What to do with a High Gradient

The short answer is:
Physicists (always) want more energy
but
Politicians will not give us more money

The Physics Case for Higher Energy

- Why an $e^+ e^-$ collider with E_{CM} = 3 to 5 TeV?
- A significant step beyond the LHC/ILC for precision measurements at high energies
  – Complete study of the Higgs boson(s)?
  – Supersymmetric spectra?
  – Deeper probes of extra dimensions?
  – New gauge bosons, excited quarks, leptons?
- More to add, whatever the LHC offers

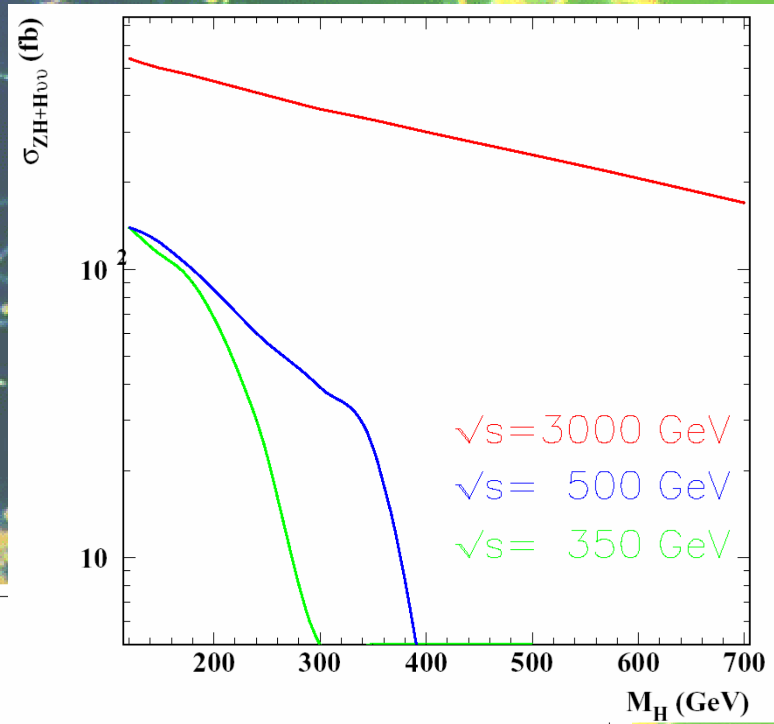
CLIC Physics Studies 1987 – now: see hep-ph/0412251

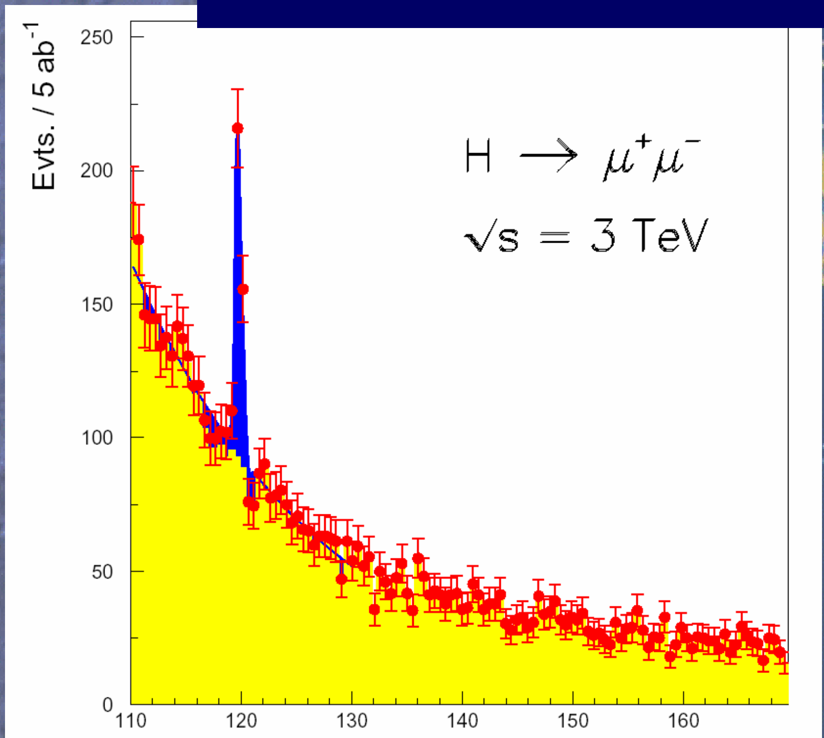
If there is a light Higgs boson …

- Large cross section @ high energy
- Measure rare Higgs decays unobservable at LHC or a lower-energy $e^+ e^-$ collider

