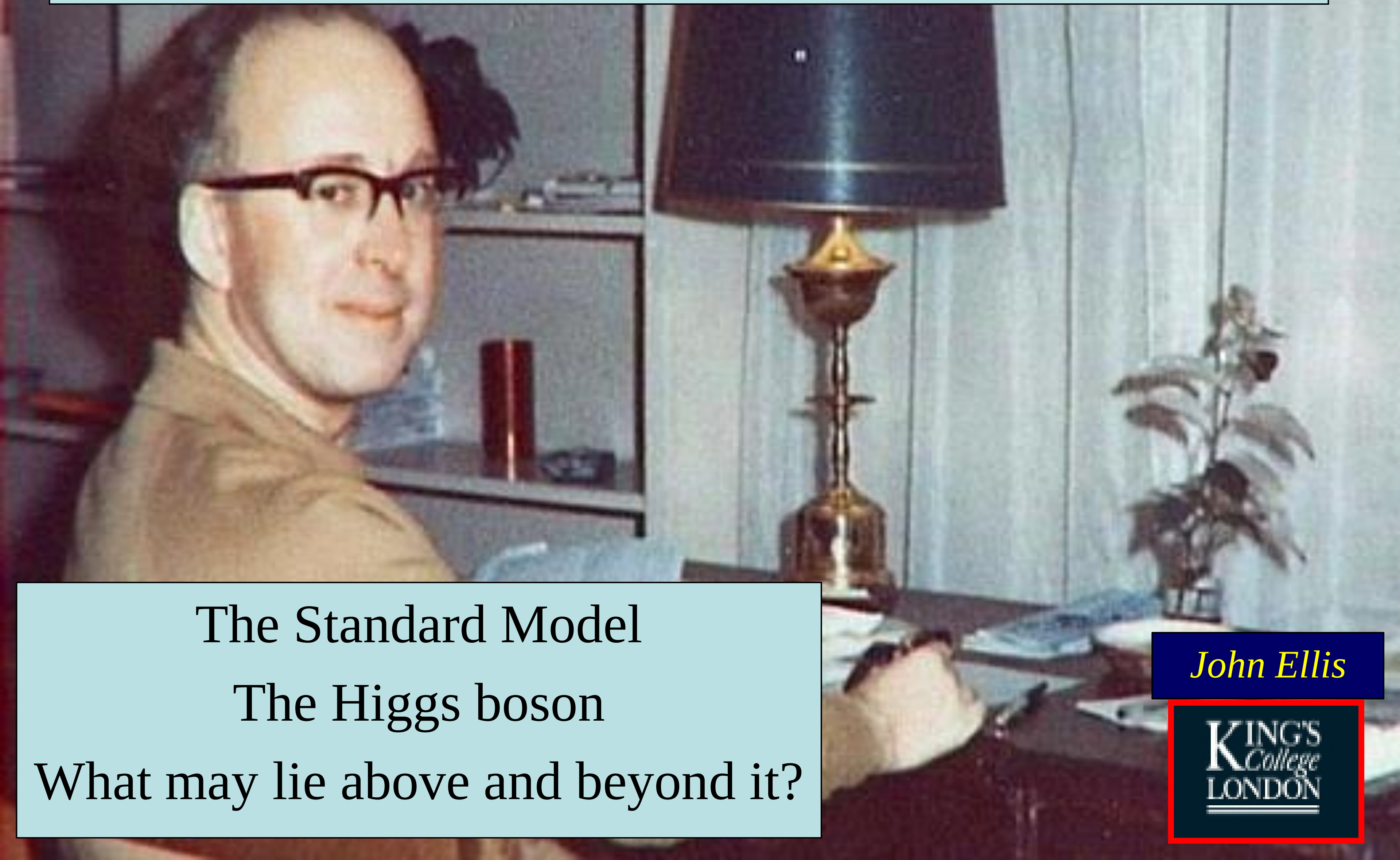
Introduction to Higgs & Beyond



The Standard Model

The Higgs boson

What may lie above and beyond it?

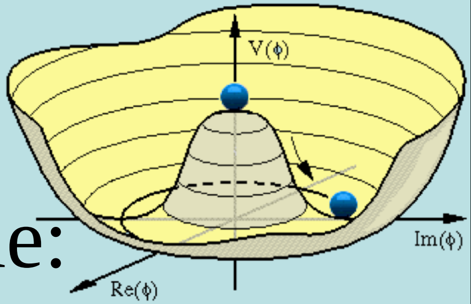
John Ellis

KING'S College LONDON

The Brout-Englert- Higgs Mechanism

- Postulated effective potential:

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



- Minimum energy at non-zero value:

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

- Components of Higgs field: $\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma(x))e^{i\pi(x)}$
- π m = 0, σ massive: $m_H^2 = 2\mu^2 = 2\lambda v$ **Higgs boson**
- After gauging: $M_W = \frac{g\,v}{2}$ **Massive gauge boson**
- Couple to fermions: non-zero masses: $M_f = y_f \frac{v}{\sqrt{2}}$

Summary of the Standard Model

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

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

- Lagrangian:

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

Untested before 2012

1975

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

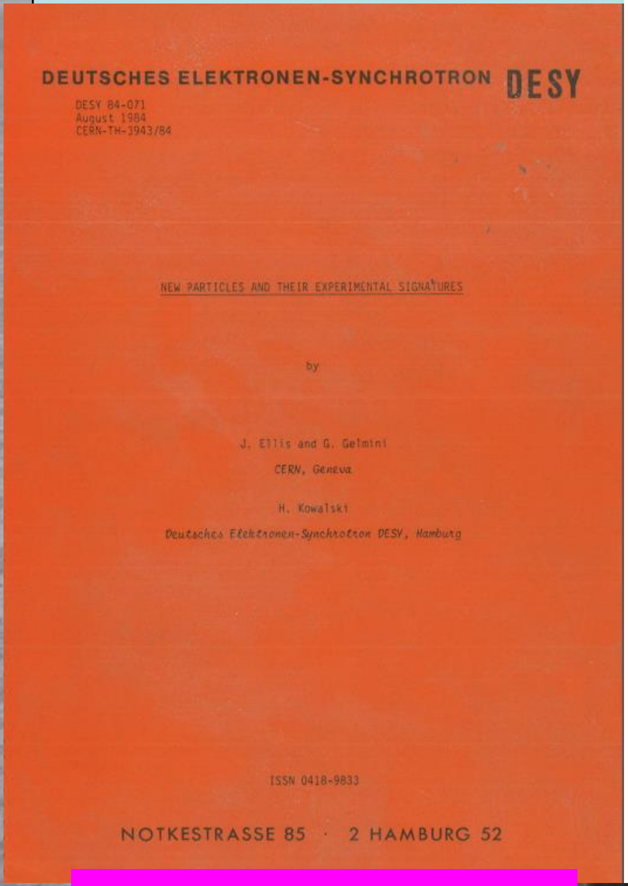
A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

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.

1984

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

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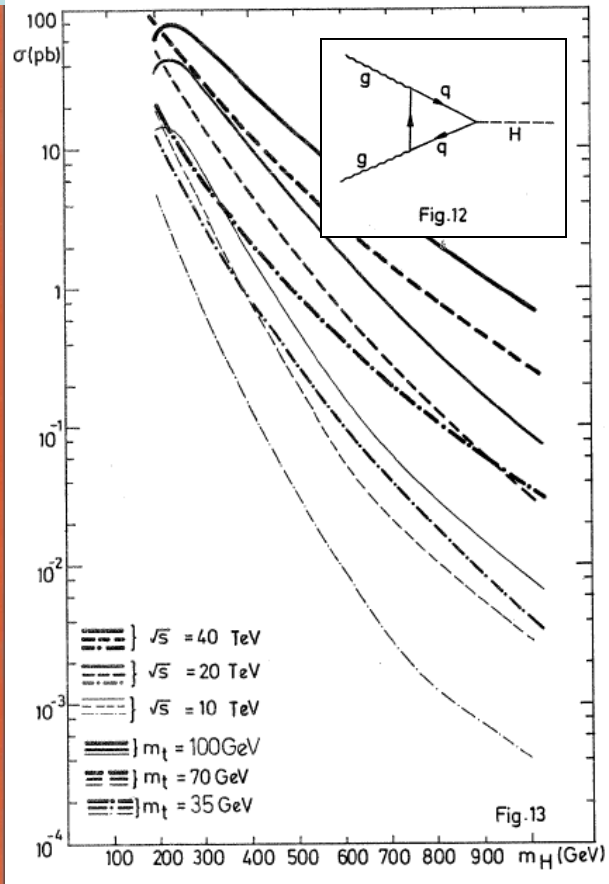
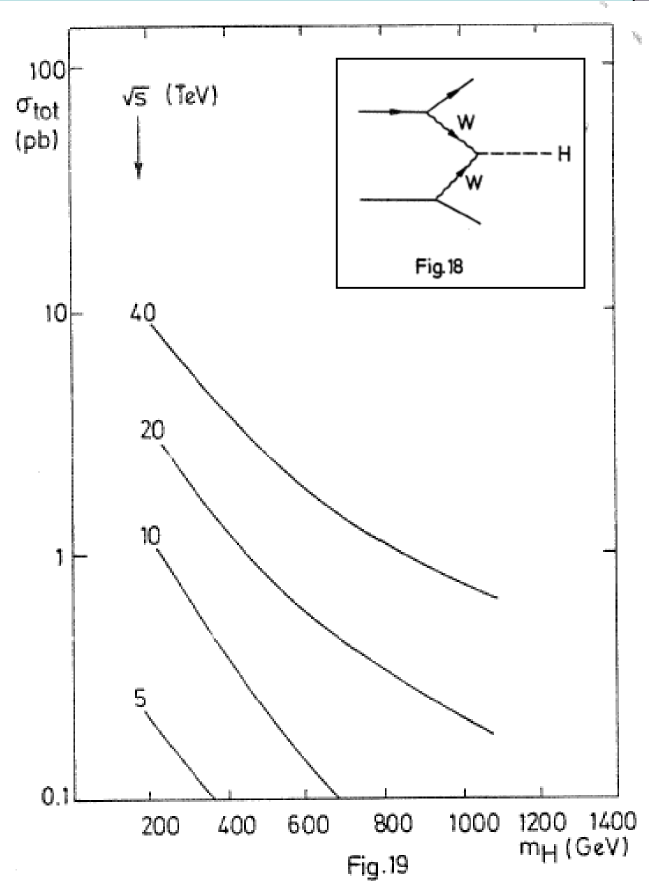




JE, Gelmini & Kowalski, 1984

2011

Constraints on Higgs Mass

- Electroweak observables sensitive via quantum loop corrections: $$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$
- Sensitivity to top, Higgs masses:

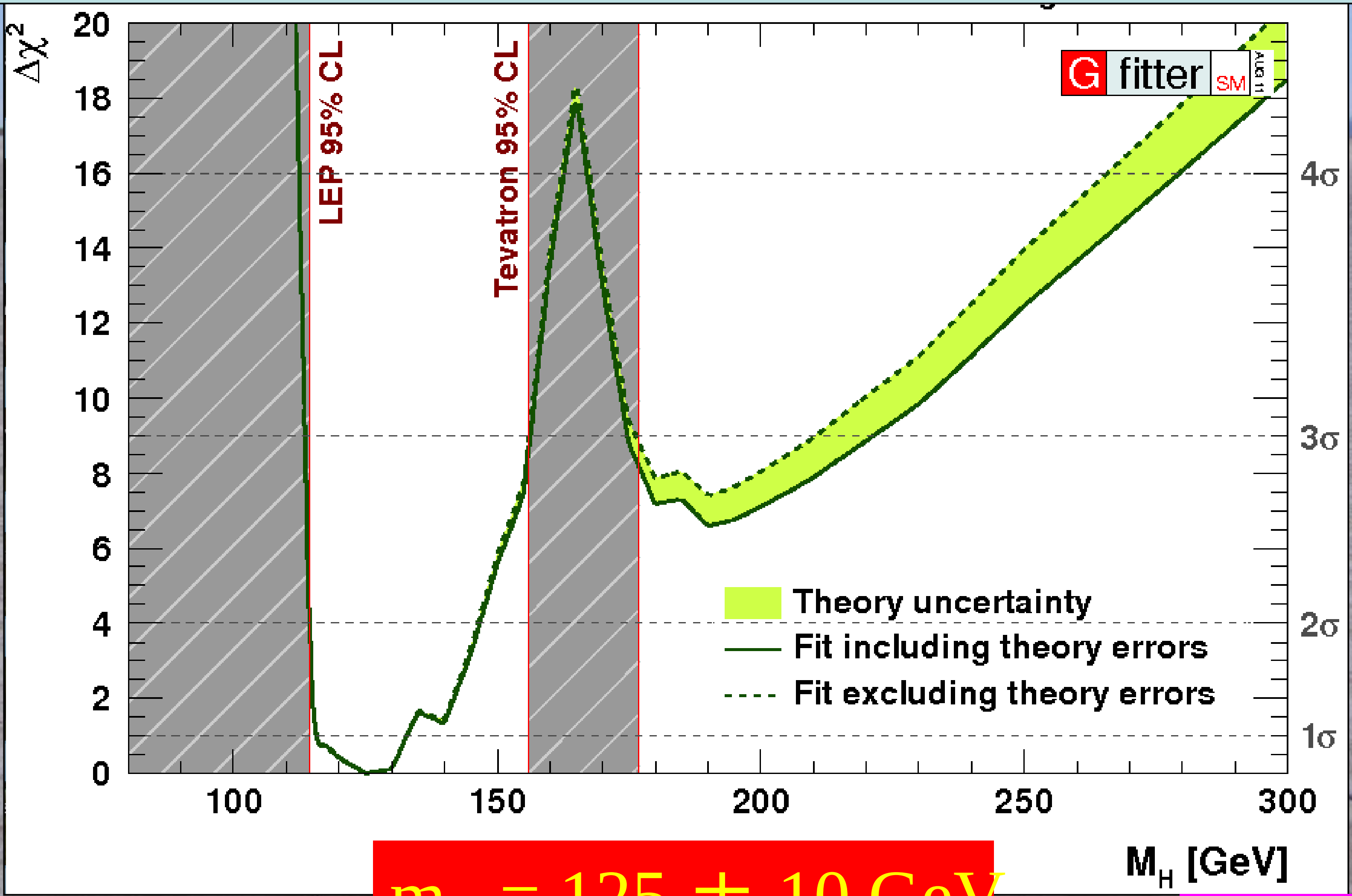
$$\frac{3G_F}{8\pi^2\sqrt{2}}m_t^2 \qquad \frac{\sqrt{2}G_F}{16\pi^2}m_W^2\left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2}+\ldots\right),\ M_H >> m_W$$

- Preferred Higgs mass: **$m_H \sim 100 \pm 30$ GeV**
- Compare with lower limit from direct search at LEP:

$m_H > 114$ GeV

and exclusion around **(160, 170 GeV)** at TeVatron

2011: Combining Information from Previous Direct Searches and Indirect Data

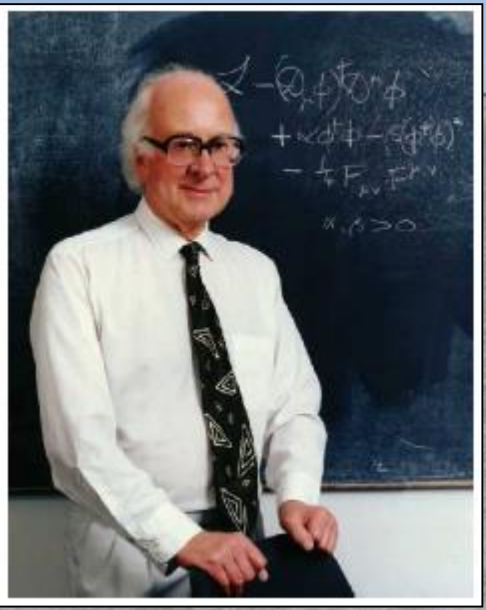


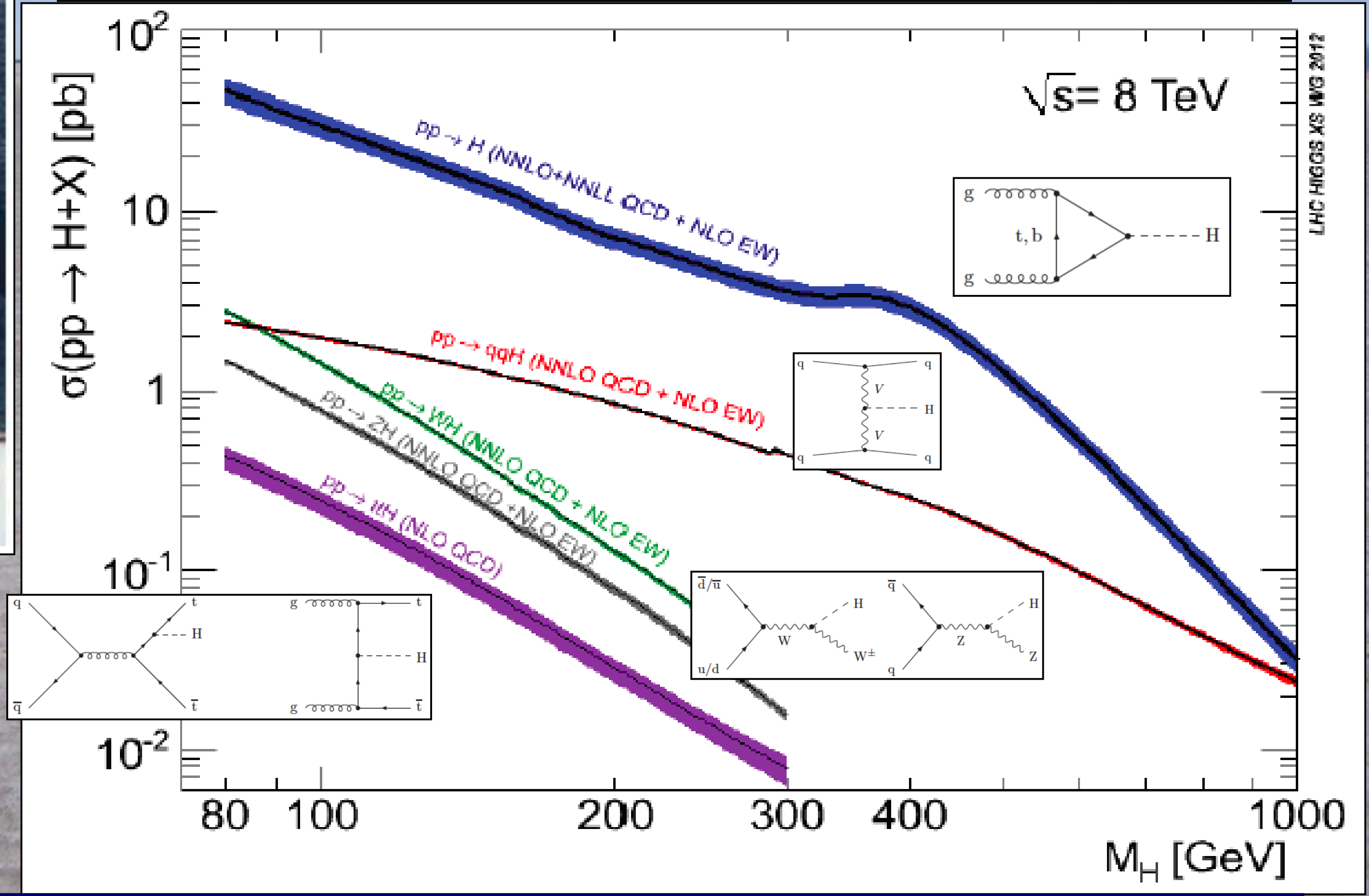
$m_H = 125 \pm 10$ GeV

Gfitter collaboration

A la recherche du Higgs perdu …

Higgs Production at the LHC

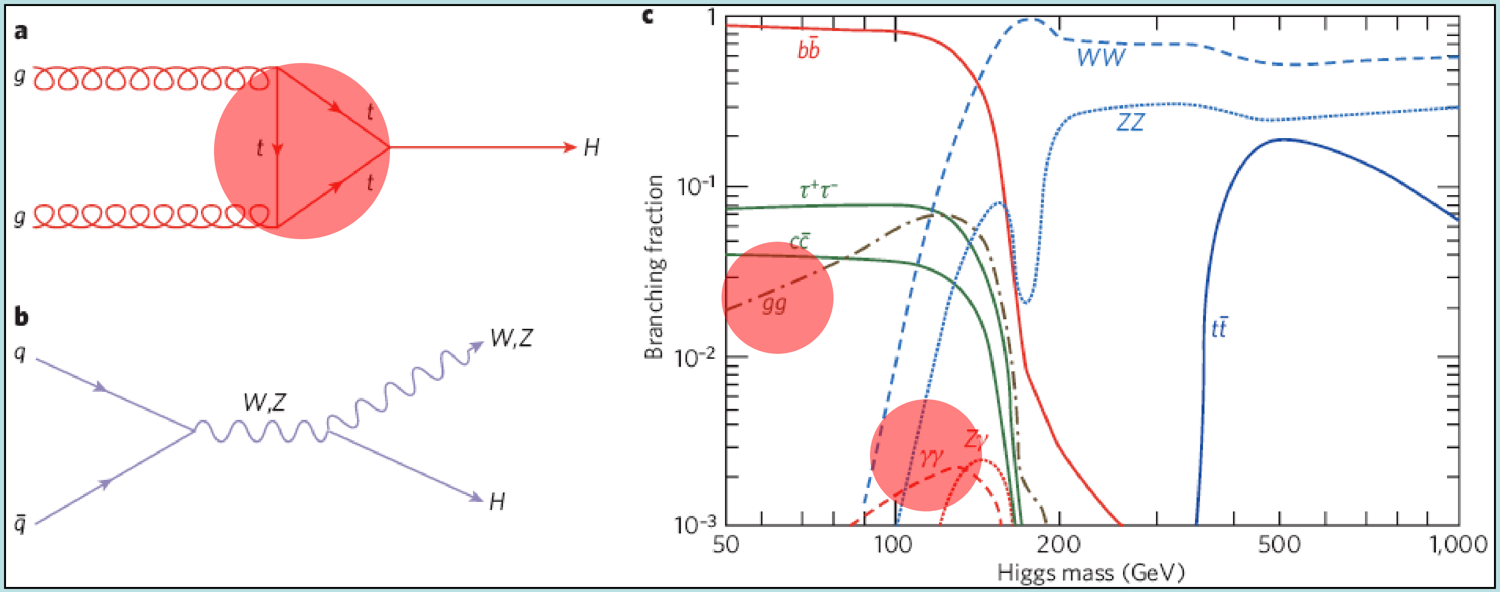




Many production modes measurable if M_h ~ 125 GeV

Higgs Decay Branching Ratios

- Couplings proportional to masses (?)

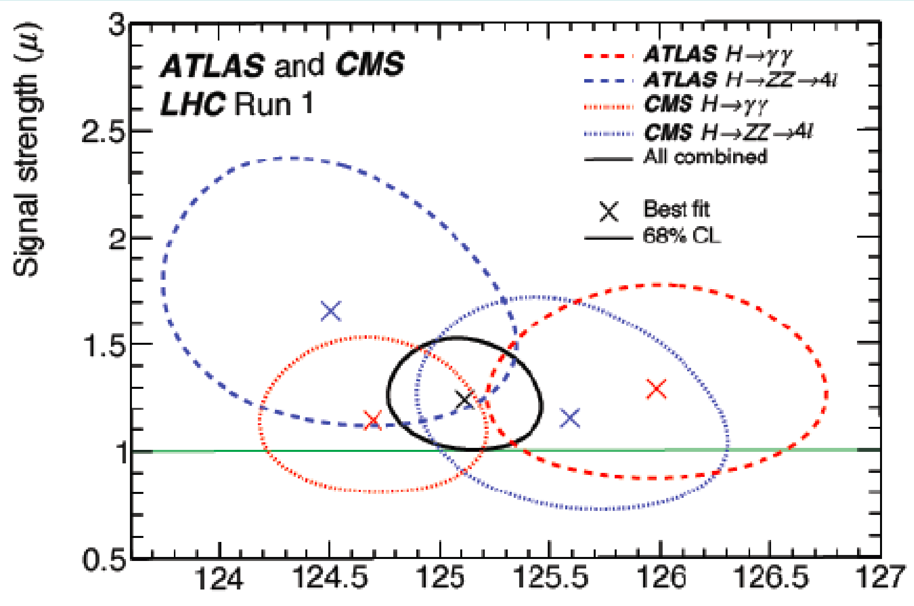


- Important couplings through loops:
  – gluon + gluon → Higgs → γγ

Many decay modes measurable if M_h ~ 125 GeV

Higgs Mass Measurements

- ATLAS + CMS ZZ^* and $\gamma\gamma$ final states



$$125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$$

- Statistical uncertainties dominate
- Allows precision tests
- **Crucial for stability of electroweak vacuum**

The Particle Higgsaw Puzzle

Did LHC find 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?
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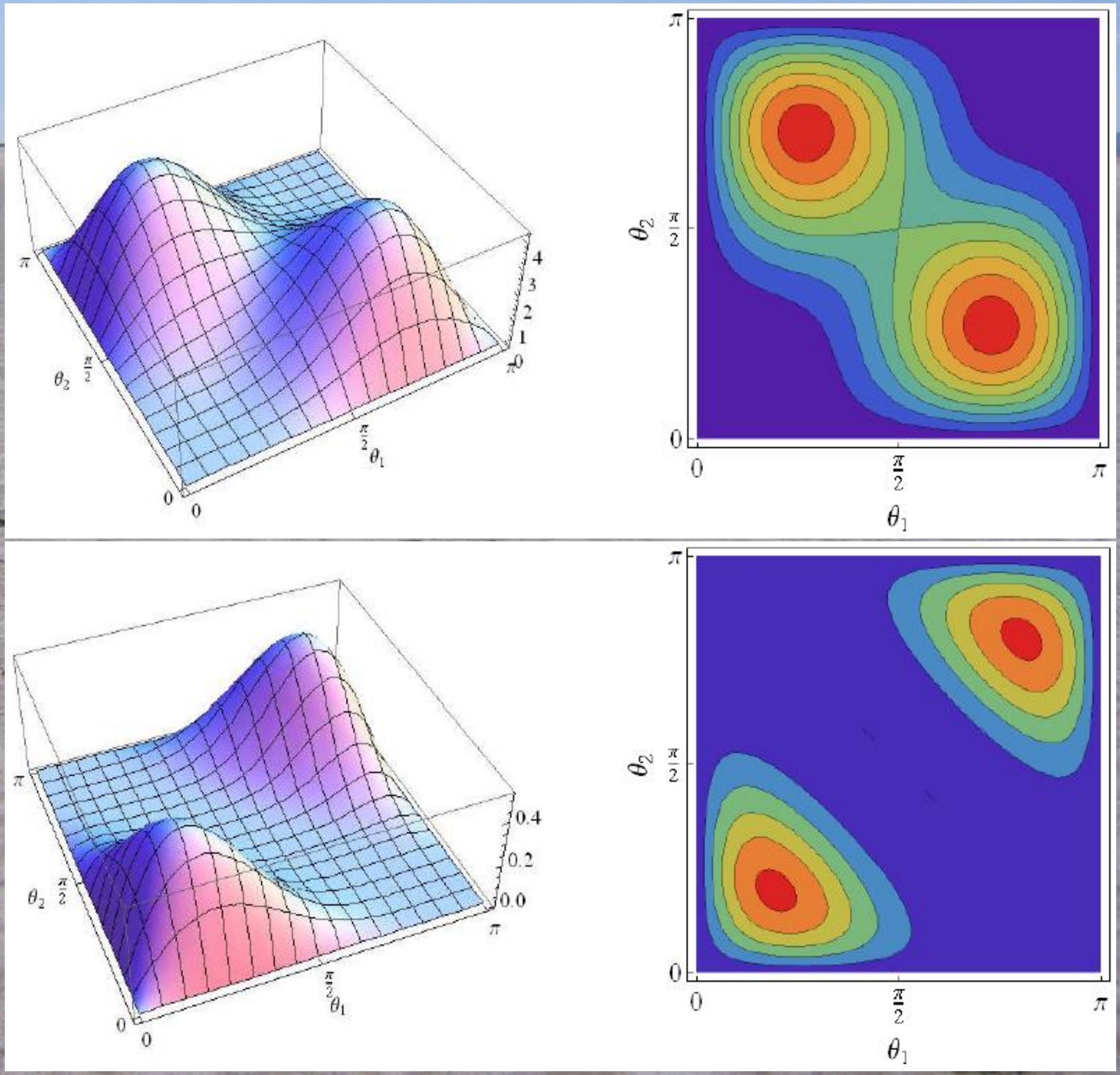
- What are its self-couplings?

