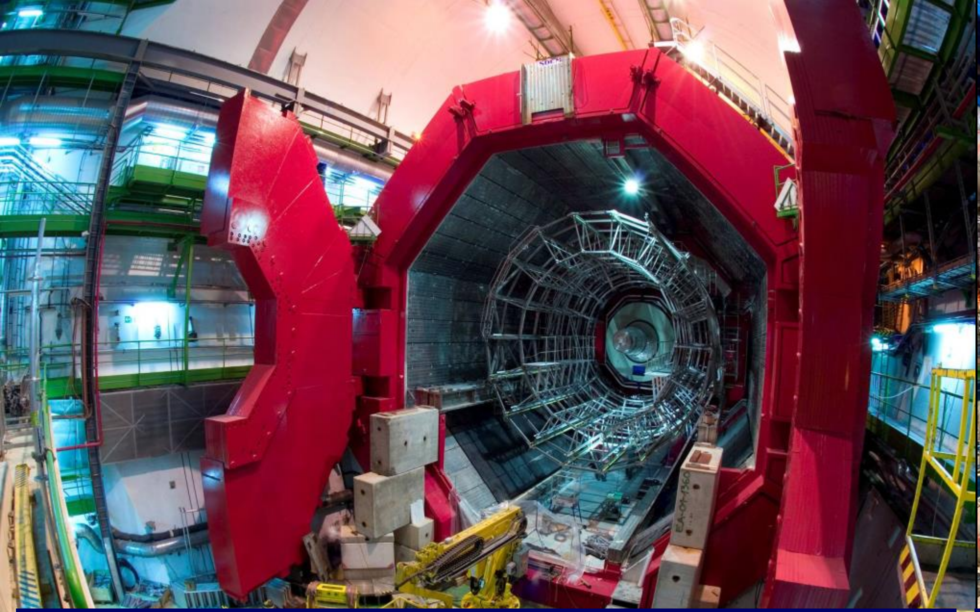


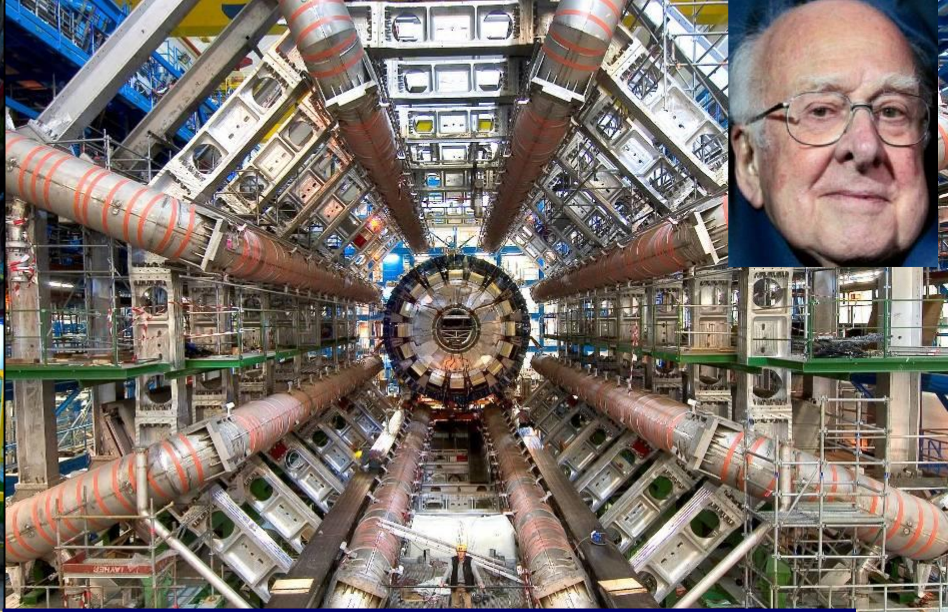

JE, Gelmini & Kowalski, 1984

# A Simulated Higgs Event @ LHC

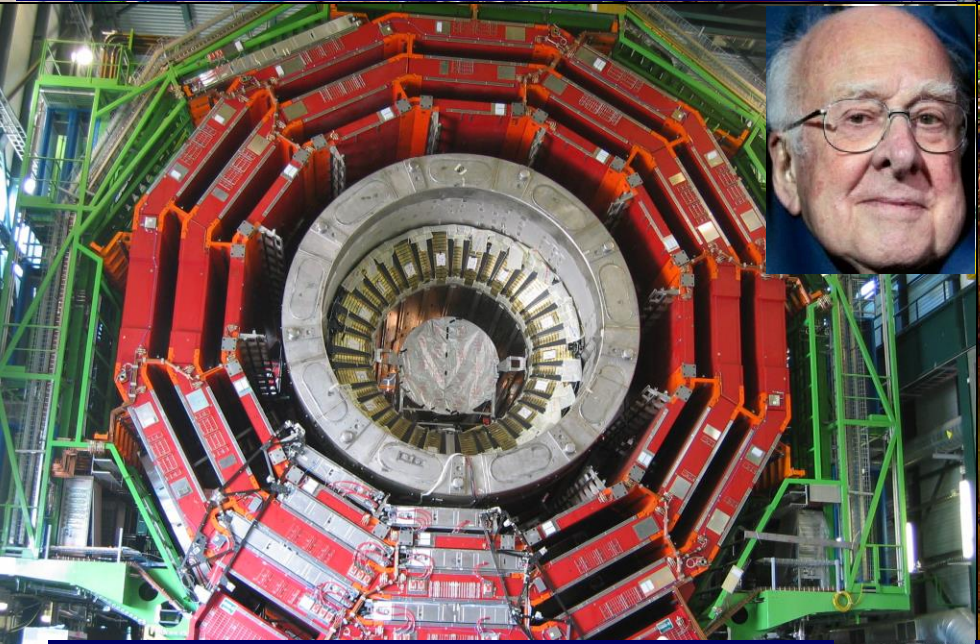




ALICE: Primordial cosmic plasma



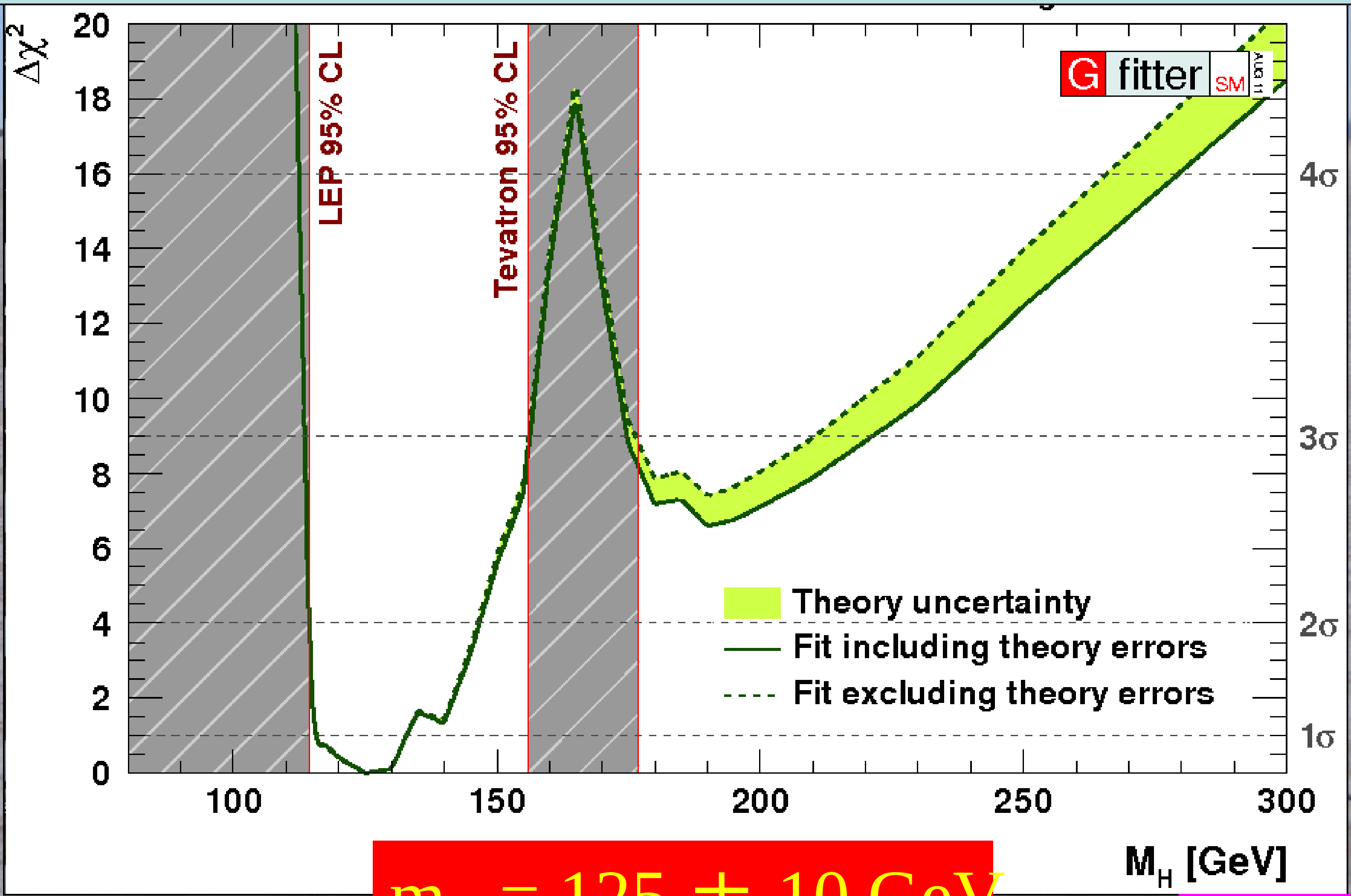
ATLAS: Higgs and dark matter



CMS: Higgs and dark matter

LHCb: Matter-antimatter difference

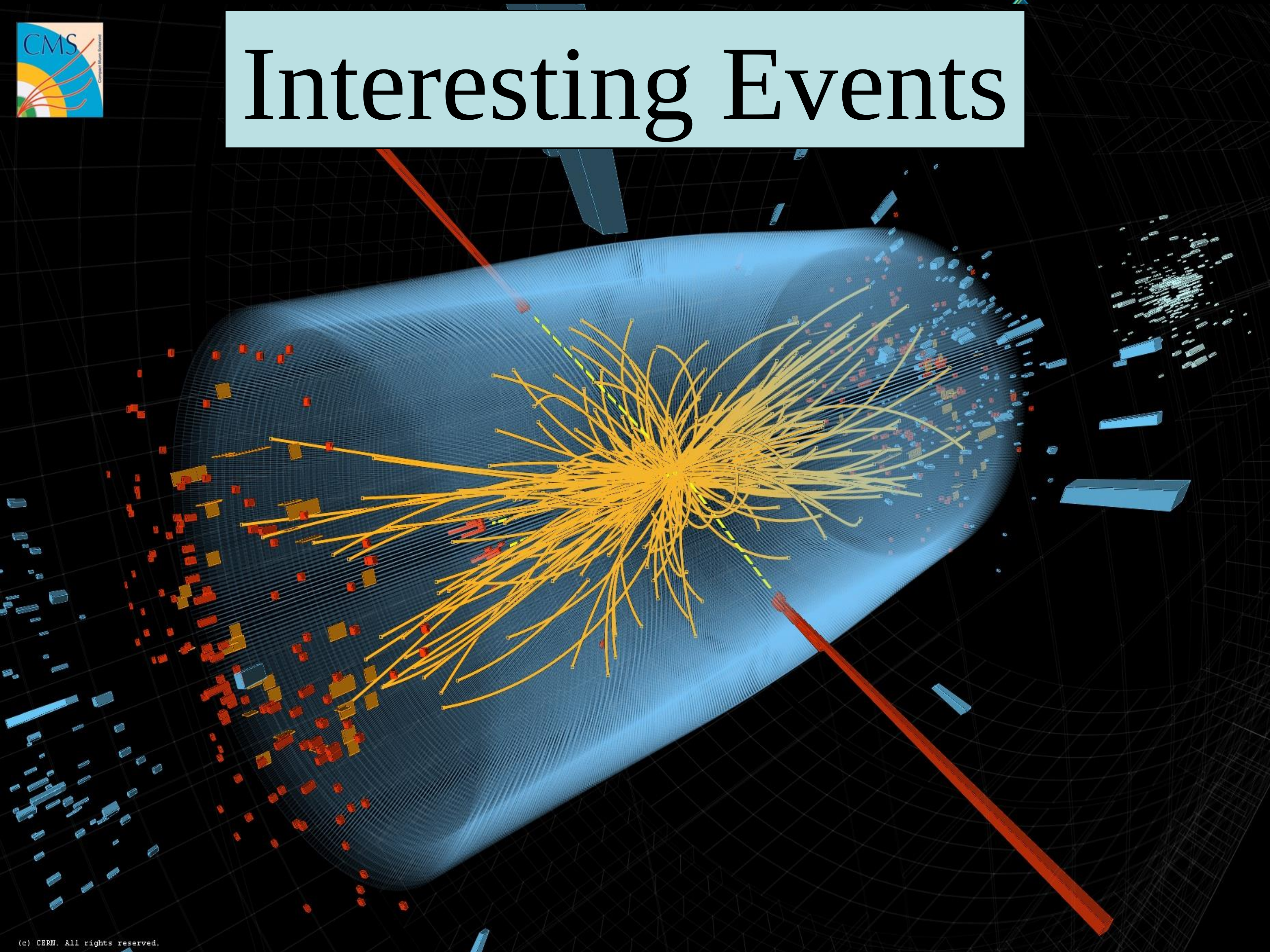
# 2011: Combining Information from Previous Direct Searches and Indirect Data




$m_H = 125 \pm 10$ GeV

Gfitter collaboration

# Interesting Events



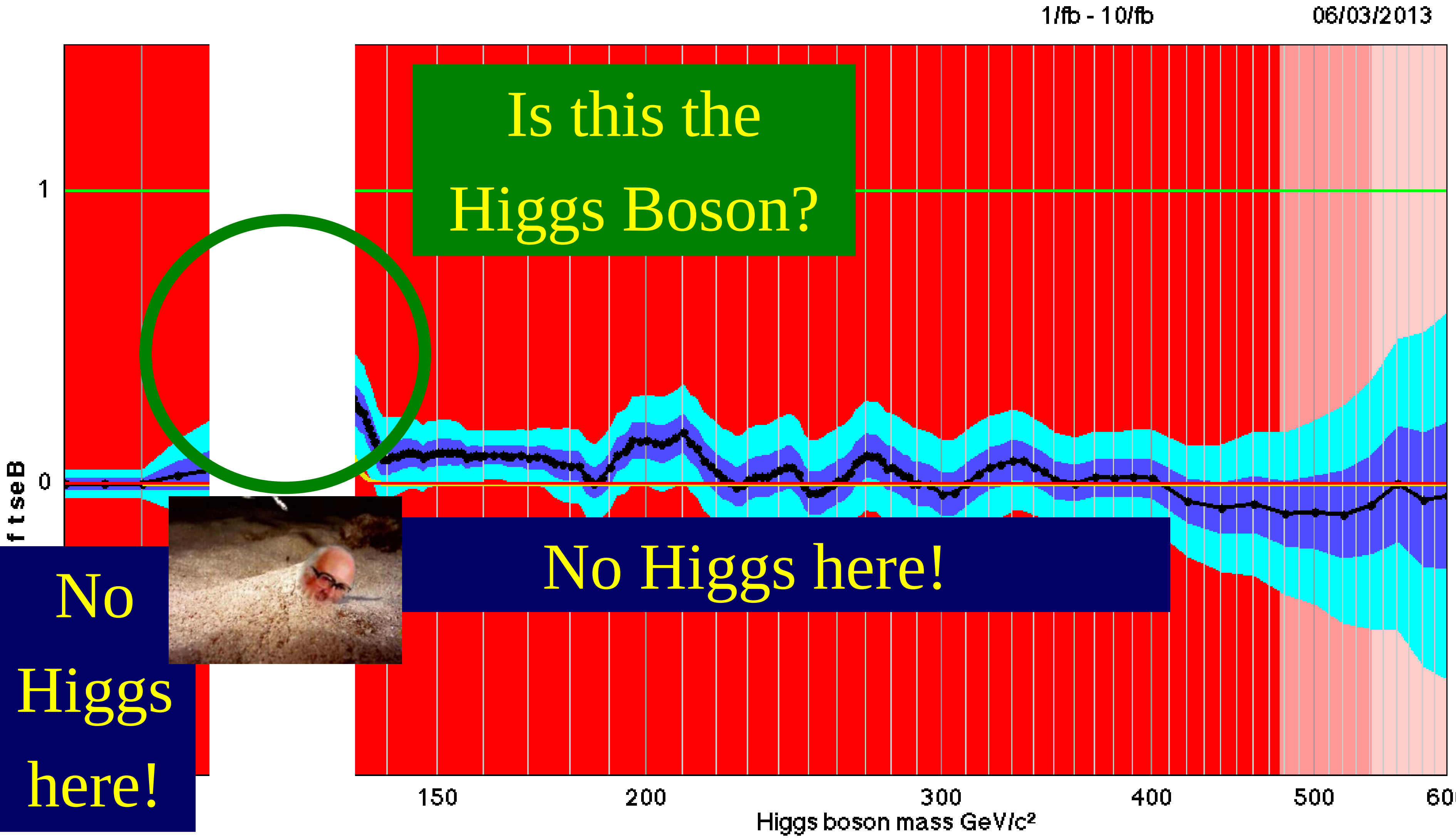
# The Discovery of the Higgs Boson

Mass Higgsteria

# July 4$^{th}$ 2012
# The Higgs discovery

# Higgsdependence Day!

# Unofficial Combination of Higgs Data



# The Particle Higgsaw Puzzle

Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

# Higgs Mass Measurements

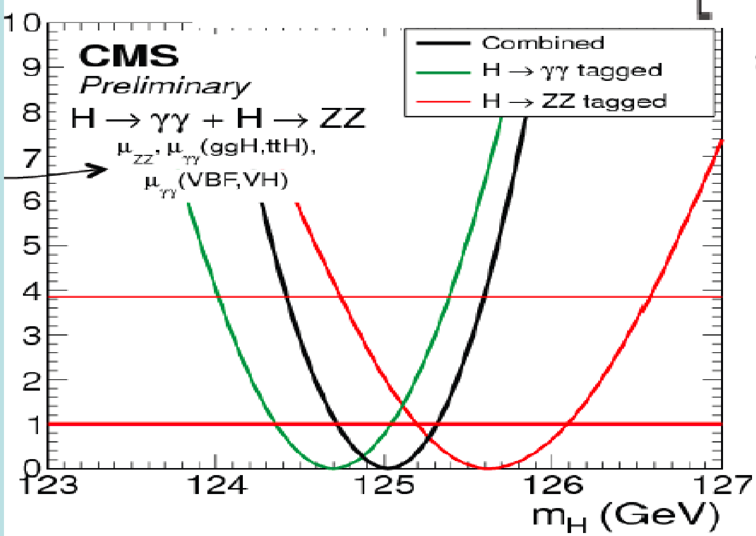
- ATLAS:

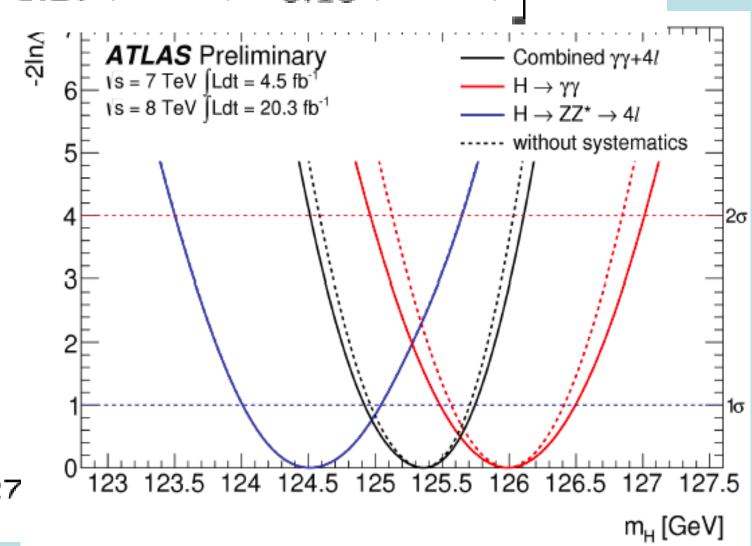
| | |
|---|---|
| $H \to \gamma\gamma$ | $125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{sys}) = 125.98 \pm 0.50$ |
| $H \to ZZ^* \to 4\ell$ | $124.51 \pm 0.52\,(\text{stat}) \pm 0.04\,(\text{sys}) = 124.51 \pm 0.52$ |
| Combined | $125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{sys}) = 125.36 \pm 0.41$ |

- CMS: $m_H = 125.6 \pm 0.4 \pm 0.2$ GeV from ZZ*

$$m_H = 124.70^{+0.35}_{-0.34}\ [\pm 0.31(\text{stat.}) \pm 0.15(\text{syst.})]\ \text{GeV}$$ from γγ