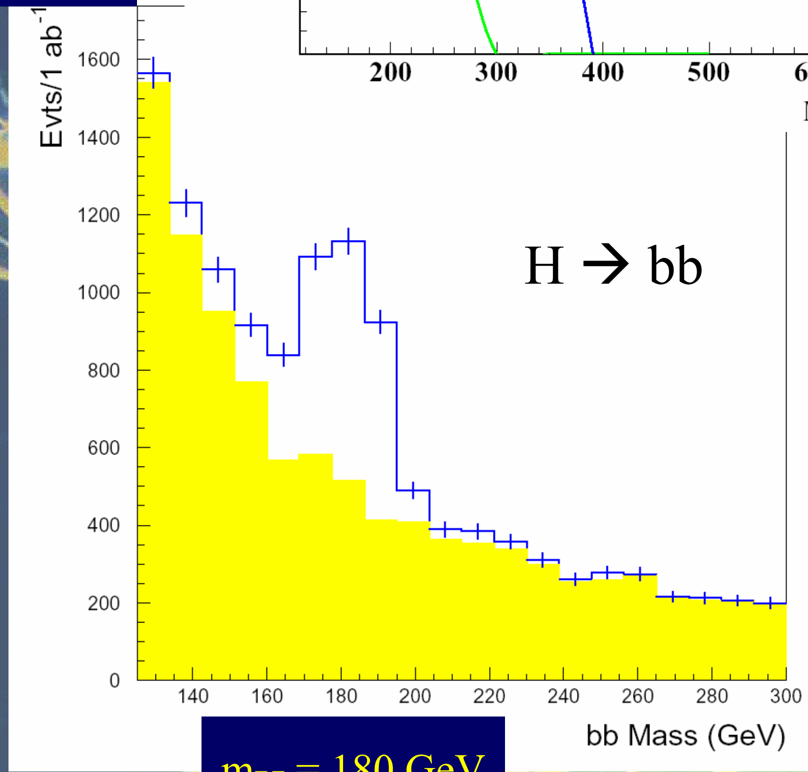
Large Cross Section @ 3 TeV

Can measure rare decay modes …





m_H = 120 GeV



m_H = 180 GeV

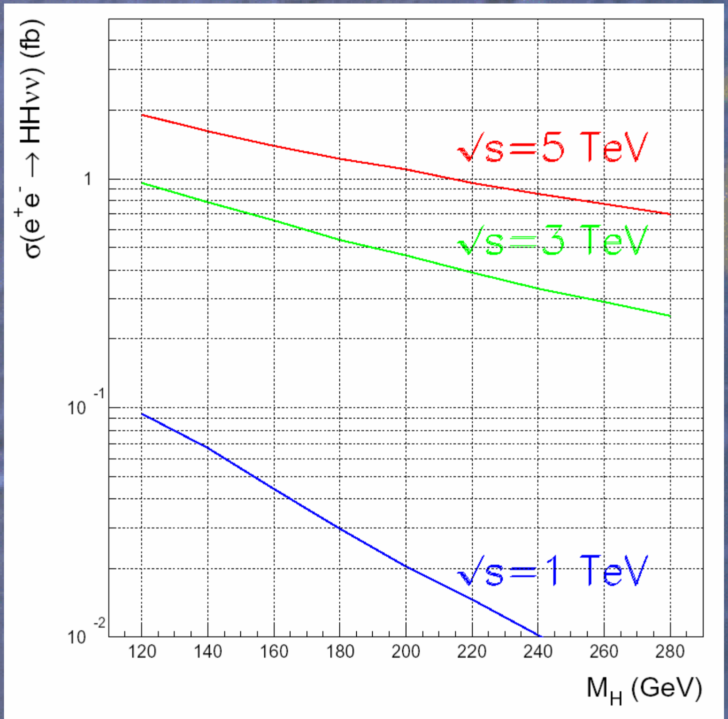
If there is a light Higgs boson …

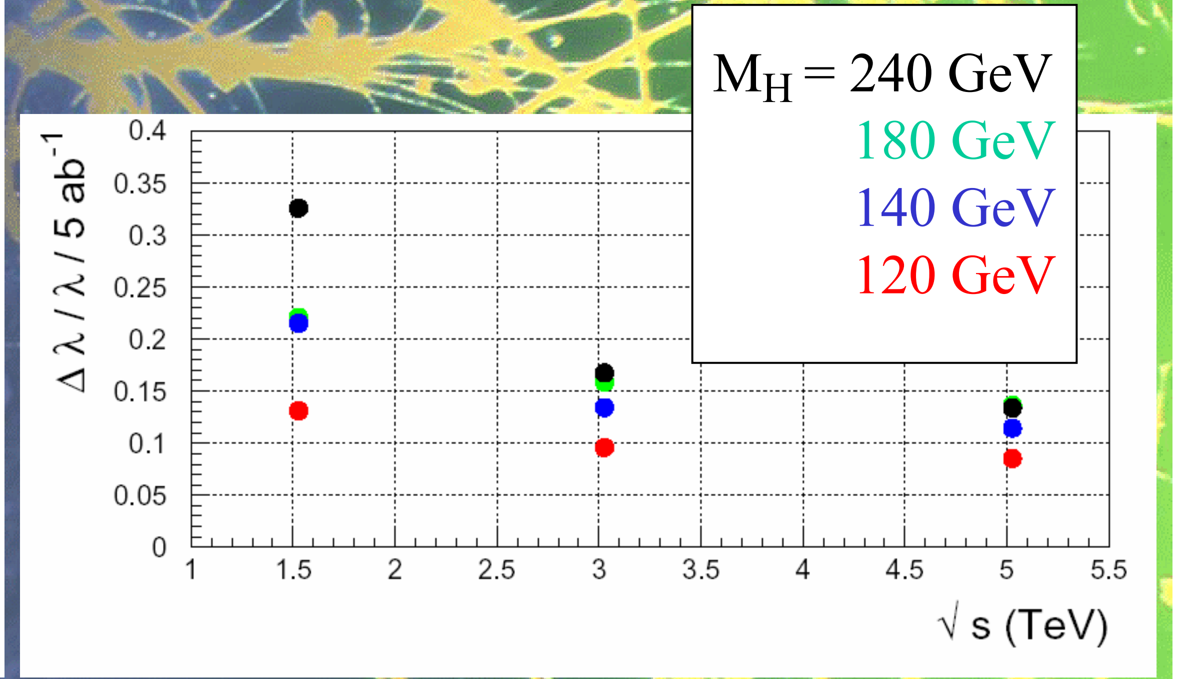
- Large cross section @ high energy
- Measure rare Higgs decays unobservable at LHC or a lower-energy $e^+ e^-$ collider
- Could measure the effective potential with 10% precision

Measure Effective Higgs Potential

Large cross section for HH pair production

Accuracy in measurement of HHH coupling

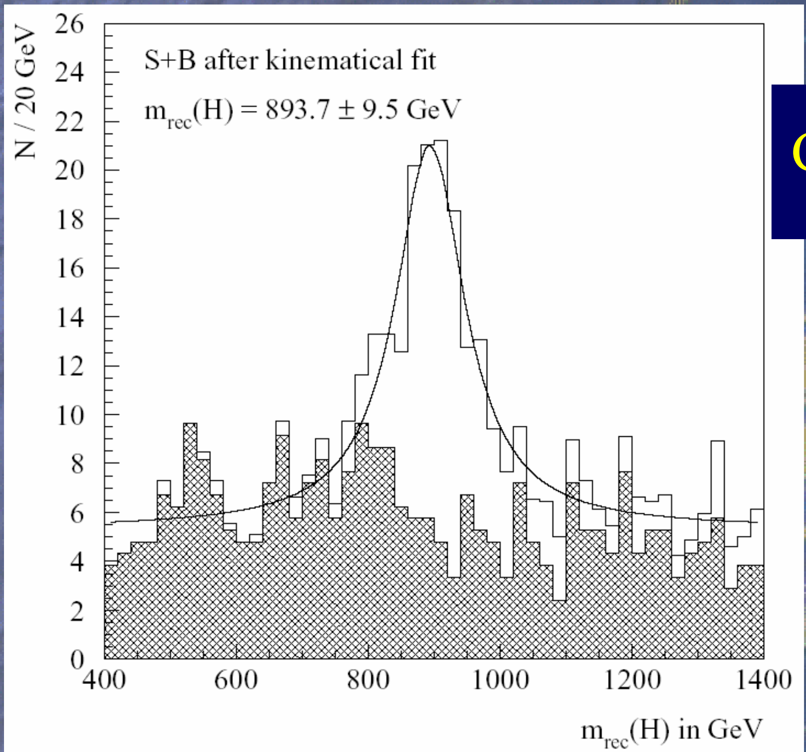




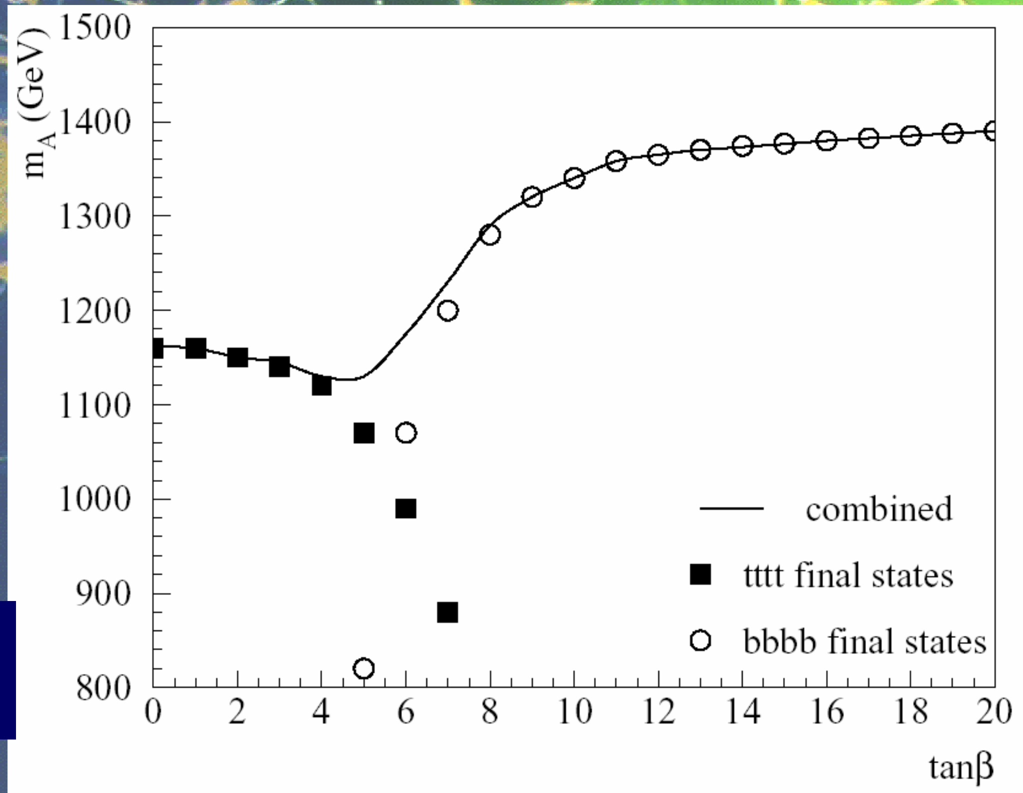
If there is a light Higgs boson …

- Large cross section @ high energy
- Measure rare Higgs decays unobservable at LHC or a lower-energy $e^+ e^-$ collider
- Could measure the effective potential with 10% precision
- Could search indirectly for accompanying new physics up to 100 TeV
- Could identify any heavier partners

