Outlook for Supersymmetry

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CoEPP Tropical Conference, Cairns

July 4th 2012 The Higgs discovery

The Particle Higgsaw Puzzle

Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

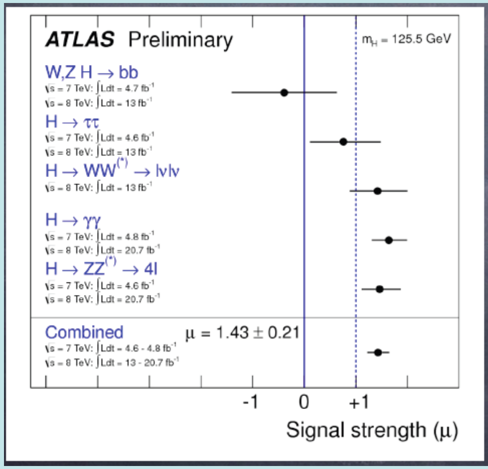
From Discovery to Measurement

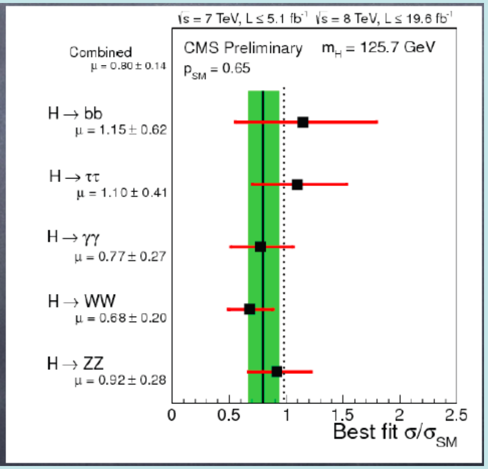
- Mass measurements:

  125.6 ± 0.3 GeV

- Signal strengths ~ SM

  in many channels



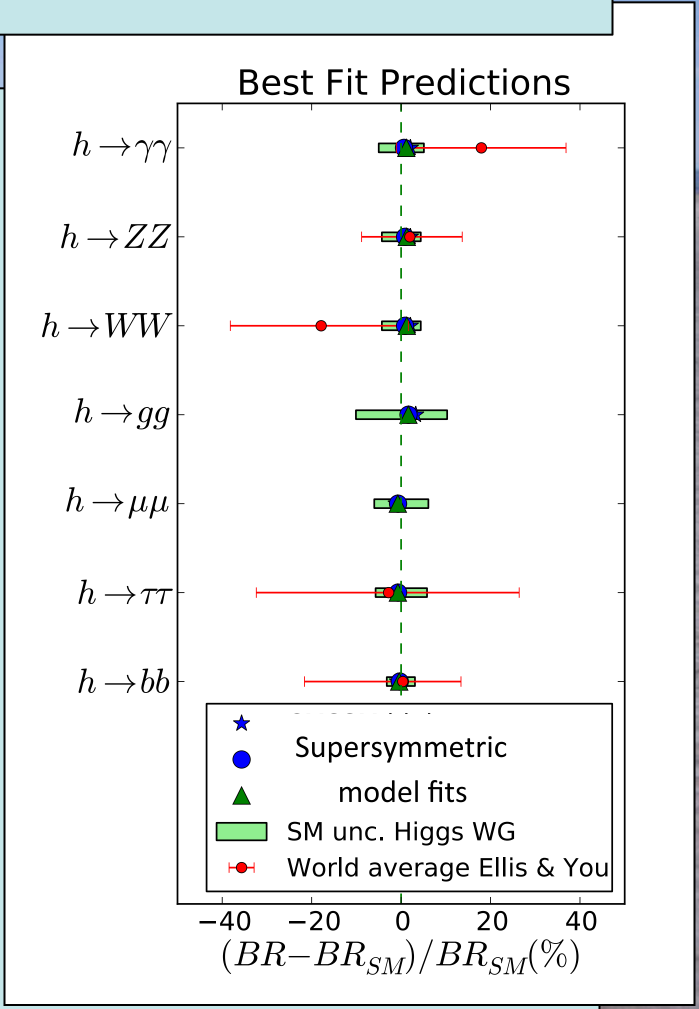


- Frontiers:
  - VBF significance >2σ in several channels, 3σ combined
  - Decay to ττ emerging, limits on μμ (μτ, eτ)
  - Decay to bbbar emerging (CMS, Tevatron)
  - Indirect evidence for ttbar coupling

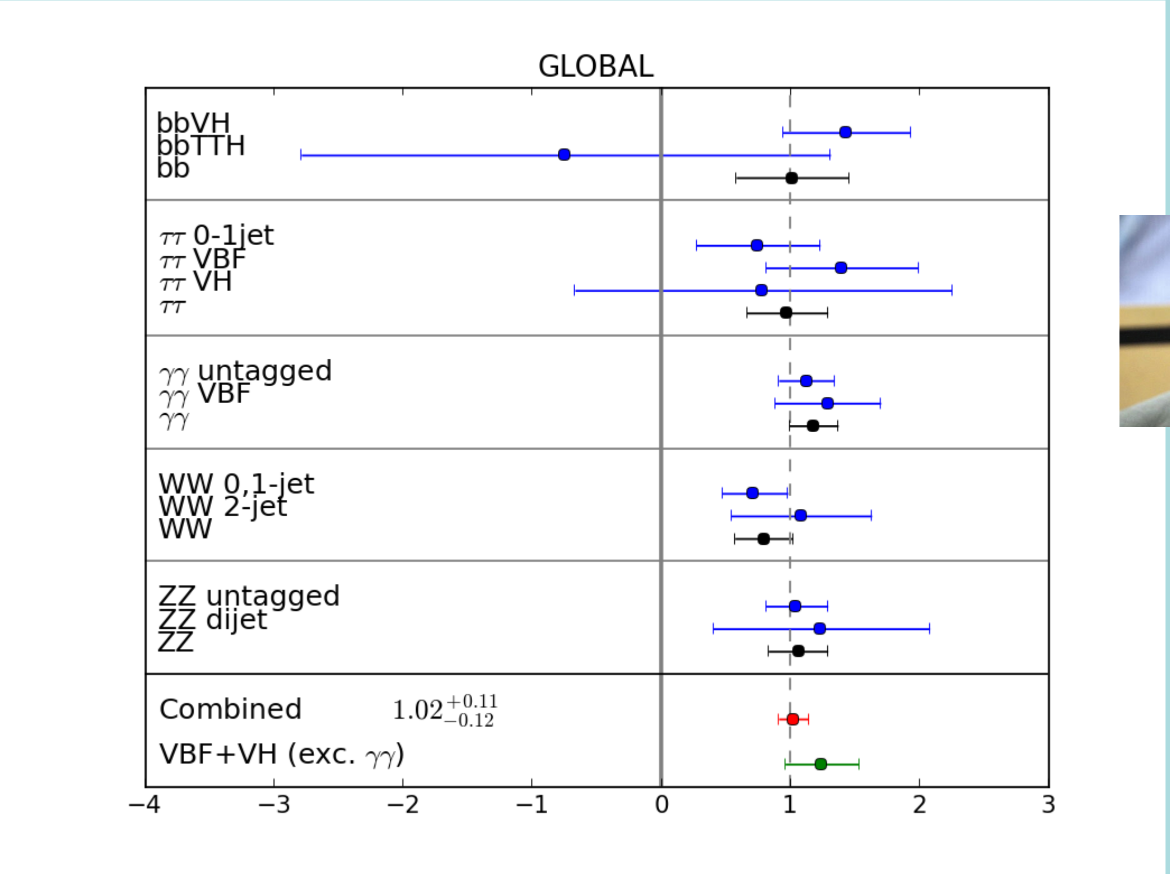
    (search for ttbar + H/W, Zγ)

Some Questions

- What is it?
  - –Higgs or …?
- What else is there?
  - –Supersymmetry …?
- What next?
  - –A Higgs factory or …?



Couplings resemble Higgs of Standard Model



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

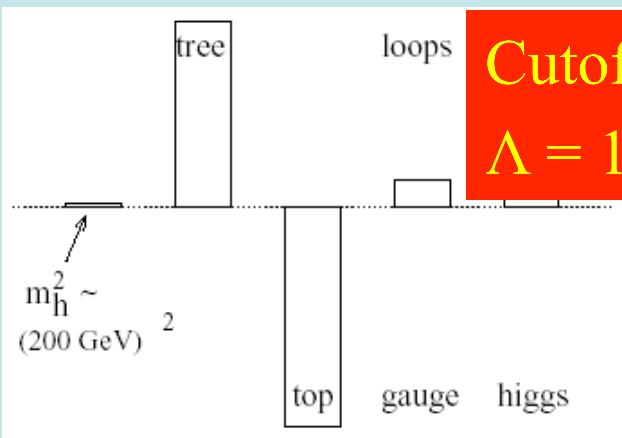
JE & Tevong You, arXiv:1303.3879

Elementary Higgs or Composite?

- Higgs field:

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

- Quantum loop problems



Cutoff

Λ = 10 TeV

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

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

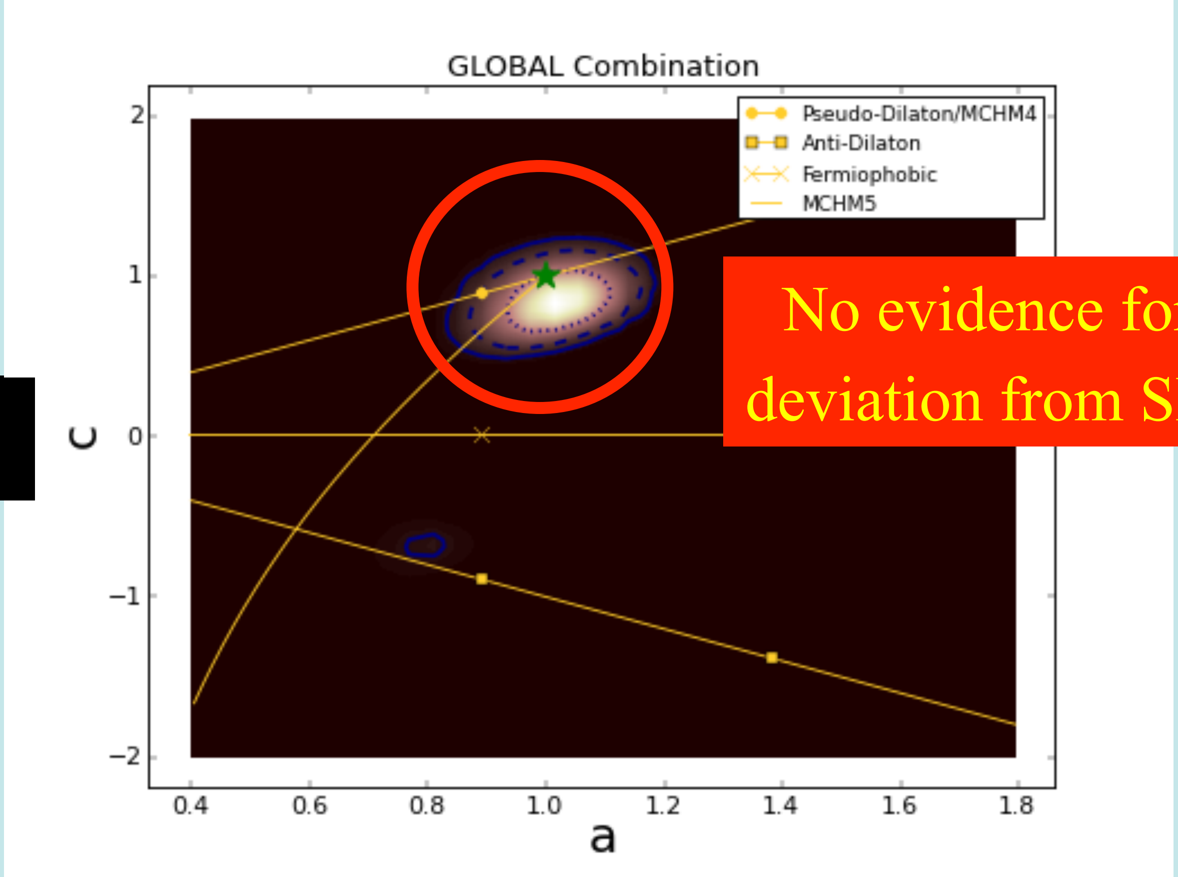
New technicolour force?

