CP Phases, Electric Dipole Moments, and a Linear Collider

Tilman Plehn

— CP phases in supersymmetric models

— Electric dipole moments: electron, neutron, mercury

— Extraction from masses and cross sections at a LC

— Observation in CP asymmetries

→ Combine all sectors

→ Simulate realistic experimental setup

together with: V. Barger, T. Falk, T. Han, J. Jiang, T. Li

SUPERSYMMETRY WITH CP PHASES

New sources for CP violation in the MSSM:

$\mu \hat{H}_1 \hat{H}_2$ $\rightarrow$ Higgsino mass matrix including ϕ_μ

$M_i \tilde{\lambda}_i \tilde{\lambda}_i$ $\rightarrow$ Gaugino mass matrix including ϕ_i

$B\mu H_1 H_2$ $\rightarrow$ Higgs boson mass and couplings

$A_i h_i \tilde{Q}_i \tilde{U}_i^c H_2 \cdots$ $\rightarrow$ trilinear squark/slepton couplings

– some (most) phases absorbed into field redefinitions

– generally unification scenarios with fewer free phases

e.g. gaugino mass unification $\rightarrow \phi_1 \equiv \phi_2 \equiv \phi_3 \equiv 0$

– only ϕ_μ and ϕ_A in mSUGRA

Neutralinos and Charginos

Neutralino/Chargino mass matrices with two additional parameters:

$$\mathcal{M}_{\rm neut} = \begin{pmatrix} |M_1|\, e^{i\phi_1} & 0 & -m_Z s_w c_\beta & m_Z s_w s_\beta \\ 0 & M_2 & m_Z c_w c_\beta & -m_z c_w s_\beta \\ -m_Z s_w c_\beta & m_Z c_w c_\beta & 0 & -|\mu|\, e^{i\phi_\mu} \\ m_Z s_w s_\beta & -m_Z c_w s_\beta & -|\mu|\, e^{i\phi_\mu} & 0 \end{pmatrix}$$

$$\mathcal{M}_{\rm char} = \begin{pmatrix} M_2 & \sqrt{2} m_W s_\beta \\ \sqrt{2} m_W c_\beta & |\mu|\, e^{i\phi_\mu} \end{pmatrix}$$

Inversion problem:

Model Parameters:
$|M_1|, M_2, |\mu|, \tan\beta$
ϕ_1, ϕ_μ

$\Updownarrow$

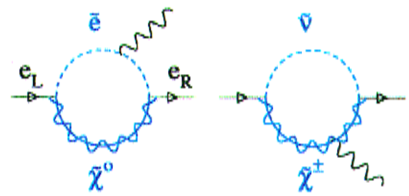
Measured Observables:
4 neutralino masses: $\tilde{\chi}_i^0$
2 chargino masses: $\tilde{\chi}_i^\pm$
9+1 neutralino cross sections
3 chargino cross sections

Additional Constraints:
electron, neutron, mercury EDM

Mass Limits:
Cold Dark Matter, Coannihilation,...

Theoretical Arguments:
fine tuning and perturbation theory

Electric Dipole Moments



(1) Electron electric dipole moment:

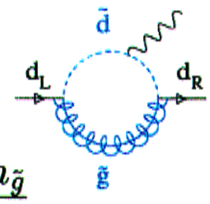
– leading chargino contribution: $\frac{d_e}{e} \sim \frac{\alpha}{4\pi \sin^2\theta_w} \tan\beta \; \sin\phi_\mu \frac{m_e}{m_{\tilde{\nu}}^2}$

– possible cancellation between chargino and neutralino:

$-\frac{m_e}{m_{\tilde{e}}^2}\left[A_e \sin(\phi_1 + \phi_A) + \mu \tan\beta \sin(\phi_\mu - \phi_1)\right]$ Ibrahim & Nath; Brhlik, Good, Kane

– experimental limit $d_e < 4 \cdot 10^{-27}\,\mathrm{e\,cm}$

$\rightarrow$ naively with $m_{\tilde{\nu}} \sim 100\,\mathrm{GeV}$: $\phi_\mu \lesssim 10^{-3}$ Ellis, Falk, Olive



(2) Neutron electric dipole moment:

– additional gluino contribution: $\frac{d_d}{e} \sim \frac{\alpha_s}{\pi} \mathrm{Im}(A^* + \mu \tan\beta) \frac{m_d m_{\tilde{g}}}{m_{\tilde{d}}^4}$

– possible cancellation between chargino and gluino:

$-\frac{m_d}{m_{\tilde{e}}^2}\left[A_d \sin(\phi_3 + \phi_A) + \mu \tan\beta \sin(\phi_\mu - \phi_3)\right]$

– experimental limit $d_N < 1.1 \cdot 10^{-25}\,\mathrm{e\,cm}$

$\rightarrow$ naively with $m_{\mathrm{SUSY}} \sim 100\,\mathrm{GeV}$: $\arg(A^* + \mu\tan\beta) \lesssim 10^{-3}$

– hadronic uncertainties, gluonic operators,...

