# The Physics Case for CLIC

**Marco Battaglia**
UC Berkeley – LBNL, Berkeley
and Universite' Claude Bernard - IPN Lyon

*From the LHC to a Future Collider*
**CERN, 19 February, 2009**

# Physics Motivations for $e^+e^-$ at and beyond 1 TeV

Precision Study of Rare/Suppressed SM Processes:

Higgs Sector: $g_{H\mu\mu}$, $g_{Hbb}$ for intermediate $M_H$, $g_{HHH}$, $g_{ttH}$

Access New Thresholds at the Tera-scale:

Identify nature of New Physics and its connection to Cosmology

Probe New Phenomena beyond LHC Reach:

Precision study of EW observables

# Physics and Experimentation at and beyond 1 TeV

## Physics Signatures

Independent of Physics Scenarios can we identify Physics Signatures most relevant to $e^+e^-$ physics at 1 TeV and beyond ?

Is the study of these Physics Signatures enabled by the Accelerator Parameters ?

## Reach and Accuracy

Is the Physics Reach complementary and supplemental to the LHC capabilities ?

Is the signature $e^+e^-$ Accuracy preserved at 1 TeV and beyond ?

## Experimental Issues

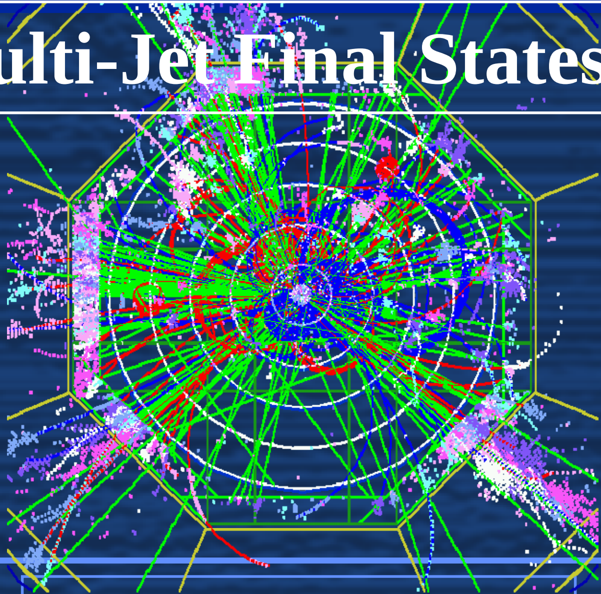
Is Particle Flow applicable to multi-TeV collisions ?

Are the Forward Regions exploitable ?

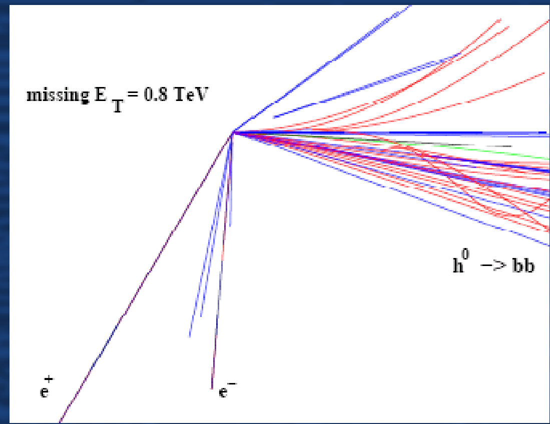
Is accurate Jet Flavour Tagging possible ?

# Physics Signatures at Multi-TeV

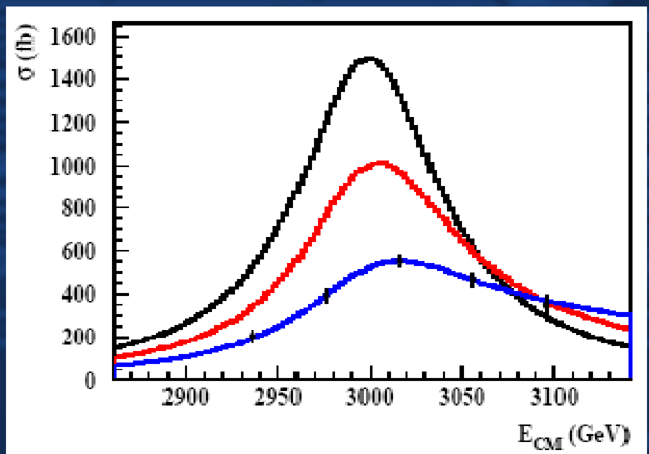
## Multi-Jet Final States



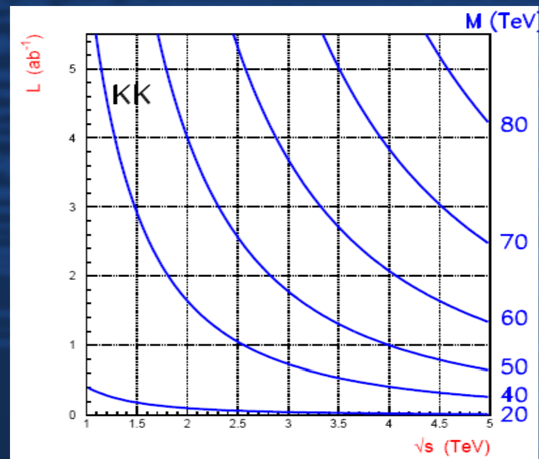
## Missing Energy Final States




## Resonance Scan

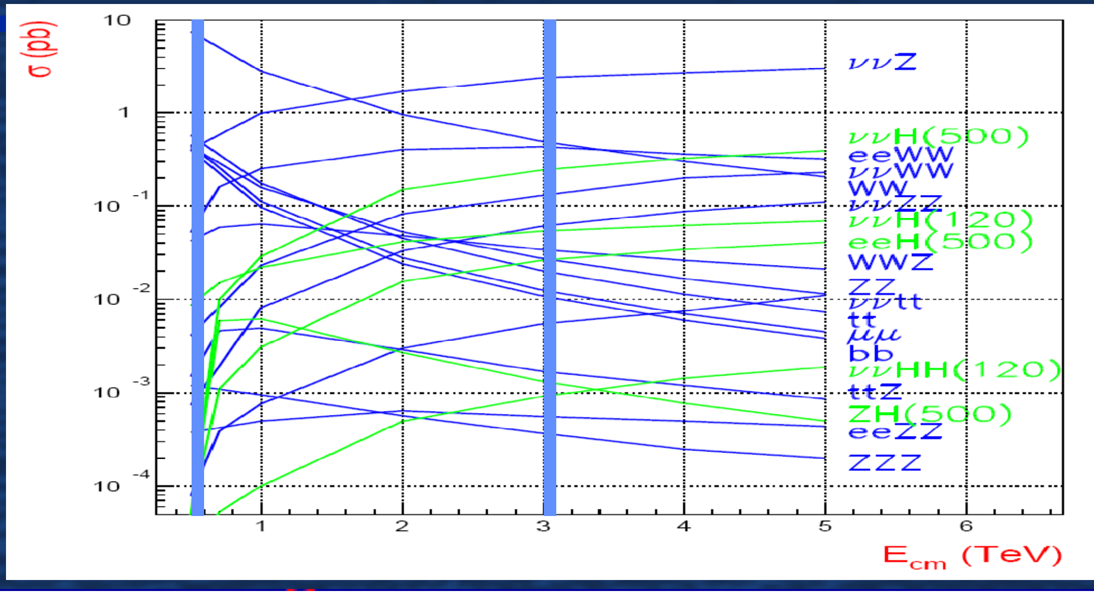



## Electro-Weak Fits

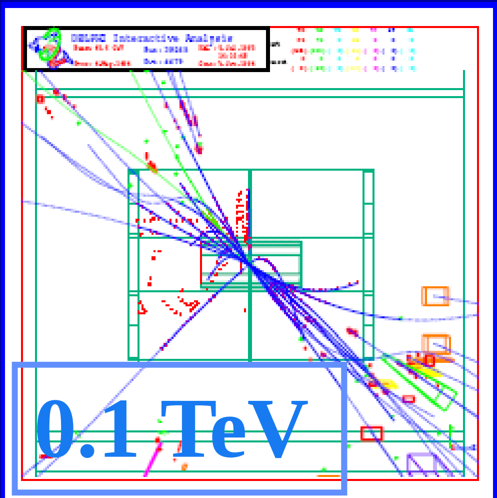


# How is physics changing from 0.2 to 3 TeV ?

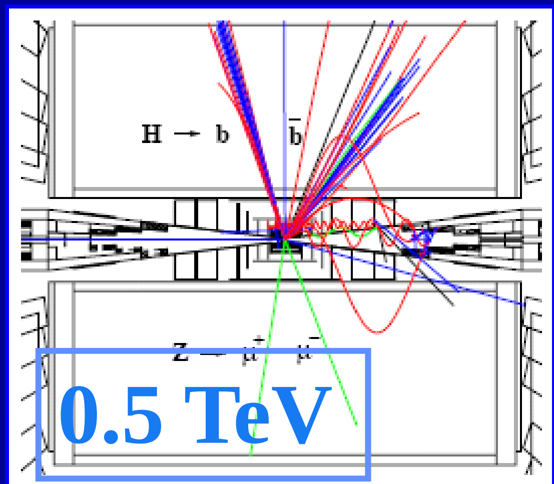
**σ(pb) for SM Processes vs. $E_{cm}$ (TeV)**




$e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}$




$e^+e^- \rightarrow Z^0H^0 \rightarrow \mu^+\mu^-b\bar{b}$




$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}\bar{t}b$

# Observables from 0.2 TeV to 3 TeV (SM Evts)

## Jet Multiplicity

| $\sqrt{s}$ (TeV) | 0.09 | 0.20 | 0.5 | 0.8 | 3.0 | 5.0 |
|---|---|---|---|---|---|---|
| $< N_{Jets} >$ | 2.8 | 4.2 | 4.8 | 5.3 | 6.4 | 6.7 |

## Parton Energy

| $\sqrt{s}$ (TeV) | 0.2 | 0.5 | 1.0 | 3.0 |
|---|---|---|---|---|
| $<E_{Parton}>$ (GeV) | 32 | 64 | 110 | 240 |

## B Hadron Decay Distance

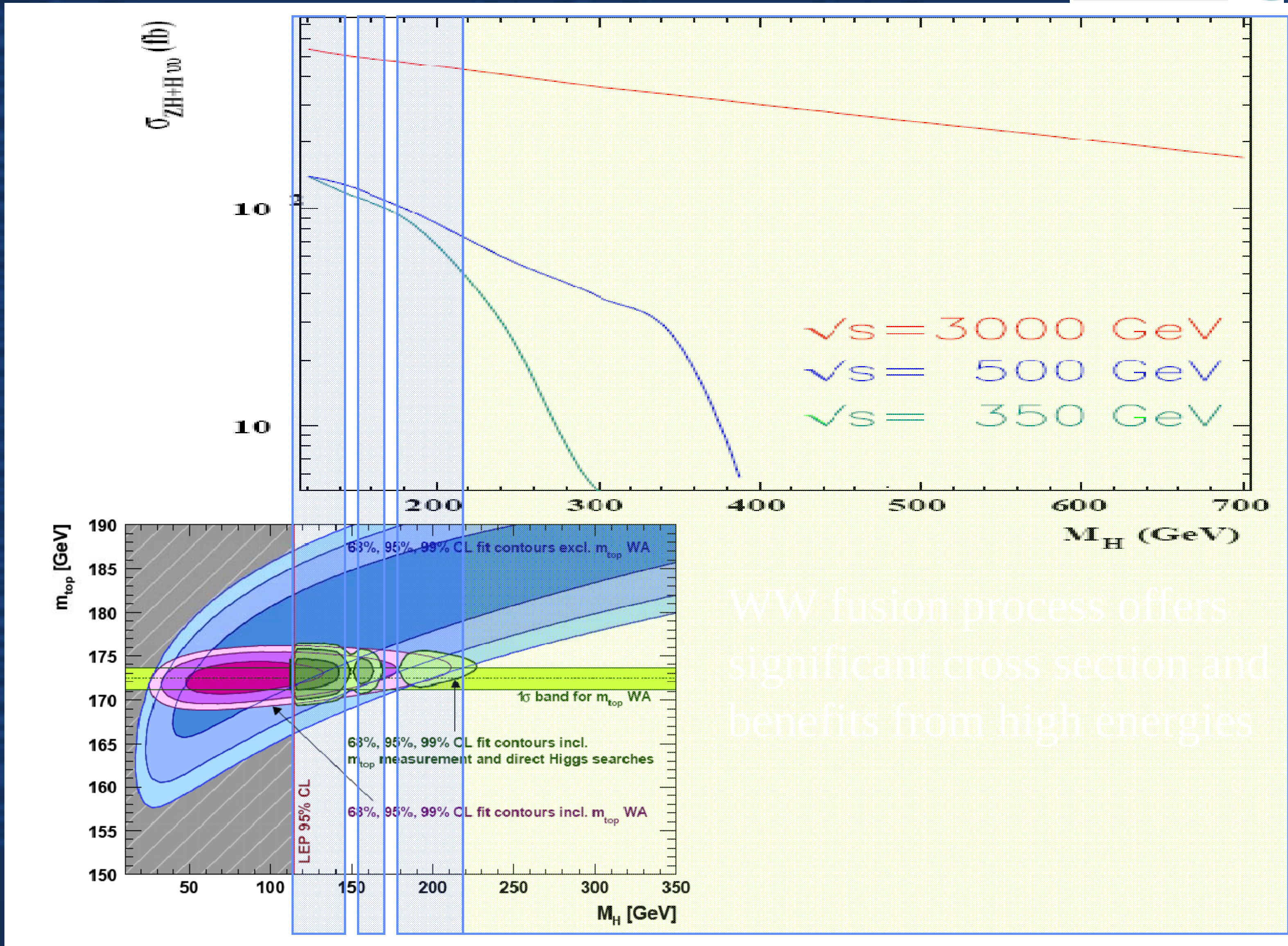
| $\sqrt{s}$ (TeV) | 0.09 | 0.2 | 0.35 | 0.5 | 3.0 | |
|---|---|---|---|---|---|---|
| Process | $Z^0$ | $HZ$ | $HZ$ | $HZ$ | $H^+H^-$ | $b\bar{b}$ |
| $d_{space}$ (cm) | 0.3 | 0.3 | 0.7 | 0.85 | 2.5 | 9.0 |



MB,
hep-ph/0103338

# Precision Study of Rare/Suppressed SM Processes

# The Higgs Boson and CLIC




WW fusion process offers significant cross section and benefits from high energies

Flaecher et al.
arXiv:0811:0009v2

MB, De Roeck,
hep-ph/0211207

# The Higgs Sector at CLIC: Light Higgs Profile

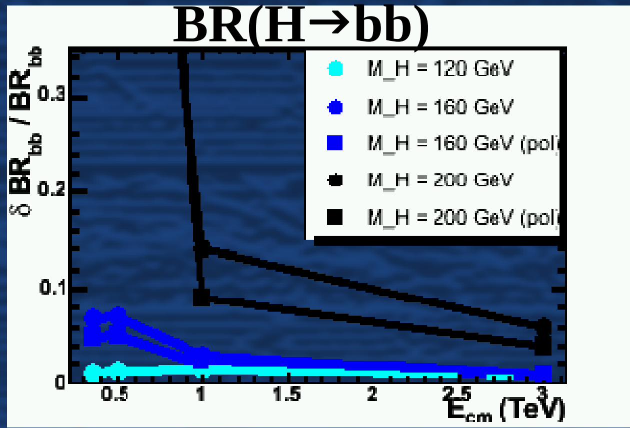
| $E_{cm}$ | L |
|---|---|
| 0.35 TeV | 0.5 $ab^{-1}$ |
| 0.50 TeV | 0.5 $ab^{-1}$ |
| 1.0 TeV | 1.0 $ab^{-1}$ |
| 3.0 TeV | 2.0 $ab^{-1}$ |

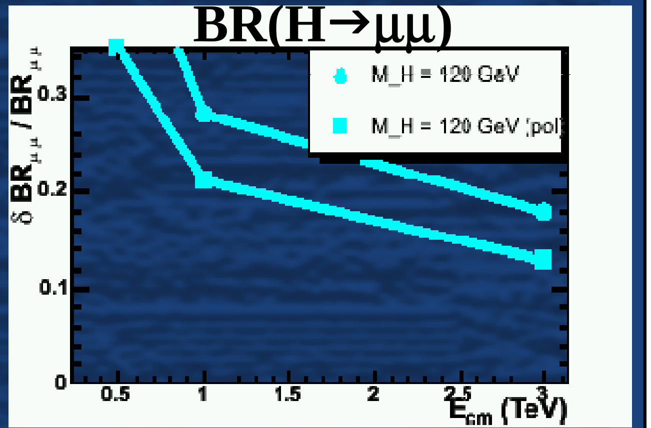
Pol: $e^-$ 80% $e^+$ 50%

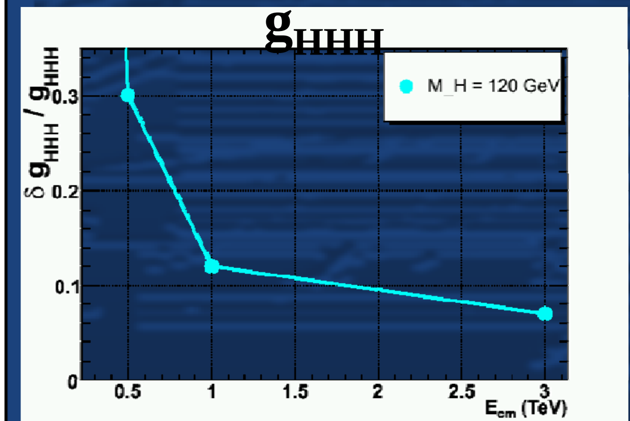
Barklow, hep-ph/0312268

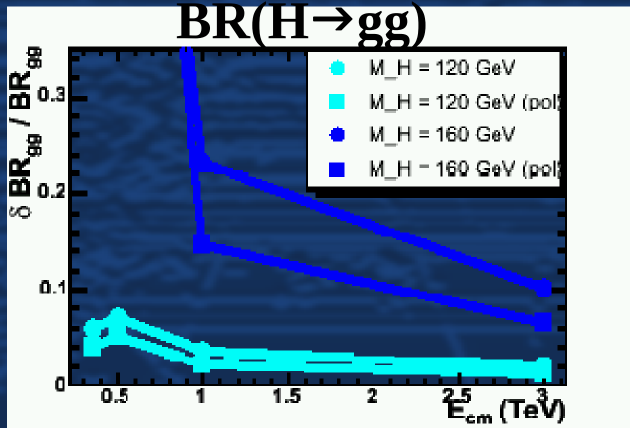
| $\sqrt{s}$ (GeV) | $e^+_{pol}$ (%) | Higgs Mass (GeV) 120 | 140 | 160 | 200 |
|---|---|---|---|---|---|
| 350 | 0 | 110280 | 89150 | 69975 | 37385 |
| 350 | +50 | 159115 | 128520 | 100800 | 53775 |
| 1000 | 0 | 386550 | 350690 | 317530 | 259190 |
| 1000 | +50 | 569750 | 516830 | 467900 | 382070 |

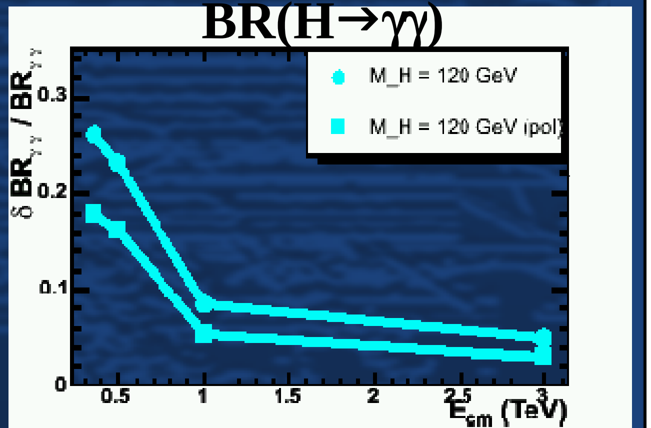
TESLA-TDR 2001
Kuhl, Desch, LC-PHSM-2007-001
Barklow, hep-ph/0312268
MB, DeRoeck, hep-ph/0211207
MB, J Phys G35 (2008) 095005



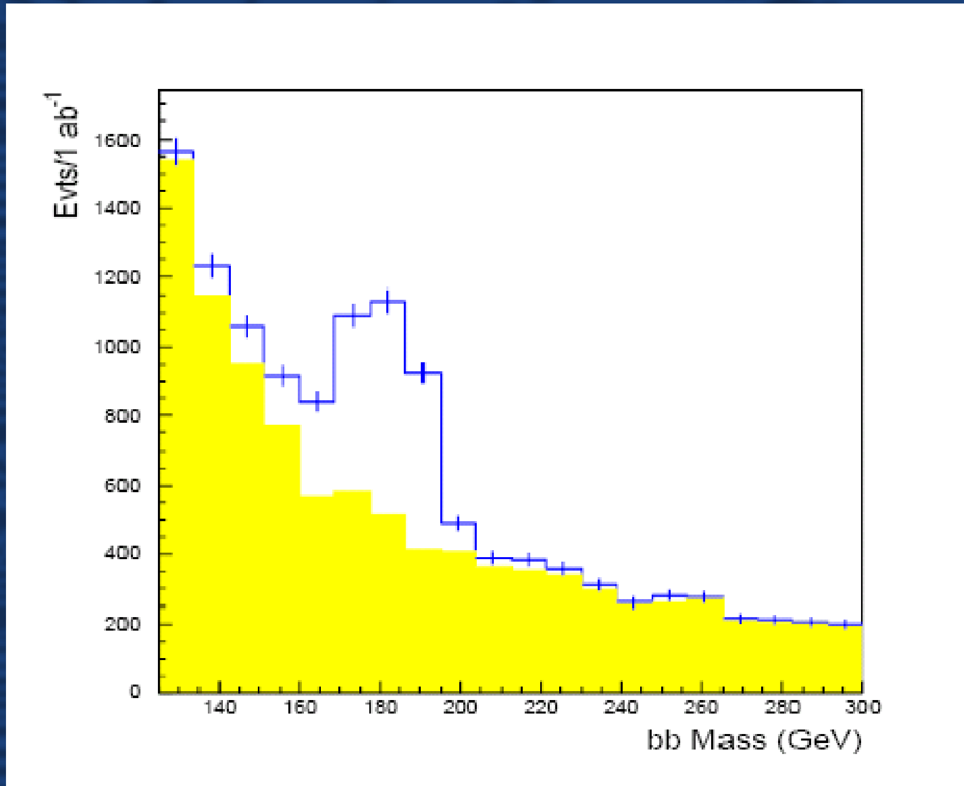



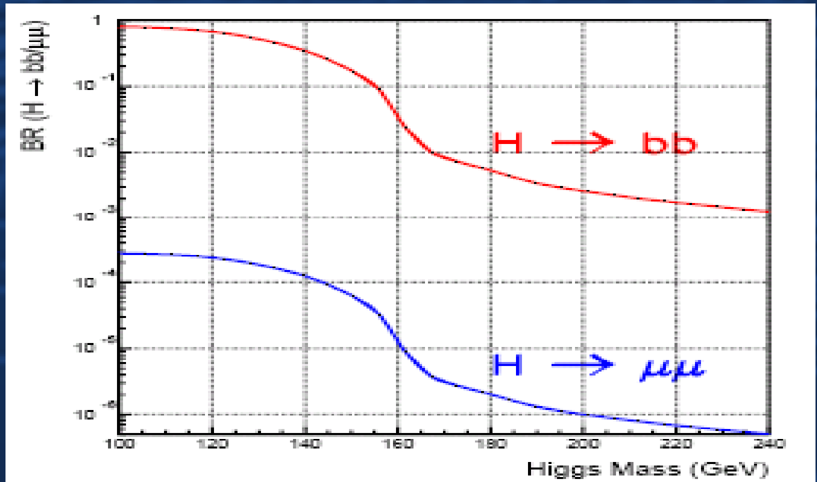



# Fermion Couplings: $e^+e^- \rightarrow \nu_e\nu_e H^0 \rightarrow bb$

Large WW fusion cross section yields samples of (0.5-1) x $10^6$ H bosons;

Gain in cross section partly offset by increasingly forward production of H, still within $|\cos\theta| < 0.92$ there is a 1.7 x gain at 3 TeV compared to 1 TeV.



