Future High Energy Colliders

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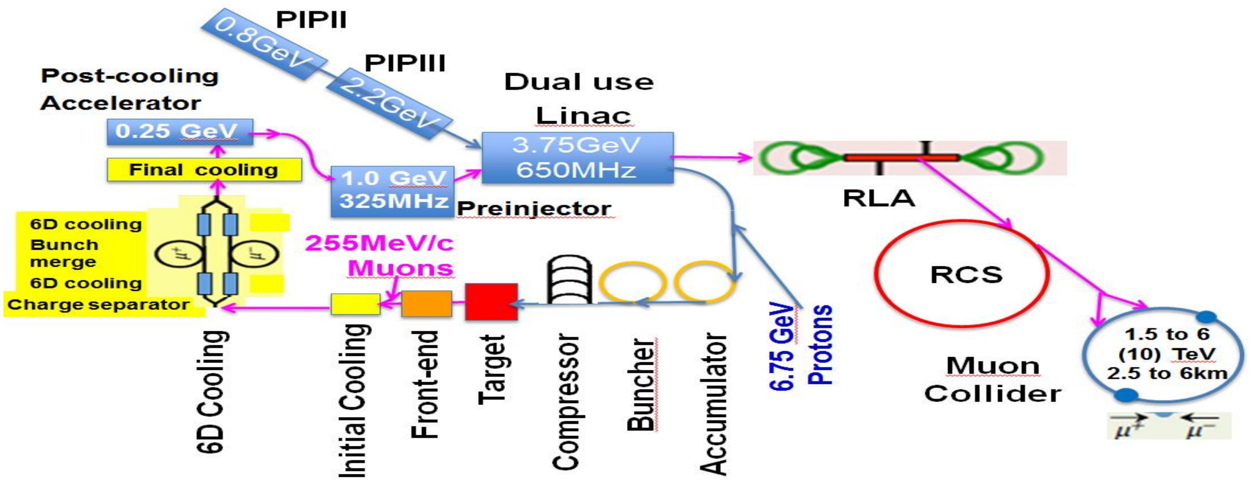
Outline:

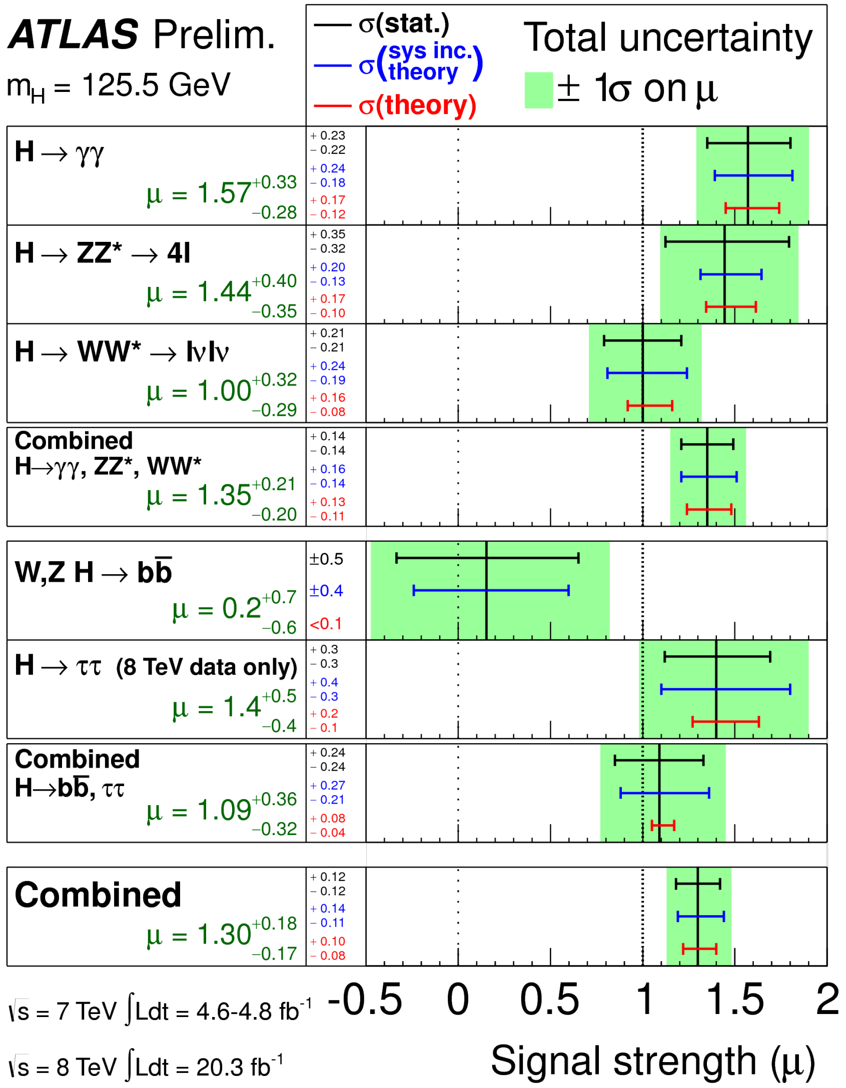
- A Higgs boson — Now what?
- Basics of Future High Energy Colliders (parallel talks Friday)
- Higgs Studies and More Scalars (Zhen Liu)
- Supersymmetry (Adam Martin)
- Other BSM physics: Dynamics, Dilatons, …
- Summary and Outlook

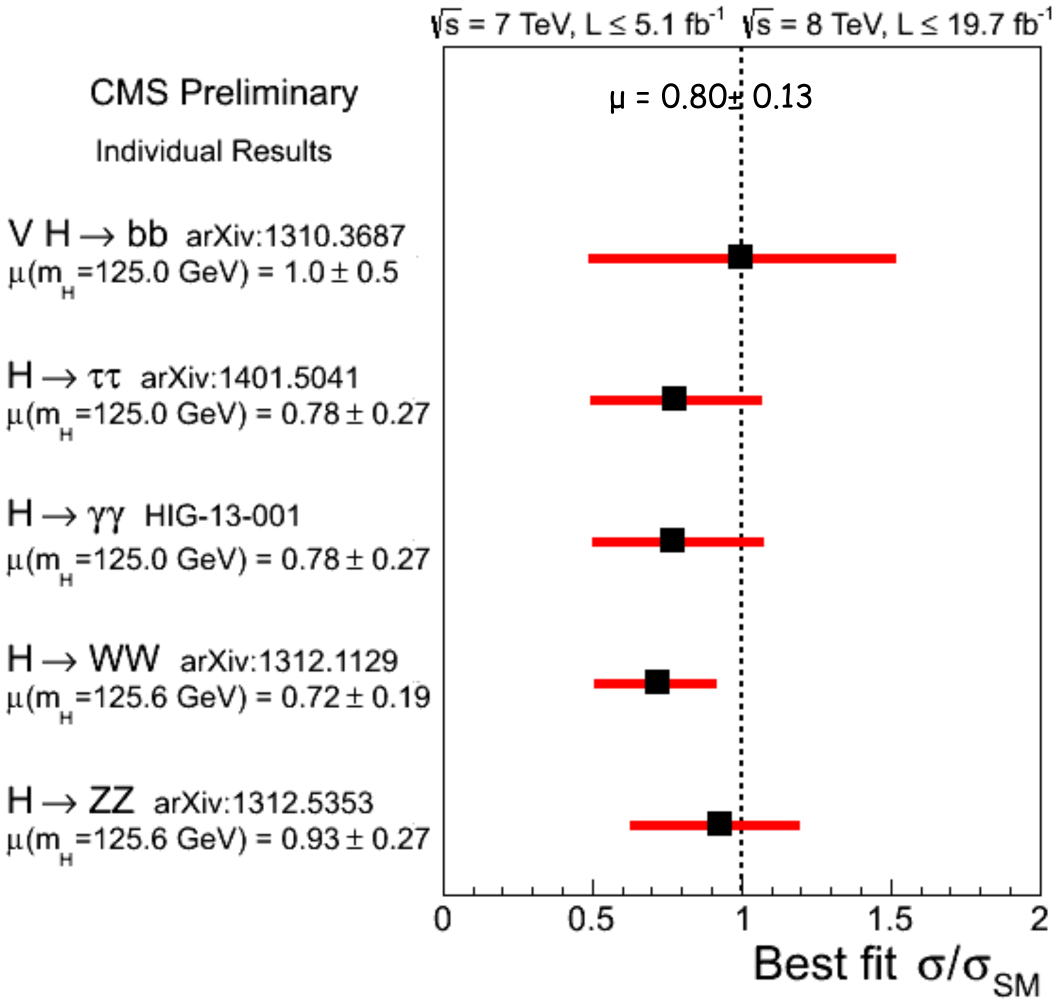
Muon Accelerator Program
Spring Meeting
Fermilab, May 27-31, 2014



A Higgs Boson - Now what?

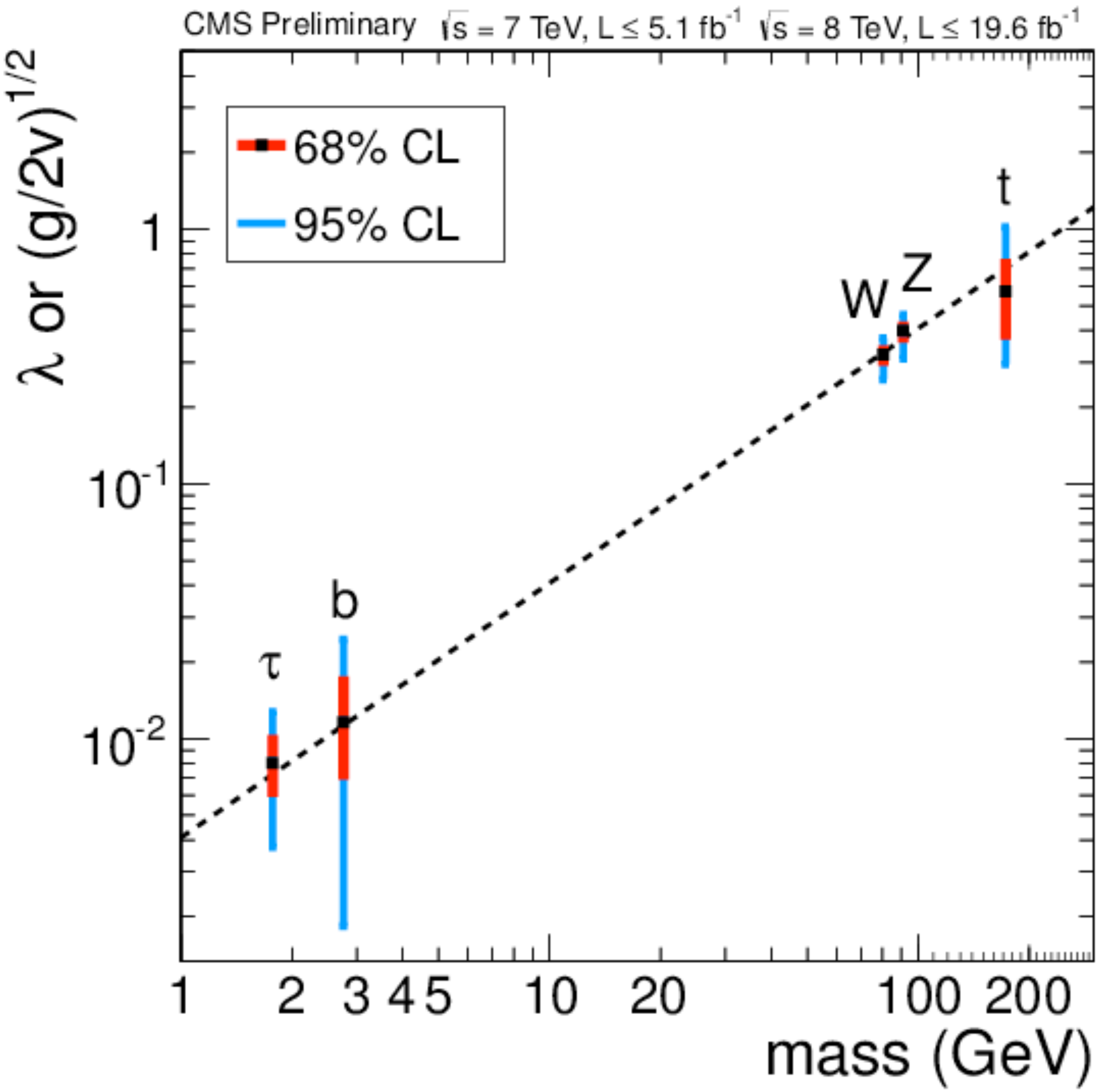
- A Higgs Boson - Observed in 2012 by Atlas and CMS experiments at the LHC
  - Completes the spectrum of the SM (Except for the origin of neutrino masses)
  - Spin and Parity consistent with 0+ (2+ and 0- ruled out > 3σ)
  - Couplings consistent with SM expectations (Within present errors)





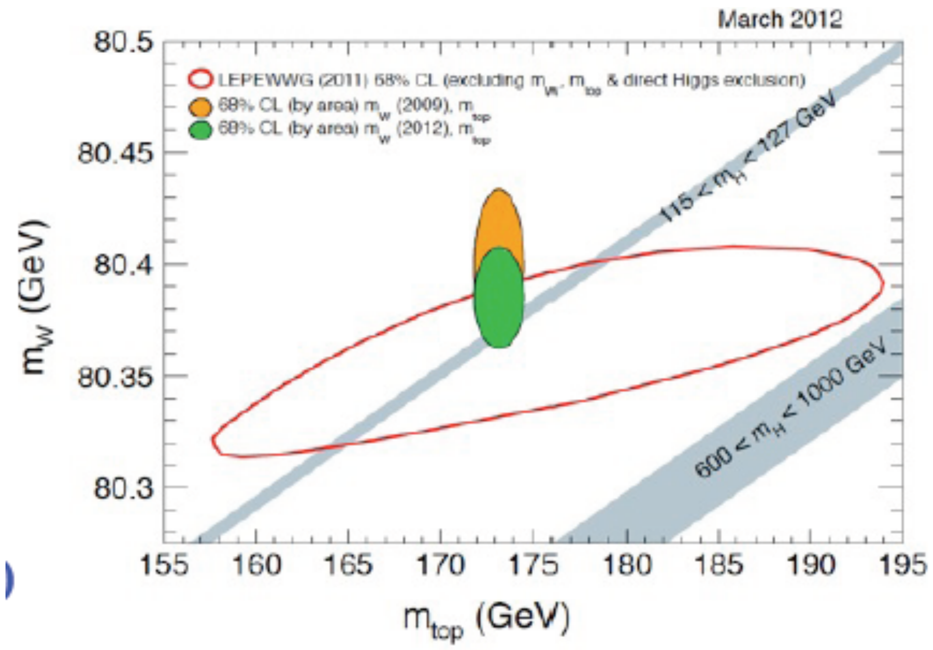
A Higgs Boson - Now what?

- Higgs coupling proportional to mass



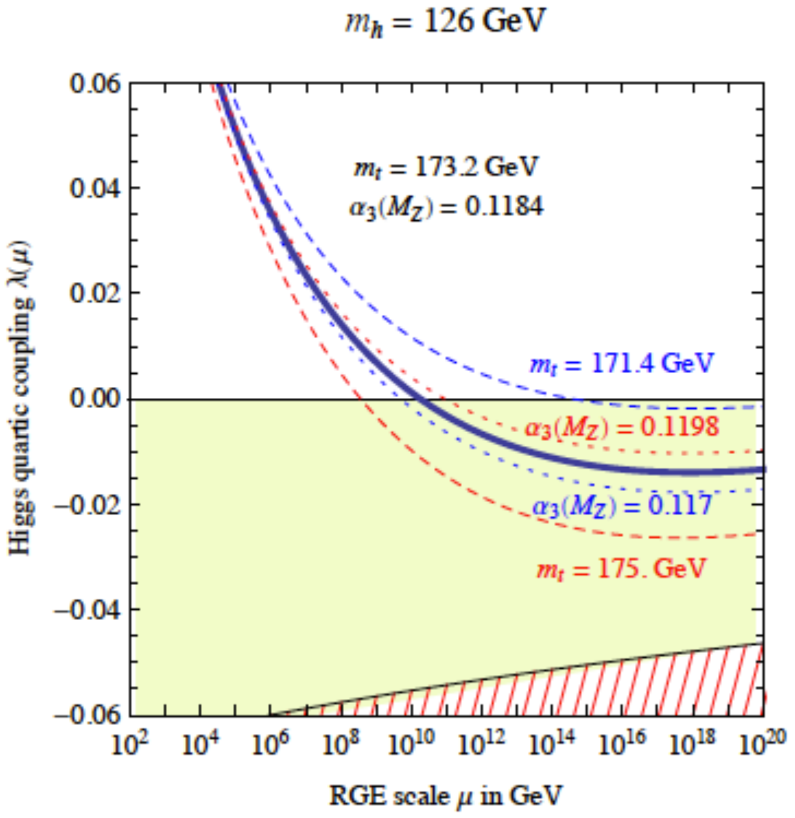
A Higgs Boson - Now what?

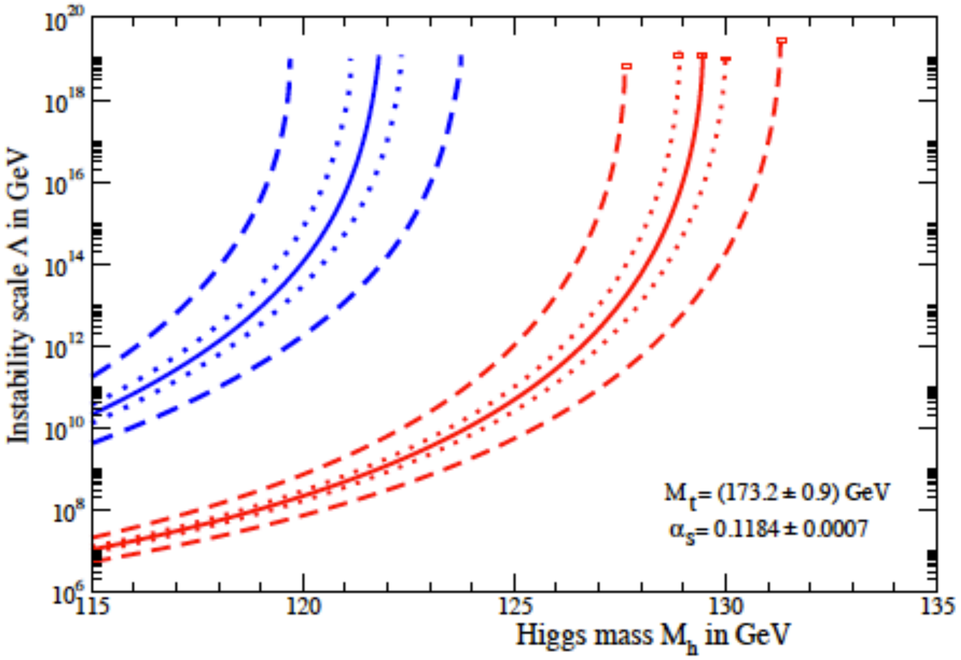
- Indirect measurements are all consistent with a 125.5 GeV Higgs



- For a 125.5 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]

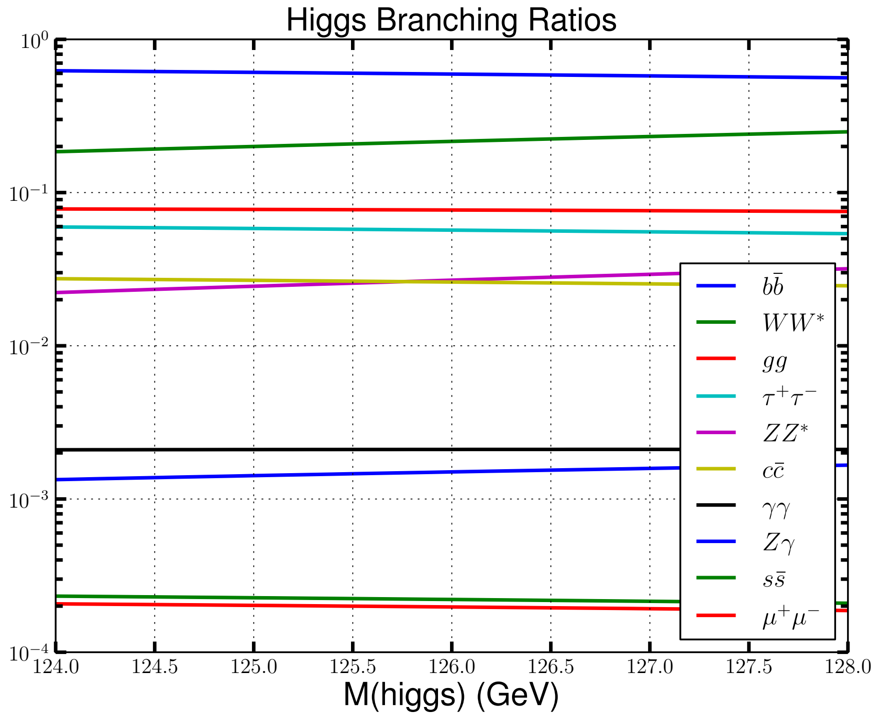




- Theorists are intrigued by this edge of stability. ★

A Higgs Boson - Now what?

- The SM Higgs:
  - All properties are determined for given mass.
  - Any deviations signal new physics.
  - SM theoretical uncertainties can be greatly reduced:



Lepage, Mackenzie, Peskin [arXiv:1404.0319]

PT -> 4th order QCD
LS -> a=0.03fm
LS^2 -> a=0.023fm
ST -> x 100

	$\delta m_b(10)$	$\delta\alpha_s(m_Z)$	$\delta m_c(3)$	δ_b	δ_c	δ_g
current errors [10]	0.70	0.63	0.61	0.77	0.89	0.78
+ PT	0.69	0.40	0.34	0.74	0.57	0.49
+ LS	0.30	0.53	0.53	0.38	0.74	0.65
+ LS^2	0.14	0.35	0.53	0.20	0.65	0.43
+ PT + LS	0.28	0.17	0.21	0.30	0.27	0.21
+ PT + LS^2	0.12	0.14	0.20	0.13	0.24	0.17
+ PT + LS^2 + ST	0.09	0.08	0.20	0.10	0.22	0.09
ILC goal				0.30	0.70	0.60

- Theoretical questions:
  - Couplings and width SM?
  - Scalar self-coupling SM?
  - Any non SM or invisible decay modes?
- The Higgs boson will be studied great detail at present and potential future colliders: LHC-14, LHC-HL, ILC, TLEP
- Muon Collider Higgs Factory (Mass and direct width measurements)

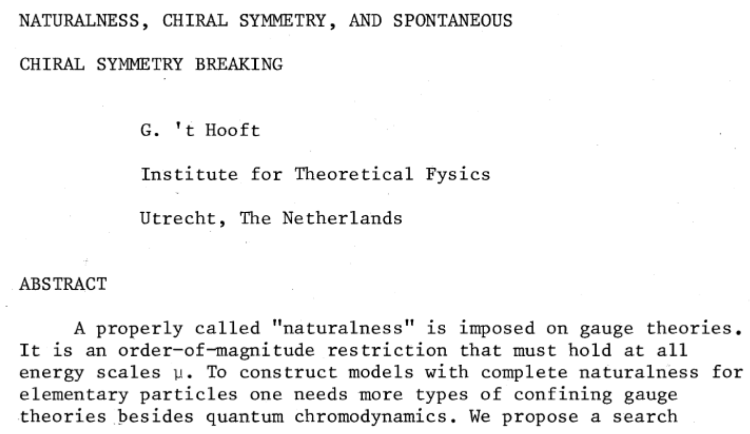
A Higgs Boson - Now what?

- 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).

  - 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 there a third way?)

G. ‘t Hooft in Proceedings of
Recent Developments in Gauge Theories,
Cargese, France (1980)



NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS

CHIRAL SYMMETRY BREAKING

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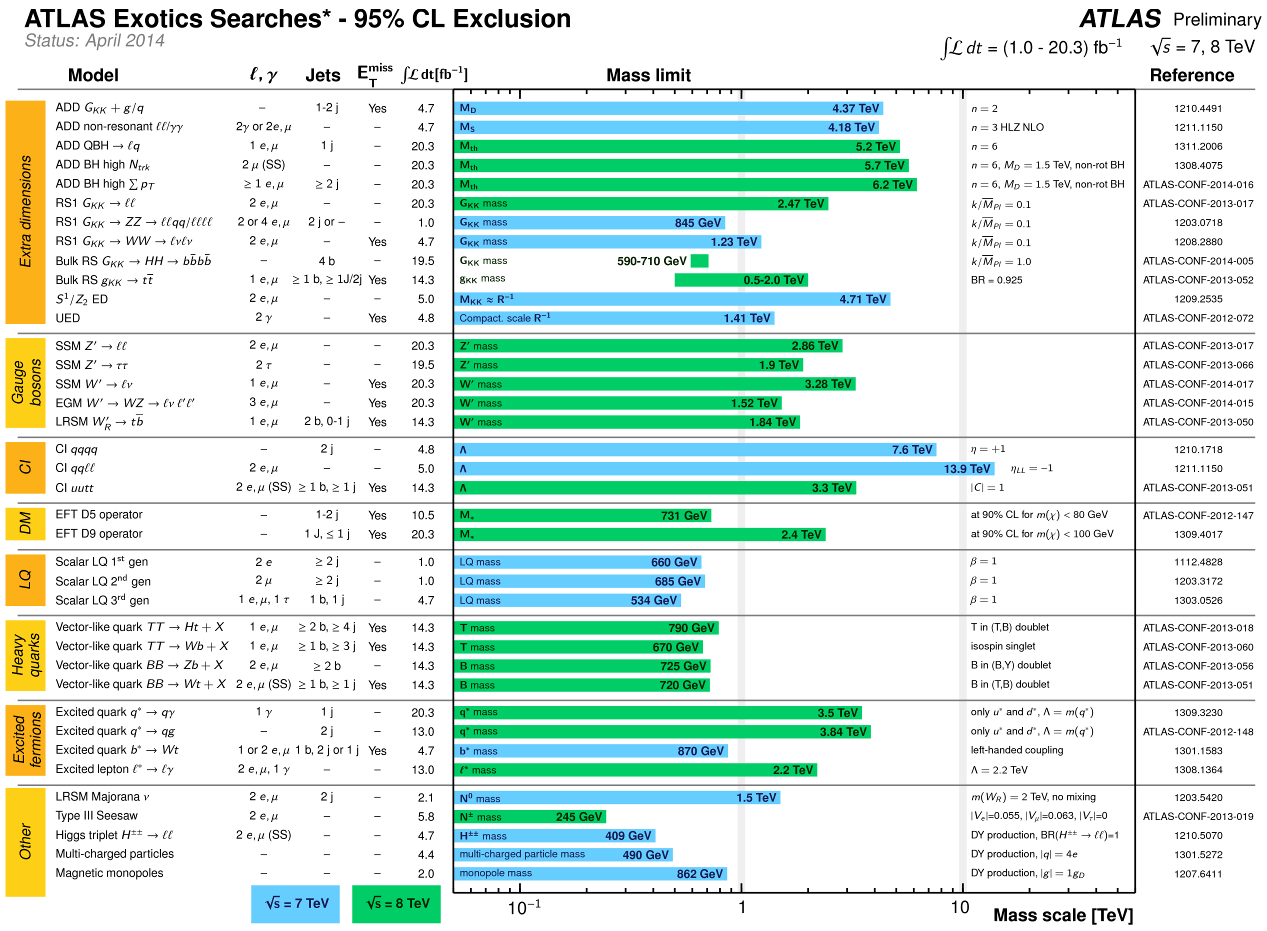
ABSTRACT

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

A Higgs Boson - Now what?