Does the ‘Higgs’ have Spin Zero ?

- Polar angle distribution for $X_2 \rightarrow W^+W^-$
- Polar angle distribution for $X_0 \rightarrow W^+W^-$

  (for $\varphi = \pi$)



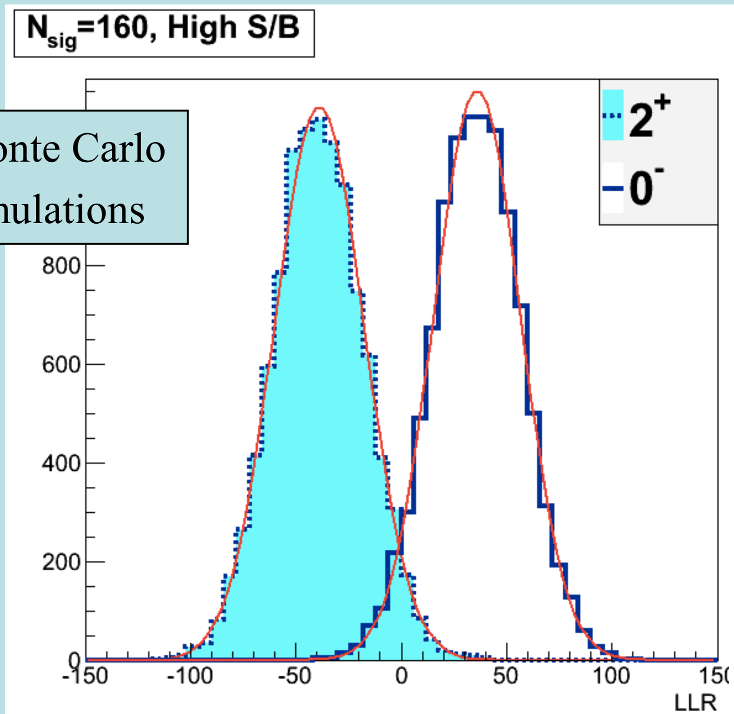
JE, Hwang: arXiv:1202.6660

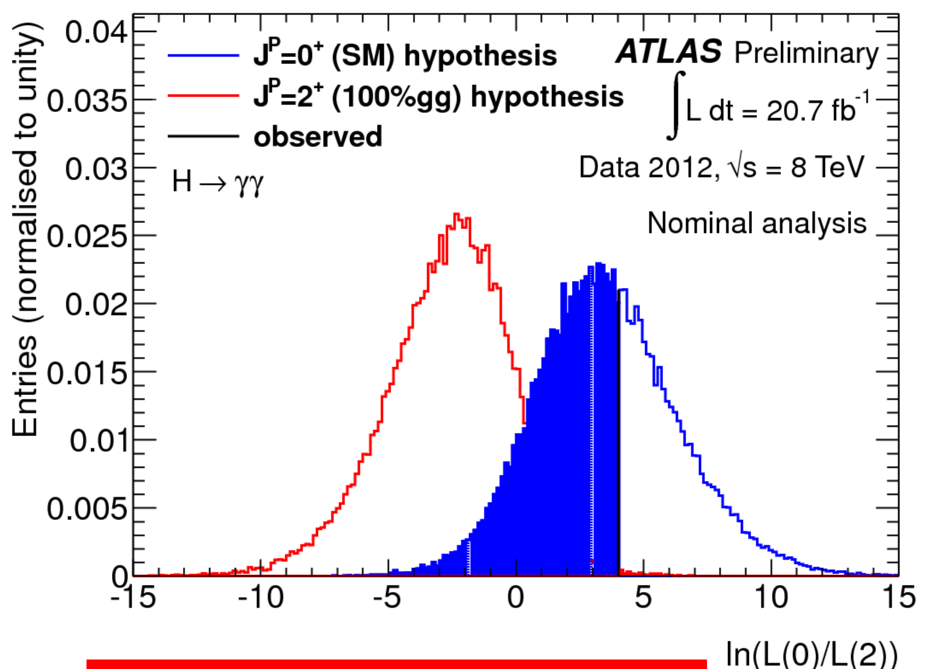
Does the 'Higgs' have Spin Two ?

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

JE & Hwang: arXiv:1202.6660

Monte Carlo simulations

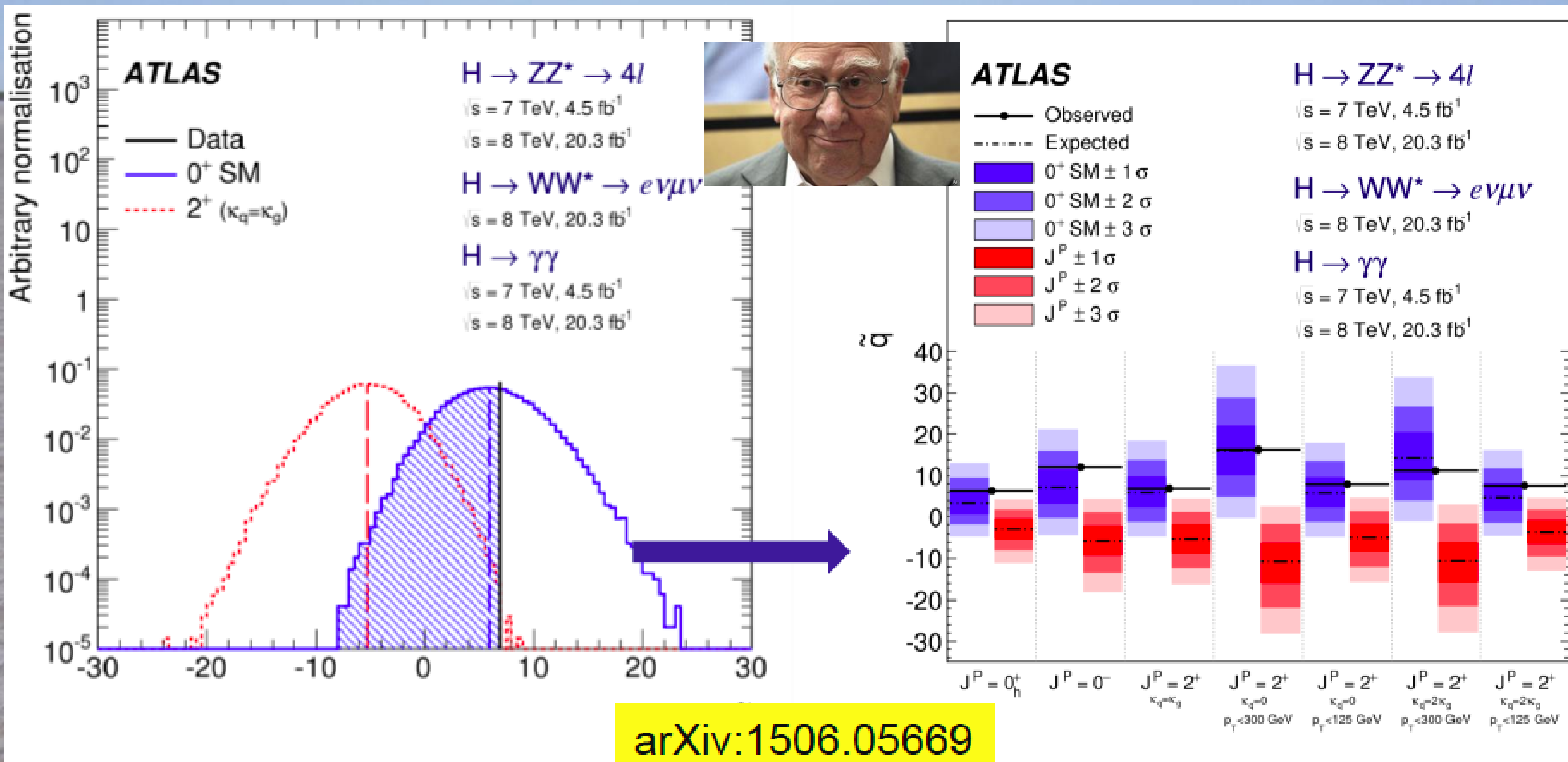




JE, Fok, Hwang, Sanz & You: arXiv:1210.5229

2^+ disfavoured @ 99%

H Spin-Parity Tests: 0^+ AOK



- Alternative spin-parities disfavoured > 99.9%

What is it ?

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  - **Pseudoscalar strongly disfavoured**
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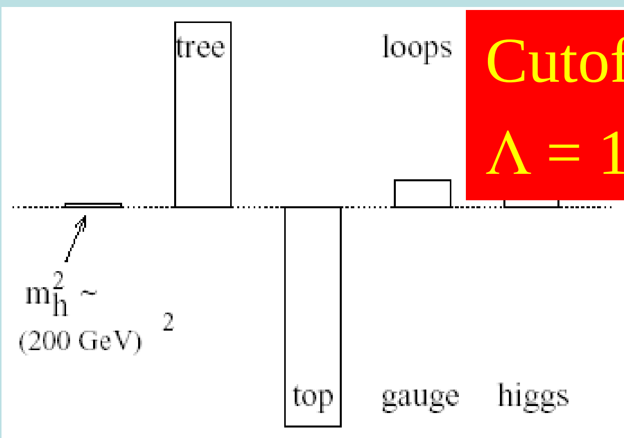
Elementary Higgs or Composite?

- Higgs field:

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

- Quantum loop problems



Cutoff

Λ = 10 TeV

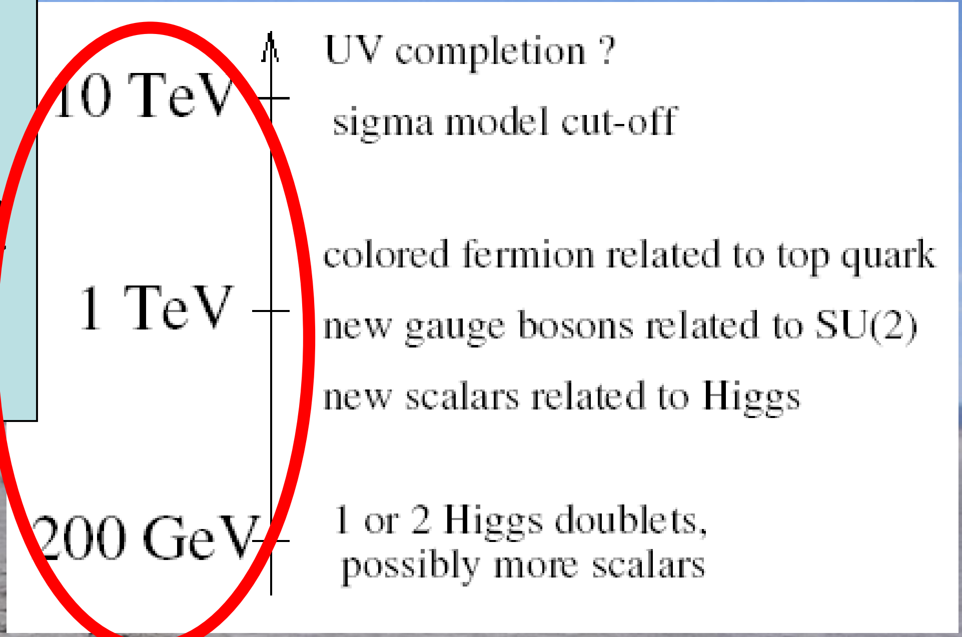
Cut-off Λ ~ 1 TeV with Supersymmetry?

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

New technicolour force?

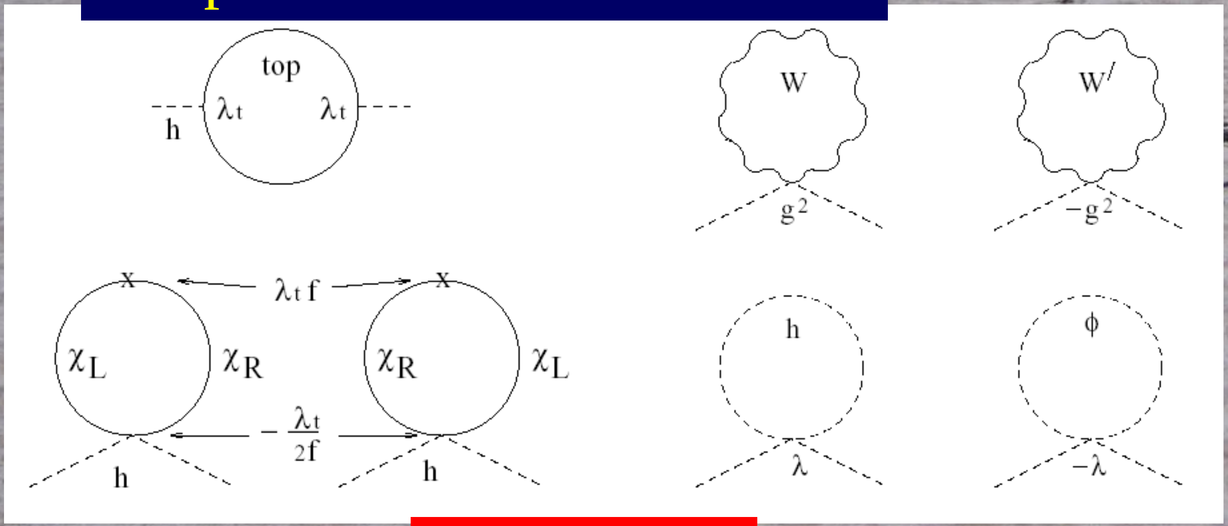
- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

Higgs as a Pseudo-Goldstone Boson

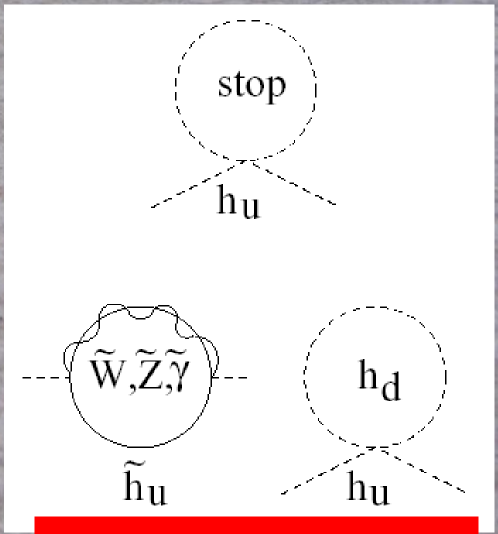


‘Little Higgs’ models
(breakdown of larger symmetry)

Loop cancellation mechanism



Little Higgs



Supersymmetry

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:

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

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

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

Examples of Higgs as Pseudo-Goldstone Boson

- Sample models:
- Dependences of couplings on model parameters:
- **To be measured!**
- Translation to experimental parameters:

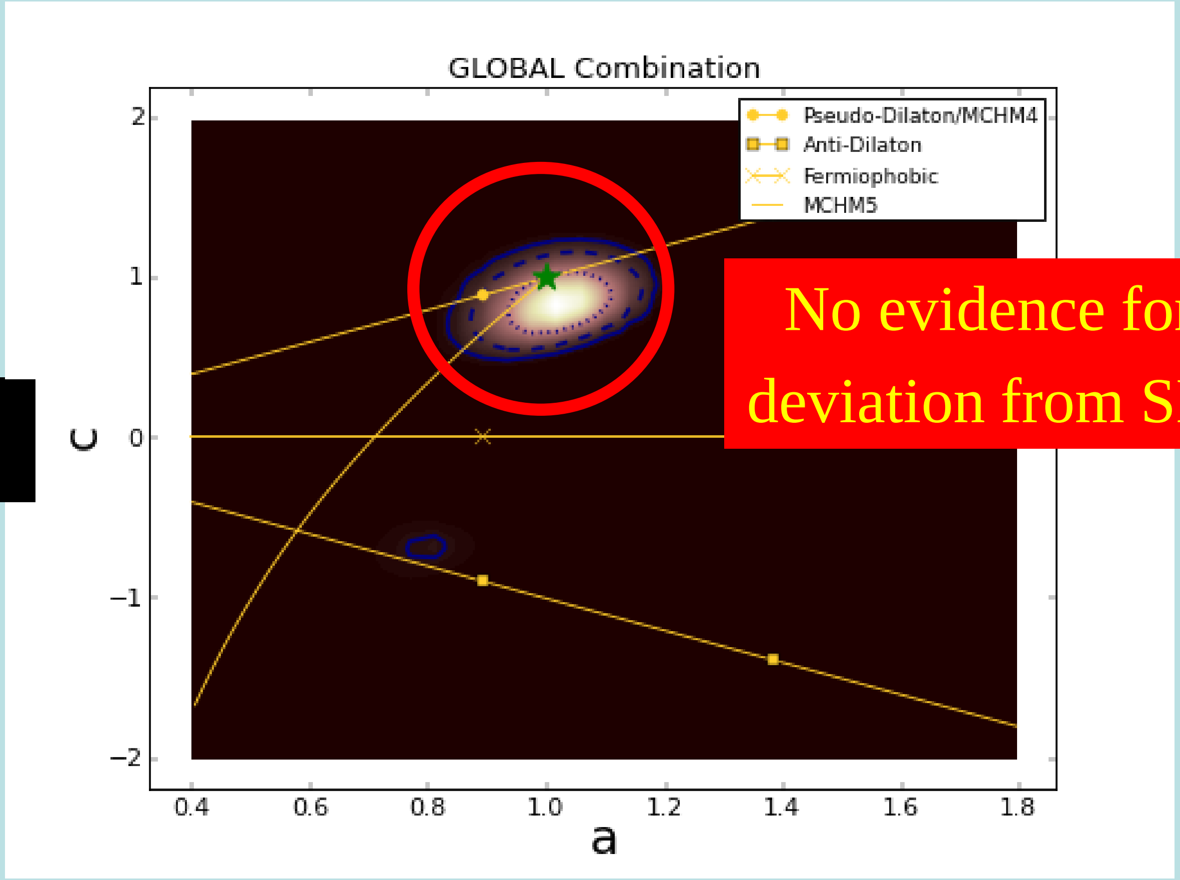
$$a = \kappa_V,\ c = \kappa_F$$

Model	Symmetry Pattern	Goldstones
SM	SO(4)/SO(3)	W_L, Z_L
—	SU(3)/SU(2)×U(1)	W_L, Z_L, h
MCHM	SO(5)/SO(4)×U(1)	W_L, Z_L, h
NMCHM	SO(6)/SO(5)×U(1)	W_L, Z_L, h, a
MCTHM	SO(6)/SO(4)×SO(2) ×U(1)	$W_L, Z_L, h, H, H^\pm, a$

Parameters	SILH	MCHM4	MCHM5
a	$1 - c_H\xi/2$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
b	$1 - 2c_H\xi$	$1 - 2\xi$	$1 - 2\xi$
b_3	$-\frac{4}{3}\xi$	$-\frac{4}{3}\xi\sqrt{1-\xi}$	$-\frac{4}{3}\xi\sqrt{1-\xi}$
c	$1 - (c_H/2 + c_y)\xi$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_2	$-(c_H + 3c_y)\xi/2$	$-\xi/2$	-2ξ
d_3	$1 + (c_6 - 3c_H/2)\xi$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
d_4	$1 + (6c_6 - 25c_H/3)\xi$	$1 - 7\xi/3$	$\frac{1-28\xi(1-\xi)/3}{1-\xi}$

Global Analysis of Higgs-like Models

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



Global

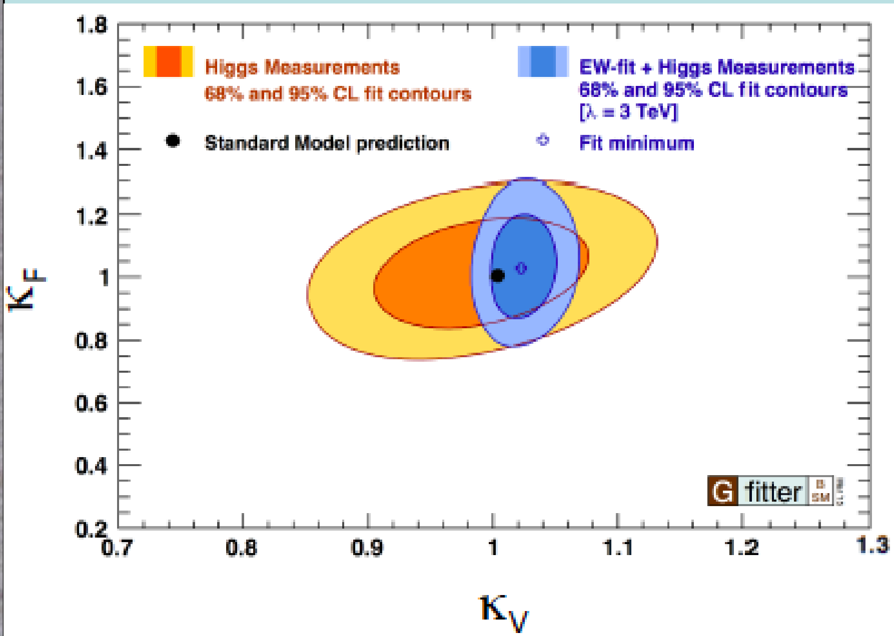
No evidence for deviation from SM

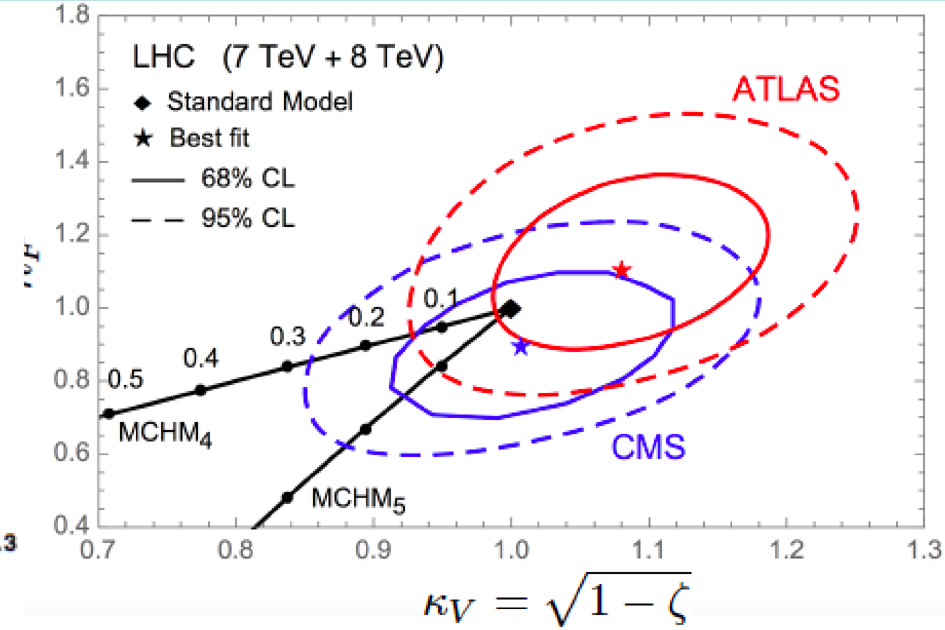
- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1303.3879

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by κ_V, to fermions by κ_f
- Standard Model: **$\kappa_V = \kappa_f = 1$**





- Consistency between Higgs and EW measurements
- **Must tune composite models to look like SM**

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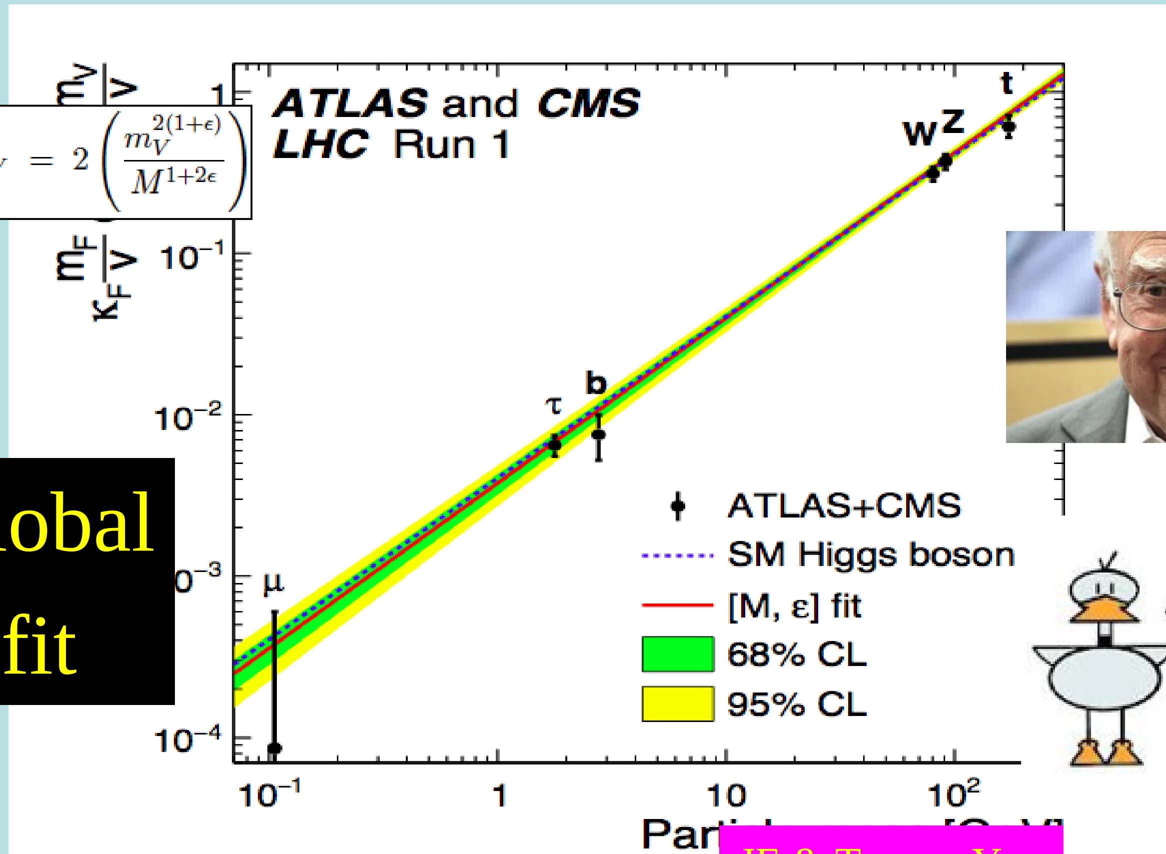
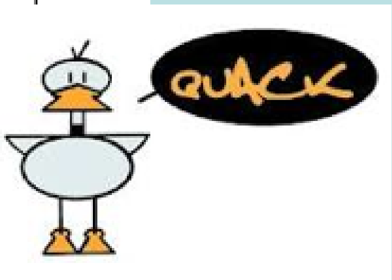
It Walks and Quacks like a Higgs

- 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

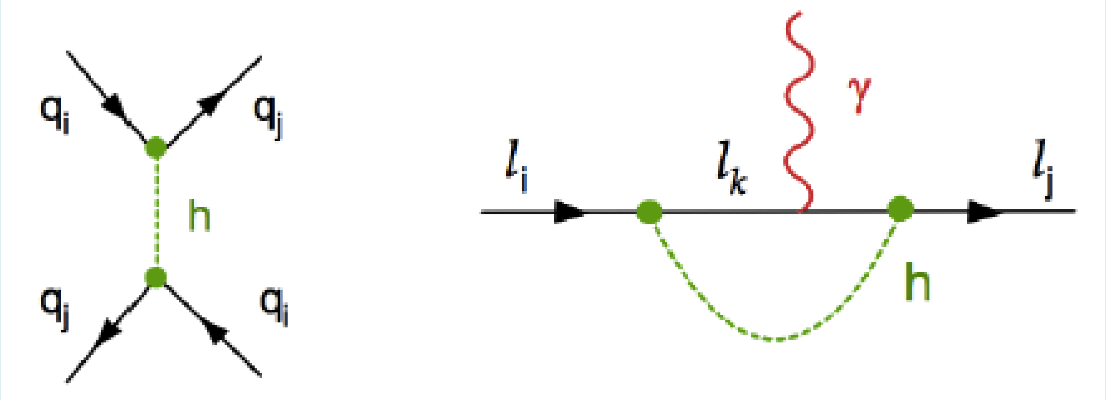


JE & Tevong You

- **Blue** dashed line = Standard Model

Flavour-Changing Couplings?