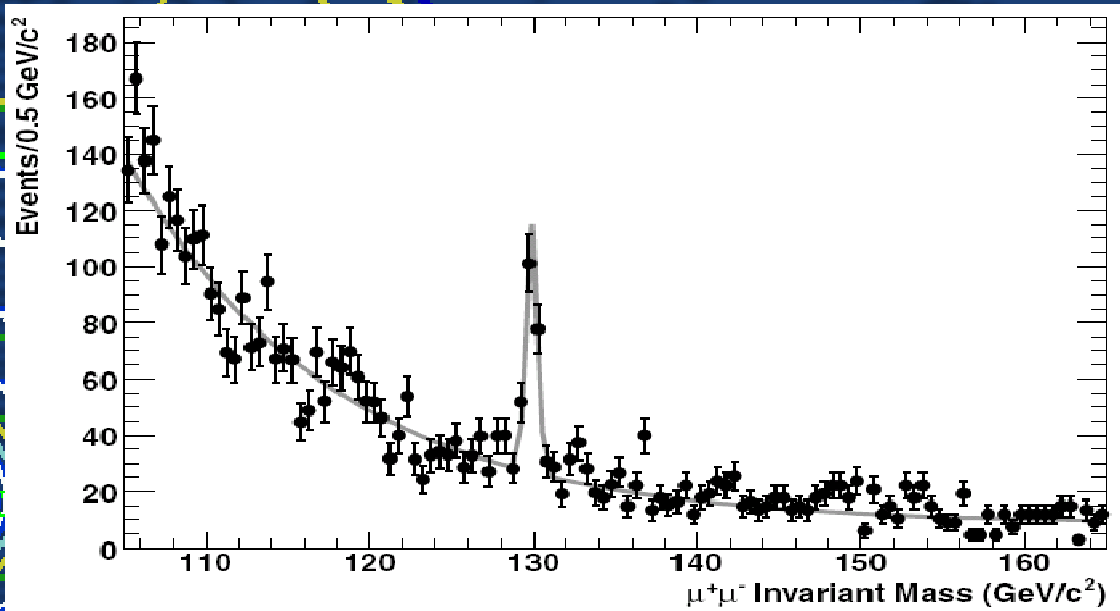




| $M_H$ (GeV) | $S/\sqrt{B}$ | $\delta\, g_{Hbb} / g_{Hbb}$ |
|---|---|---|
| 180 | 40.5 | 0.016 |
| 200 | 25.0 | 0.025 |
| 220 | 18.0 | 0.034 |

MB, De Roeck, hep-ph/0211207

# Fermion couplings: $e^+e^- \to \nu_e\nu_e H \to \mu^+\mu^-$

Full simulation CLIC analysis based on ILC C++ software and SiD detector model: $e^+e^- \to \nu_e\nu_e H \to \mu^+\mu^-$




| $M_H$ (GeV) | Nb. signal evts. | Nb. bkg. evts. | $S/\sqrt{B}$ | $\delta BR/BR$ |
|---|---|---|---|---|
| 120 | 229.6 | 161.1 | 18.1 | 0.086 |
| 130 | 153.1 | 88.1 | 16.3 | 0.101 |
| 140 | 103.2 | 64.3 | 12.9 | 0.125 |
| 150 | 68.1 | 58.1 | 9.5 | 0.160 |
| 155 | 68.1 | 58.0 | 5.2 | 0.253 |
| 160 | 12.1 | 33.0 | 2.1 | |



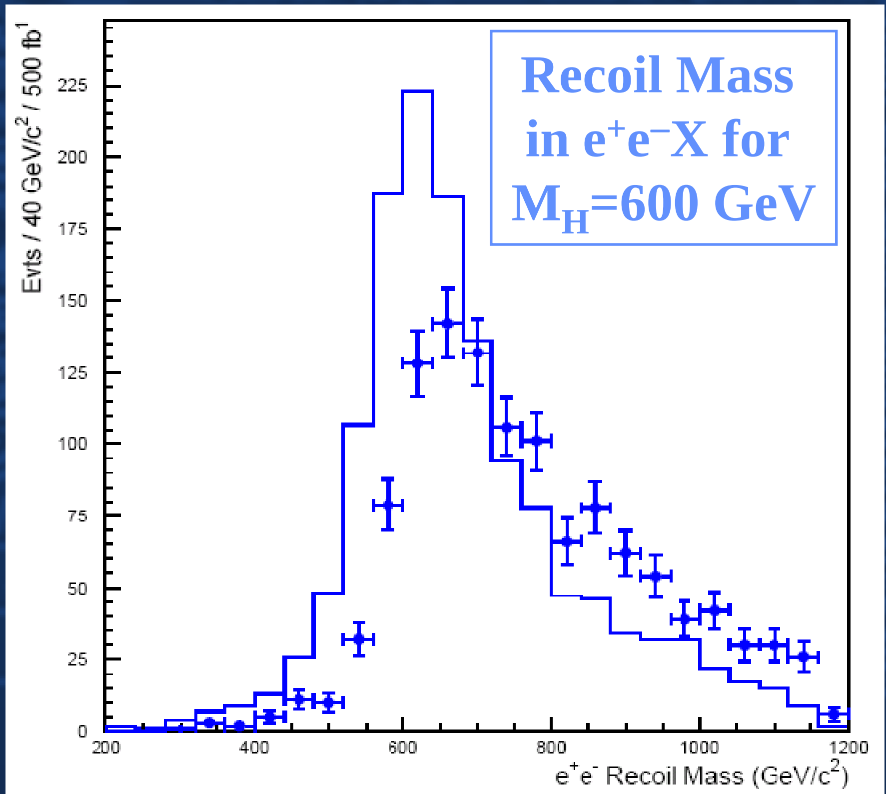
MB, JPhys G35 (2008)

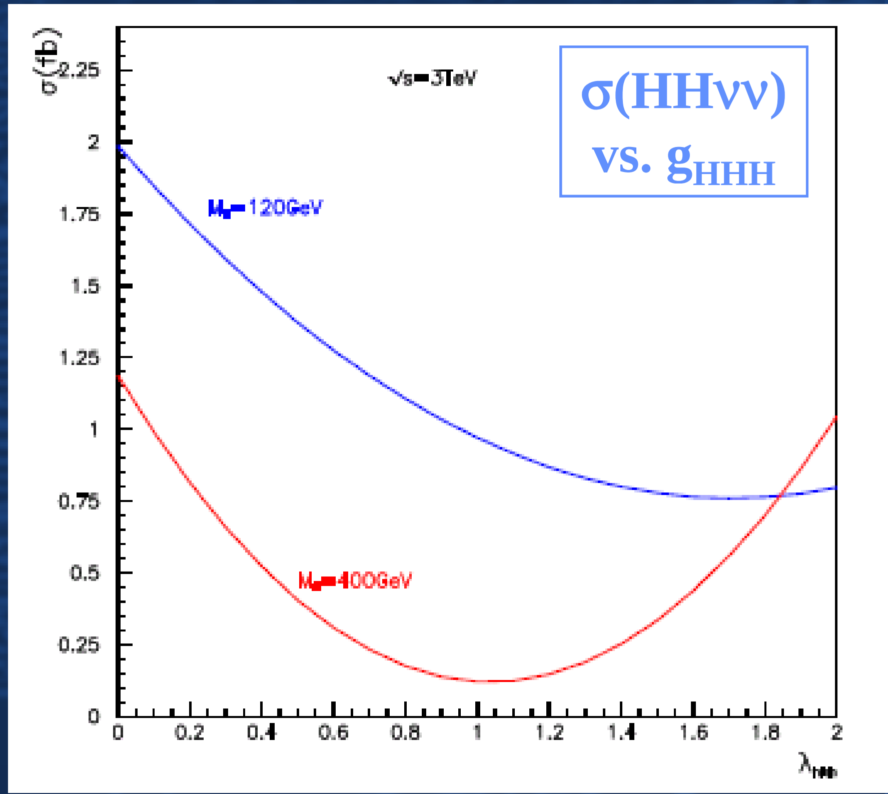
# The Higgs Sector at CLIC: Heavy Higgs Profile

CLIC promises to preserve LC signature capabilities for Higgs studies at large boson masses:

Decay-independent Higgs observation and mass measurement in $e^+e^- \to e^+e^- H^0$

Possible sensitivity to triple Higgs coupling for heavy Higgs bosons

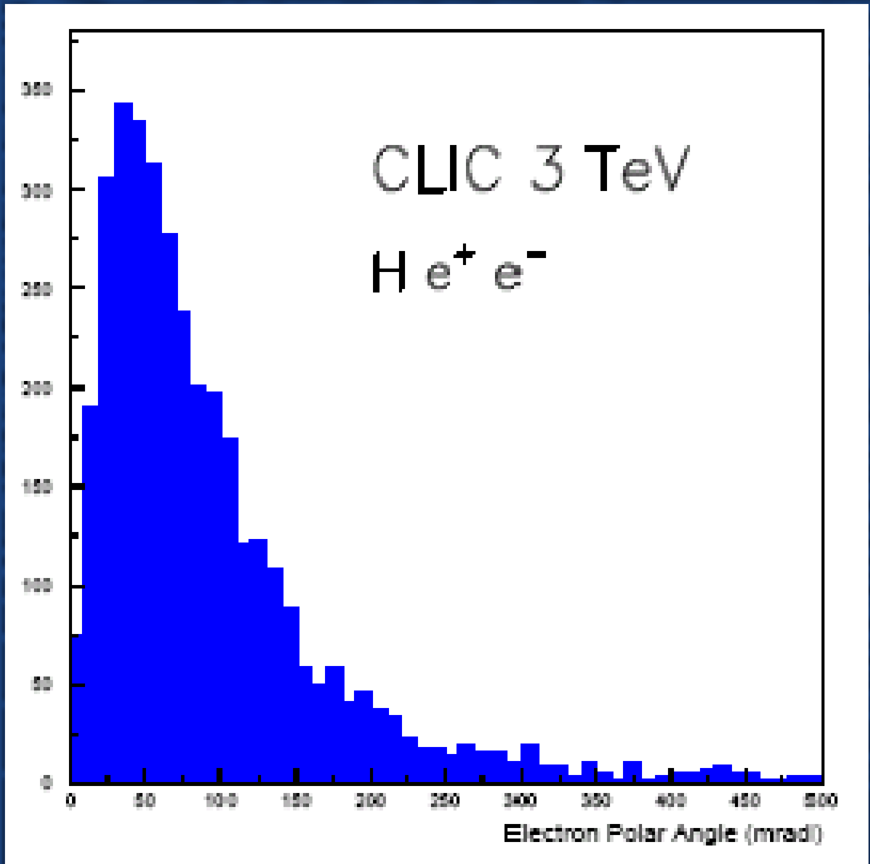


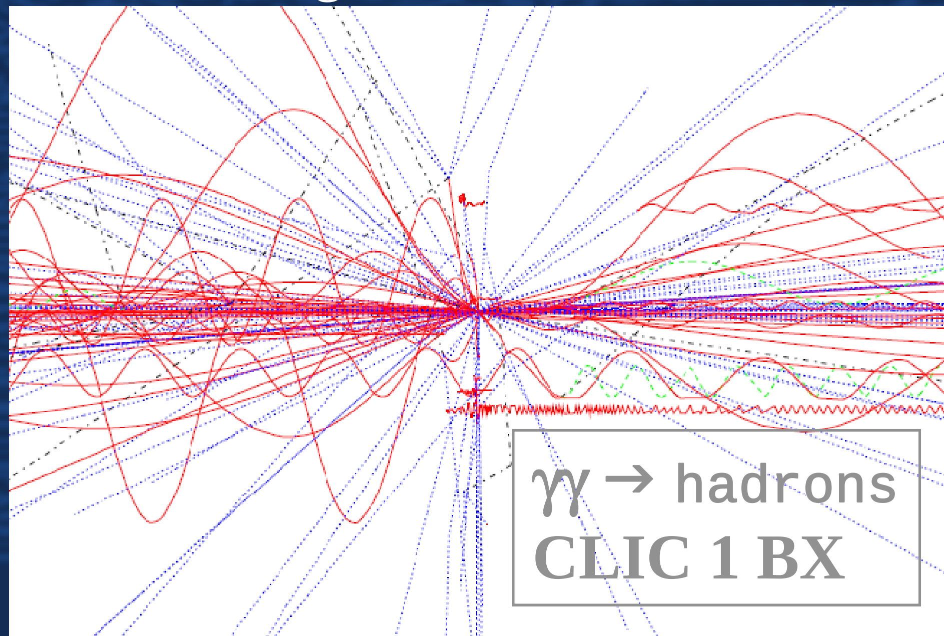

MB, hep-ph/0103338

# Experimental Issues

Tag and measure ~250 GeV forward electrons in presence of $\gamma\gamma \rightarrow$ hadrons background




Simulation shows that background is manageable down to 300 mrad for hadronic jets and 100 mrad for isolated energetic electrons;



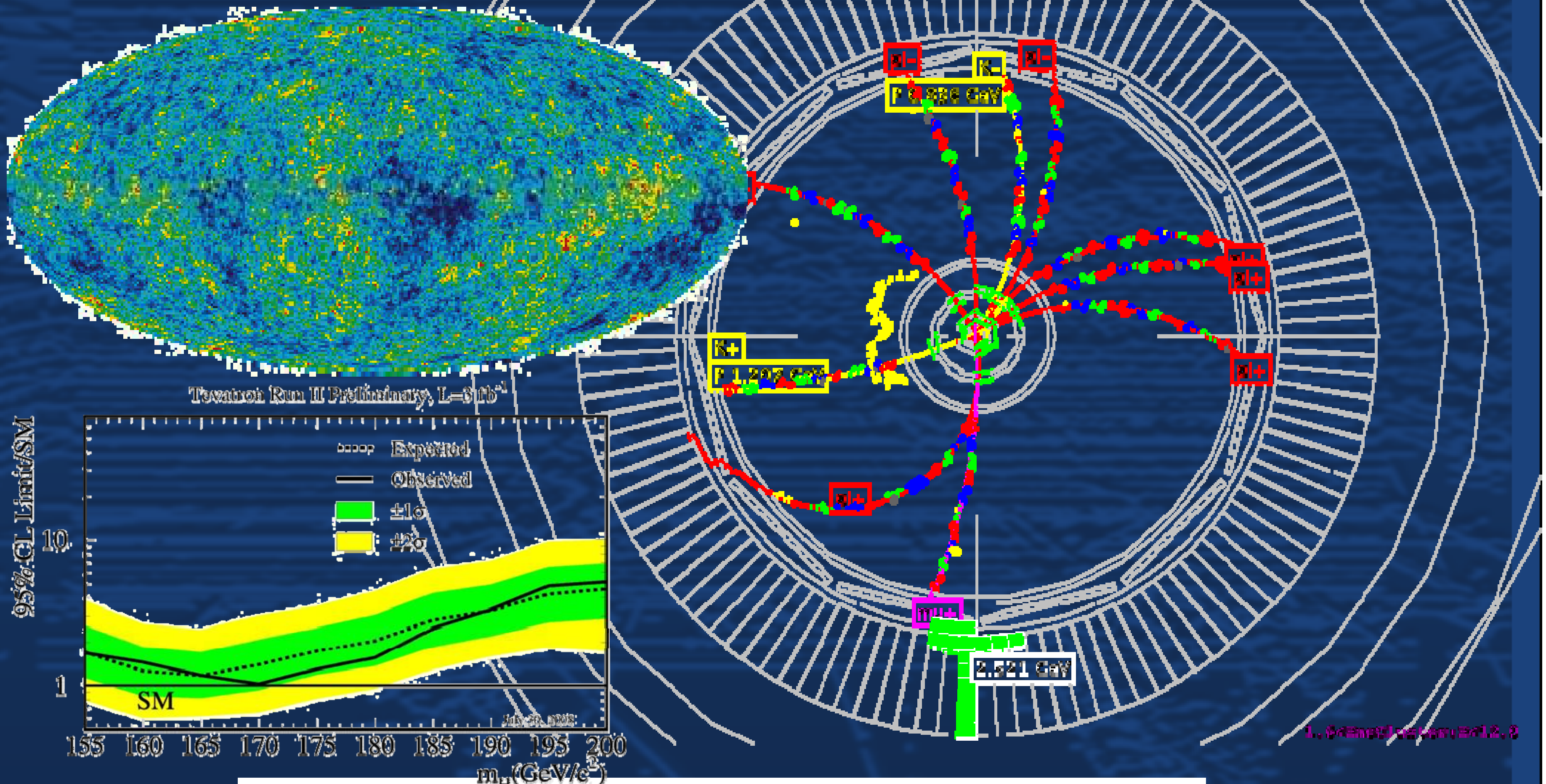

MB,
hep-ph/0103338

# Access New Thresholds at the Tera-scale

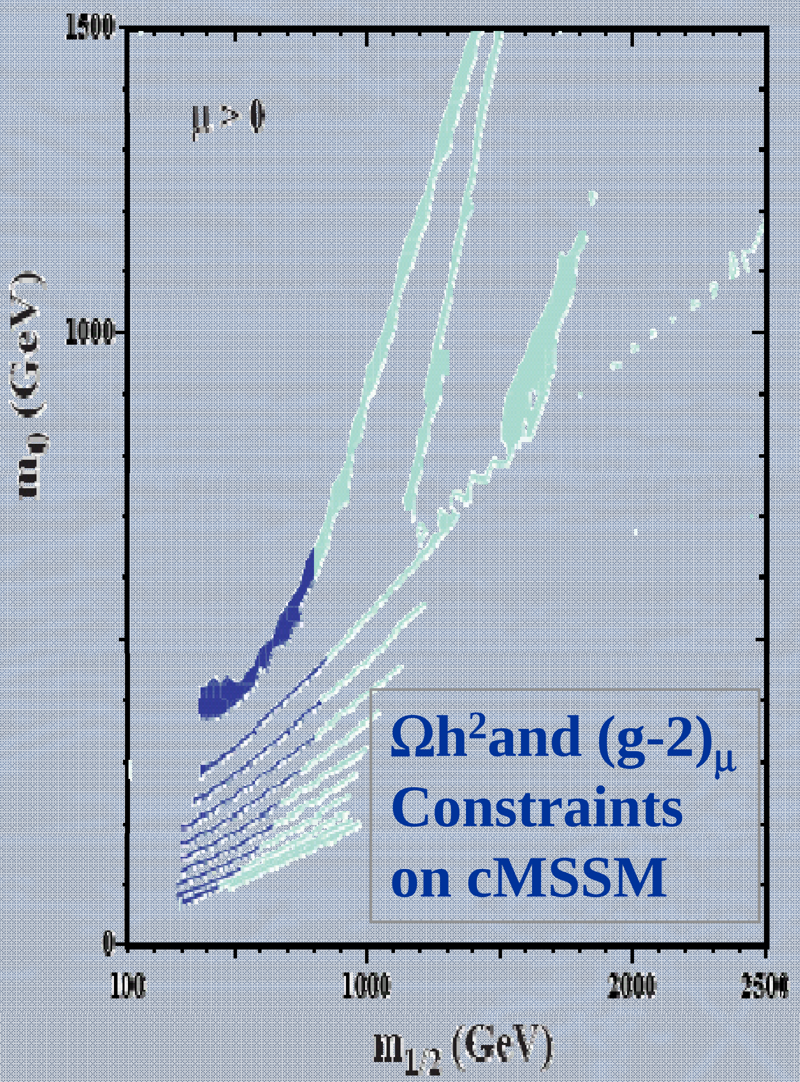
# Which is the scale of New Physics ?