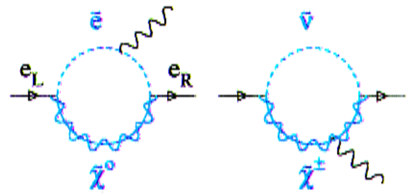
(3) Mercury electric dipole moment:

– experimental constraint $d_{Hg} < 9 \cdot 10^{-28}\,\mathrm{e\,cm}$

$\rightarrow$ naively with $m_{\mathrm{SUSY}} \sim 100\,\mathrm{GeV}$: $\arg(A^* + \mu\tan\beta) \lesssim 10^{-4}$

Falk, Olive, Pospelov, Roiban

EDM CONSTRAINTS



Dipole moments of electron, neutron, mercury can be suppressed through:

(1) small phases $\phi \lesssim 10^{-3}$ Ellis, Falk, Olive, Pospelov, Roiban

(2) large SUSY masses $m_{\mathrm{SUSY}} \gtrsim 1\mathrm{TeV}$

(3) large cancellations between diagrams Ibrahim & Nath; Brhlik, Good, Kane

(4) some of (1) to (3)

Check fine tuning:

— scan over parameter space (SUSY masses below 1TeV)

(collider phenomenology, relic density constraints)

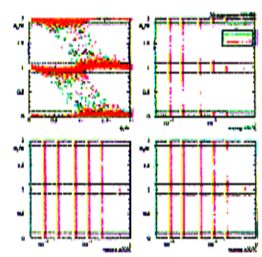
— find solutions to all EDM constraints

— vary all parameter by $\Delta X/X = 0.1 \cdots 0.01 \cdots 0.001$

— require that all EDM constraints are still fulfilled

(stability of regions in perturbaxtion theory)

→ mainly ϕ_μ correlated with fine tuning



Observed neutralino sector:

— require $m_{\tilde{\chi}_1} + m_{\tilde{\chi}_2} < 500\,\mathrm{GeV}$

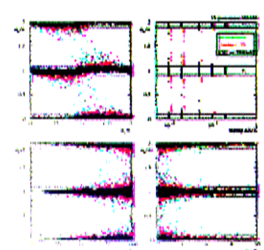
— require tuning parameter $> 1\%$

→ $\phi_\mu \lesssim \pi/10$ for $M_2, \mu \lesssim 800\,\mathrm{GeV}$

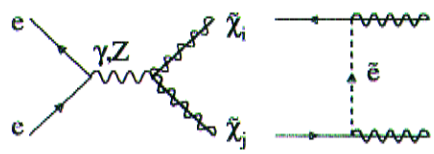
→ $\phi_\mu \lesssim \pi/20$ for $\tan\beta \gtrsim 4$

→ $\phi_\mu \lesssim \pi/20$ for mSUGRA

→ in other words: *ϕ_μ is small*



NEUTRALINOS AND CHARGINOS AT A LC



Previous LC analysis: Barger, Han, Li, T.P

– determine complete set of neutralino/chargino parameters

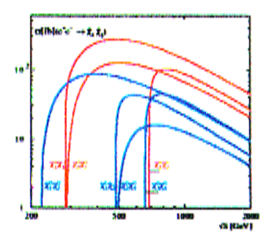
– experimental (statistical) errors included

→ large set of masses and cross sections needed c.f. Kneur & Moultaka; Choi et al.

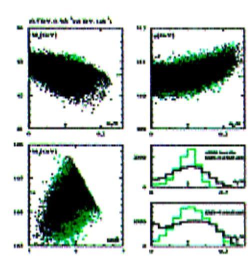
→ mass measurements from threshold scan Blair & Martyn

→ large luminosity required for heavy higgsinos *e.g.* (1TeV, 1ab^{-1})

→ phases $\phi_1, \phi_\mu \lesssim \pi/10$ not distinguishable from zero



Measurement at Linear Collider:	
1.	define scenario with 'true' set masses and cross sections
2.	assume mass measurements through threshold scan
3.	choose 10000 smeared pseudo-mesurements
4.	fit mass and phase parameters to each pseudo-measurement
5.	determine phase distribution of pseudo-measurements
6.	central value, width, Gaussian?



Improved analysis:

(A) How can we make use of the EDM constraints?

(B) Can we measure something with a smaller collider?

