International Conference on Linear Colliders

Paris, April 19-23, 2004

Theoretical Introduction

John Ellis

Open Questions beyond the Standard Model

- What is the origin of particle masses?

  due to a Higgs boson? + other physics?

  solution at energy < 1 TeV (1000 GeV)

  LC

- Why so many types of matter particles?

  matter-antimatter difference?

- Unification of the fundamental forces?

  at very high energy ~ 10^{16} GeV?

  probe directly via neutrino physics, indirectly via masses, couplings

  LC

- Quantum theory of gravity?

  extra space-time dimensions?

  LC

The Physics Case for the LC

- The LHC will make the first exploration of the TeV energy range

  discover Higgs, other physics (susy?, extra D?)

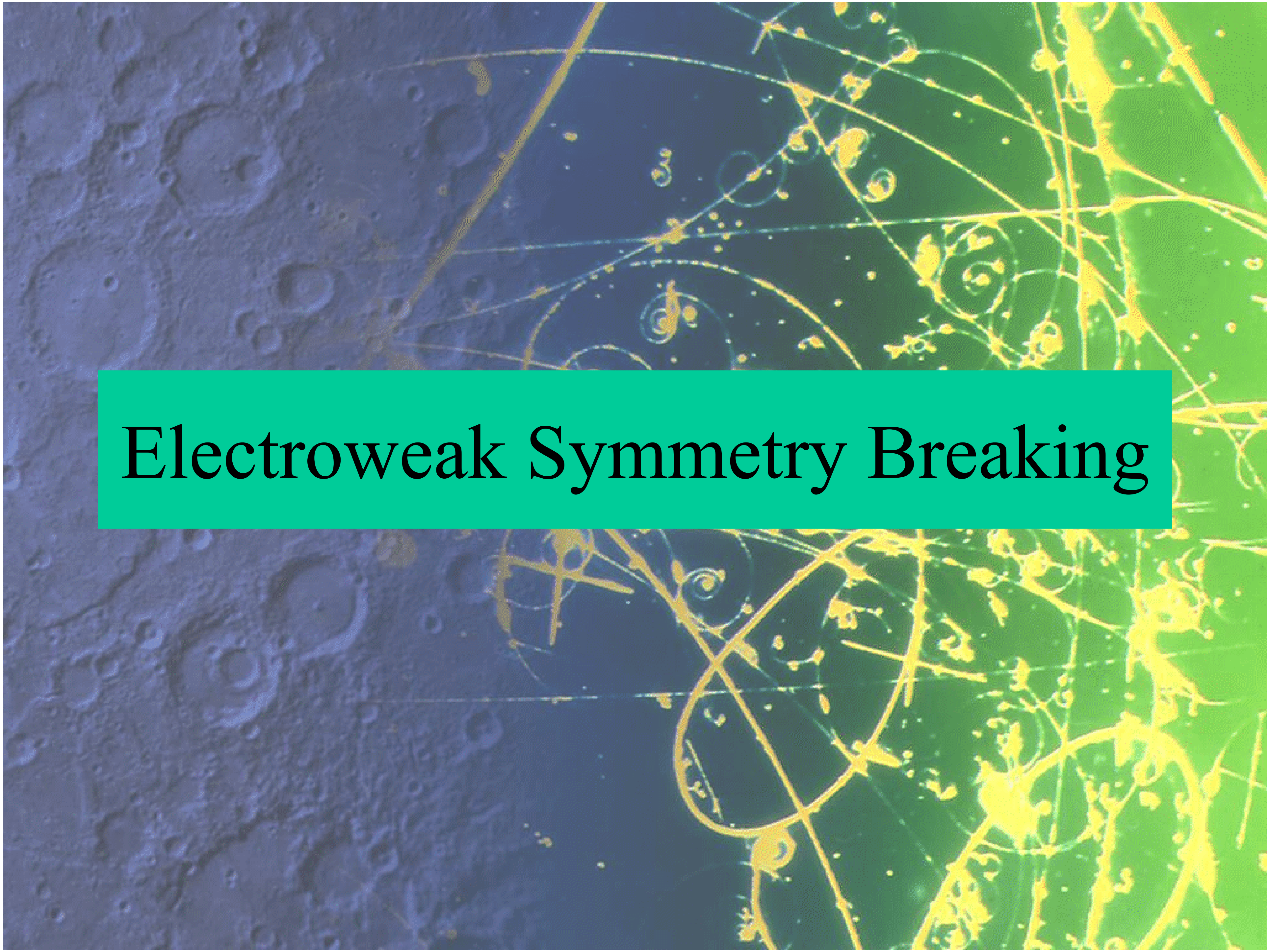
- **The LC will add value**

  study Higgs, new physics @ EW scale

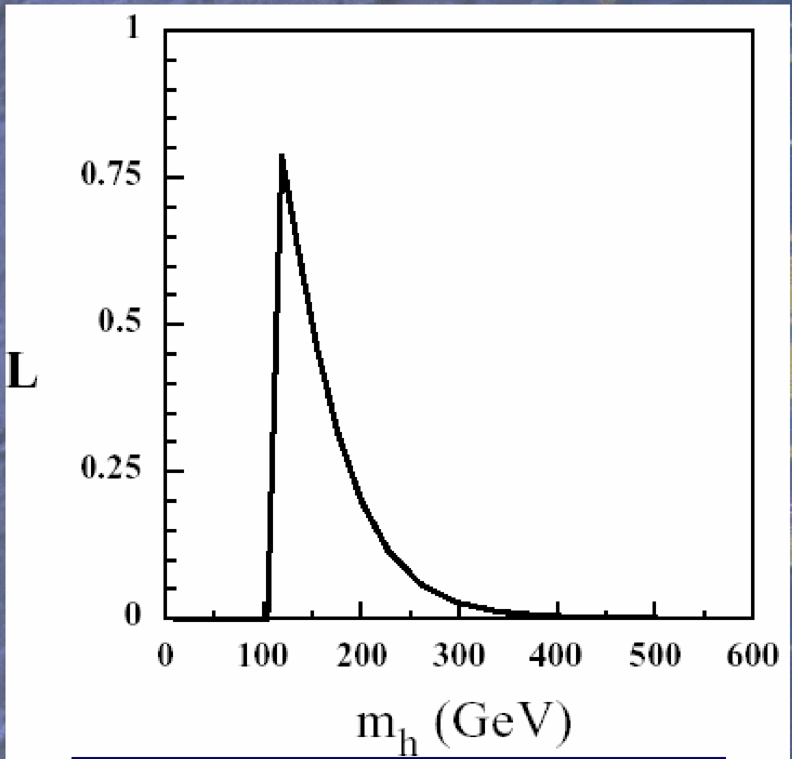
- How sure can we be?

  convince our community, outside world

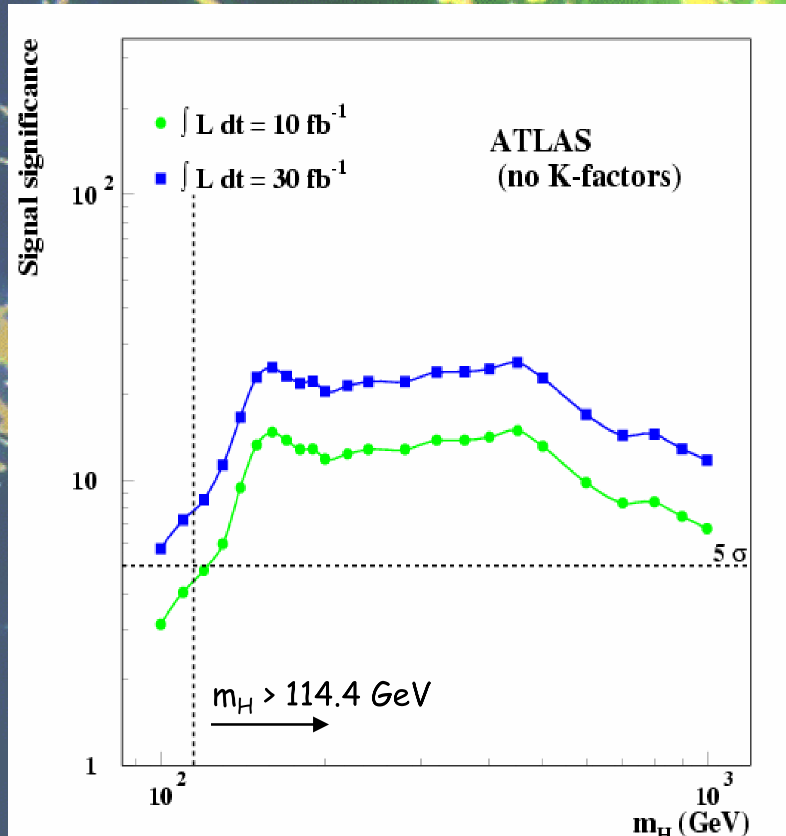
Electroweak Symmetry Breaking



Waiting for the Higgs boson



Higgs probability distribution:
combining direct,
indirect information



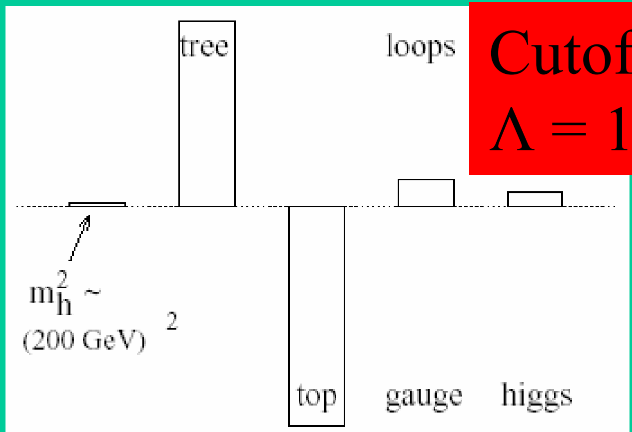
How soon will the Higgs be found? …

Elementary Higgs or Composite?

- Higgs field:

  $\langle 0|H|0\rangle =/= 0$

- Problems with loops



Cutoff
Λ = 10 TeV

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

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

- New technicolour force? inconsistent with precision electroweak data?

Theorists getting Cold Feet

- Interpretation of EW data?

  consistency of measurements? Discard some?
- Higgs + higher-dimensional operators?

  corridors to higher Higgs masses?
- Little Higgs models

  extra `Top', gauge bosons, `Higgses'
- Higgsless models

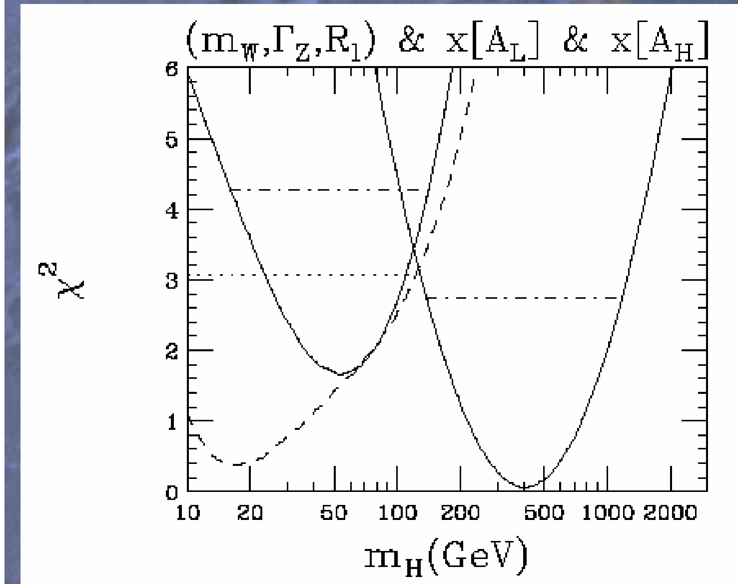
  strong WW scattering, extra D?

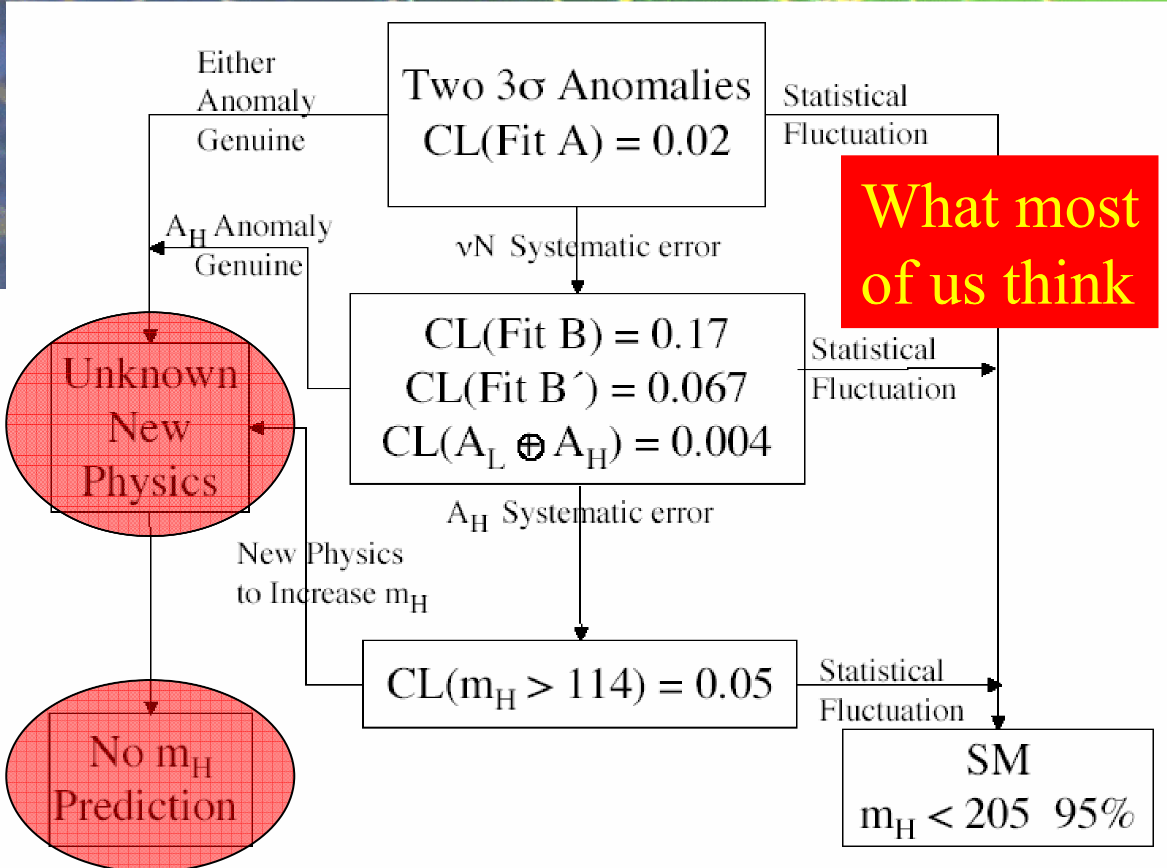
Heretical Interpretation of EW Data

Do all the data tell the same story?

e.g., A_L vs A_H

What attitude towards LEP, NuTeV?





Higgs + Higher-Order Operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^p} \mathcal{O}_i^{(4+p)}$$

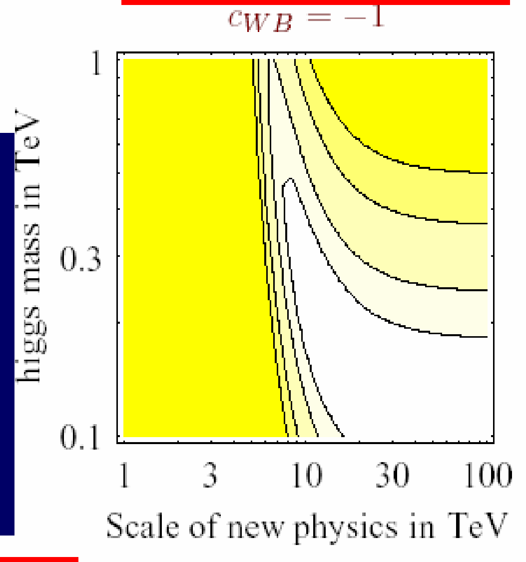
Precision EW data suggest they are small: why?

Corridor to heavy Higgs?

Dimension six operator	$c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB} = (H^+ \sigma^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.0	13
$\mathcal{O}_H = \lvert H^+ D_\mu H \rvert^2$	4.2	7.0
$\mathcal{O}_{LL} = \frac{1}{2} (\bar{L} \gamma_\mu \sigma^a L)^2$	8.2	8.8
$\mathcal{O}_{HL} = i (H^+ D_\mu H)(\bar{L} \gamma_\mu L)$	14	8.0

95% lower bounds on Λ / TeV

But conspiracies are possible: m_H could be large, even if believe EW data …?



Do not discard possibility of heavy Higgs

Little Higgs Models

- Embed SM in larger gauge group
- Higgs as pseudo-Goldstone boson
- Cancel top loop

$$\delta m^2_{H,top}(SM) \sim (115GeV)^2(\frac{\Lambda}{400GeV})^2$$

with new heavy T quark $m_T > 2\lambda_t f \sim 2f$ $f > 1$ TeV

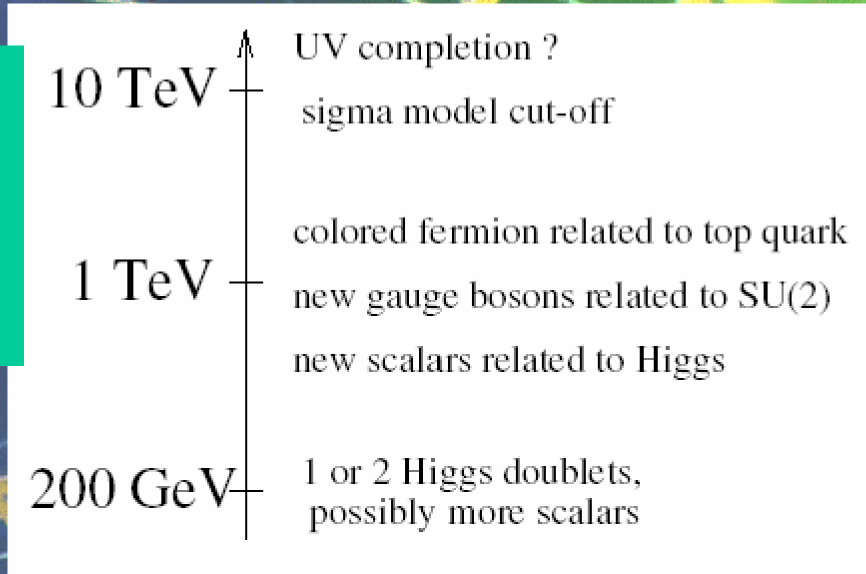
$$\delta m^2_{H,top}(LH) \sim \frac{6G_F m_t^2}{\sqrt{2}\pi^2} m_T^2 log\frac{\Lambda}{m_T} \gtrsim 1.2f^2$$

- New gauge bosons, Higgses
- Higgs light, other new physics heavy

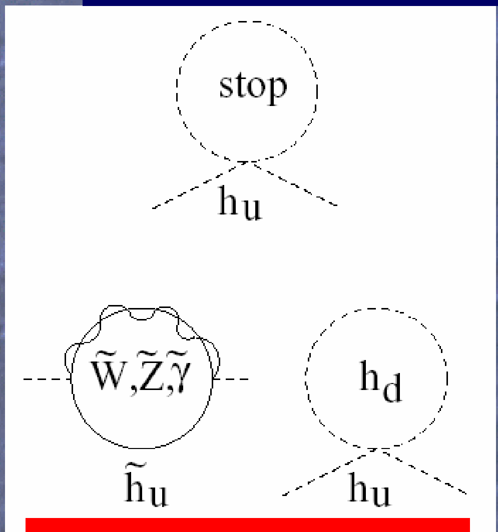
$M_T < 2$ TeV $(m_h / 200$ GeV$)^2$
$M_{W'} < 6$ TeV $(m_h / 200$ GeV$)^2$
$M_{H++} < 10$ TeV

Not as complete as susy: more physics > 10 TeV

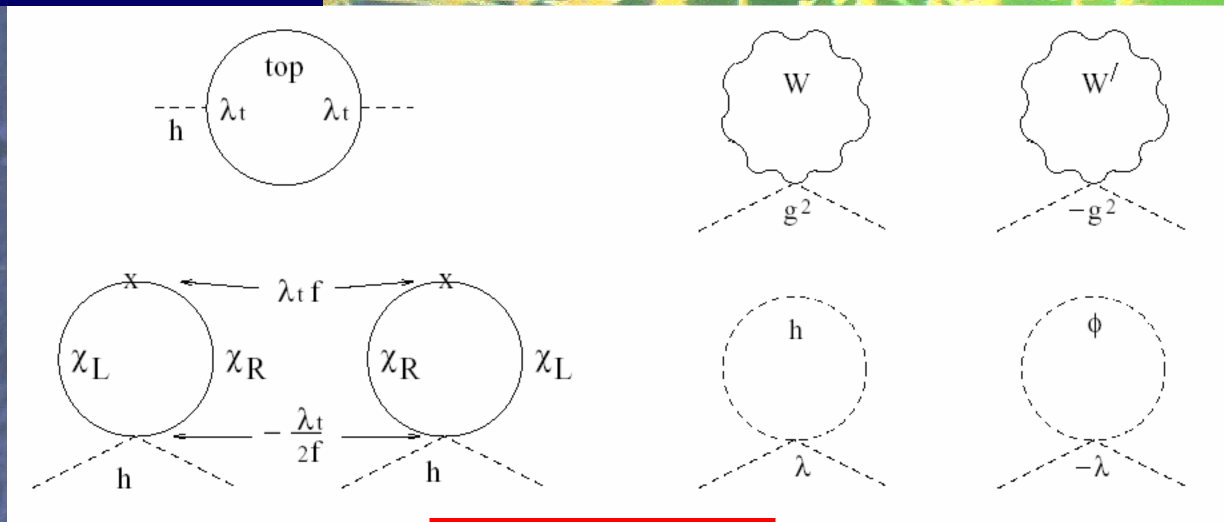
Generic Little Higgs Spectrum



Loop cancellation mechanisms

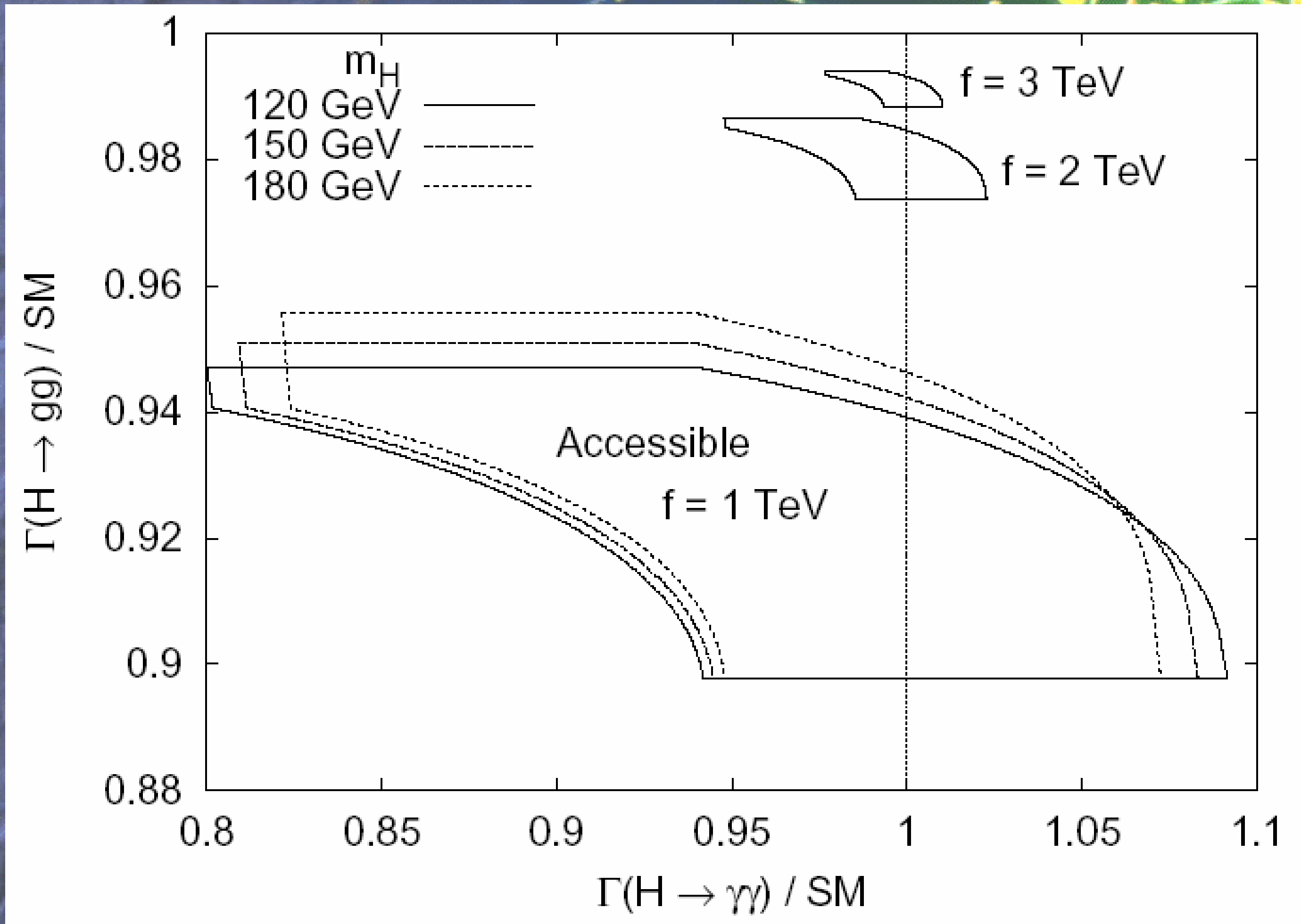


Supersymmetry



Little Higgs

Measure Little Higgs Decays @ LC



Higgsless Models

- Four-dimensional versions:

  Strong WW scattering @ TeV, incompatible with precision data?

- Break EW symmetry by boundary conditions in extra dimension:

  delay strong WW scattering to ~ 10 TeV?

  Kaluza-Klein modes: $m_{KK} > 300$ GeV?

  compatibility with precision data?

- Warped extra dimension + brane kinetic terms?