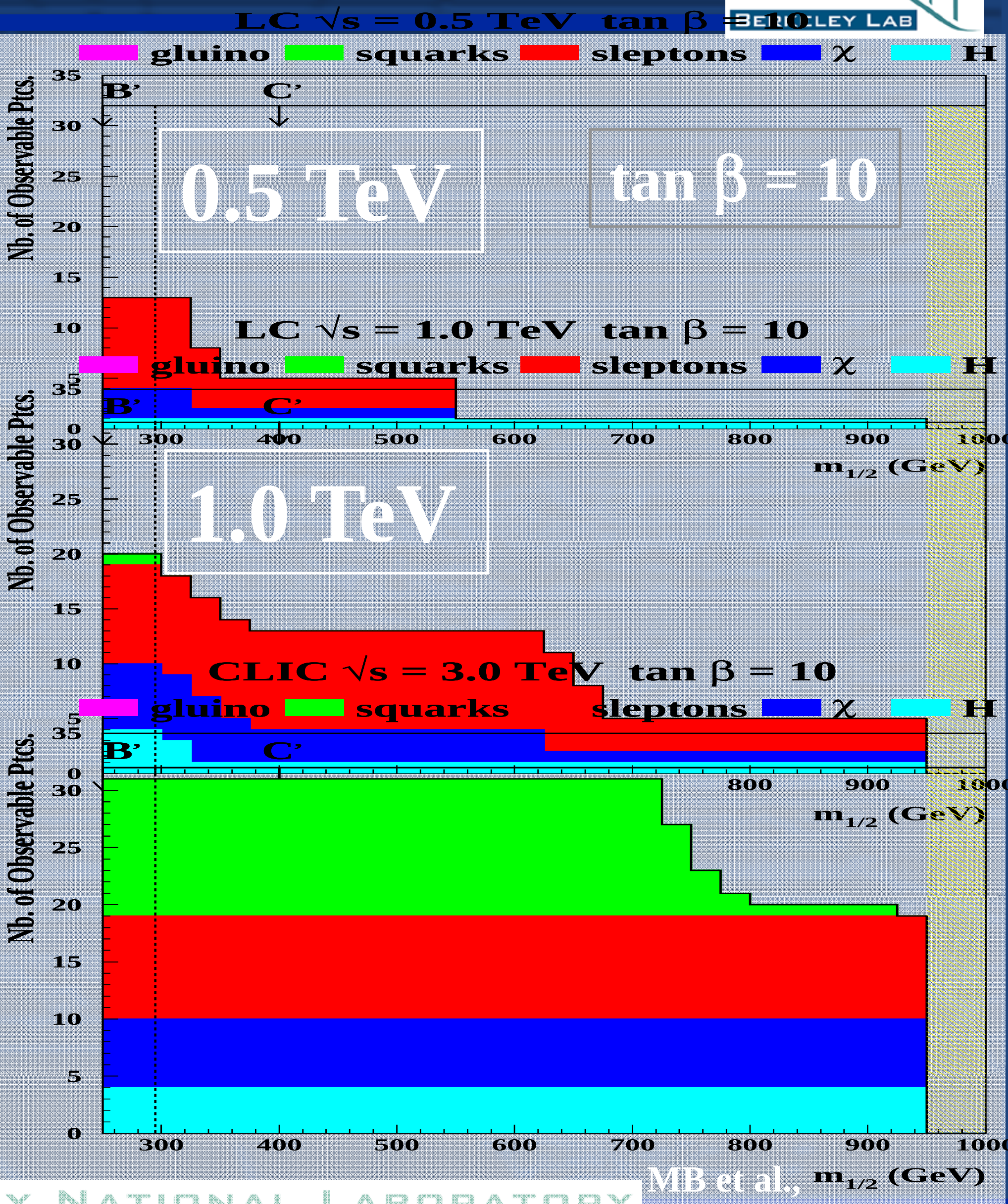
Berkeley Lab

Waiting for LHC results, many attempts to define "most likely" region(s) of parameters based on LEP+Tevatron, low energy data and Cosmology (DM and BBN):



# How Many Observable Particle ?



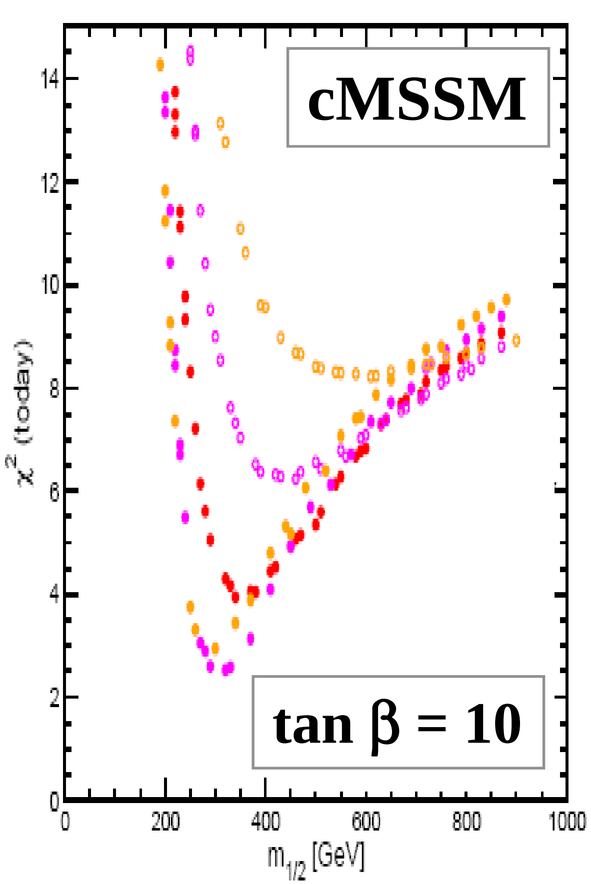



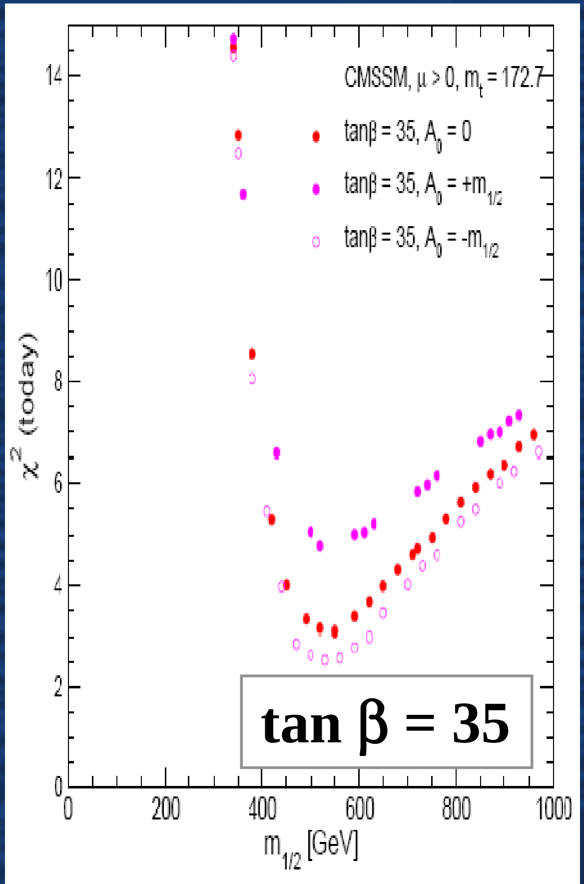

Ellis et al.,
PLB565 (2003)

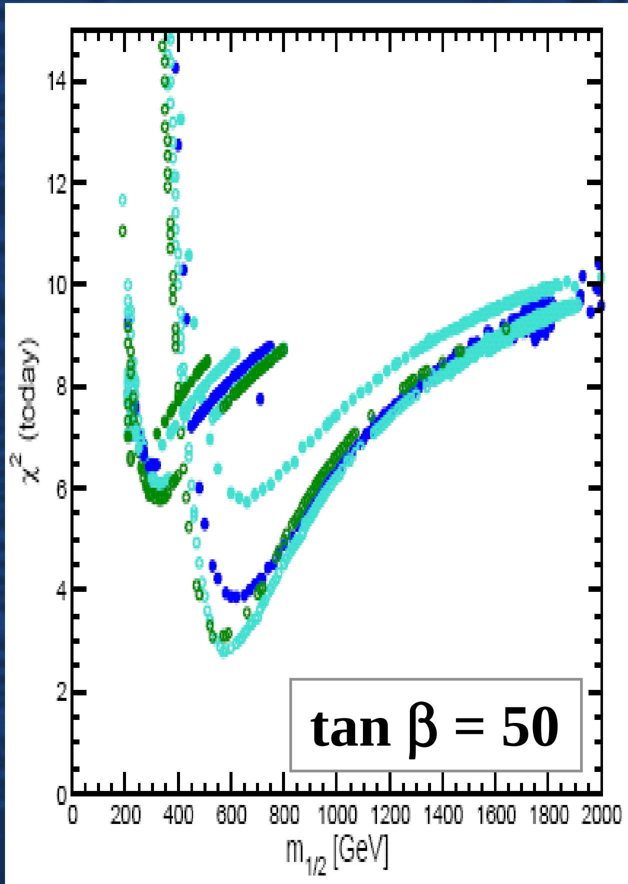
MB et al.,
Eur Phys J C33 (2004)

# Which is the scale of New Physics ?

**1)** cMSSM with $M_W, \sin^2\vartheta_{eff}, M_h, (g-2)_\mu, BR(b \to s\gamma)$ constraints and $m_0$ tuned to match $\Omega_{CDM}h^2$ at various tan β values



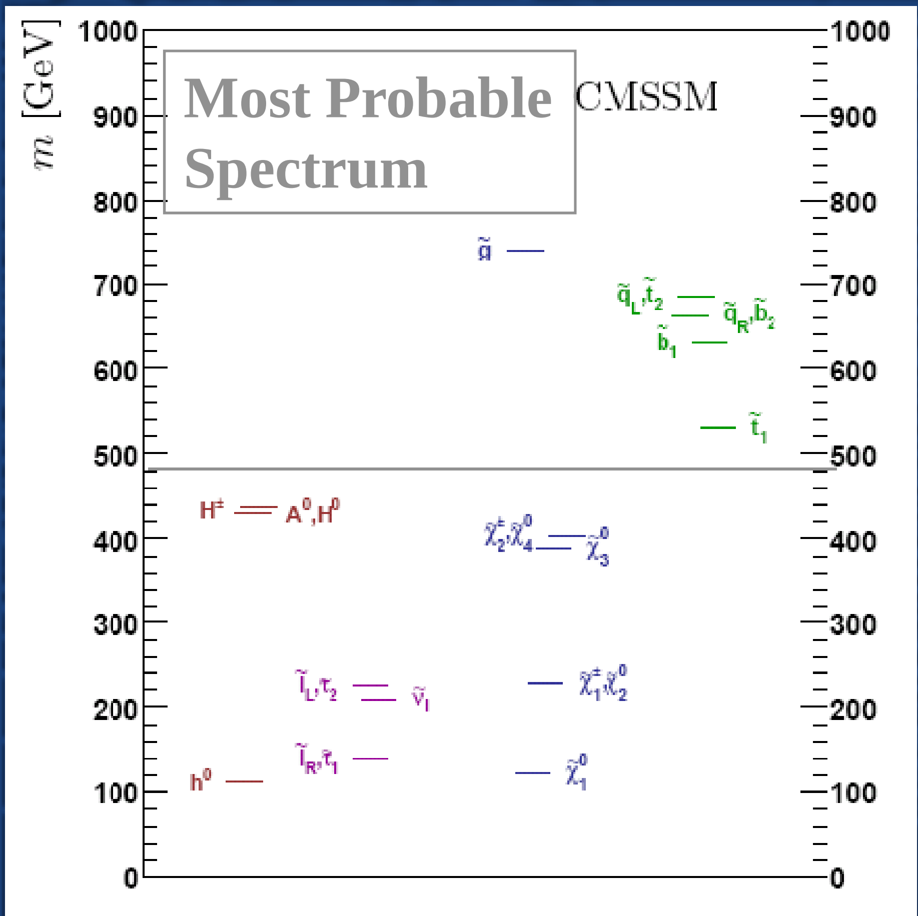



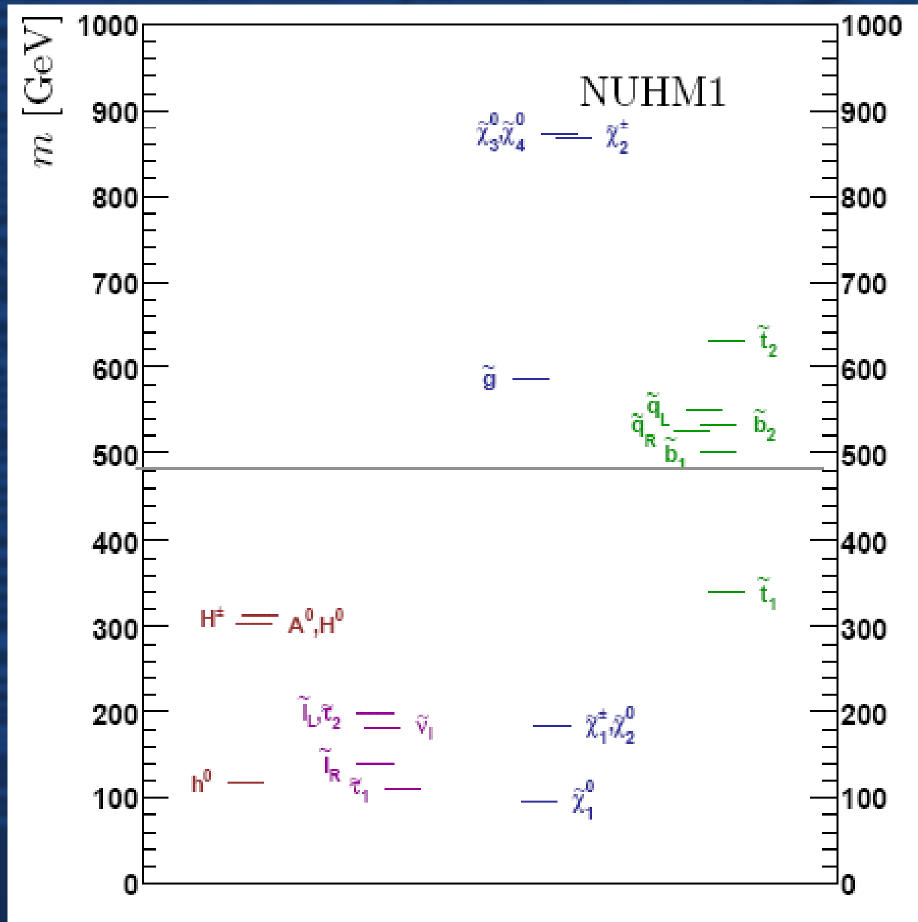

Ellis et al., JHEP 0605 (2006)

# Which is the scale of New Physics ?

**2)** cMSSM with 15 constraints (EW, B physics, $(g\text{-}2)_\mu$ and $\Omega_{CDM}h^2$)




**3)** NUHM SUSY with 15 constraints (EW, B physics, $(g\text{-}2)_\mu$ and $\Omega_{CDM}h^2$)

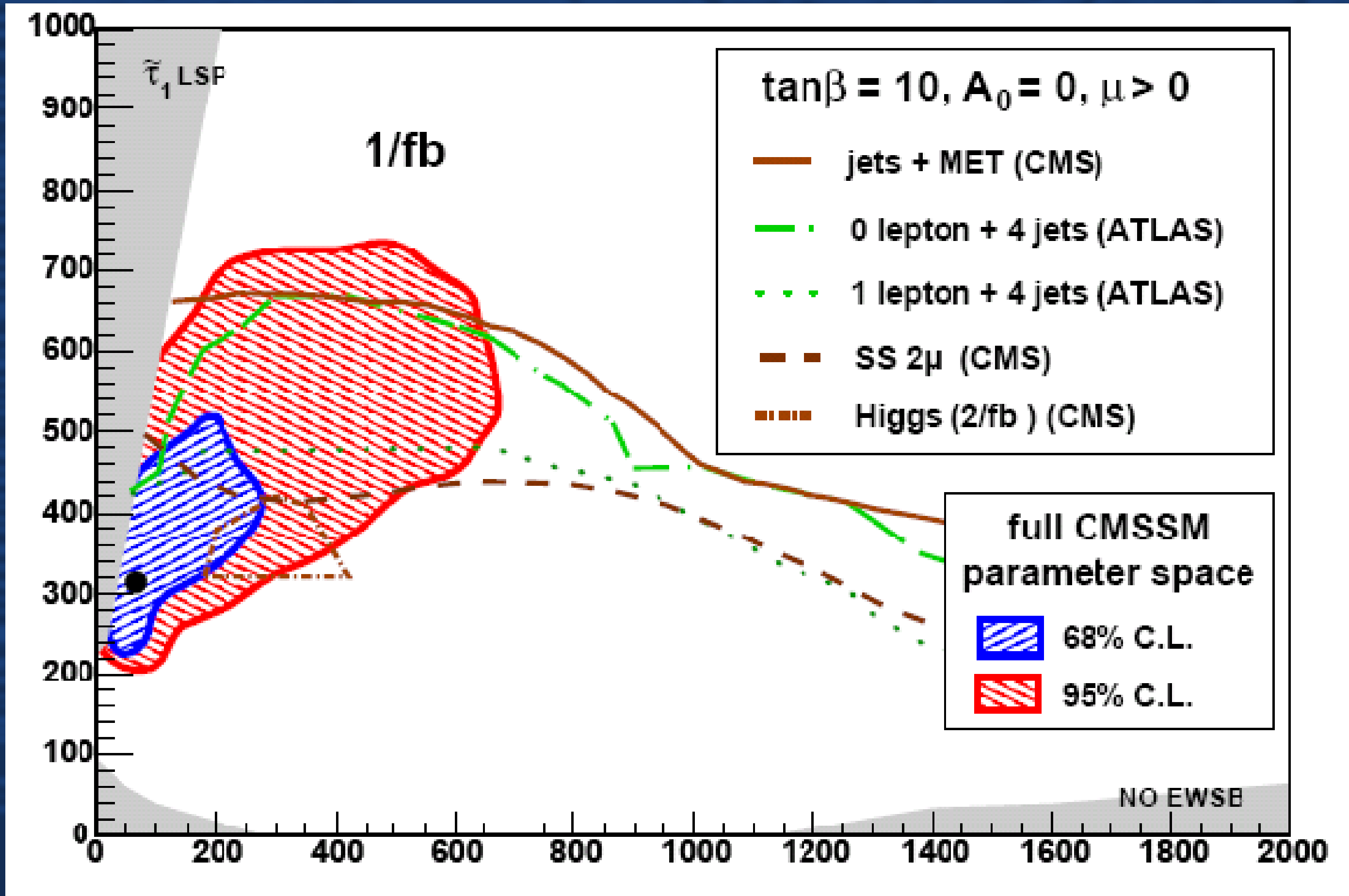



**Buchmuller et al., JHEP 0809 (2008)**

# Which is the scale of New Physics ?

**2)** cMSSM with 15 constraints (EW, B physics, $(g-2)_\mu$ and $\Omega_{CDM}h^2$)

allowed region largely extends towards high mass solutions

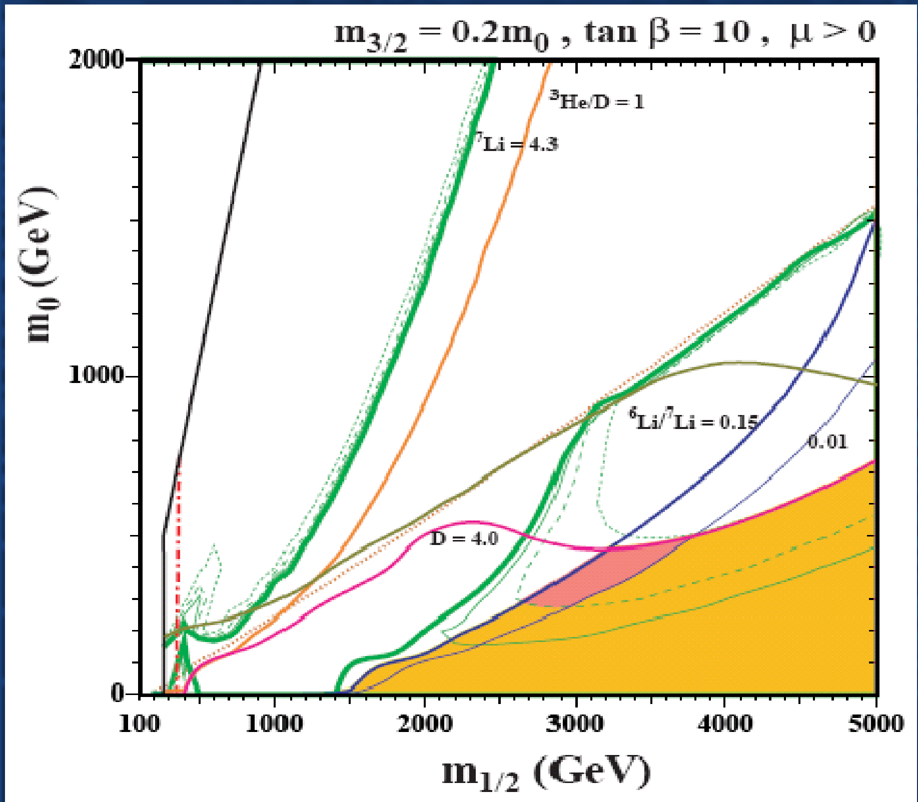


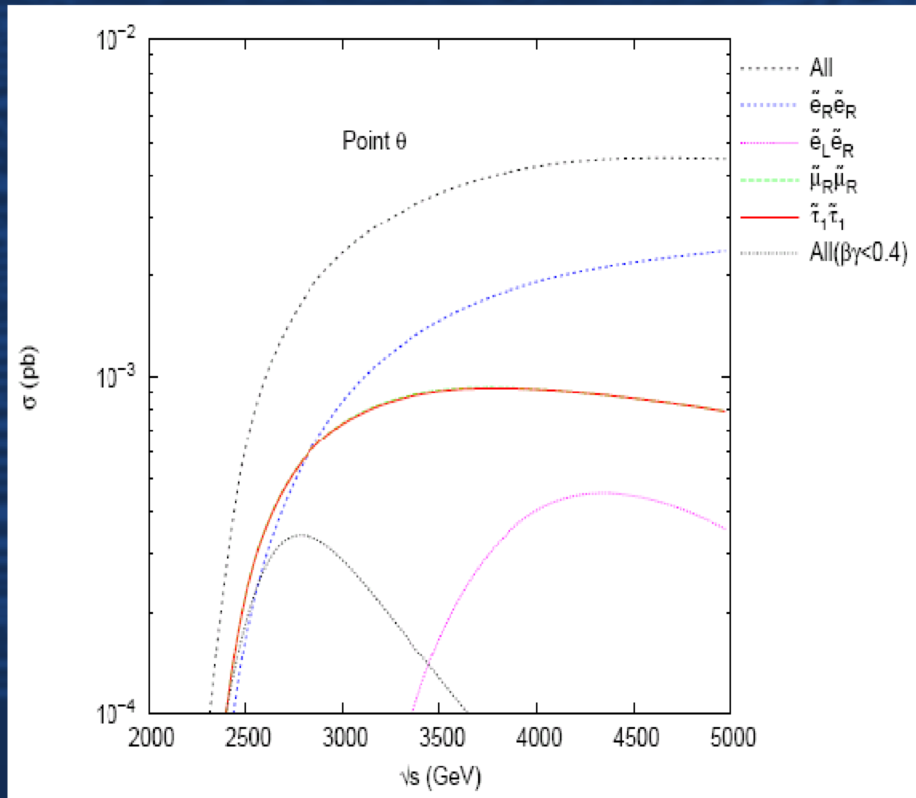

Buchmuller et al., JHEP 0809 (2008)

# Which is the scale of New Physics ?

**4)** In scenarios with gravitino LSP, long-lived staus may form metastables states with nuclei affecting Big Bang Nucleosynthesis;