Identify Heavier Partner Higgses



Charged …

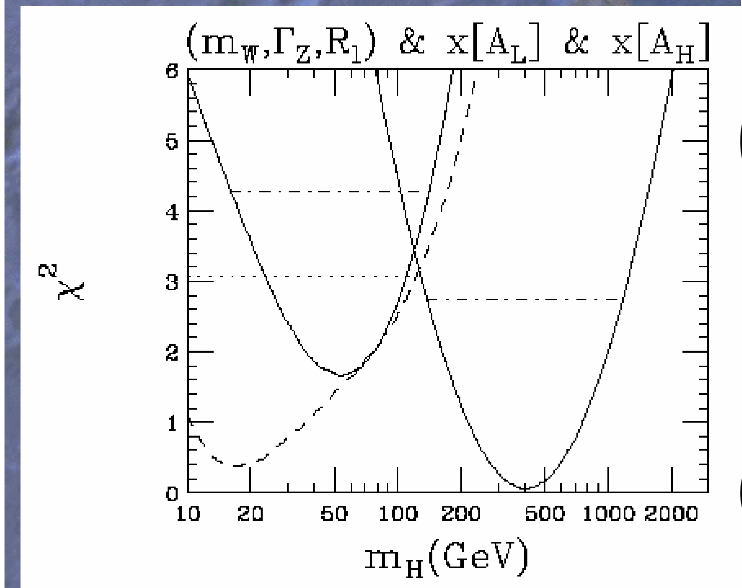


… or neutral

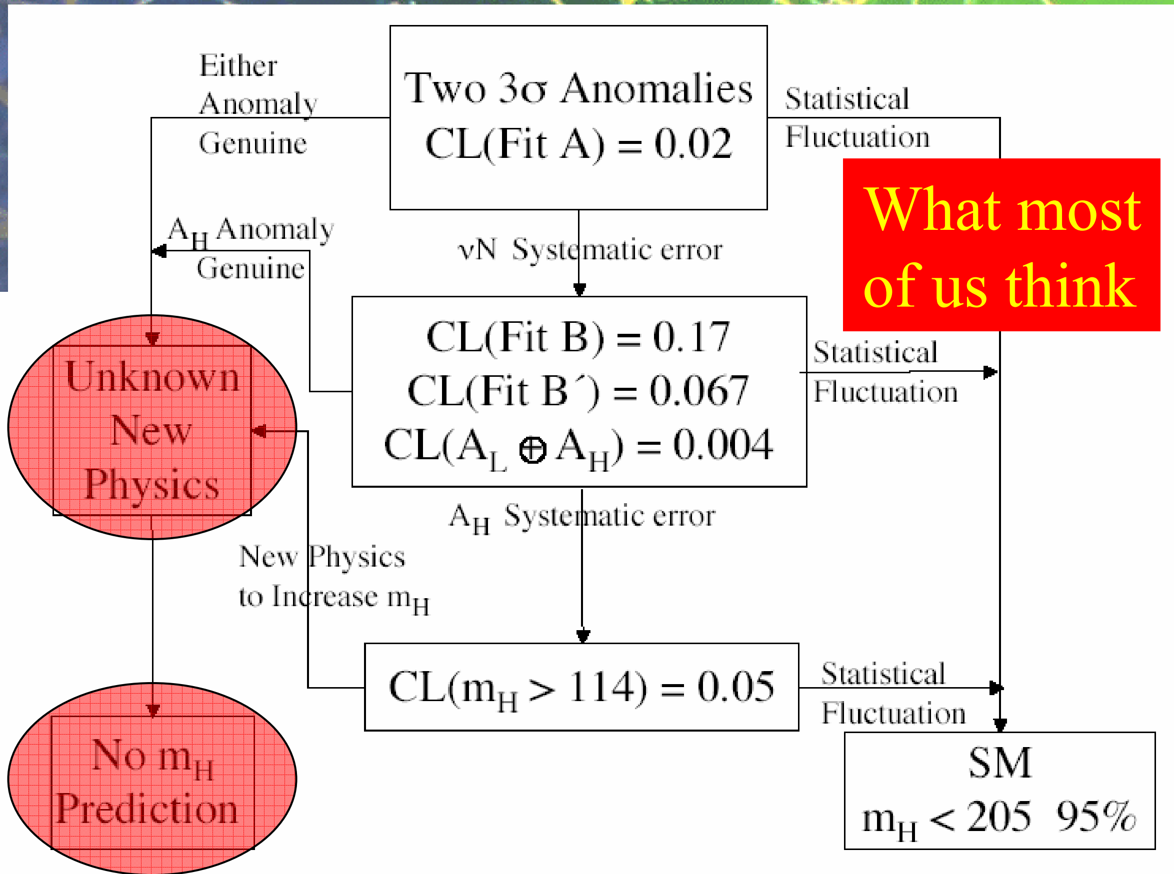
Do not assume that the Higgs is light

Do all the data tell the same story?

e.g., A_L vs A_H



What attitude towards LEP, NuTeV?



Higgs + Higher-Order Operators

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

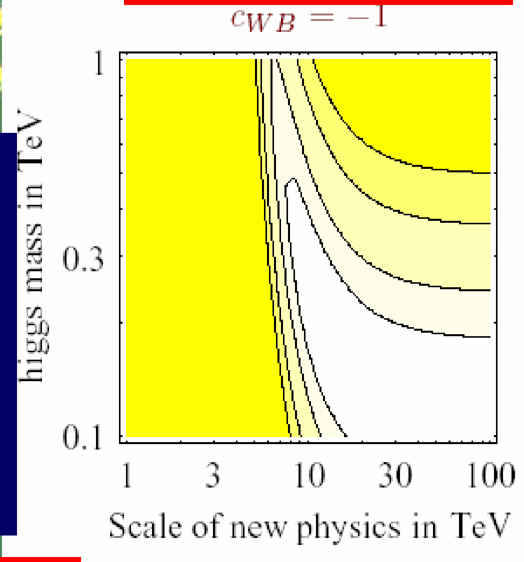
Precision EW data suggest they are small: why?

