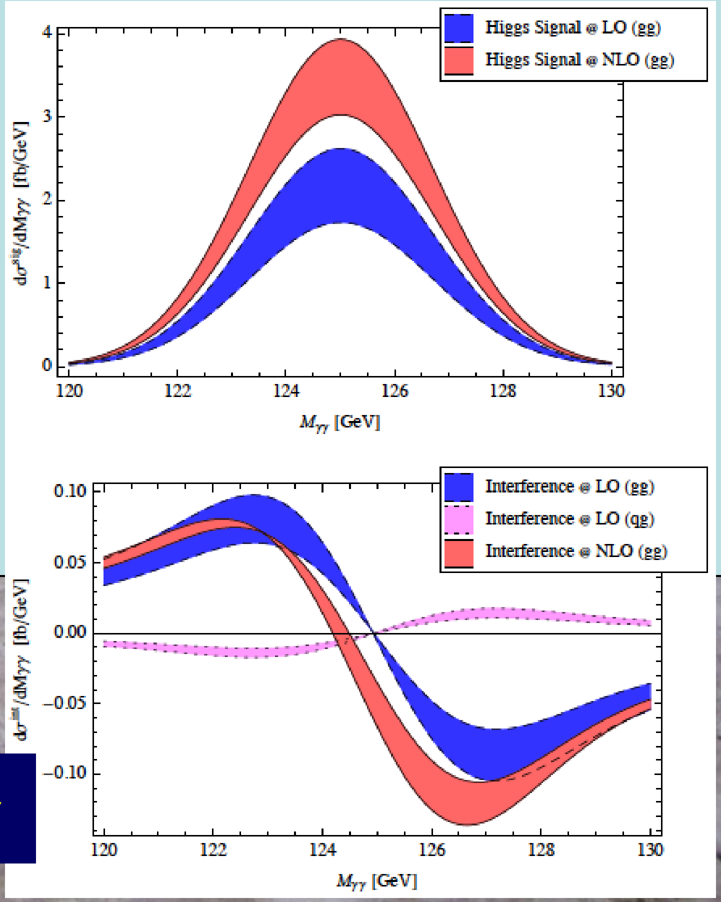
Programme of Lectures

- Motivations and introduction
- What we know now
- The future?
  - Supersymmetric Higgses
  - Higgs factories



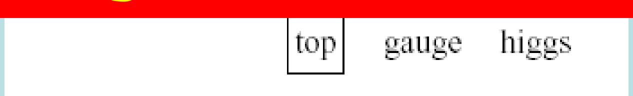
Interference in H ➔γγ

Elementary Higgs or Composite?

- Higgs field:

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

- Quantum loop problems



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

- Fermion-antifermion condensate
- Just like QCD, BCS

New technicolour force?
- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

No visible hint of anything beyond the Standard Model

Theoretical Confusion

- High mortality rate among theories
- (M_H, M_t) close to stability bound
- Λ close to Weinberg upper 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!**

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

The Dog(s) that did not Bark

- To Sherlock Holmes:

  “Is there any other point to which you would wish to draw my attention?”

- Holmes:

  "To the curious incident of the dog in the night-time."

- To Holmes:

  "The dog did nothing in the night-time."

- Holmes:

  "That was the curious incident.”

- We have many clues:

  Waiting for our Holmes: maybe a string player?

Why is there Nothing rather than Something?

- 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:

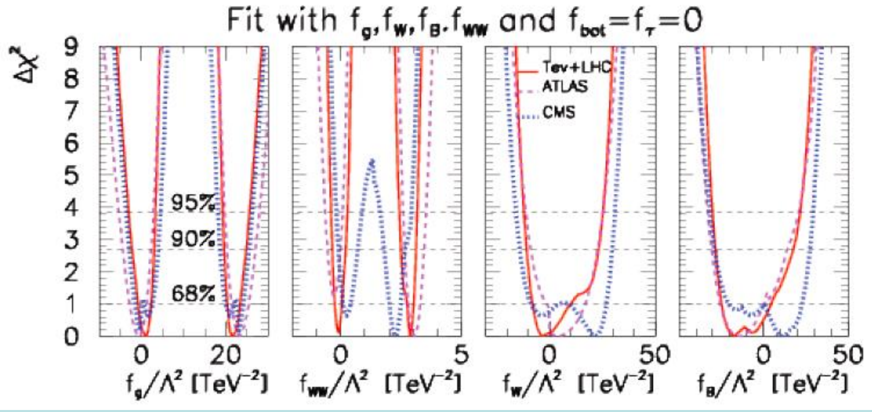
$$\mathcal{O}_{GG} = \Phi^\dagger\Phi \; G^a_{\mu\nu}G^{a\mu\nu} \;, \qquad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi \;, \qquad \mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi \;,$$

$$\mathcal{O}_W = (D_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\Phi) \;, \quad \mathcal{O}_B = (D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\Phi) \;, \quad \mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger \,\Phi\, \Phi^\dagger\,(D^\mu\Phi)$$

$$\mathcal{L}_{eff} = -\frac{\alpha_s v}{8\pi}\frac{f_g}{\Lambda^2}\mathcal{O}_{GG} + \frac{f_{WW}}{\Lambda^2}\mathcal{O}_{WW} + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_B}{\Lambda^2}\mathcal{O}_B + \frac{f_{\rm bot}}{\Lambda^2}\mathcal{O}_{d\Phi,33} + \frac{f_\tau}{\Lambda^2}\mathcal{O}_{e\Phi,33}$$

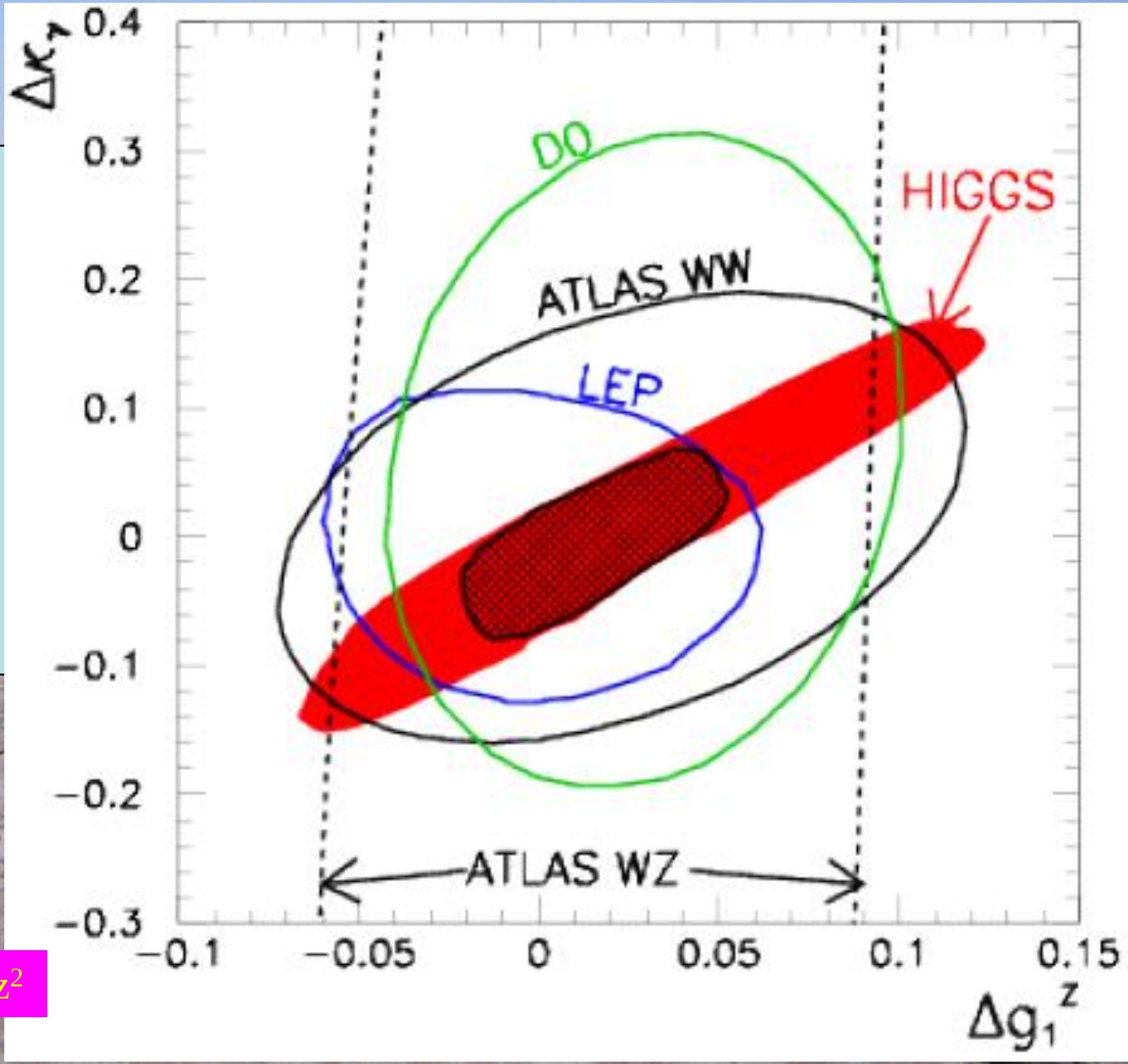
Corbett, Eboli & Gonzalez[2]

- Constrain using LHC + Tevatron Higgs measurements



Why is there Nothing rather than Something?

Combine with constraints on anomalous triple-gauge boson couplings



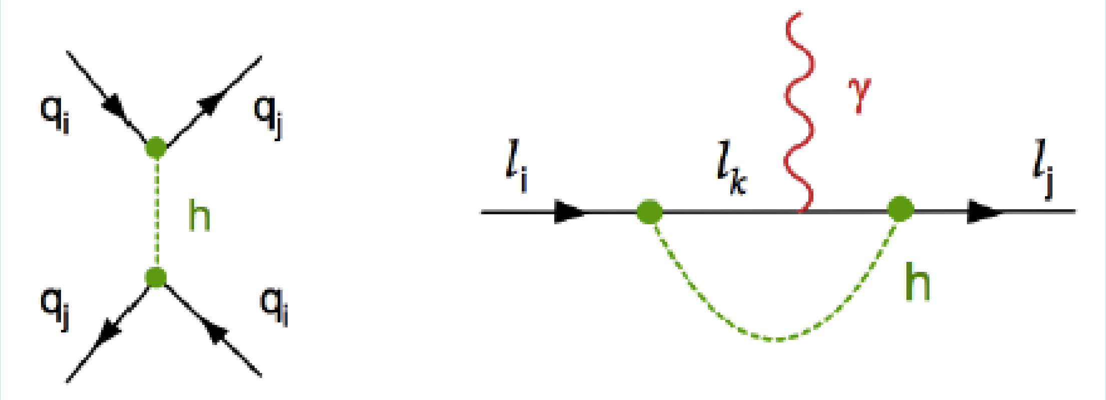
Corbett, Eboli & Gonzalez[2]

A or The?

- Others?
  - Upper limits on couplings of massive H'
  - Extra singlet? 2HDM? Fermiophobic? MSSM?
- Non-SM decays?
  - Invisible decays? SM4? μμ? μτ? eτ? aa? $H^{\pm\pm}$?
- VV scattering?
  - Closure test (does Higgs cure high-energy behaviour)
- Another way? Other scenarios?
  - Precision of BSM predictions?
- Will the HL-LHC be enough?

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 Couplings?

- Constraints on quark-flavour-changing couplings from FCNC

Operator	Eff. couplings	95% C.L. Bound		Observables
		$\lvert c_{\rm eff}\rvert$	$\lvert {\rm Im}(c_{\rm eff})\rvert$	
$(\bar s_R d_L)(\bar s_L d_R)$	$c_{sd}\, c^*_{ds}$	1.1×10^{-10}	4.1×10^{-13}	$\Delta m_K;\ \epsilon_K$
$(\bar s_R d_L)^2,\ (\bar s_L d_R)^2$	$c^2_{ds},\ c^2_{sd}$	2.2×10^{-10}	0.8×10^{-12}	
$(\bar c_R u_L)(\bar c_L u_R)$	$c_{cu}\, c^*_{uc}$	0.9×10^{-9}	1.7×10^{-10}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar c_R u_L)^2,\ (\bar c_L u_R)^2$	$c^2_{uc},\ c^2_{cu}$	1.4×10^{-9}	2.5×10^{-10}	
$(\bar b_R d_L)(\bar b_L d_R)$	$c_{bd}\, c^*_{db}$	0.9×10^{-8}	2.7×10^{-9}	$\Delta m_{B_d};\ S_{B_d \to \psi K}$
$(\bar b_R d_L)^2,\ (\bar b_L d_R)^2$	$c^2_{db},\ c^2_{bd}$	1.0×10^{-8}	3.0×10^{-9}	
$(\bar b_R s_L)(\bar b_L s_R)$	$c_{bs}\, c^*_{sb}$	2.0×10^{-7}	2.0×10^{-7}	Δm_{B_s}
$(\bar b_R s_L)^2,\ (\bar b_L s_R)^2$	$c^2_{sb},\ c^2_{bs}$	2.2×10^{-7}	2.2×10^{-7}	

Eff. couplings	Bound	Constraint
$\lvert c_{sb}\rvert^2,\ \lvert c_{bs}\rvert^2$	2.9×10^{-5}	$\mathcal{B}(B_s \to \mu^+\mu^-) < 1.4 \times 10^{-8}$
$\lvert c_{db}\rvert^2,\ \lvert c_{bd}\rvert^2$	1.3×10^{-5}	$\mathcal{B}(B_d \to \mu^+\mu^-) < 3.2 \times 10^{-9}$