- The observed Higgs Boson resolves the unitarity crisis: m_H = 125.5 GeV (New physics must appear at or below theTeV scale)
- The second argument remains strong. but is now less rigorously tied to the TeV scale and
  - 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



ATLAS Exotics Searches* - 95% CL Exclusion

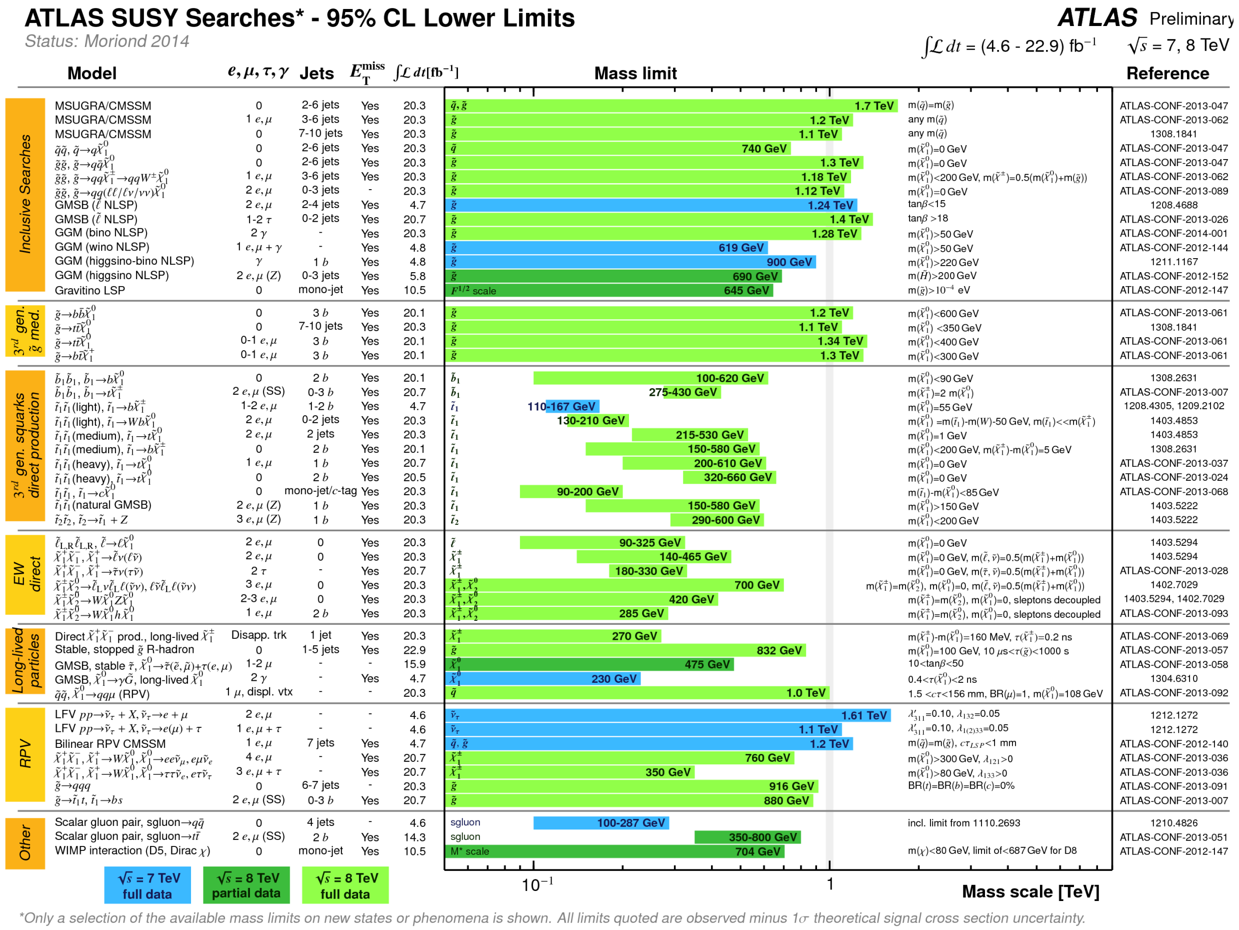
Status: April 2014

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (1.0 - 20.3) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

	Model	ℓ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt$[fb^{-1}]	Mass limit		Reference
Extra dimensions	ADD $G_{KK}+g/q$	–	1-2 j	Yes	4.7	🟦 M_D 4.37 TeV	$n=2$	1210.4491
	ADD non-resonant $\ell\ell/\gamma\gamma$	2γ or $2e,\mu$	–	–	4.7	🟦 M_S 4.18 TeV	$n=3$ HLZ NLO	1211.1150
	ADD QBH $\to \ell q$	$1\ e,\mu$	1 j	–	20.3	🟩 M_{th} 5.2 TeV	$n=6$	1311.2006
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	🟩 M_{th} 5.7 TeV	$n=6$, $M_D=1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e,\mu$	≥ 2 j	–	20.3	🟩 M_{th} 6.2 TeV	$n=6$, $M_D=1.5$ TeV, non-rot BH	ATLAS-CONF-2014-016
	RS1 $G_{KK}\to\ell\ell$	$2\ e,\mu$	–	–	20.3	🟩 G_{KK} mass 2.47 TeV	$k/\overline{M}_{Pl}=0.1$	ATLAS-CONF-2013-017
	RS1 $G_{KK}\to ZZ\to\ell\ell qq/\ell\ell\ell\ell$	2 or 4 e,μ	2 j or –	–	1.0	🟦 G_{KK} mass 845 GeV	$k/\overline{M}_{Pl}=0.1$	1203.0718
	RS1 $G_{KK}\to WW\to\ell\nu\ell\nu$	$2\ e,\mu$	–	Yes	4.7	🟦 G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl}=0.1$	1208.2880
	Bulk RS $G_{KK}\to HH\to b\bar{b}b\bar{b}$	–	4 b	–	19.5	🟩 G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl}=1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK}\to t\bar{t}$	$1\ e,\mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	🟩 g_{KK} mass 0.5-2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e,\mu$	–	–	5.0	🟦 $M_{KK}\approx R^{-1}$ 4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	🟦 Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z'\to\ell\ell$	$2\ e,\mu$	–	–	20.3	🟩 Z' mass 2.86 TeV		ATLAS-CONF-2013-017
	SSM $Z'\to\tau\tau$	$2\ \tau$	–	–	19.5	🟩 Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W'\to\ell\nu$	$1\ e,\mu$	–	Yes	20.3	🟩 W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W'\to WZ\to\ell\nu\,\ell'\ell'$	$3\ e,\mu$	–	Yes	20.3	🟩 W' mass 1.52 TeV		ATLAS-CONF-2014-015
	LRSM $W'_R\to t\bar{b}$	$1\ e,\mu$	2 b, 0-1 j	Yes	14.3	🟩 W' mass 1.84 TeV		ATLAS-CONF-2013-050
CI	CI $qqqq$	–	2 j	–	4.8	🟦 Λ 7.6 TeV	$\eta=+1$	1210.1718
	CI $qq\ell\ell$	$2\ e,\mu$	–	–	5.0	🟦 Λ 13.9 TeV	$\eta_{LL}=-1$	1211.1150
	CI $uutt$	$2\ e,\mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	🟩 Λ 3.3 TeV	$\lvert C\rvert=1$	ATLAS-CONF-2013-051
DM	EFT D5 operator	–	1-2 j	Yes	10.5	🟩 M_* 731 GeV	at 90% CL for $m(\chi)<80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator	–	1 J, ≤ 1 j	Yes	20.3	🟩 M_* 2.4 TeV	at 90% CL for $m(\chi)<100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	1.0	🟦 LQ mass 660 GeV	$\beta=1$	1112.4828
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	1.0	🟦 LQ mass 685 GeV	$\beta=1$	1203.3172
	Scalar LQ 3rd gen	$1\ e,\mu, 1\ \tau$	1 b, 1 j	–	4.7	🟦 LQ mass 534 GeV	$\beta=1$	1303.0526
Heavy quarks	Vector-like quark $TT\to Ht+X$	$1\ e,\mu$	≥ 2 b, ≥ 4 j	Yes	14.3	🟩 T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT\to Wb+X$	$1\ e,\mu$	≥ 1 b, ≥ 3 j	Yes	14.3	🟩 T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $BB\to Zb+X$	$2\ e,\mu$	≥ 2 b	–	14.3	🟩 B mass 725 GeV	B in (B,Y) doublet	ATLAS-CONF-2013-056
	Vector-like quark $BB\to Wt+X$	$2\ e,\mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	🟩 B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^*\to q\gamma$	$1\ \gamma$	1 j	–	20.3	🟩 q* mass 3.5 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1309.3230
	Excited quark $q^*\to qg$	–	2 j	–	13.0	🟩 q* mass 3.84 TeV	only u^* and d^*, $\Lambda=m(q^*)$	ATLAS-CONF-2012-148
	Excited quark $b^*\to Wt$	1 or 2 e,μ	1 b, 2 j or 1 j	Yes	4.7	🟦 b* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^*\to\ell\gamma$	$2\ e,\mu, 1\ \gamma$	–	–	13.0	🟩 ℓ^* mass 2.2 TeV	$\Lambda=2.2$ TeV	1308.1364
Other	LRSM Majorana ν	$2\ e,\mu$	2 j	–	2.1	🟦 N^0 mass 1.5 TeV	$m(W_R)=2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\ e,\mu$	–	–	5.8	🟩 $N^\pm$ mass 245 GeV	$\lvert V_e\rvert$=0.055, $\lvert V_\mu\rvert$=0.063, $\lvert V_\tau\rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm}\to\ell\ell$	$2\ e,\mu$ (SS)	–	–	4.7	🟦 $H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm}\to\ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	🟦 multi-charged particle mass 490 GeV	DY production, $\lvert q\rvert=4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	🟦 monopole mass 862 GeV	DY production, $\lvert g\rvert=1g_D$	1207.6411

🟦 $\sqrt{s}$ = 7 TeV   🟩 $\sqrt{s}$ = 8 TeV



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Moriond 2014

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (4.6 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

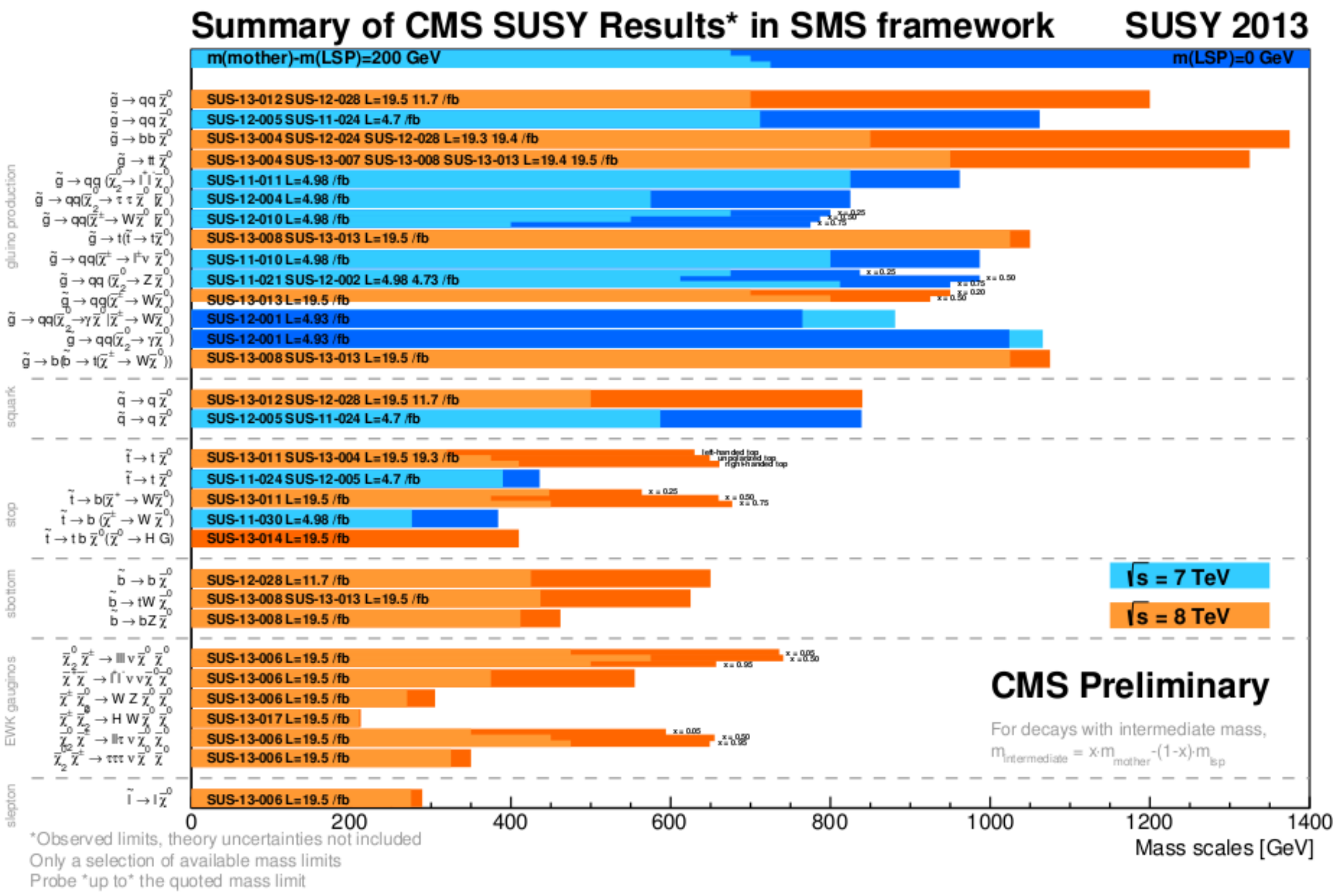
	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt$[fb^{-1}]	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	🟩 $\tilde{q},\tilde{g}$ 1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	$1\ e,\mu$	3-6 jets	Yes	20.3	🟩 $\tilde{g}$ 1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	🟩 $\tilde{g}$ 1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	🟩 $\tilde{q}$ 740 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	🟩 $\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	$1\ e,\mu$	3-6 jets	Yes	20.3	🟩 $\tilde{g}$ 1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	$2\ e,\mu$	0-3 jets	-	20.3	🟩 $\tilde{g}$ 1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	$2\ e,\mu$	2-4 jets	Yes	4.7	🟦 $\tilde{g}$ 1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	🟩 $\tilde{g}$ 1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	$2\ \gamma$	-	Yes	20.3	🟩 $\tilde{g}$ 1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	$1\ e,\mu+\gamma$	-	Yes	4.8	🟦 $\tilde{g}$ 619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	$1\ b$	Yes	4.8	🟦 $\tilde{g}$ 900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	$2\ e,\mu\ (Z)$	0-3 jets	Yes	5.8	▩ $\tilde{g}$ 690 GeV	m($\tilde{H}$)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	▩ $F^{1/2}$ scale 645 GeV	m($\tilde{g}$)>10^{-4} eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	$3\ b$	Yes	20.1	🟩 $\tilde{g}$ 1.2 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	🟩 $\tilde{g}$ 1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	$3\ b$	Yes	20.1	🟩 $\tilde{g}$ 1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	$3\ b$	Yes	20.1	🟩 $\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	$2\ b$	Yes	20.1	🟩 $\tilde{b}_1$ 100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	$2\ e,\mu$ (SS)	0-3 b	Yes	20.7	🟩 $\tilde{b}_1$ 275-430 GeV	m($\tilde{\chi}_1^\pm$)=2 m($\tilde{\chi}_1^0$)	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	🟦 $\tilde{t}_1$ 110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	$2\ e,\mu$	0-2 jets	Yes	20.3	🟩 $\tilde{t}_1$ 130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^\pm$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	$2\ e,\mu$	2 jets	Yes	20.3	🟩 $\tilde{t}_1$ 215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	$2\ b$	Yes	20.1	🟩 $\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	$1\ e,\mu$	$1\ b$	Yes	20.7	🟩 $\tilde{t}_1$ 200-610 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	$2\ b$	Yes	20.5	🟩 $\tilde{t}_1$ 320-660 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	🟩 $\tilde{t}_1$ 90-200 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	$2\ e,\mu\ (Z)$	$1\ b$	Yes	20.3	🟩 $\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	$3\ e,\mu\ (Z)$	$1\ b$	Yes	20.3	🟩 $\tilde{t}_2$ 290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	$2\ e,\mu$	0	Yes	20.3	🟩 $\tilde{\ell}$ 90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	$2\ e,\mu$	0	Yes	20.3	🟩 $\tilde{\chi}_1^\pm$ 140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	$2\ \tau$	-	Yes	20.7	🟩 $\tilde{\chi}_1^\pm$ 180-330 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	$3\ e,\mu$	0	Yes	20.3	🟩 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 700 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 420 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	$1\ e,\mu$	$2\ b$	Yes	20.3	🟩 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 285 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	🟩 $\tilde{\chi}_1^\pm$ 270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	🟩 $\tilde{g}$ 832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	▩ $\tilde{\chi}_1^0$ 475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	$2\ \gamma$	-	Yes	4.7	🟦 $\tilde{\chi}_1^0$ 230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	$1\ \mu$, displ. vtx	-	-	20.3	🟩 $\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	$2\ e,\mu$	-	-	4.6	🟦 $\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	$1\ e,\mu+\tau$	-	-	4.6	🟦 $\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	$1\ e,\mu$	7 jets	Yes	4.7	🟦 $\tilde{q},\tilde{g}$ 1.2 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	$4\ e,\mu$	-	Yes	20.7	🟩 $\tilde{\chi}_1^\pm$ 760 GeV	m($\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	$3\ e,\mu+\tau$	-	Yes	20.7	🟩 $\tilde{\chi}_1^\pm$ 350 GeV	m($\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	🟩 $\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	$2\ e,\mu$ (SS)	0-3 b	Yes	20.7	🟩 $\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	🟦 sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	$2\ e,\mu$ (SS)	$2\ b$	Yes	14.3	▩ sgluon 350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	▩ M* scale 704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

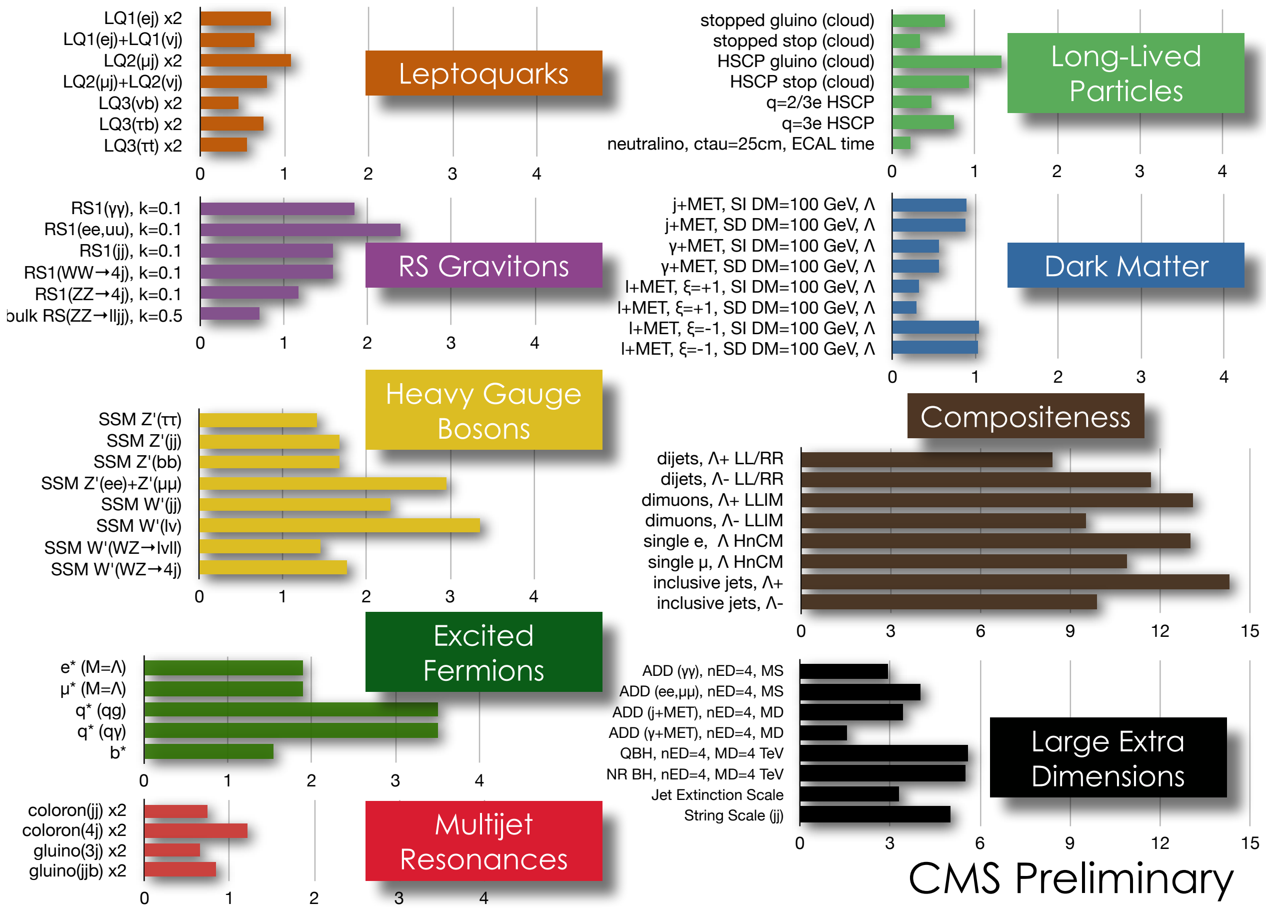
🟦 $\sqrt{s}$ = 7 TeV full data   ▩ $\sqrt{s}$ = 8 TeV partial data   🟩 $\sqrt{s}$ = 8 TeV full data

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

A Higgs Boson - Now what?

- CMS limits





- Similarly B, D, K decays don't show evidence for BSM physics.

– BUT

A Higgs Boson - Now what?

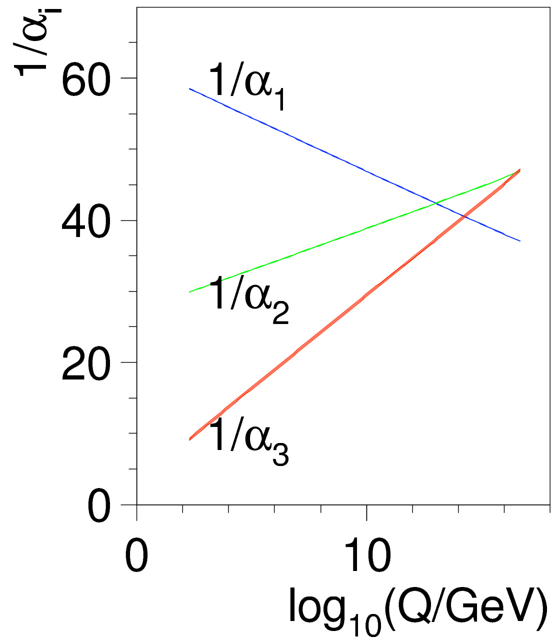
- There must be new physics:
  - The Standard Model is incomplete:
    - dark matter; neutrino masses and mixing -> new fields or interactions;
    - baryon asymmetry in the universe -> more CP violation
    - gauge unification -> new interactions;
    - gravity: strings and extra dimensions
  - Experimental hints of new physics: $(g\text{-}2)_\mu$,
  - Scalar sector problematic:

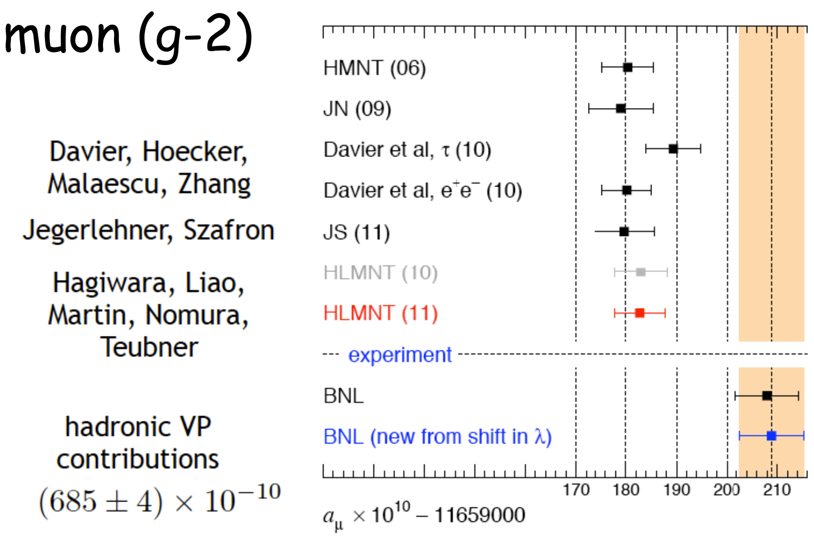
$$\mu^2(\Phi^\dagger\Phi) + \lambda\ (\Phi^\dagger\Phi)^2 + \Gamma_{ij}\psi_{iL}^\dagger\psi_{jR}\Phi + \text{h.c.}$$

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

vacuum stability

large range of fermion masses





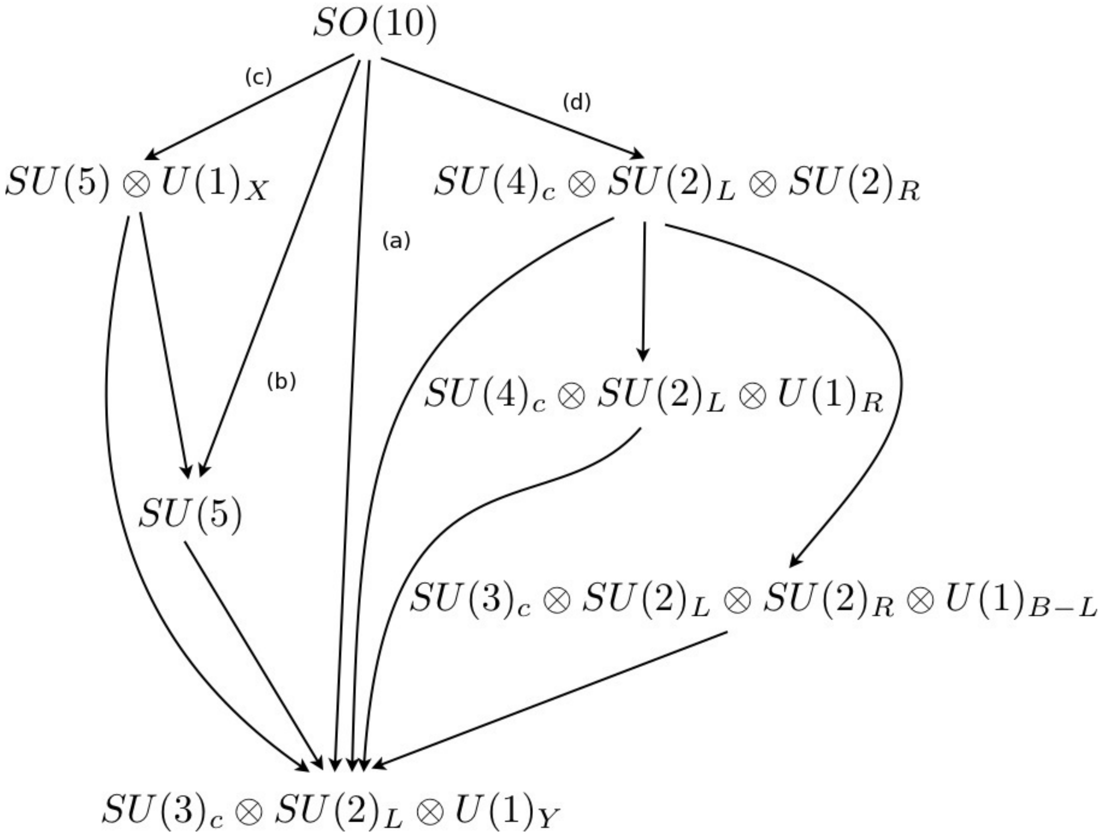
There remains a persistent discrepancy of 3.3-3.6 σ

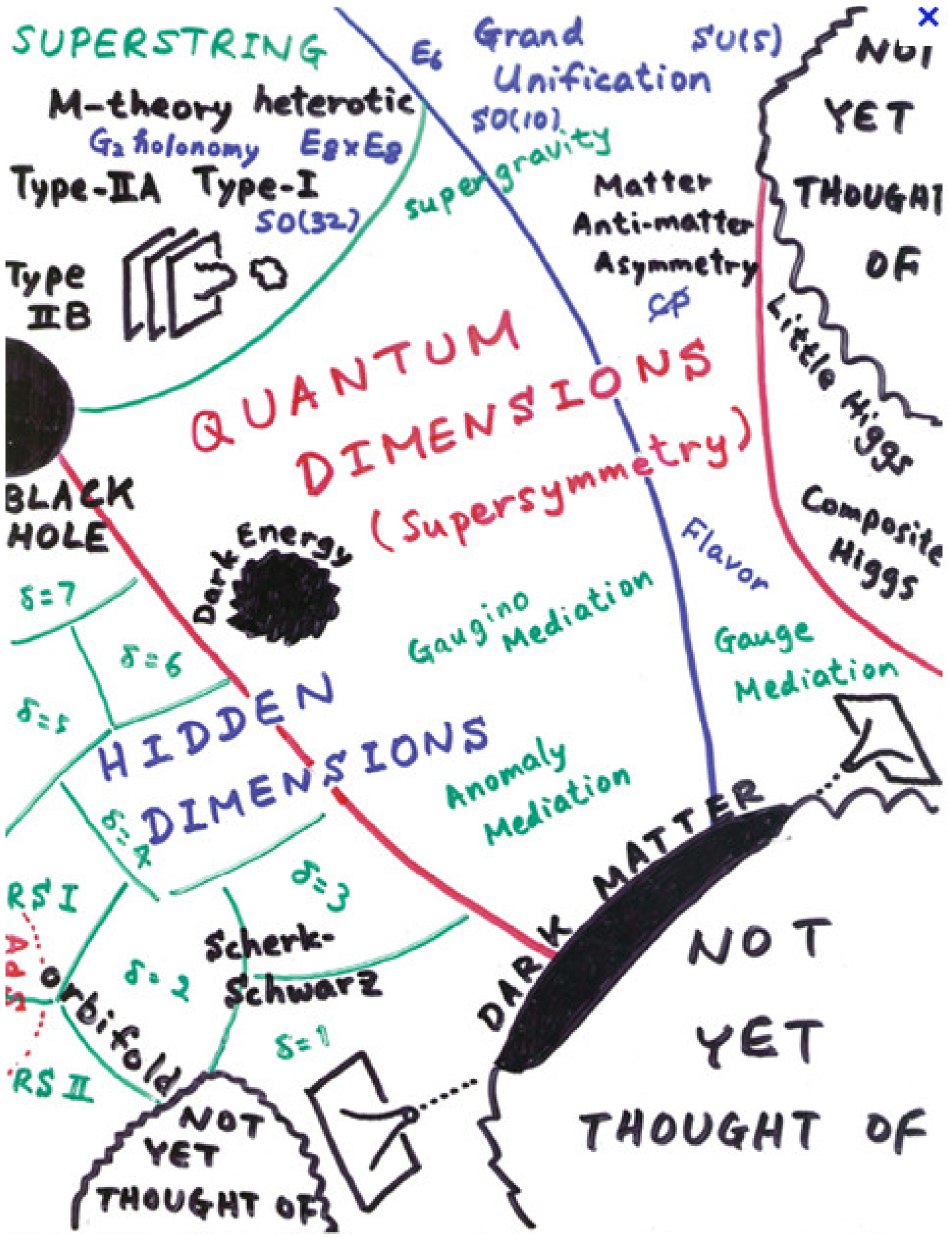
- Scales already probed at the LHC suggest that to study BSM new physics a future energy frontier collider must have $\sqrt{\hat{s}}$ in the multi-TeV range even for EW processes !!

