The Physics Case for CLIC

- Outline of the CLIC project
- Why an $e^+ e^-$ collider with E_{CM} = 3 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

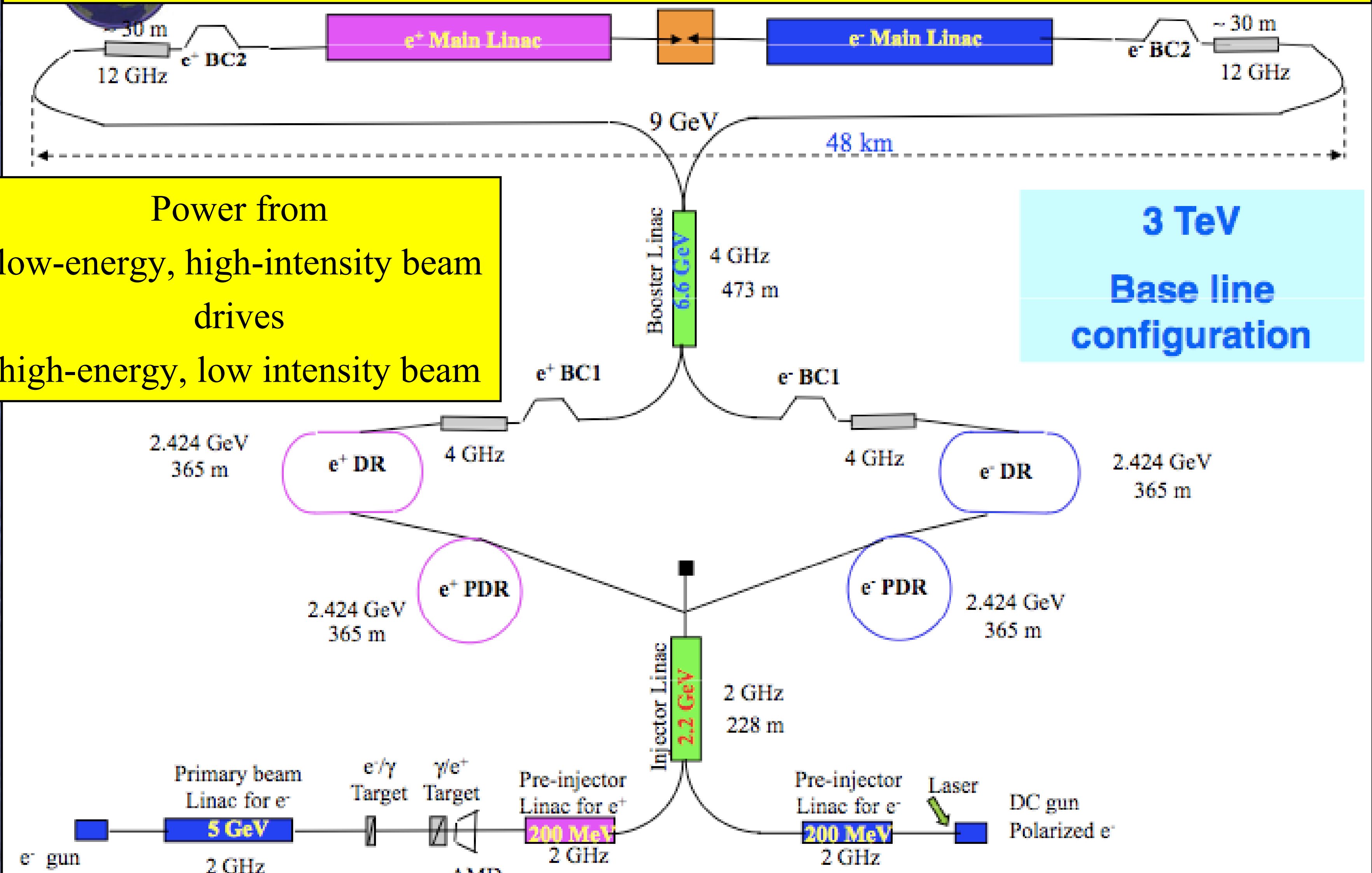
CLIC Physics Studies 1987 -

World-Wide CLIC Collaboration

24 members representing 27 institutes involving 17 funding agencies of 15 countries

Ankara University (Turkey)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
Gazi Universities (Turkey)
IRFU/Saclay (France)
Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
Instituto de Fisica Corpuscular (Spain)
INFN / LNF (Italy)
J.Adams Institute, (UK)
JINR (Russia)
JLAB (USA)
KEK (Japan)
LAL/Orsay (France)
LAPP/ESIA (France)
NCP (Pakistan)
North-West. Univ. Illinois (USA)
Oslo University (norway)
PSI (Switzerland),
Polytech. University of Catalonia (Spain)
RRCAT-Indore (India)
Royal Holloway, Univ. London, (UK)
SLAC (USA)
Uppsala University (Sweden)

The Conceptual Layout of CLIC



Power from
low-energy, high-intensity beam
drives
high-energy, low intensity beam

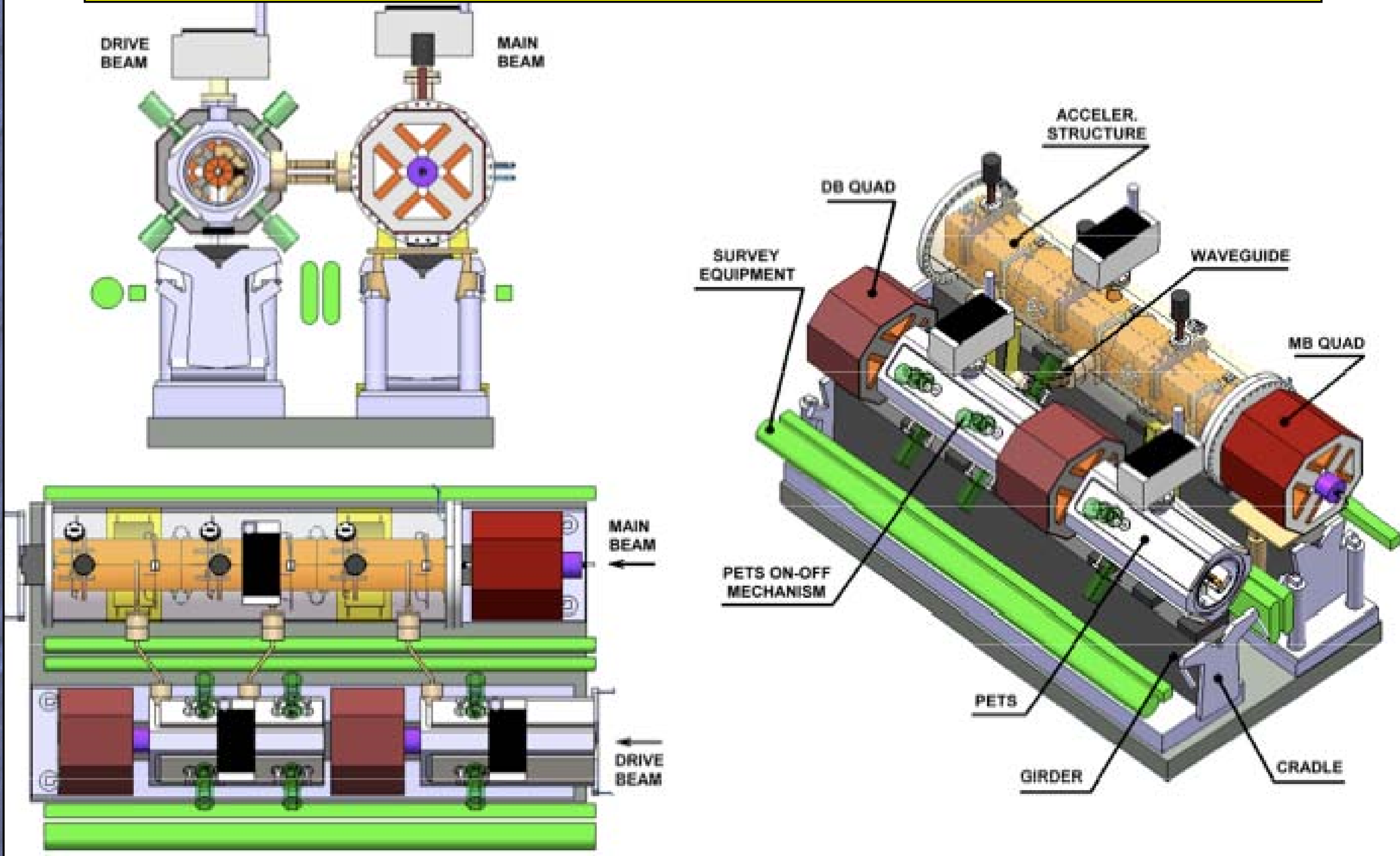
3 TeV

Base line configuration

Nominal CLIC Parameters

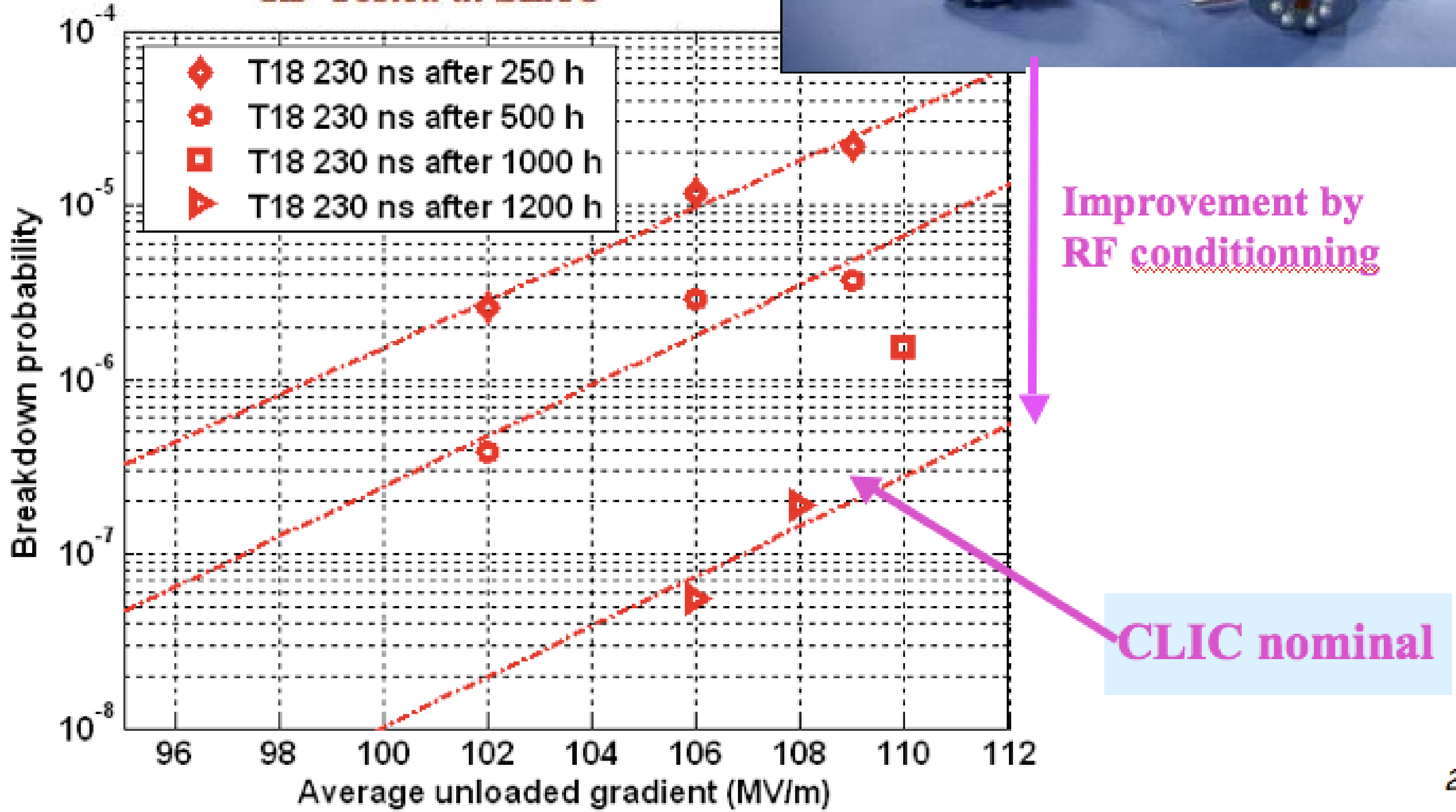
Center-of-mass energy	CLIC 500 GeV		CLIC 3 TeV	
Beam parameters	Conservative	Nominal	Conservative	Nominal
Accelerating structure	502		G	
Total (Peak 1%) luminosity	$0.9(0.6)\cdot10^{34}$	$2.3(1.4)\cdot10^{34}$	$2.7(1.3)\cdot10^{34}$	$5.9(2.0)\cdot10^{34}$
Repetition rate (Hz)	50			
Loaded accel. gradient MV/m	80		100	
Main linac RF frequency GHz	12			
Bunch charge10^9	6.8		3.72	
Bunch separation (ns)	0.5			
Beam pulse duration (ns)	177		156	
Beam power/beam MWatts	4.9		14	
Hor./vert. norm. emitt ($10^{-6}/10^{-9}$)	3/40	2.4/25	2.4/20	0.66/20
Hor/Vert FF focusing (mm)	10/0.4	8 / 0.1		4 / 0.1
Hor./vert. IP beam size (nm)	248 / 5.7	202 / 2.3	83 / 1.1	40 / 1
Hadronic events/crossing at IP	0.07	0.19	0.75	2.7
Coherent pairs at IP	10	100	$5.\ 10^7$	$3.8\ 10^8$
BDS length (km)	1.87		2.75	
Total site length km	13.0		48.3	
Wall plug to beam transfert eff	7.5%		6.8%	
Total power consumption MW	129.4		415	

CLIC Accelerating Structure

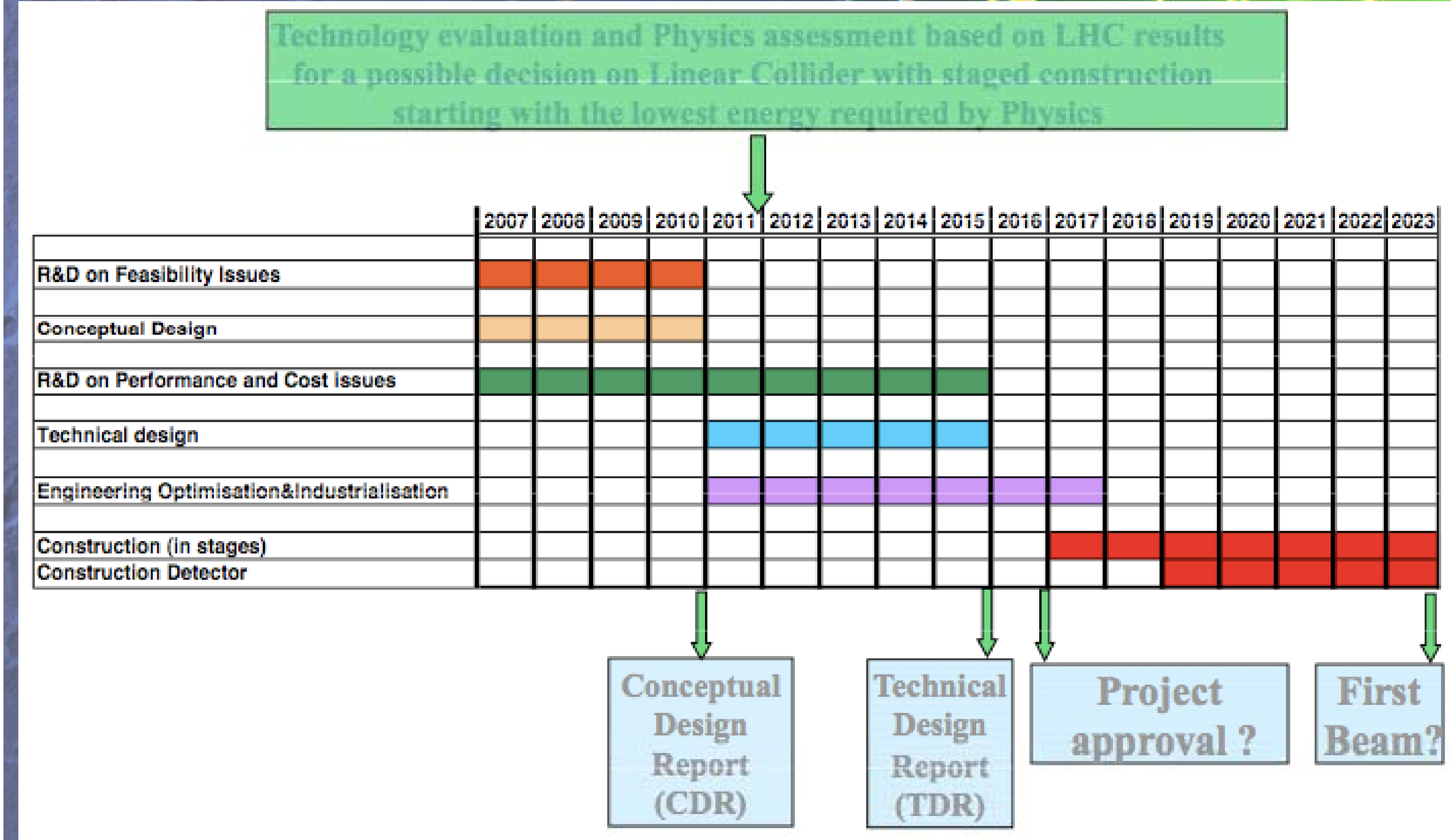


Nominal Performance Demonstrated

A shining example of fruitful collaboration: *Designed at CERN,*
Built at KEK,
RF Tested at SLAC

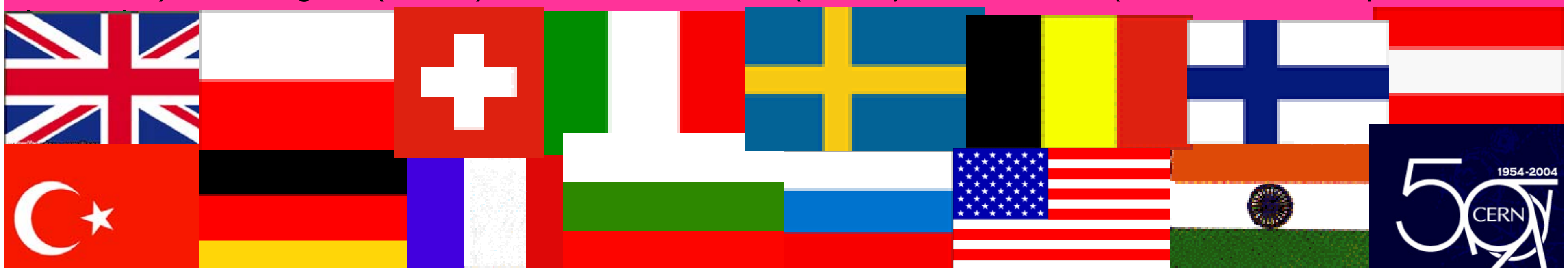


Possible CLIC Timeline

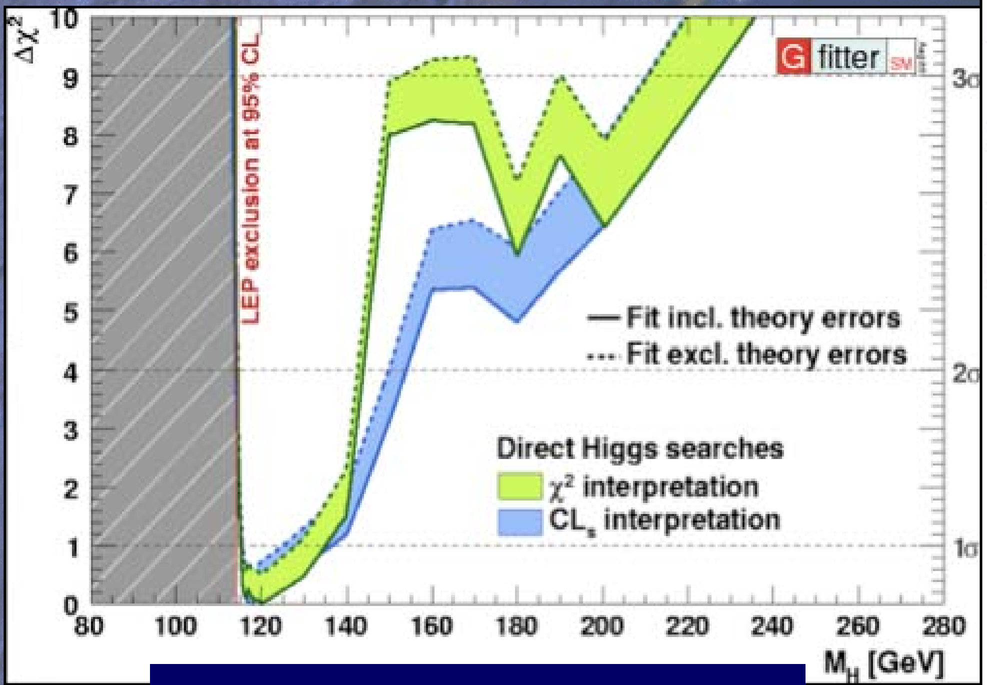


Physics at the CLIC Multi-TeV Linear Collider

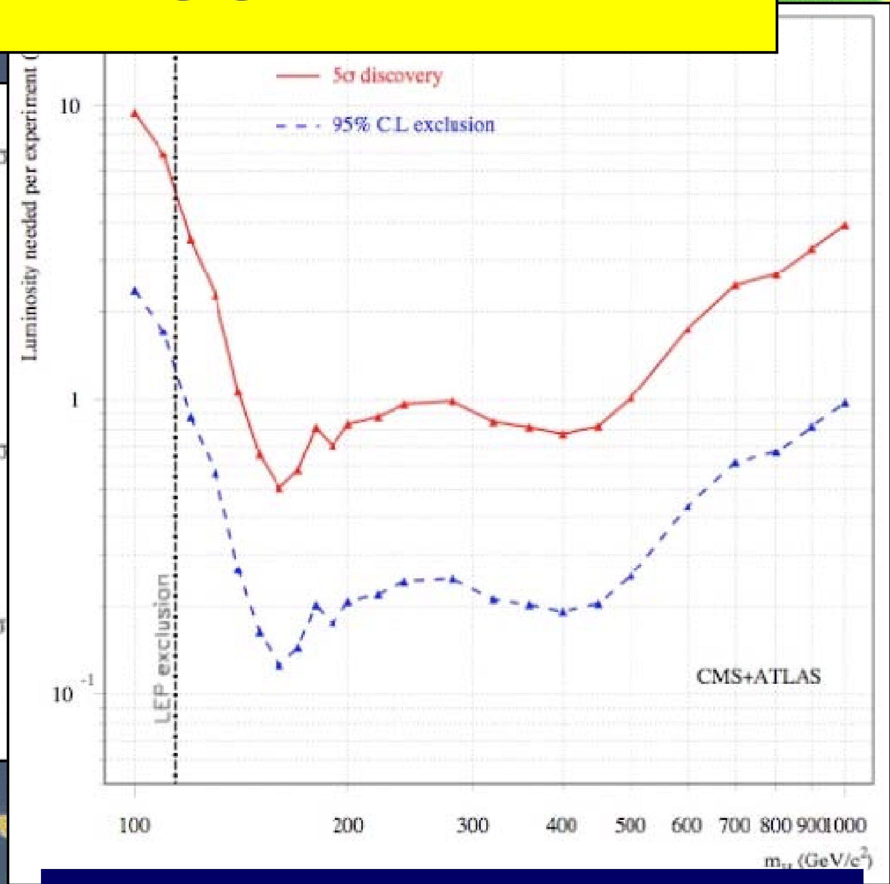
E. Accomando (INFN, Torino), **E. Ateser** (Kafkas Univ.), **D. Bardin** (JINR, Dubna), **M. Battaglia** (LBL and UC Berkeley), **T. Barklow** (SLAC), **S. Berge** (Univ. of Hamburg), **G. Blair** (Royal Holloway College, Univ. of London), **E.Boos** (INP, Moscow), **F. Boudjema** (LAPP, Annecy), **H. Braun** (CERN), **H.Burkhardt** (CERN), **M.Cacciari** (Univ. Parma), **O. Çakir** (Univ. of Ankara), **S. De Curtis** (INFN and Univ. of Florence), **A. De Roeck** (CERN), **M. Diehl** (DESY), **A. Djouadi** (Montpellier), **D. Dominici** (Univ. of Florence), **J. Ellis** (CERN), **A. Ferrari** (Uppsala Univ.), **A. Frey** (CERN), **G. Giudice** (CERN), **R. Godbole** (Bangalore), **M. Gruwe** (CERN), **G. Guignard** (CERN), **S. Heinemeyer** (CERN), **C. Heusch** (UC Santa Cruz), **J. Hewett** (SLAC), **S. Jadach** (INP, Krakow), **P. Jarron** (CERN), **M. Klasen** (Univ. of Hamburg), **Z. Kirca** (Univ. of Meselik), **M. Kraemer** (Univ. of Edinburgh), **S. Kraml** (CERN), **G. Landsberg** (Brown Univ.), **K. Matchev** (Univ. of Florida), **G. Moortgat-Pick** (Univ. of Durham), **M.Muehlleitner** (PSI, Villigen), **O. Nachtmann** (Univ. of Heidelberg), **F. Nagel** (Univ. of Heidelberg), **K.Olive** (Univ. of Minnesota), **G.Pancheri** (LNF, Frascati), **L. Pape** (CERN), **M. Piccolo** (LNF, Frascati), **W. Porod** (Univ. of Zurich), **P. Richardson** (Univ. of Durham), **T. Rizzo** (SLAC), **M. Ronan** (LBL, Berkeley), **C. Royon** (CEA, Saclay), **L. Salmi** (HIP, Helsinki), **R. Settles** (MPI, Munich), **D. Schulte** (CERN), **T.Sjöstrand** (Lund Univ.), **M. Spira** (PSI, Villigen), **S. Sultansoy** (Univ. of Ankara), **V. Telnov** (Novosibirsk, IYF), **D. Treille** (CERN), **C. Verzegnassi** (Univ. of Trieste), **J. Weng** (CERN, Univ. of Karlsruhe), **T.Wengler** (CERN), **A. Werthenbach** (CERN), **G. Wilson** (Univ. of Kansas), **I. Wilson**



Waiting for the Higgs boson



Higgs probability distribution:
combining direct,
indirect information



How soon will the Higgs be found? …

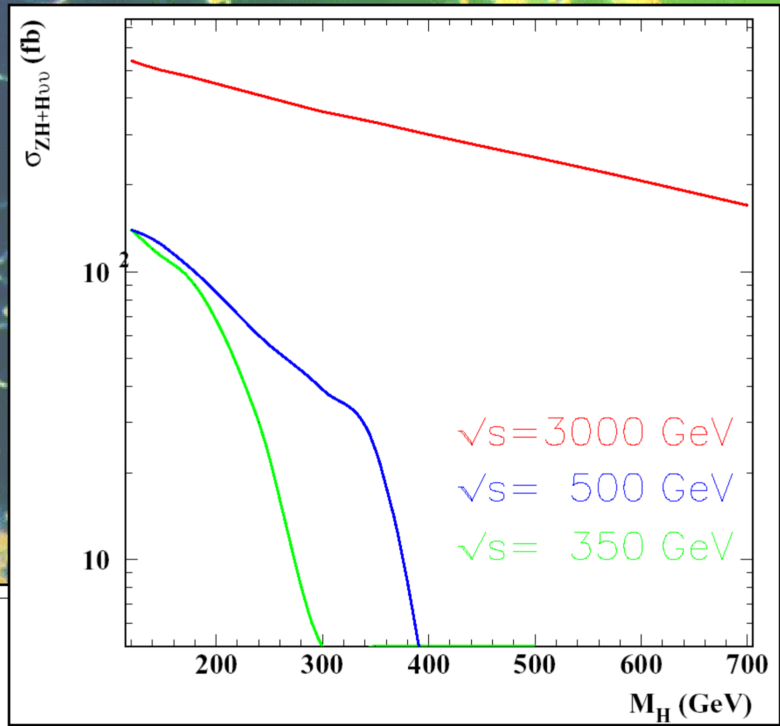
The Tevatron or LHC may soon say the Higgs cannot have an intermediate mass: must be either LIGHT, or HEAVY …?