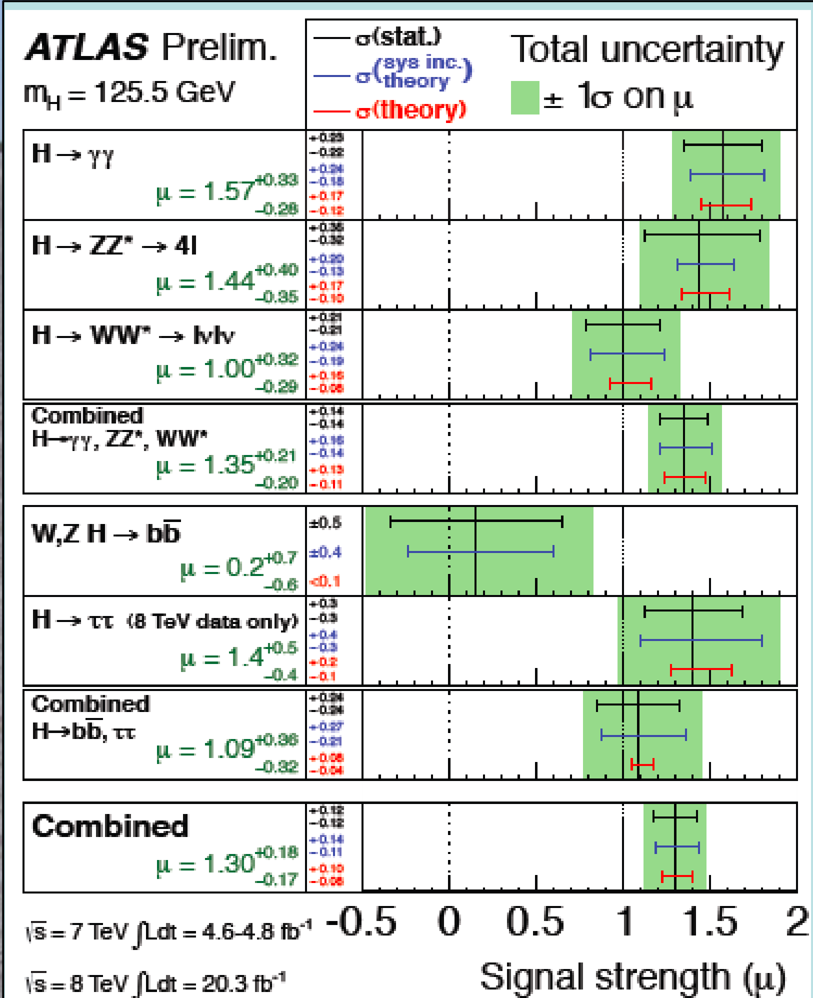
Combined: $$m_H = 125.03 \pm 0.30 \left[{}^{+0.26}_{-0.27}(\text{stat.})\,{}^{+0.13}_{-0.15}(\text{syst.})\right]\ \text{GeV}$$

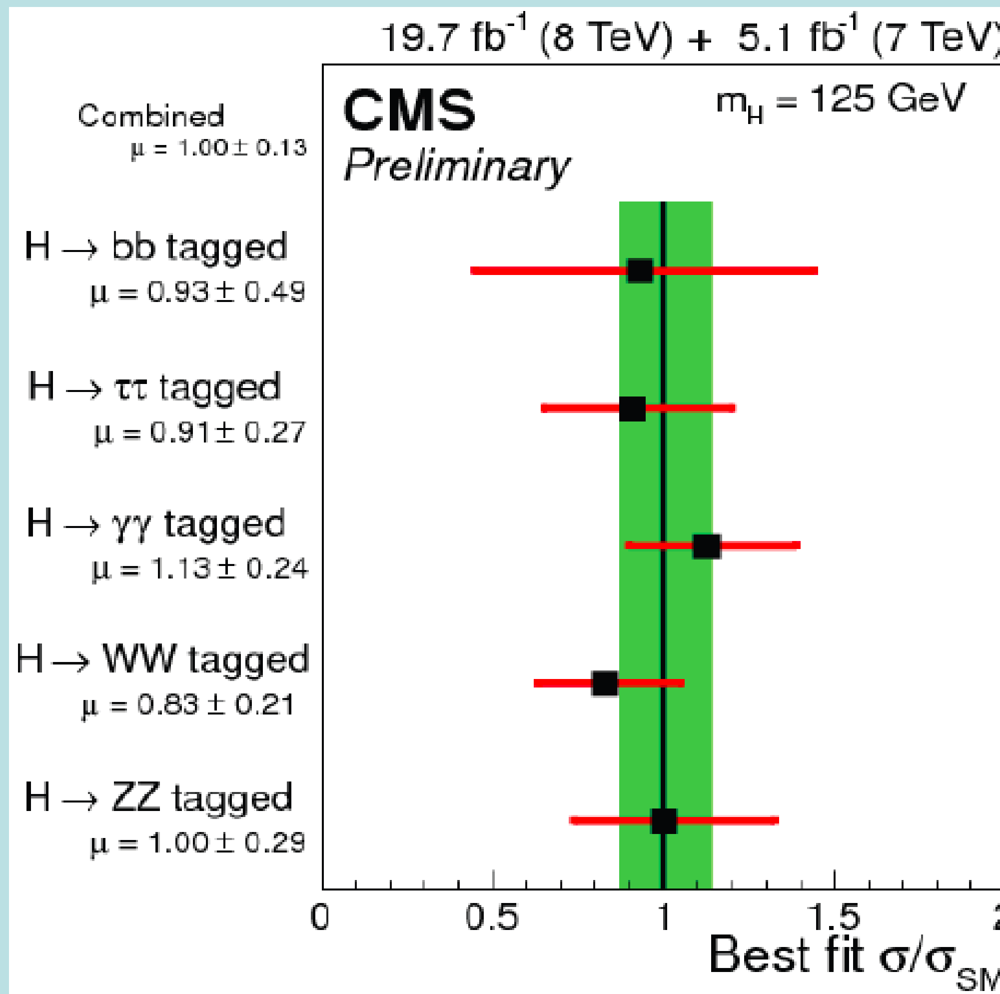



- **Crucial for stability of electroweak vacuum**

# Higgs Signal Strengths




$\mu = 1.30 \pm 0.12\ \text{(stat)}\ \pm 0.10\ \text{(th)}\ \pm 0.09\ \text{(syst)}$

$\sigma/\sigma_{\rm SM} = 1.00 \pm 0.13\ \left[\pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.07(\text{syst.})\right]$

# 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?

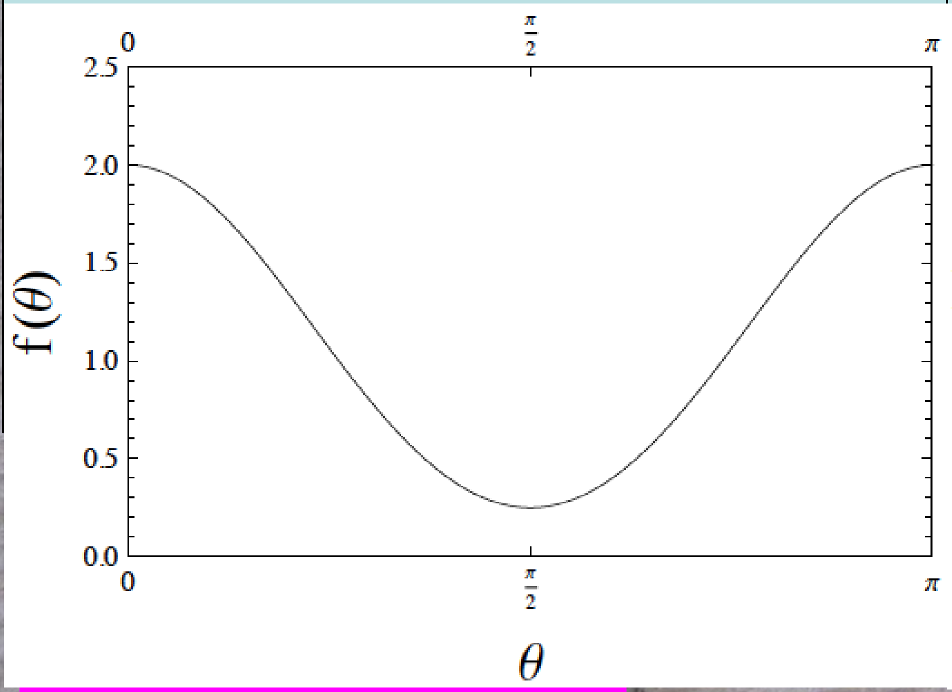
# What is the Spin of the ‘Higgs’?

- Decays into γγ, 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 γγ
  - angular correlations of leptons in WW, ZZ decays
  - production in association with W or Z

# Does the 'Higgs' have Spin Zero ?

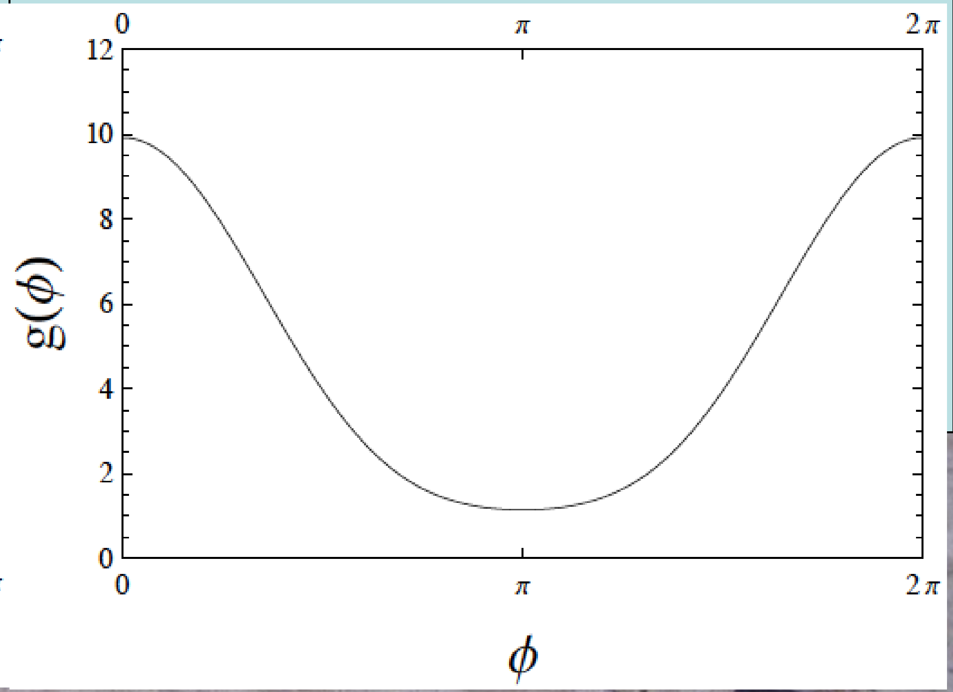
- Polar angle distribution: $X_2 \rightarrow \gamma\gamma$

  (flat for $X_0$)




- Azimuthal angle distribution: $X_0 \rightarrow WW$

  (flat for $X_2$)



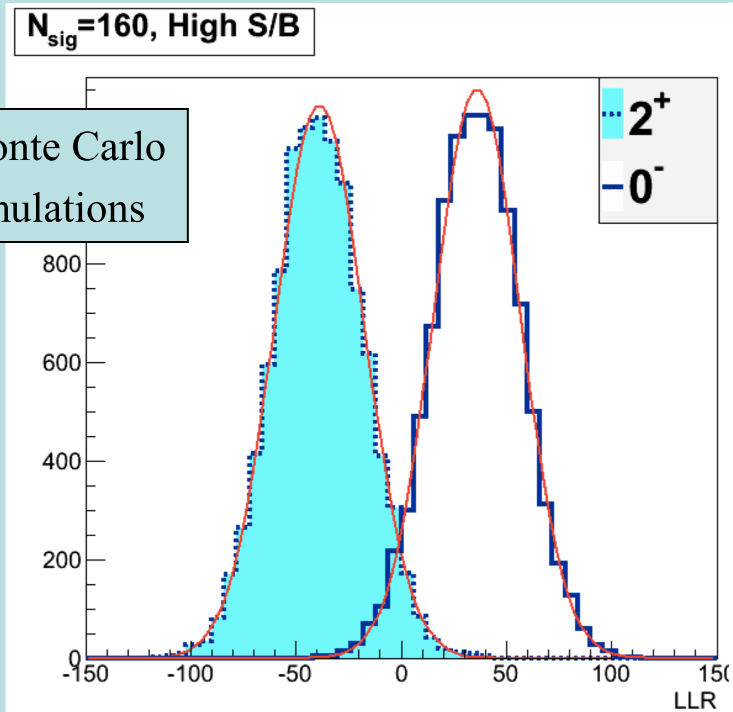

JE, Hwang: arXiv:1202.6660

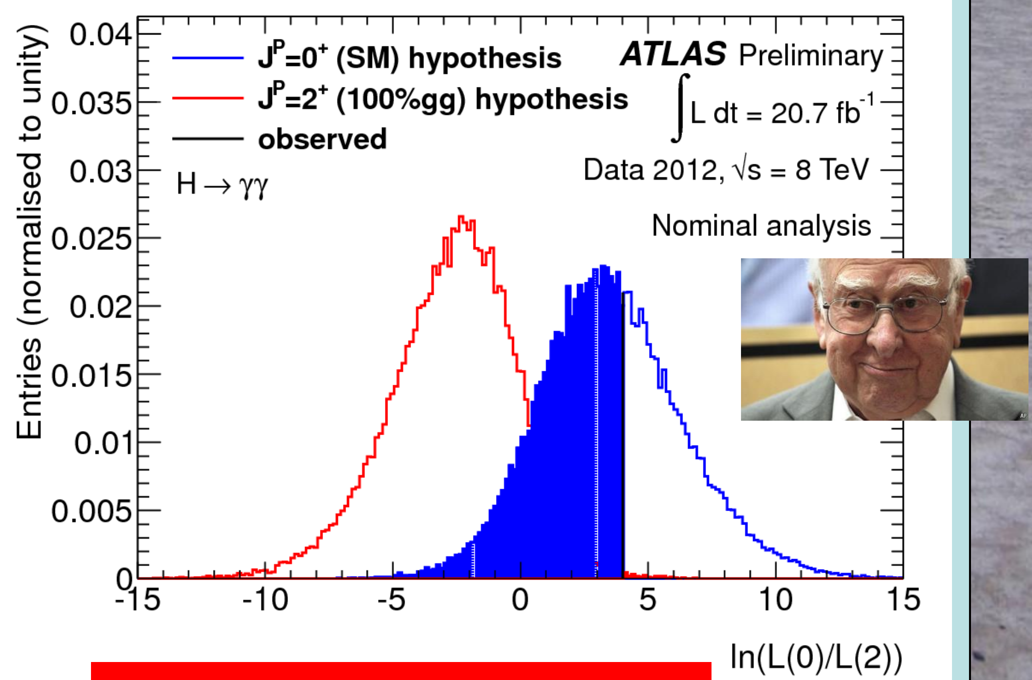
# Does the 'Higgs' have Spin Two ?

- Discriminate spin 2 vs spin 0 via angular distribution of decays into $\gamma\gamma$

JE & Hwang: arXiv:1202.6660

Monte Carlo simulations

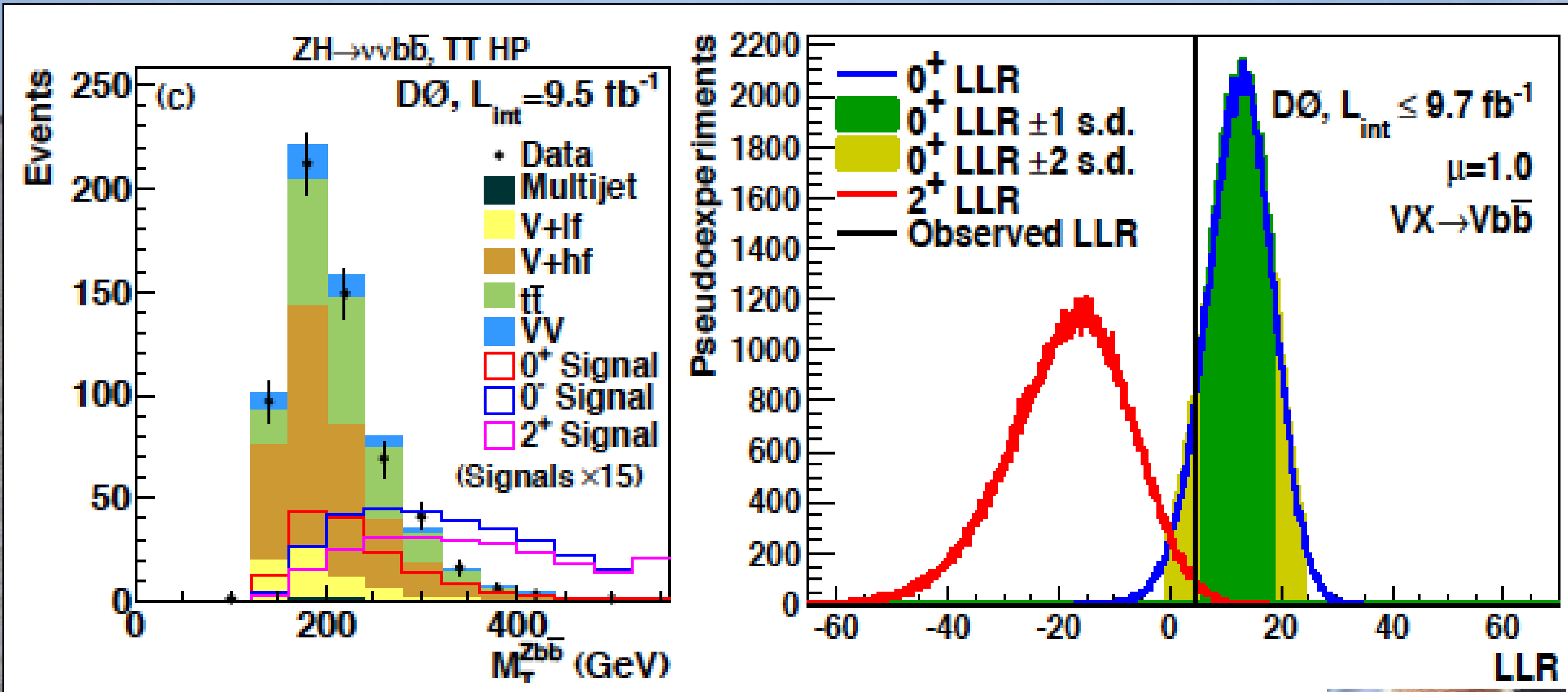



JE, Fok, Hwang, Sanz & You: arXiv:1210.5229

$2^+$ disfavoured @ 99%

# The ‘Higgs’ probably a Scalar




- Production kinematics depends on spin
- Pseudoscalar, graviton-like spin-2 disfavoured

# What is it ?

- Does it have spin 0 or 2?
  - **Spin 2 strongly disfavoured**
- Is it scalar or pseudoscalar?
- Is it elementary or composite?
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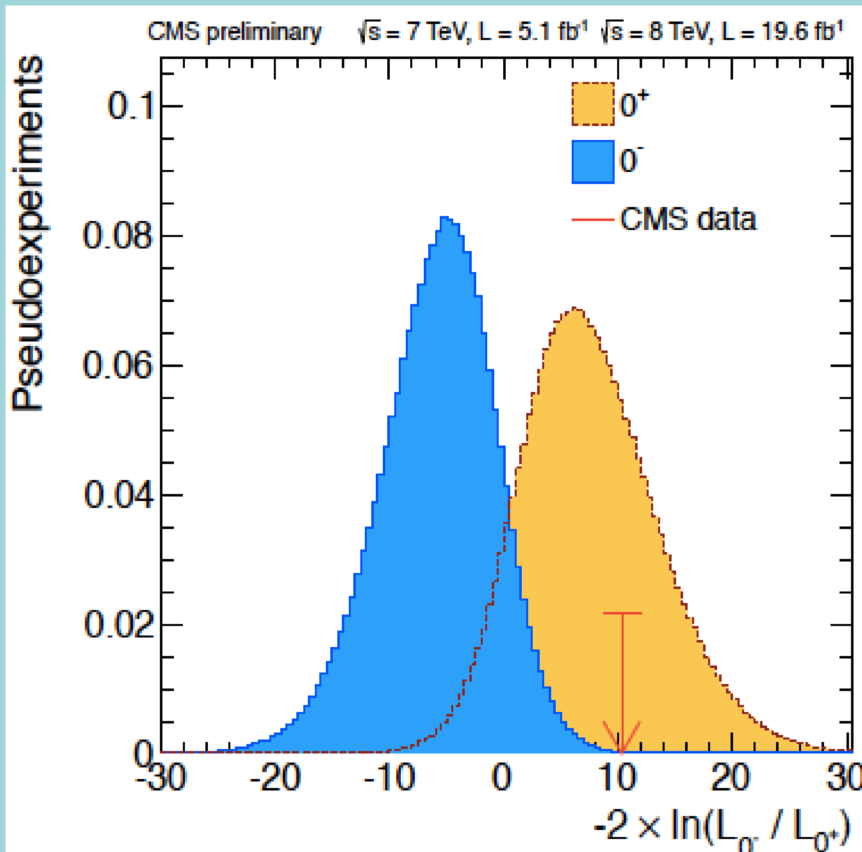
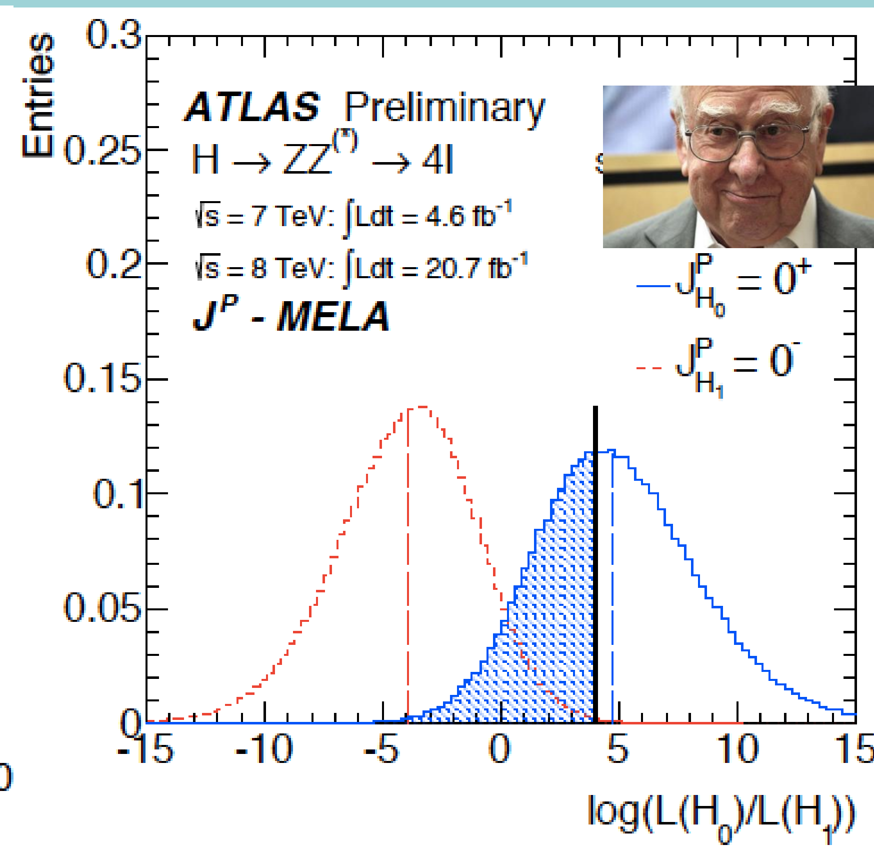
- Quantum (loop) corrections?
- What are its self-couplings?