Putting the Pieces Together

EDM constraints and a medium energy Linear Collider:

+ $\tan\beta$ small i.e. measured in Higgs sector?!
+ ϕ_μ could as well be zero $\rightarrow$ no phase in chargino sector
+ ϕ_1 unconstrained and uncorrelated
– not all neutralinos/charginos observed (no mass measurement)
– t channel selectrons/sneutrinos not seen

Minimal inversion problem:

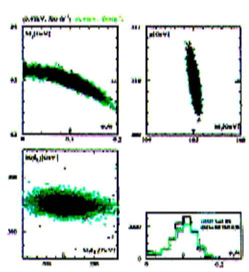
Model Parameters:
$\lvert M_1\rvert, M_2, \mu, m_{\tilde{e}_L}, m_{\tilde{e}_R}, \phi_1$

$\Longleftrightarrow$

Measured Observables:
3 neutralino masses: $\tilde{\chi}_i^0$
1 chargino mass: $\tilde{\chi}_1^\pm$
3 neutralino cross sections
1 chargino cross section

Variety of models:

	Fit ϕ_1	RMS
complete analysis	0.097	0.030
free sleptons, fixed $\tan\beta$	0.099	0.028
only one phase ϕ_1	0.101	0.030
only $\tilde{\chi}_3^0$ ($E = 400\,\mathrm{GeV}$)	0.101	0.028
'true' $\phi_\mu = \pi/20$	0.100	0.028
'true' $\phi_\mu = \pi/20, \tan\beta = 4.2$	0.083	0.028
decoupled sleptons	0.105	0.041
low luminosity $300\,\mathrm{fb}^{-1}$	0.102	0.034
large $\phi_1 = \pi/2$	0.501	0.025
light higgsinos $\mu = 150\,\mathrm{GeV}$	0.100	0.014



Particle	Mass [GeV]	Error [GeV]
$\tilde{\chi}_1^0$	71.9	0.05
$\tilde{\chi}_2^0$	130.3	0.07
$\tilde{\chi}_3^0$	319.8	0.30
$\tilde{\chi}_4^0$	348.0	0.52
$\tilde{\chi}_1^+$	127.7	0.04
$\tilde{\chi}_2^+$	345.8	0.25
$\tilde{e}_L$	250	fitted
$\tilde{e}_R$	218	fitted

Looking for an Asymmetry

Define a CP asymmetry in $\tilde{\chi}_1^0 \tilde{\chi}_i^0$ production:

– best proof of CP phases: asymmetry

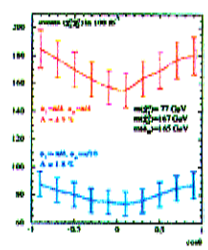
– non-identical pair production (*s* channel Z vs. *t* channel $\tilde{e}$ with destructive interference)
dominant diagrams: *s* channel for higgsinos, *t* channel for gauginos

– one particle decaying $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 \, e^- e^+$ (Z and $\tilde{e}$ diagram on/off shell)

– reconstructed momenta: $p_{e^-}^{(\text{in})}, k_{e^-}^{(\text{out})}, k_{e^+}^{(\text{out})} \to \cos\theta \propto \vec{p}_{e^-} \cdot \left(\vec{k}_{e^-} \wedge \vec{k}_{e^+} \right)$

→ spectacular but small signal

→ large asymmetry disfavored by couplings



CONCLUSIONS

⋆ CP violating MSSM phases an exciting theoretical feature

⋆ Tevatron/LHC most likely only discovery machine

⋆ LC precision analysis the right tool

– Large phases well measurable at the LC $(\Delta\phi_1 \gtrsim \pi/30\ \Delta\phi_\mu \gtrsim \pi/20)$

