Fermilab

Higgs Physics: Theoretical Developments

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- The SM Higgs
- What Happened to Naturalness?
- Measuring Higgs Parameters
- Beyond the Standard Model
- Summary

2013 TLEP Workshop

Fermilab

July 25-26, 2013

The Standard Model Higgs

- The SM Higgs:
  - *All properties are determined for given mass.*
  - *Any deviations signal new physics.*

Theory errors (LHC Higgs Cross Section WG) [arXiv:1107.5909v2]

$m(H) = 126\ \text{GeV} \qquad \Gamma(H) = 4.21 \pm 0.16\ \text{MeV}$

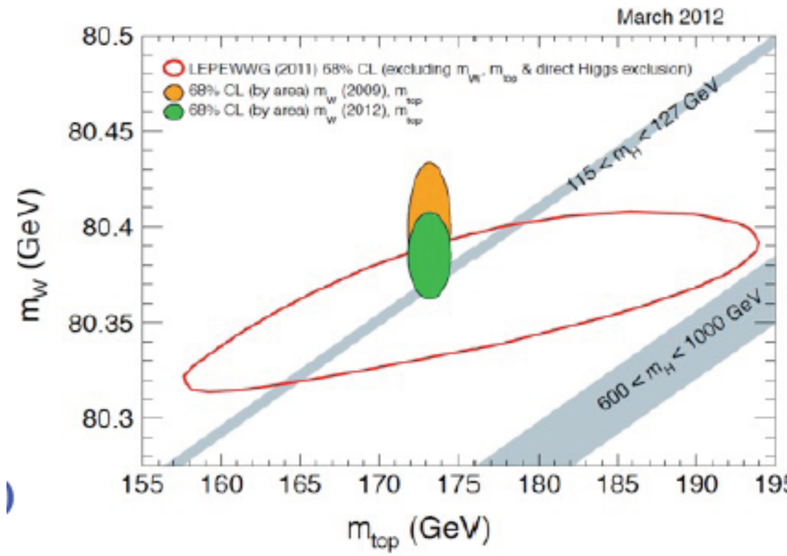
branching fractions : error(%)

$b\bar{b} = 0.561$	(3.4%)	$WW^* = 0.231$	(4.1%)
$\tau\bar{\tau} = 6.15 \times 10^{-2}$	(5.8%)	$ZZ^* = 2.89 \times 10^{-2}$	(4.1%)
$c\bar{c} = 2.83 \times 10^{-2}$	(12.2%)	$gg = 8.48 \times 10^{-2}$	(10.0%)
$\mu^+\mu^- = 2.14 \times 10^{-4}$	(5.8%)	$\gamma\gamma = 2.28 \times 10^{-3}$	(4.9%)
		$Z^0\gamma = 1.62 \times 10^{-3}$	(8.8%)

- Theoretical questions:
  - *Couplings and width SM?*
  - *Scalar self-coupling SM?*
  - *Any additional scalars? EW doublets, triplets or singlets? (e.g. SUSY requires two Higgs doublets)*
  - *Any invisible decay modes?*

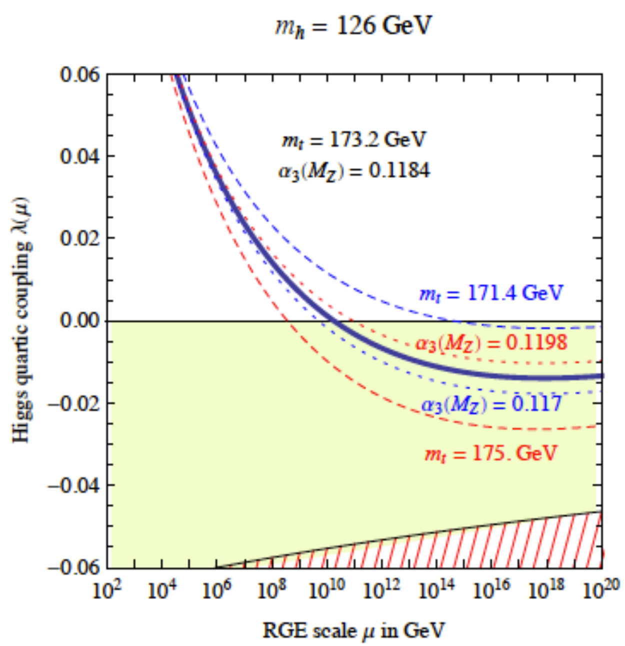
The Standard Model Higgs ?

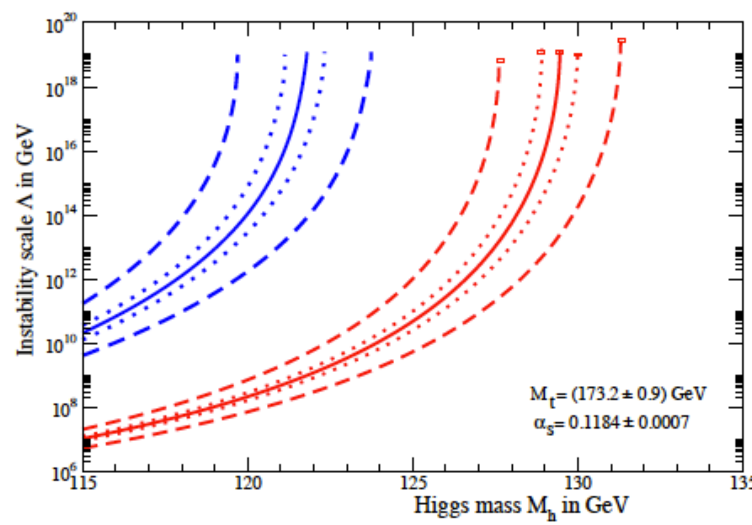
- Indirect measurements are all consistent with a 126 GeV Higgs



- For a 126 GeV Higgs the SM is consistent to the Planck scale; but the vacuum is only metastable above 10^{10} GeV.

Jean Elias-Miro et. al. [arXiv:1112.3022]





- Theorists are intrigued by this edge of stability.

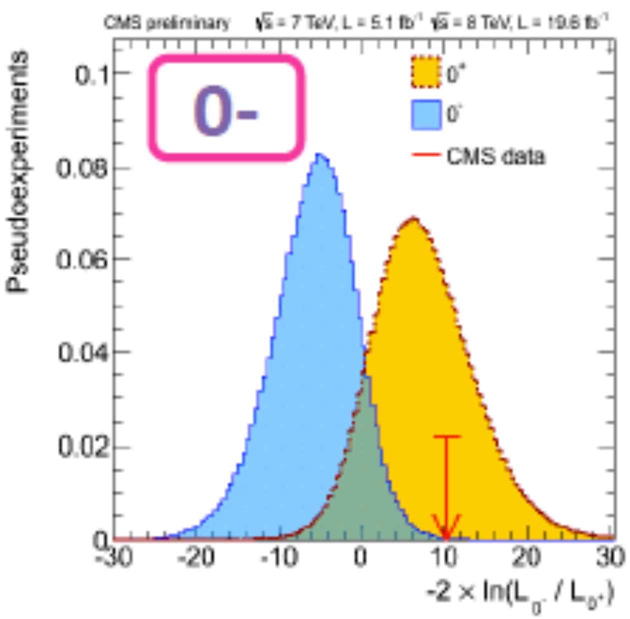
The Standard Model Higgs ?

– EPS 2013 results: (F. Cerutti)

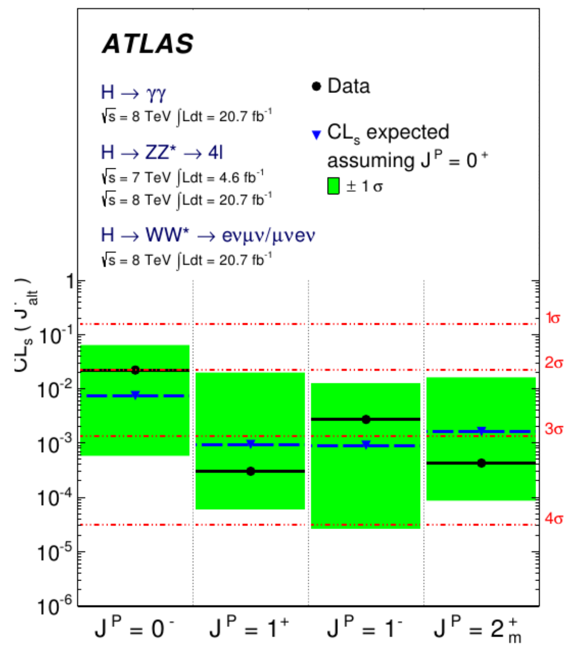
- ATLAS (M. Duehrssen)
  - m_h = 125.5 ± 0.2 (stat) ± 0.6 (sys) GeV
  - μ = 1.33 ± 0.20 ($\gamma\gamma$, WW*, ZZ*)
    1.23 ± 0.18 (+ bb, $\tau\tau$)
  - $\mu_{VBF}/\mu_{ggF+ttH}$ = 1.4 + (stat) (+0.4/-0.3) + (sys) (+0.6/-0.4)
  - VBF production 3.3 σ
- CMS (J. Bendavid)
  - m_h = 125.7 ± 0.3 (stat) ± 0.3 (sys) GeV
  - μ = 0.80 ± 0.14 ($\gamma\gamma$, WW*, ZZ*, bb, $\tau\tau$)
  - $\Gamma < 6.9$ GeV
  - V mediated production 3.2 σ
- Tevatron
  - μ = 1.44 ± 0.60 (bb, WW*, $\tau\tau$, $\gamma\gamma$)

The Standard Model Higgs ?

- Spin and CP:
    - Light pseudoscalars often appear in dynamical EWSB models
    - However they don't couple to WW/ZZ in lowest order.
    - Assuming spin zero - a pure pseudoscalar is experimentally disfavored.
    - Spin 2 is also disfavored.