A Higgs Boson - Now what?

- But we don't know the scale of new physics. From electroweak scale to Planck scale. Worse case - no nearby scale. Dark matter is axions and right handed neutrinos get mass at high scale. Only an axion would be directly observable. Best case - nearby physics

Desert or Oasis



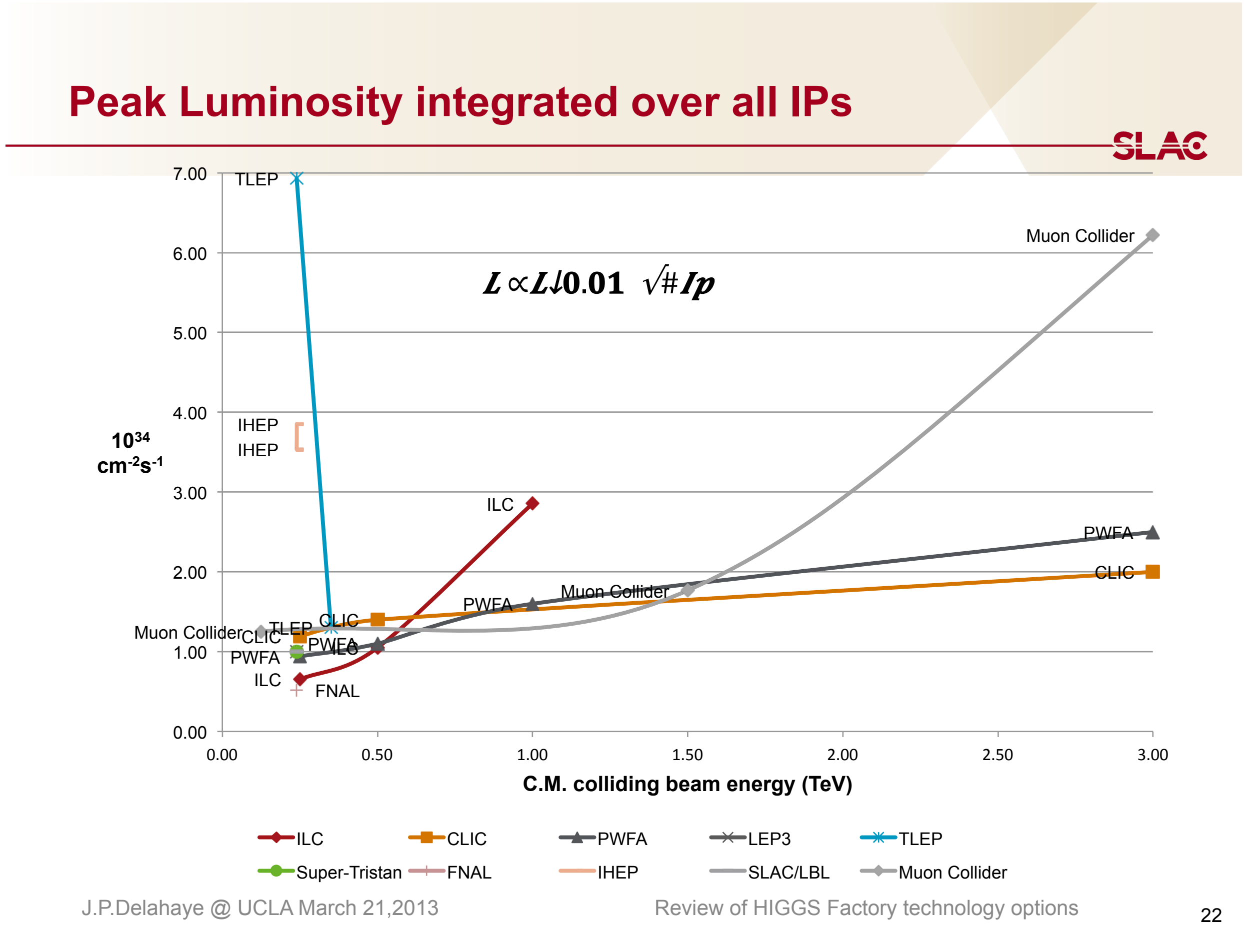


H. Murayama

- Possible new gauge bosons and fermions.
- Naturalness requires nearby new physics.

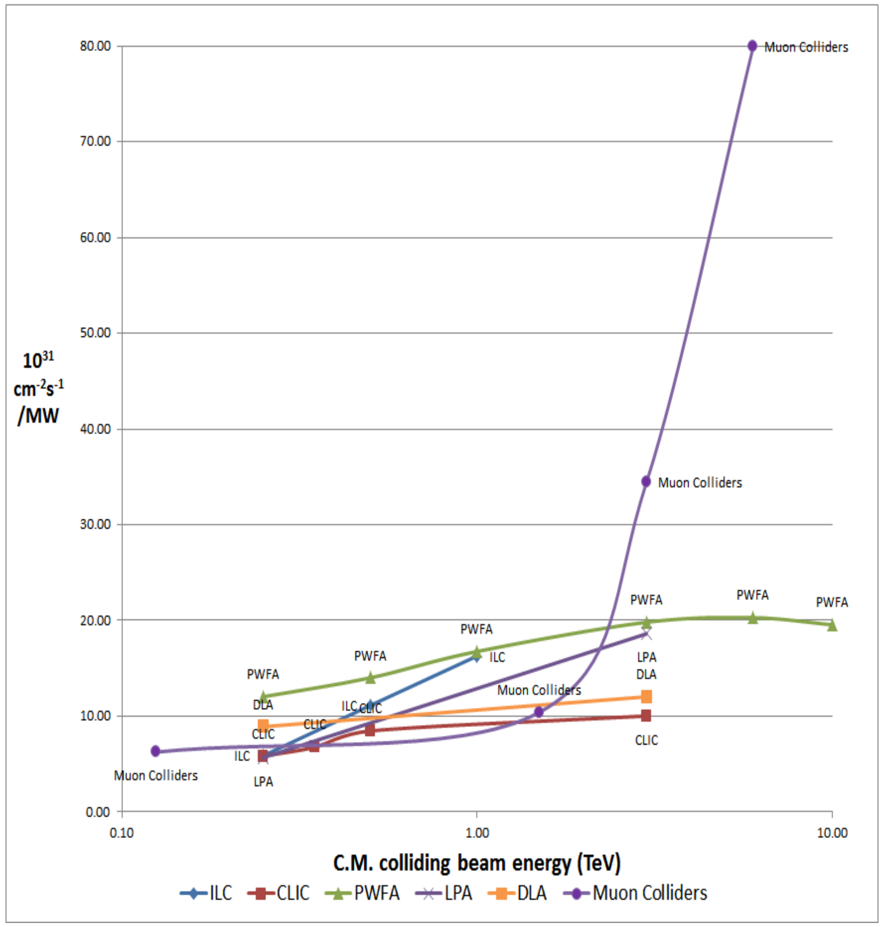
Basics of Future High Energy Colliders

- Hadron colliders - LHC-14, LHC-HL, VLHC ≤ 100 TeV pp collider [(CERN), (China), (USA)],…
- Comparison of lepton colliders:



Peak Luminosity integrated over all IPs

J.P.Delahaye @ UCLA March 21,2013 Review of HIGGS Factory technology options 22



J-P. Delahaye, *et al.* [arXiv:1308.0494]

- Increase of luminosity with energy. Needed for new physics.
- Wall power in operation a major concern.
- For √s above a few TeV only the muon collider remains a potentially viable lepton collider.

Basics of Future High Energy Colliders

– Limitations on energy and luminosity of a muon collider (a theorist's view)

- Production of muons: N_μ = 2x10^{12} ($\mu^\pm$ /beam) x 12 (beams/$\sec^{-1}$) -> 7.5 x 10^{20} ($\mu^\pm$ /year)

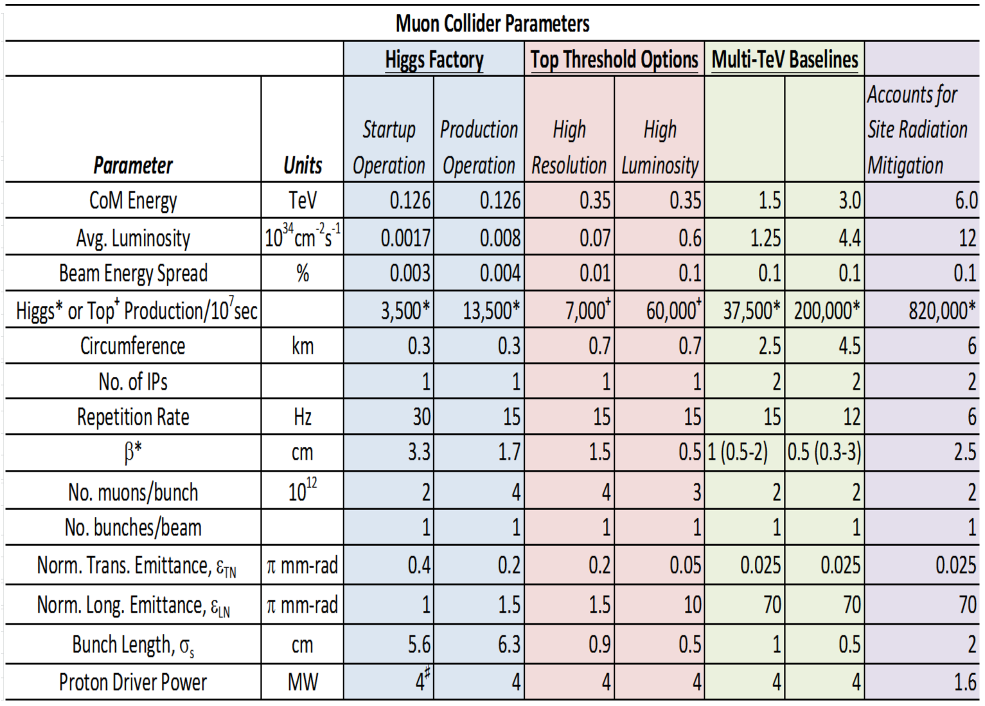
J-P. Delahaye, *et al.* [arXiv:1308.0494]

- $\int dt\mathscr{L}$ = 1.32 ab^{-1} $(E_{cm}/(3TeV))^2$ $(N_\mu/(7.5 \times 10^{20}))^2$
- Neutrino beams far radiation: $\theta_{\frac{1}{2}} = \frac{mc^2}{E} = 1.057\frac{10^{-4}}{E\mu(TeV)}$

Table 1: Radial distance, R, from the ring center with center-of-mass energy, $\sqrt{s}$, and depth, d, needed to reduce neutrino-induced dose at surface to DOE (100 mrem) and Fermilab (10 mrem) annual off-site limits at N_D decays/yr.

	$\sqrt{s}$ (TeV)	0.5	1	2	3	4
	$N_D \times 10^{21}$	0.2	0.2	2	2	2
100 mrem	R (km)	0.4	1.1	6.5	12	18
	d (m)	≤ 1	≤ 1	3.3	11	25
10 mrem	R (km)	1.2	3.2	21	37	57
	d (m)	≤ 1	≤ 1	34	107	254

N. V. Mokhov and A. VanGinneken
Conf. Proc. **C990329**, 3074(1999).



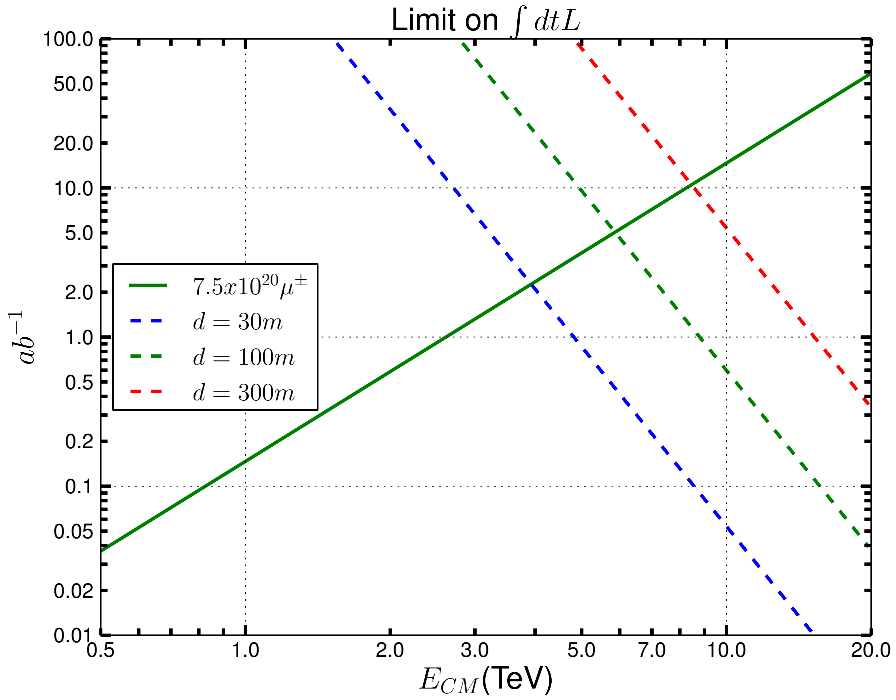
Muon Collider Parameters

		Higgs Factory		Top Threshold Options		Multi-TeV Baselines		
Parameter	***Units***	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top$^+$ Production/10^7sec		3,500*	13,500*	7,000$^+$	60,000$^+$	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	2.5
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	2
Proton Driver Power	MW	$4^\sharp$	4	4	4	4	4	1.6

- dose ∝ N_μ $E_{cm}{}^3 R^{-2}$: If maximum dose = 0.3 mSv/yr = 30 mrem/yr

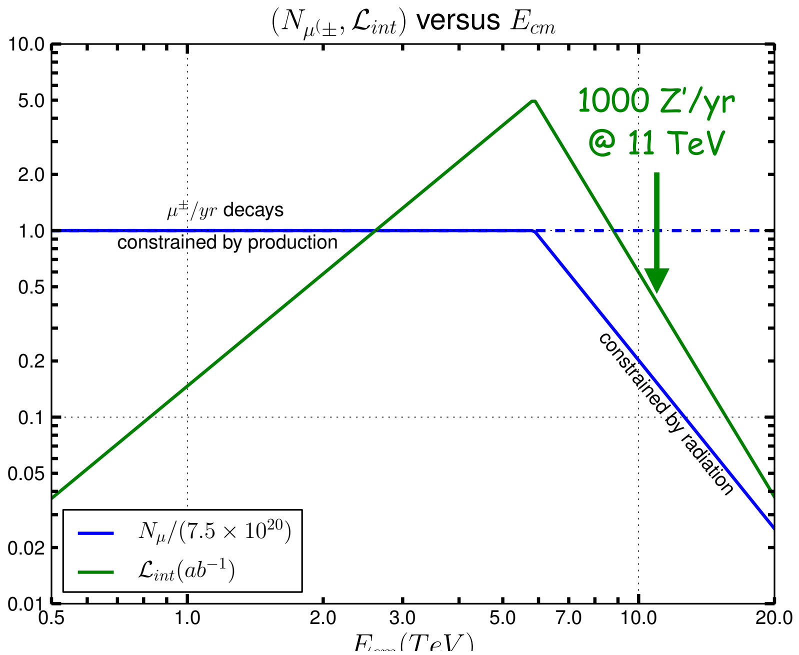
$$\left(\frac{N_\mu}{7.5 \times 10^{20}}\right) \leq 7.48\frac{dose}{(0.3mSv)}\left(\frac{3TeV}{E_{cm}}\right)^3\frac{d}{(100m)}$$

- For 7.5 x 10^{20} ($\mu^\pm$ /year) and ring depth = 100 m:
  - Maximum luminosity ~ 4.6 ab^{-1}/yr at E_{cm} ~ 6 TeV.



Basics of Future High Energy Colliders

- Variation of total muons per year with the constraints:
  - E_{cm} = 6 TeV —> 7.0×10^{20} ($\mu^{\pm}$/year) $\int dt\mathscr{L} = 4.6\ \mathrm{ab}^{-1}/\mathrm{yr}$
  - E_{cm} = 10 TeV —> 1.5×10^{20} ($\mu^{\pm}$/year) $\int dt\mathscr{L} = 0.6\ \mathrm{ab}^{-1}/\mathrm{yr}$



- Cross Sections at a Muon Collider:
  - For s-channel pair production (|θ| > 10°)
    R = $\sigma/\sigma_{QED}(\mu^+\mu^- \to e^+e^-)$ ~ flat:

$$\sigma_{\mathrm{QED}}(\mu^+\mu^- \to e^+e^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8\ \mathrm{fb}}{s(\mathrm{TeV}^2)}$$

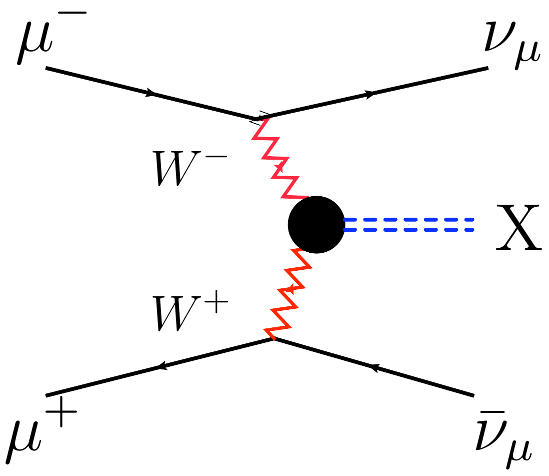
Sweet spot
~ 6 TeV

  - Resonance production: R large

$$\boxed{R_{\mathrm{peak}} = (2J+1)3\frac{B(\mu^+\mu^-)B(visible)}{\alpha^2_{\mathrm{EM}}}}$$

1000 Z'/yr
@ 11 TeV

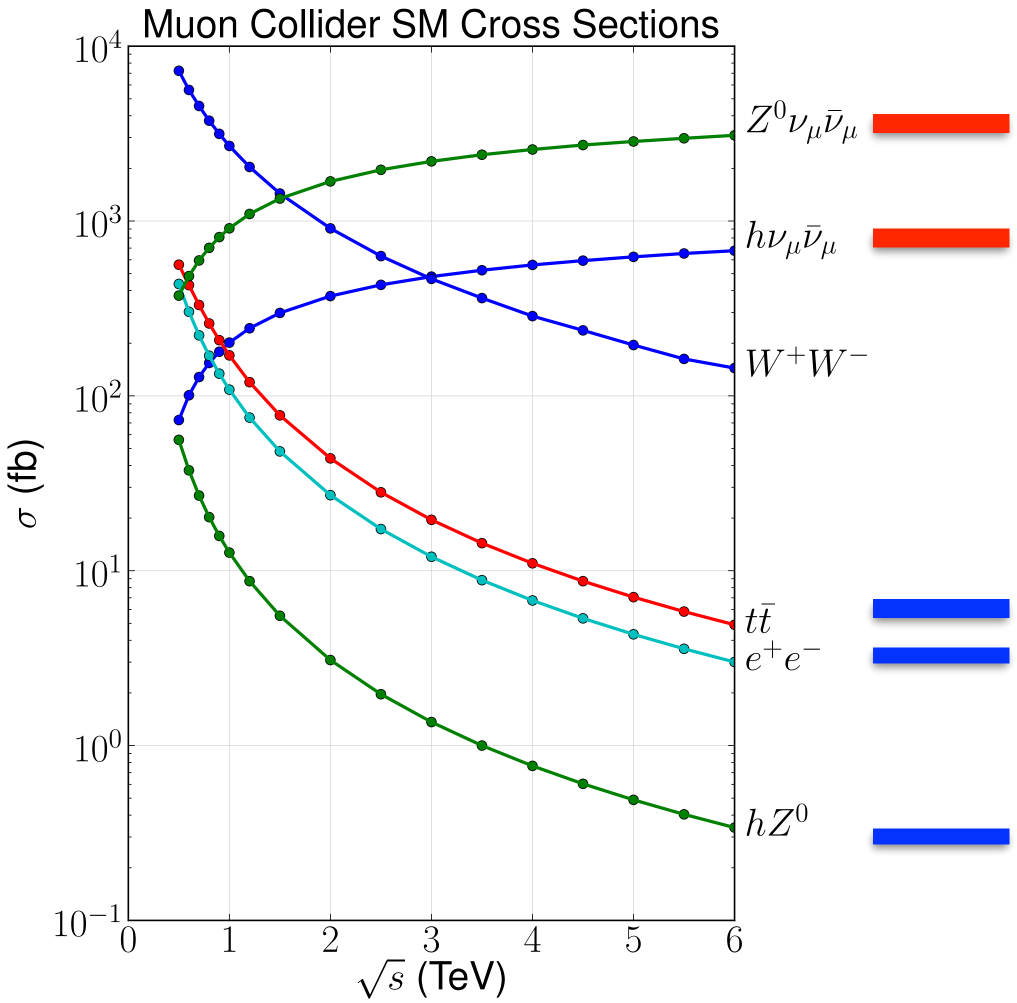
  - Fusion Processes: For SM pair production (|θ| > 10°)



$$\sigma(s) = C\ln\left(\frac{s}{M_X^2}\right) + \ldots$$

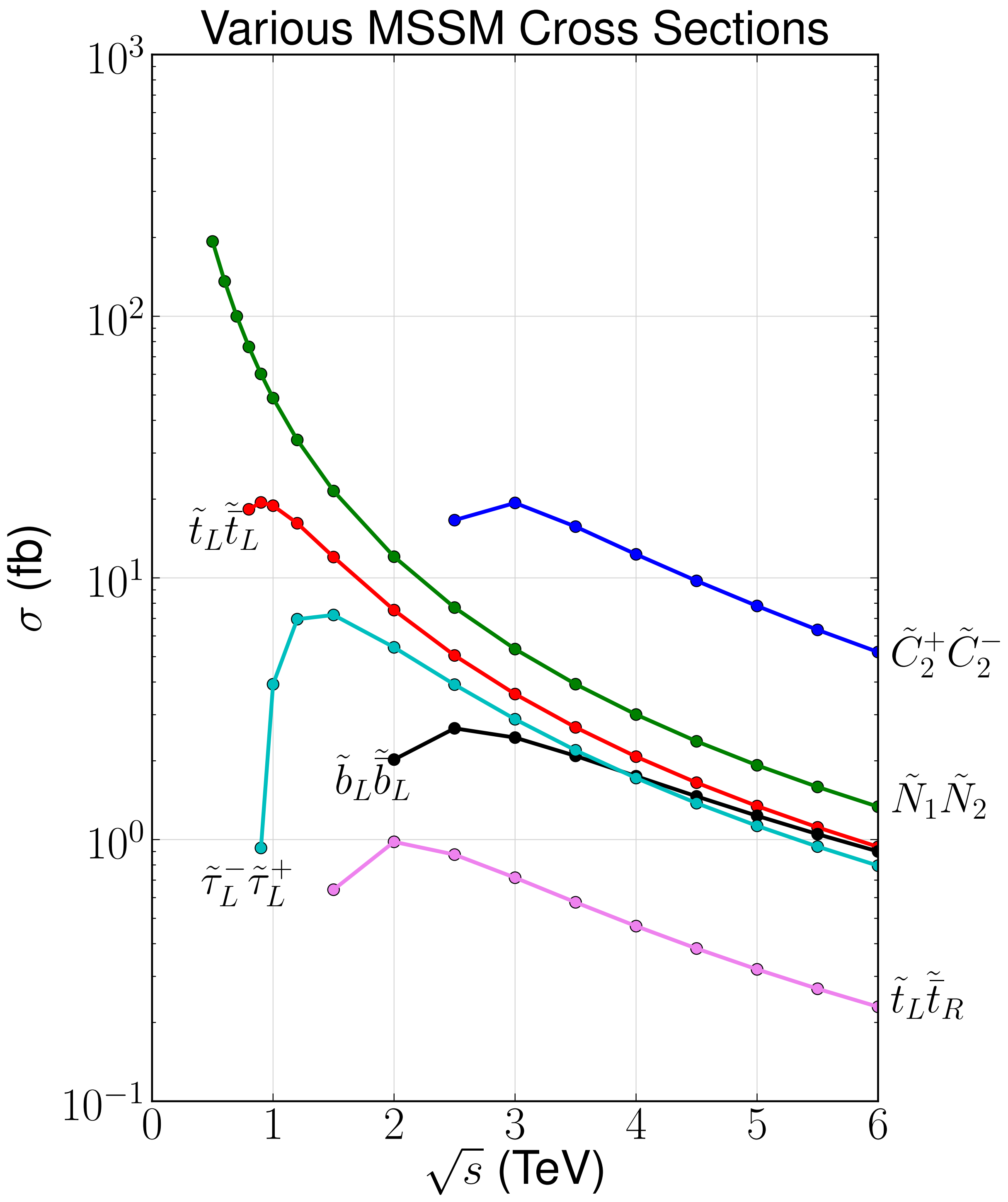
Cross sections rise
with energy

  - An EW boson collider !!