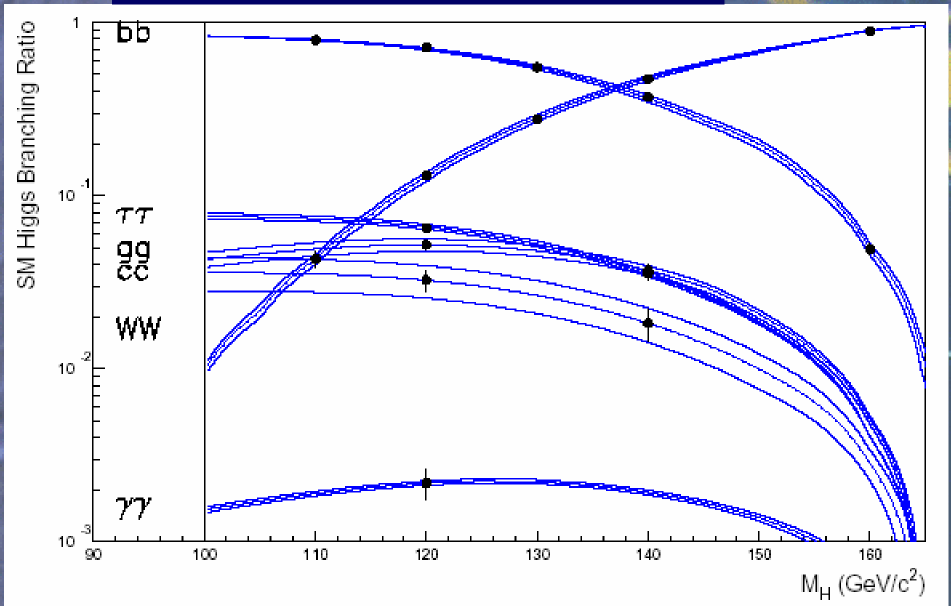
Lightest KK mode @ 300 GeV, strong WW @ 6-7 TeV

Measuring Properties of Light Higgs

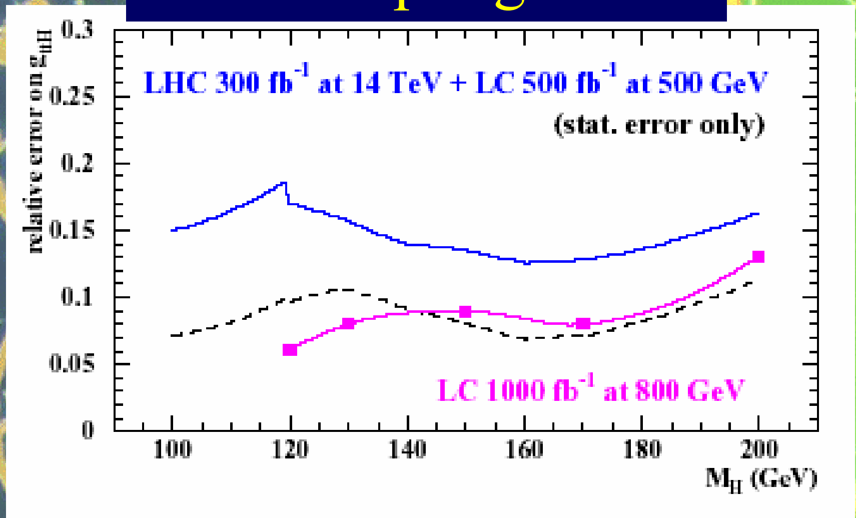
LC capabilities

Some new studies …

bb, ττ, gg, cc, WW, γγ

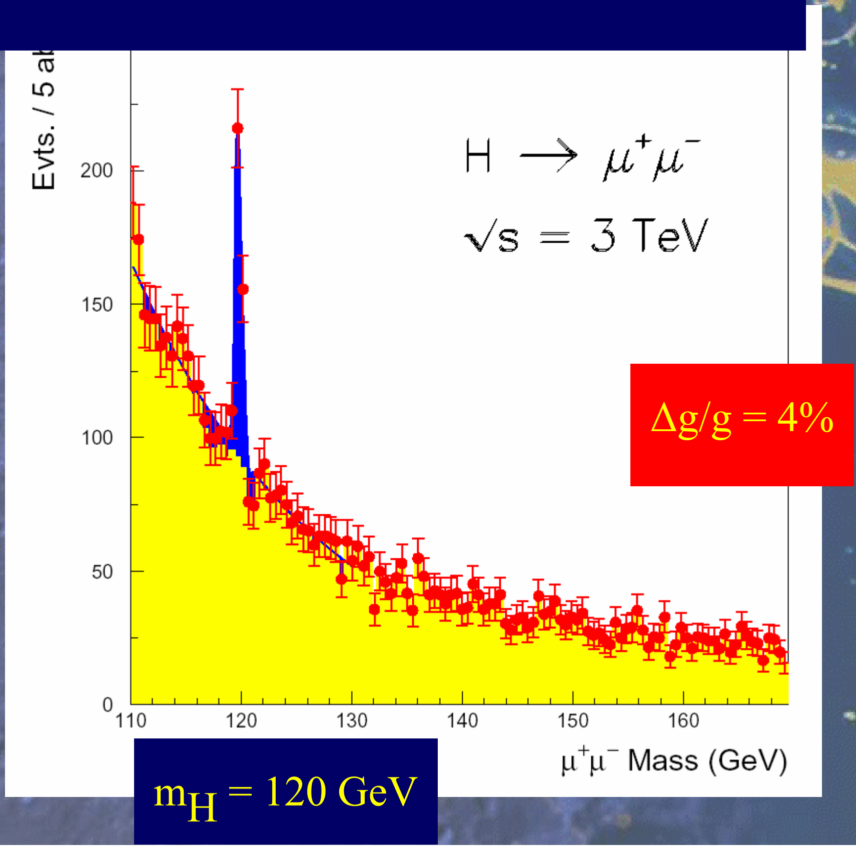


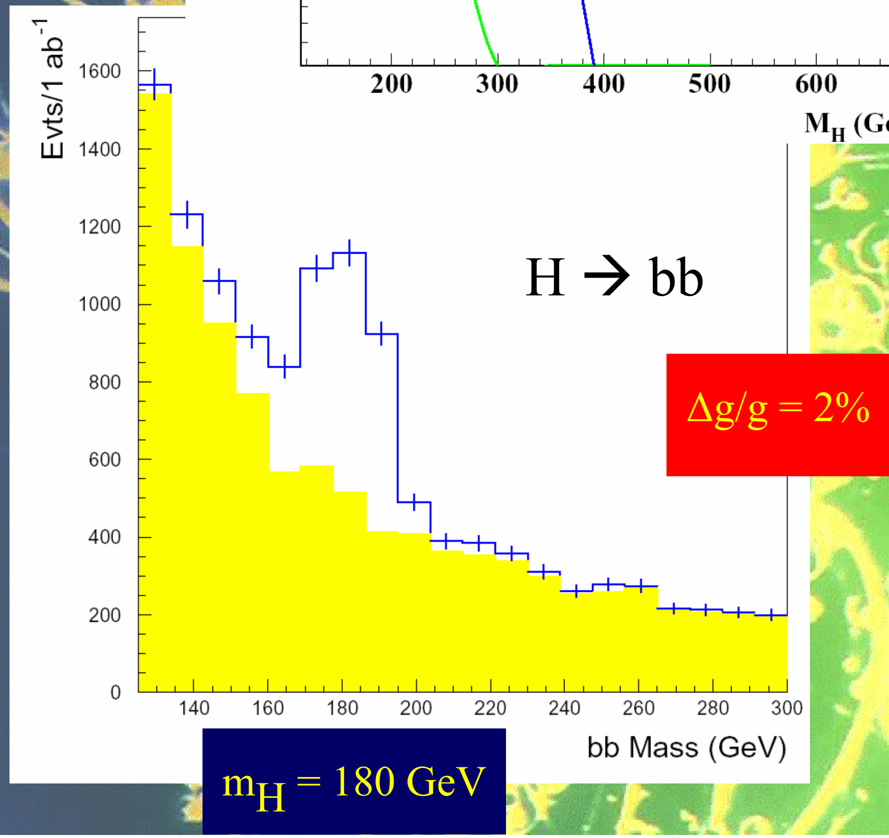
Measuring top-Higgs couplings

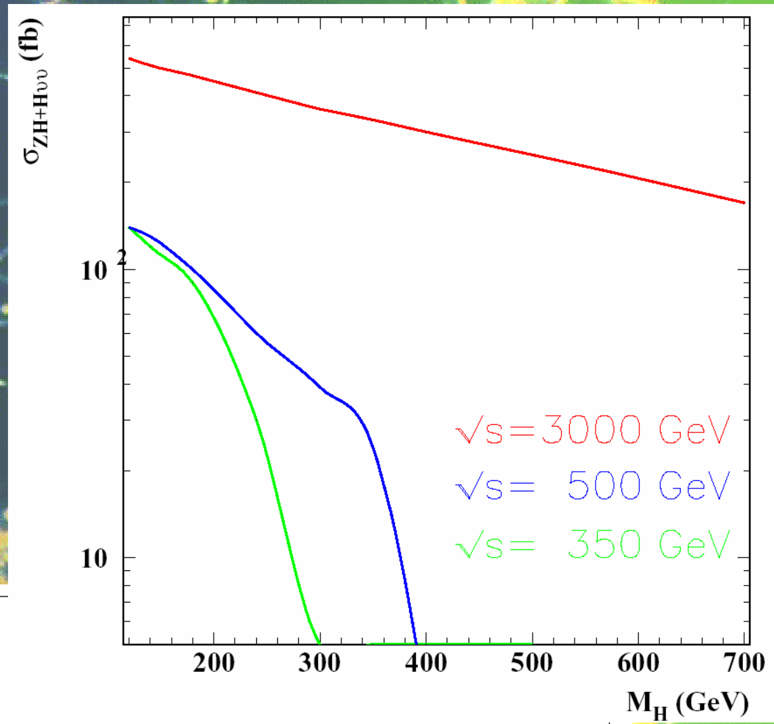


Advantages of Higher Energy LC

Larger cross section @ 3 TeV can measure rare decay modes

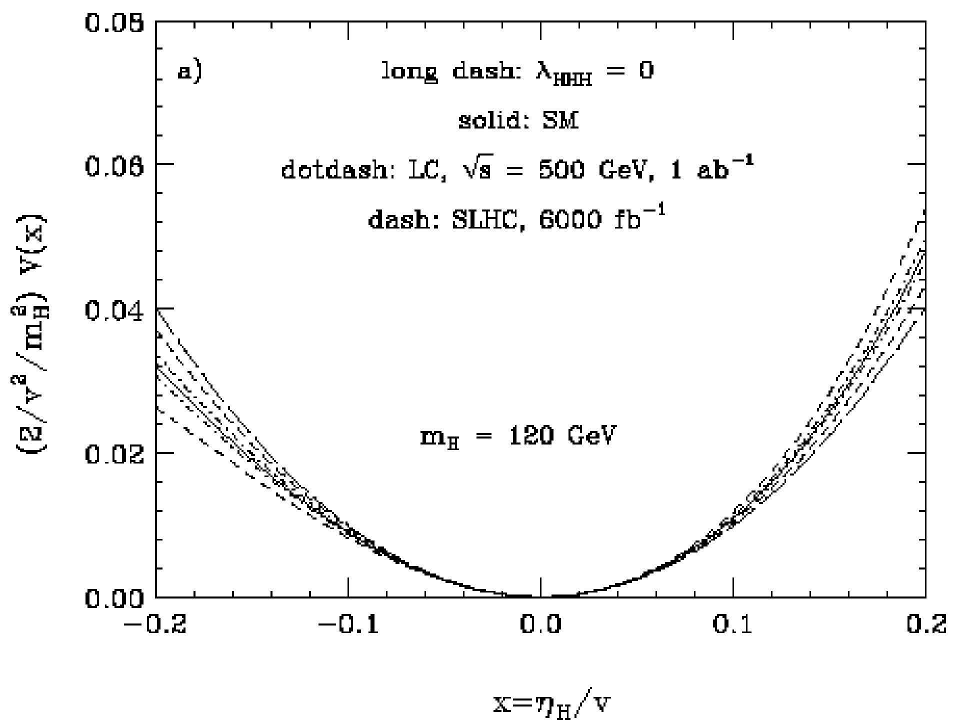




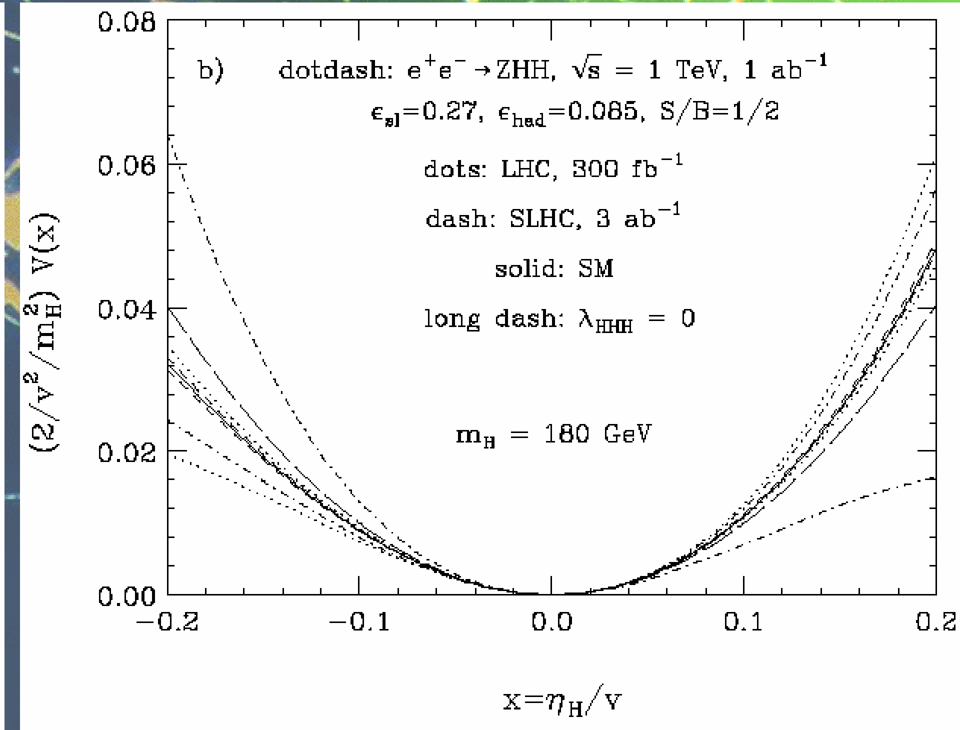


Measuring Higgs Self-Coupling

Light Higgs @ low-energy LC

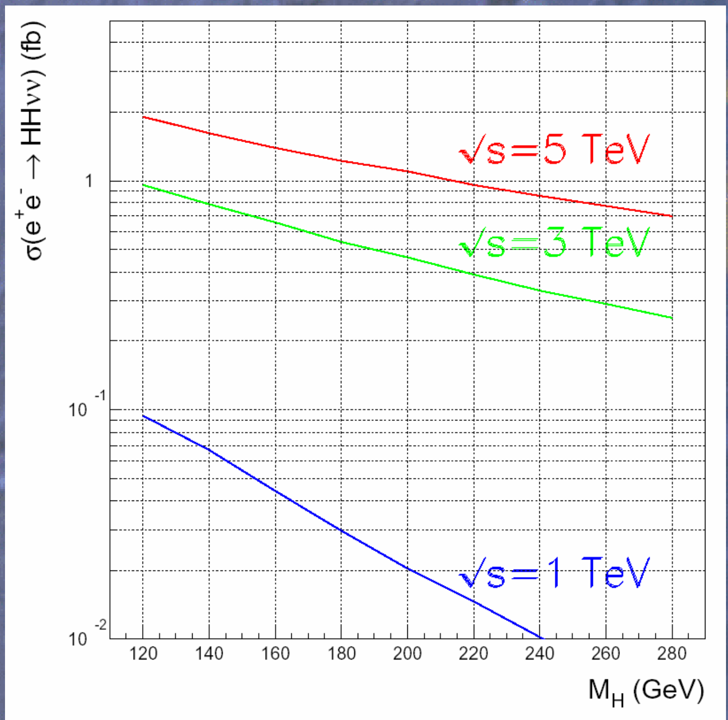


Heavier Higgs possible @ SLHC

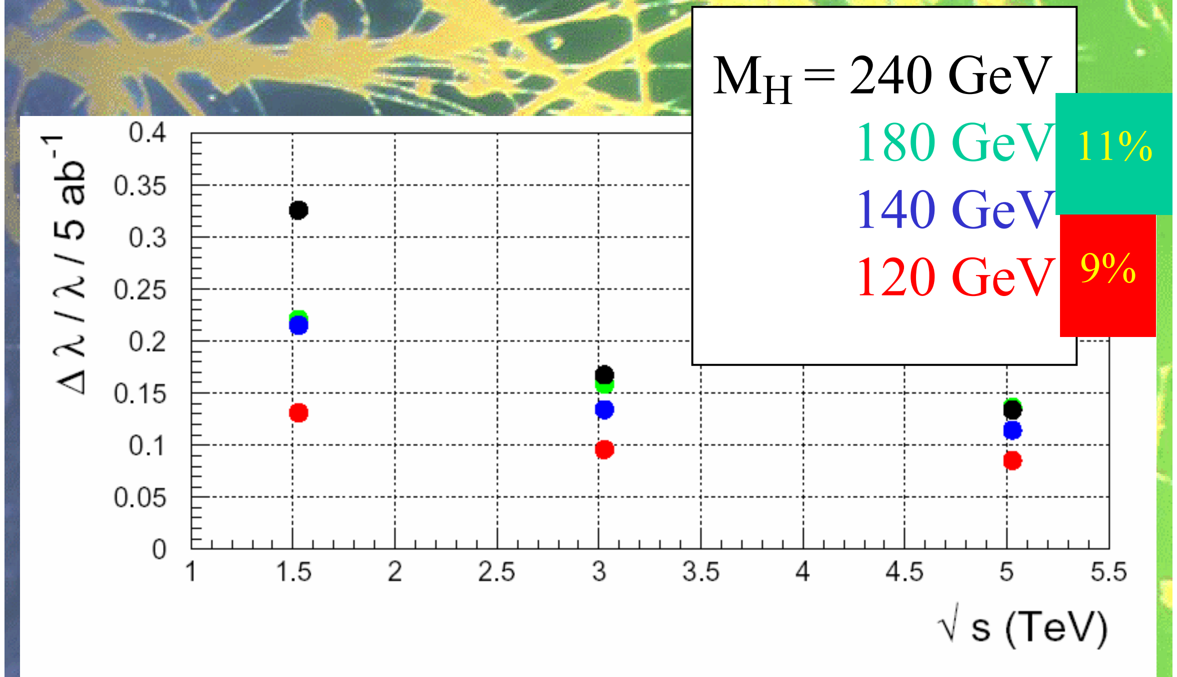


Measuring Effective Higgs Potential @ 3 TeV

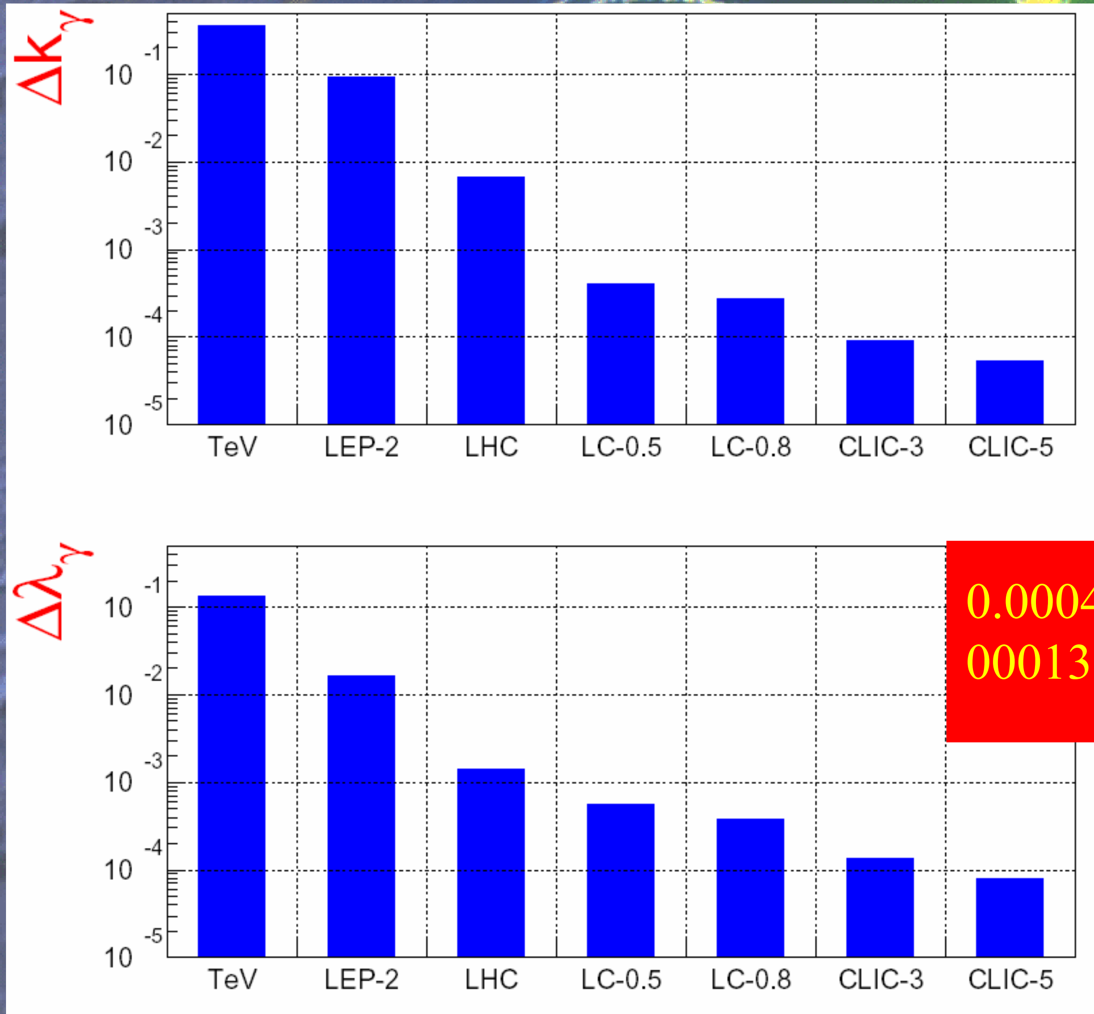
Large cross section for HH pair production