- Upper limits from FCNC, EDMs, …



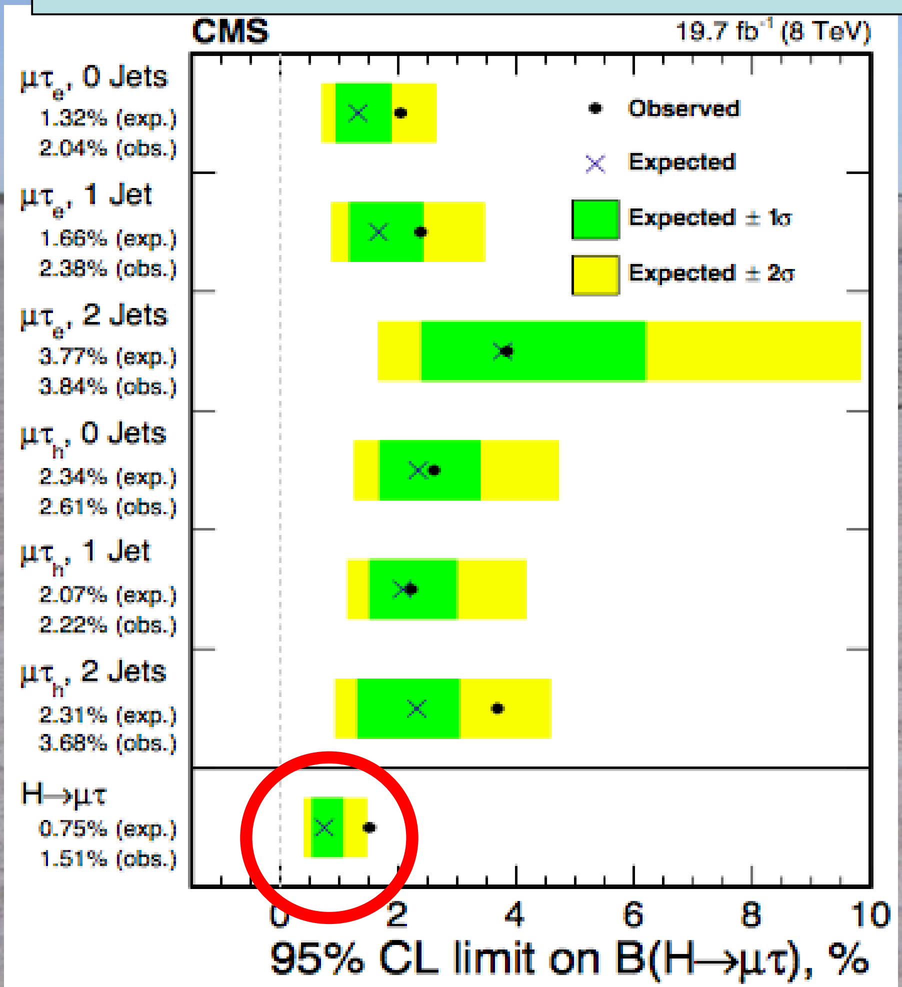
- Quark FCNC bounds exclude observability of quark-flavour-violating *h* decays
- Lepton-flavour-violating *h* decays could be large:

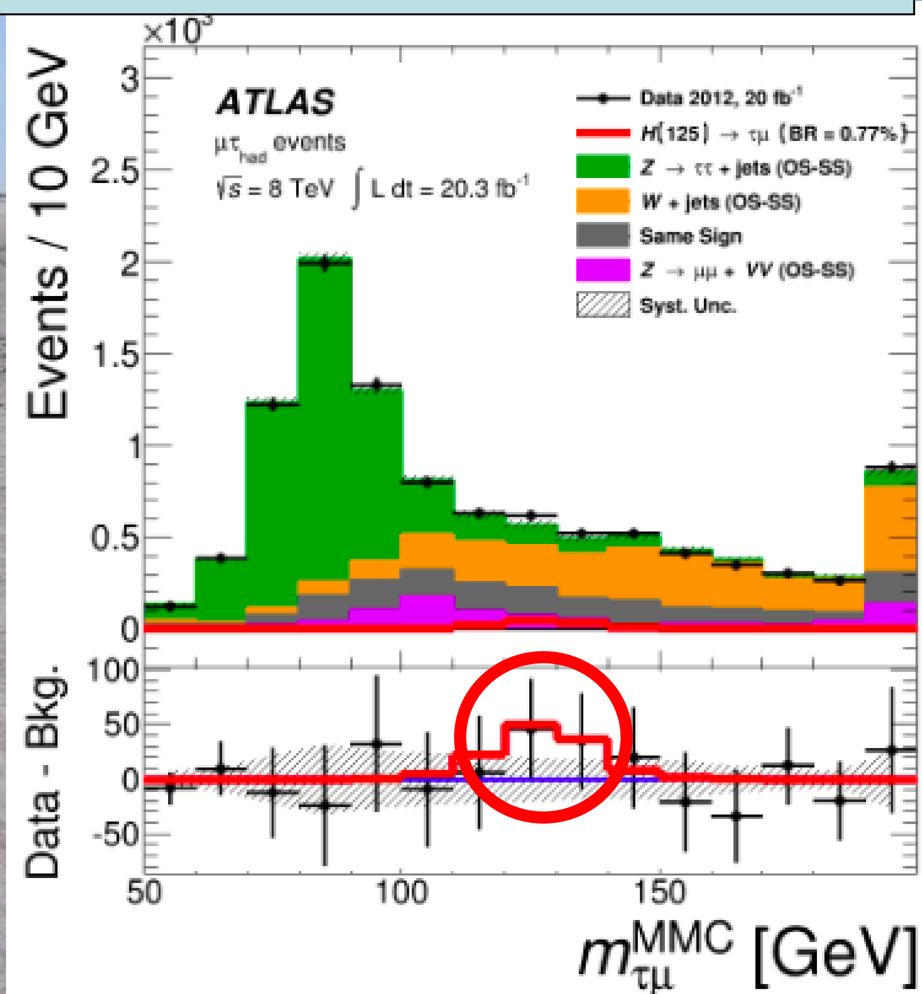
BR(τμ) or BR(τe) could be O(10)%

Blankenburg, JE, Isidori: arXiv:1202.5704

BR(μe) must be $< 2 \times 10^{-5}$

Flavour-Changing Higgs Coupling?



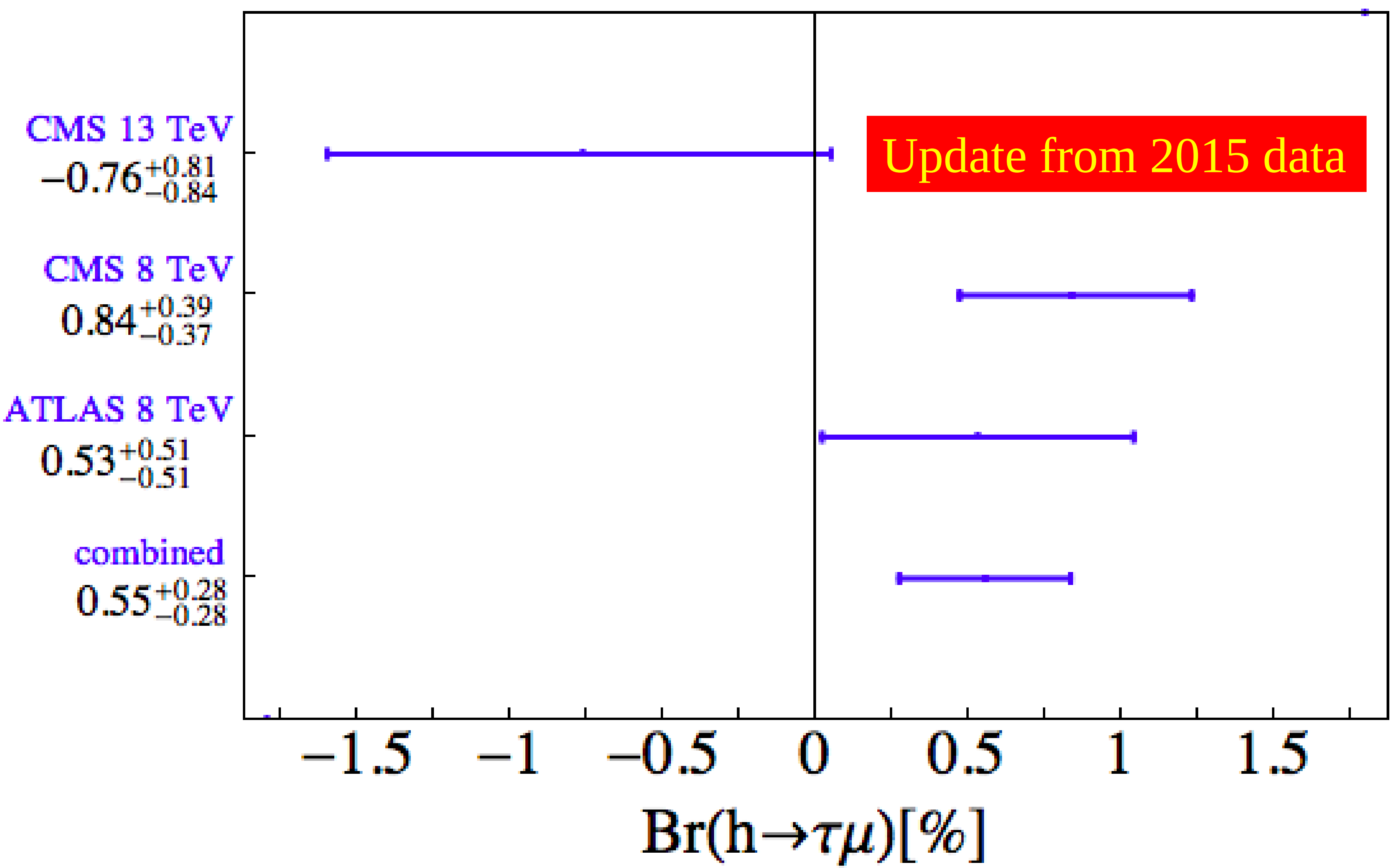


$\mathcal{B}(\mathrm{H} \rightarrow \mu\tau) = (0.84^{+0.39}_{-0.37})\%$

$\mathrm{Br}(H \rightarrow \mu\tau) = (0.77 \pm 0.62)\%$

Also: BR(eτ) < 0.69%, BR(eμ) < 0.036%

Flavour-Changing Higgs Coupling?



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

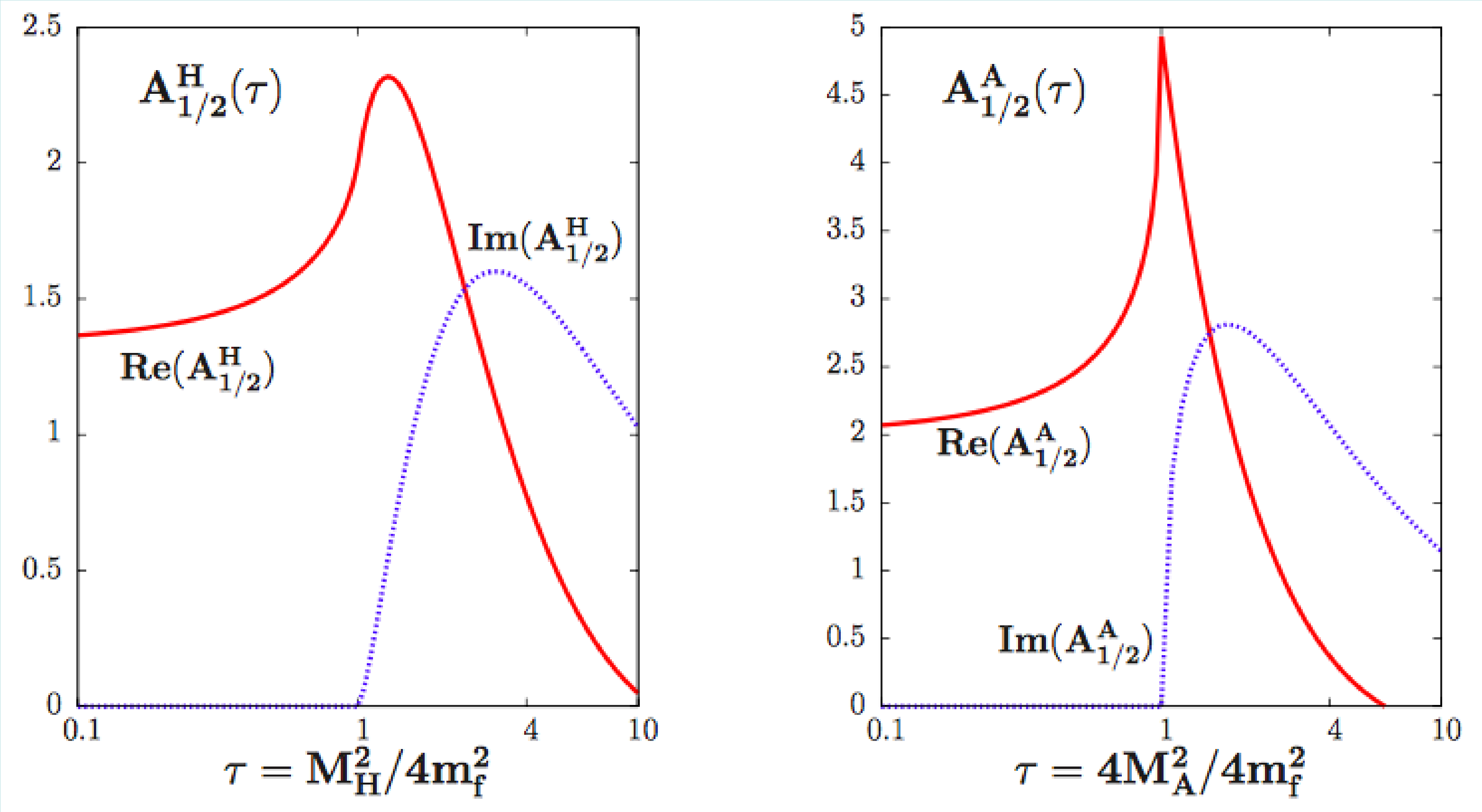
- What are its self-couplings?

Triangle Diagrams for gg ➔Spin-0 ➔γγ

- Effective vertices:
$$\mathcal{L}_{\rm eff}^{H} = \frac{e}{v} c_{H\gamma\gamma}\, H F_{\mu\nu} F^{\mu\nu} + \frac{g_s}{v} c_{Hgg}\, H G_{\mu\nu} G^{\mu\nu}$$
$$\mathcal{L}_{\rm eff}^{A} = \frac{e}{v} c_{A\gamma\gamma}\, A F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_s}{v} c_{Agg}\, A G_{\mu\nu} \tilde{G}^{\mu\nu},$$
- Decay rates:
$$\Gamma(\Phi \to gg) = \frac{G_\mu \alpha_s^2 M_\Phi^3}{64\sqrt{2}\pi^3} \left| \sum_Q \hat{g}_{\Phi QQ} A_{1/2}^{\Phi}(\tau_Q) \right|^2,$$
$$\Gamma(\Phi \to \gamma\gamma) = \frac{G_\mu \alpha^2 M_\Phi^3}{128\sqrt{2}\pi^3} \left| \sum_F \hat{g}_{\Phi FF} N_c e_F^2 A_{1/2}^{\Phi}(\tau_F) \right|^2$$
- Vertex form factors:
$$A_{1/2}^{H}(\tau) = 2\left[\tau + (\tau - 1) f(\tau)\right] \tau^{-2}, \quad A_{1/2}^{A}(\tau) = 2\tau^{-1} f(\tau)$$
$$f(\tau) = \begin{cases} \arcsin^2 \sqrt{\tau} & \text{for } \tau \le 1, \\ -\frac{1}{4}\left[\log \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \text{for } \tau > 1. \end{cases}$$
- Vanish for fermion mass << spin-0 mass

Triangle Diagrams for gg ➔Spin-0 ➔γγ

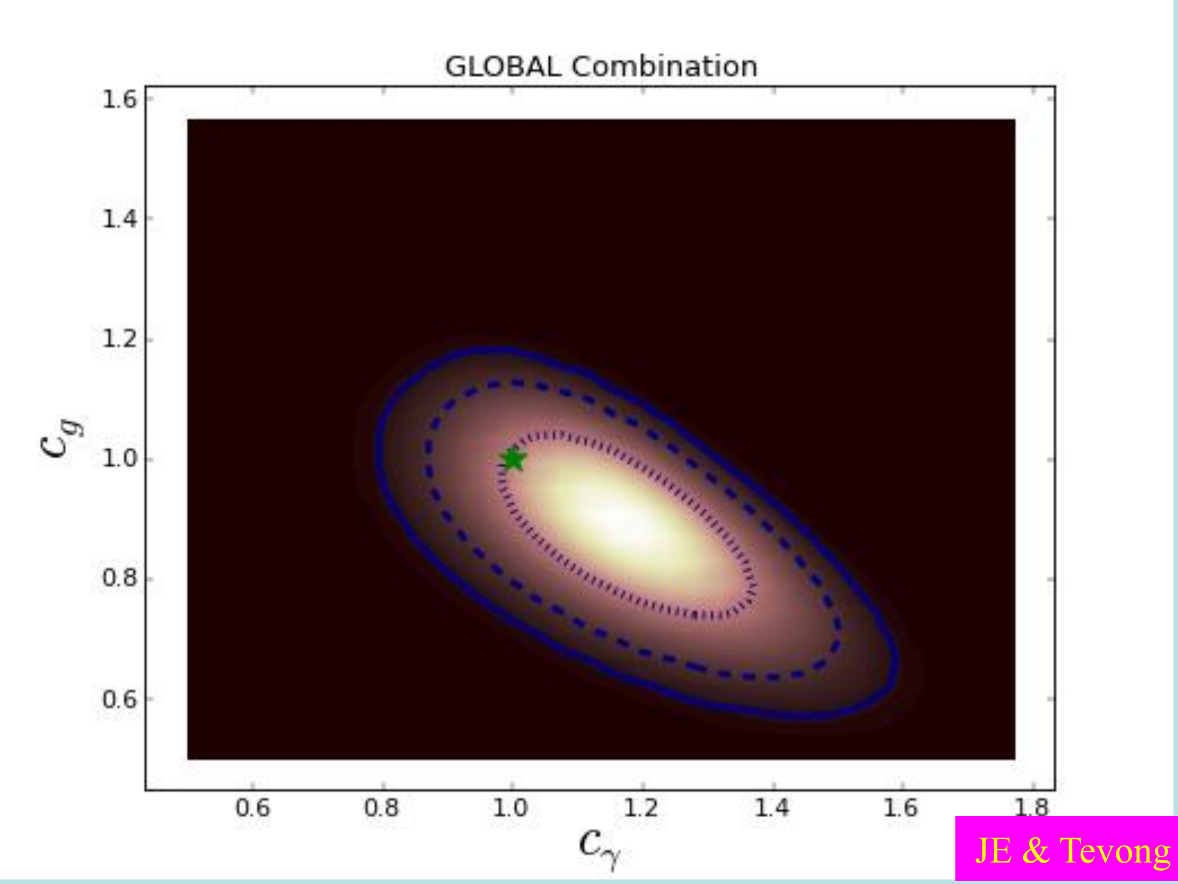
- Form factors for triangle diagrams



- Vanish for fermion mass << spin-0 mass

Loop Corrections ?

- Combination of data on γγ, gluon-gluon couplings



JE & Tevong You, arXiv:1303.3879

- Loop diagrams ~ Standard Model?

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  - **γγ, gg couplings ~ Standard Model**
- What are its self-couplings?

H^0 $J = 0$

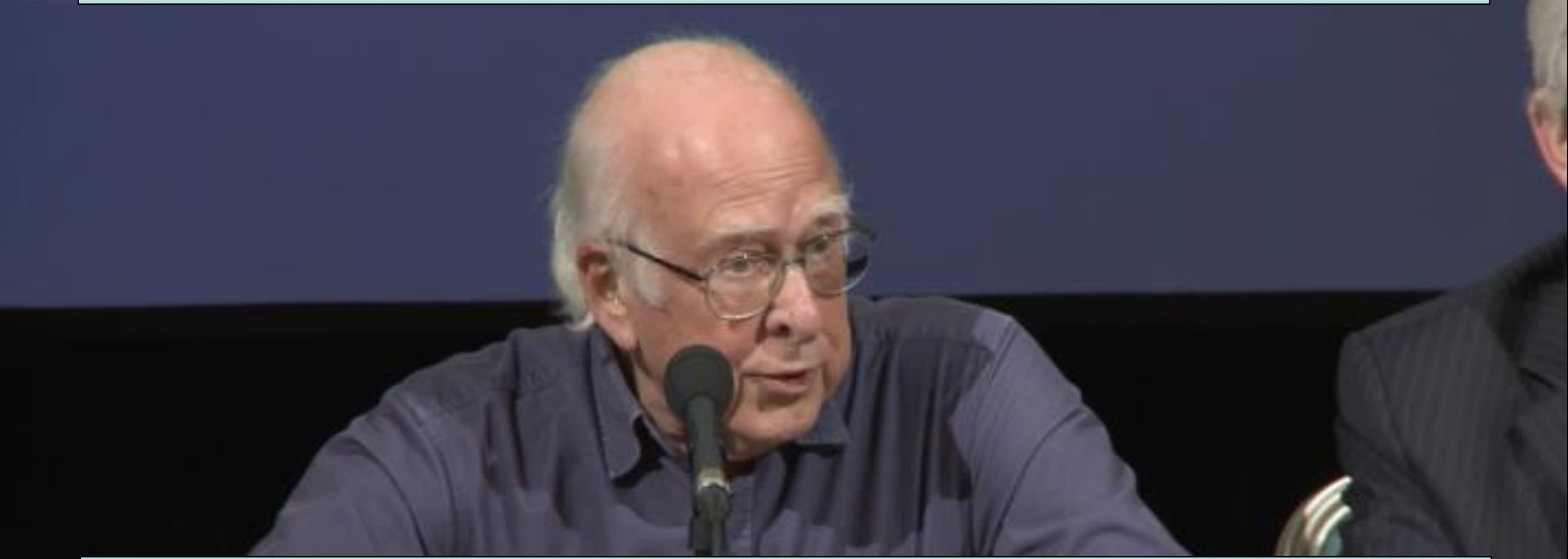
Mass $m = 125.09 \pm 0.24$ GeV

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)
$WW^* = 0.81 \pm 0.16$
$ZZ^* = 1.15^{+0.27}_{-0.23}$ (S = 1.2)
$\gamma\gamma = 1.17^{+0.19}_{-0.17}$
$b\bar{b} = 0.85 \pm 0.29$
$\mu^+\mu^- < 7.0$, CL = 95%
$\tau^+\tau^- = 0.79 \pm 0.26$
$Z\gamma < 9.5$, CL = 95%
$t\bar{t}H^0$ Production $= 2.5^{+0.9}_{-0.8}$

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

Assuming H(125) is SM-like: Model-independent search for new physics

Standard Model Effective Field Theory

- Higher-dimensional operators as relics of higher-energy physics, e.g., dimension 6: $\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$
- Operators constrained by SU(2) × U(1) symmetry:

$$\begin{aligned}
\mathcal{L} \supset\ & \frac{\bar{c}_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{g'^2\ \bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\ \bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu} \\
+\ & \frac{2ig\ \bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\ \bar{c}_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu} \\
+\ & \frac{ig\ \bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'\ \bar{c}_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu} \\
+\ & \frac{\bar{c}_t}{v^2}y_t\Phi^\dagger\Phi\ \Phi^\dagger\cdot\bar{Q}_L t_R + \frac{\bar{c}_b}{v^2}y_b\Phi^\dagger\Phi\ \Phi\cdot\bar{Q}_L b_R + \frac{\bar{c}_\tau}{v^2}y_\tau\ \Phi^\dagger\Phi\ \Phi\cdot\bar{L}_L\tau_R
\end{aligned}$$