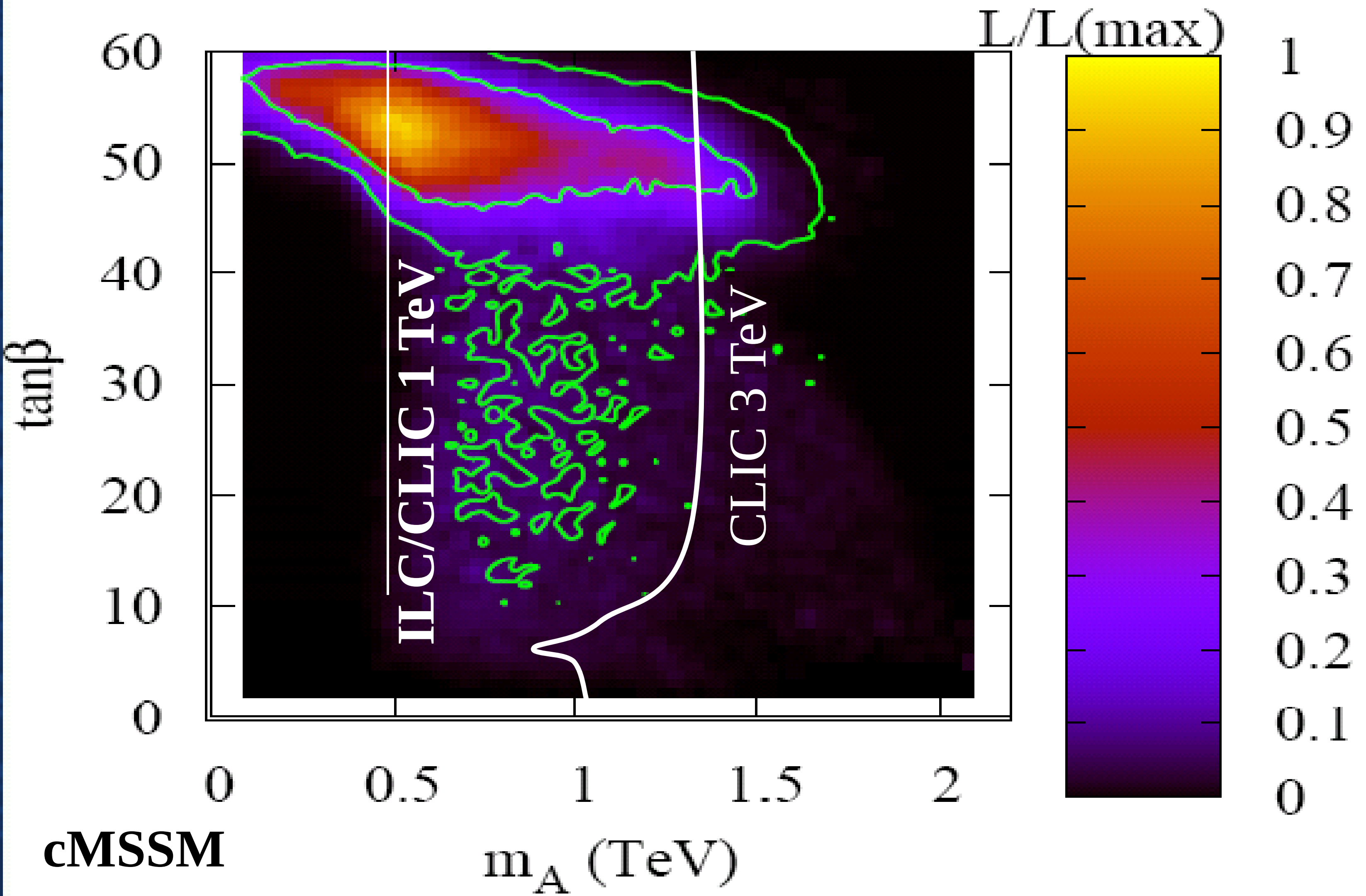
These scenarios indicate very large sparticle masses, even too large for detection at LHC but well suited for CLIC:




Cakir et al, hep-ph/0203121

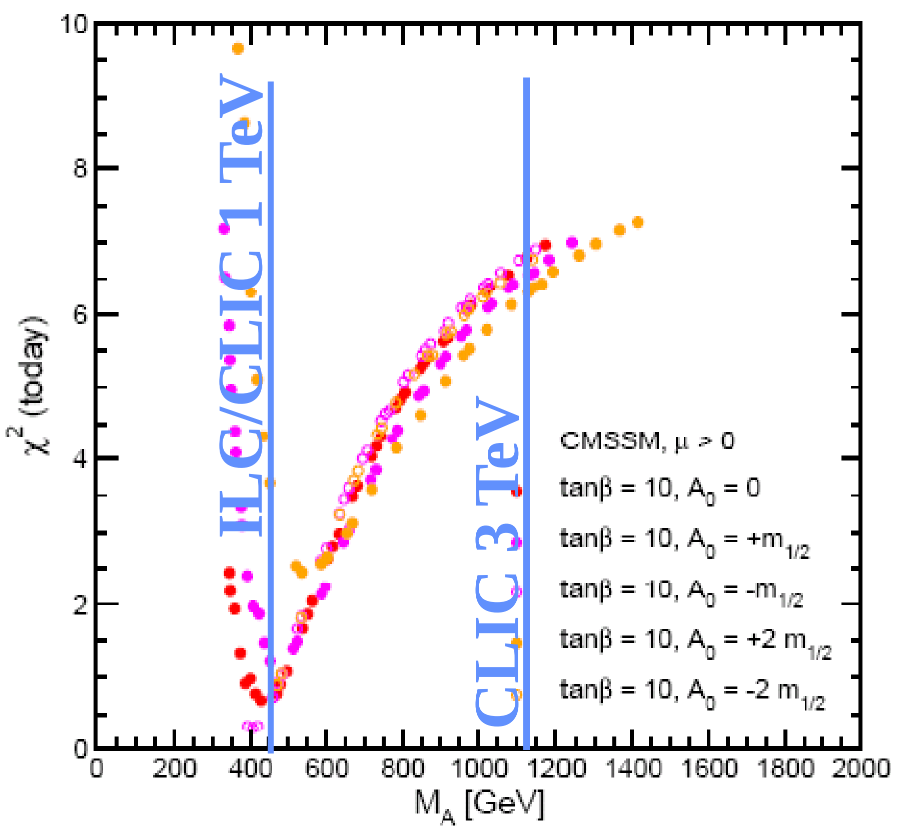
# SUSY Heavy Higgs Bosons: $M_A$ – tan β

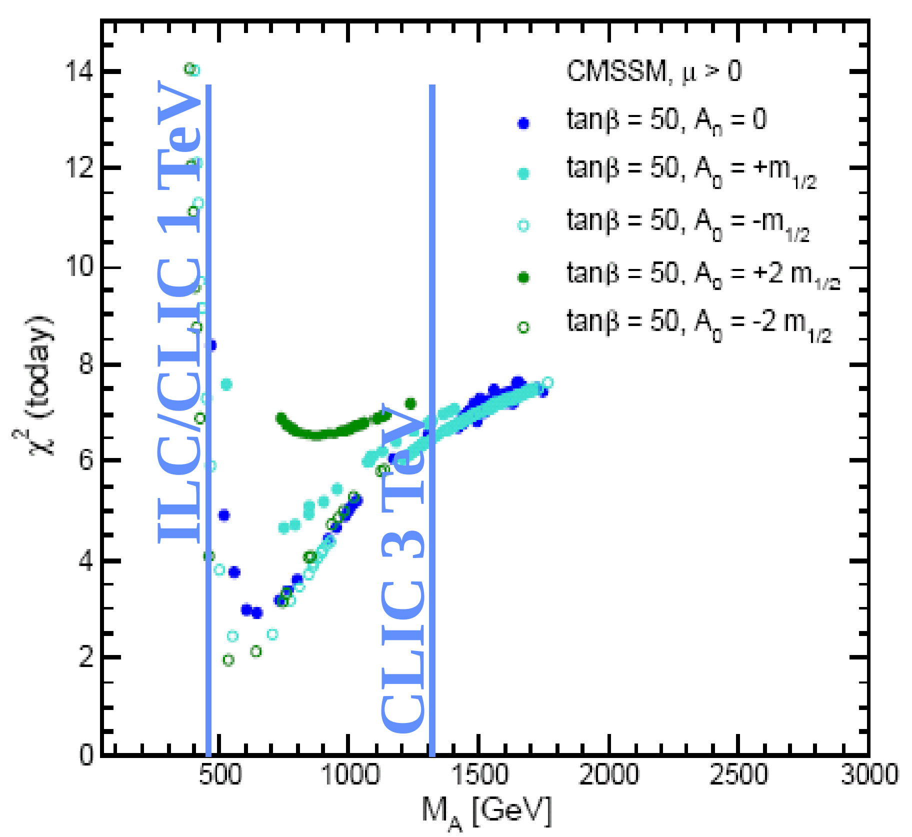



Allanach et al., PRD 73 (2006)

# SUSY Heavy Higgs Bosons: $M_A$

1) cMSSM with $M_W, \sin^2 \vartheta_{eff}, M_h, (g-2)_\mu, BR(b \to s\gamma)$ constraints and $m_0$ tuned to match $\Omega_{CDM} h^2$

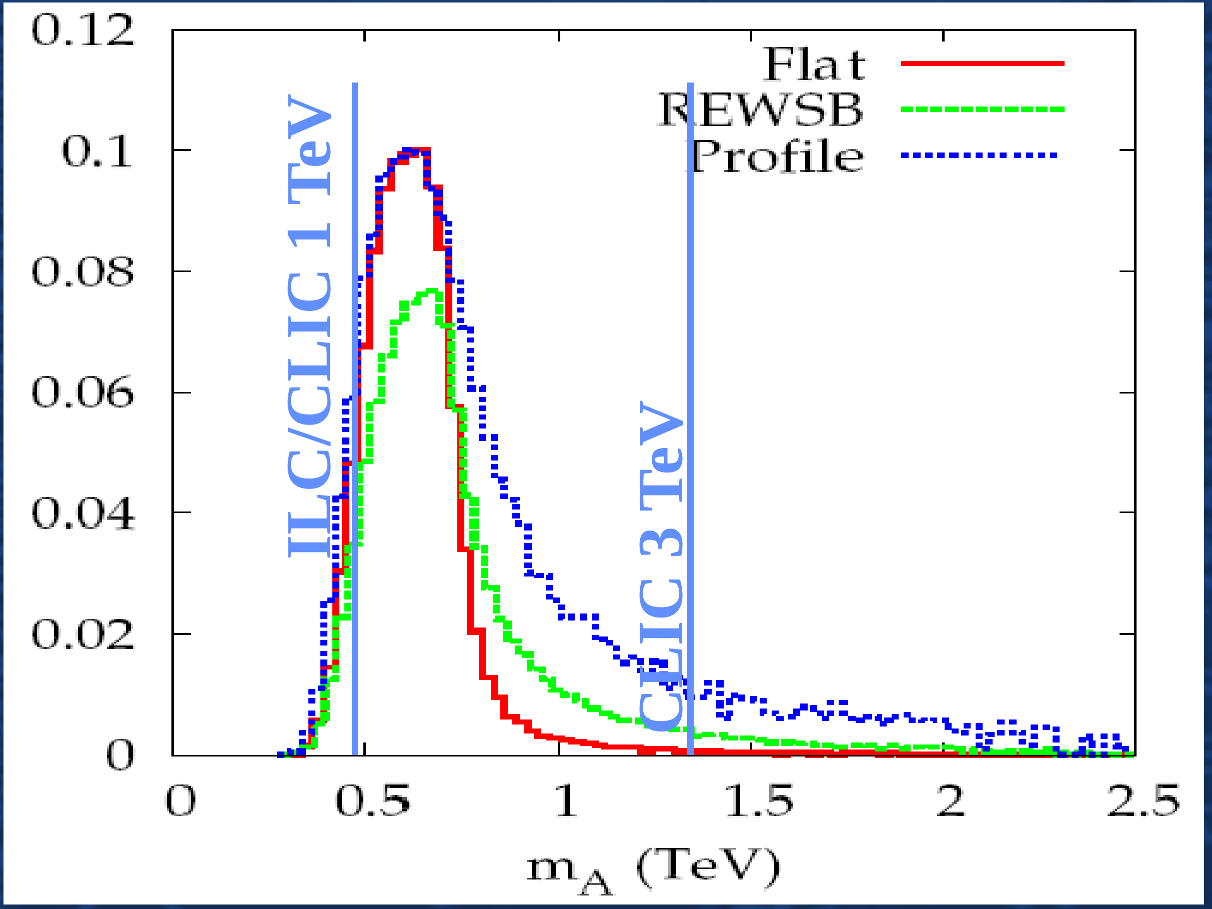



Ellis et al., JHEP 0502 (2005)

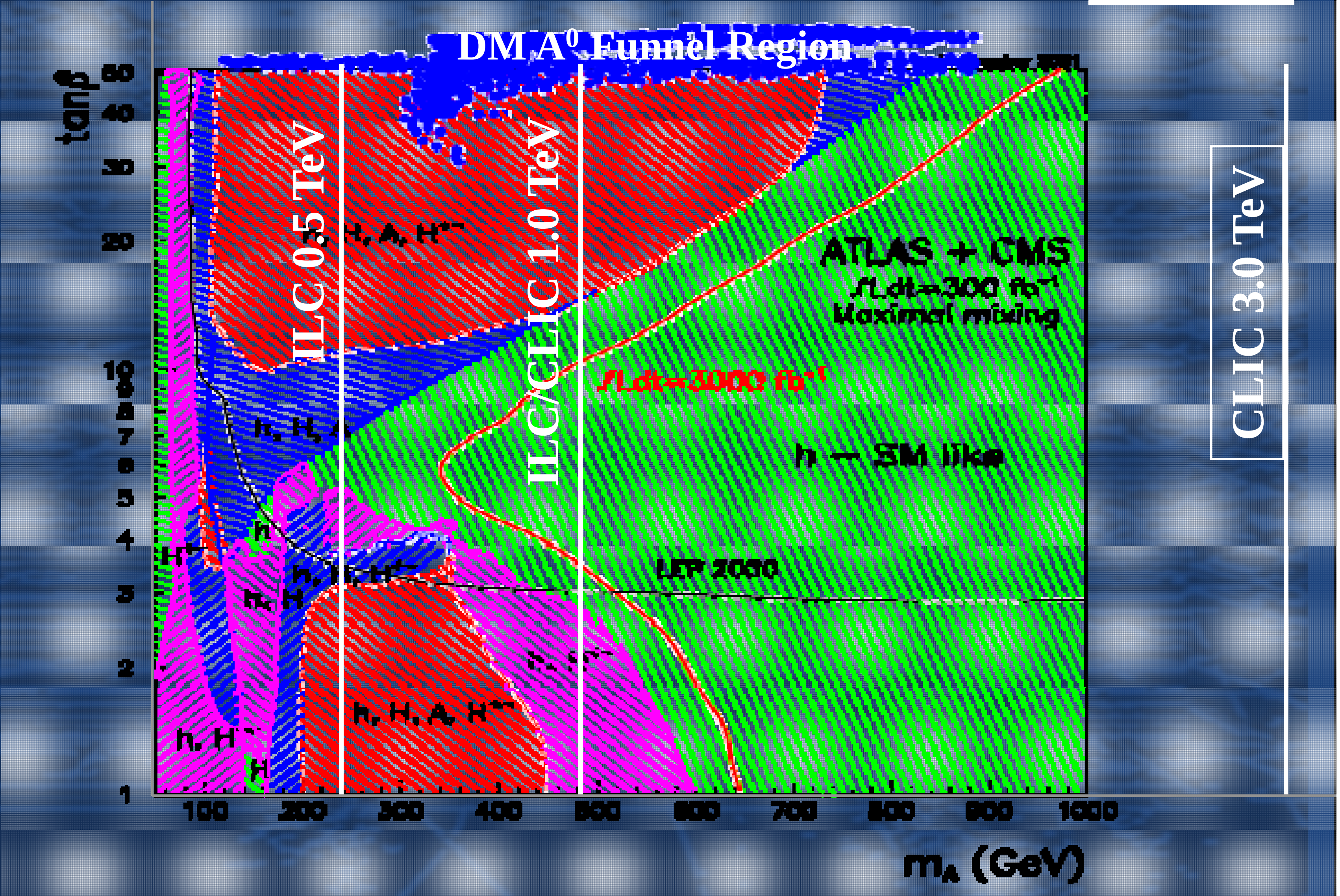
# SUSY Heavy Higgs Bosons: $M_A$

**5)** String-inspired Large Volume Scenario SUSY with MCMC in Bayesian statistics formalism



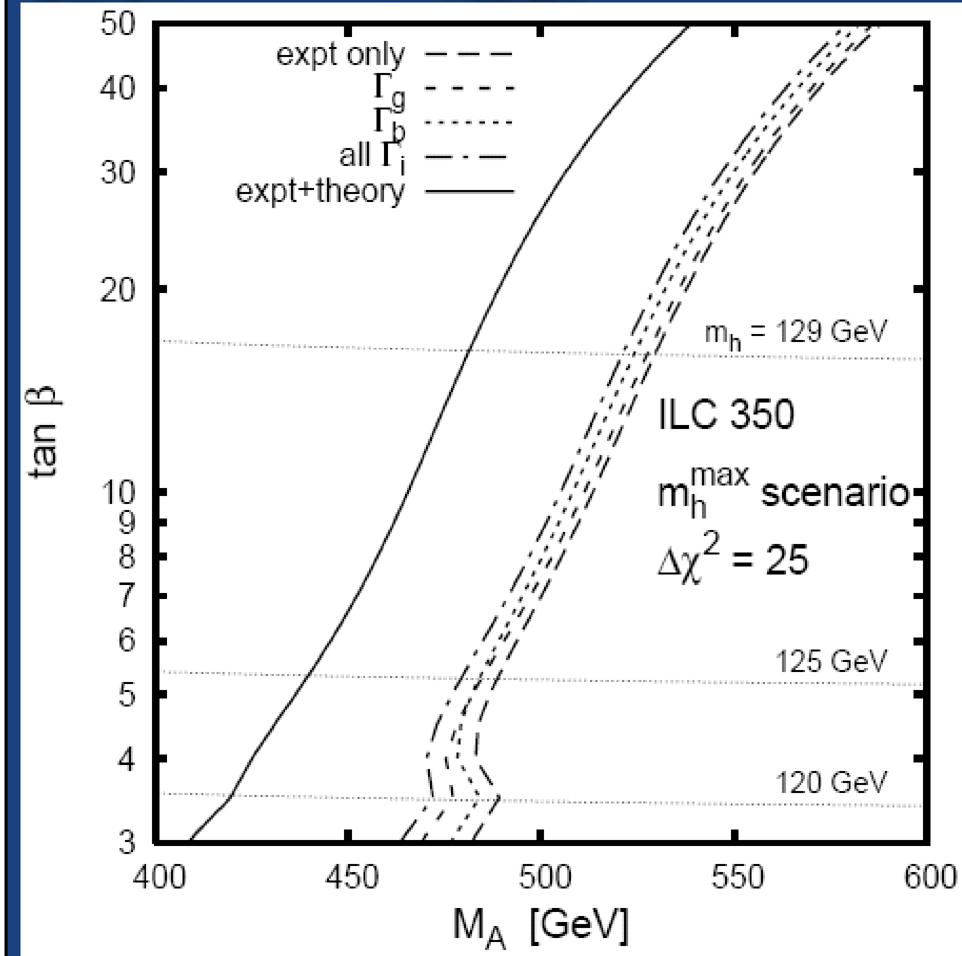

Allanach et al., JHEP 0808 (2008)

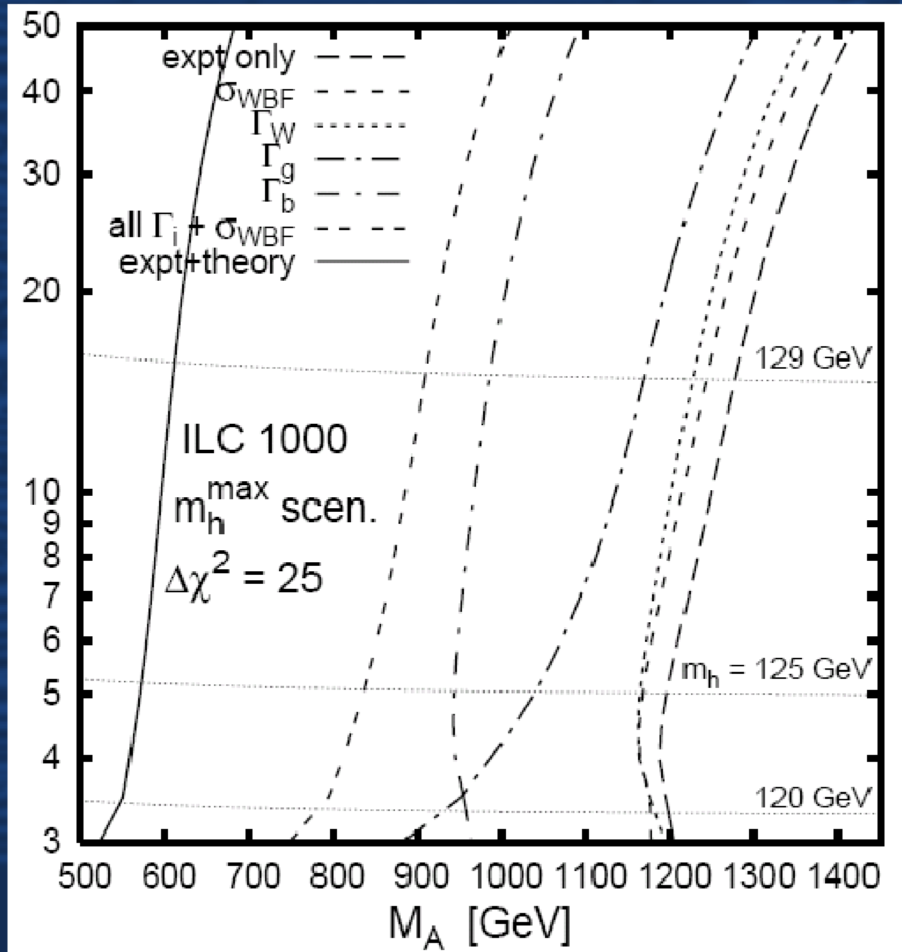
# LHC/ILC/CLIC Reach in $M_A$ – tan β



# SUSY Heavy Higgs Bosons: $M_A$ – tan β

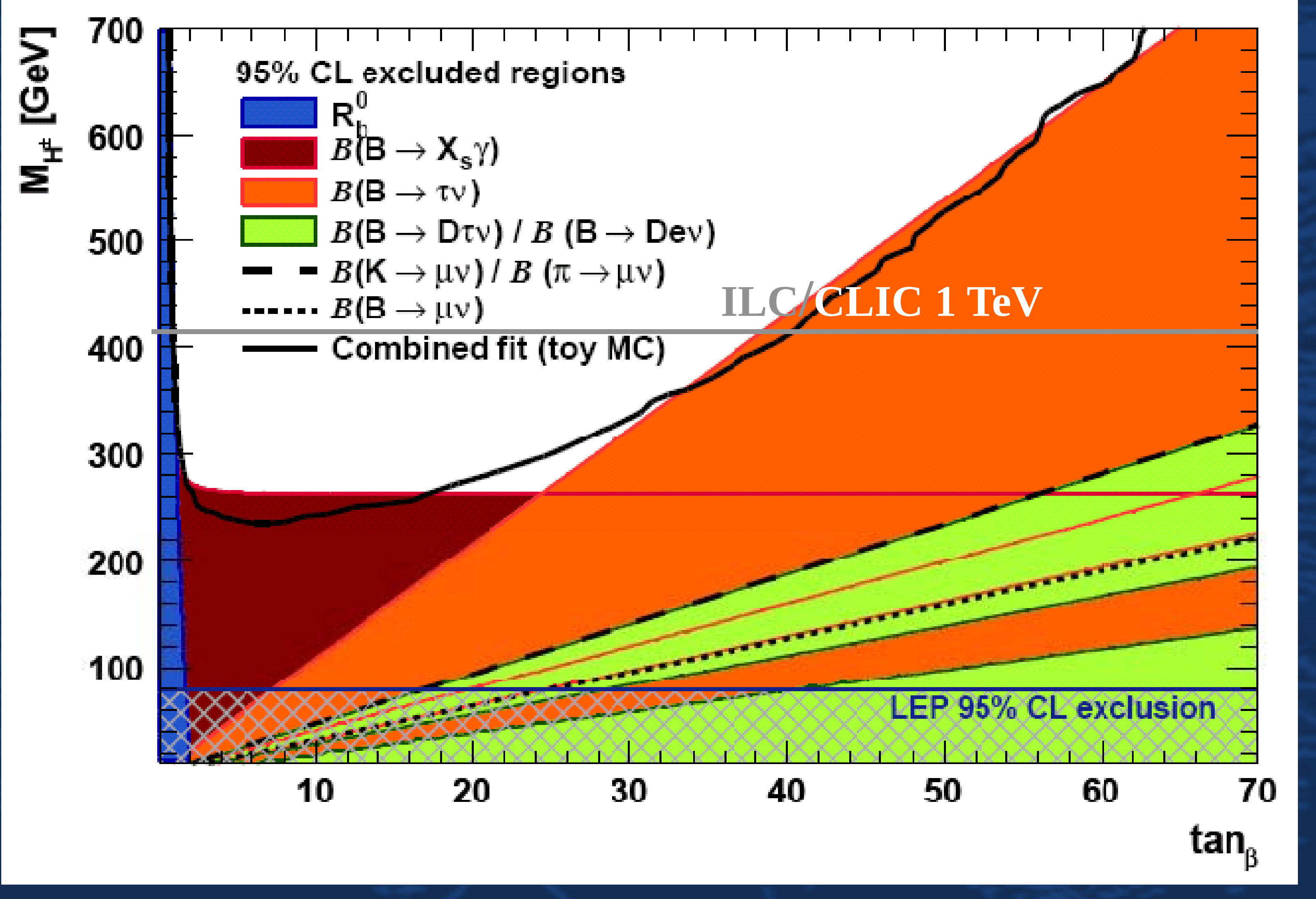
Lower energy LC Higgs data interpretation requires excellent control of parametric and theoretical uncertainties:



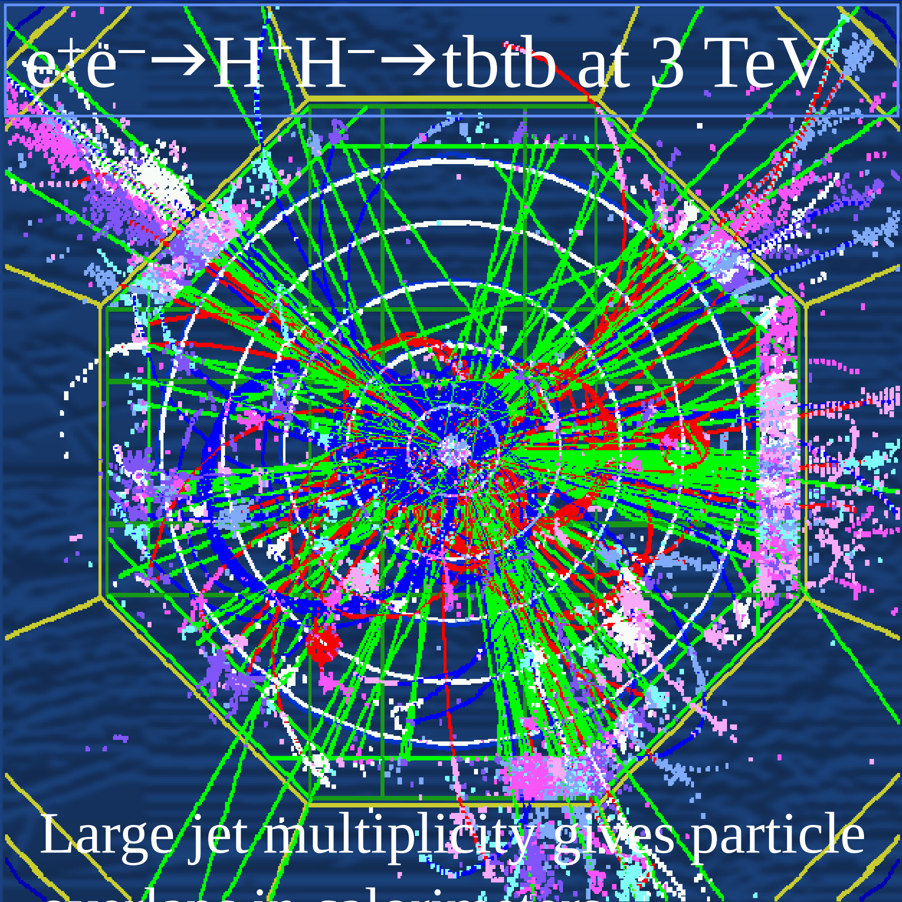

Droll and Logan, PRD 76 (2007)

# 2HDM Model: $M_H$ - tan β

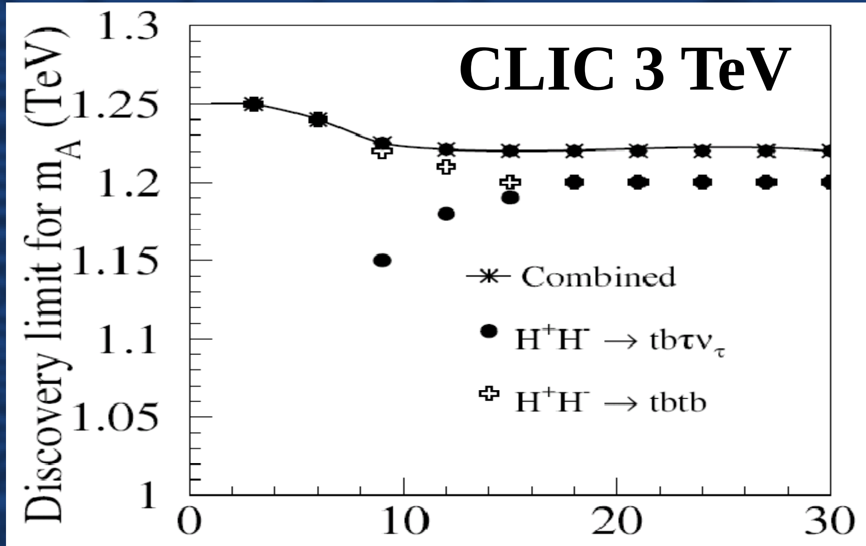



Flaecher et al.
arXiv:0811:0009v2

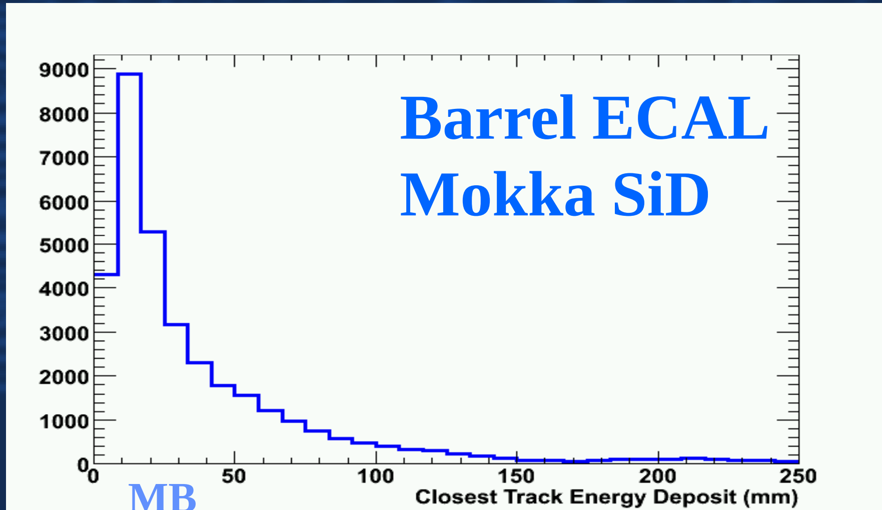
# Heavy Higgs Bosons: $H^{\pm}$ at 3 TeV




Large jet multiplicity gives particle overlaps in calorimeters.
study distance (charged particle to closest cluster) (full G4 simulation)



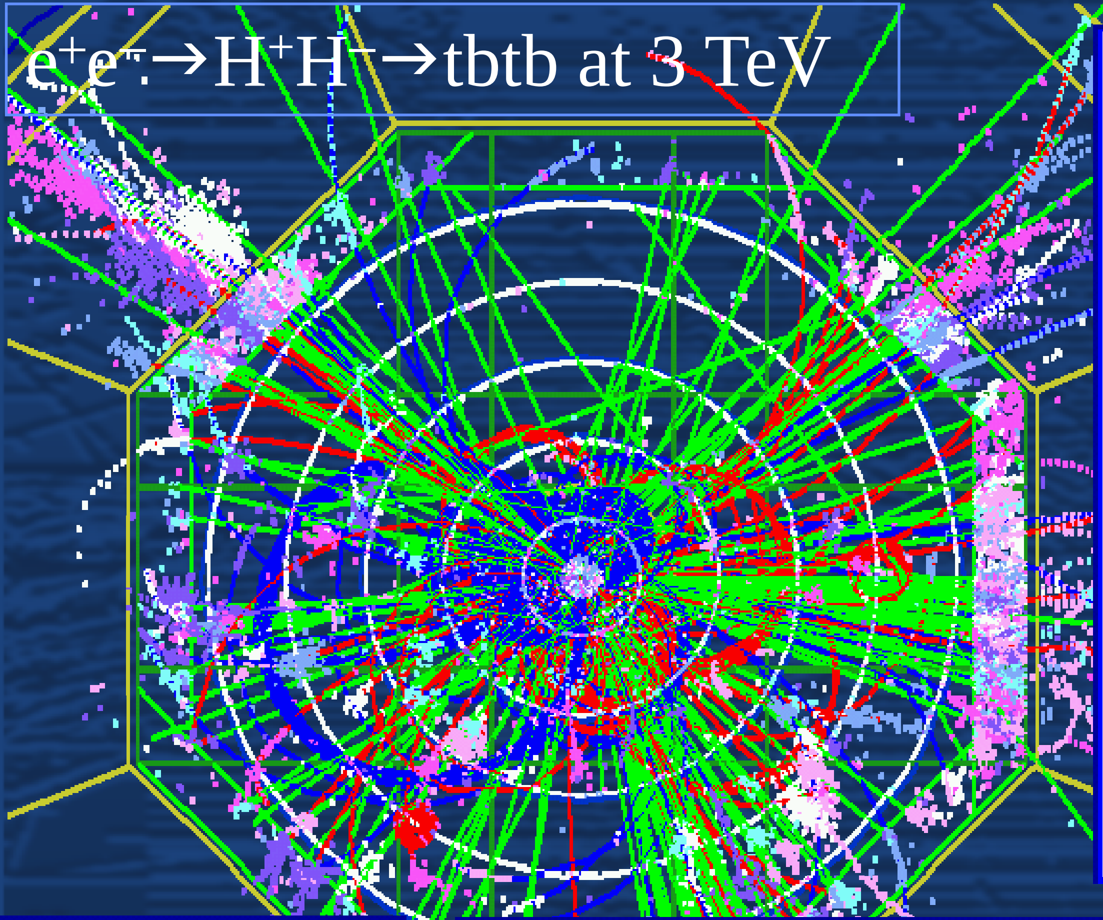

Ferrari, Pramana 69 (2007)

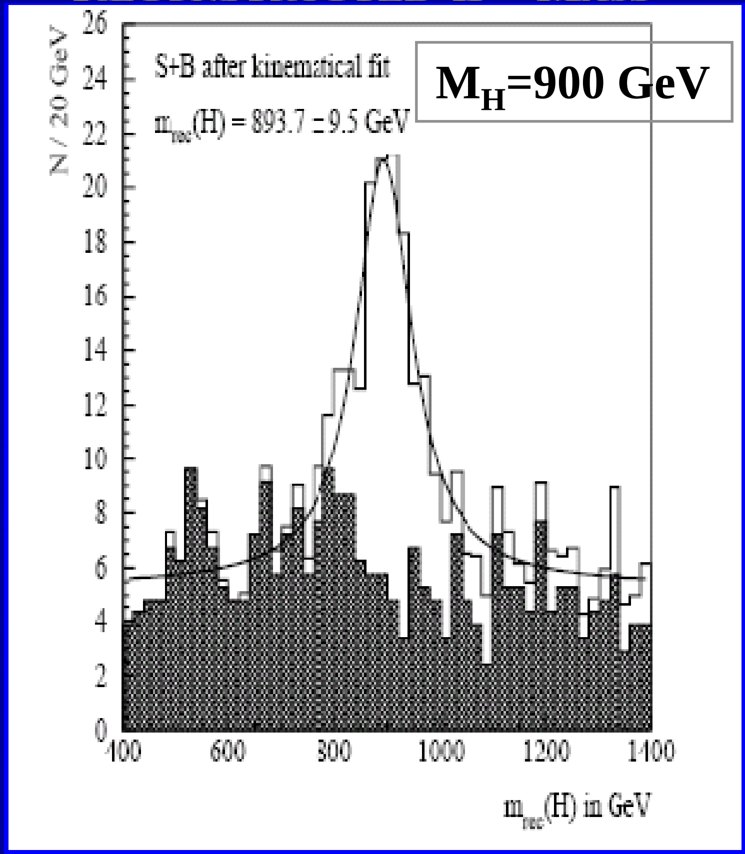



MB

# Heavy Higgs Bosons: $H^{\pm}$ at 3 TeV

$e^+e^- \rightarrow H^+H^- \rightarrow tbtb$ at 3 TeV






$$\frac{\delta M_H}{M_H} = 0.01$$

$$\frac{\delta(\sigma \times BR)}{\sigma(e^+e^- \rightarrow H^+H^-) \times BR(H^+ \rightarrow t\bar{b})} = 0.05$$

Ferrari, in CERN-2004-005

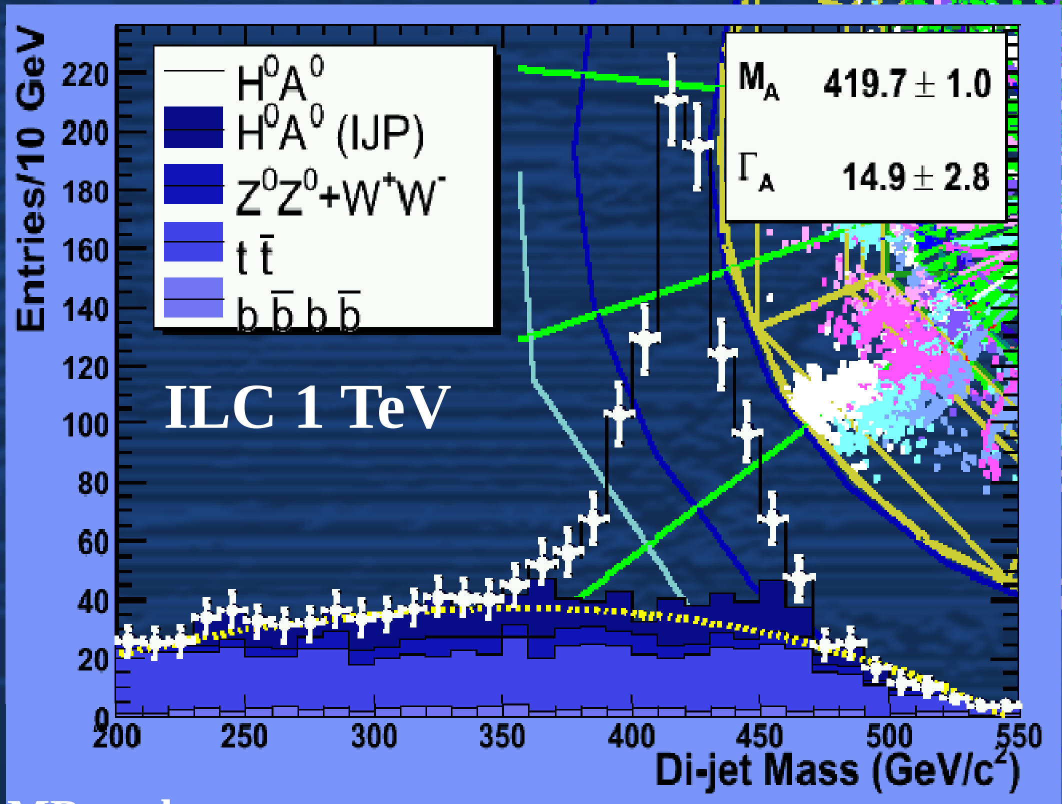
# Heavy Higgs Bosons: $H^0$, $A^0$ at 1-3 TeV

Analysis of 1 TeV Events with ILC Detector

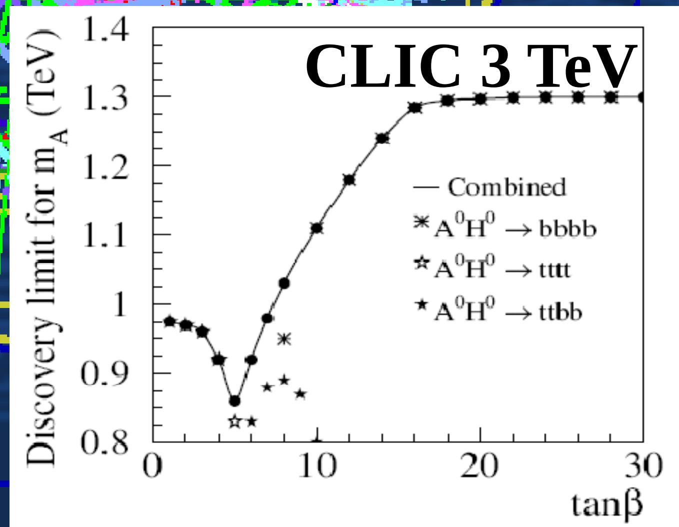
Study $e^+e^- \rightarrow HA \rightarrow bbbb$ with LDC

$\Omega_{CDM}h^2$ gives tight requirement of

$M_A \pm 1 GeV$




MB et al
PRD 78 (2008)

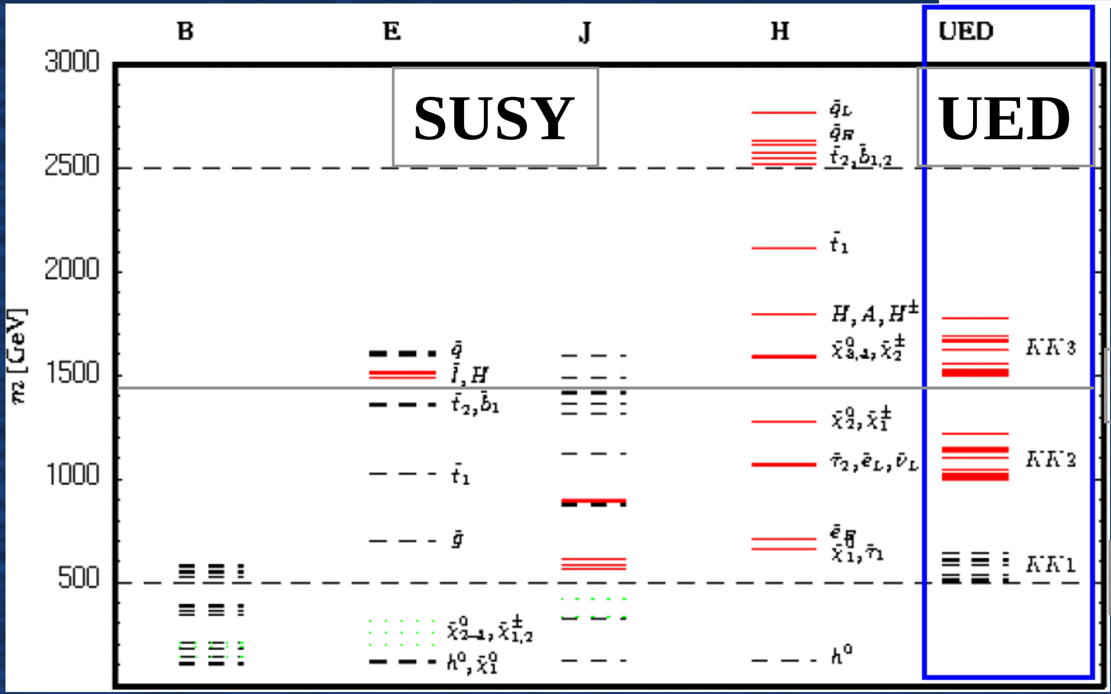


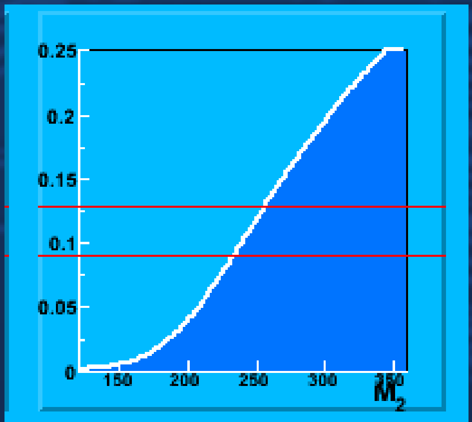

Ferrari,
Pramana 69 (2007)

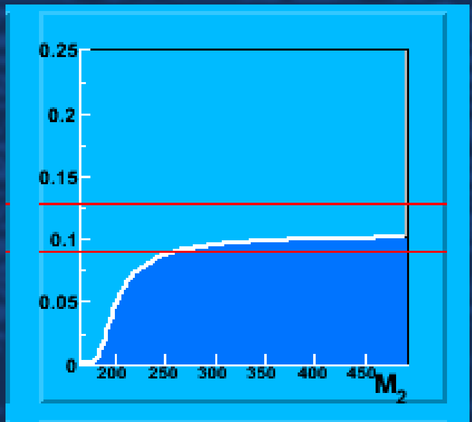
# Establishing the Nature of New Physics