Accuracy in measurement of HHH coupling



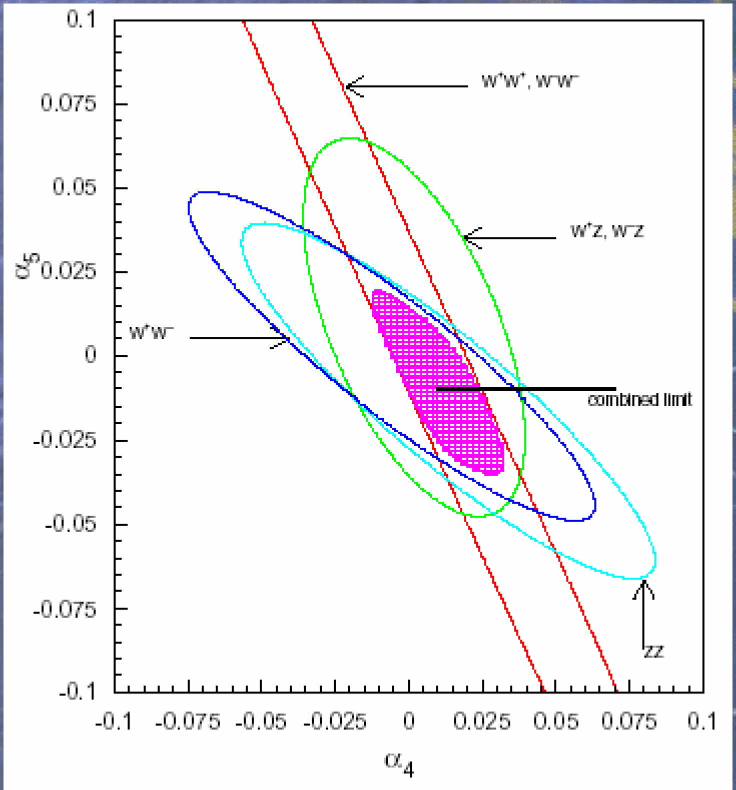
Constraining Triple-Gauge Coupling



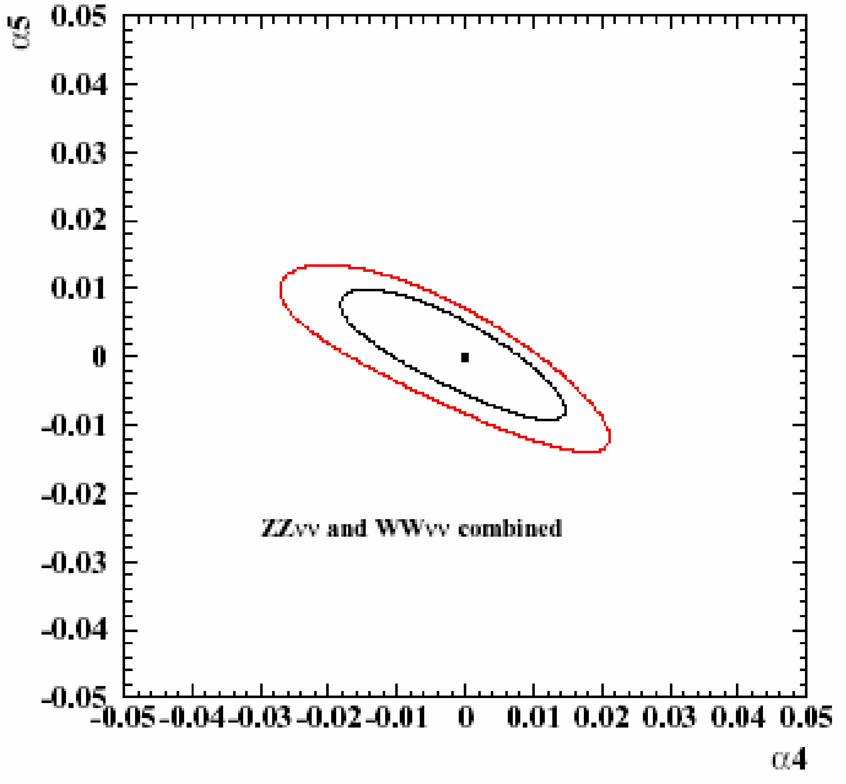
0.0004 @ 0.8 TeV
00013 @ 3 TeV

Sensitivity to Strong WW scattering

@ LHC

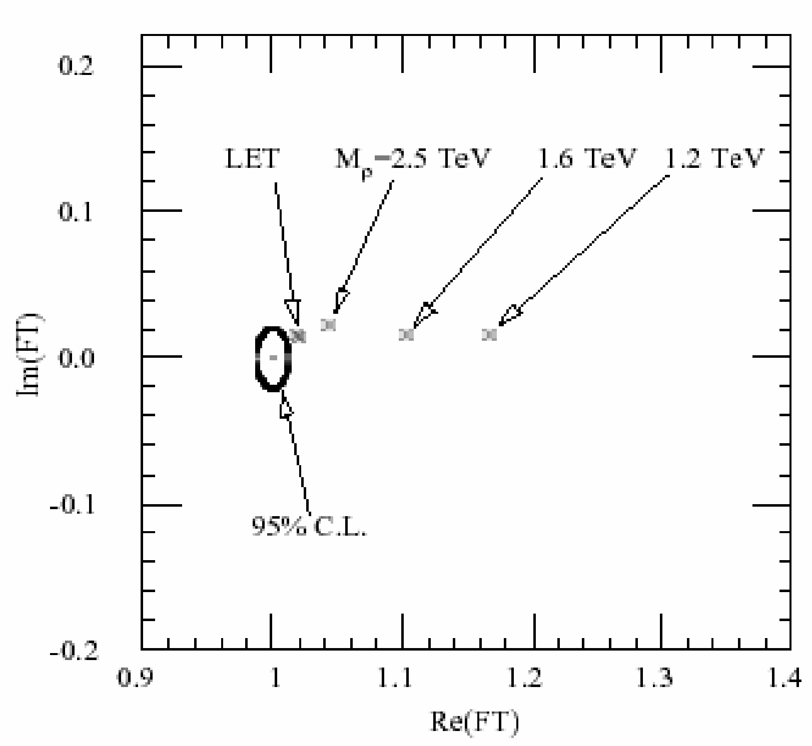


@ 800 GeV LC

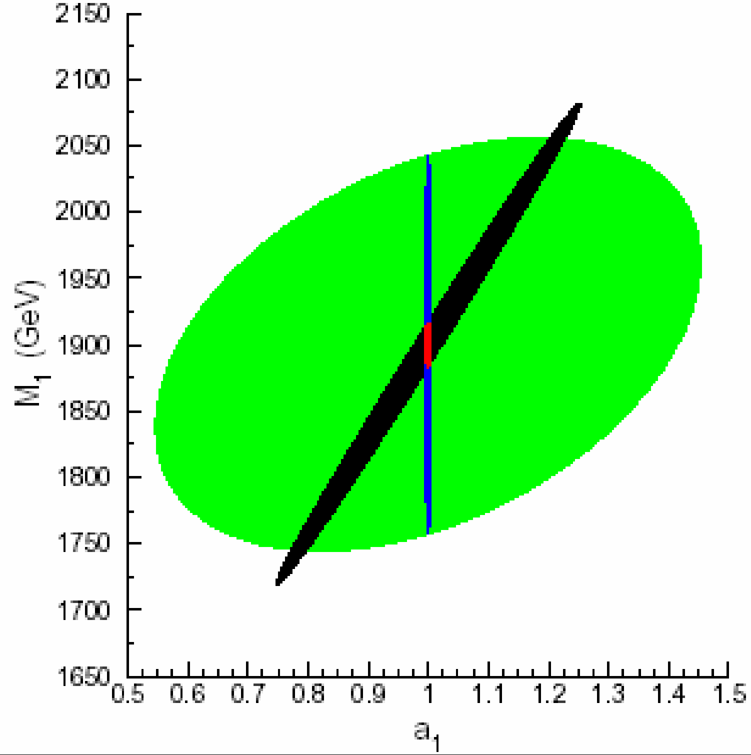


Measuring WW Resonance

Form factor measurements
@ 500 GeV LC



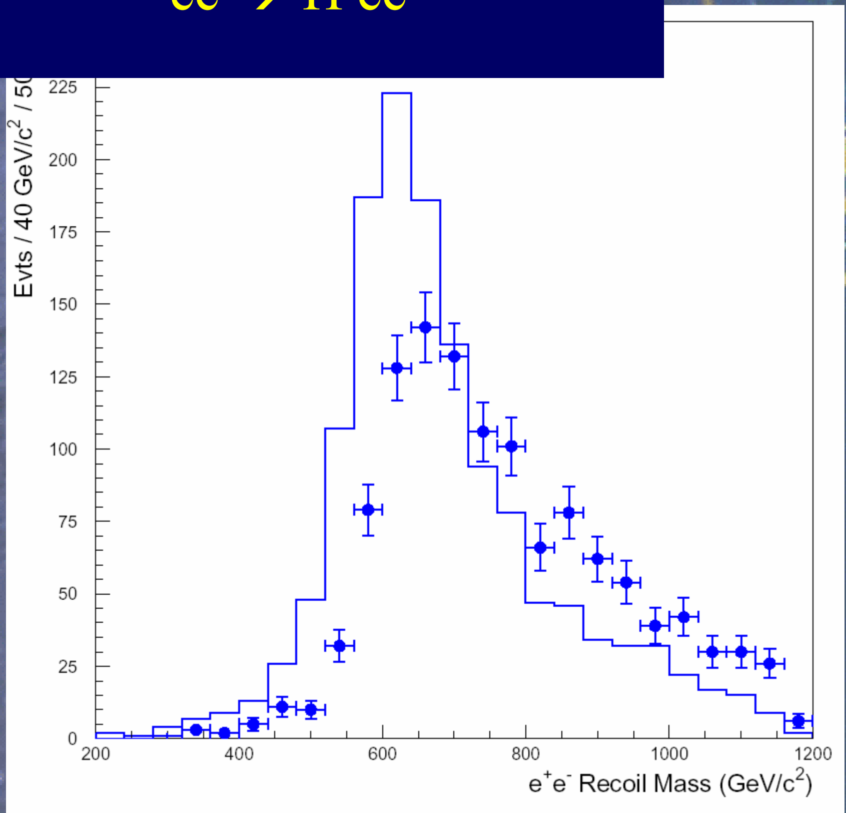
Resonance parameters
@ LHC



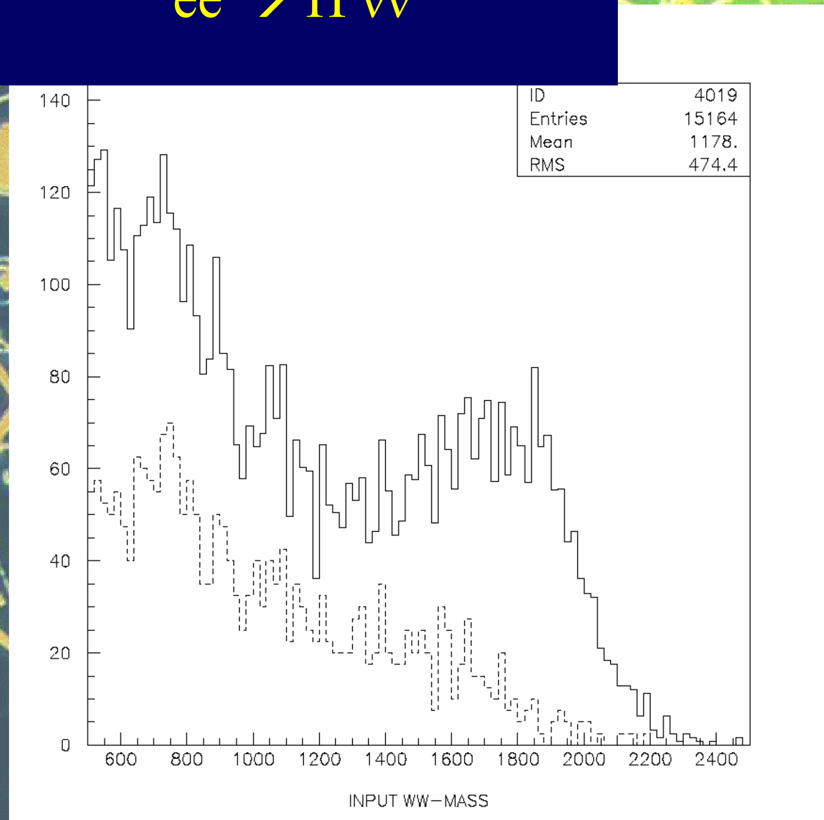
Resonance parameters @ 500 GeV LC

WW Resonance Observable @ 3 TeV

Can establish its existence beyond any doubt if < 1 TeV:
ee → H ee

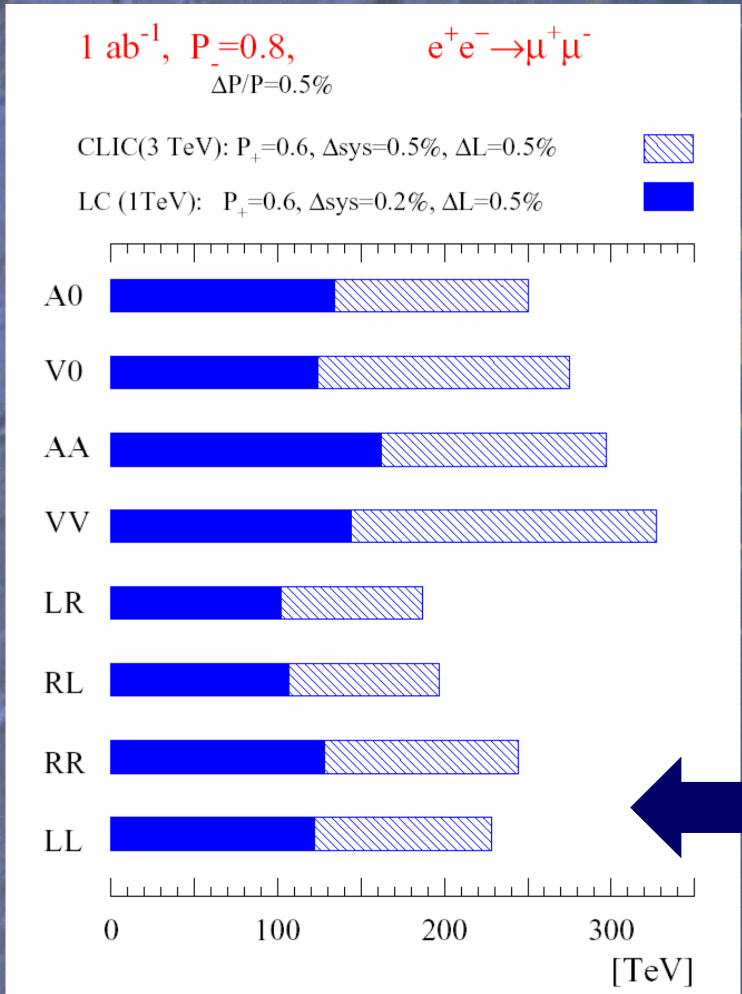


Find resonance in strong WW scattering if > 1 TeV:
ee → H νν

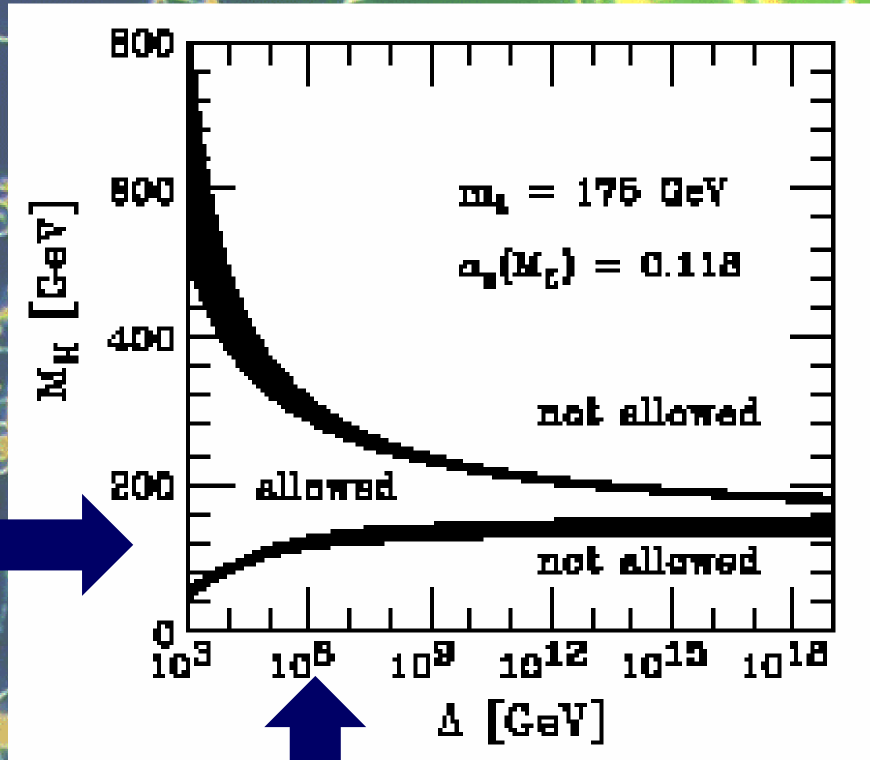


Other Physics @ EW Scale

If the Higgs is light …



LEP ?



There must be new physics below 1000 TeV …

… and may find it in contact interactions

Why Supersymmetry (Susy)?

- Hierarchy problem: why is $m_W << m_P$?

  ($m_P \sim 10^{19}$ GeV is scale of gravity)
- Alternatively, why is

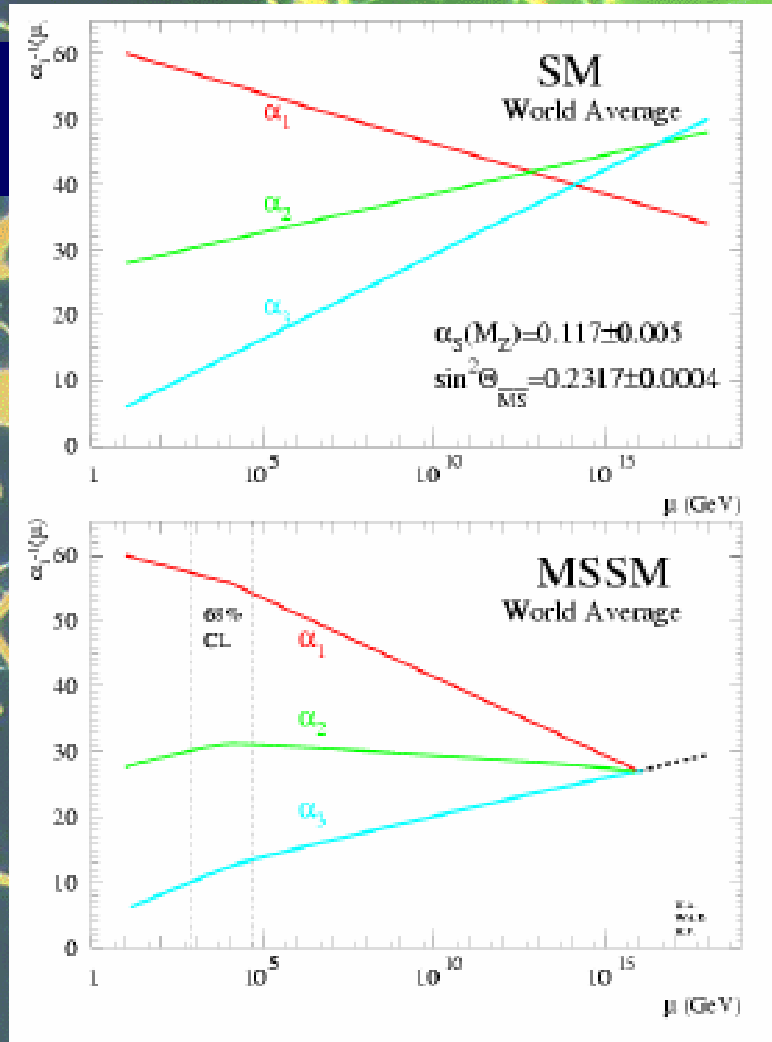
  $G_F = 1/ m_W^2 >> G_N = 1/m_P^2$?
- Or, why is

  $V_{Coulomb} >> V_{Newton}$? $e^2 >> G\, m^2 = m^2 / m_P^2$
- Set by hand? What about loop corrections?

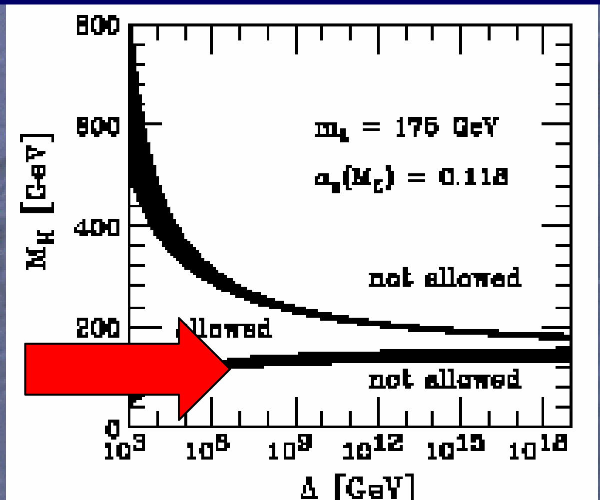
  $\delta m_{H,W}^2 = O(\alpha/\pi)\, \Lambda^2$
- Cancel boson loops ⇔ fermions
- Need $| m_B^2 – m_F^2| < 1\ \text{TeV}^2$

Other Reasons to like Susy

It enables the gauge couplings to unify



It stabilizes the Higgs potential for low masses



Approved by Fabiola Gianotti

Current Constraints on CMSSM

Focus-point region above 7 TeV for m_t = 178 GeV

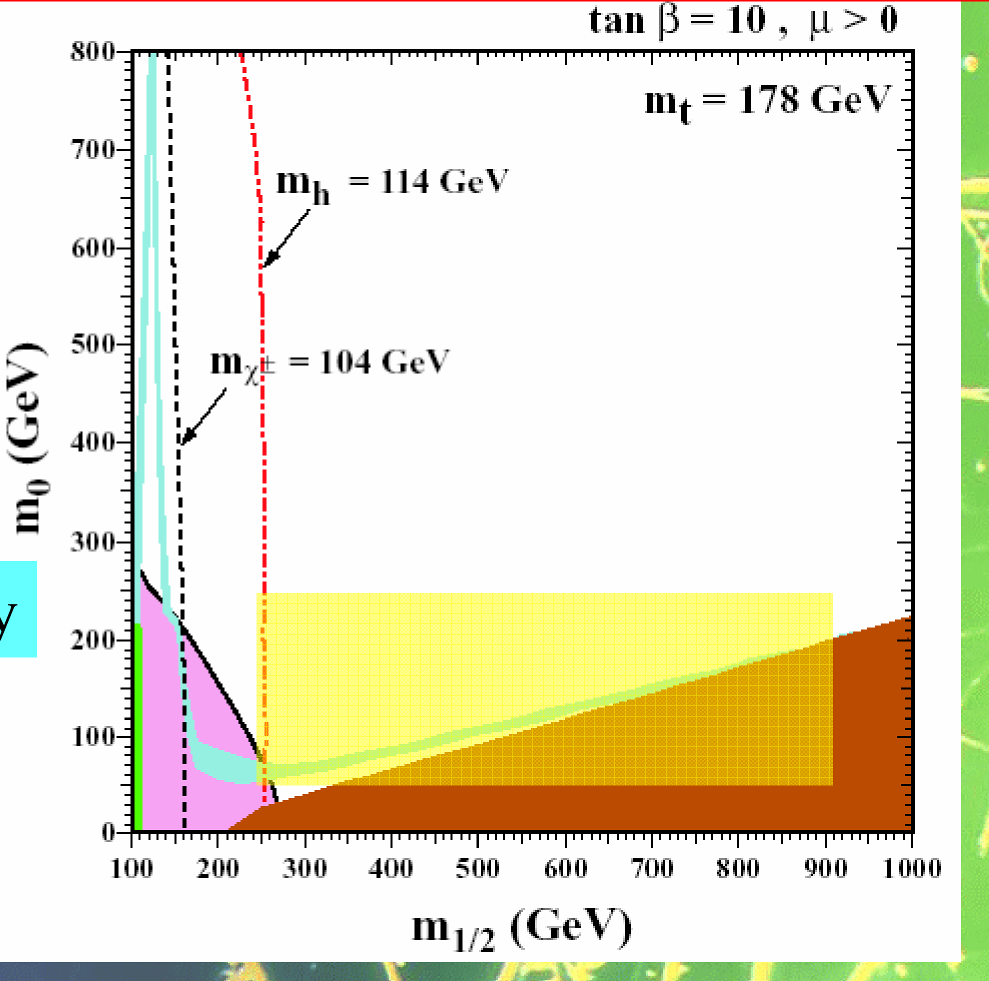
Excluded because stau LSP

Excluded by b → s gamma

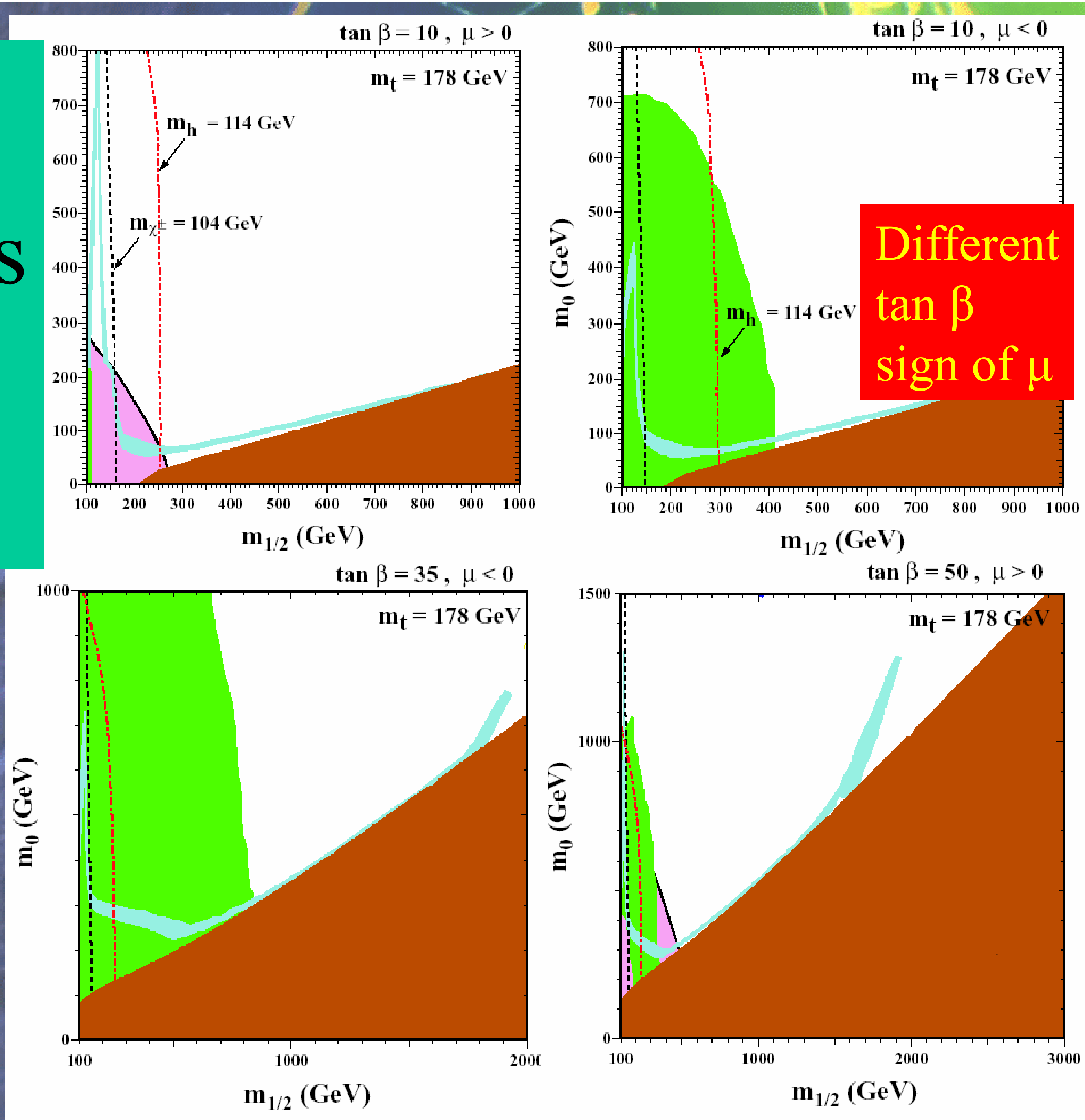
WMAP constraint on relic density

Excluded (?) by latest g - 2

Latest CDF/D0 top mass



Current Constraints on CMSSM



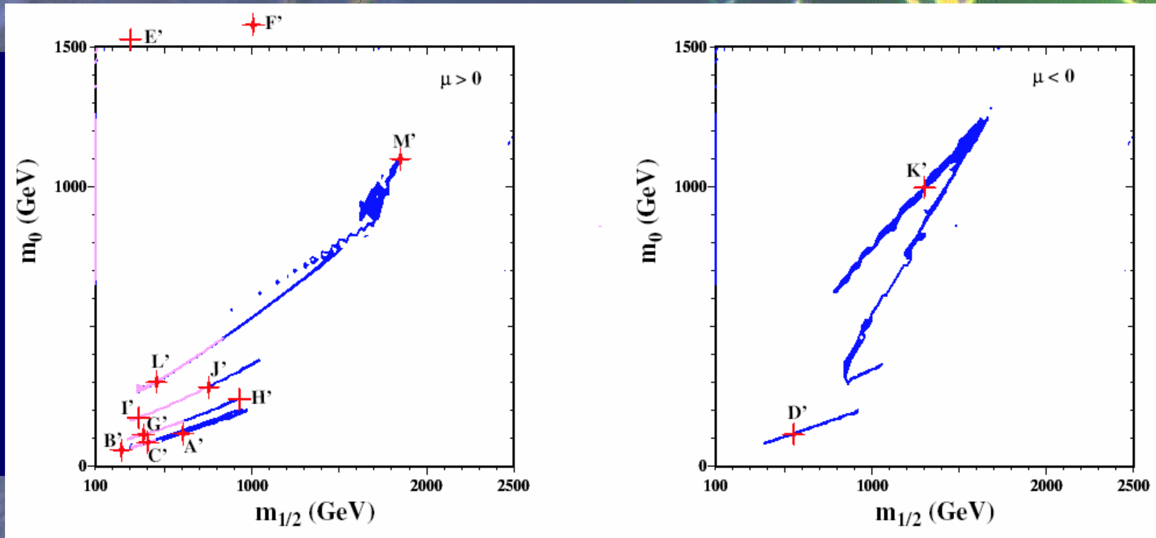
Different tan β
sign of μ

Impact of Higgs constraint reduced if larger m_t

Focus-point region far up

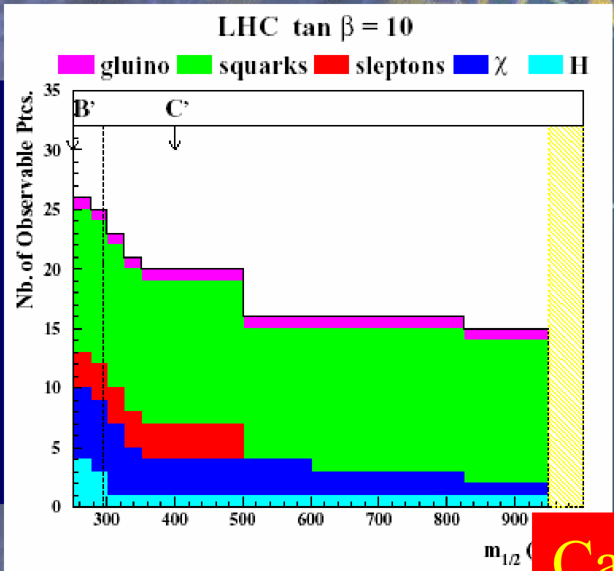
Supersymmetric Benchmark Studies

Lines in susy space allowed by accelerators, WMAP data

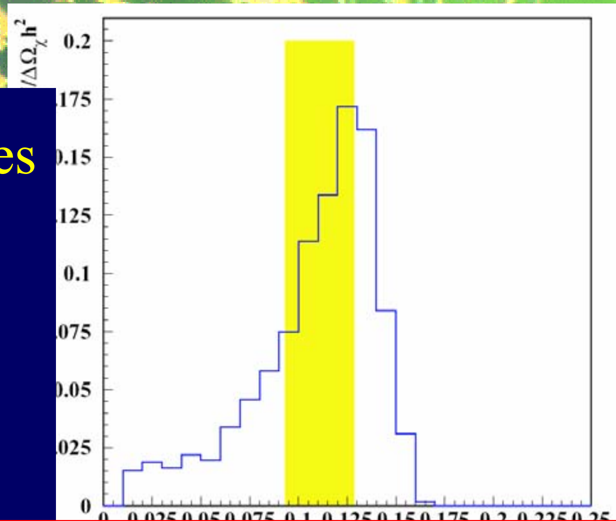


Specific benchmark Points along WMAP lines

Sparticle Detectability @ LHC along one WMAP line



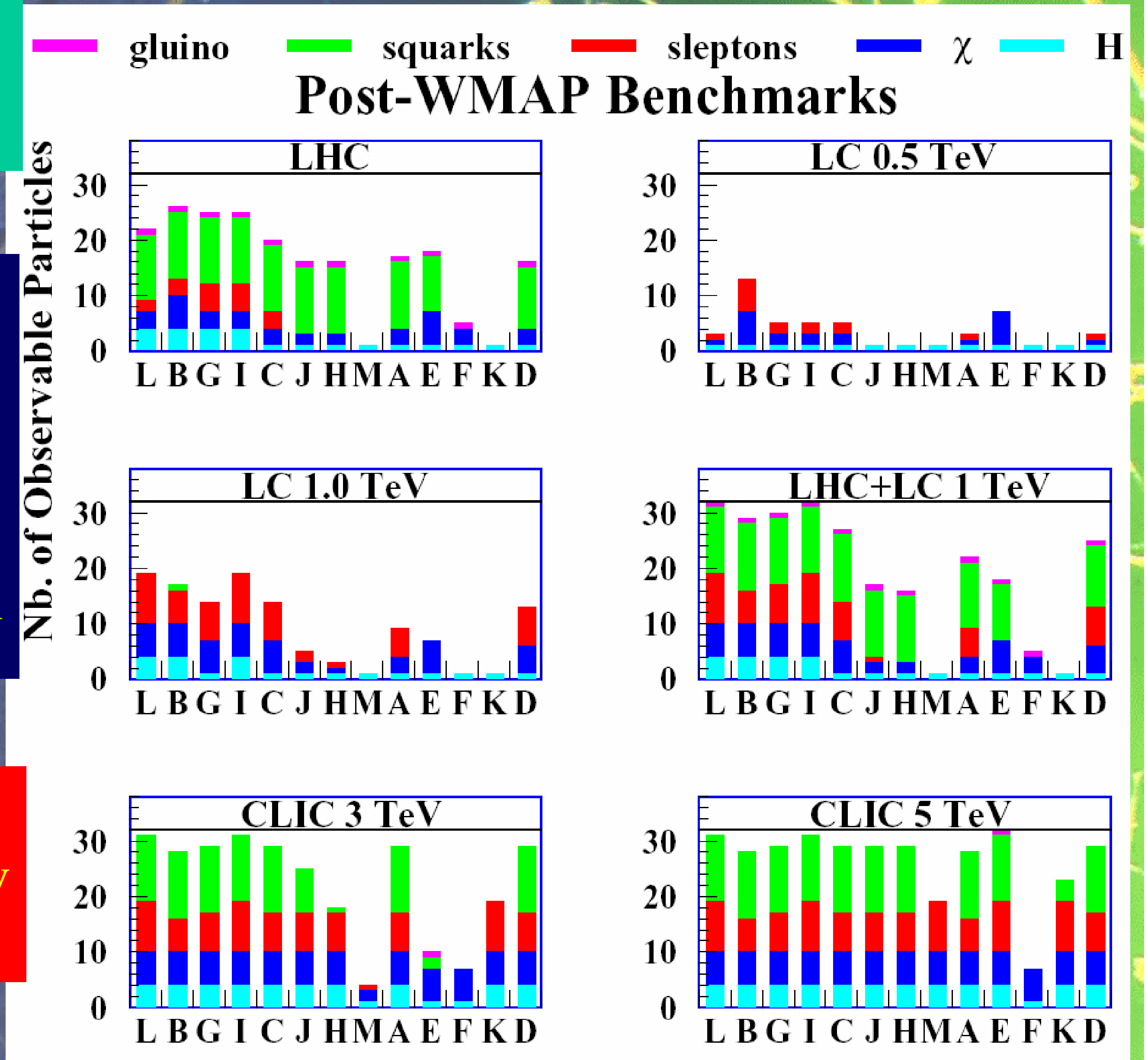
LHC enables calculation of relic density at a benchmark point