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

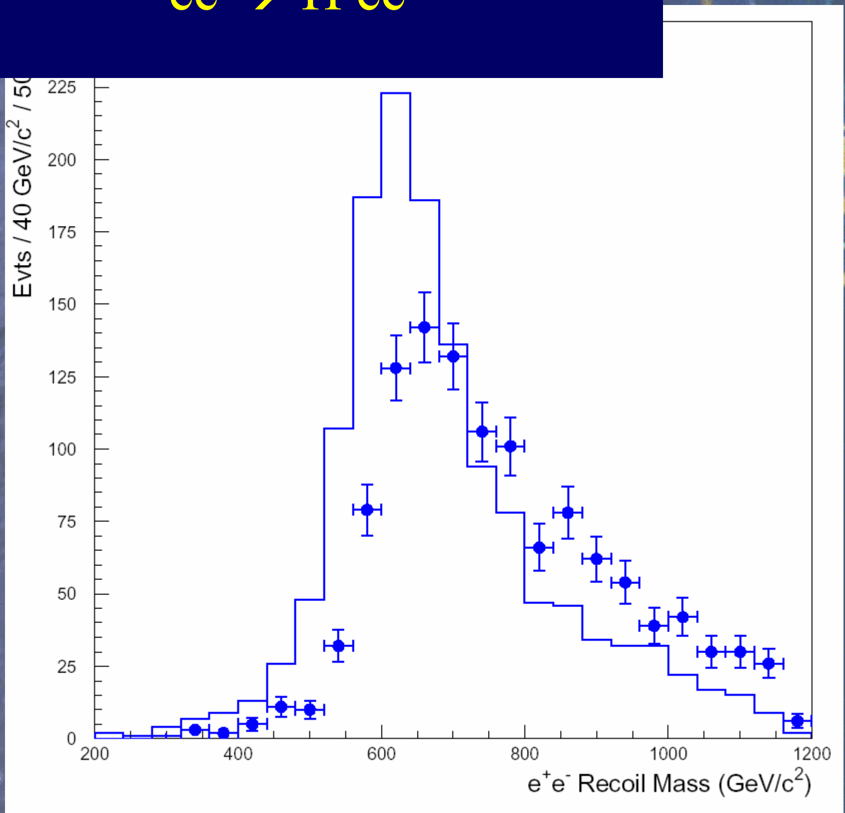
But conspiracies are possible: m_H could be large, even if believe EW data …?



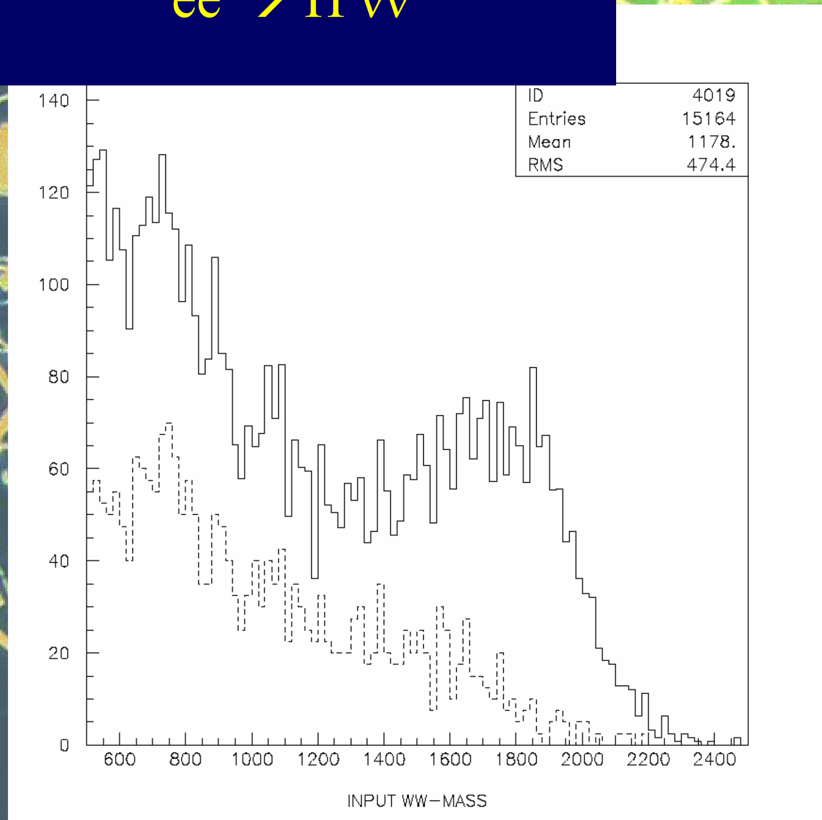
Do not discard possibility of heavy Higgs

If the Higgs boson is heavier …

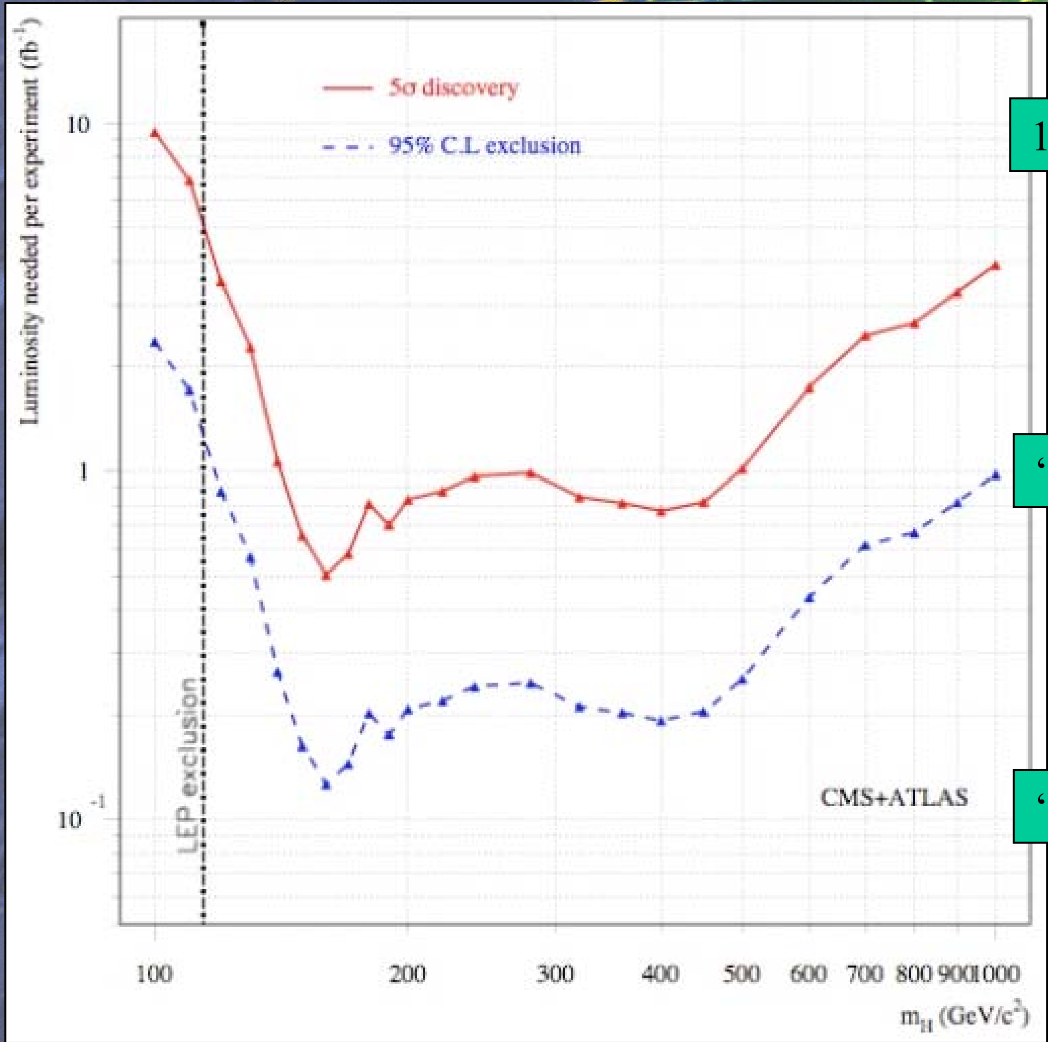
Can establish its existence beyond any doubt if < 1 TeV:
ee → H ee



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



When will the LHC discover the Higgs boson?



1 ‘year’ @ 10^{33}

‘month’ @ 10^{33}

‘month’ @ 10^{32}

What is Supersymmetry (Susy)?