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

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: $a = c = 1$

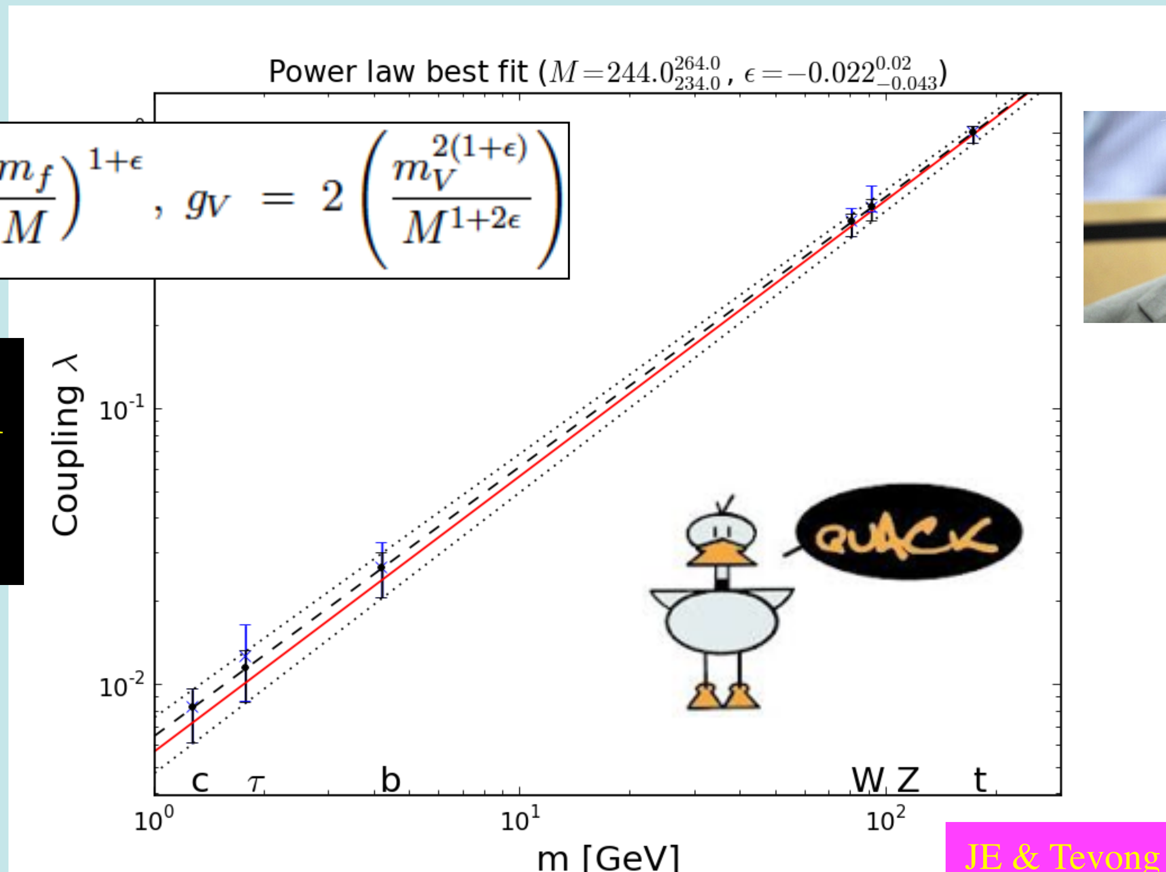
JE & Tevong You, arXiv:1303.3879

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

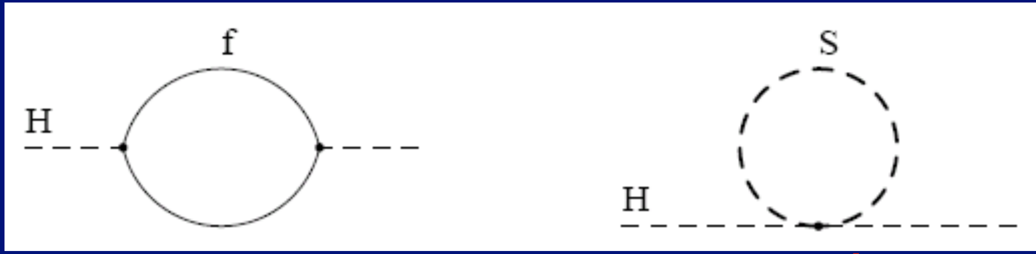
What else is there?

Supersymmetry

- Successful prediction for Higgs mass
  - Should be < 130 GeV in simple models
- Successful predictions for Higgs couplings
  - Should be within few % of SM values
- Could explain the dark matter
- Naturalness, GUTs, string, … (???)

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



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

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

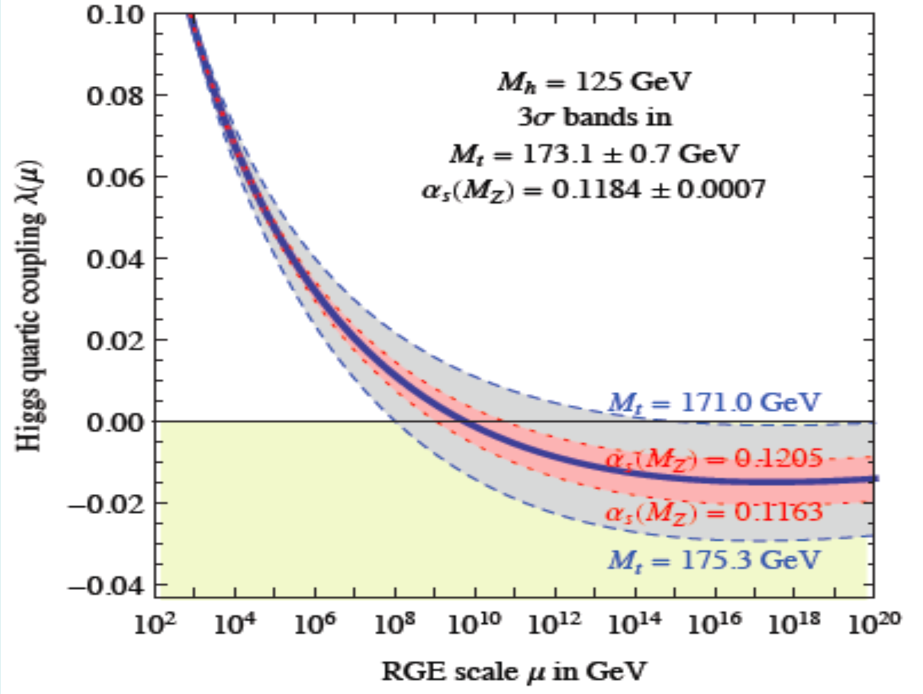
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + \ldots]$$

- Leading divergence cancelled if

$\lambda_S = y_f^2$ x 2 **Supersymmetry!**

Theoretical Constraints on Higgs Mass

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

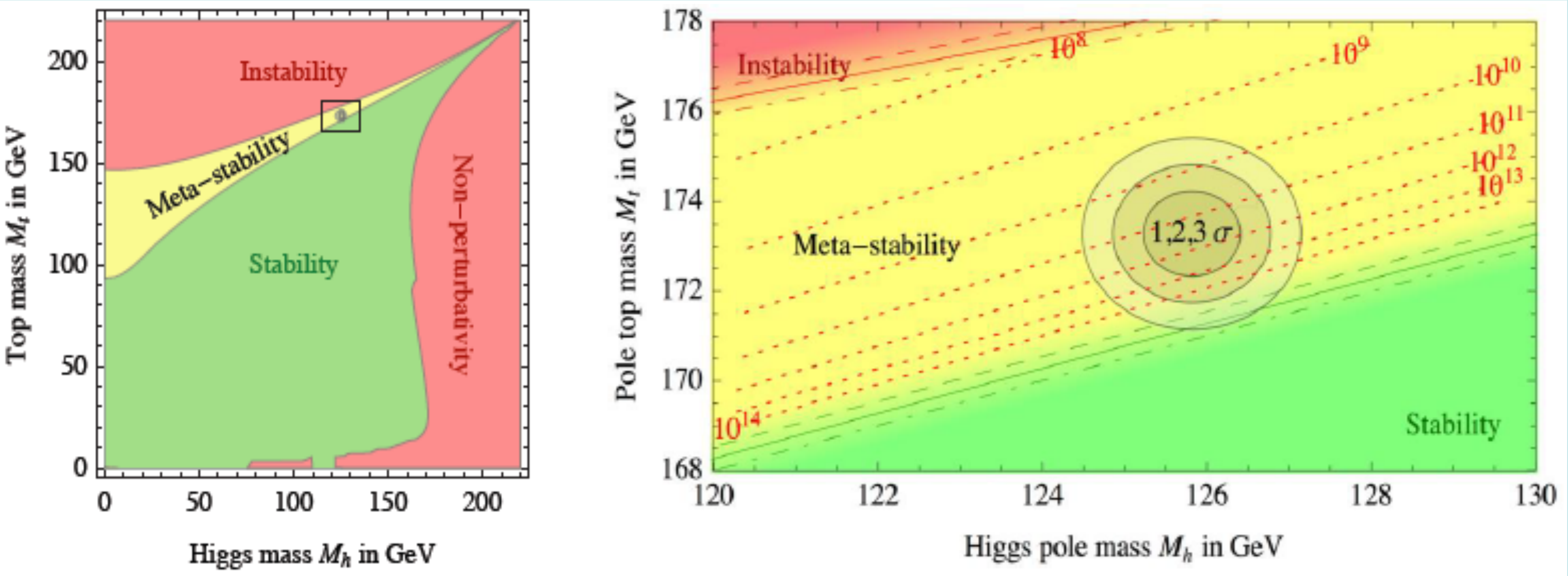


- Vacuum could be stabilized by **Supersymmetry**

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

Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H



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

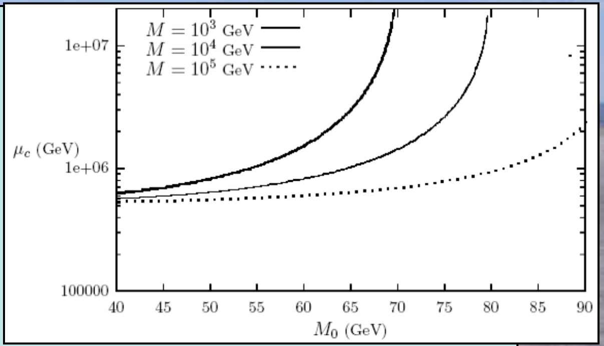
Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

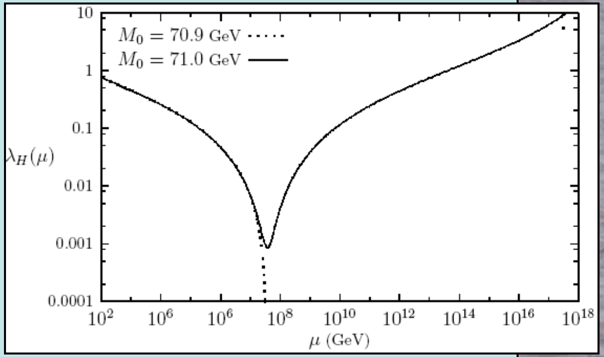
How to Stabilize a Light Higgs Boson?

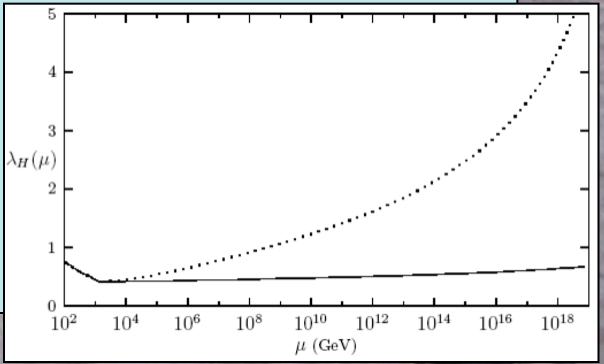
- Top quark destabilizes potential: introduce stop-like scalar:

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

- 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

If you have a Problem …

- … postulate a new particle:
  - QM and Special Relativity: Antimatter
  - Nuclear spectra: Neutron
  - Continuous spectrum in β decay: Neutrino
  - Nucleon-nucleon interactions: Pion
  - Absence of lepton number violation: Second neutrino
  - Flavour SU(3): Ω^-
  - Flavour SU(3): Quarks
  - FCNC: Charm
  - CP violation: Third generation
  - Strong dynamics: Gluons
  - Weak interactions: $W^\pm$, Z^0
  - Renormalizability: H (48 years)
  - **Hierarchy: Supersymmetry?** **(40 years)**

Dark Matter in the Universe

Astronomers say that most of the matter in the Universe is invisible Dark Matter

Supersymmetric particles ?