Can be refined with LC measurements

LHC and LC Scapabilities

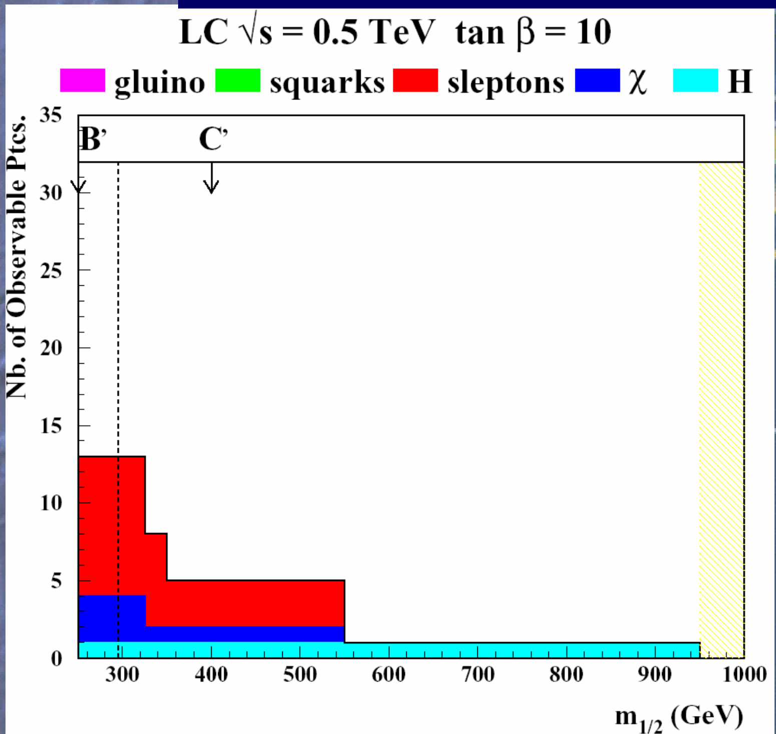
LHC almost
`guaranteed'
to discover
supersymmetry
if it is relevant
to the mass problem

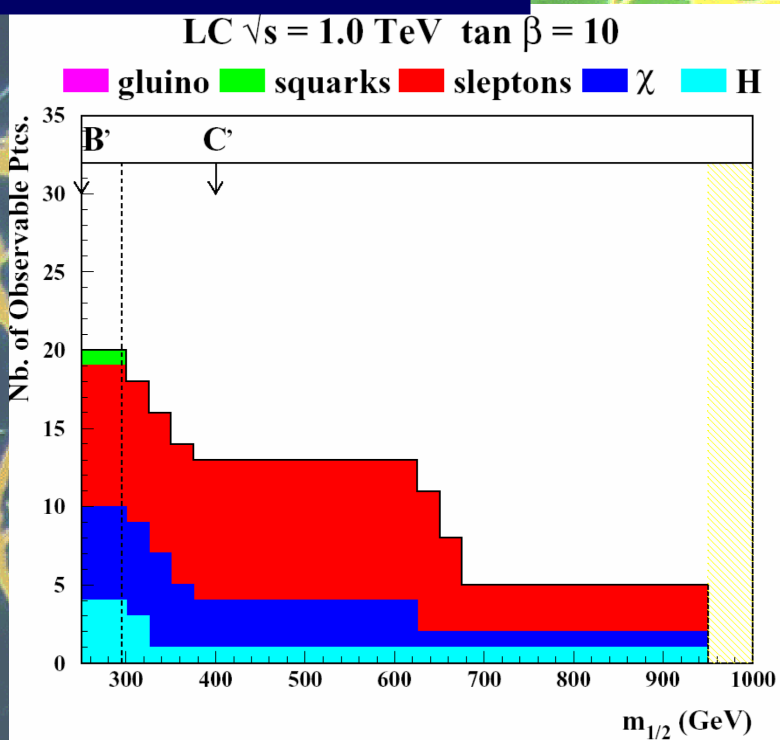


LC oberves
complementary
sparticles

Sparticles at LC along WMAP Line

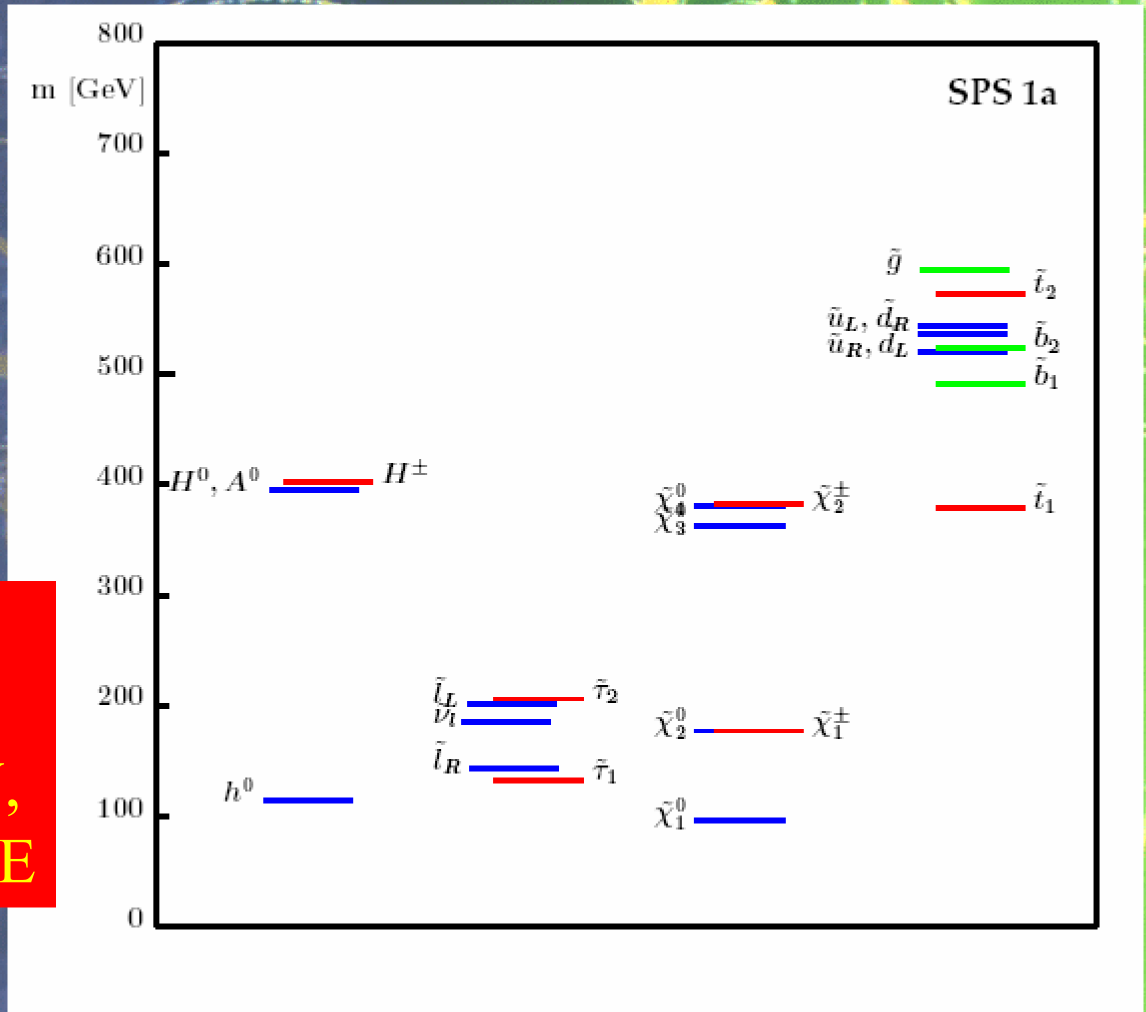
Complementary to LHC: weakly-interacting sparticles





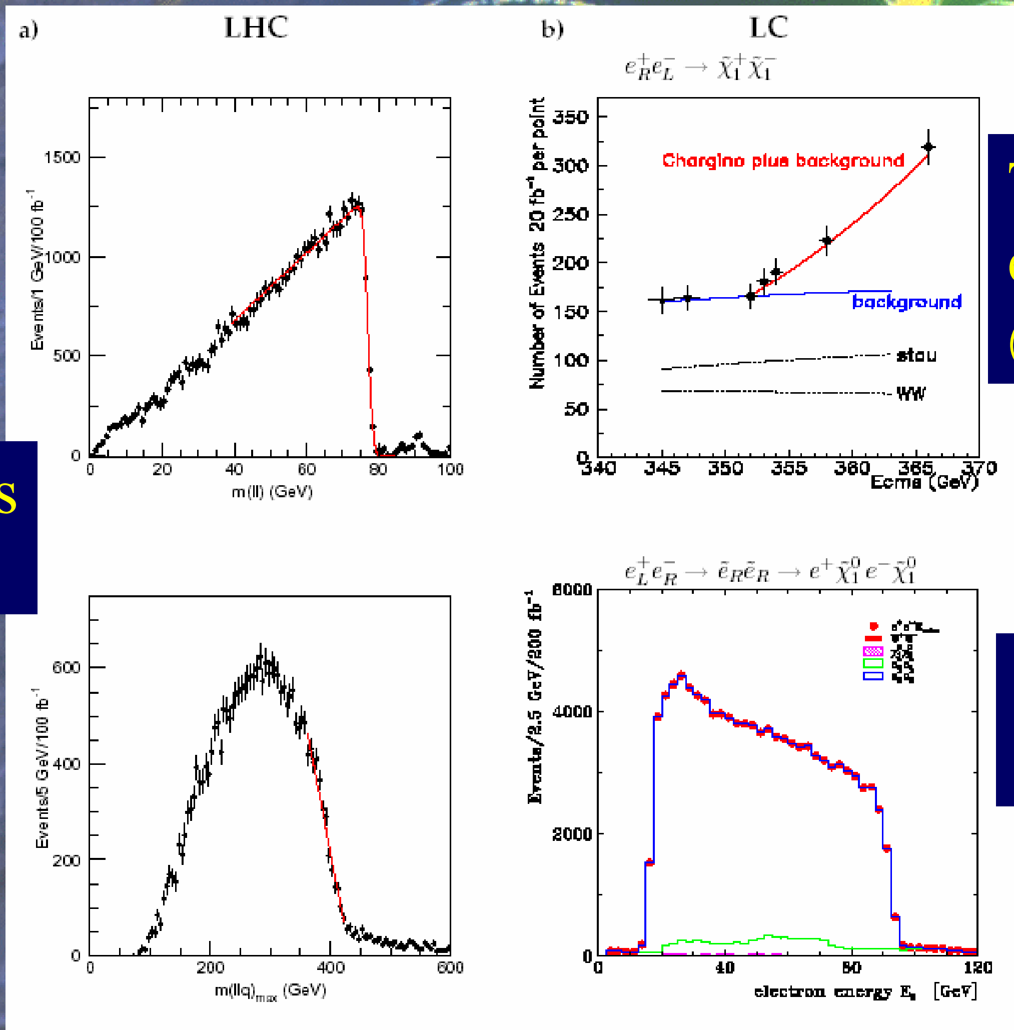
Example of Benchmark Point

Spectrum of Benchmark SPS1a ~ Point B of *Battaglia et al*



Several sparticles at 500 GeV LC, more at 1000 GeV, some need higher E

Examples of Sparticle Measurements



Spectrum edges @ LHC

Threshold excitation @ LC

Spectra @ LHC

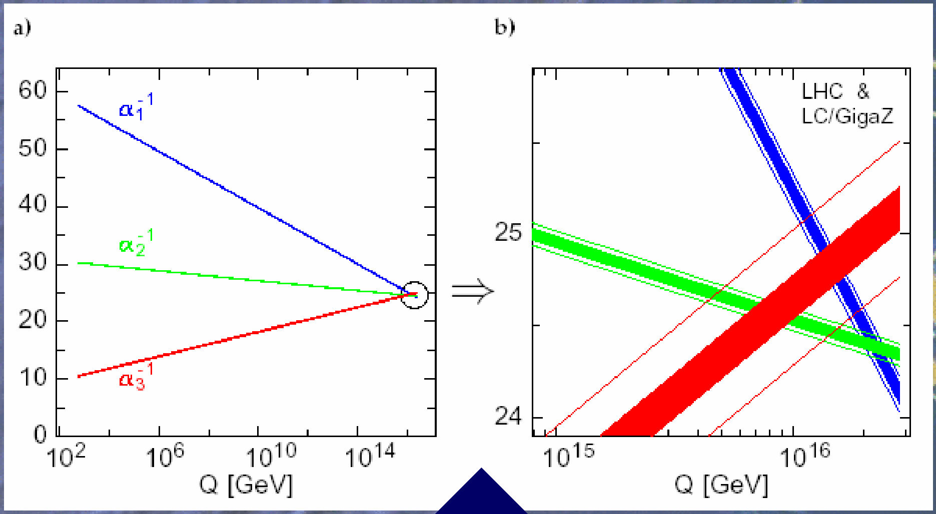
Added Value of LC Measurements

	m_{SPS1a}	LHC	LC	LHC+LC		m_{SPS1a}	LHC	LC	LHC+LC
h	111.6	0.25	0.05	0.05	H	399.6		1.5	1.5
A	399.1		1.5	1.5	$H+$	407.1		1.5	1.5
χ_1^0	97.03	4.8	0.05	0.05	χ_2^0	182.9	4.7	1.2	0.08
χ_3^0	349.2		4.0	4.0	χ_4^0	370.3	5.1	4.0	2.3
$\chi_1^\pm$	182.3		0.55	0.55	$\chi_2^\pm$	370.6		3.0	3.0
$\tilde{g}$	615.7	8.0		6.5					
$\tilde{t}_1$	411.8		2.0	2.0					
$\tilde{b}_1$	520.8	7.5		5.7	$\tilde{b}_2$	550.4	7.9		6.2
$\tilde{u}_1$	551.0	19.0		16.0	$\tilde{u}_2$	570.8	17.4		9.8
$\tilde{d}_1$	549.9	19.0		16.0	$\tilde{d}_2$	576.4	17.4		9.8
$\tilde{s}_1$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		9.8
$\tilde{c}_1$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
$\tilde{e}_1$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\tilde{\mu}_1$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\tilde{\tau}_1$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\tilde{\nu}_e$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

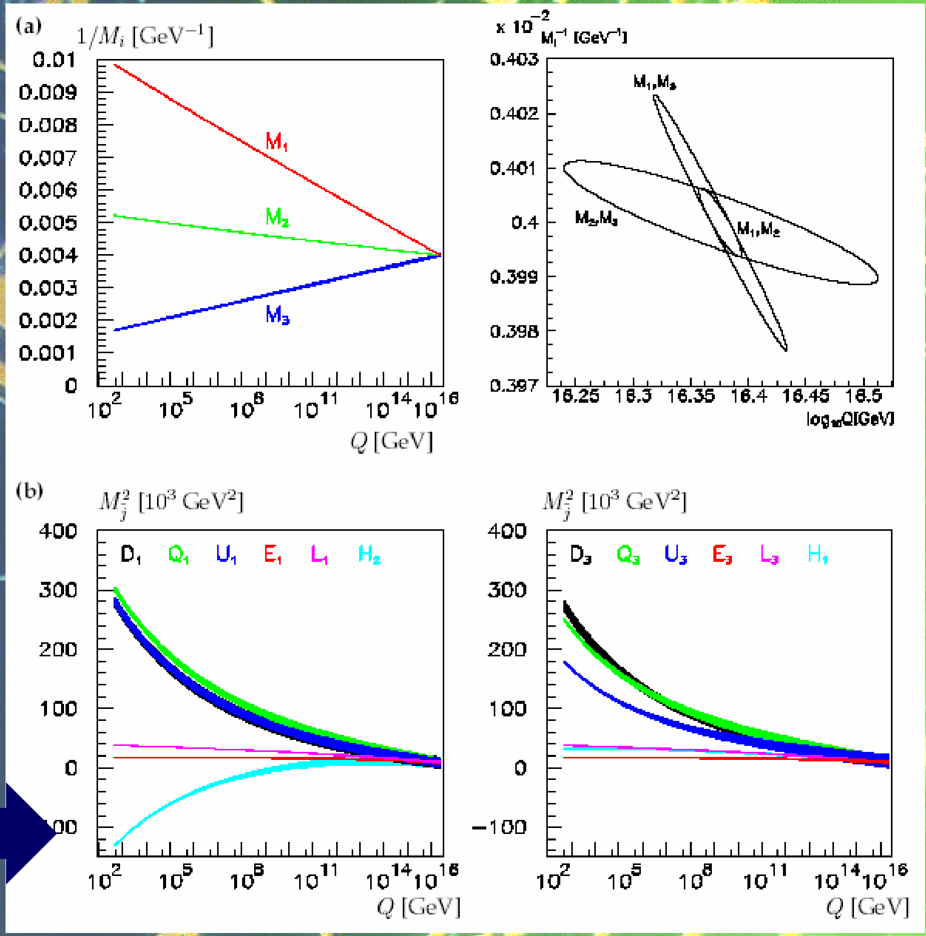
Determination of mSUGRA parameters

	SPS1a	StartFit	LHC	Δ_{LHC}	LC	Δ_{LC}	LHC+LC	Δ_{LHC+LC}
M_0	100	500	100.03	4.0	100.03	0.09	100.04	0.08
$M_{1/2}$	250	500	249.95	1.8	250.02	0.13	250.01	0.11
$\tan\beta$	10	50	9.87	1.3	9.98	0.14	9.98	0.14
A_0	-100	0	-99.29	31.8	-98.26	4.43	-98.25	4.13

Tests of Unification Ideas



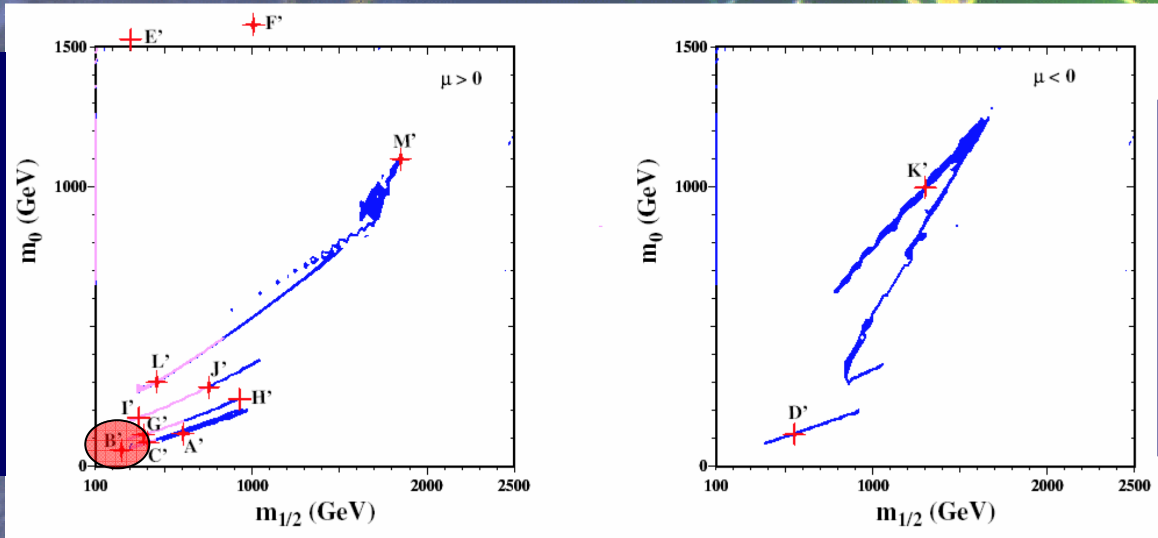
For gauge couplings



For sparticle masses

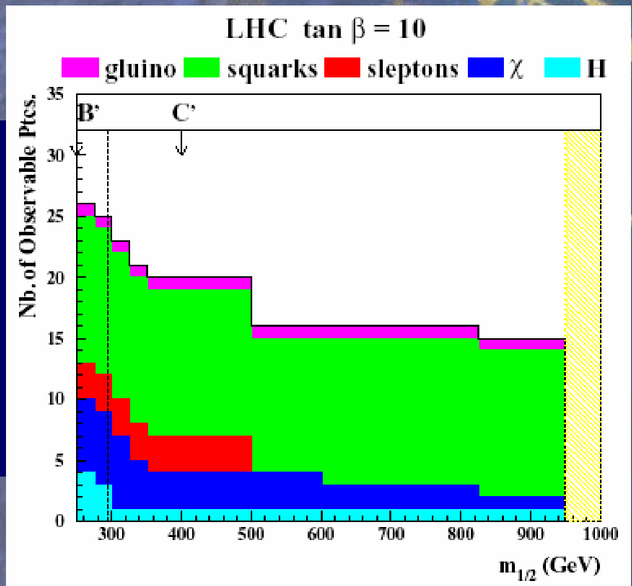
Supersymmetric Benchmark Studies

Lines in susy space allowed by accelerators, WMAP data

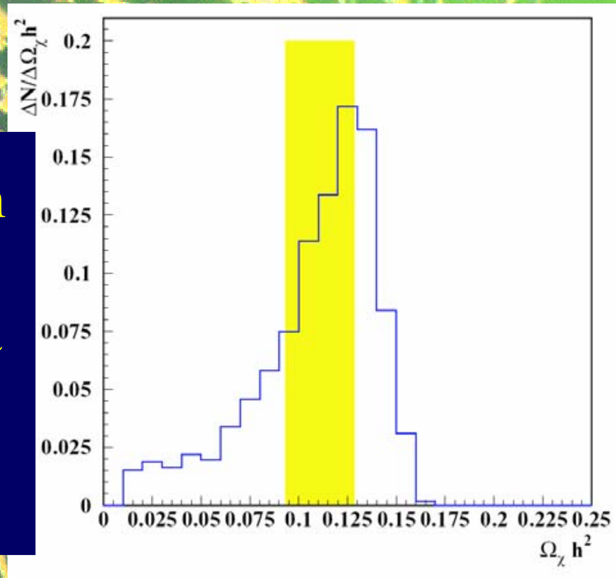


Specific benchmark Points along WMAP lines

Sparticle detectability Along one WMAP line

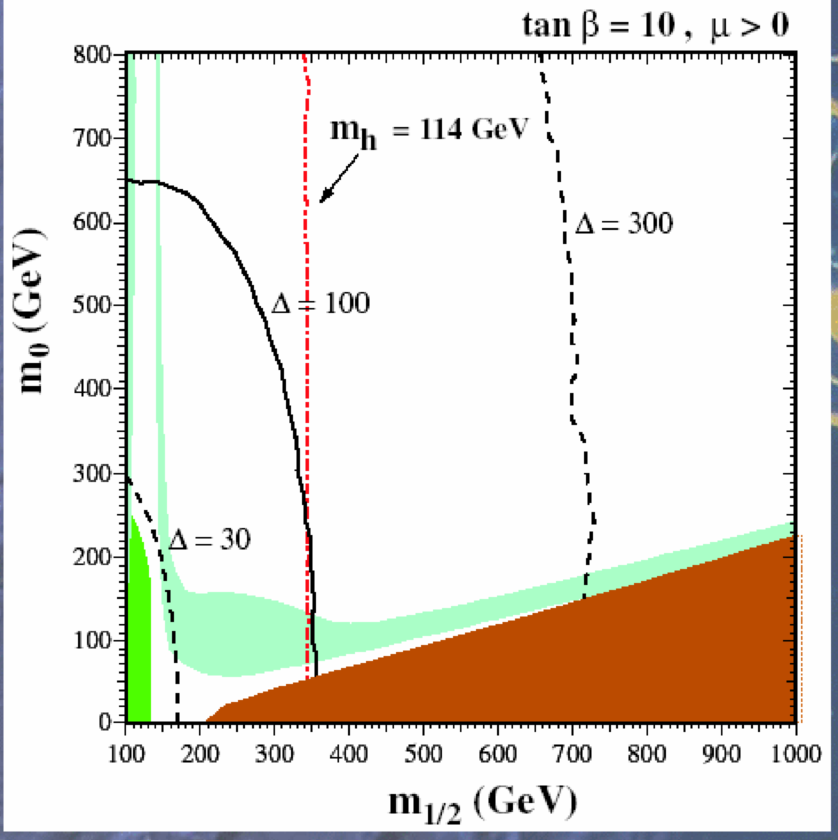


Calculation of relic density at a benchmark point

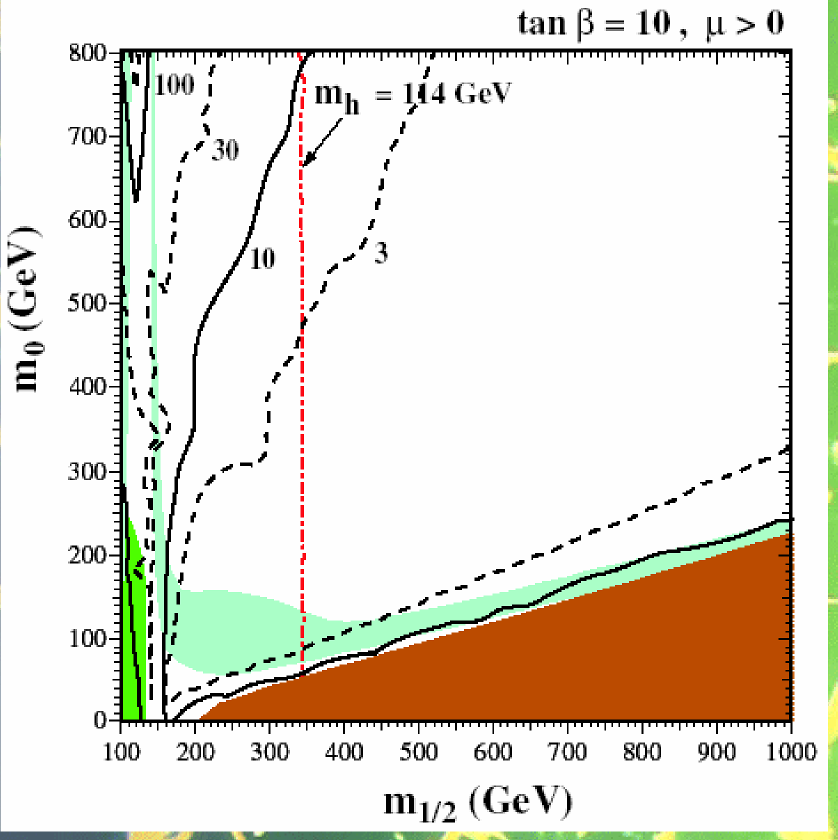


How `Likely' are Large Sparticle Masses?