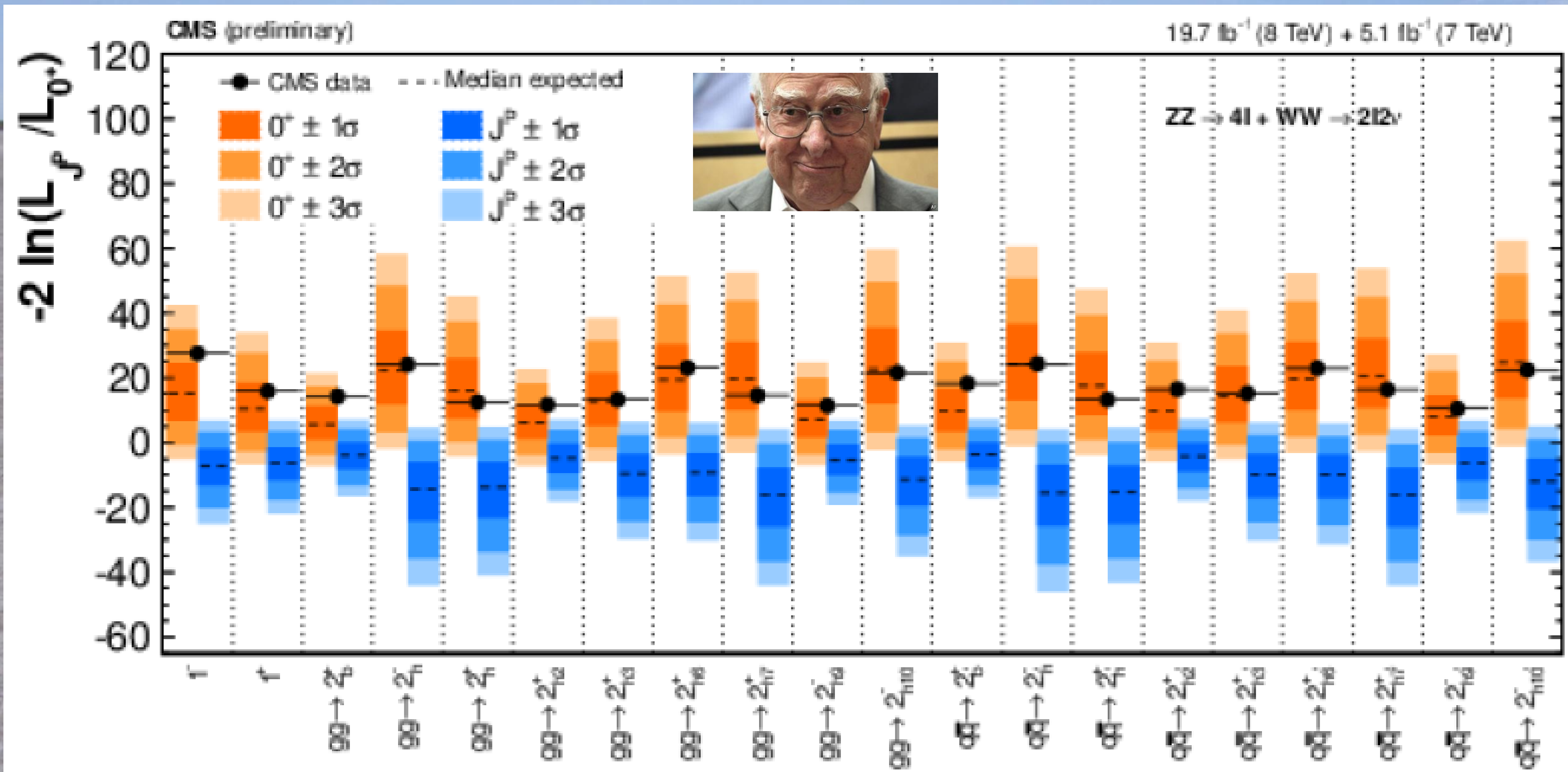
# The ‘Higgs’ is probably a scalar




- Pseudoscalar $0^-$ disfavoured at > 99% CL

# The ‘Higgs’ is probably a Scalar




- Alternative spin-parity hypotheses disfavoured

# What is it ?

- Does it have spin 0 or 2?
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  - **Pseudoscalar strongly disfavoured**
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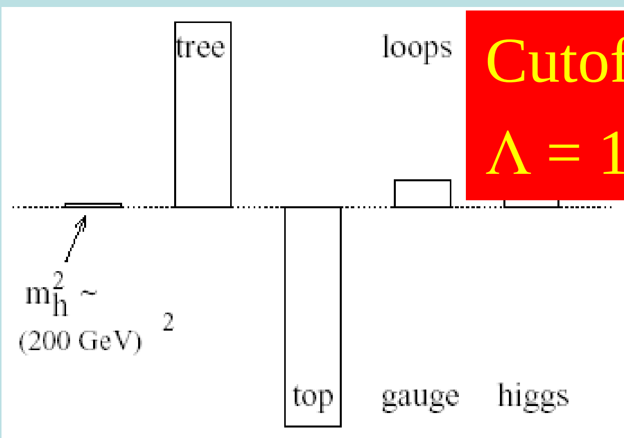
- What are its self-couplings?

# Elementary Higgs or Composite?

- Higgs field:

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

- Quantum loop problems




Cutoff

$\Lambda = 10$ TeV

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

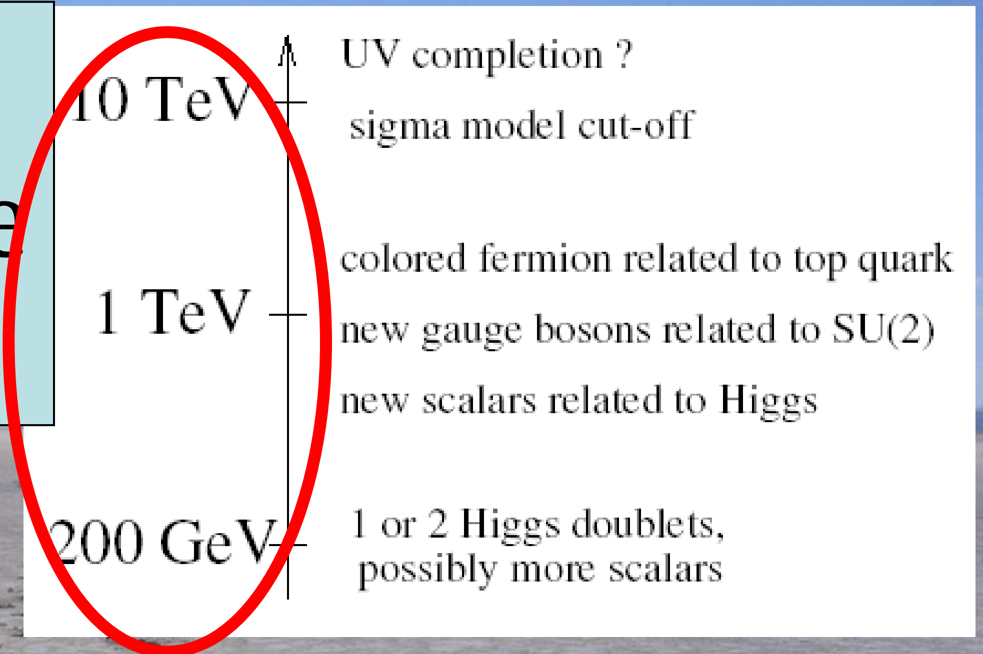
Supersymmetry?

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

New technicolour force?

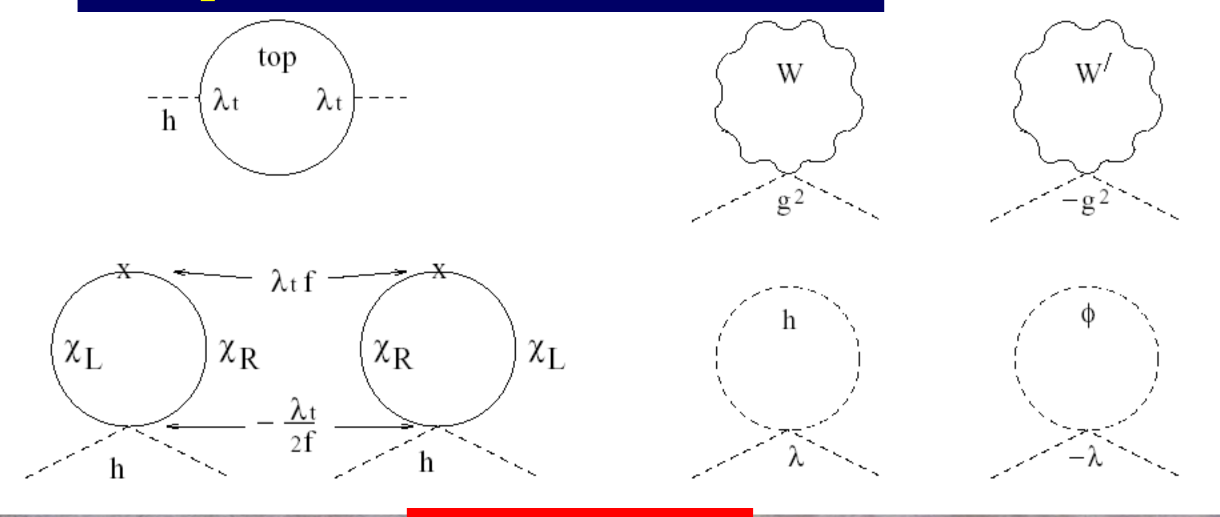
- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

# Higgs as a Pseudo-Goldstone Boson

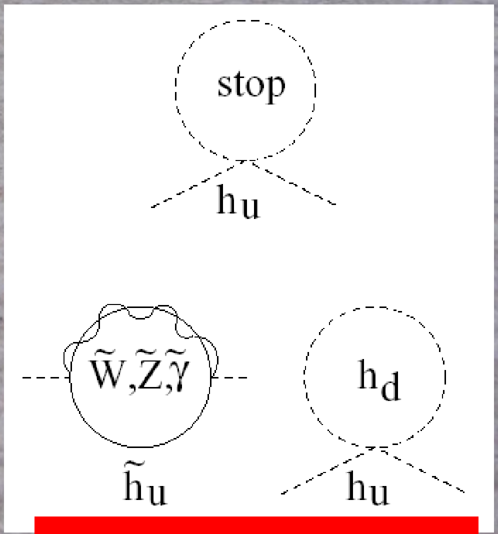



'Little Higgs' models
(breakdown of larger symmetry)

Loop cancellation mechanism




Little Higgs




Supersymmetry

# Phenomenological Framework

- Assume custodial symmetry:

$$SU(2) \times SU(2) \to SU(2)_V \qquad (\rho \equiv M_W / M_Z \cos\theta_w \sim 1)$$

- Parameterize gauge bosons by 2 × 2 matrix Σ:

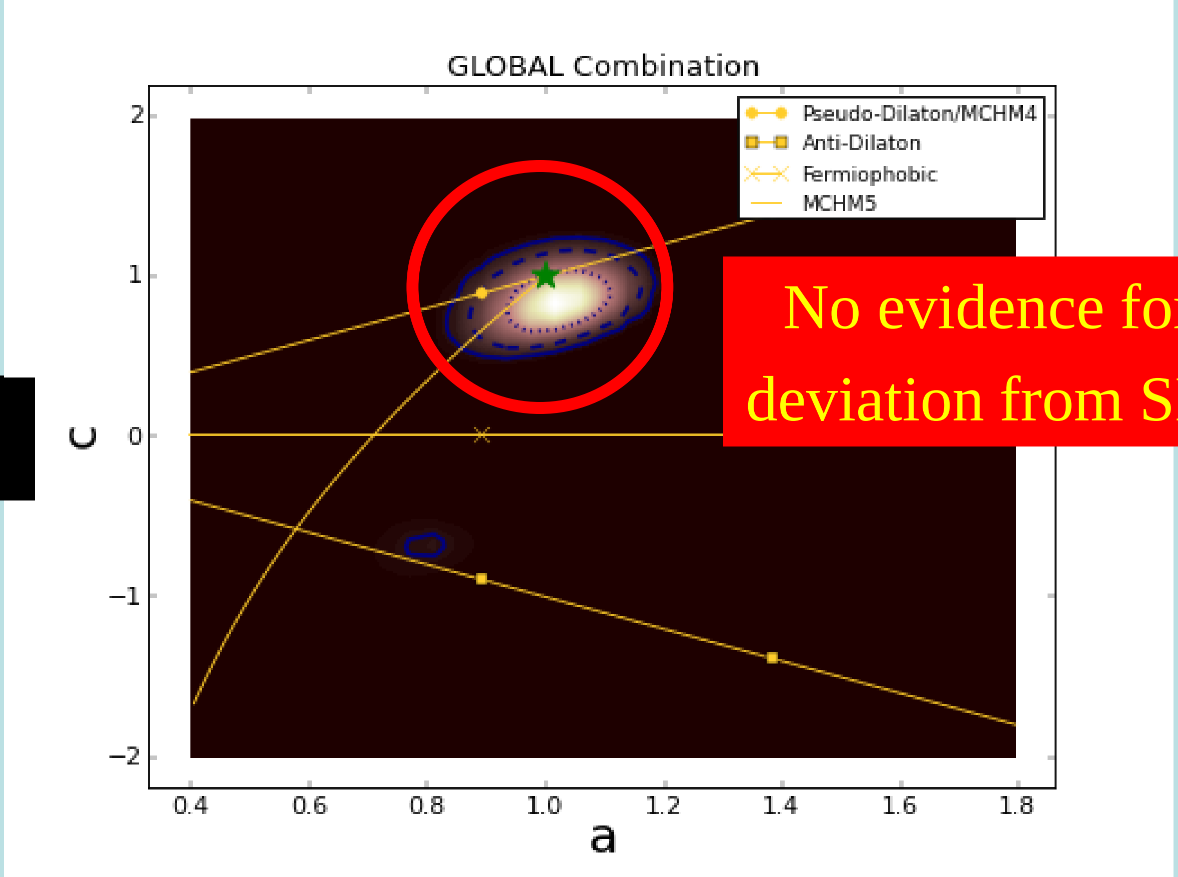
$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr} D_\mu \Sigma^\dagger D^\mu \Sigma \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right) - m_i \bar{\psi}_L^i \Sigma \left(1 + c\frac{h}{v} + \ldots\right)\psi_R^i + \mathrm{h.c.}$$
$$+ \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}m_h^2 h^2 + d_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4 \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots \quad ,$$

$$\Sigma = \exp\left(i\frac{\sigma^a \pi^a}{v}\right) \quad \mathcal{L}_\Delta = -\left[\frac{\alpha_s}{8\pi} b_s G_{a\mu\nu} G_a^{\mu\nu} + \frac{\alpha_{em}}{8\pi} b_{em} F_{\mu\nu} F^{\mu\nu}\right]\left(\frac{h}{V}\right)$$

- Coefficients ***a* = *c* = *1*** in Standard Model

# Global Analysis of Higgs-like Models

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




Global

No evidence for deviation from SM

- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1303.3879

# What is it ?

- Does it have spin 0 or 2?
  - **Spin 2 strongly disfavoured**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar strongly disfavoured**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?

- Quantum (loop) corrections?

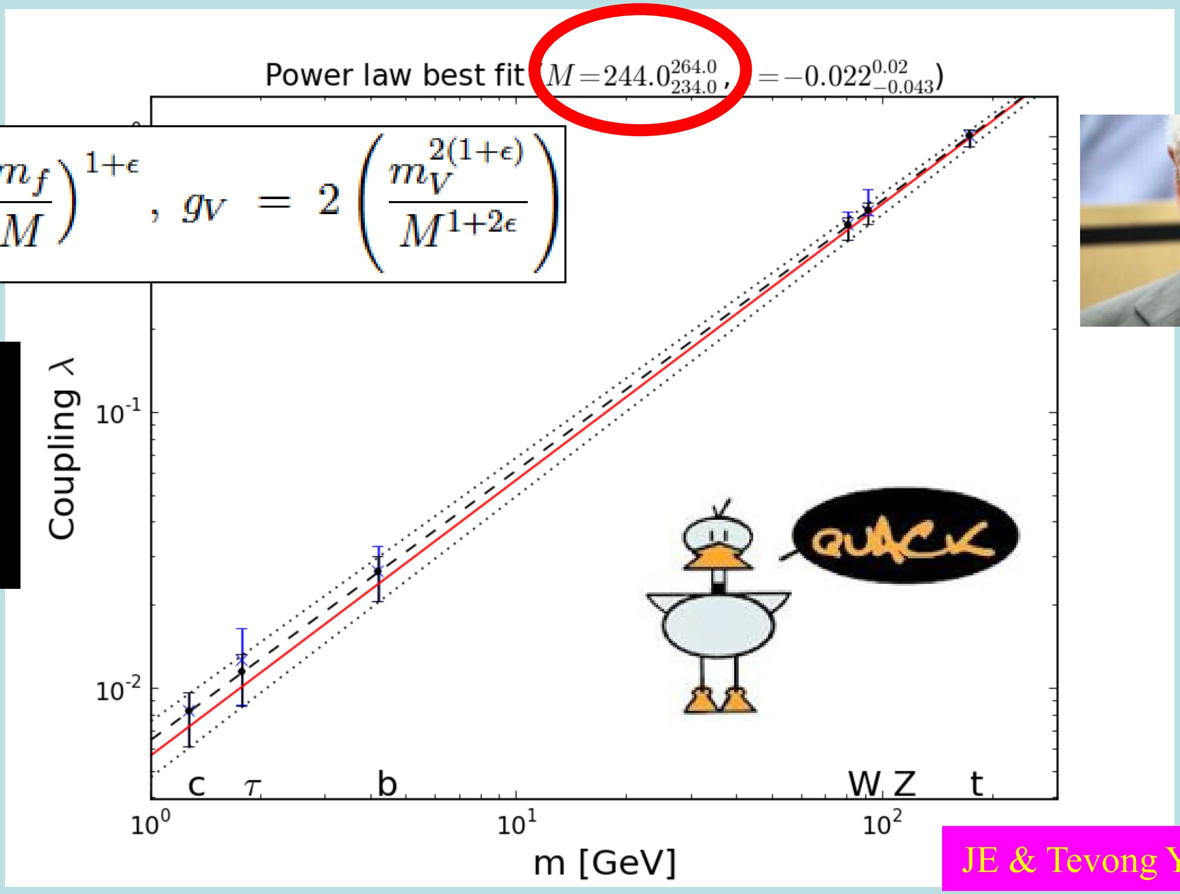
- What are its self-couplings?