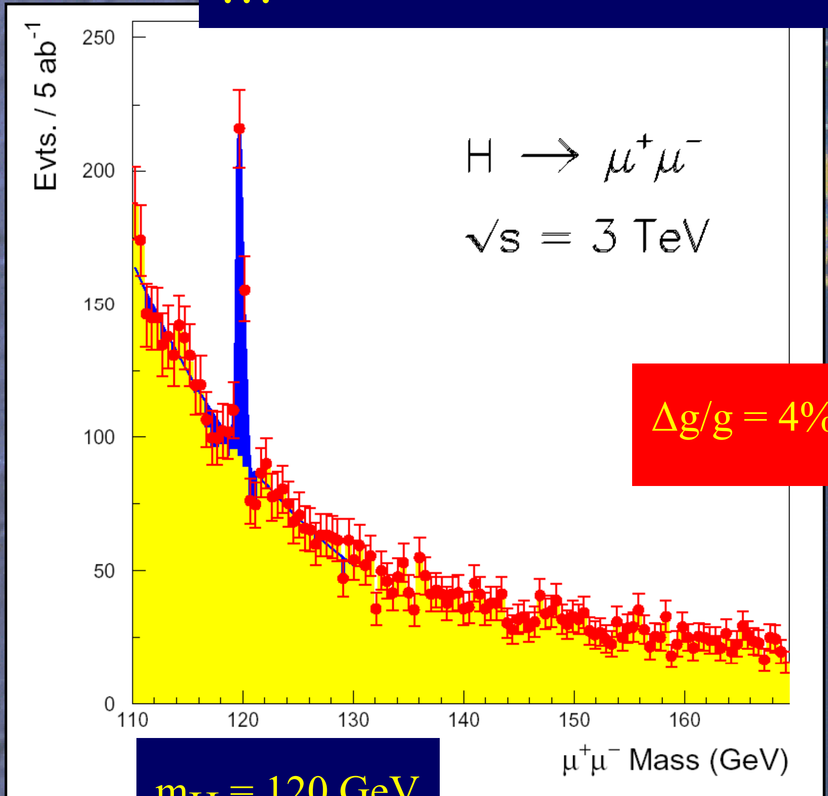
If there is a light Higgs boson …

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

Large Cross Section @ CLIC

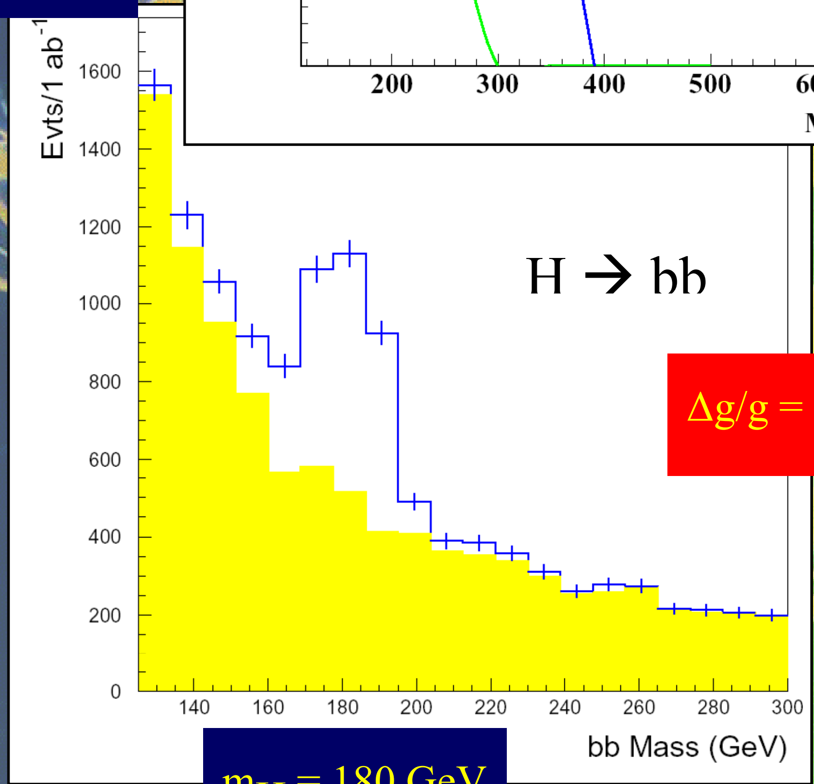
Can measure rare decay modes …





$\Delta g/g = 4\%$

$m_H = 120$ GeV



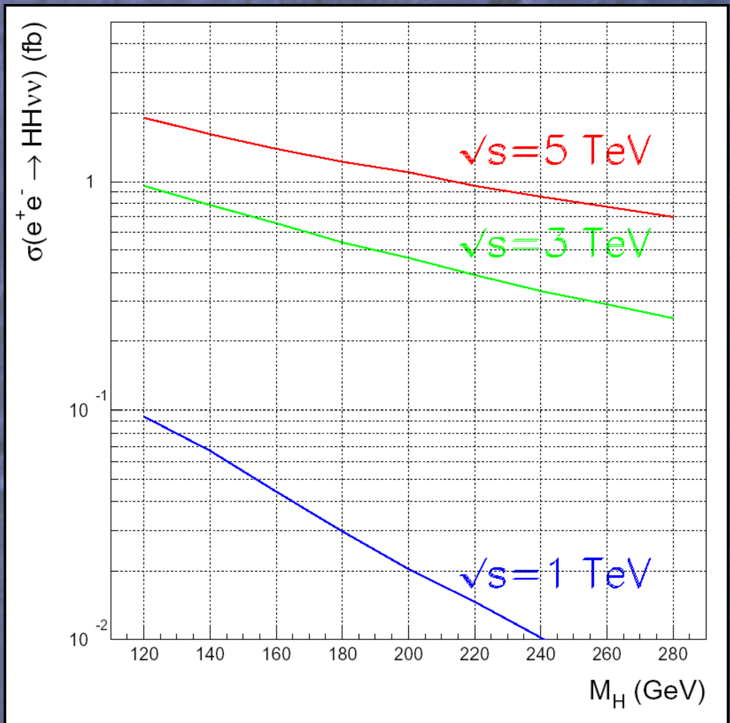
$\Delta g/g = 2\%$

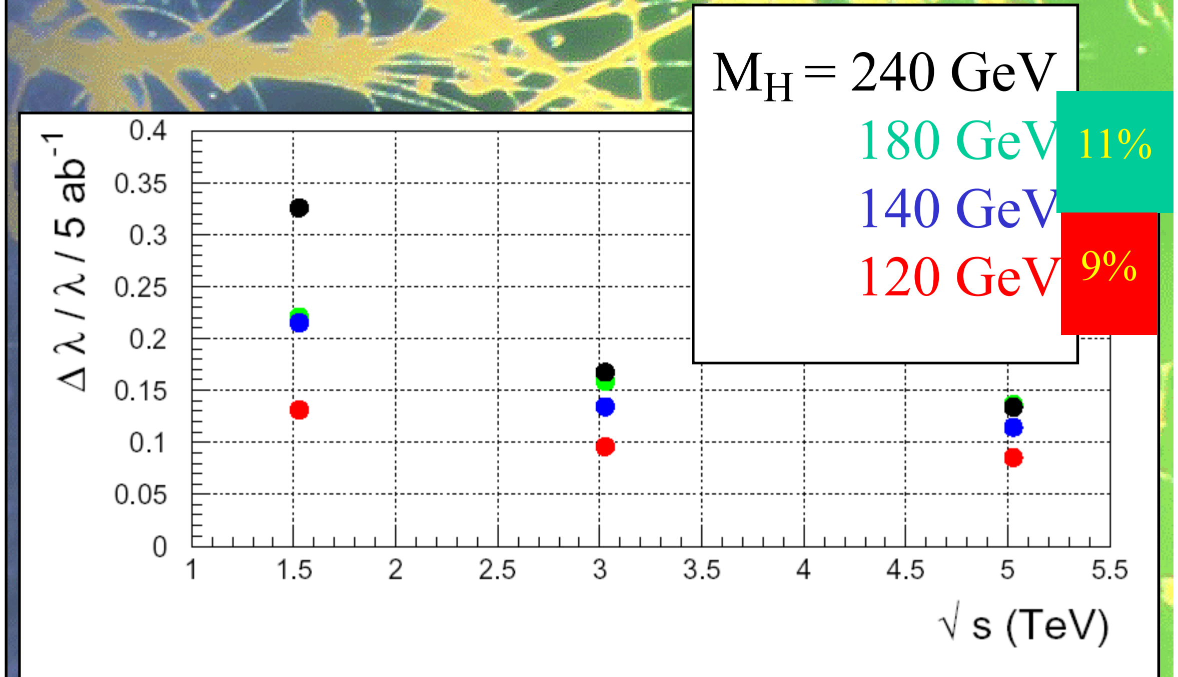
$m_H = 180$ GeV

Measure Effective Higgs Potential

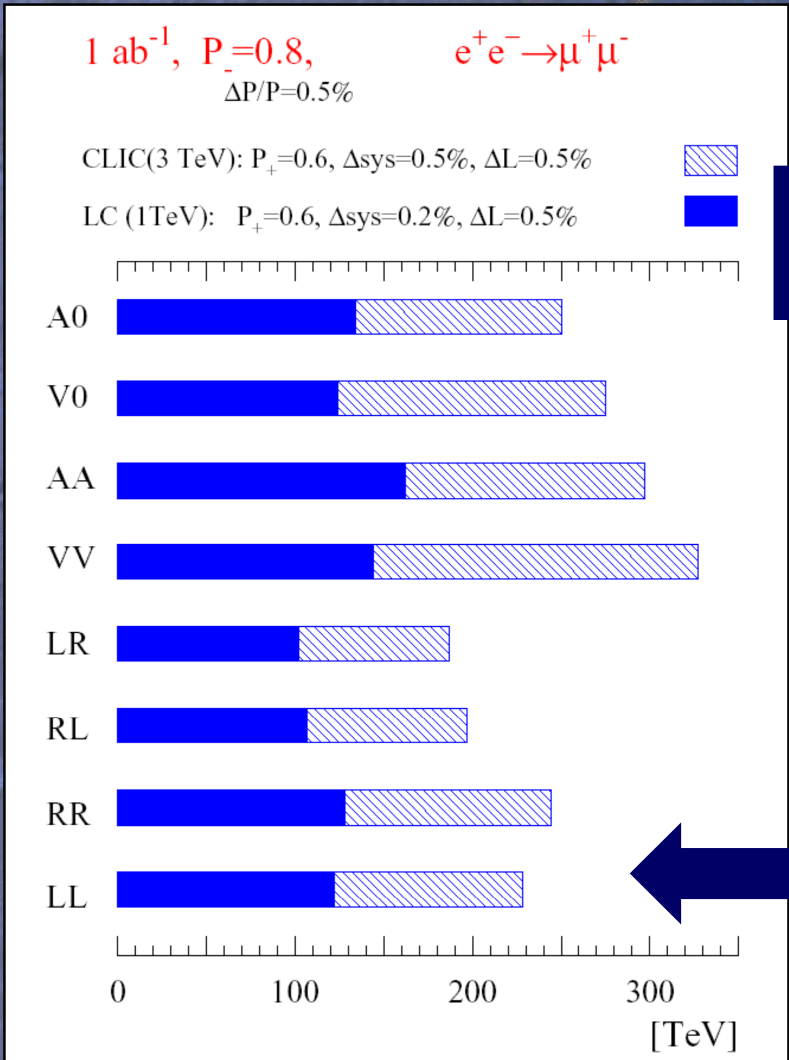
Large cross section
for HH pair production

Accuracy in measurement of HHH coupling

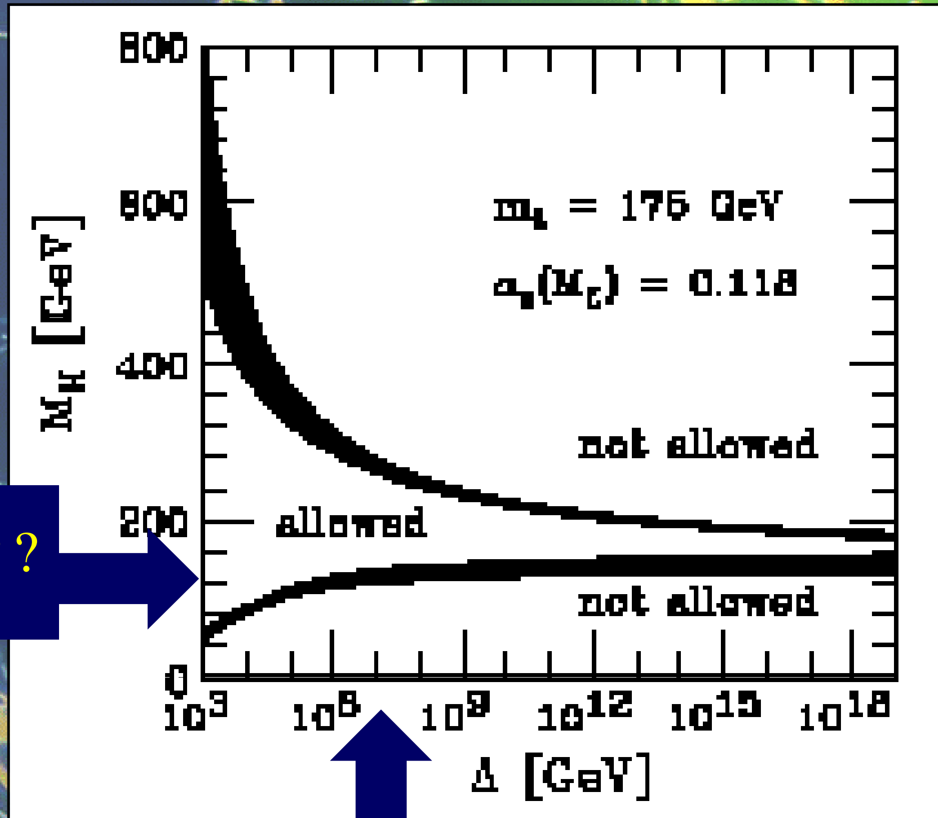




If the Higgs is light …



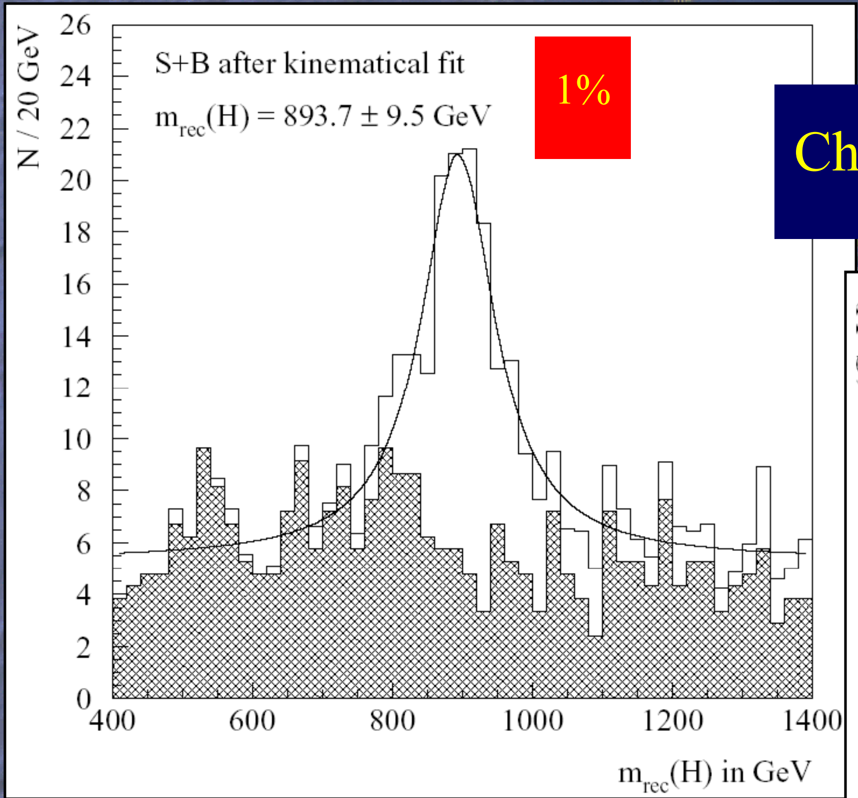
LEP ?



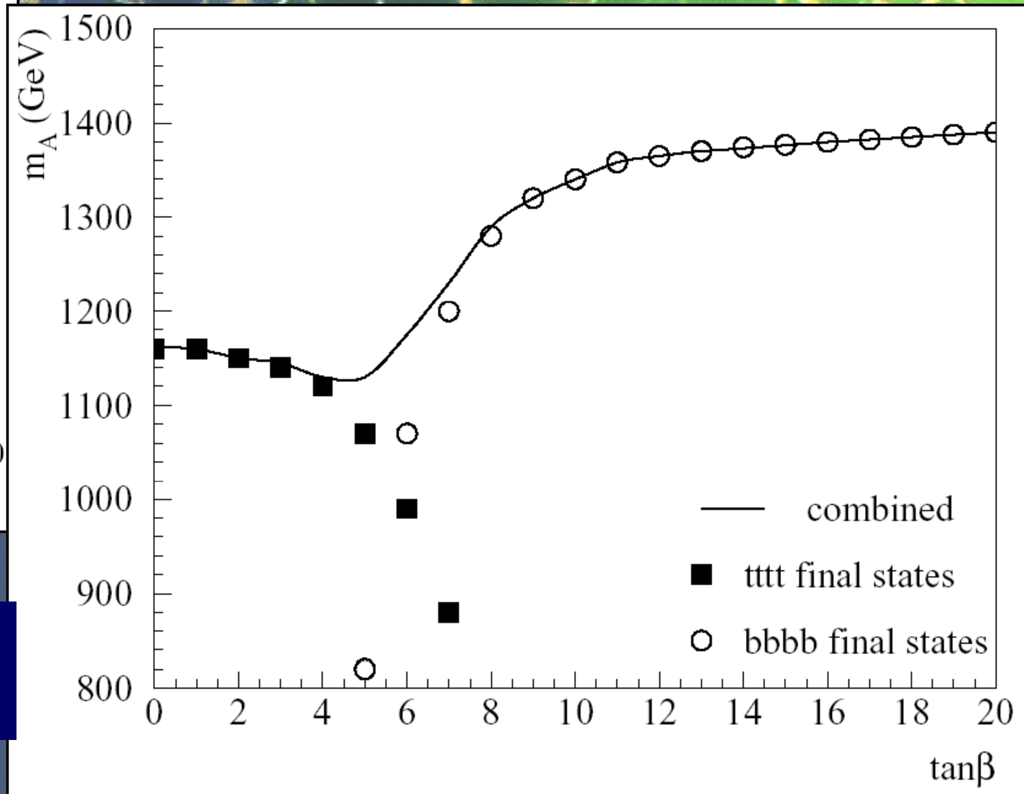
There must be new physics below 1000 TeV …

… and CLIC has a good chance to find it in contact interactions

Identify Heavier Partner Higgses



Charged …



… or neutral

Theorists getting Cold Feet

- Little Higgs models

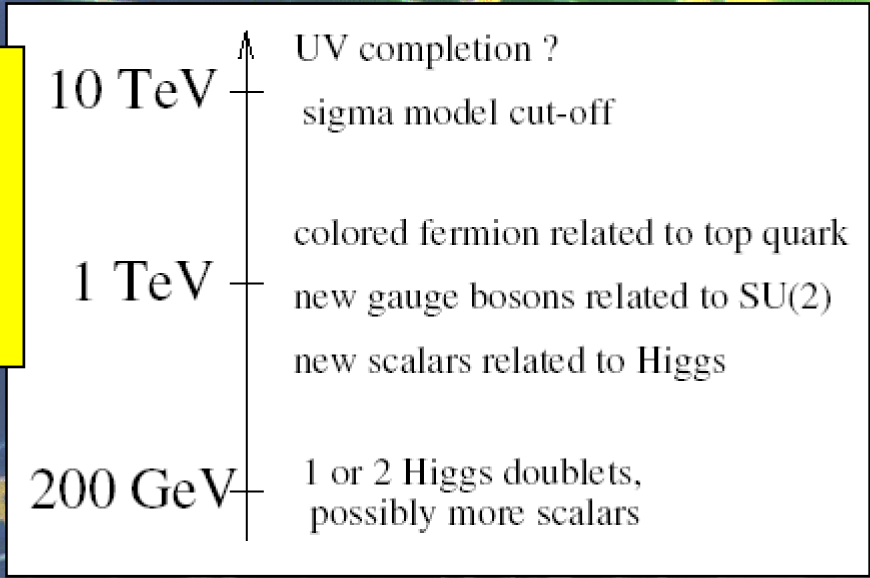
  extra ‘Top’, gauge bosons, ‘Higgses’
- Interpretation of EW data?

  consistency of measurements? heavier Higgs?
- Higgs + higher-dimensional operators?

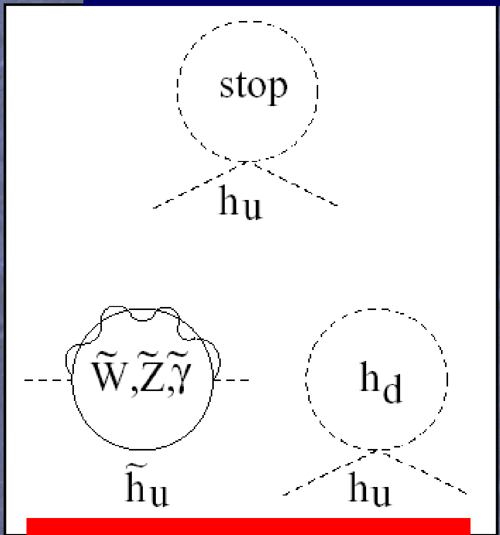
  corridors to higher Higgs masses?
- Higgsless models

  strong WW scattering, extra D?

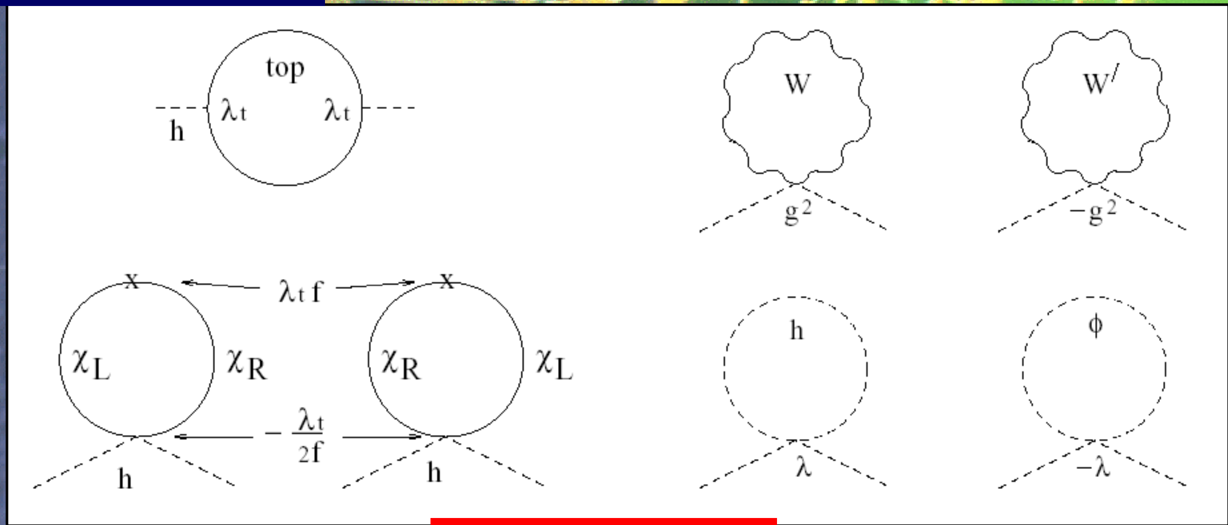
Generic Little Higgs Spectrum



Loop cancellation mechanisms



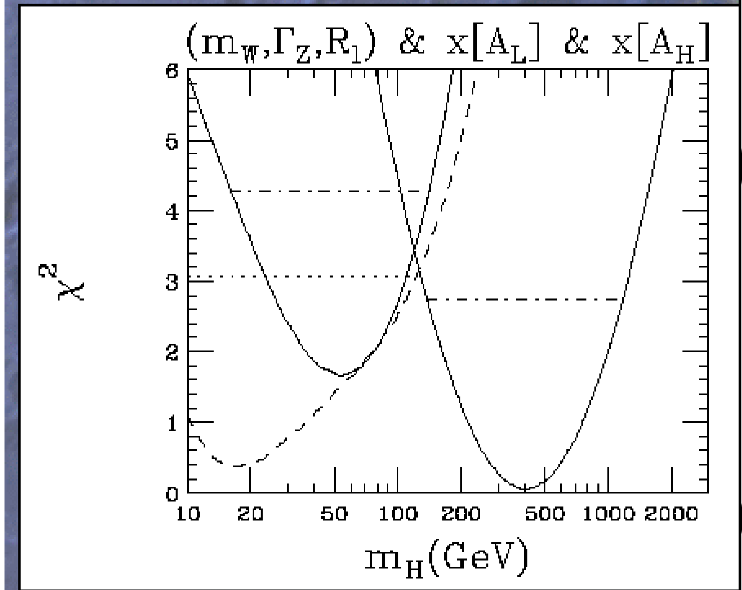
Supersymmetry



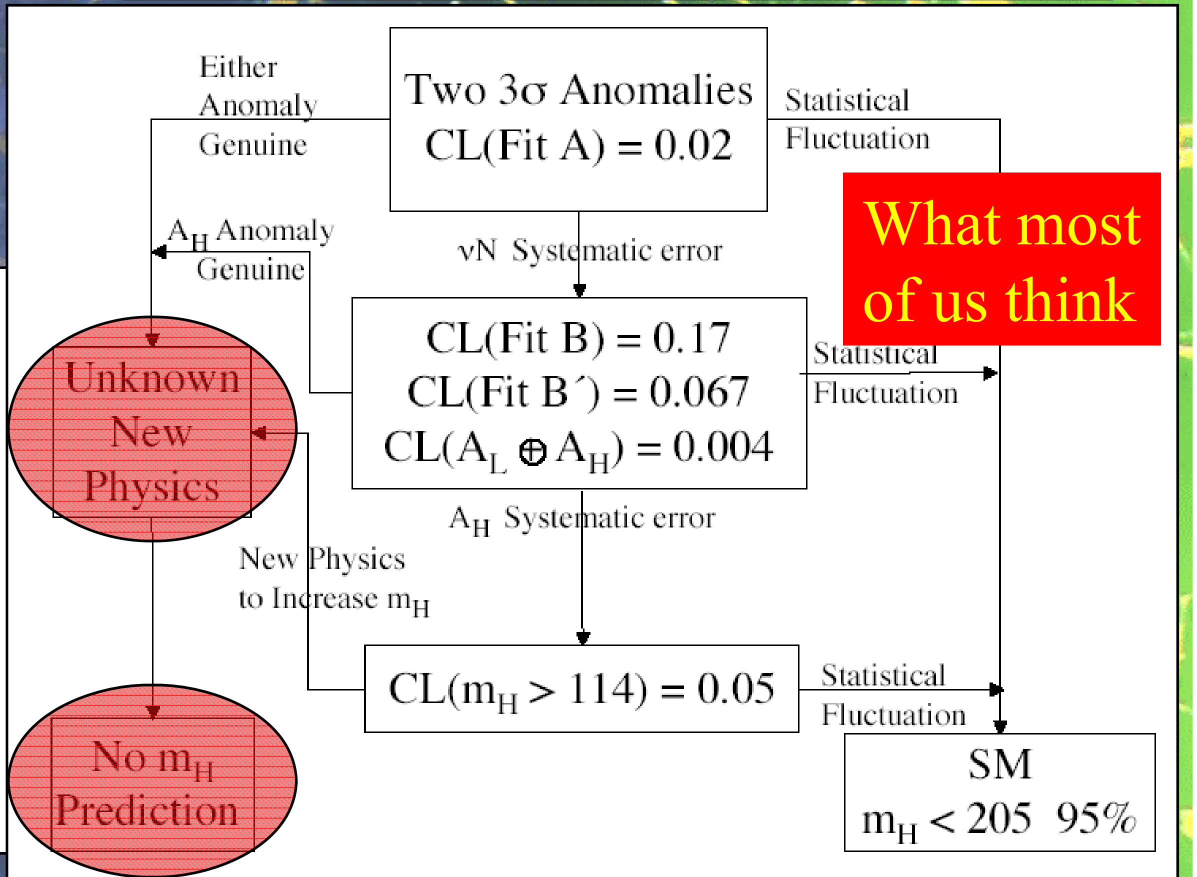
Little Higgs

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?



