LHC Physics – A Theoretical Perspective

Some 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?
  due to a Higgs boson? LHC
- 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

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)

The first

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

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

The only one to point out the existence of 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)

Without Higgs …

… there would be no atoms

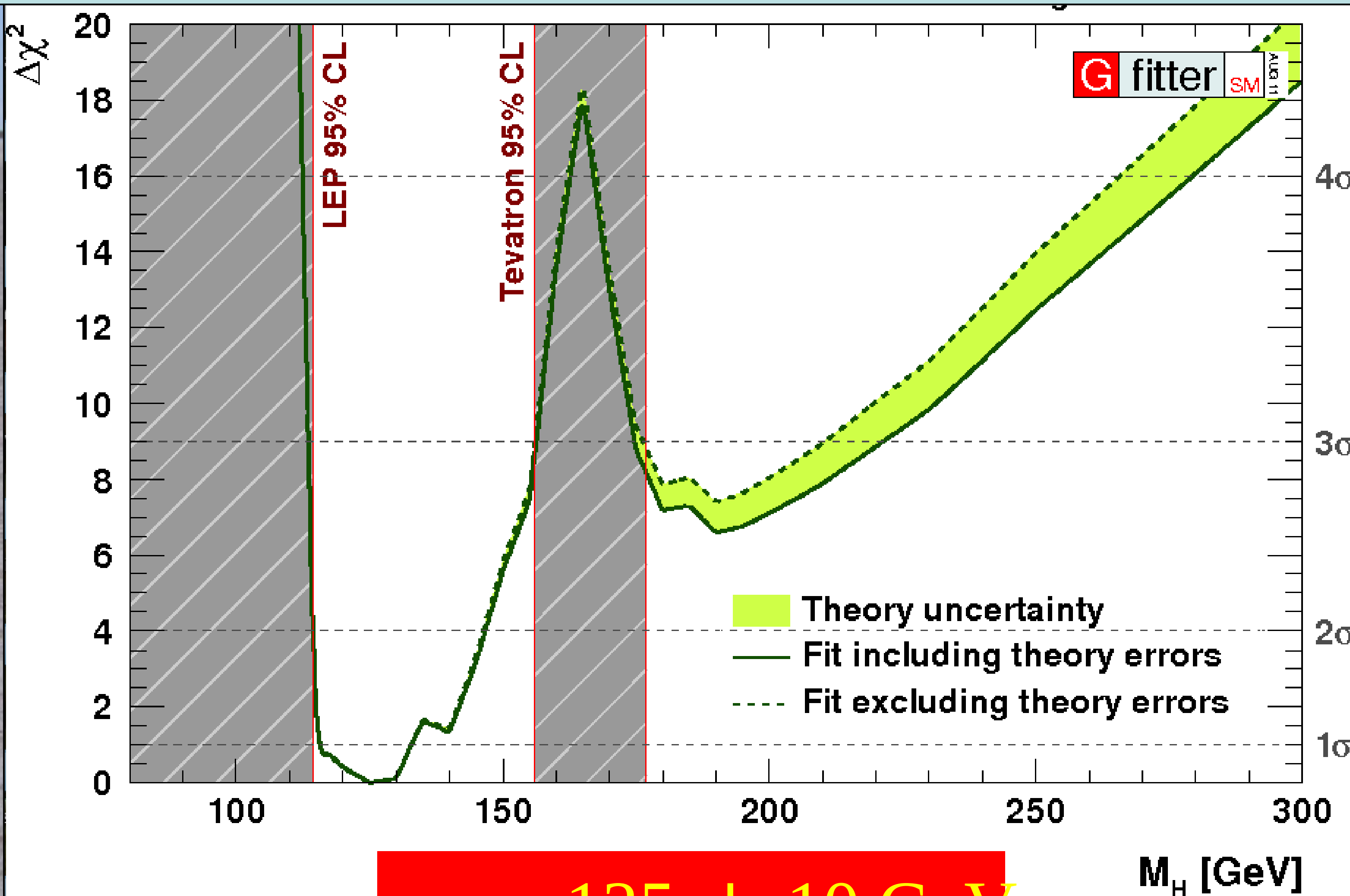
– Electrons would escape at the speed of light

… weak interactions would not be weak

– Life would be impossible: there would be no nuclei, everything would be radioactive

Its existence is a big deal!

2011: Combining Information from Previous Direct Searches and Indirect Data

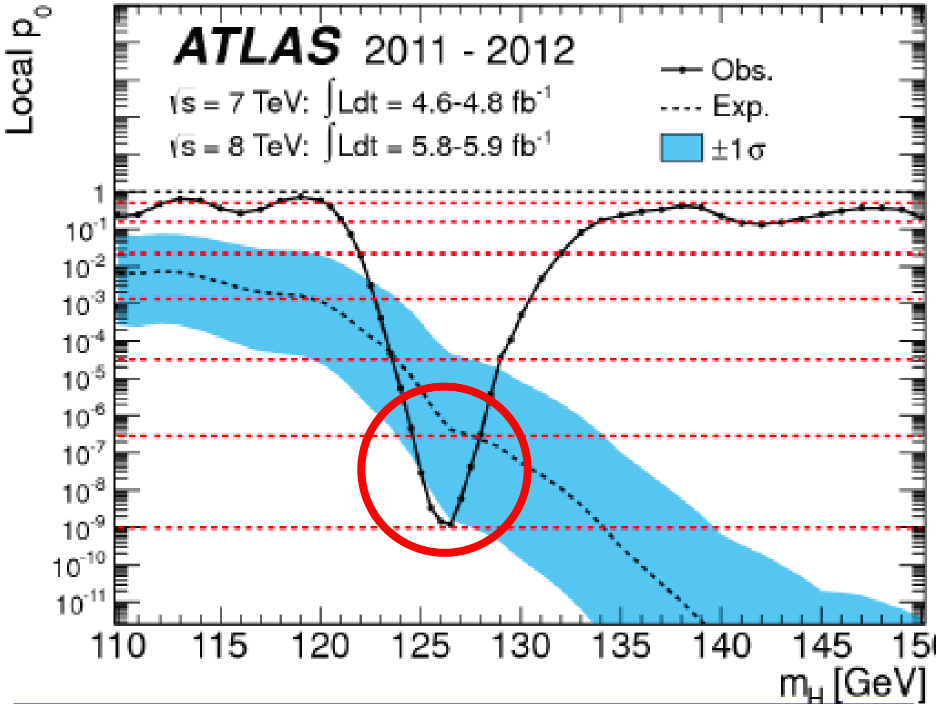


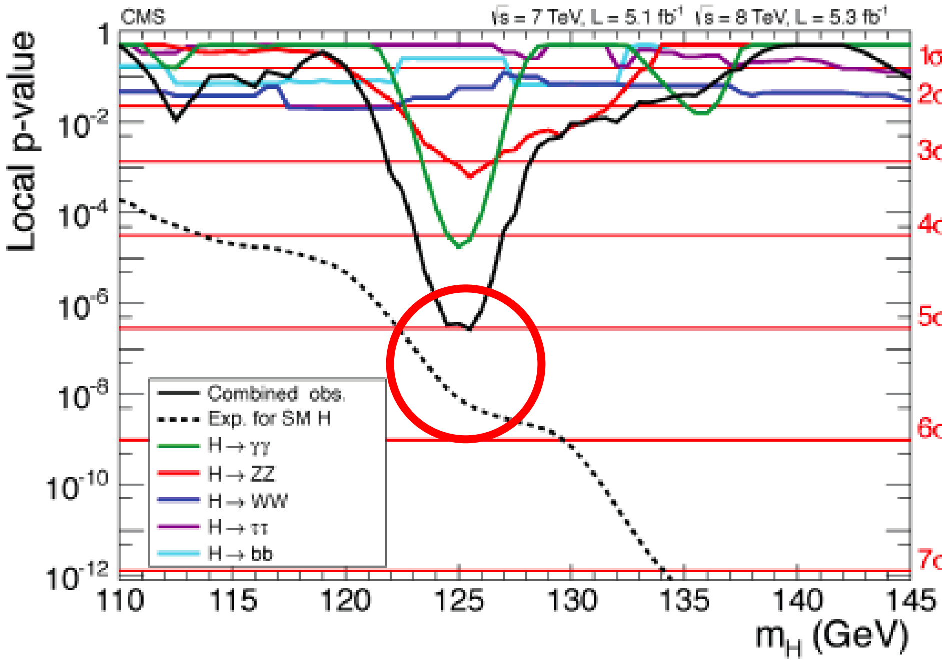
$m_H = 125 \pm 10$ GeV

Gfitter collaboration

A New Particle has been Discovered

Independent discoveries around M_h = 125 to 126 GeV





ATLAS signal

M_H = 126.0 ± 0.4 ± 0.4 GeV

(1.4 ± 0.3) × SM

CMS signal

M_H = 125.3 ± 0.4 ± 0.5 GeV

(0.87 ± 0.23) × SM

The Particle Higgsaw Puzzle

Is LHC finding the missing piece?