Basics of Future High Energy Colliders

- Sample cross sections for Sparticles



At 6 TeV with particle
masses below threshold

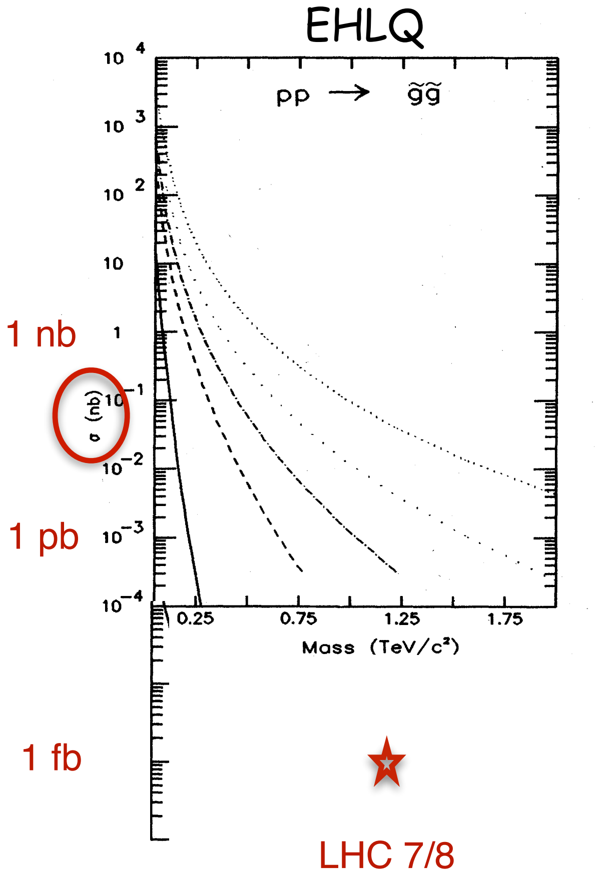
22,000 chargino $\chi^{\pm}_2$ pairs/year

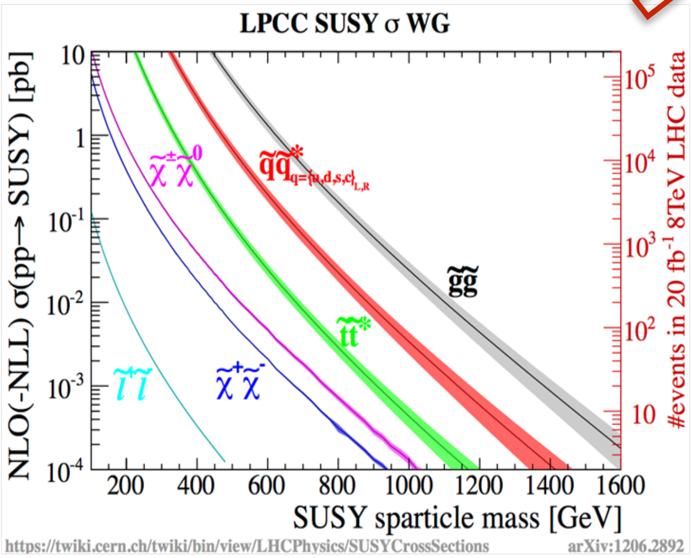
5,700 neutralino $\chi^0_2\,\chi^0_1$ pairs/year

3,600 stop pairs/year

Basics of Future High Energy Colliders

- VLHC: up to 100 TeV
  - The physics reach of these colliders is relatively simple to estimate.
  - Since EHLQ (30 yrs ago) there have been great advances in theory and experiment:
    - Background measurements, detector advances, improved PDF's, higher order QCD/EW calculations.
    - Integrated luminosities (300 fb^{-1}/yr) - Almost two orders of magnitude greater were assumed for the SSC.





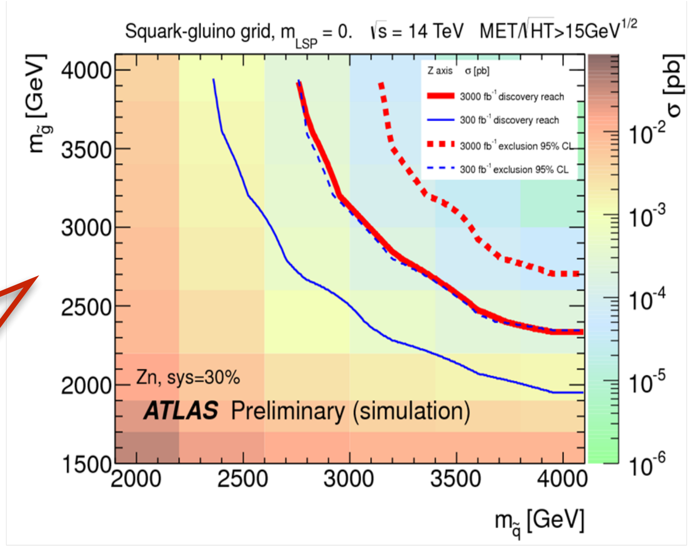
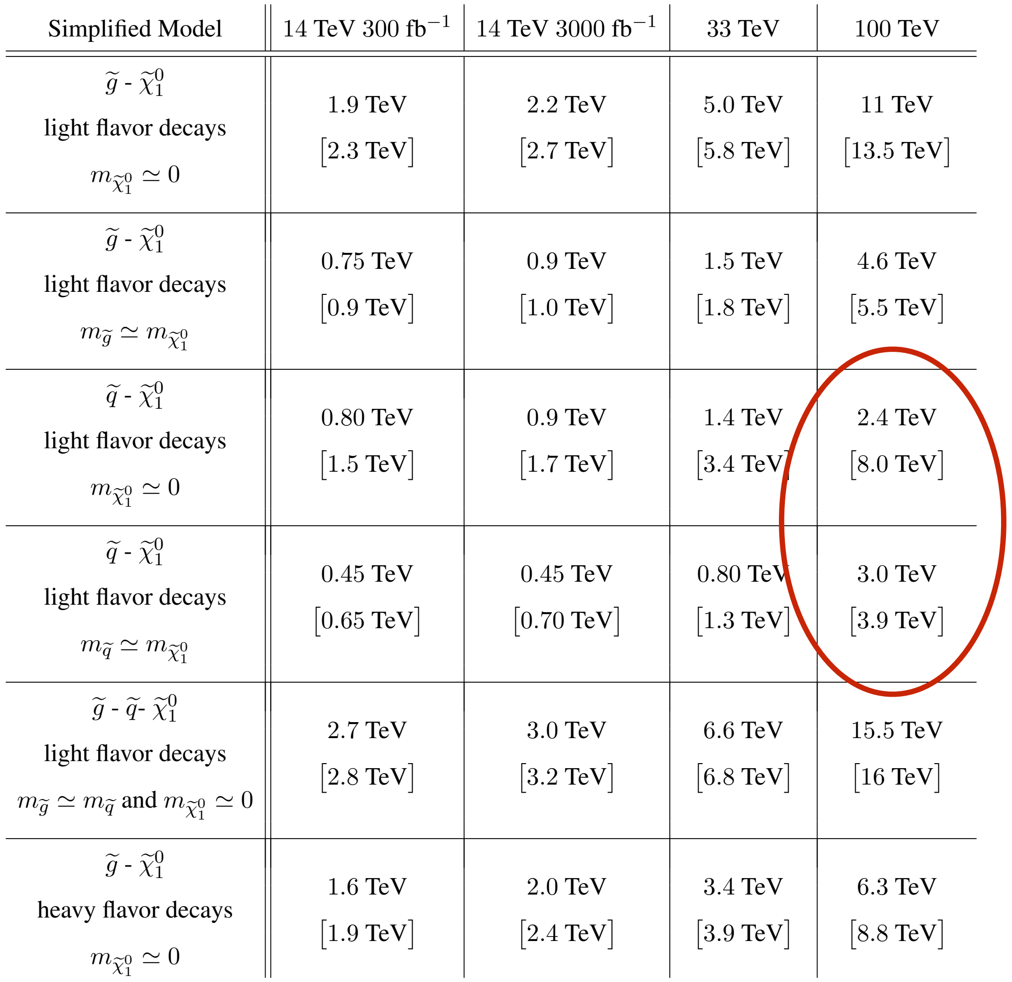


Figure 9: Expected gluino mass limit using 300 /fb and 3000 /fb at 14 TeV in ATLAS [14].

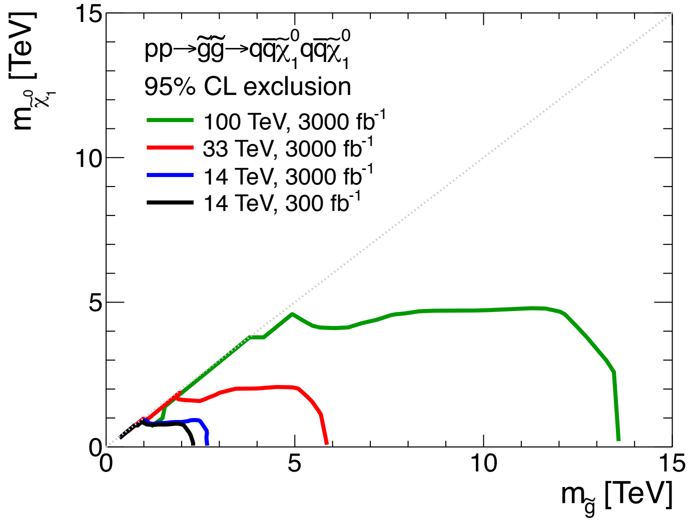
Basics of Future High Energy Colliders

- 5σ discovery/[95% cl limits] at future hadron colliders:
  - squarks and gluinos

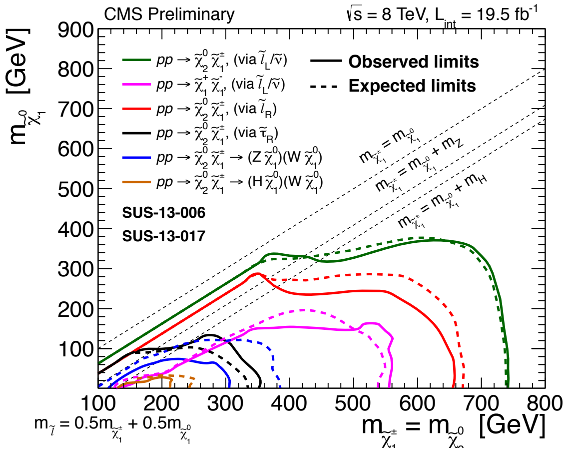


Simplified Model	14 TeV 300 fb^{-1}	14 TeV 3000 fb^{-1}	33 TeV	100 TeV
$\tilde{g}$ - $\tilde{\chi}_1^0$ light flavor decays $m_{\tilde{\chi}_1^0} \simeq 0$	1.9 TeV [2.3 TeV]	2.2 TeV [2.7 TeV]	5.0 TeV [5.8 TeV]	11 TeV [13.5 TeV]
$\tilde{g}$ - $\tilde{\chi}_1^0$ light flavor decays $m_{\tilde{g}} \simeq m_{\tilde{\chi}_1^0}$	0.75 TeV [0.9 TeV]	0.9 TeV [1.0 TeV]	1.5 TeV [1.8 TeV]	4.6 TeV [5.5 TeV]
$\tilde{q}$ - $\tilde{\chi}_1^0$ light flavor decays $m_{\tilde{\chi}_1^0} \simeq 0$	0.80 TeV [1.5 TeV]	0.9 TeV [1.7 TeV]	1.4 TeV [3.4 TeV]	2.4 TeV [8.0 TeV]
$\tilde{q}$ - $\tilde{\chi}_1^0$ light flavor decays $m_{\tilde{q}} \simeq m_{\tilde{\chi}_1^0}$	0.45 TeV [0.65 TeV]	0.45 TeV [0.70 TeV]	0.80 TeV [1.3 TeV]	3.0 TeV [3.9 TeV]
$\tilde{g}$ - $\tilde{q}$- $\tilde{\chi}_1^0$ light flavor decays $m_{\tilde{g}} \simeq m_{\tilde{q}}$ and $m_{\tilde{\chi}_1^0} \simeq 0$	2.7 TeV [2.8 TeV]	3.0 TeV [3.2 TeV]	6.6 TeV [6.8 TeV]	15.5 TeV [16 TeV]
$\tilde{g}$ - $\tilde{\chi}_1^0$ heavy flavor decays $m_{\tilde{\chi}_1^0} \simeq 0$	1.6 TeV [1.9 TeV]	2.0 TeV [2.4 TeV]	3.4 TeV [3.9 TeV]	6.3 TeV [8.8 TeV]

[arXiv:1311.6480]



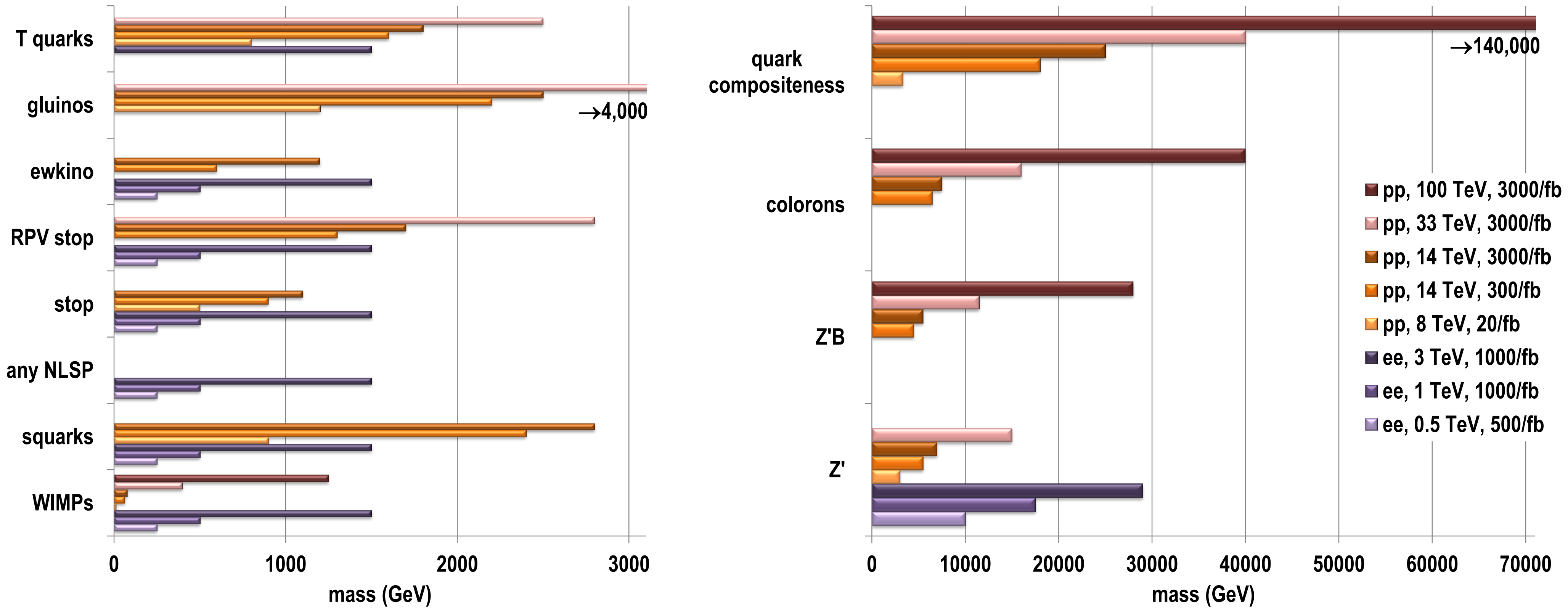
[arXiv:1405.2993]



- Limits very dependent on LSP mass and decay modes.

Basics of Future High Energy Colliders

- BSM 95% exclusion limits: Snowmass Study [arXiv:1311.0299]



- For comparison: a 6 TeV MC will be a factory for:
  - T quarks, squarks, stops, sleptons, ewkinos, and NLSP's < 3 TeV
  - Compositeness scales > 300 TeV
- For m(Z') < 11 TeV discovered at a hadron collider, the decay modes could be studied in detail at a MC.
- A 3-6 TeV Muon Collider would be complimentary to a 100 TeV hadron collider and would have significant discovery potential of its own.

Higgs Studies and More Scalars

P5: Science Questions and Science Drivers

1. Use the Higgs boson as a new tool for discovery
2. ….

- LHC -> HL-LHC (5%-10%) errors on couplings
- Statistics dominate for lepton colliders ILC (500), TLEP(350) ultimately 1%

S. Dawson et.al. Snowmass 2013:
Higgs working group report [arXiv:1310.8361]

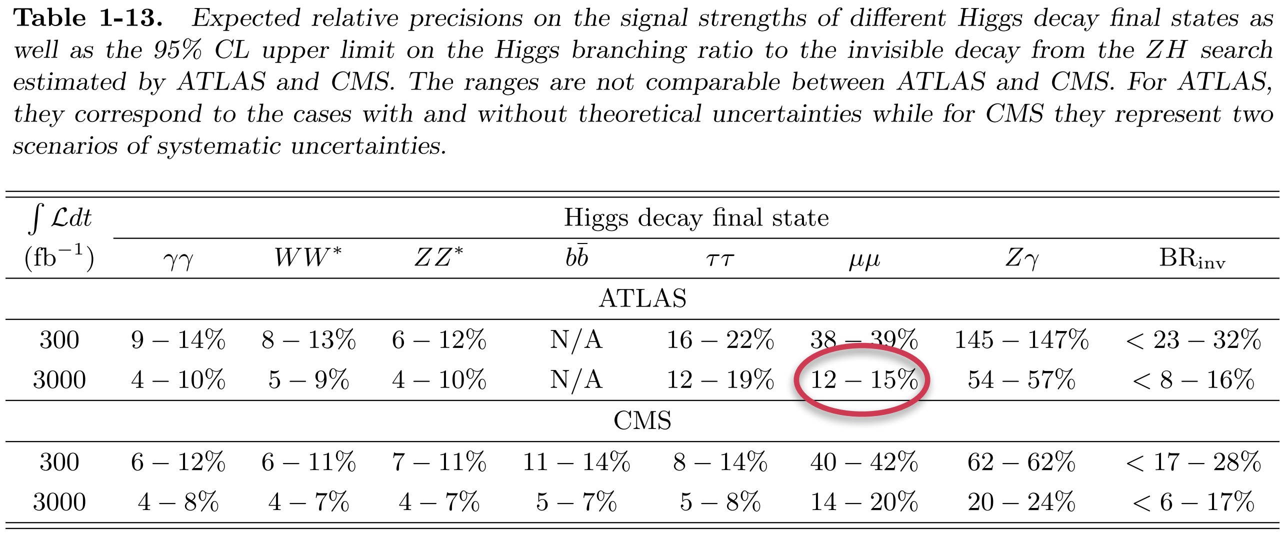


Table 1-13. *Expected relative precisions on the signal strengths of different Higgs decay final states as well as the 95% CL upper limit on the Higgs branching ratio to the invisible decay from the ZH search estimated by ATLAS and CMS. The ranges are not comparable between ATLAS and CMS. For ATLAS, they correspond to the cases with and without theoretical uncertainties while for CMS they represent two scenarios of systematic uncertainties.*

$\int \mathcal{L}dt$	Higgs decay final state							
(fb^{-1})	$\gamma\gamma$	WW^*	ZZ^*	$b\bar{b}$	$\tau\tau$	$\mu\mu$	$Z\gamma$	BR_{inv}
ATLAS								
300	9 – 14%	8 – 13%	6 – 12%	N/A	16 – 22%	38 – 39%	145 – 147%	< 23 – 32%
3000	4 – 10%	5 – 9%	4 – 10%	N/A	12 – 19%	12 – 15%	54 – 57%	< 8 – 16%
CMS								
300	6 – 12%	6 – 11%	7 – 11%	11 – 14%	8 – 14%	40 – 42%	62 – 62%	< 17 – 28%
3000	4 – 8%	4 – 7%	4 – 7%	5 – 7%	5 – 8%	14 – 20%	20 – 24%	< 6 – 17%

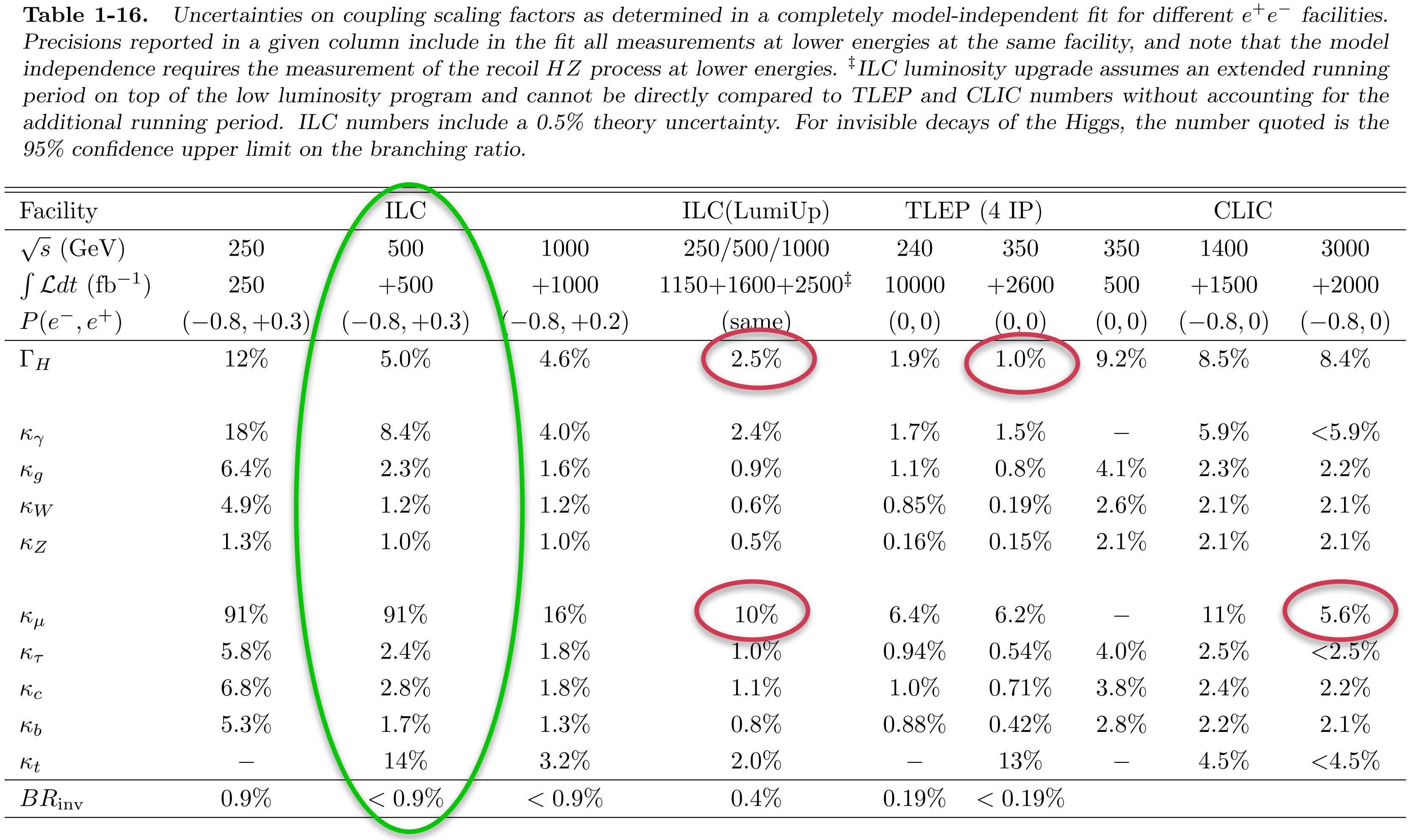


Table 1-16. *Uncertainties on coupling scaling factors as determined in a completely model-independent fit for different e^+e^- facilities. Precisions reported in a given column include in the fit all measurements at the same facility, and note that the model independence requires the measurement of the recoil HZ process at lower energies. ‡ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to TLEP and CLIC numbers without accounting for the additional running period. ILC numbers include a 0.5% theory uncertainty. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.*

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

Higgs Studies and More Scalars

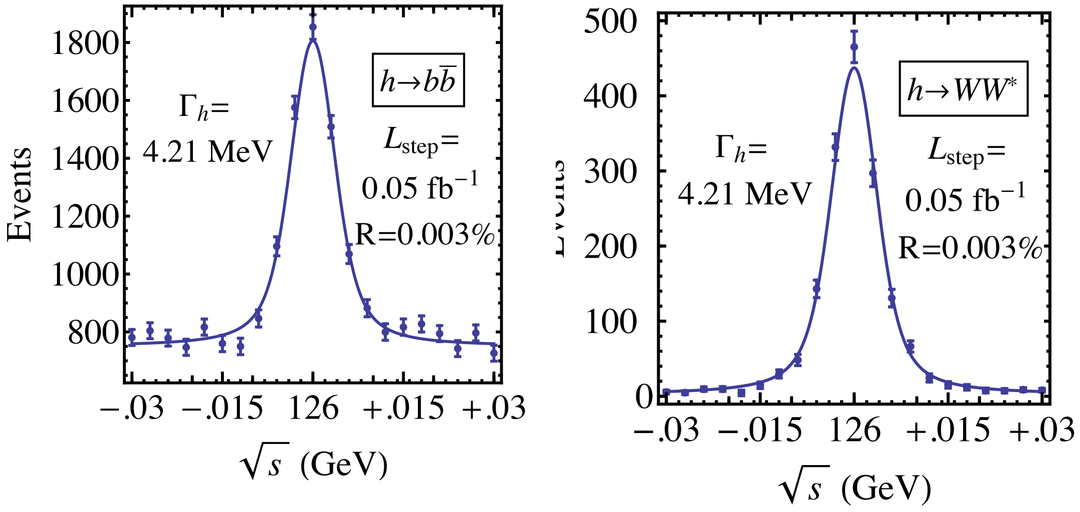
- A Role for a future Muon Collider Higgs Factory?
  - Only a muon collider can produce the Higgs boson as an s-channel resonance.
  - $\sigma(e^+e^- \to Zh \to l^+l^- h) = 19.1$ fb (250 GeV) versus
    $\sigma(\mu^+\mu^- \to h) = 26$ pb (for $\Delta=\Gamma$ and including ISR and a 15° forward cut)

$$\left[\frac{m_\mu}{m_e}\right]^2 = 4.28 \times 10^{\ 4}$$

$$\sigma_{\rm eff}(s) = \int d\sqrt{\hat s}\,\frac{dL(\sqrt{s})}{d\sqrt{\hat s}}\sigma(\mu^+\mu^- \to h \to X)$$

$$\propto \begin{cases} \Gamma_h^2 B/[(s-m_h^2)^2+\Gamma_h^2 m_h^2] & (\Delta \ll \Gamma_h), \\ B\exp[\frac{-(m_h-\sqrt{s})^2}{2\Delta^2}](\frac{\Gamma_h}{\Delta})/m_h^2 & (\Delta \gg \Gamma_h). \end{cases}$$