What most of us think

Higgs + Higher-Order Operators

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

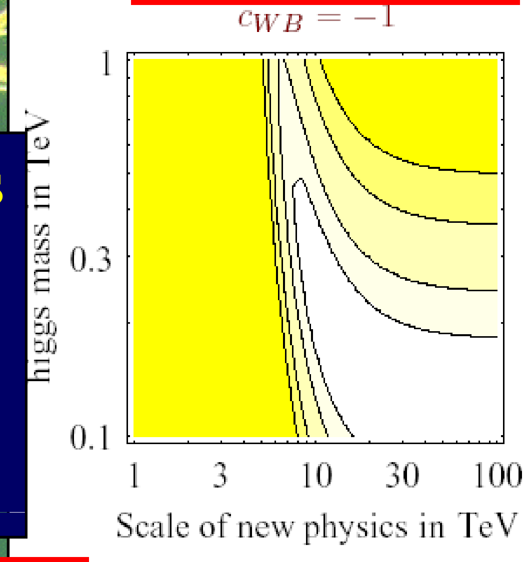
Precision EW data suggest they are small: why?

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 …?

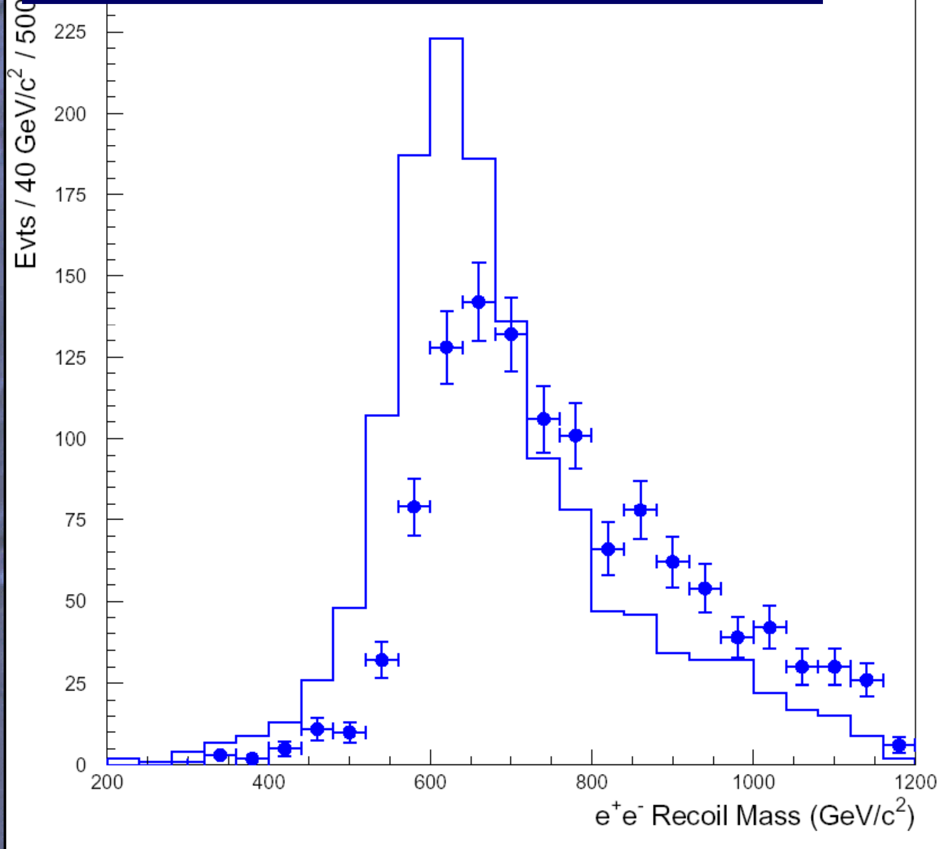
Corridor to heavy Higgs?



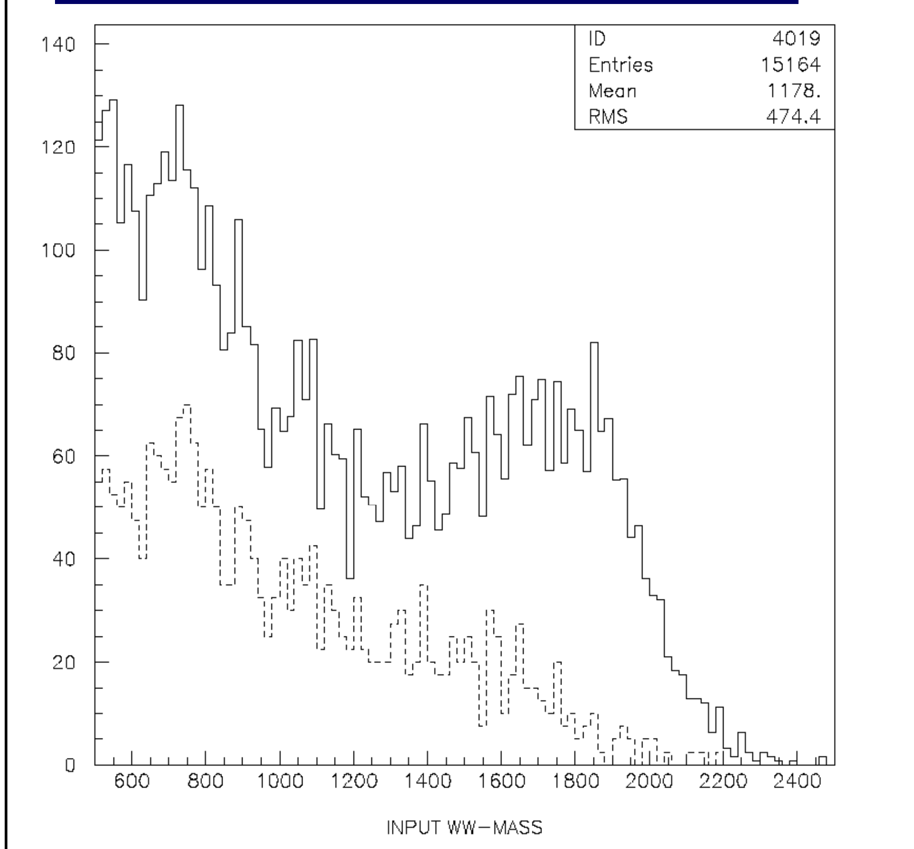
Do not discard possibility of heavy Higgs

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



If there is no Higgs boson …

- The LHC might find a hint of strong WW scattering
- The new physics might be invisible at a lower-energy $e^+ e^-$ collider
- CLIC could study strong WW scattering with high statistics and precision
- CLIC best placed to see/understand scenarios with composite Higgs/quarks/leptons

Why Supersymmetry (Susy)?

- Intrinsic beauty
- Hierarchy/naturalness problem
- Unification of the gauge couplings
- Predict light Higgs < 150 GeV
  - As suggested by precision electroweak data
- Cold dark matter
- Essential ingredient in string theory (?)

Current Constraints on the CMSSM

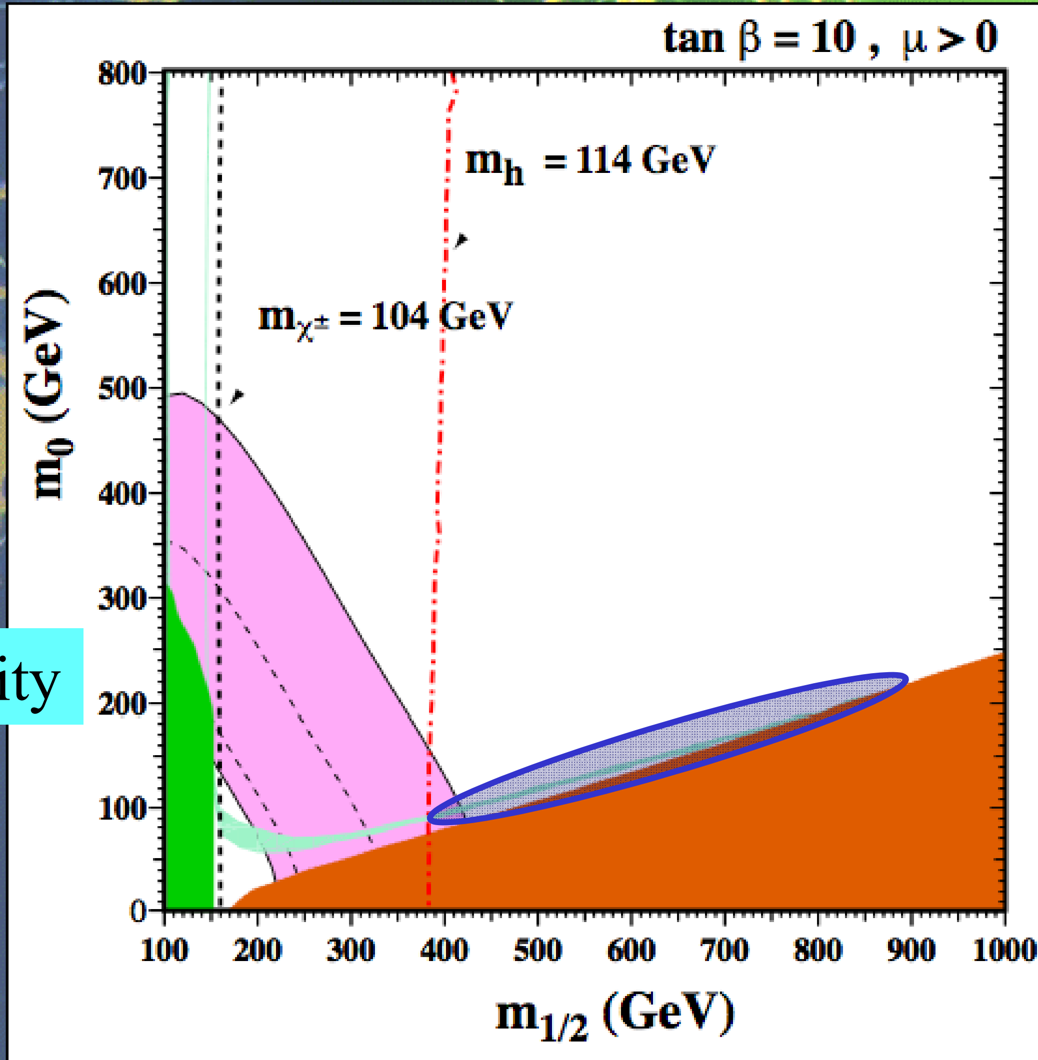
assuming neutralino LSP

Excluded because stau LSP

Excluded by b → s gamma

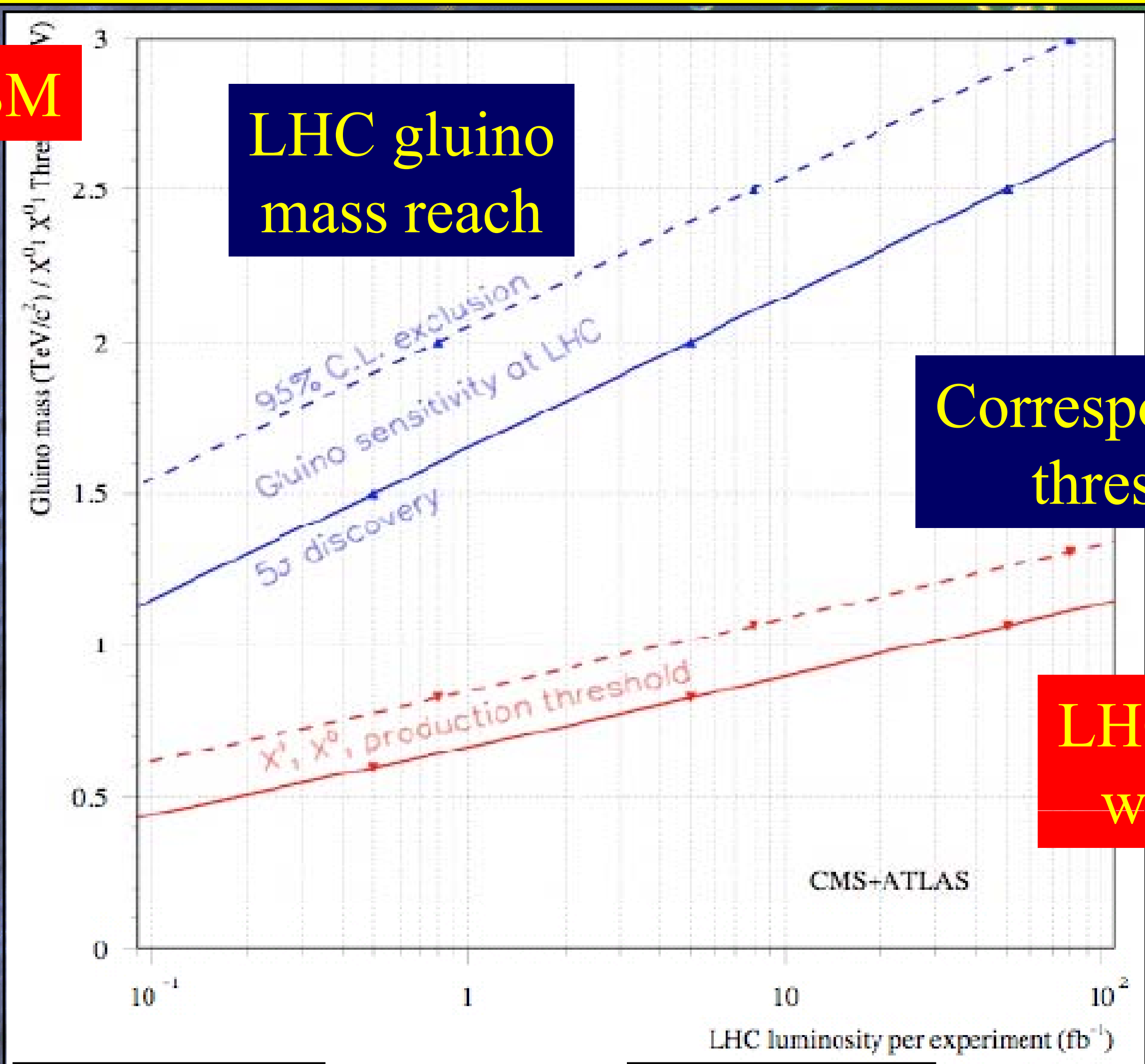
WMAP constraint on relic density

Favoured (?) by latest g - 2



Implications of LHC Search for LC

In CMSSM



Corresponding sparticle thresholds @ LC

LHC will tell LC where to look

‘month’ @ 10^{32}	‘month’ @ 10^{33}	1 ‘year’ @ 10^{33}	1 ‘year’ @ 10^{34}

Blaising, JE et al: 2006

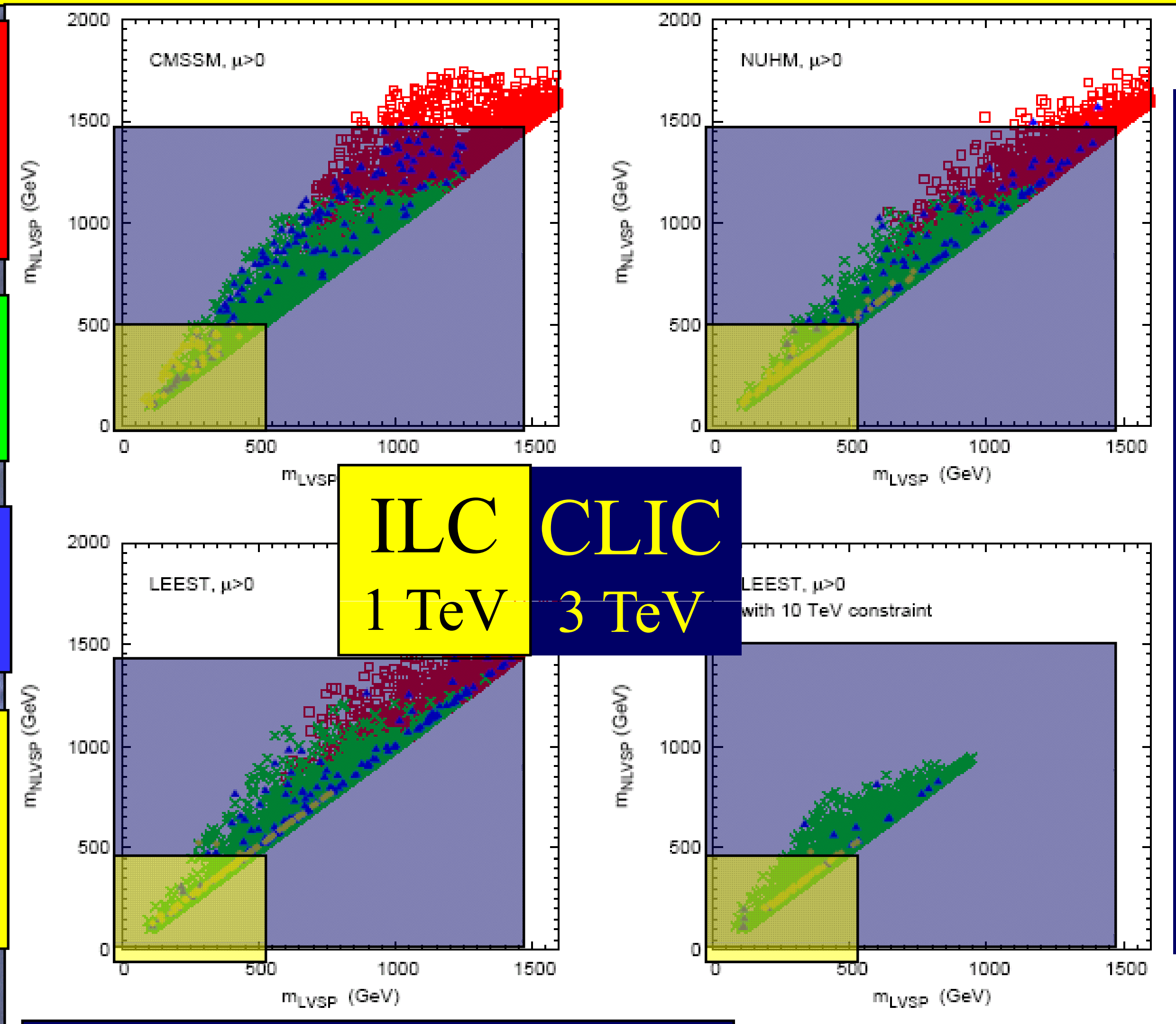
Sparticles may not be very light

Full Model samples

Detectable @ LHC

Provide Dark Matter

Dark Matter Detectable Directly

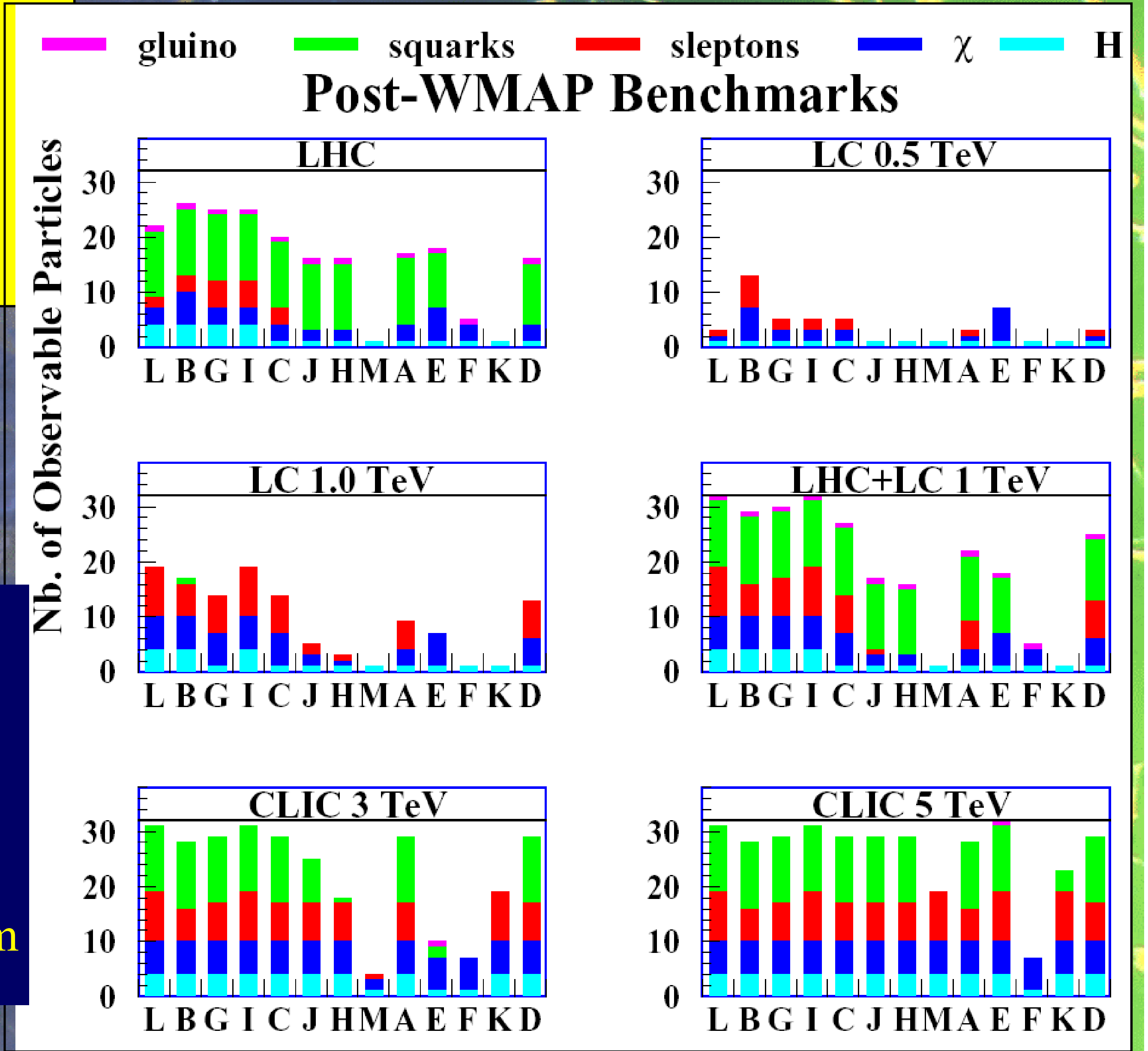


Lightest visible sparticle →

↑ Second lightest visible sparticle

JE + Olive + Santoso + Spanos

LHC and CLIC Scapabilities … and Other Accelerators

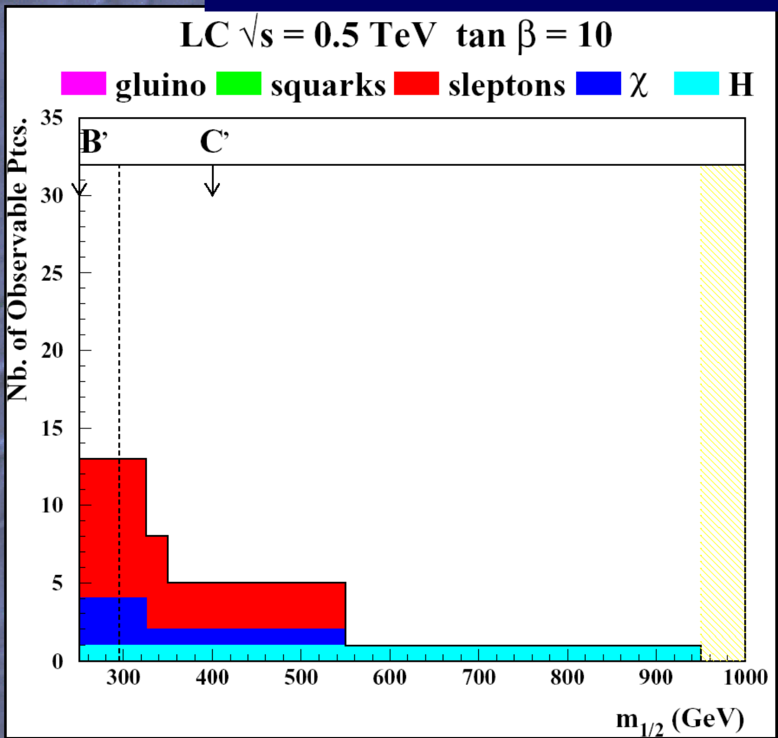


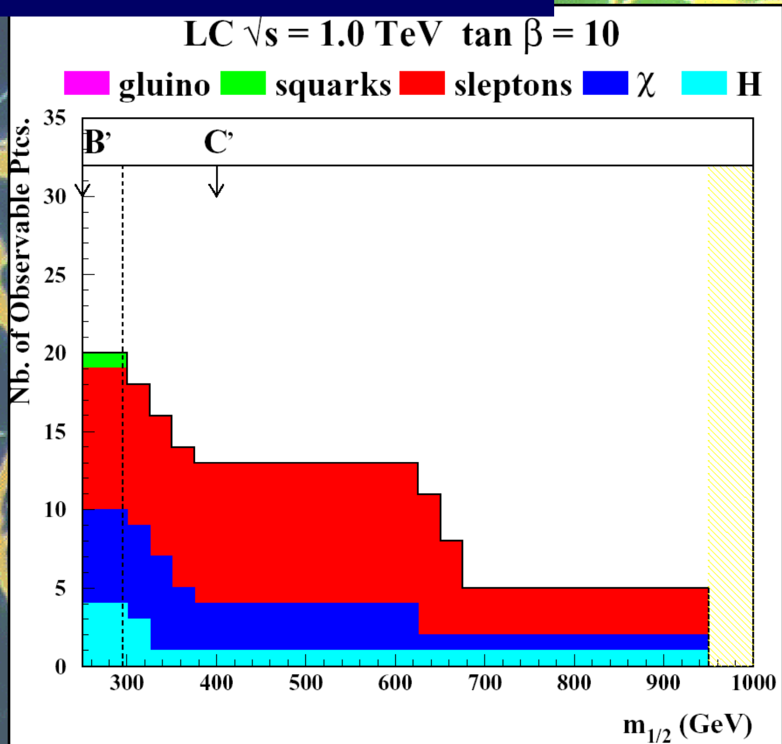
LHC almost 'guaranteed' to discover supersymmetry if it is relevant to the mass problem