0- Excluded at 3.2 σ



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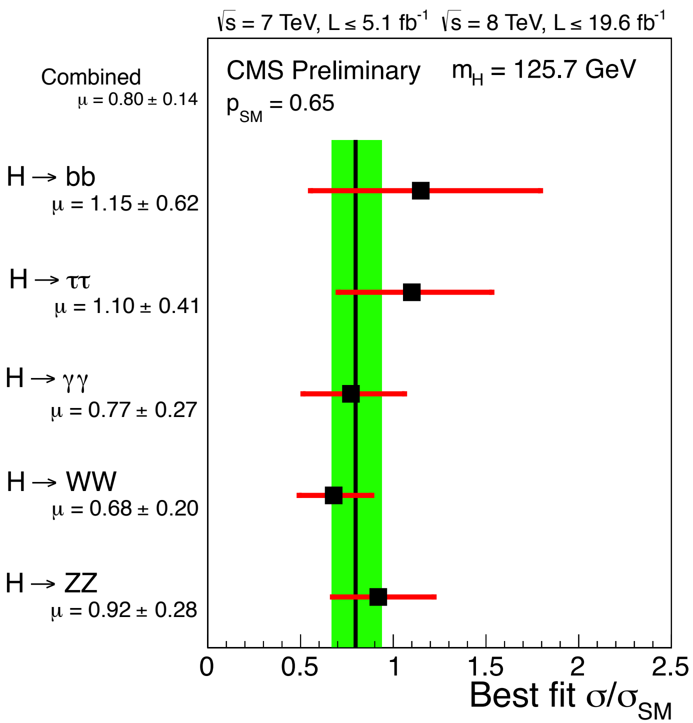
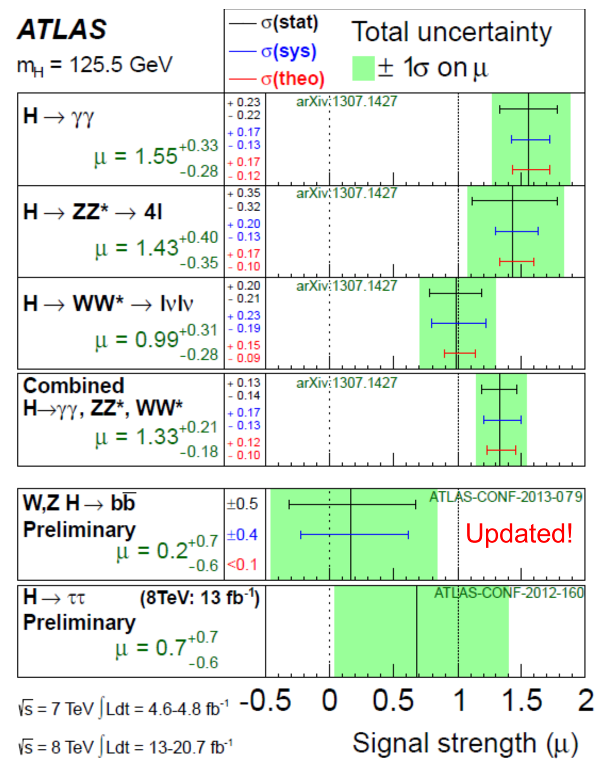
The Standard Model Higgs ?

- Branching Fractions:





- Within present errors, ATLAS and CMS results consistent with SM Higgs expectations.

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The SM Higgs and BSM

- The strong case for a TeV scale hadron collider rested on two arguments:
  1. Unitarity required that a mechanism for EWSB was manifest at or below the TeV scale.
  2. The SM is unnatural ('t Hooft conditions) and incomplete (dark matter, insufficient CP violation for the observed baryon excess, gauge unification, gravity and strings)
- If after the analysis of the 2012 CMS/ATLAS data, the 126 GeV state is found to be a 0+ state with couplings consistent with the SM Higgs, the first argument is satisfied.
  - The second argument remains strong. but is less strongly tied to the TeV scale.
  - Scales already probed at the LHC suggest that any new collider (of LHC level costs) should be able the probe the BSM physics in the multi-TeV range.

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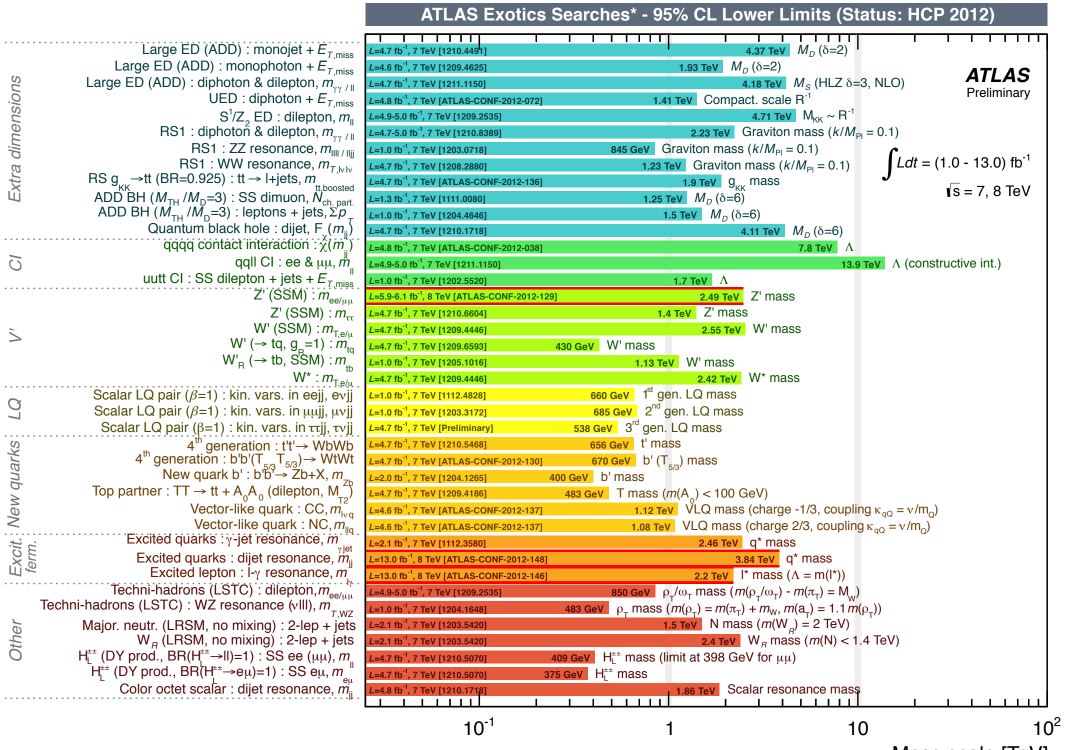
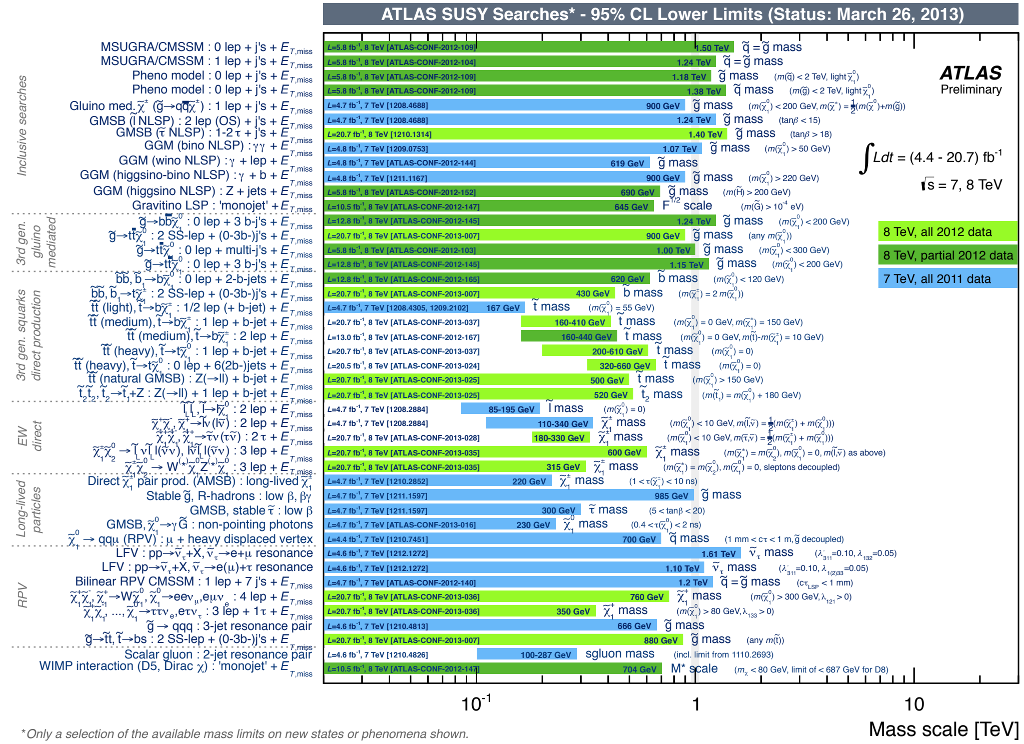
Implications of early LHC Results

- No evidence for new physics beyond the Standard Model (BSM) to date:
  - BSM (SUSY, Strong Dynamics, Extra Dimensions, New fermions or gauge bosons,...)
    - ATLAS limits