Fine-tuning of EW scale



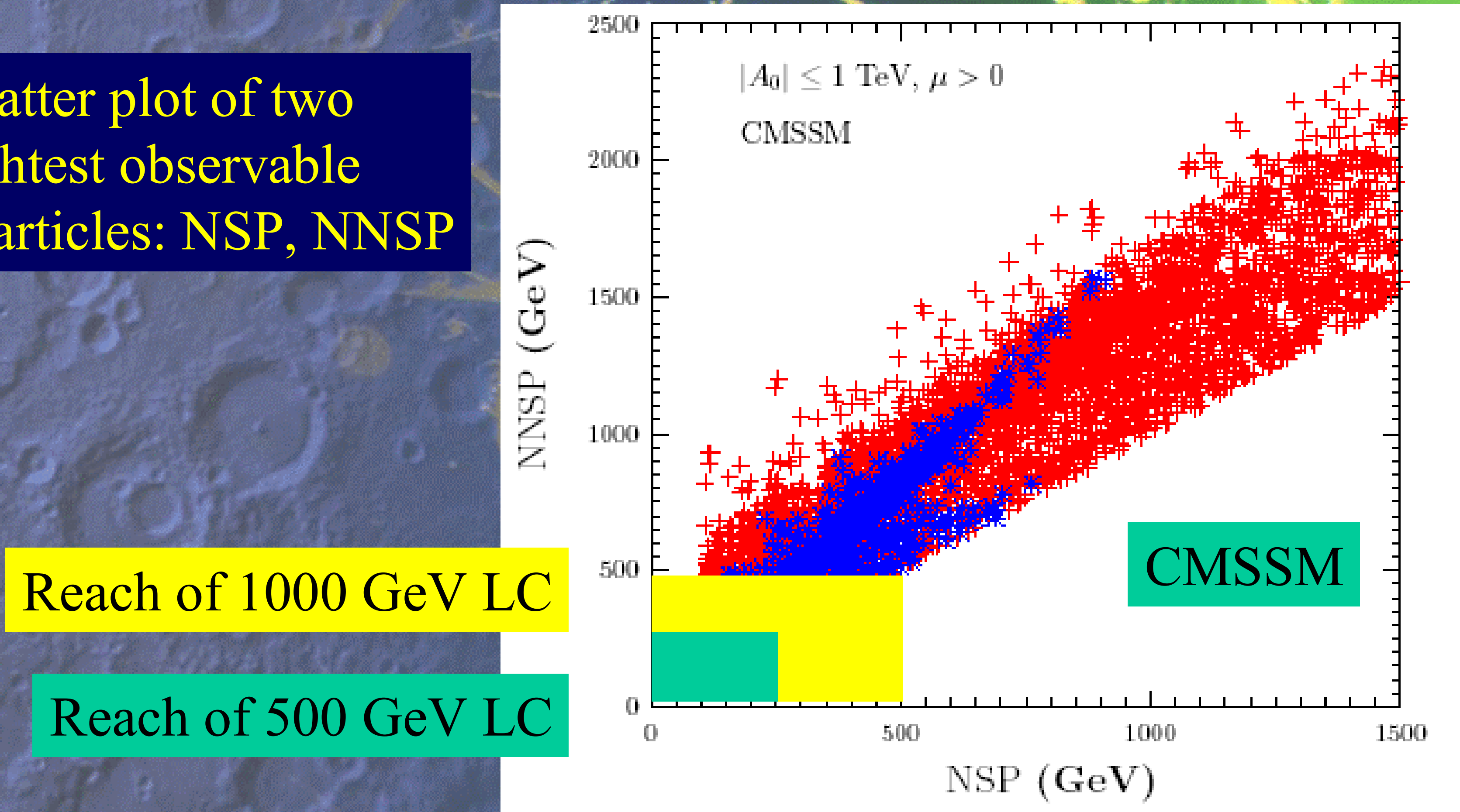
Fine-tuning of relic density



Larger masses require more fine-tuning: but how much is too much?

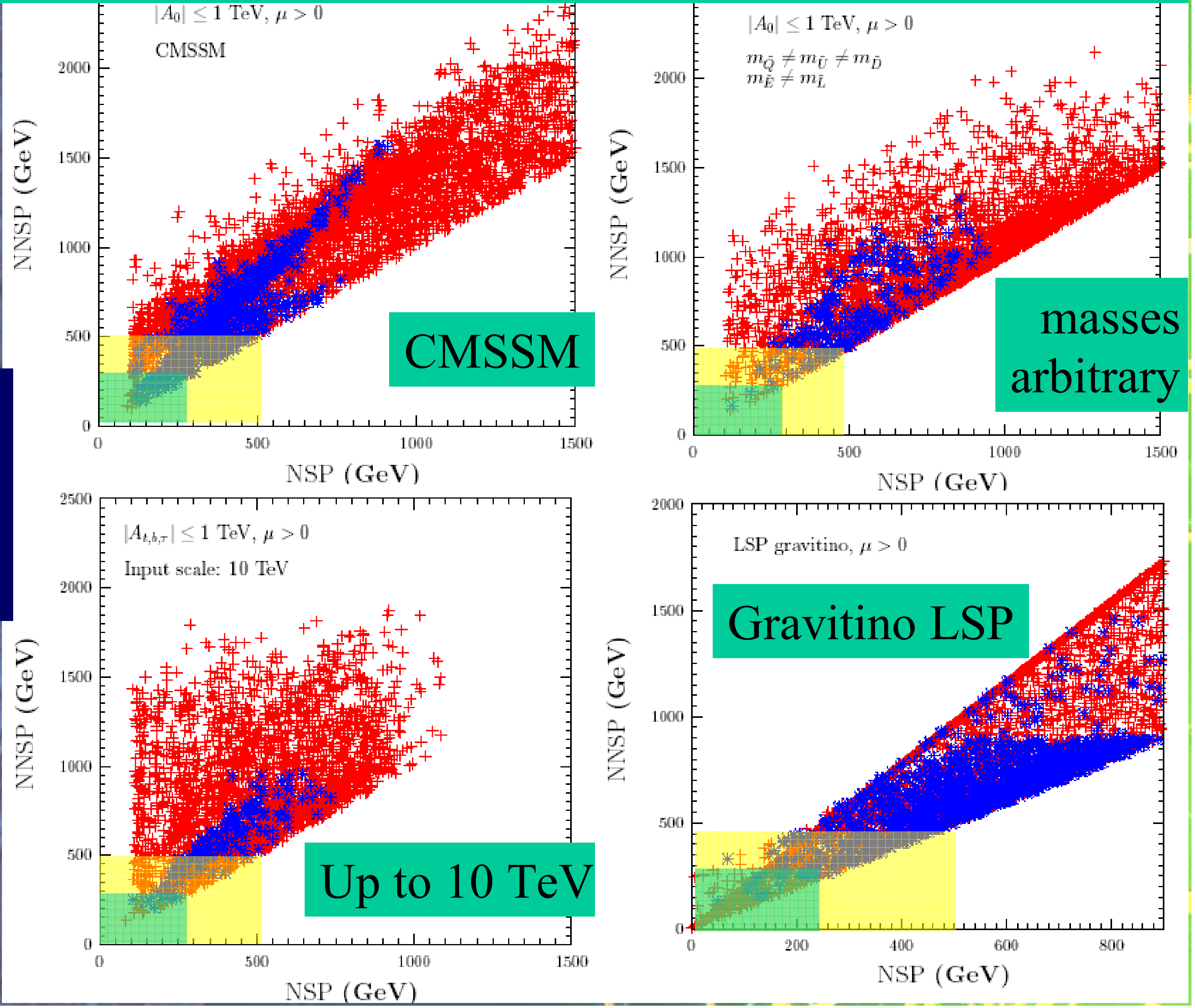
How much of Susy Parameter Space Covered by LC?

Scatter plot of two lightest observable sparticles: NSP, NNSP

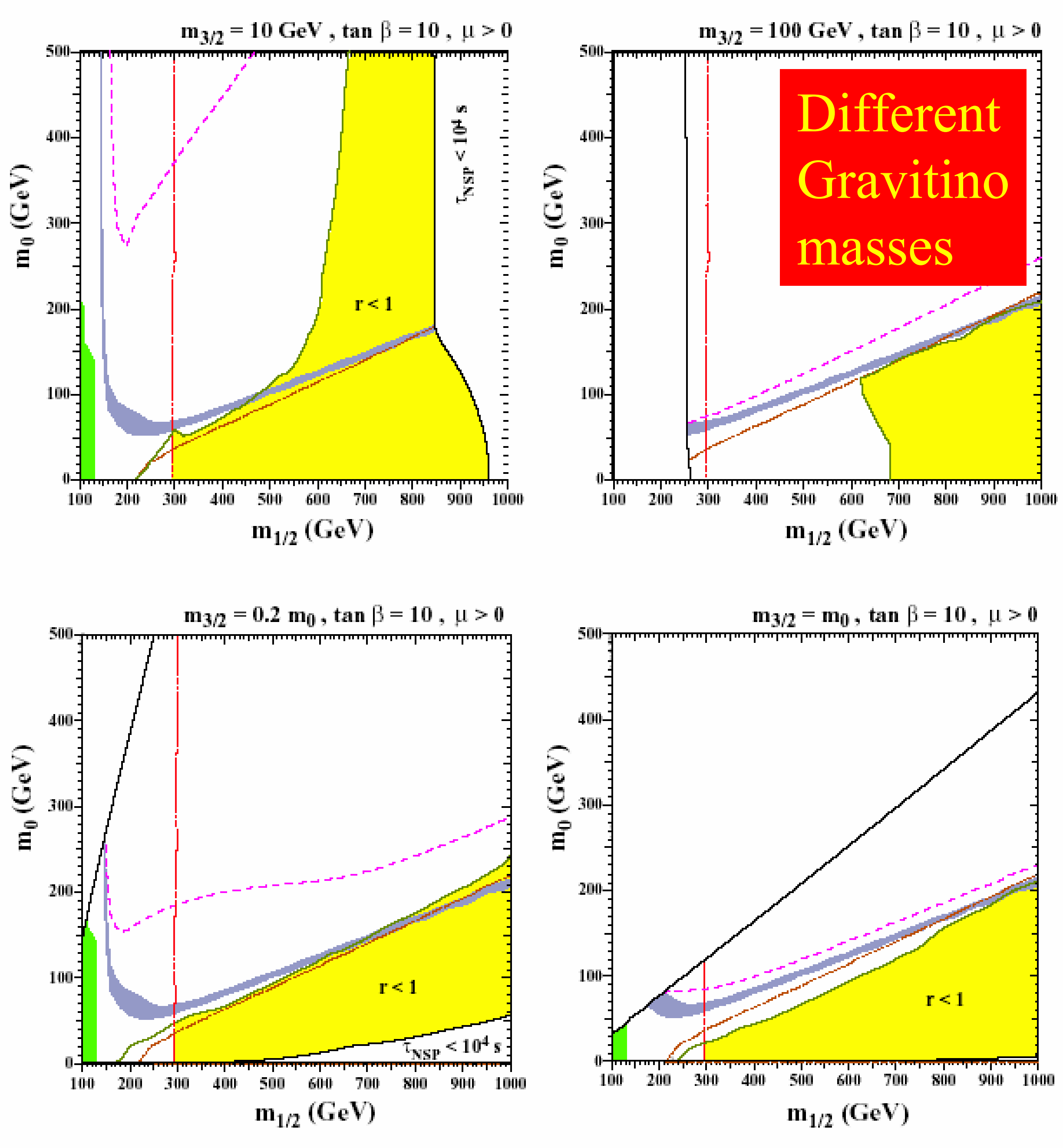


Coverage in Different Supersymmetric Models

500 (1000) GeV LC covers part of space



Different Regions of Sparticle Parameter Space if Gravitino LSP



Density below WMAP limit

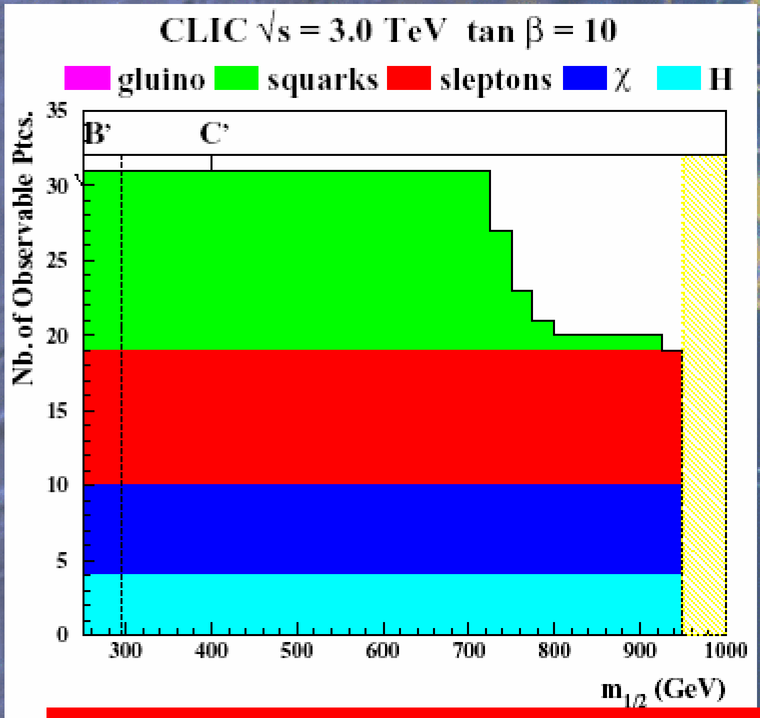
Decays do not affect BBN/CMB agreement

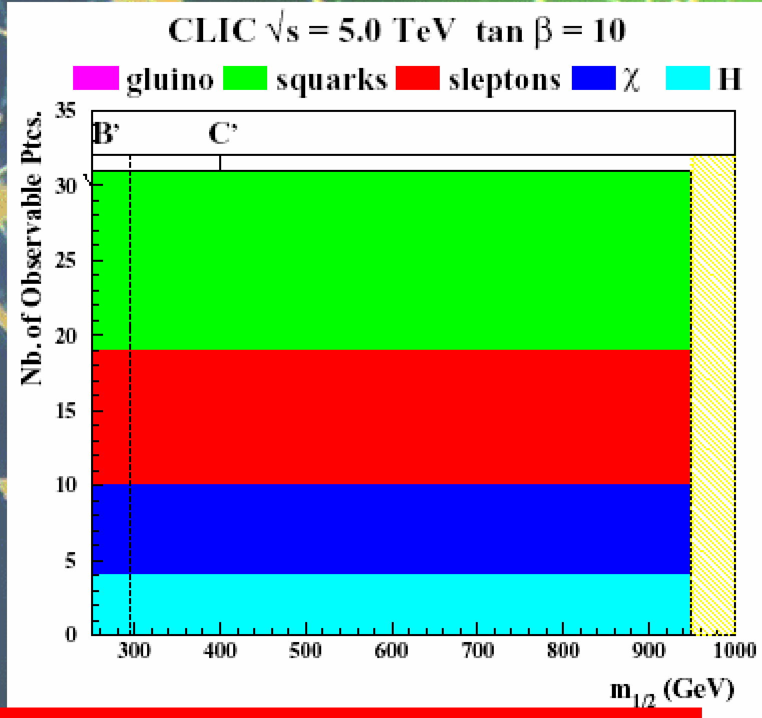
Sparticle Visibility at Higher E

CMSSM

3 TeV

5 TeV

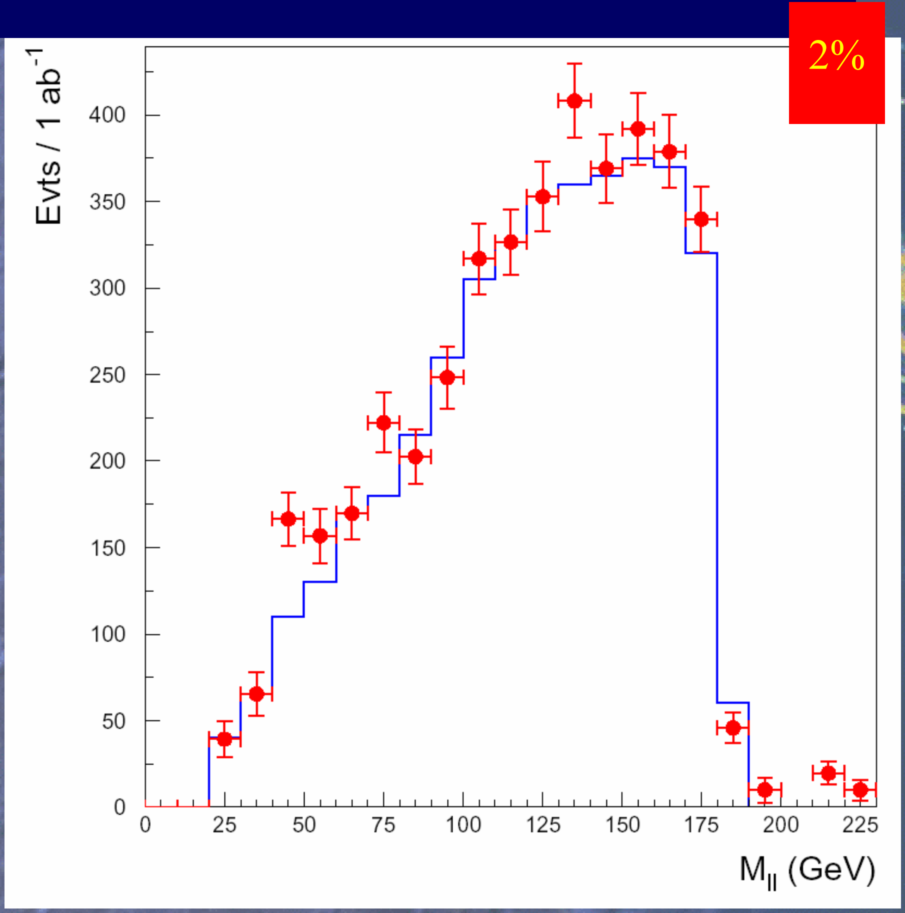




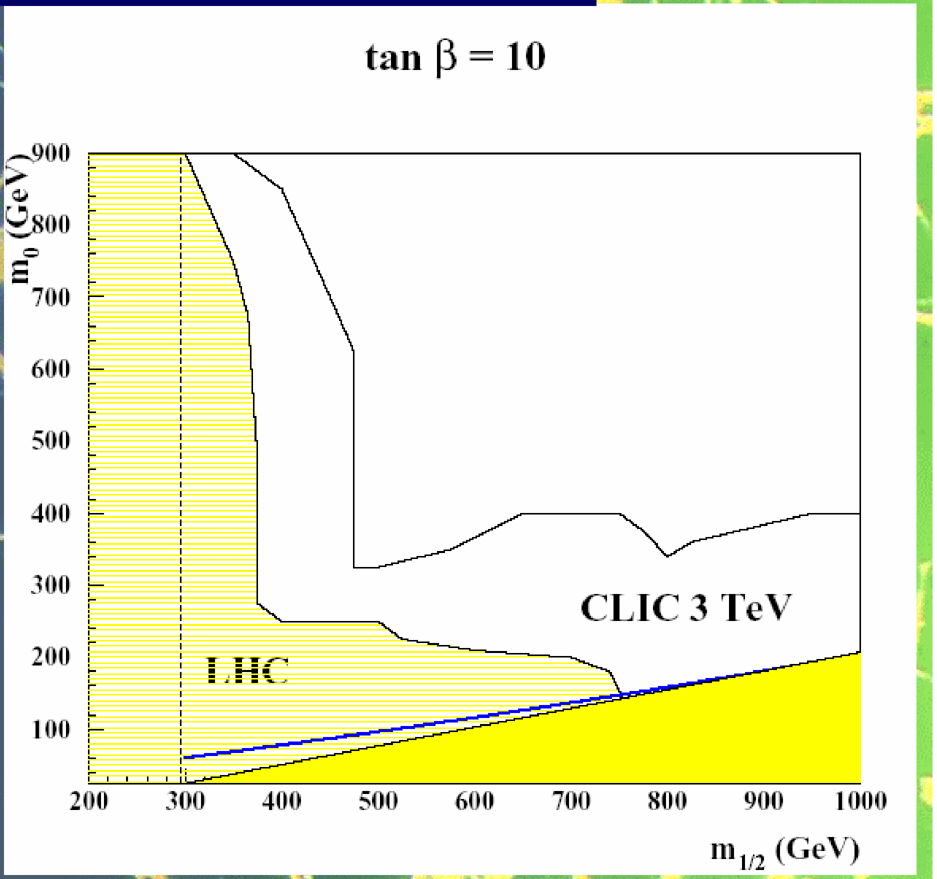
See `all' sparticles: measure heavier ones better than LHC

Example of CLIC Sparticle Search

Dilepton spectrum in neutralino decay

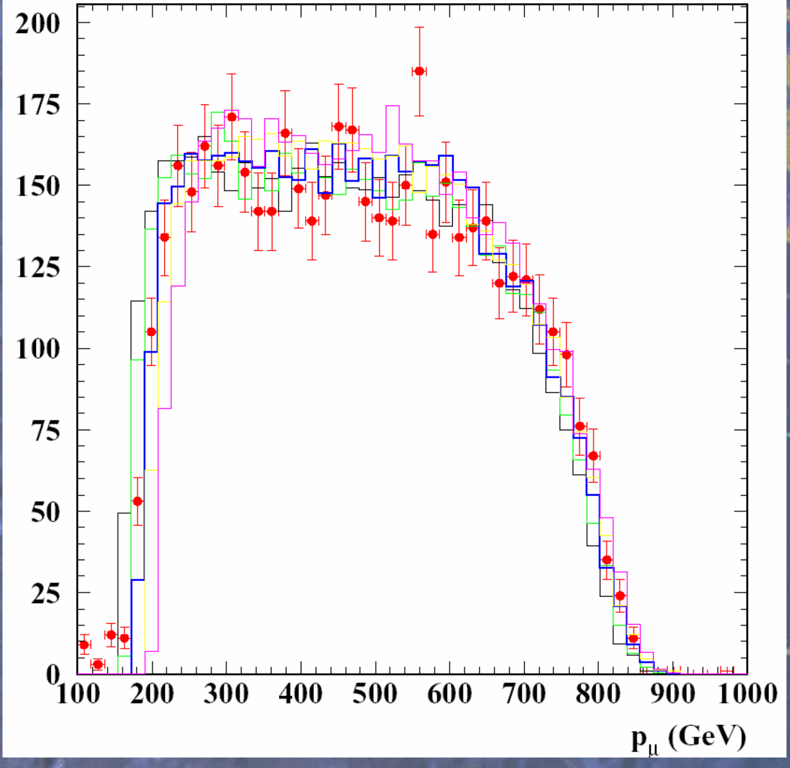


Reach in parameter space



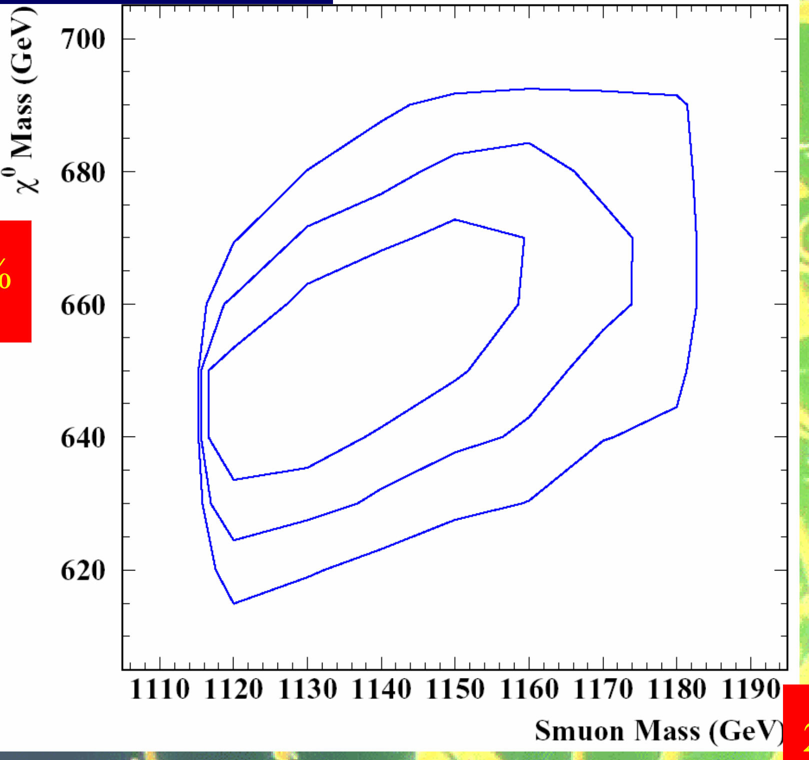
Measure Heavy Sleptons @ CLIC

Can measure smuon decay spectrum



Can measure sparticle masses

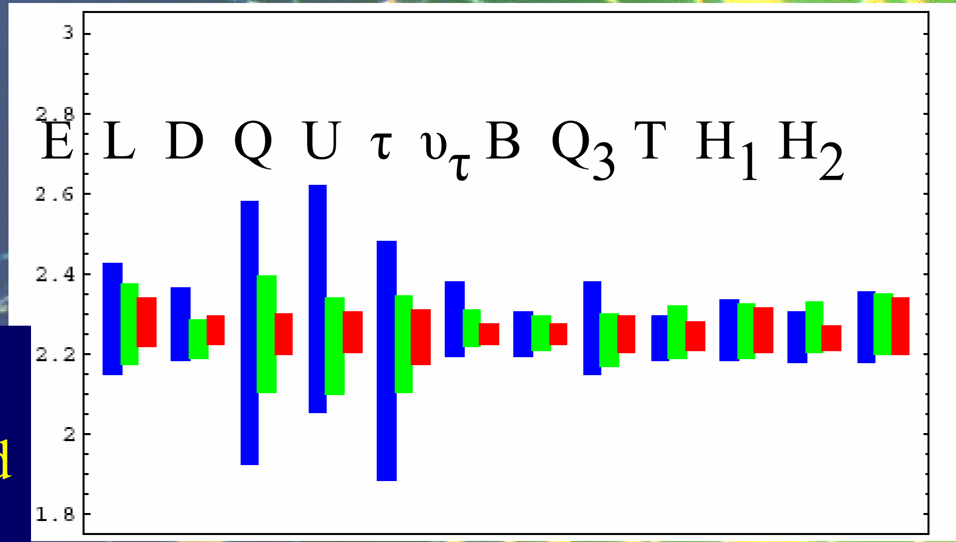
3%



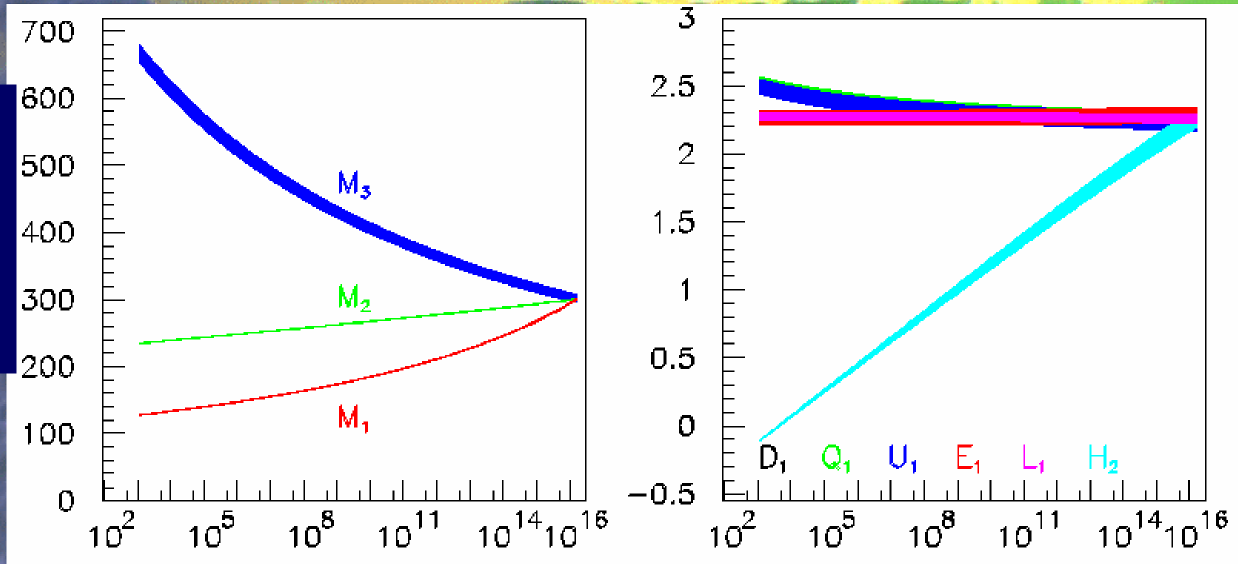
2.5%

Sparticle Mass Unification ?

Accuracy in measuring sparticle masses squared



Can test unification of sparticle masses – probe of string models?



If not supersymmetry, what ?

Extra Dimensions ?