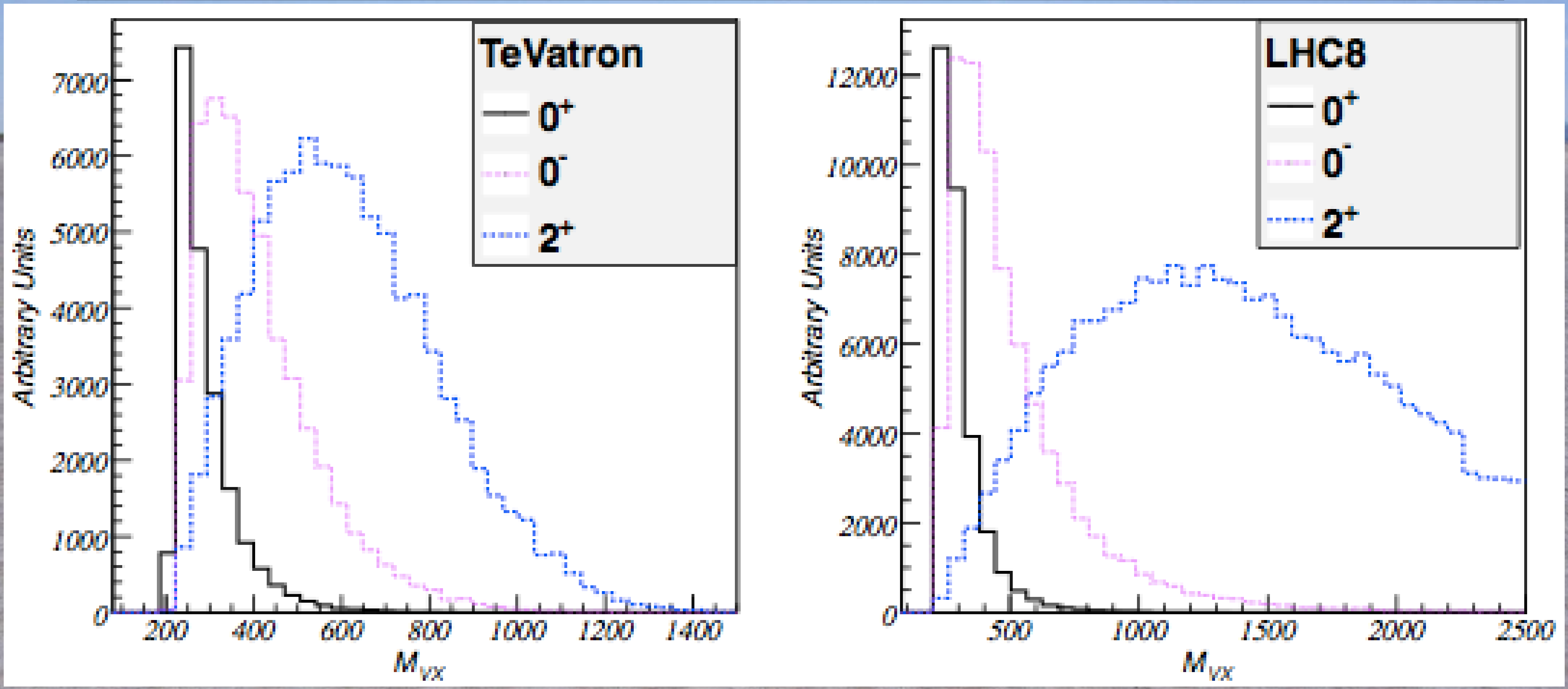
Is it the right shape?

Is it the right size?

Does the 'Higgs' have Spin Zero ?

- Decays into γγ, so cannot have spin 1
- **Spin 0 or 2?**
- Can diagnose spin via
  - angular distribution of γγ
  - angular correlations of leptons in WW, ZZ decays
  - Production in association with W or Z
- Do selections of WW and ZZ events already favour spin 0?

Does the ‘Higgs’ have Spin Zero ?

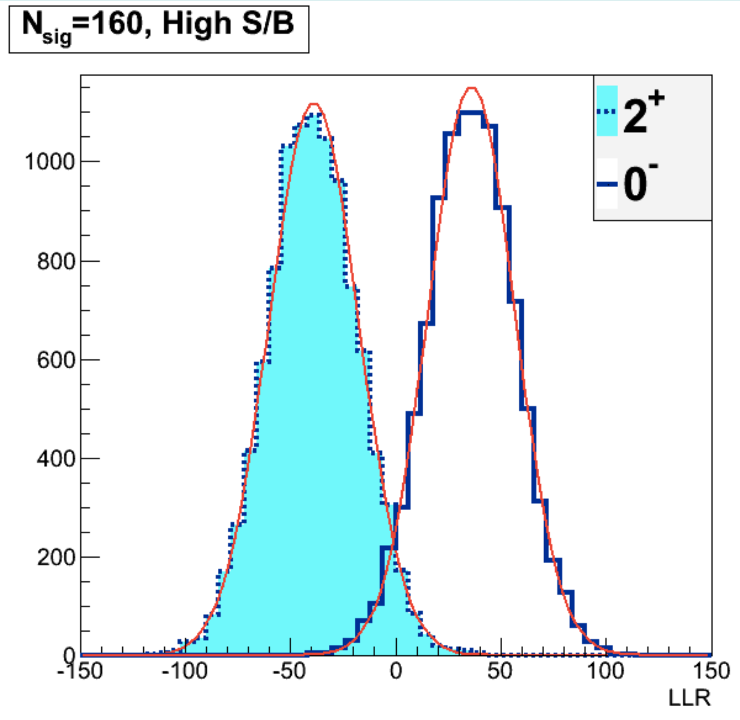


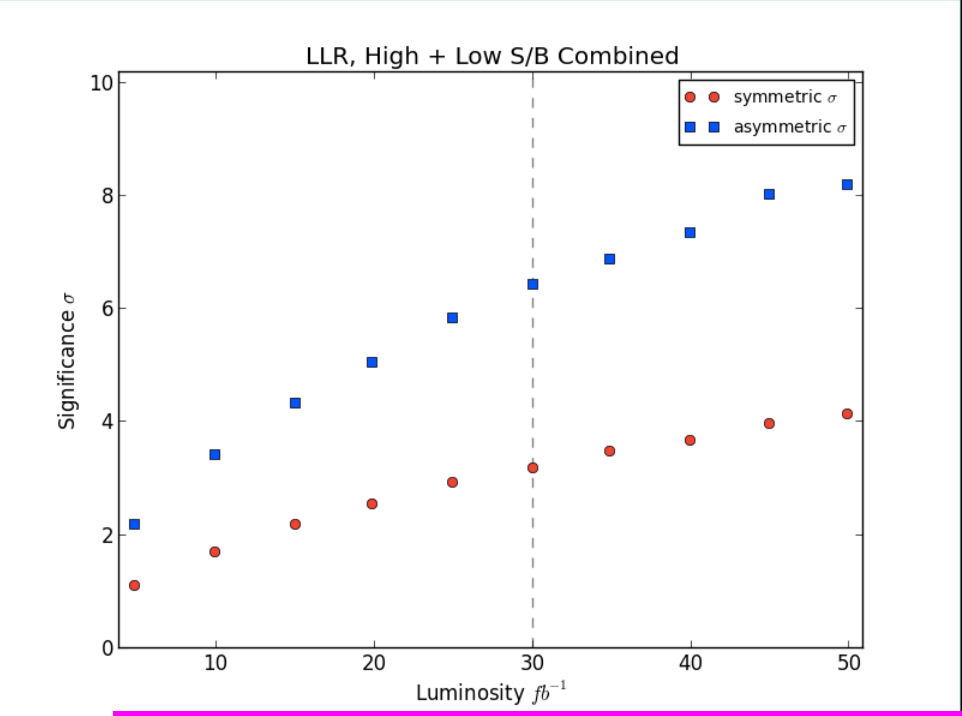
Vector boson + ‘Higgs’ combined invariant mass very different for spins 0 and 2

JE, Hwang. Sanz & You: arXiv:1208.6002

Does the 'Higgs' have Spin Zero ?

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





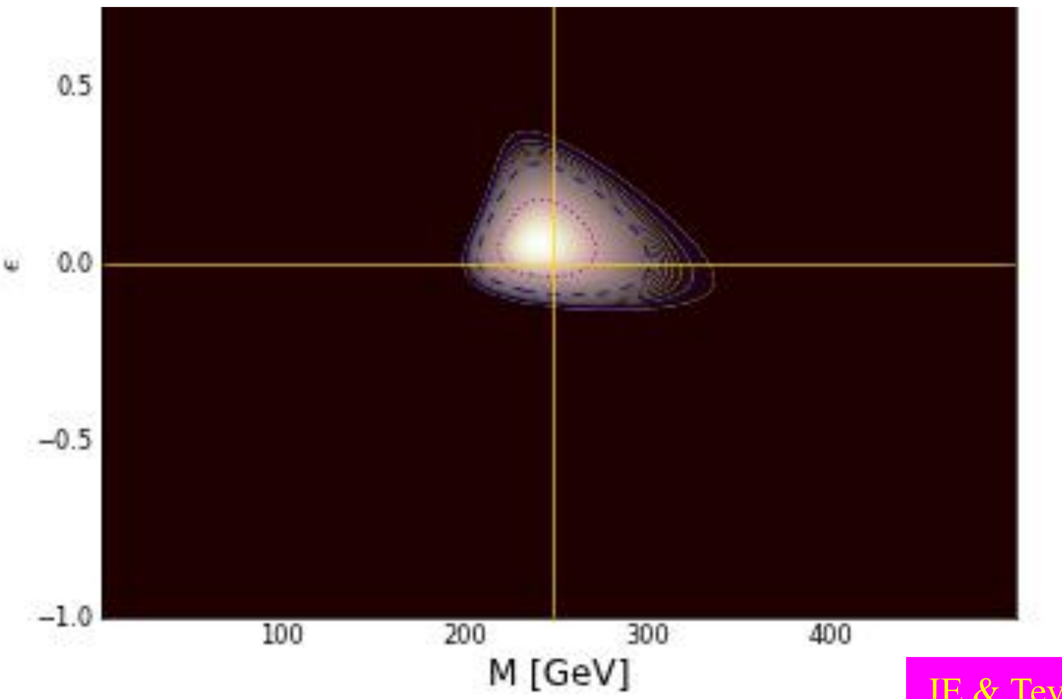
•JE, Fok, Hwang, Sanz & You: arXiv:1210.5229