– Small phases unobservable $\phi \lesssim \pi/10$

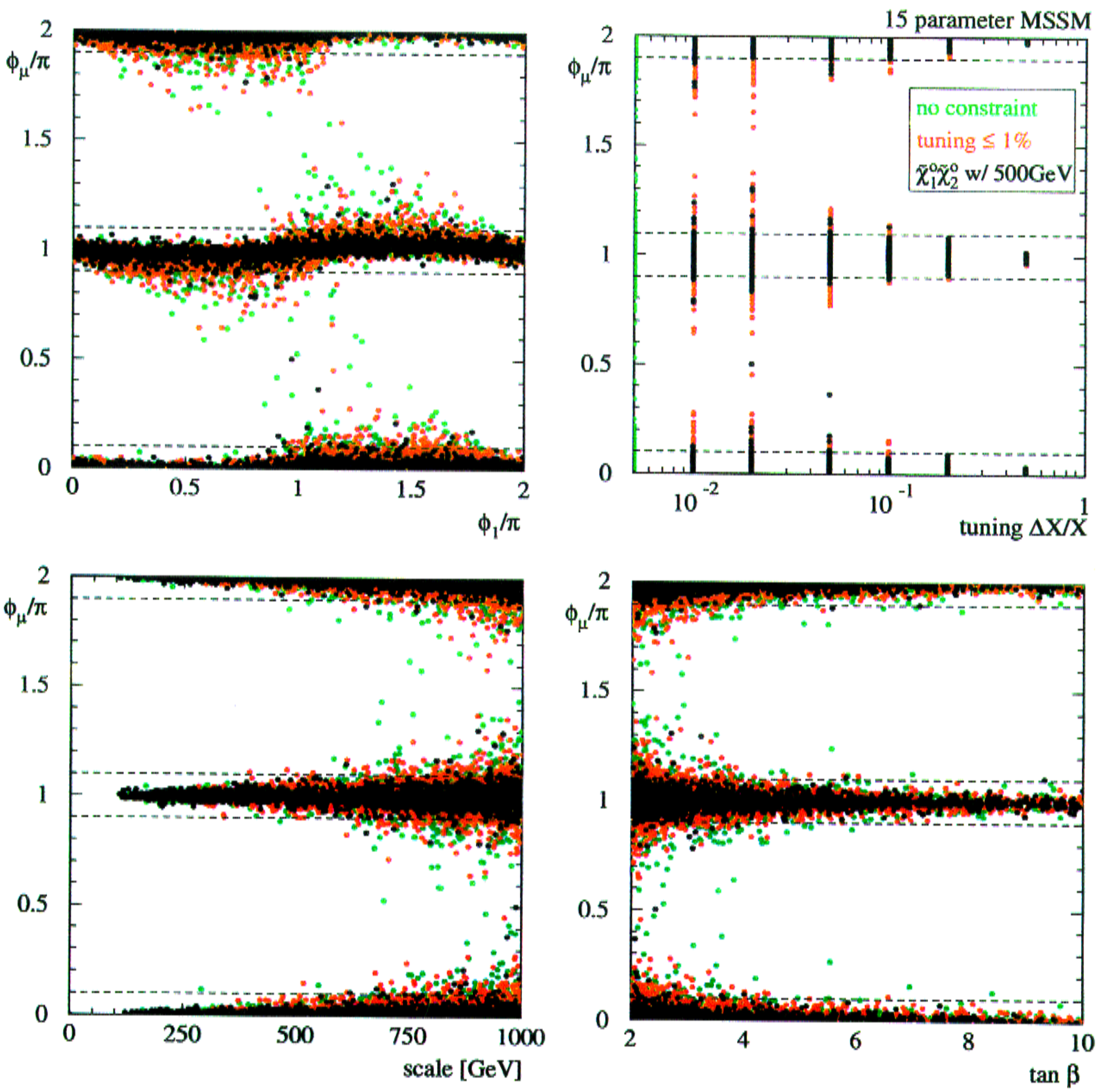
– EDM constraints exclude large $\phi_\mu \gtrsim \pi/10$

– Improved analysis of $\phi_1 \neq 0$ alone for $E \lesssim 500\,\text{GeV}$

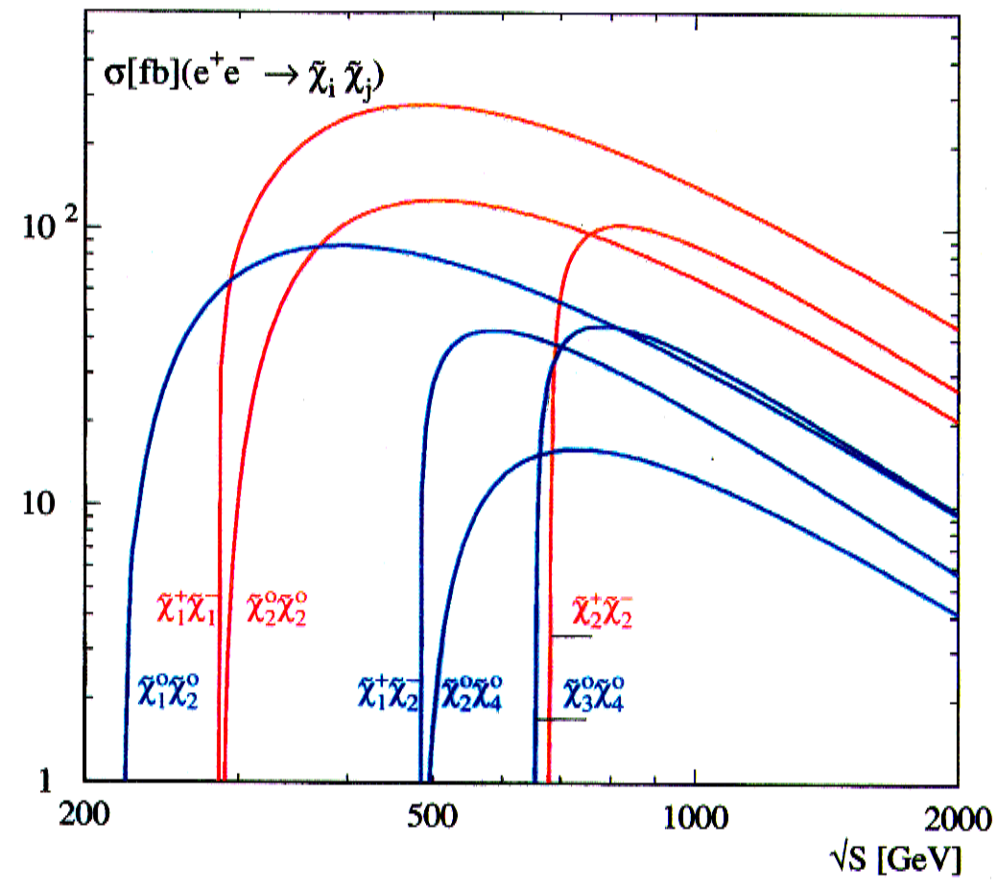
– Unknown slepton masses not critical (small systematic error)