- Constraints on lepton-flavour-changing couplings

Operator	Eff. couplings	Bound	Constraint
$(\bar\mu_R e_L)(\bar q_L q_R),\ (\bar\mu_L e_R)(\bar q_L q_R)$	$\lvert c_{\mu e}\rvert^2,\ \lvert c_{e\mu}\rvert^2$	3.0×10^{-8}	$\mathcal{B}_{\mu \to e}({\rm Ti}) < 4.3 \times 10^{-12}$
$(\bar\tau_R \mu_L)(\bar\mu_L \mu_R),\ (\bar\tau_L \mu_R)(\bar\mu_L \mu_R)$	$\lvert c_{\tau\mu}\rvert^2,\ \lvert c_{\mu\tau}\rvert^2$	2.0×10^{-1}	$\Gamma(\tau \to \mu\bar\mu\mu) < 2.1 \times 10^{-8}$
$(\bar\tau_R e_L)(\bar\mu_L \mu_R),\ (\bar\tau_L e_R)(\bar\mu_L \mu_R)$	$\lvert c_{\tau e}\rvert^2,\ \lvert c_{e\tau}\rvert^2$	4.8×10^{-1}	$\Gamma(\tau \to e\bar\mu\mu) < 2.7 \times 10^{-8}$
$(\bar\tau_R e_L)(\bar\mu_L e_R),\ (\bar\tau_L e_R)(\bar\mu_L e_R)$	$\lvert c_{\mu e} c^*_{e\tau}\rvert,\ \lvert c_{\mu e} c_{\tau e}\rvert$	0.9×10^{-4}	$\Gamma(\tau \to \bar\mu e e) < 1.5 \times 10^{-8}$
$(\bar\tau_R e_L)(\bar\mu_R e_L),\ (\bar\tau_L e_R)(\bar\mu_R e_L)$	$\lvert c^*_{e\mu} c^*_{e\tau}\rvert,\ \lvert c^*_{e\mu} c_{\tau e}\rvert$		
$(\bar\tau_R \mu_L)(\bar e_L \mu_R),\ (\bar\tau_L \mu_R)(\bar e_L \mu_R)$	$\lvert c_{e\mu} c^*_{\mu\tau}\rvert,\ \lvert c_{e\mu} c_{\tau\mu}\rvert$	1.0×10^{-4}	$\Gamma(\tau \to \bar e\mu\mu) < 1.7 \times 10^{-8}$
$(\bar\tau_R \mu_L)(\bar e_R \mu_L),\ (\bar\tau_L \mu_R)(\bar e_R \mu_L)$	$\lvert c^*_{\mu e} c^*_{\mu\tau}\rvert,\ \lvert c^*_{\mu e} c_{\tau\mu}\rvert$		

Eff. couplings	Bound	Constraint
$\lvert c_{e\tau} c_{\tau e}\rvert \quad (\lvert c_{e\mu} c_{\mu e}\rvert)$	$1.1 \times 10^{-2} \quad (1.8 \times 10^{-1})$	$\lvert\delta m_e\rvert < m_e$
$\lvert{\rm Re}(c_{e\tau} c_{\tau e})\rvert \quad (\lvert{\rm Re}(c_{e\mu} c_{\mu e})\rvert)$	$0.8 \times 10^{-2} \quad (1.4 \times 10^{-1})$	$\lvert\delta a_e\rvert < 6 \times 10^{-12}$
$\lvert{\rm Im}(c_{e\tau} c_{\tau e})\rvert \quad (\lvert{\rm Im}(c_{e\mu} c_{\mu e})\rvert)$	$1.1 \times 10^{-7} \quad (1.9 \times 10^{-6})$	$\lvert d_e\rvert < 1.6 \times 10^{-27}$ ecm
$\lvert c_{\mu\tau} c_{\tau\mu}\rvert$	2	$\lvert\delta m_\mu\rvert < m_\mu$
$\lvert{\rm Re}(c_{\mu\tau} c_{\tau\mu})\rvert$	2×10^{-2}	$\lvert\delta a_\mu\rvert < 4 \times 10^{-9}$
$\lvert{\rm Im}(c_{\mu\tau} c_{\tau\mu})\rvert$	8	$\lvert d_\mu\rvert < 1.2 \times 10^{-19}$ ecm
$\lvert c_{e\tau} c_{\tau\mu}\rvert,\ \lvert c_{\tau e} c_{\mu\tau}\rvert$	2.4×10^{-6}	$\mathcal{B}(\mu \to e\gamma) < 2.4 \times 10^{-12}$
$\lvert c_{\mu\tau}\rvert^2,\ \lvert c_{\tau\mu}\rvert^2$	6.6×10^{-1}	$\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$
$\lvert c_{e\tau}\rvert^2,\ \lvert c^*_{\tau e}\rvert^2$	4.7×10^{-1}	$\mathcal{B}(\tau \to e\gamma) < 3.3 \times 10^{-8}$

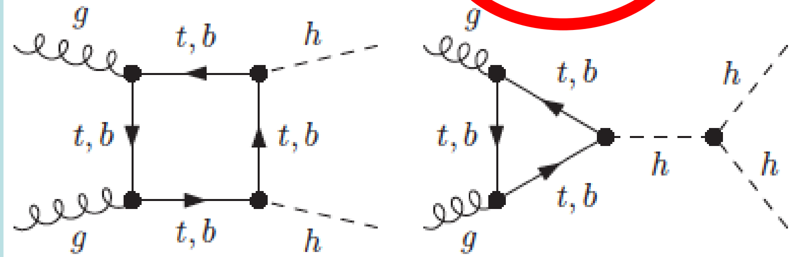
Blankenburg, JE, Isidori: arXiv:1202.5704

Measuring the Triple-Higgs Coupling?

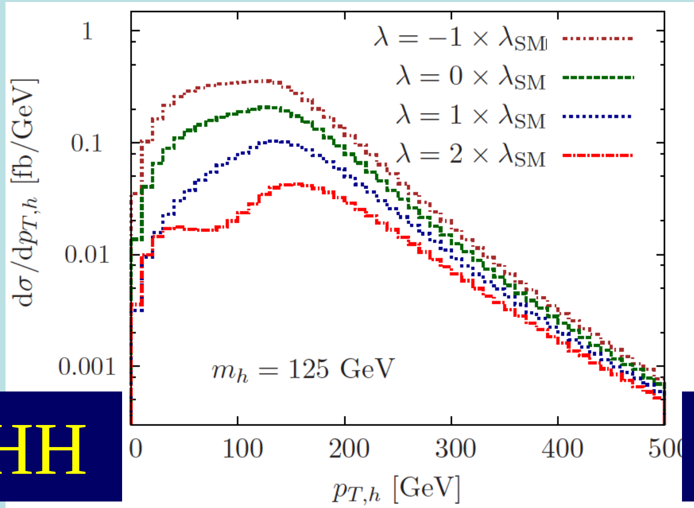
- What gives the Higgs mass?
- The Higgs itself!
- Measure via HH production
- May be possible @ LHC

  with accuracy ~ 30%:

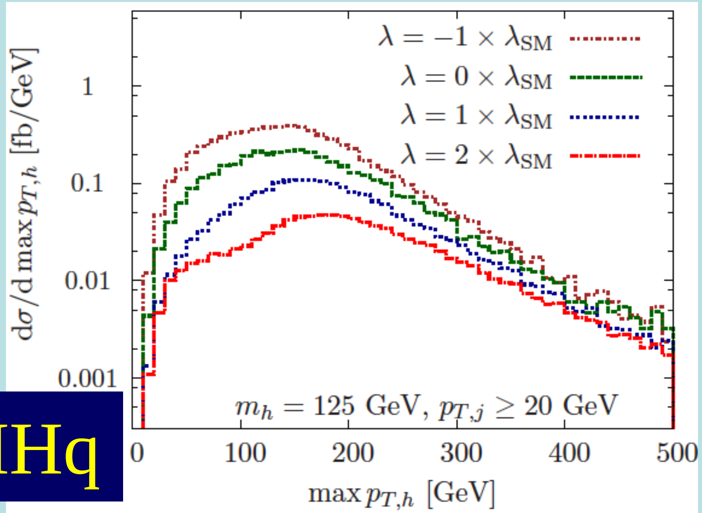
$$V(H^\dagger H) = \mu^2 H^\dagger H + \eta (H^\dagger H)^2$$
$$\supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta}{4} h^4$$



Dolan, Englert & Spannowsky



gg → HH



gq → HHq

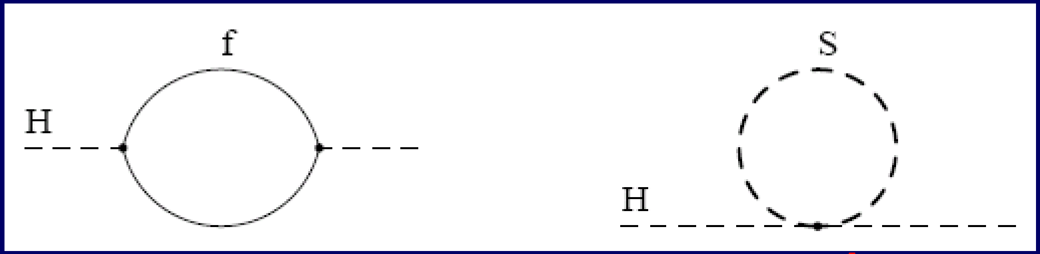
What else is there?

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: $\int^{\Lambda} d^4k/k^2$

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

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

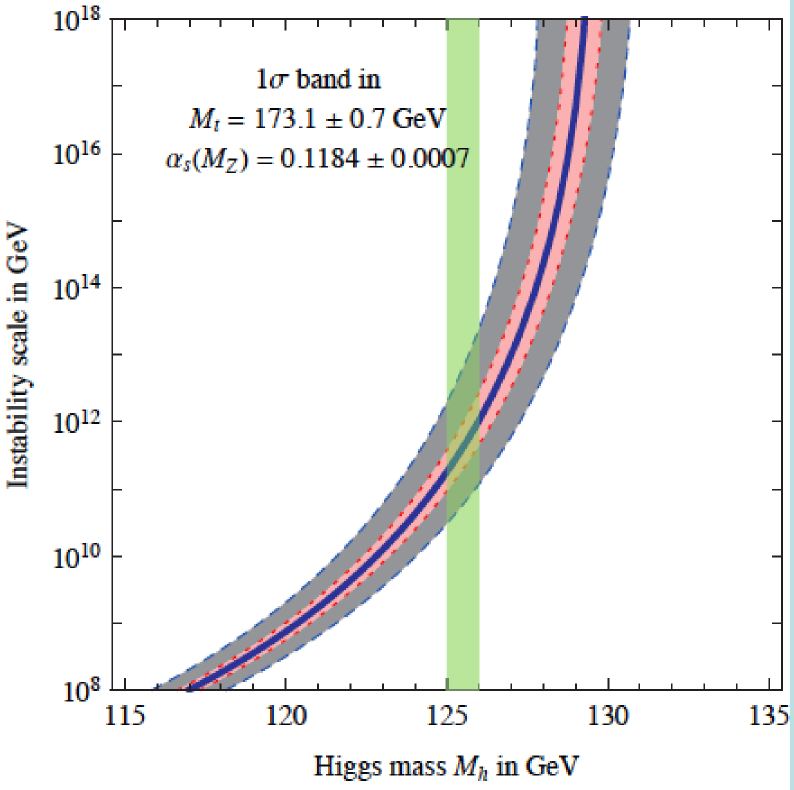
- Leading divergence cancelled if

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

Supersymmetry!

Theoretical Constraints on Higgs Mass

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



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

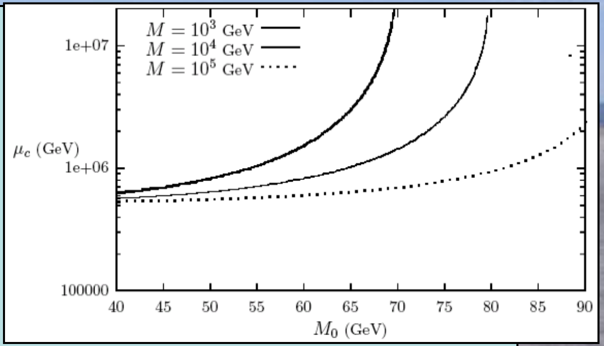
Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

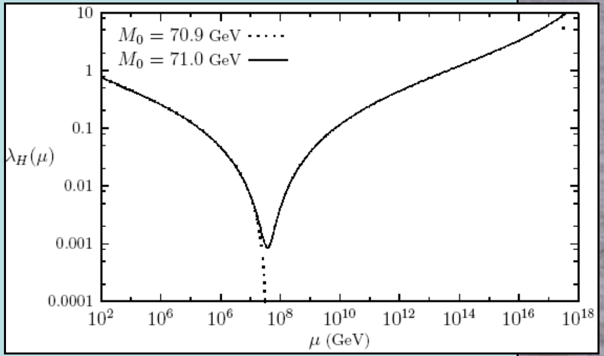
How to Stabilize a Light Higgs Boson?

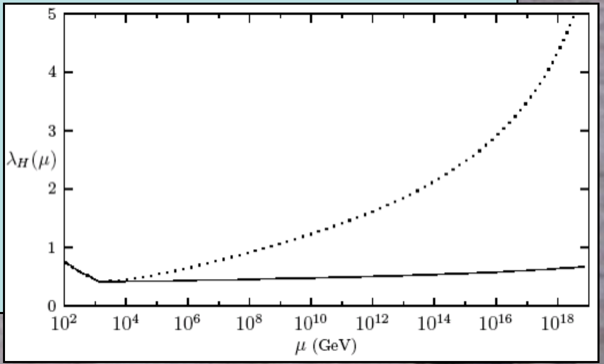
- Top quark destabilizes potential: introduce stop-like scalar:

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

- 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!**





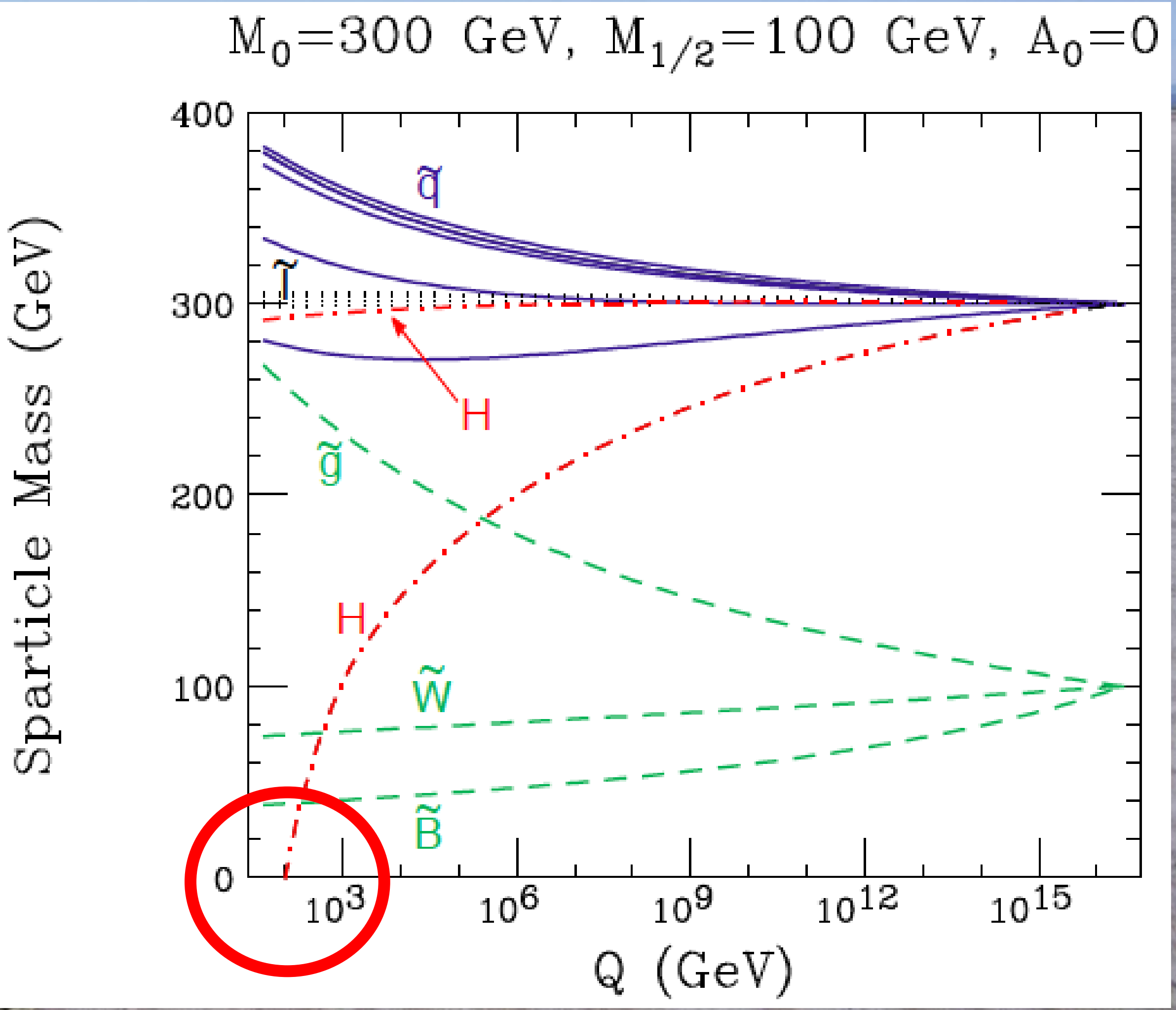


JE + D. Ross

Electroweak Symmetry Breaking

Could be driven by radiative corrections due to top quark

A bonus: supersymmetry may explain why $\mu^2 < 0$



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:

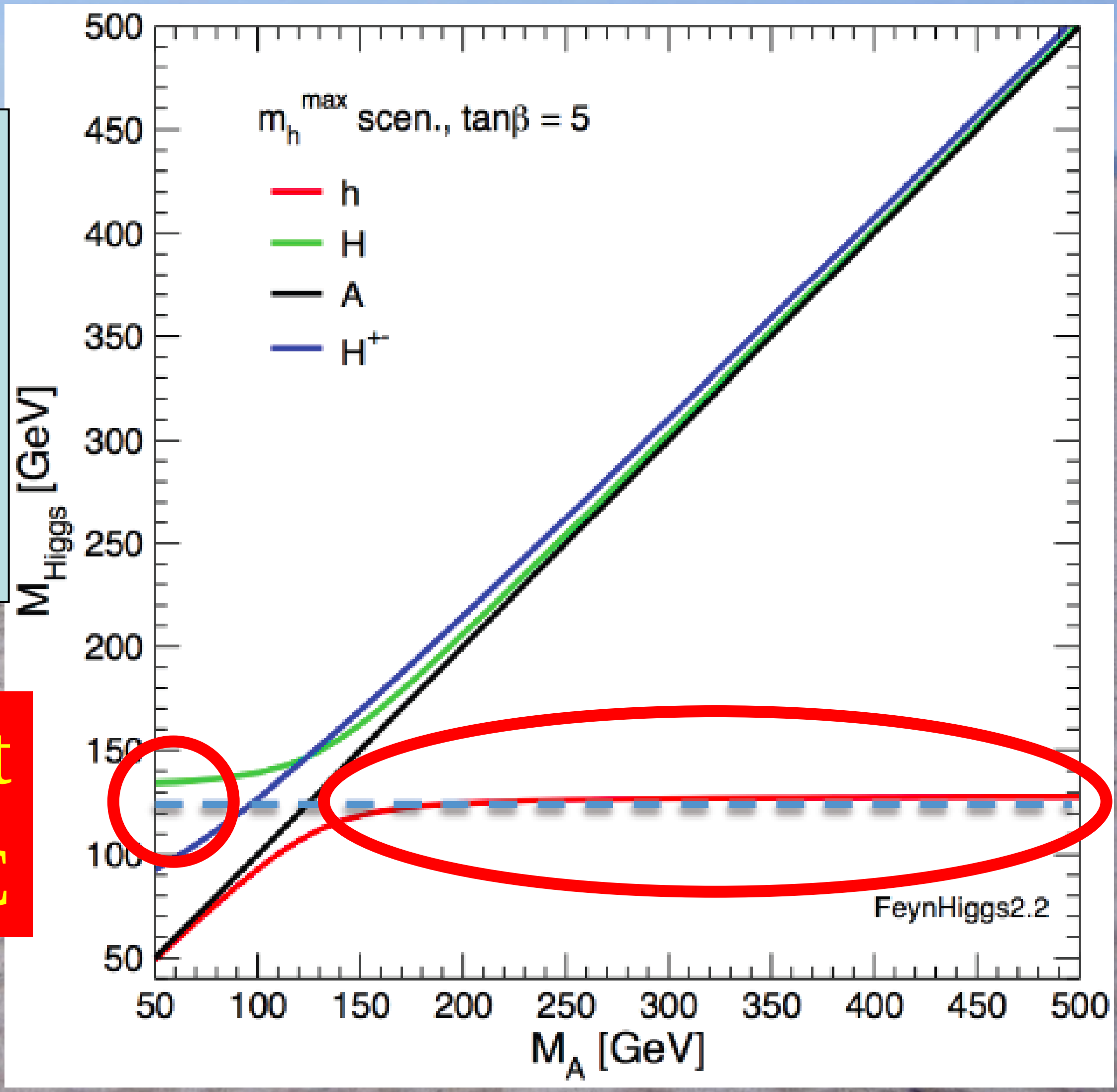
$$G_\mu m^4_{\mathrm{t}} \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m^2_{\mathrm{t}}}\right)\Big|_{\mathrm{TH}} \sim 1.5\ \mathrm{GeV}$$

MSSM Higgs Masses & Couplings

Lightest Higgs mass up to ~ 130 GeV

Heavy Higgs masses quite close

Consistent With LHC



MSSM Higgs Couplings

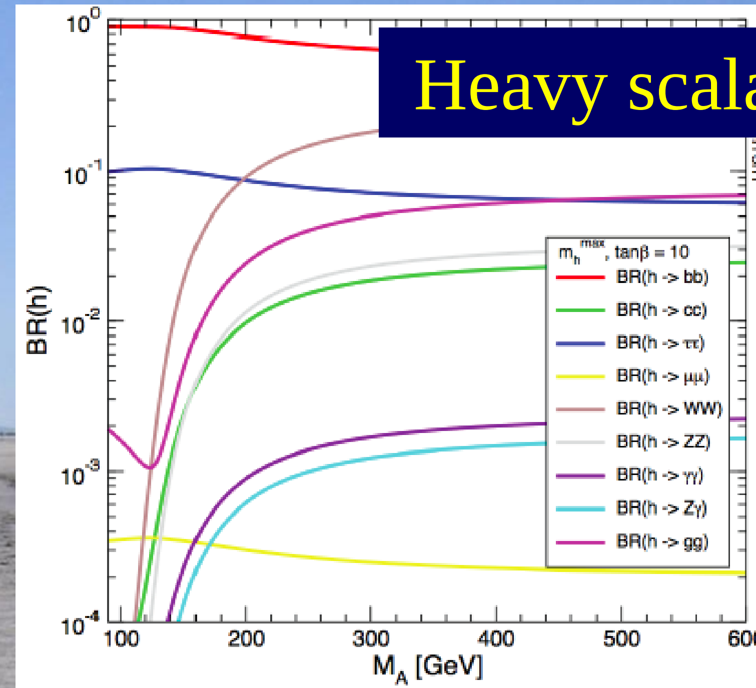
$$g_{hVV} = \sin(\beta-\alpha)\, g_{HVV}^{SM},$$

$$g_{HVV} = \cos(\beta-\alpha)\, g_{HVV}^{SM}$$

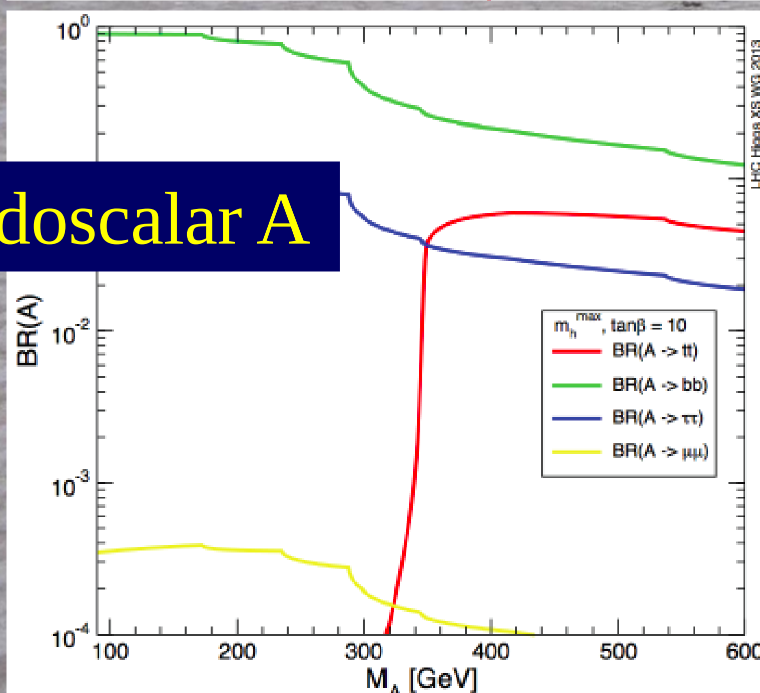
$$g_{hAZ} = \cos(\beta-\alpha)\, \frac{g'}{2\cos\theta_W}.$$

$$g_{hb\bar{b}}, g_{h\tau^+\tau^-} = -\frac{\sin\alpha}{\cos\beta}\, g_{Hb\bar{b},H\tau^+\tau^-}^{SM}$$