Sparticles at Lower-Energy LC

CMSSM

Complementary to LHC: weakly-interacting sparticles

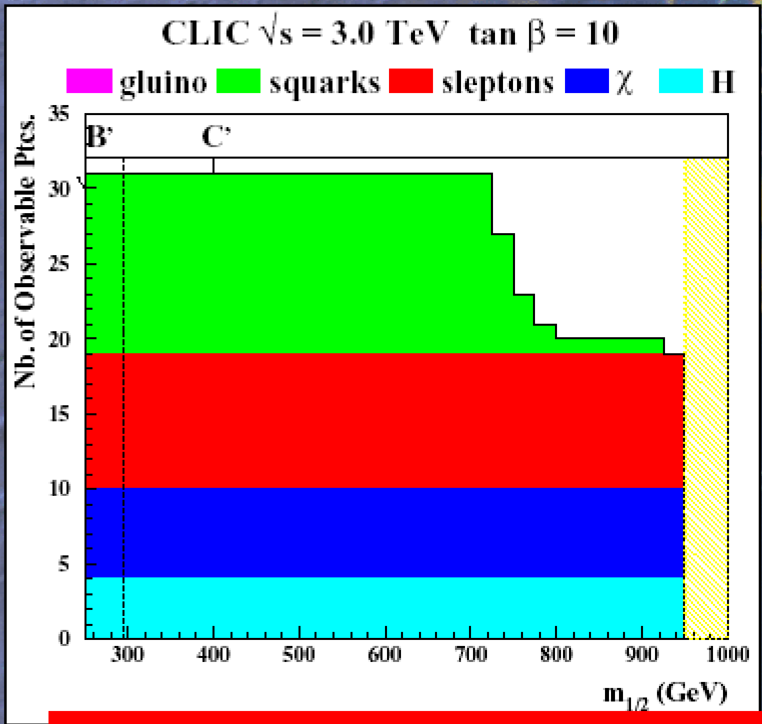




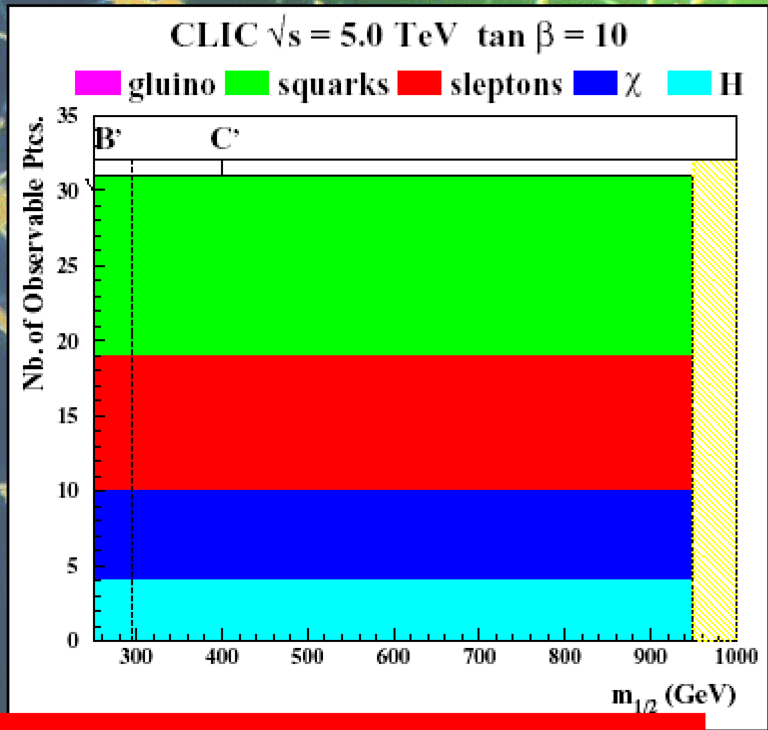
Sparticle Visibility at CLIC

CMSSM

3 TeV

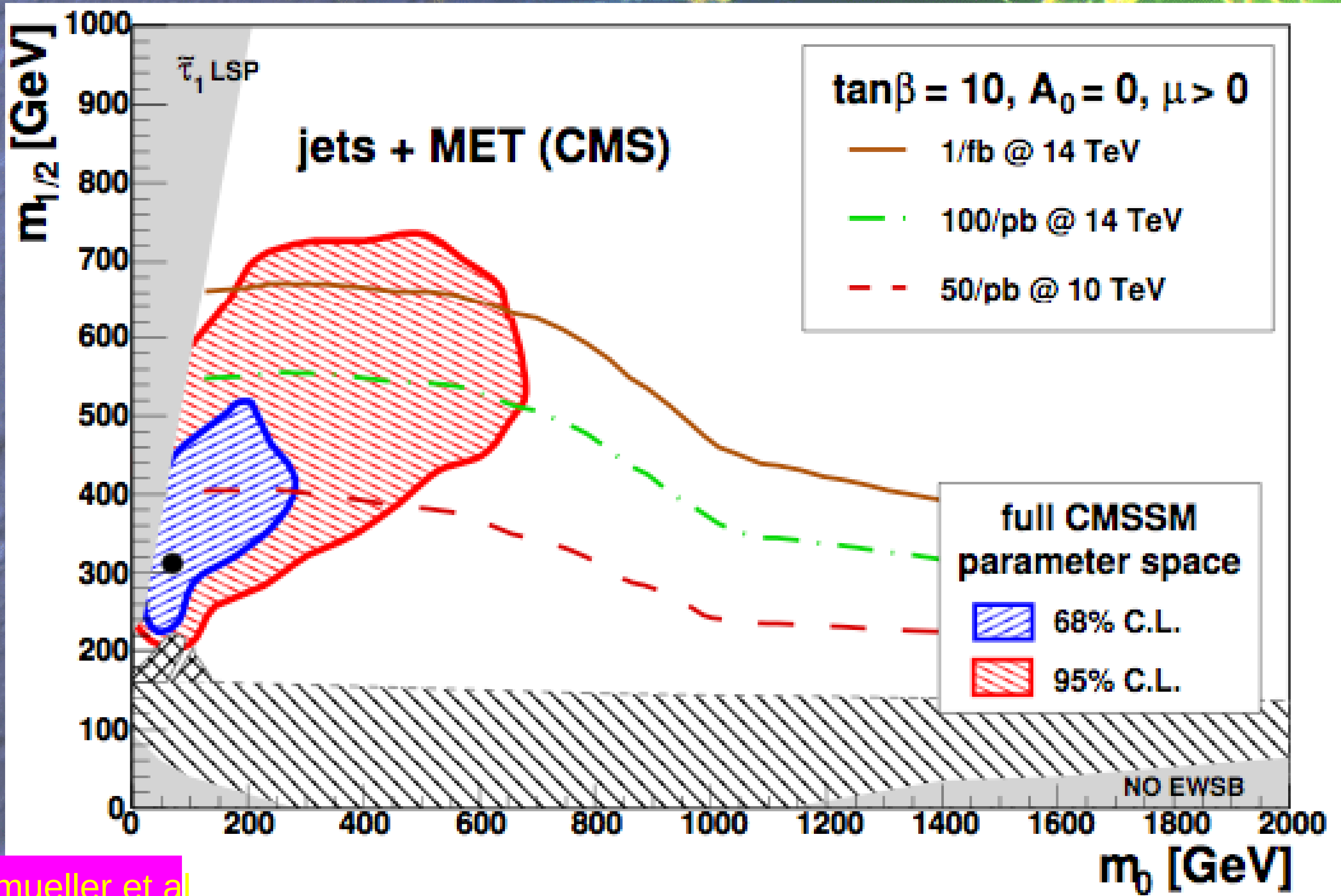


5 TeV



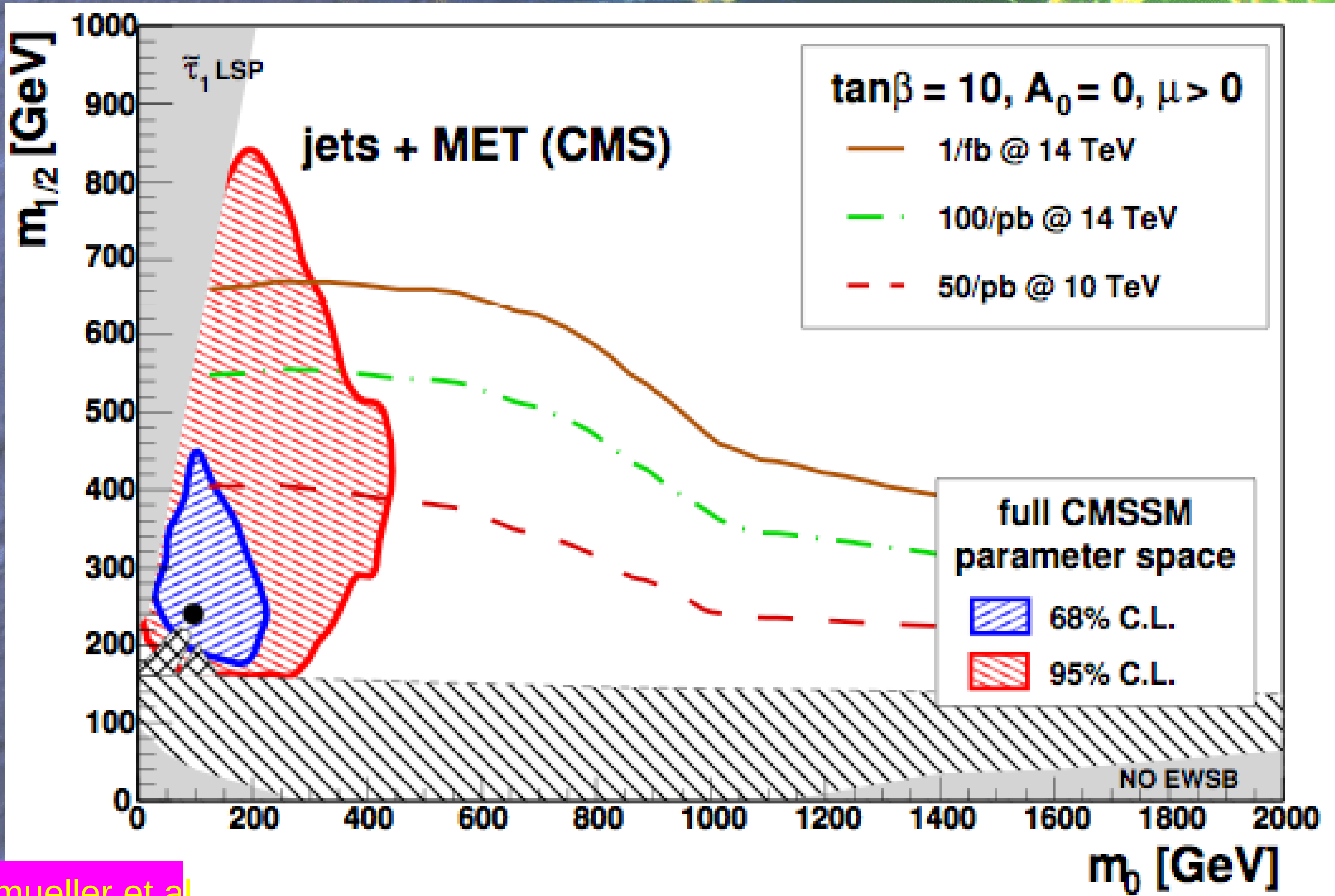
See 'all' sparticles: measure heavier ones better than LHC

How Soon Might the CMSSM be Detected?



O.Buchmueller et al

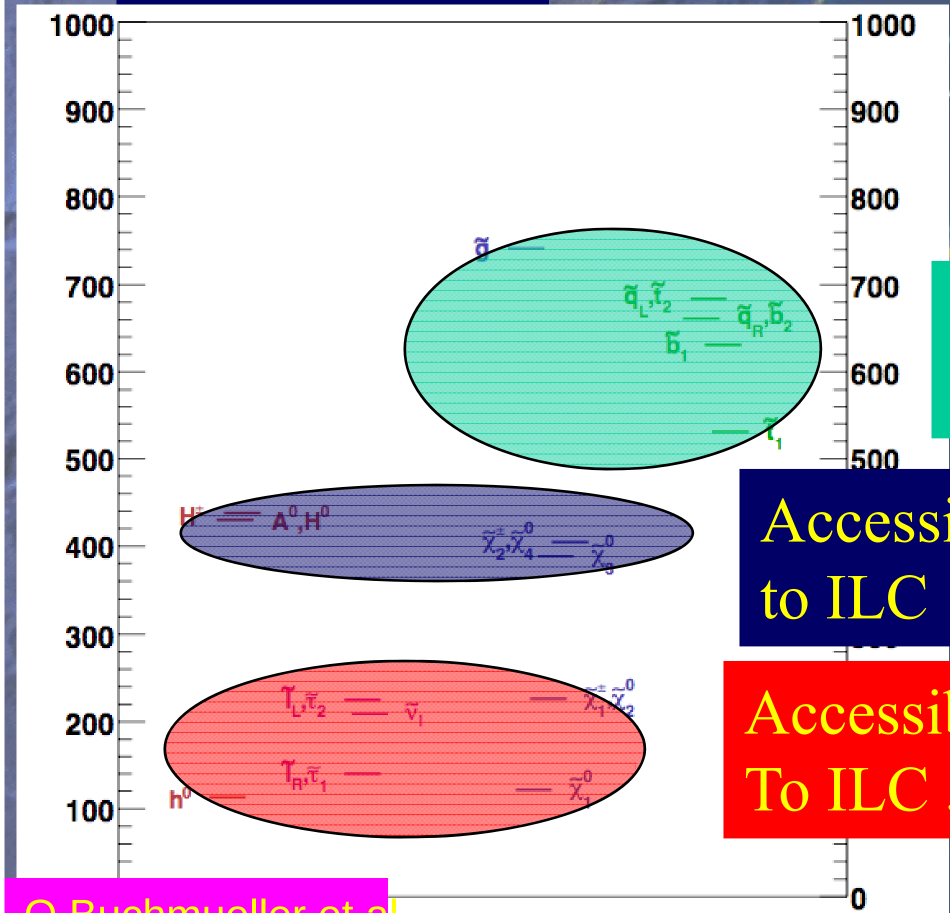
How Soon Might the NUHM1 be Detected?



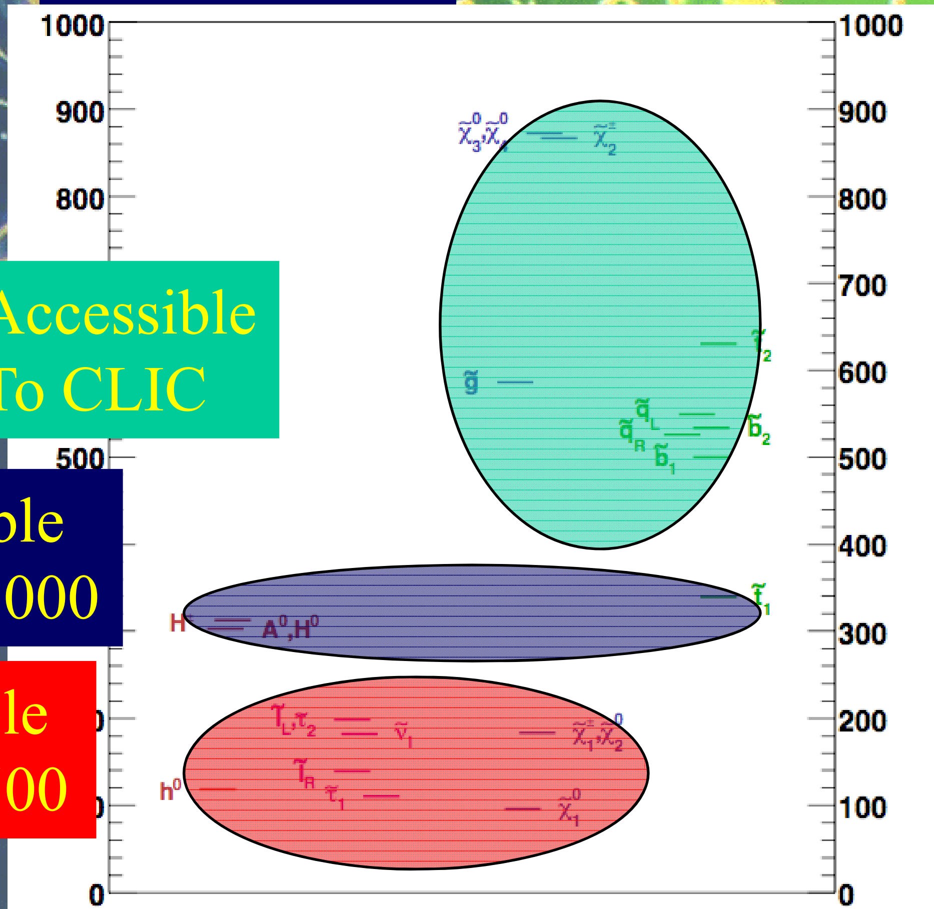
O.Buchmueller et al

Best-Fit Spectra

- CMSSM



- NUHM1



Accessible
To CLIC

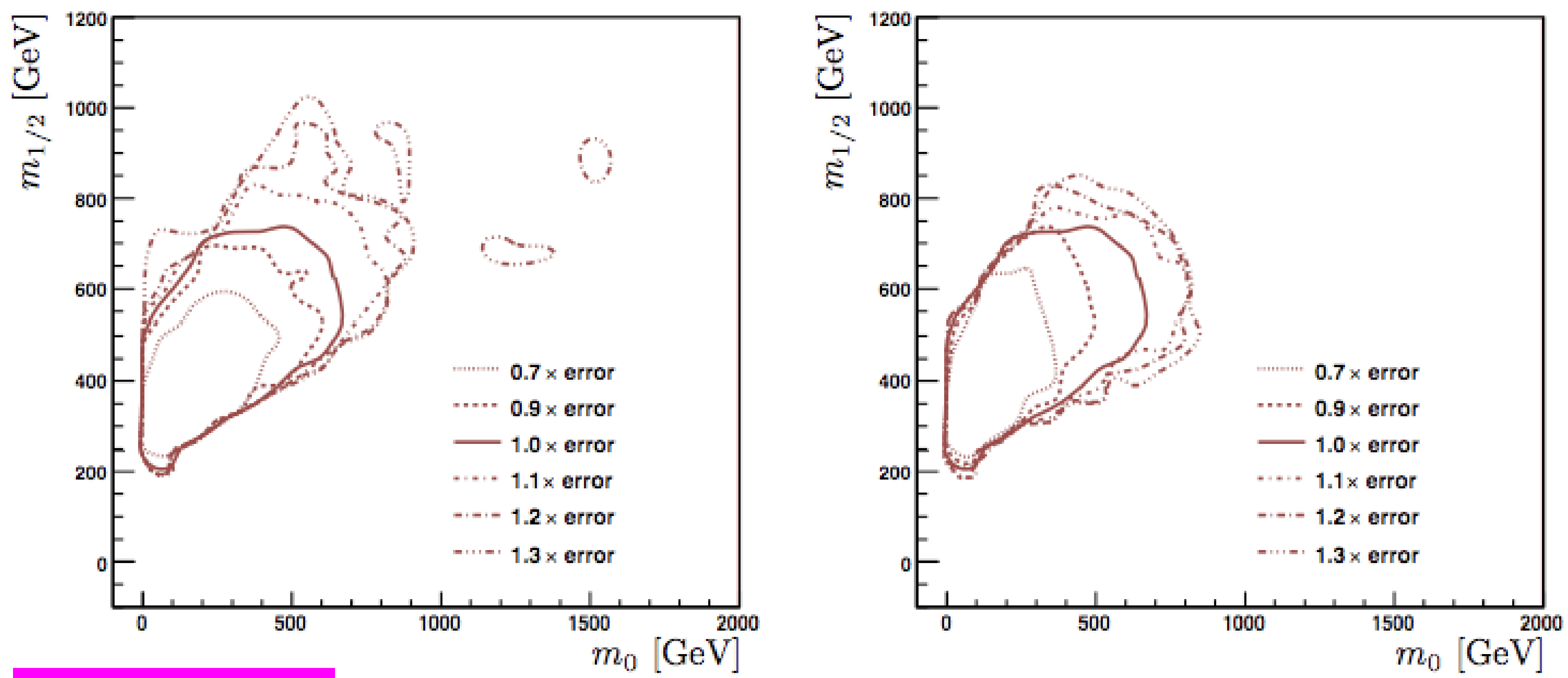
Accessible
to ILC 1000

Accessible
To ILC 500

O.Buchmueller et al

Sensitivity to Uncertainties

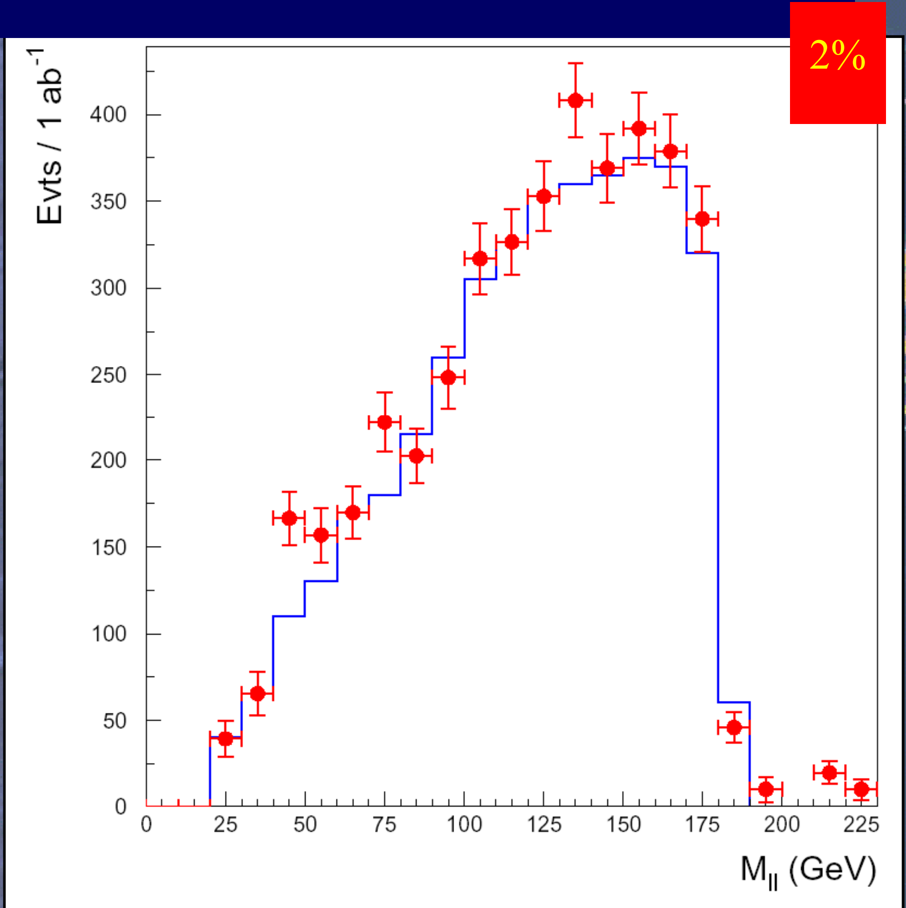
- $g_\mu - 2$
- $b \to s\gamma$



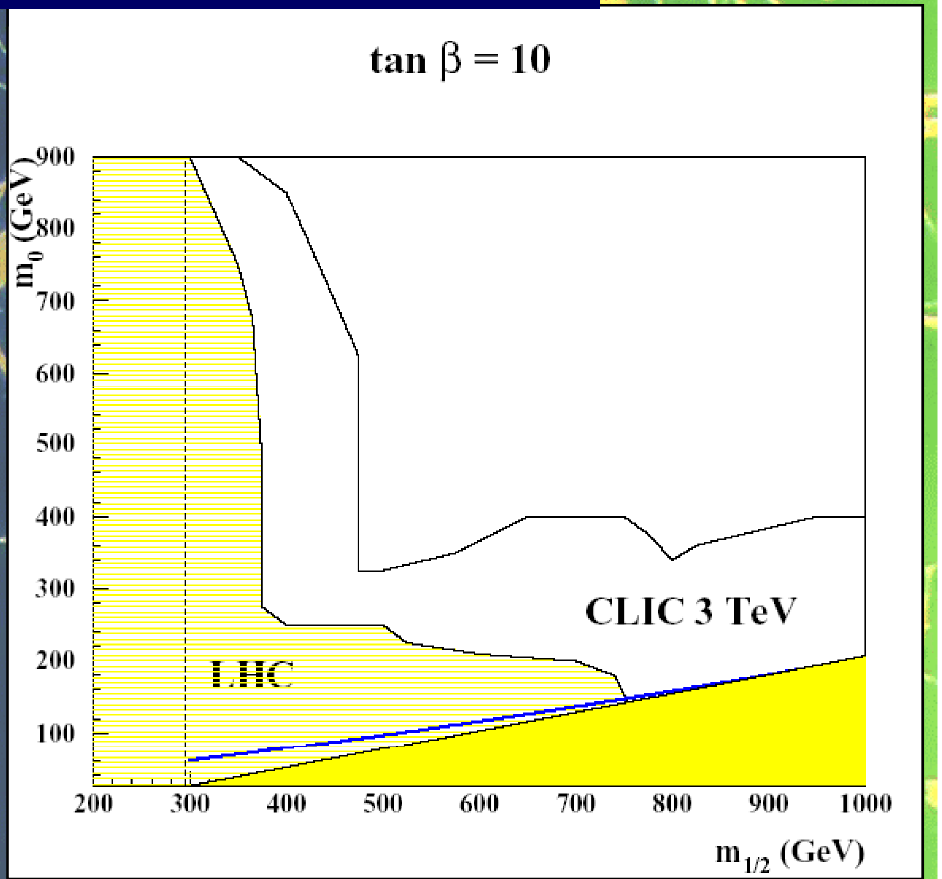
O.Buchmueller et al

Example of CLIC Sparticle Search

Dilepton spectrum in neutralino decay

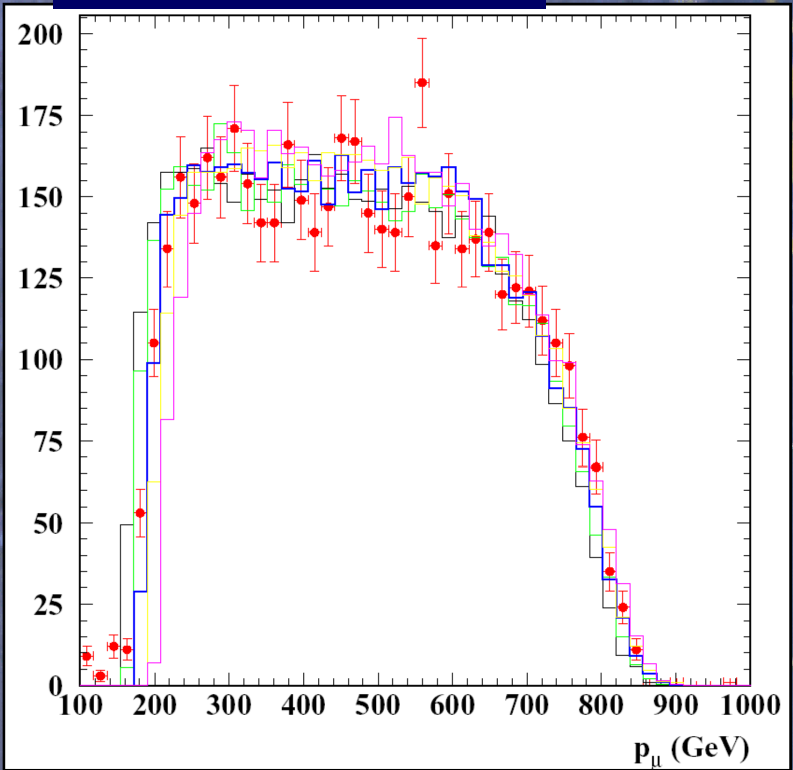


Reach in parameter space



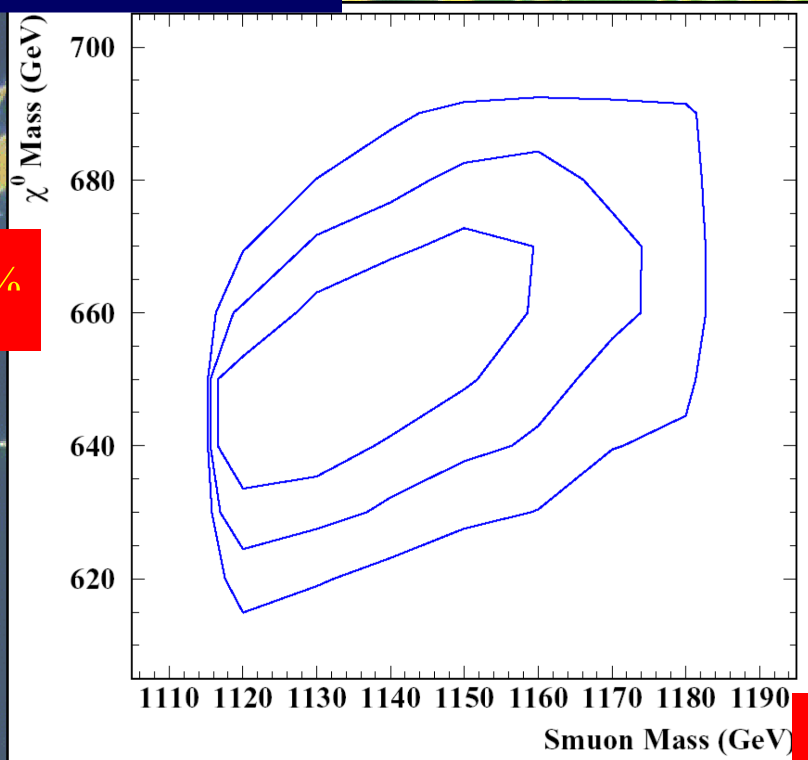
Measure Heavy Sleptons @ CLIC

Can measure smuon decay spectrum



Can measure sparticle masses

3%

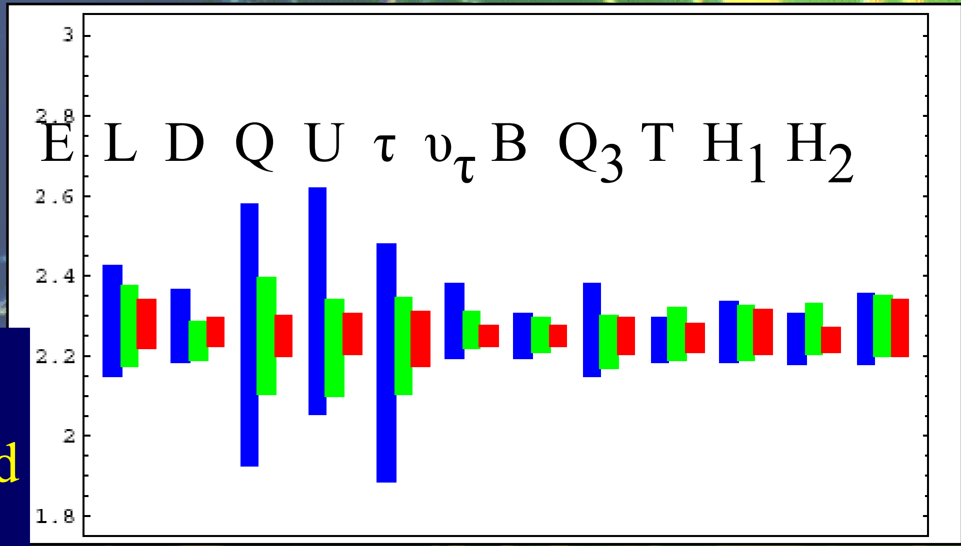


2.5%

If the LHC discovers supersymmetry …

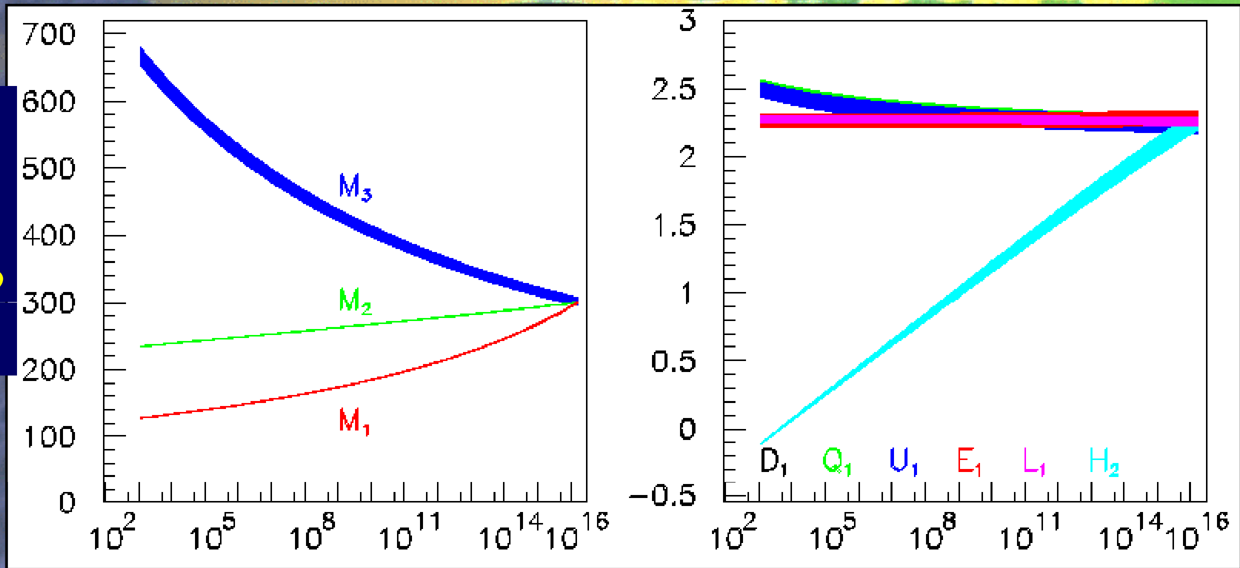
- CLIC could complete the spectrum
- CLIC would make many novel, detailed measurements
- Cast light on mechanism of supersymmetry breaking?
- Open a window on string physics?