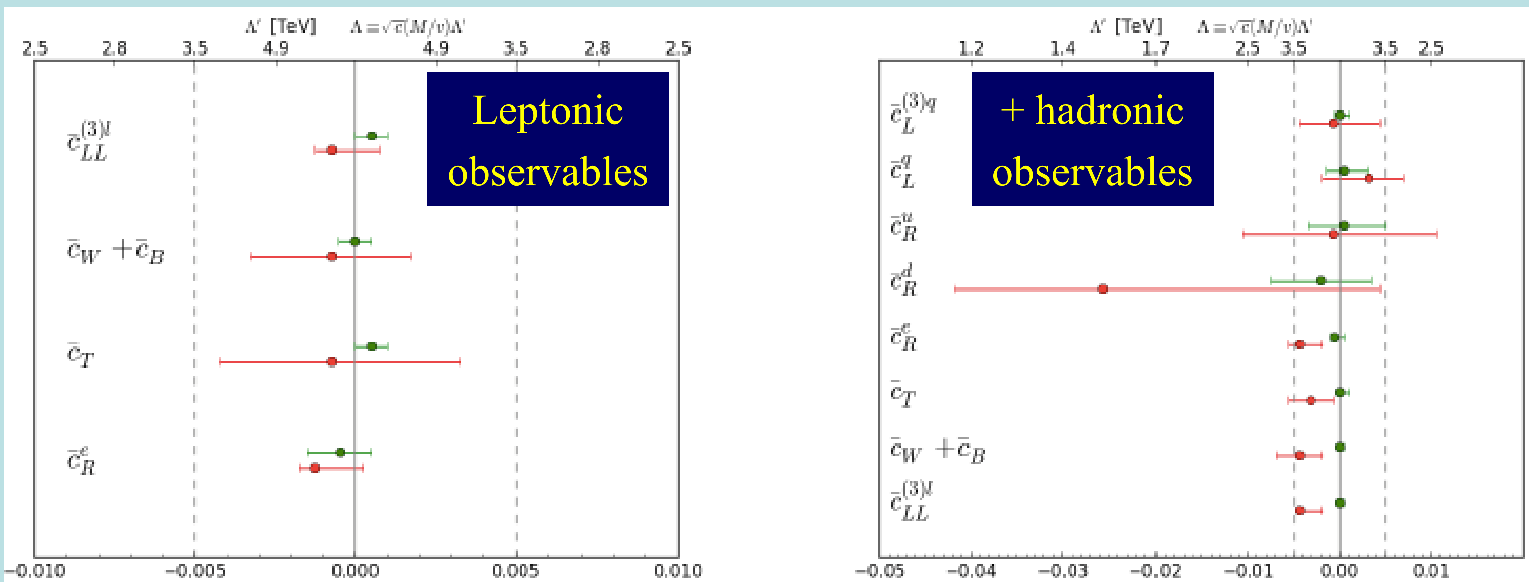
- Constrain with precision EW, Higgs data, TGCs …

Electroweak Precision Data

- Operators affecting oblique parameters

$$\mathcal{L}_{\text{dim-6}} \subset \frac{\bar{c}_{WB}}{m_W^2}\mathcal{O}_{WB} + \frac{\bar{c}_W}{m_W^2}\mathcal{O}_W + \frac{\bar{c}_B}{m_W^2}\mathcal{O}_B + \frac{\bar{c}_T}{v^2}\mathcal{O}_T + \frac{\bar{c}_{2W}}{m_W^2}\mathcal{O}_{2W} + \frac{\bar{c}_{2B}}{m_W^2}\mathcal{O}_{2B}$$

- Also other electroweak tests
- Constraints from LEP et al. data



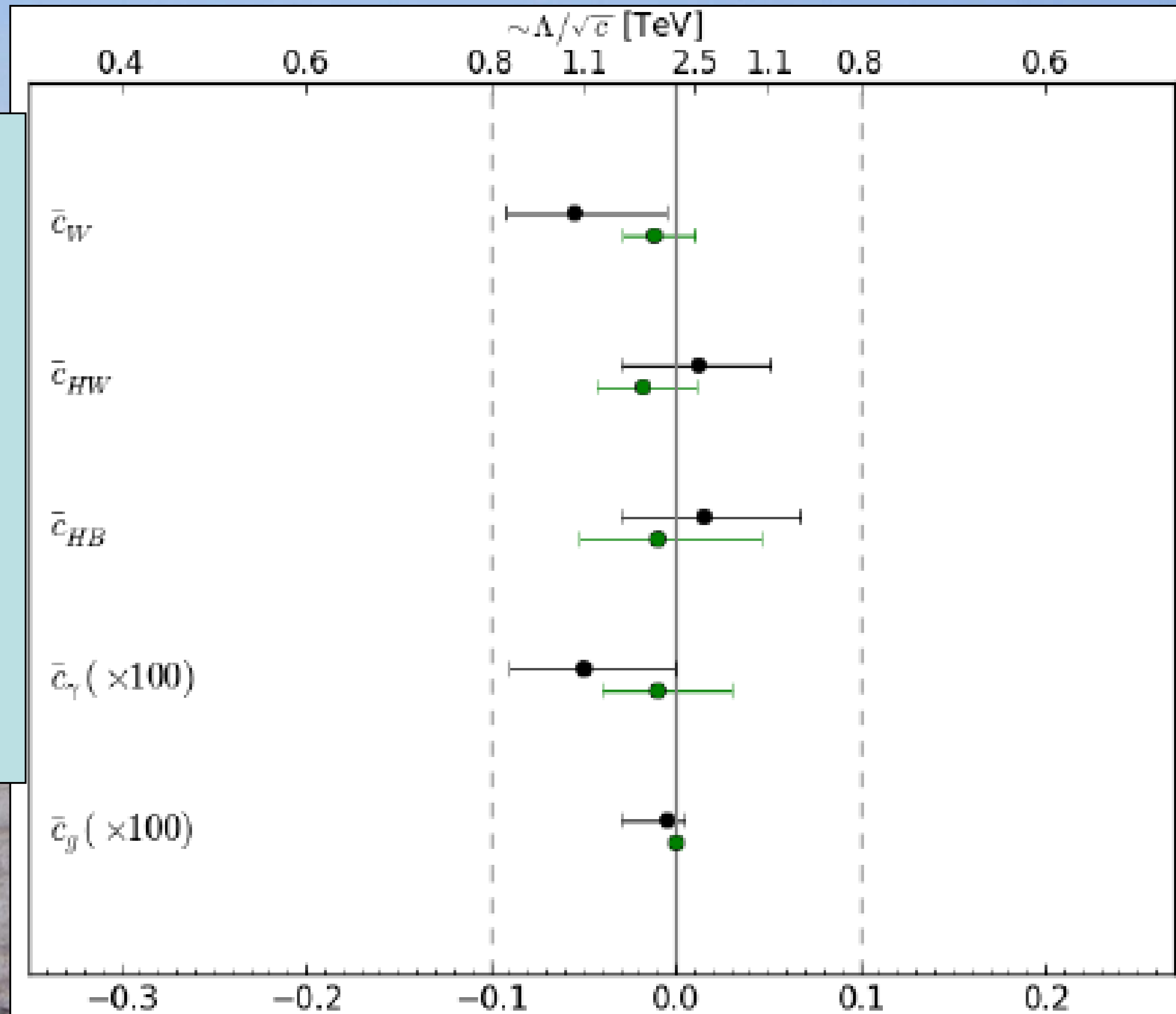
Fits to individual dimension-6 operators

Global fit to dimension-6 operators

JE, Sanz & Tevong You, arXiv:1410.7703

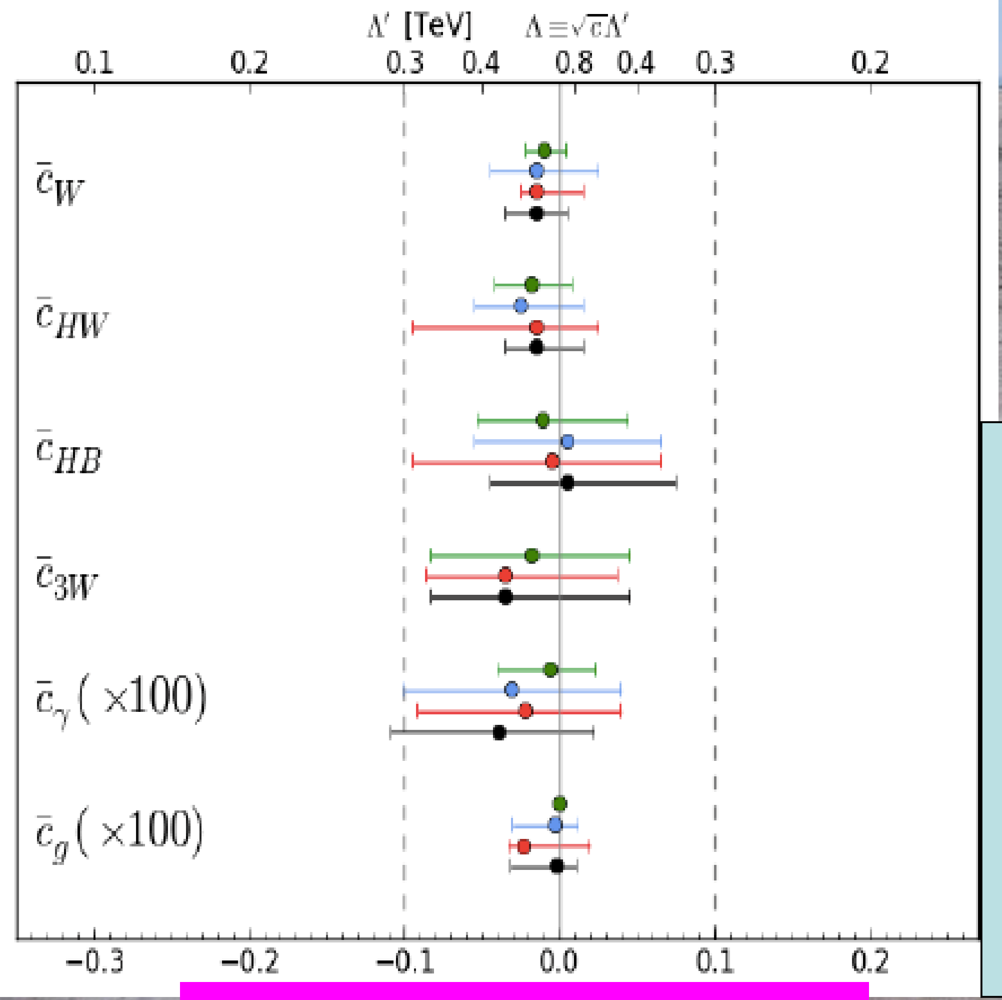
Fits including Higgs Production

- Using signal strengths & VH kinematics in global fit
- **Single-parameter fits**

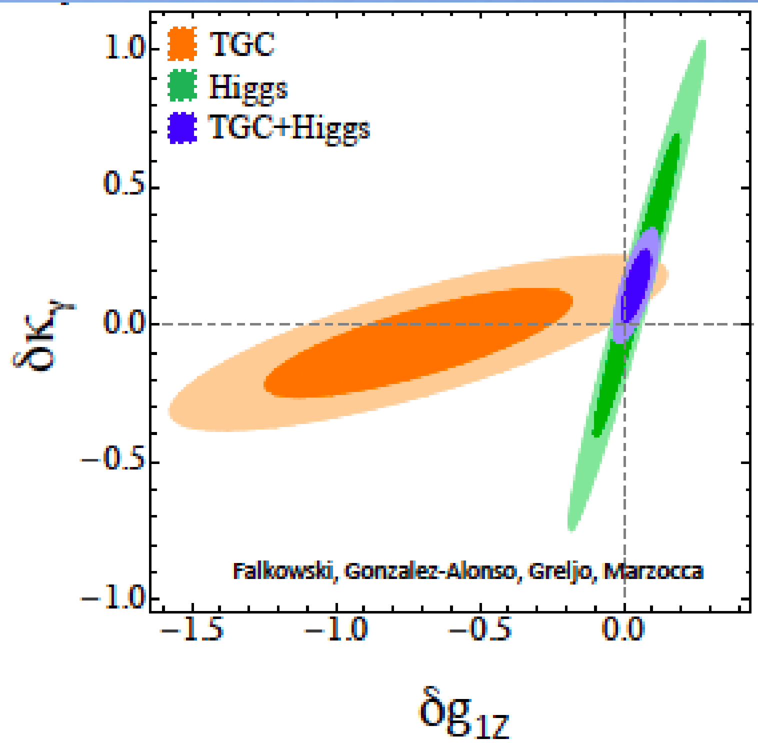


JE, Sanz & Tevong You, arXiv:1404.3667

Global Fits including LHC TGCs



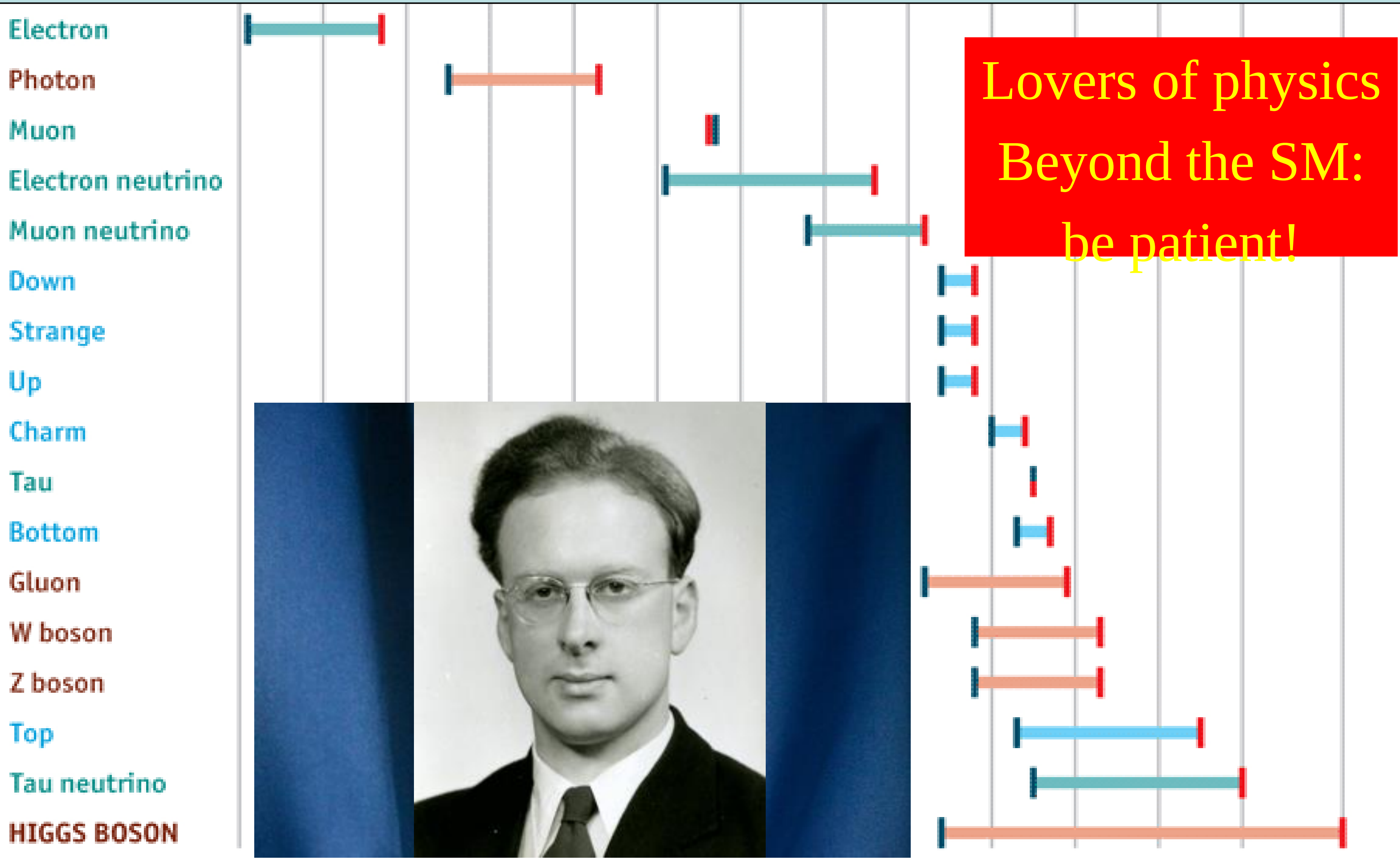
JE, Sanz & Tevong You, arXiv:1410.7703



- **Associated production**
- **LHC Triple-gauge couplings**
- Global combination
- **Individual operators**

Standard Model Particles:

Years from Proposal to Discovery

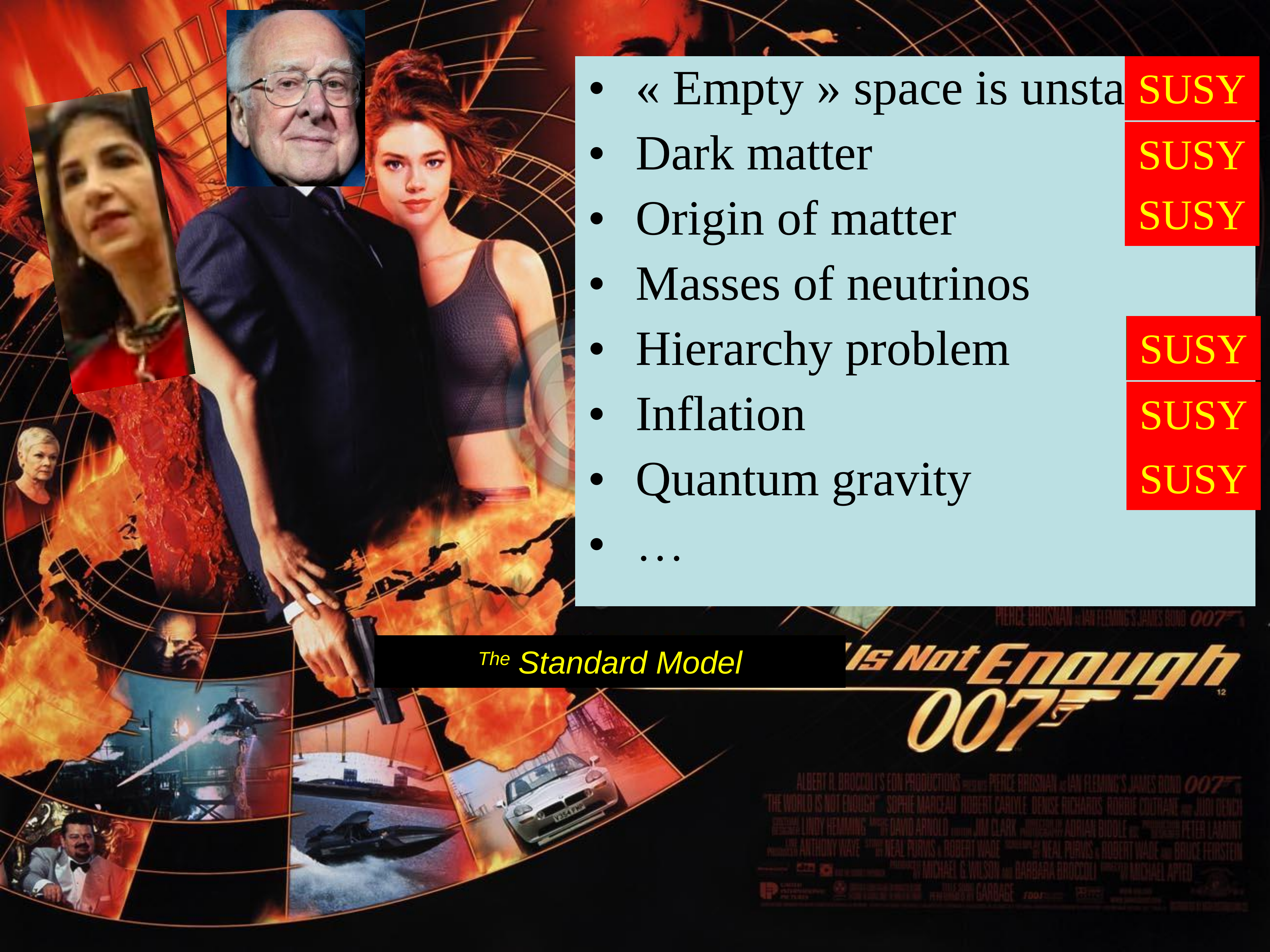


Source: *The Economist*

Lovers of physics
Beyond the SM:
be patient!

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

The Standard Model



What lies beyond the Standard Model?

Supersymmetry

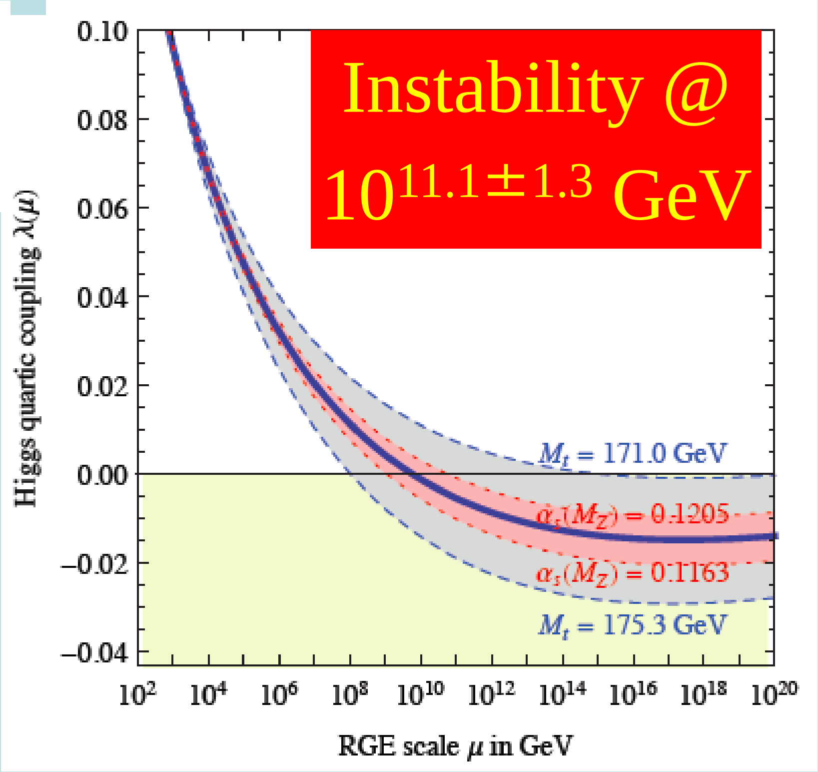
New motivations
From LHC Run 1

- **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, GUTs, string, …, **dark matter**

Theoretical Constraints on Higgs Mass

- Large $M_h \rightarrow$ large self-coupling $\rightarrow$ blow up at

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

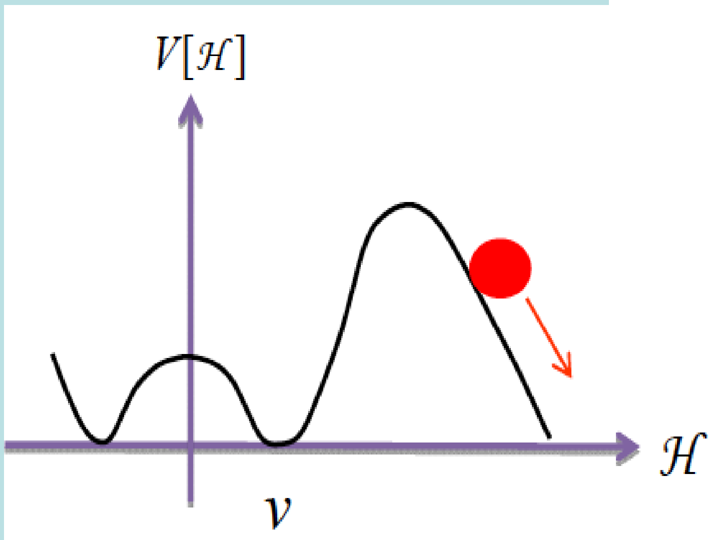


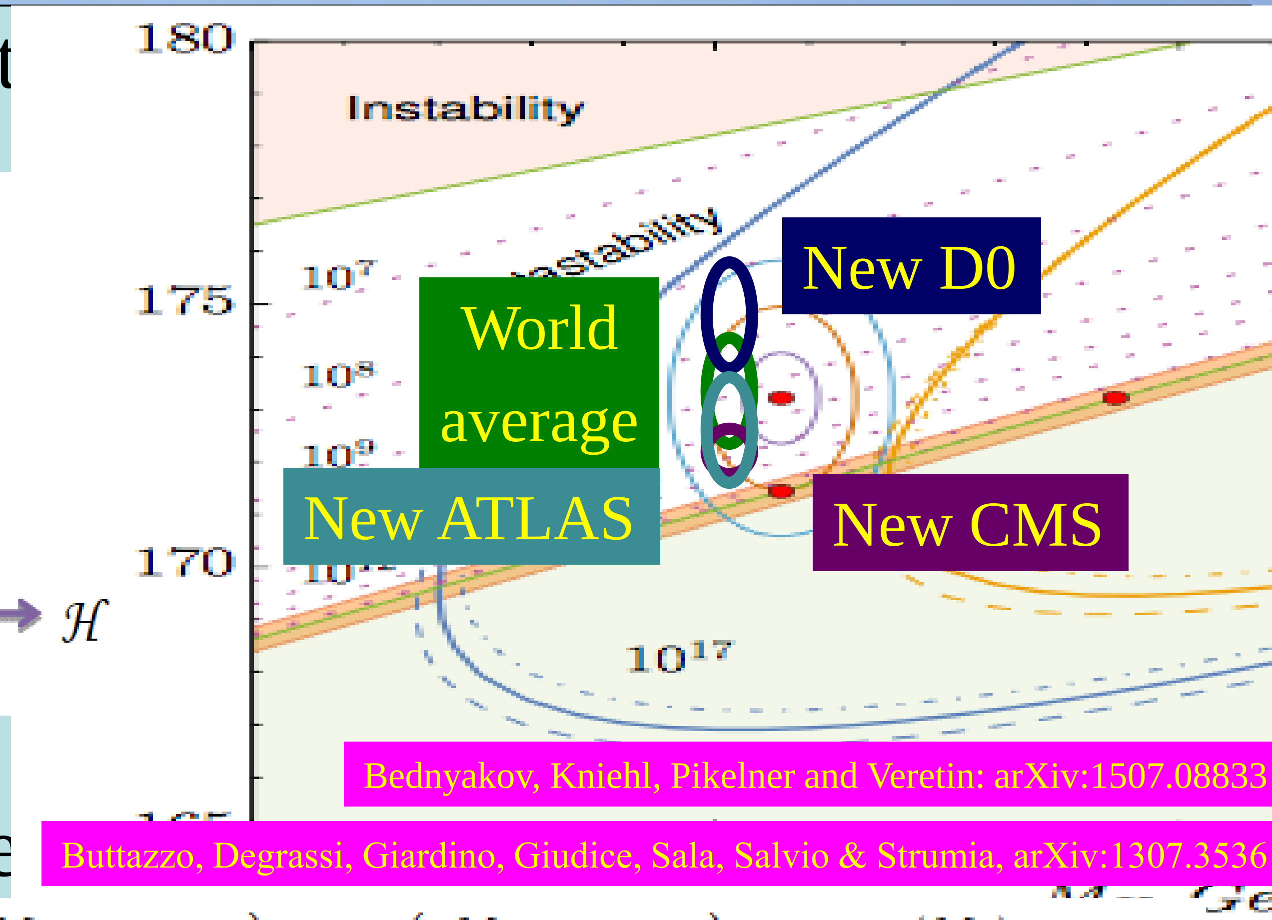
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ $\rightarrow$ vacuum unstable
- Vacuum could be stabilized by **Supersymmetry**