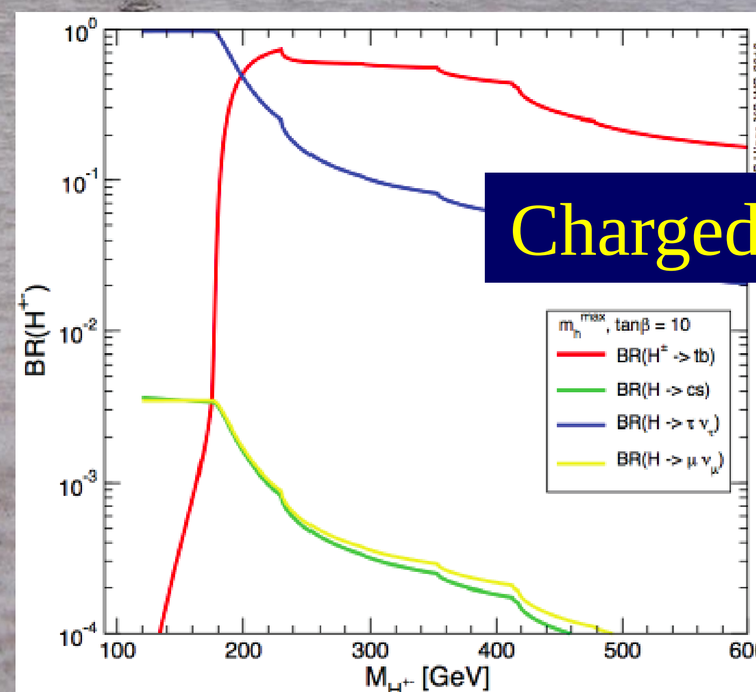
Heavy scalar H



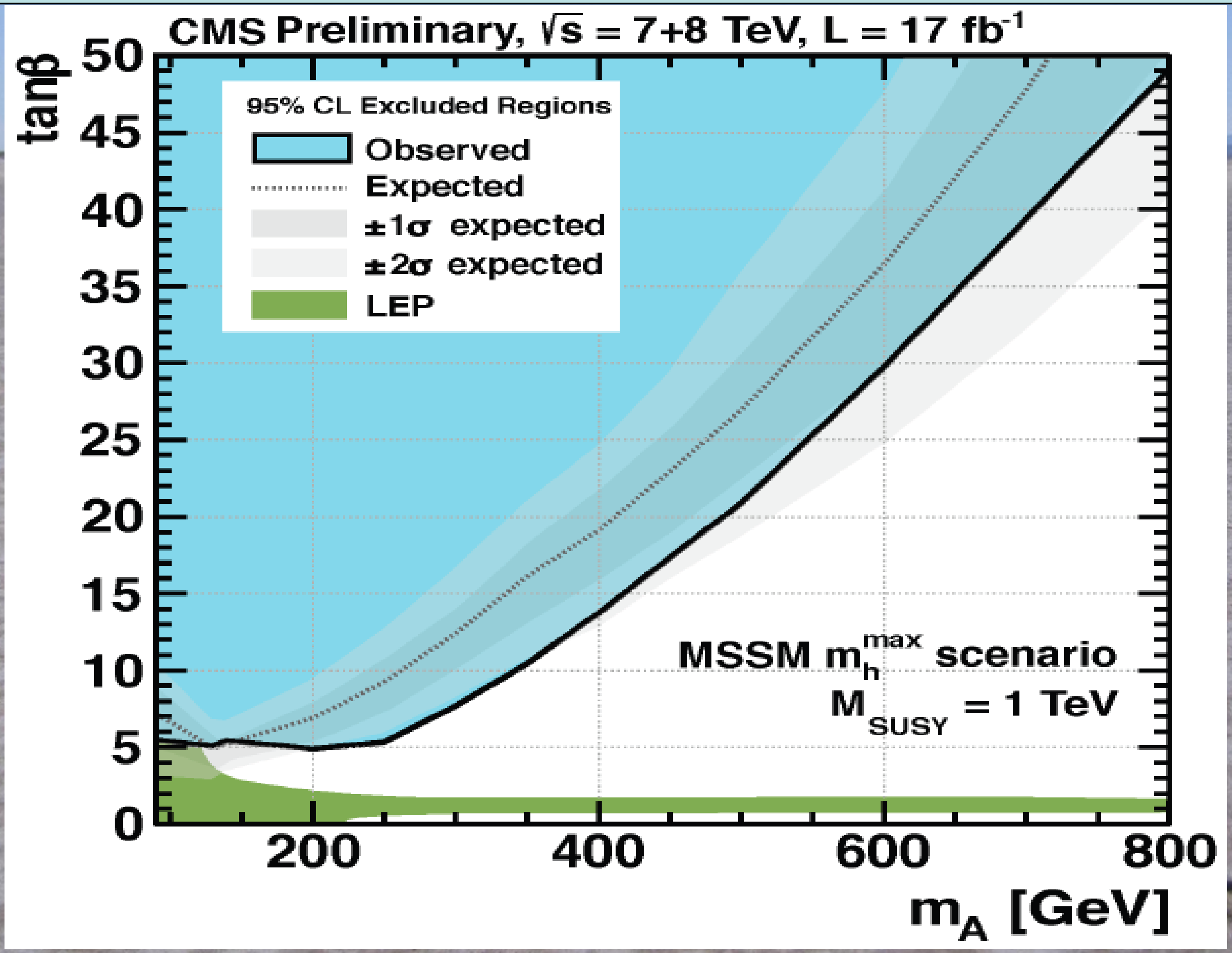
Pseudoscalar A



Charged $H^\pm$



Limits on Heavy MSSM Higgses

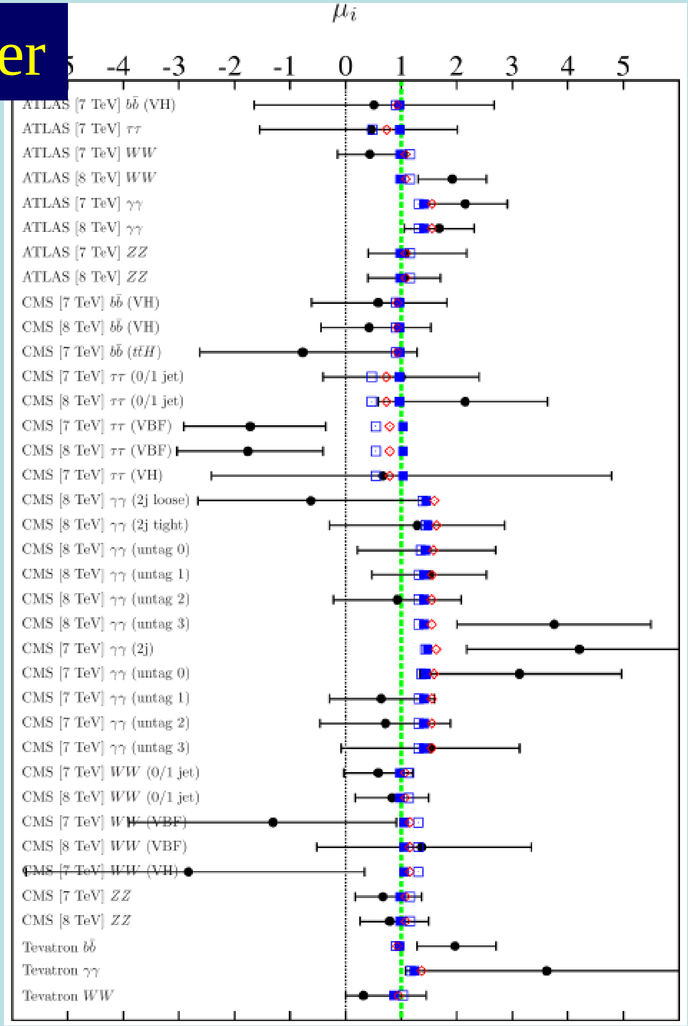


Bechtle et al., arXiv:1211.1955

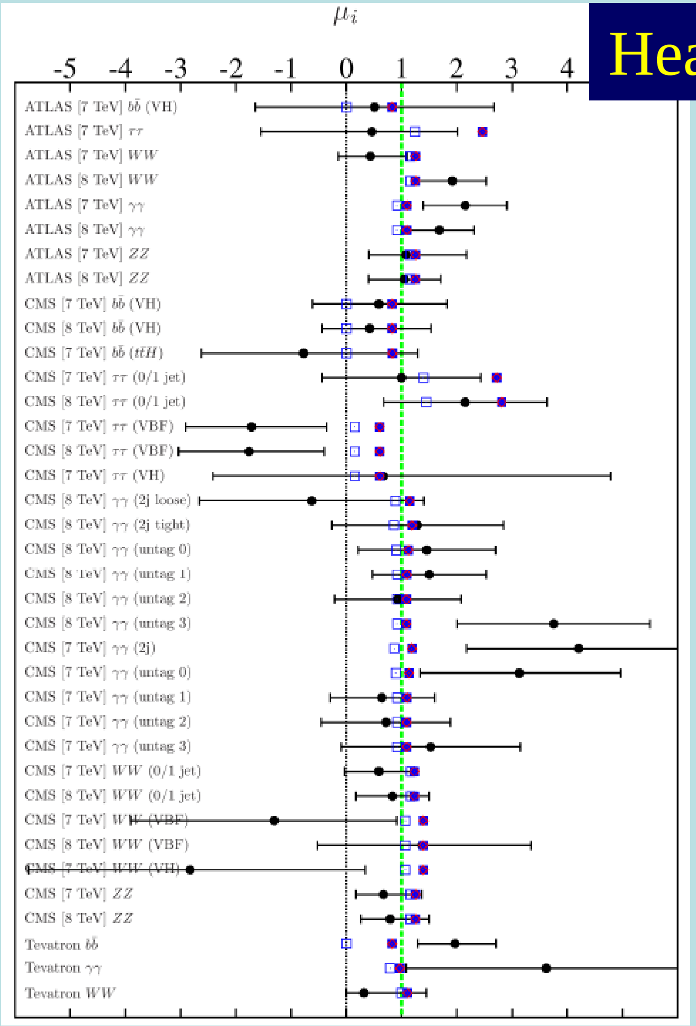
Maybe it is a Supersymmetric Duck?

- Fits with lighter/heavier scalar Higgs at 125 GeV

Lighter



Heavier



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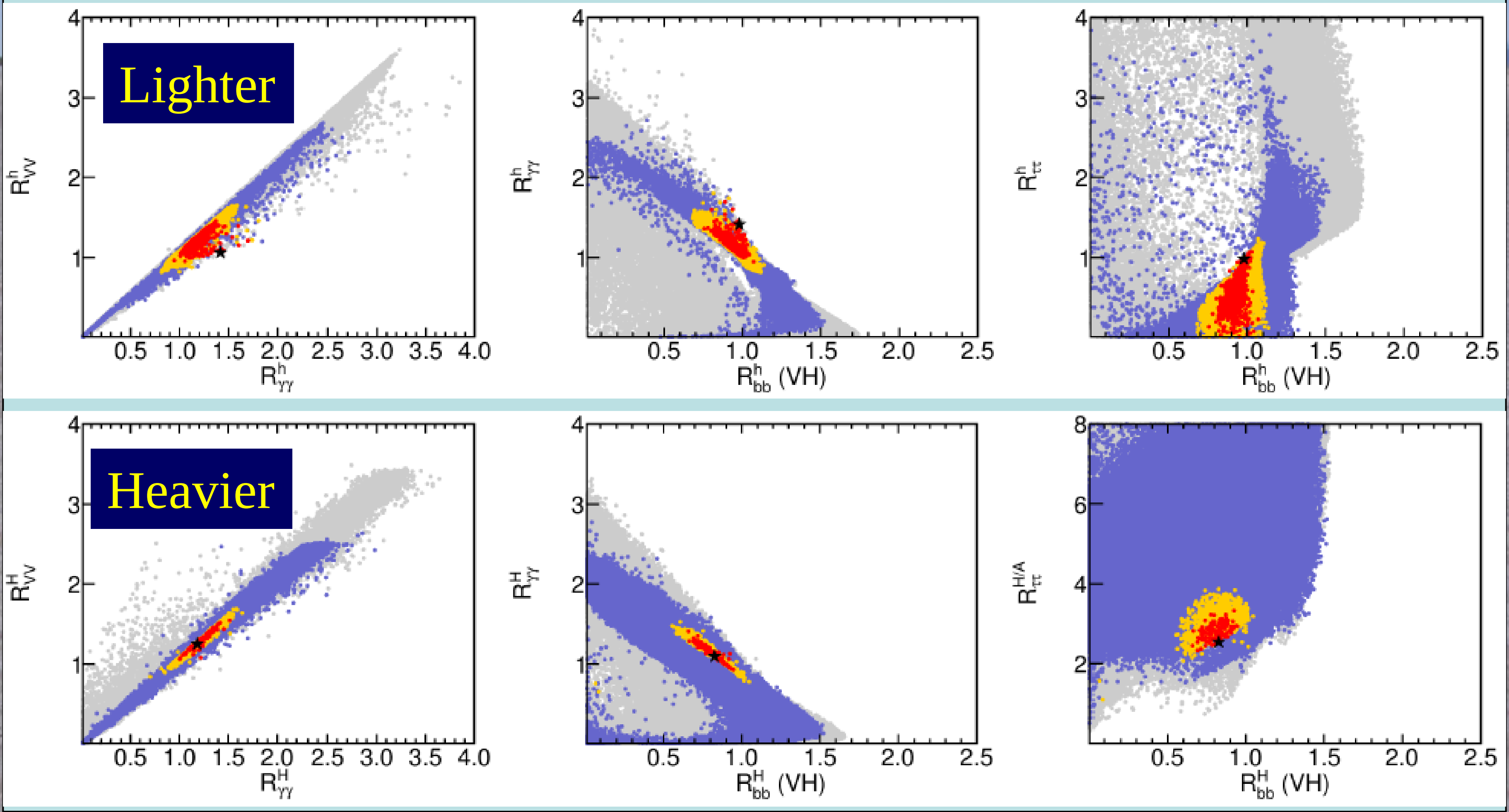


Data

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

Deviation from Standard Model:

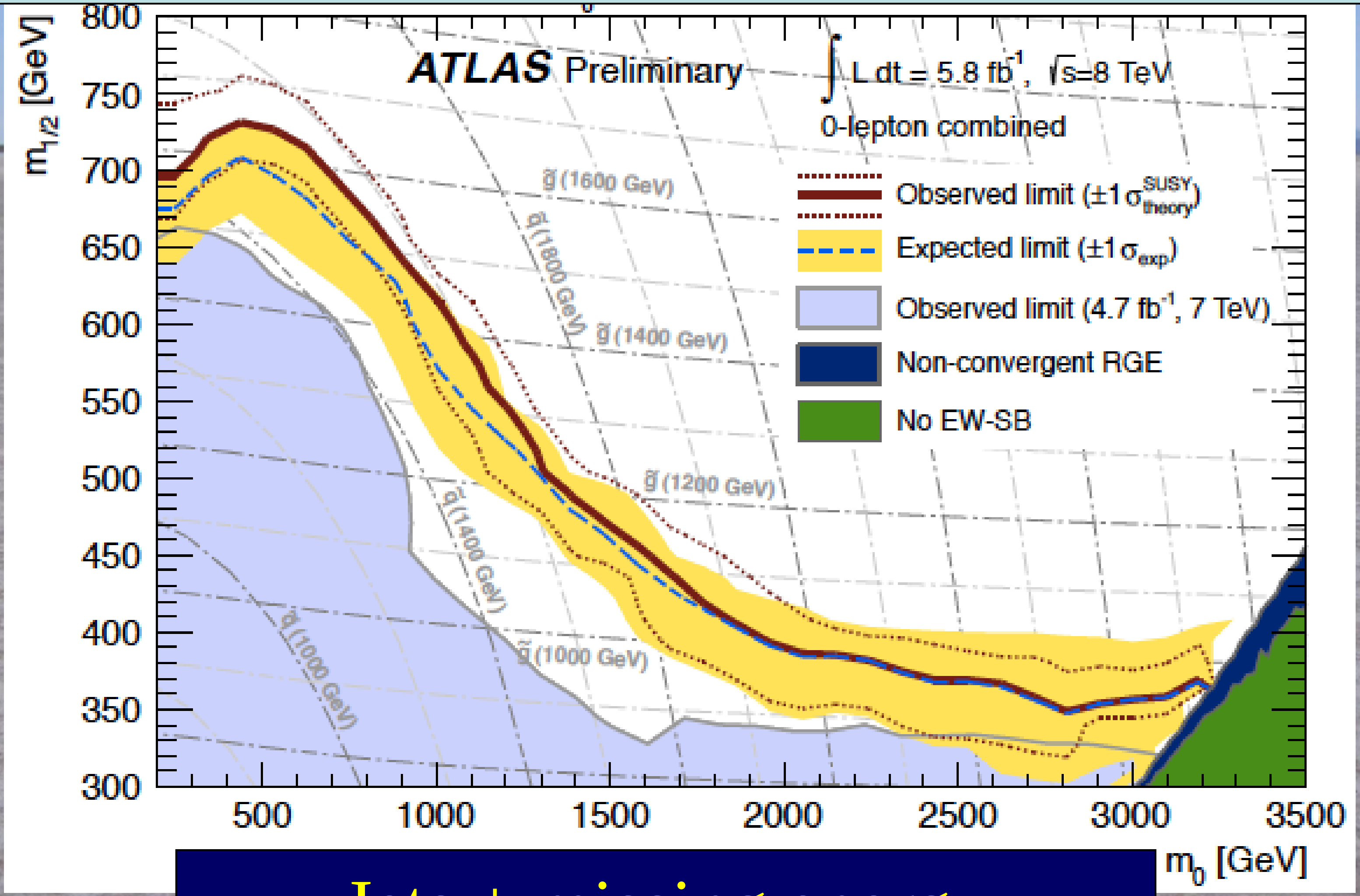
Supersymmetry at low scale, or …?

Observable	Source Th./Ex.	Constraint
m_t [GeV]	[39]	173.2 ± 0.90
$\Delta\alpha_{\rm had}^{(5)}(m_Z)$	[38]	0.02749 ± 0.00010
M_Z [GeV]	[40]	91.1875 ± 0.0021
Γ_Z [GeV]	[24] / [40]	$2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$
$\sigma_{\rm had}^0$ [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
$\sin^2\theta_{\rm w}^\ell(Q_{\rm fb})$	[24] / [40]	0.2324 ± 0.0012
M_W [GeV]	[24] / [40]	$80.399 \pm 0.023 \pm 0.010_{\rm SUSY}$
$\mathrm{BR}_{b\to s\gamma}^{\rm EXP}/\mathrm{BR}_{b\to s\gamma}^{\rm SM}$	[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
$\mathrm{BR}_{K\to\mu\nu}$ [illegible]	[27] / [44]	$1.008 \pm 0.014_{\rm EXP+TH}$
$\mathrm{BR}_{K\to\pi\nu\bar\nu}^{\rm EXP}/\mathrm{BR}_{K\to\pi\nu\bar\nu}^{\rm SM}$	[45]/ [46]	< 4.5
$\Delta M_{B_s}^{\rm EXP}/\Delta M_{B_s}^{\rm SM}$	[45] / [47,48]	$0.97 \pm 0.01_{\rm EXP} \pm 0.27_{\rm SM}$
$\frac{(\Delta M_{B_s}^{\rm EXP}/\Delta M_{B_s}^{\rm SM})}{(\Delta M_{B_d}^{\rm EXP}/\Delta M_{B_d}^{\rm SM})}$	[27] / [42,47,48]	$1.00 \pm 0.01_{\rm EXP} \pm 0.13_{\rm SM}$
$\Delta\epsilon_K^{\rm EXP}/\Delta\epsilon_K^{\rm SM}$	[45] / [47,48]	$1.08 \pm 0.14_{\rm EXP+TH}$
$a_\mu^{\rm EXP} - a_\mu^{\rm SM}$	[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

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

MasterCode: O.Buchmueller, JE et al.