- The last undiscovered symmetry?
- Could unify matter and force particles
- Links fermions and bosons

$$Q|Boson> = |Fermion>$$
$$Q|Fermion> = |Boson> .$$

- Relates particles of different spins

0 - ½ - 1 - 3/2 - 2

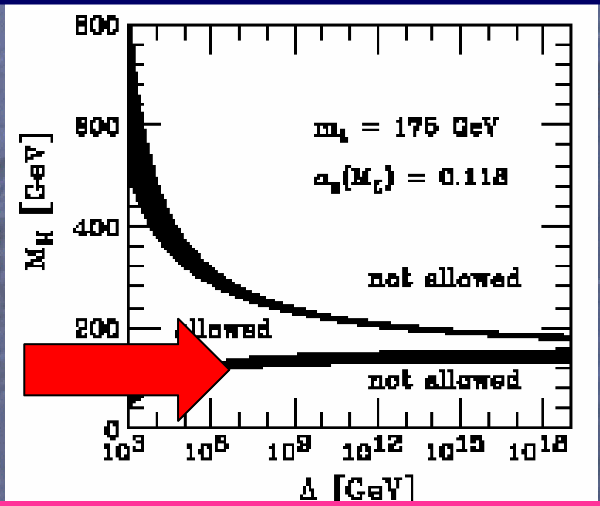
Higgs - Electron - Photon - Gravitino - Graviton