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



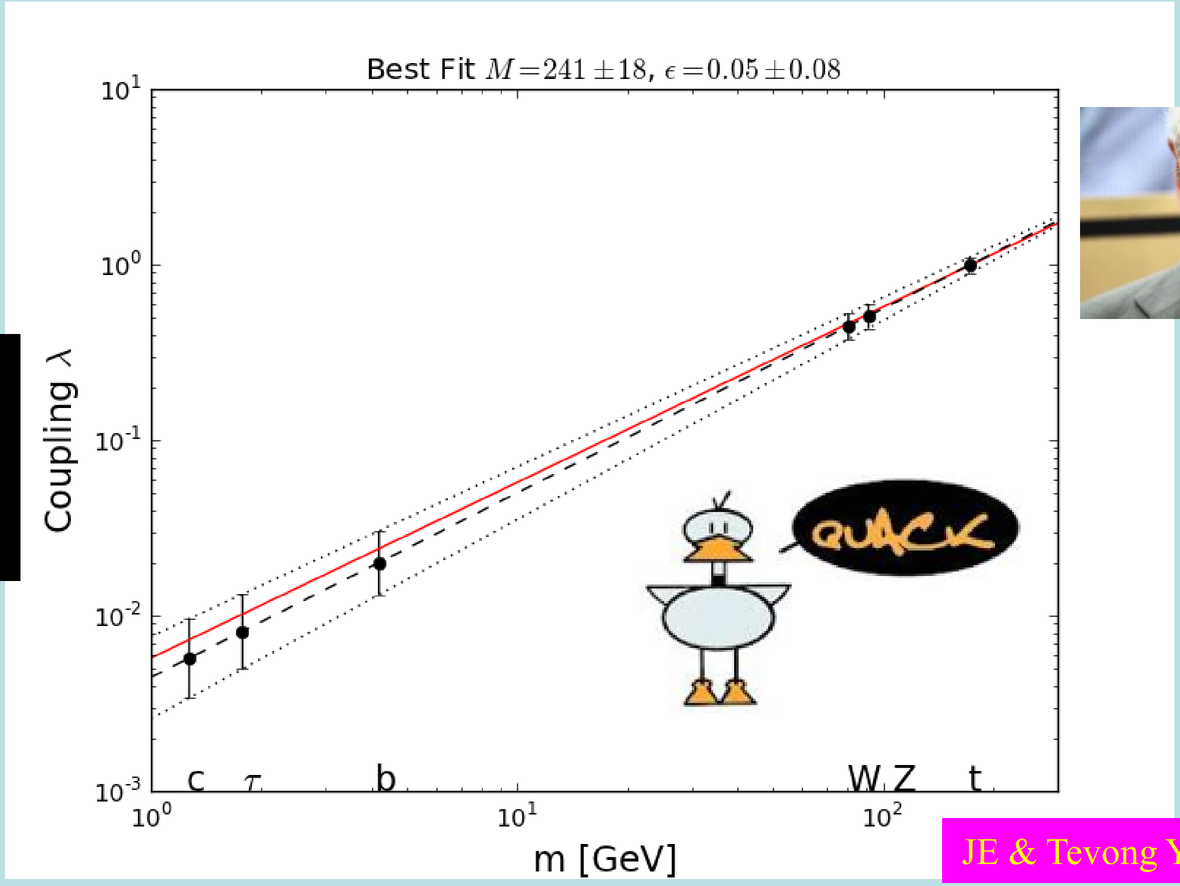
JE & Tevong You, arXiv:1207.1693

- Standard Model Higgs: ε = 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

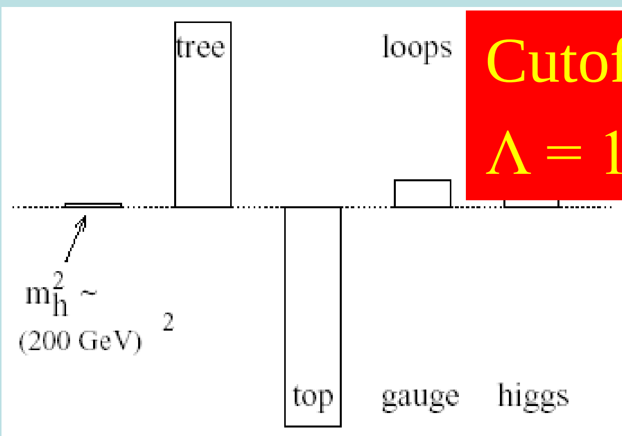
- **Red line = SM**, dashed line = best fit

Elementary Higgs or Composite?

- Higgs field:

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

- Quantum loop problems



Cutoff

Λ = 10 TeV

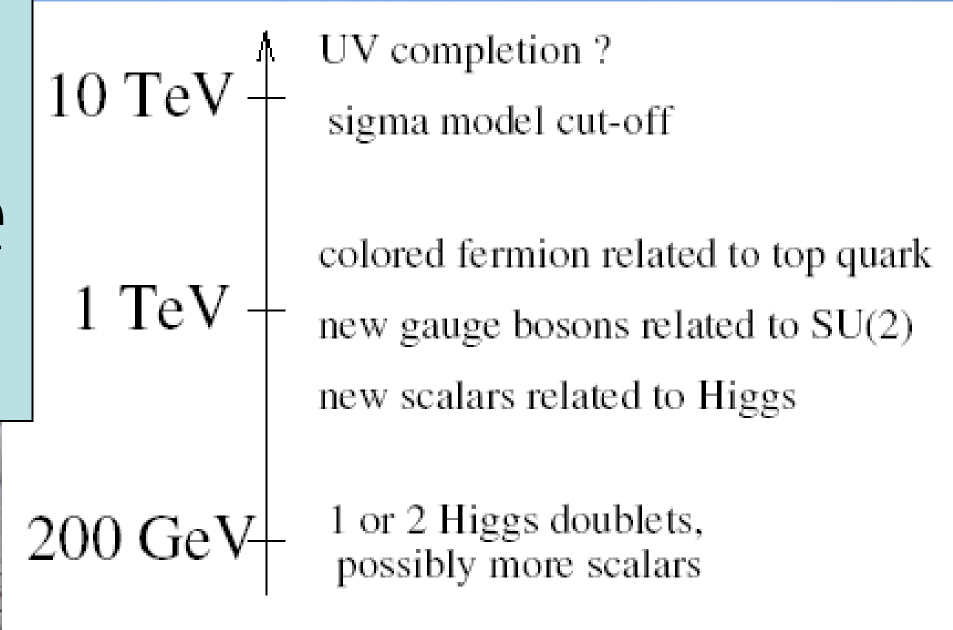
Cut-off Λ ~ 1 TeV with Supersymmetry?

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

New technicolour force?

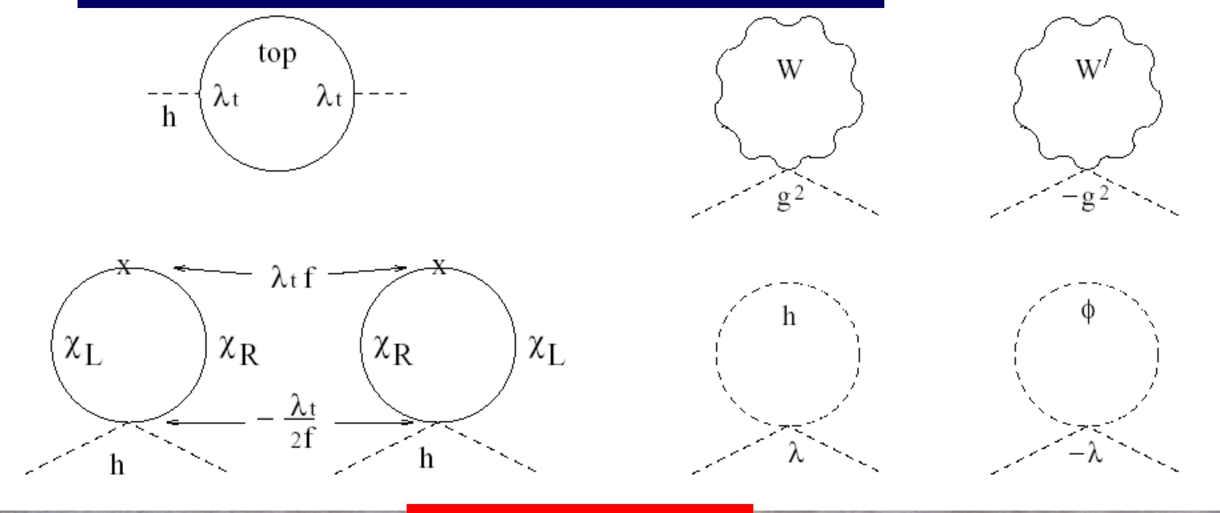
- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

Higgs as a Pseudo-Goldstone Boson

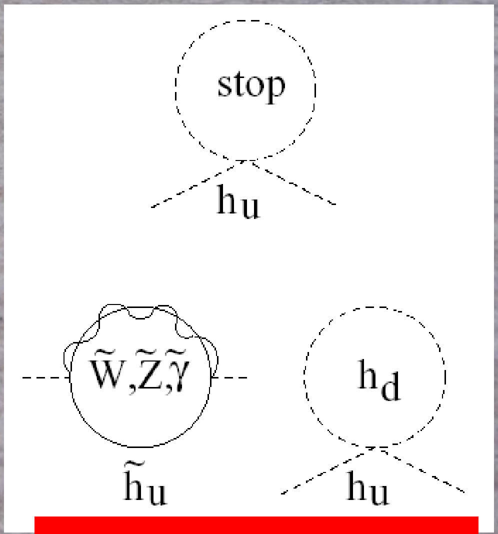


'Little Higgs' models
(breakdown of larger symmetry)

Loop cancellation mechanism



Little Higgs



Supersymmetry

General Analysis of ‘unHiggs’ Models

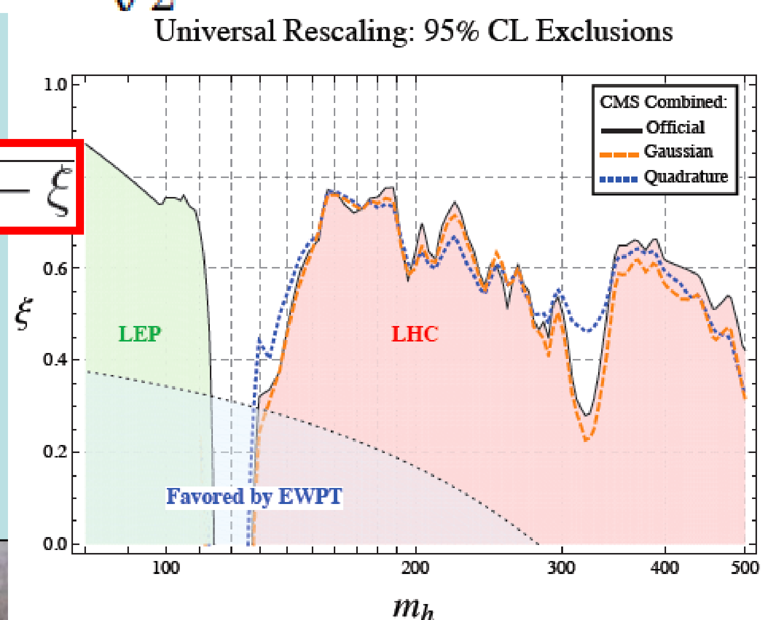
- Parametrization of effective Lagrangian:

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

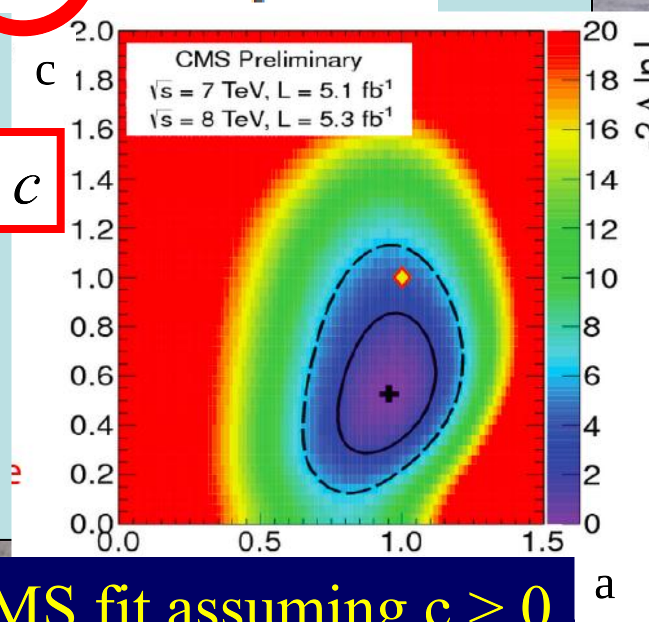
$$- \frac{v}{\sqrt{2}}\lambda^u_{ij}\left(\bar{u}^{(i)}_L, \bar{d}^{(i)}_L\right)\Sigma\left(u^{(i)}_R, 0\right)^T\left(1 + c_u\,\frac{h}{v} + c_{2u}\,\frac{h^2}{v^2} + \cdots\right)$$