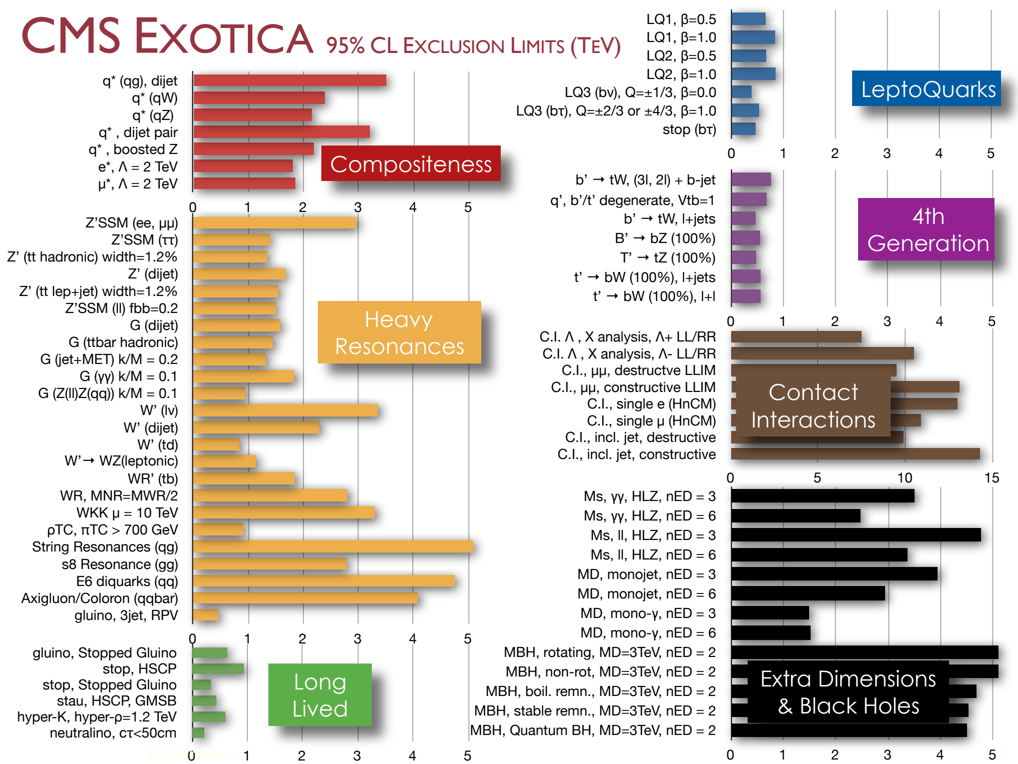
*Only a selection of the available mass limits on new states or phenomena shown

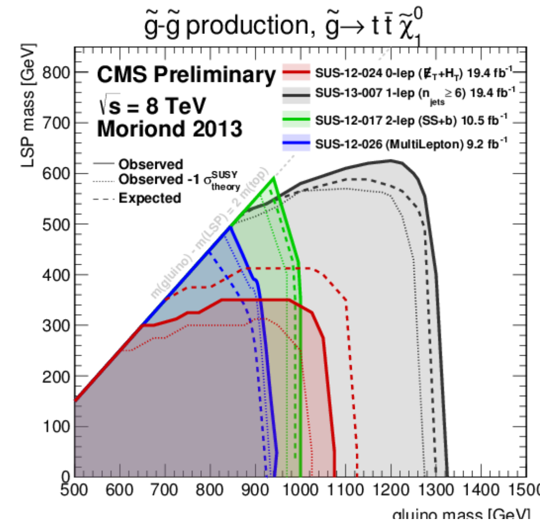


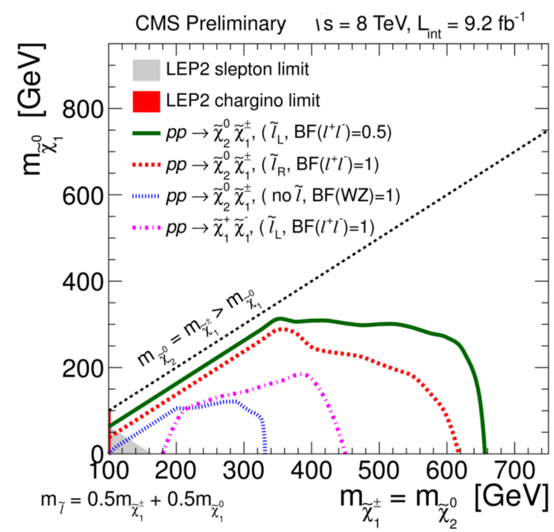
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Implications of early LHC Results

- CMS limits



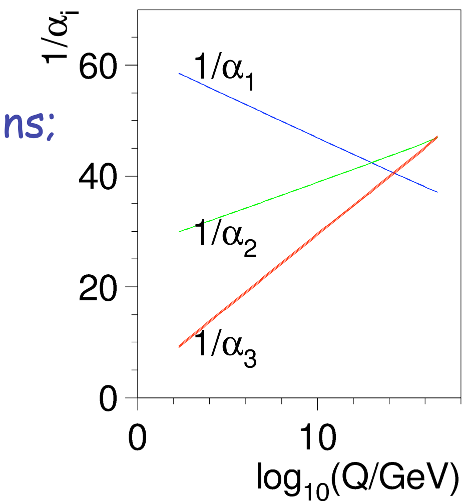




- Scales already probed at the LHC suggest that to study BSM new physics the next energy frontier collider must have $\sqrt{\hat{s}}$ in the multi-TeV range even for EW processes.
- However there must be new physics !!! WHY? Let me list the reasons

Implications of early LHC Results

1. The Standard Model is incomplete:
   - dark matter; neutrino masses and mixing -> new fields or interactions;
   - baryon asymmetry in the universe -> more CP violation
   - gauge unification -> new interactions;
   - gravity: strings and extra dimensions



2. Experimental hints of new physics: $(g\text{-}2)_\mu$, top A_{fb}, ...

3. Theoretical problems with the SM:
   - Scalar sector problematic:
     $\mu^2 (\Phi^\dagger\Phi) + \lambda (\Phi^\dagger\Phi)^2 + \Gamma_{ij}\psi_{iL}^\dagger\psi_{jR}\Phi$ + h.c.

     $m_H^2/M_{planck}^2 \approx 10^{-34}$ Hierarchy problem

     vacuum stability

     large range of fermion masses
   - The SM Higgs boson is unnatural. (m_H^2/μ^2)
   - Solutions: SUSY, New Strong Dynamics, ...

muon (g-2)

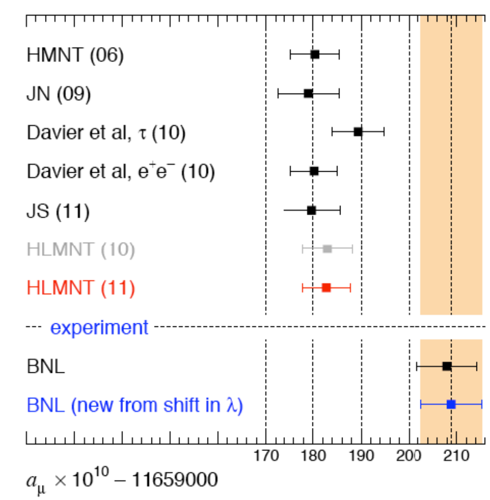
Davier, Hoecker, Malaescu, Zhang

Jegerlehner, Szafron

Hagiwara, Liao, Martin, Nomura, Teubner

hadronic VP contributions

$(685 \pm 4) \times 10^{-10}$



There remains a persistent discrepancy of 3.3-3.6 σ

What Happened to Naturalness?

- Concept of naturalness.
  - K. Wilson, G. 't Hooft
  - A theory [L(μ)] is natural at scale μ ⇔ for any small dimensionless parameter λ (e.q. m/μ) in L(μ) the limit λ -> 0 enhances the symmetries of L(μ)
- The SM Higgs boson is unnatural. (m_H^2/μ^2)
  - Maybe no large gap in scales (Extra Dimensions)
- Two potential solutions:
  - scalars not elementary
    - New strong dynamics (TC, walking TC, little Higgs, top color, ...)
  - fermion masses are natural
    - Symmetry coupling fermions and bosons (SUSY)
- Quest for the "natural" theory to replace the SM has preoccupied theorists since the early 80's
- Is a third way required after the discovery of a Higgs boson?

G. 't Hooft in Proceedings of
Recent Developments in Gauge Theories,
Cargese, France (1980)

NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS

CHIRAL SYMMETRY BREAKING

G. 't Hooft

Institute for Theoretical Fysics

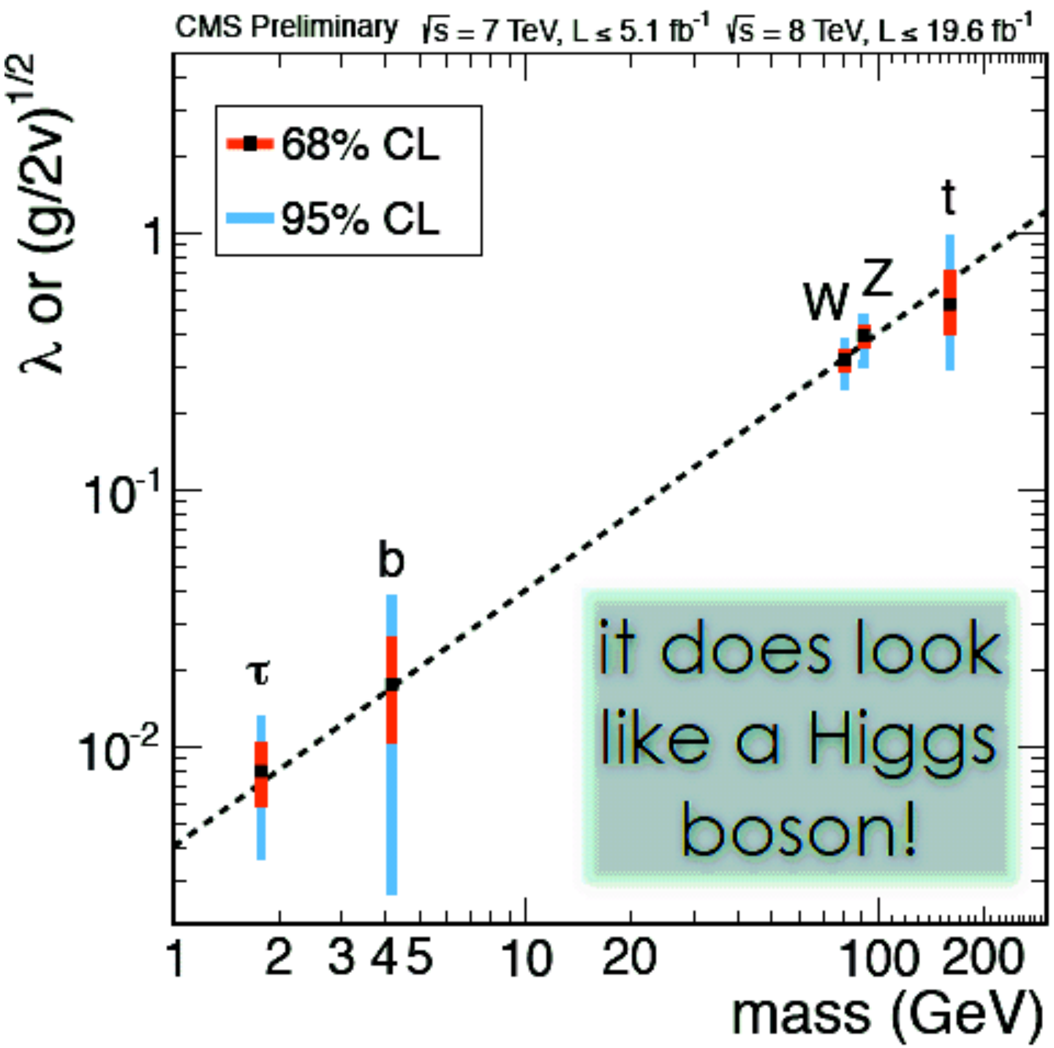
Utrecht, The Netherlands

ABSTRACT

A properly called "naturalness" is imposed on gauge theories. It is an order-of-magnitude restriction that must hold at all energy scales μ. To construct models with complete naturalness for elementary particles one needs more types of confining gauge theories besides quantum chromodynamics. We propose a search

What Happened to Naturalness?