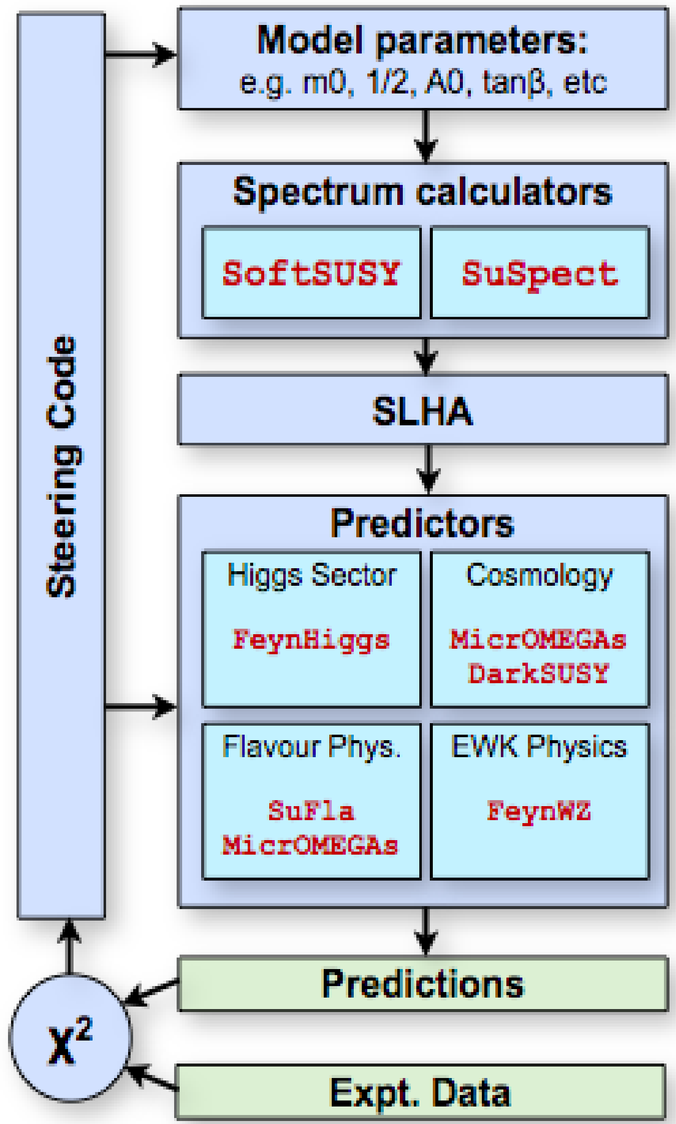
Search with ~ 5/fb @ 8 TeV



Jets + missing energy

MasterCode

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

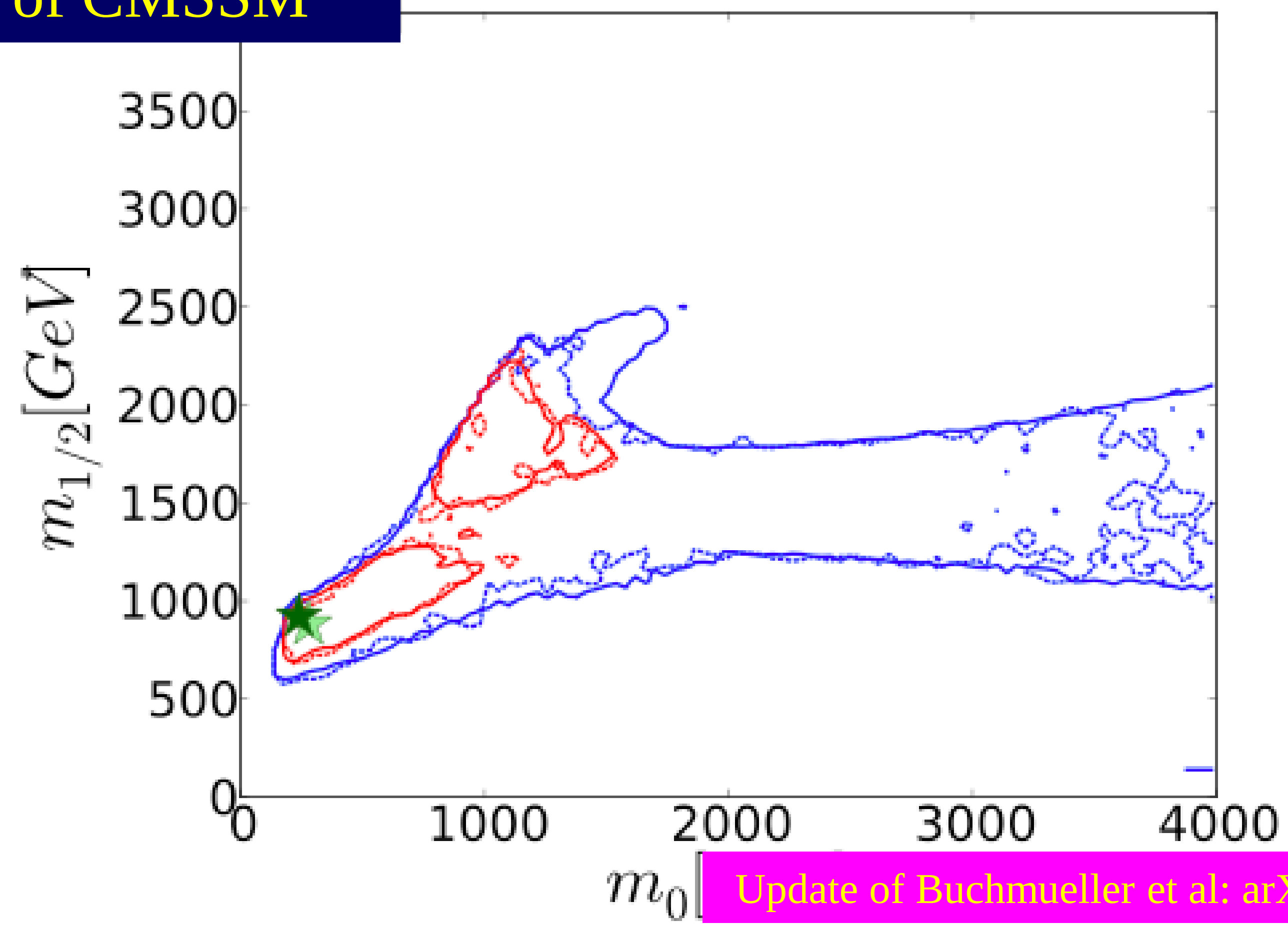


O. Buchmueller, R. Cavanaugh, *M. Citron*, A. De Roeck, M.J. Dolan, J.E., H. Flacher, S. Heinemeyer, G. Isidori, J. Marrouche, D. Martinez Santos, *S. Nakach*, K.A. Olive, *S. Rogerson*, F.J. Ronga, *K.J. de Vries*, G. Weiglein

Post-LHC, Post-XENON100

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

Scan of CMSSM



Update of Buchmueller et al: arXiv:1207.3715

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

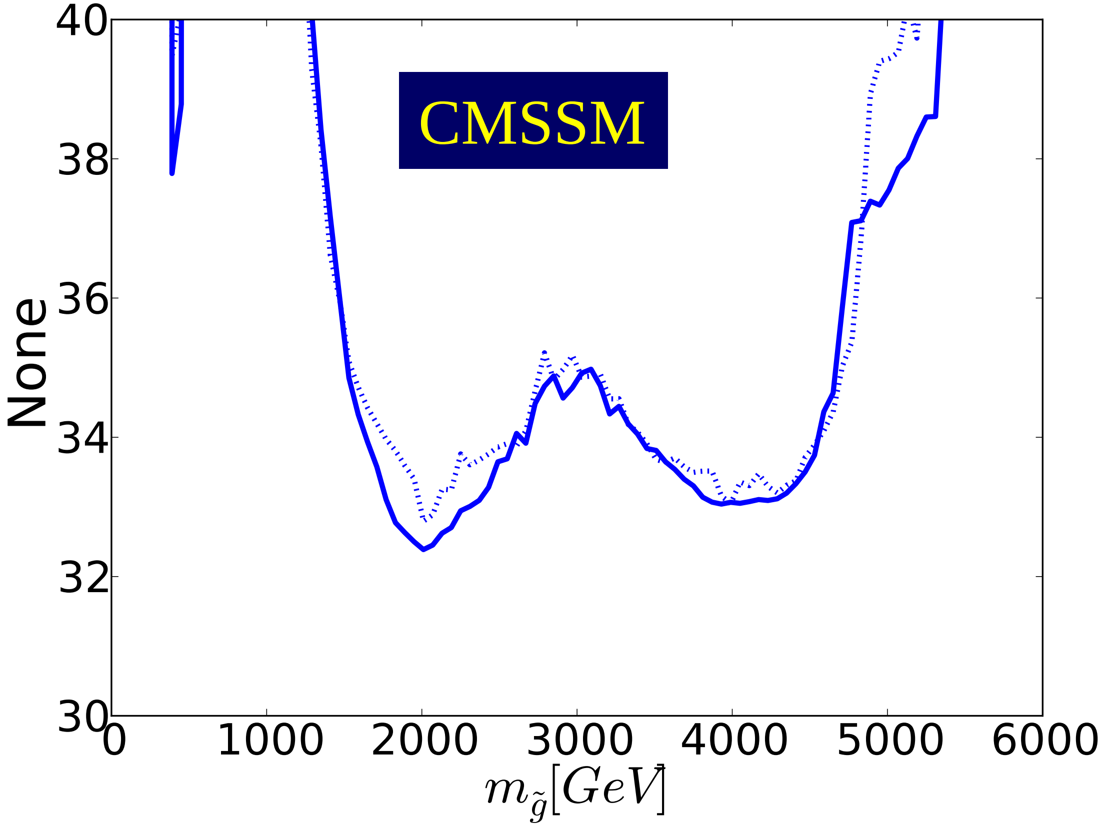
p-value of simple models < 10%

Post-LHC, Post-XENON100

mastercode

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

Gluino mass



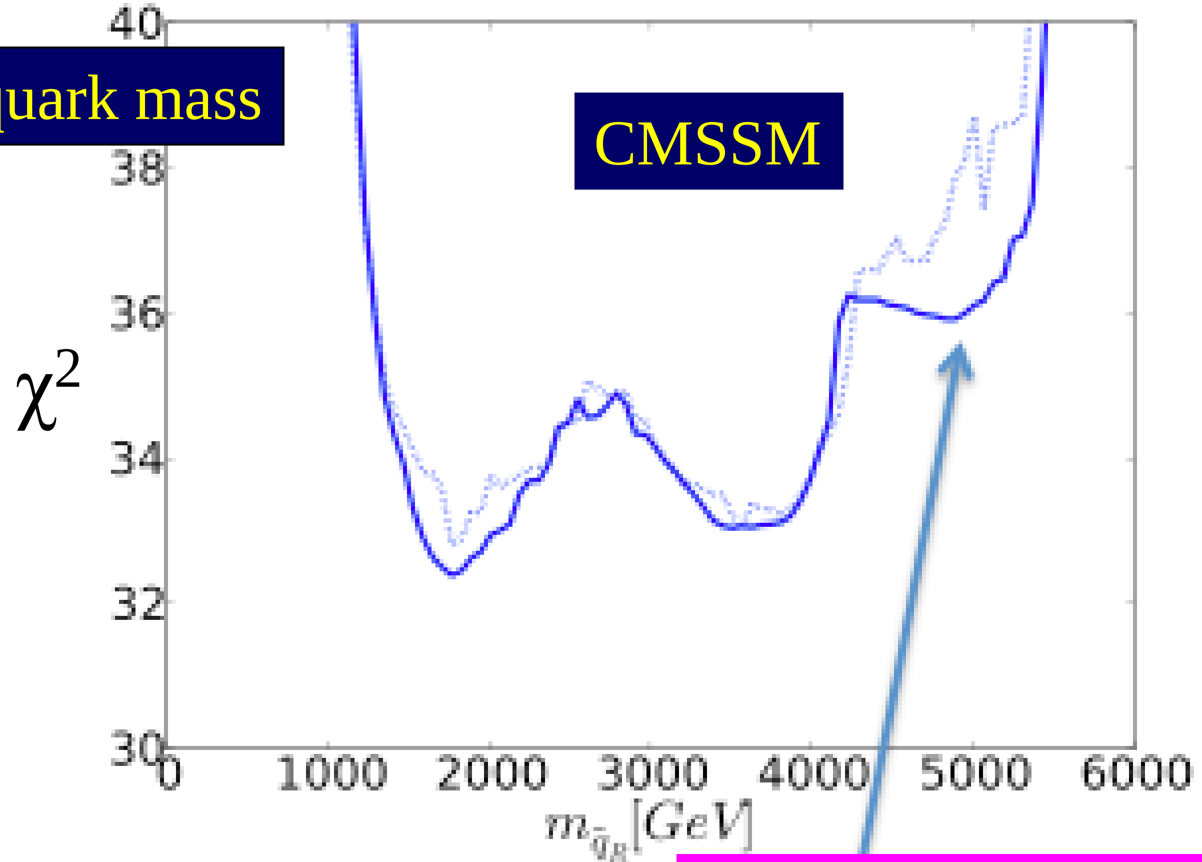
Update of Buchmueller, JE et al: arXiv:1207.3715