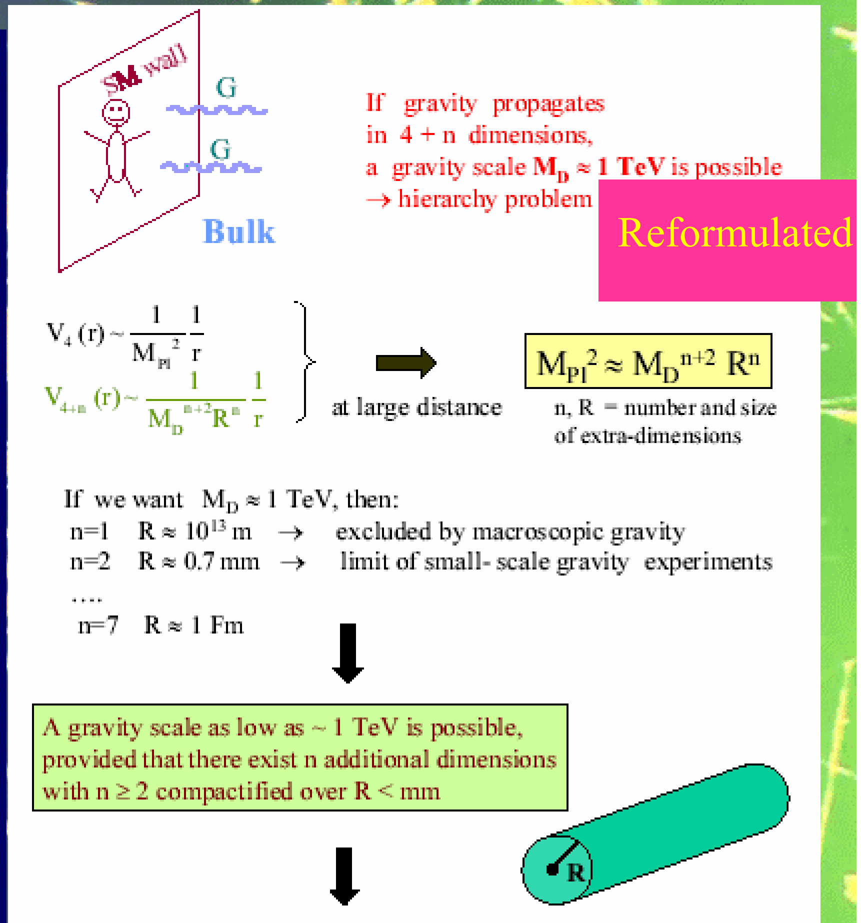
- Suggested by Kaluza and Klein to unify gravity and electromagnetism

- Required for consistency of string theory

- Could help unify strong, weak and electromagnetic forces with gravity if $\gg l_P$

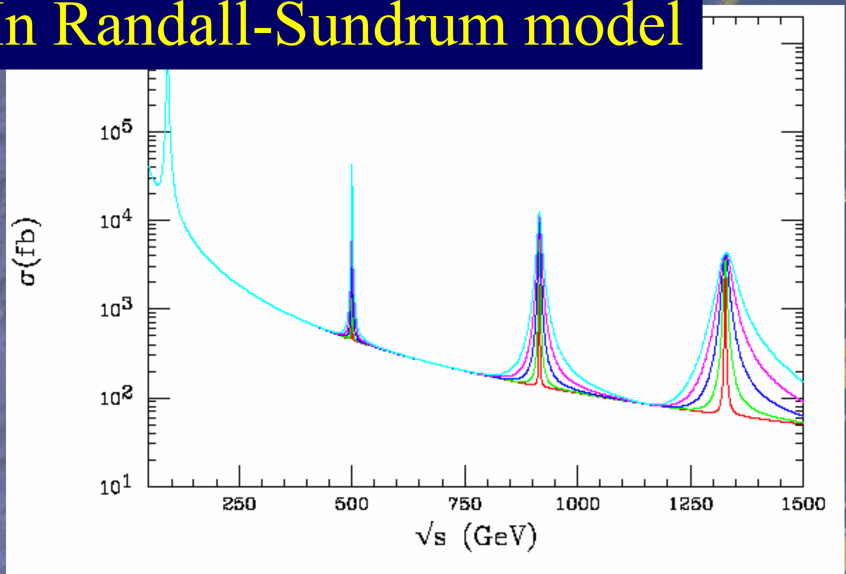
- Could be origin of supersymmetry breaking

- Enable reformulation of the hierarchy problem

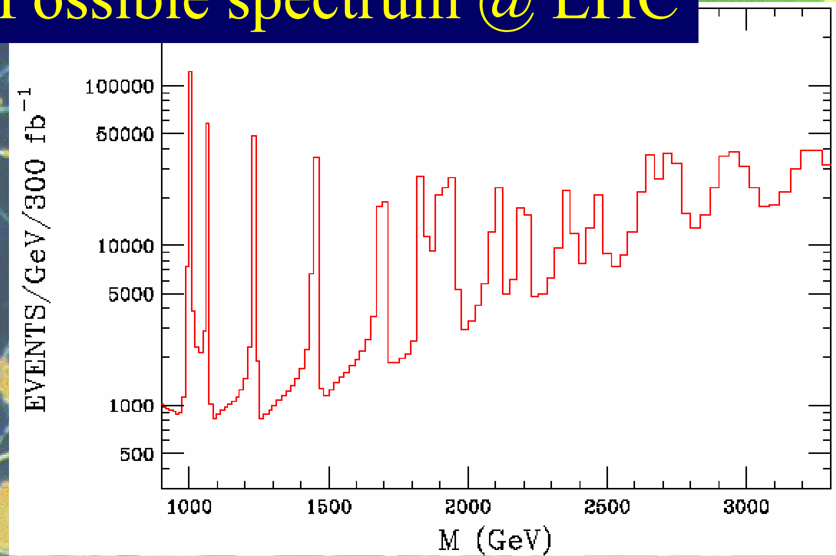


Sequence of KK Resonances?

In Randall-Sundrum model



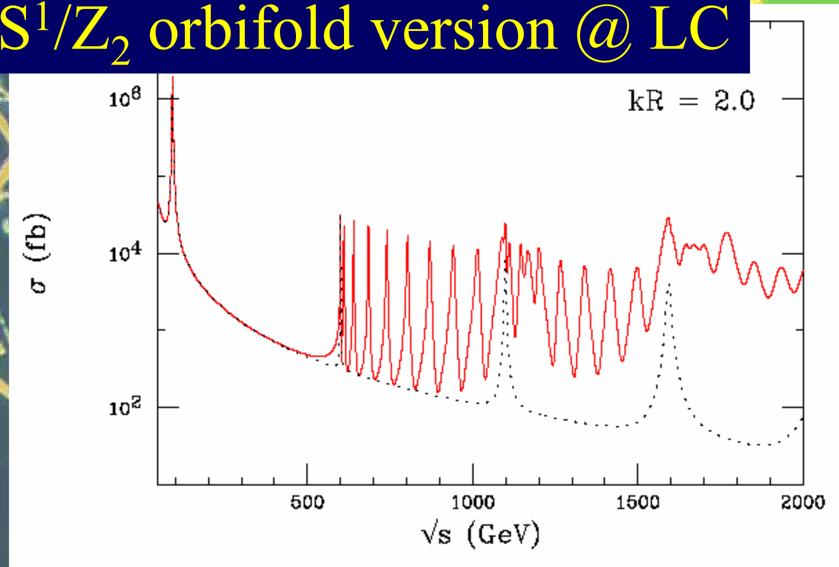
Possible spectrum @ LHC



Sensitivity in contact-interaction regime

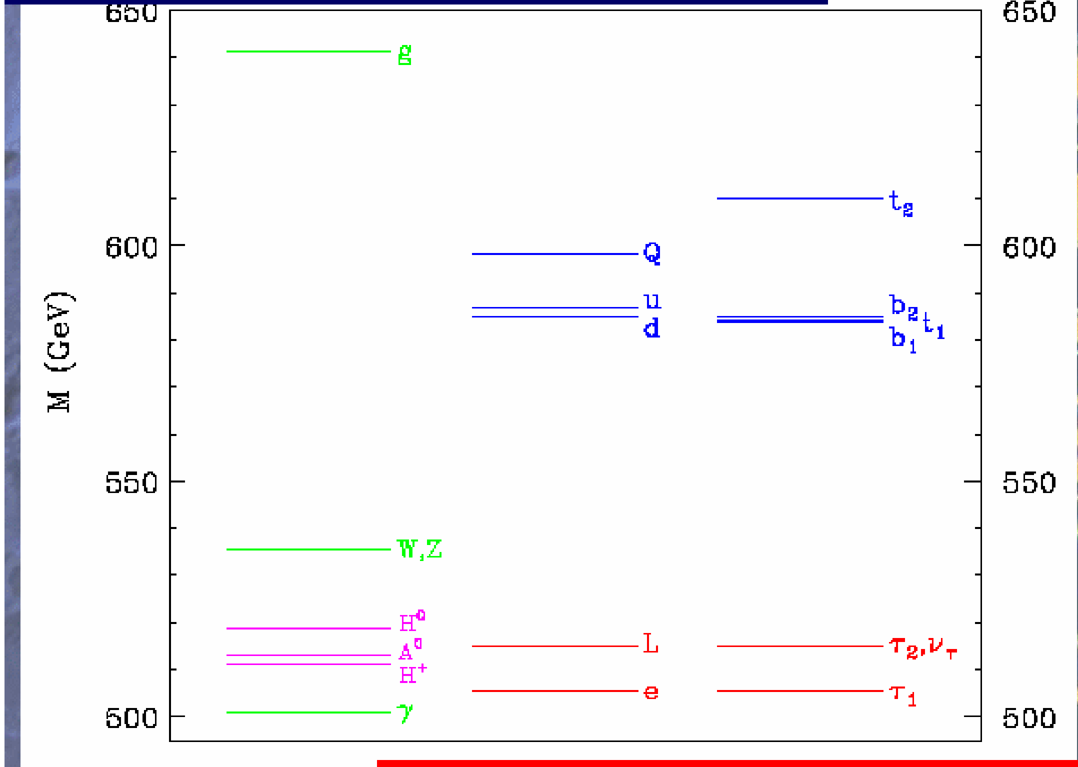
	$k/\overline{M}_{Pl}$		
	0.01	0.1	1.0
LC $\sqrt{s} = 0.5$ TeV	20.0	5.0	1.5
LC $\sqrt{s} = 1.0$ TeV	40.0	10.0	3.0
LHC	20.0	7.0	3.0

S^1/Z_2 orbifold version @ LC

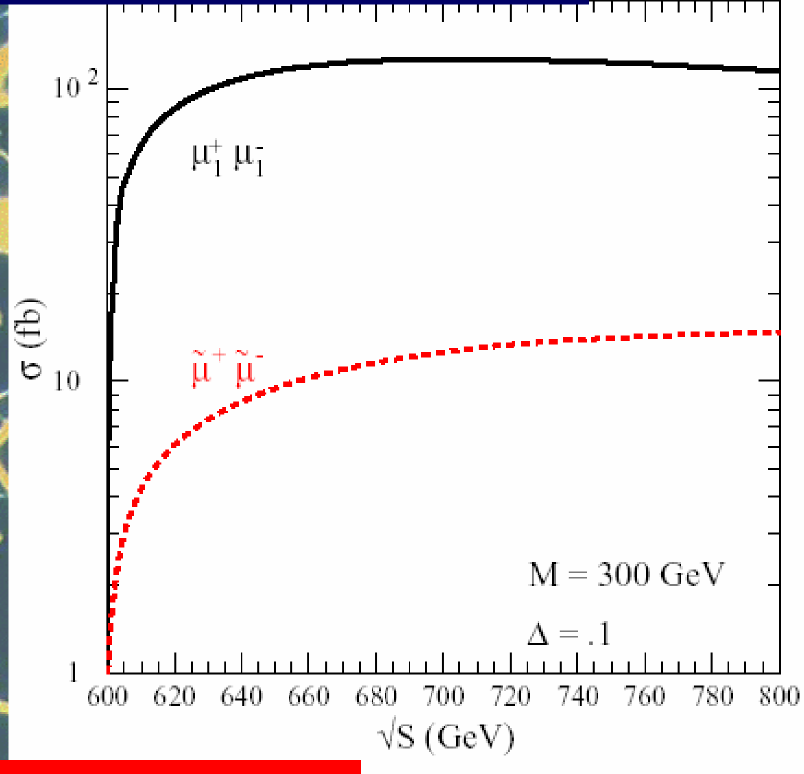


Scenario with Universal Extra D

Spectrum like supersymmetry:
More degenerate



Distinguish from susy
via LC cross sections



Lightest KK particle stable: dark matter?

Physics Reaches Of Various Colliders

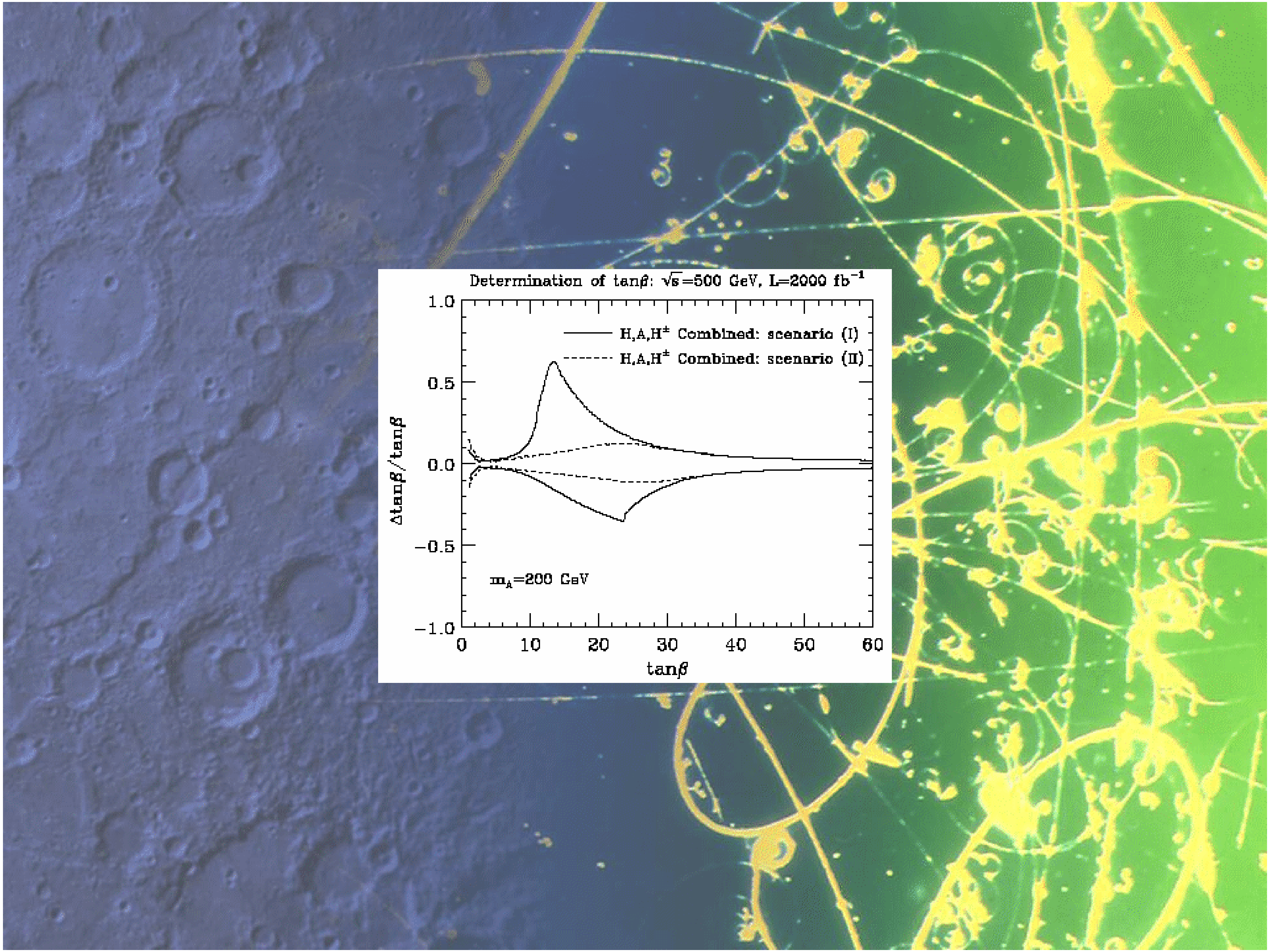
Process	LHC	LC	SLHC	CLIC 3,	5 TeV
Squarks	2.5	0.4	3	1.5	2.5
Sleptons	0.34	0.4		1.5	2.5
New gauge boson Z′	5	8	6	22	28
Excited quark q*	6.5	0.8	7.5	3	5
Excited lepton l*	3.4	0.8		3	5
Two extra space dimensions	9	5–8.5	12	20-35	30–55
Strong $W_L W_L$ scattering	2σ	several σ	4σ	70σ	90σ
Triple-gauge Coupling(TGC) (95%)	.0014	0.0004	0.0006	0.00013	0.00008

LC Provides Many Precision measurements

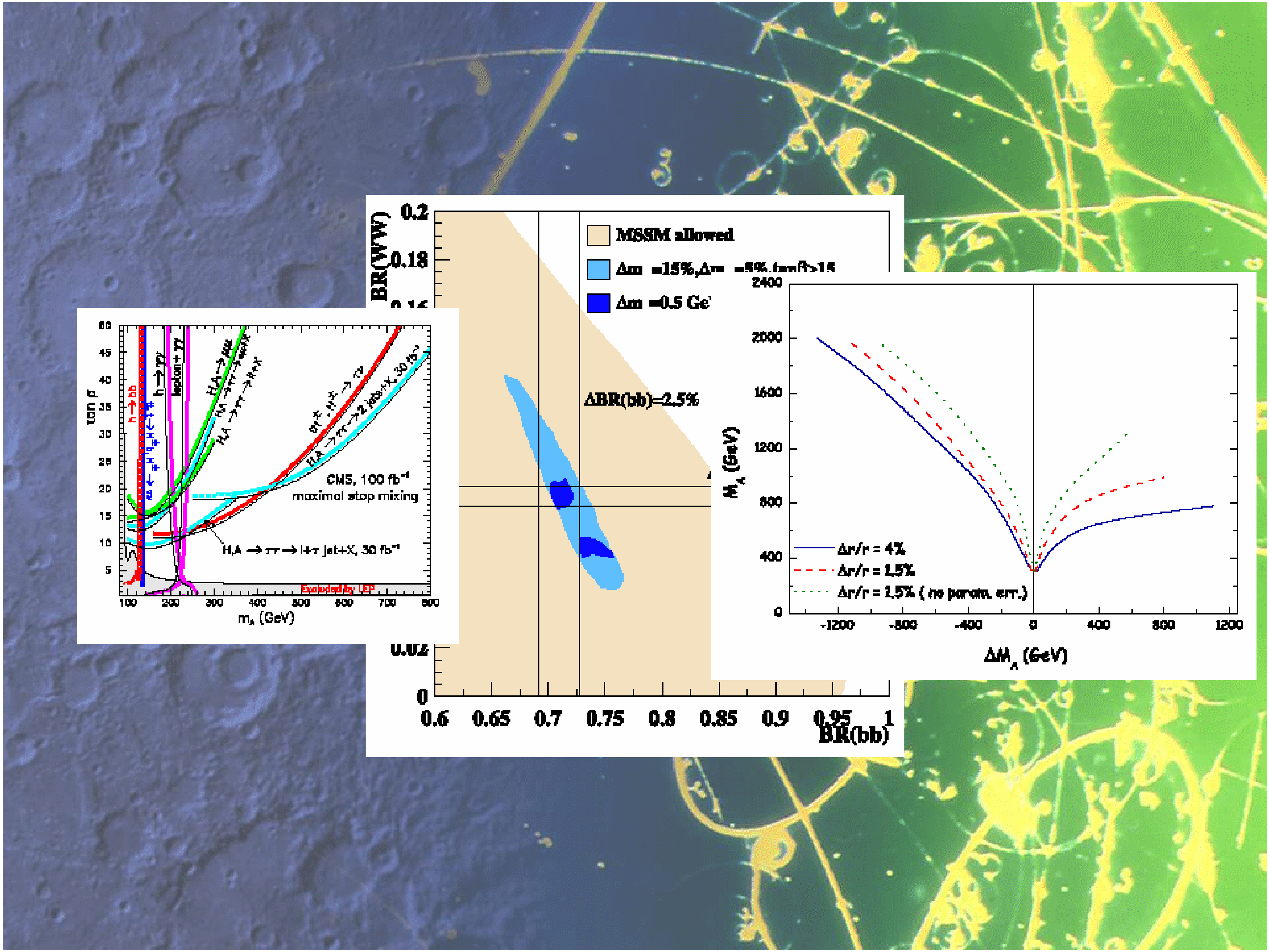
Integrated luminosities used are 100 fb–1 for the LHC, 500 fb–1 for the 800 GeV LC, and 1000 fb–1 for the SLHC and CLIC. Most numbers given are TeV, but for strong WLWL scattering the numbers of standard deviations, and pure numbers for the triple gauge coupling (TGC).

Summary

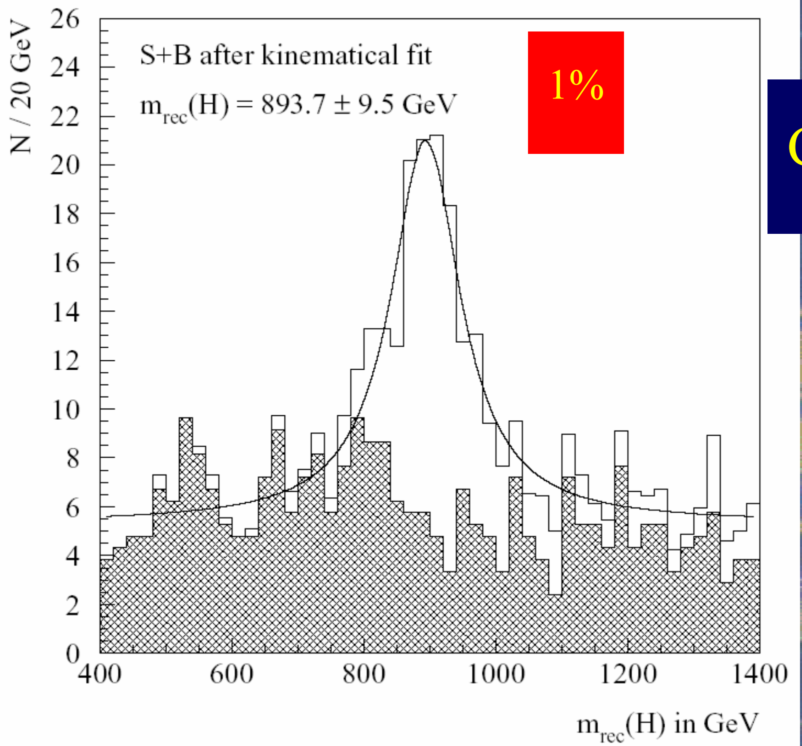
- There are (still) good reasons to expect new physics in the TeV range
- We shall not know what and where before the LHC starts providing results
- Any LC above a threshold for new physics will provide tremendous added value
- **Energy flexibility is desirable**



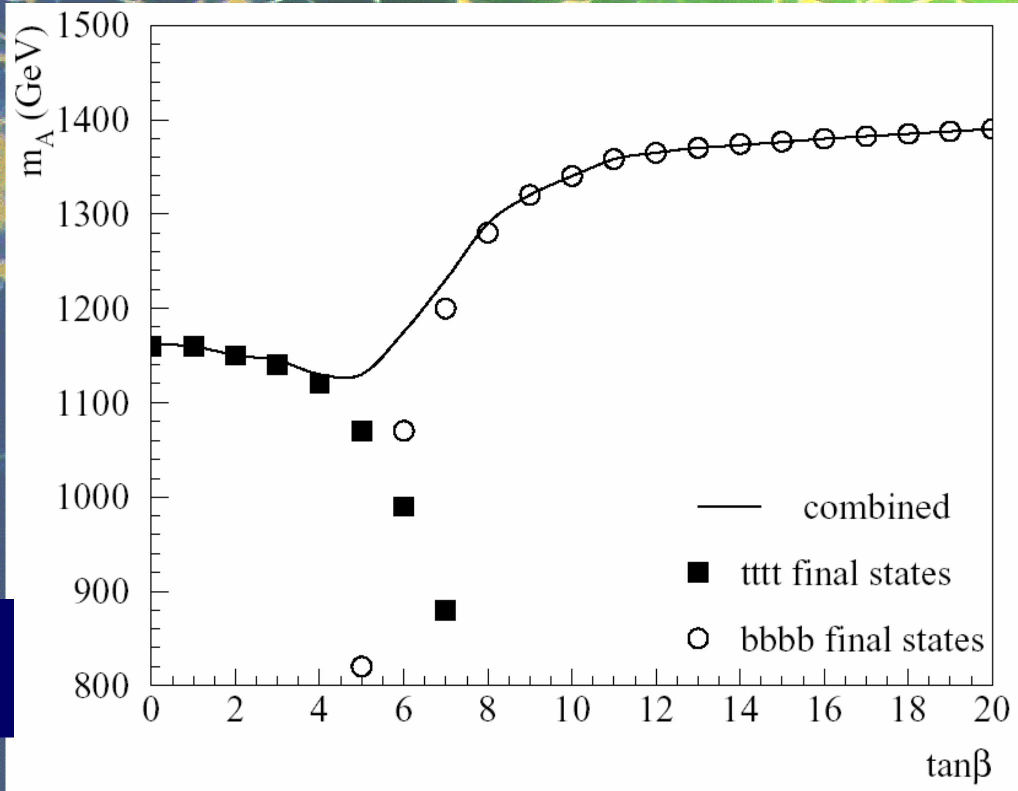
Determination of tanβ: √s=500 GeV, L=2000 fb^-1
H,A,H± Combined: scenario (I)
H,A,H± Combined: scenario (II)
m_A=200 GeV
Δtanβ/tanβ
tanβ
1.0
0.5
0.0
−0.5
−1.0
0
10
20
30
40
50
60


MSSM allowed
ΔBR(bb)=2.5%
BR(WW)
BR(bb)
CMS, 100 fb⁻¹
maximal stop mixing
H,A → ττ → l+τ jet+X, 30 fb⁻¹
Excluded by LEP
tan β
m_A (GeV)
M_A (GeV)
ΔM_A (GeV)
Δr/r = 4%
Δr/r = 1.5%
Δr/r = 1.5% (no param. err.)