We shall look for them with the LHC

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:

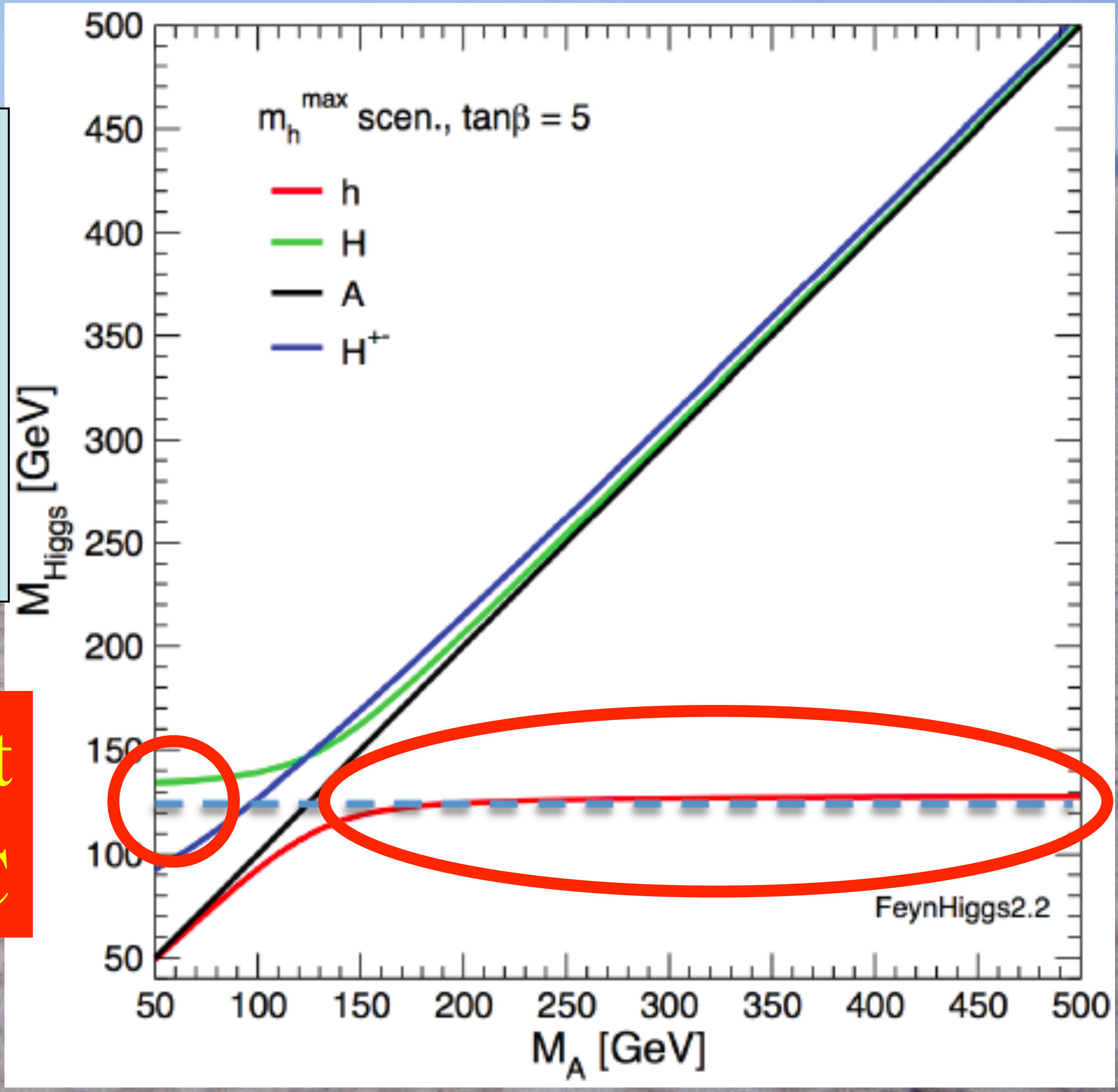
$$G_\mu m_{\mathrm{t}}^4 \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m_{\mathrm{t}}^2}\right) \quad \Delta M_H\big|_{TH} \sim 1.5\ \mathrm{GeV}$$

MSSM Higgs Masses & Couplings

Lightest Higgs mass up to ~ 130 GeV

Heavy Higgs masses bunch together

Consistent With LHC



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_b	[24] / [40]	0.21629 ± 0.00066
R_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
$\mathrm{BR}^{\rm EXP}_{K\to\mu\nu}/\mathrm{BR}^{\rm SM}_{K\to\mu\nu}$	[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]	$1.08 \pm 0.14_{\rm EXP+TH}$
$a^{\rm EXP}_\mu - a^{\rm SM}_\mu$	[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]
σ_p	[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

$M_H = 125.6 \pm 0.3 \pm 1.5$ GeV

MasterCode: O.Buchmueller, JE et al.

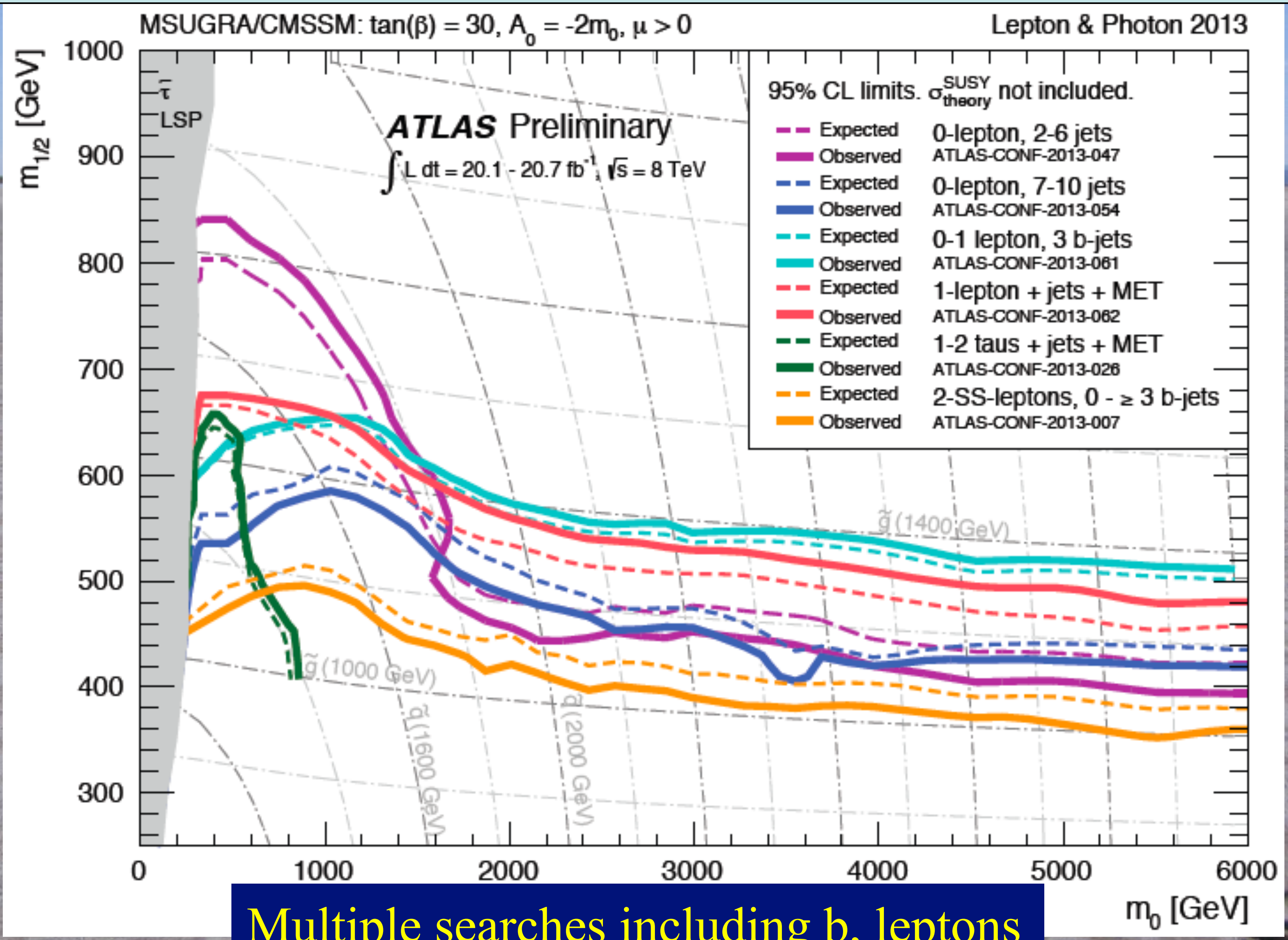
Minimal Supersymmetric Extension of Standard Model (MSSM)

- Particles + spartners

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

- 2 Higgs doublets, coupling μ, ratio of v.e.v.'s = $\tan \beta$
- Unknown supersymmetry-breaking parameters:
  - Scalar masses m_0, gaugino masses $m_{1/2}$,
  - trilinear soft couplings A_λ, bilinear soft coupling B_μ
- Often assume universality:
  - Single m_0, single $m_{1/2}$, single A_λ, B_μ: not string?
- Called constrained* MSSM = CMSSM (* at what scale?)
- Minimal supergravity (mSUGRA) predicts gravitino mass: $m_{3/2} = m_0$ and relation: $B_\mu = A_\lambda - m_0$