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

Vacuum Instability in the Standard Model

- Very sensitive t





- Instability scale

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

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

Hard QCD: the Top Mass

- Basic parameter of SM; **stability of EW vacuum?**
- World average:

$m_t = 173.34 \pm 0.76$ GeV

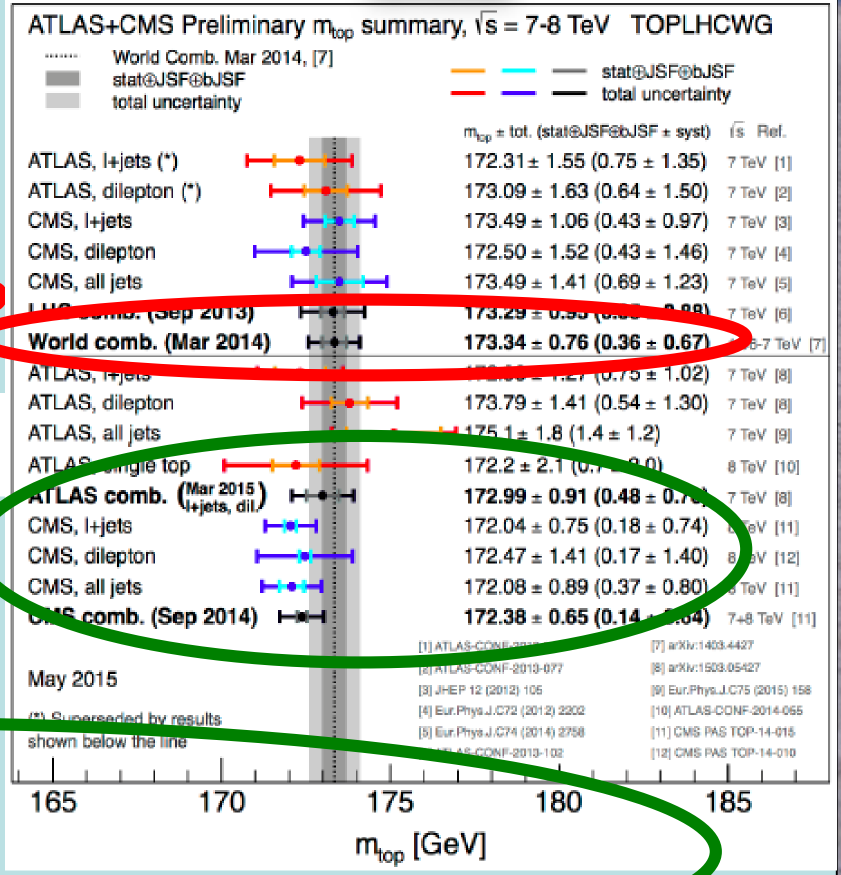
- **Running → pole mass OK?**

$+ 7.557 + 1.617 + 0.501 + 0.195)$

- Monte Carlo mass ✓?
- New measurements:

ATLAS: 172.99±0.91 GeV

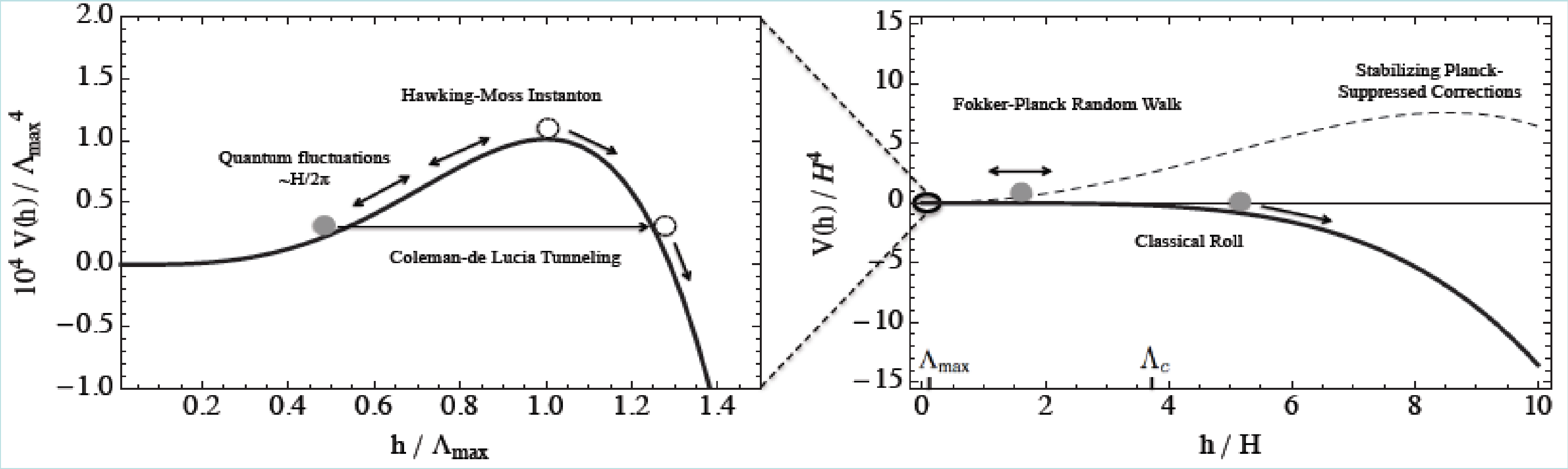
CMS: 172.38±0.65, D0: 174.98±0.58±0.49 GeV



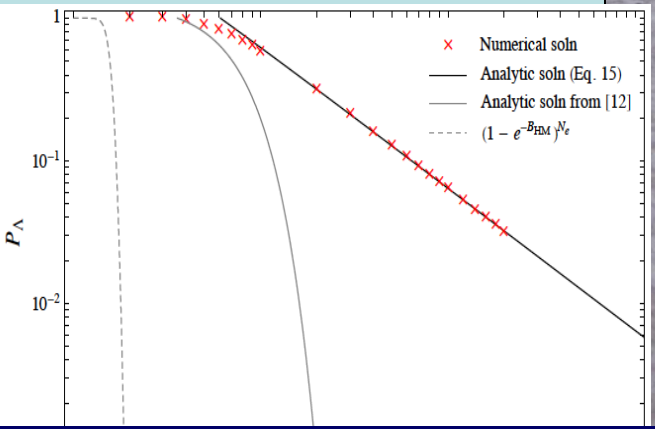
Instability during Inflation?

Hook, Kearns, Shakya & Zurek: arXiv:1404.5953

- Do inflation fluctuations drive us over the hill?



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



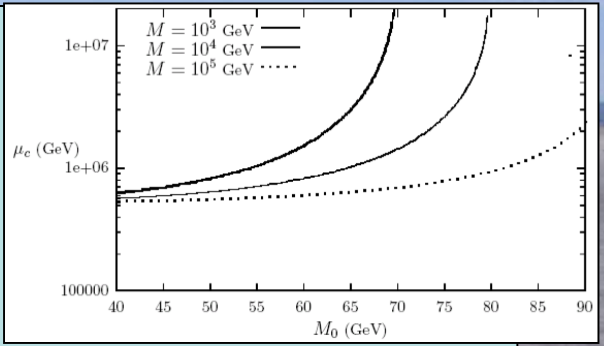
Stabilize vacuum with some physics beyond the SM?

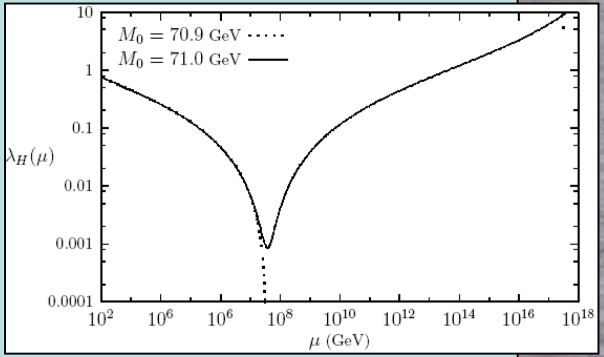
How to Stabilize a Light Higgs Boson?

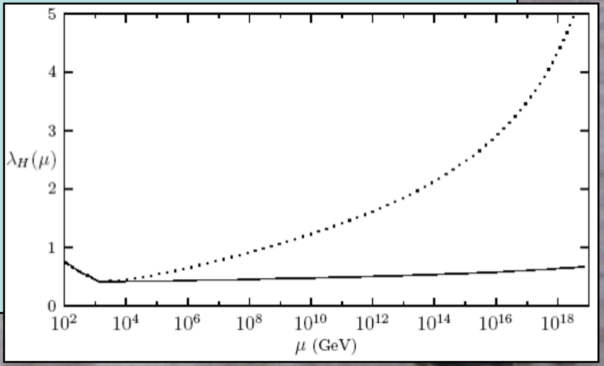
- Top quark destabilizes potential: introduce stop-like scalar:

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

- 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!**

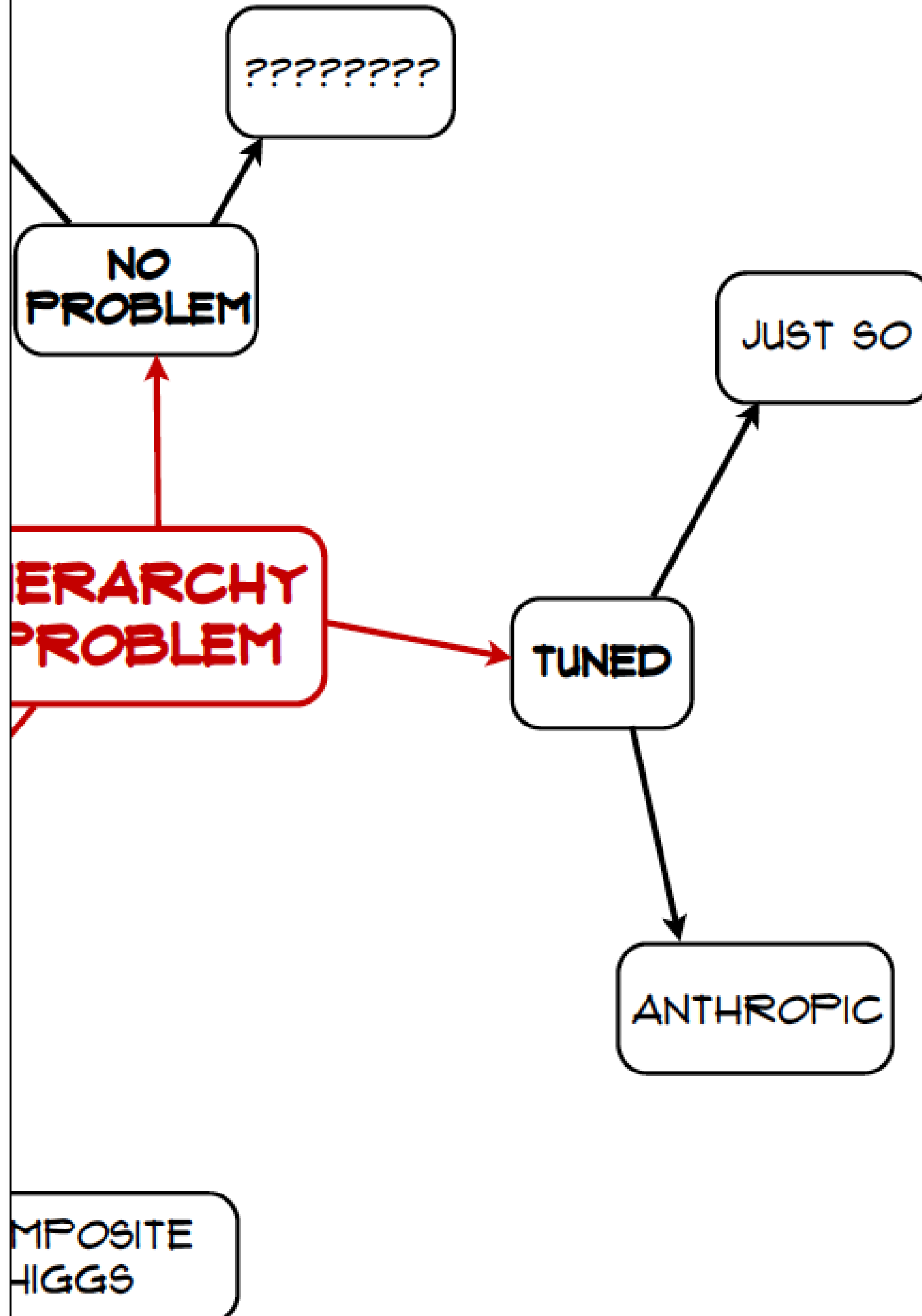






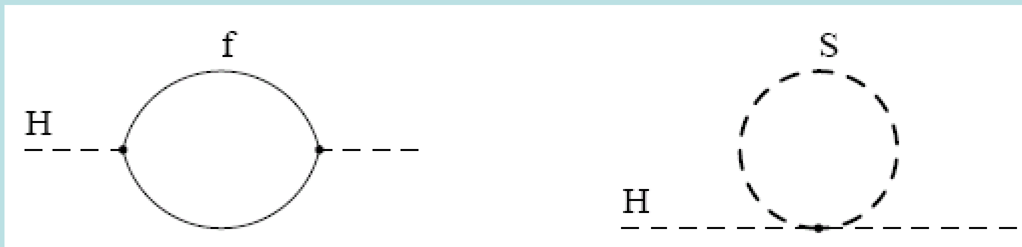
JE + D. Ross

"WELL, IF YOU KNOWS OF A BETTER 'OLE, GO TO IT!"



Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

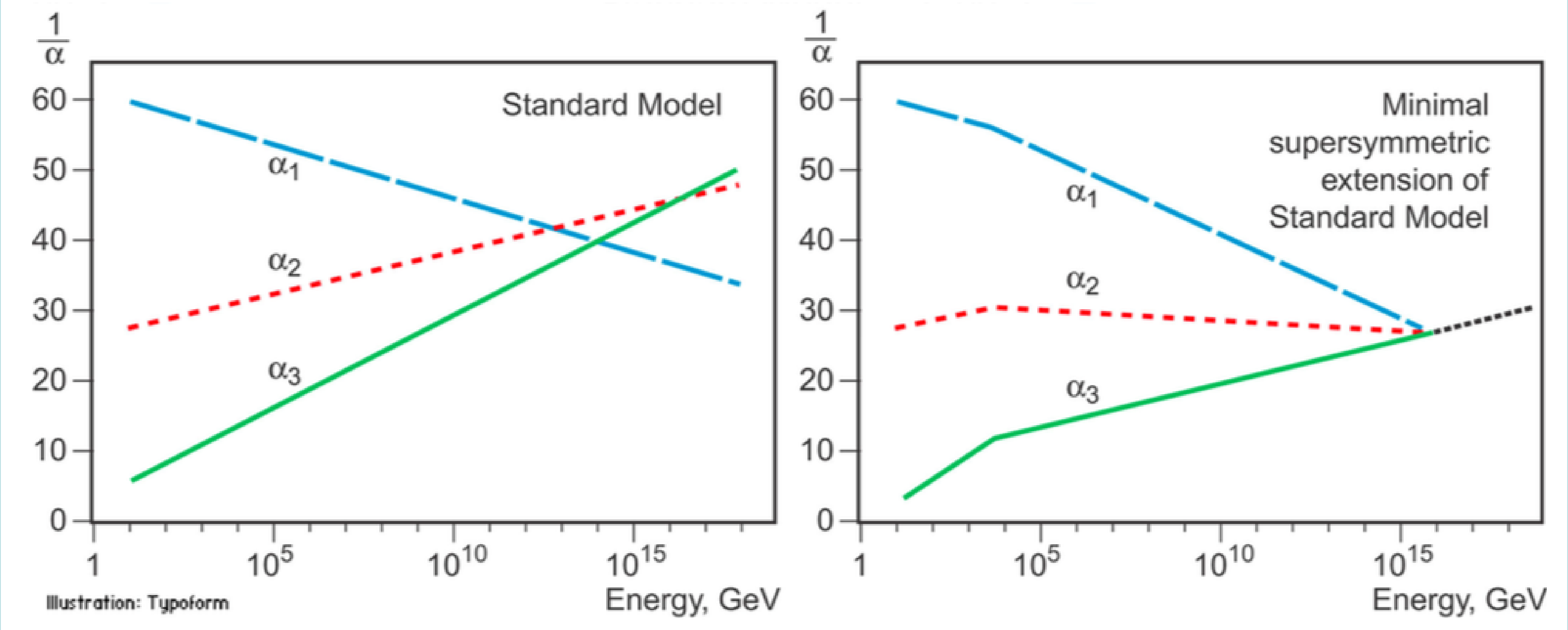
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Leading divergence cancelled if

$$\lambda_S = y_f^2 \times 2$$

Supersymmetry!

Unification of Gauge Couplings



- **Impressive!**
- **Over-ambitious? Hubristic?**

Minimal Supersymmetric Extension of Standard Model (MSSM)

- Double up the known particles:

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell \; (lepton) \\ \tilde{\ell} \; (slepton) \end{pmatrix} \; or \; \begin{pmatrix} q \; (quark) \\ \tilde{q} \; (squark) \end{pmatrix}$$

$$\begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma \; (photon) \\ \tilde{\gamma} \; (photino) \end{pmatrix} \; or \; \begin{pmatrix} g \; (gluon) \\ \tilde{g} \; (gluino) \end{pmatrix}$$

- Two Higgs doublets
  - 5 physical Higgs bosons:
  - 3 neutral, 2 charged
- Lightest neutral supersymmetric Higgs looks like the single Higgs in the Standard Model

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:

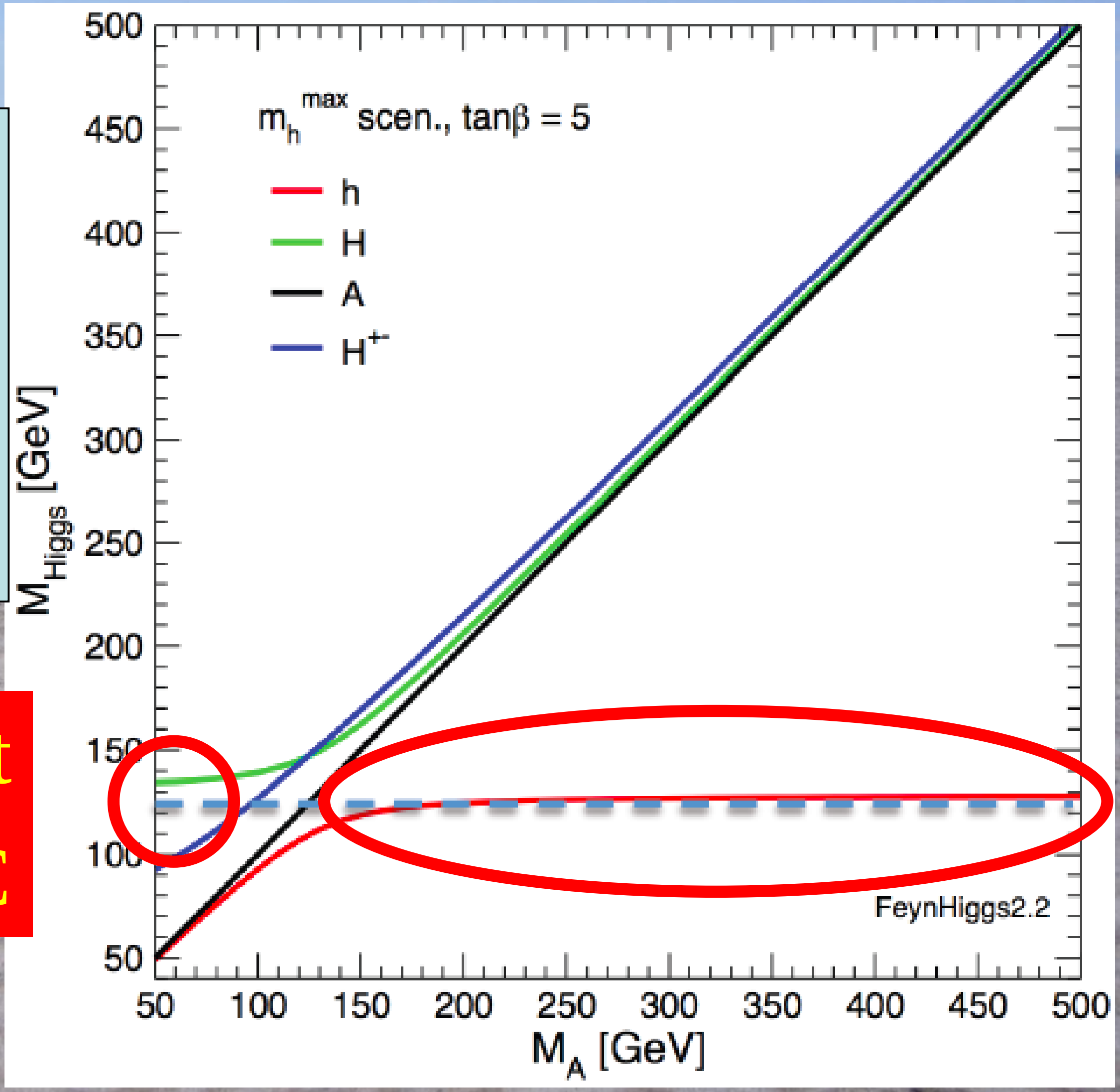
$$G_\mu m^4_{\mathrm{t}} \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m^2_{\mathrm{t}}}\right) \quad \Delta M_H\big|_{TH} \sim 1.5\ \mathrm{GeV}$$

MSSM Higgs Masses & Couplings

Lightest Higgs mass up to ~ 130 GeV

Heavy Higgs masses quite close

750?



Consistent With LHC

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**

Lightest Sparticle as Dark Matter?

- No strong or electromagnetic interactions

  Otherwise would bind to matter

  Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates

  Sneutrino

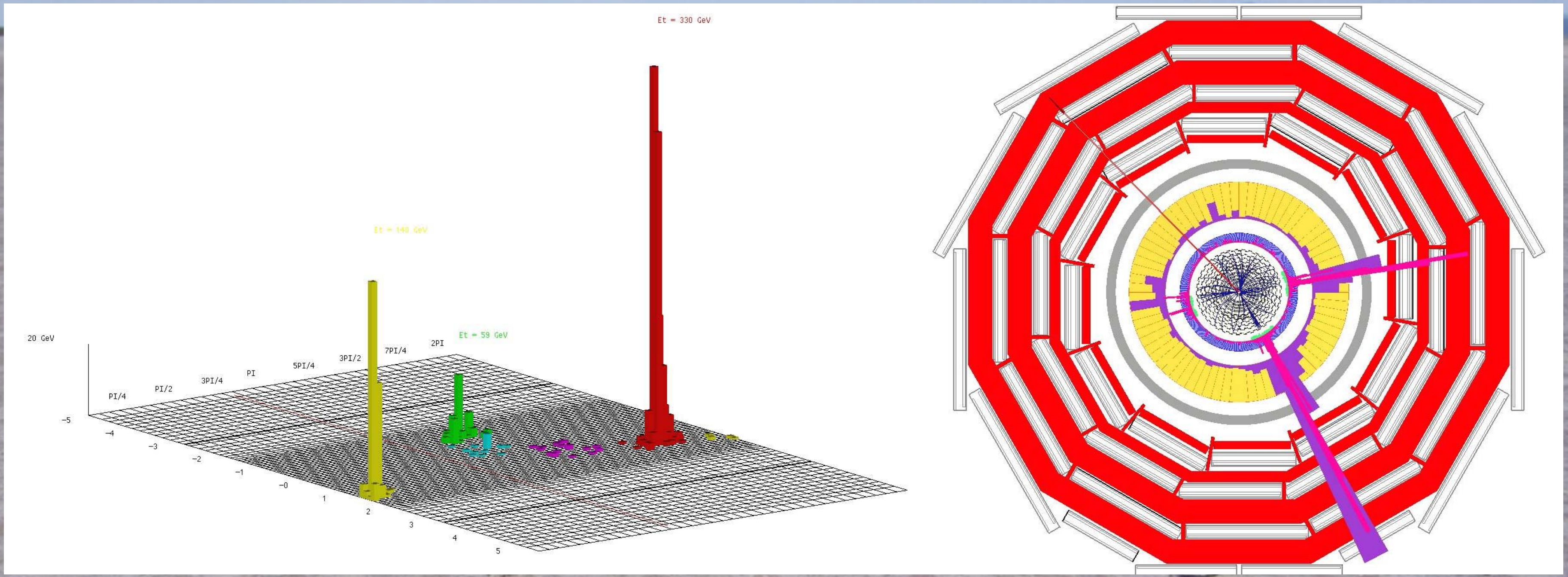
  (Excluded by LEP, direct searches)

  Lightest neutralino χ (partner of Z, H, γ)

  Gravitino

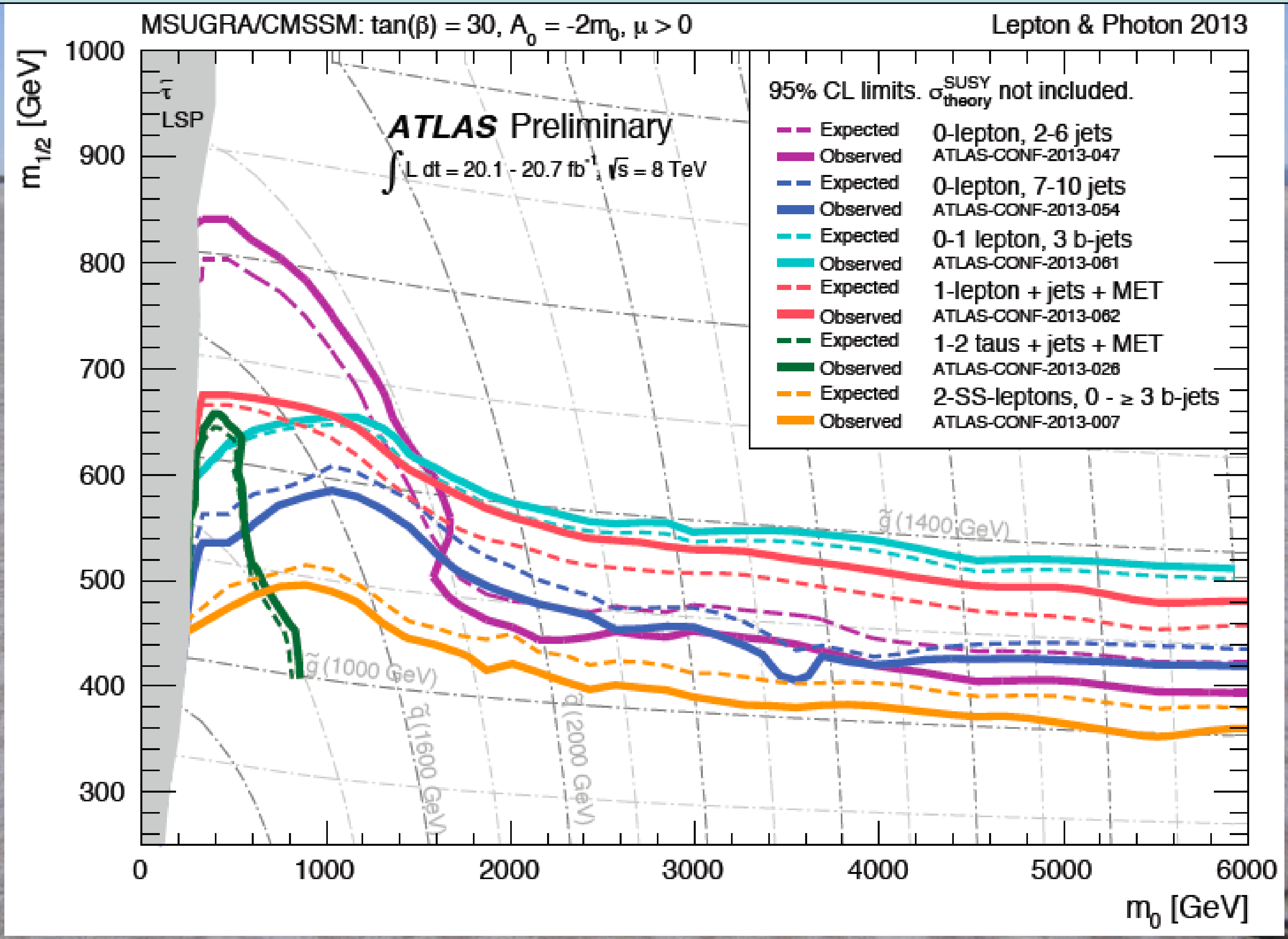
  (nightmare for detection)