Identify Heavier Partner Higgses



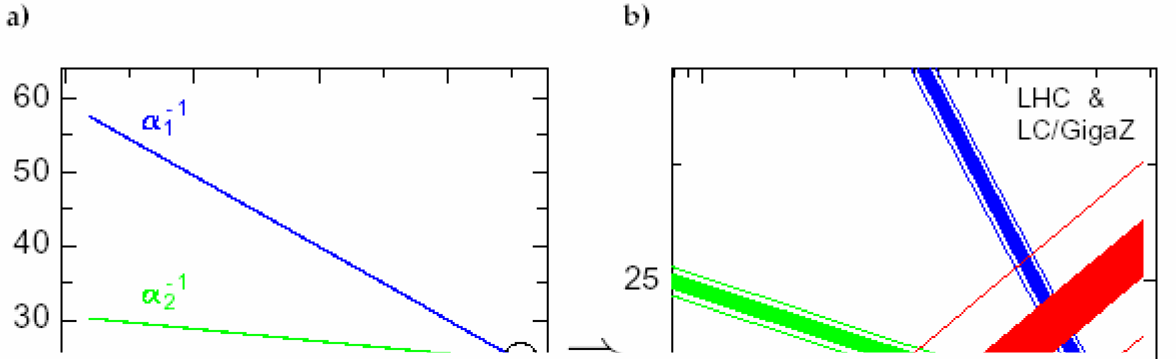
Charged …

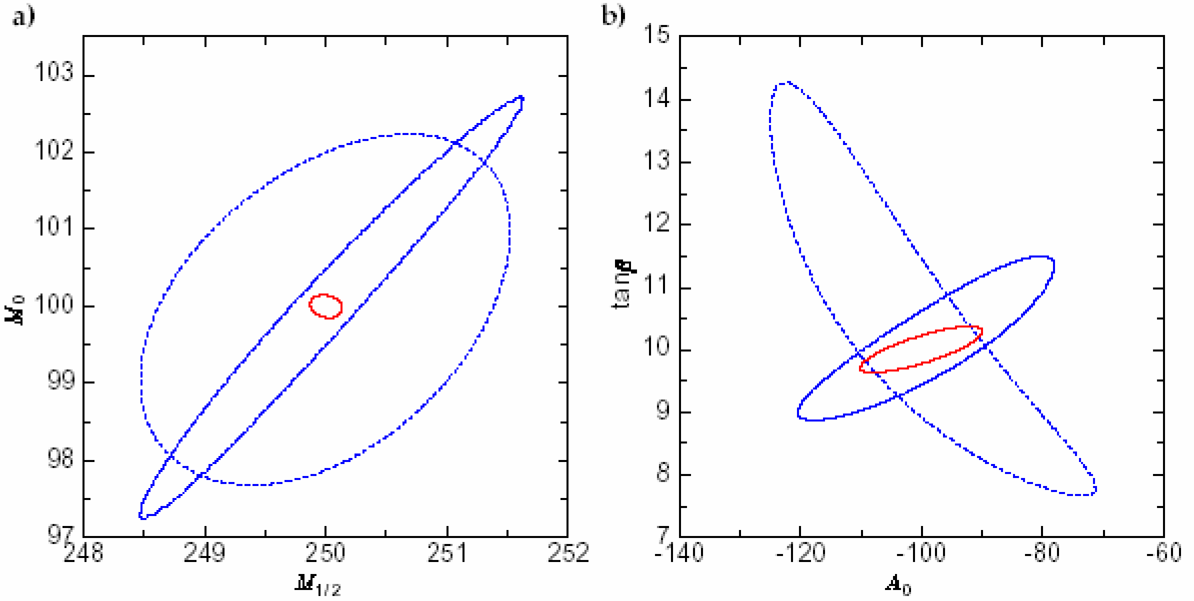


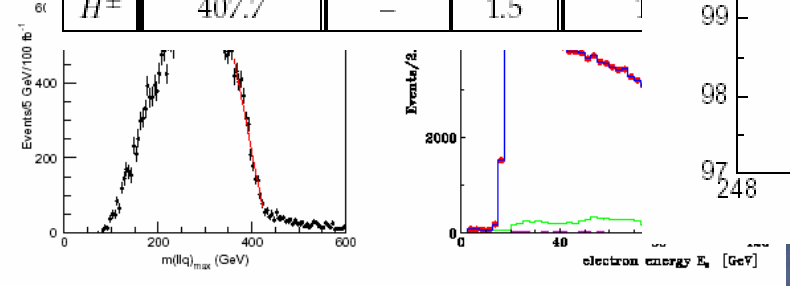
… or neutral

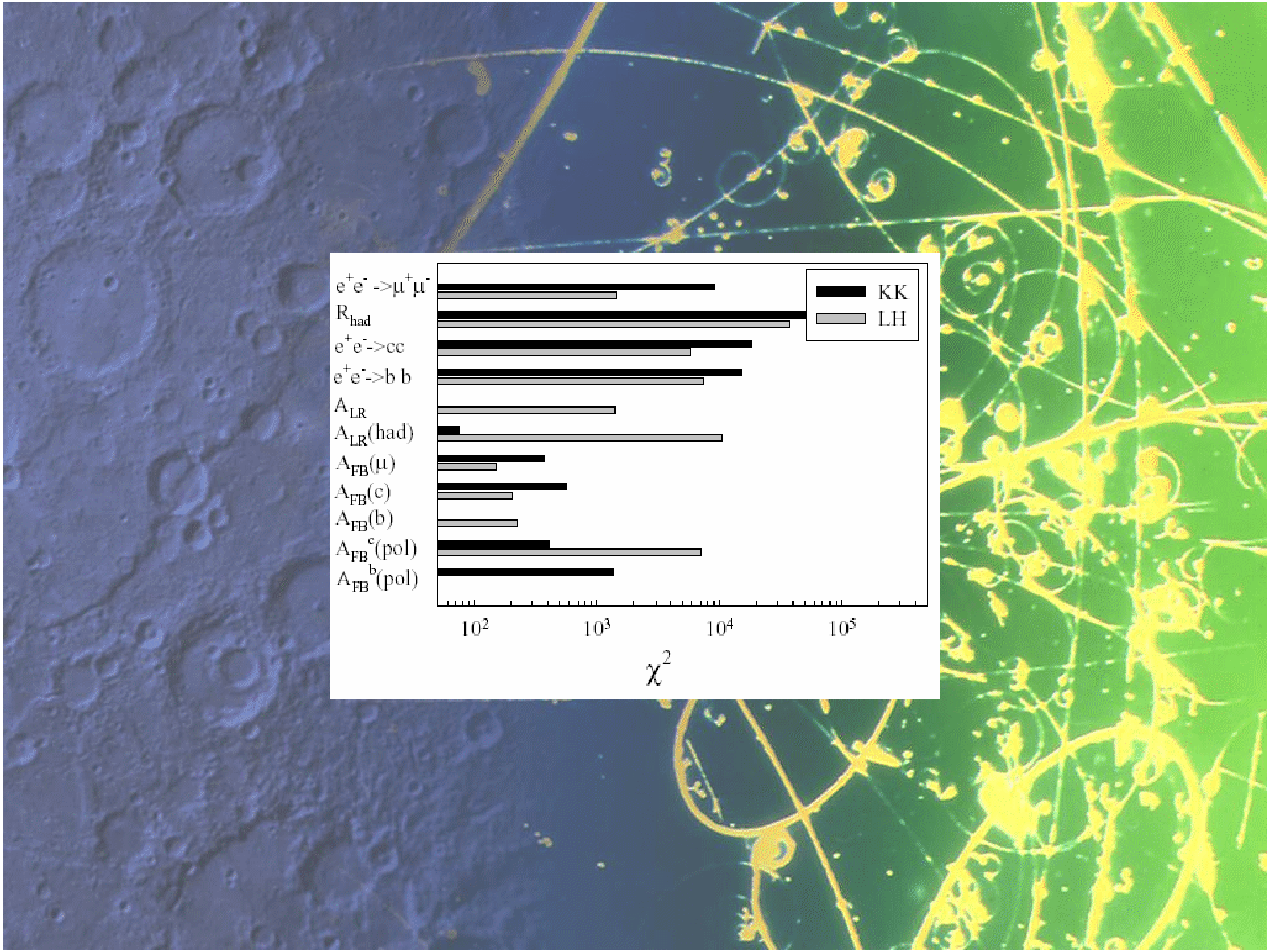
	Mass, ideal	"LHC"	"LC"	"LHC+
$\tilde{\chi}_1^{\pm}$	179.7		0.55	0.55
$\tilde{\chi}_2^{\pm}$	382.3	–	3.0	3.0
$\tilde{\chi}_1^0$	97.2	4.8	0.05	0.05
$\tilde{\chi}_2^0$	180.7	4.7	1.2	0.08
$\tilde{\chi}_3^0$	364.7		3-5	3-5
$\tilde{\chi}_4^0$	381.9	5.1	3-5	2.23
$\tilde{e}_R$	143.9	4.8	0.05	0.05
$\tilde{e}_L$	207.1	5.0	0.2	0.2
$\tilde{\nu}_e$	191.3	–	1.2	1.2
$\tilde{\mu}_R$	143.9	4.8	0.2	0.2
$\tilde{\mu}_L$	207.1	5.0	0.5	0.5
$\tilde{\nu}_\mu$	191.3	–		
$\tilde{\tau}_1$	134.8	5-8	0.3	0.3
$\tilde{\tau}_2$	210.7	–	1.1	1.1
$\tilde{\nu}_\tau$	190.4	–	–	–
$\tilde{q}_R$	547.6	7-12	–	5-11
$\tilde{q}_L$	570.6	8.7	–	4
$\tilde{t}_1$	399.5		2.0	2
$\tilde{t}_2$	586.3		–	
$\tilde{b}_1$	515.1	7.5	–	5
$\tilde{b}_2$	547.1	7.9	–	6
$\tilde{g}$	604.0	8.0	–	6
h^0	110.8	0.25	0.05	0
H^0	399.8		1.5	1
A^0	399.4		1.5	1
$H^{\pm}$	407.7	–	1.5	1

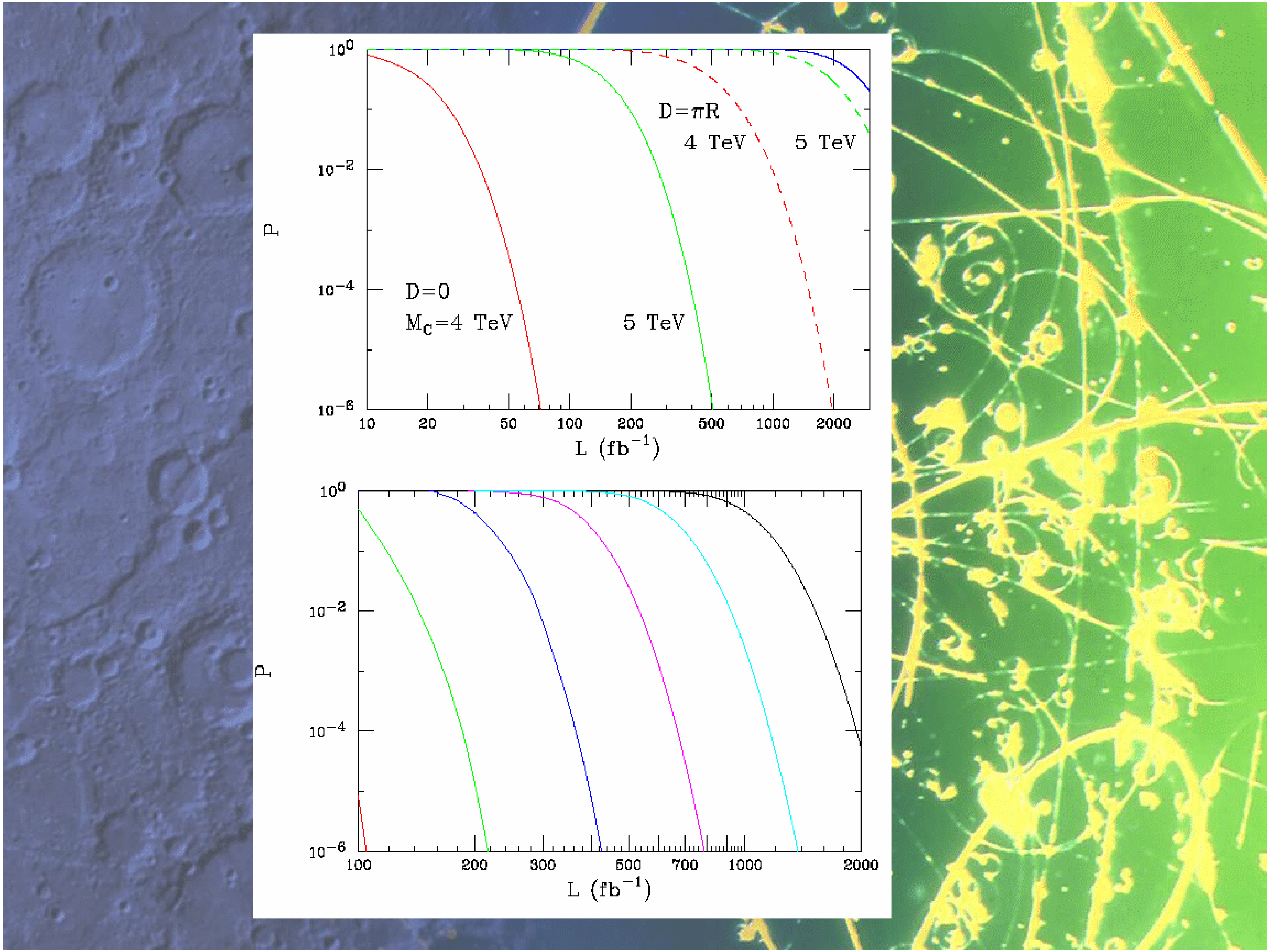
	"LHC"	"LC"	"LHC+LC"
$M_{1/2}$	250.0 ± 2.1	250.0 ± 0.4	250.0 ± 0.2
M_0	100.0 ± 2.8	100.0 ± 0.2	100.0 ± 0.2
A_0	-100.0 ± 34	-100.0 ± 27	-100.0 ± 14
$\tan\beta$	10.0 ± 1.8	10.0 ± 0.6	10.0 ± 0.4

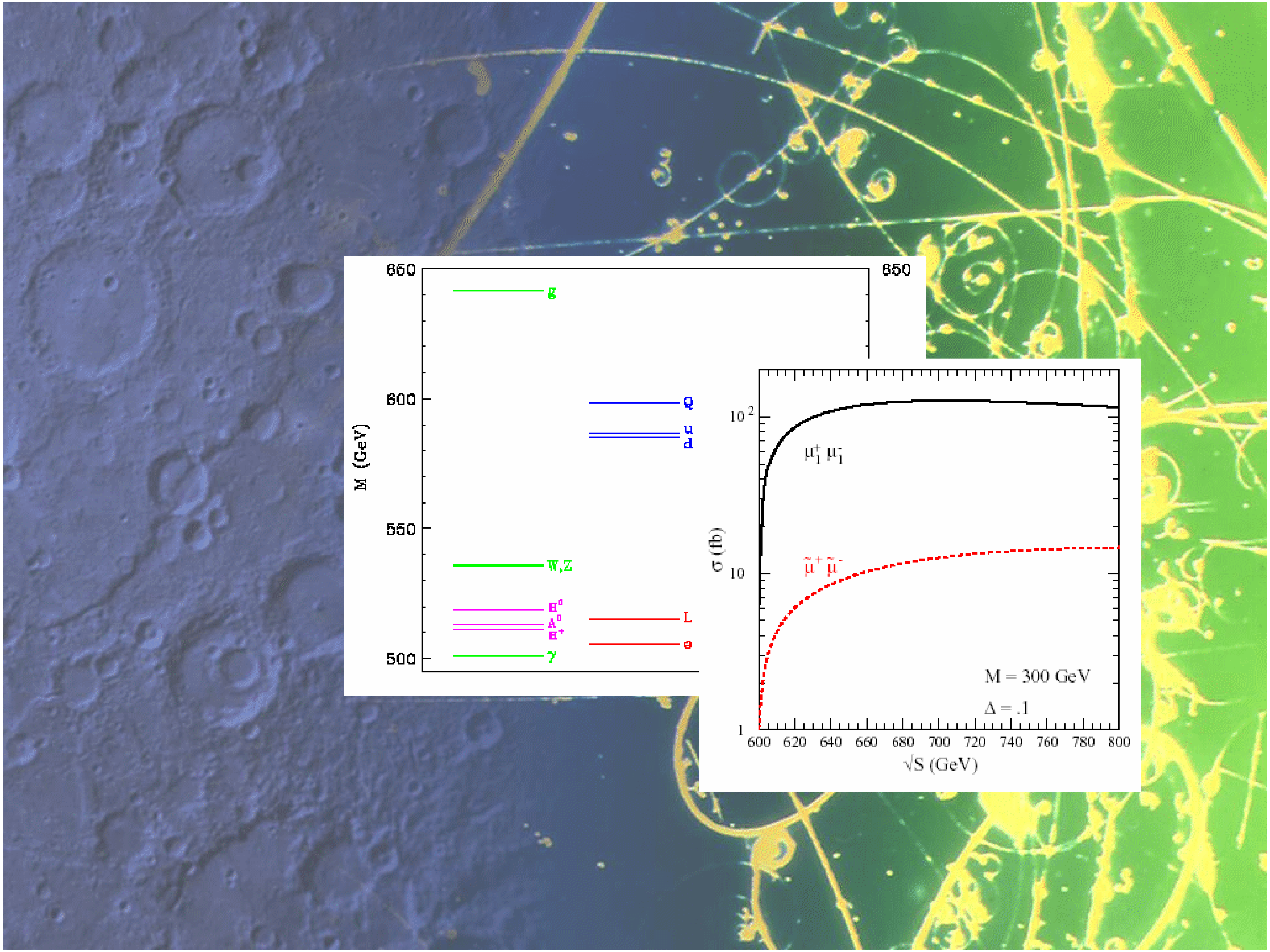







$e^+e^- \to \mu^+\mu^-$
R_{had}
$e^+e^- \to cc$
$e^+e^- \to b\,b$
A_{LR}
A_{LR}(had)
$A_{FB}(\mu)$
A_{FB}(c)
A_{FB}(b)
A_{FB}^{c}(pol)
A_{FB}^{b}(pol)
KK
LH
10^2
10^3
10^4
10^5
χ^2

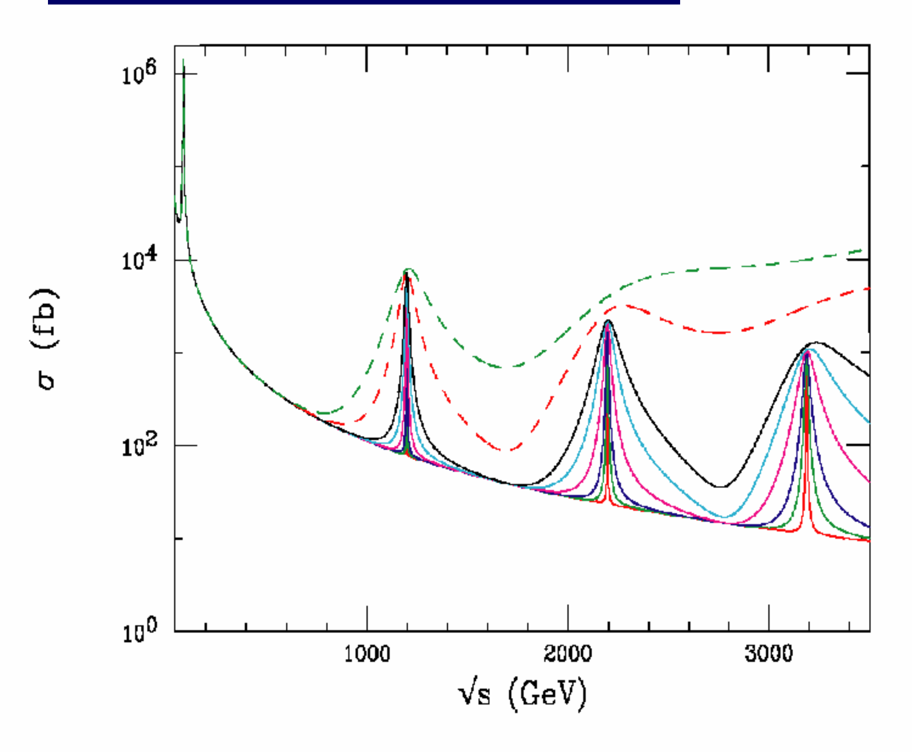

D=πR
4 TeV
5 TeV
D=0
M_c=4 TeV
5 TeV
P
L (fb^-1)
P
L (fb^-1)



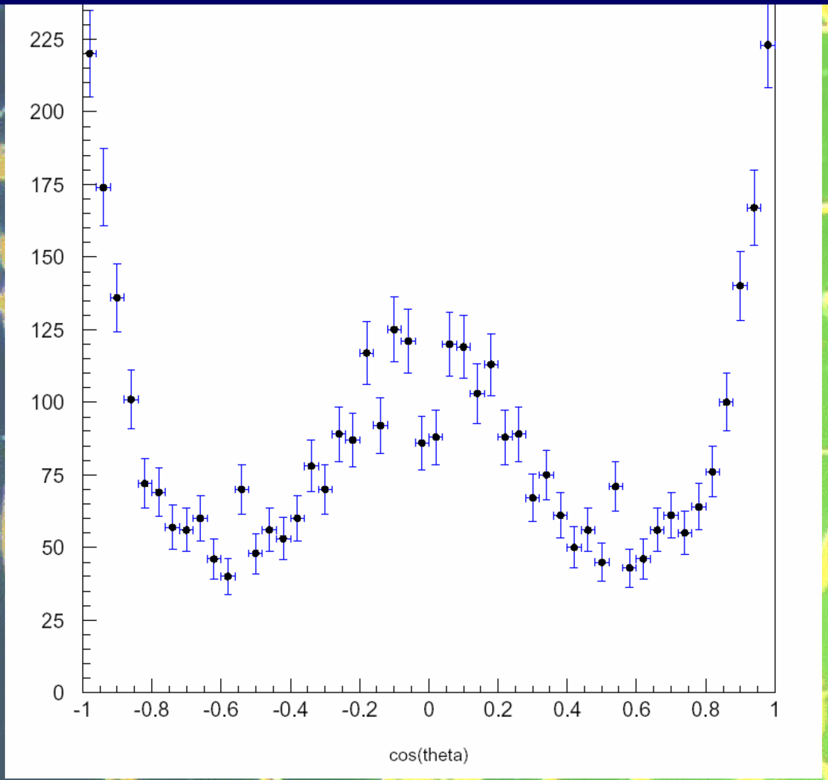
650
600
550
500
M (GeV)
g
W,Z
H0
A0
H+
γ
Q
u
d
L
e
650
10 2
10
1
σ (fb)
μ1+ μ1-
μ̃+ μ̃-
M = 300 GeV
Δ = .1
600 620 640 660 680 700 720 740 760 780 800
√S (GeV)

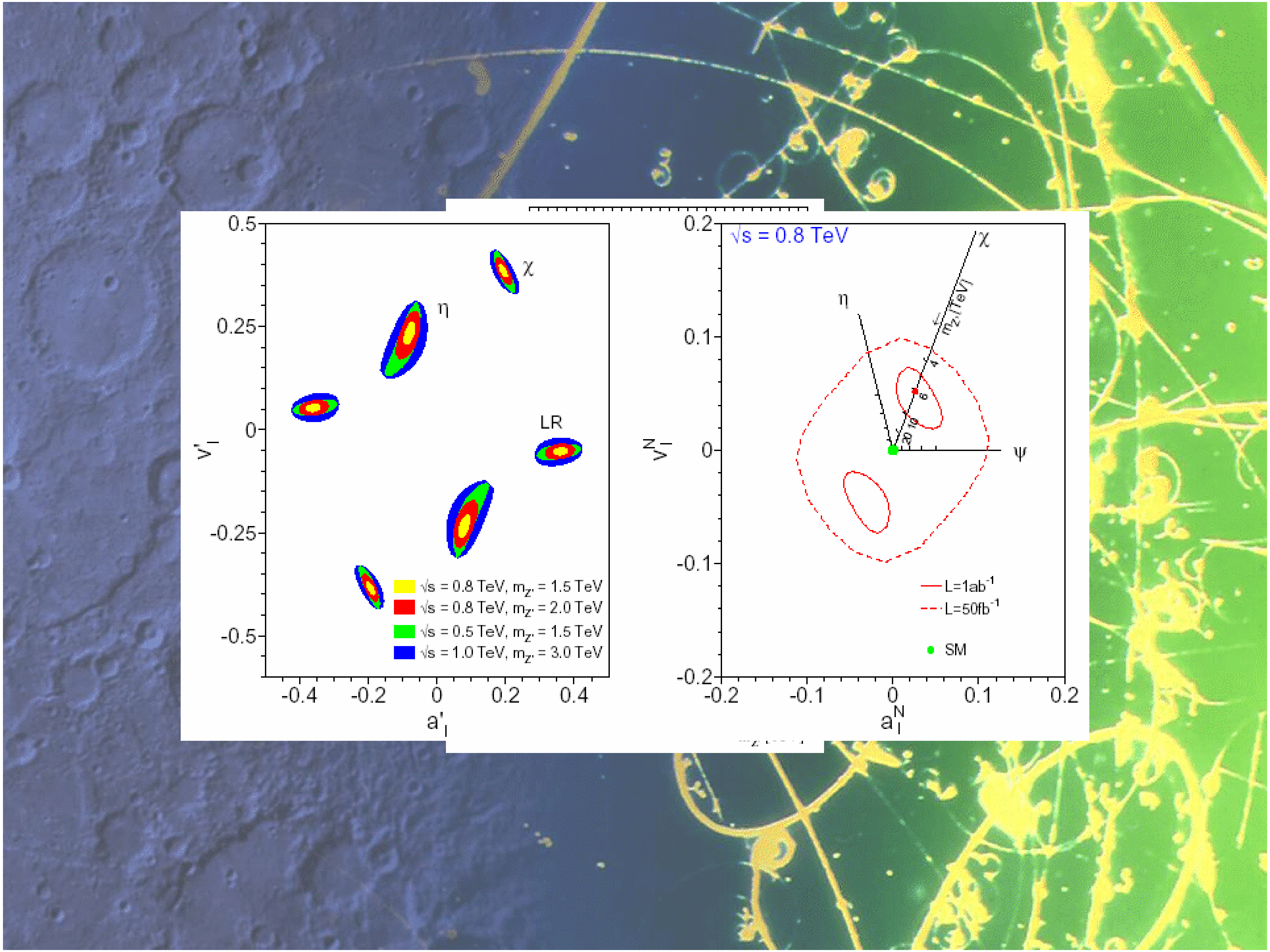
CLIC could measure Kaluza-Klein excitations

Direct-channel resonances



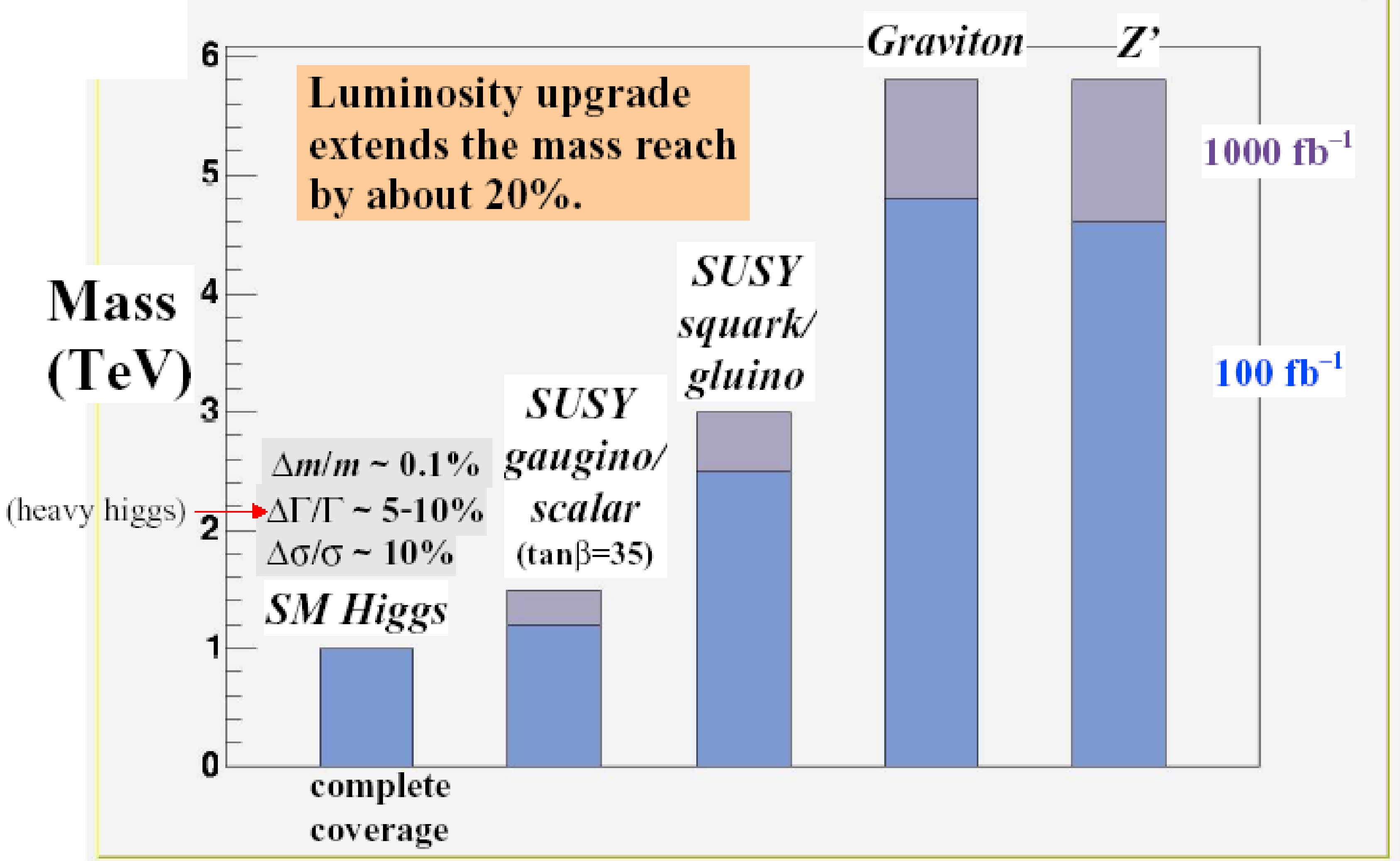
Angular distribution in graviton decay





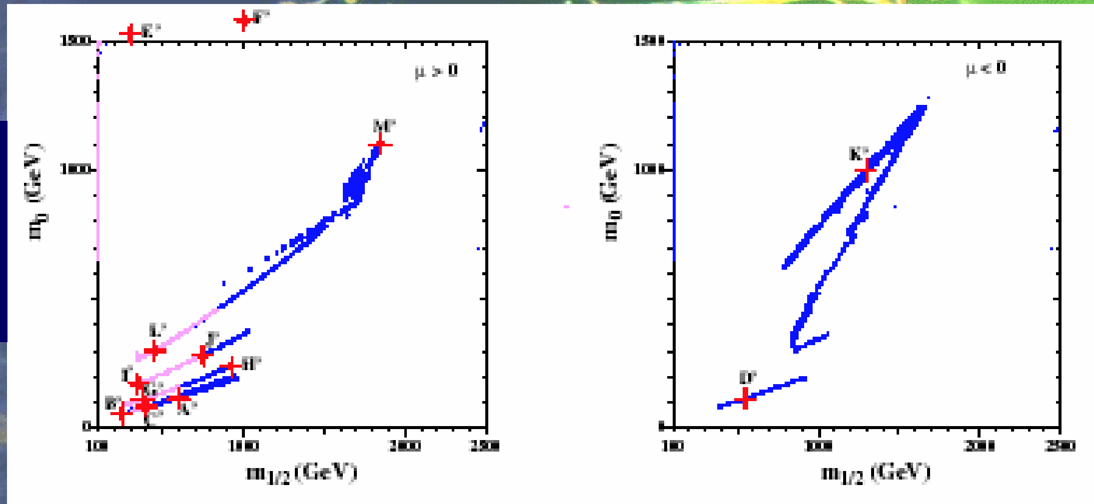
χ
η
LR
√s = 0.8 TeV, m_Z' = 1.5 TeV
√s = 0.8 TeV, m_Z' = 2.0 TeV
√s = 0.5 TeV, m_Z' = 1.5 TeV
√s = 1.0 TeV, m_Z' = 3.0 TeV
v'_l
a'_l
√s = 0.8 TeV
ψ
m_Z' [TeV]
L=1ab^-1
L=50fb^-1
SM
v_l^N
a_l^N