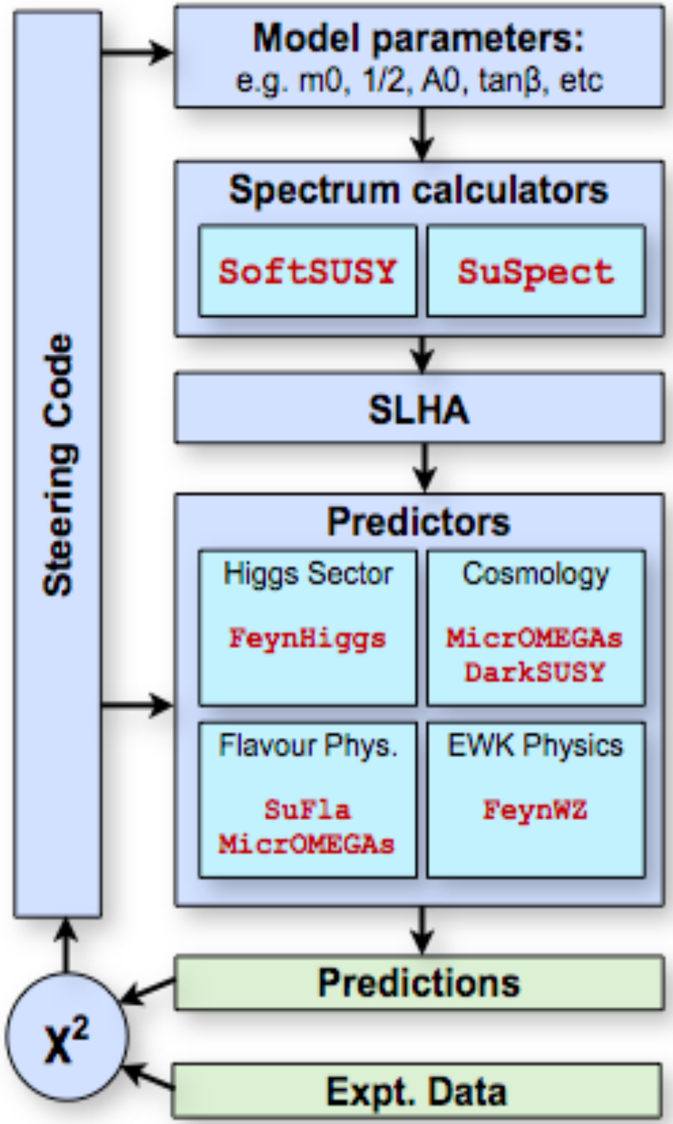
Searches with 8 TeV Data



Multiple searches including b, leptons

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

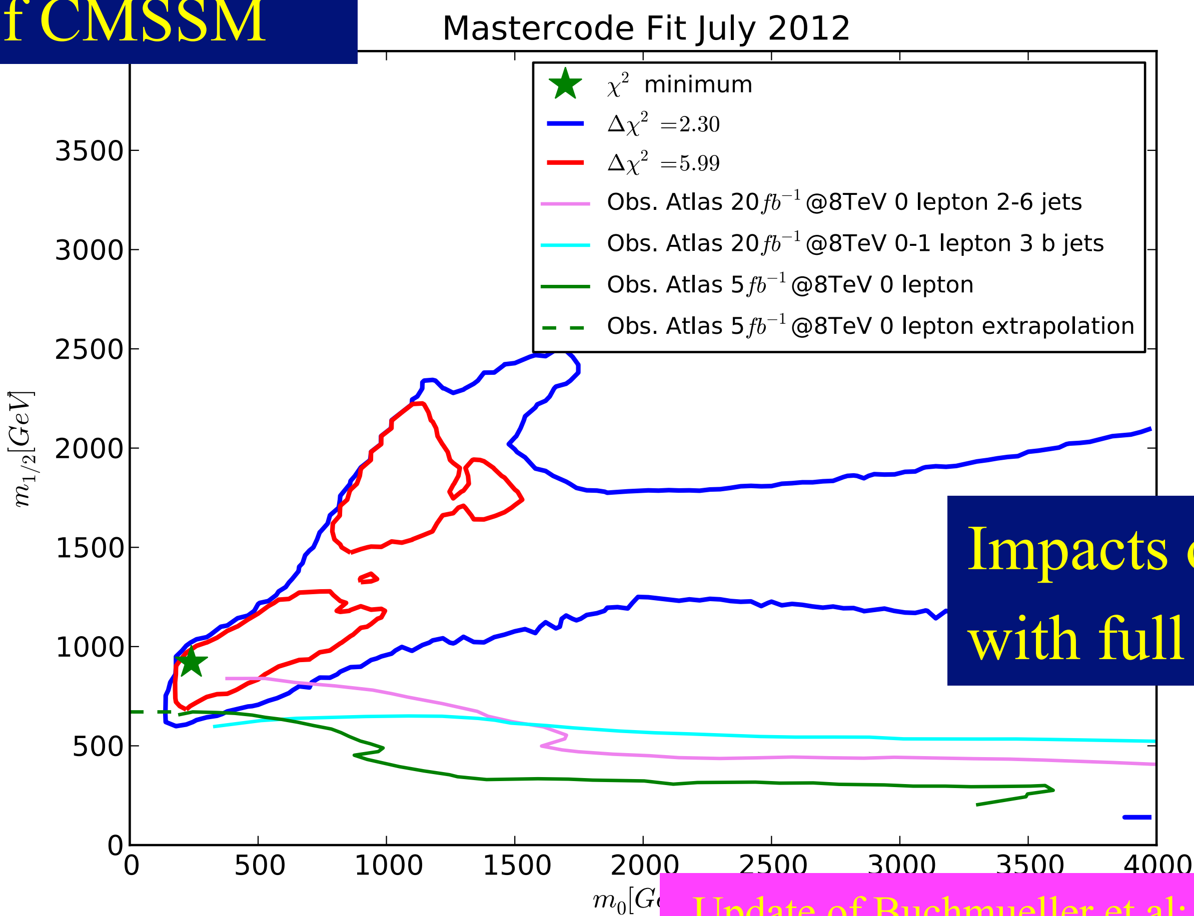


O. Buchmueller, R. Cavanaugh, *M. Citron*, A. De Roeck, M.J. Dolan, J.E., H. Flacher, S. Heinemeyer, G. Isidori, J. Marrouche, D. Martinez Santos, *S. Nakach*, K.A. Olive, *S. Rogerson*, F.J. Ronga, *K.J. de Vries*, G. Weiglein

Post-LHC, Post-XENON100

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

Scan of CMSSM



Impacts of searches with full 2012 data

Update of Buchmueller et al: arXiv:1207.3715

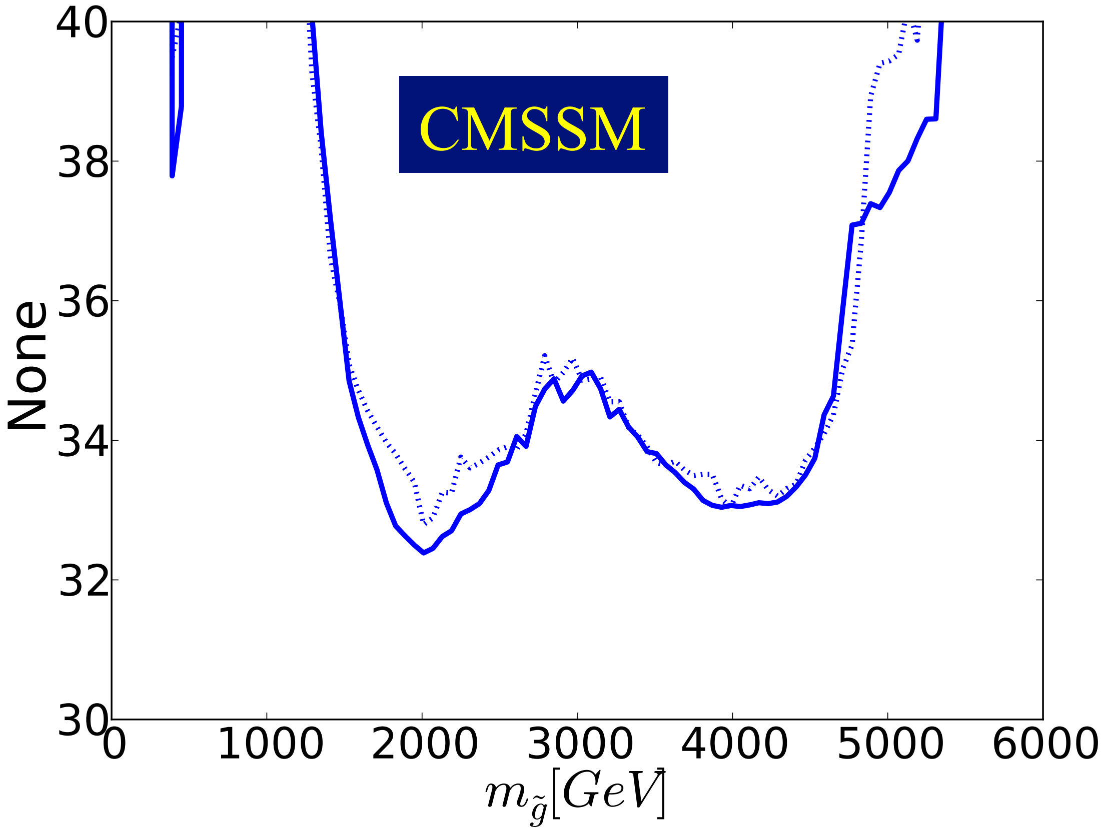
Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

p-value of simple models < 10%

Post-LHC, Post-XENON100

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

Gluino mass

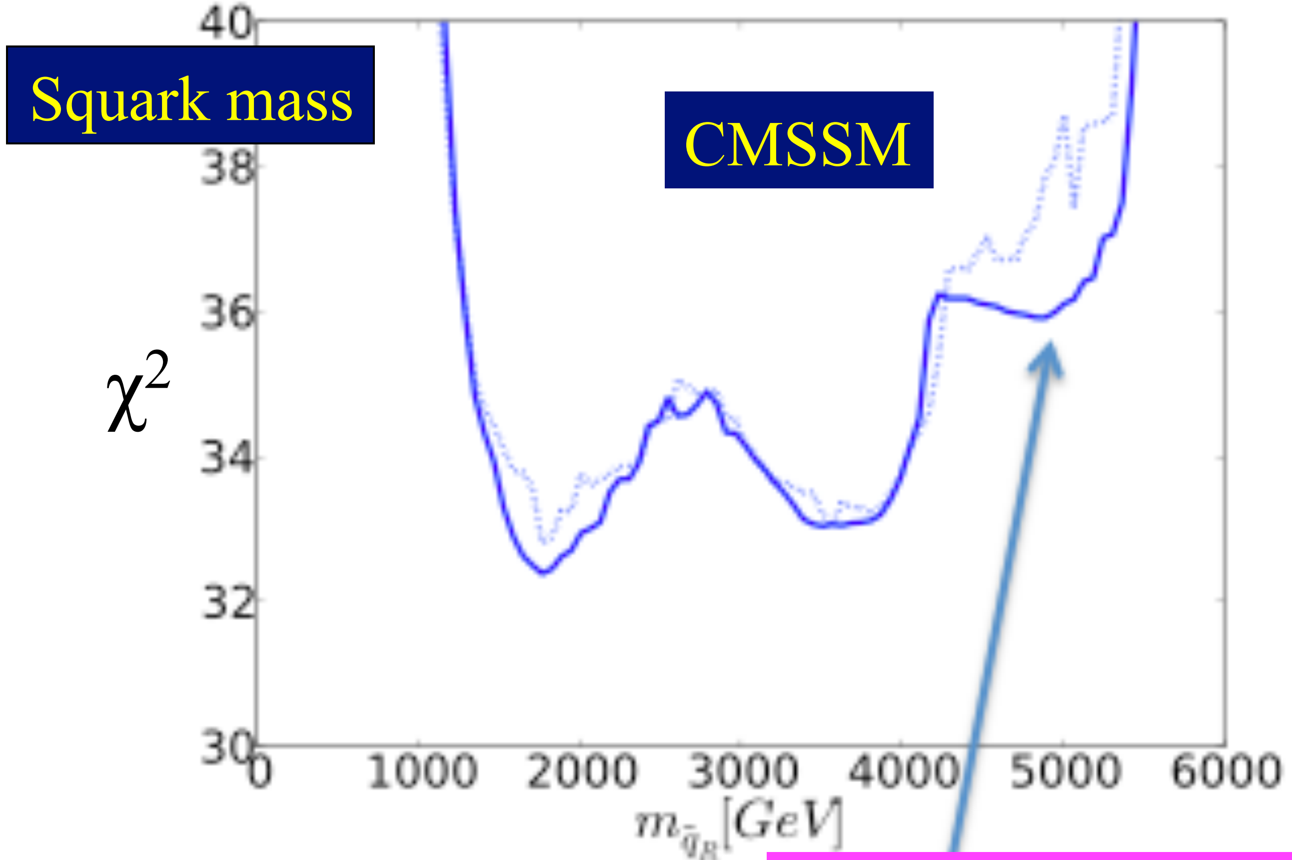


Update of Buchmueller, JE et al: arXiv:1207.3715

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

Post-LHC, Post-XENON100

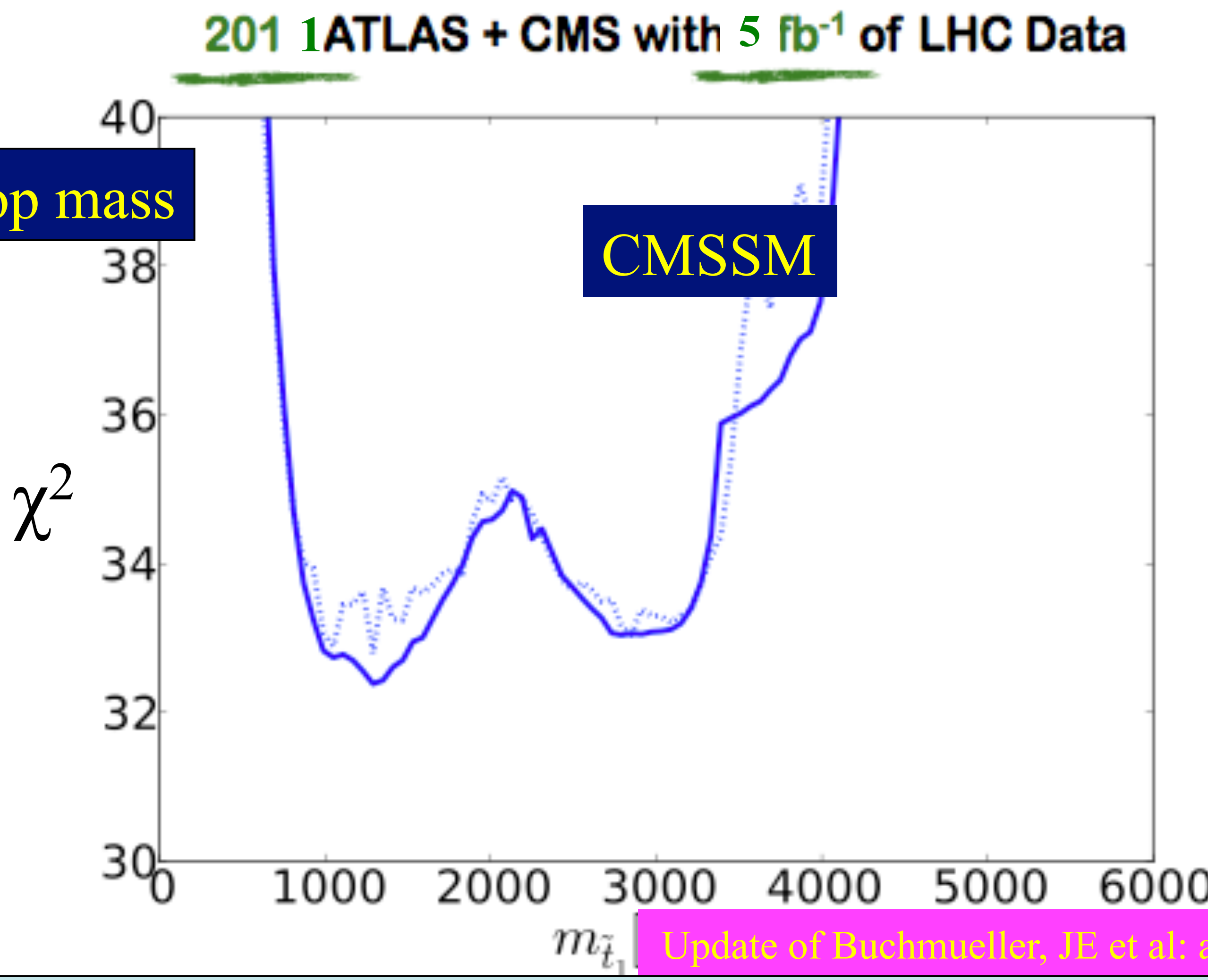
201 1ATLAS + CMS with 5 fb-1 of LHC Data