# It Walks and Quacks like a Higgs

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

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

**Global fit**




JE & Tevong You, arXiv:1303.3879

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

# What is it ?

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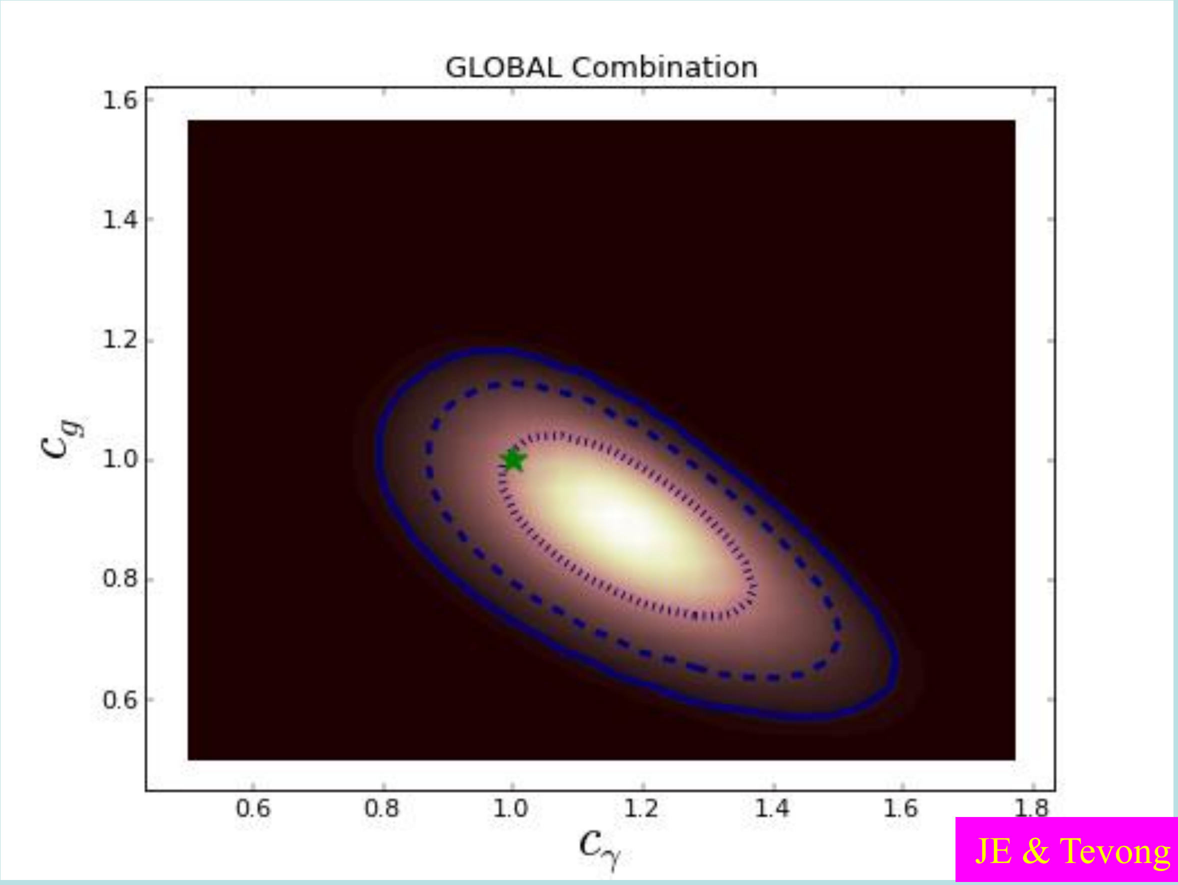
- Does it couple to particle masses?
  - ***Prima facie* evidence that it does**
- Quantum (loop) corrections?

- What are its self-couplings?

# Loop Corrections ?

- ATLAS sees excess in γγ, CMS sees deficit



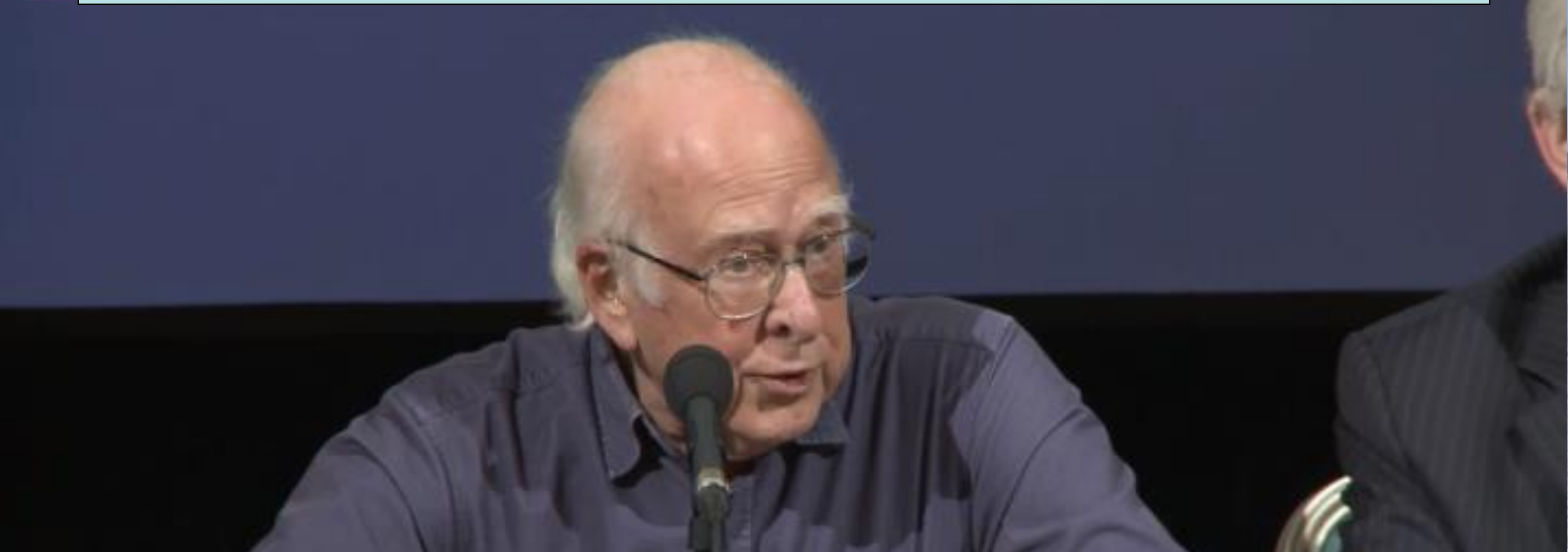

JE & Tevong You, arXiv:1303.3879

- Loop diagrams ~ Standard Model?

# Beyond any Reasonable Doubt

- Does it have spin 0 or 2?
  - **Spin 2 strongly disfavoured**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar strongly disfavoured**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
  - ***Prima facie* evidence that it does**
- Quantum (loop) corrections?
  - **γγ coupling >~ Standard Model?**
- What are its self-couplings? **Hi-lumi LHC or …?**

# Dixit Swedish Academy



*Today we believe that “Beyond any reasonable doubt, it is a Higgs boson.” [1]*

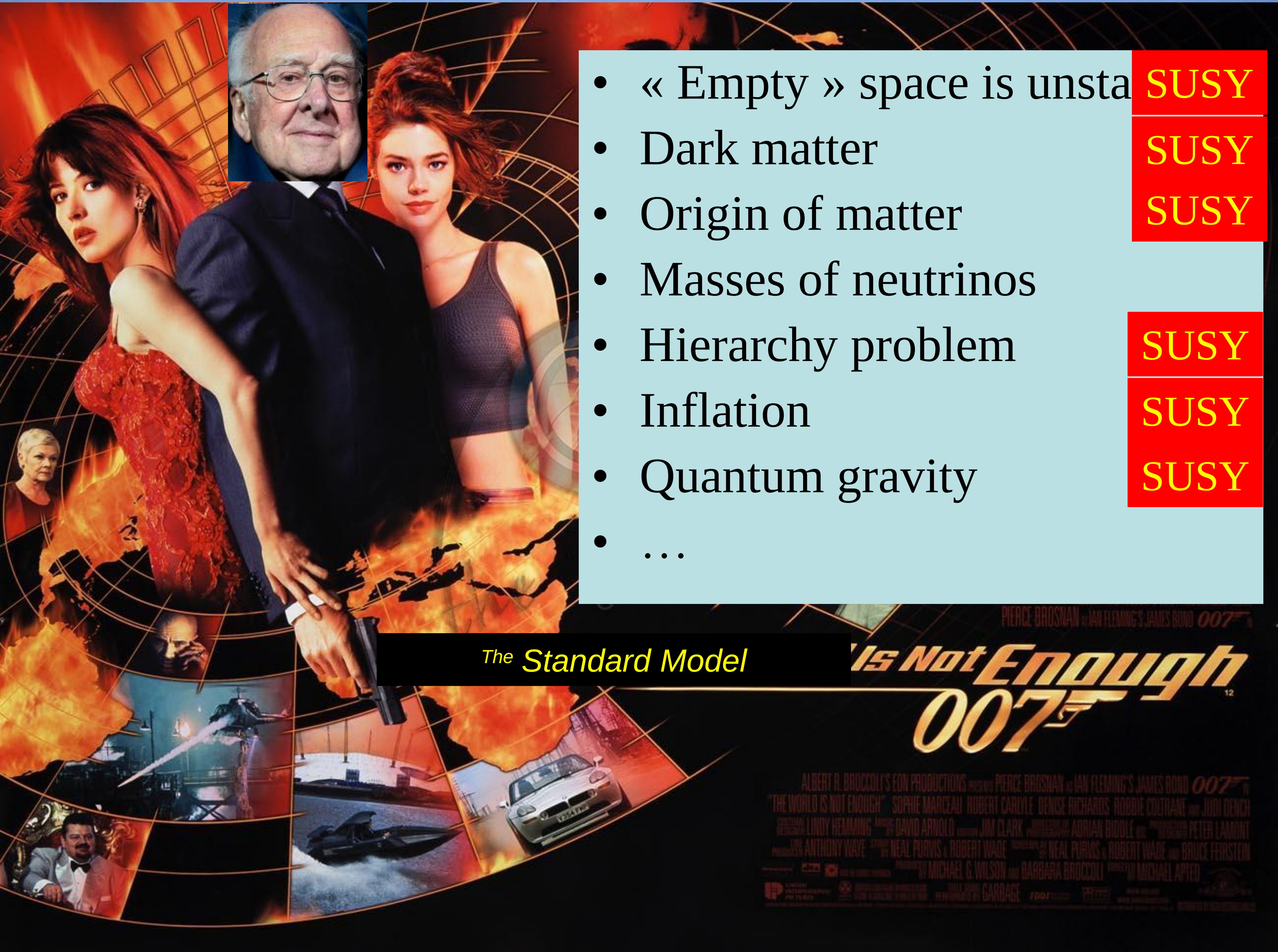
http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

[1] = JE & Tevong You, arXiv:1303.3879

# No BSM? Beware Historical Hubris

- ***"So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value"*** **- Spanish Royal Commission, rejecting Christopher Columbus proposal to sail west, < 1492**
- *"The more important fundamental laws and facts of physical science have all been discovered"* – Albert Michelson, 1894
- *"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement"* - Lord Kelvin, 1900
- *"Is the End in Sight for Theoretical Physics?"* – Stephen Hawking, 1980

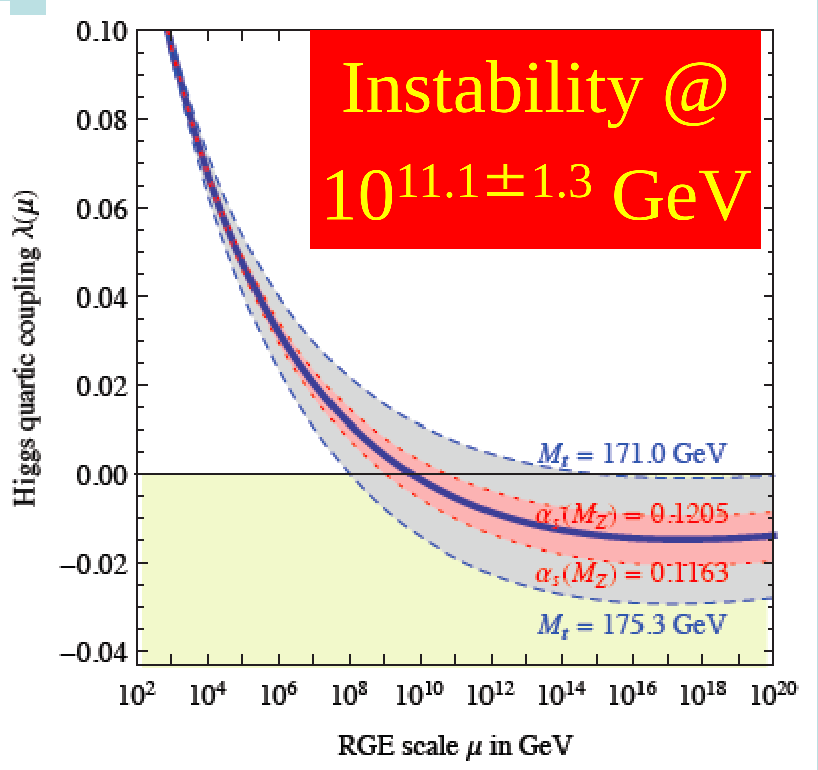
- « Empty » space is unsta SUSY
- Dark matter SUSY
- Origin of matter SUSY
- Masses of neutrinos
- Hierarchy problem SUSY
- Inflation SUSY
- Quantum gravity SUSY
- …



# Theoretical Constraints on Higgs Mass

- Large $M_h$ → large self-coupling → blow up at

$$\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4} \log \frac{Q}{v}$$

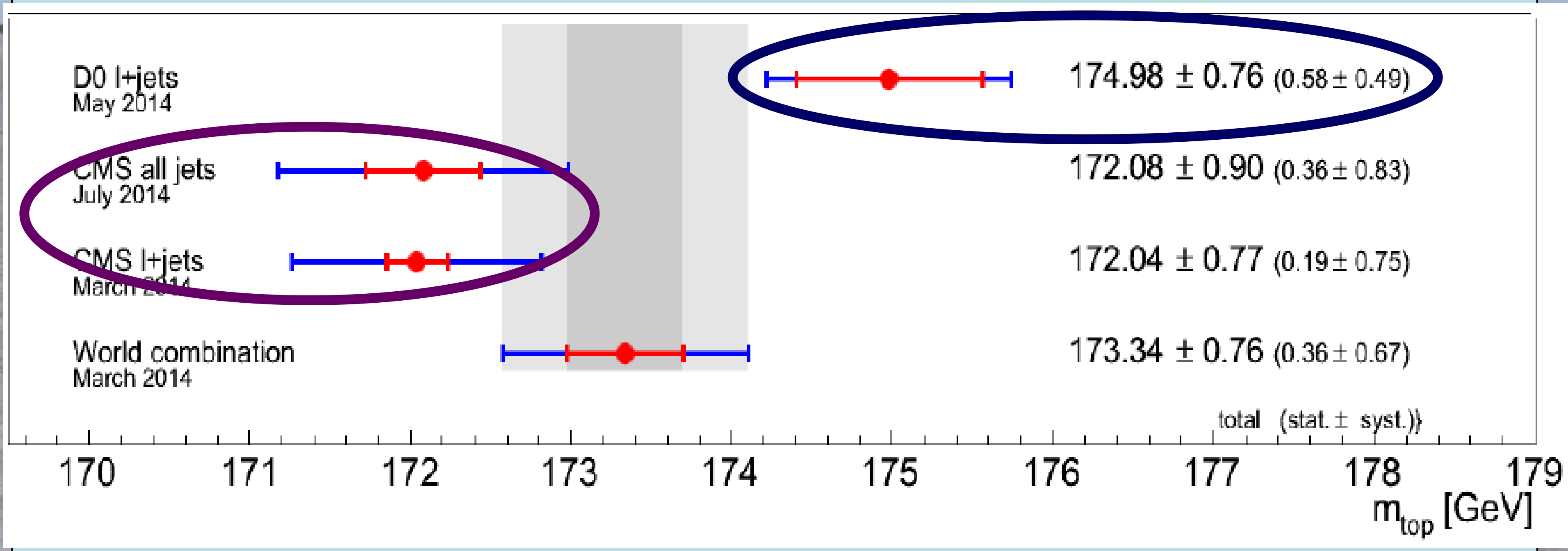



- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable
- Vacuum could be stabilized by **Supersymmetry**

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 $M_H$




- Instability scale:

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

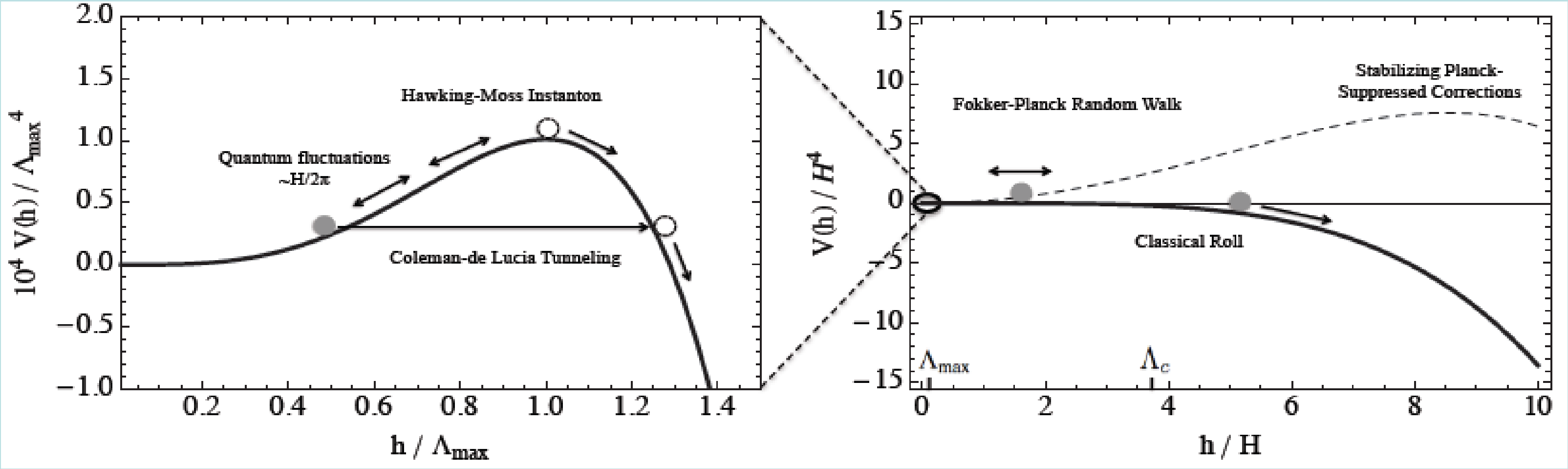
$$\log_{10}\frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\text{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\text{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

**$m_t = 173.3 \pm 1.0$ GeV → $\log_{10}(\Lambda/\text{GeV}) = 11.1 \pm 1.3$**

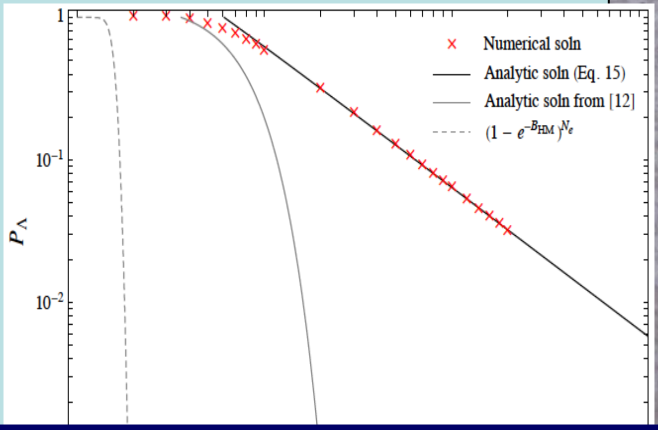
# Instability during Inflation?

Hook, Kearns, Shakya & Zurek: arXiv:1404.5953

- Do inflation fluctuations drive us over the hill?




- Then Fokker-Planck evolution
- Do 'Big Crunch' regions eat us?
  - Disaster if so
  - If not, OK if more inflation




OK if dim-6 operator? Non-minimal gravity coupling?