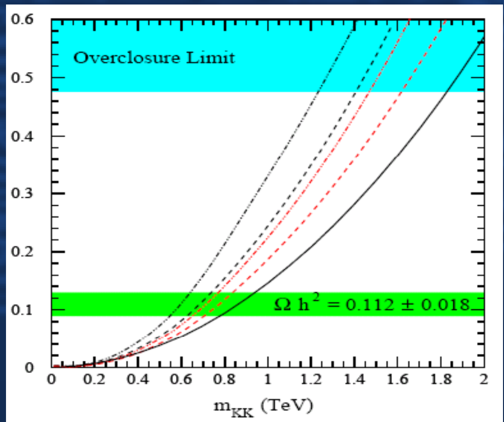
Given limited nb. of observable particles determine the nature of new physics:

Example:
tell UED from SUSY



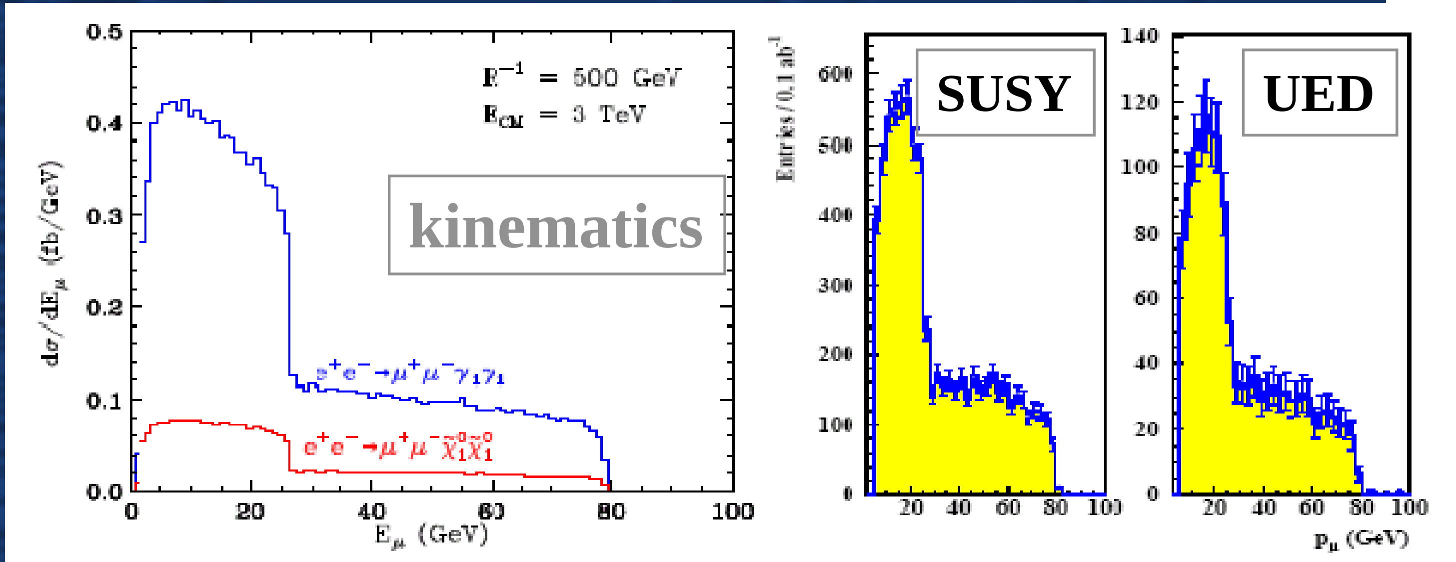



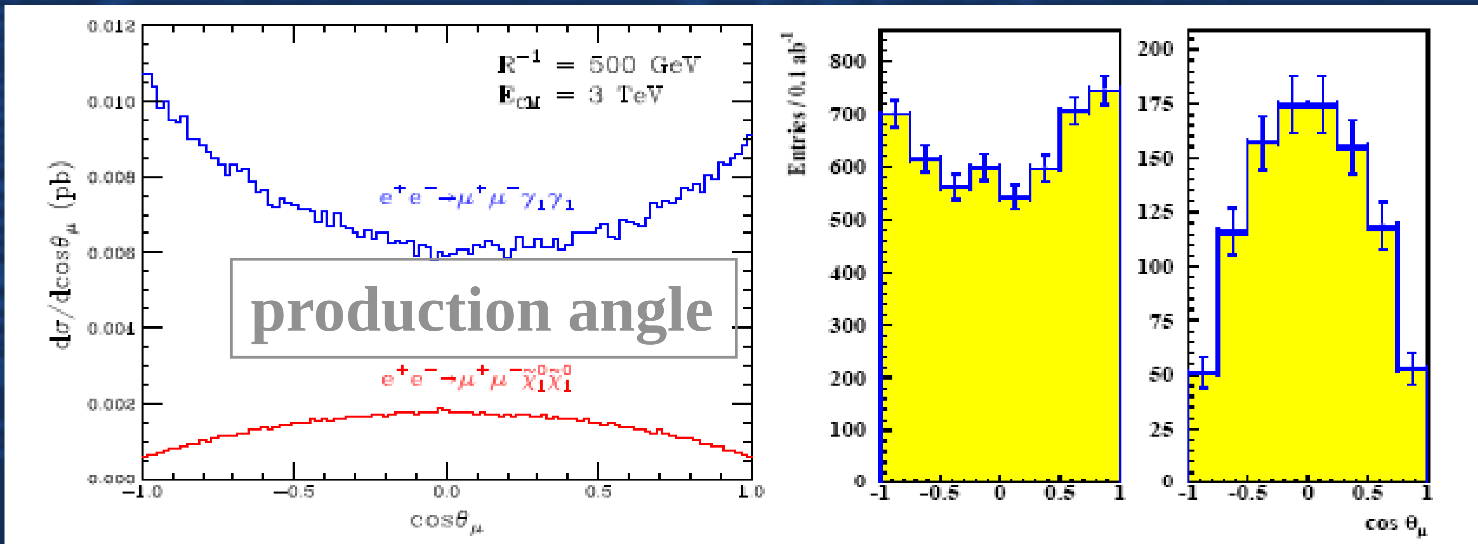






Tait and Servant

# Establishing the Nature of New Physics



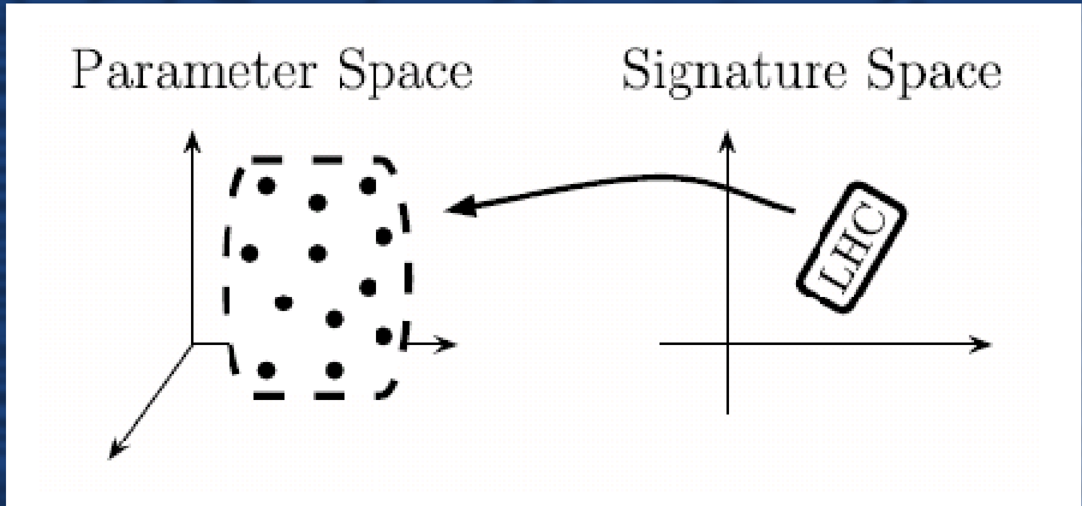

MB et al,
JHEP 0507 (2005)

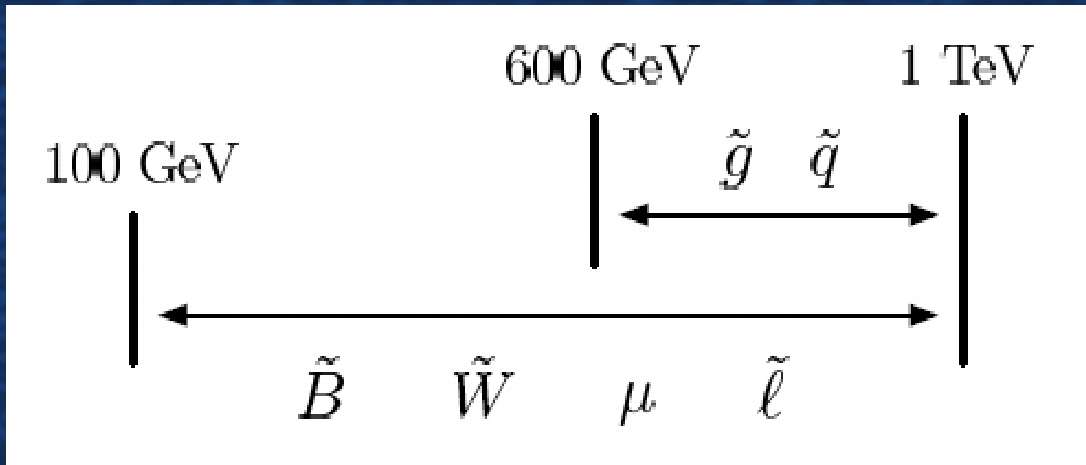
# The LHC SUSY Inverse Problem

Given LHC data can we identify the nature of the underlying theory ?

Study the inverse map from the LHC signature space to the parameter space of a given theory model: MSSM.

43026 models tested in 15-dim parameter space → 283 pairs of models have indistinguishable signatures at LHC.






Arkani Hamed et al, JHEP 0608 (2006)

# Solving the SUSY Inverse Problem at LC

Consider 162 pairs indistinguishable at LHC:

only 52% (85 pairs) have charged SUSY particles kinematically accessible at 0.5 TeV, 100 % accessible > 1 TeV;

79% (57 out of 73 pairs) can be distinguished at 5 $\sigma$ level at 0.5 TeV;

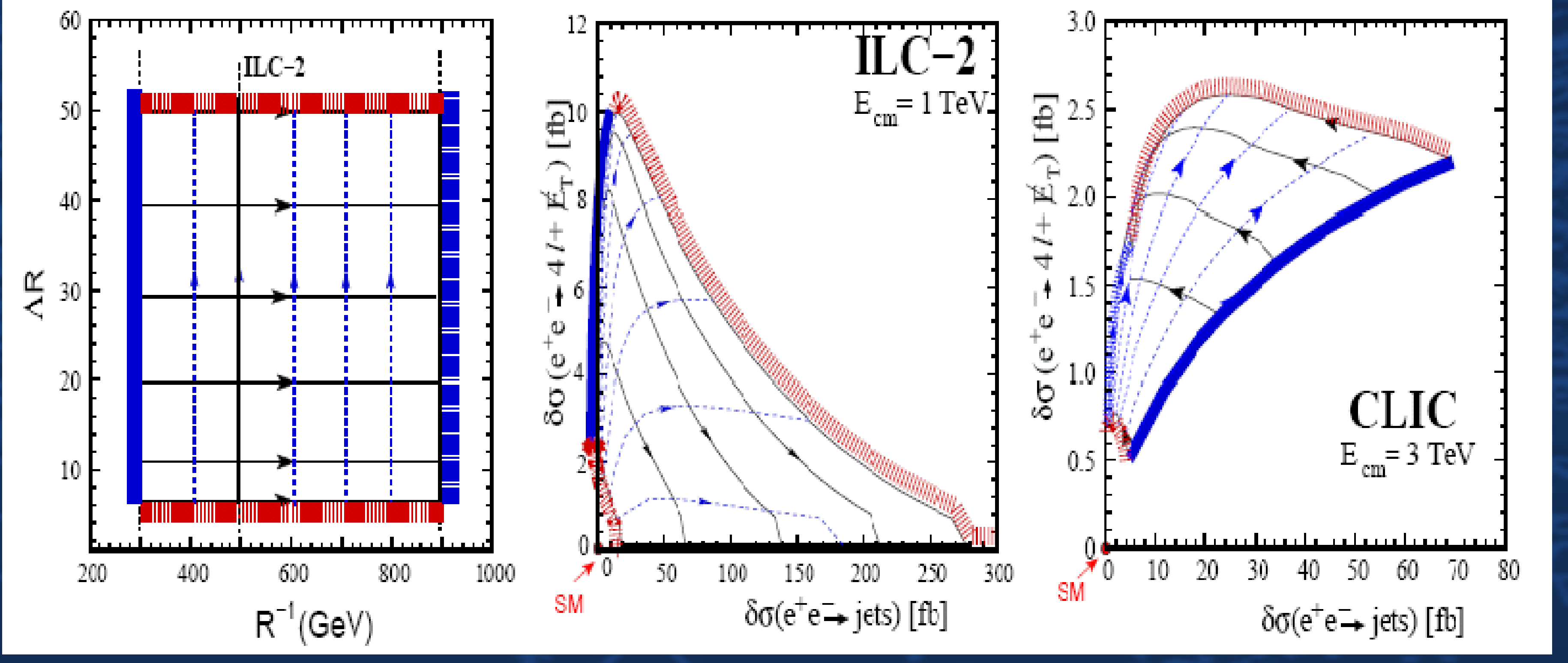
1-3 TeV data needed to extend sensitivity and solve the LHC inverse problem over (almost) full parameter space.

| Final State | 500 GeV | 1 TeV |
|---|---|---|
| $\tilde{e}_L^+\tilde{e}_L^-$ | 9 | 82 |
| $\tilde{e}_R^+\tilde{e}_R^-$ | 15 | 86 |
| $\tilde{e}_L^\pm\tilde{e}_R^\mp$ | 2 | 61 |
| $\tilde{\mu}_L^+\tilde{\mu}_L^-$ | 9 | 82 |
| $\tilde{\mu}_R^+\tilde{\mu}_R^-$ | 15 | 86 |
| Any selectron or smuon | 22 | 137 |
| $\tilde{\tau}_1^+\tilde{\tau}_1^-$ | 28 | 145 |
| $\tilde{\tau}_2^+\tilde{\tau}_2^-$ | 1 | 23 |
| $\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp$ | 4 | 61 |
| $\tilde{\nu}_{e\mu}\tilde{\nu}^*_{e\mu}$ | 11 | 83 |
| $\tilde{\nu}_\tau\tilde{\nu}^*_\tau$ | 18 | 83 |
| $\tilde{\chi}_1^+\tilde{\chi}_1^-$ | 53 | 92 |
| Any charged sparticle | 85 | 224 |
| $\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$ | 7 | 33 |
| $\tilde{\chi}_1^0\tilde{\chi}_1^0$ | 180 | 236 |
| $\tilde{\chi}_1^0\tilde{\chi}_1^0$ only | 91 | 0 |
| $\tilde{\chi}_1^0+\tilde{\nu}$ only | 5 | 0 |
| $\tilde{\chi}_1^0\tilde{\chi}_2^0$ | 46 | 178 |
| $\tilde{\chi}_1^0\tilde{\chi}_3^0$ | 10 | 83 |
| $\tilde{\chi}_2^0\tilde{\chi}_2^0$ | 38 | 91 |
| $\tilde{\chi}_2^0\tilde{\chi}_3^0$ | 4 | 41 |
| $\tilde{\chi}_3^0\tilde{\chi}_3^0$ | 2 | 23 |
| Nothing | 61 | 3 |

**Berger et al, arXiv:0712.2965**

# An UED Inverse Problem

Mapping UED the parameter space from measurements at 1 TeV and 3 TeV linear collider:

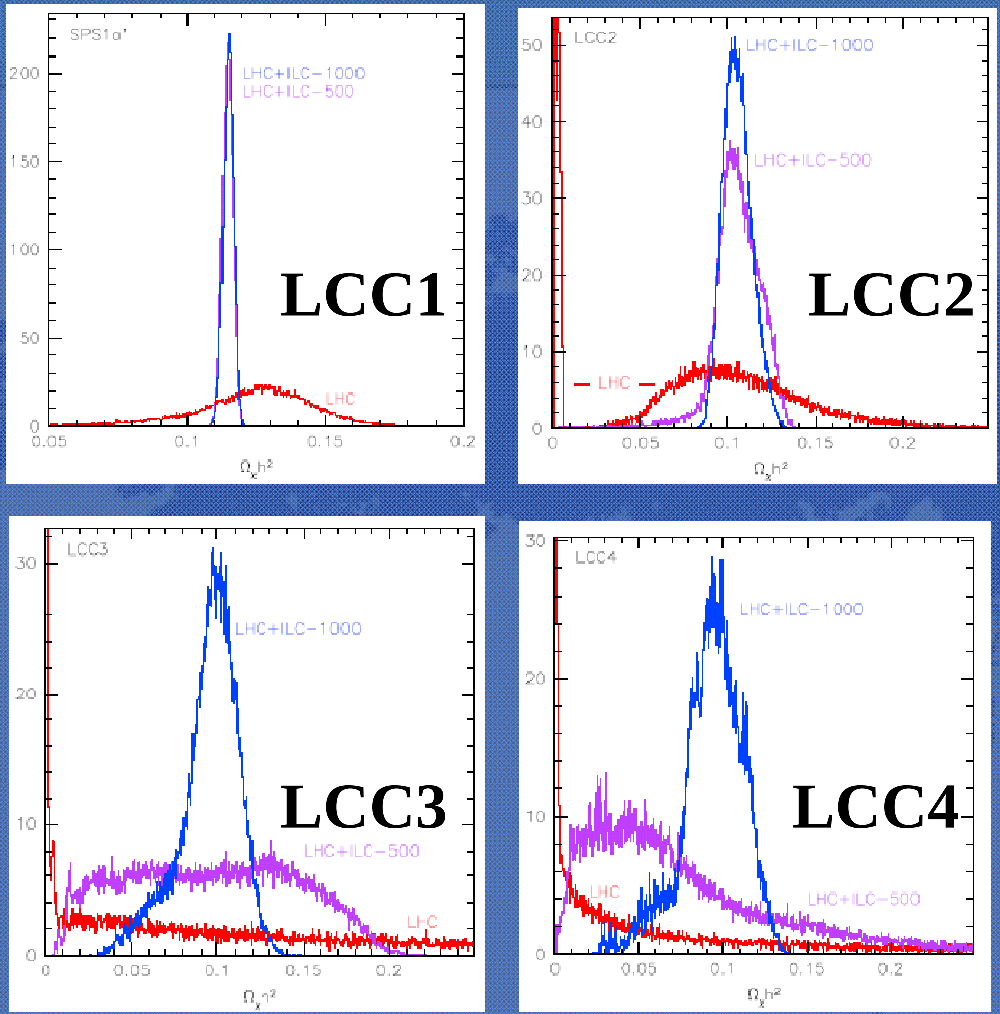





Bhattacherjee et al., PRD78 (2008)

# Understand SUSY-Cosmology Connection

## Dark Matter Density




Baltz, MB, Peskin, Wiszanski, PRD74 (2006)

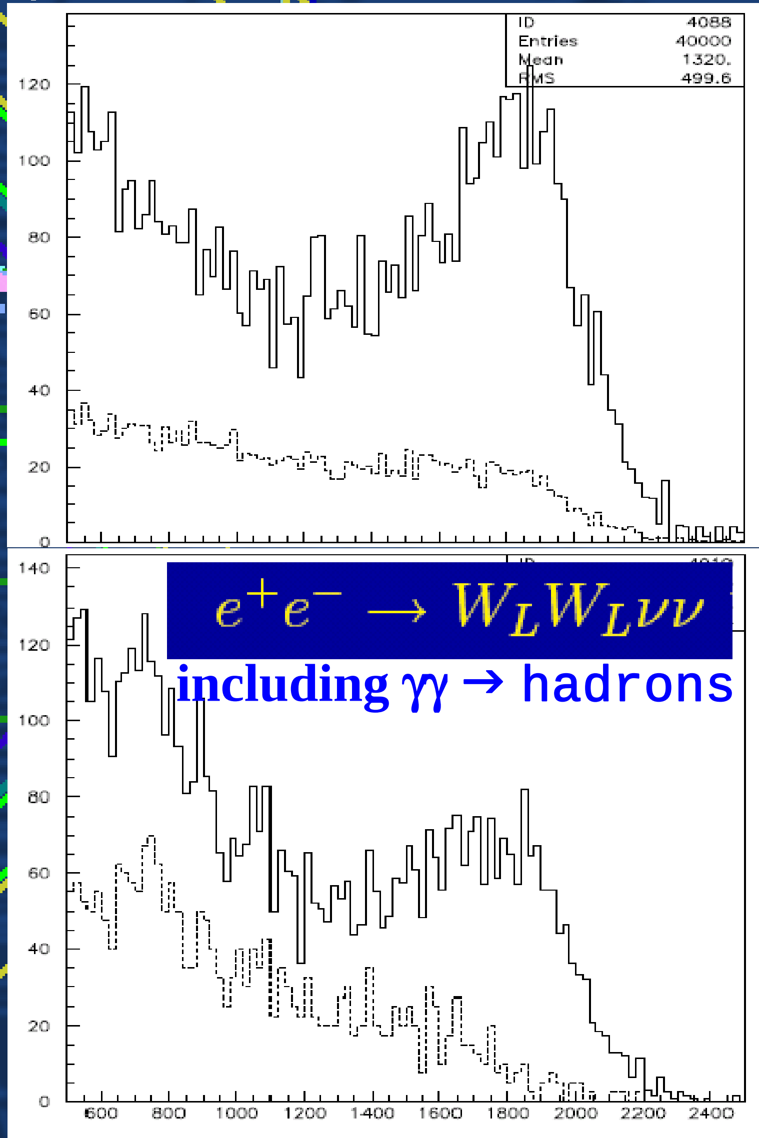
LC precision motivated by need to match $\Omega h^2$ accuracy from CMB data ($\pm 3\%$):

| | $\Omega h^2$ | LHC | ILC-500 | ILC-1000 |
|---|---|---|---|---|
| LCC1 | 0.192 | 7.2% | 1.8% | 0.24% |
| LCC2 | 0.109 | 82.% | 14.% | 7.6% |
| LCC3 | 0.101 | 167% | 50.% | 18.% |
| LCC4 | 0.114 | 405% | 85.% | 8% |
| | $\sigma v$ | | | |
| LCC1 | 0.0121 | 165.% | 54.% | 11.% |
| LCC2 | 0.547 | 143.% | 32.% | 8.7% |
| LCC3 | 0.109 | 154.% | 178.% | 10.% |
| LCC4 | 0.475 | 557.% | 228.% | 20.% |
| | $\sigma(\chi p)$ | | | |
| LCC1 | 0.418 | 44.% | 45.% | 5.7% |
| LCC2 | 1.866 | 62.% | 63.% | 22.% |
| LCC3 | 0.925 | 184.% | 146.% | 8.6% |
| LCC4 | 1.046 | 150.% | 190.% | 7.5% |