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

Squark mass

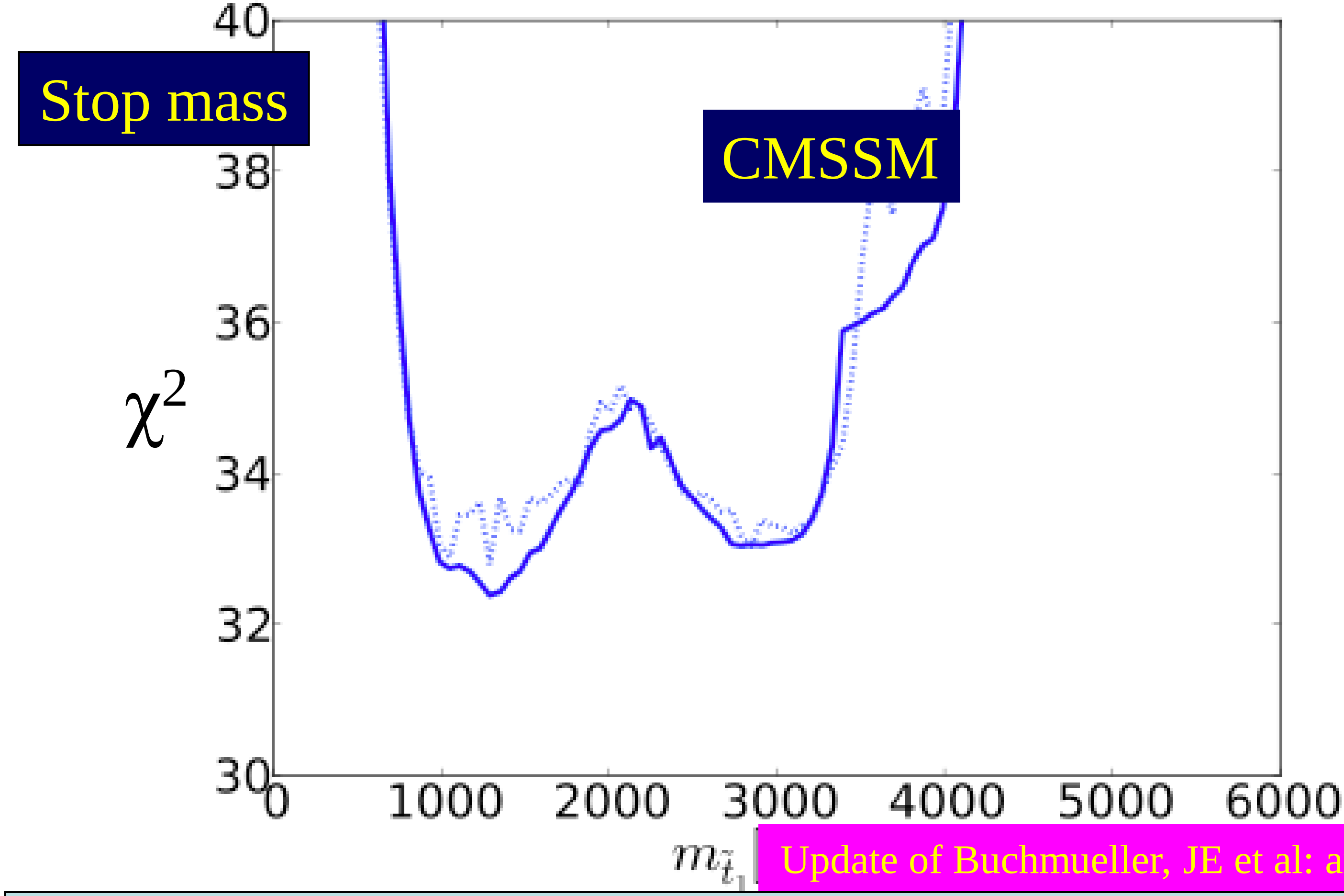


Update of Buchmueller, JE et al: arXiv:1207.3715

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

Post-LHC, Post-XENON100

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



Update of Buchmueller, JE et al: arXiv:1207.3715

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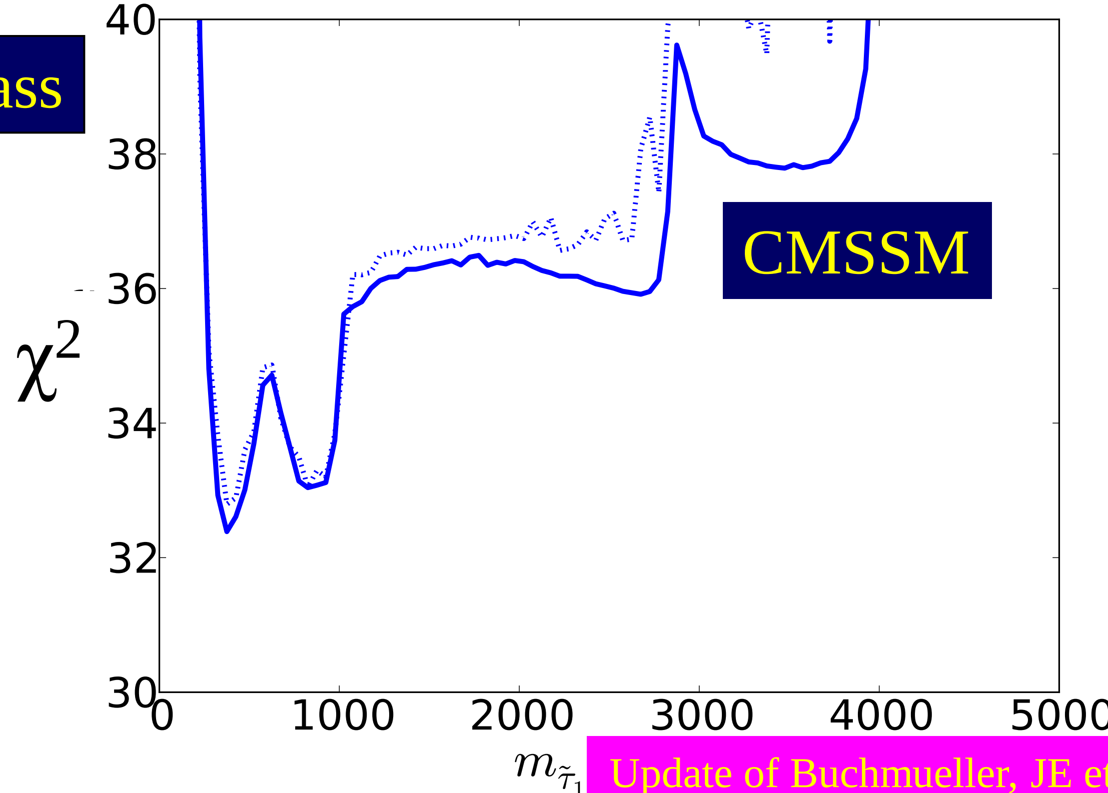
Favoured values of stop mass significantly below gluino, other squarks

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

Some Questions

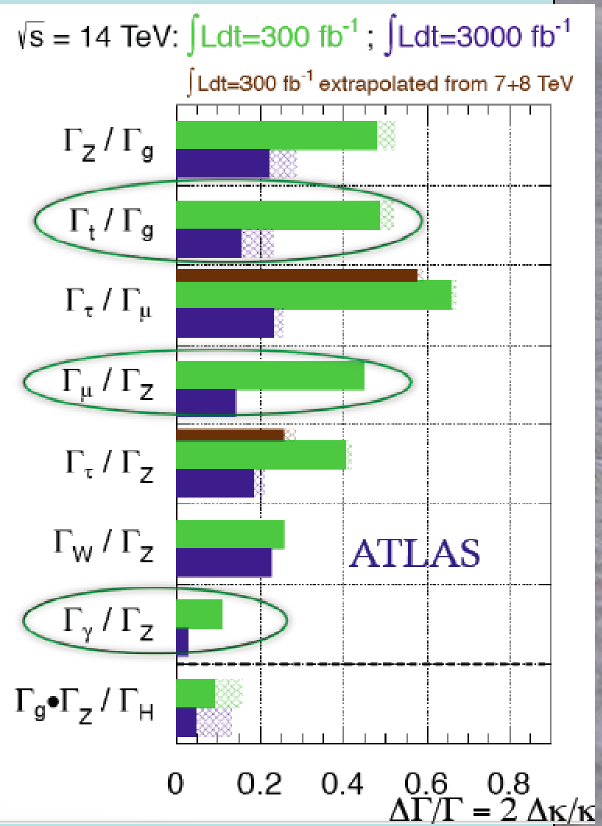
- What is it?
  - –Higgs or …?
- What else is there?
  - –Supersymmetry or …?
- What next?
  - –A Higgs factory or …?

What Next: A Higgs Factory?

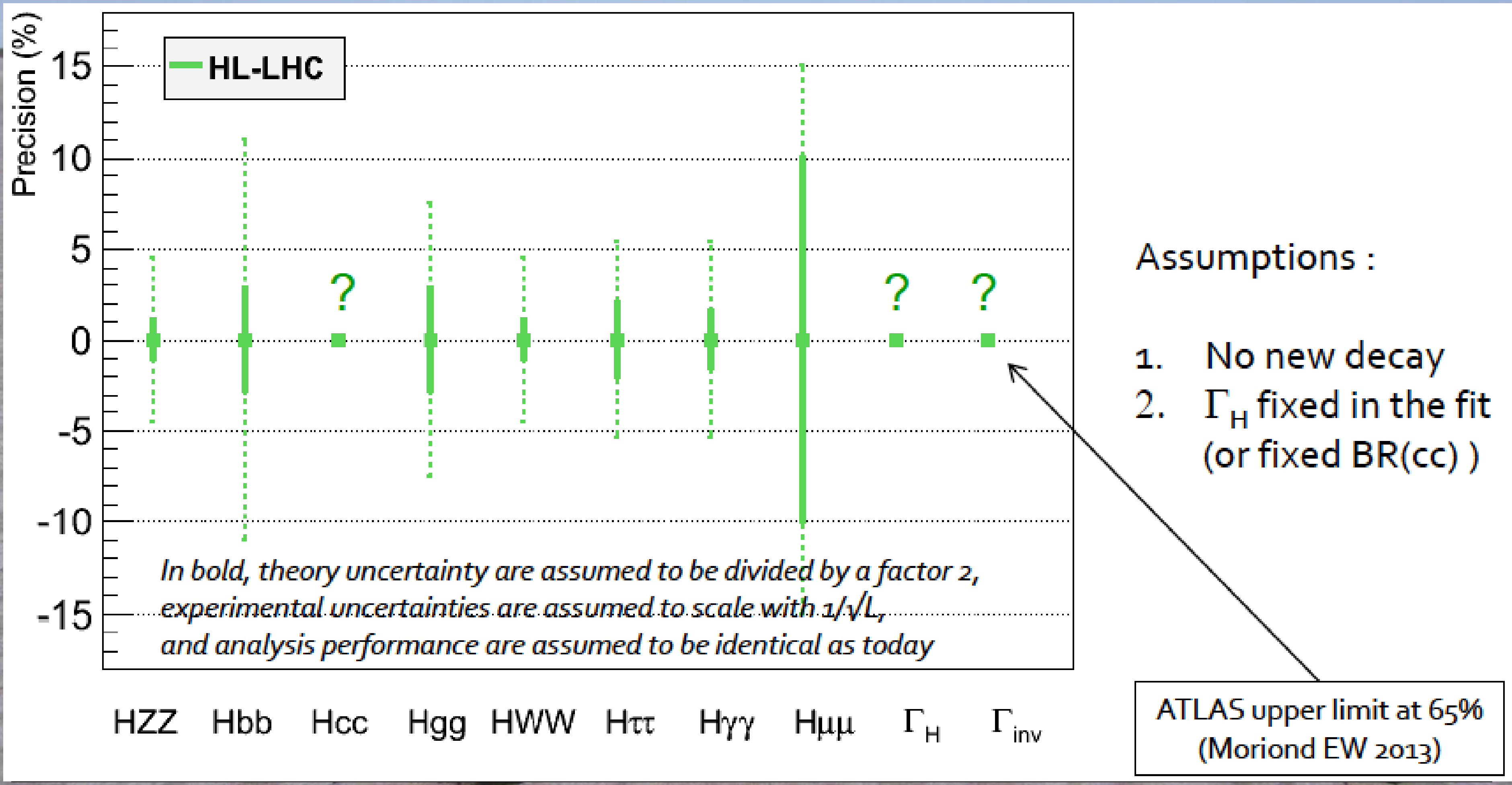
To study the ‘Higgs’ in detail:

- 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



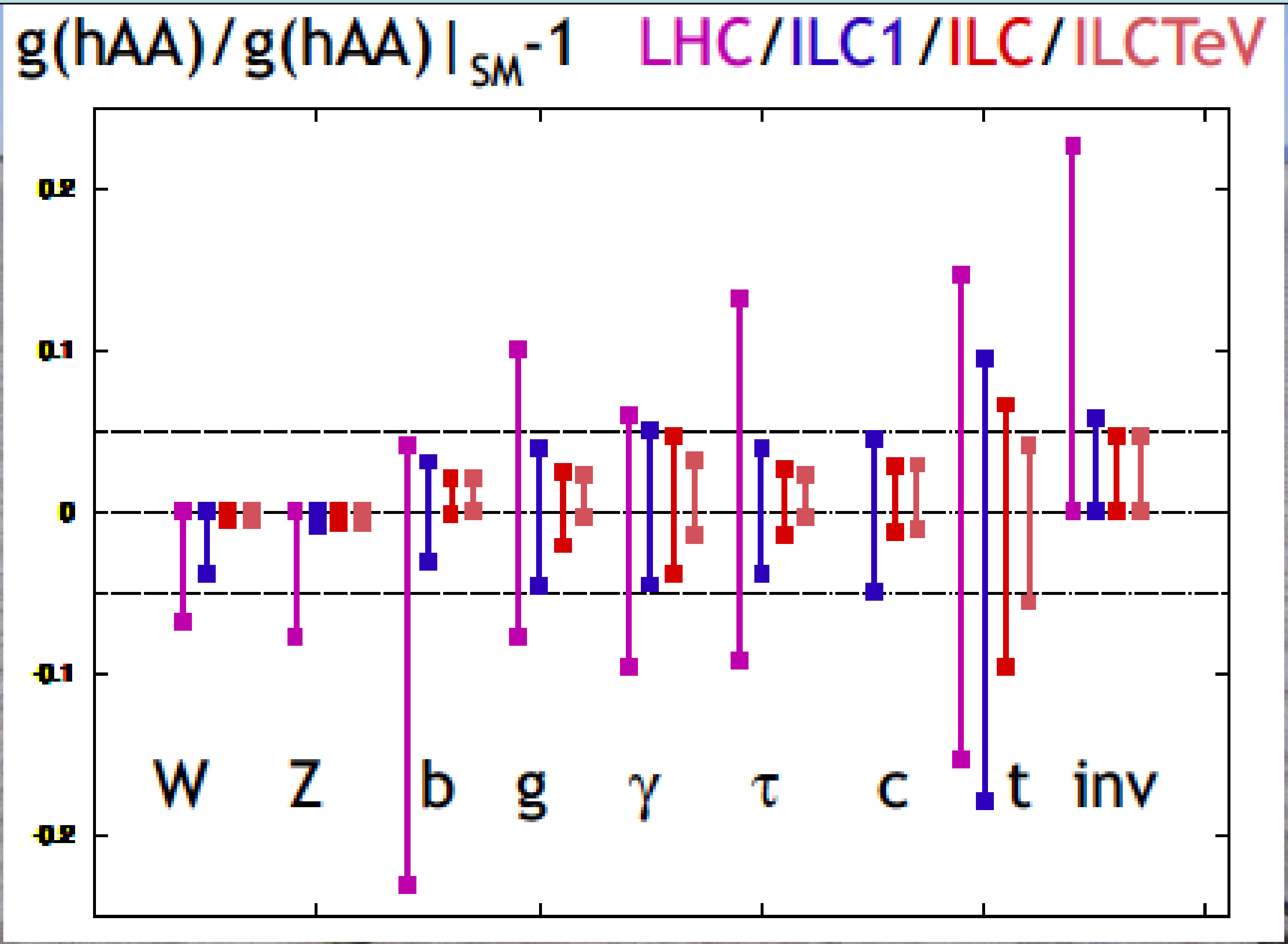
Possible High-Luminosity LHC Measurements