# What else is there?

# Supersymmetry

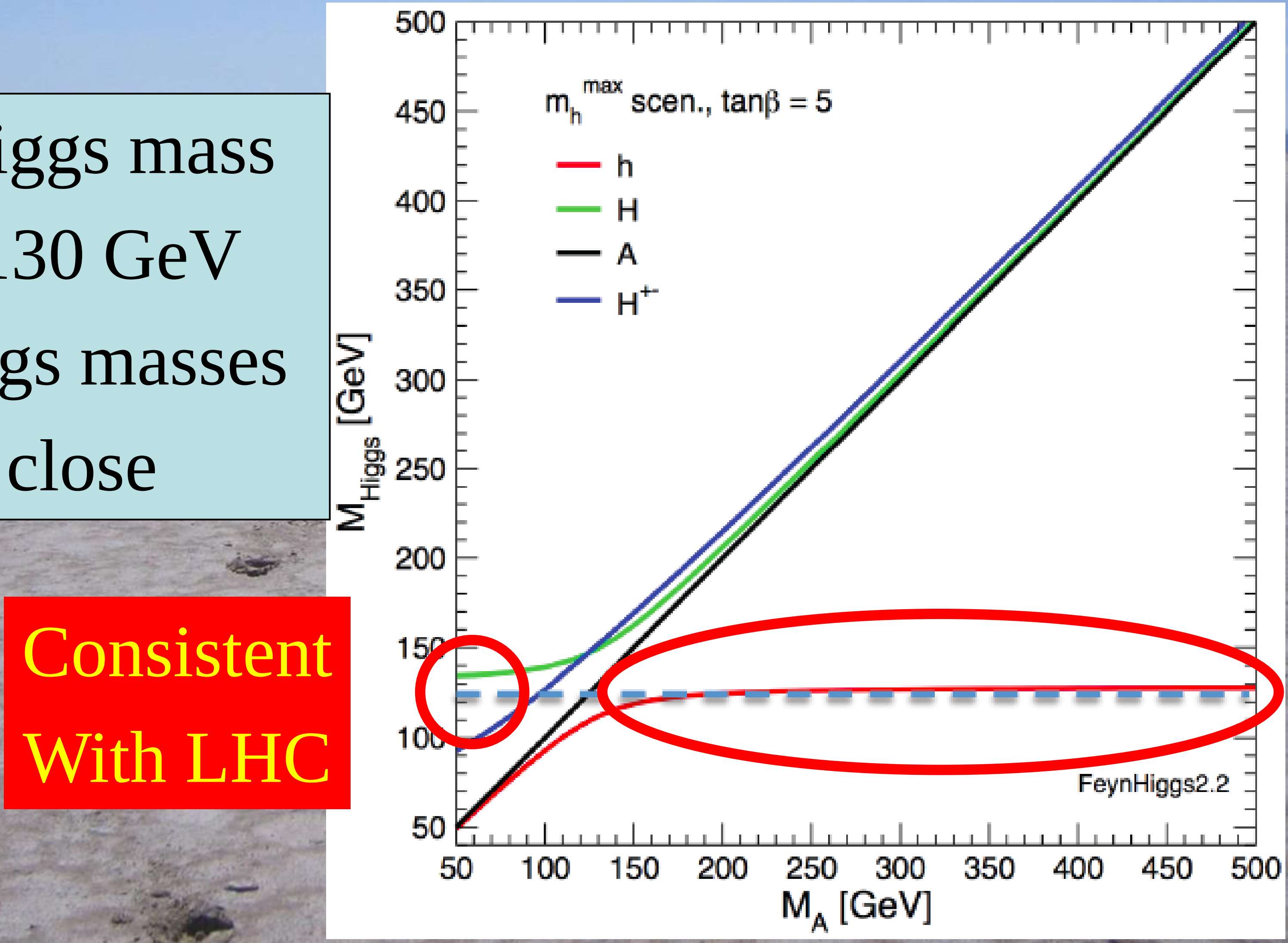
New motivations
From LHC Run 1

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, dark matter, GUTs, string, …

# MSSM Higgs Masses & Couplings

Lightest Higgs mass up to ~ 130 GeV

Heavy Higgs masses quite close



# Without Higgs …

… there would be no atoms

- massless electrons would escape at the speed of light

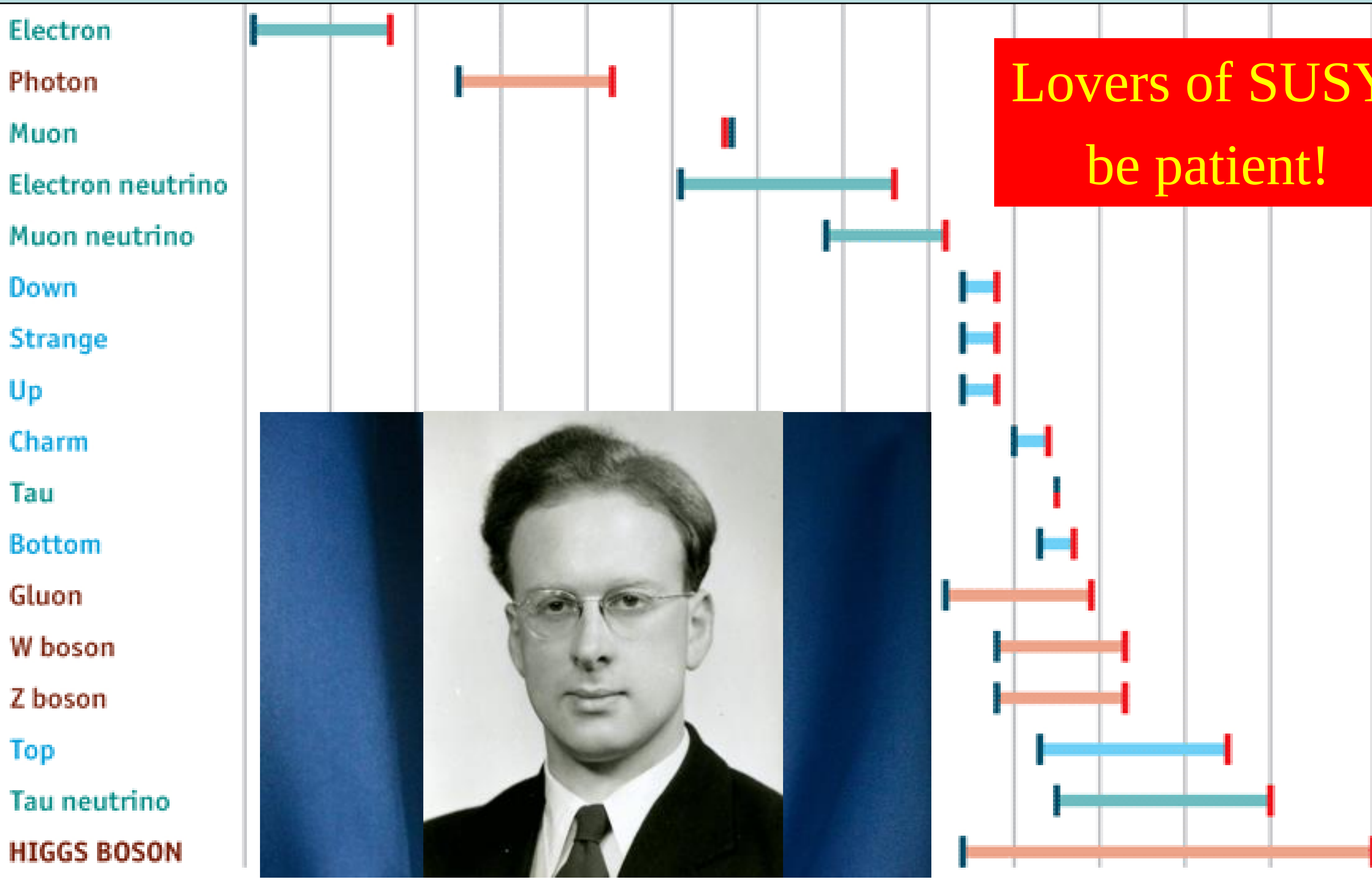
… there would be no heavy nuclei

… weak interactions would not be weak

- Life would be impossible: everything would be radioactive

Its existence is a big deal!

# Standard Model Particles:
# Years from Proposal to Discovery




Source: *The Economist*

**Lovers of SUSY: be patient!**

# Possible Future Circular Colliders

Exploration of the 10 TeV scale

Direct (100 TeV pp) + Indirect ($e^+e^-$)

# Data

- **Electroweak precision observables**
- **Flavour physics observables**
- **$g_\mu$ - 2**
- **Higgs mass**
- **Dark matter**
- **LHC**

Deviation from Standard Model:
Supersymmetry at low scale, or …?

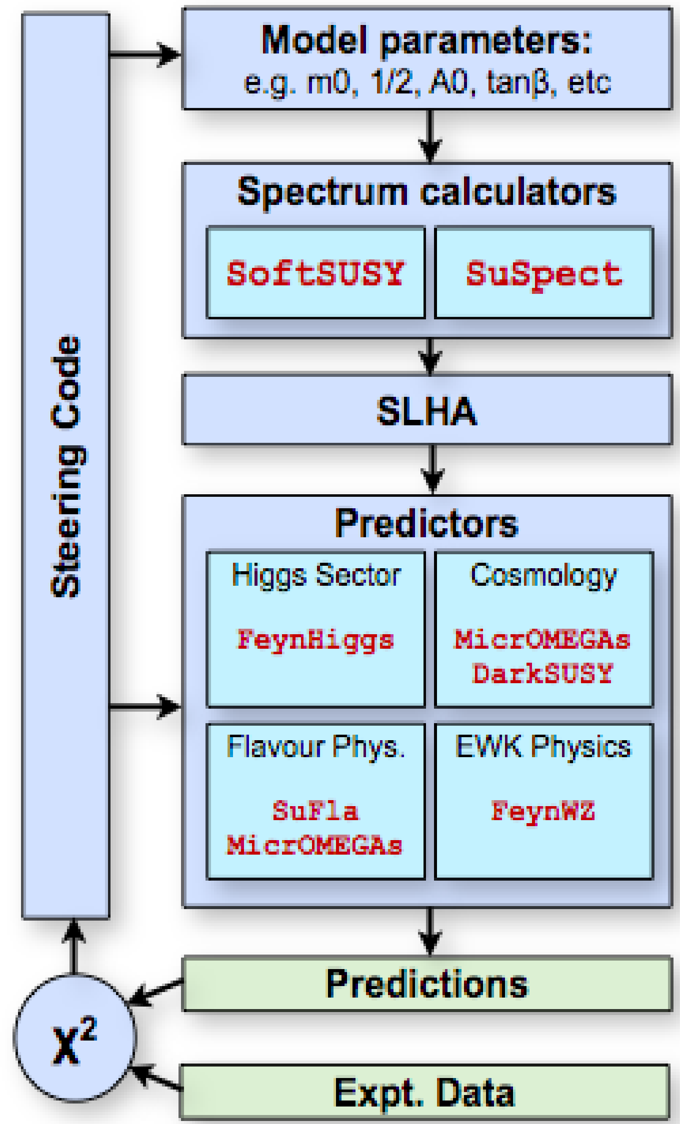
| Observable | Source Th./Ex. | Constraint |
|---|---|---|
| $m_t$ [GeV] | [39] | $173.2 \pm 0.90$ |
| $\Delta\alpha^{(5)}_{\rm had}(m_Z)$ | [38] | $0.02749 \pm 0.00010$ |
| $M_Z$ [GeV] | [40] | $91.1875 \pm 0.0021$ |
| $\Gamma_Z$ [GeV] | [24] / [40] | $2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$ |
| $\sigma^0_{\rm had}$ [nb] | [24] / [40] | $41.540 \pm 0.037$ |
| $R_l$ | [24] / [40] | $20.767 \pm 0.025$ |
| $A_{\rm fb}(\ell)$ | [24] / [40] | $0.01714 \pm 0.00095$ |
| $A_\ell(P_\tau)$ | [24] / [40] | $0.1465 \pm 0.0032$ |
| $R_b$ | [24] / [40] | $0.21629 \pm 0.00066$ |
| $R_c$ | [24] / [40] | $0.1721 \pm 0.0030$ |
| $A_{\rm fb}(b)$ | [24] / [40] | $0.0992 \pm 0.0016$ |
| $A_{\rm fb}(c)$ | [24] / [40] | $0.0707 \pm 0.0035$ |
| $A_b$ | [24] / [40] | $0.923 \pm 0.020$ |
| $A_c$ | [24] / [40] | $0.670 \pm 0.027$ |
| $A_\ell$(SLD) | [24] / [40] | $0.1513 \pm 0.0021$ |
| $\sin^2\theta^\ell_{\rm w}(Q_{\rm fb})$ | [24] / [40] | $0.2324 \pm 0.0012$ |
| $M_W$ [GeV] | [24] / [40] | $80.399 \pm 0.023 \pm 0.010_{\rm SUSY}$ |
| ${\rm BR}^{\rm EXP}_{b\to s\gamma}/{\rm BR}^{\rm SM}_{b\to s\gamma}$ | [41] / [42] | $1.117 \pm 0.076_{\rm EXP}$ $\pm 0.082_{\rm SM} \pm 0.050_{\rm SUSY}$ |
| [illegible] | [27] / [37] | $(< 1.08 \pm 0.02_{\rm SUSY}) \times 10^{-8}$ |
| [illegible] | [27] / [42] | $1.43 \pm 0.43_{\rm EXP+TH}$ |
| [illegible] | [27] / [42] | $< (4.6 \pm 0.01_{\rm SUSY}) \times 10^{-9}$ |
| [illegible] | [43]/ [42] | $0.99 \pm 0.32$ |
| ${\rm BR}_{K\to\mu\nu}/{\rm BR}_{K\to\mu\nu}$ | [27] / [44] | $1.008 \pm 0.014_{\rm EXP+TH}$ |
| ${\rm BR}^{\rm EXP}_{K\to\pi\nu\bar\nu}/{\rm BR}^{\rm SM}_{K\to\pi\nu\bar\nu}$ | [45]/ [46] | $< 4.5$ |
| $\Delta M^{\rm EXP}_{B_s}/\Delta M^{\rm SM}_{B_s}$ | [45] / [47, 48] | $0.97 \pm 0.01_{\rm EXP} \pm 0.27_{\rm SM}$ |
| $\frac{(\Delta M^{\rm EXP}_{B_s}/\Delta M^{\rm SM}_{B_s})}{(\Delta M^{\rm EXP}_{B_d}/\Delta M^{\rm SM}_{B_d})}$ | [27] / [42, 47, 48] | $1.00 \pm 0.01_{\rm EXP} \pm 0.13_{\rm SM}$ |
| $\Delta\epsilon^{\rm EXP}_K/\Delta\epsilon^{\rm SM}_K$ | [45] / [47, 48] | $1.08 \pm 0.14_{\rm EXP+TH}$ |
| $a^{\rm EXP}_\mu - a^{\rm SM}_\mu$ | [49] / [38, 50] | $(30.2 \pm 8.8 \pm 2.0_{\rm SUSY}) \times 10^{-10}$ |
| [illegible] | [illegible] | [illegible] $\pm 1.5_{\rm SUSY}$ |
| [illegible] | [illegible] | [illegible]$56 \pm 0.012_{\rm SUSY}$ |
| $\sigma_p^{\rm SI}$ | [23] | [illegible] plane |
| jets + $\not\!\!E_T$ | [16, 18] | $(m_0, m_{1/2})$ plane |
| $H/A, H^\pm$ | [19] | $(M_A, \tan\beta)$ plane |

$M_H$ = 125.6 ± 0.3 ± 1.5 GeV

MasterCode: O.Buchmueller, JE et al.