- Fits

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



$a \neq c$



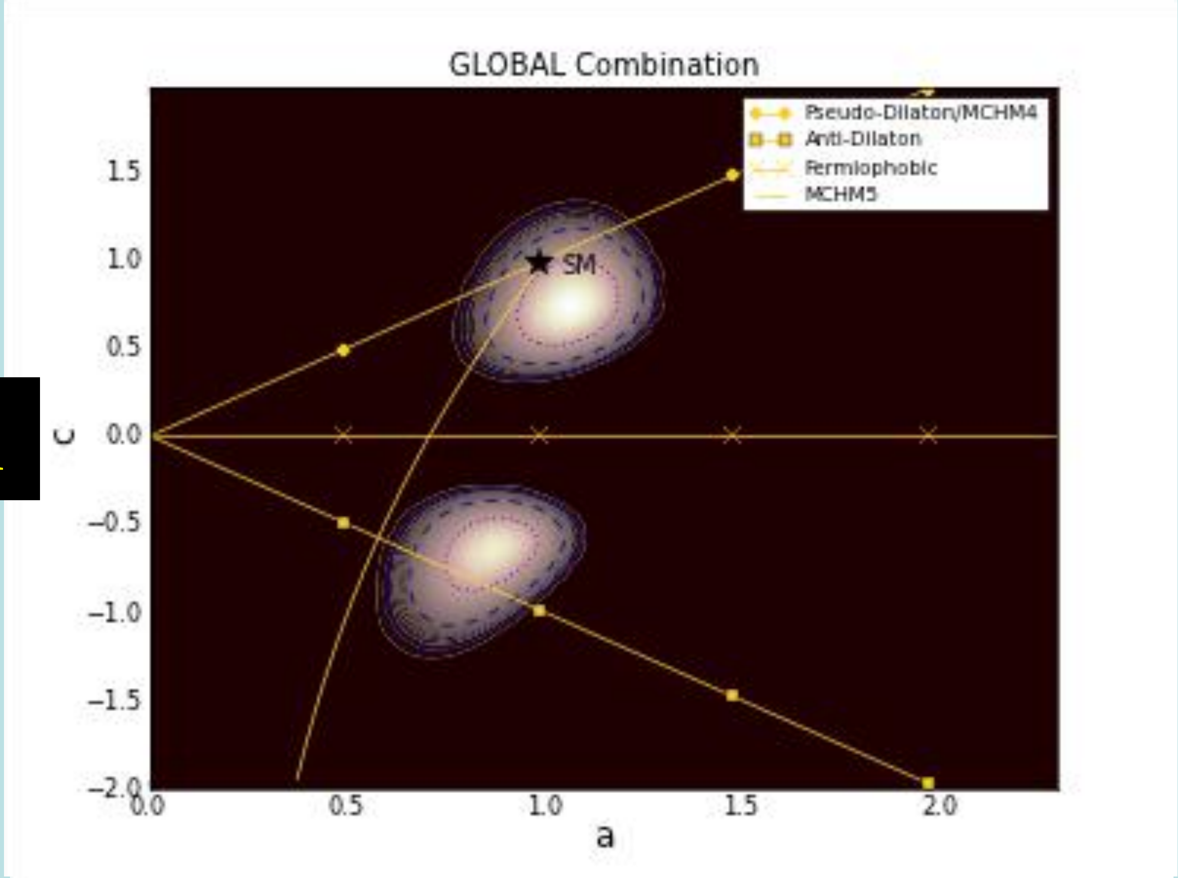
CMS fit assuming c > 0

Azatov, Contino, Galloway: arXiv:1202.3415

Global Analysis of Higgs-like Models

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

Global 0

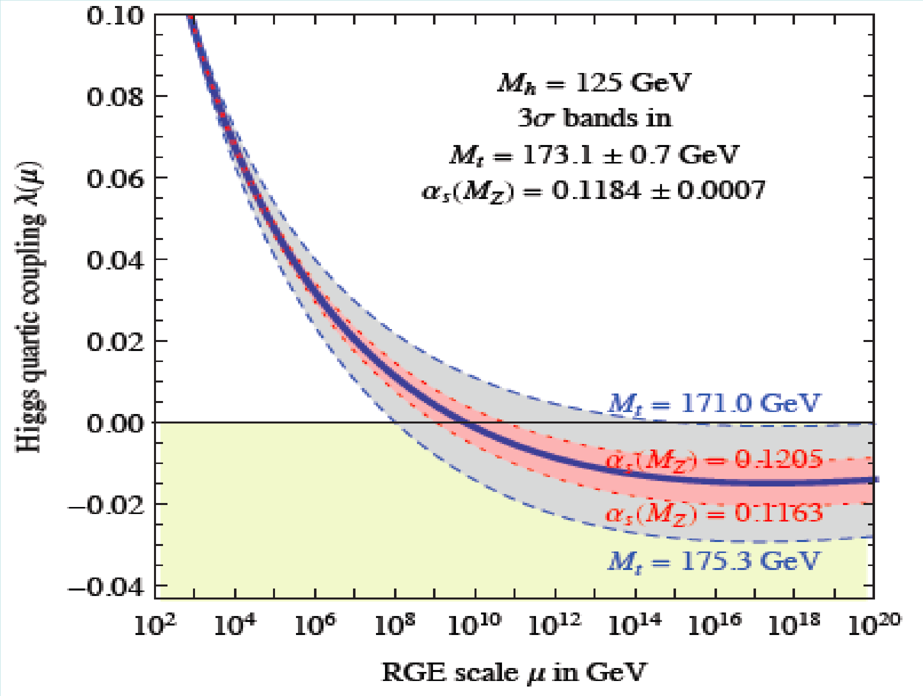


- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1207.1693

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

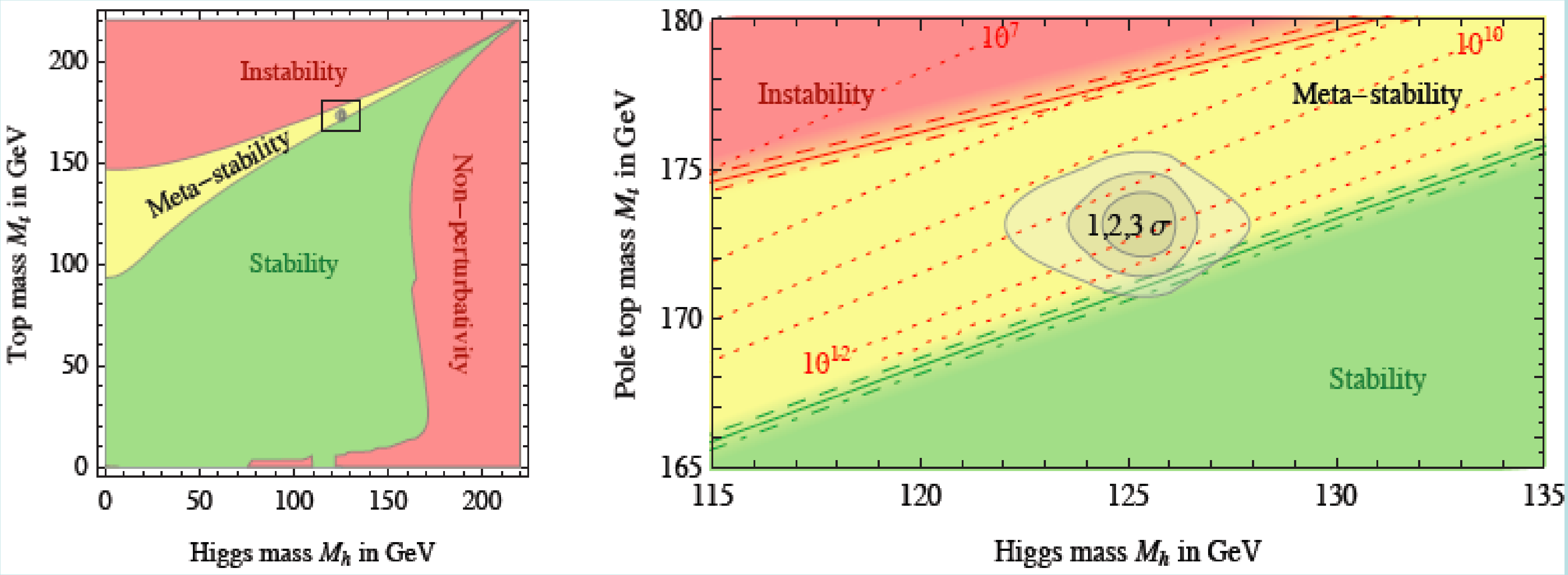


- Vacuum could be stabilized by **Supersymmetry**

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

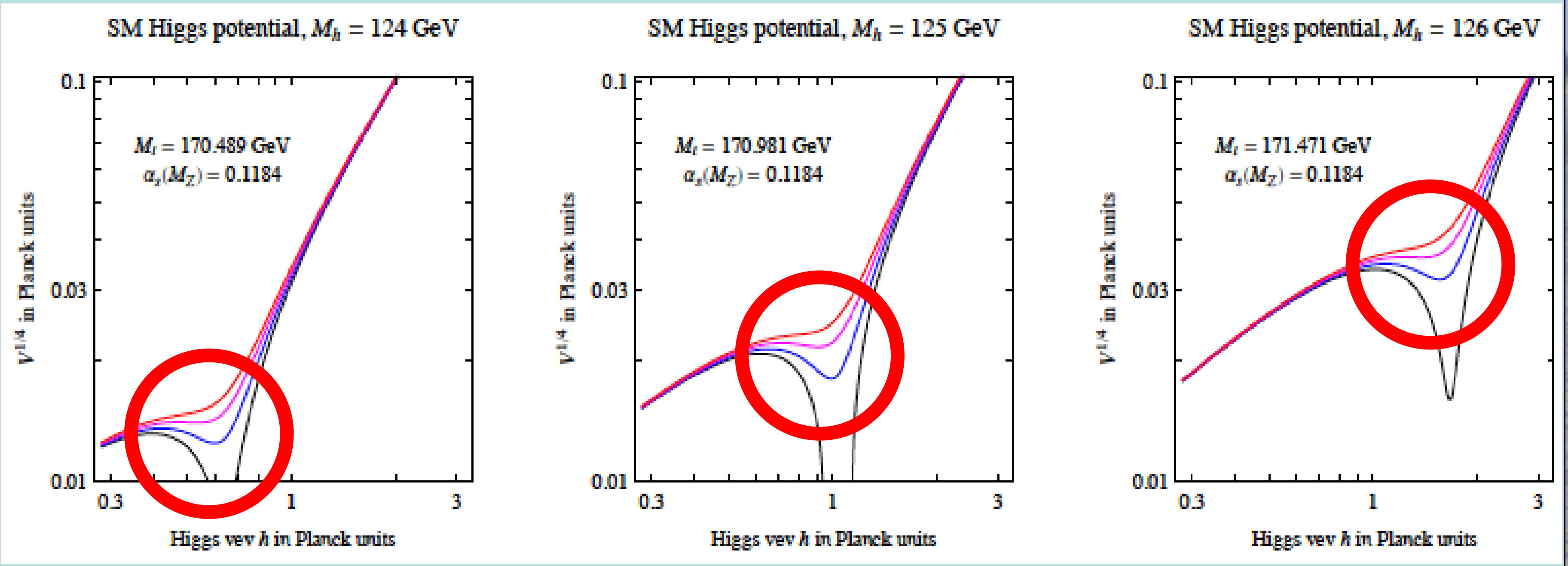


- Present vacuum probably metastable with lifetime >> age of the Universe

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

Higgs Inflation – A Long Shot?

- Higgs potential may have second stationary point



- **Vacuum energy could have driven inflation**
- Requires low value of m_t
- Extra tricks to get correct density perturbations

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!**

Lightest Supersymmetric Particle

- Stable in many models because of conservation of R parity:

  $R = (-1)^{2S - L + 3B}$

  where S = spin, L = lepton #, B = baryon #

- Particles have R = +1, sparticles R = -1:

  Sparticles produced in pairs

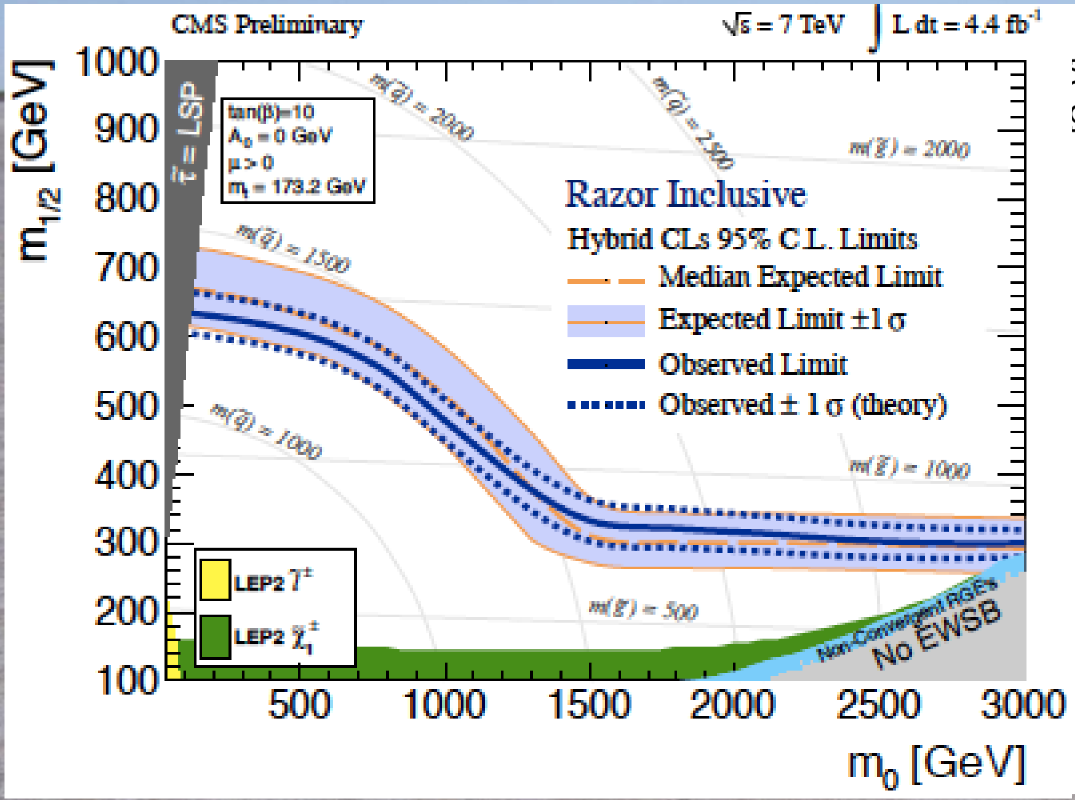
  Heavier sparticles → lighter sparticles

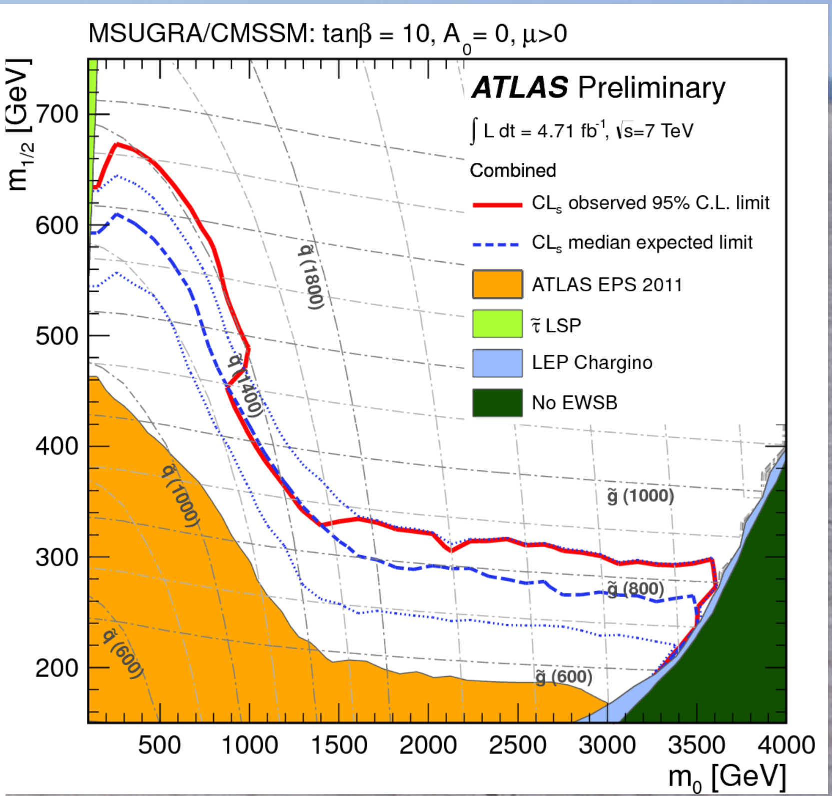
- Lightest supersymmetric particle (LSP) stable

Possible Nature of LSP

- No strong or electromagnetic interactions
  - Otherwise would bind to matter
  - Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates
  - Sneutrino
    - (Excluded by LEP, direct searches)
  - Lightest neutralino χ (partner of Z, H, γ)
  - Gravitino
    - (nightmare for astrophysical detection)