– CP asymmetry theoretically disfavored

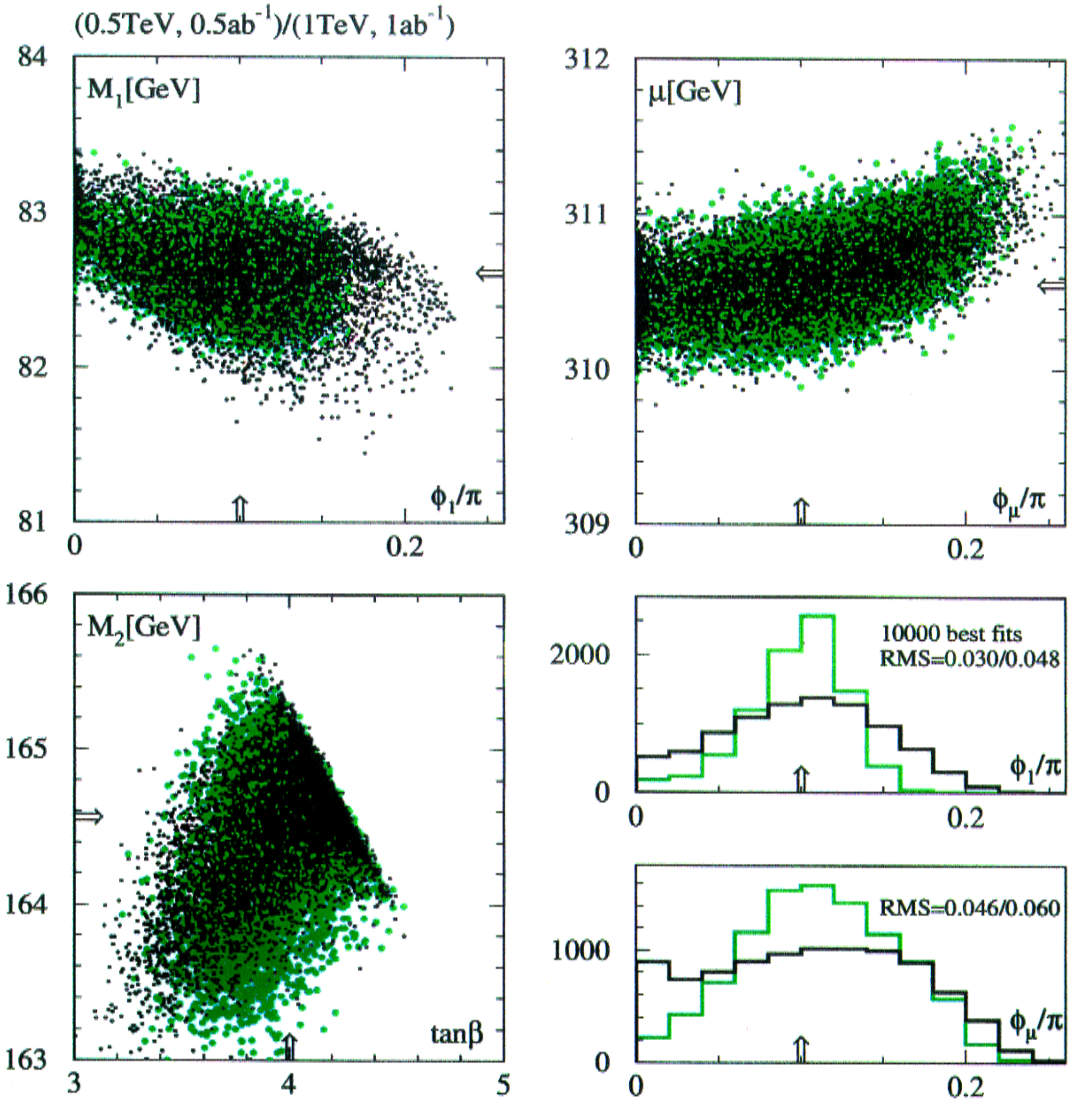
- LC energy hopefully covers many particle thresholds
- Quality of actual measurement dominated by luminosity
- We can see CP phases!