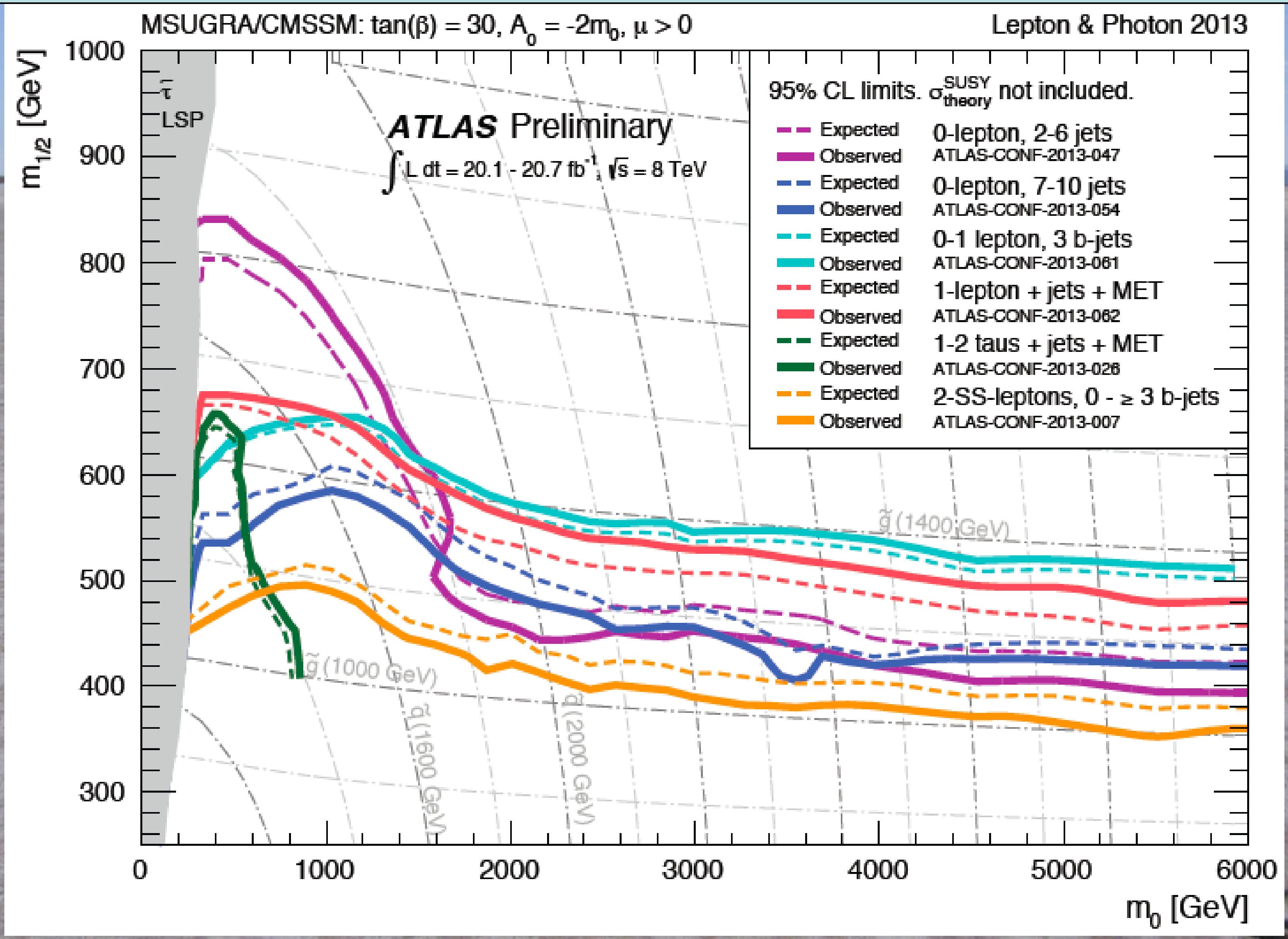
# MasterCode

- **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

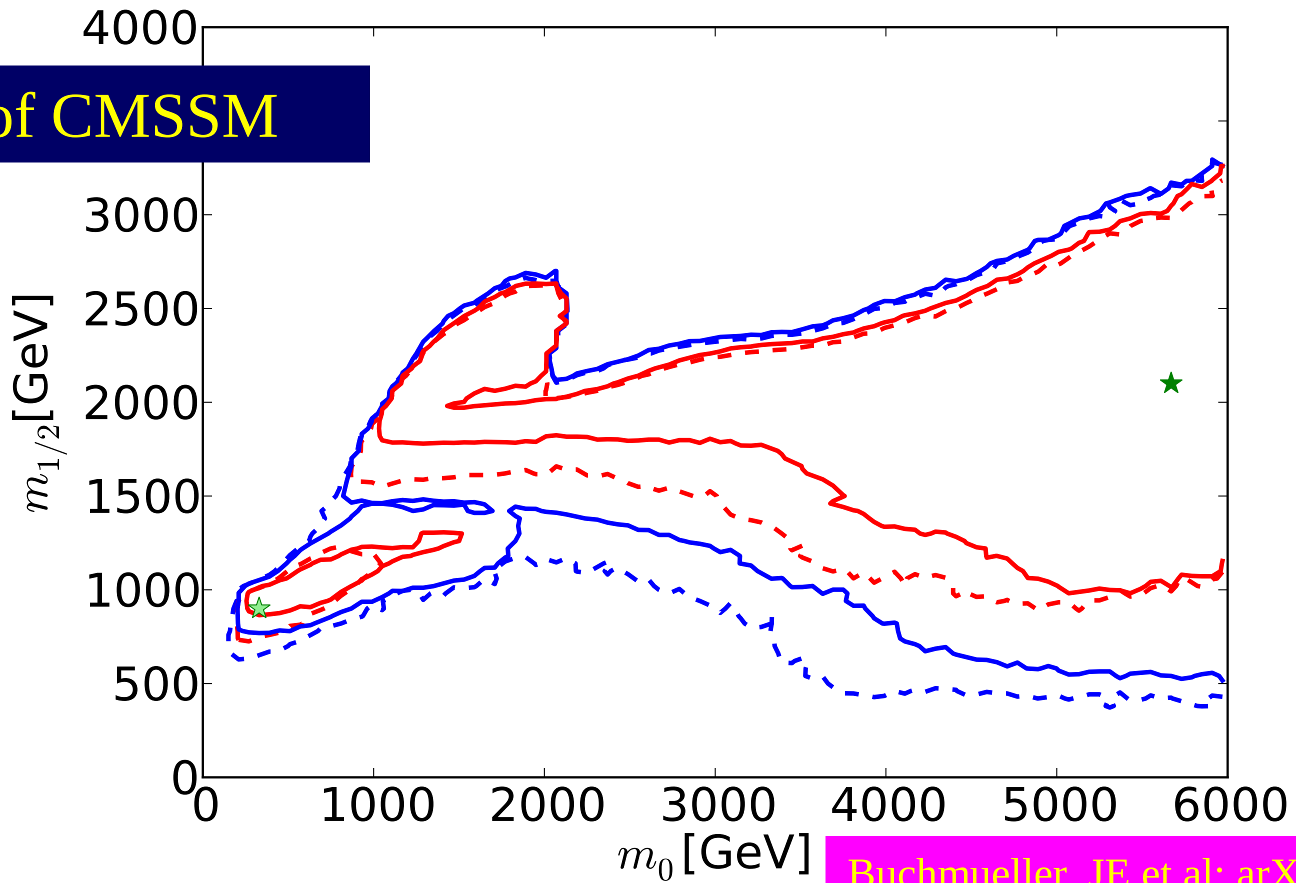
# Search with ~ 20/fb @ 8 TeV



# Post-LHC, Post-XENON100

**2012** ATLAS + CMS with **20/fb** of LHC Data

Scan of CMSSM

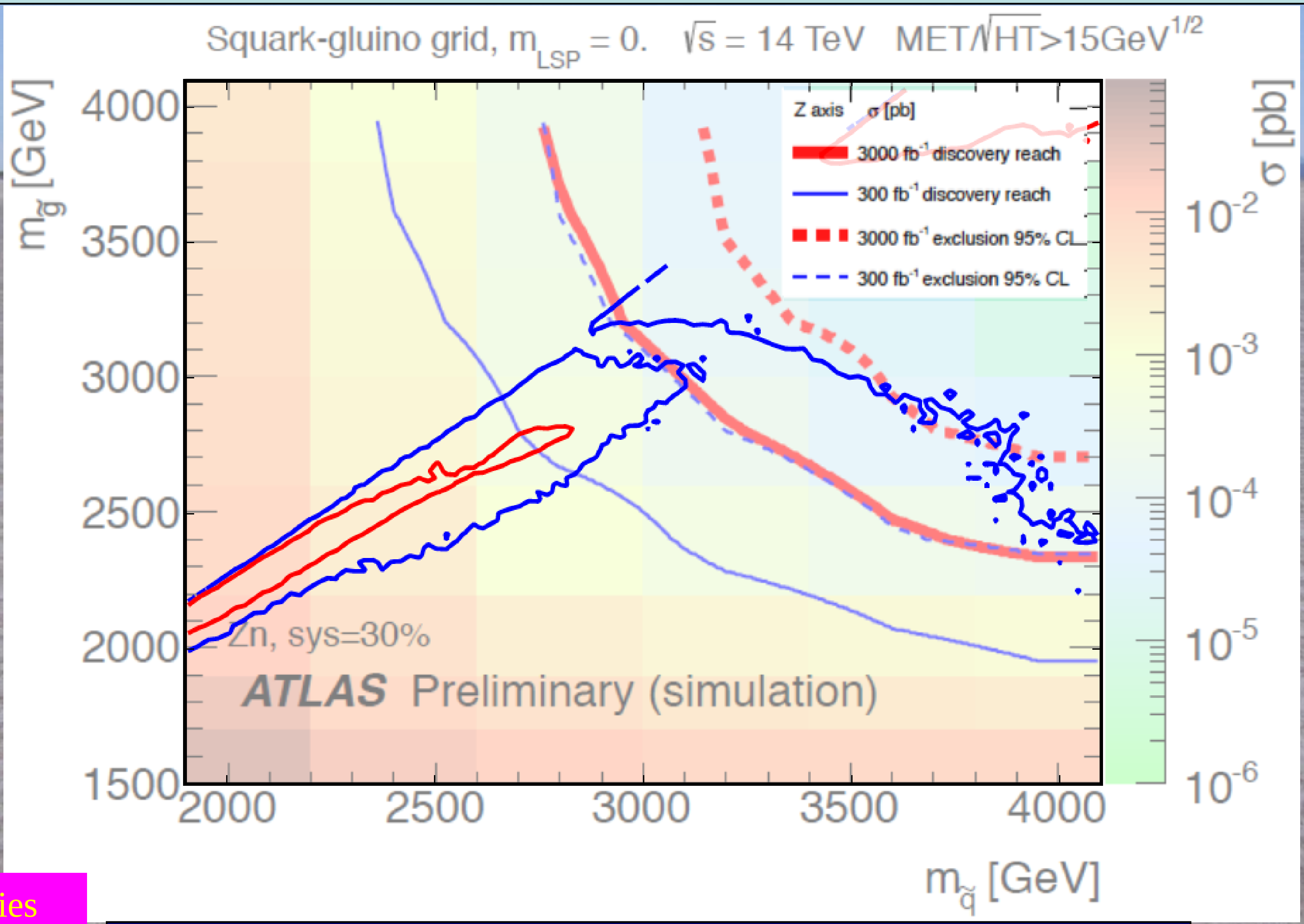



Buchmueller, JE et al: arXiv:1312.5250

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

p-value of simple models ~ 5% (also SM)

# LHC Reach for Supersymmetry

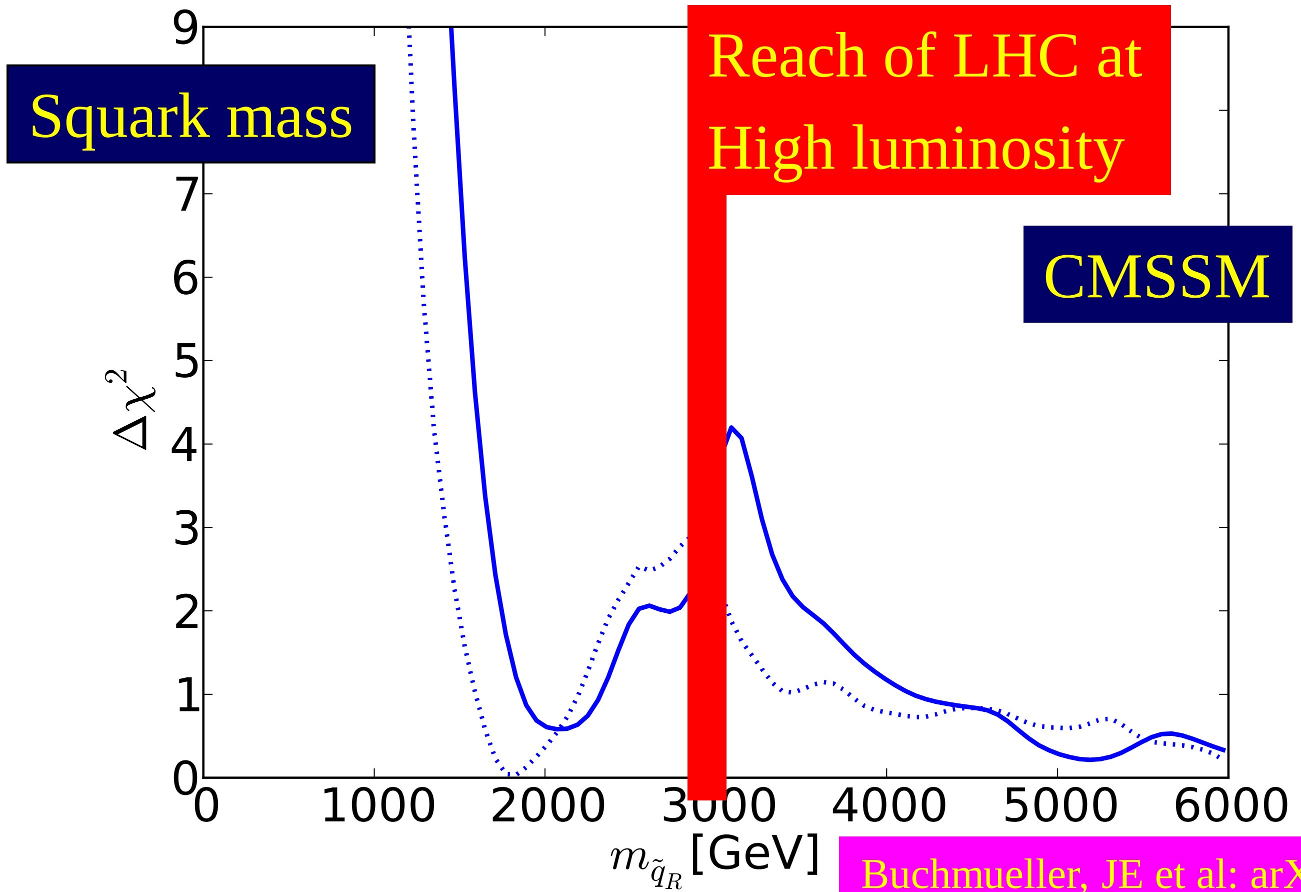



K. De Vries (MasterCode)

Confronted with likelihood analysis of CMSSM

# Post-LHC, Post-XENON100

2012 ATLAS + CMS with 20/fb of LHC Data

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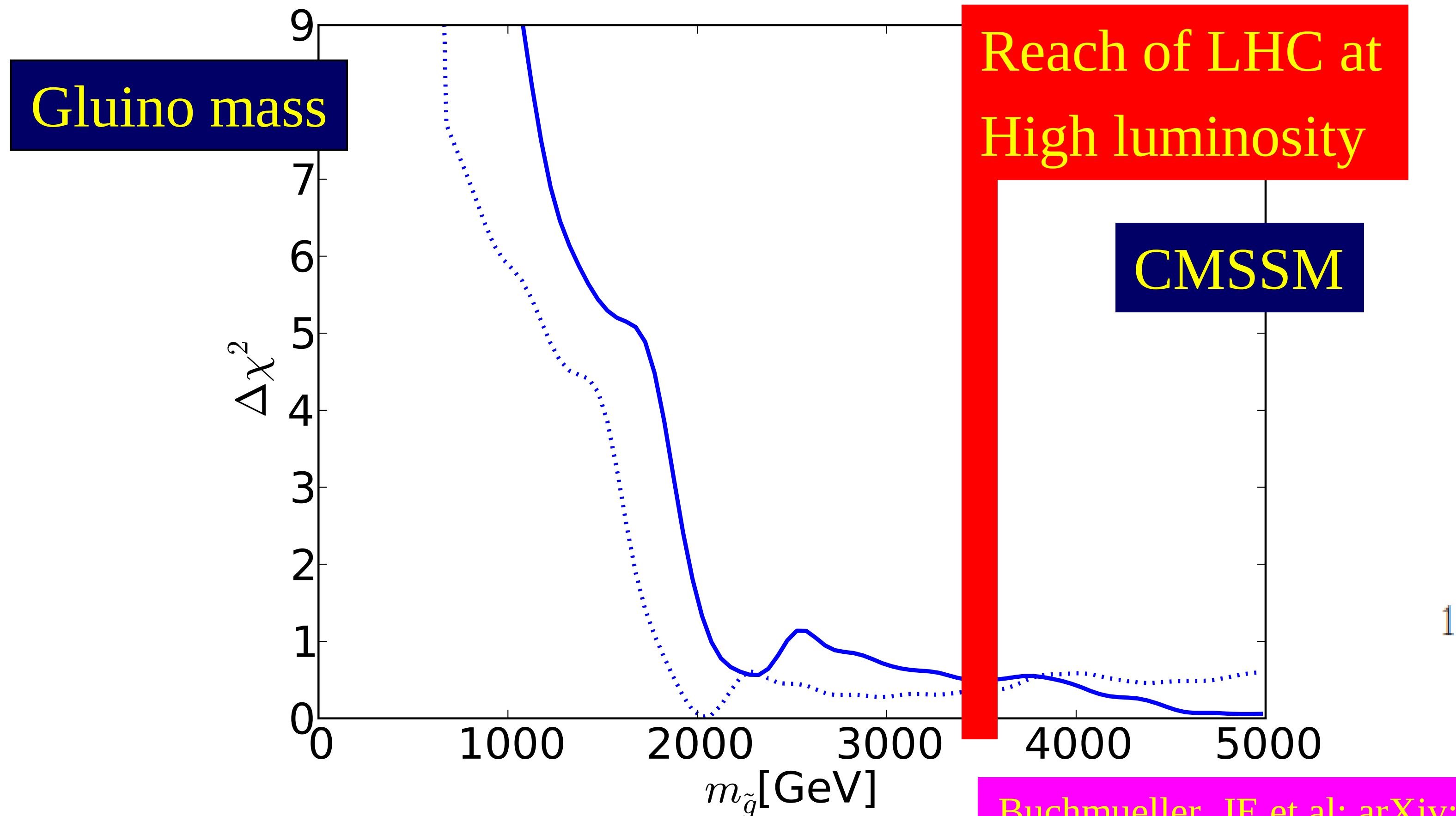
Buchmueller, JE et al: arXiv:1312.5250

Favoured values of squark mass also significantly above pre-LHC, > 1.6 TeV

# Post-LHC, Post-XENON100

2012 ATLAS + CMS with 20/fb of LHC Data



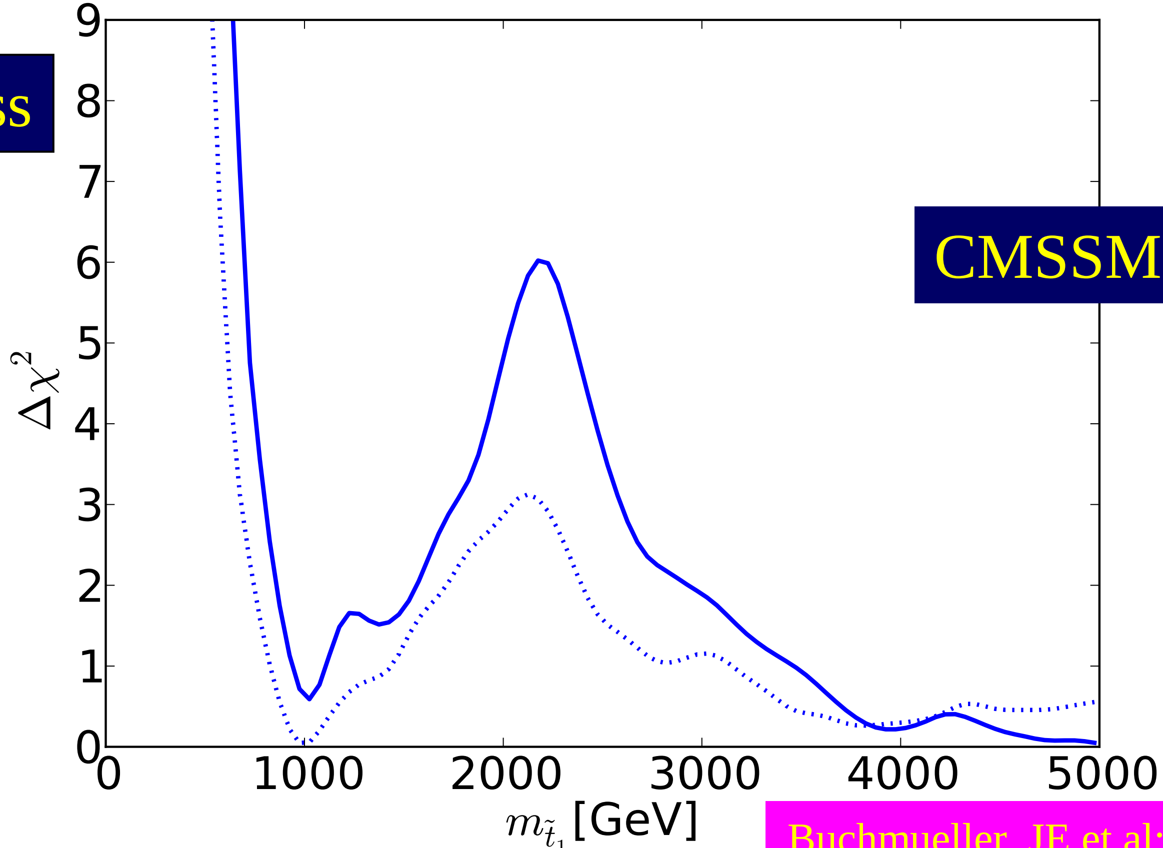

Buchmueller, JE et al: arXiv:1312.5250

Favoured values of gluino mass significantly above pre-LHC, > 1.8 TeV

# Post-LHC, Post-XENON100

2012 ATLAS + CMS with 20/fb of LHC Data

Stop mass




CMSSM

1

Buchmueller, JE et al: arXiv:1312.5250

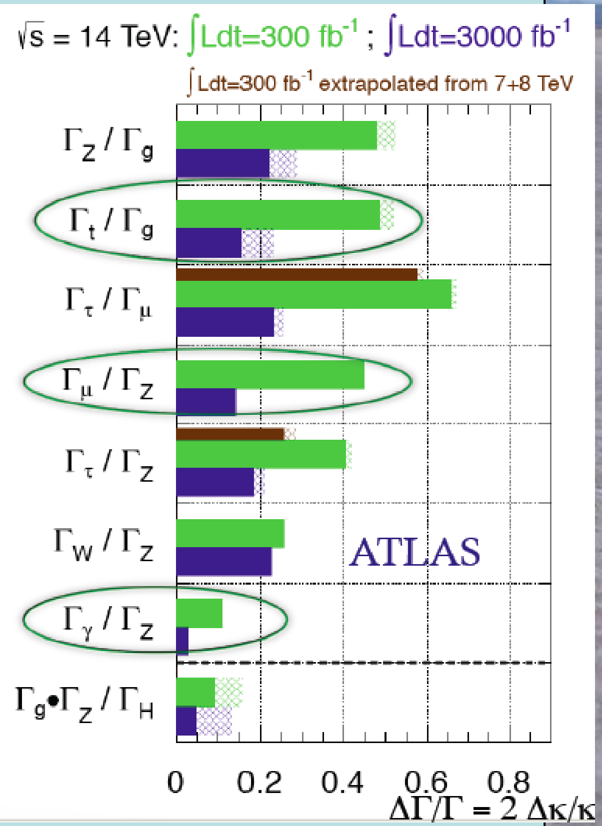
Favoured values of stop mass significantly below gluino, other squarks