Searches with ~ 5/fb @ 7 TeV

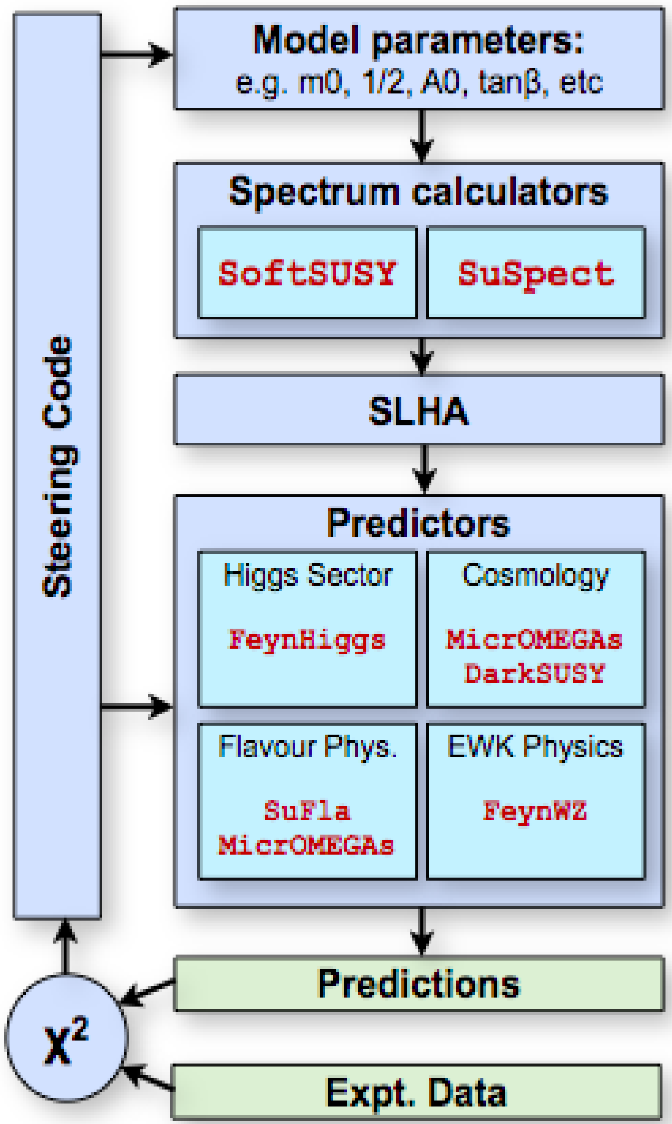




Jets + missing energy

MasterCode

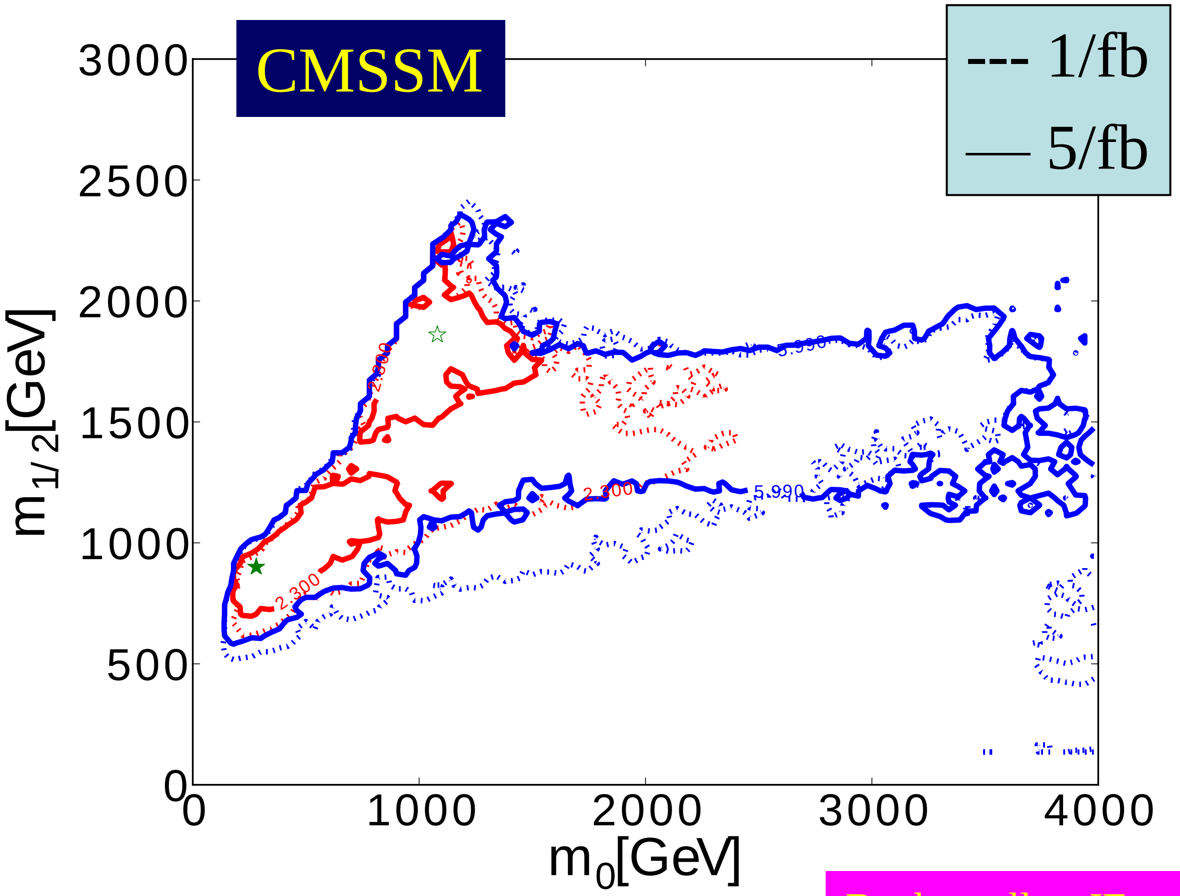
- **Combines diverse set of tools**
  - different codes : all state-of-the-art
    - Electroweak Precision (FeynWZ)
    - Flavour (SuFla, micrOMEGAs)
    - Cold Dark Matter (DarkSUSY, micrOMEGAs)
    - Other low energy (FeynHiggs)
    - Higgs (FeynHiggs)
  - different precisions (one-loop, two-loop, 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