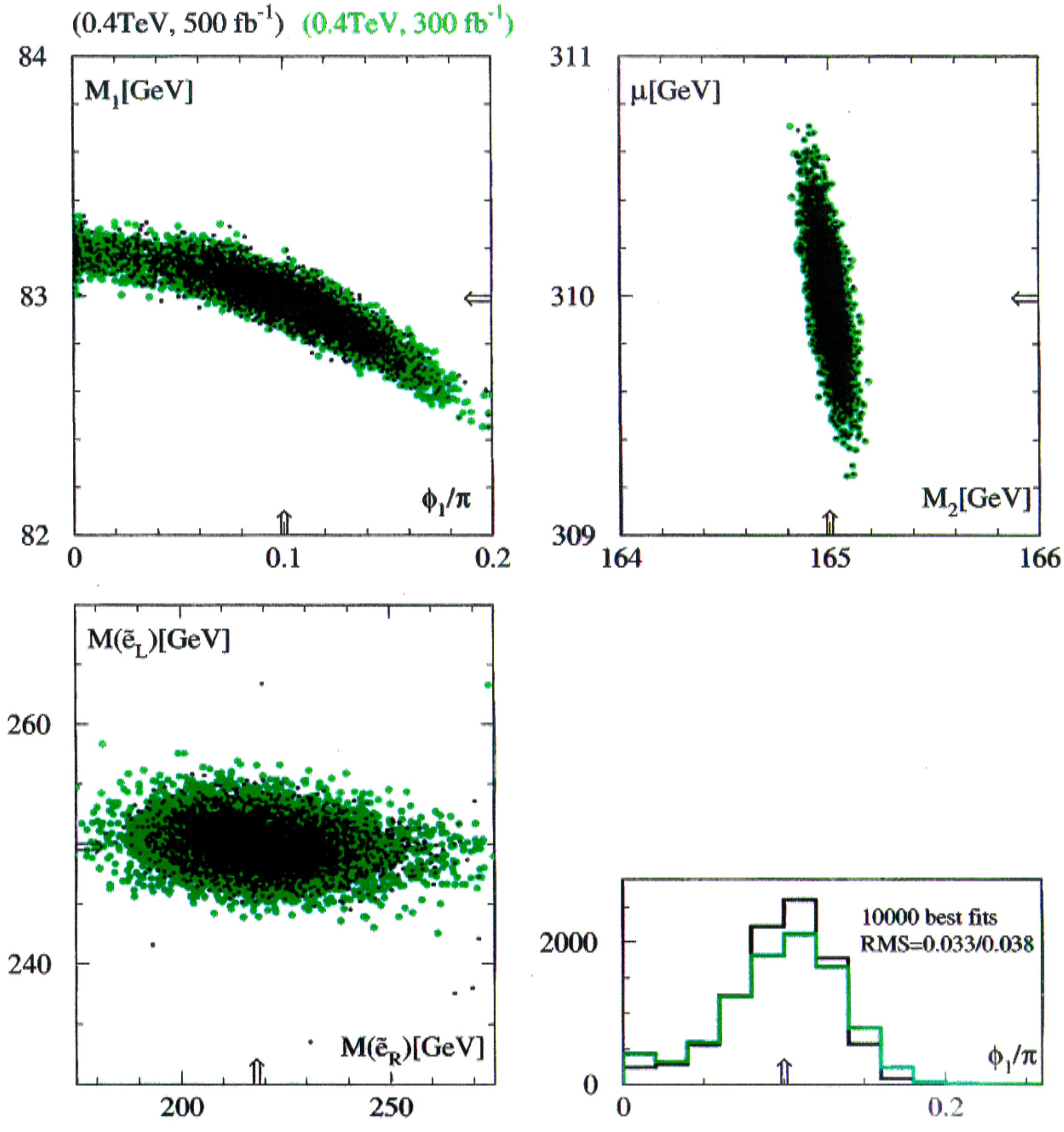
15 parameter MSSM
no constraint
tuning ≤ 1%
$\tilde{\chi}^o_1\tilde{\chi}^o_2$ w/ 500GeV
ϕ_μ/π
ϕ_1/π
tuning $\Delta X/X$
scale [GeV]
tan β