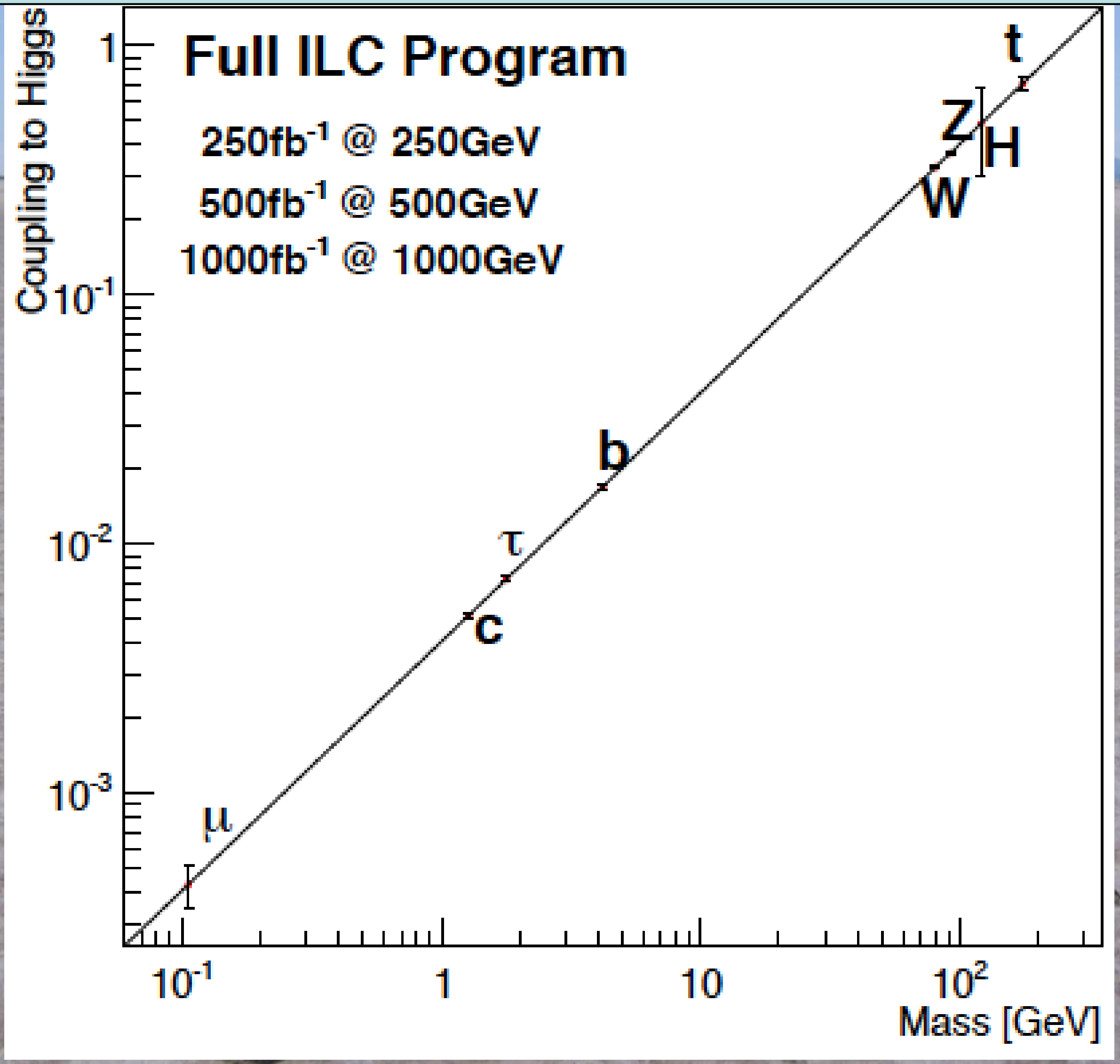
Assumptions :

1. No new decay
2. Γ_H fixed in the fit (or fixed BR(cc))

Possible ILC Measurements

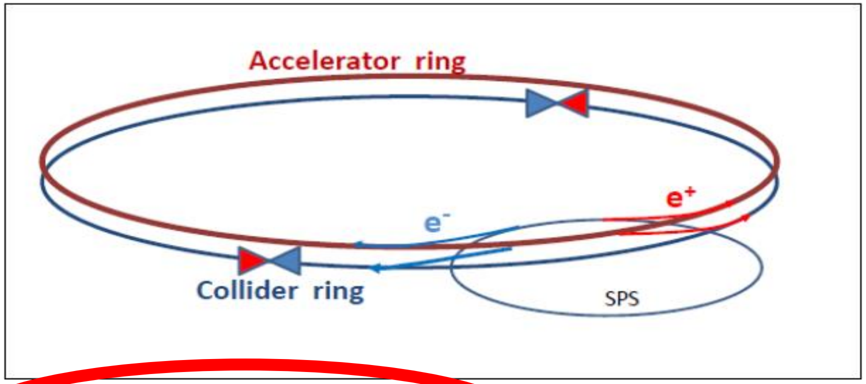


Coupling Measurements @ ILC



What Higgs Factory?

Circular e^+e^- colliders



E.g., LEP3:

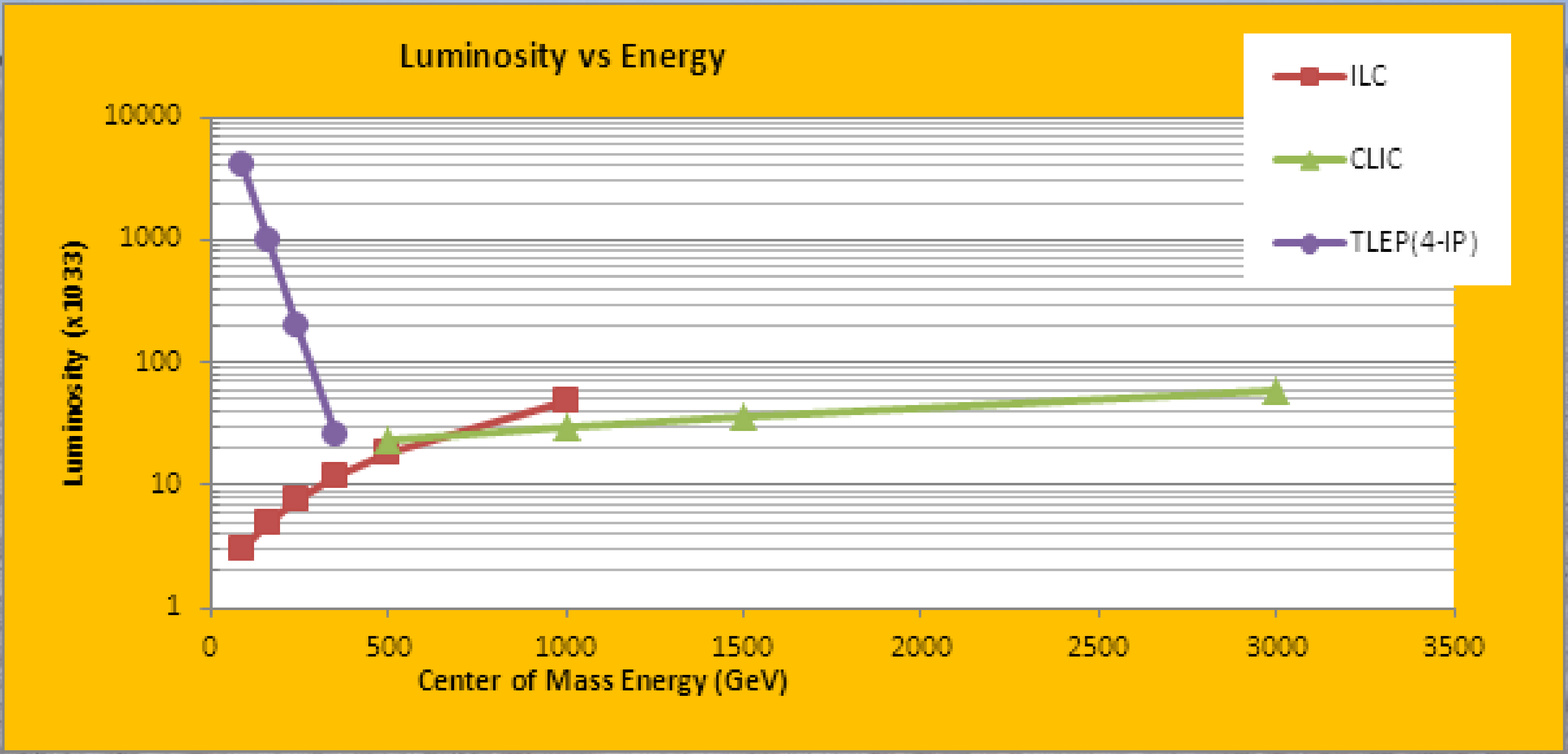
- $\sqrt{s}$ = 240 GeV in the LHC tunnel to produce $e^+e^- \rightarrow ZH$ events
- Short beam lifetime (~10 mins) requires two ring scheme
  - Top up injection from 240 GeV "accelerator ring"
  - "Collider ring" supplying 2-4 interaction points $L = 10^{34}\ cm^{-2}s^{-1}$ per IP
    - Re-use ATLAS 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 of LHC ring
  - 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

E.g., TLEP:

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

New large tunnel could also be used for VHE pp collisions

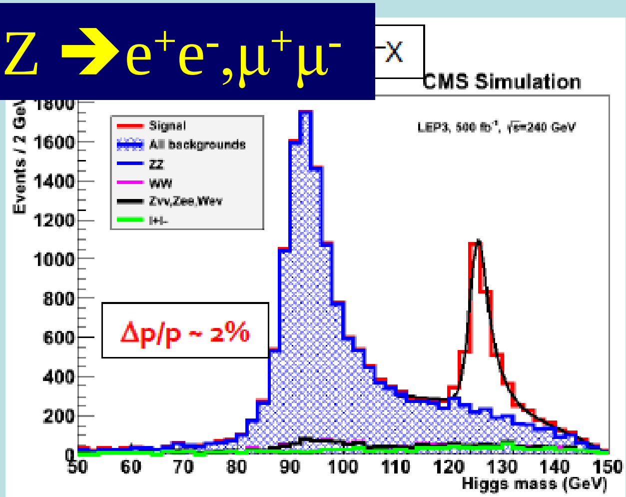
Possible Luminosities of e^+e^- Colliders