# What if there is no Higgs ?

Study strong interaction of W/Z bosons and identify resonance formation in the TeV region;

Example 2 TeV resonance with 12 fb production cross section at 3 TeV, ~4 fb after acceptance cuts:

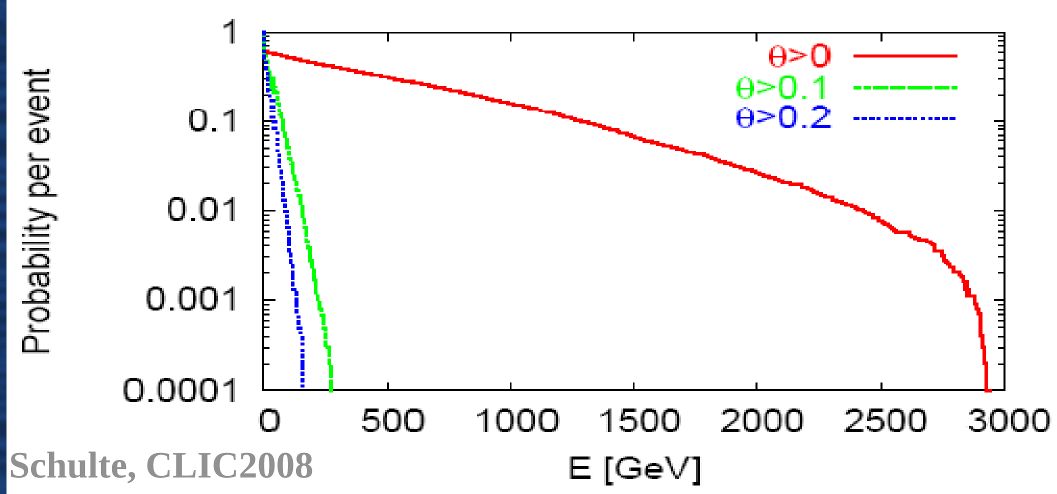





De Roeck,
Snowmass 2001

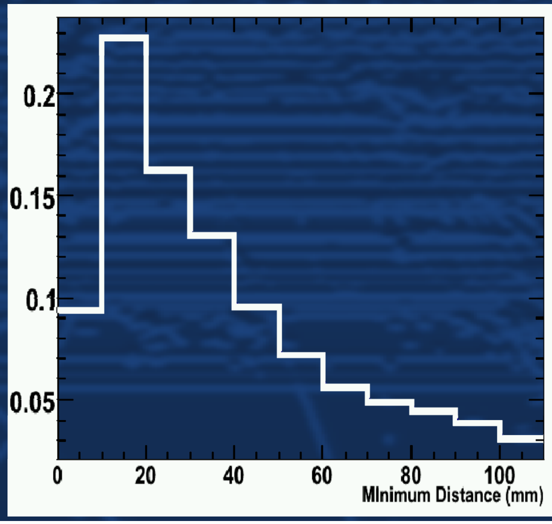
# Experimental Issues

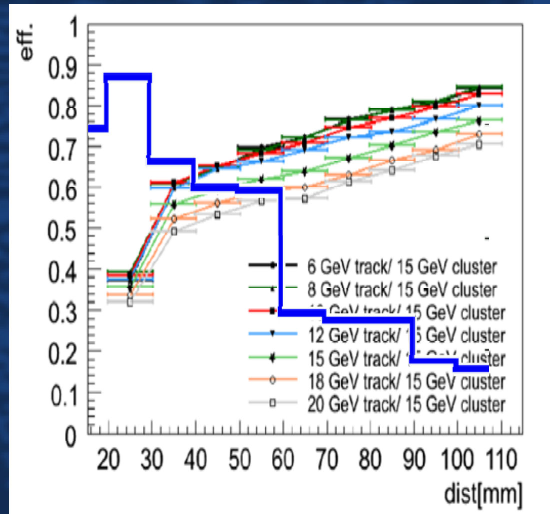
## $\gamma\gamma \rightarrow$ hadrons background




## Charged-Neutral Particle Distance in Calorimeters

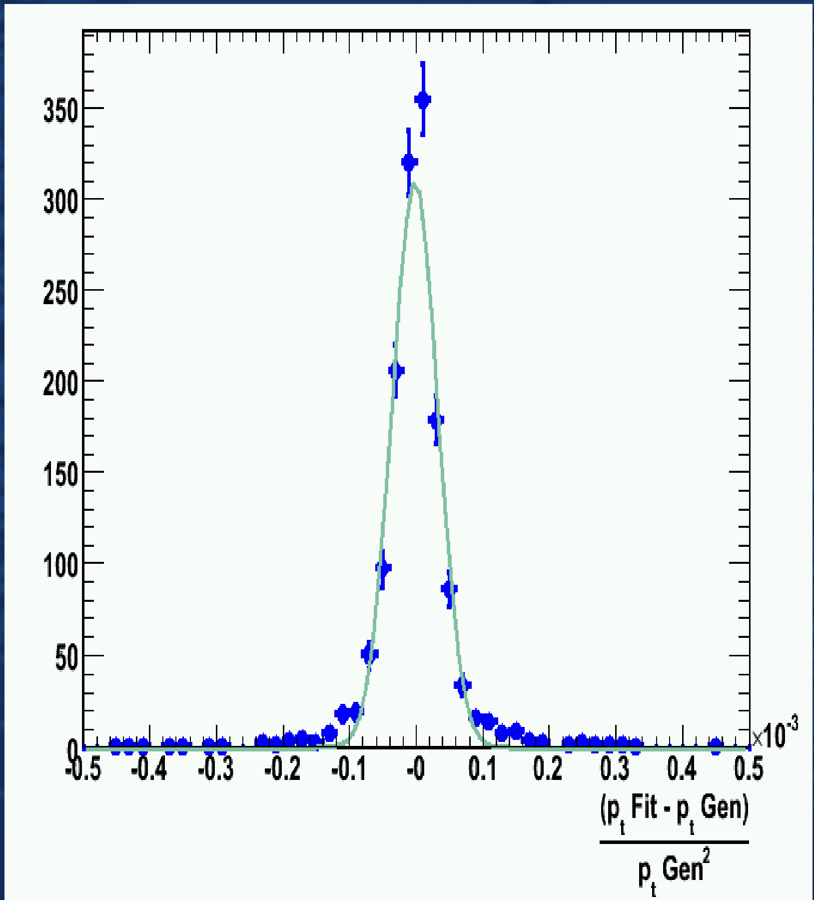
**ECal** **HCal**



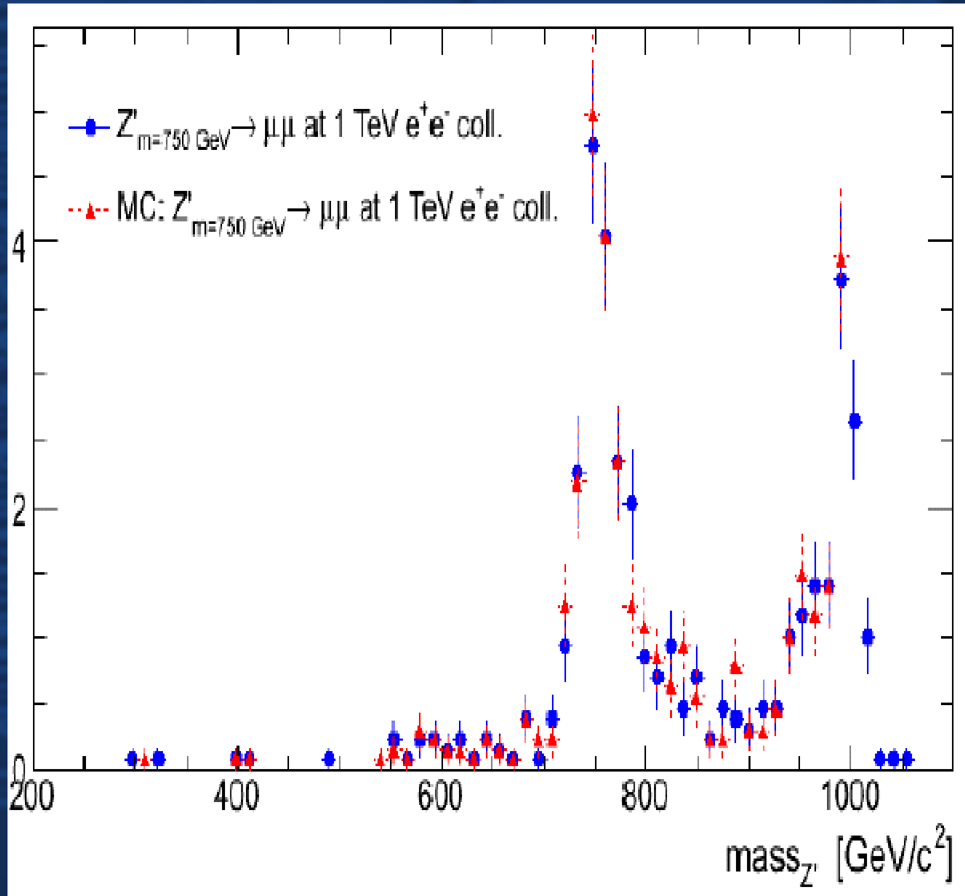



# New Resonances at CLIC

$$\frac{\delta p}{p^2}$$

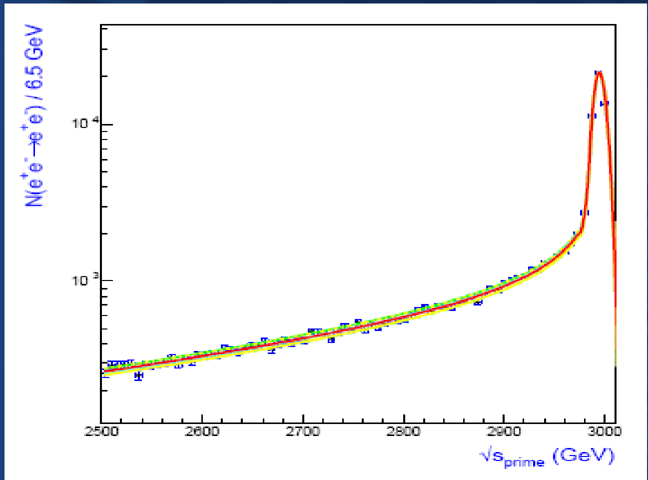



$$e^+e^- \rightarrow Z' \rightarrow \mu^+\mu^-$$

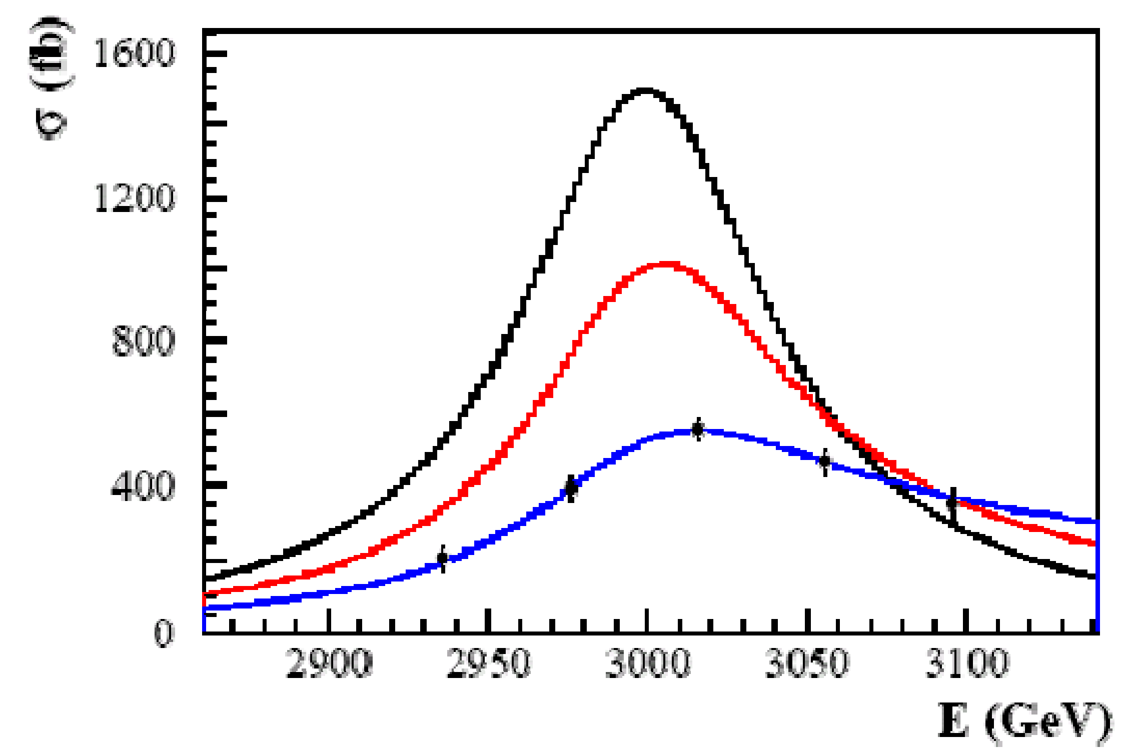


# New Resonances at CLIC

<u>Luminosity spectrum</u> effect on mass and width reconstruction at CLIC:




5-point scan of broad resonance (3 TeV SSM Z') with ~ 1 year of data under two assumptions for luminosity spectrum (CLIC.01 and CLIC.02)

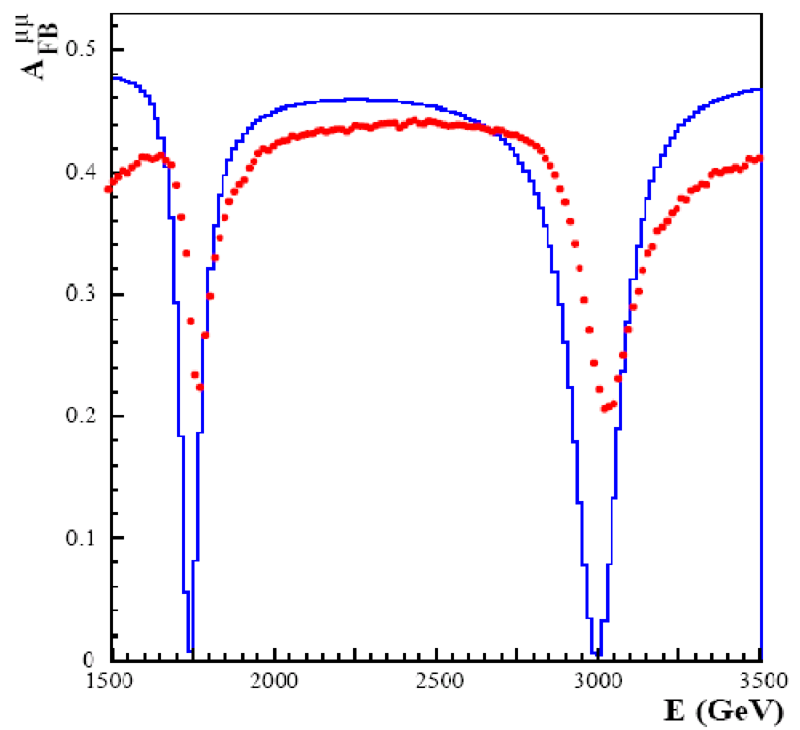


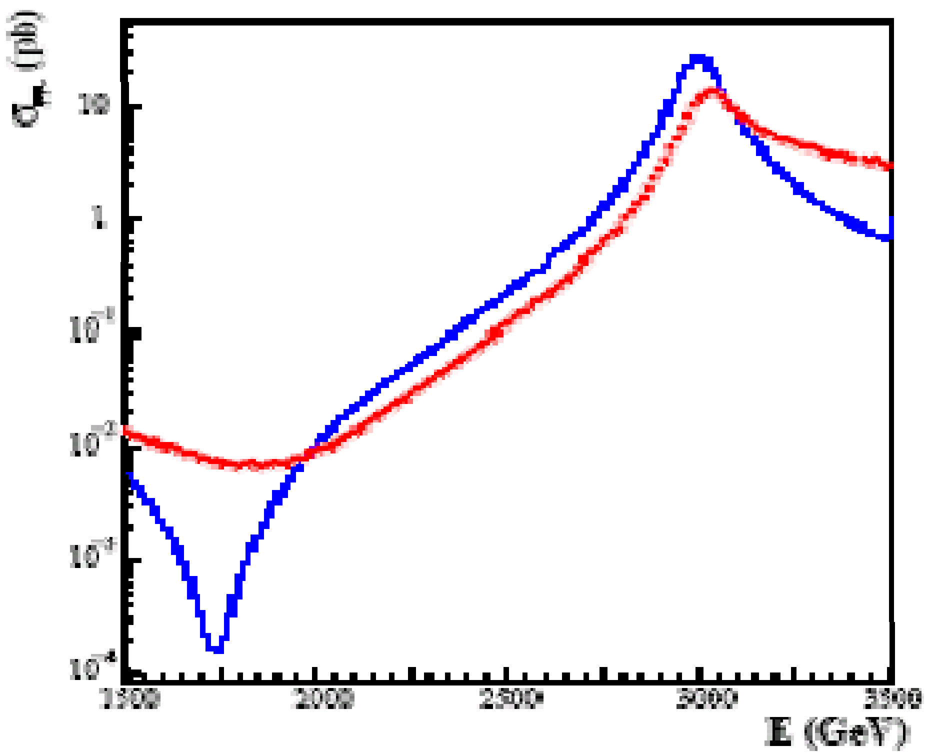

| Observable | Breit Wigner | CLIC.01 | CLIC.02 |
|---|---|---|---|
| $M_{Z'}$ (GeV) | $3000 \pm .12$ | $\pm .15$ | $\pm .21$ |
| $\Gamma(Z')/\Gamma_{SM}$ | $1. \pm .001$ | $\pm .003$ | $\pm .004$ |
| $\sigma^{eff}_{peak}$ (fb) | $1493 \pm 2.0$ | $564 \pm 1.7$ | $669 \pm 2.9$ |

MB et al., JHEP 0212 (2002)

# KK Resonances in ED Scenarios

Observe interference between Z and γ KK excitations accounting for CLIC luminosity spectrum:





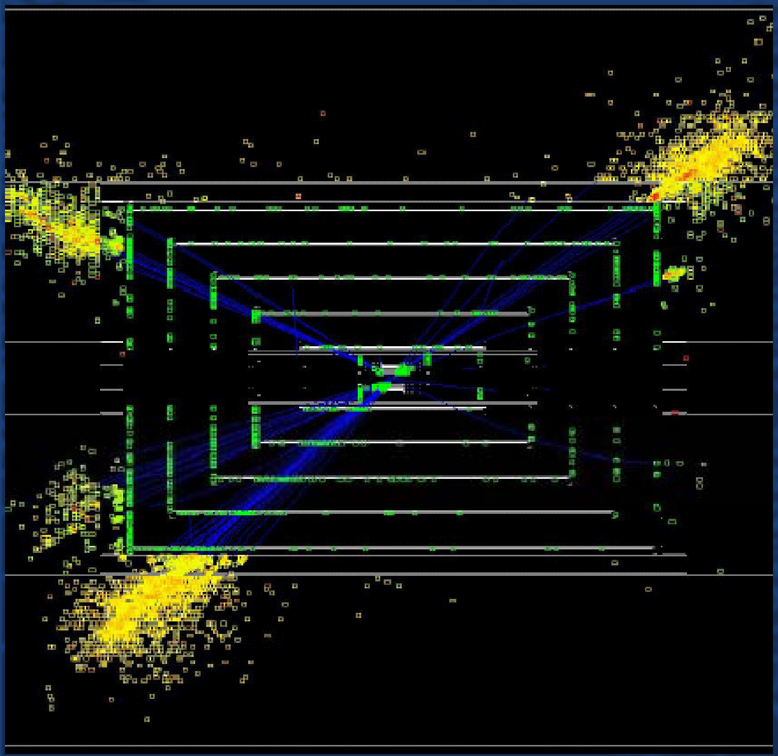

MB et al., JHEP 0212 (2002)

# Probe New Phenomena beyond LHC Reach

# New Physics beyond the LHC Reach

Precision electro-weak observables in $e^+e^- \rightarrow f\bar{f}$ at 1- 3 TeV

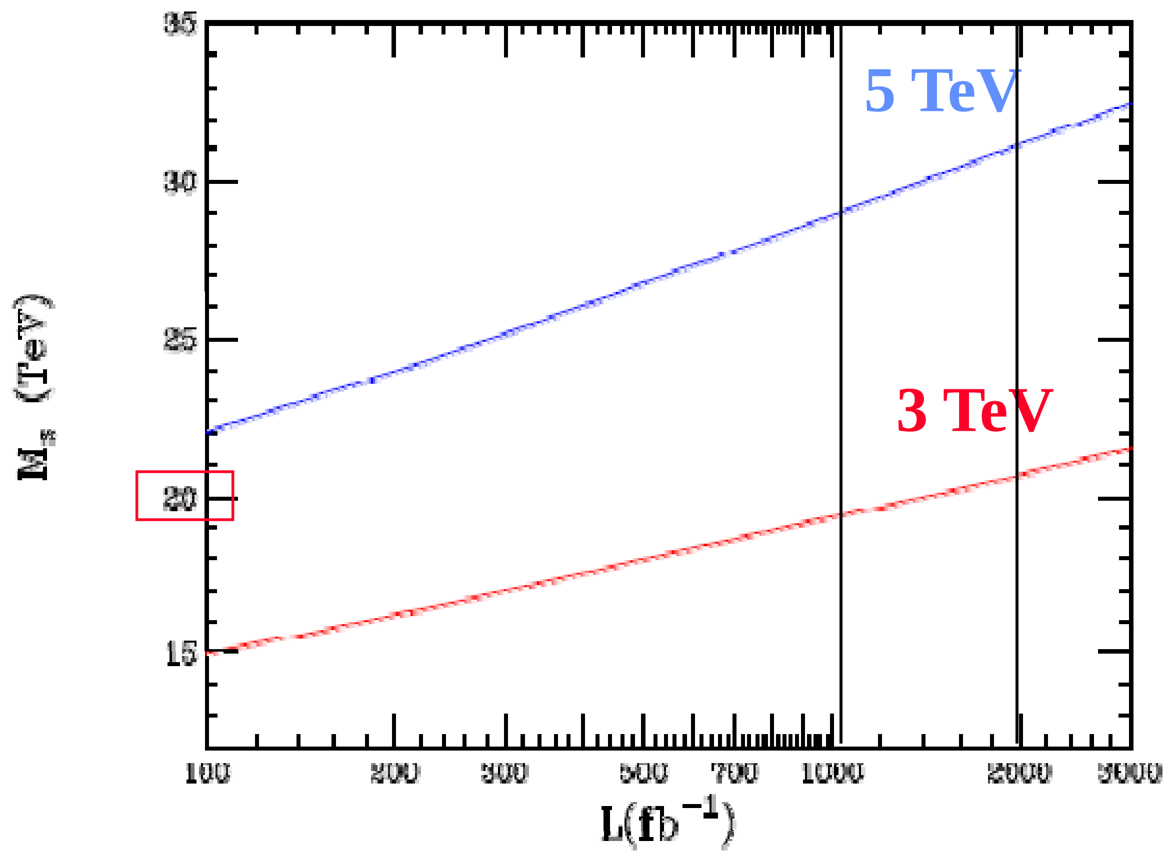
$$\frac{|\sigma^{SM} - \sigma^{SM+Z'}|}{\delta\sigma} \propto \frac{1}{M_{Z'}^2}\sqrt{sL} > \sqrt{\Delta\chi^2}$$



| Observable | Relative stat. accuracy $\delta\mathcal{O}/\mathcal{O}$ for 1 ab$^{-1}$ |
|---|---|
| $\sigma_{\mu^+\mu^-}$ | $\pm\, 0.010$ |
| $\sigma_{b\bar{b}}$ | $\pm\, 0.012$ |
| $\sigma_{t\bar{t}}$ | $\pm\, 0.014$ |
| $A_{\rm FB}^{\mu\mu}$ | $\pm\, 0.018$ |
| $A_{\rm FB}^{bb}$ | $\pm\, 0.055$ |
| $A_{\rm FB}^{tt}$ | $\pm\, 0.040$ |