Update of Buchmueller, JE et al: arXiv:1207.3715

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

Post-LHC, Post-XENON100



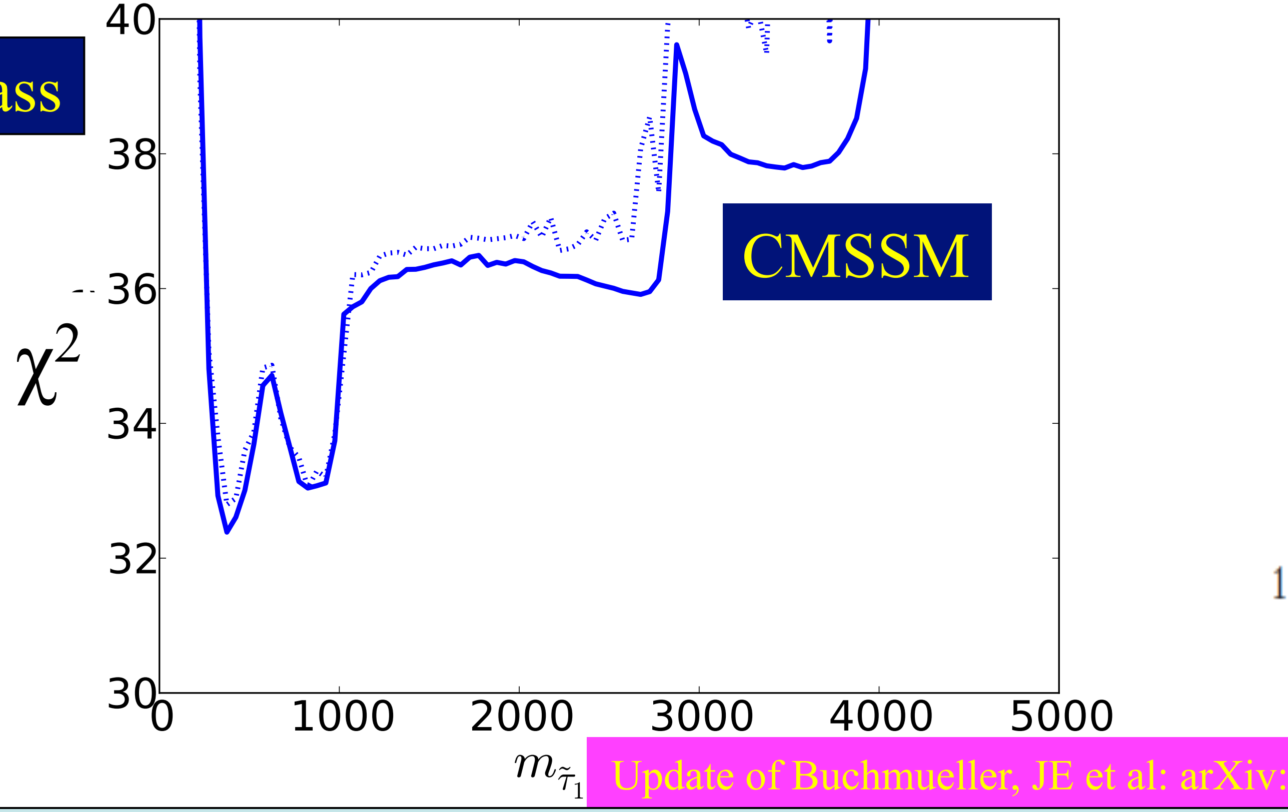
Update of Buchmueller, JE et al: arXiv:1207.3715

Favoured values of stop mass significantly below gluino, other squarks

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 5 fb^{-1} of LHC Data

Stau mass



Update of Buchmueller, JE et al: arXiv:1207.3715

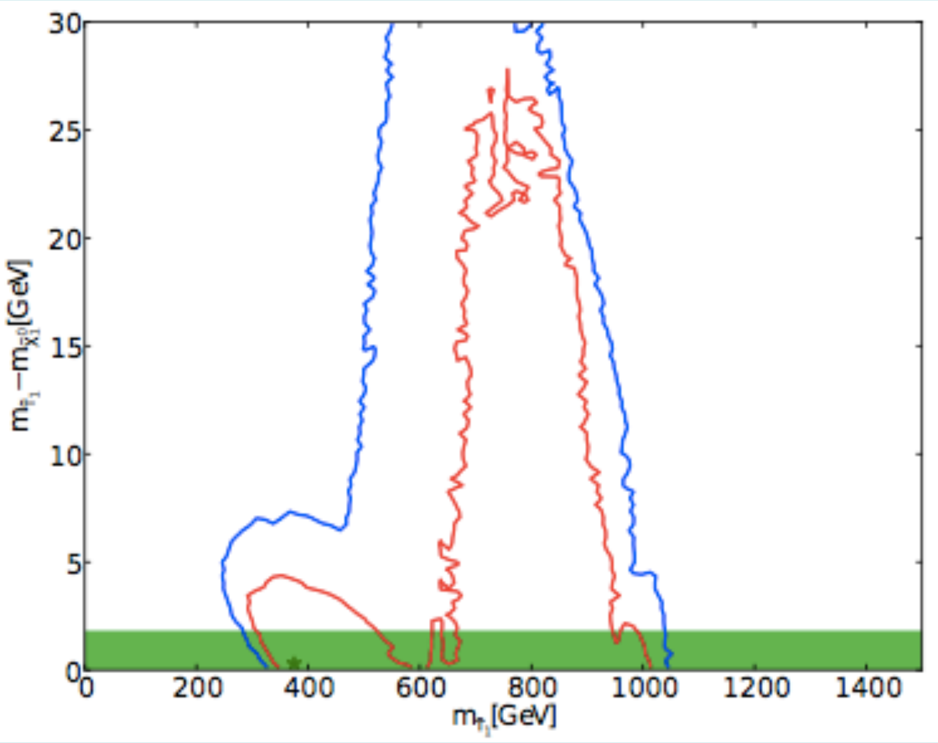
Favoured values of stau mass:

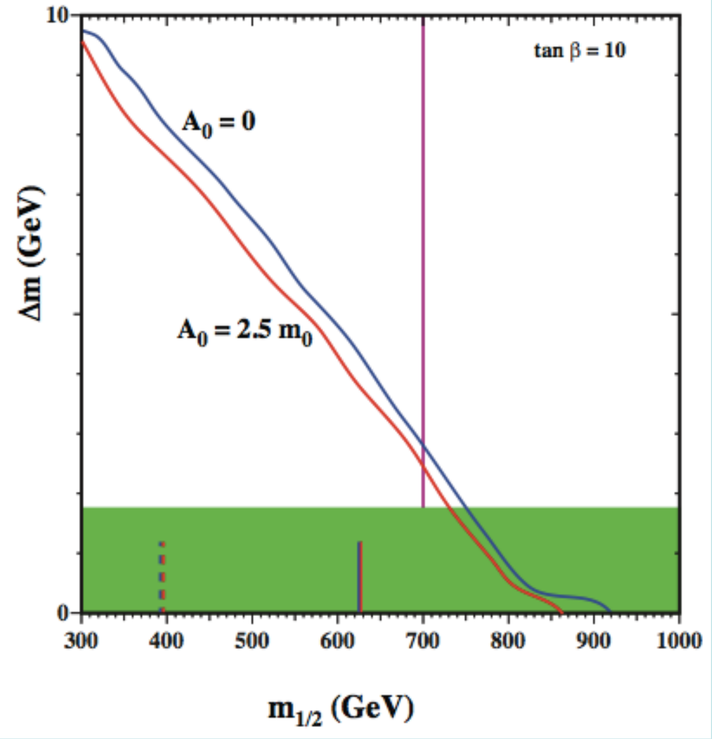
Several hundred GeV

What remains for the CMSSM?

Citron, JE, Luo, Marrouche, Olive, de Vries: arXiv:1212.2886

- Favoured regions of parameter space

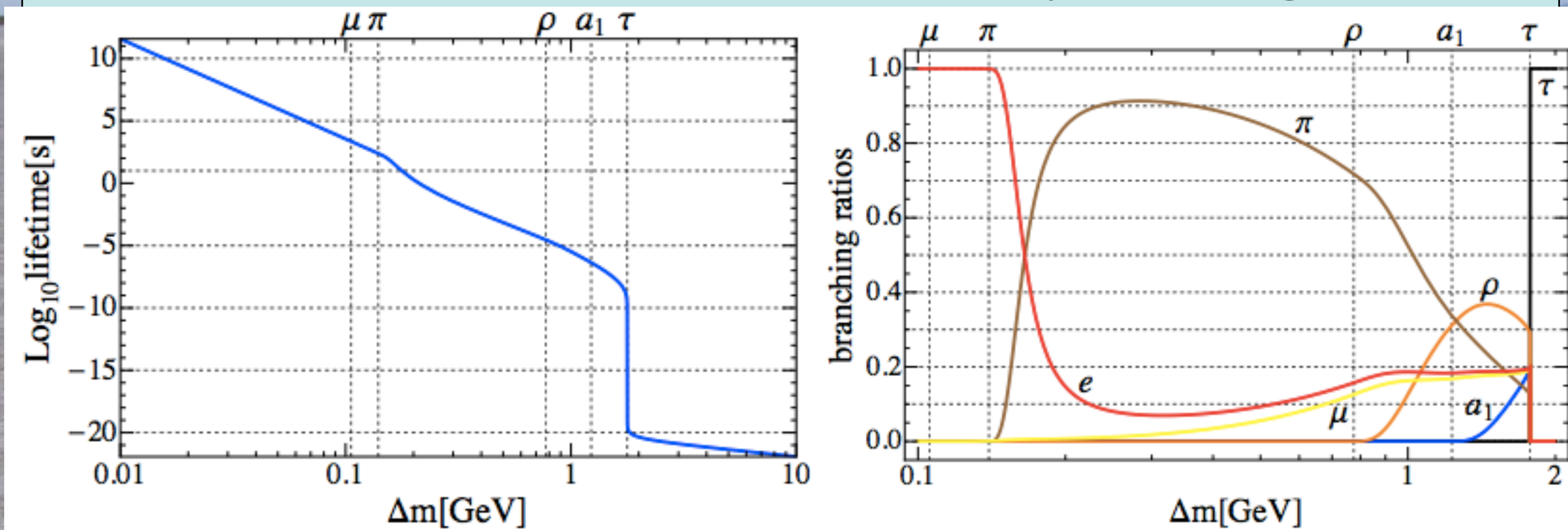




- Focus on the coannihilation strip
- Small mass difference – long-lived stau?

What remains for the CMSSM?

- Stau lifetime sensitive to Δm, may be long

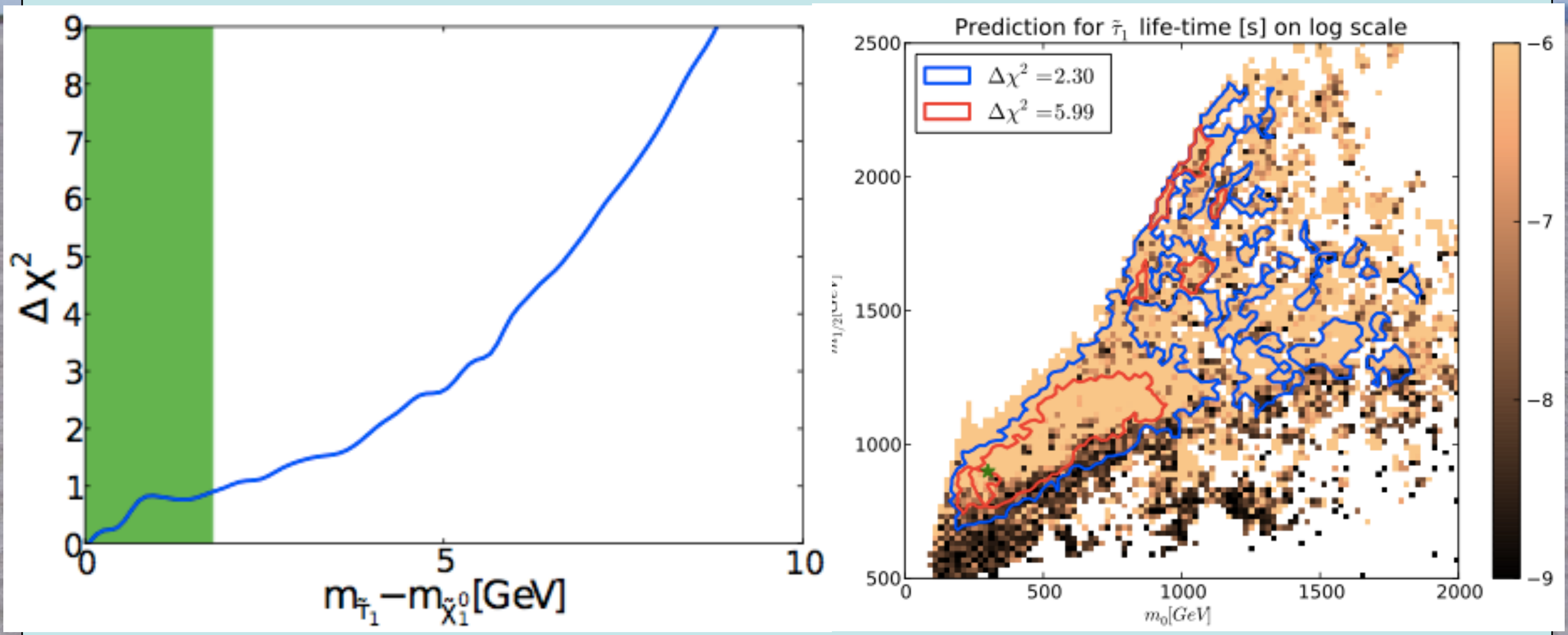


- May decay inside or outside the detector
- Decays into 1 or 3 charged particles, also neutrals

Citron, JE, Luo, Marrouche, Olive, de Vries: arXiv:1212.2886

Search for long-lived Staus?