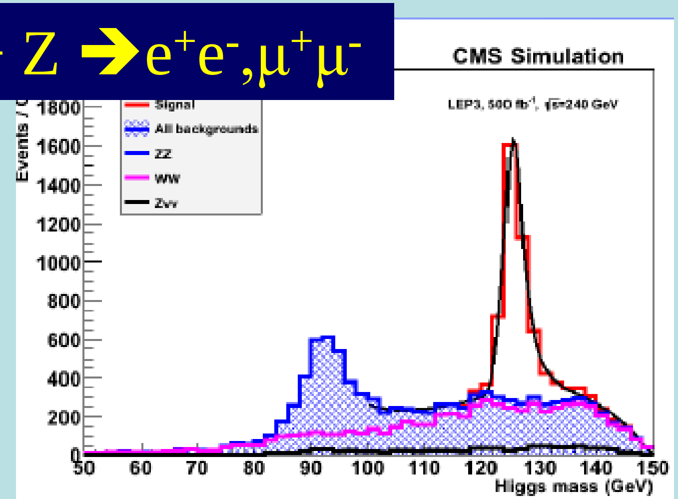
Possible LEP3 Measurements

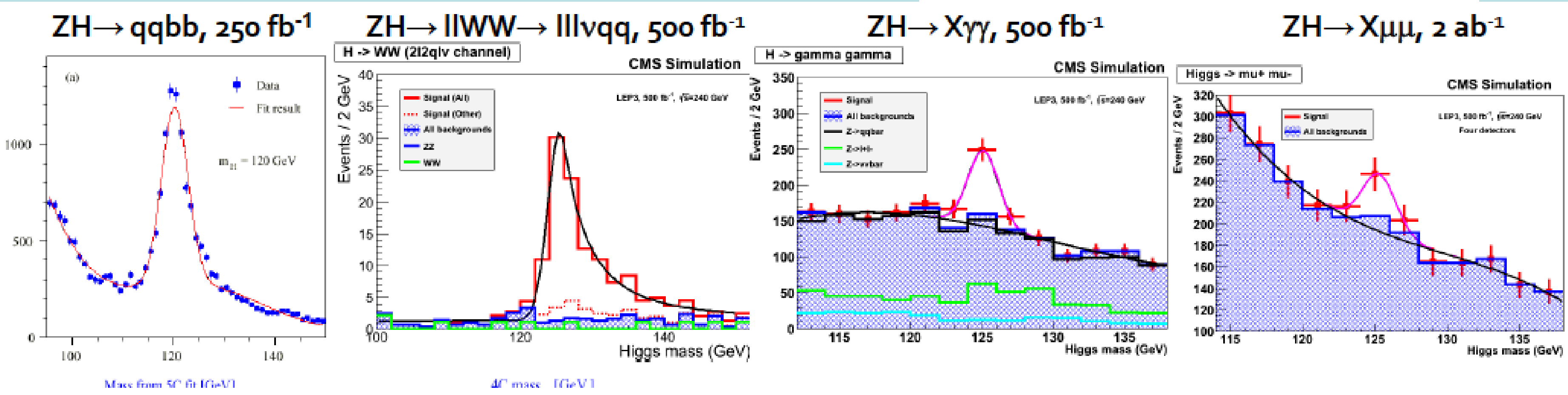
- Simulations based on CMS detector

Higgs + Z $\rightarrow e^+e^-, \mu^+\mu^-$

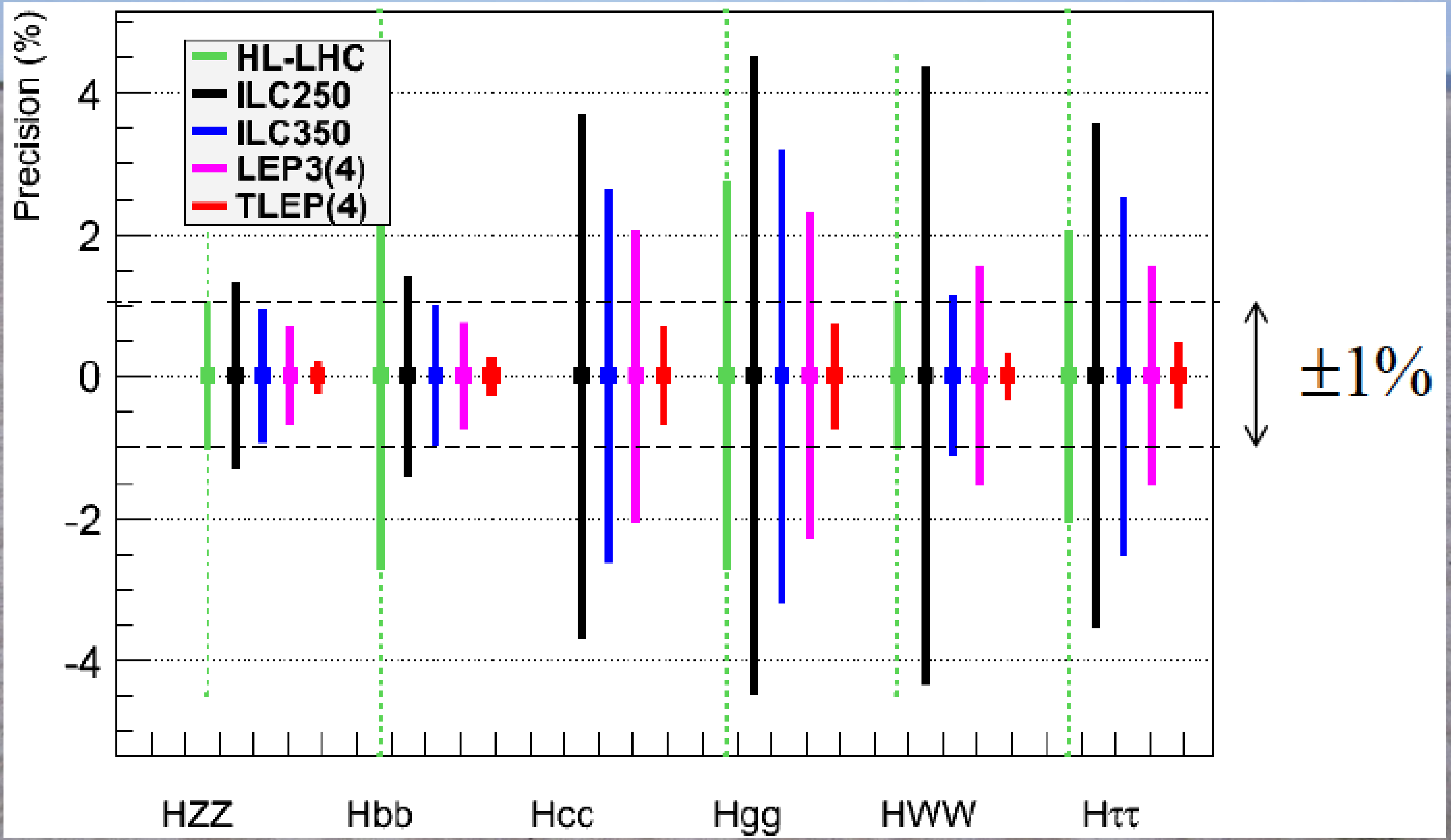


H_{inv} + Z $\rightarrow e^+e^-, \mu^+\mu^-$





Comparison of Possible Higgs Factory Measurements



Higgs Factory Summary

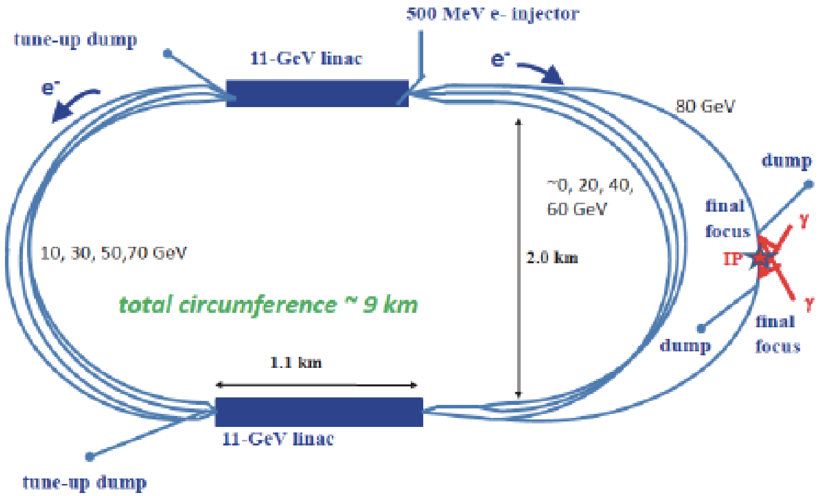
Best precision

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%

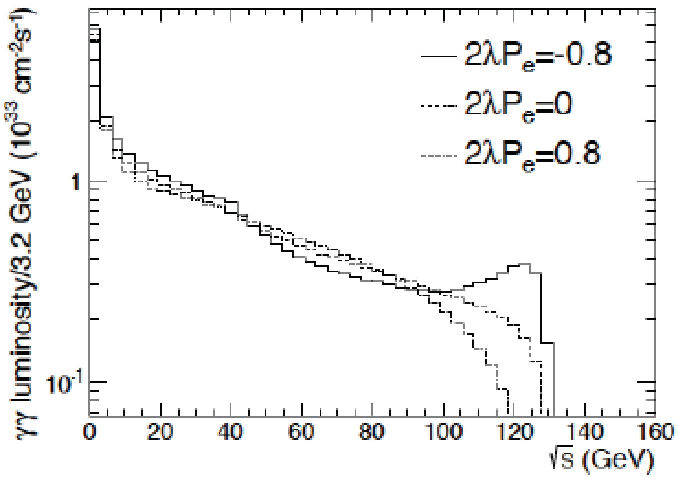
ICFA Higgs Factory Workshop
Fermilab, Nov. 2012

What Higgs Factory?

Photon-photon colliders



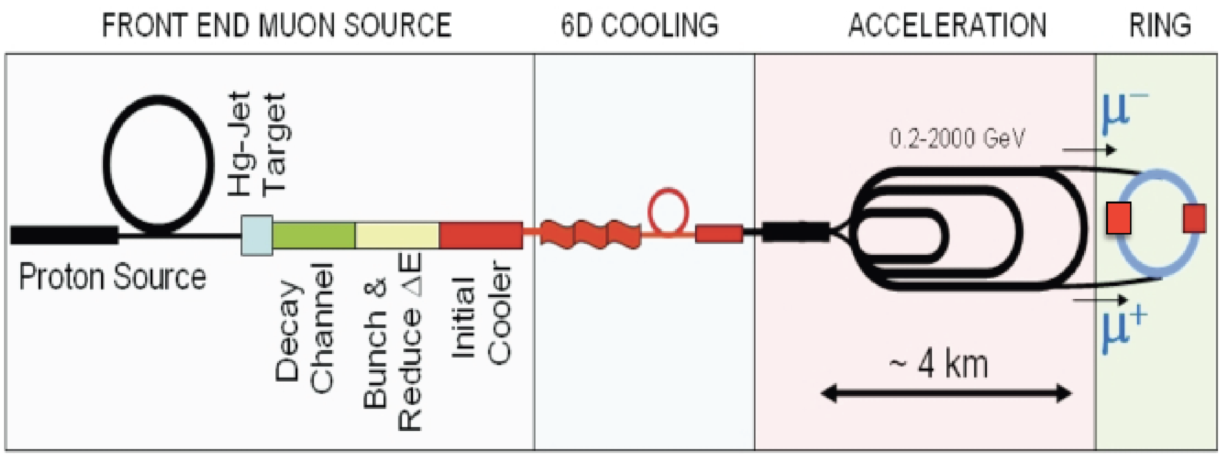
$\gamma\gamma$ luminosity as function of √s for different polarization of laser photons (λ) and electrons (P_e)



- Photon-photon collisions at √s = 125 GeV for $\gamma\gamma \rightarrow$ H (s-channel)
- E.g., SAPPHiRE:
- Pair of recirculating linacs similar in design to those proposed for the LHeC
  - E_{beam} = 80 GeV
- Laser back-scatter system peak power 6 x 10^{21} Wm^{-2}
  - Needs R&D!
- $\gamma\gamma$ Luminosity ~0.3 x 10^{34} $cm^{-2}s^{-1}$ for √s ≈ 125 GeV
- Some advantages over e^+e^- for Higgs
  - Lower beam energy
  - Do not need positron source

What Higgs Factory?

Muon collider



- Potential advantages wrt. e^+e^-
- Smaller facility size
  - Synchrotron radiation losses ~ E^4/m^4r
- Smaller energy spread
  - Beamsstrahlung ~ E^4/m^4
- s-channel Higgs production ~m^2

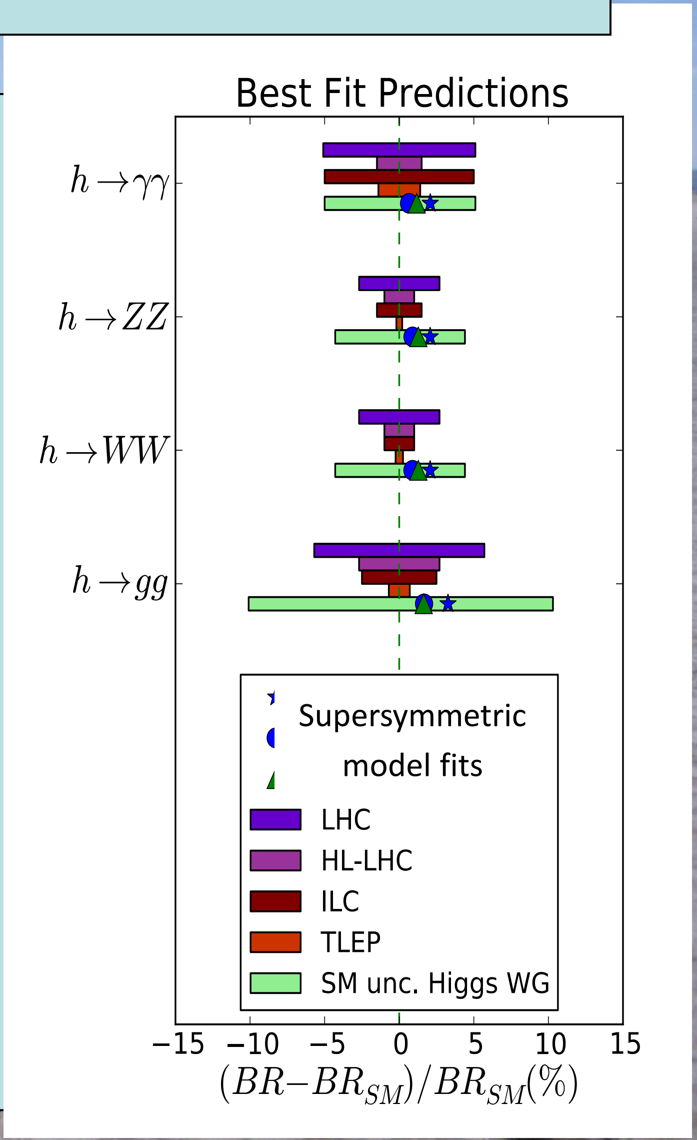
- Target L = 10^{34} $cm^{-2}s^{-1}$ per IP
- Many technical challenges to be faced
  - Intense proton source
  - Muon cooling
  - Can detectors survive muon decay rate and still do the physics?
- Could be a follow-on from (or precursor to) a ν-factory

Future Accelerators

- (What) precision, (how) high energy, neutrinos?
- Which is THE top priority accelerator?
  - Precision: HL-LHC, ILC/CLIC, TLEP, MC, γγ
  - Energy: HE-LHC, VHE-LHC, CLIC, MC
  - Neutrinos: from superbeam to ν factory
- HL-LHC is not a done deal, needs high-tech:
  - 11T dipoles, 13T quads, 500m HTS link, crab cavities
- Worldwide collaborative R&D needed

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**



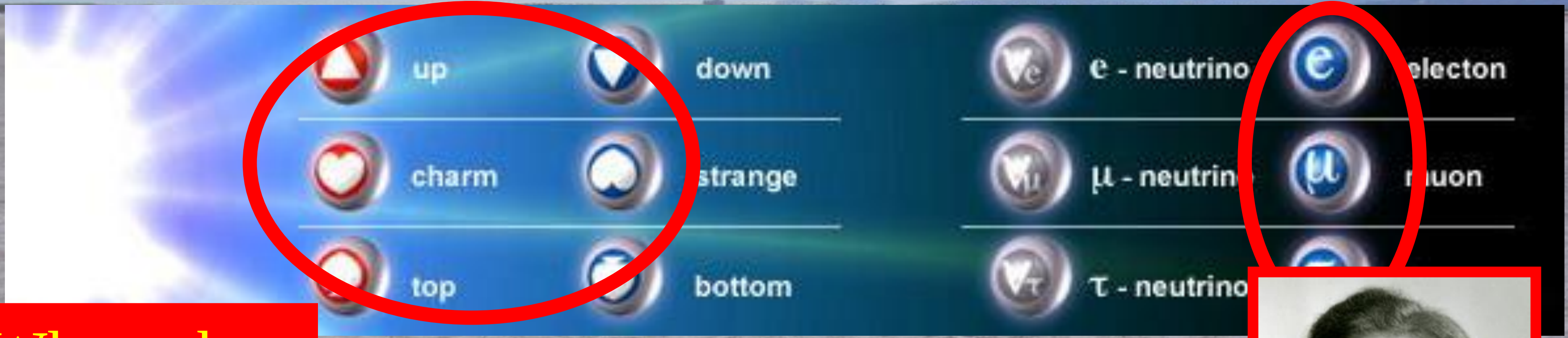
Summary

- 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

The Standard Model

= Cosmic DNA

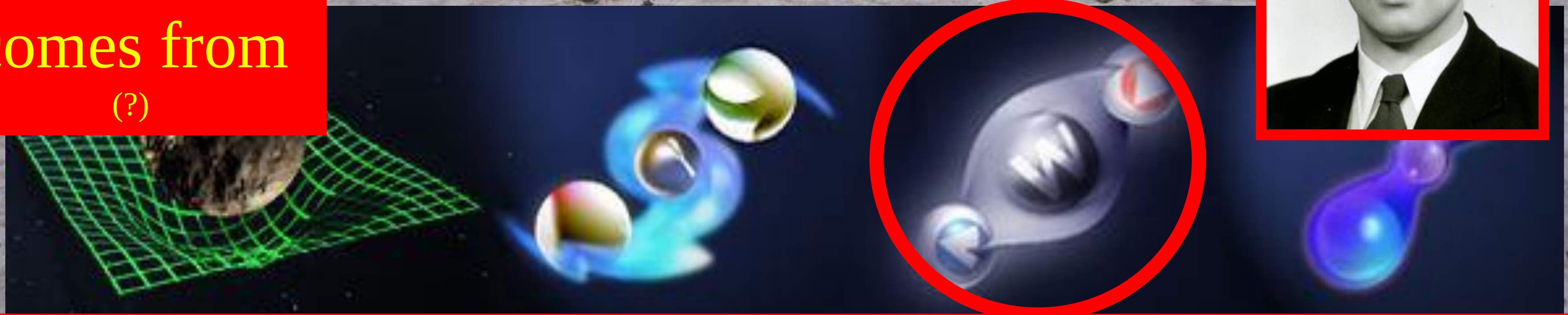
The matter particles



Where the mass comes from

(?)

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force