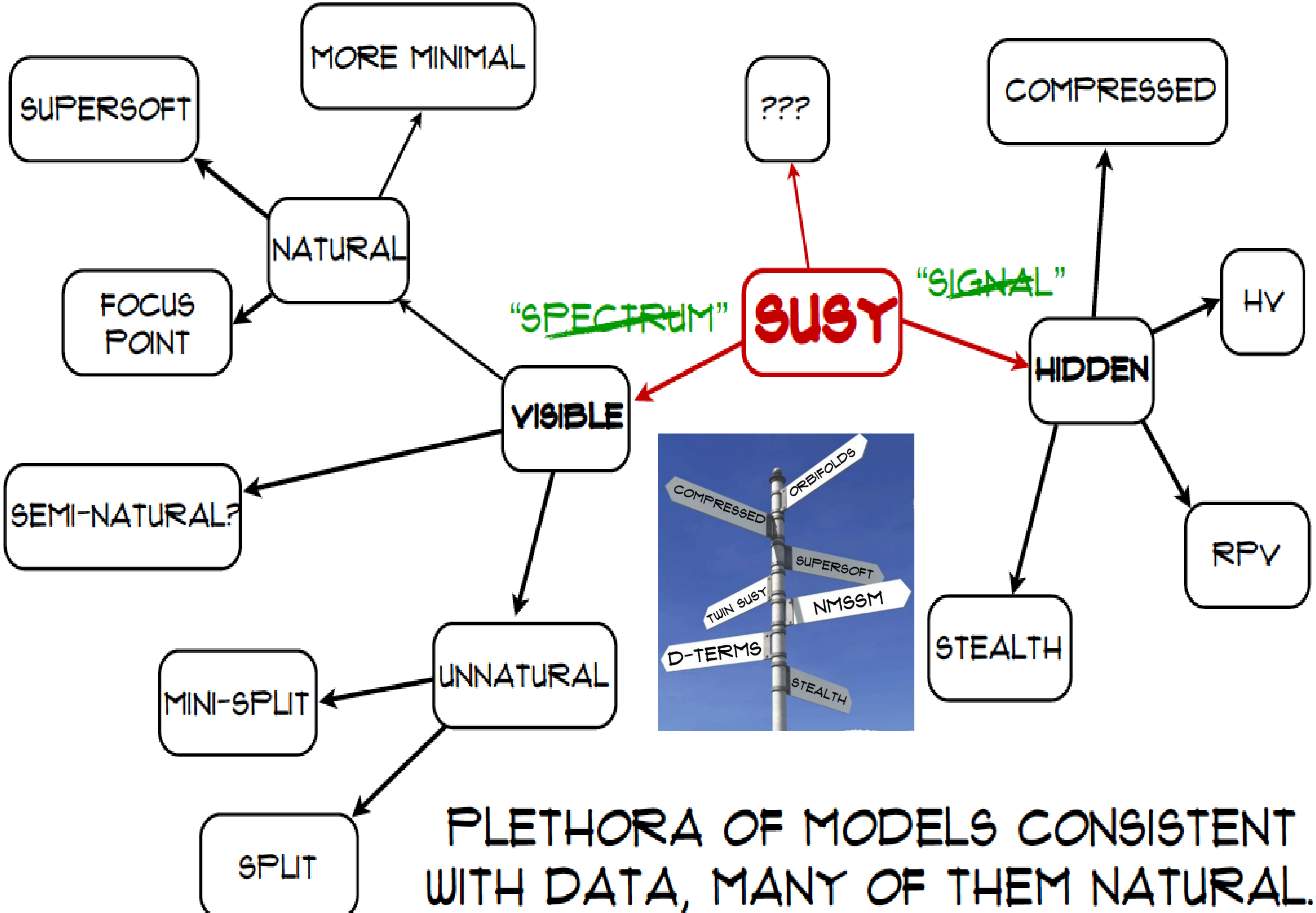
Classic Dark Matter Signature



Missing transverse energy
carried away by dark matter particles

Searches with ~ 20/fb @ 8 TeV





PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL. WHERE DOES THE DATA POINT US?

Craig@LHCP

(Non-)Universal Scalar Masses?

- Different sfermions with same quantum #s?

  e.g., d, s squarks?

  disfavoured by upper limits on flavour-changing neutral interactions

- Squarks with different #s, squarks and sleptons?

  disfavoured in various GUT models

  e.g., $d_R = e_L$, $d_L = u_L = u_R = e_R$ in SU(5), all in SO(10)

- Non-universal susy-breaking masses for Higgses?

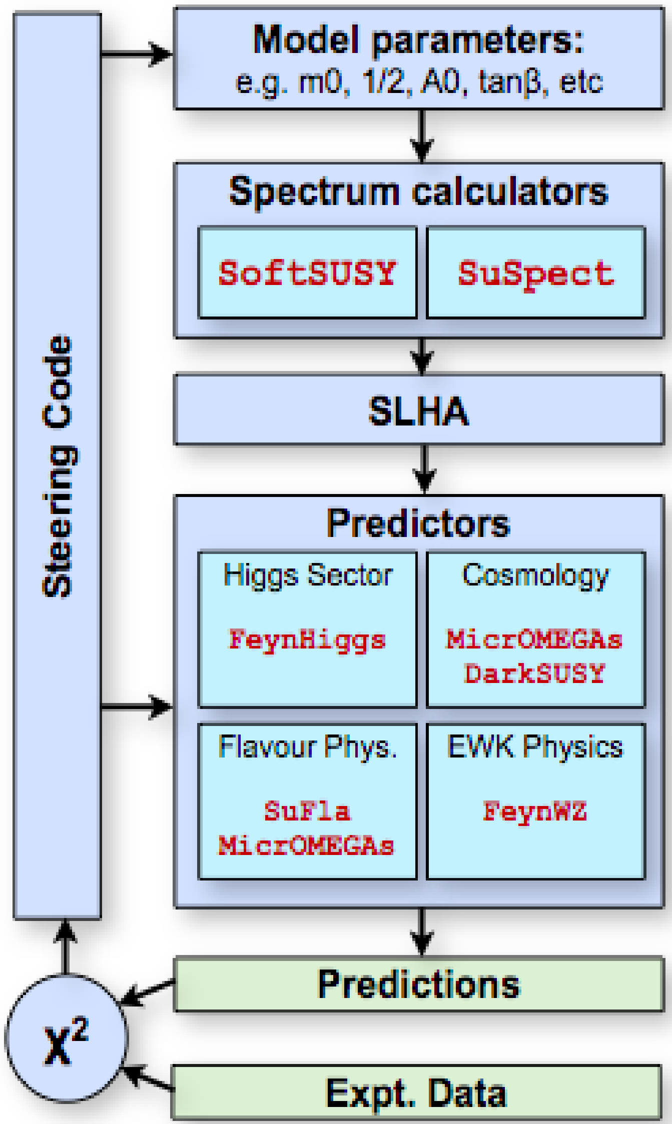
  No reason why not! NUHM

Sample Supersymmetric Models

- Universal soft supersymmetry breaking at input GUT scale?
  - For gauginos and all scalars: CMSSM
  - Non-universal Higgs masses: NUHM1,2
- **Strong pressure from LHC (p ~ 0.1)**
- Treat soft supersymmetry-breaking masses as phenomenological inputs at EW scale
  - pMSSMn (n parameters)
  - With universality motivated by upper limits on flavour-changing neutral interactions: pMSSM10
- **Less strongly constrained by LHC (p ~ 0.3)**

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



E. Bagnaschi, M. Borsato, O. Buchmueller, R. Cavanaugh, V. Chobanova, M. Citron, J. Costa, A. De Roeck, M.J. Dolan, J.E., H. Flacher, S. Heinemeyer, G. Isidori, M. Lucio, D. Martinez Santos, K.A. Olive, A. Richards, K. Sakurai, G. Weiglein

Data

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

Deviation from Standard Model:

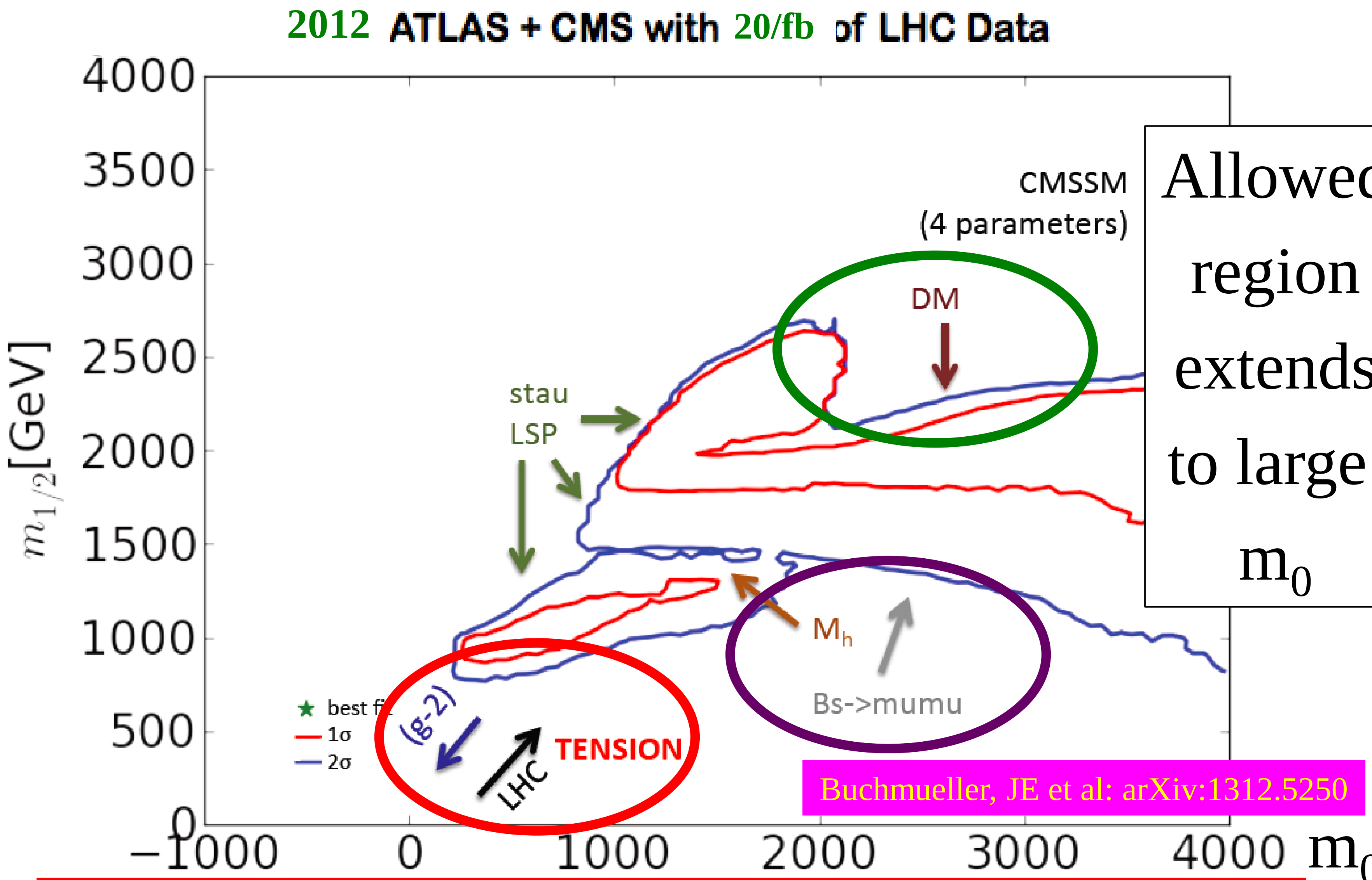
Supersymmetry at low scale, or …?

Observable	Source Th./Ex.	Constraint
m_t [GeV]	[39]	173.2 ± 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]	$80.399 \pm 0.023 \pm 0.010_{\rm SUSY}$
$\mathrm{BR}^{\rm EXP}_{b\to s\gamma}/\mathrm{BR}^{\rm SM}_{b\to s\gamma}$	[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 ± 0.32
$\mathrm{BR}_{K\to\mu\nu}/\mathrm{BR}_{K\to\mu\nu}$ [illegible]	[27] / [44]	$1.008 \pm 0.014_{\rm EXP+TH}$
$\mathrm{BR}^{\rm EXP}_{K\to\pi\nu\bar\nu}/\mathrm{BR}^{\rm SM}_{K\to\pi\nu\bar\nu}$	[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]	$1.08 \pm 0.14_{\rm EXP+TH}$
$a^{\rm EXP} - a^{\rm SM}$	[49] / [38, 50]	$(30.2 \pm 8.8 \pm 2.0_{\rm SUSY}) \times 10^{-10}$
[illegible]	[illegible]	[illegible] $1.5_{\rm SUSY}$
[illegible]	[illegible]	[illegible] $\pm 0.012_{\rm SUSY}$
σ_p [illegible]	[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

$M_H = 125.09 \pm 0.21 \pm 0.11$ GeV

MasterCode: O.Buchmueller, JE et al.

Fit to Constrained MSSM (CMSSM)



Allowed region extends to large m_0

p-value of simple models ~ 10% (also SM)

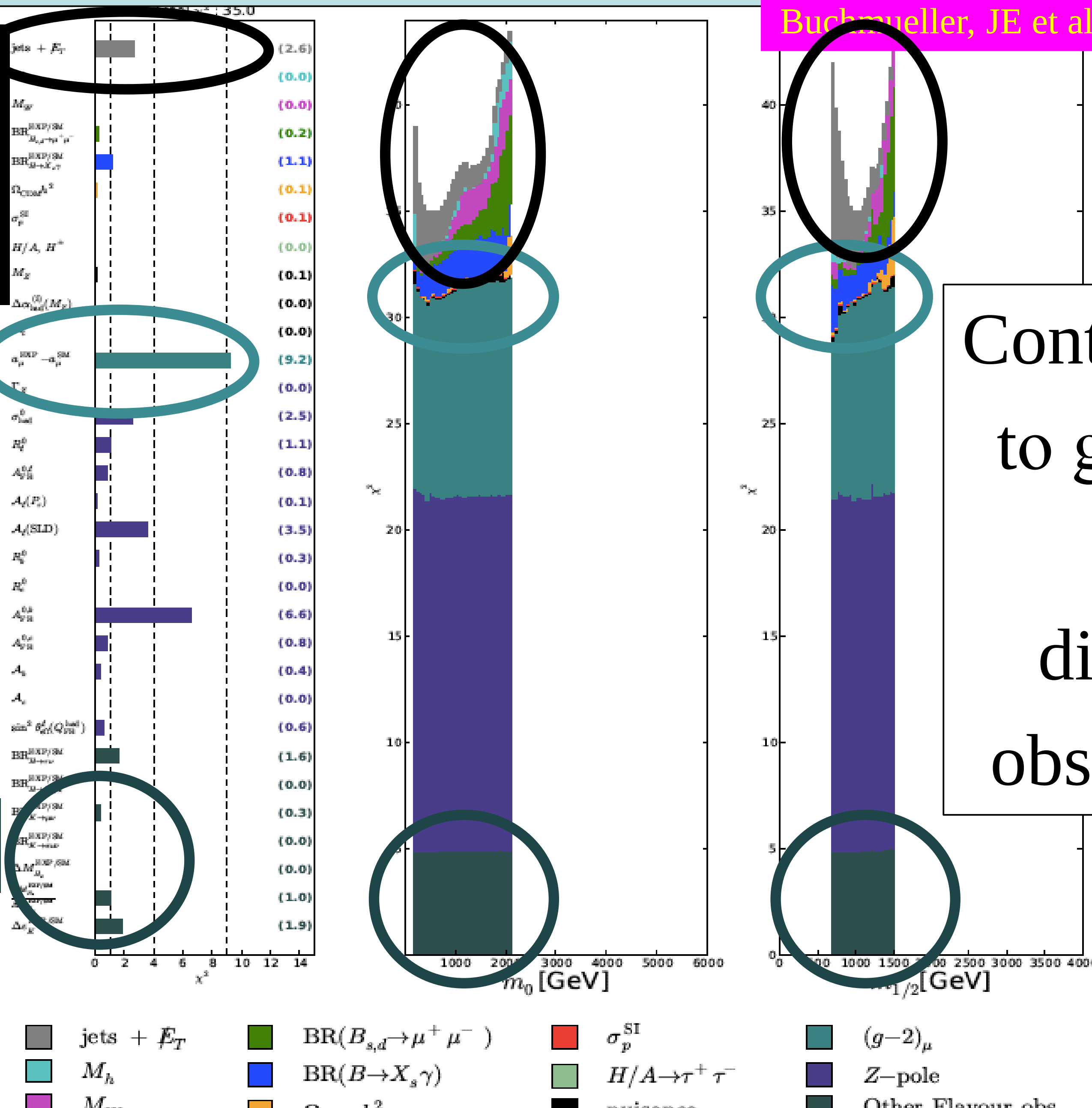
Constrained MSSM (CMSSM)