$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2 {\rm Br}(h\to\mu^+\mu^-){\rm Br}(h\to X)}{(\hat s - m_h^2)^2 + \Gamma_h^2 m_h^2}.$$



  - Finding the Higgs requires ~ 250 pb^{-1}
  - Assuming ∫ℒ dt = 1 fb R = ΔE/E = 0.003%
  - Unique results:

1. Higgs mass to 60 keV
2. Direct measurement of Higgs width to 150 keV
3. Measurement δ κ_μ = 1% using the known width and coupling to WW*

T. Han and Z. Liu [arXiv:1210.7803]
also see Zhen Liu's talk on Friday

$\Gamma_h = 4.21$ MeV	$L_{\rm step}$ (fb^{-1})	$\delta\Gamma_h$ (MeV)	δB	δm_h (MeV)
$R = 0.01\%$	0.005	0.73	6.5%	0.25
	0.025	**0.35**	**3.0%**	**0.12**
	0.2	0.17	1.1%	0.06
$R = 0.003\%$	0.01	0.30	4.4%	0.12
	0.05	**0.15**	**2.0%**	**0.06**
	0.2	0.08	1.0%	0.03

Higgs Studies and More Scalars

- Higgs Self-Coupling (λ):
  - SM: $m_H^2 = (8\lambda/g^2)\, m_W^2$ + loop corrs.
  - LHC; HL-LHC; VLHC: 50%; 20%; 8% (stat only)
  - ILC (500); ILC (1000); CLIC (3000): 83%; 21%; 16%

Table 1-22. *Signal significance for $pp \to HH \to bb\gamma\gamma$ and percentage uncertainty on the Higgs self-coupling at future hadron colliders, from [102].*

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

  - Measurement improves with energy at a lepton collider
  - Muon Collider (6 TeV): 8%

	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡	1500	+2000
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0,0)/(-0.8,0)$	$(0,0)/(-0.8,0)$
$\sigma(ZHH)$	42.7%		42.7%	23.7%	–	–
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%		
λ	83%	46%	21%	13%	28/21%	16/10%

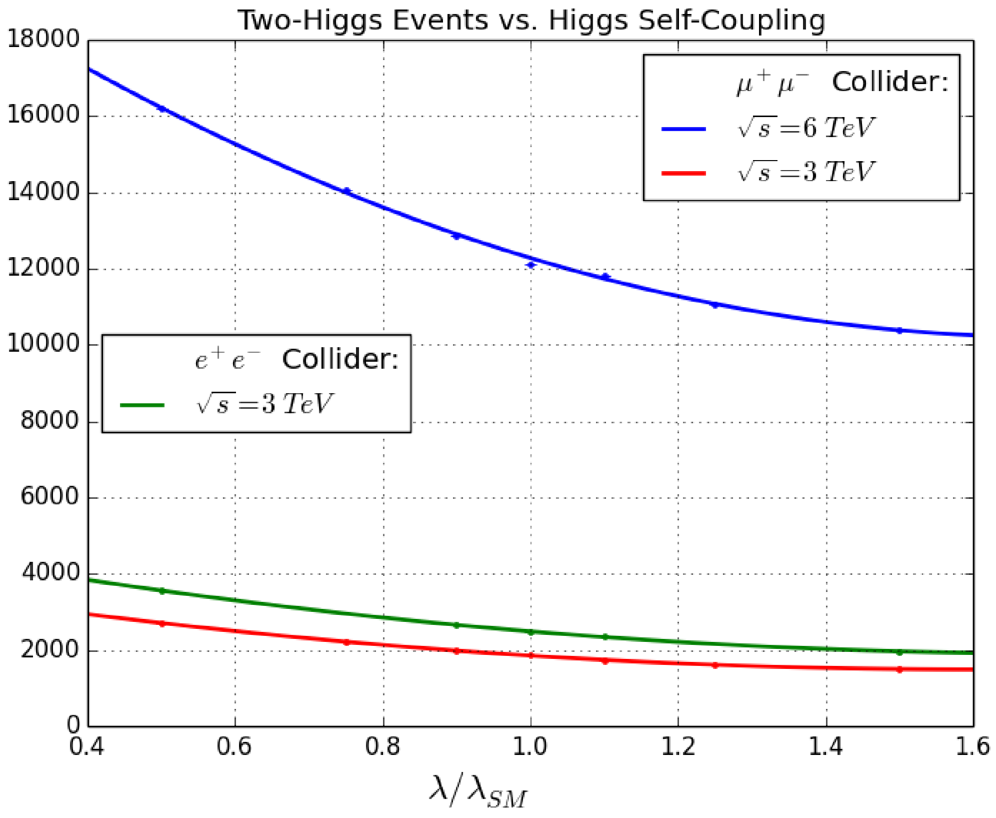
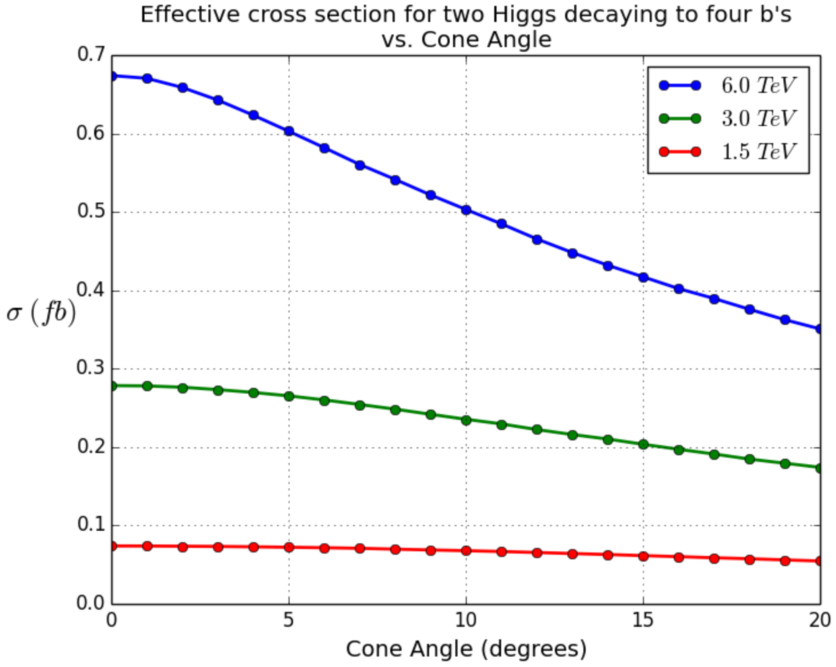


Figure 3: Estimated number of double-Higgs events after five Snowmass years, or $5 \times 10^7 s$.



Higgs Studies and More Scalars

- Given evidence of non-standard Higgs Couplings, what is the BSM origin ?

Table 1-8. *Generic size of Higgs coupling modifications from the Standard Model values when all new particles are $M \sim 1$ TeV and mixing angles satisfy precision electroweak fits. The Decoupling MSSM numbers assume $\tan\beta = 3.2$ and a stop mass of 1 TeV with $X_t = 0$ for the κ_γ prediction.*

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

  - Higgs inverse problem
  - Many models might lead to similar deviations.
  - Generic dependence: $(v/M_{bsm})^2$ [decoupling MSSM $\varkappa_v \sim (v/M_{bsm})^4$]
  - ILC (500) $\varkappa_v = 1.0\%$: $\varkappa_b = 1.7\%$ $\varkappa_\gamma = 8.7\%$
  - Scales probed: $0.3 \text{ TeV} < M_{bsm} < 3\text{TeV}$
  - Would need a lepton collider with 6 TeV to directly observe the physics suggested by these deviations and disentangle the possibilities.

Higgs Studies and More Scalars

- Two Higgs Doublet Models (eg. Type II)

$$V = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \tfrac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2] \quad .$$

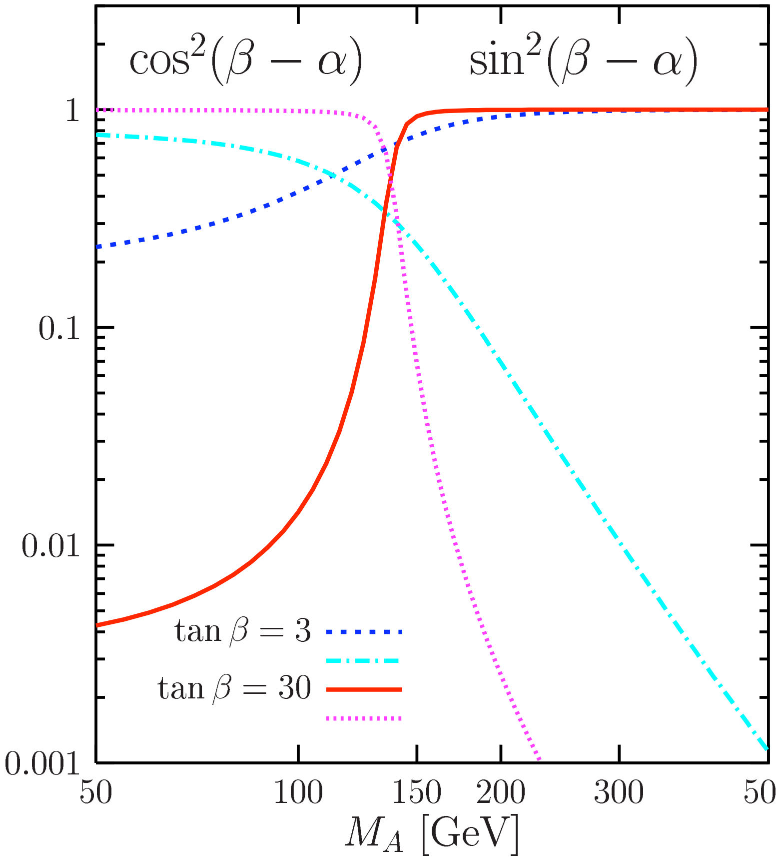
$$\tan\beta = v_2/v_1 \quad , \quad \beta-\alpha \quad , \quad m_{12}^2 \quad , \quad m_H \quad , \quad m_A \quad , \quad m_{H^\pm}$$

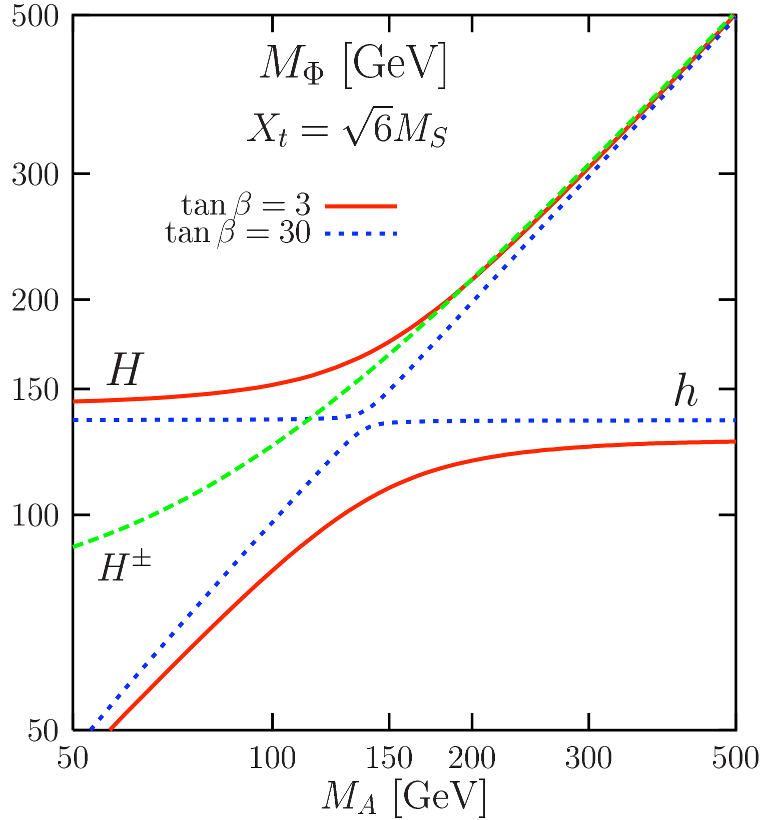
  - Five scalar particles: h^0, H^0, A^0, $H^\pm$
  - Decay amplitudes depend on two parameters: (α, β)

	$\mu^+\mu^-, b\bar{b}$	$t\bar{t}$	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

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

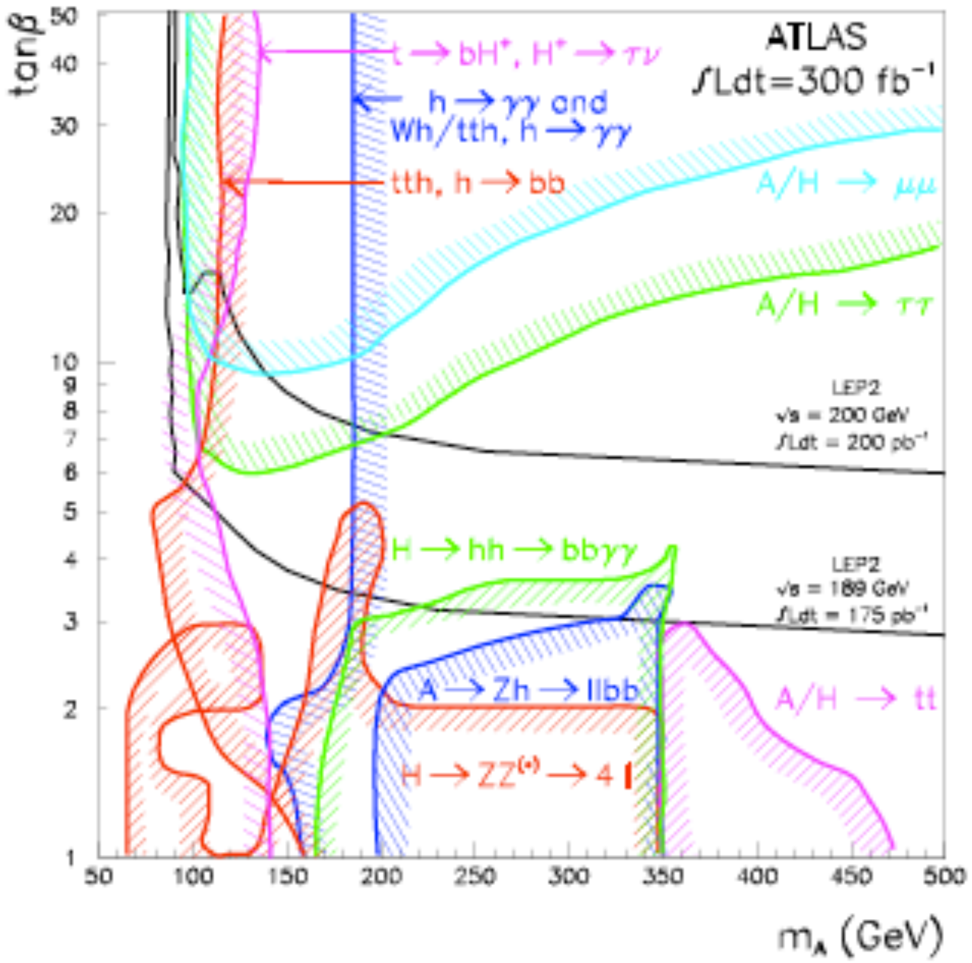
  - decoupling limit $m_{A^0} \gg m_{Z^0}$ $\cos(\beta-\alpha) \to 0$:
    - h^0 couplings close to SM values
    - H^0, $H^\pm$ and A^0 nearly degenerate in mass
    - H^0 small couplings to VV, large couplings to ZA^0
    - For large tanβ, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced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

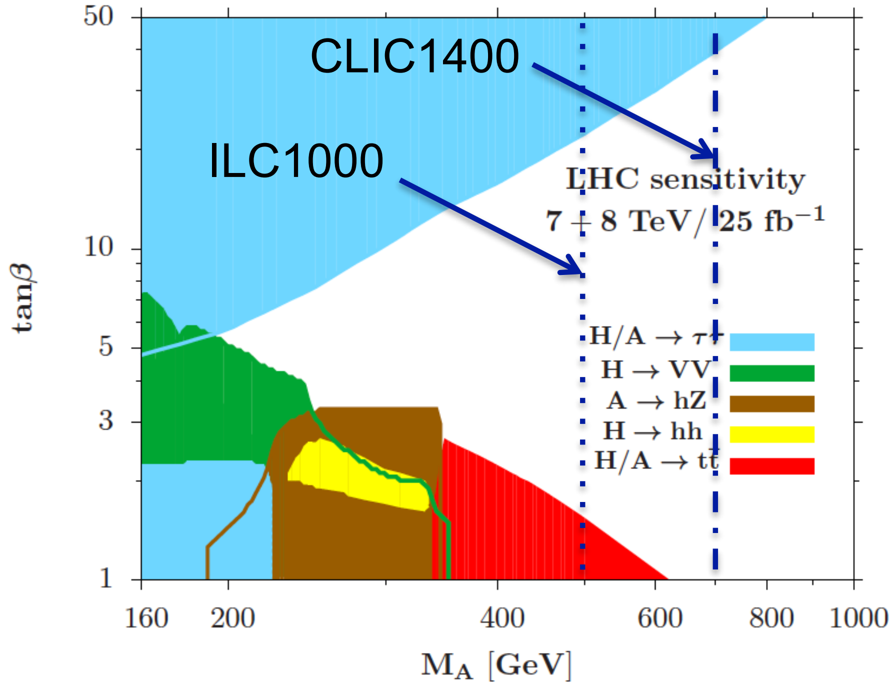




Higgs Studies and More Scalars

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





Higgs Studies and More Scalars

J. Gunion and H. Haber [arXiv:hep-ph/0207010], …

M. Carena, I. Low, N. R. Shah and C. Wagner [arXiv:1310.2244]

- Loophole - Alignment without decoupling.
  - The lightest CP-even Higgs mimics the SM higgs.

$$\begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} = -\frac{v^2}{m_A^2} \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} + \frac{m_h^2}{m_A^2} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} .$$

Mass and eigenvector eq. for h in THDM

α - mixing angle; $\tan\beta = v_2/v_1$

$L_{11} = \lambda_1 c_\beta^2 + \lambda_5 s_\beta^2$; $L_2 = \lambda_2 s_\beta^2 + \lambda_5 c_\beta^2$;

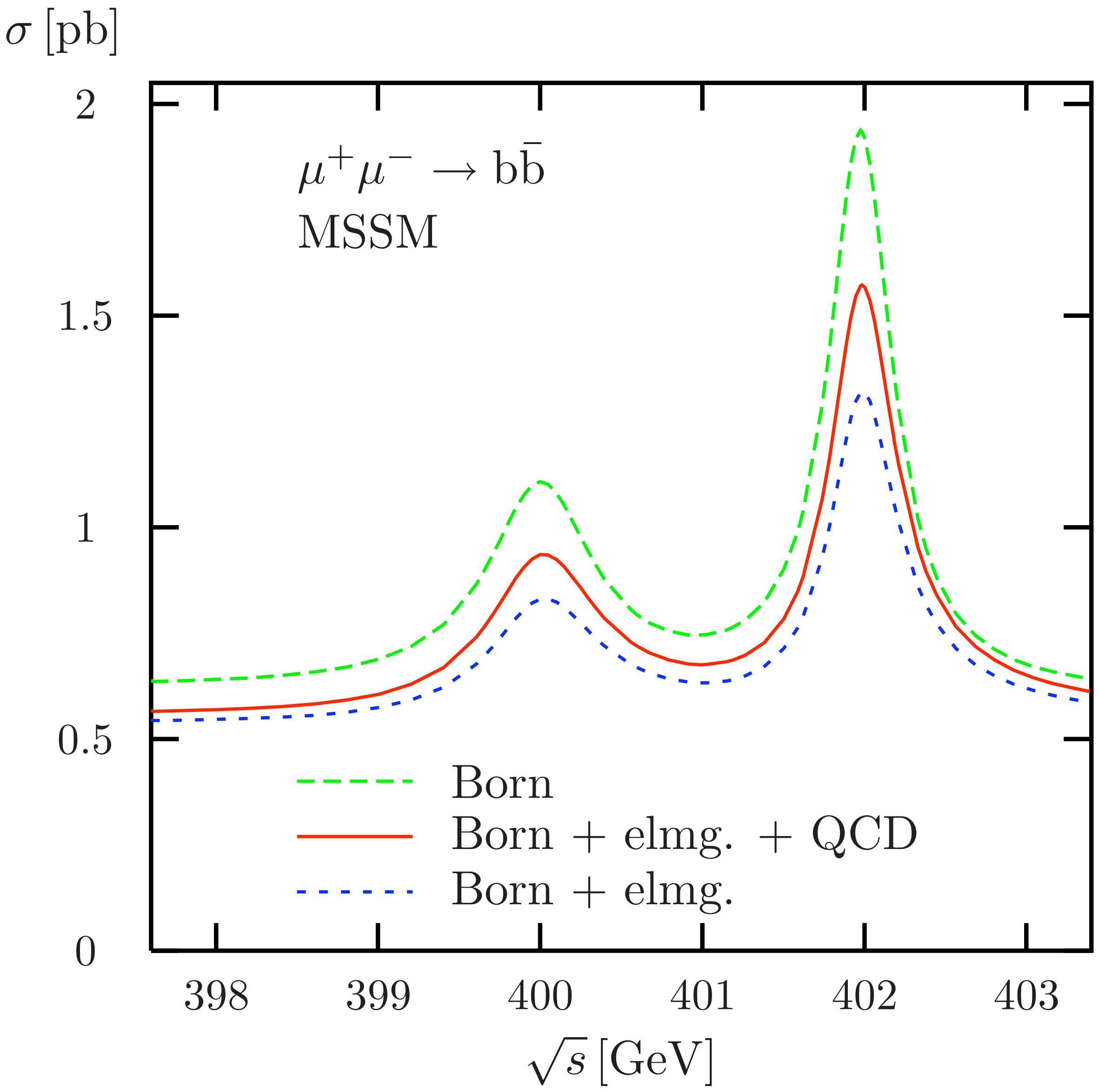
$L_{12} = (\lambda_3+\lambda_4) s_B c_B$

  - $\cos(\beta - \alpha) = 0$ —> h has SM couplings: $1/m_A \to 0$ usual decoupling.
  - RHS = 0 —> alignment: independent of m_A but requires a specific value of tan β
  - In lowest order H/A, $H^\pm$ states do not couple to W and Z's.
  - Only the lightest CP even neutral higgs contributes to the EW symmetry breaking.
  - However these states do have Yukawa couplings to fermions.
  - Signals at LHC are different from the usual decoupling THDM signals

- The muon collider can observe these states as s-channel resonances. (if the branching ratio to $\mu^+\mu^-$ is not much smaller than for the SM higgs)

Higgs Studies and More Scalars

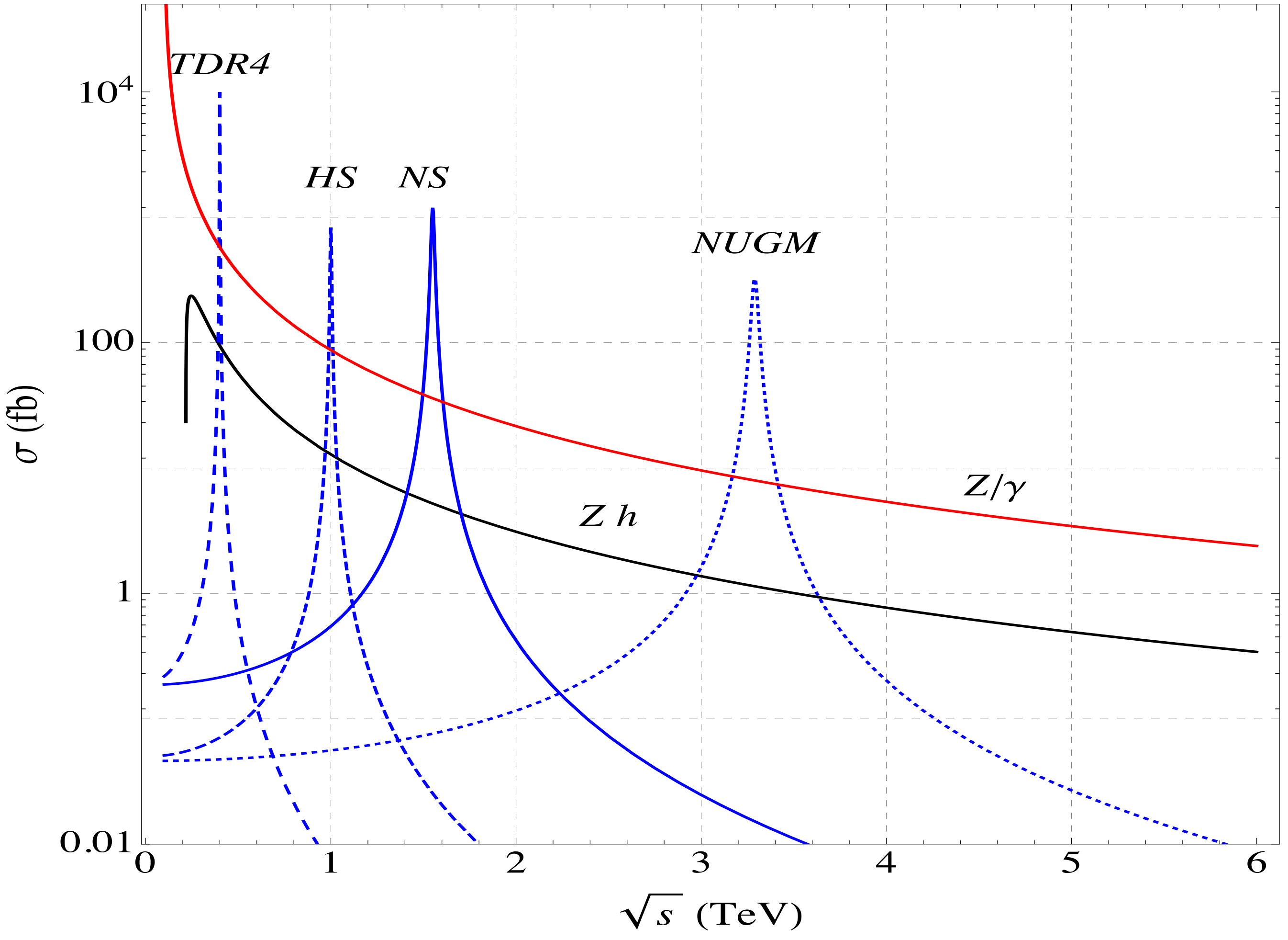
- Early studies have shown the power of a Muon Collider to separate these states.
- Good energy resolution is needed for H^0 and A^0 studies:



Dittmaier and Kaiser
[hep-ph/0203120]

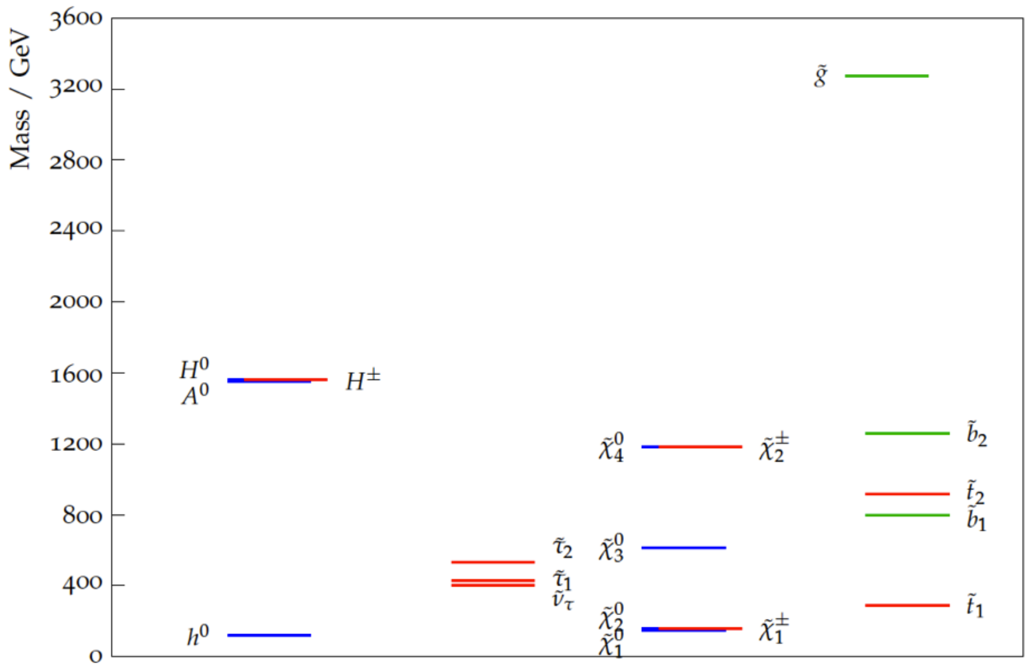
Higgs Studies and More Scalars

- However generally expect heavy: $H^\pm$, H^0 and A^0
  - LHC limits on $H^\pm$: ~ 350 (ATLAS) (CMS)
  - SUSY models that evade the all present experimental constraints often have very heavy THDM scalars
- The H/A are observable as s-channel resonances at a MC!