- Small Δm favoured in χ^2 analysis

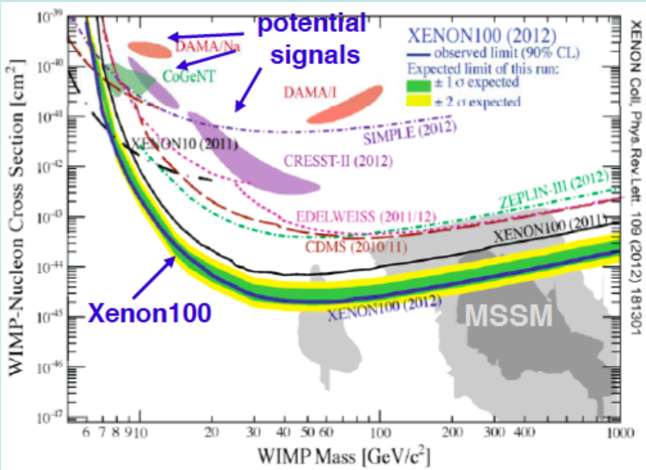


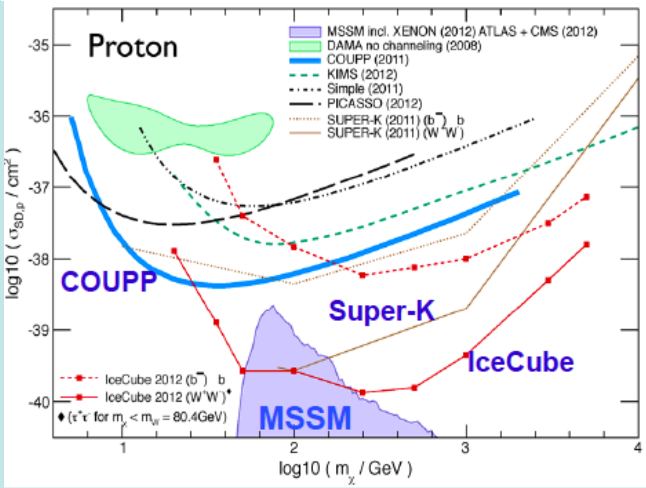
- May decay inside or outside the detector

Citron, JE, Luo, Marrouche, Olive, de Vries: arXiv:1212.2886

Direct WIMP Searches

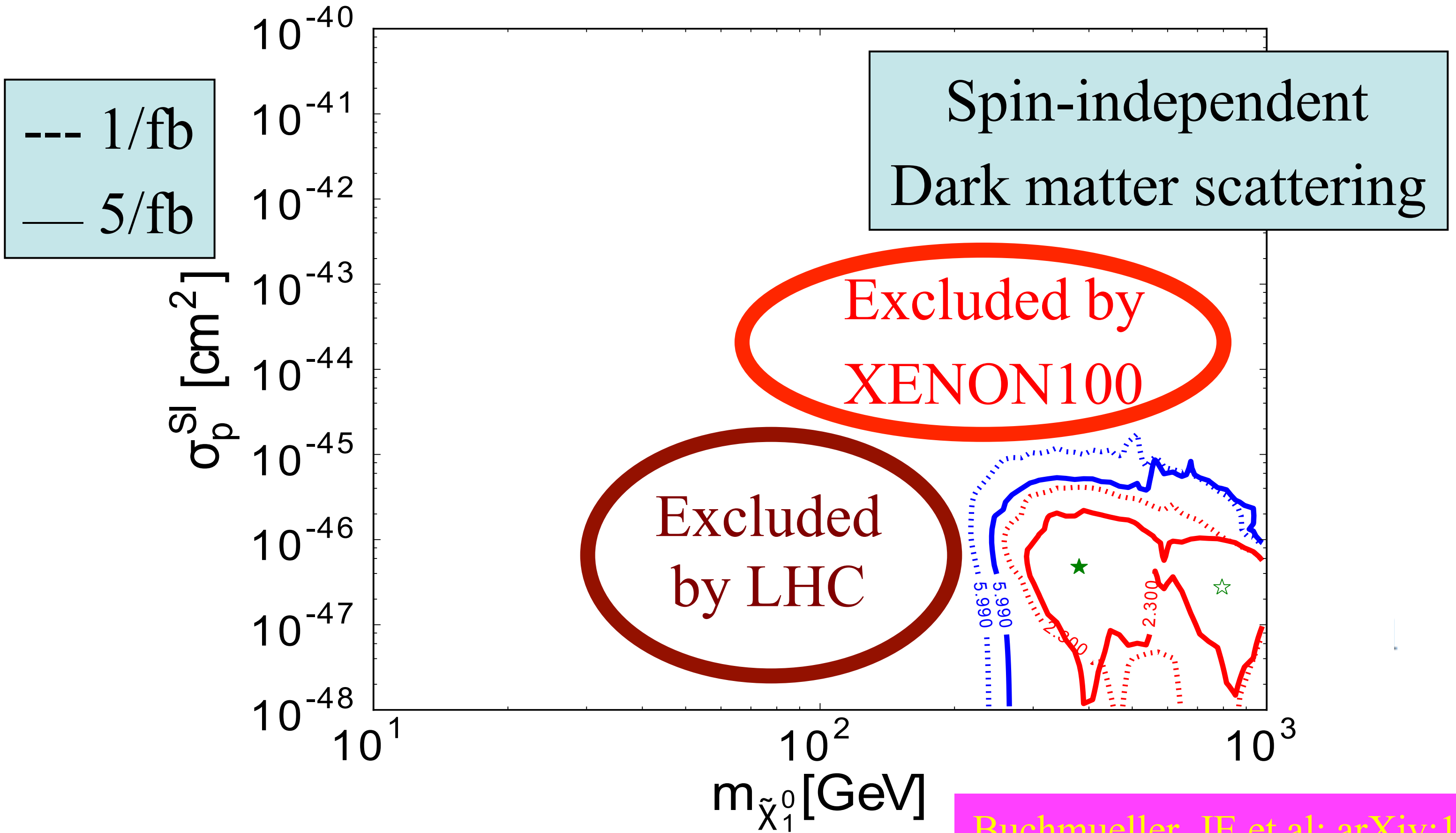
- Direct search for dark matter scattering:
  - Spin-independent and –dependent σ limits from XENON100, COUPP
  - CoGeNT & DAMA well excluded
  - 3 CDMS candidates (~ threshold, compatibility with XENON100?)
- Cf, monojet searches at LHC:
  - LHC wins for interactions with quarks and gluons
- XENON, DARWIN, EURECA





Post-LHC, Post-XENON100

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



Buchmueller, JE et al: arXiv:1207.3715

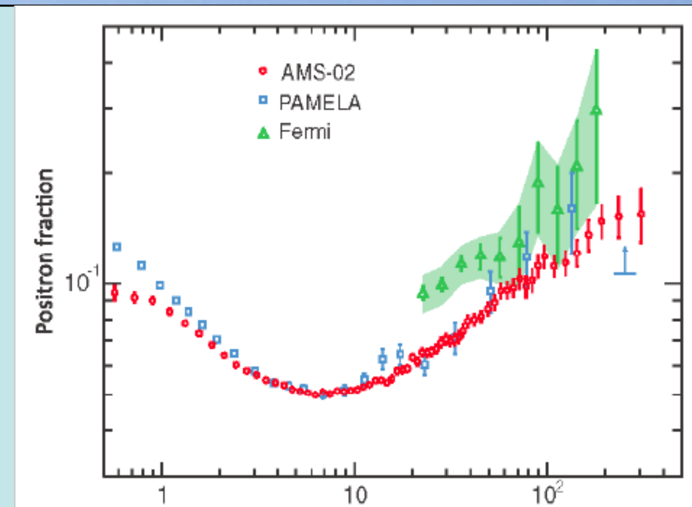
Favoured values of dark matter scattering cross section significantly below XENON100

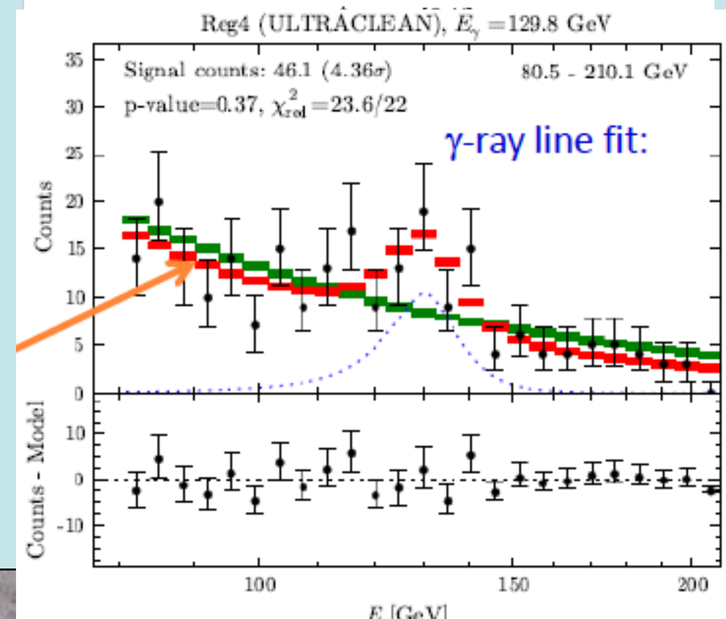
Indirect WIMP Searches

- Rising positron fraction?
  - Require large boost factor
  - Limits from γ rays
  - No antiproton signal
- Fermi γ line @ 130 GeV: 4.6 σ

  (3.3 σ with look-elsewhere effect)
  - Need σ > SUSY?
  - Seen from earth's limb!

  Falsifies WIMP hypothesis?





Some Questions

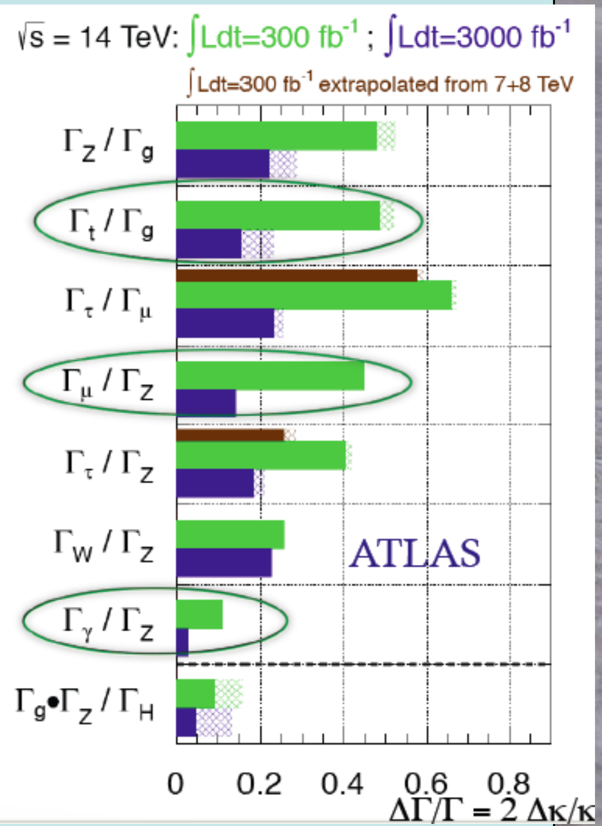
- What is it?
  - –Higgs or …?
- What else is there?
  - –Supersymmetry or …?
- What next?
  - –A Higgs factory or …?