Buchmueller, JE et al: arXiv:1312.5250

LHC MET searches

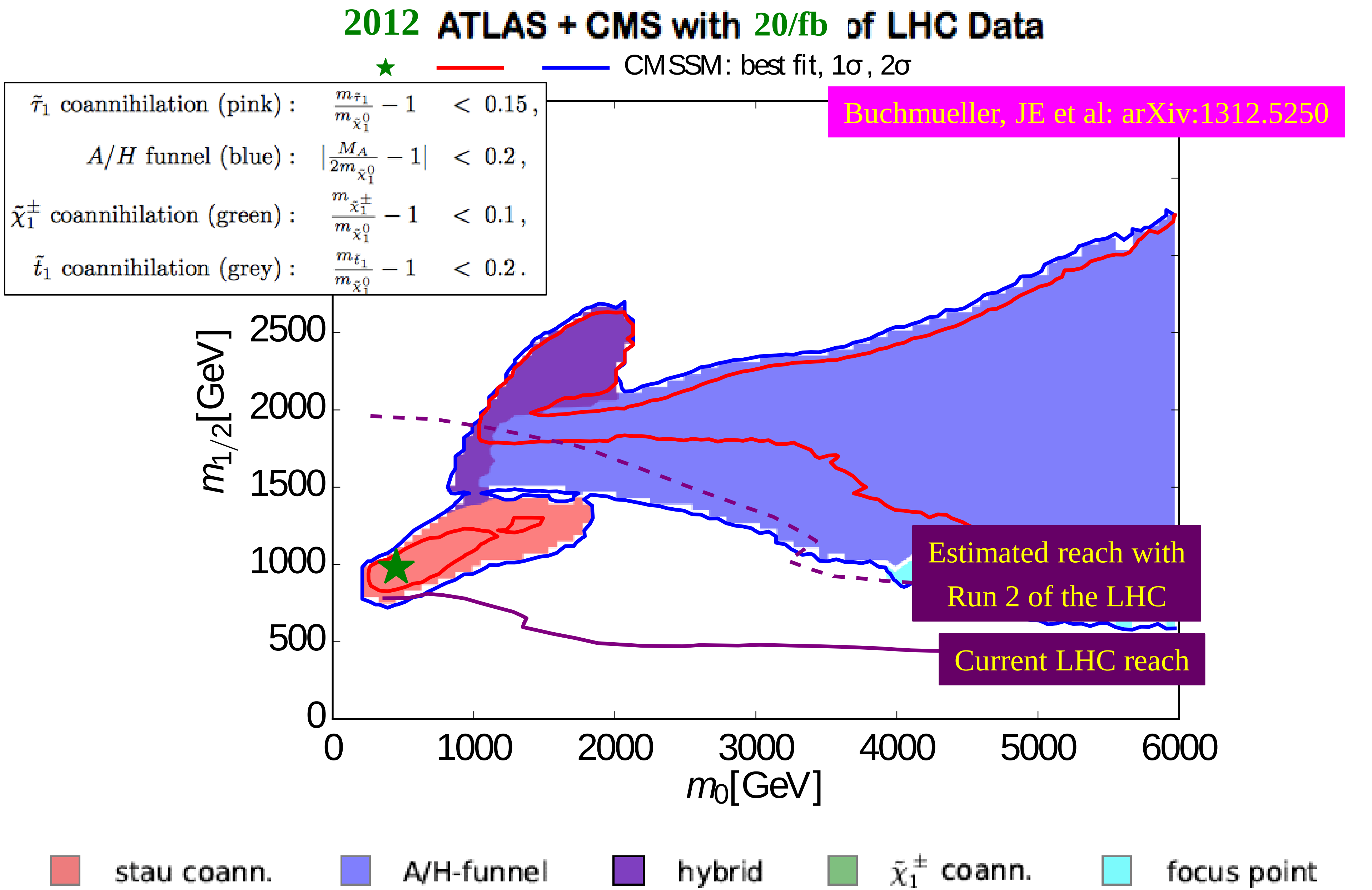
$g_\mu - 2$

Flavour

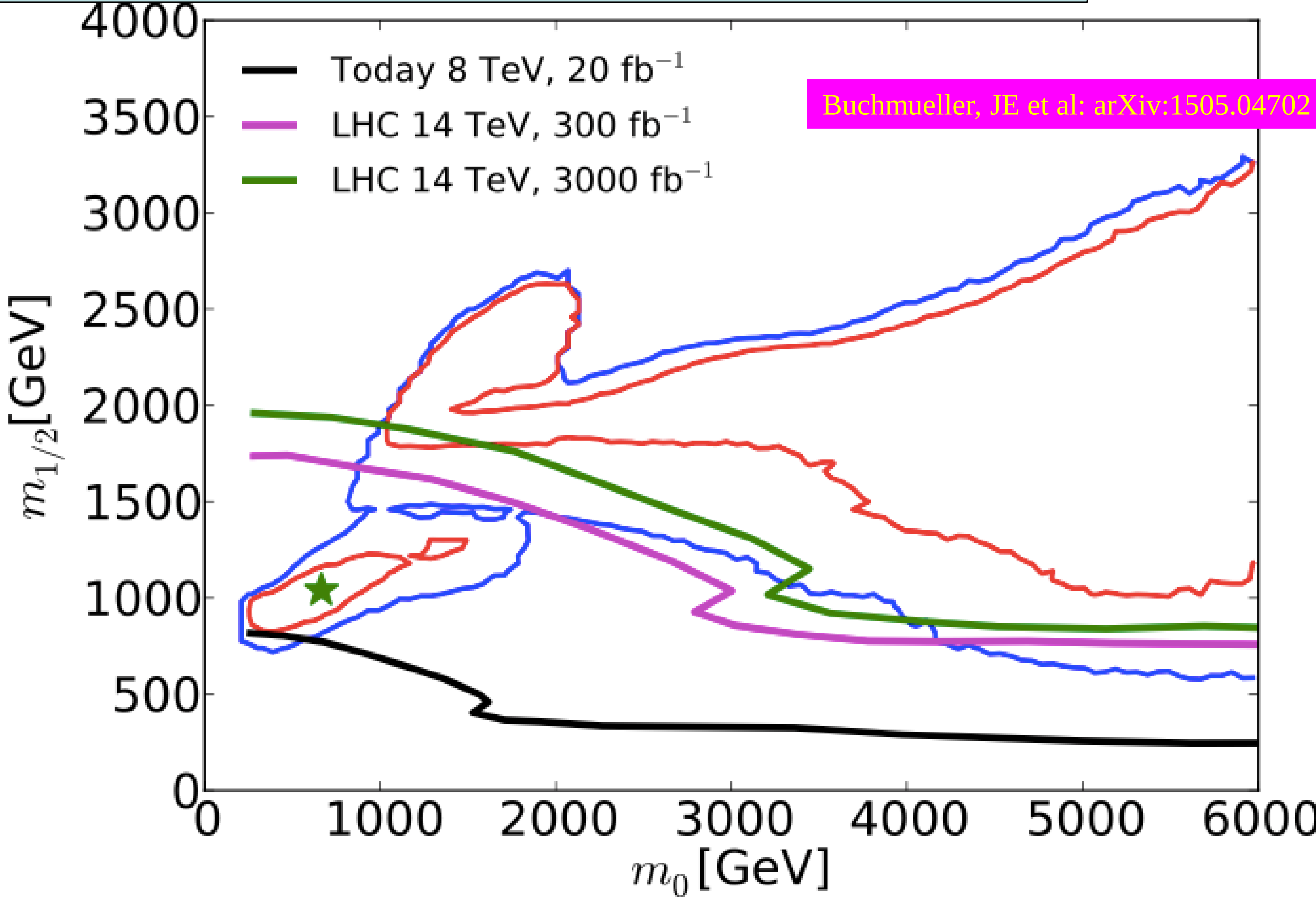


Contributions to global χ^2 from different observables

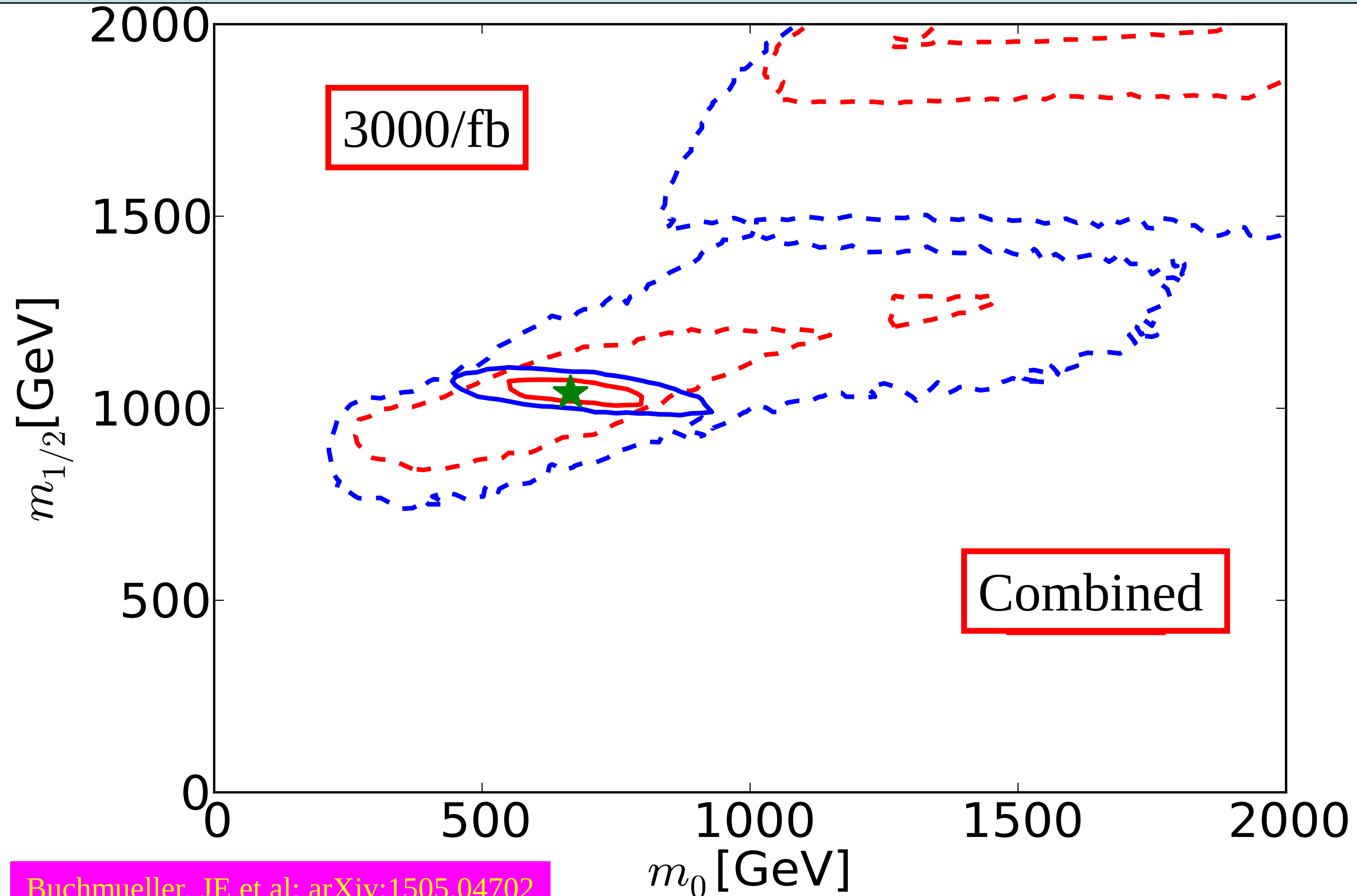
Dark Matter Density Mechanisms



Probing the CMSSM with the LHC

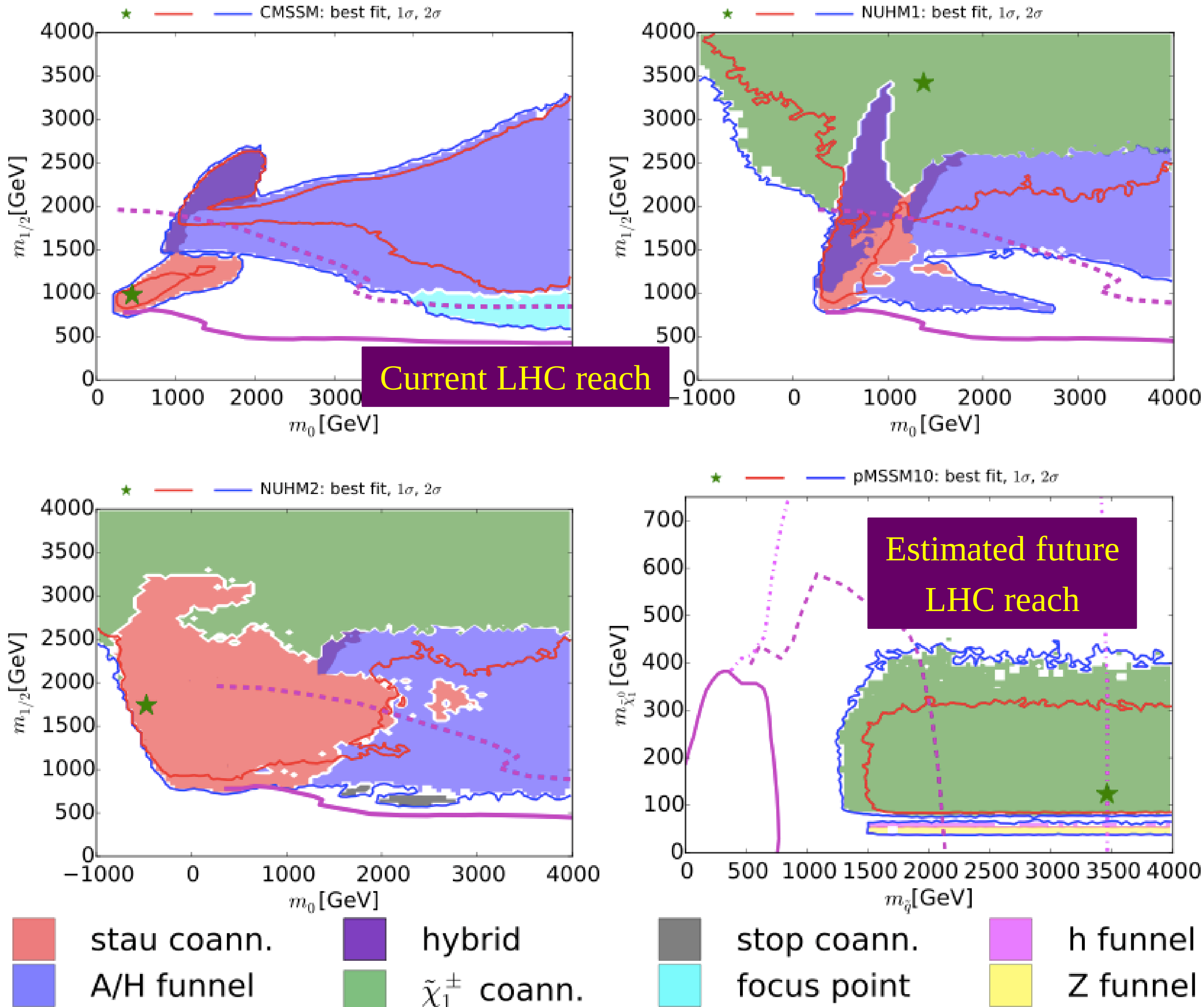


Measuring the CMSSM with the LHC



Buchmueller, JE et al: arXiv:1505.04702

Dark Matter in CMSSM, NUHM1/2, pMSSM10



Bagnaschi, JE et al: arXiv:1508.01173

Phenomenological MSSM (pMSSM10)

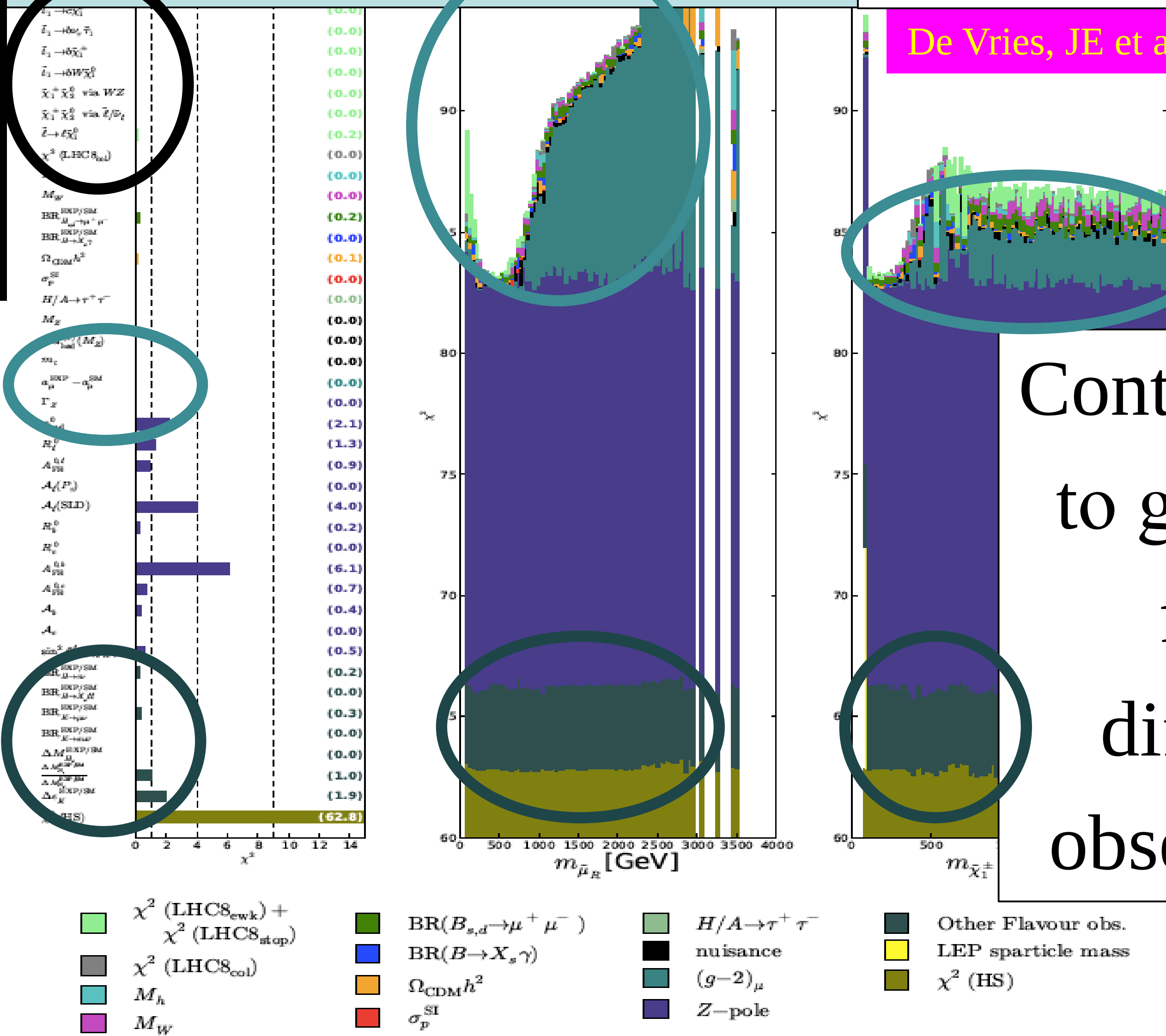
$$\begin{aligned}
\text{3 gaugino masses}: &\ M_{1,2,3}\,, \\
\text{2 squark masses}: &\ m_{\tilde q_1} = m_{\tilde q_2} \neq m_{\tilde q_3}\,, \\
\text{1 slepton mass}: &\ m_{\tilde \ell}\,, \\
\text{1 trilinear coupling}: &\ A\,, \\
\text{Higgs mixing parameter}: &\ \mu\,, \\
\text{Pseudoscalar Higgs mass}: &\ M_A\,, \\
\text{Ratio of vevs}: &\ \tan\beta\,.
\end{aligned}$$

De Vries, JE et al: arXiv:1504.03260

LHC MET searches

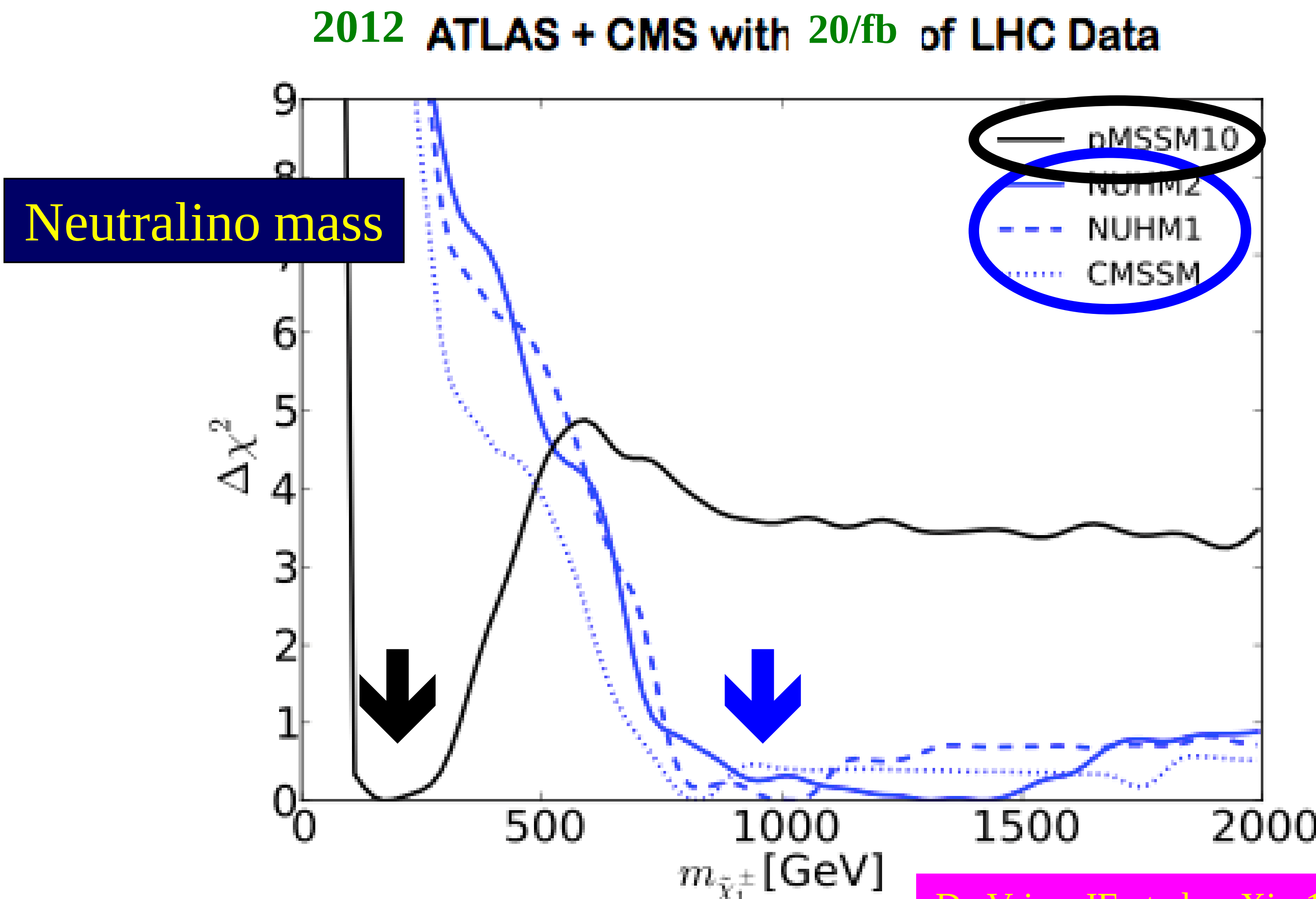
g_μ - 2

Flavour



Contributions to global χ^2 from different observables

Possible Dark Matter Particle Mass



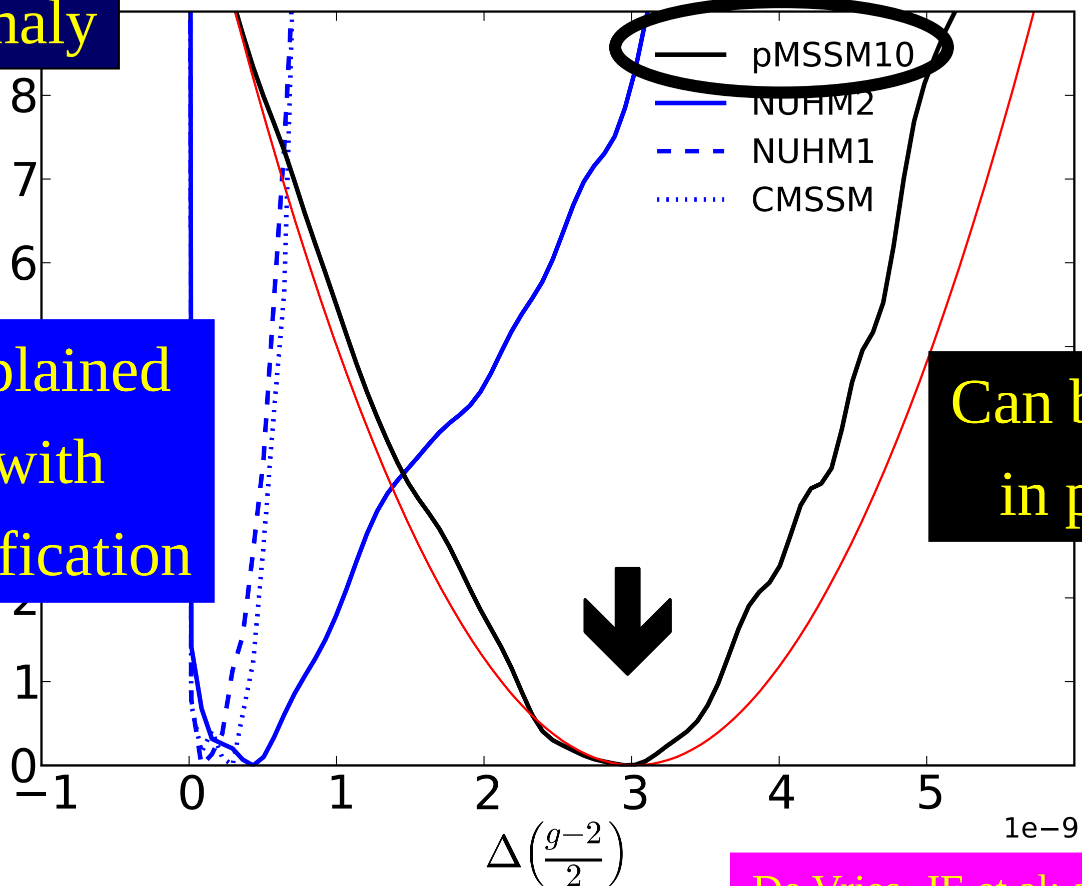
De Vries, JE et al: arXiv:1504.03260

pMSSM10 favours smaller masses than in models with GUT-scale unification

Anomalous Magnetic Moment of Muon

2012 ATLAS + CMS with 20/fb of LHC Data

$g_\mu - 2$ anomaly



Cannot be explained by models with GUT-scale unification

Can be explained in pMSSM10

1

De Vries, JE et al: arXiv:1504.03260

pMSSM10 can explain experimental measurements of g_μ - 2

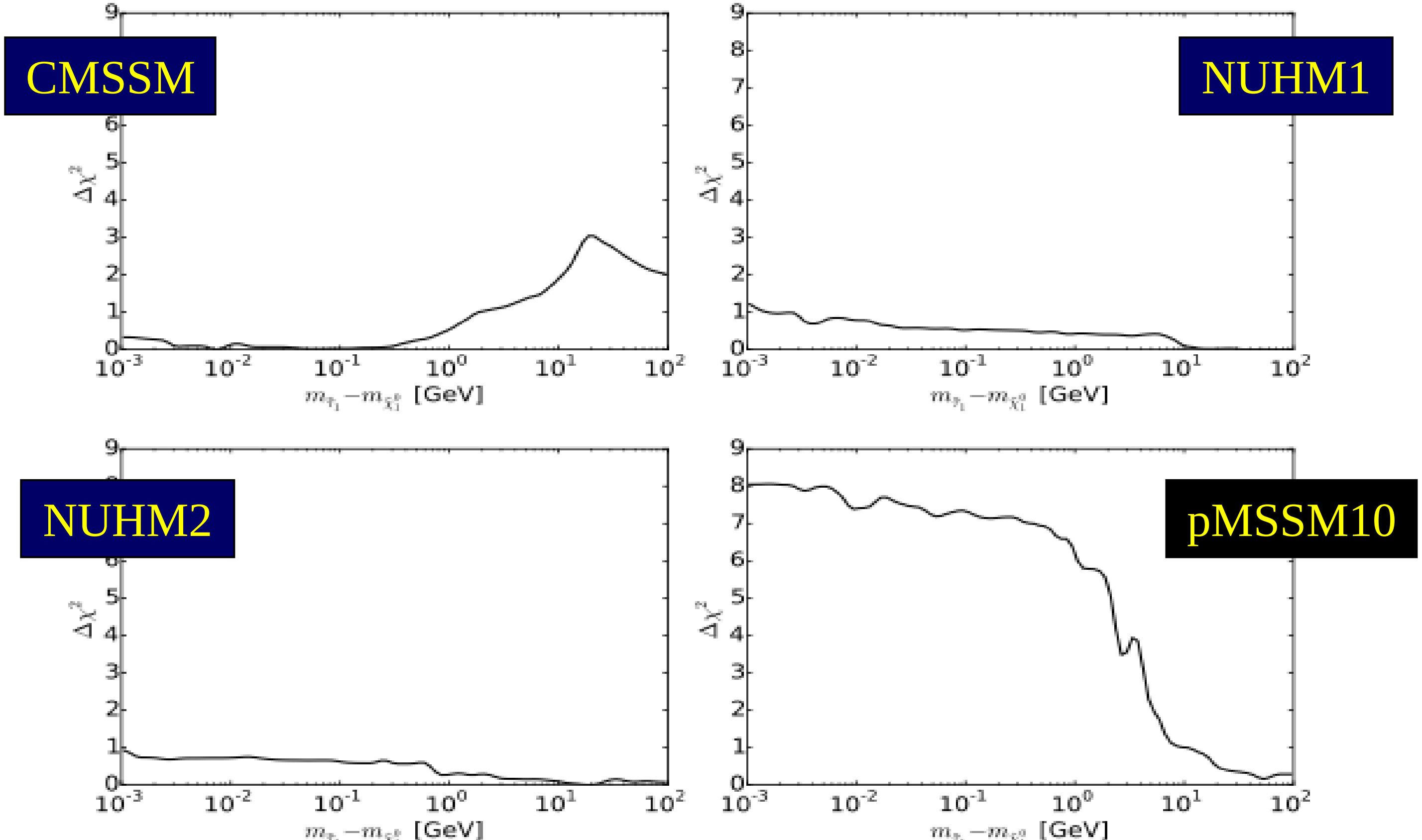
Long-Lived Stau in CMSSM, NUHM?

Possible if $m_{stau} - m_{LSP} < m_{\tau}$

Generic possibility in CMSSM, NUHM1, NUHM2

(stau coannihilation region)

Bagnaschi, JE et al: arXiv:1508. 01173



$\tau_{stau} > 10^3$ s gives problems with nucleosynthesis

$\tau_{stau} > 10^{-7}$ s gives separated vertex signature

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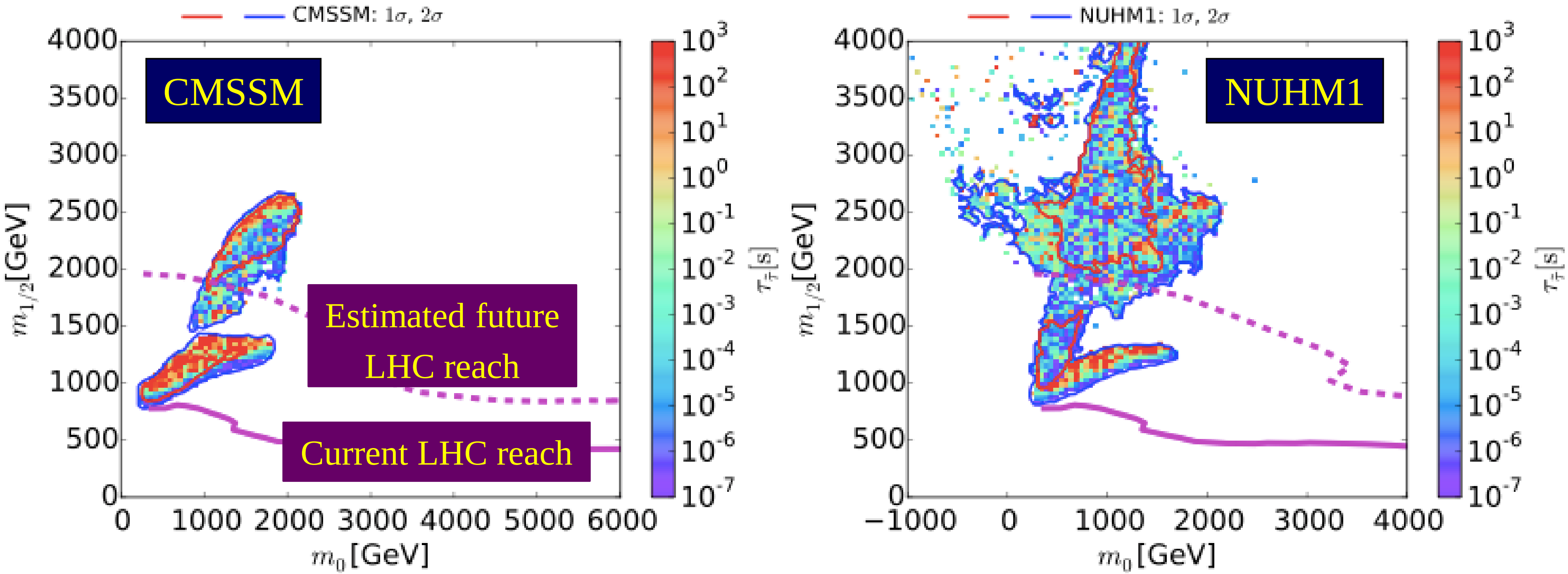