# What Next: A Higgs Factory?

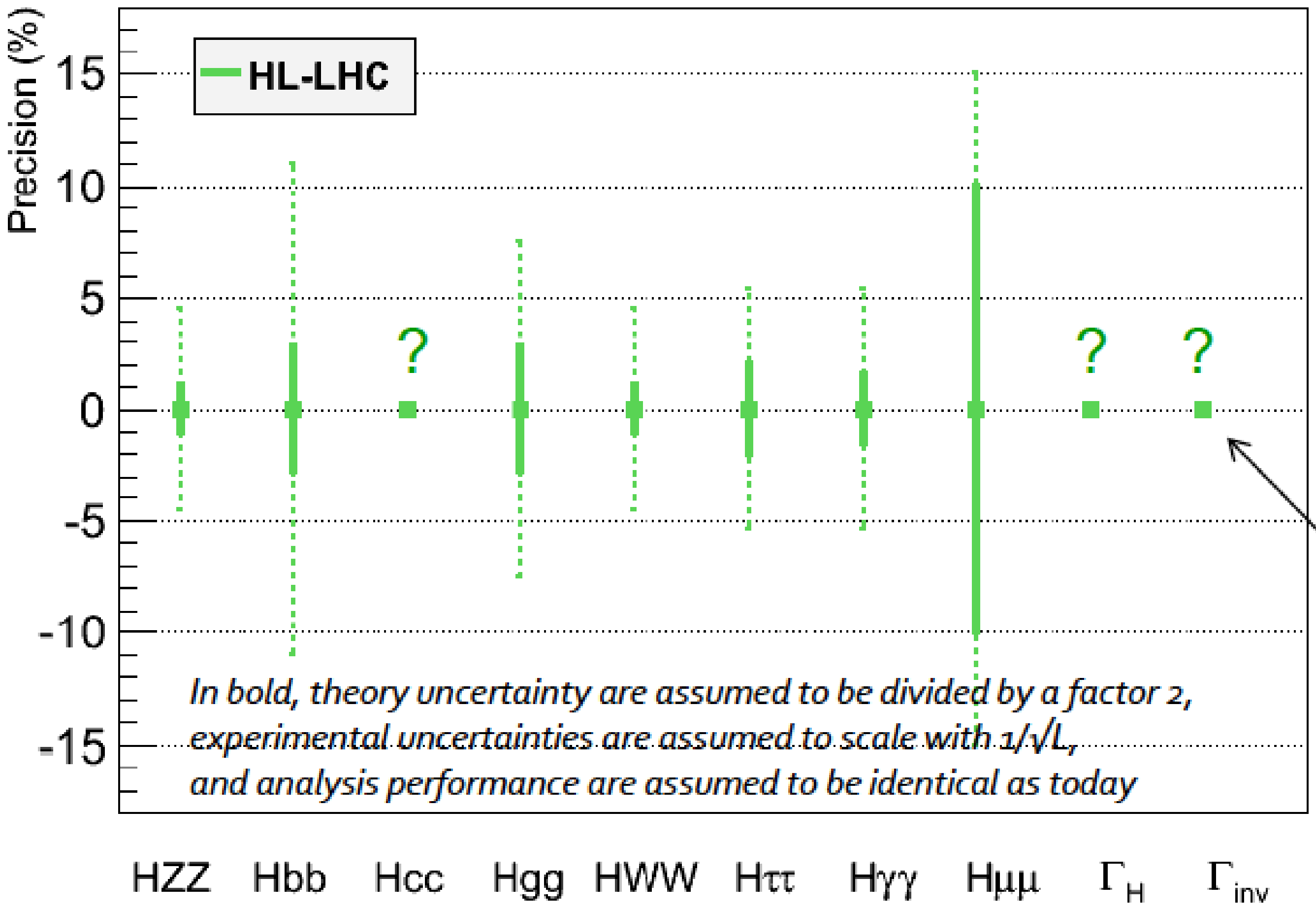
To study the 'Higgs' in detail:

- The LHC
  - Consider LHC upgrades in this perspective
- A linear collider?
  - ILC up to 500 GeV
  - CLIC up to 3 TeV

    (Larger cross section at higher energies)
- **A circular $e^+e^-$ collider?**
- An ep collider?
- A γγ collider? A muon collider?
- **Wait for results from LHC @ 13/14 TeV**



# Possible High-Luminosity LHC Measurements

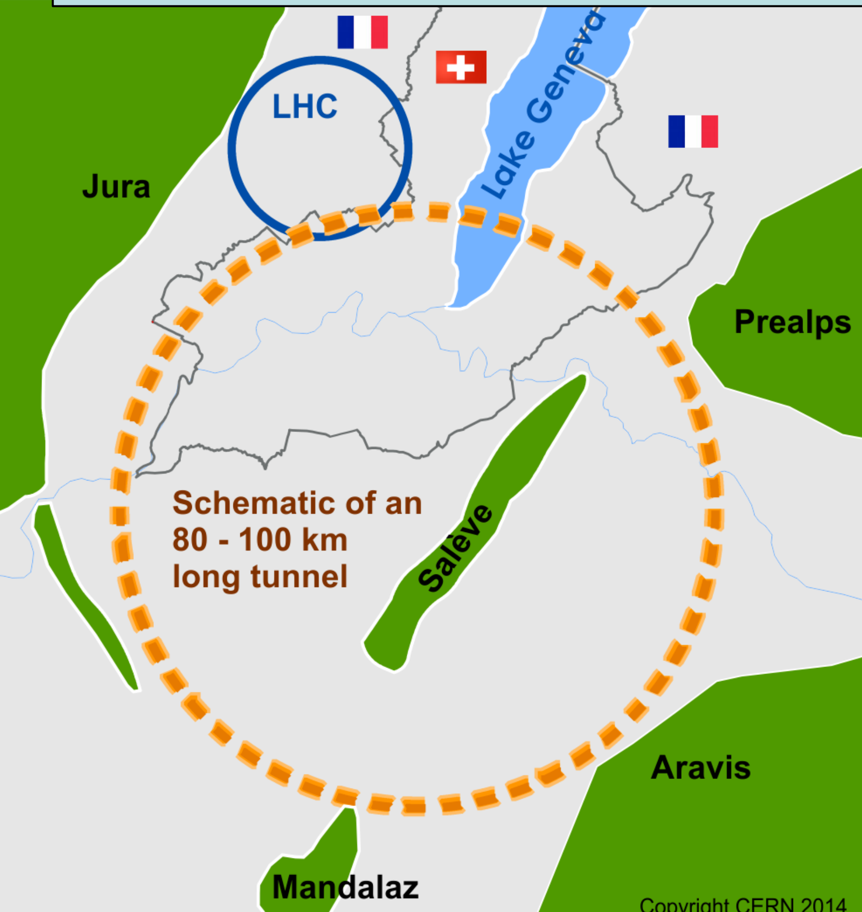


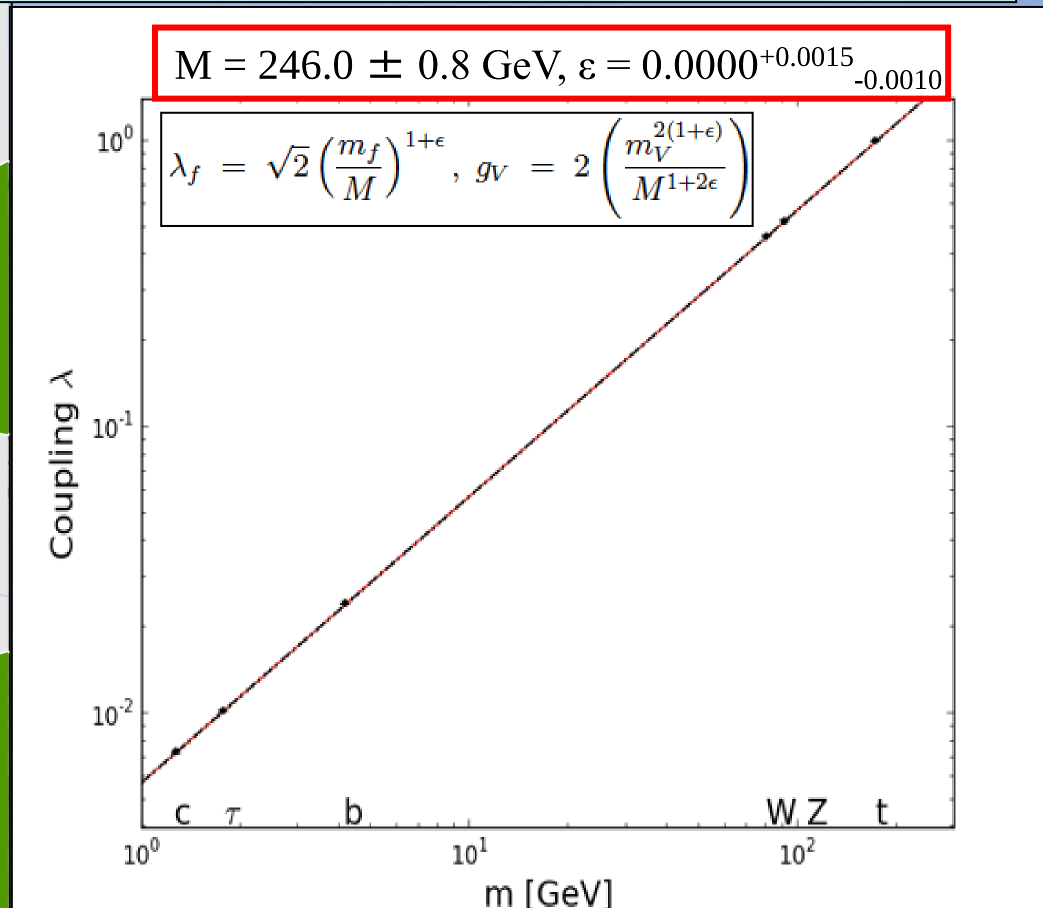

Assumptions :

1. No new decay
2. $\Gamma_H$ fixed in the fit (or fixed BR(cc) )

ATLAS upper limit at 65% (Moriond EW 2013)

# Future Circular $e^+e^-$ Collider?

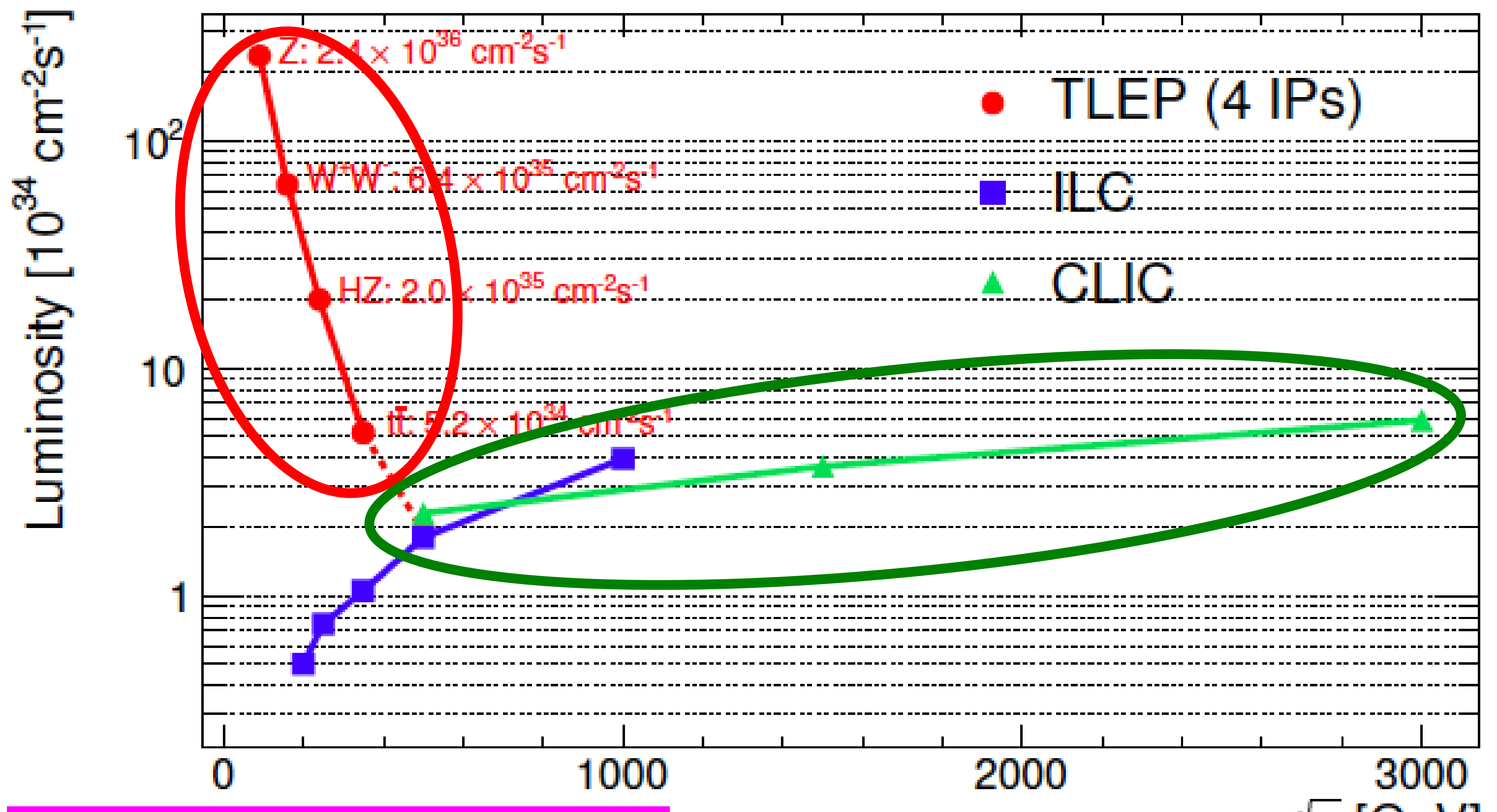



Not just Higgs physics:

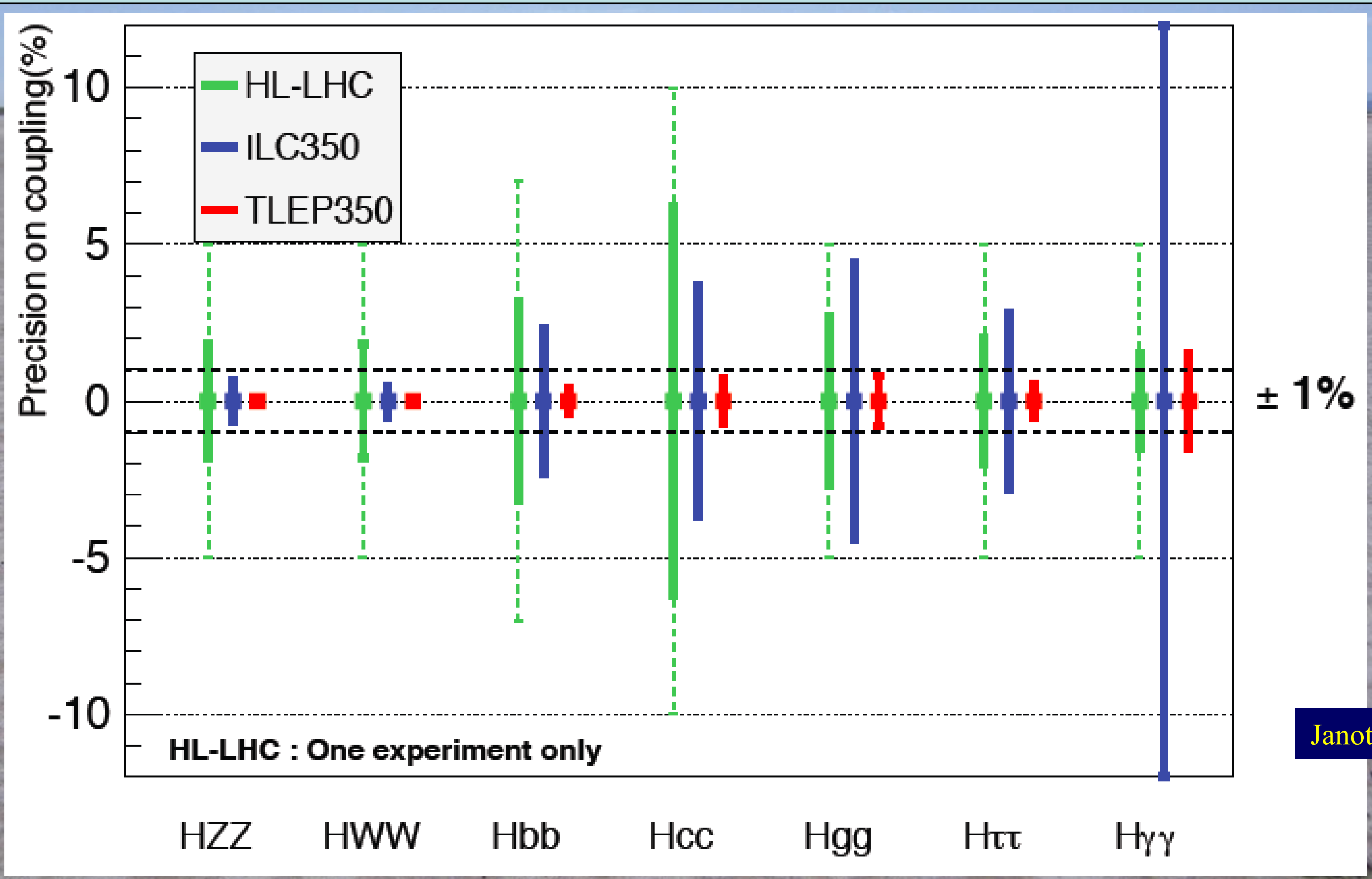
Also Tera-Z, Oku-W, Mega-t

# Projected $e^+e^-$ Colliders: Luminosity vs Energy




TLEP physics study group: arXiv:1308.6176

# Possible Future Higgs Measurements

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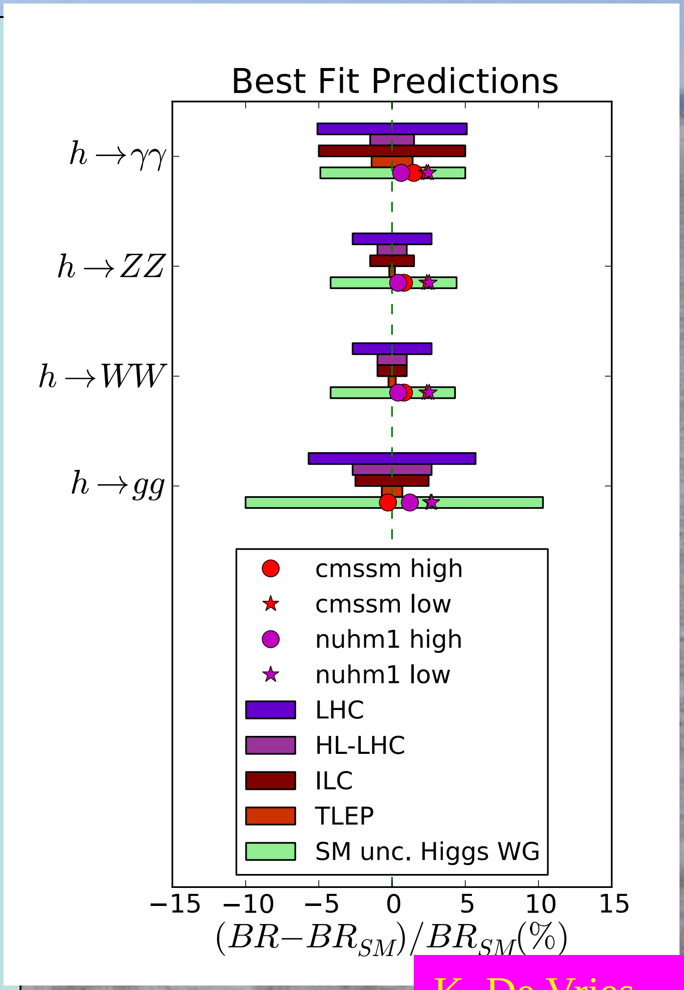
# Impact of Higgs Measurements

- Predictions of current best fits in simple SUSY models
- Current uncertainties in SM calculations [LHC Higgs WG]
- Comparisons with
  - **LHC**
  - **HL-LHC**
  - **ILC**
  - **TLEP (= FCC-ee)**

  **(Able to distinguish from SM)**




K. De Vries (MasterCode)

# TLEP:
# Part of a Vision for the Future

Exploration of the 10 TeV scale

Direct (VHE-LHC) + Indirect (TLEP)

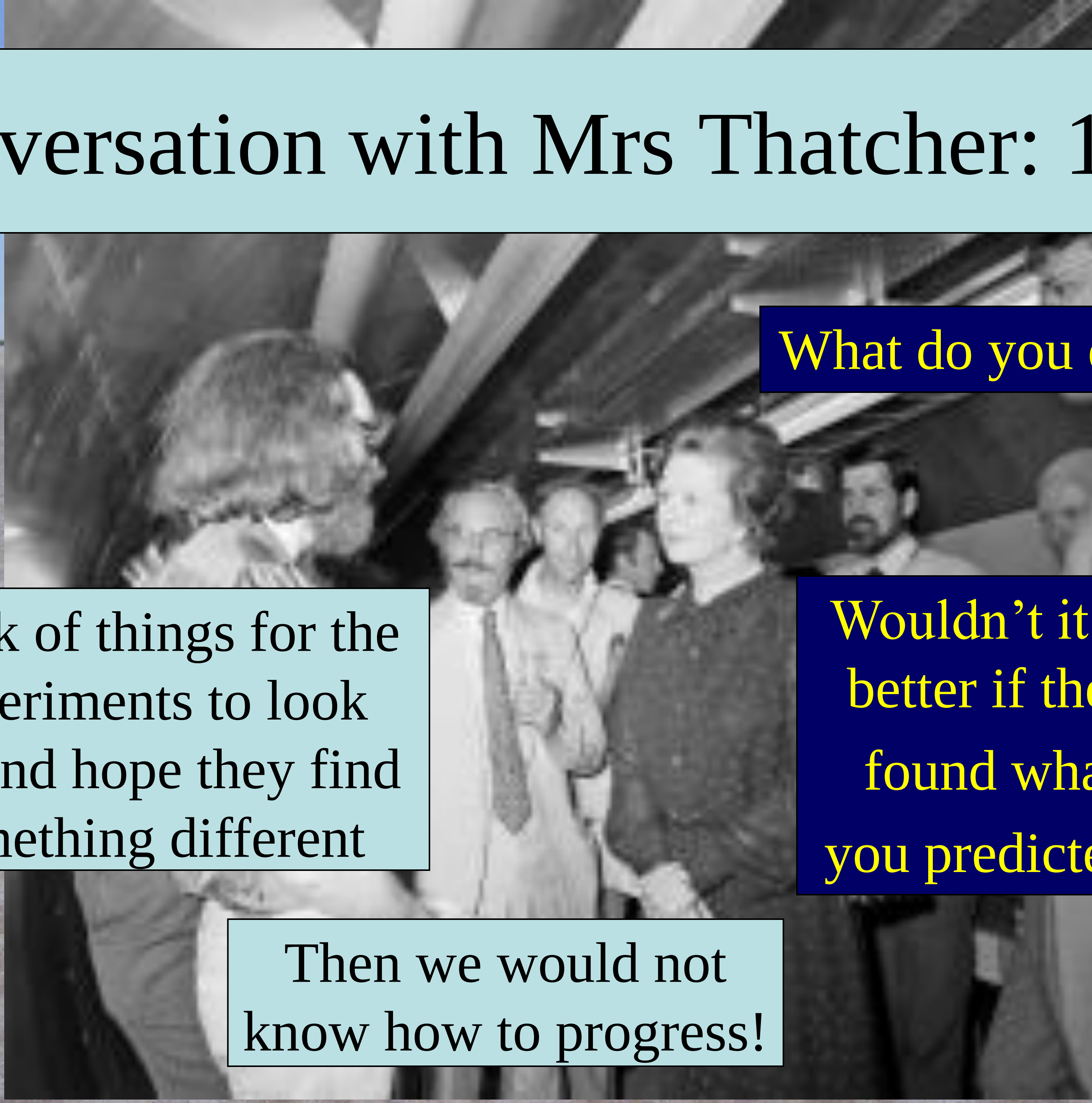
Need major effort to develop the physics case