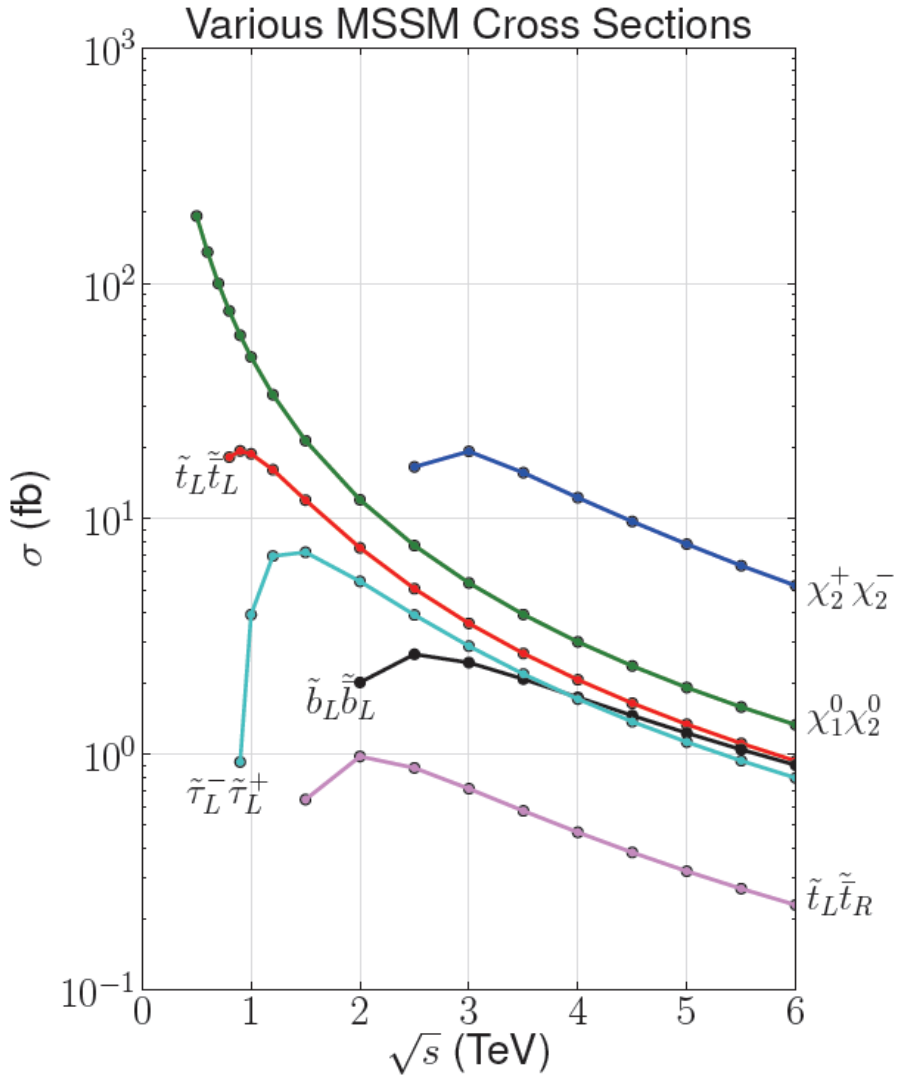
Higgs Studies and More Scalars

- Example of Natural SUSY
  - Low-lying spectrum



  - For electroweakinos, sleptons, …

A ≥ 3TeV muon collider has discovery reach beyond a 100 TeV pp collider !

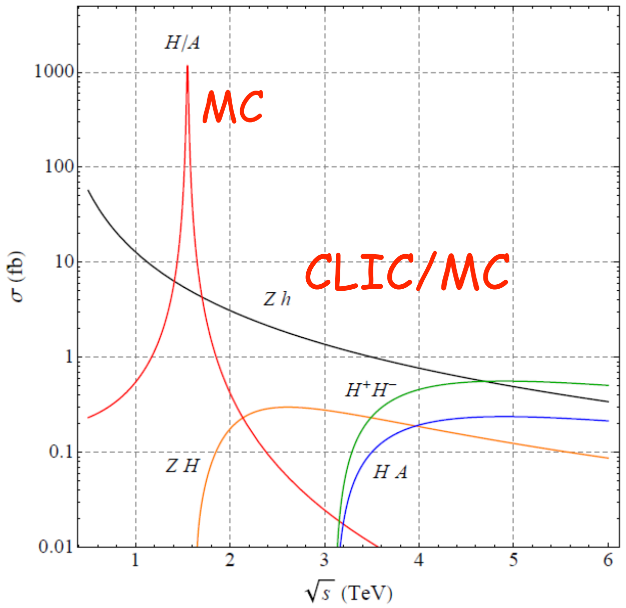


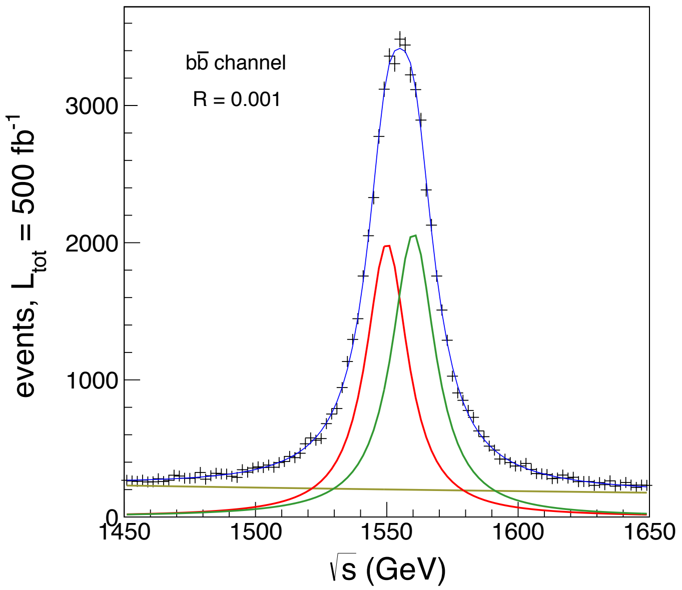
- The H/A are observable as s-channel resonances at a MC!
  - $M_H \simeq M_A \sim 1.5\ \mathrm{TeV}/c^2$, $\Gamma \sim 19$ GeV
  - Large tanβ ~ 20
  - Limited spectrum of SUSY particle decays.
  - Expect 10^6 H/A decays per 1 ab^{-1}
- From this model we see the power of resonance production:
  - The states H/A are separable: $\Delta M \simeq 10$ MeV. Widths and branching ratios can be disentangled
  - Tau decays (~8%) may allow H/A CP determination.
  - Decays to supersymmetric particles (~ 20%): Self-analysing ewkinos - (Initial state beam polarization not essential)

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

TABLE I. Properties of the H and A states in the Natural Supersymmetry benchmark model [35]. In addition to masses and total widths, the branching ratios for various decay modes are shown.

	H		A	
Mass	1.560 TeV		1.550 TeV	
Width	19.5 GeV		19.2 GeV	
	(Decay)	Br	(Decay)	Br
	$(b\bar{b})$	0.64	$(b\bar{b})$	0.65
	$(\tau^+\tau^-)$	8.3×10^{-2}	$(\tau^+\tau^-)$	8.3×10^{-3}
	$(s\bar{s})$	3.9×10^{-4}	$(s\bar{s})$	4.0×10^{-3}
	$(\mu^+\mu^-)$	2.9×10^{-4}	$(\mu^+\mu^-)$	2.9×10^{-4}
	$(t\bar{t})$	6.6×10^{-3}	$(t\bar{t})$	7.2×10^{-3}
	(gg)	1.4×10^{-5}	(gg)	6.1×10^{-5}
	$(\gamma\gamma)$	1.1×10^{-7}	$(\gamma\gamma)$	3.8×10^{-9}
	(Z^0Z^0)	2.6×10^{-5}	$(Z^0\gamma)$	4.3×10^{-8}
	(h^0h^0)	4.4×10^{-5}		
	(W^+W^-)	5.3×10^{-5}		
	$(\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp)$	9.2×10^{-3}	$(\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp)$	9.5×10^{-3}
	$(\tilde{t}_1\tilde{t}_1^*)$	3.1×10^{-3}	$(\tilde{t}_1\tilde{t}_2^*)$	1.1×10^{-3}
	$(\chi_1^0\chi_1^0)$	2.6×10^{-3}	$(\chi_1^0\chi_1^0)$	3.2×10^{-3}
	$(\chi_2^0\chi_2^0)$	1.3×10^{-3}	$(\chi_2^0\chi_2^0)$	1.1×10^{-3}
	$(\chi_1^0\chi_3^0)$	2.8×10^{-2}	$(\chi_1^0\chi_3^0)$	3.9×10^{-2}
	$(\chi_1^0\chi_4^0)$	1.7×10^{-2}	$(\chi_1^0\chi_4^0)$	4.0×10^{-2}
	$(\chi_2^0\chi_3^0)$	3.8×10^{-2}	$(\chi_2^0\chi_3^0)$	2.7×10^{-2}
	$(\chi_2^0\chi_4^0)$	4.0×10^{-2}	$(\chi_2^0\chi_4^0)$	1.5×10^{-2}
	$(\chi_1^\pm\chi_2^\mp)$	5.7×10^{-2}	$(\chi_1^\pm\chi_2^\mp)$	6.0×10^{-2}





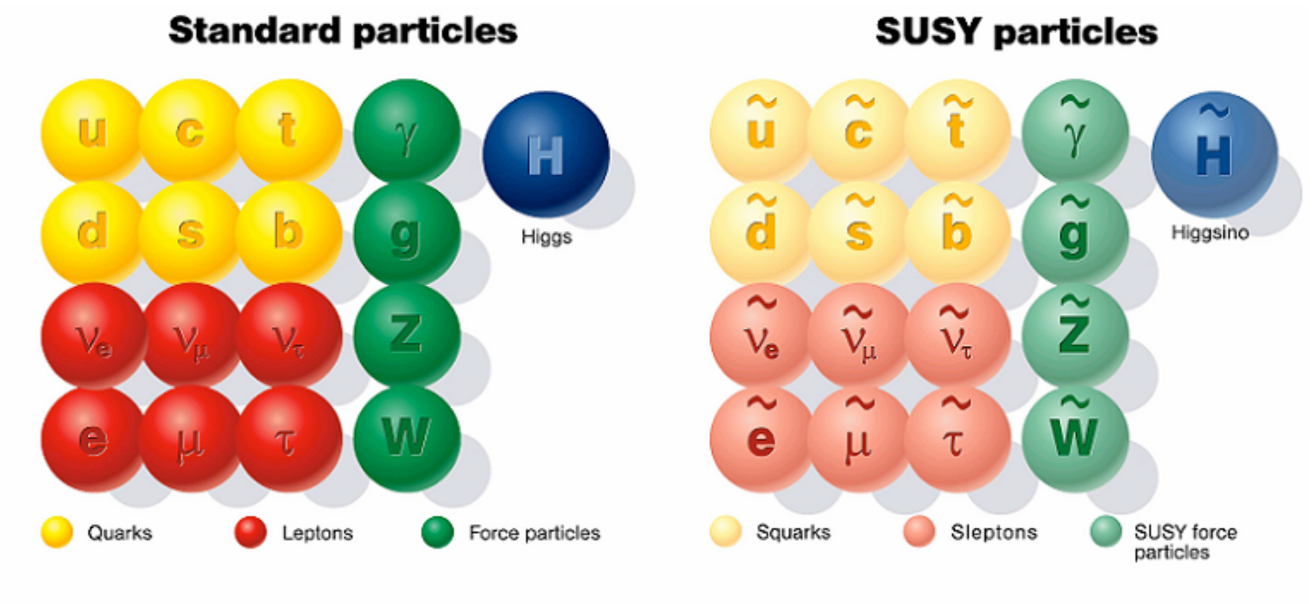
- The H/A resonances are a factory for SUSY studies at a Muon Collider.

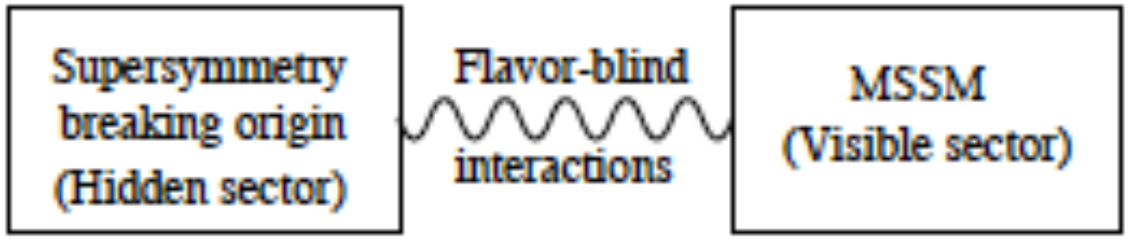
Supersymmetry

- Supersymmetry

$$Q|\text{boson}>=|\text{fermion}>;\ Q|\text{fermion}>=|\text{boson}>$$

- The symmetry is not manifest at presently observable energies.
- If the breaking occurs near the EWSB scale, SUSY can be a solution of the naturalness problem of the standard model.
- Questions:
  - What breaks the symmetry?
    - mSUGRA (gravity)
    - GMSB (gauge)
    - AMSB (anomalies)
  - What is the spectrum of superpartner masses?





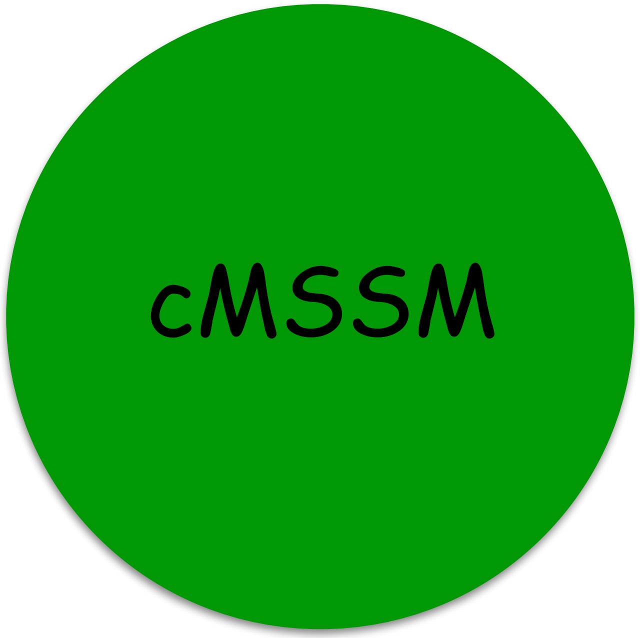
Supersymmetry breaking origin (Hidden sector)

Flavor-blind interactions

MSSM (Visible sector)

Supersymmetry

- Ten years ago:



cMSSM

Supersymmetry

- cMSSM - simple model with only 5 parameters (m0, m1/2, tanβ, A/m0, sign(μ)); pMSSM (19 parameters), unconstrained (104+)
- LHC limits on SUSY sparticles in various cMSSM scenerios:
  - Gluino and light squark masses limits ~ 1.2TeV
  - The detailed study of the full SUSY spectrum will require a multiTev lepton collider.
- Bounds on cMSSM from all present data: LHC, B decays, Dark matter limits, $(g-2)_\mu$,…

O. Buchmueller et.al. [arXiv:1312.5250]

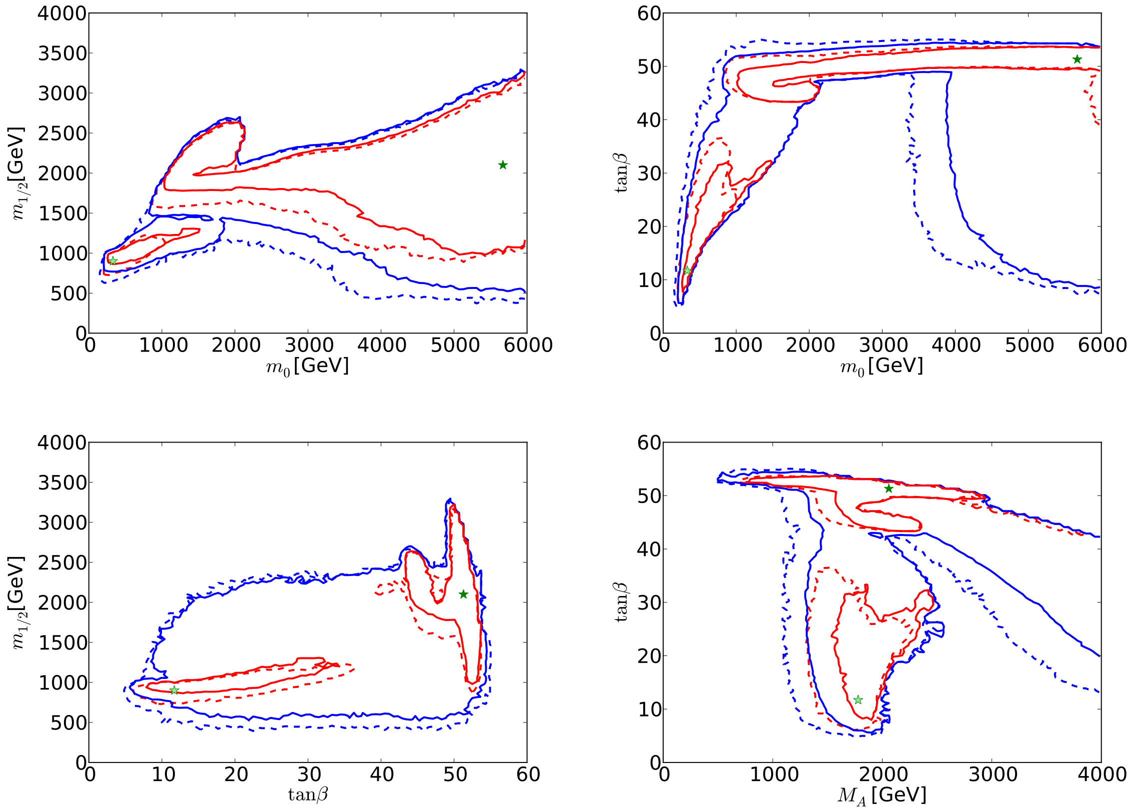
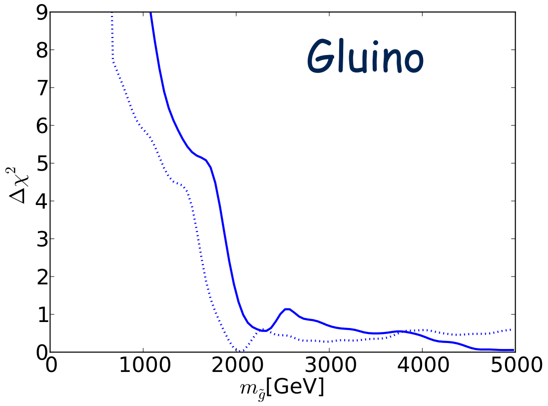
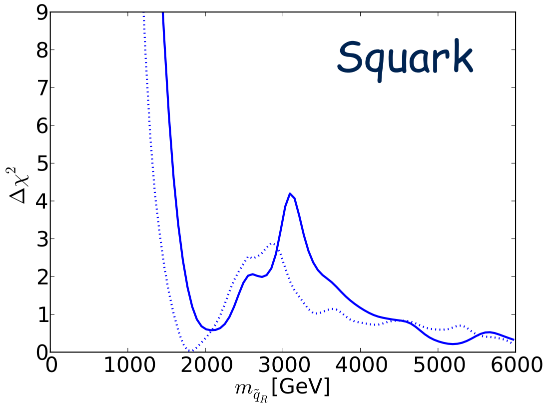


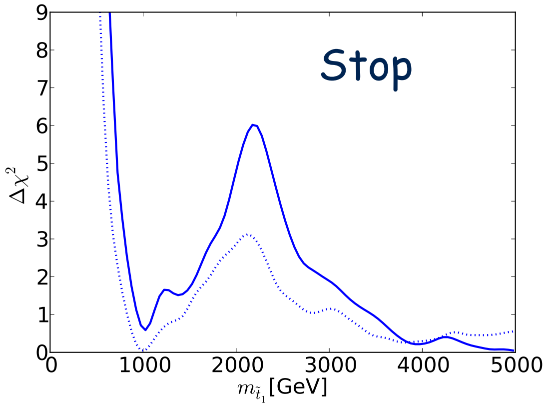
Figure 3. *A compilation of parameter planes in the CMSSM for $\mu > 0$, including the $(m_0, m_{1/2})$ plane (upper left), the $(m_0, \tan\beta)$ plane (upper right), the $(\tan\beta, m_{1/2})$ plane (lower left), and the $(M_A, \tan\beta)$ plane (lower right), after implementing the ATLAS 20/fb jets + $\not\!\!E_T$, $\mathrm{BR}(B_{s,d} \to \mu^+\mu^-)$, M_h, $\Omega_\chi h^2$, LUX constraints and other constraints as described in the text. The results of the current CMSSM fit are indicated by solid lines and filled stars, and a fit to previous data [21] using the same implementations of the M_h, σ_p^{SI} and other constraints is indicated by dashed lines and open stars. The red lines denote $\Delta\chi^2 = 2.30$ contours (corresponding approximately to the 68% CL), and the red lines denote $\Delta\chi^2 = 5.99$ (95% CL) contours.*

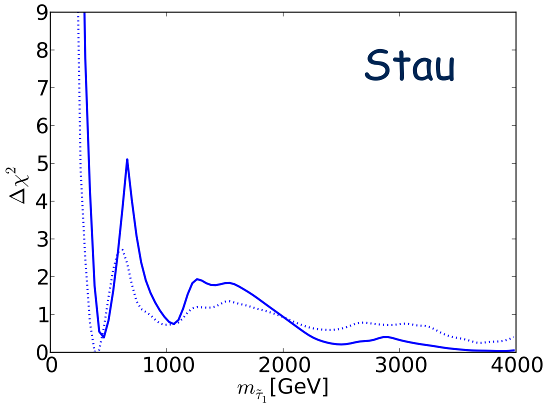
Supersymmetry

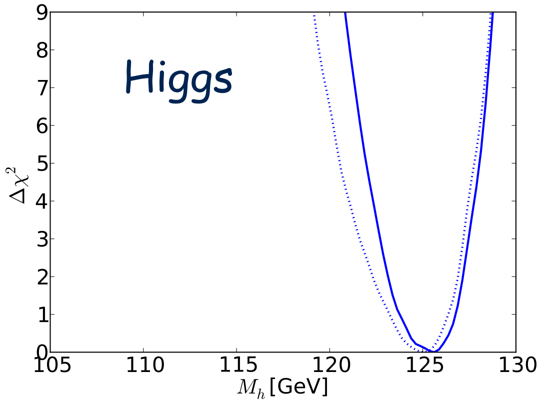
- Projecting into one dimensional bounds - most likely sparticle masses rise

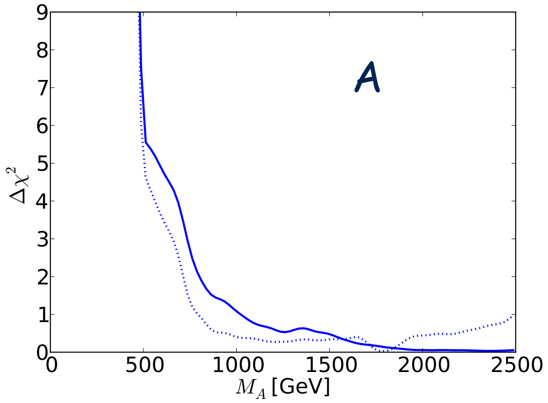








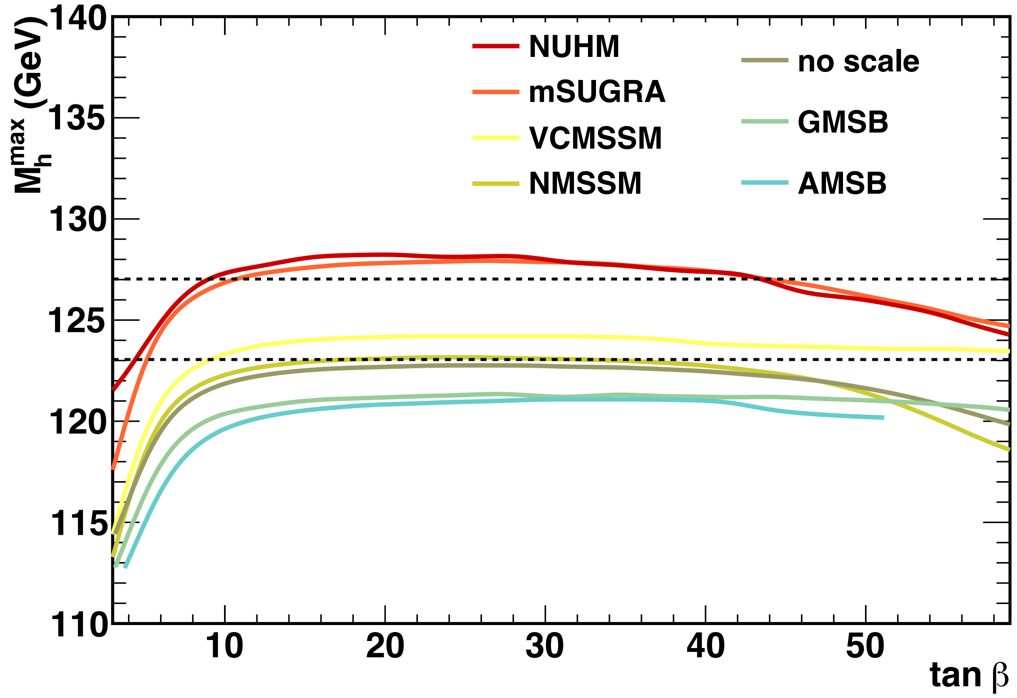




Supersymmetry

- Are various constrained models consistent with a Higgs mass of 125.5 GeV?
  - Parameters varied in wide range.
    Upper bound - mh in top 1%
  - GMSB, AMSB ✖
  - mSUGRA ✔
    - NUHM: non universal m0
    - VCMSSM: m0 ≃ -A0
    - NMSSM: m0 ≃0 A0 ≃ $-1/4m_{\frac{1}{2}}$
    - no scale: m0 ≃ A0 ≃ 0

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



- As mass scales increase (μ^2 increases) more fine tuning. The little hierarchy problem.