- Helps fix masses, unify fundamental forces

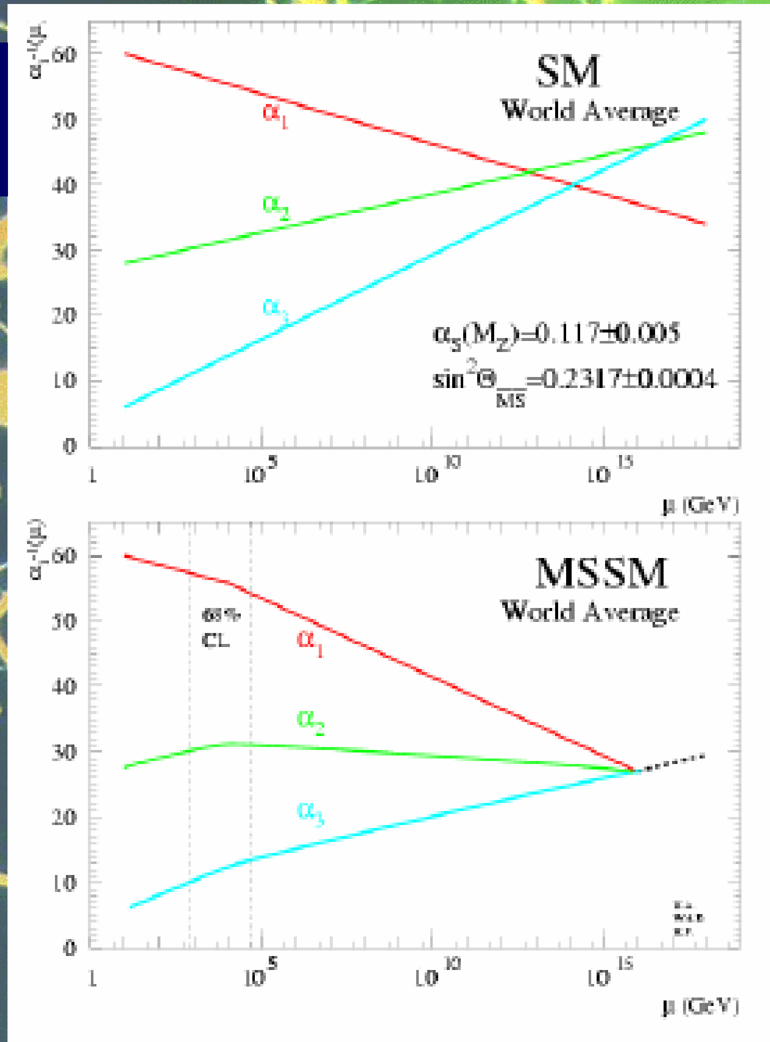
Other Reasons to like Susy

It enables the gauge couplings to unify

It stabilizes the Higgs potential for low masses



Approved by Fabiola Gianotti



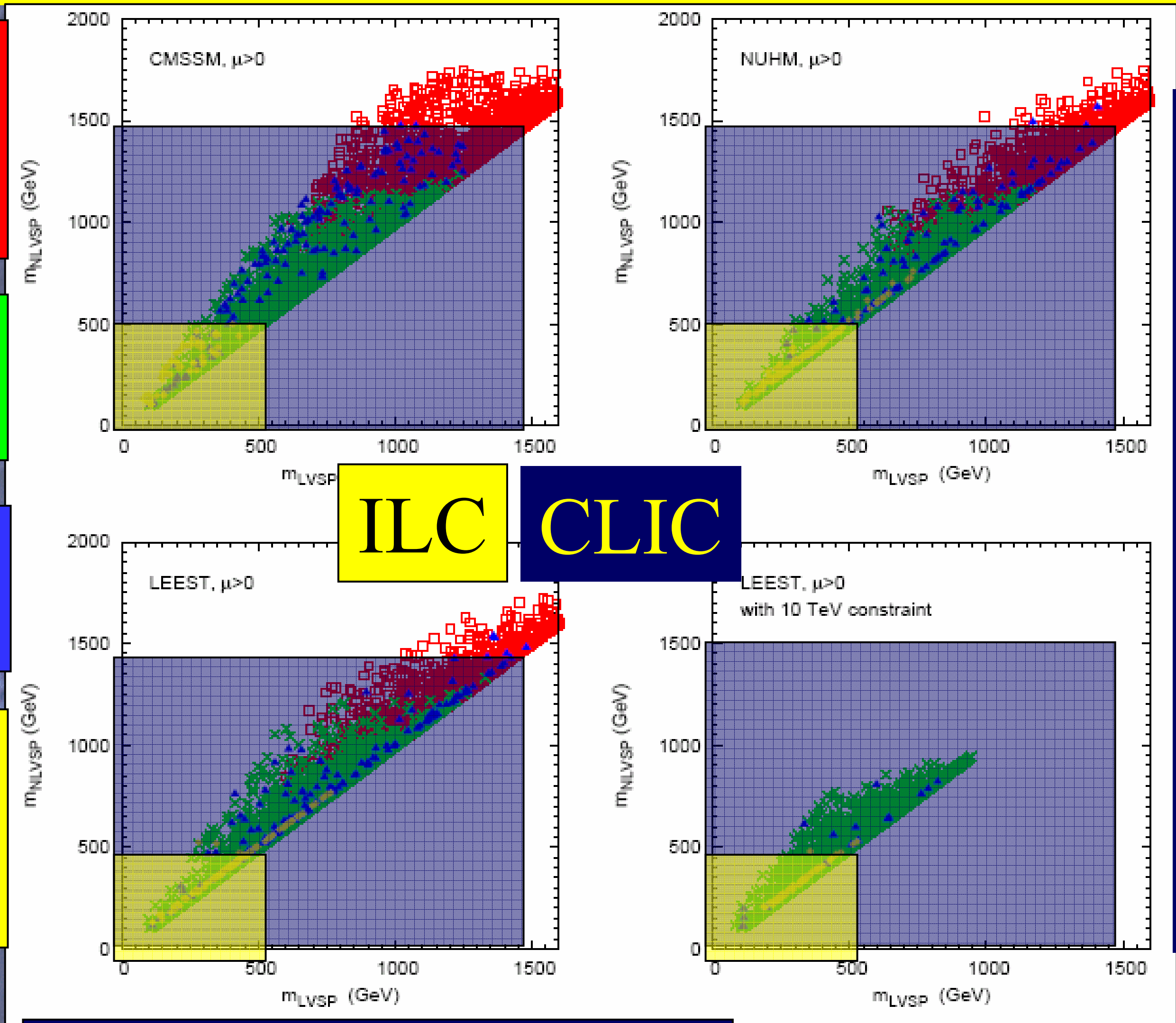
Sparticles may not be very light

Full Model samples

Detectable @ LHC

Provide Dark Matter

Dark Matter Detectable Directly



← Second lightest visible sparticle

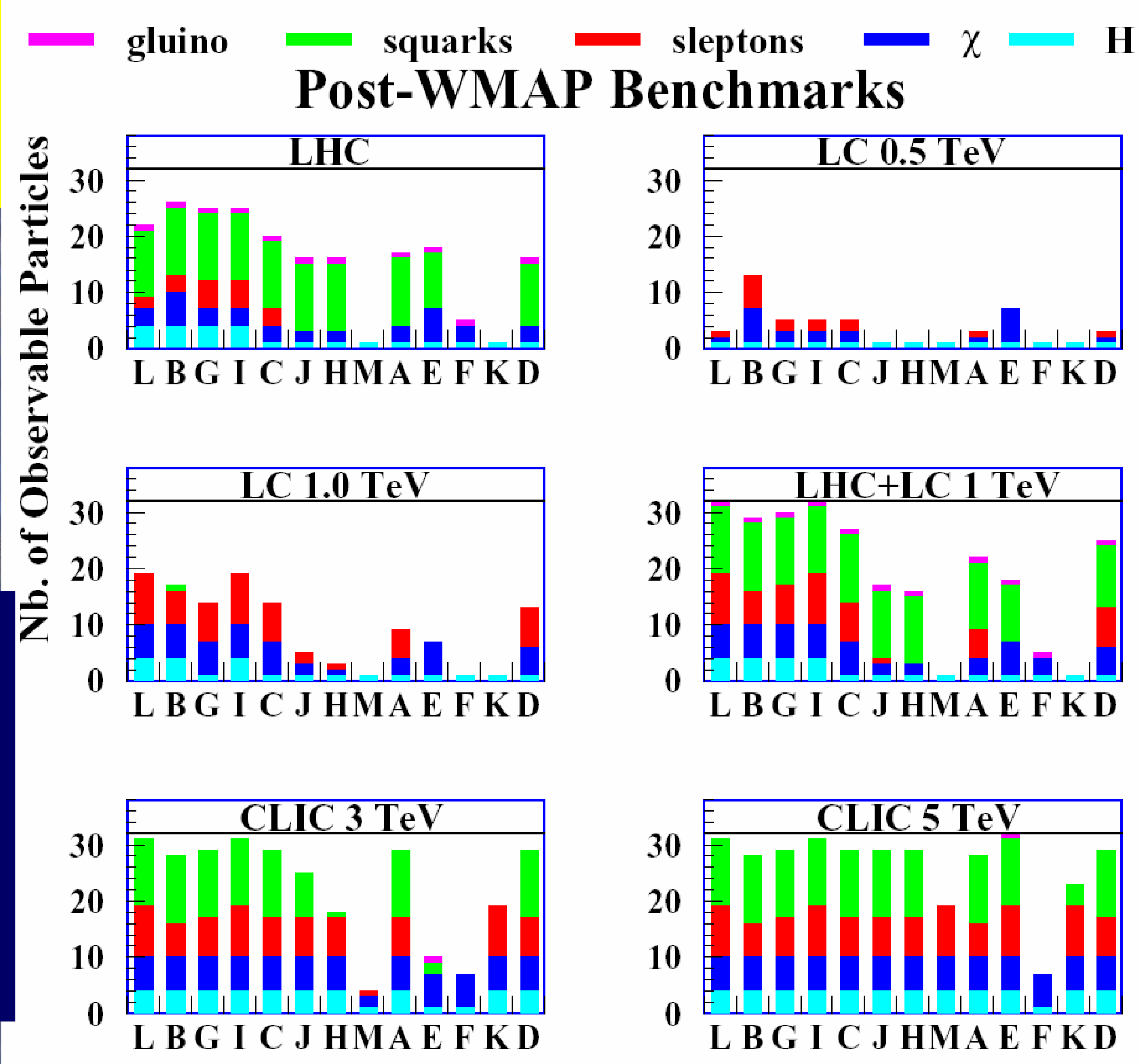
Lightest visible sparticle →

JE + Olive + Santoso + Span

If the LHC discovers supersymmetry …

- Could complete the spectrum
- Could make many novel, detailed measurements
- Cast light on mechanism of supersymmetry breaking?
- Open a window on string physics?

LHC Scapabilities … and Other Accelerators

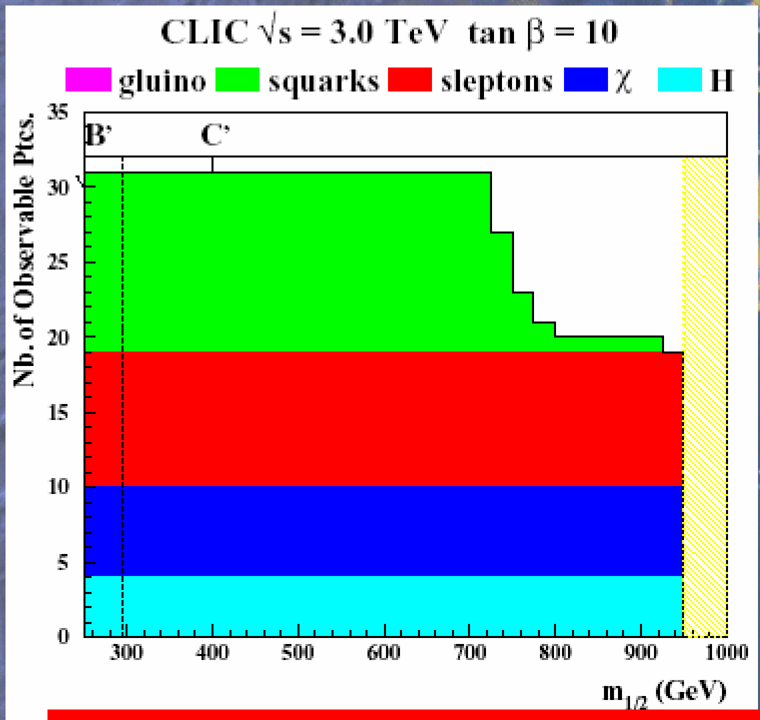


LHC almost
`guaranteed'
to discover
supersymmetry
if it is relevant
to the mass problem