Sparticle Mass Unification ?



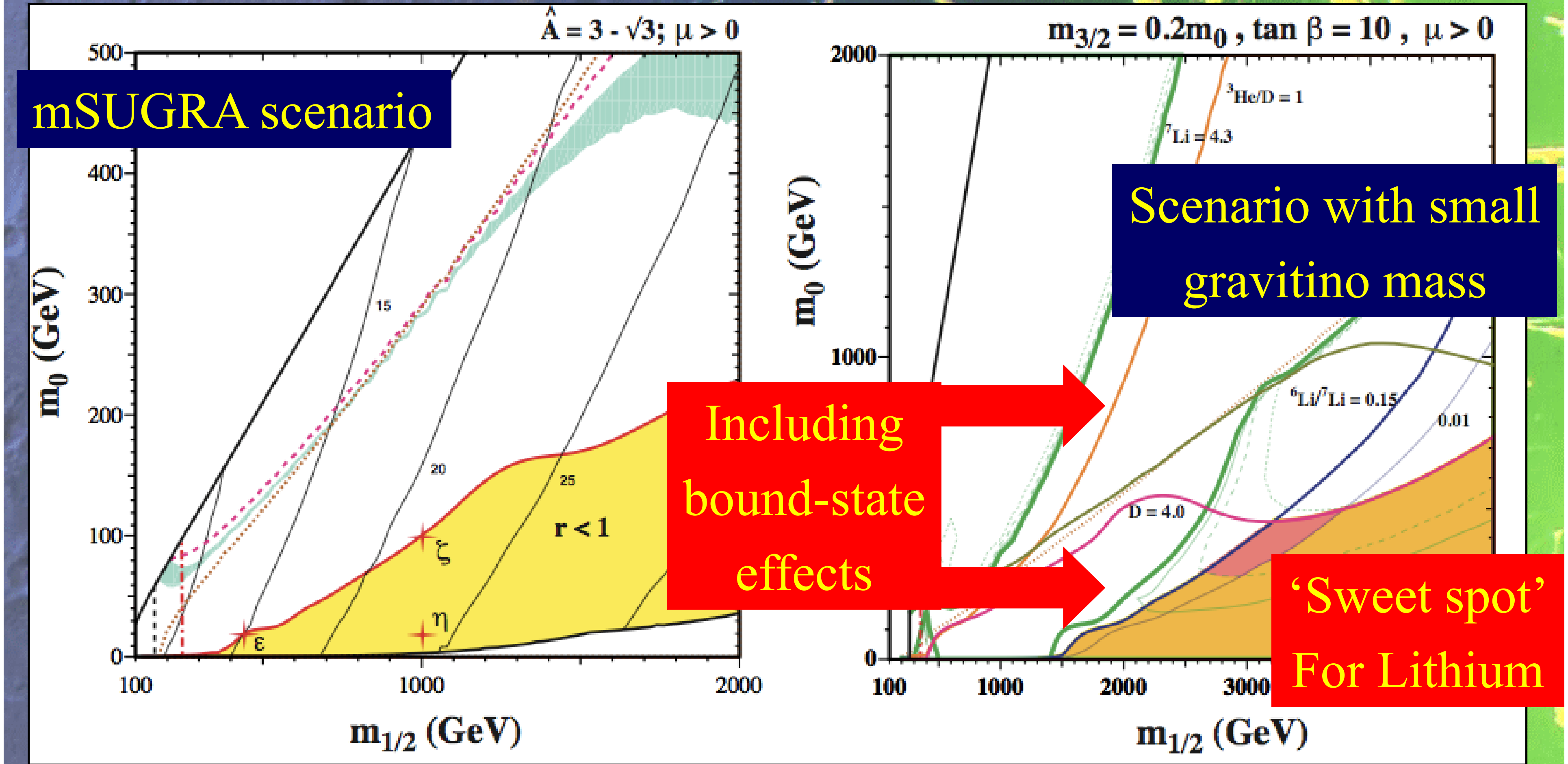
Accuracy in measuring sparticle masses squared

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



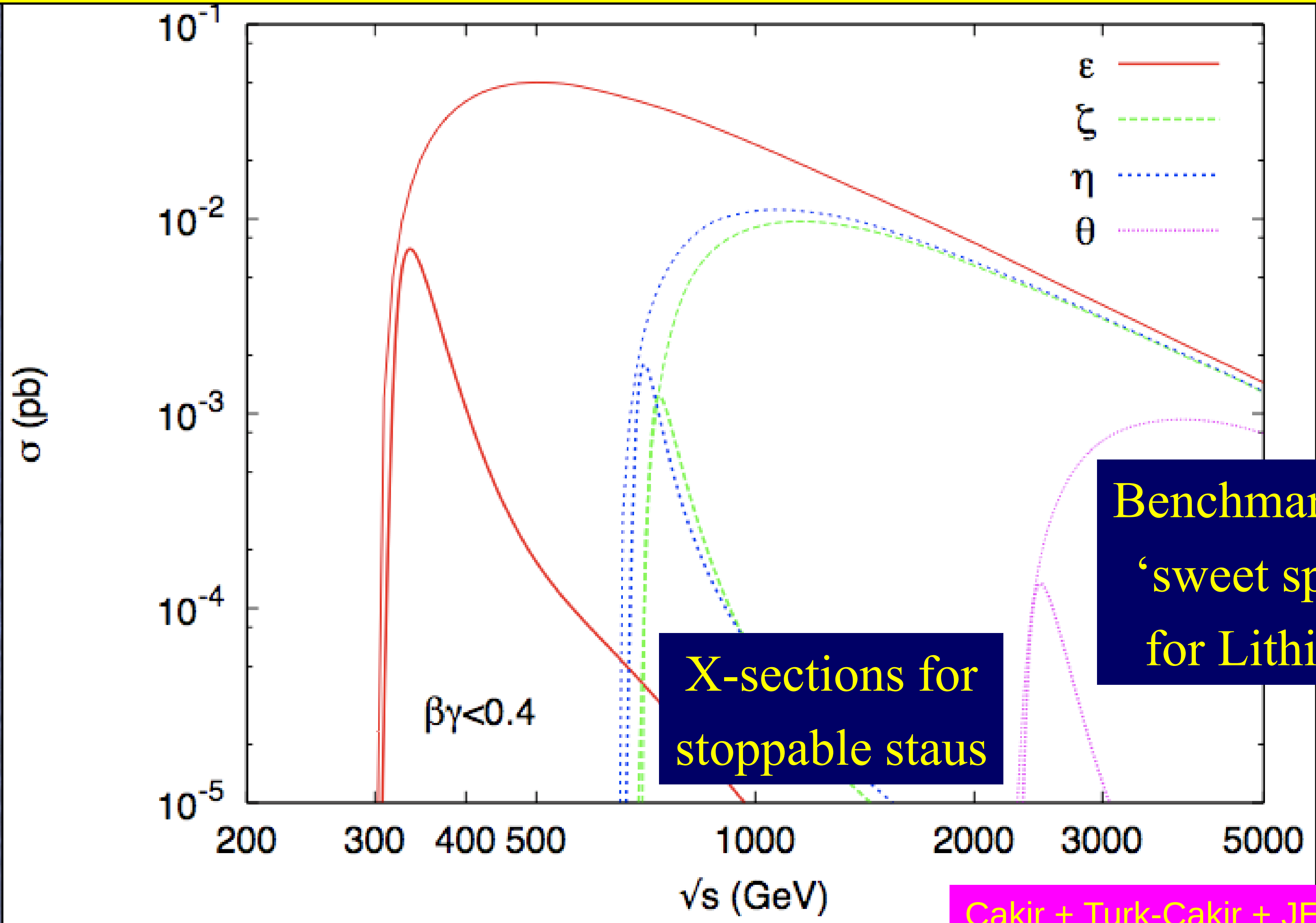
Gravitino Dark Matter Scenarios

with metastable stau as next-to-lightest sparticle



Cyburt, JE, Fields, Olive + Spanos

Cross Section for Stau Production in e^+e^- Annihilation



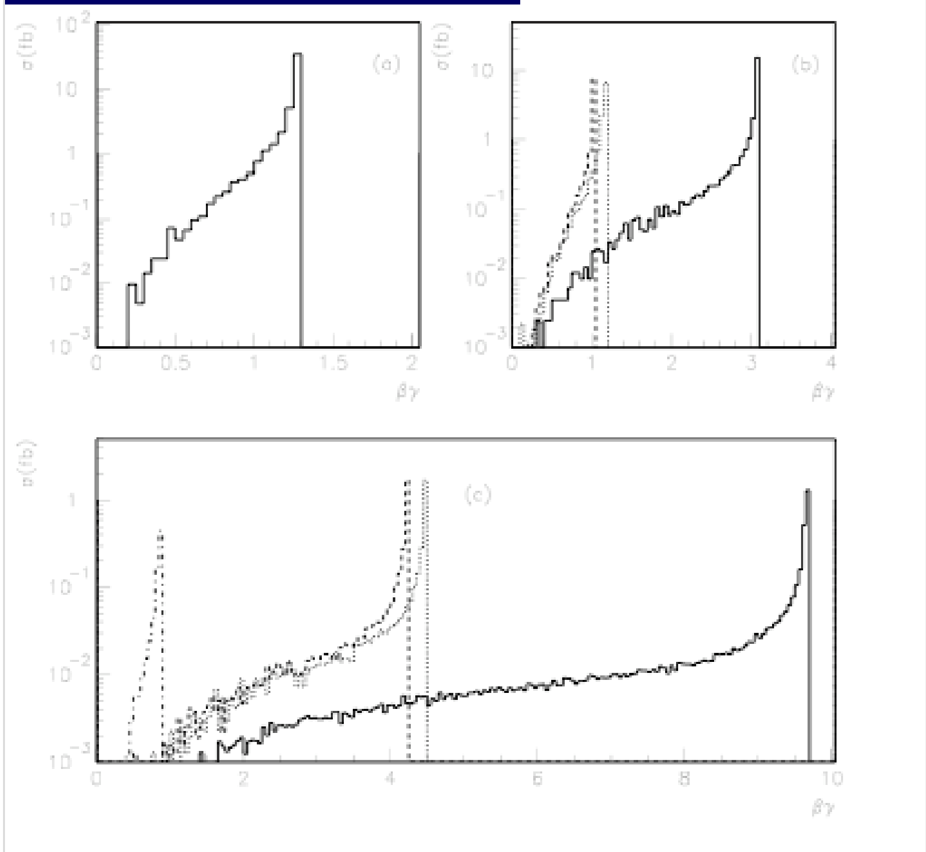
X-sections for stoppable staus

Benchmark in 'sweet spot' for Lithium

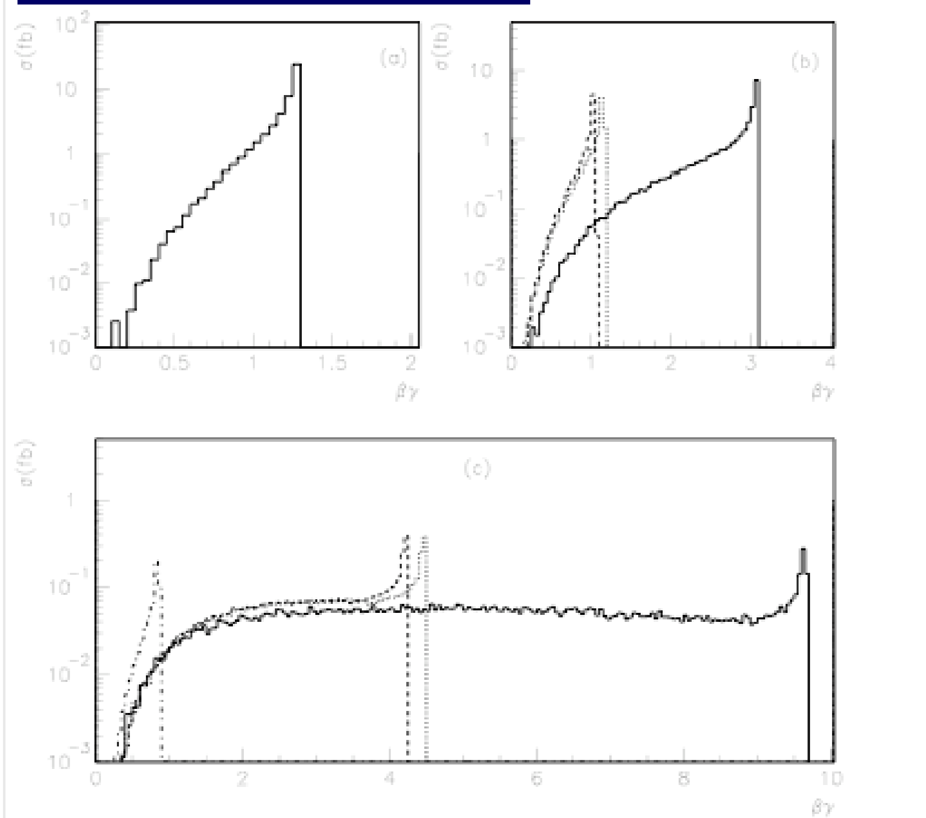
Cakir + Turk-Cakir + JE + Kirca

Slow-Moving Staus Stop in Detector

Beam conditions optimized for total cross section

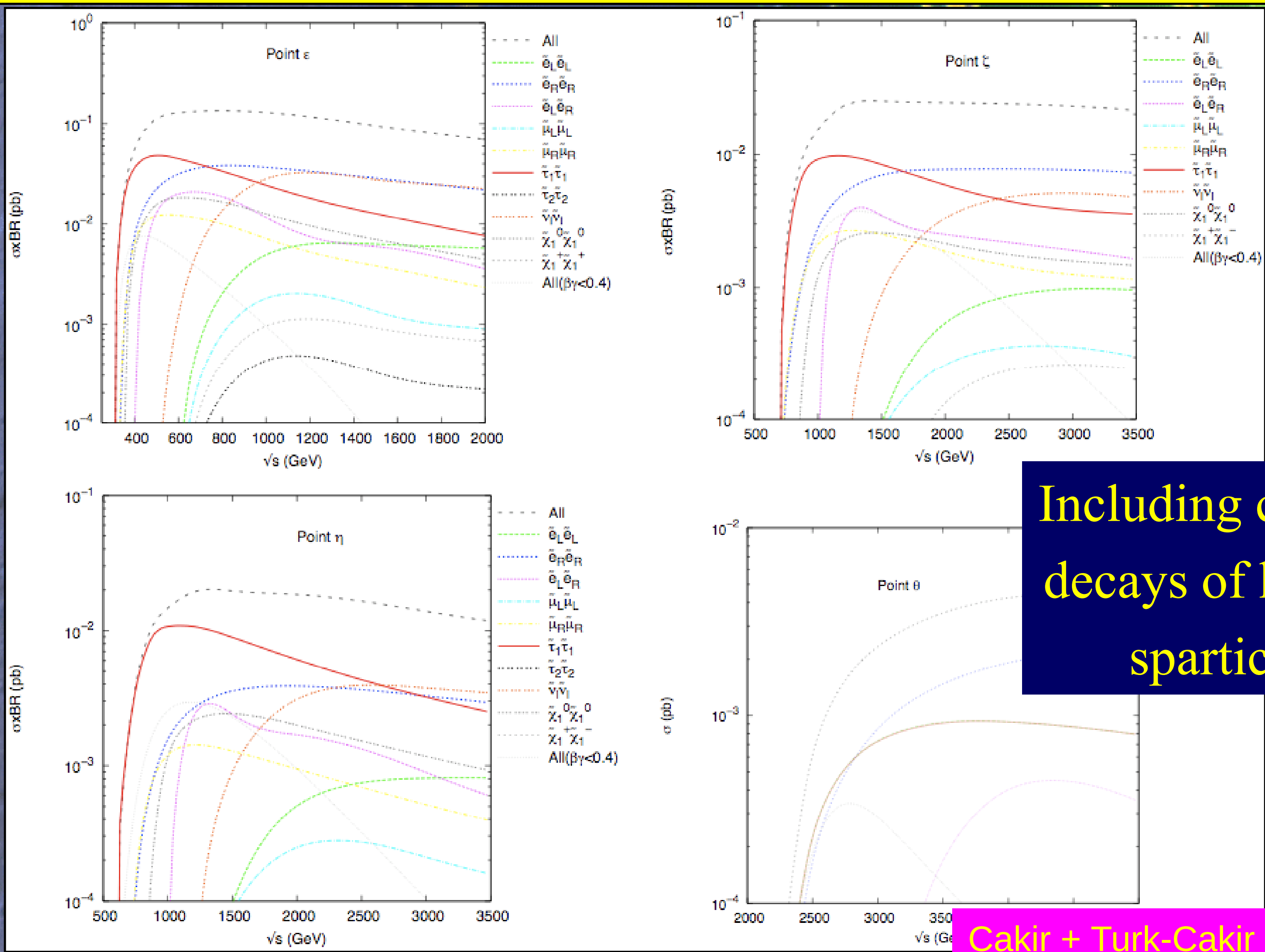


Beam conditions optimized for Staus with low $\beta\gamma$



Cakir + Turk-Cakir + JE + Kirca

Total Rates for Stoppable Stau Production in e^+e^- Annihilation

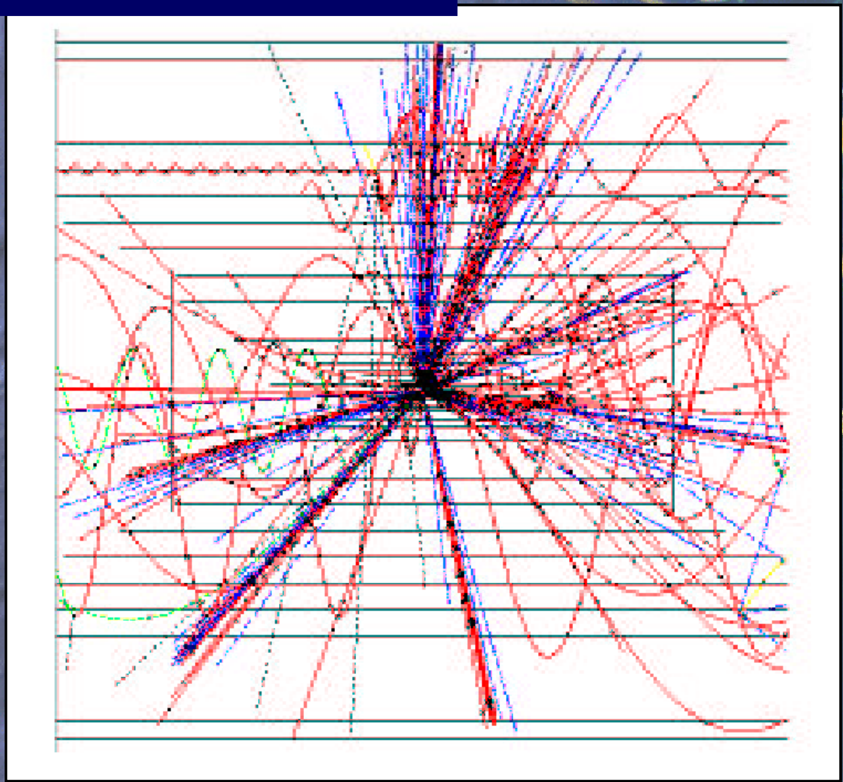


Including cascade decays of heavier sparticles

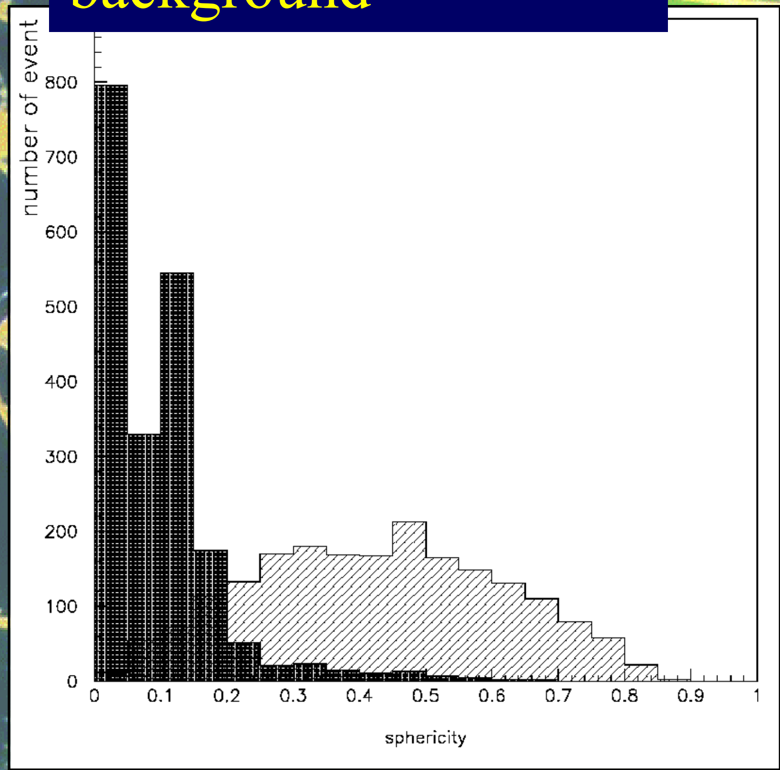
Cakir + Turk-Cakir + JE + Kirca

If the LHC discovers extra dimensions

Mini-black hole at CLIC

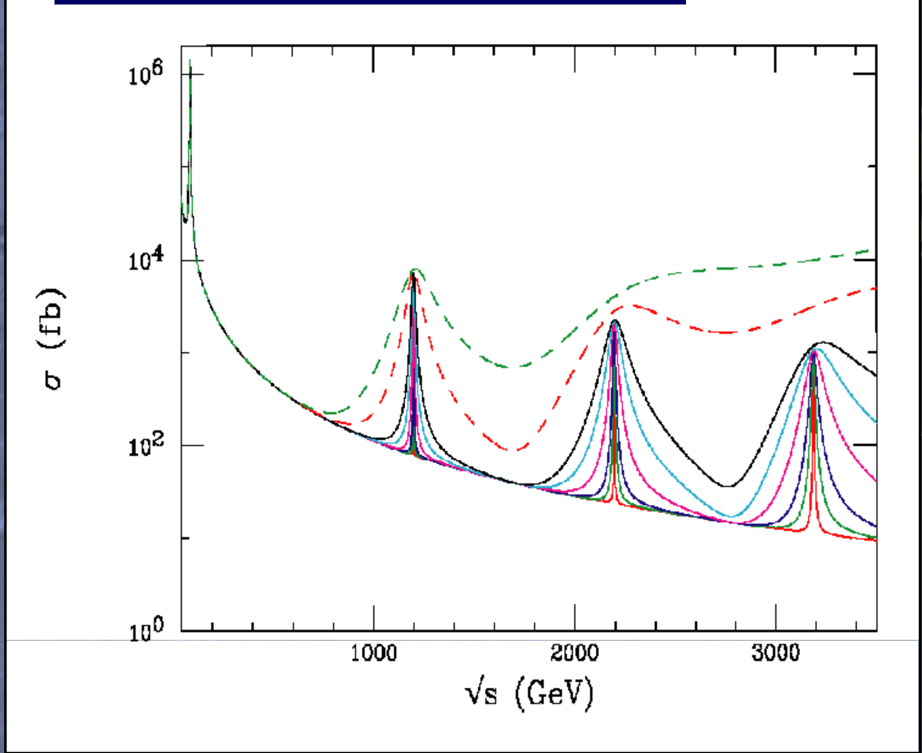


Easily distinguishable from Standard Model background

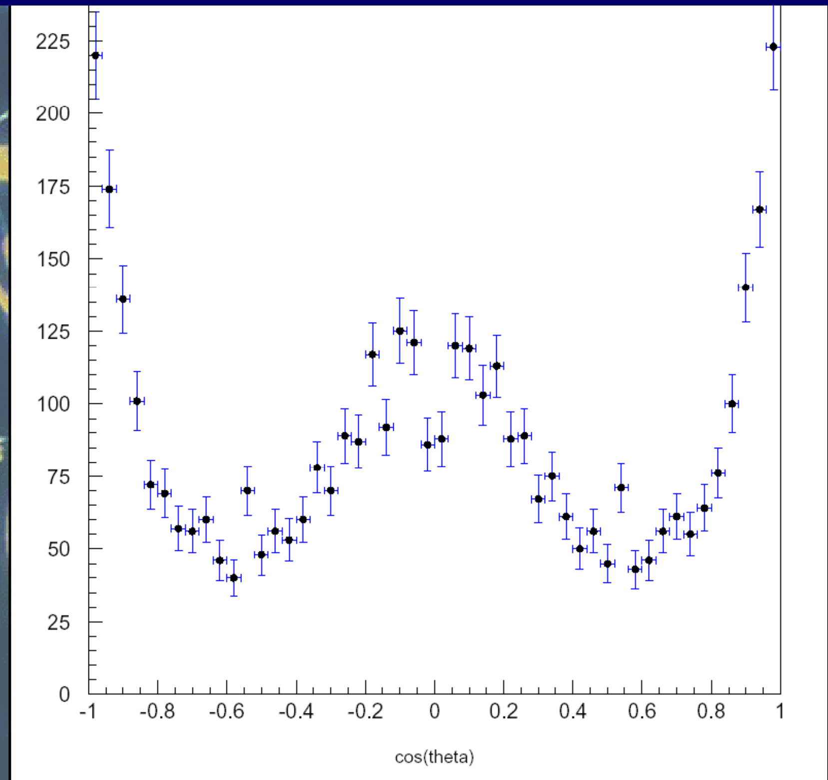


CLIC could measure Kaluza-Klein excitations

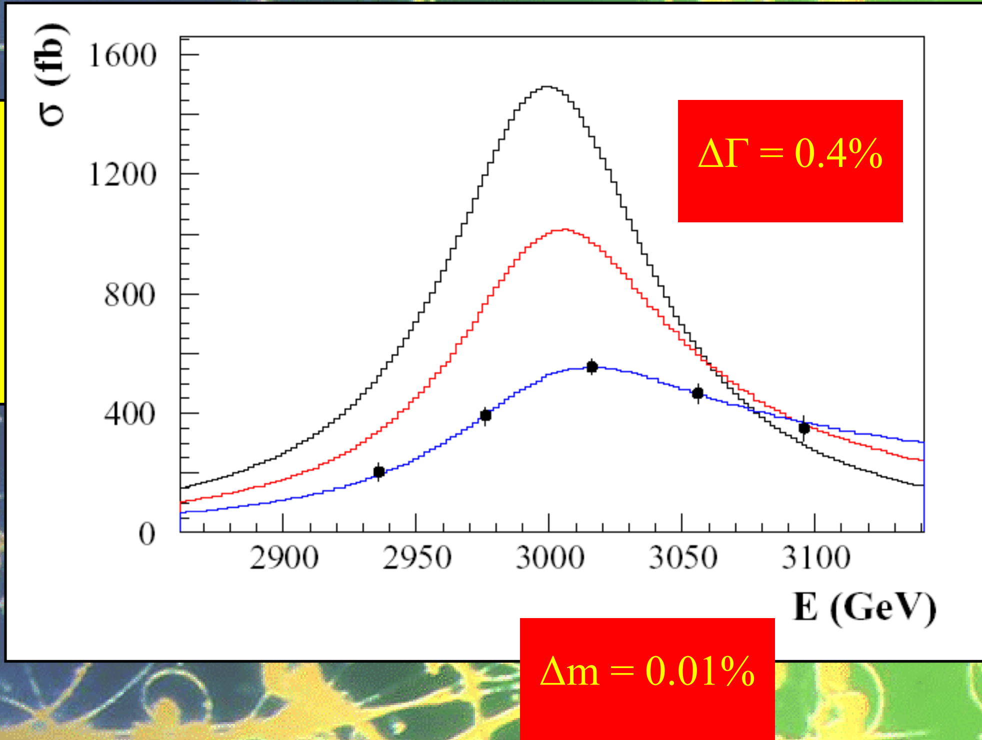
Direct-channel resonances

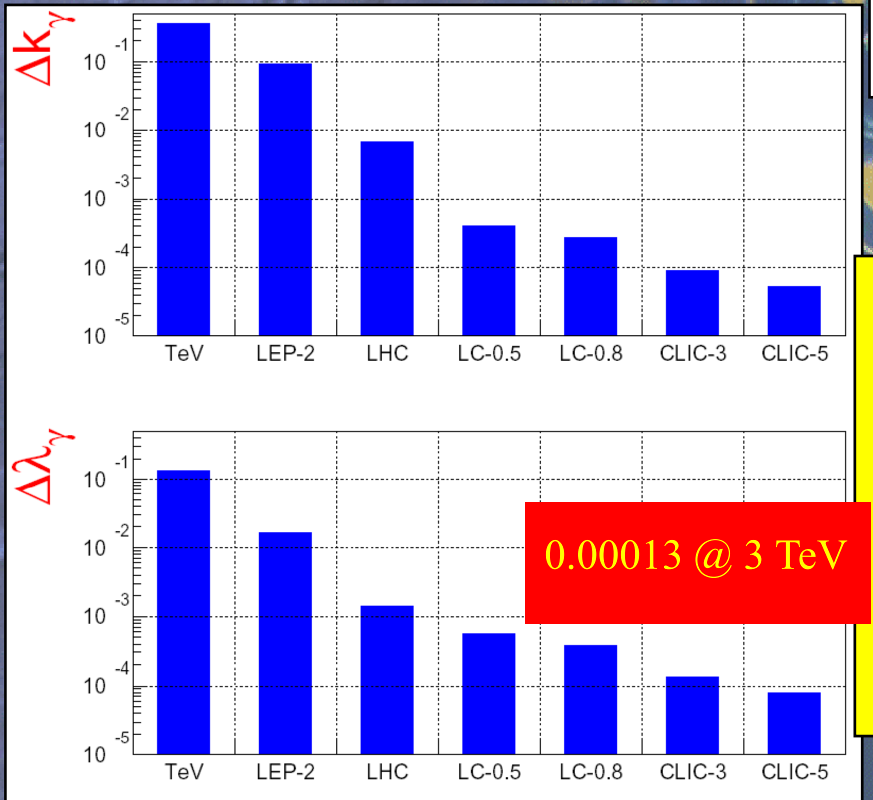


Angular distribution in graviton decay



CLIC can measure a Z’