- Higgs coupling proportional to mass



What Happened to Naturalness?

- A Third Way
  - The standard model is natural?
    - Bardeen - Fermilab/CONF-95-391-T (1995); "Aspects of the Dynamical Breaking of Scale Symmetries", Myron Bander Symposium (6/2013)
  - At a classical level the SM is conformally invariant except for the quadratic term in the scalar potential. (Ignoring gravity)
  - Scale current: $S_\mu = x^\nu T_{\mu\nu}$ divergence: $\partial_\mu S^\mu = T^\mu_\mu$
    - QCD Classically $T_{\mu\nu} = Tr[G_{\mu\rho}G^\rho_\nu] - \frac{1}{4} g_{\mu\nu} Tr[G_{\rho\sigma}G^{\rho\sigma}] \longrightarrow \partial_\mu S^\mu = T^\mu_\mu = 0$
    - Scale Anomaly - Quantum corrections: $\partial_\mu S^\mu = \frac{\beta(g)}{g} Tr[G_{\rho\sigma}G^{\rho\sigma}]$
  - Imagine the limit of the SM in which the scalar potential vanishes with v fixed.

$$V(\phi^\dagger\phi) = \mu^2(\phi^\dagger\phi) + \frac{1}{2}\lambda_{(\phi^\dagger\phi)}(\phi^\dagger\phi)^2 \qquad \mu^2 \text{ and } \lambda \to 0 \qquad \text{with } \frac{-2\mu^2}{\lambda} = v^2 \text{ fixed}$$

  - In that theory the EW symmetry is broken and the W/Z and all the fermions get mass just like normal, BUT the Higgs boson remains massless.
  - If there is a dynamical symmetry breaking for a flat potential then the Higgs boson would be the Goldstone boson of scale symmetry breaking.

What Happened to Naturalness?

- Renormalization Group

$$-\mathcal{L}_{int} = \left\{ \bar{e}\mathbf{F_L}\phi^\dagger l + \bar{d}\mathbf{F_D}\phi^\dagger q + \bar{u}\mathbf{F_R}\phi^\dagger q + h.c + m^2\phi^\dagger\phi + \frac{\lambda}{2}(\phi^\dagger\phi)^2 \right\}$$

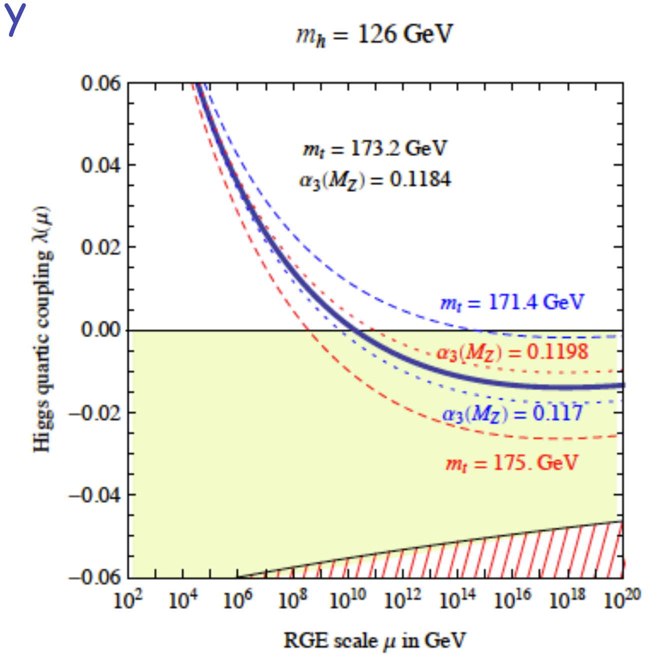
  - For SM the quartic coupling runs with scale:

$$\frac{d\ \lambda}{d\ \ln\mu} = \frac{1}{16\pi^2}\Big(12\lambda^2 - (\frac{9}{5}g_1^2 + 9g_2^2)\lambda + (\frac{27}{100}g_1^4 + \frac{9}{10}g_1^2 g_2^2 + \frac{9}{4}g_2^4)$$
$$+ 12Tr[\mathbf{F_U}^\dagger\mathbf{F_U} + \mathbf{F_D}^\dagger\mathbf{F_D} + 1/3\mathbf{F_L}^\dagger\mathbf{F_L}]\lambda - 12Tr[(\mathbf{F_U}^\dagger\mathbf{F_U})^2 + (\mathbf{F_D}^\dagger\mathbf{F_D})^2 + 1/3(\mathbf{F_L}^\dagger\mathbf{F_L})^2]\Big)$$

  - Only the top Yukawa coupling is important: $F_D = F_L = 0$, $F_U \equiv y$
  - Simplify by ignoring the gauge couplings (g_1, g_2) as well:

$$\frac{d\ \lambda}{d\ \ln\mu} = \frac{12}{16\pi^2}\left(\lambda^2 + y^2\lambda - y^4\right) < 0$$

(λ~1/4 and y~1)



  - Adding the gauge couplings not enough to change the sign.
  - Need to add additional boson loops -> new coupled scalars

What Happened to Naturalness?

- Numerics
  - v = 173 GeV, $\lambda = m^2_h/(2v^2) \sim 1/4$ $\qquad V(\phi^\dagger\phi) = \frac{1}{2}\lambda_{(\phi^\dagger\phi)}(\phi^\dagger\phi - v^2)^2$

$$\lambda_{(\phi^\dagger\phi)} = \lambda_0 + \frac{1}{2}\frac{A}{(4\pi)^2}\log(\frac{\phi^\dagger\phi}{\sqrt{e}v^2})$$

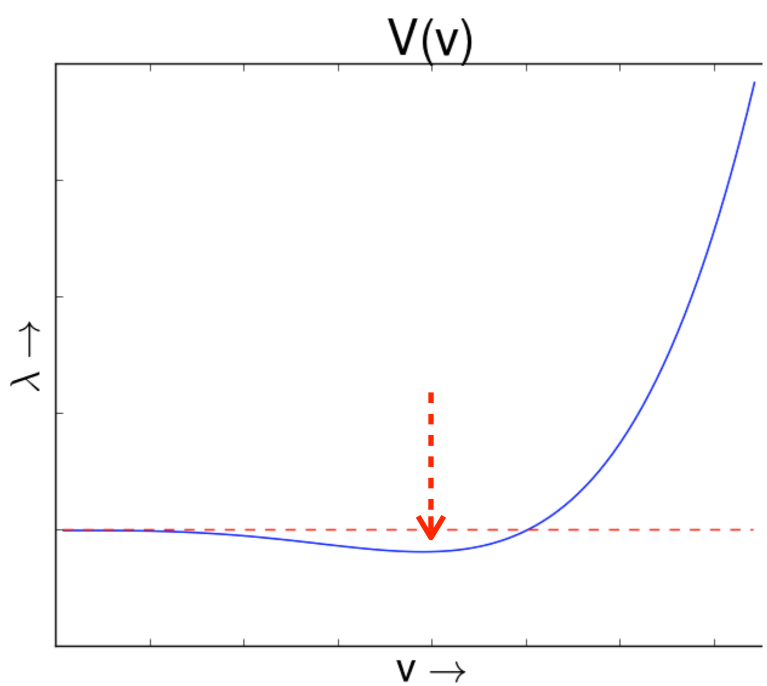
$$A = \sum_{dof}\left[(\frac{m}{v})^4_{\text{boson}} - (\frac{m}{v})^4_{\text{fermion}}\right] \sim -11.5$$

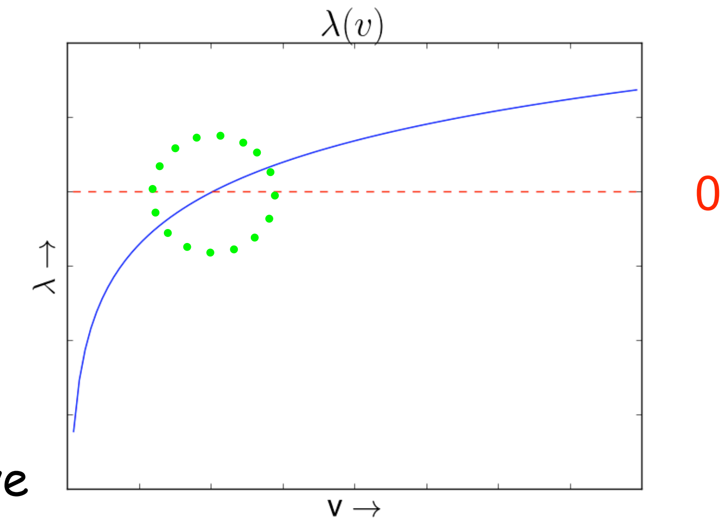
  - The loop corrections: $A = 6(m/v)^4_W + 3(m/v)^4_Z - 12\,(m/v)^4_{top} + \dots$ only provide 13% of the required λ.
  - If want the whole mass come from loop corrections must add a large positive contribution. New bosons.