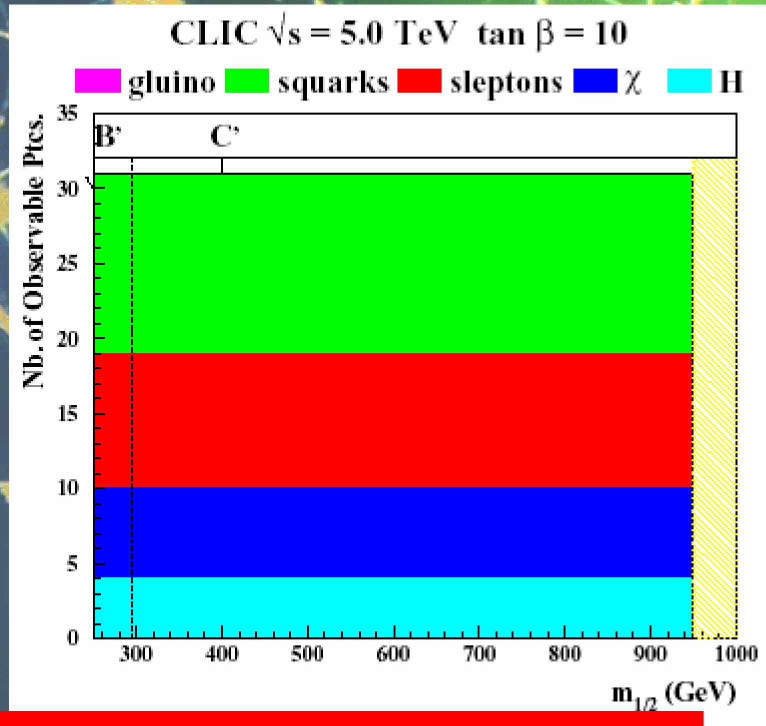
Sparticle Visibility at Higher E

CMSSM

3 TeV



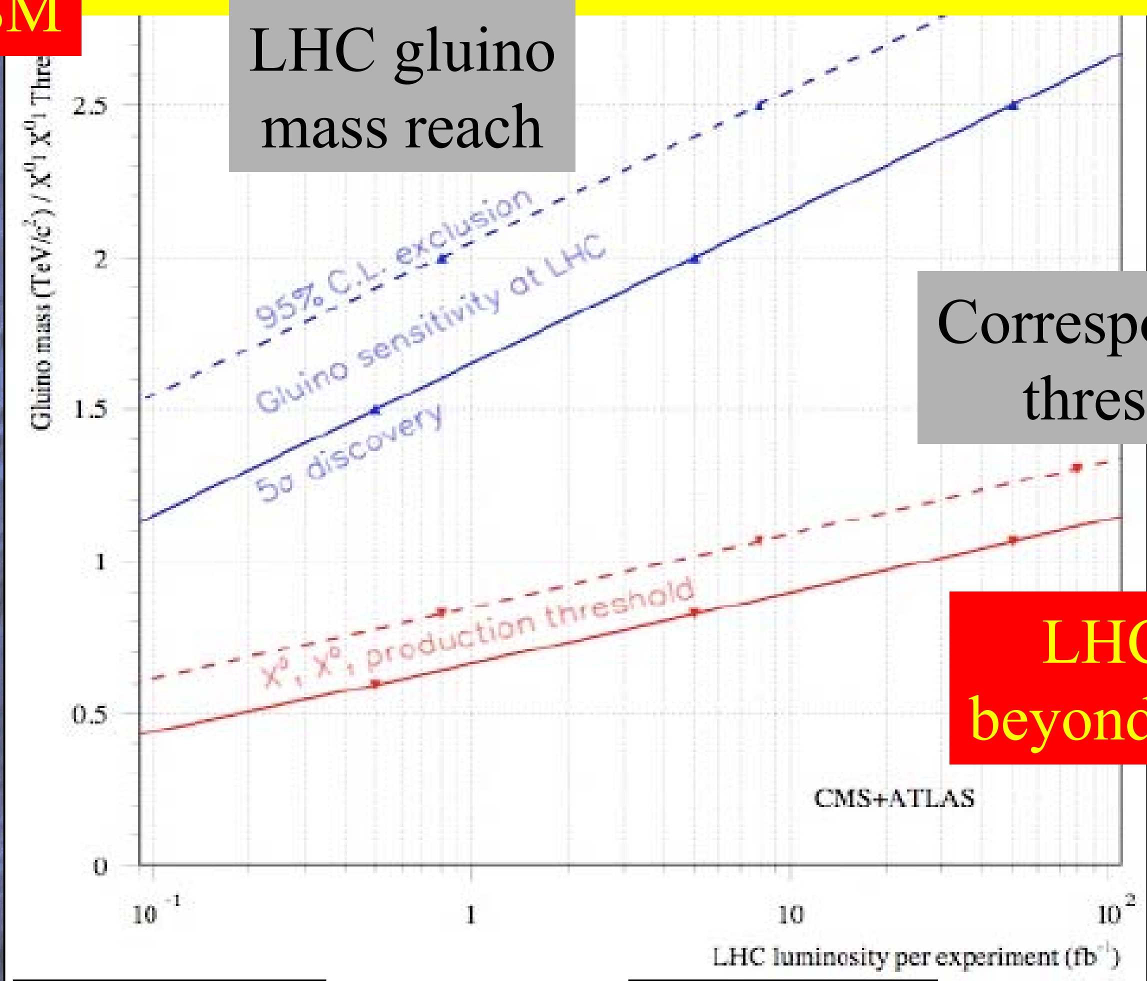
5 TeV



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

Implications of LHC Search for ILC

In CMSSM



LHC gluino mass reach

Corresponding sparticle thresholds @ ILC

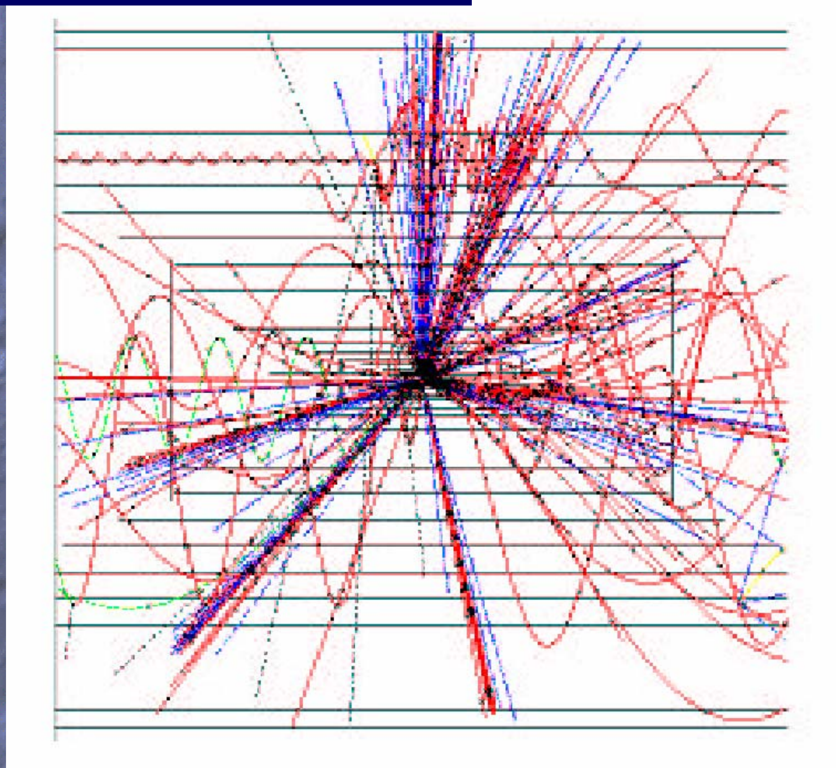
LHC already sees beyond ILC 'at turn-on'