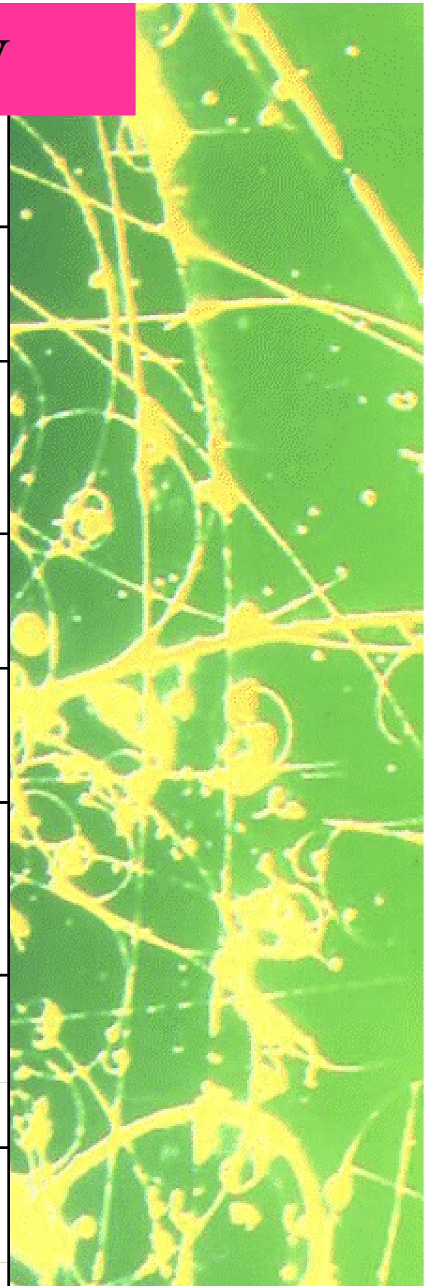


and constrain the triple-gauge coupling

Physics Reaches Of Various Colliders

Process LHC/ILC/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_LW_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 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).

Conclusions

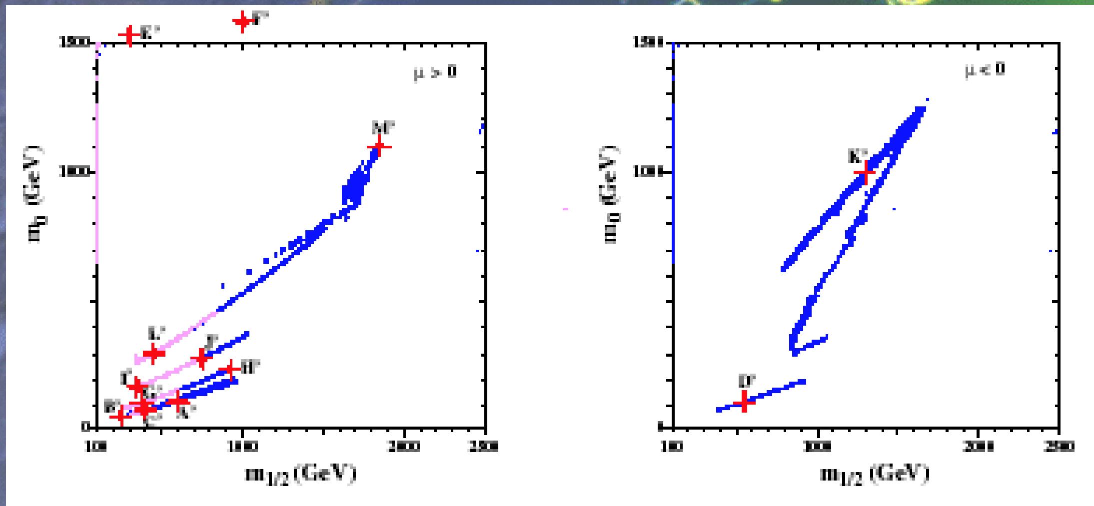
- CLIC will provide unique physics @ energy frontier
- Beamstrahlung and backgrounds not insurmountable problems
- Can exploit fully high c.o.m. energy
- Added value for light Higgs, heavy Higgs, supersymmetry, extra dimensions, …
- Whether light or heavy!

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
- CLIC and ILC are working together
- Determine feasibility of CLIC technology by the end of this decade

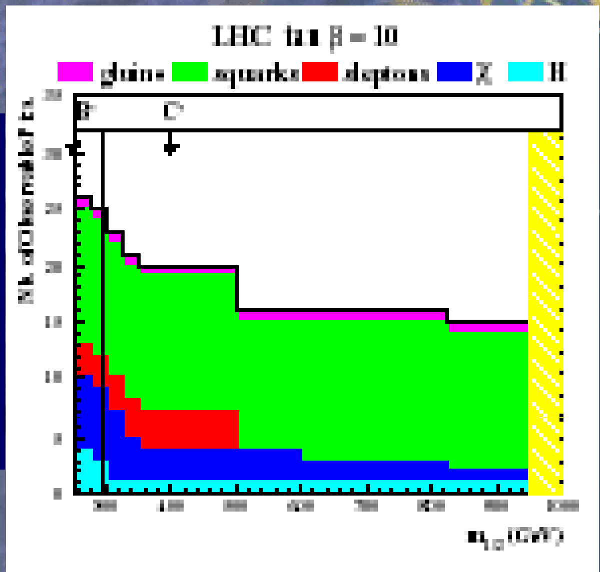
Supersymmetric Benchmark Studies

Lines in susy space allowed by accelerators, WMAP data

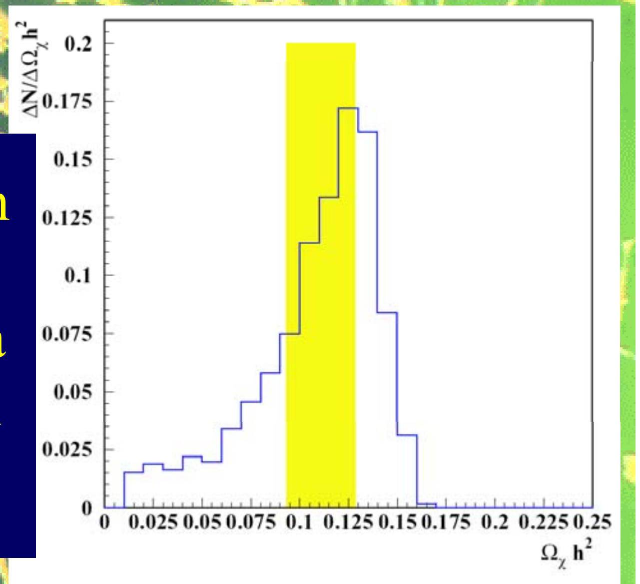


Specific benchmark Points along WMAP lines

Sparticle detectability Along one WMAP line

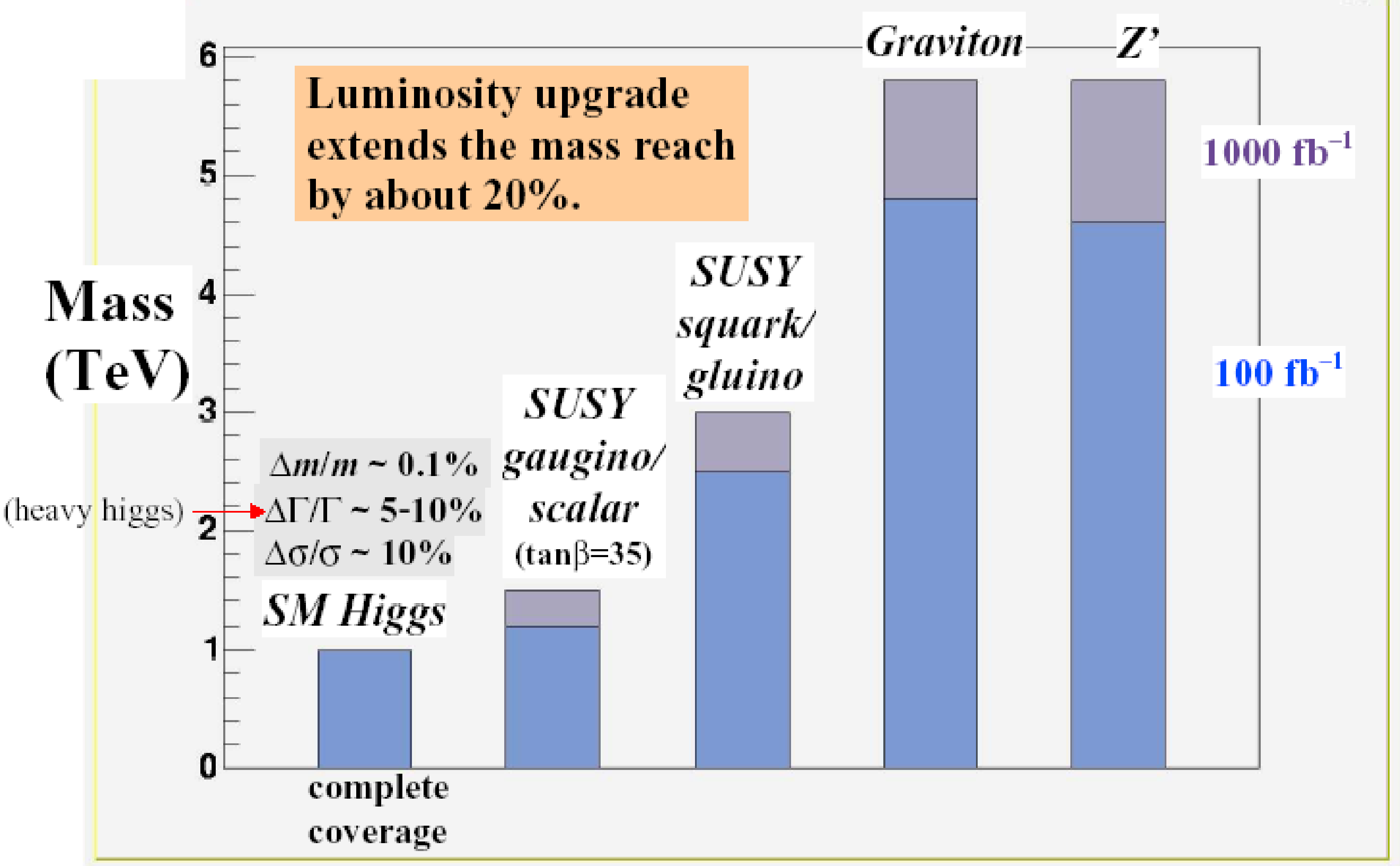


Calculation of relic density at a benchmark point



BDEG(M)OP(W)

The Reach of the LHC for New High-Mass Physics



Huge Statistics thanks to High Energy and Luminosity

Event rates in ATLAS or CMS at $L = 10^{33}\ cm^{-2}\ s^{-1}$

Process	Events/s	Events per year	Total statistics collected at previous machines by 2007
$W \to e\nu$	15	10^8	10^4 LEP / 10^7 Tevatron
$Z \to ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	1	10^7	10^4 Tevatron
$b\bar{b}$	10^6	$10^{12} - 10^{13}$	10^9 Belle/BaBar ?
H m=130 GeV	0.02	10^5	?
$\tilde{g}\tilde{g}$ m= 1 TeV	0.001	10^4	---
Black holes m > 3 TeV (M_D=3 TeV, n=4)	0.0001	10^3	---

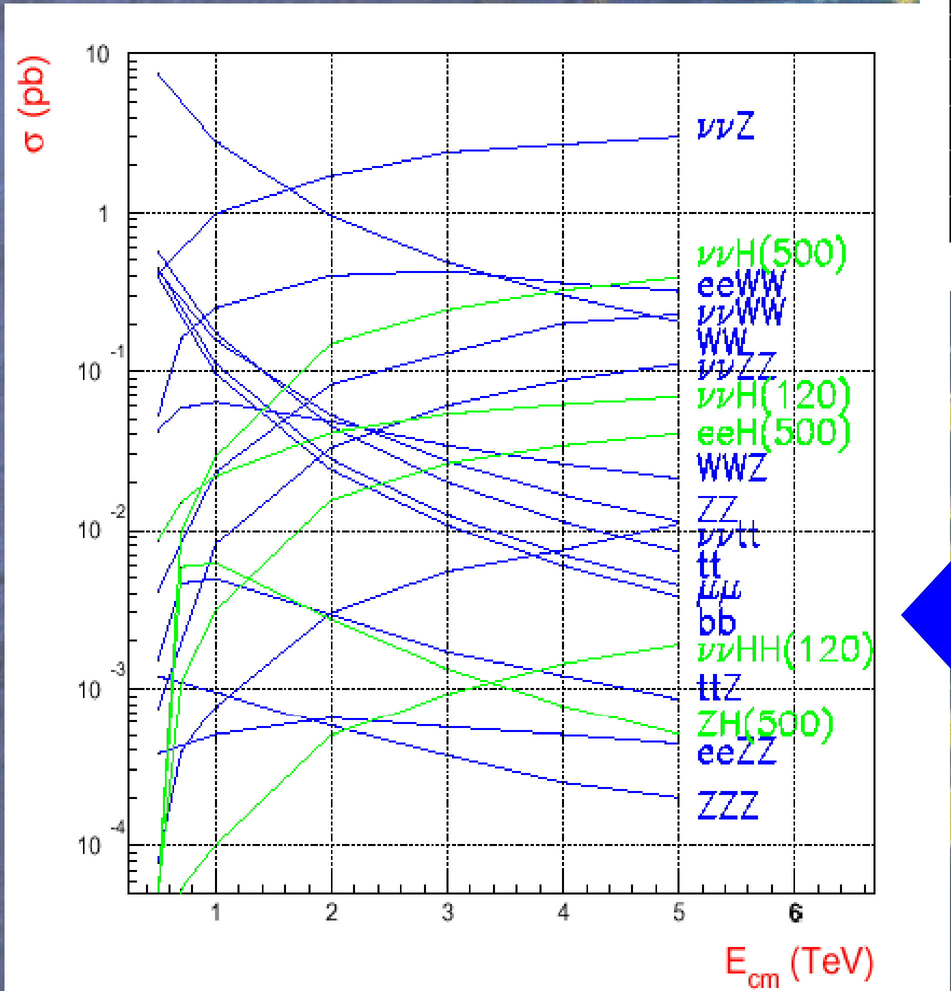
LHC-b

+ Ion Collisions

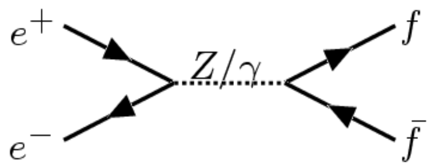
LHC is a factory for anything: top, W/Z, Higgs, SUSY, etc….
mass reach for discovery of new particles up to m ~ 5 TeV

Cross Sectio

Event Rates/Year (1000 fb^{-1})	3 TeV 10^3 events	5 TeV 10^3 events
$e^+e^- \to t\bar{t}$	20	7.3
$e^+e^- \to b\bar{b}$	11	3.8
$e^+e^- \to ZZ$	27	11
$e^+e^- \to WW$	490	205
$e^+e^- \to hZ/h\nu\nu$ (120 GeV)	1.4/530	0.5/690
$e^+e^- \to H^+H^-$(1 TeV)	1.5	0.95
$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$ (1 TeV)	1.3	1.0

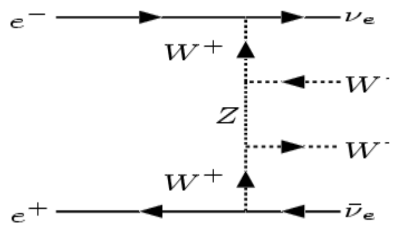


s-Channel Production



$\sigma \propto 1/s$

t-Channel Production



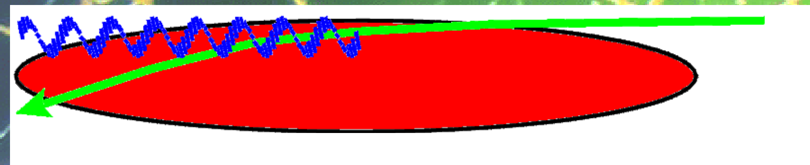
$\sigma \propto log(s)$

CLIC 3 TeV e+e- collider with a luminosity ~ $10^{35}cm^{-2}s^{-1}$ (1 ab^{-1}/year)

E_{cm}	[TeV]	0.5	3	3
$\mathcal{L}$	$[10^{34}cm^{-2}s^{-1}]$	2.1	10.0	8.0
$\mathcal{L}_{0.99}$	$[10^{34}cm^{-2}s^{-1}]$	1.5	3.0	3.1
f_r	[Hz]	200	100	100
N_b		154	154	154
Δ_b	[ns]	0.67	0.67	0.67
N	$[10^{10}]$	0.4	0.4	0.4
σ_z	[μm]	35	30	35
ϵ_x	[μm]	2	0.68	0.68
ϵ_y	[μm]	0.01	0.02	0.01
σ_x^*	[nm]	202	43	≈ 60
σ_y^*	[nm]	≈ 1.2	1	≈ 0.7
δ	[%]	4.4	31	21
n_γ		0.7	2.3	1.5
$N_\perp$		7.2	60	43
N_{Hadr}		0.07	4.05	2.3
N_{MJ}		0.003	3.40	1.5

Report → Old Values

To reach this high luminosity: CLIC has to operate in a regime of high beamstrahlung

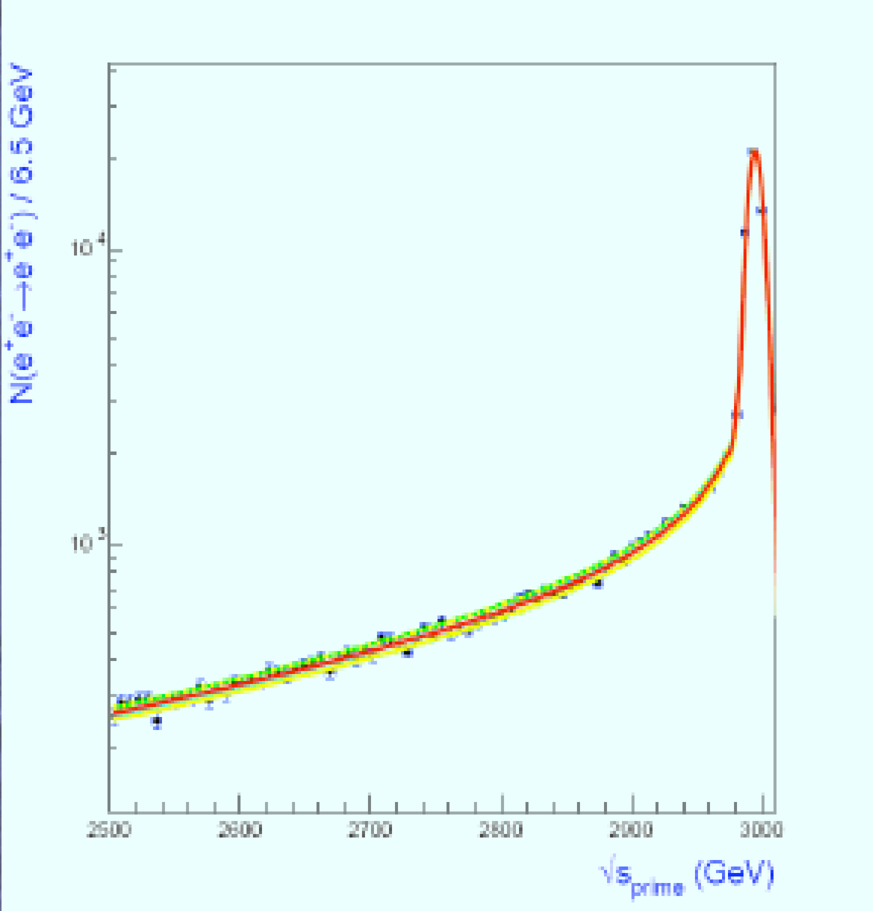


Expect large backgrounds
# of photons/beam particle

- e+e- pair production
- γ γ events
- Muon backgrounds
- Neutrons
- Synchrotron radiation

Expect distorted lumi spectrum

Experimental issues: Luminosity Spectrum



Reconstructed $\sqrt{s'}$ Spectrum from Bhabha Angles

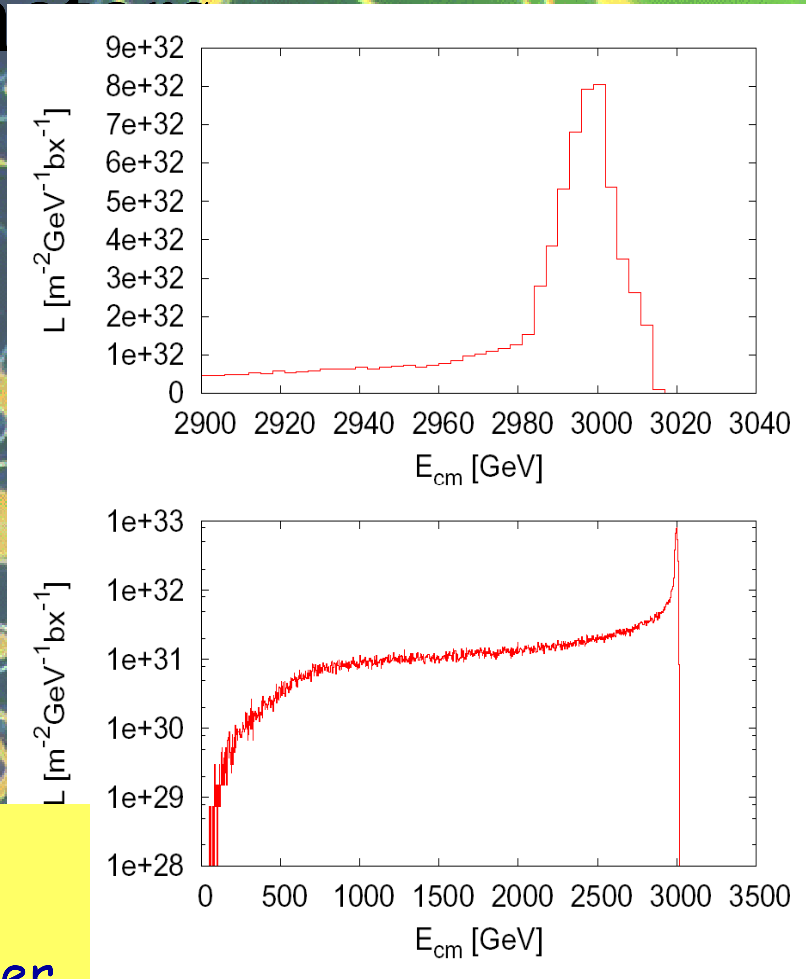
Preliminary Results: expect accuracy $\frac{\delta\sqrt{s'}}{\sqrt{s}} \simeq 10^{-4}$ for 100 fb^{-1}

Luminosity spectrum not as sharply peaked as e.g. at LEP or TESLA/NLC

See D. Schulte

New Param

		CLIC	CLIC	CLIC	ILC	NLC
E_{cms}	$[GeV]$	0.5	1.0	3.0	0.5	0.5
f_{rep}	[Hz]	100	75	50	5	120
N	$[10^9]$	4.0	4.0	4.0	20	7.5
ϵ_y	$[nm]$	20	20	20	40	40
L	$10^{34}cm^{-2}s^{-1}$	1.07	1.79	7.0	2.0	2.0
L_1	$10^{34}cm^{-2}s^{-1}$	1.36	1.5	2.0	1.45	1.28
n_γ		1.10	1.20	2.4	1.30	1.26
$\Delta E/E$		0.07	0.11	0.31	0.024	0.046
N_{coh}	10^5	0.01	7.19	5.5×10^3	—	—
E_{coh}	$10^3 TeV$	0.15	216.28	3.9×10^5	—	—
n_{incoh}	10^6	0.05	0.09	0.44	0.1	?
E_{incoh}	$[10^6 GeV]$	0.25	1.30	32.4	0.2	?
n_t		11.5	17.1	66	28	12
n_{had}		0.10	0.29	3.2	0.12	0.1

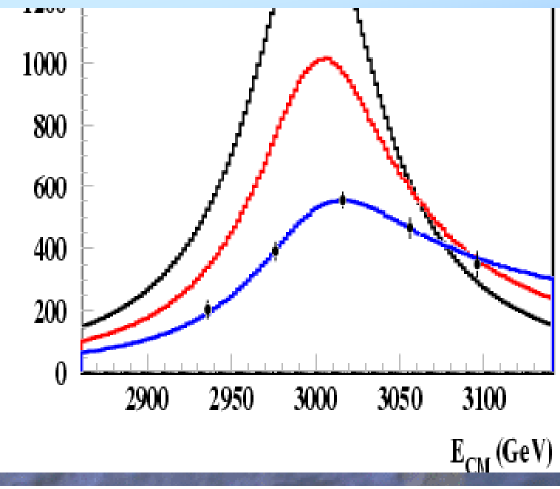


- Same bunch distance (0.6 nsec)
- 2 x more bunches per train
- Backgrounds similar or somewhat better