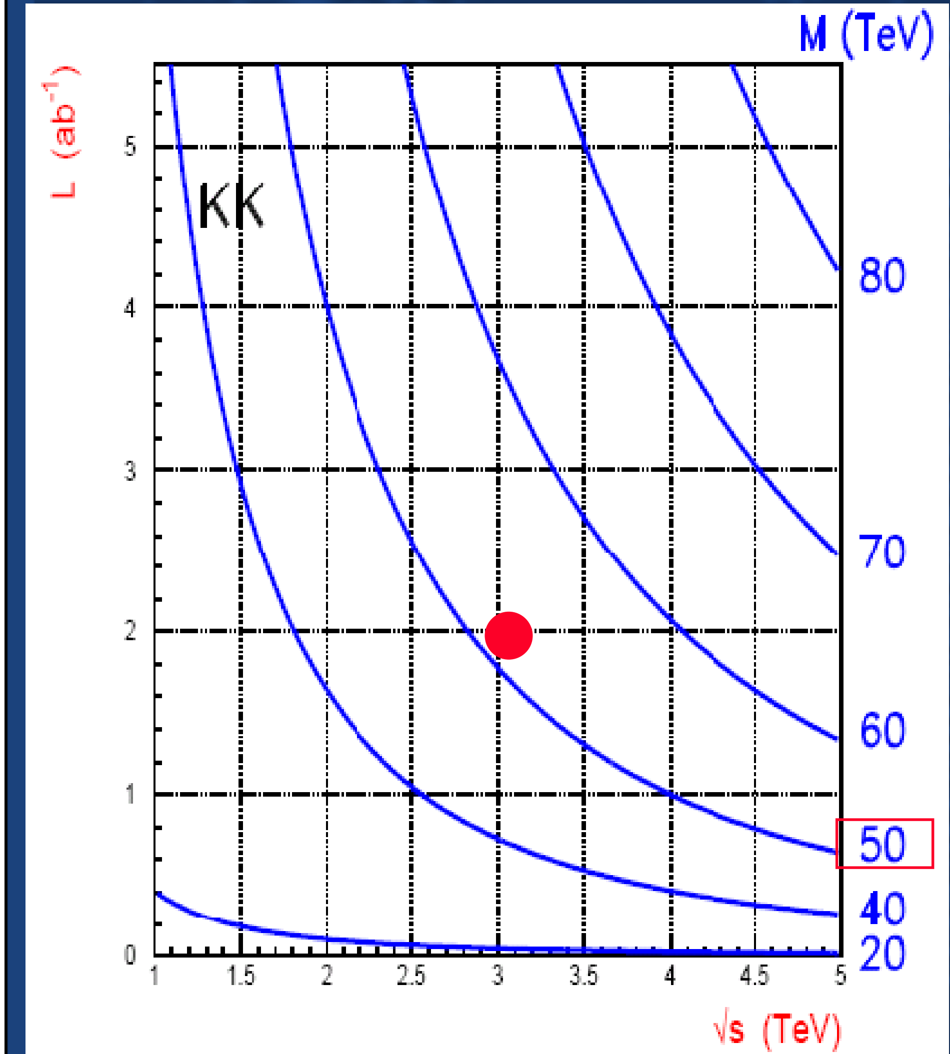
# New Physics beyond the LHC Reach: ED

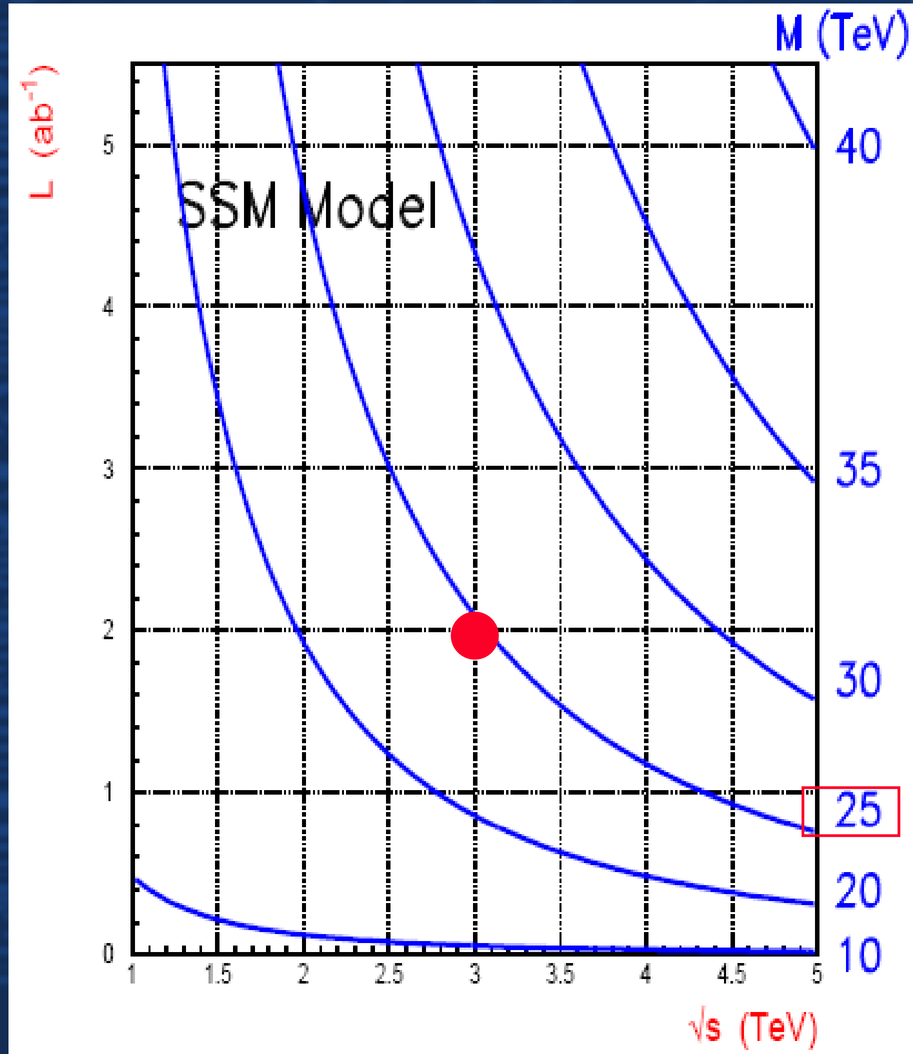
Reach for ADD model scale $M_s$ vs. integrated luminosity for 3 TeV and 5 TeV data:




$$M_S \cong 6\sqrt{s}$$

# New Physics beyond the LHC Reach: ED, Z'

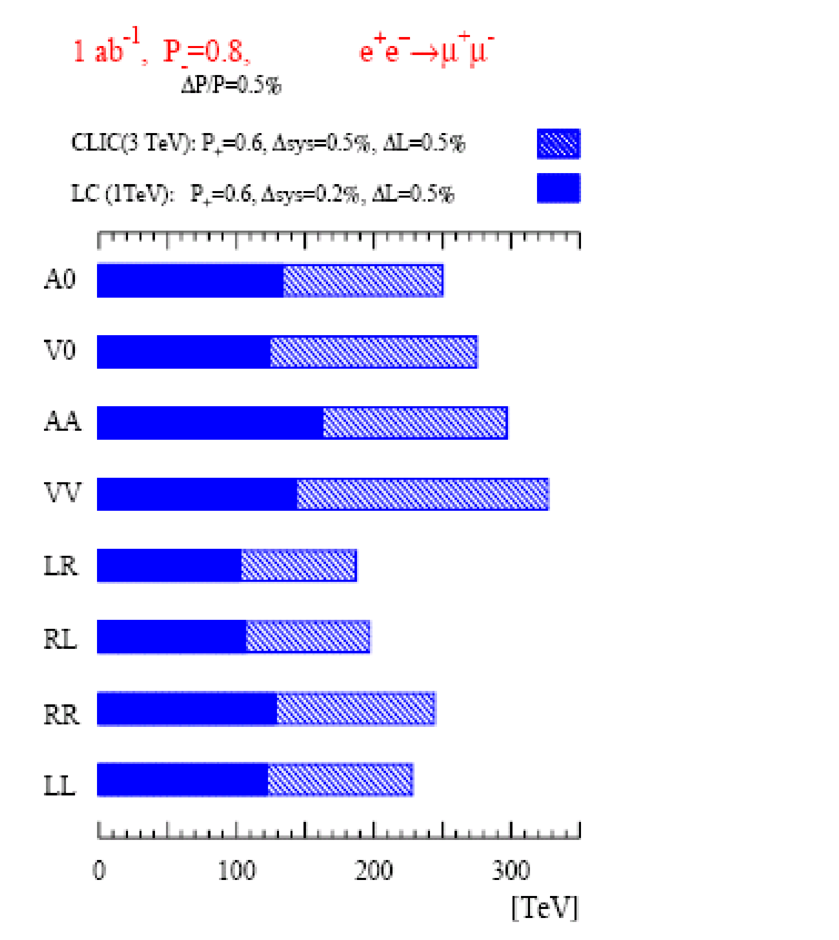


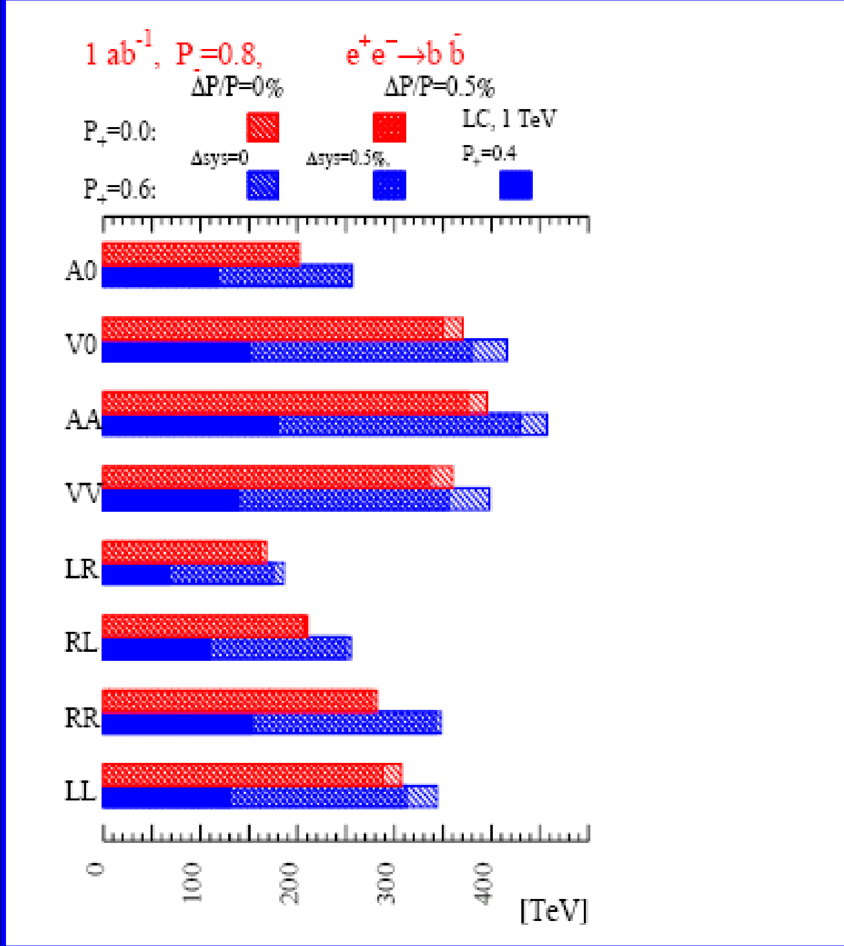




MB et al,
hep-ph/0112270

# New Physics beyond the LHC Reach: Contact Interactions

## $\Lambda$ reach for $\sqrt{s} = 3$ TeV and $\int \mathcal{L} = 1$ ab$^{-1}$



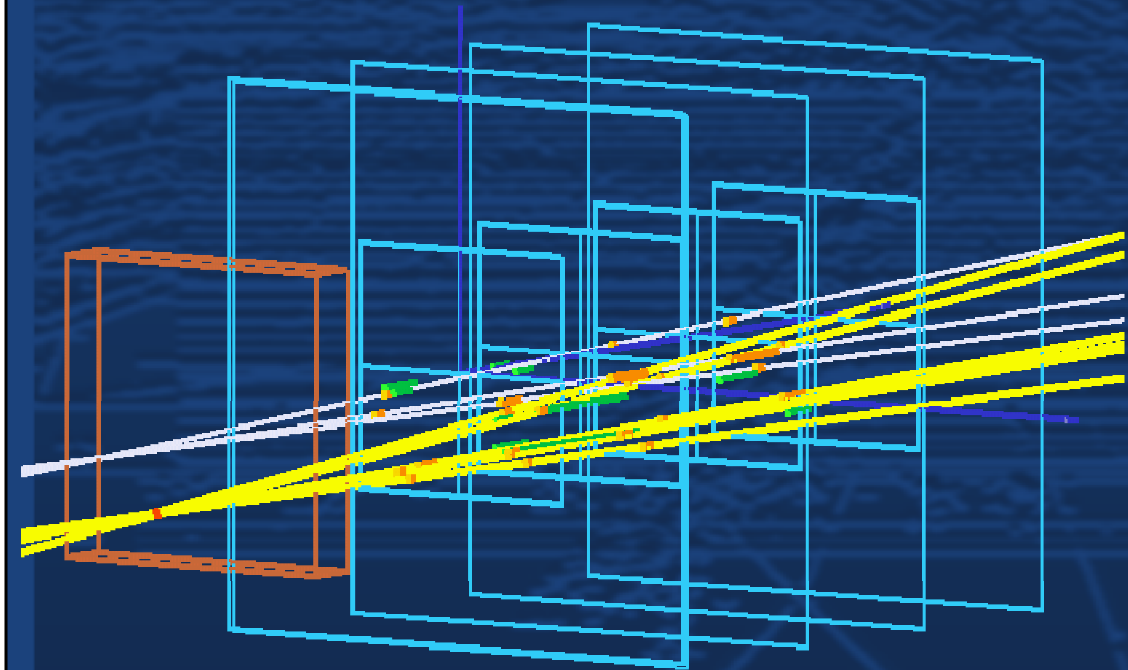


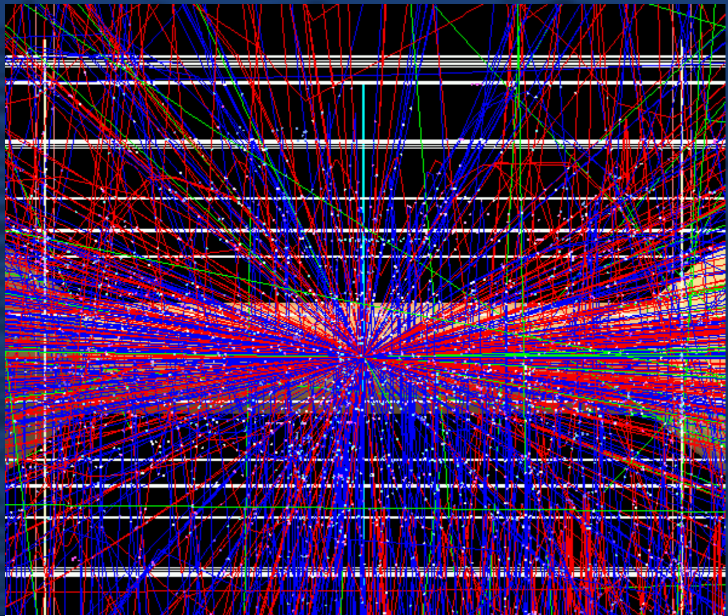

MB et al,
hep-ph/0112270

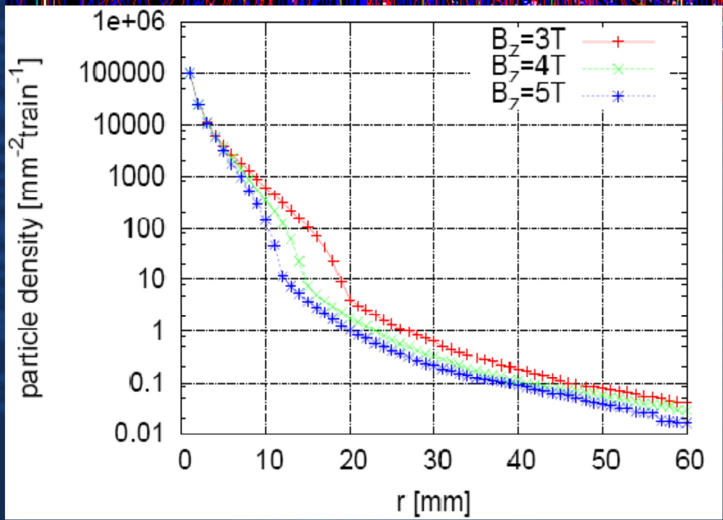
# Experimental Issues

Perform precision tracking and vertexing accounting for beam stay clear and hit density from pair background;

Optimise pixel size, bunch tagging,...





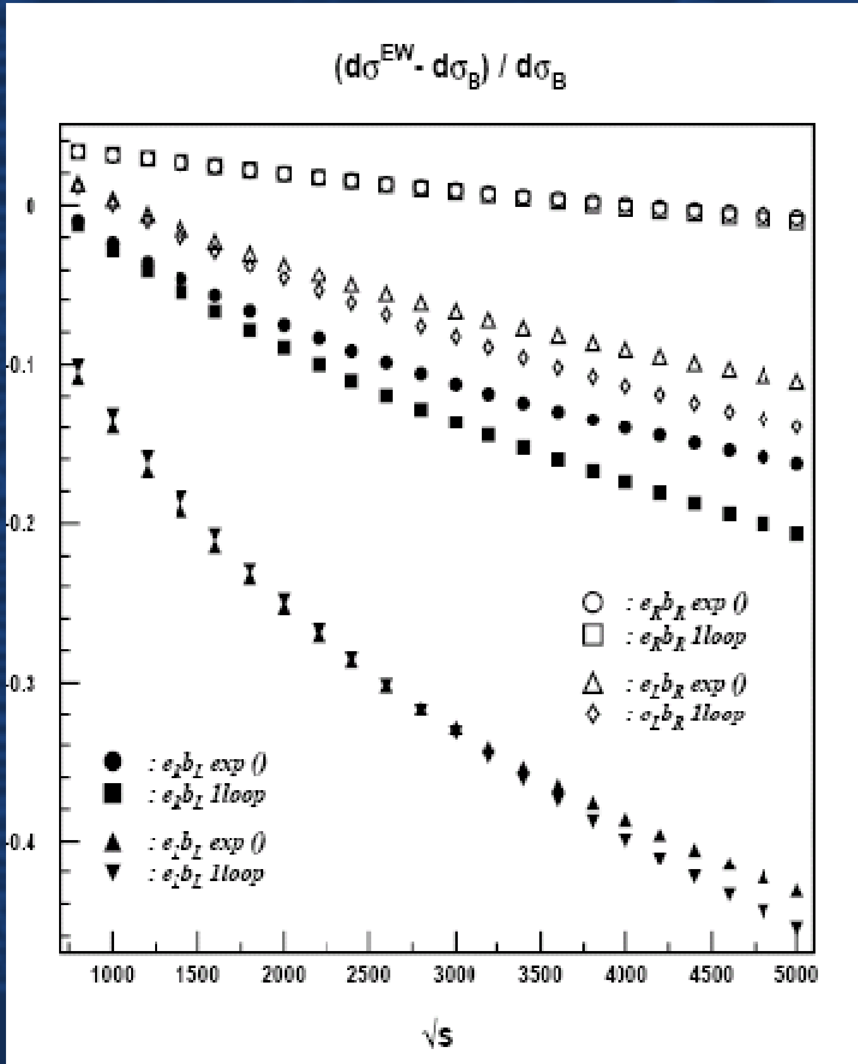


# Theory Issues

Anticipated experimental accuracy in determination of EW observables at and beyond 1 TeV, needs to be matched by theoretical predictions accurate at $O(1\%)$ to ensure sensitivity to New Physics;

Electroweak radiative corrections include large Sudakov logarithms $\propto \alpha^n \log^{2n}(M^2/s)$ which will contribute sizeable uncertainties

Example: at 1 TeV W-boson corrections of the form $\alpha \log^2(M_W^2/s)$ amount to 19%.




LAWRENCE BERKELEY NATIONAL LABORATORY

Beccaria, CERN-2004-005

# Outlook

Waiting for first LHC data, there is a compelling case for vigorously pursuing a technology able to offer $e^+e^-$ collisions at, and beyond, 1 TeV with high luminosity;

CLIC offers unmatched energy range from 0.5 TeV up to 3 TeV making it an extremely appealing option for accessing the energy scale of LHC and beyond with $e^+e^-$ collisions;

Physics potential at 1 – 3 TeV appears very rich, preserving the signature $e^+e^-$ features of cleanliness and accuracy represents a challenge, which needs a combined effort from physics benchmarking, detector R&D, machine parameter optimisation;

Optimal balance between very high precision at high energy and high precision at very high energy can be assessed only with first LHC results at hand. For now enough to do tackling the issues above.