The Reach of the LHC for New High-Mass Physics

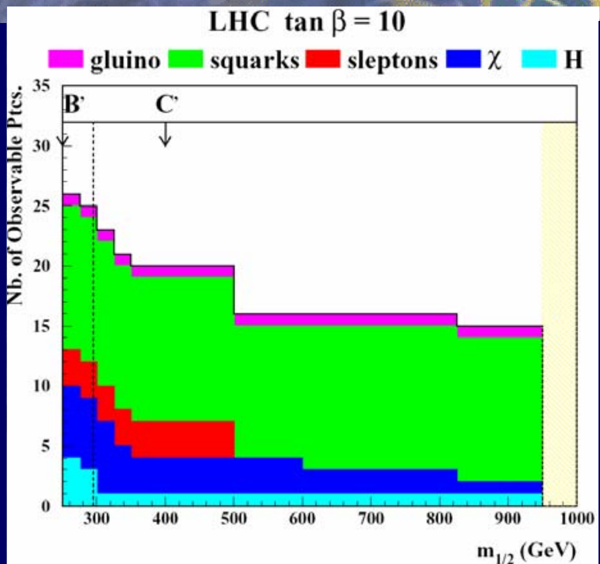


Exploring the Supersymmetric Parameter Space

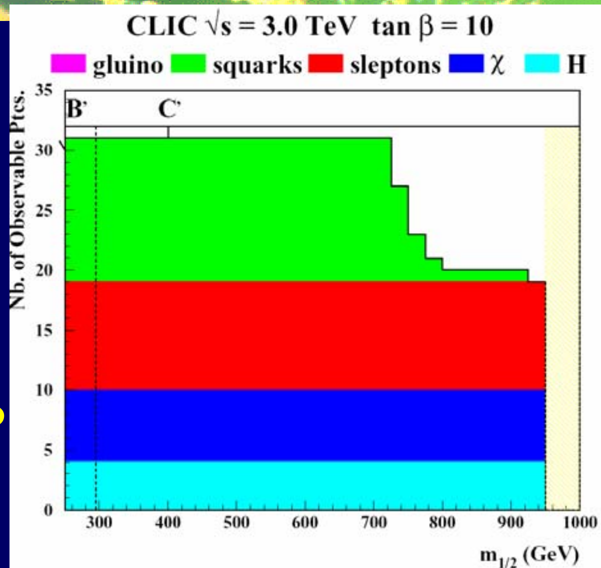
Strips allowed by WMAP and other constraints



Numbers of sparticle species detected at LHC along WMAP strip

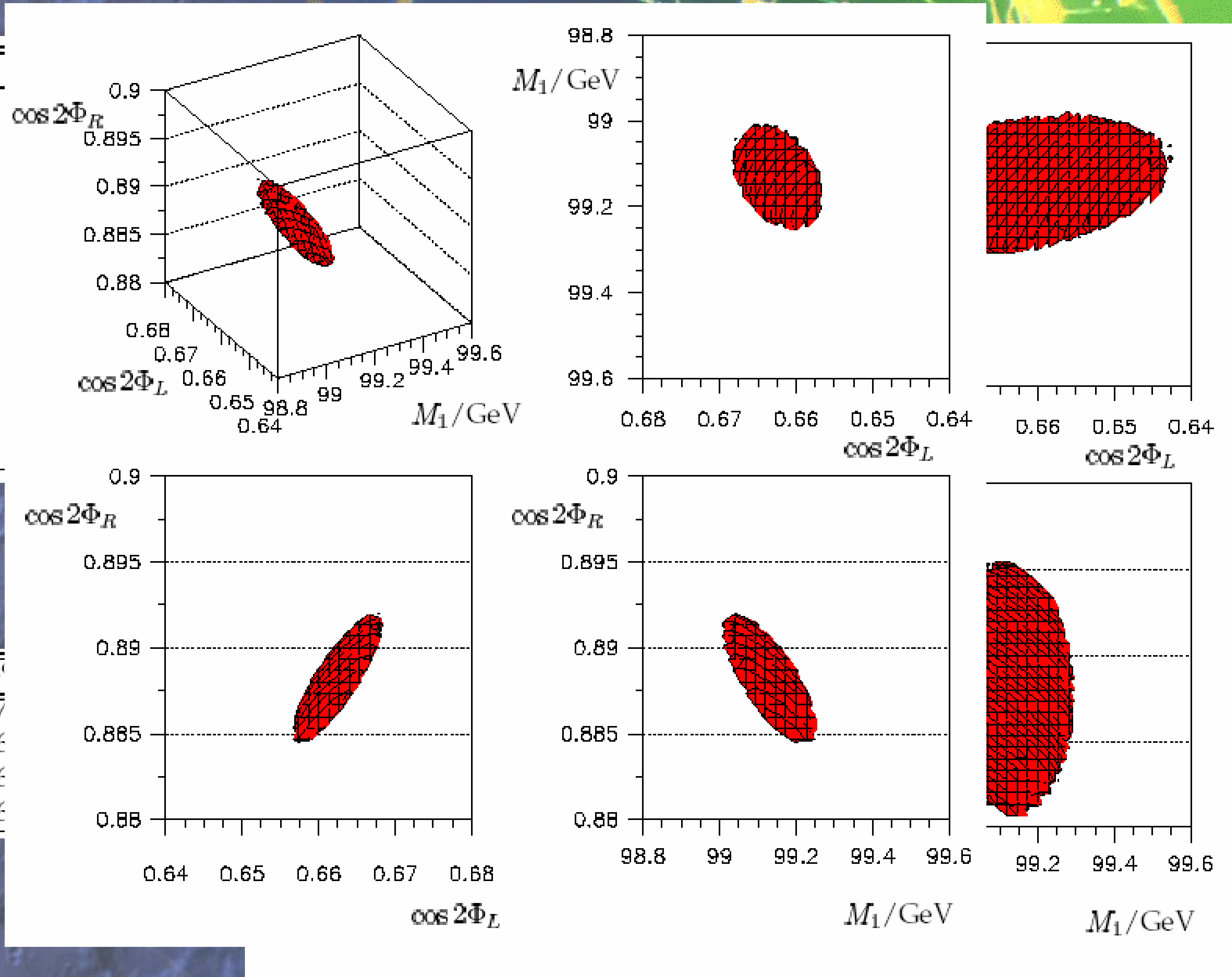


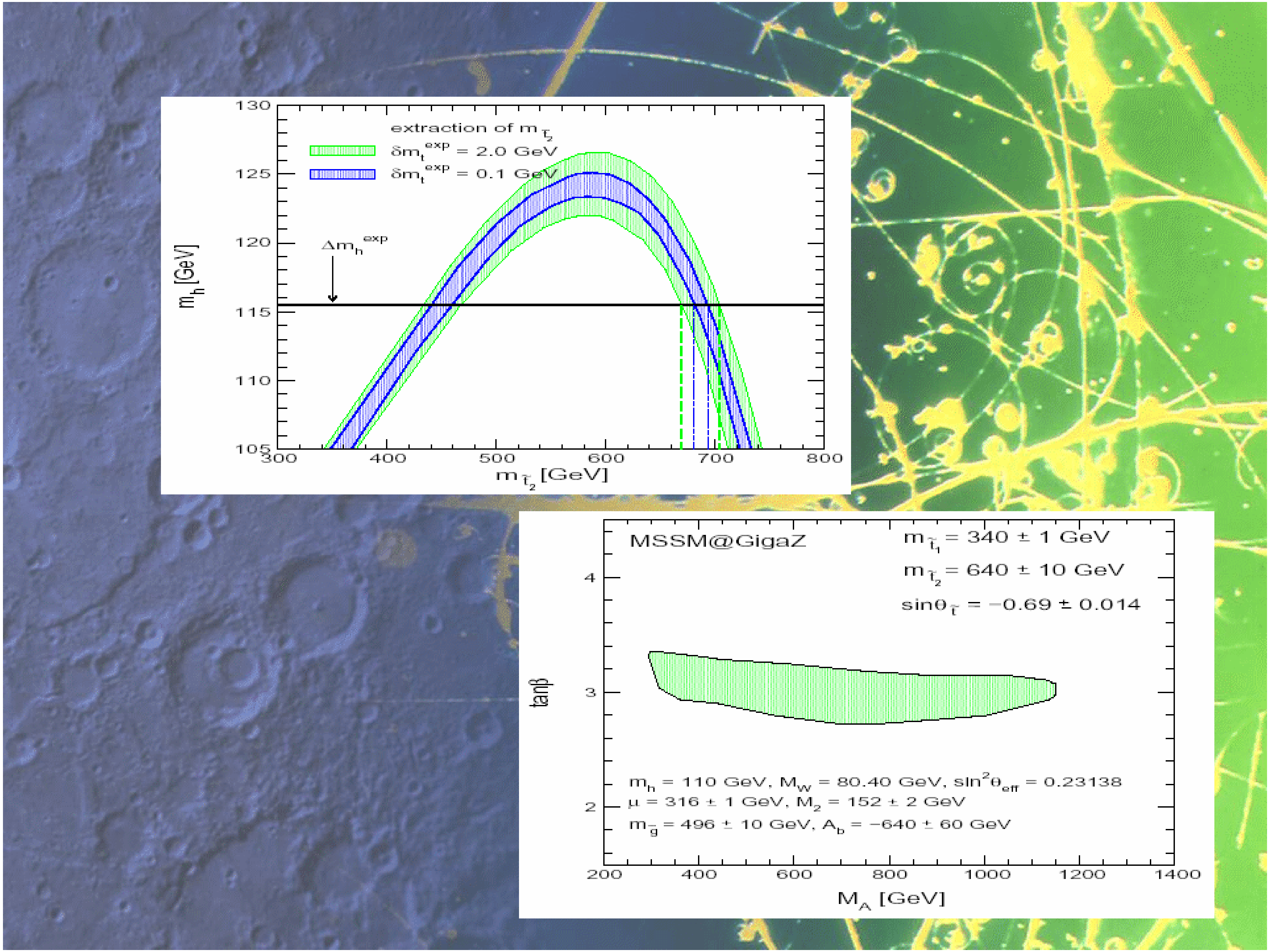
Numbers of sparticle species detected at CLIC along WMAP strip



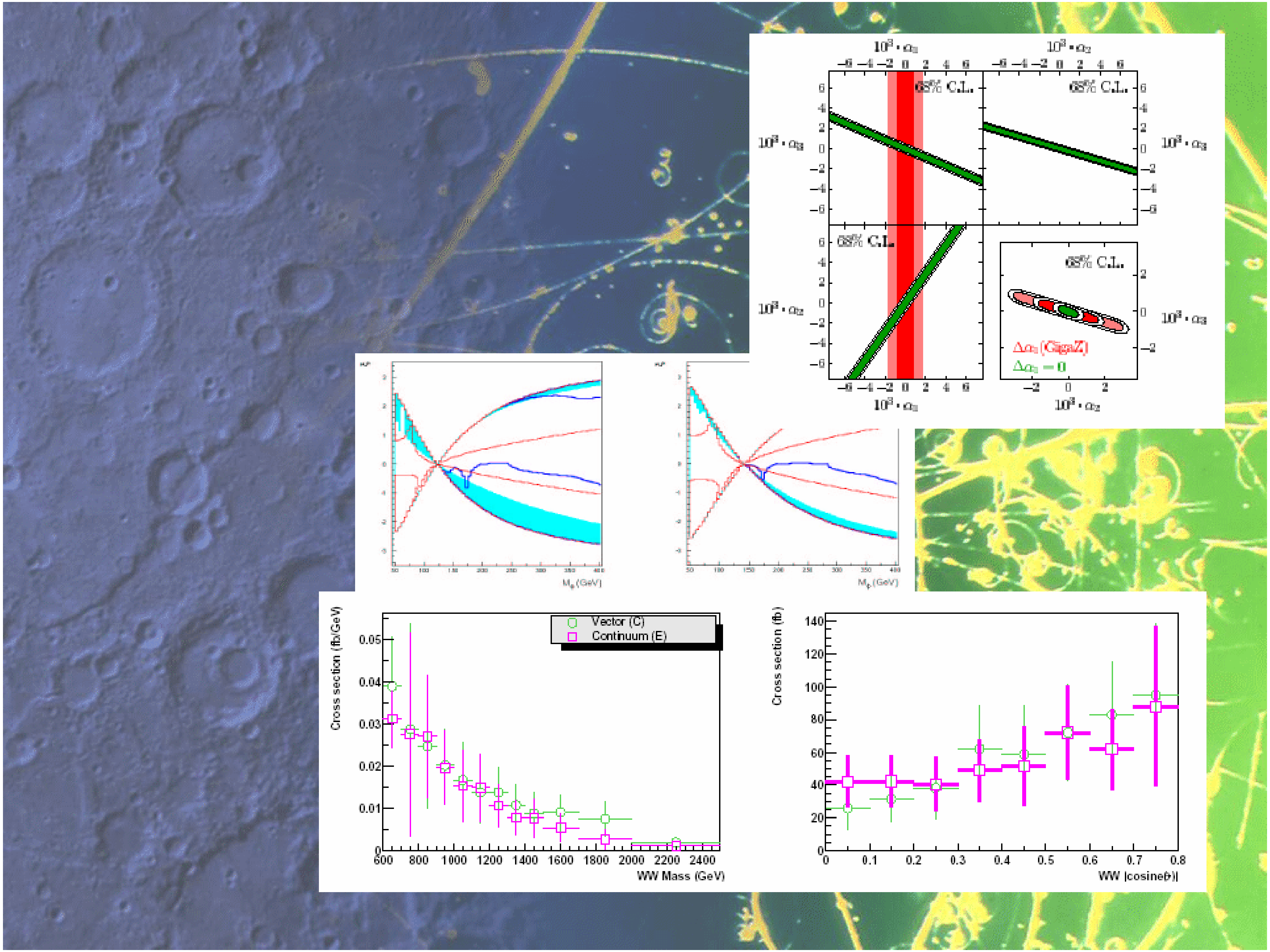
	LHC
$\Delta m_{\tilde{\chi}_1^0}$	4.8
$\Delta m_{\tilde{\chi}_2^0}$	4.7
$\Delta m_{\tilde{\chi}_4^0}$	5.1
$\Delta m_{\tilde{l}_R}$	4.8
$\Delta m_{\tilde{l}_L}$	5.0
Δm_{τ_1}	5-8
$\Delta m_{\tilde{q}_L}$	8.7
$\Delta m_{\tilde{q}_R}$	7-12
$\Delta m_{\tilde{b}_1}$	7.5
$\Delta m_{\tilde{b}_2}$	7.9
$\Delta m_{\tilde{g}}$	8.0

	LHC (0.5
$\Delta m_{\tilde{q}_L}$	7
$\Delta m_{\tilde{b}_1}$	6
$\Delta m_{\tilde{b}_2}$	6
$\Delta m_{\tilde{g}}$	6





extraction of m t̃2
δmt exp = 2.0 GeV
δmt exp = 0.1 GeV
Δmh exp
mh [GeV]
130
125
120
115
110
105
300
400
500
600
700
800
m t̃2 [GeV]
MSSM@GigaZ
m t̃1 = 340 ± 1 GeV
m t̃2 = 640 ± 10 GeV
sinθ t̃ = −0.69 ± 0.014
mh = 110 GeV, MW = 80.40 GeV, sin2θeff = 0.23138
μ = 316 ± 1 GeV, M2 = 152 ± 2 GeV
mg̃ = 496 ± 10 GeV, Ab = −640 ± 60 GeV
tanβ
4
3
2
200
400
600
800
1000
1200
1400
MA [GeV]



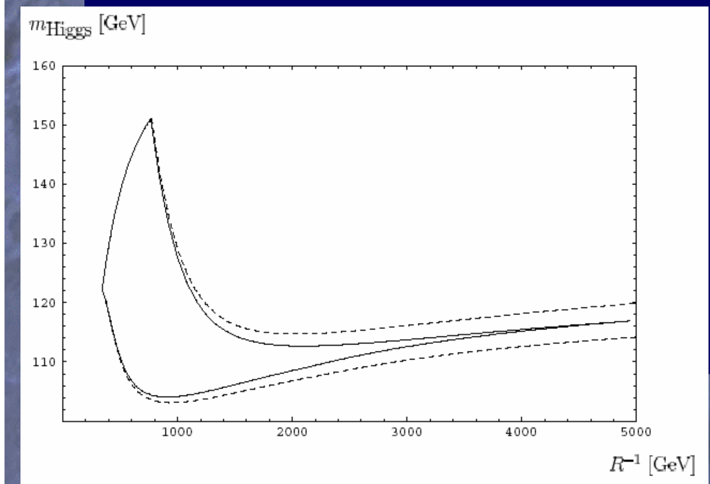
10³ · α1
10³ · α2
10³ · α3
68% C.L.
Δα1 (GigaZ)
Δα1 = 0
Mφ (GeV)
Vector (C)
Continuum (E)
Cross section (fb/GeV)
WW Mass (GeV)
Cross section (fb)
WW |cosine θ|

`Constrained Standard Model'

- Break supersymmetry by boundary conditions in extra dimension
- If top quark not localized, 1-parameter potential:

  m_H = 130 GeV, 1/R ~ 400 GeV

- Relaxed if top quark partially localized



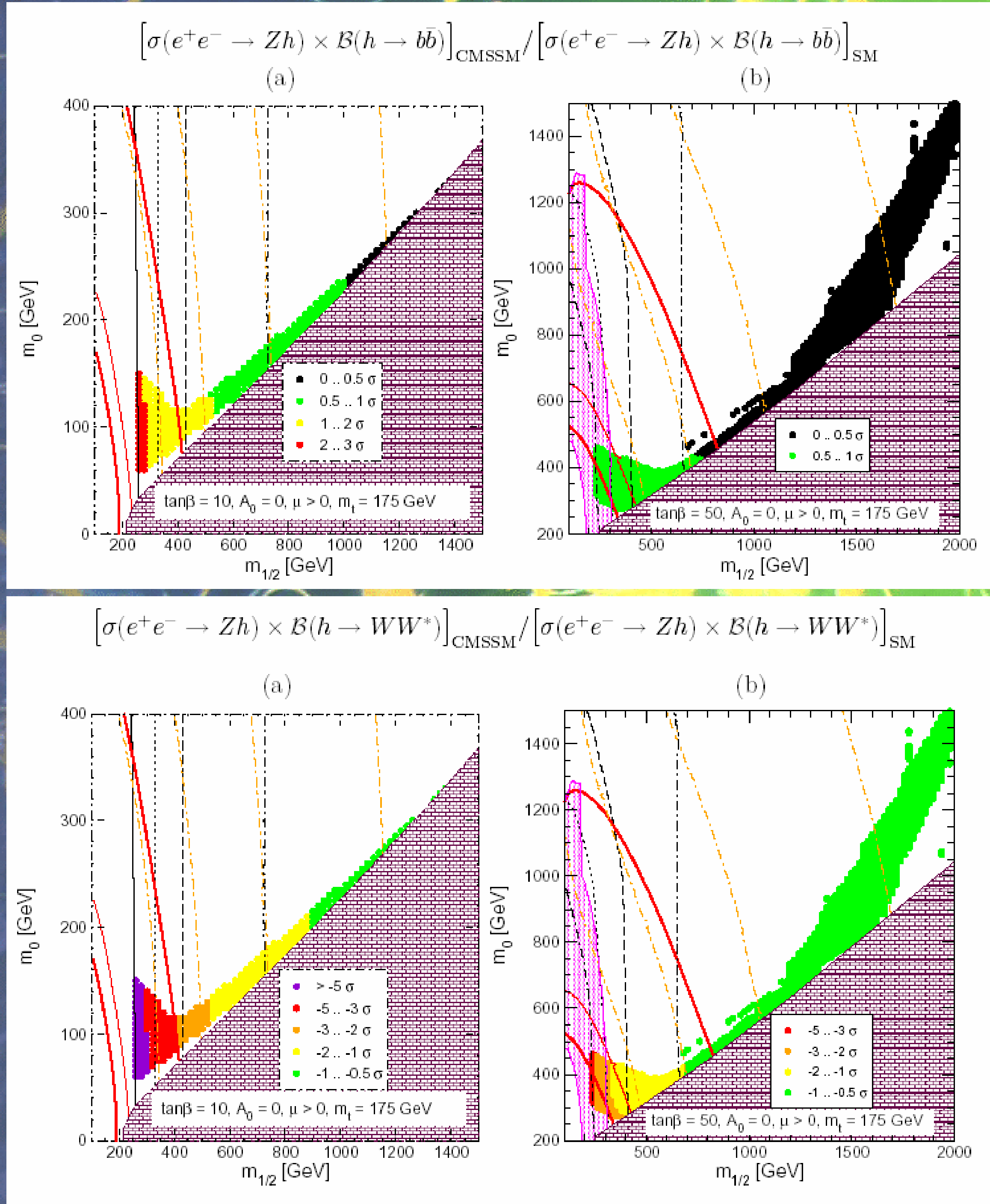
LSP is stop

$1/R$	360 ± 70
h	133 ± 10
$\tilde{t}_1, \tilde{u}_1$	210 ± 20
$\chi^{\pm}, \chi^0, \tilde{g}, \tilde{q}, \tilde{l}$	360 ± 70
$\tilde{t}_2, \tilde{u}_2$	540 ± 30
A_1, q_1, l_1, h_1	720 ± 140

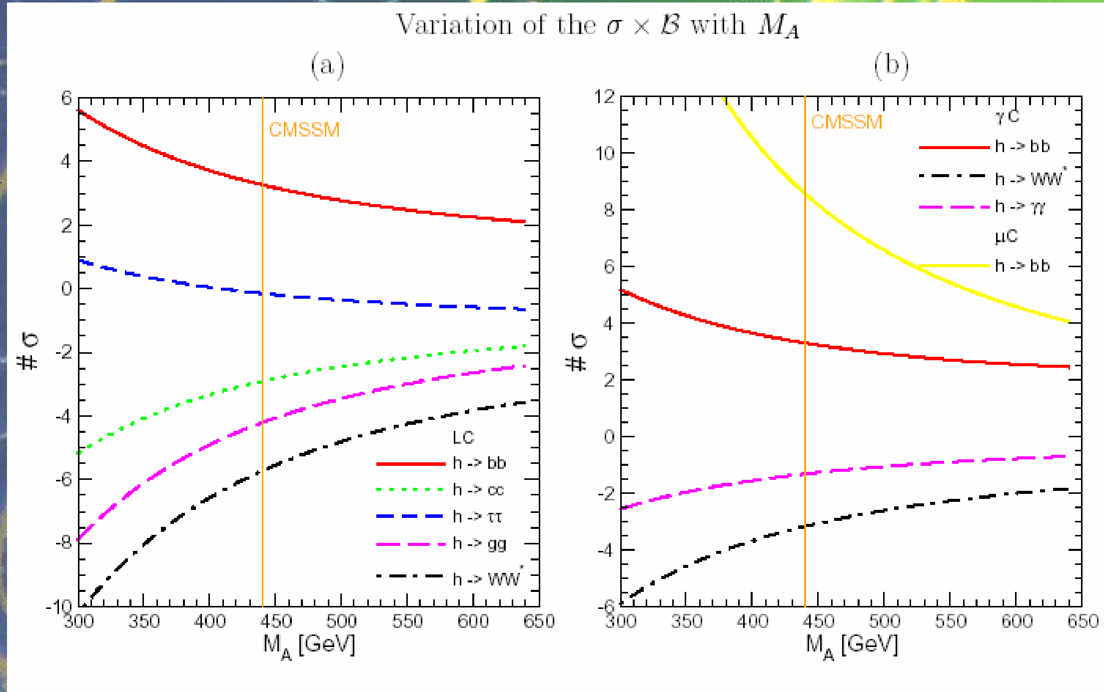
All entries are in GeV

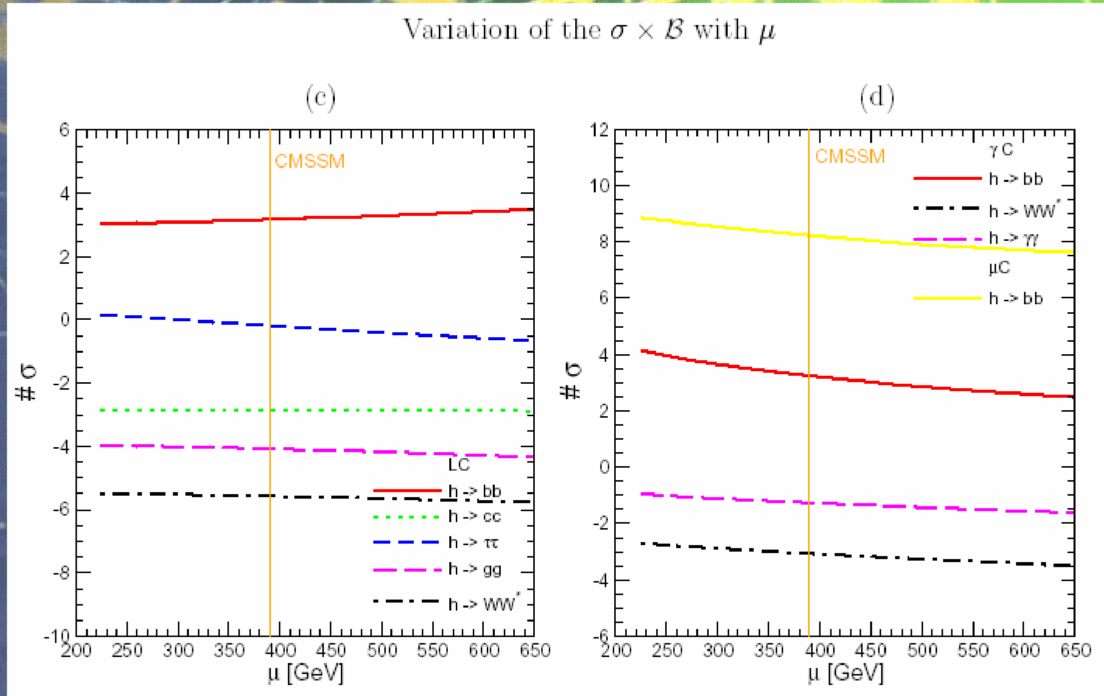
How well can LC distinguish CMSSM from SM?

Numbers of standard deviations in Higgs measurements



How well can LC distinguish CMSSM from SM?





Numbers of standard deviations in Higgs measurements