What Happened to Naturalness?

- Can get EWSB in a scale invariant theory:
  - Must ignore quadratic divergences - related to preserving scale invariance?
    - Bardeen - Fermilab/CONF-95-391-T (1995); "Aspects of the Dynamical Breaking of Scale Symmetries", Myron Bander Symposium (6/2013)
  - Effective potential (m=0), define v = |ϕ|

$$V(\phi^\dagger\phi) \quad = \quad \frac{1}{2}\lambda_{(\phi^\dagger\phi)}(\phi^\dagger\phi)^2$$





positive slope

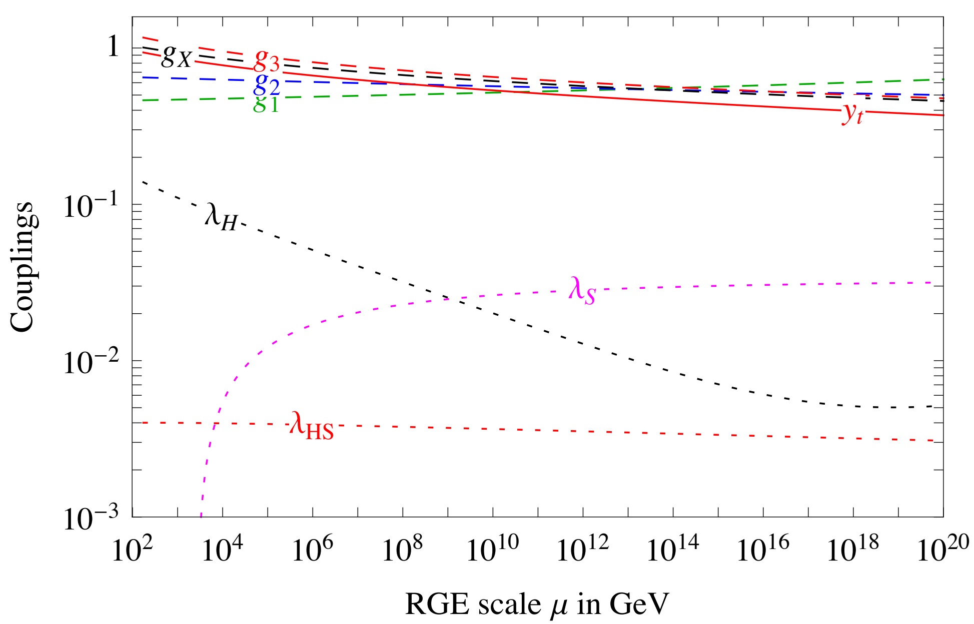
Coleman-Weinberg

What Happened to Naturalness?

- An example of how this could work: T. Hambye and A. Strumia [arXiv:1306.2329]
  - Add new scalars S: A complex double under a hidden $SU(2)_X$ but a singlet under the SM.
  - The hidden sector provides dark matter candidates.
  - Scalar potential:

$$V = \lambda_H |H|^4 - \lambda_{HS} |HS|^2 + \lambda_S |S|^4.$$

  - Running of λ_S : $\beta_{\lambda_S} \equiv \frac{d\lambda_S}{d\ln\mu} = \frac{1}{(4\pi)^2}\left[\frac{9g_X^4}{8} - 9g_X^2\lambda_S + 2\lambda_{HS}^2 + 24\lambda_S^2\right].$



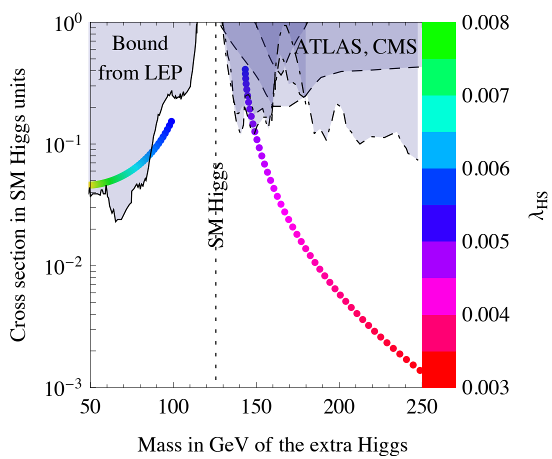
What Happened to Naturalness?

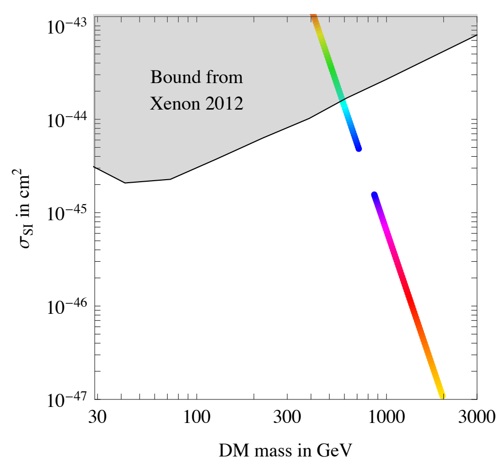
- EWSB occurs dynamically.

$$4\lambda_H \lambda_S - \lambda_{HS}^2 < 0,$$

- Conditions needed are easily satisfied because no fermions in X sector. Exponential ratio of scales like $\Lambda_{qcd}/\ \Lambda_{planck}$.

- Constraints on viable models:





- Many others working on related ideas - a third way: S. Iso [arXiv:1304.0293]; G. Wouda [arXiv:1306.6855], W. Bardeen, C.T. Hill, EE (in progress), ...

What to measure and how well ?

- Measurements for a Higgs factory
  - partial decay widths into WW^* and ZZ^*:
    - Establishes whether the Higgs is the sole agent of EWSB.
    - If additional contributors to EWSB are all $SU_L(2)$ doublets then $\Gamma/\Gamma_{SM} < 1$
    - The relative couplings of the Higgs to WW and ZZ is fixed by EW symmetry.
  - mass, total width and self coupling λ:
    - $< \Phi^\dagger\Phi > = v^2/2 = m_h^2 /2\lambda$ $[v = (G_F\sqrt{2})^{-1/2} \approx 247 \text{ GeV}]$
    - look for invisible decays associated with BSM particles
  - Branching fractions into fermions:
    - Establishes whether the Higgs is the sole agent of fermion masses.
    - N.B. The original technicolor model provided for EWSB but not fermion masses.
    - Measure coupling to (top, bottom, tau) 3rd gen. and (charm, muon) 2nd gen. (2HDM)
  - Branching fractions into gauge bosons ($Z\gamma$, gg, $\gamma\gamma$)
    - Sensitive to BSM particles contributing in loops.

Higgs Factories

- Comparison of Higgs factories: (Jianming Qian)
  (Higgs working group report for CSS 2013)

Facility	LHC	HL-LHC	ILC	Full ILC	CLIC	LEP3 (4 IP)	TLEP (4 IP)
Energy (GeV)	14,000	14,000	250	250+500+1000	350+500+1500	240	240+350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250	250+500+1000	500+500+1500	2000	10000+1400
N_H produced	1.7×10^7	1.7×10^8	80,000	370,000	618,000	600,000	3,200,000
				Measurement precision			
m_H (MeV)	100	50	35	35	70	26	7
$\Delta\Gamma_H$	–	–	11%	6%	6%	4%	1.3%
$\mathrm{BR}_{\mathrm{inv}}$	NA	NA	<0.8%	<0.8%	NA	<0.7%	<0.3%
$\Delta g_{H\gamma\gamma}$	5.1 – 6.5%	1.5 – 5.4%	18%	4.1%	NA	3.4%	1.4%
Δg_{Hgg}	5.7 – 11%	2.7 – 7.5%	6.4%	1.8%	NA	2.2%	0.7%
Δg_{HWW}	2.7 – 5.7%†	1.0 – 4.5%†	4.8%	1.4%	1%	1.5%	0.25%
Δg_{HZZ}	2.7 – 5.7%†	1.0 – 4.5%†	1.3%	1.3%	1%	0.25%	0.2%
$\Delta g_{H\mu\mu}$	< 30%	< 10%	–	16%	15%	14%	7%
$\Delta g_{H\tau\tau}$	5.1 – 8.5%	2.0 – 5.4%	5.7%	2.0%	3%	1.5%	0.4%
Δg_{Hcc}	–	–	6.8%	2.0%	4%	2.0%	0.25%
Δg_{Hbb}	6.9 – 15%	2.7 – 11%	5.3%	1.5%	2%	0.7%	0.22%
Δg_{Htt}	8.7 – 14%	3.9 – 8.0%	–	4.0%	3%	–	30%
Δg_{HHH}	–	30%‡	–	26%	16%	–	–

Higgs Factory

Handbook of LHC Higgs cross sections: 3. Higgs properties [arXiv:1307.1347]

Table 1: SM Higgs partial widths and their relative parametric (PU) and theoretical (THU) uncertain selection of Higgs masses. For PU, all the single contributions are shown. For these four columns, percentage value (with its sign) refers to the positive variation of the parameter, while the lower one ref negative variation of the parameter.