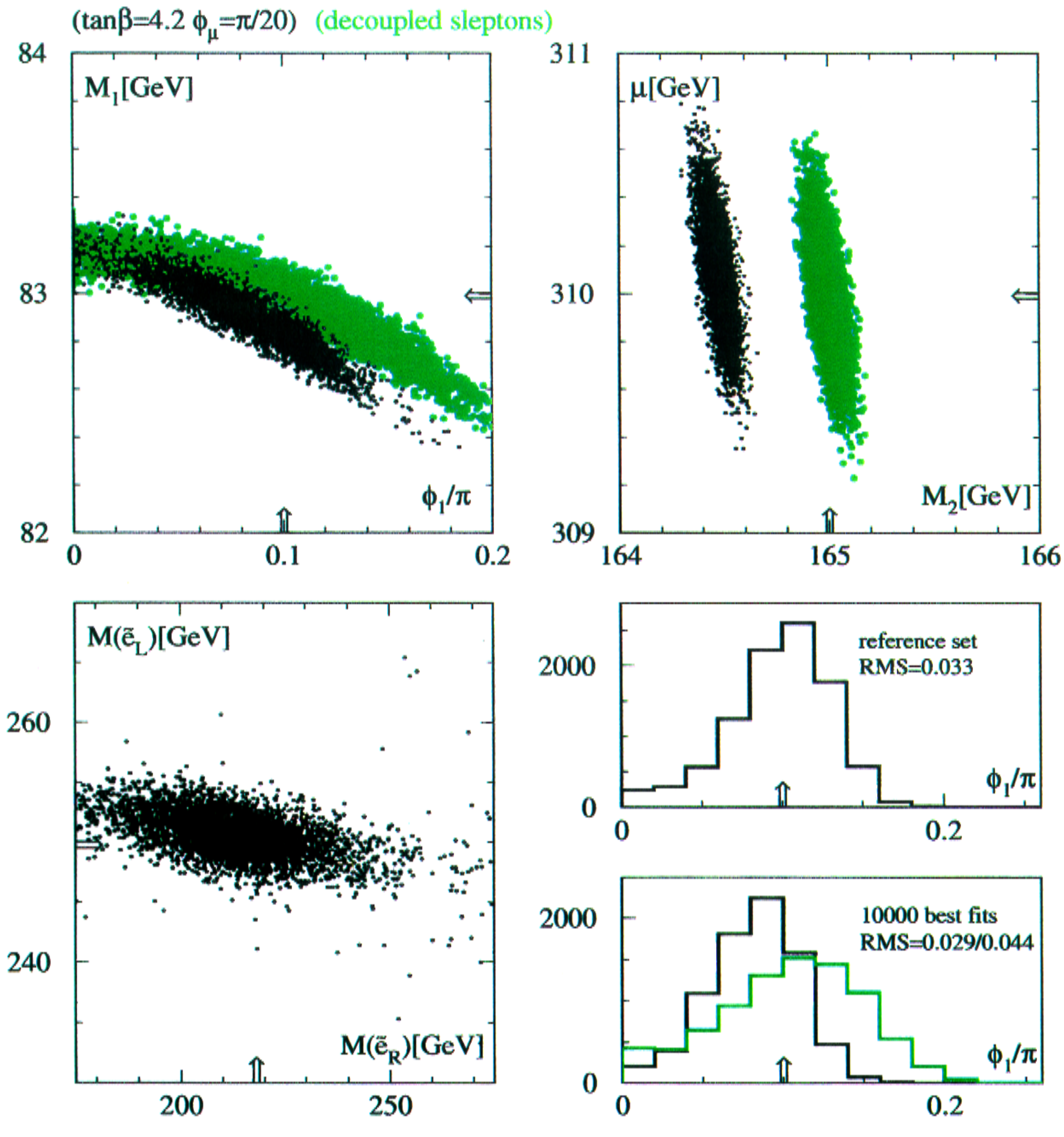
σ[fb](e⁺e⁻ → χ̃ᵢ χ̃ⱼ)
10²
10
1
200
500
1000
2000
√S [GeV]
χ̃₁⁺χ̃₁⁻
χ̃₂⁰χ̃₂⁰
χ̃₁⁰χ̃₂⁰
χ̃₁⁺χ̃₂⁻
χ̃₂⁰χ̃₄⁰
χ̃₂⁺χ̃₂⁻
χ̃₃⁰χ̃₄⁰