Work together

# Summary

- Beyond any reasonable doubt, the LHC has discovered a (the) Higgs boson
- A big challenge for theoretical physics!
- The LHC may discover physics beyond the SM when it restarts at ~ 13 TeV
- If it **does**, priority will be to study it
- If it does **not**, natural to focus on the Higgs
- In this case, TLEP offers the best prospects
  - and also other high-precision physics

# Conversation with Mrs Thatcher: 1982



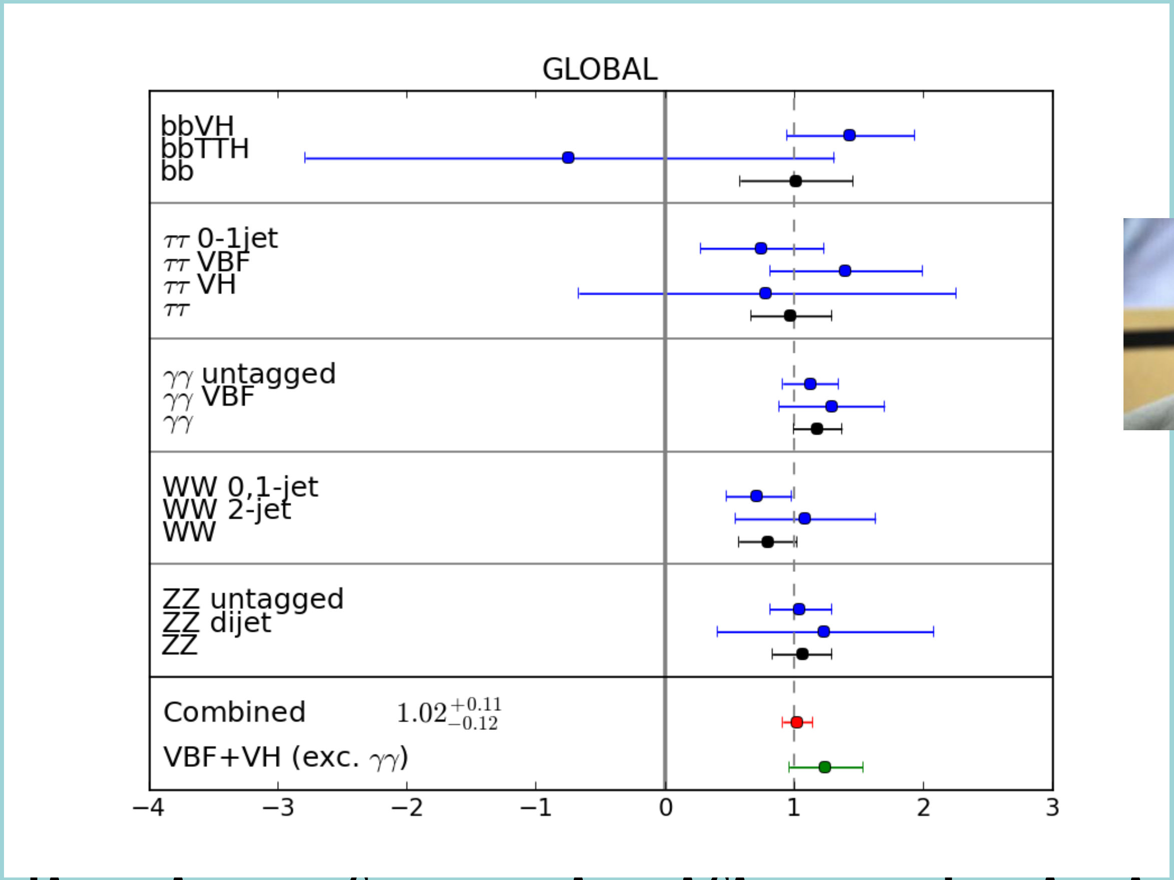
What do you do?

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 know how to progress!

# Couplings resemble Higgs of Standard Model



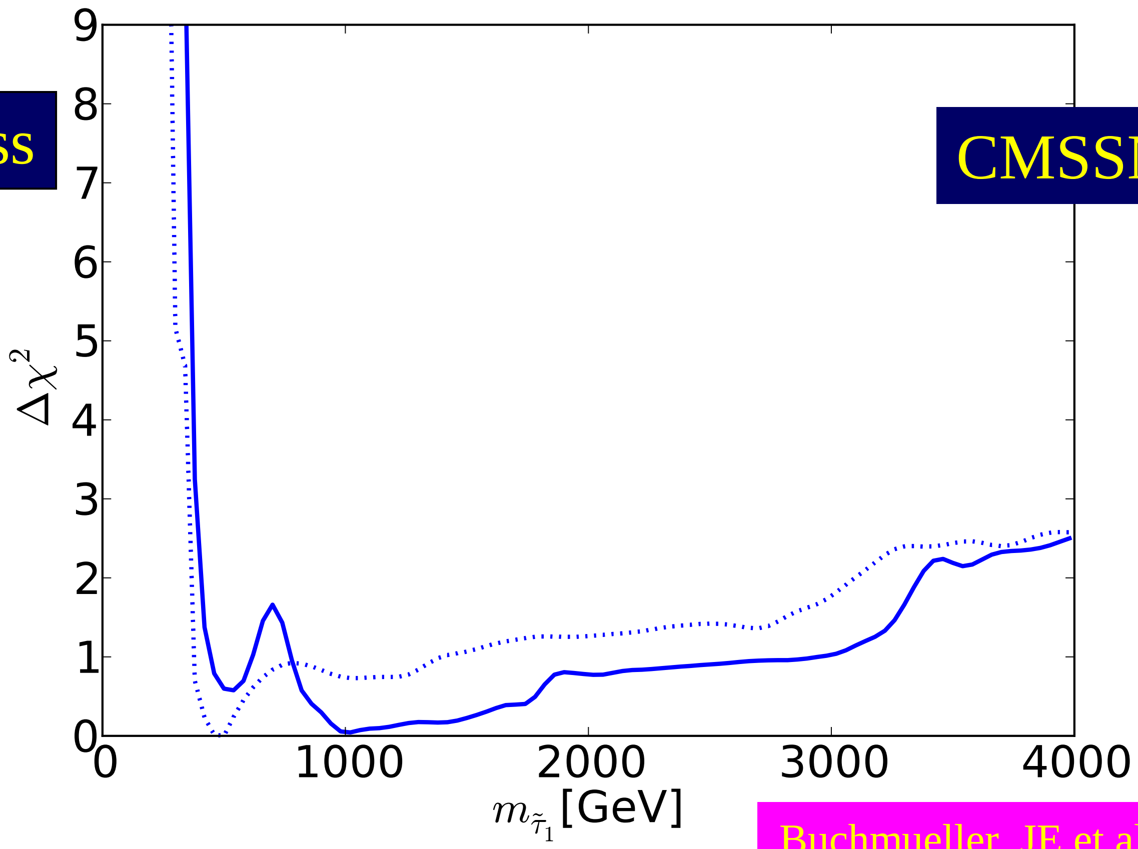

- No indication of any significant deviation from the Standard Model predictions

JE & Tevong You, arXiv:1303.3879

# Post-LHC, Post-XENON100

**2012** ATLAS + CMS with **20/fb** of LHC Data

Stau mass




CMSSM

1

Buchmueller, JE et al: arXiv:1312.5250

Favoured values of stau mass:

> five hundred GeV

# Proton-Proton Colliders: Luminosity and Energy

- Future runs of the LHC:
  - Run 2: 30/fb @ 13/14 TeV
  - Run 3: 300/fb @ 14 TeV
- HL-LHC: 3000/fb @ 14 TeV?

  (advanced planning, not formally approved)
- HE-LHC: 3000/fb @ 33 TeV??

  (high-field magnets in the LHC tunnel)
- VHE-LHC: 3000/fb @ 100 TeV??

  (high-field magnets in 80/100 km tunnel)

# Higgs Bosons in Supersymmetry

- Need 2 complex Higgs doublets
  (cancel anomalies, form of SUSY couplings)
- 8 – 3 = 5 physical Higgs bosons
  Scalars h, H; pseudoscalar A; charged $H^{\pm}$
- Lightest Higgs < MZ at tree level:

$$M^2_{\mathrm{H,h}} = \frac{1}{2}\left[M^2_{\mathrm{A}} + M^2_{\mathrm{Z}} \pm \sqrt{(M^2_{\mathrm{A}} + M^2_{\mathrm{Z}})^2 - 4M^2_{\mathrm{Z}}M^2_{\mathrm{A}}\cos^2 2\beta}\right]$$

- Important radiative corrections to mass:

$$G_\mu m^4_{\mathrm{t}} \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m^2_{\mathrm{t}}}\right)$$

$\Delta M_H|_{TH} \sim 1.5$ GeV

# Theoretical Confusion

- High mortality rate among theories
- ($M_H$, $M_t$) close to stability bound
- Split SUSY? High-scale SUSY?
- Modify/abandon naturalness? Does Nature care?
- String landscape?
- SUSY anywhere better than nowhere
- SUSY could not explain the hierarchy
- **New ideas needed!**

# Deviations from Standard Model?

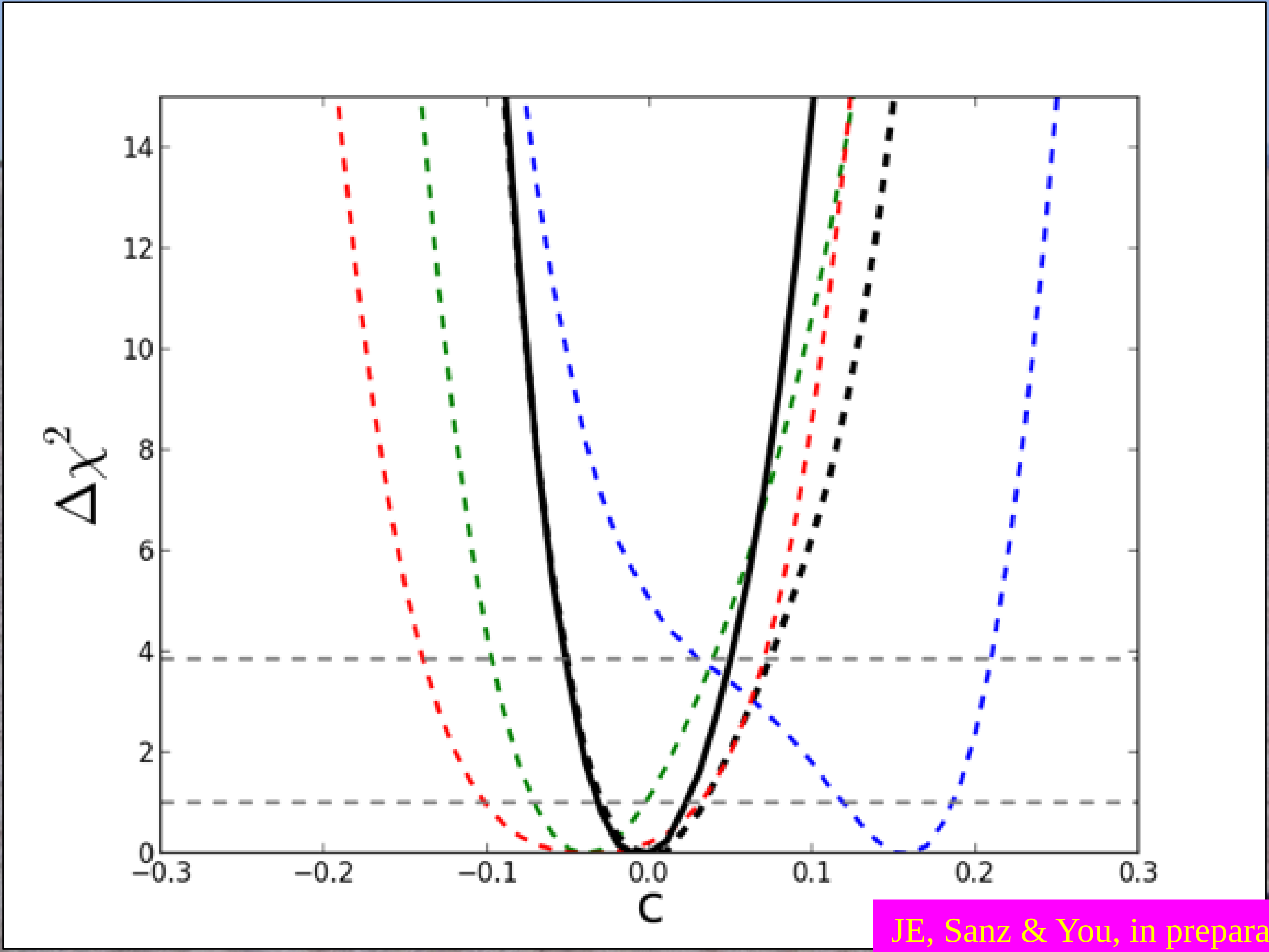
- Higher-dimensional operators as relics of higher-energy physics: $\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$
- Operators constrained by SU(2) × U(1) symmetry:

$$\begin{aligned}
\mathcal{L}_{\rm SILH} = & \frac{\bar{c}_H}{2v^2} \partial^\mu \big[\Phi^\dagger \Phi\big] \partial_\mu \big[\Phi^\dagger \Phi\big] + \frac{\bar{c}_T}{2v^2} \big[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\big] \big[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\big] - \frac{\bar{c}_6 \lambda}{v^2} \big[H^\dagger H\big]^3 \\
& - \Big[\frac{\bar{c}_u}{v^2} y_u \Phi^\dagger \Phi \ \Phi^\dagger \cdot \bar{Q}_L u_R + \frac{\bar{c}_d}{v^2} y_d \Phi^\dagger \Phi \ \Phi \bar{Q}_L d_R + \frac{\bar{c}_l}{v^2} y_\ell \ \Phi^\dagger \Phi \ \Phi \bar{L}_L e_R + \text{h.c.}\Big] \\
& + \frac{ig \ \bar{c}_W}{m_W^2} \big[\Phi^\dagger T_{2k} \overleftrightarrow{D}^\mu \Phi\big] D^\nu W^k_{\mu\nu} + \frac{ig' \ \bar{c}_B}{2m_W^2} \big[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\big] \partial^\nu B_{\mu\nu} \\
& + \frac{2ig \ \bar{c}_{HW}}{m_W^2} \big[D^\mu \Phi^\dagger T_{2k} D^\nu \Phi\big] W^k_{\mu\nu} + \frac{ig' \ \bar{c}_{HB}}{m_W^2} \big[D^\mu \Phi^\dagger D^\nu \Phi\big] B_{\mu\nu} \\
& + \frac{g'^2 \ \bar{c}_\gamma}{m_W^2} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} + \frac{g_s^2 \ \bar{c}_g}{m_W^2} \Phi^\dagger \Phi G^a_{\mu\nu} G_a^{\mu\nu}
\end{aligned}$$

Alloul, Fuks & Sanz, arXiv:1310.5150

- Constrain with Higgs data, triple-gauge couplings…

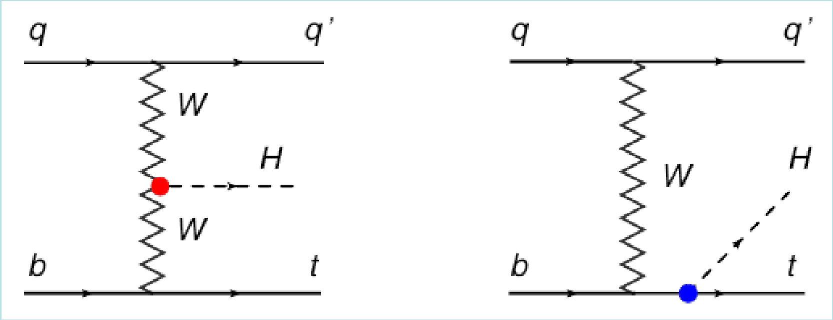
# Constraints from Associated V + H Production



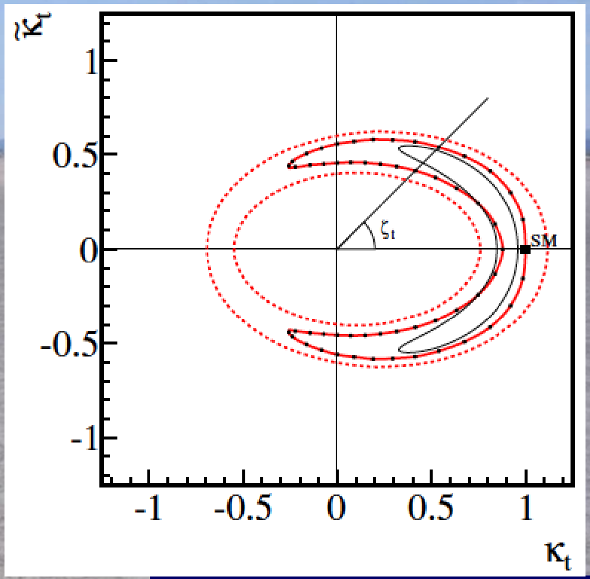

JE, Sanz & You, in preparation

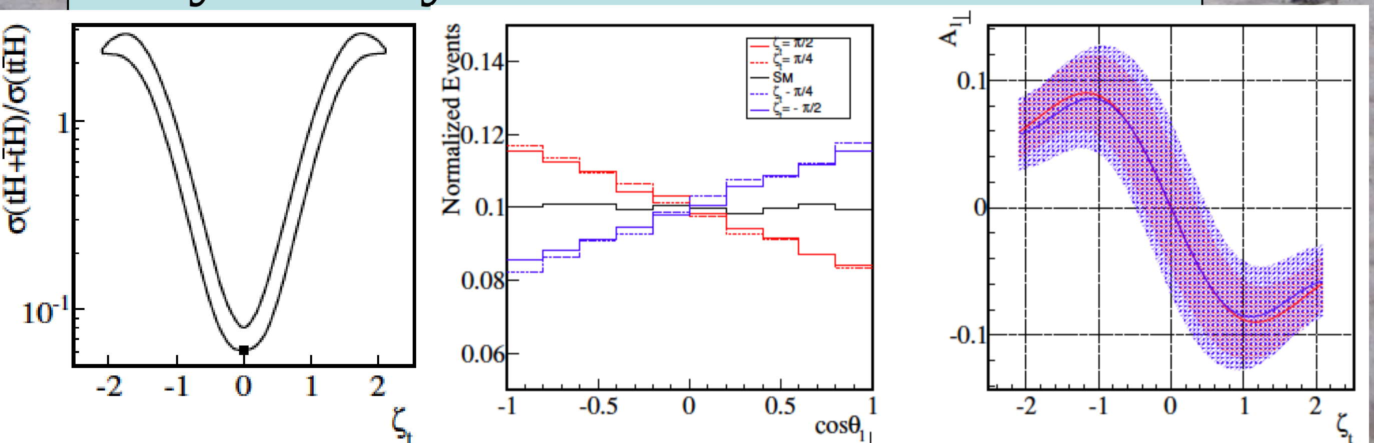
# Single Higgs + Top Production

- Sensitive to sign of H-t coupling, CP-odd admixture




- Cross-section, out-of-plane symmetry sensitive to CP-odd




Significant measurement possible @ LHC14?

JE, Hwang, Sakurai & Takeuchi, arXiv:1312.5736