Channel	M_{H} [GeV]	Γ [MeV]	$\Delta\alpha_{\mathrm{s}}$	Δm_{b}	Δm_{c}	Δm_{t}	THU	TLEP (2xΔg)
	122	2.30	−2.3% +2.3%	+3.2% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%	
$\mathrm{H} \to \mathrm{bb}$	126	2.36	−2.3% +2.3%	+3.3% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%	0.44%
	130	2.42	−2.4% +2.3%	+3.2% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%	
	122	$2.51 \cdot 10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+2.0% −2.0%	
$\mathrm{H} \to \tau^+\tau^-$	126	$2.59 \cdot 10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%	0.8%
	130	$2.67 \cdot 10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%	
	122	$8.71 \cdot 10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%	
$\mathrm{H} \to \mu^+\mu^-$	126	$8.99 \cdot 10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	−0.1% −0.0%	+0.0% −0.1%	+2.0% −2.0%	14%
	130	$9.27 \cdot 10^{-4}$	+0.1% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.0%	+2.0% −2.0%	
	122	$1.16 \cdot 10^{-1}$	−7.1% +7.0%	−0.1% −0.1%	+6.2% −6.0%	+0.0% −0.1%	+2.0% −2.0%	
$\mathrm{H} \to \mathrm{c\bar{c}}$	126	$1.19 \cdot 10^{-1}$	−7.1% +7.0%	−0.1% −0.1%	+6.2% −6.1%	+0.0% −0.1%	+2.0% −2.0%	0.5%
	130	$1.22 \cdot 10^{-1}$	−7.1% +7.0%	−0.1% −0.1%	+6.3% −6.0%	+0.1% −0.1%	+2.0% −2.0%	
	122	$3.25 \cdot 10^{-1}$	+4.2% −4.1%	−0.1% −0.1%	+0.0% −0.0%	−0.2% +0.2%	+3.0% −3.0%	
$\mathrm{H} \to \mathrm{gg}$	126	$3.57 \cdot 10^{-1}$	+4.2% −4.1%	−0.1% −0.1%	+0.0% −0.0%	−0.2% +0.2%	+3.0% −3.0%	1.4%
	130	$3.91 \cdot 10^{-1}$	+4.2% −4.1%	−0.1% −0.2%	+0.0% −0.0%	−0.2% +0.2%	+3.0% −3.0%	
	122	$8.37 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%	
$\mathrm{H} \to \gamma\gamma$	126	$9.59 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%	2.8%
	130	$1.10 \cdot 10^{-2}$	+0.1% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%	
	122	$4.74 \cdot 10^{-3}$	+0.0% −0.1%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+5.0% −5.0%	
$\mathrm{H} \to \mathrm{Z}\gamma$	126	$6.84 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+0.0% −0.1%	+5.0% −5.0%	
	130	$9.55 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+5.0% −5.0%	
	122	$6.25 \cdot 10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%	
$\mathrm{H} \to \mathrm{WW}$	126	$9.73 \cdot 10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%	0.5%
	130	1.49	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%	
	122	$7.30 \cdot 10^{-2}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%	
$\mathrm{H} \to \mathrm{ZZ}$	126	$1.22 \cdot 10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%	0.44%
	130	$1.95 \cdot 10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%	

Theory needs improvement:

(a) α_s -> lattice

(b) m_b, m_c -> lattice

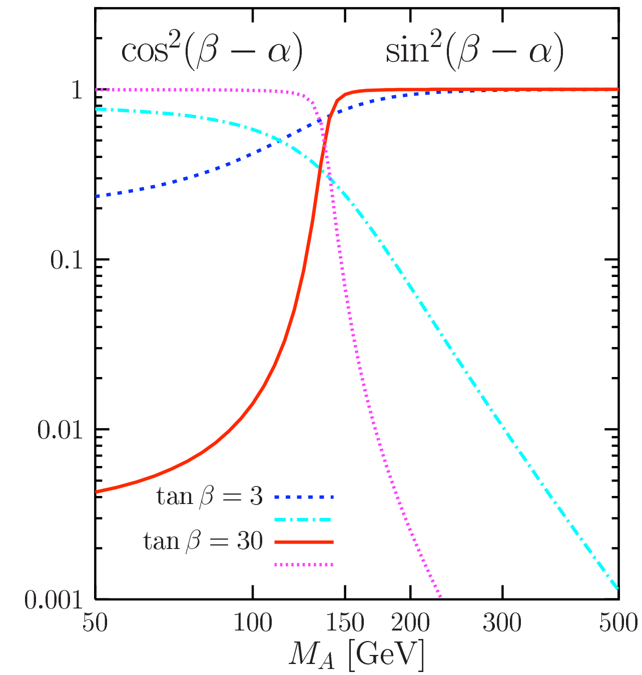
(c) THU -> pQCD

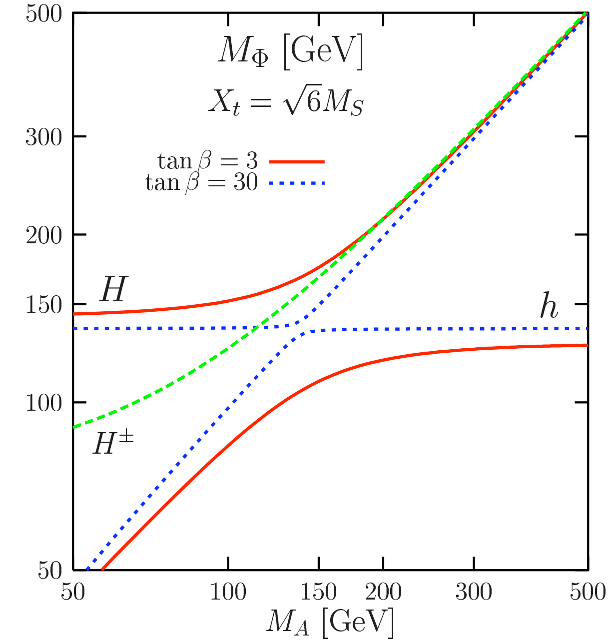
Beyond the Standard Model

- Two Higgs doublets (MSSM):
  - Five scalar particles: h^0, H^0, A^0, $H^\pm$
  - Decay amplitudes depend on two parameters: (α, β)

	$\mu^+\mu^-, b\bar{b}$	$t\bar{t}$	ZZ, W^+W^-	ZA^0
h^0	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$
H^0	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos(\beta-\alpha)$	$-\sin(\beta-\alpha)$
A^0	$-i\gamma_5\tan\beta$	$-i\gamma_5/\tan\beta$	0	0

$$\tan 2\alpha = \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}\tan 2\beta.$$



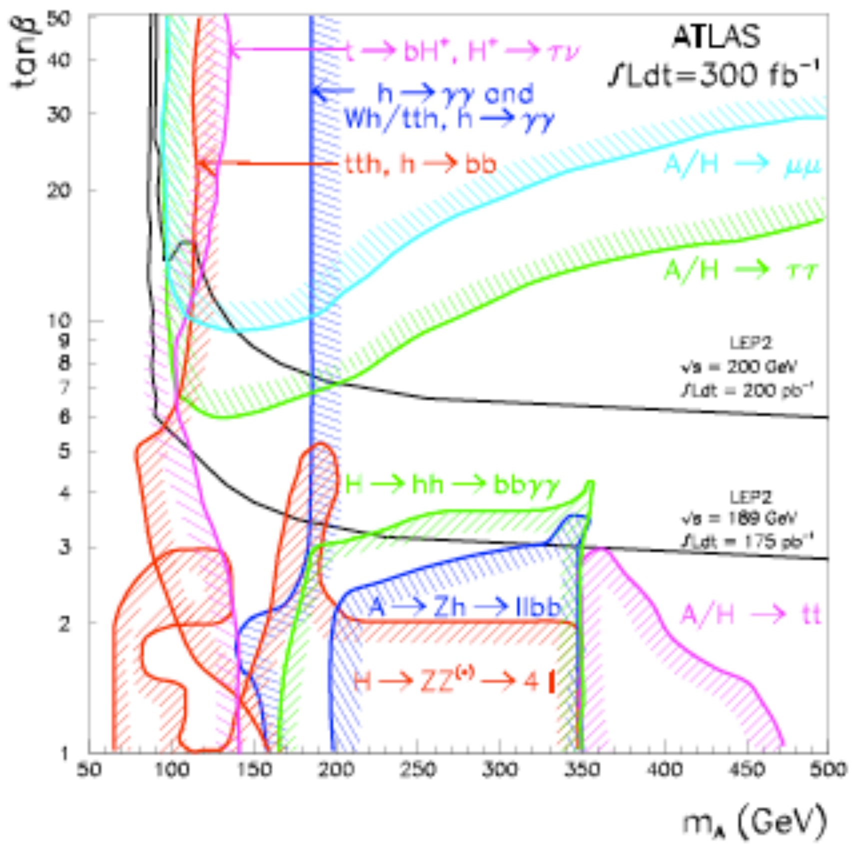


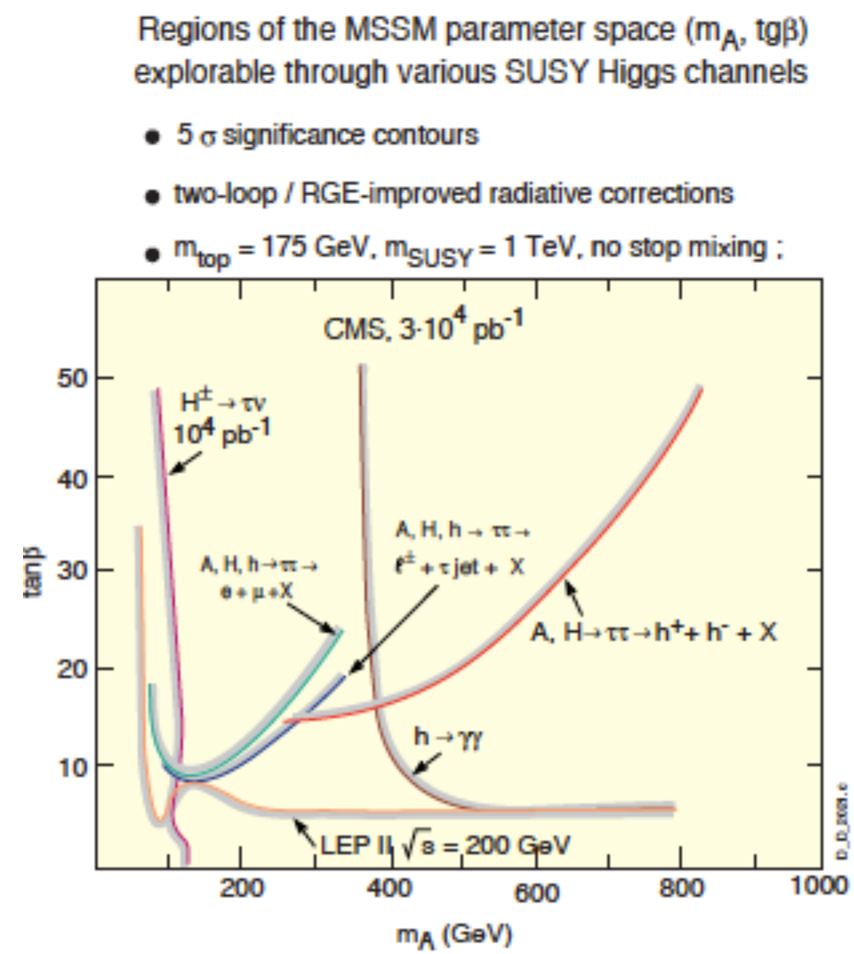
  - decoupling limit $m_{A^0} \gg m_{Z^0}$:
    - » h^0 couplings close to SM values
    - » H^0, $H^\pm$ and A^0 nearly degenerate in mass
    - » H^0 small couplings to VV, large couplings to ZA^0
    - » For large $\tan\beta$, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by $\tan\beta$. Couplings to top quarks suppressed by $1/\tan\beta$ factor.