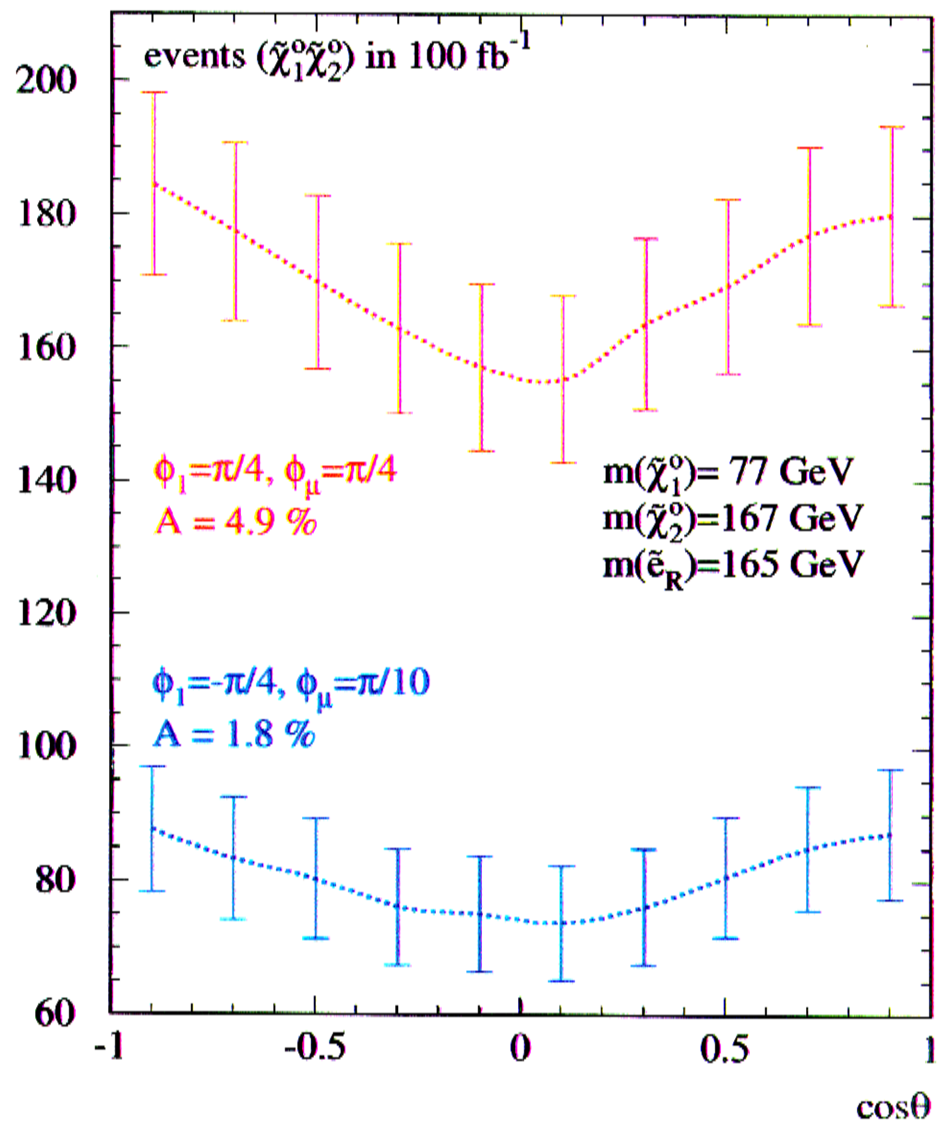


(0.5TeV, 0.5ab^{-1})/(1TeV, 1ab^{-1})
M_1[GeV]
ϕ_1/π
μ[GeV]
ϕ_μ/π
M_2[GeV]
$\tan\beta$
10000 best fits
RMS=0.030/0.048
RMS=0.046/0.060



(0.4TeV, 500 fb-1) (0.4TeV, 300 fb-1)
M1[GeV]
φ1/π
μ[GeV]
M2[GeV]
M(ẽL)[GeV]
M(ẽR)[GeV]
10000 best fits
RMS=0.033/0.038
φ1/π


(tanβ=4.2 ϕ_μ=π/20) (decoupled sleptons)
M_1[GeV]
ϕ_1/π
μ[GeV]
M_2[GeV]
$M(\tilde{e}_L)$[GeV]
$M(\tilde{e}_R)$[GeV]
reference set
RMS=0.033
10000 best fits
RMS=0.029/0.044
84
83
82
0
0.1
0.2
311
310
309
164
165
166
260
240
200
250
2000


events $(\tilde{\chi}^o_1\tilde{\chi}^o_2)$ in 100 fb^{-1}
200
180
160
140
120
100
80
60
$\phi_1=\pi/4$, $\phi_\mu=\pi/4$
A = 4.9 %
$\phi_1=-\pi/4$, $\phi_\mu=\pi/10$
A = 1.8 %
$m(\tilde{\chi}^o_1)$= 77 GeV
$m(\tilde{\chi}^o_2)$=167 GeV
$m(\tilde{e}_R)$=165 GeV
-1
-0.5
0
0.5
1
cosθ