Do not except significant differences with studies in the report

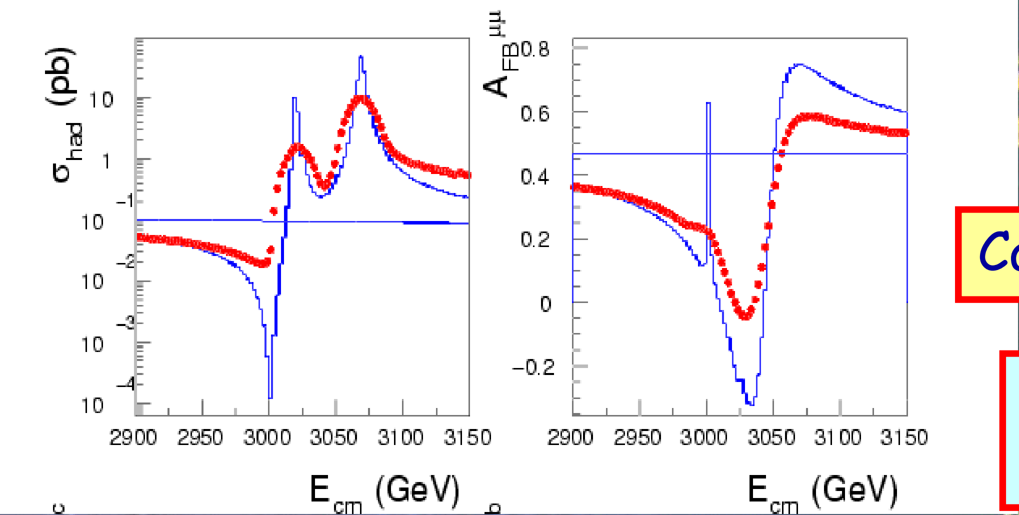
Example: Resonance Production

Resonance scans, e.g. a Z′



$M_{Z'}$ (GeV)	$3000 \pm .12$	$\pm .15$	$\pm .21$
$\Gamma(Z')/\Gamma_{SM}$	$1. \pm .001$	$\pm .003$	$\pm .004$
σ^{eff}_{peak} (fb)	1493 ± 2.0	564 ± 1.7	669 ± 2.9

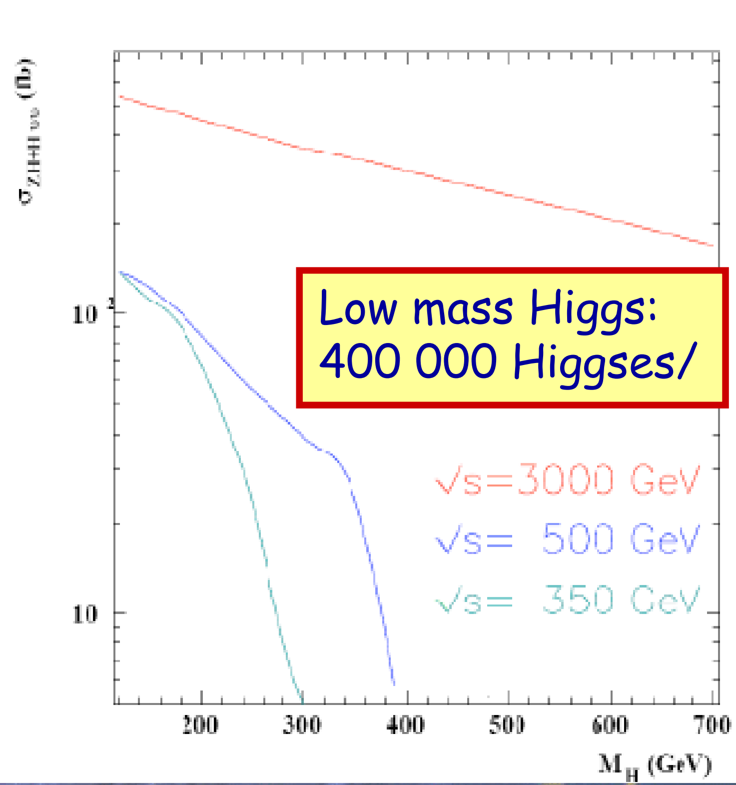
1 ab^{-1} $\Rightarrow \delta M/M \sim 10^{-4}$ & $\delta\Gamma/\Gamma = 3.10^{-3}$

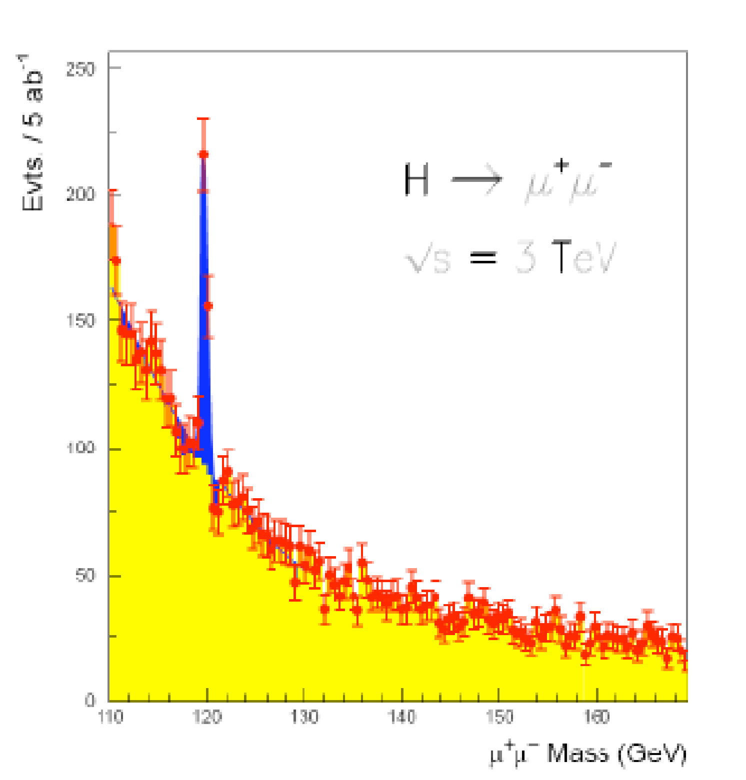


Degenerate resonances e.g. D-BESS model

Can measure ΔM down to 13 GeV

Smeared lumi spectrum allows still for precision measurement





- Large cross sections
- Large CLIC luminosity

→Large events statistics

- Keep large statistics also
  for highest Higgs masses

⇒ O(500 K) Higgses/year

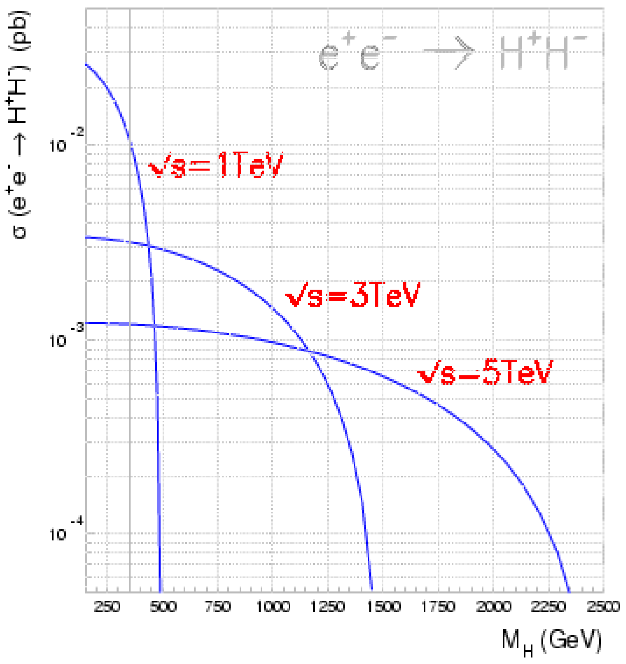
Allows to study the decay modes with BRs ~ 10^{-4} such as $H \to \mu\mu$ and $H \to bb$ (>180 GeV)

Eg: determine $g_{H\mu\mu}$ to ~4%

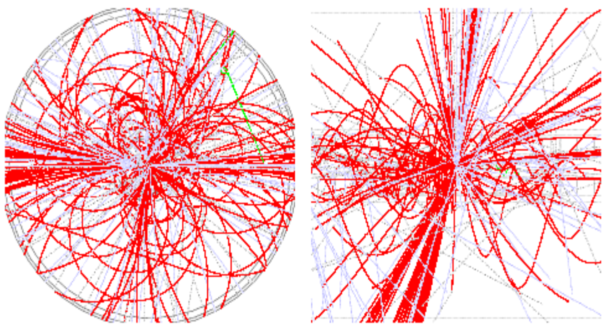
: Heavy Higgs

SSM)

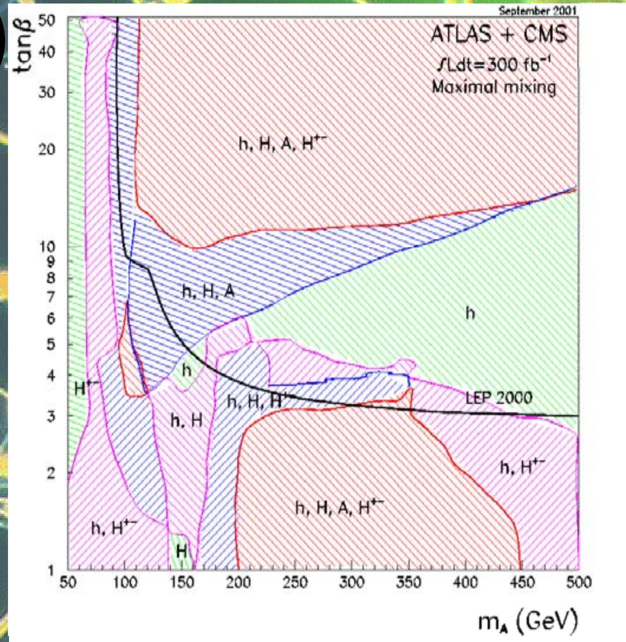
Cross section as function of Higgs mass



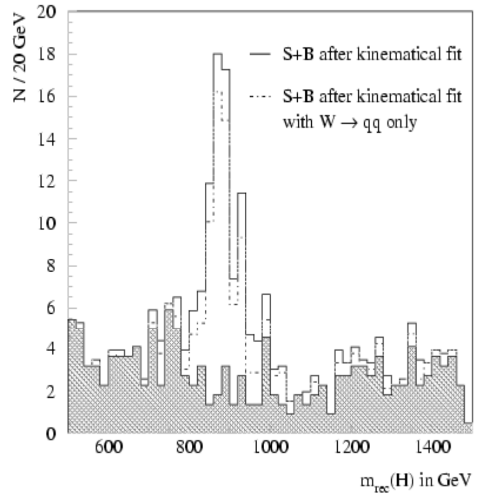
$e^+e^- \to H^+H^-$ $M_H = 900$ GeV



LHC: Plot for 5 σ discovery



3 TeV CLIC
⇒ H, A
detectable
up to ~ 1.2
TeV



surements

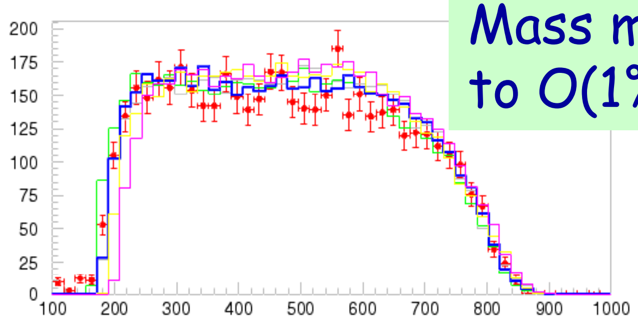
Momentum resolution (G3)

E.G. $m_{1/2} = 1500$ GeV, $m_0 = 420$ GeV, $\tan\beta = 20,\ A = 0$ GeV, $sign(\mu) > 0$ (mSUGRA) (point H)

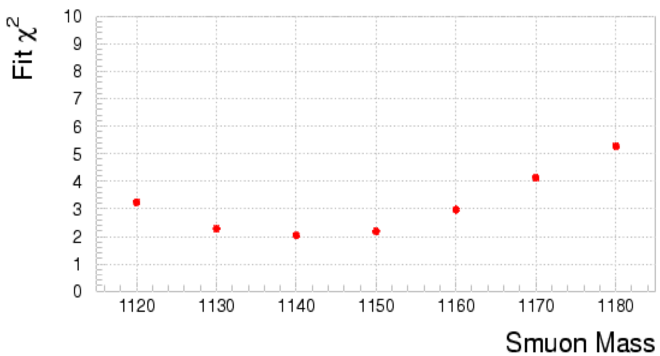
$\Rightarrow M_{\tilde{\mu}} = 1150$ GeV

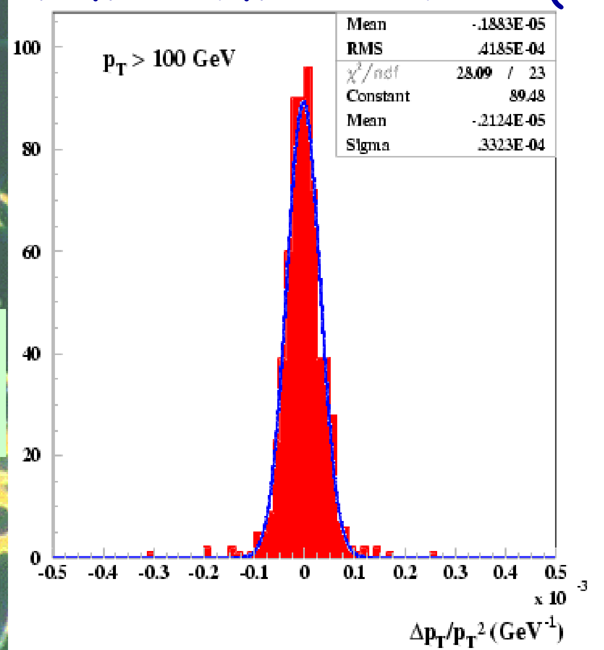
Measure inclusive muon spectrum in $\tilde{\mu} \to \mu\chi^0$

$$\Rightarrow E_{max/min} = \frac{E_{beam}}{2}\left(1 - \frac{M^2_{\chi^0}}{M^2_{tilde\mu}}\right) \times \left(1 \pm \sqrt{1 - \frac{M^2_{\tilde{\mu}}}{E^2_{beam}}}\right)$$



Mass measurements to O(1%)



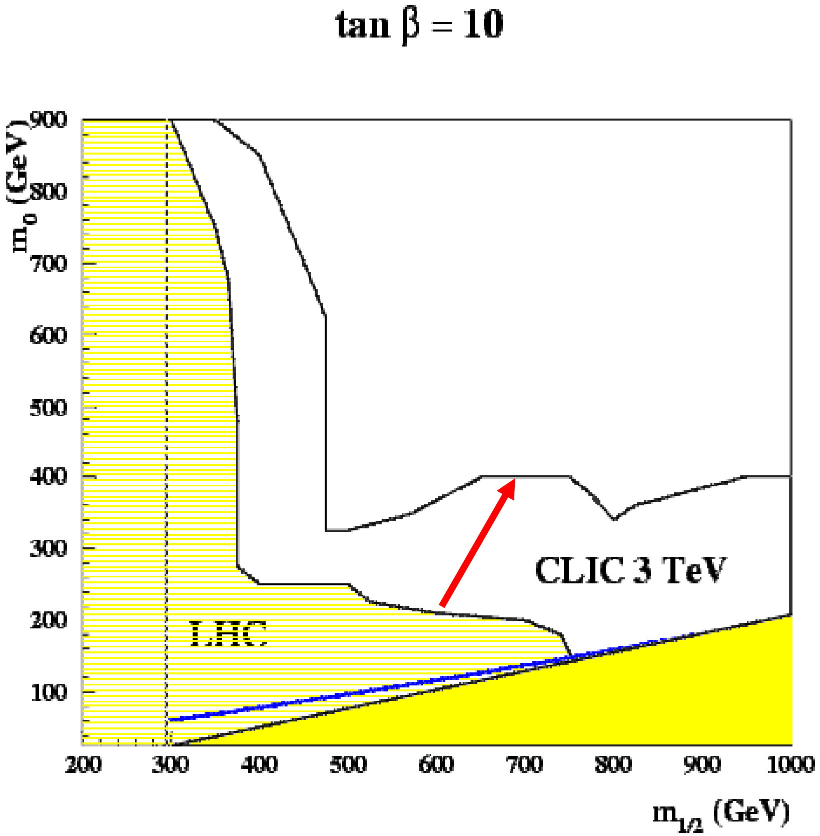


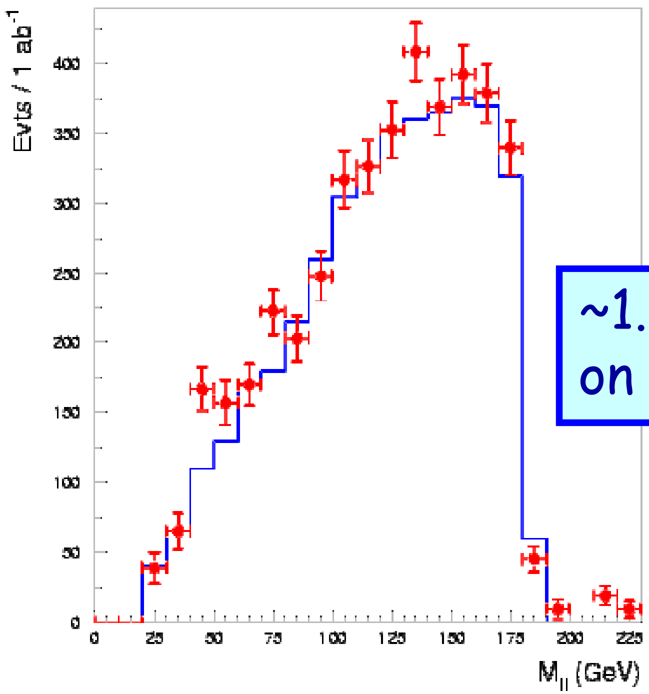
Momentum resolution $\delta p_t/p_t^2 \sim 10^{-4}$ GeV^{-1} adequate for this measurement

Sensitivity Case study: χ_2 +2 leptons

Sensitivity (5σ) for LHC and LC

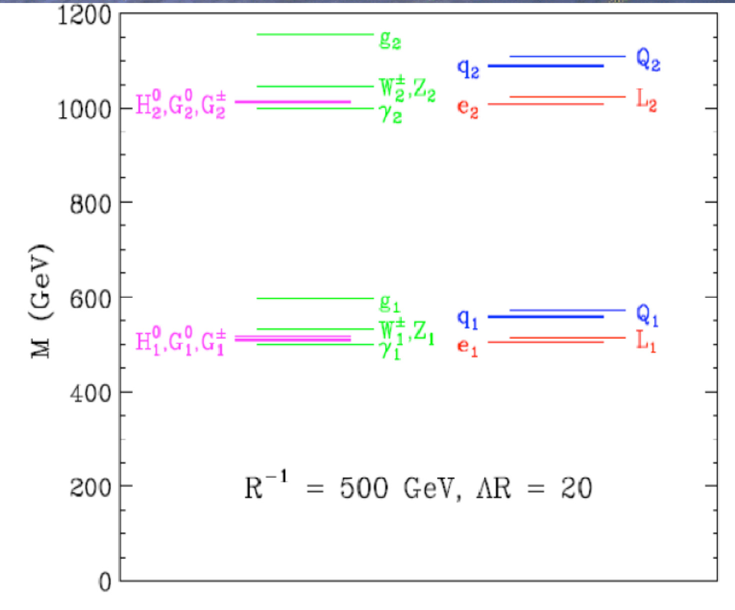
Mass measurement precision
$m\chi_2$= 540 GeV, $m\chi_1$=290 GeV

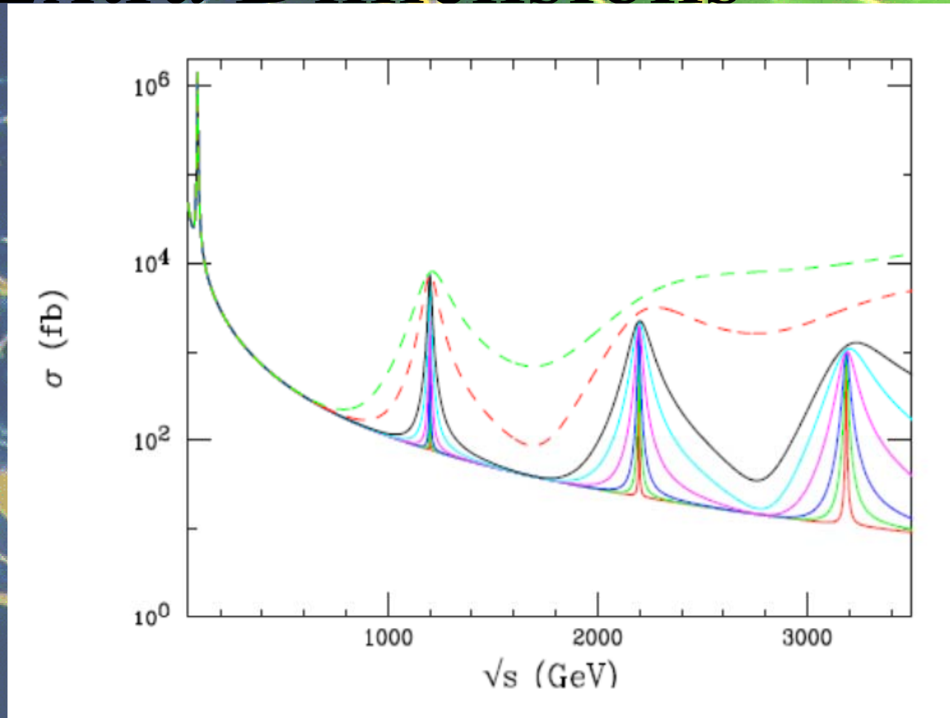




~1.5% precision
on χ_2 mass

Physics Case: Extra Dimensions



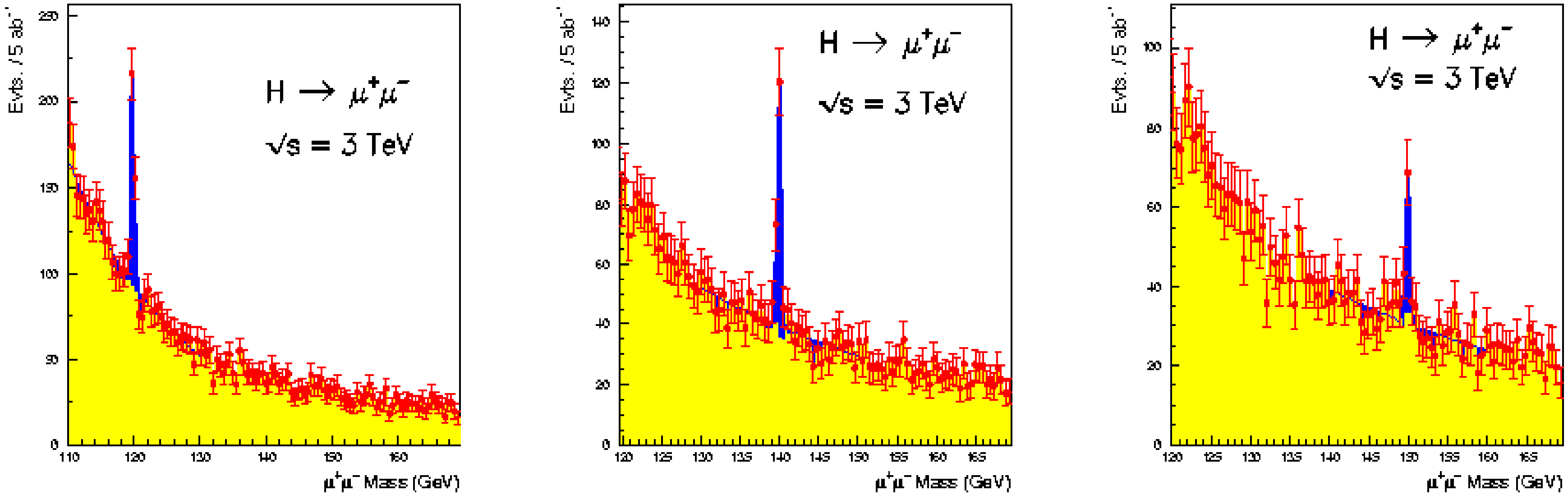


Universal extra dimensions:
⇒ Measure all (pair produced) new particles and see the higher level excitations

RS KK resonances…
Scan the different states

$H \to \mu^+\mu^-$: Branching Ratio $\sim 10^{-4}$

Not easy to access at a 500 GeV collider



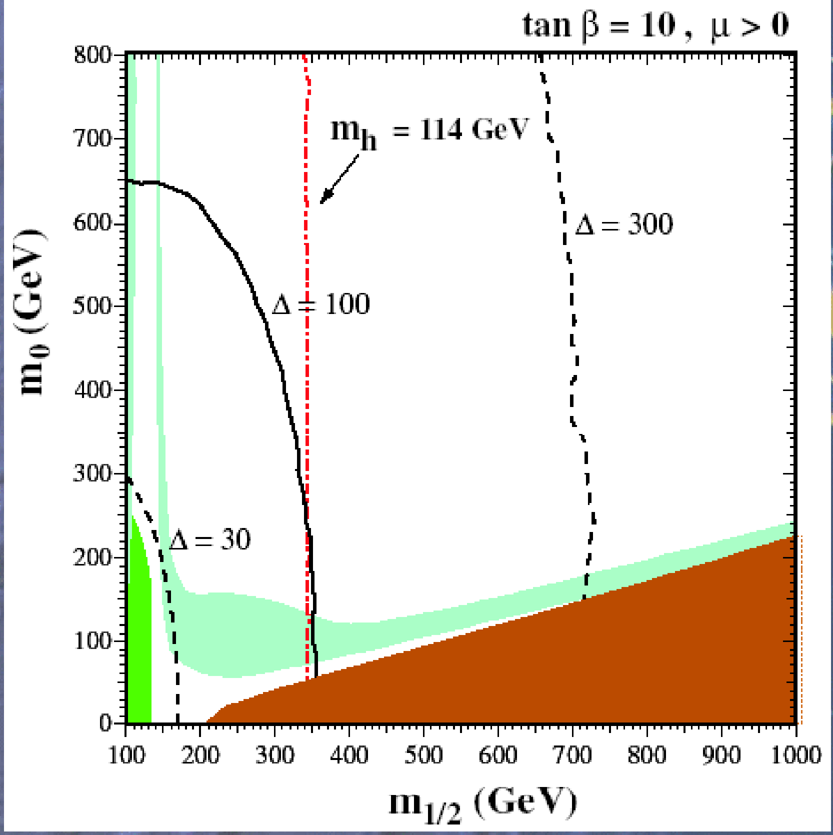
Result for $\sqrt{s} = 3.0$ TeV with $\int \mathcal{L} = 5$ ab^{-1}

M_H	120 GeV	140 GeV	150 GeV
δBR/BR	0.072	0.121	0.210

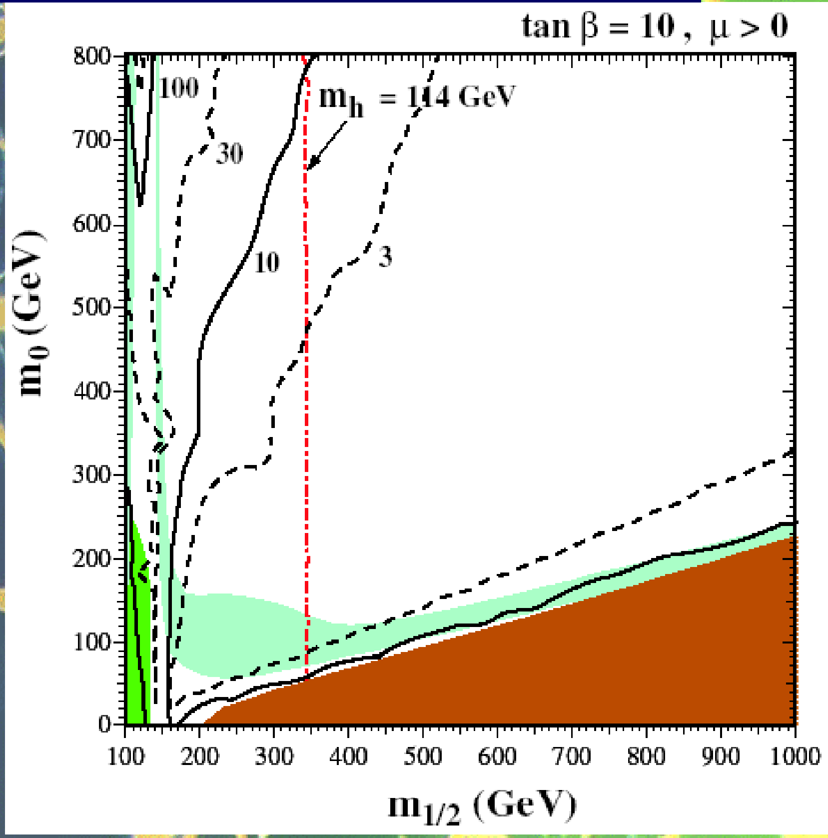
$\Rightarrow$ Precision on $g_{H\mu\mu}$: $3.5\% \to 10\%$

How `Likely' are Large Sparticle Masses?