Beyond the Standard Model

- The LHC has difficulty observing the H, A especially for masses > 500 GeV. Even at $\sqrt{s}$ = 14 TeV and 300 fb^{-1}.

Significance contours for SUSY Higgses



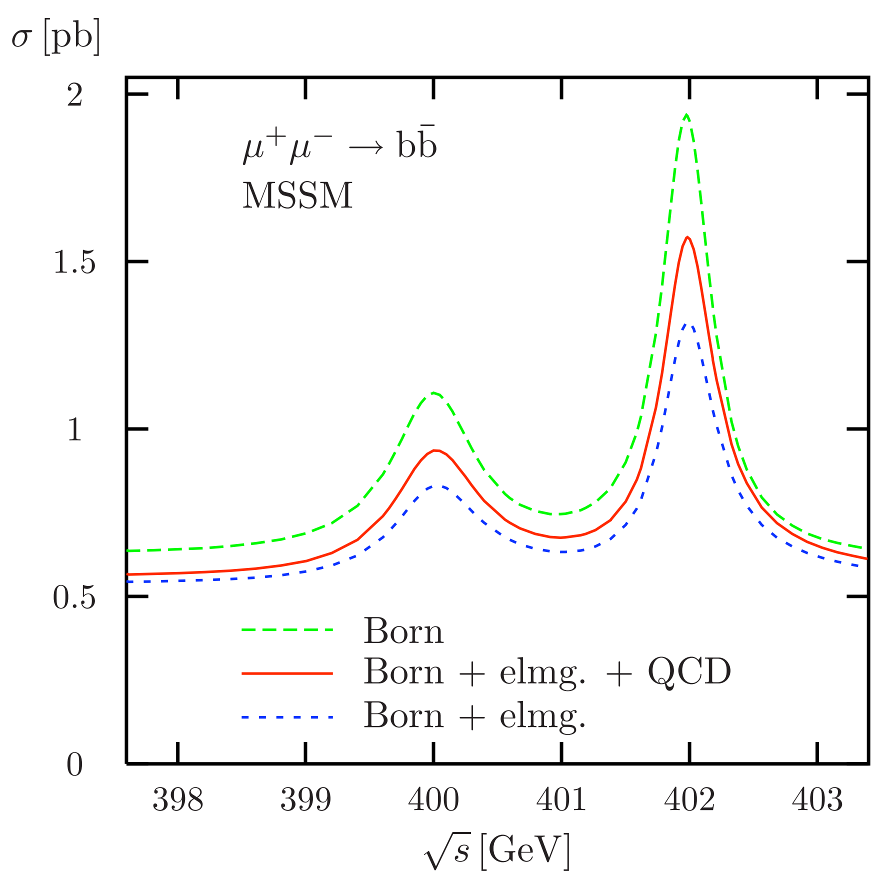


- Pair produced with easy at a multi-TeV lepton collider.

Beyond the Standard Model

- If the LHC discovers an enlarged scalar section (as in SUSY), then there is a special role for muon colliders.
  - Can be produced in the s-channel.
  - Good energy resolution is needed for H^0 and A^0 studies:

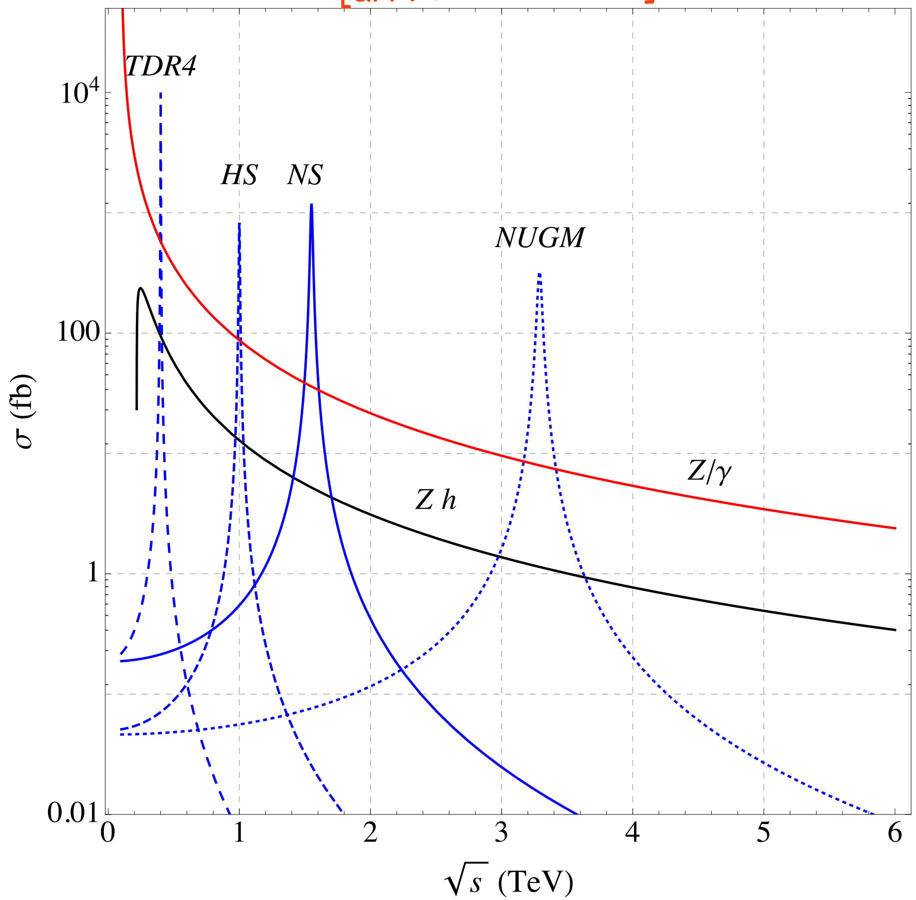
Dittmaier and Kaiser [hep-ph/0203120]



Beyond the Standard Model

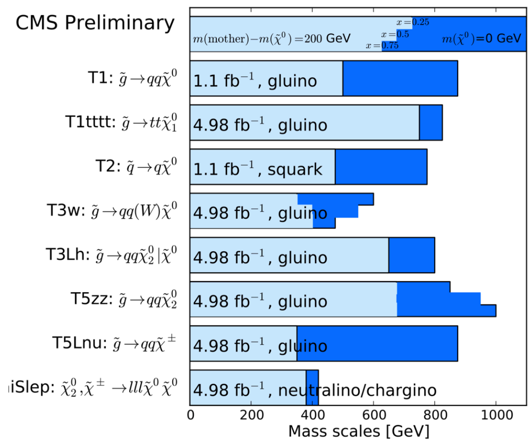
- LHC bounds on the H/A (H^{+})
  - Present bounds: 300 GeV (tan β = 10); 600 GeV (tan β = 40)
  - LHC 14 TeV with 150 fb^{-1}: 900 GeV (tan β = 10); 1.5 TeV (tan β = 40)
- Viable SUSY models with present LHC limits favor:
  - heavy H/A ->
    - nearly degenerate masses
    - alignment limit -> small couplings to WW and ZZ
  - few sparticles below 500 GeV
    - -> narrow widths (10's of GeV's)
  - Some ILC Benchmark examples:
    - light-slepton NLSP model (TDR4)
    - hidden supersymmetry (HS)
    - natural supersymmetry (NS)
    - non-universal Higgs mass (NUHM)
- High Energy Muon Collider can study H/A as s-channel resonances

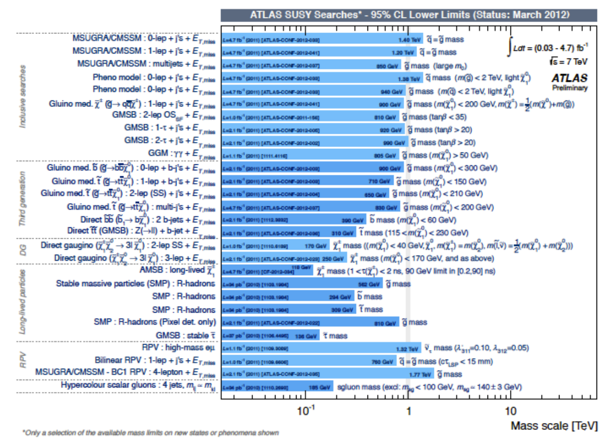
E.E and A. Martin [arXiv:1306.2609]