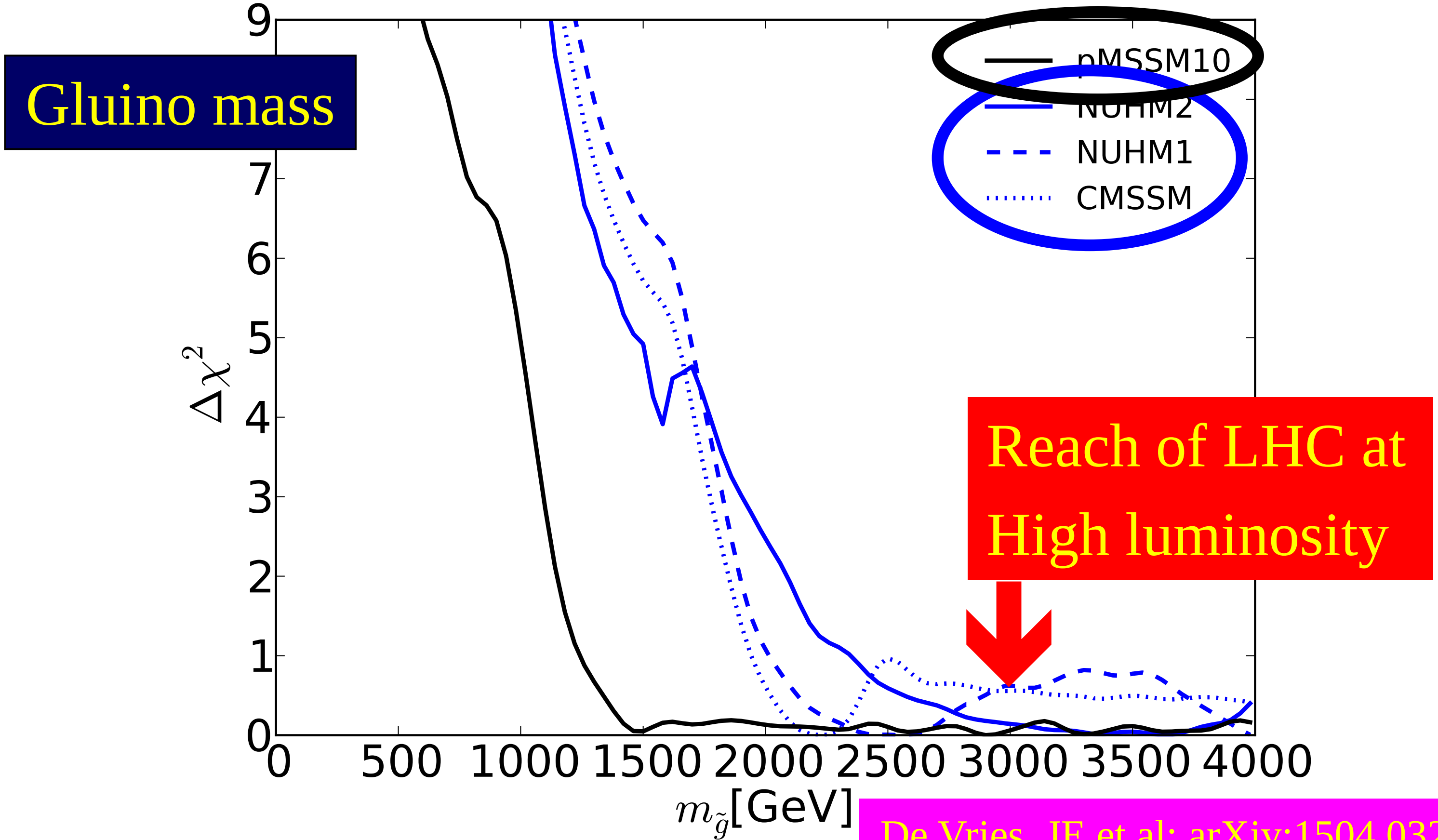
$\tau_{stau} > 10^3$ s gives problems with nucleosynthesis

$\tau_{stau} > 10^{-7}$ s gives separated vertex signature **for τ-like decays**

Bagnaschi, JE et al: arXiv:1508. 01173

Fits to Supersymmetric Models

2012 ATLAS + CMS with 20/fb of LHC Data

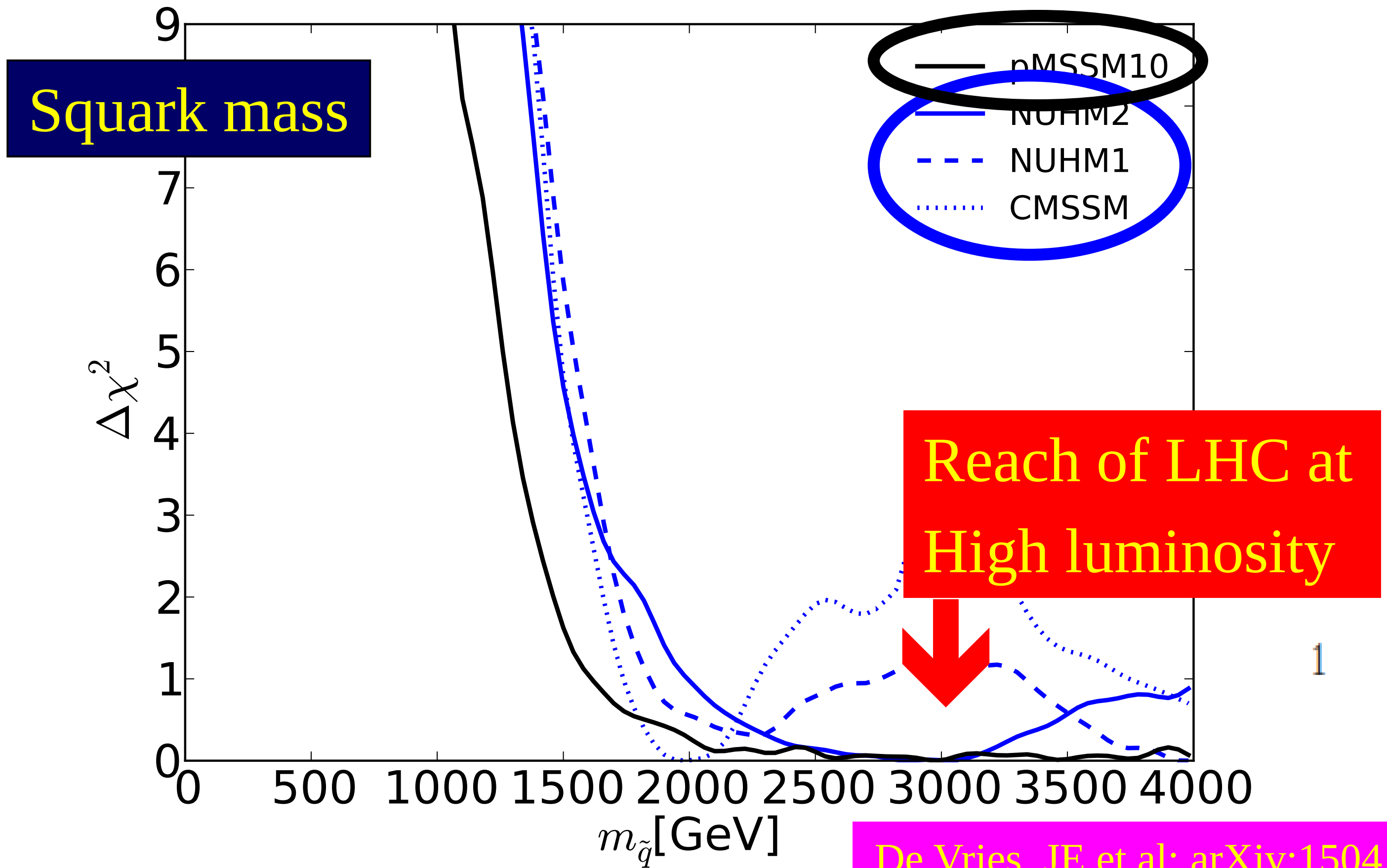


De Vries, JE et al: arXiv:1504.03260

Favoured values of gluino mass also significantly above pre-LHC, > 1.2 TeV

Fits to Supersymmetric Models

2012 ATLAS + CMS with 20/fb of LHC Data



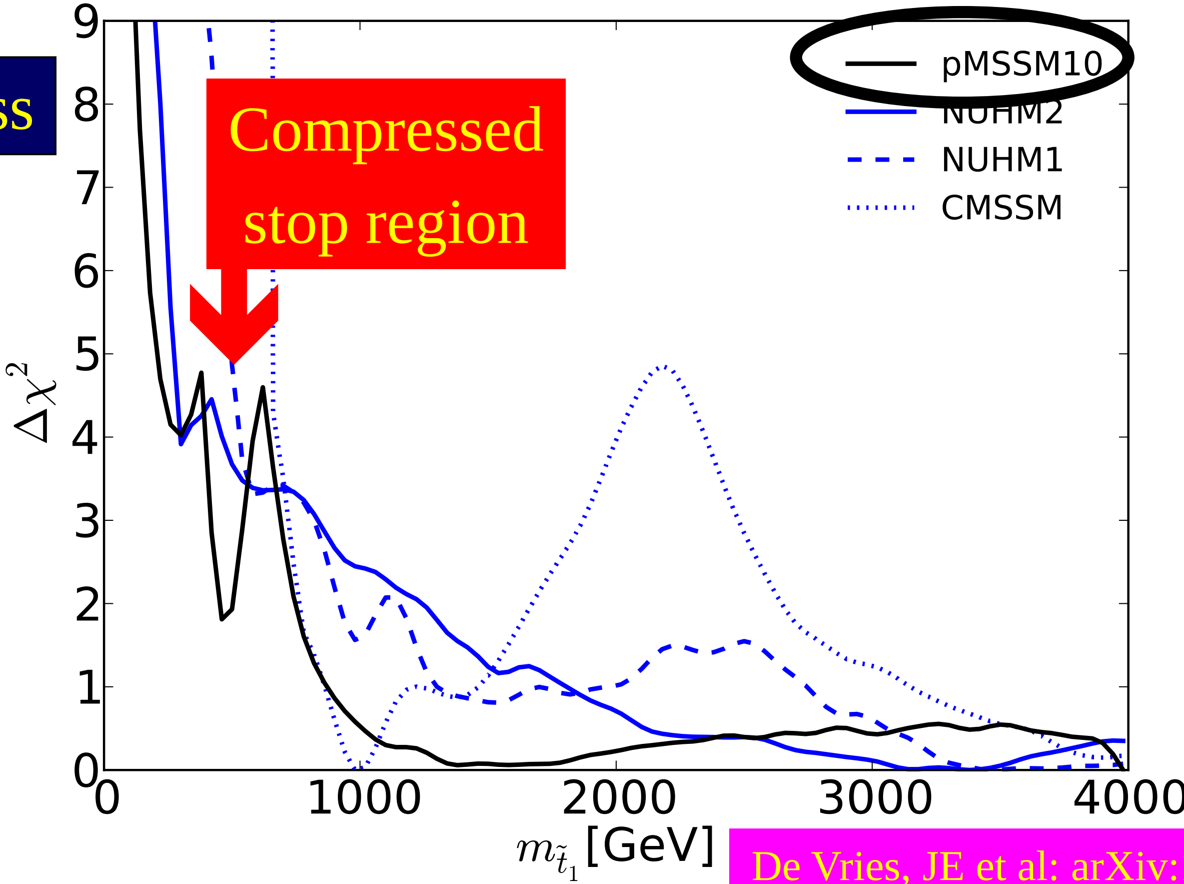
De Vries, JE et al: arXiv:1504.03260

Favoured values of squark mass significantly above pre-LHC, ~ 1.5 TeV or more

Fits to Supersymmetric Models

2012 ATLAS + CMS with 20/fb of LHC Data

Stop mass



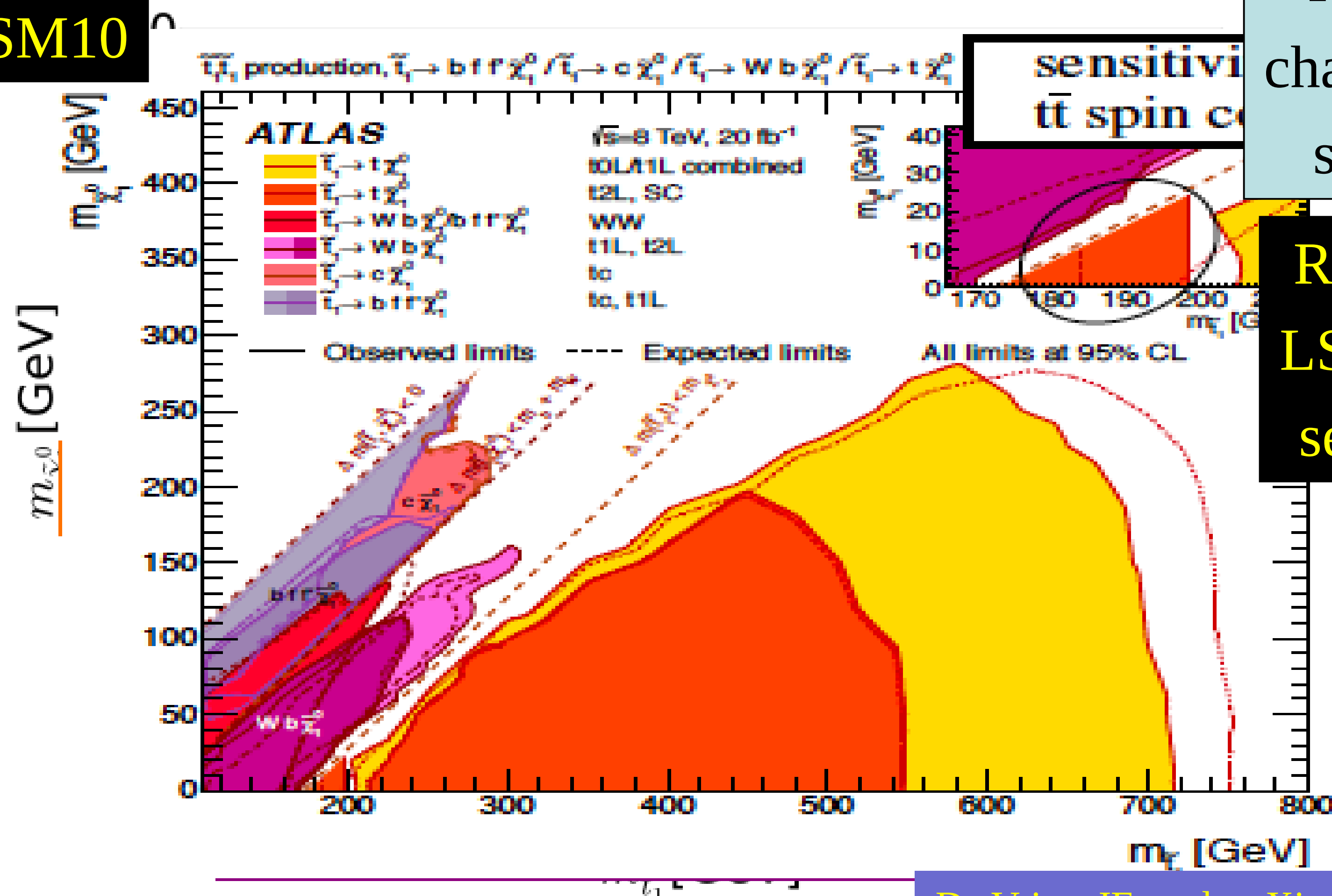
De Vries, JE et al: arXiv:1504.03260

Remaining possibility of a light "natural" stop weighing ~ 400 GeV

Exploring Light Stops @ Run 2

pMSSM10

2012 ATLAS + CMS with 20/fb of LHC Data



Reach of chargino + b searches

Reach of LSP + top searches

De Vries, JE et al: arXiv:1504.03260

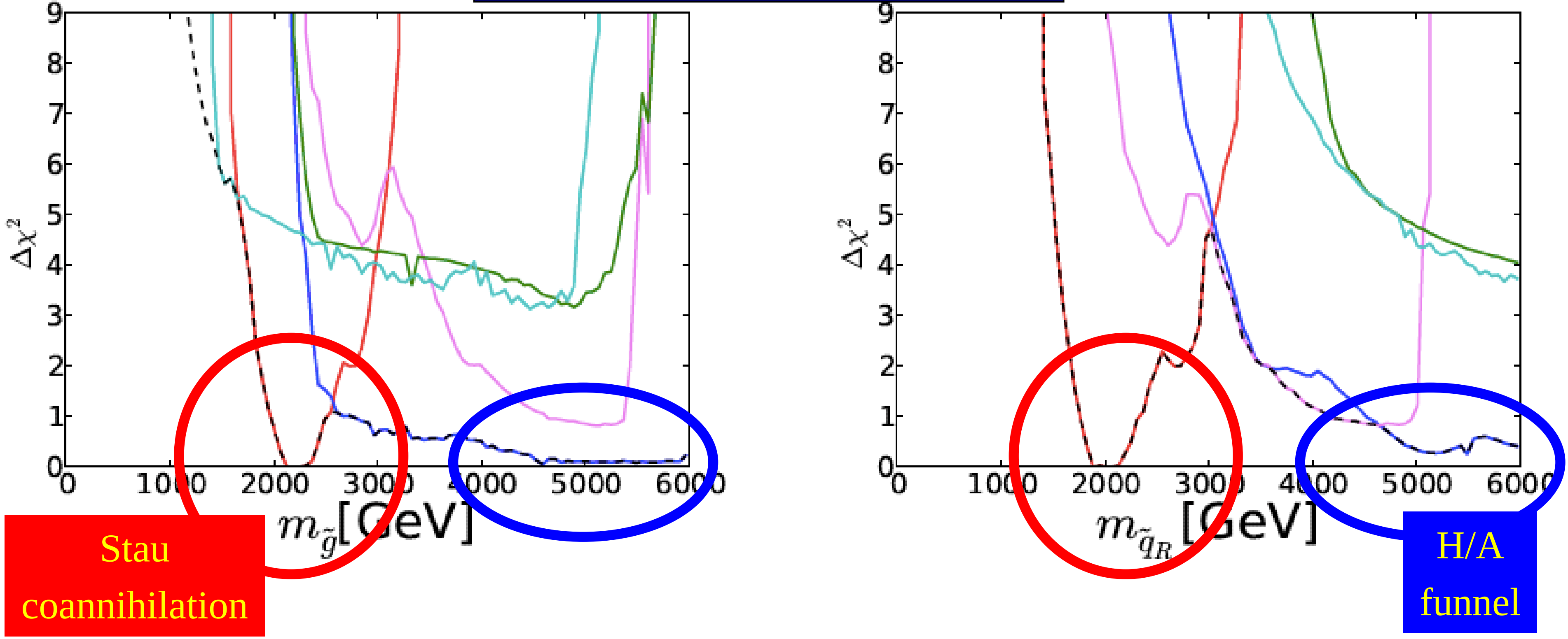
Part of region of light "natural" stop weighing ~ 400 GeV can be covered

Fits to Supersymmetric Models

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

Buchmueller, JE et al: arXiv:1312.5250

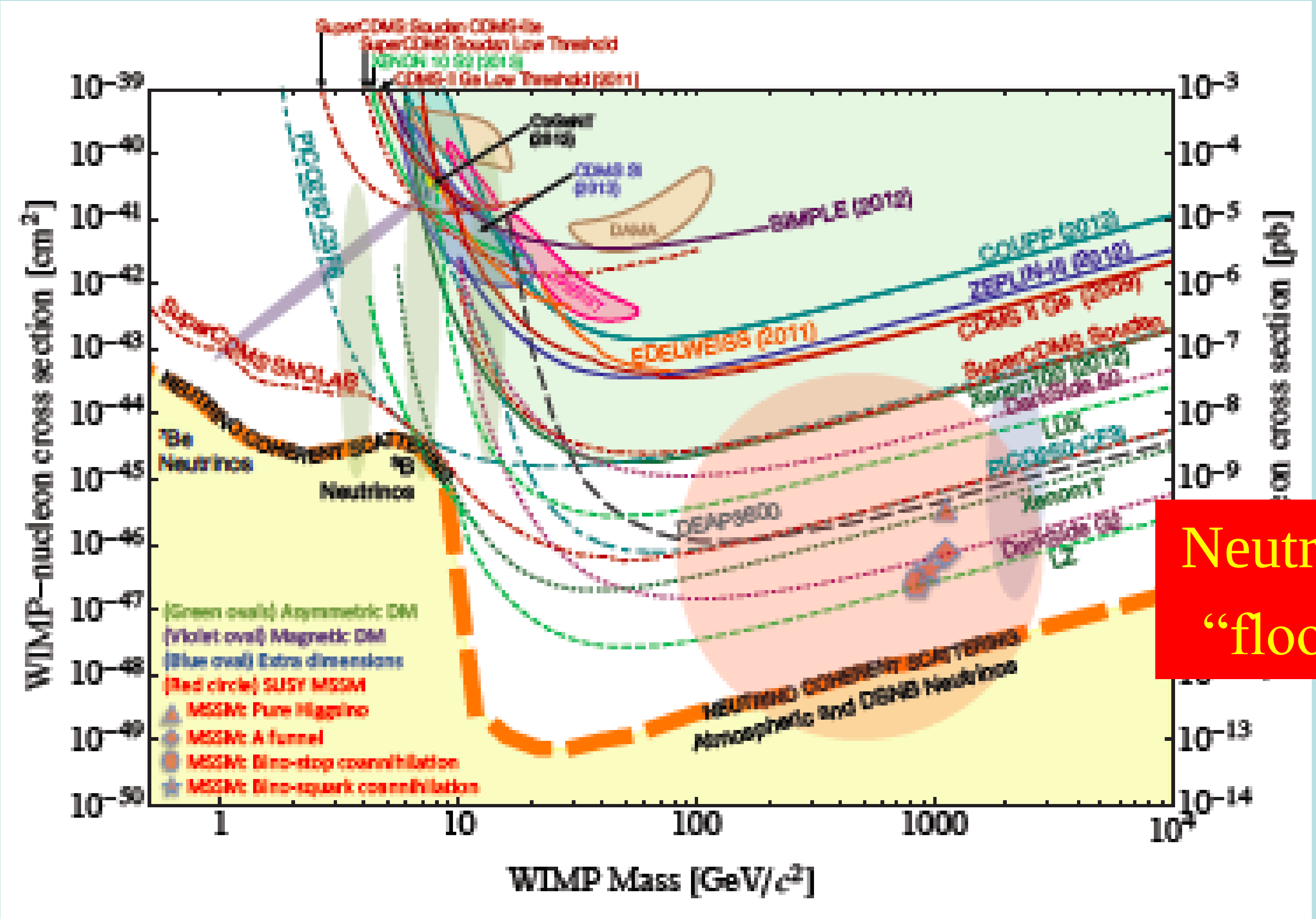
Gluino and squark masses



Favoured values of gluino and squark masses significantly above pre-LHC, ~ 2 TeV or more

Direct Dark Matter Searches

- Compilation of present and future sensitivities



Neutrino "floor"

Direct Dark Matter Search

Spin-independent dark matter scattering

CMSSM

NUHM1

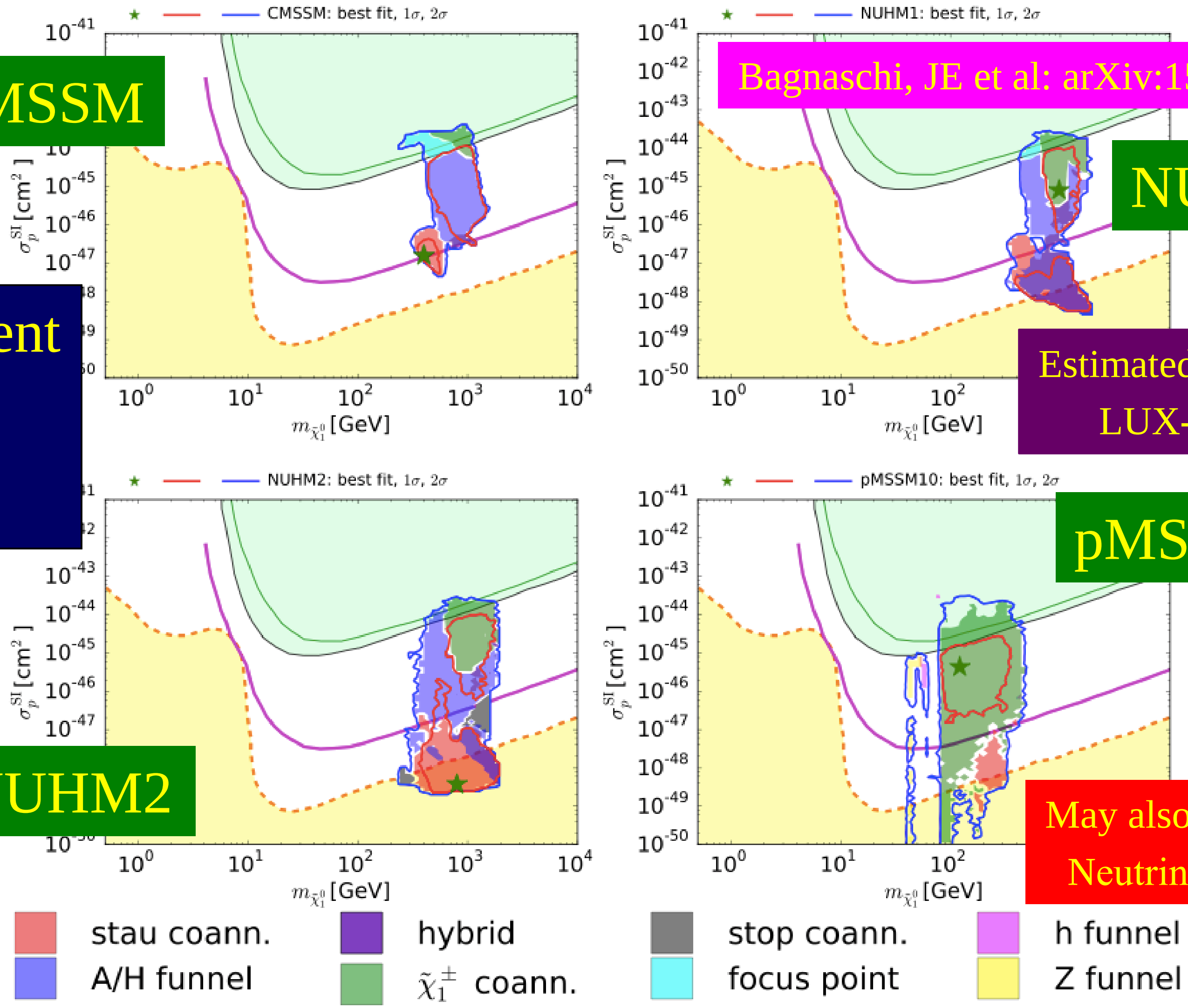
NUHM2

pMSSM10

Bagnaschi, JE et al: arXiv:1508. 01173

Estimated reach with LUX-Zepelin

May also be below Neutrino ‘floor’



Direct scattering cross-section may be very close to LUX upper limit, accessible to LZ experiment

Prospects for SUSY Searches

- Different models, various dark matter mechanisms

DM mechanism	Exp't	Models: CMSSM	NUHM1	NUHM2	pMSSM10
$\tilde{\tau}_1$ coann.	LHC	✓ $\not\!\!E_T$, ✓ LL	(✓ $\not\!\!E_T$, ✓ LL)	(✓ $\not\!\!E_T$, ✓ LL)	(✓ $\not\!\!E_T$), × LL
	DM	(✓)	(✓)	×	×
$\tilde{\chi}_1^{\pm}$ coann.	LHC	–	×	×	(✓ $\not\!\!E_T$)
	DM	–	✓	✓	(✓)
$\tilde{t}_1$ coann.	LHC	–	–	✓ $\not\!\!E_T$	–
	DM	–	–	×	–
A/H funnel	LHC	✓ A/H	(✓ A/H)	(✓ A/H)	–
	DM	✓	✓	(✓)	–
Focus point	LHC	(✓ $\not\!\!E_T$)	–	–	–
	DM	✓	–	–	–
h, Z funnels	LHC	–	–	–	(✓ $\not\!\!E_T$)
	DM	–	–	–	(✓)

- No guarantees, but good prospects

Bagnaschi, JE et al: arXiv:1508. 01173