What Next: A Higgs Factory?

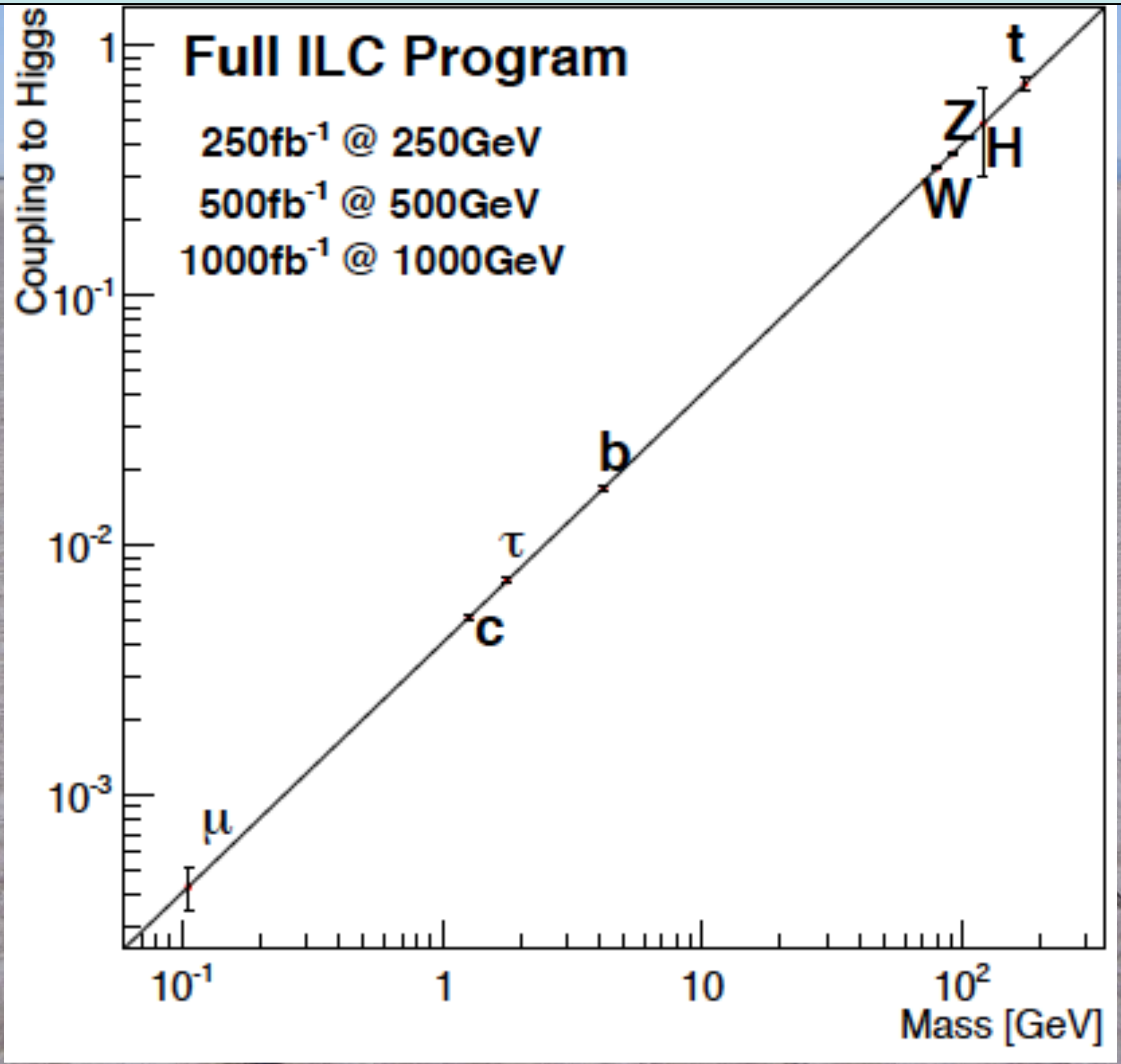
To study the 'Higgs' in detail:

- The LHC
  - Rethink 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: LEP3, TLEP
  - A photon-photon collider: SAPPHiRE
- A muon collider

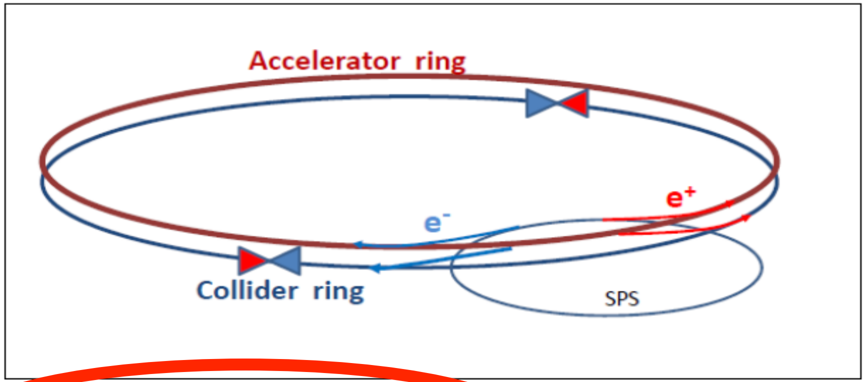


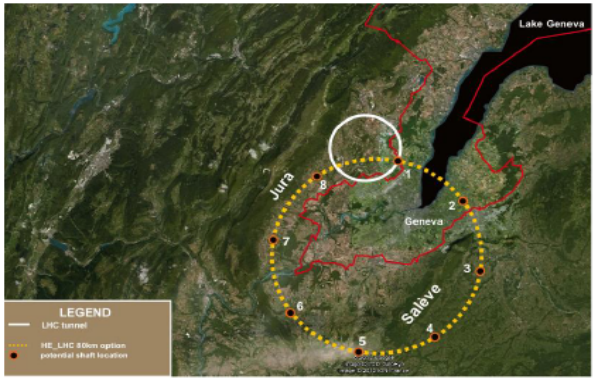
Coupling Measurements @ ILC



What Higgs Factory?

Circular e^+e^- colliders





E.g., LEP3:

- $\sqrt{s}$ = 240 GeV in the LHC tunnel to produce $e^+e^- \rightarrow ZH$ events
- Short beam lifetime (~16 mins) requires two ring scheme
  - Top up injection from 240 GeV "accelerator ring"
  - "Collider ring" supplying 2-4 interaction points L = 10^{34} cm^{-2}s^{-1} per IP
    - Re-use ATLAS and CMS and/or install two dedicated LC-type detectors
- Current design uses arc optics from LHeC ring
  - Dipole fill factor 0.75 (smaller than for LEP)
  - increased synchrotron energy loss (7 GeV per turn)
  - redesign possible?
- $e^{\pm}$ polarization probably not possible at $\sqrt{s}$ = 240 GeV
- In principle space is available to install compact e^+e^- facility on top
  - Is this really feasible?
  - Alternatively wait until completion of LHC physics programme and removal of LHC ring?
- SuperTRISTAN is a proposal for a similar machine in Japan

New large tunnel could also be used for pp collisions E_{CM} up to 100 TeV

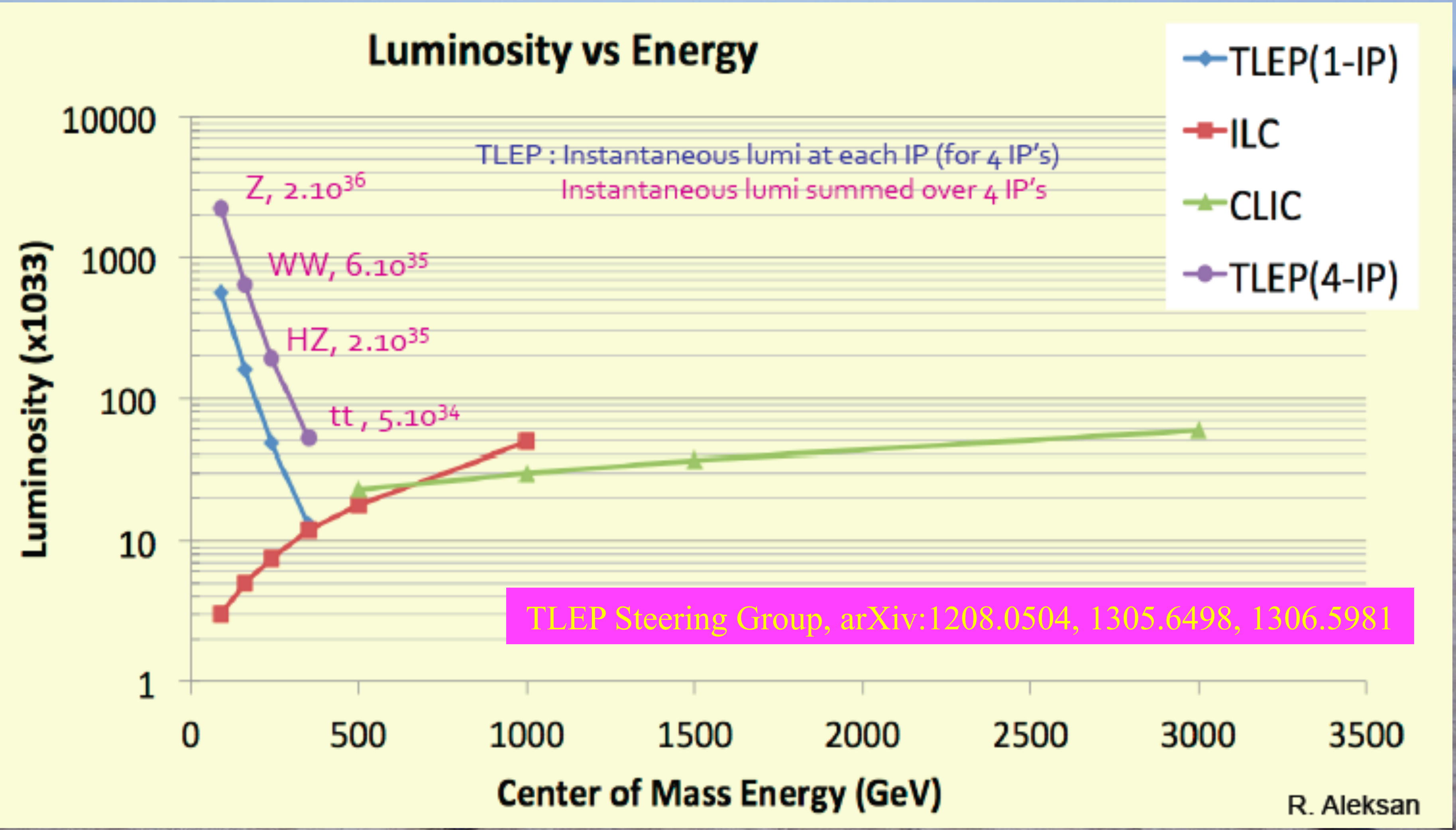
E.g., TLEP:

- $\sqrt{s}$ = 350 GeV in 80 km LHC tunnel to reach thresholds for top pair and $e^+e^- \rightarrow \nu\nu WW \rightarrow \nu\nu H$