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 5 fb^{-1} of LHC Data



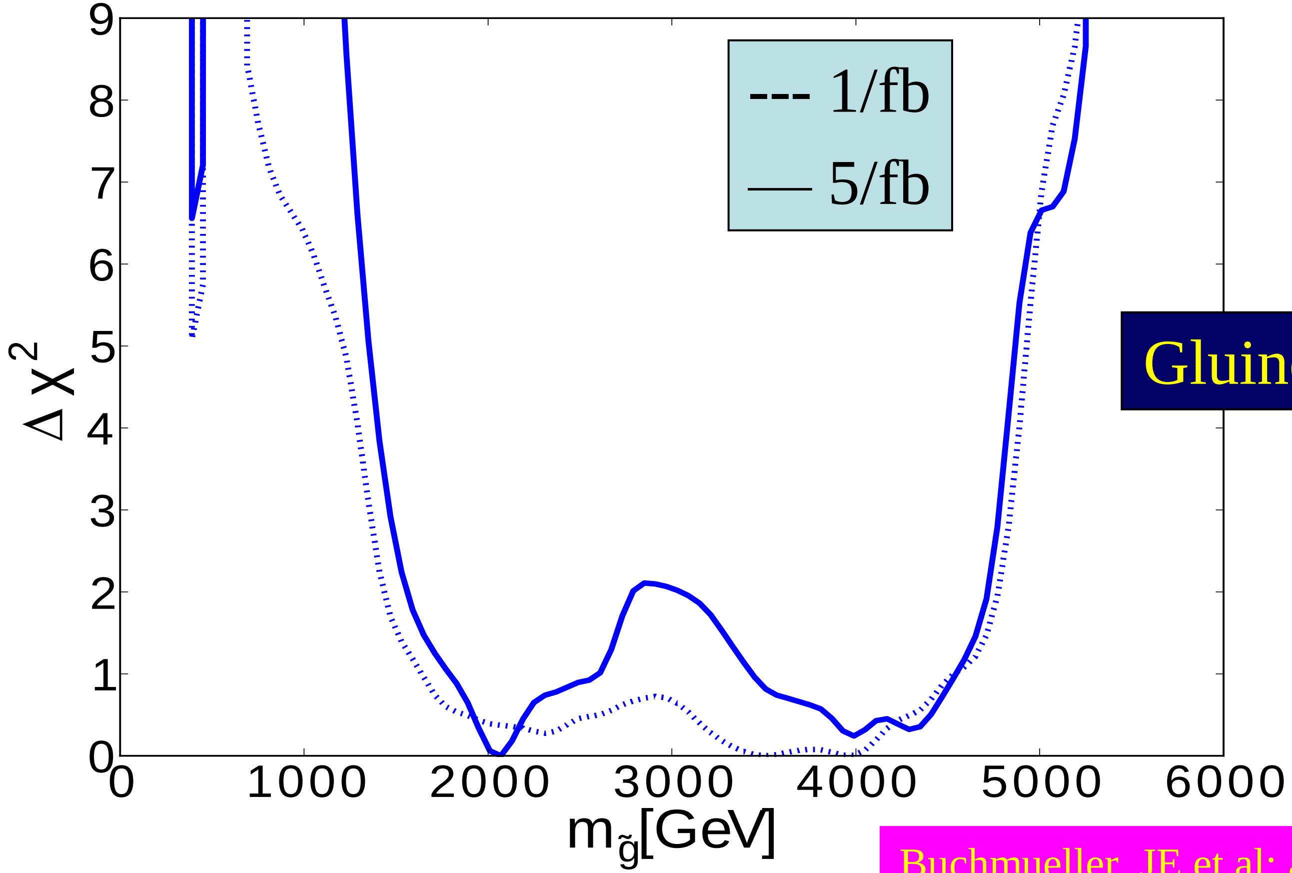
Buchmueller, JE et al: arXiv:1207.3715

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

p-value of simple models < 10%

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 5 fb^{-1} of LHC Data

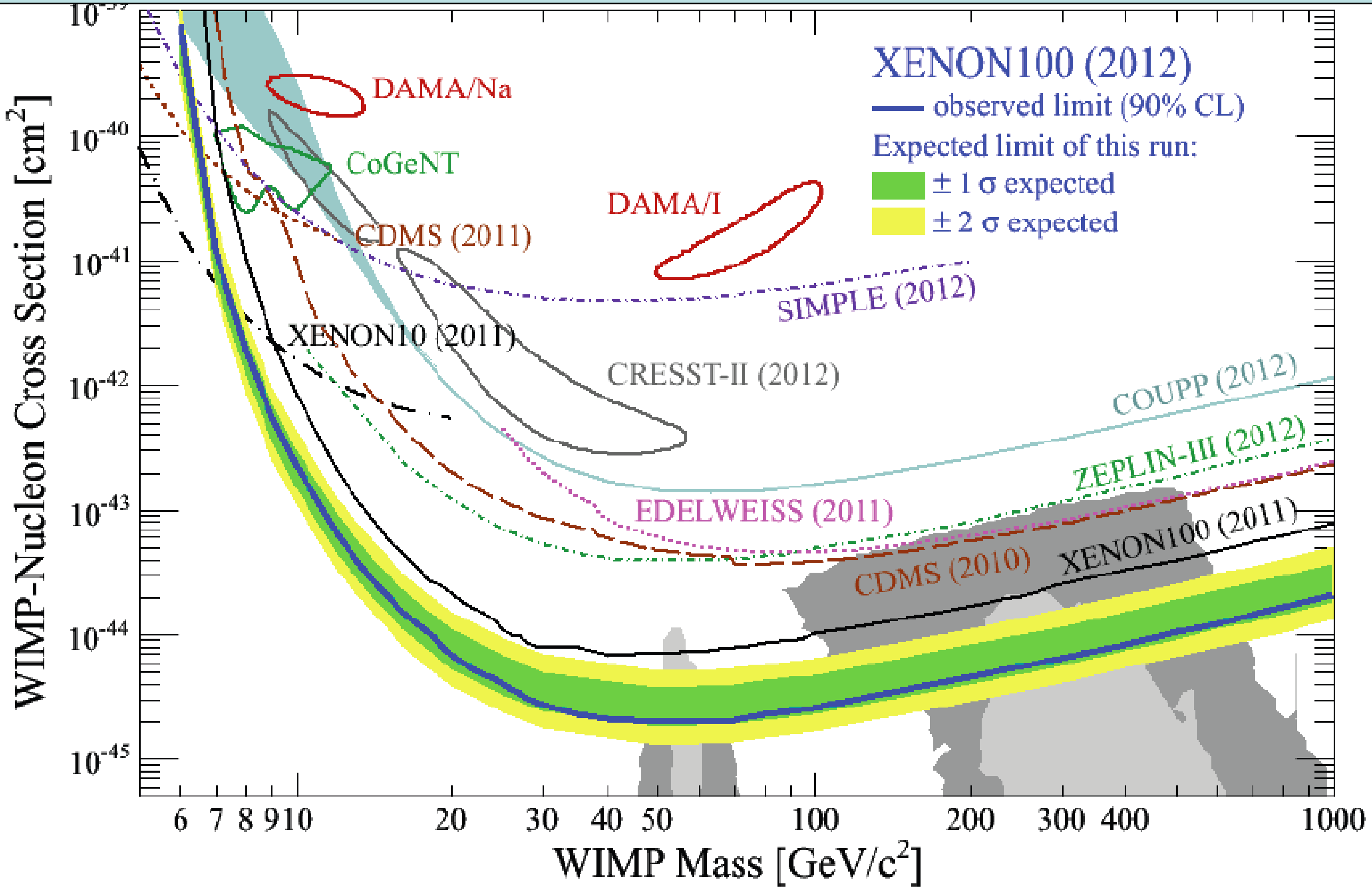


Gluino mass

Buchmueller, JE et al: arXiv:1207.3715

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

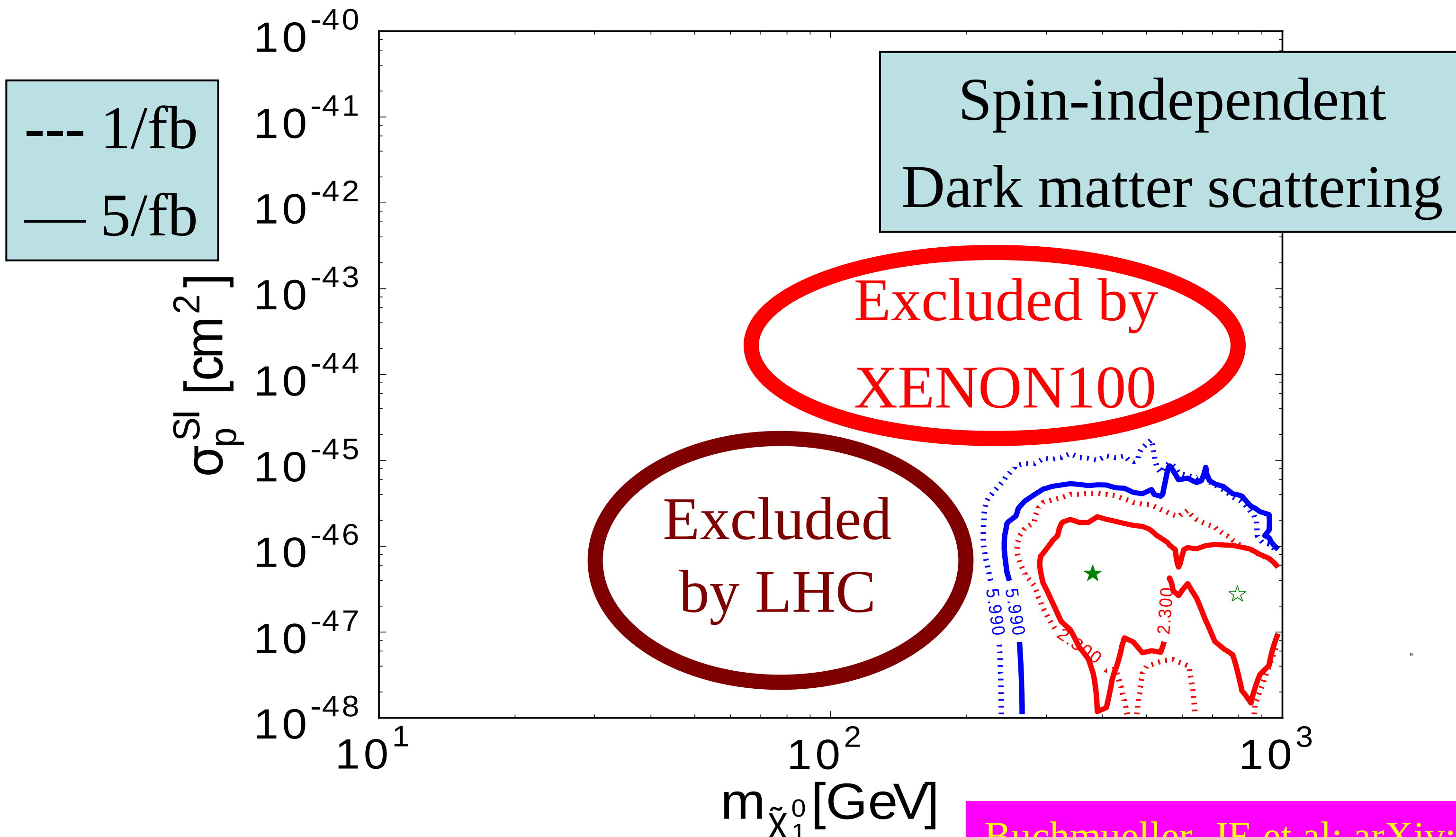
XENON100 & other Experiments



Upper Limit (90% C.L.) is 2×10^{-45} cm^2 for 55 GeV/c^2 WIMP

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 5 fb^{-1} of LHC Data



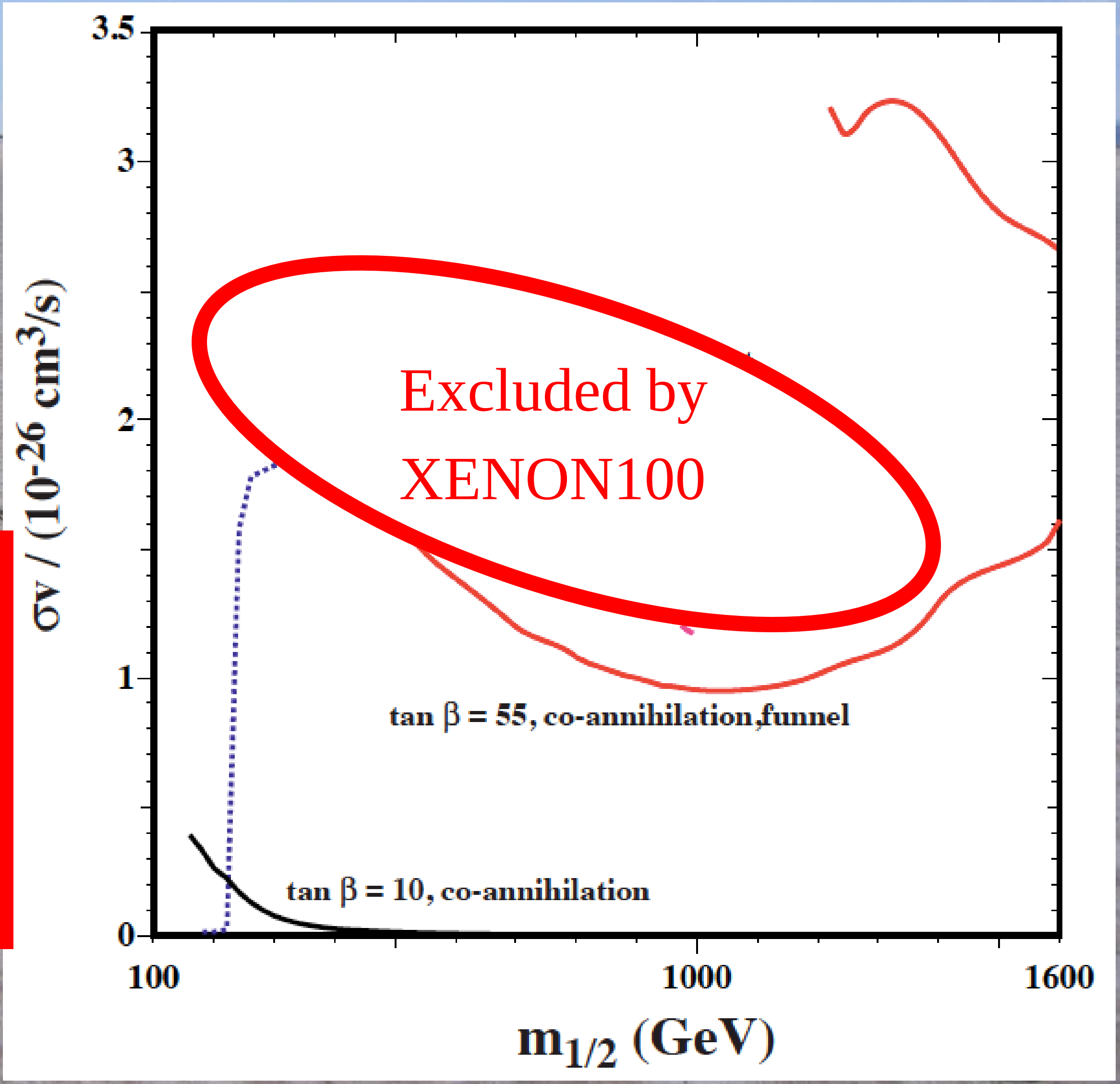
Buchmueller, JE et al: arXiv:1207.3715

Favoured values of dark matter scattering
cross section significantly below XENON100