Fine-tuning of EW scale



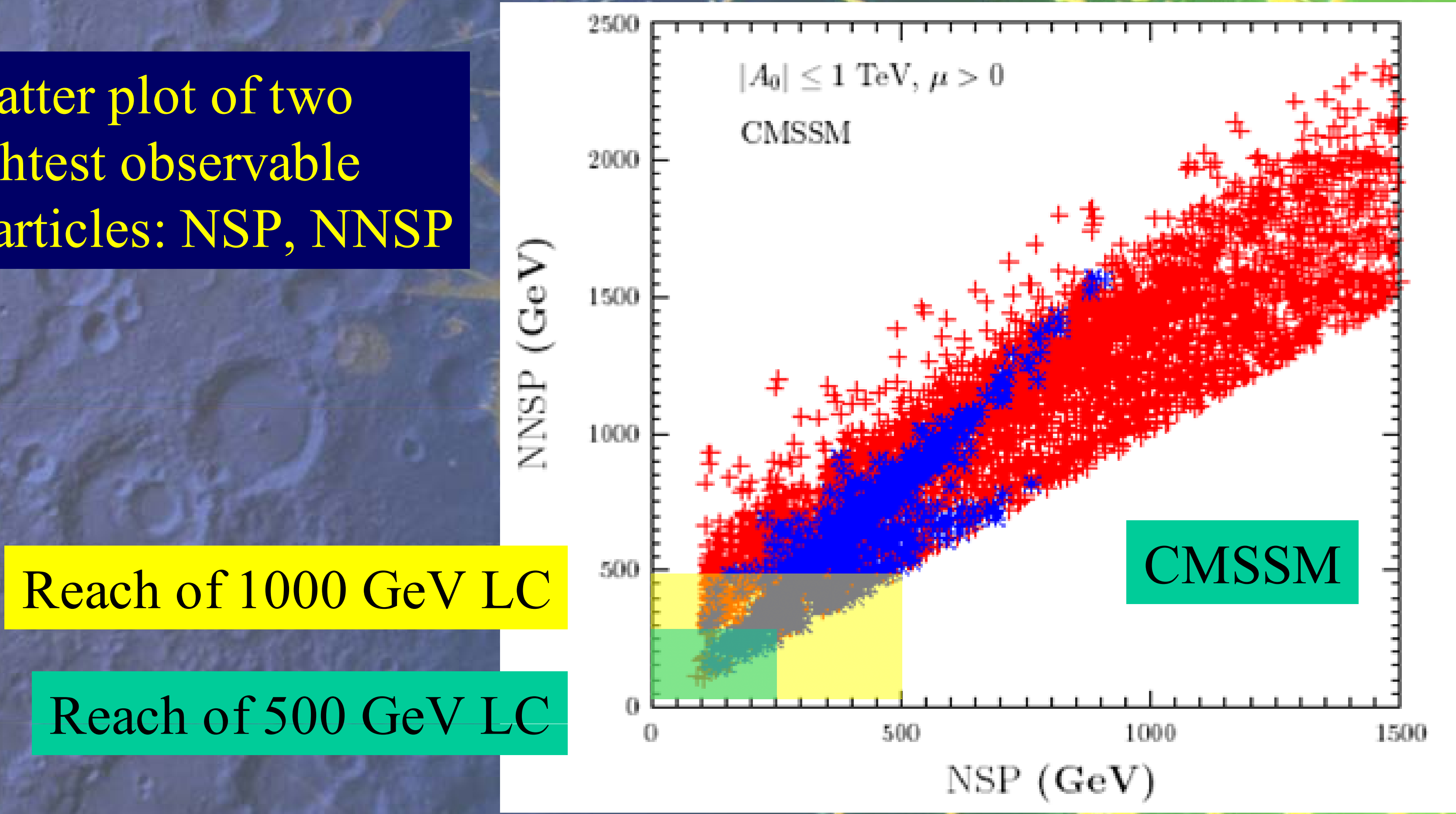
Fine-tuning of relic density

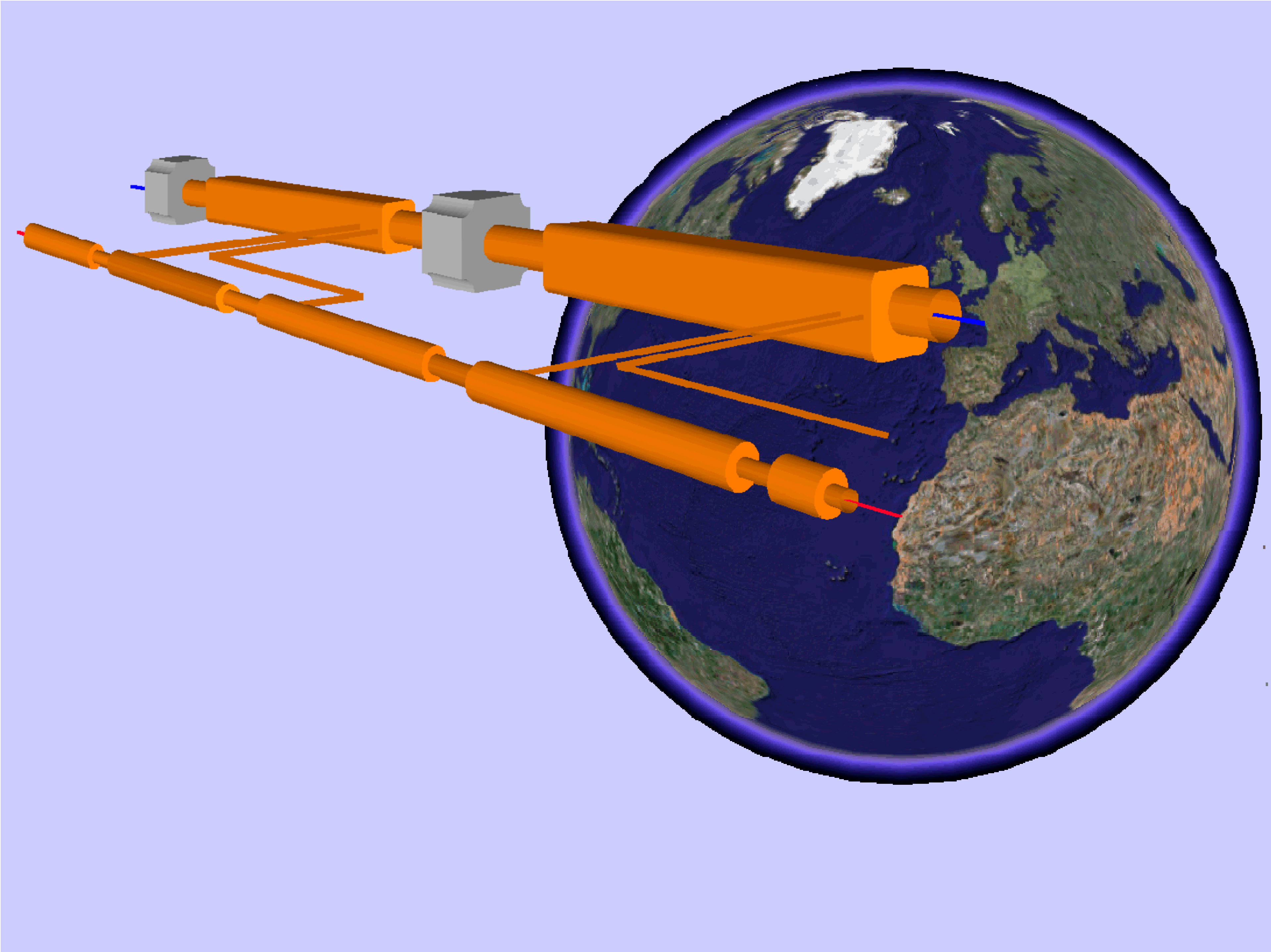


Larger masses require more fine-tuning: but how much is too much?

How much of Susy Parameter Space Covered by LC?

Scatter plot of two lightest observable sparticles: NSP, NNSP





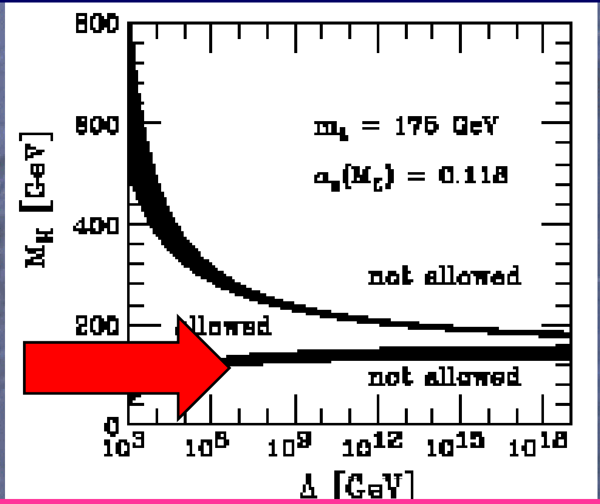
Why Supersymmetry (Susy)?

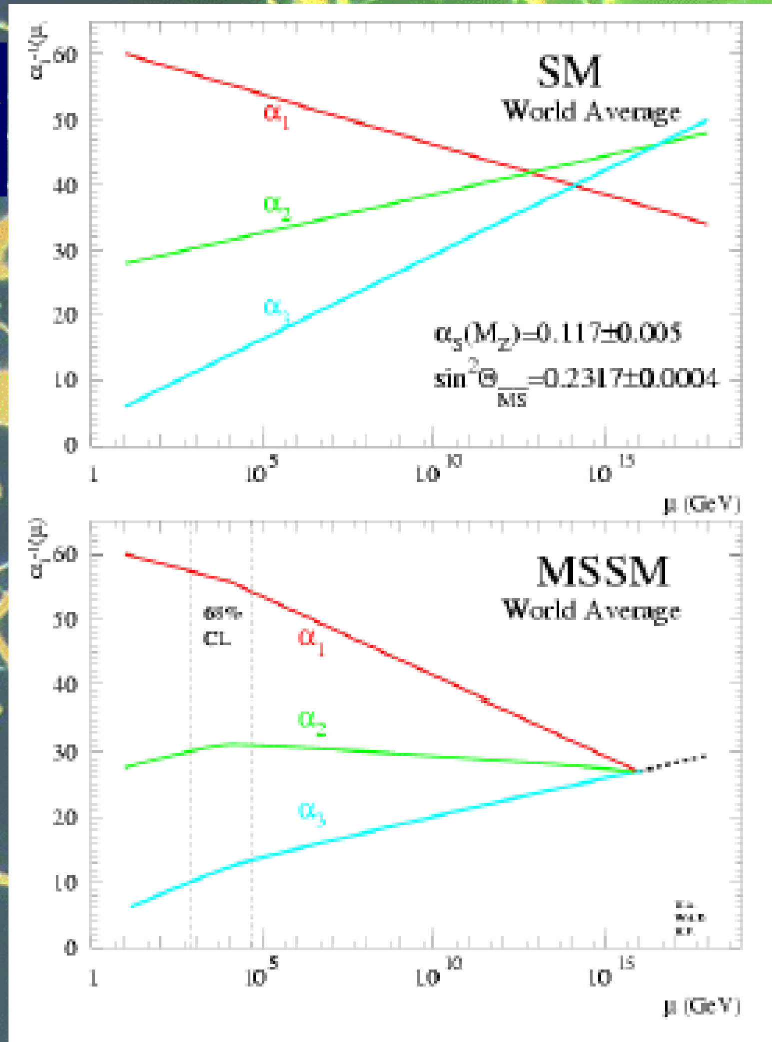
- Hierarchy problem: why is $m_W << m_P$?
  ($m_P \sim 10^{19}$ GeV is scale of gravity)
- Alternatively, why is
  $G_F = 1/\, m_W^2 >> G_N = 1/m_P^2$?
- Or, why is
  $V_{Coulomb} >> V_{Newton}$? $e^2 >> G\, m^2 = m^2 / m_P^2$
- Set by hand? What about loop corrections?
  $\delta m_{H,W}^2 = O(\alpha/\pi)\, \Lambda^2$
- Cancel boson loops ⇔ fermions
- Need $| m_B^2 - m_F^2| < 1$ TeV^2

Other Reasons to like Susy

It enables the gauge couplings to unify

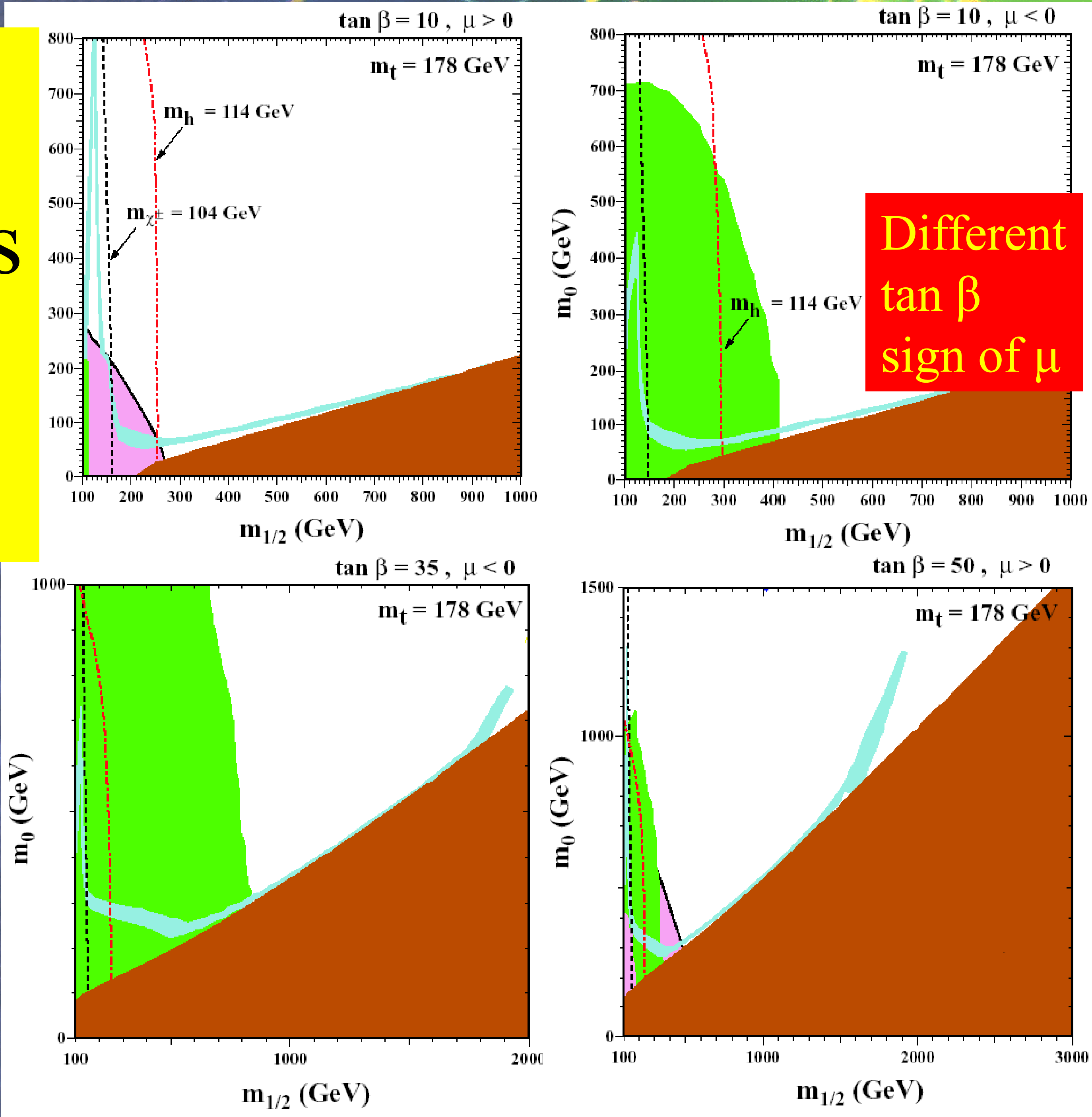
It stabilizes the Higgs potential for low masses





Approved by Fabiola Gianotti

Current Constraints on CMSSM



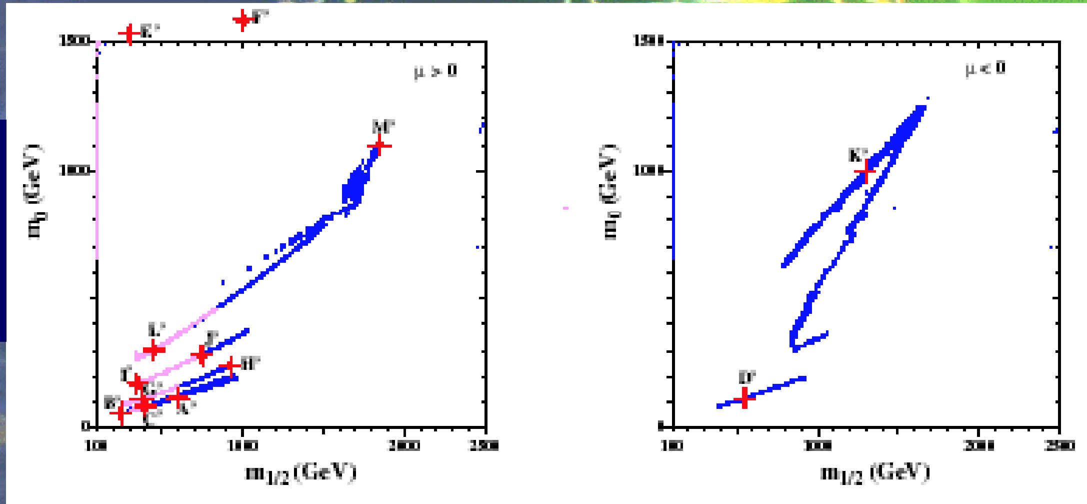
Different tan β sign of μ

Impact of Higgs constraint reduced if larger m_t

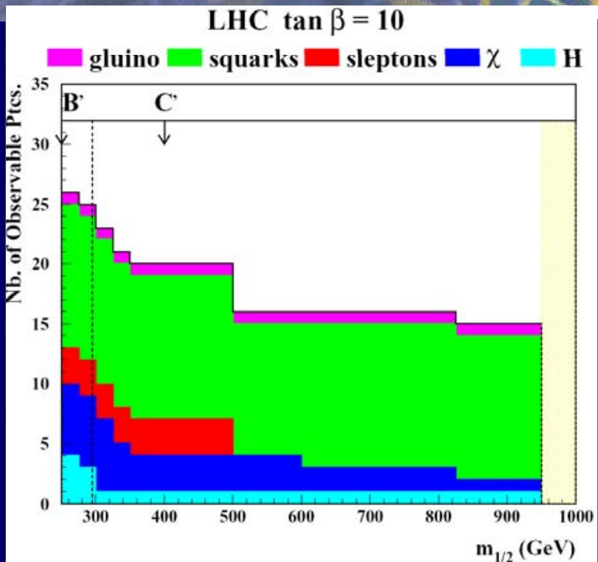
Focus-point region far up

Exploring the Supersymmetric Parameter Space

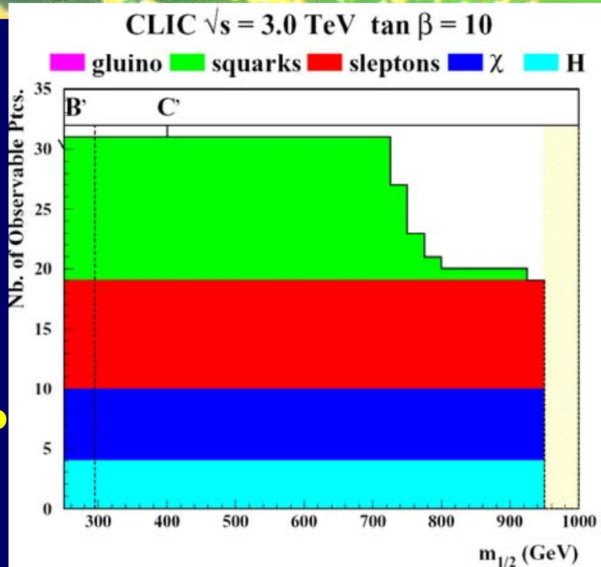
Strips allowed by WMAP and other constraints



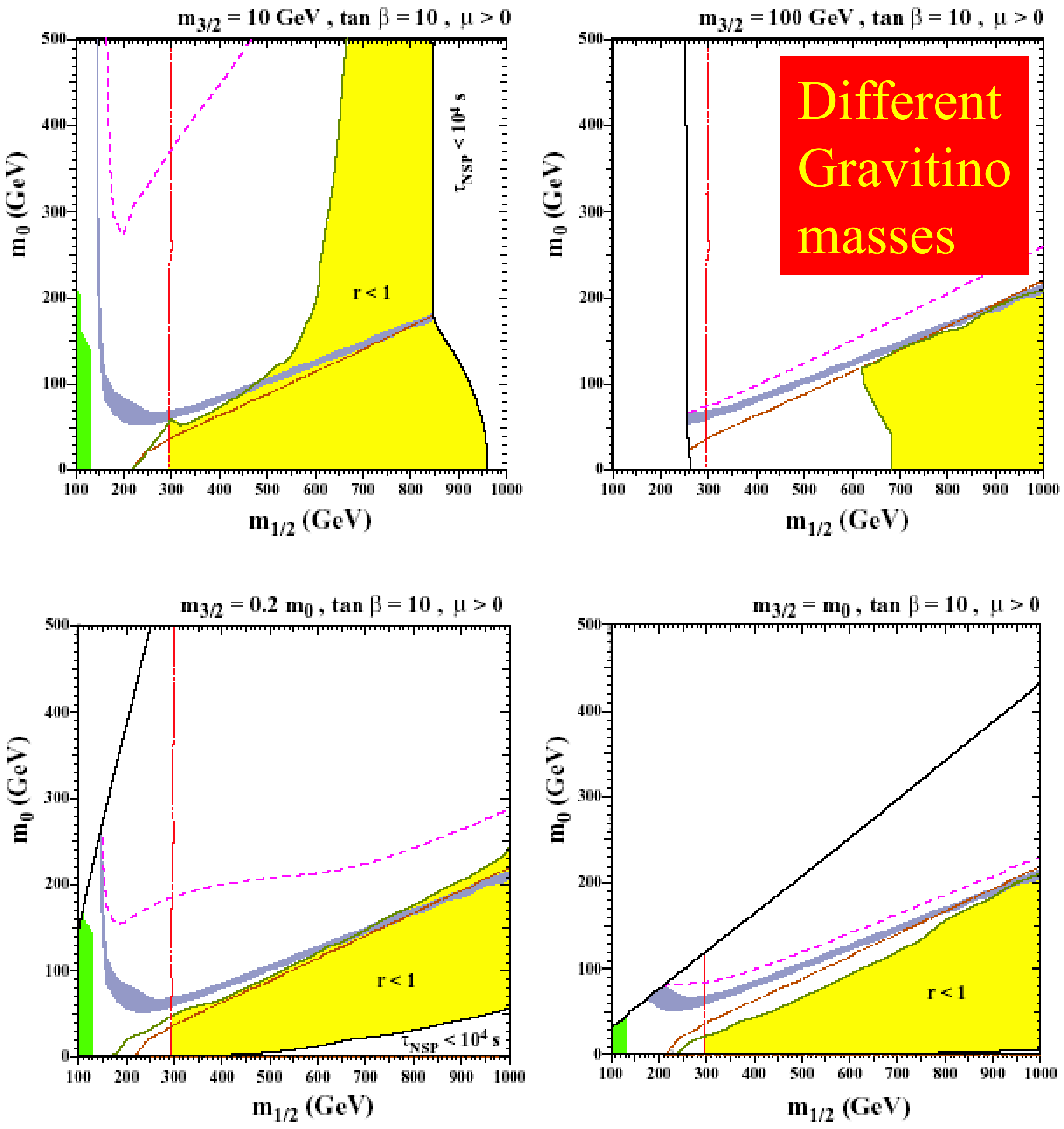
Numbers of sparticle species detected at LHC along WMAP strip



Numbers of sparticle species detected at CLIC along WMAP strip



Different Regions of Sparticle Parameter Space if Gravitino LSP



Different Gravitino masses

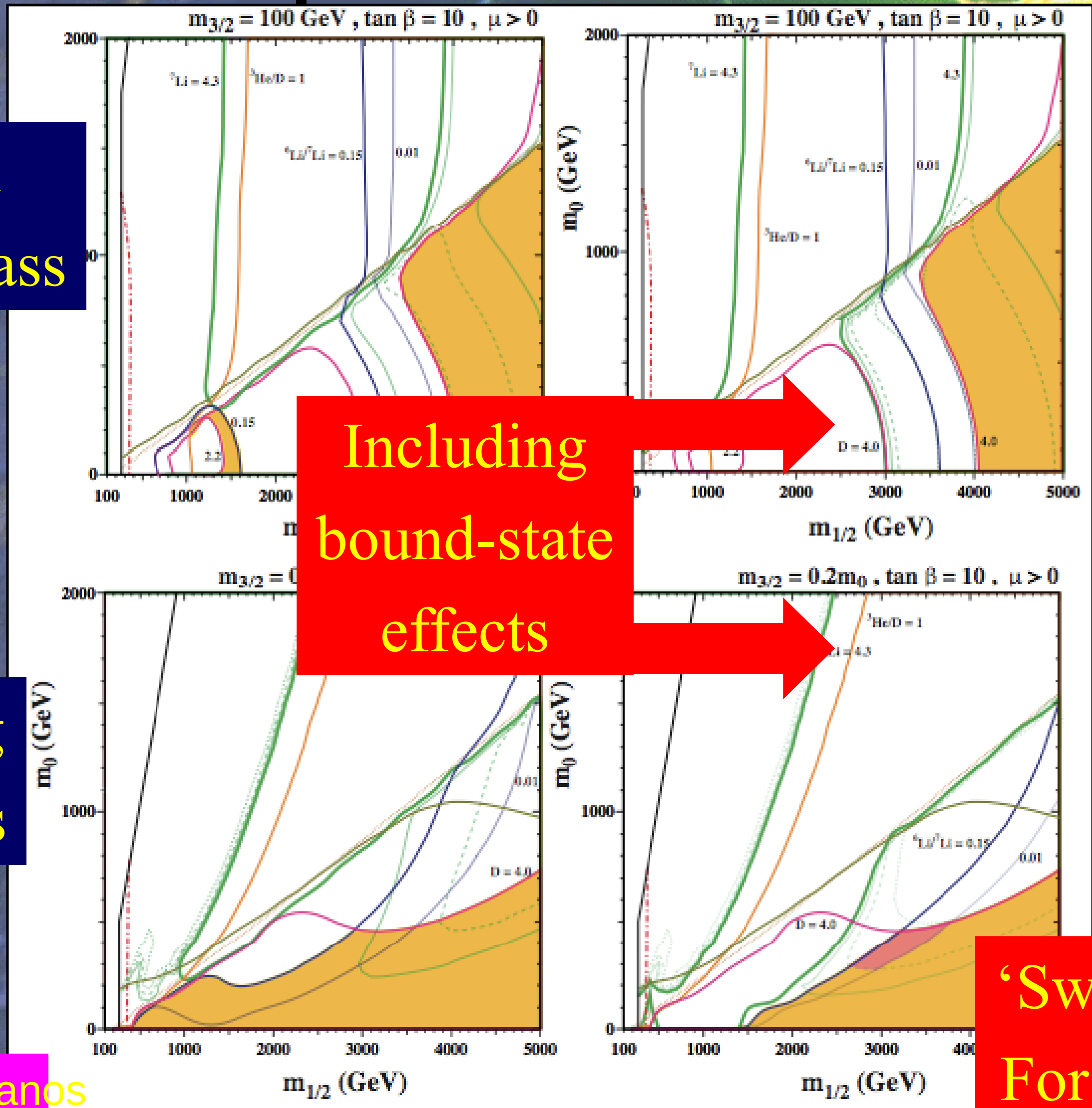
Density below WMAP limit

Decays do not affect BBN/CMB agreement

Effects on GDM parameter Space

Scenario with fixed gravitino mass

Scenario with varying gravitino mass



Including bound-state effects

'Sweet spot' For Lithium

Cyburt, JE, Fields, Olive + Spanos

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

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

- 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

Many extra particles accessible to CLIC

If the LHC discovers supersymmetry …

- CLIC could complete the spectrum

If there is a light Higgs boson …

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

If there is a light Higgs boson …

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

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