TLEP Steering Group, arXiv:1208.0504, 1305.6498, 1306.5981

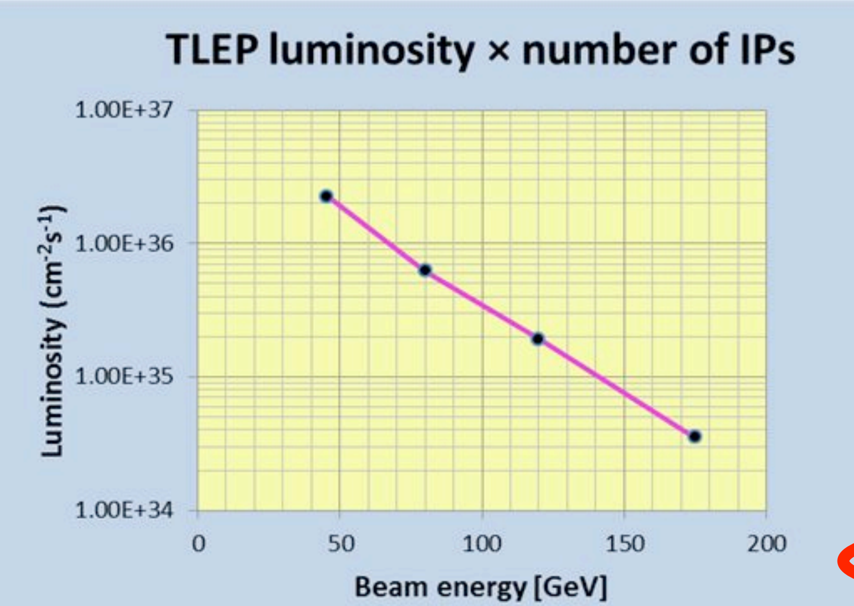
Possible Layouts for TLEP

Possible Luminosities of e^+e^- Colliders



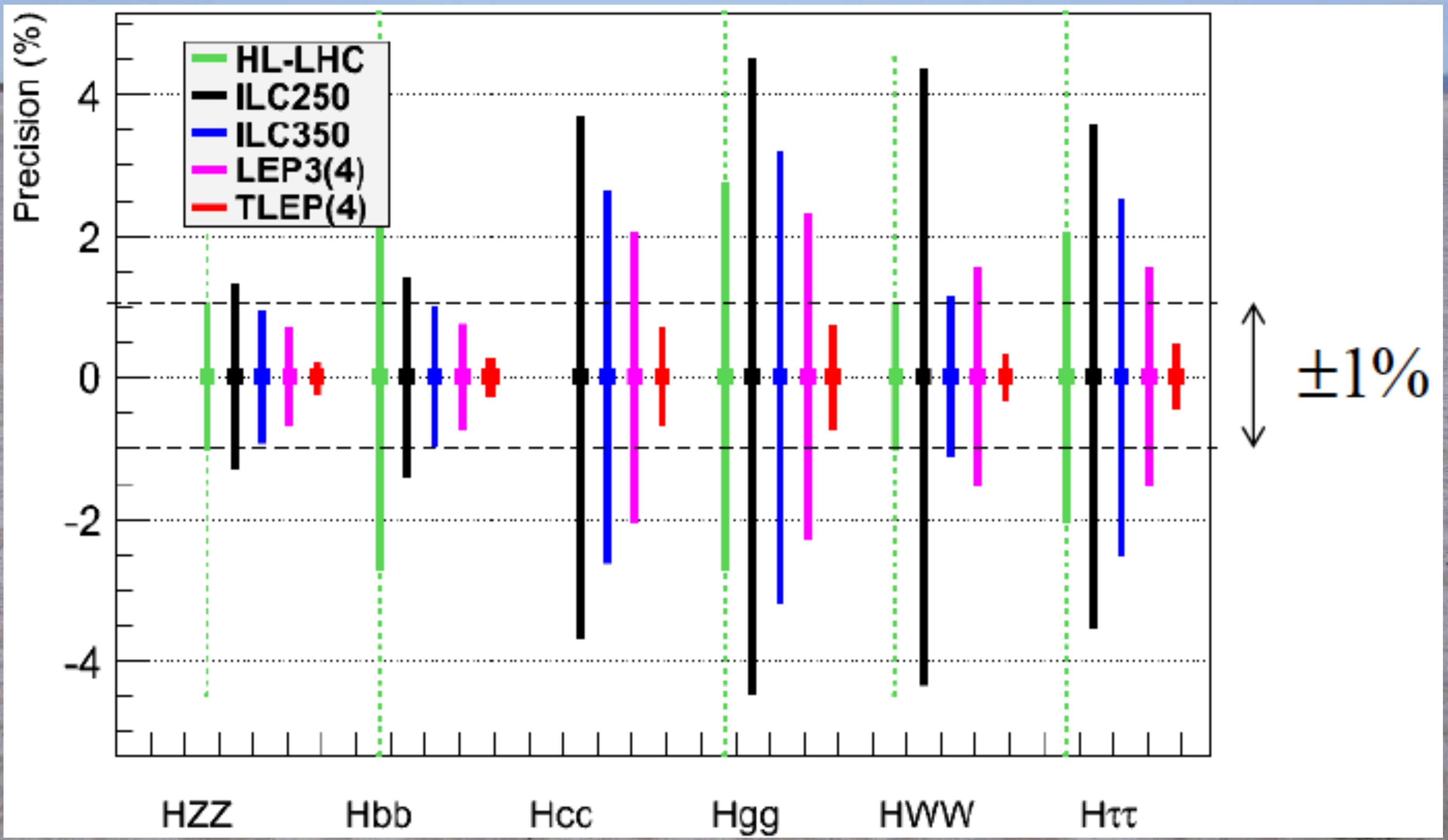
TLEP Parameters & Performance at different energies

	TLEP Z	TLEP W	TLEP H	TLEP t
E_{beam} [GeV]	45	80	120	175
circumf. [km]	80	80	80	80
beam current [mA]	1180	124	24.3	5.4
#bunches/beam	4400	600	80	12
#e-/beam [10^{12}]	1960	200	40.8	9.0
horiz. emit. [nm]	30.8	9.4	9.4	10
vert. emit. [nm]	0.07	0.02	0.02	0.01
bending rad. [km]	9.0	9.0	9.0	9.0
κ_ε	440	470	470	1000
mom. c. α_c [10^{-5}]	9.0	2.0	1.0	1.0
$P_{loss,SR}$/beam [MW]	50	50	50	50
β^*_x [m]	0.5	0.5	0.5	1
β^*_y [cm]	0.1	0.1	0.1	0.1
σ^*_x [μm]	124	78	68	100
σ^*_y [μm]	0.27	0.14	0.14	0.10
hourglass F_{hg}	0.71	0.75	0.75	0.65
E^{SR}_{loss}/turn [GeV]	0.04	0.4	2.0	9.2
V_{RF},tot [GV]	2	2	6	12
?$_{max,RF}$ [%]	4.0	5.5	9.4	4.9
ξ_x/IP	0.07	0.10	0.10	0.10
ξ_y/IP	0.07	0.10	0.10	0.10
f_s [kHz]	1.29	0.45	0.44	0.43
E_{acc} [MV/m]	3	3	10	20
eff. RF length [m]	600	600	600	600
f_{RF} [MHz]	700	700	700	700
δ^{SR}_{rms} [%]	0.06	0.10	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	0.19	0.22	0.17	0.25
$\mathcal{L}$/IP[10^{32}cm^{-2}s^{-1}]	5600	1600	480	130
number of IPs	4	4	4	4
beam lifet. [min]	67	25	16	20



TLEP Steering Group, arXiv:1306.5981

Comparison of Possible Higgs Factory Measurements



Higgs Factory Summary

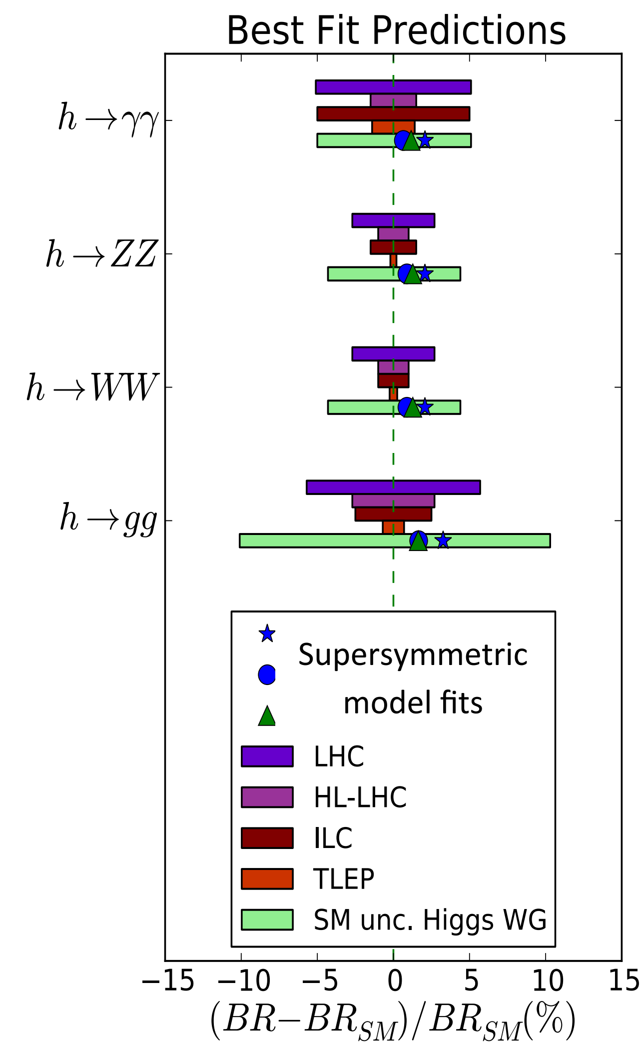
Best precision

Accelerator →Physical quantity ↓	LHC $300fb^{-1}$ /exp	HL-LHC $3000fb^{-1}$ /exp	ILC (250) 250 fb^{-1}	ILC (250+350+1000)	LEP3 240 4 IP	TLEP 240 +350 4 IP
Approx. date	2021	2030	2035	2045	2035	2035
N_H	1.7×10^7	1.7×10^8	$5\ 10^4$ ZH	(10^5 ZH) ($1.4\ 10^5$ Hvv)	$4\ 10^5$ZH	$2\ 10^6$ ZH
m_H (MeV)	100	50	35	35	26	7
$\Delta\Gamma_H/\Gamma_H$	--	--	10%	3%	4%	1.3%
$\Delta\Gamma_{inv}/\Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	0.35%	0.15%
$\Delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	3.4%	1.4%
$\Delta g_{Hgg}/g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	2.2%	0.7%
$\Delta g_{Hww}/g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	1.5%	0.25%
$\Delta g_{HZZ}/g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	0.65%	0.2%
$\Delta g_{HHH}/g_{HHH}$	--	< 30% (2 exp.)	--	~30%	--	--
$\Delta g_{H\mu\mu}/g_{H\mu\mu}$	<30	<10	--	--	14%	7%

ICFA Higgs Factory Workshop
Fermilab, Nov. 2012

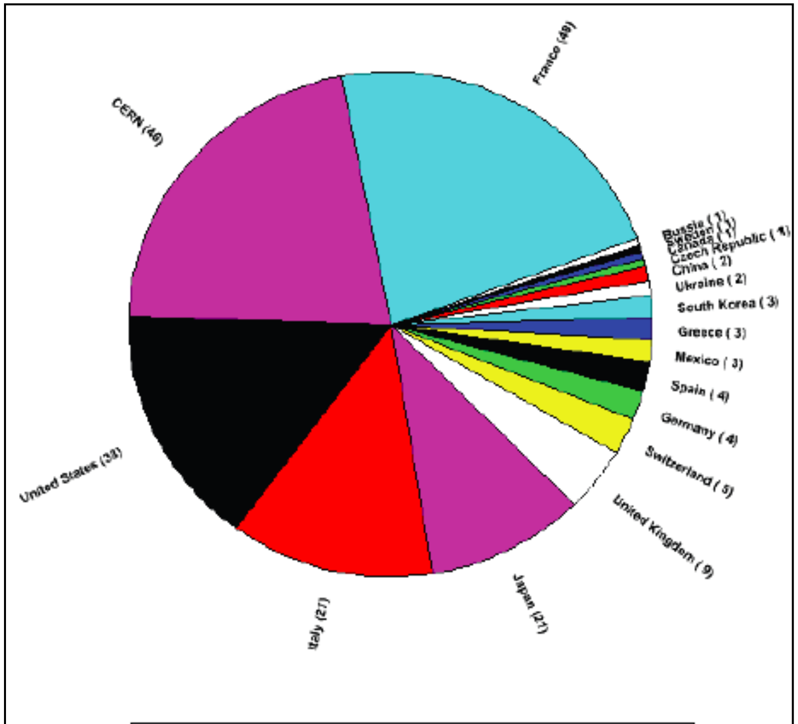
Impact of Higgs Factory?

- Predictions of current best fits in simple SUSY models
- Current uncertainties in SM calculations [LHC Higgs WG]
- Comparisons with
  - LHC
  - HL-LHC
  - ILC
  - TLEP
- **Don't decide before LHC 13/4**



TLEP Physics Study

- Experimental Studies : Preliminary Structure (Being discussed)
  - 11 working groups
    - WG1 : Electroweak Physics at the Z pole
    - WG2 : Di-boson physics : W mass measurement, ..
    - WG3 : H(126) properties
    - WG4 : Top Quark Physics
    - WG5 : b, c and τ physics
    - WG6 : QCD and $\gamma\gamma$ physics
    - WG7 : Rare Physics
    - WG8 : Experimental environment
    - WG9 : Offline software and computing
    - WG10 : Online software and computing
    - WG11 : Detector designs



219 subscribers, 13-Jun-13

More information, registration at http://tlep.web.cern.ch

Part of a Vision for the Future

- A large circular tunnel
  - Circumference ~ 80 to 100 km
- Could accommodate TLEP and VHE-LHC
  - E_{CM} up to 100 TeV with 15 Tesla magnets
- Could be sited around Geneva
  - Interest in China, US
- TLEP Study Group under way
- Timely to study VHE-LHC

Summary

- Beyond any reasonable doubt, the LHC has discovered a (the) Higgs boson
- A big challenge for theoretical physics!
- The best option: supersymmetry
- The LHC may discover supersymmetry when it restarts at ~ 13 TeV
- If it **does**, priority will be to study it
- If it does **not**, natural to study the Higgs
- Either way, TLEP/VHE-LHC offers vision