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

for large masses need big cancellations

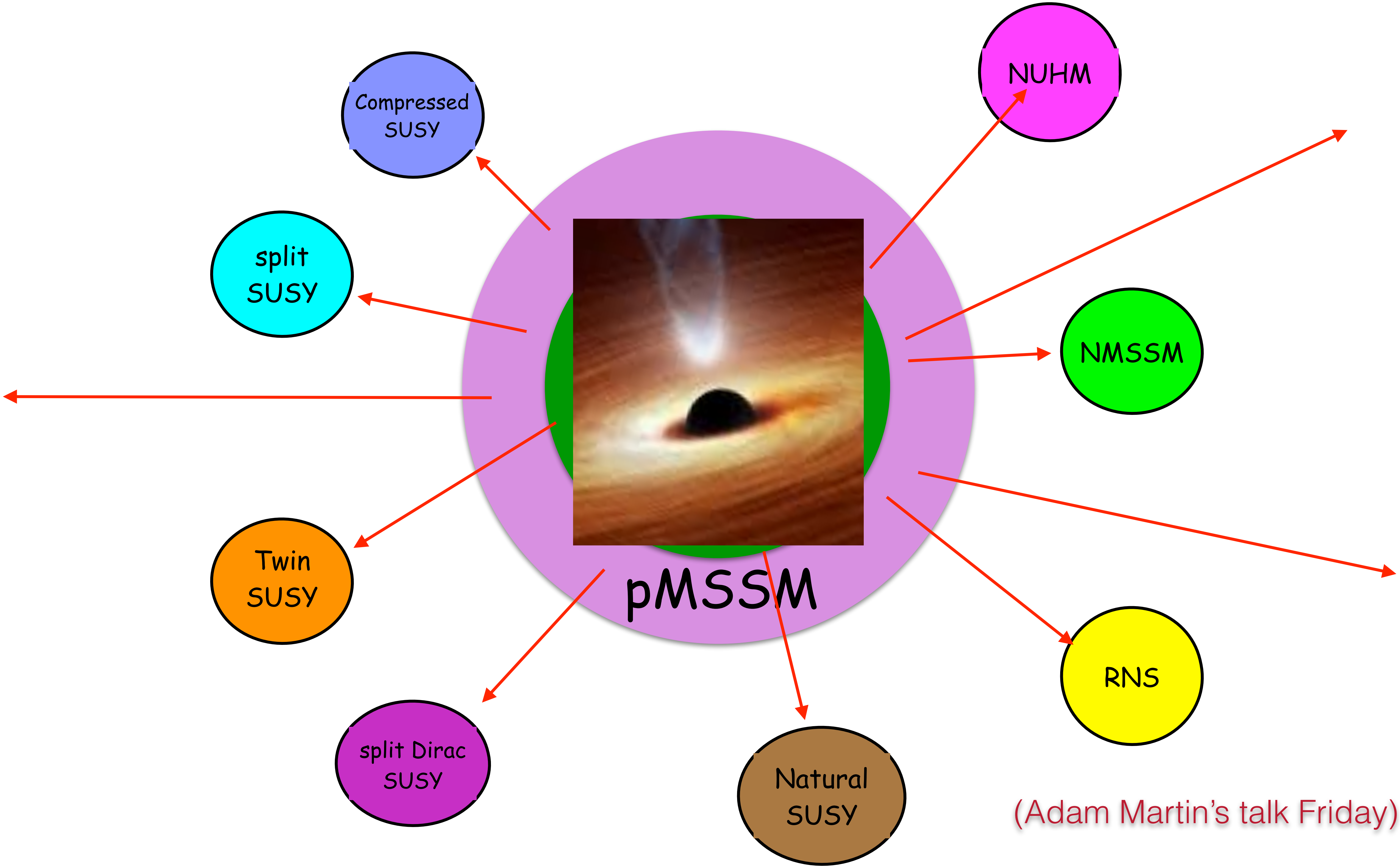
[one loop]

$$\Sigma_t^t = \frac{3g^2}{8\pi^2}\frac{m_t^4}{m_W^4}\left[ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2}\right)\right]$$

$$\tilde{X}_t = \frac{2\tilde{A}_t^2}{M_S^2}\left(1 - \frac{A_t^2}{12M_S^2}\right), \qquad \tilde{A}_t = A_t - \mu\cot\beta$$

Supersymmetry

- 2014: Escape from the Black Hole of Experimental Limits



Compressed SUSY

NUHM

split SUSY

NMSSM

Twin SUSY

pMSSM

RNS

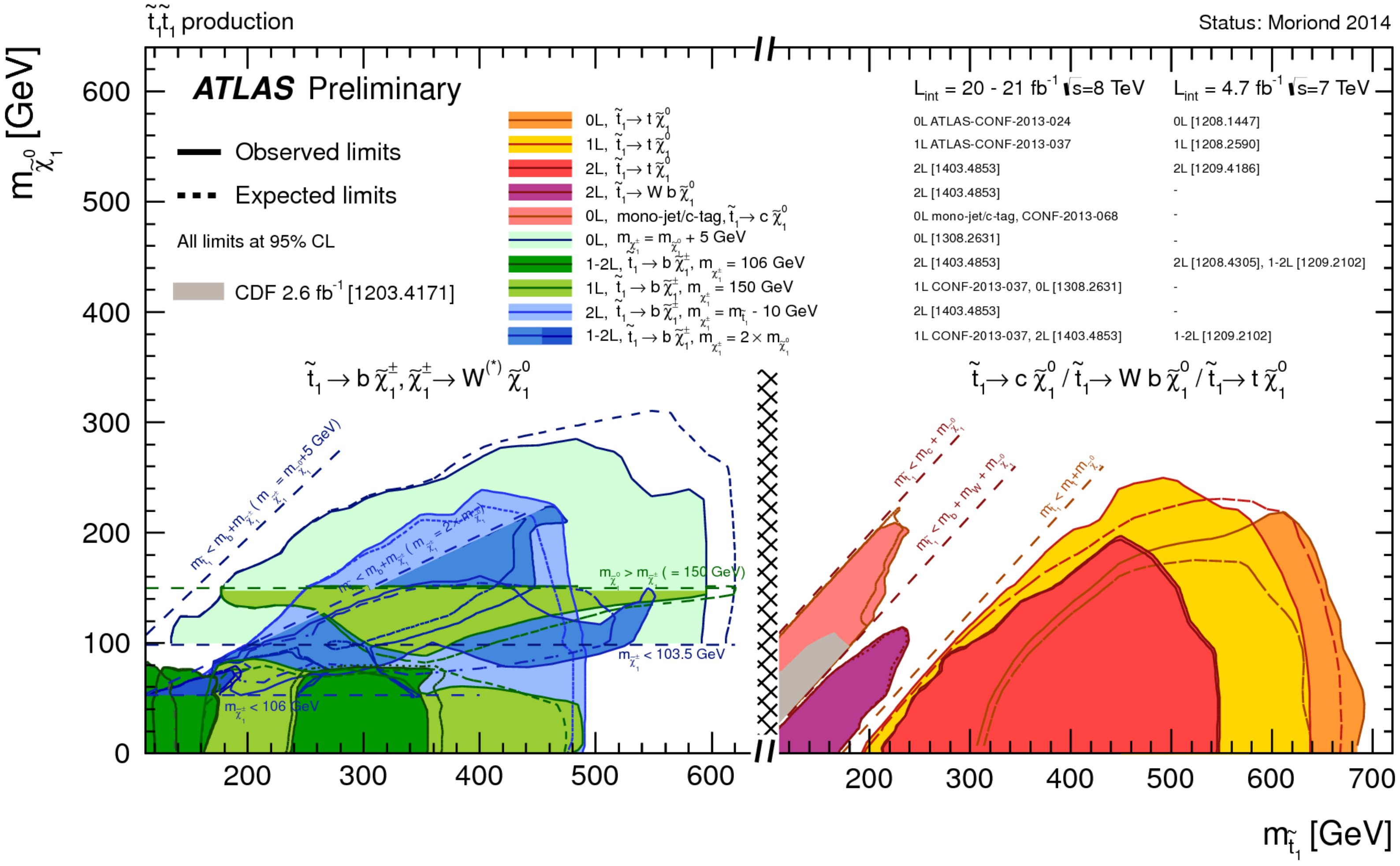
split Dirac SUSY

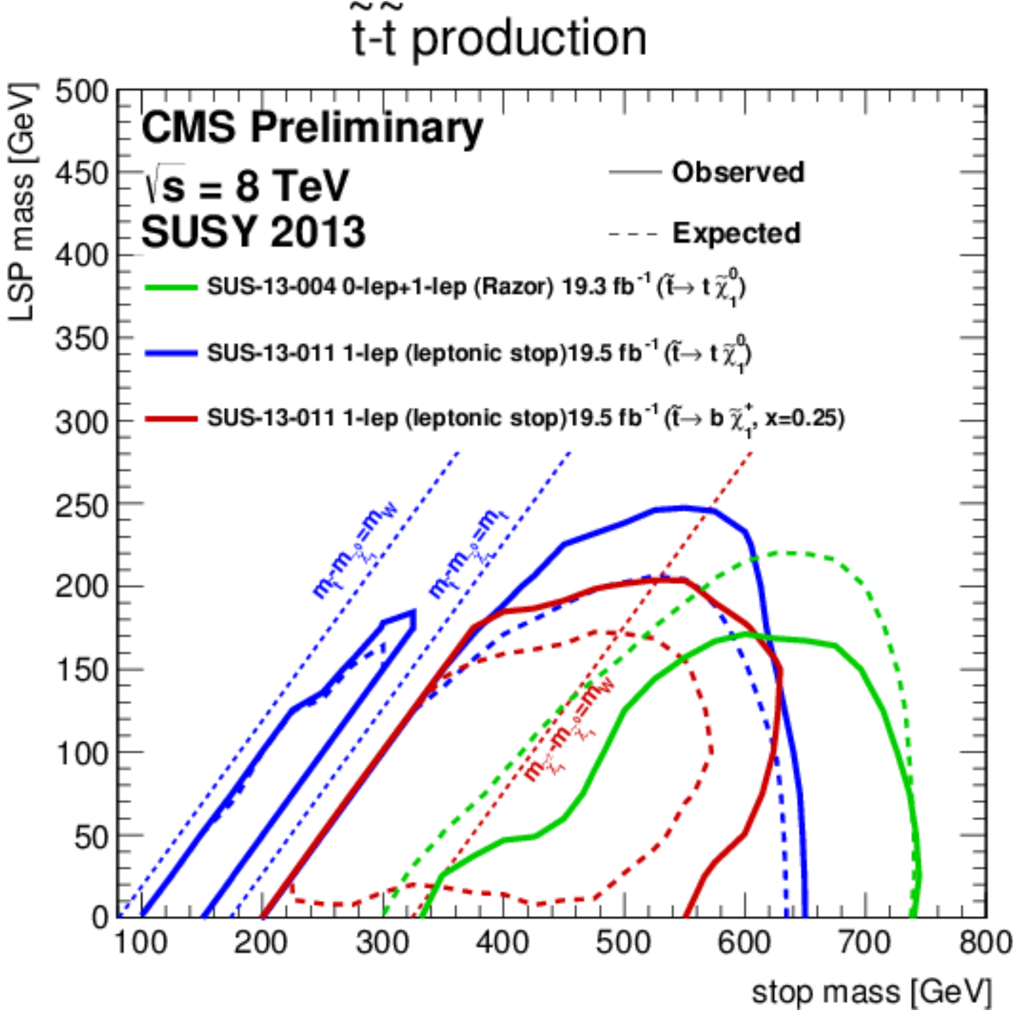
Natural SUSY

(Adam Martin's talk Friday)

Supersymmetry

- LHC stop limits pushing theories to stronger nominal fine tuning..
  - Masses up to 700 GeV excluded (beyond the reach of even a 1 TeV ILC)

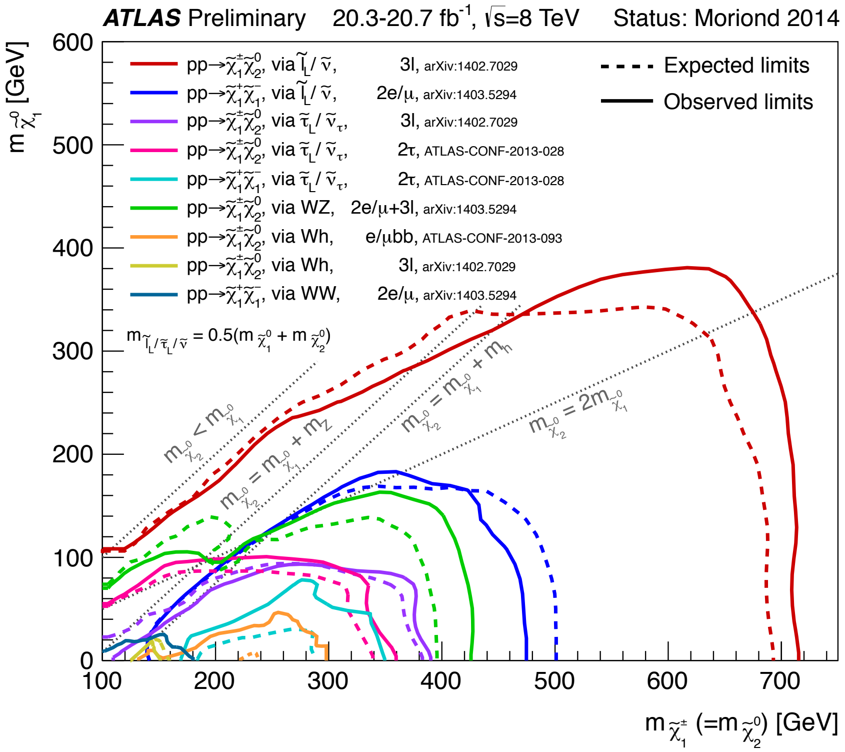


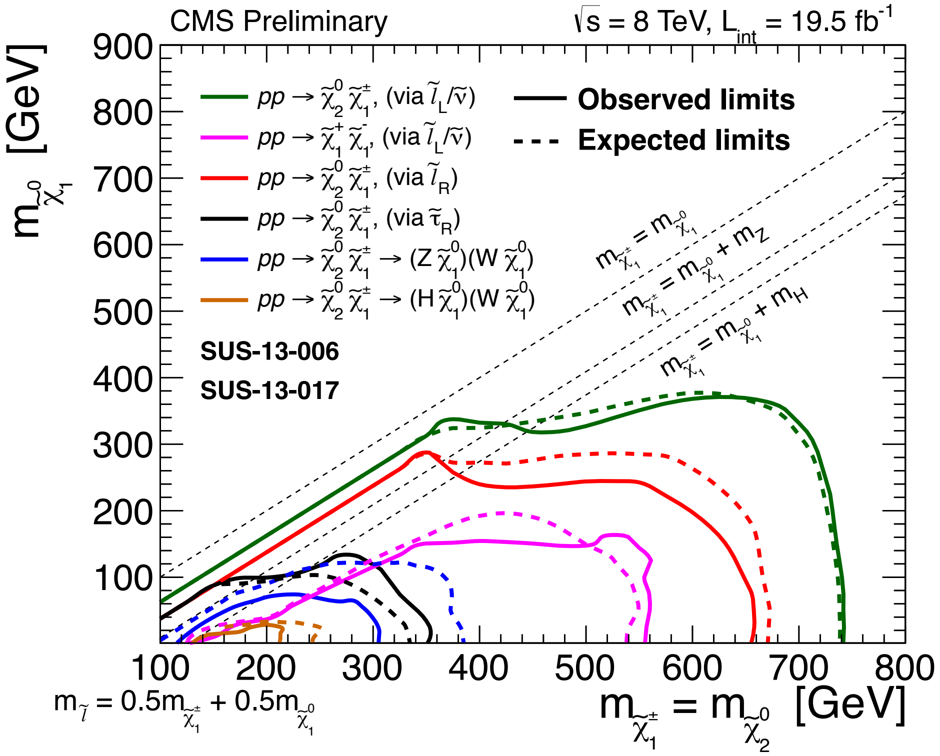


- But still gaps in the exclusion plots depending on decay mode and decay product masses.
- Look forward to the LHC run 2 at 13+ TeV.

Supersymmetry

- Need to observe and study all 4 charginos and 2 neutralinos. Limits for χ_1^+, x_2^0 already exist from LHC 8/7 TeV run.



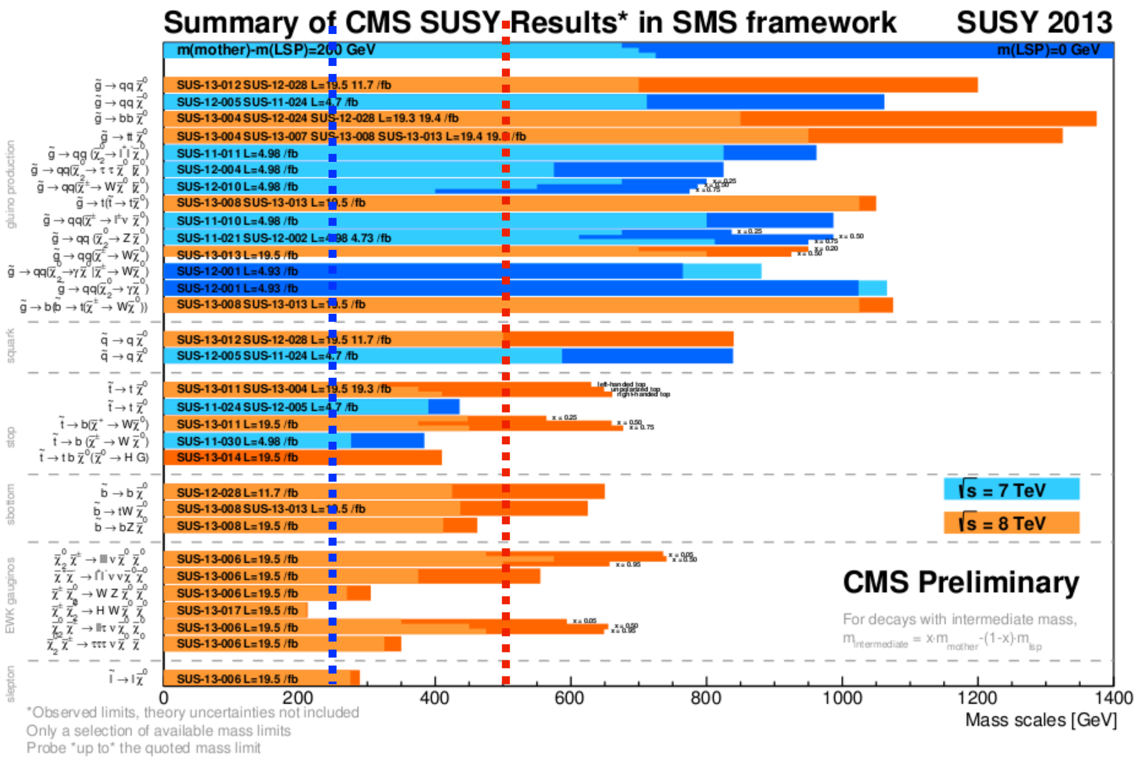


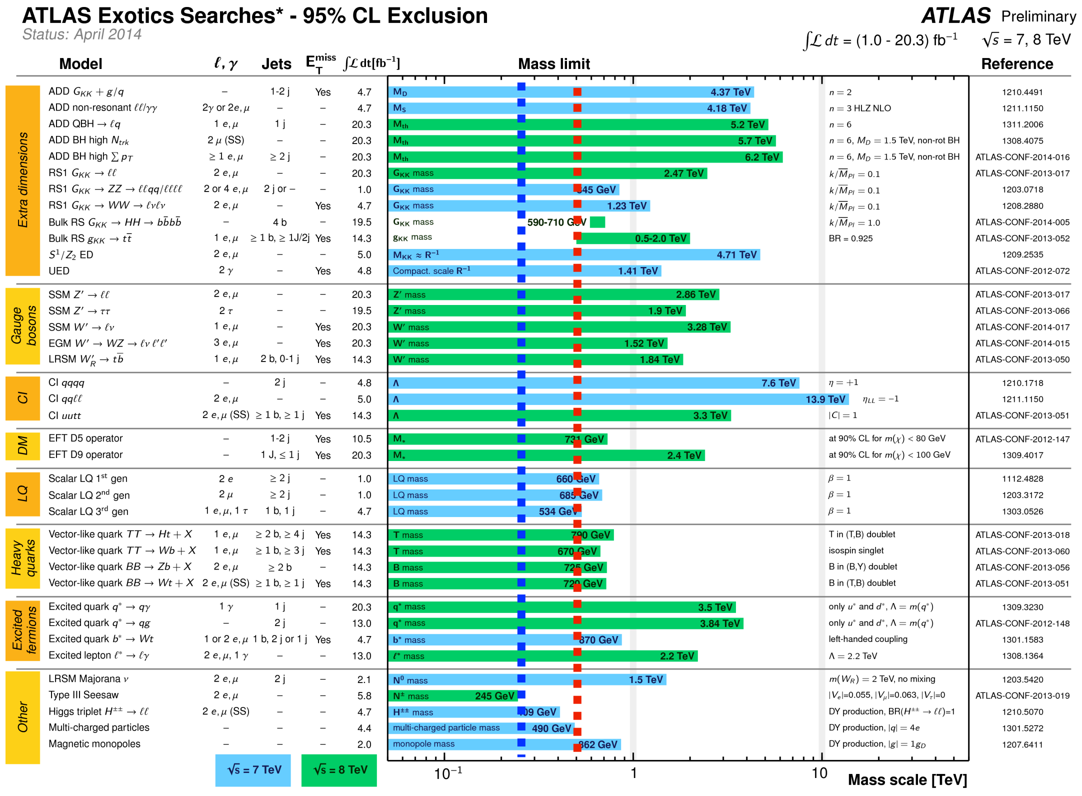
- Seems to rule out study of even these lowest at the ILC even upgraded to 1 TeV.
- Focussing on higgs decays of x_2^0 A. Bharucha[1†], S. Heinemeyer[2‡], F. von der Pahlen studied this issue [arXiv:1404.0365]. Based on existing data they conclude:

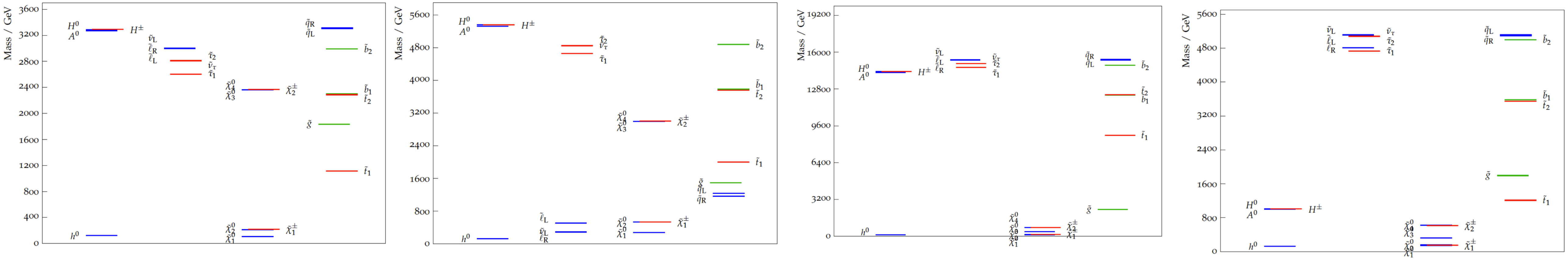
> Altogether these results show, on the one hand, how important it is to look at a realistic spectrum (i.e. where the decays to a Higgs boson are not neglected), and on the other hand that dedicated searches for the $Wh + E_T^{\text{miss}}$ channel are beneficial [43]. The results indicate that there is ample room for chargino/neutralino production at the ILC with $\sqrt{s} \leq 1$ TeV.

Supersymmetry

- Determining the nature of SUSY dynamics and hence the nature of SUSY breaking will require detailed measurements of almost the full spectrum. This is not possible at the ILC (500) [·····] and by the end of run 2 we will know the fate of an ILC(1000) [·····].







Sample spectra (2012) that try to minimize fine tuning in a 100+ parameter space.

Dynamics, Dilatons, and …

- QCD-like Technicolor is dead but ETC and Walking Technicolor lives
  - QCD-like technicolor failed to give quark and lepton masses -> ETC
  - ETC could produce flavor changing neutral currents too large -> Walking Technicolor
  - Walking requires near conformal strong dynamics. Is this possible?
- Spectrum not QCD like - what does it look like?
  - Can light scalars arise in walking technicolor theories?
  - Can the Higgs be a pseudodilaton?
  - What would rest of spectrum look like?
  - What are low-lying states?
- What is role of ETC and 4 fermion interactions?
  - Not presently in lattice studies
  - EWSB driven by four fermion interactions

R. Sekhar Chivukula, Andrew G. Kenneth Lane [NP B343, 554 (1990):
W.~A.~Bardeen, C.~T.~Hill and M.~Lindner
[Phys.Rev. D41,1647(1990)]

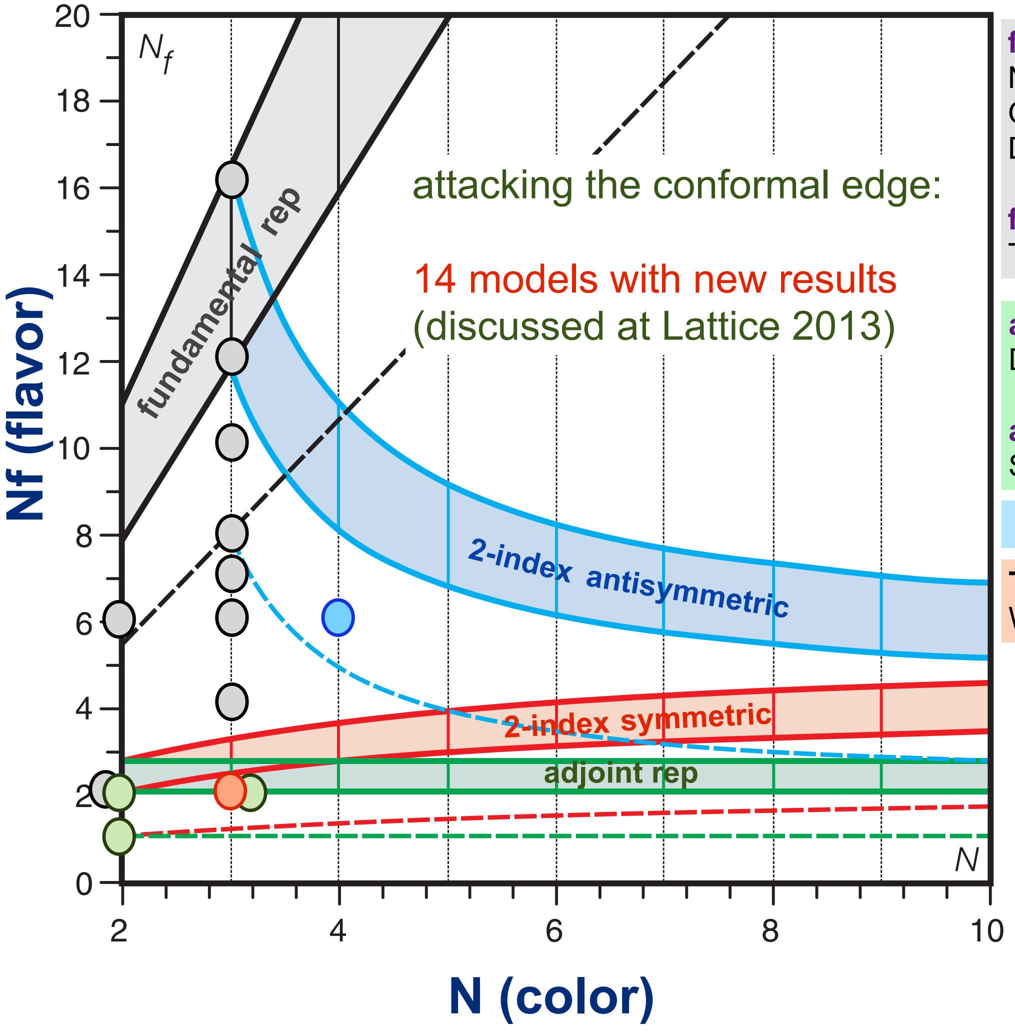
Dynamics, Dilatons, and ...