'month' @ 10^{32}	'month' @ 10^{33}	1 'year' @ 10^{33}	1 'year' @ 10^{34}

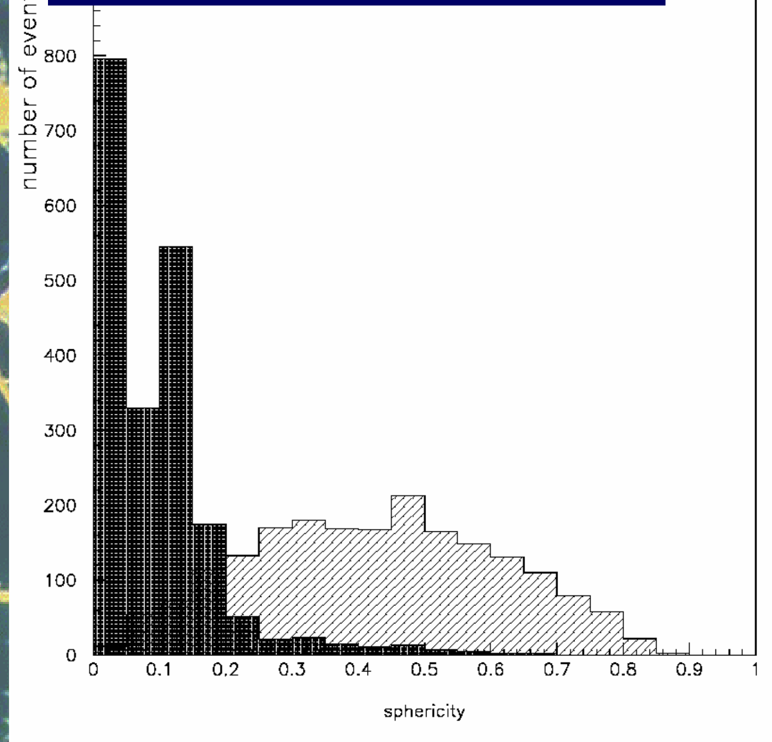
Blaising et al: 2006

If the LHC discovers extra dimensions

Mini-black hole at 3 TeV

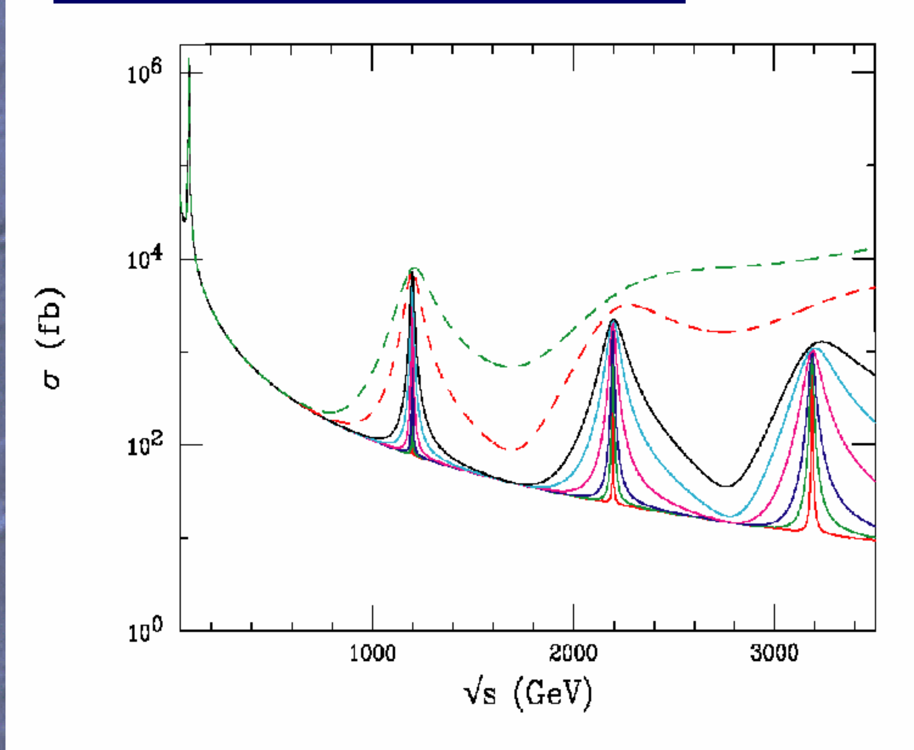


Easily distinguishable from Standard Model background

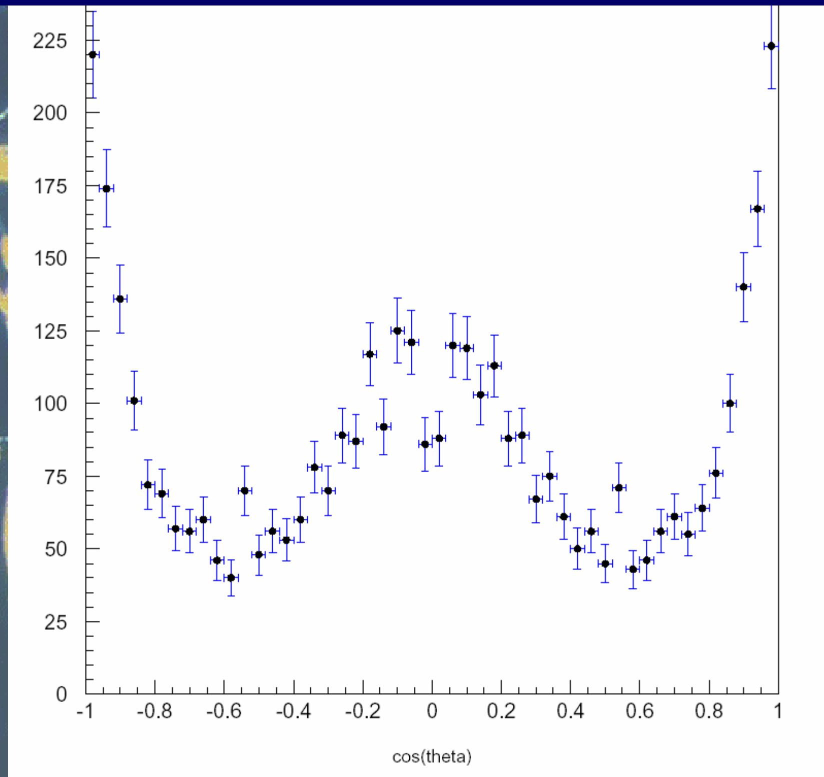


Could measure Kaluza-Klein excitations

Direct-channel resonances

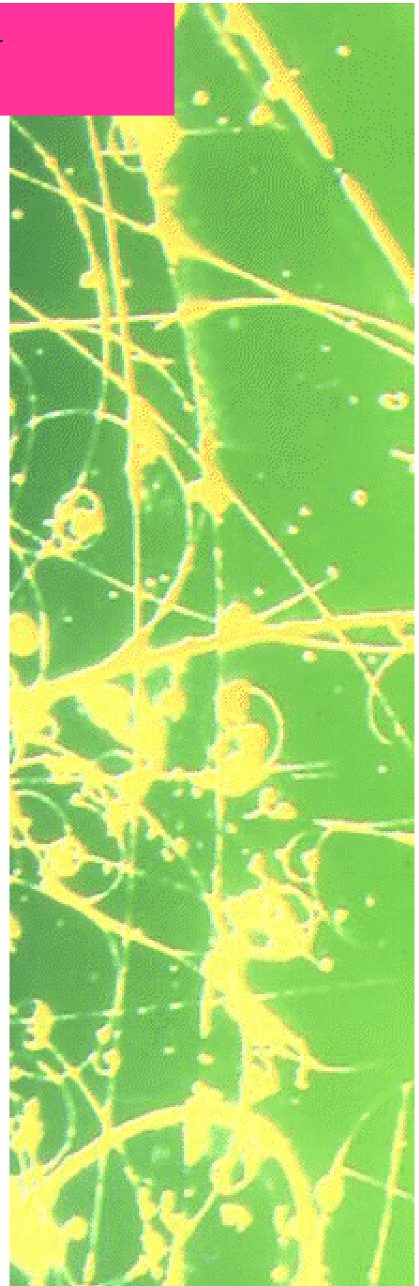


Angular distribution in graviton decay



Physics Reaches Of Various Colliders

Process	LC	LHC	SLHC	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	-	4σ	70σ	90σ
Triple-gauge Coupling(TGC) (95%)	.0014	0.0004	0.0006	0.00013	0.00008



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 high-energy LC. Most numbers given are TeV, but for strong $W_L W_L$ scattering numbers of standard deviations, pure numbers for the triple gauge coupling (TGC).

Conclusions

- Unique physics @ energy frontier
- Beamstrahlung and backgrounds not insurmountable problems
- Can exploit fully high c.o.m. energy
- Added value for light Higgs, heavy Higgs, supersymmetry, extra dimensions, …

Meta-Conclusions

- The LHC will define the future course of high-energy physics
- All scenarios best explored by a high-energy $e^+ e^-$ collider
- Should have widest possible technology choice when LHC results appear
- Determine feasibility of high gradient by the end of this decade