Neutralino Annihilation Rates

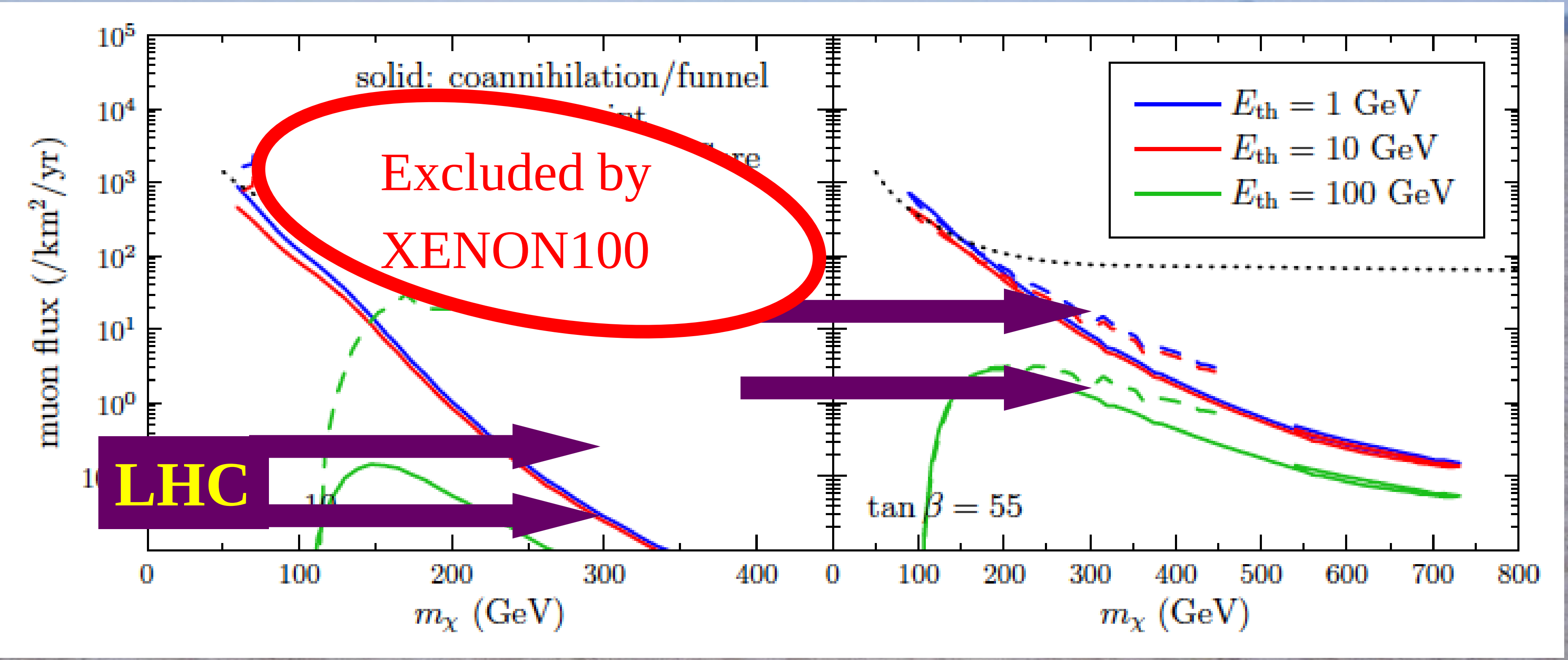
Small in coannihilation strip @ small tan β

Constraints potentially along focus-point strip and @ large tan β



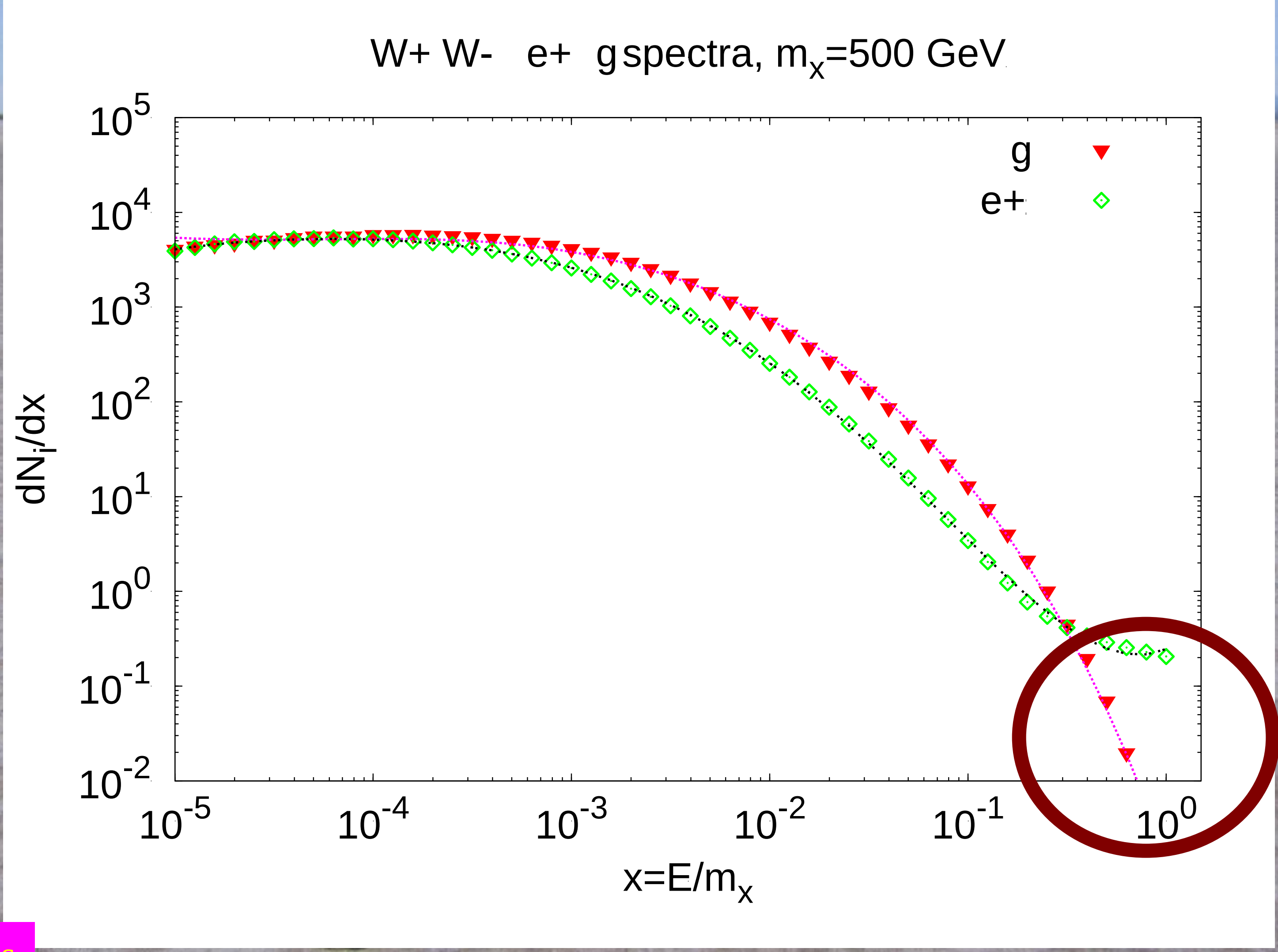
JE, Olive & Spanos: arXiv:1106.0768

Neutrinos from Annihilations inside the Sun



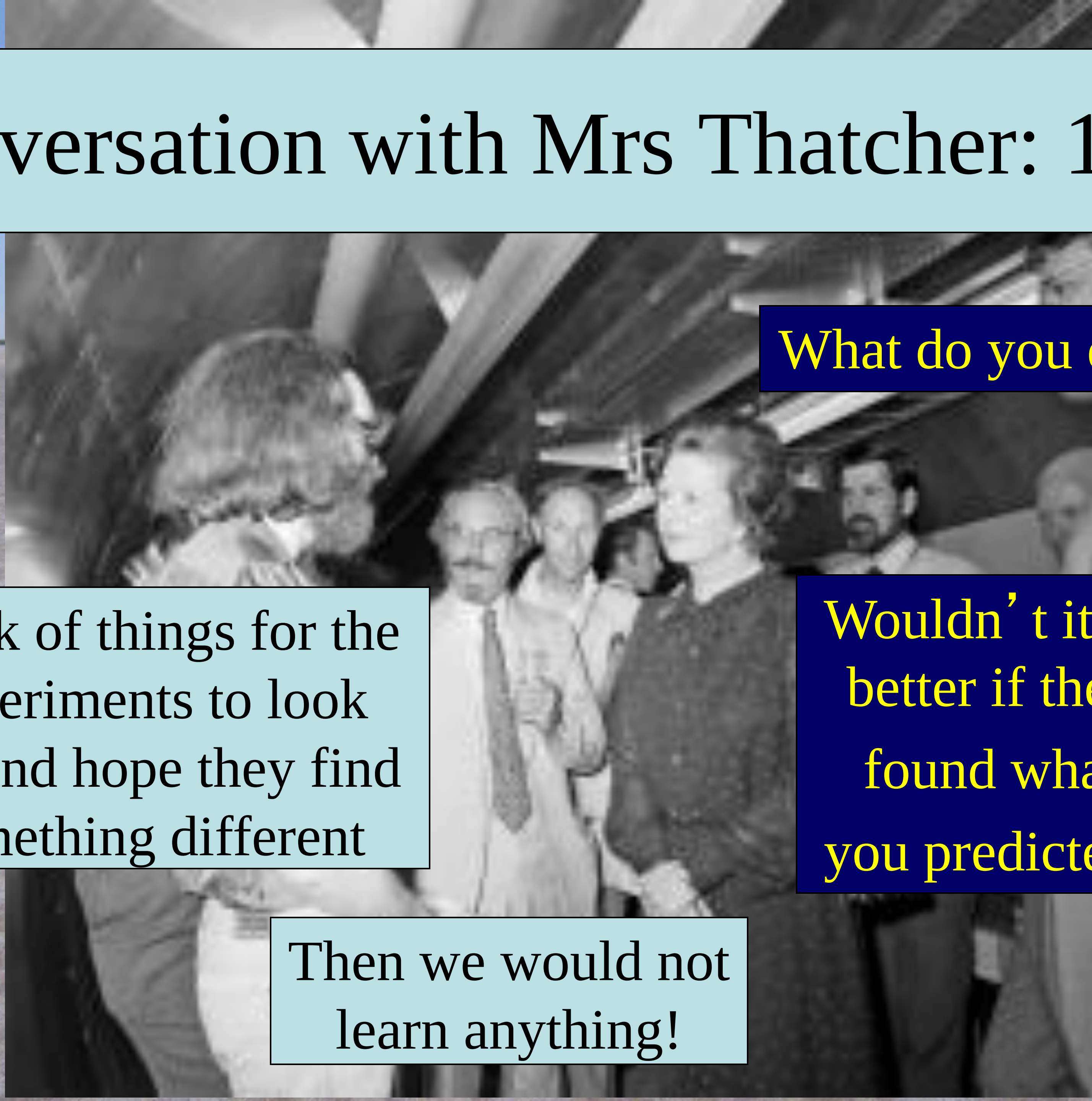
JE, Olive, Savage and Spanos: arXiv:0912.3137

Positron End-Point Signature from Annihilations to WW?



JE & Spanos

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!