- Lattice Studies
  - Look for theories in which walking can be realized.
  - Evidence for conformal behaviour: SU(2) adjoint fermion doublet (U,D)
  - SU(3) 16 fundamental fermions

J. Kuti Summary Lattice 2013

SCGT: theory space and conformal window
important for composite Higgs realization

space of color, flavor, and fermion representation



attacking the conformal edge:

14 models with new results
(discussed at Lattice 2013)

fundamental SU(3) color:
Nagai, Ohki, Schaich, Rinaldi, Miura, Hasenfratz, Ogawa, Yamazaki, Liu, Petropoulos, Yamada, Da Silva, Aoki, Iwasaki, Buchoff, Cheng

fundamental SU(2) color:
Tomii, Voronov

adjoint SU(2) color
Del Debbio, Rantaharju, Pica, Athenodoru

adjoint SU(3) color
Shamir

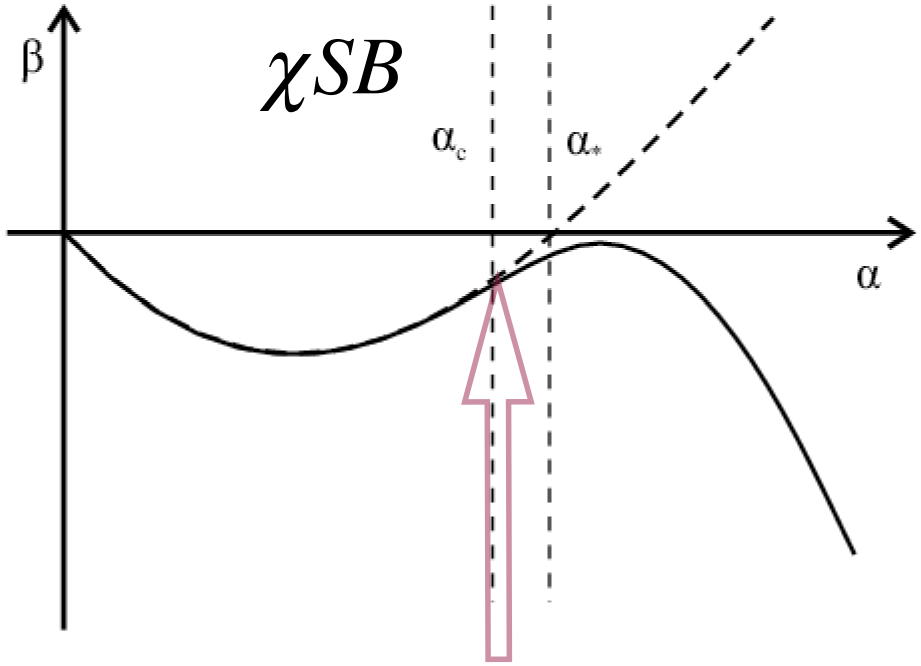
Two-index antisymmetric SU(4) color

Two-index symmetric SU(3) color
Wong, Sinclair, Holland

although ~30 talks, SCGT is only part of the BSM theory space! **SUSY, 5D, ...**

Dynamics, Dilatons, and …

- Walking technicolor toy models



when chiral symmetry breaking turns conformal FP into walking

  - SU(4) 6 antisymmetric rank 2 tensor
  - SU(3) 2 adjoint fermions (octets)

- Much progress but still much to learn to have the tools to make realistic models of a strong dynamics solution.

T. DeGrand, Y. Shamir and B. Svetitsky [arXiv:1307.2425].

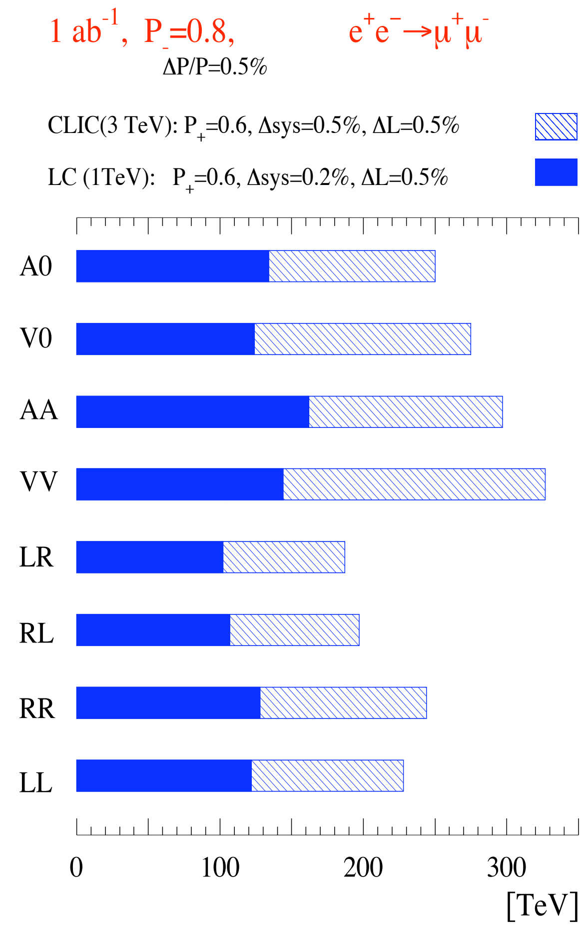
- Will likely need more experimental hints. Low-lying spectrum.
- Requires high energy colliders.

Dynamics, Dilatons, and ...

- Electroweak Symmetry Breaking is generated dynamically at nearby scale
  - Technicolor, ETC, walking TC, topcolor, Two Scale TC, composite Higgs models, ...
  - New strong interactions nearby:
    - What is the spectrum of low-lying states? What makes the Higgs light?
    - What is the ultraviolet completion? Gauge group? Fermion representations?
    - What is the energy scale of the new dynamics?
    - Any new insight into quark and/or lepton flavor mixing and CP violation?

- Contact interactions
  - e.g. Compositeness, broken flavor symmetries, ...
  - Present LHC bounds (~ 10 TeV)
  - Muon collider (3 TeV) sensitive to scales > 200 TeV
    - Forward cone cut not important
    - Polarization useful in determining chiral character of the

$$\mathcal{L} = \frac{g^2}{\Lambda^2}(\bar{\Psi}\Gamma\Psi)(\bar{\Psi}\Gamma'\Psi)$$

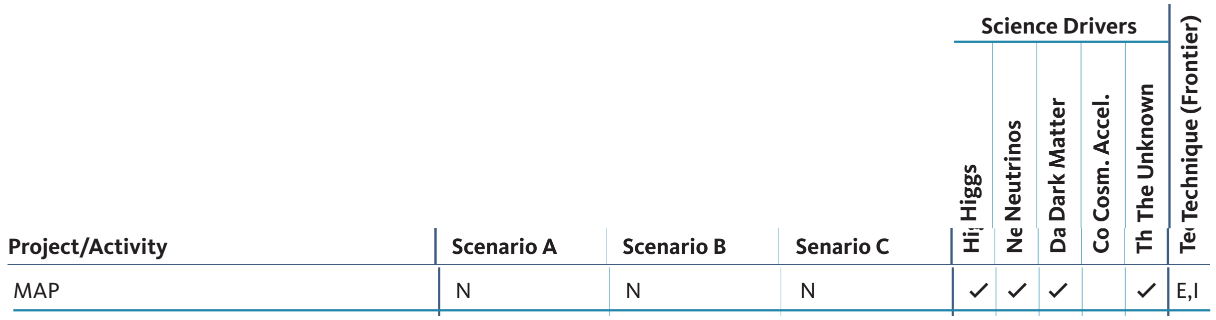


Summary and Outlook

- The Higgs discovery has changed the theory landscape. SUSY and strong Dynamics ideas survive present LHC results (but cMSSM and QCD-like Technicolor are dead)
- Naturalness is still a powerful motivation for BSM physics, What is the fate of naturalness? SUSY with some fine tuning? Higgs as a composite state? or another not yet imagined solution?
- The direction of BSM physics is not yet clear. Much will be learned from the 13+ TeV LHC running. Further clues from a ILC/TLEP Higgs Factory, rare processes and dark matter searches may appear.
- However it is already clear that the full exploration of Terascale physics will require new high energy colliders with sensitivity to pair production of multiTeV BSM particles.
    - HL-LHC for new QCD colored particles. (e.g. squarks, gluions,..) -> 100 TeV Collider ?
    - A staged muon collider at $\sqrt{s}$ up to 6 TeV and integrated luminosity of 5 ab^{-1}.. Complimentary to a 100 TeV pp collider but also having its own unique discovery and detailed study potential. Particularly strong case for SUSY.
    - Narrow s-channel states played an important role in past lepton colliders. A new element is the possibility of additional scalar higgs-like resonances. If such states exist in the multi-TeV region, they will play a similar role in precision studies for new physics.

Summary and Outlook

- P5 statement on Muon Collider:
  - Muon colliders can reach higher energies than e^+e^- accelerators, but have many technical challenges. Addressing all of the necessary challenges would require a very strong physics motivation based on results from ongoing or future accelerators.

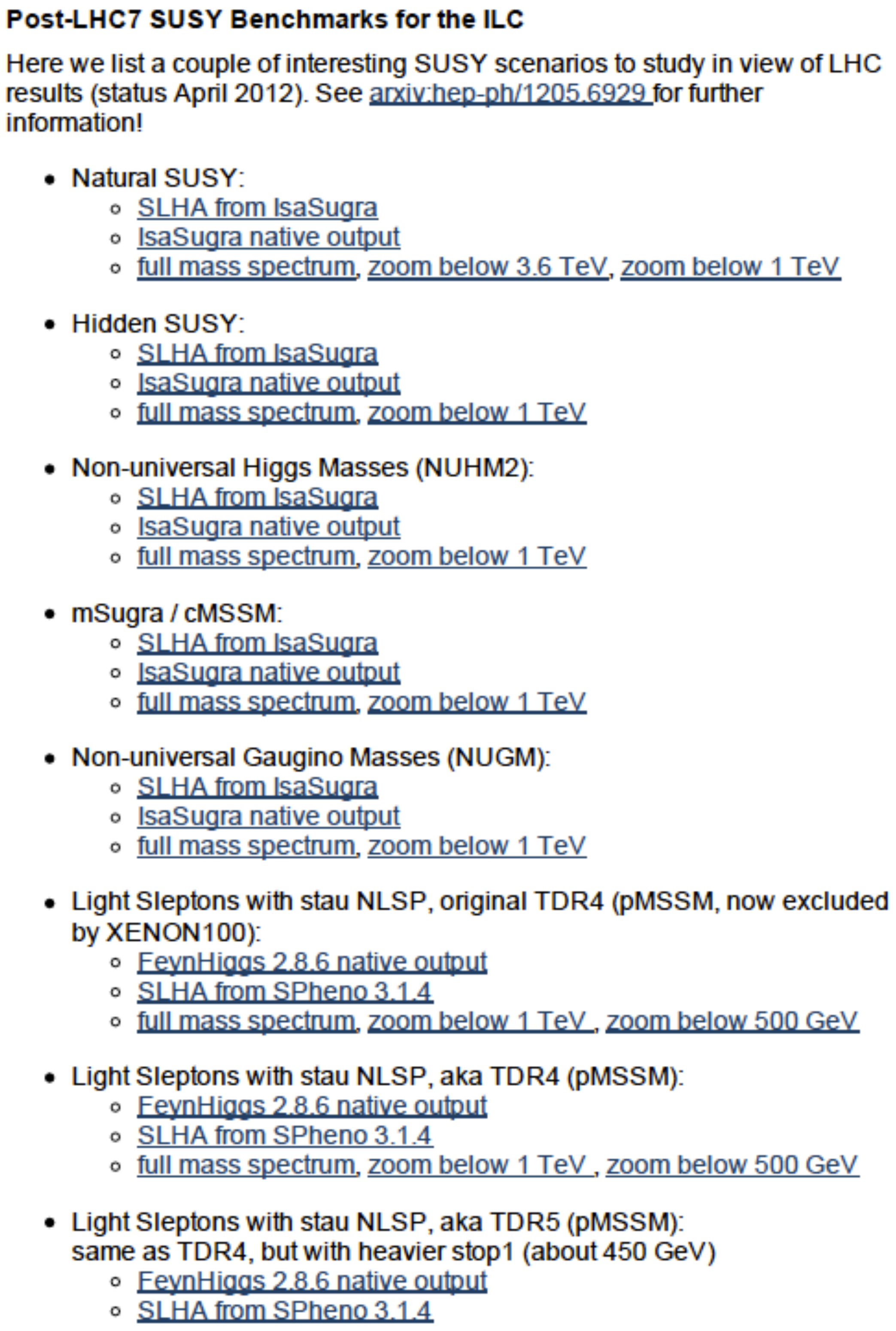


Project/Activity	Scenario A	Scenario B	Senario C	Science Drivers					
				Hi Higgs	Ne Neutrinos	Da Dark Matter	Co Cosm. Accel.	Th The Unknown	Te Technique (Frontier)
MAP	N	N	N	✓	✓	✓		✓	E,I

- New physics will provide this clear and compelling case for a Muon Collider with E_{cm} in the multi-Tev range. This is likely to happen during run 2 of the LHC.
- Many technical challenges need to be met (6D cooling, target design, backgrounds from muon decays, detector design, ..). We should explore the technology feasibility of a MC and find ways to make it affordable.

BACKUP SLIDES

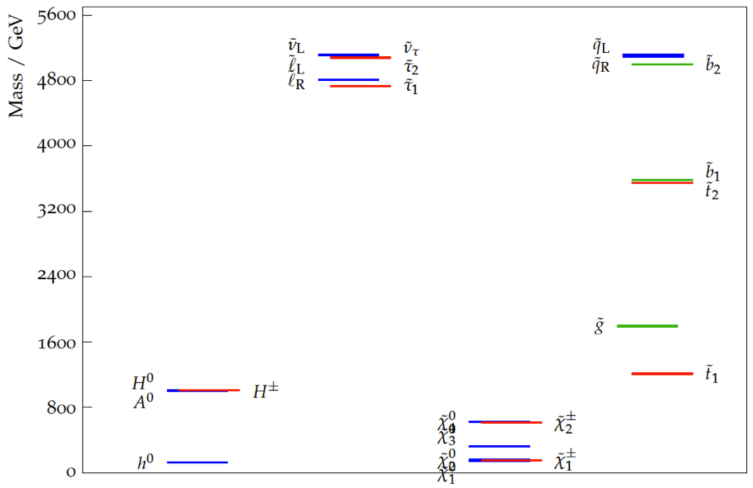
CSS 2013 SUSY Benchmarks

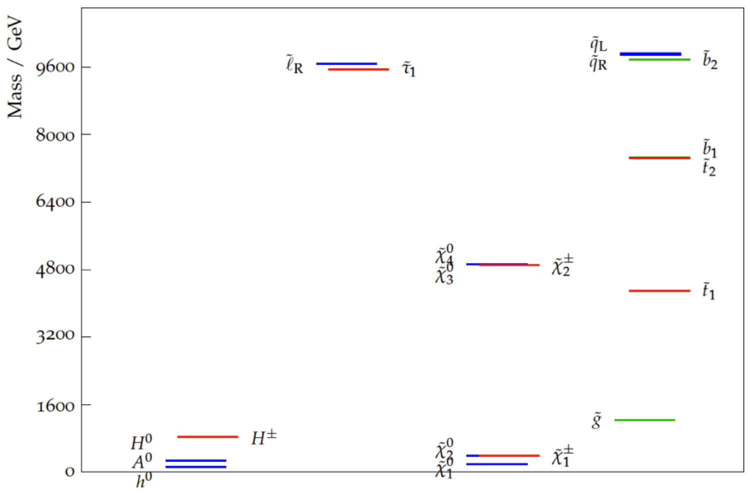


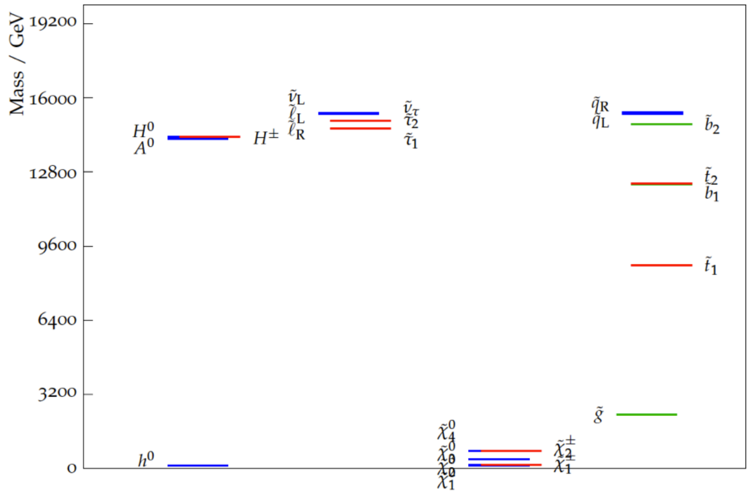
Post-LHC7 SUSY Benchmarks for the ILC

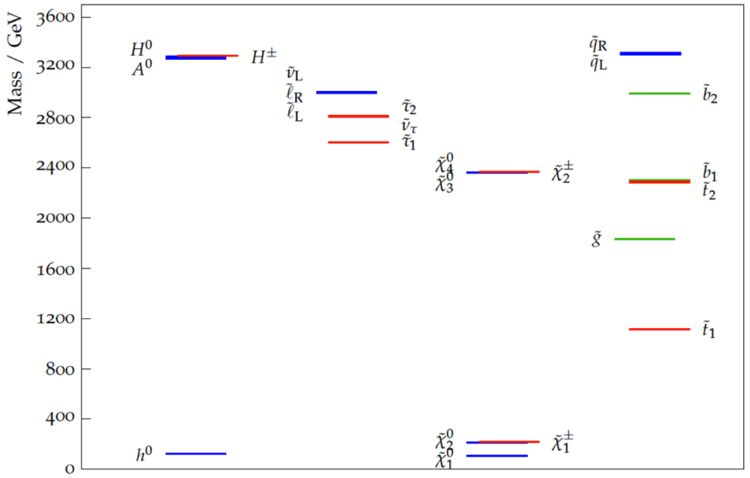
Here we list a couple of interesting SUSY scenarios to study in view of LHC results (status April 2012). See arxiv:hep-ph/1205.6929 for further information!

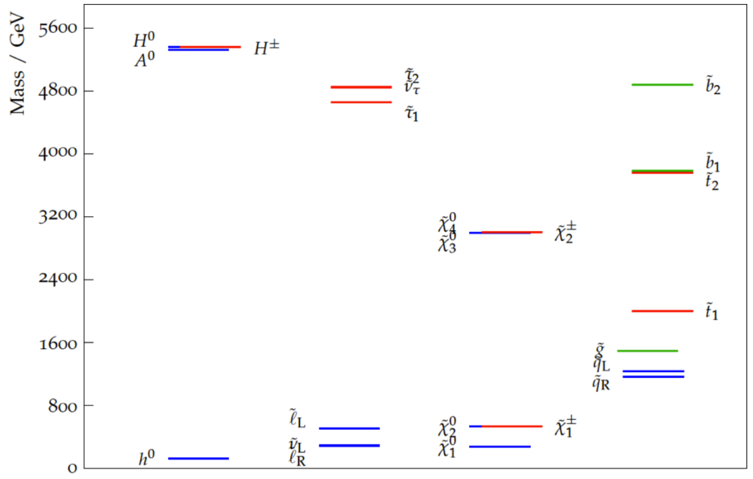
- Natural SUSY:
  - SLHA from IsaSugra
  - IsaSugra native output
  - full mass spectrum, zoom below 3.6 TeV, zoom below 1 TeV
- Hidden SUSY:
  - SLHA from IsaSugra
  - IsaSugra native output
  - full mass spectrum, zoom below 1 TeV
- Non-universal Higgs Masses (NUHM2):
  - SLHA from IsaSugra
  - IsaSugra native output
  - full mass spectrum, zoom below 1 TeV
- mSugra / cMSSM:
  - SLHA from IsaSugra
  - IsaSugra native output
  - full mass spectrum, zoom below 1 TeV
- Non-universal Gaugino Masses (NUGM):
  - SLHA from IsaSugra
  - IsaSugra native output
  - full mass spectrum, zoom below 1 TeV
- Light Sleptons with stau NLSP, original TDR4 (pMSSM, now excluded by XENON100):
  - FeynHiggs 2.8.6 native output
  - SLHA from SPheno 3.1.4
  - full mass spectrum, zoom below 1 TeV , zoom below 500 GeV
- Light Sleptons with stau NLSP, aka TDR4 (pMSSM):
  - FeynHiggs 2.8.6 native output
  - SLHA from SPheno 3.1.4
  - full mass spectrum, zoom below 1 TeV , zoom below 500 GeV
- Light Sleptons with stau NLSP, aka TDR5 (pMSSM): same as TDR4, but with heavier stop1 (about 450 GeV)
  - FeynHiggs 2.8.6 native output
  - SLHA from SPheno 3.1.4

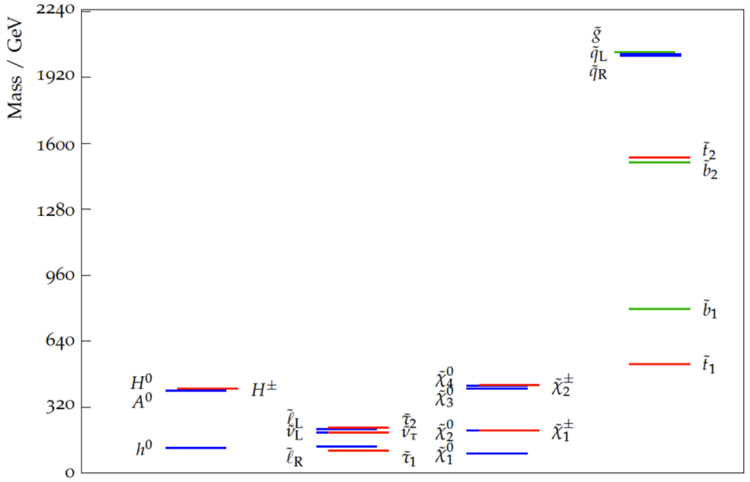








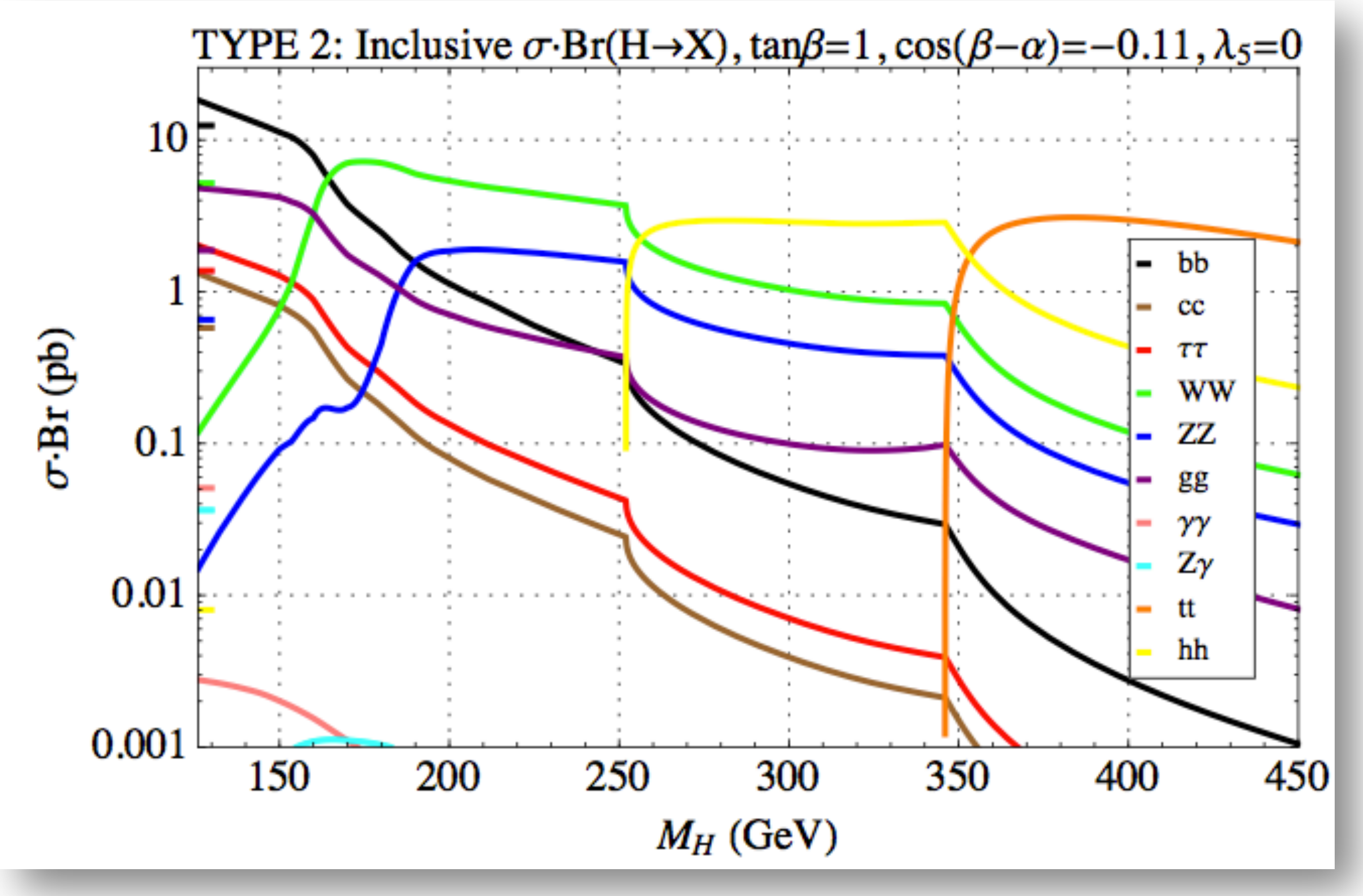




Higgs Studies and More Scalars

Search strategies for the extra scalars in “Alignment without decoupling” could be very different:

Craig, Galloway, Thomas:1305.242



Dominant decay channels are WW, hh and tt, which are very different from the most considered bb and tau tau!

Ian Low's talk at AWLC (5/13/2014)

Staged Approach

- The path from the intensity frontier back to the energy frontier has physics at each step.
- A staged Muon Collider can provide a Neutrino Factory to fully disentangle neutrino physics.
- The observation of a new state at 125 GeV by both ATLAS and CMS revitalizes consideration of a Higgs factory as part of a staged multi-Tev muon collider. This is particularly attractive if there is an enlarged scalar sector (eg. THDM, SUSY)
- The unique measurements of the Muon Higgs factory.
  - Most precise measurement of Higgs mass: $\Delta m_H = 0.06$ MeV; direct Higgs width measurement: $\Delta\Gamma_H = 0.18$ MeV; measurement of $BR(\mu^+\mu^-)$ $BR(WW^*)$ to 2% and can separate nearly degenerate scalar resonances.
- A multiTeV lepton collider will be required for full coverage of Terascale physics.
  - The physics potential for a muon collider at $\sqrt{s}$ up to 6 TeV and integrated luminosity of 5 ab^{-1} is outstanding. Particularly strong case for SUSY and new strong dynamics.
  - Narrow s-channel states played an important role in past lepton colliders. The new element now is the possibility of new scalar higgs-like resonances. If such states exist in the multi-TeV region, they will play a similar role in precision studies for new physics.