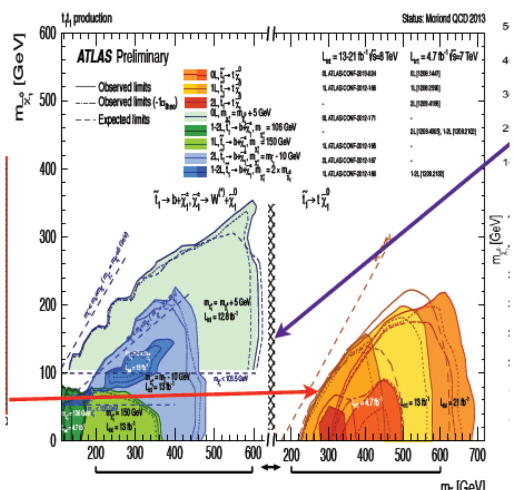
Supersymmetry

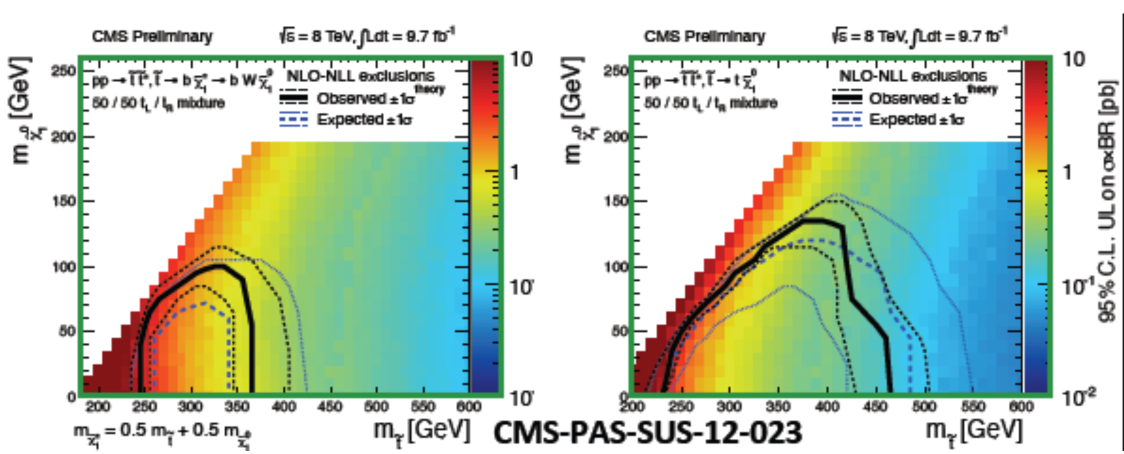
- LHC limits on SUSY sparticles in various cMSSM scenerios:
  - Gluino and light squark masses limits ~ 1 TeV





  - Stop (3rd generation) ~ 600 GeV (except very near top mass)





  - The full study of SUSY will require a multiTev lepton collider or a VLHC.

Supersymmetry

- cMSSM - simple model with only 5 parameters (m_0, $m_{1/2}$, tanβ, A/m_0, sign(μ)) severely constrained
- As mass scales increase (μ^2 increases) more fine tuning

$$m_Z^2 = 2\,\frac{M_{Hd}^2 - \tan^2\beta M_{Hu}^2}{\tan^2\beta - 1} - 2\mu^2$$ + loop corrections: logs($m_{\tilde{t}}/m_t$)

- The noose is tightening due to the non observation of SUSY partners, the 126 GeV Higgs mass, B decays, cosmology, ...
- Theory response - more alternative models to cMSSM:

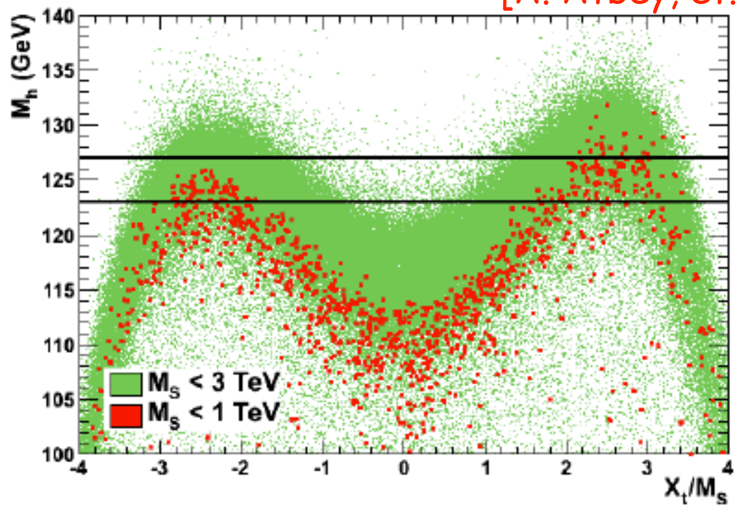
Studies for CSS 2013

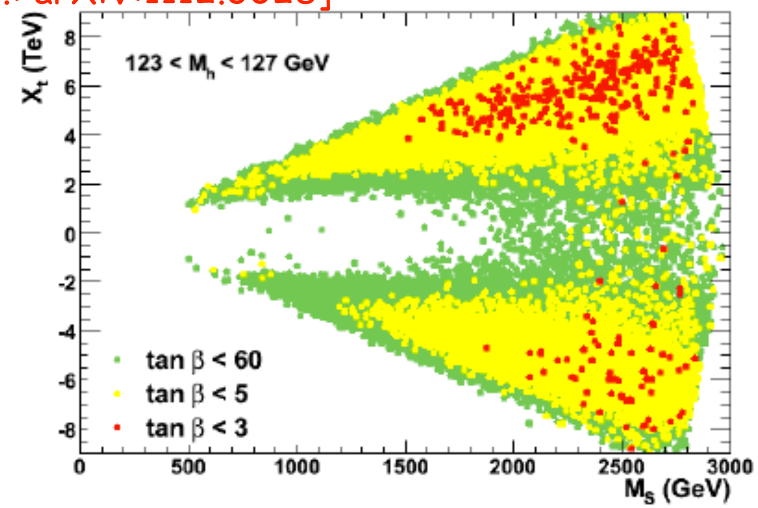
- Natural SUSY
- Hidden SUSY
- Non-universal Higgs Masses (NUHM2) mSugra / cMSSM
- Non-universal Gaugino Masses (NUGM)
- Light Sleptons with stau NLSP (pMSSM)
- Kallosh-Linde or G2MSSM
- Buchmller-Brmmer
- Normal Mass Hierarchy:

Supersymmetry

- pMSSM - minimal assumptions on SUSY breaking parameters
  - 19 parameters varied $1 \le \tan\beta \le 60\,,\; 50\text{ GeV} \le M_A \le 3\text{ TeV}\,,\; -9\text{ TeV} \le A_f \le 9\text{ TeV}\,,$ $50\text{ GeV} \le m_{\tilde{f}_L}, m_{\tilde{f}_R}, M_3 \le 3\text{ TeV}\,,\; 50\text{ GeV} \le M_1, M_2, |\mu| \le 1.5\text{ TeV}.$
  - stop mixing parameter $X_t = A_t - \mu\cot\beta$; $M_S = \sqrt{m_{\tilde{t}_R} m_{\tilde{t}_L}}$

[A. Atbey, et. al.: arXiV:1112.3028]

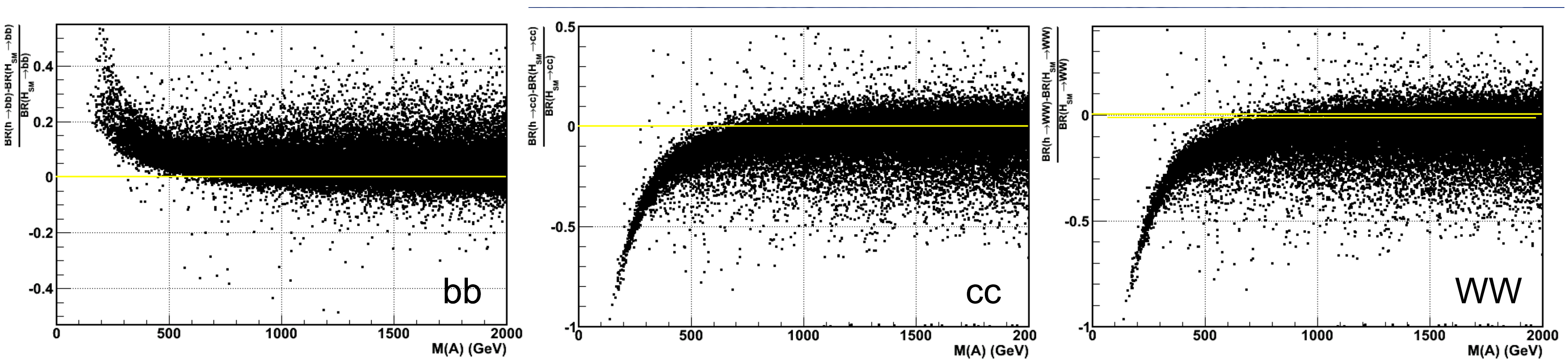




  - Consistence requires: $M_A \gg M_h$; tan β > 10; M_S large; maximal mixing $\sim \sqrt{6}\, M_S$
- Sleptons, charginos and neutralinos still remain easily assessible at a multi-TeV lepton collider. But most remaining models do not have many supersymmetry partners below 500 GeV. This makes the measurements at a Higgs factory essential.

Supersymmetry

- Present constraints still allow a wide range of variation from the SM Higgs couplings in pMSSM models. [M. Battaglia, INFN, ILC workshop, Cernobbio, May 2013]



  - What will be the expected range after 300 fb^{-1} at 14 TeV at the LHC?
  - How well can you extract detailed information about the SUSY model from any deviation in Higgs couplings? The inverse problem for Higgs decays

In Summary

- A Higgs factory provides a window on possible BSM physics:
  - All BSM scenarios adds new particles -- in particular new spin zero bosons.
  - Expect deviations from SM properties of the 126 GeV Higgs boson.
  - Any future Higgs factory must be viable in an era when HL-LHC results are known. The LHC will provide significant constraints on properties of the Higgs boson (and possibly new discoveries).
  - TLEP has the largest Higgs Boson statistics and therefore the smallest errors on branching fractions and invisible width.
- Issues to address for TLEP Higgs factory:
  - How much can theoretical uncertainties on the SM Higgs width and branching fractions be reduced?
  - How high a luminosity can TLEP deliver at 250 GeV and ~2m_{top} threshold?
- TLEP provides a platform for a future ~ 100 TeV hadron collider.

BACKUP SLIDES

Which Accelerator for Higgs Physics?

1. The LHC is the Higgs Accelerator - Continue -> HL-LHC
2. Continue research and development of lepton colliders. In particular the muon collider needs a convincing proof of 6D cooling.
3. Push neutrino physics - Lepton sector
4. After 300 fb^{-1} of ~14 TeV running OR the discovery of BSM physics, chose the next accelerator for Higgs physics.