Confusing Signals of Supersymmetry

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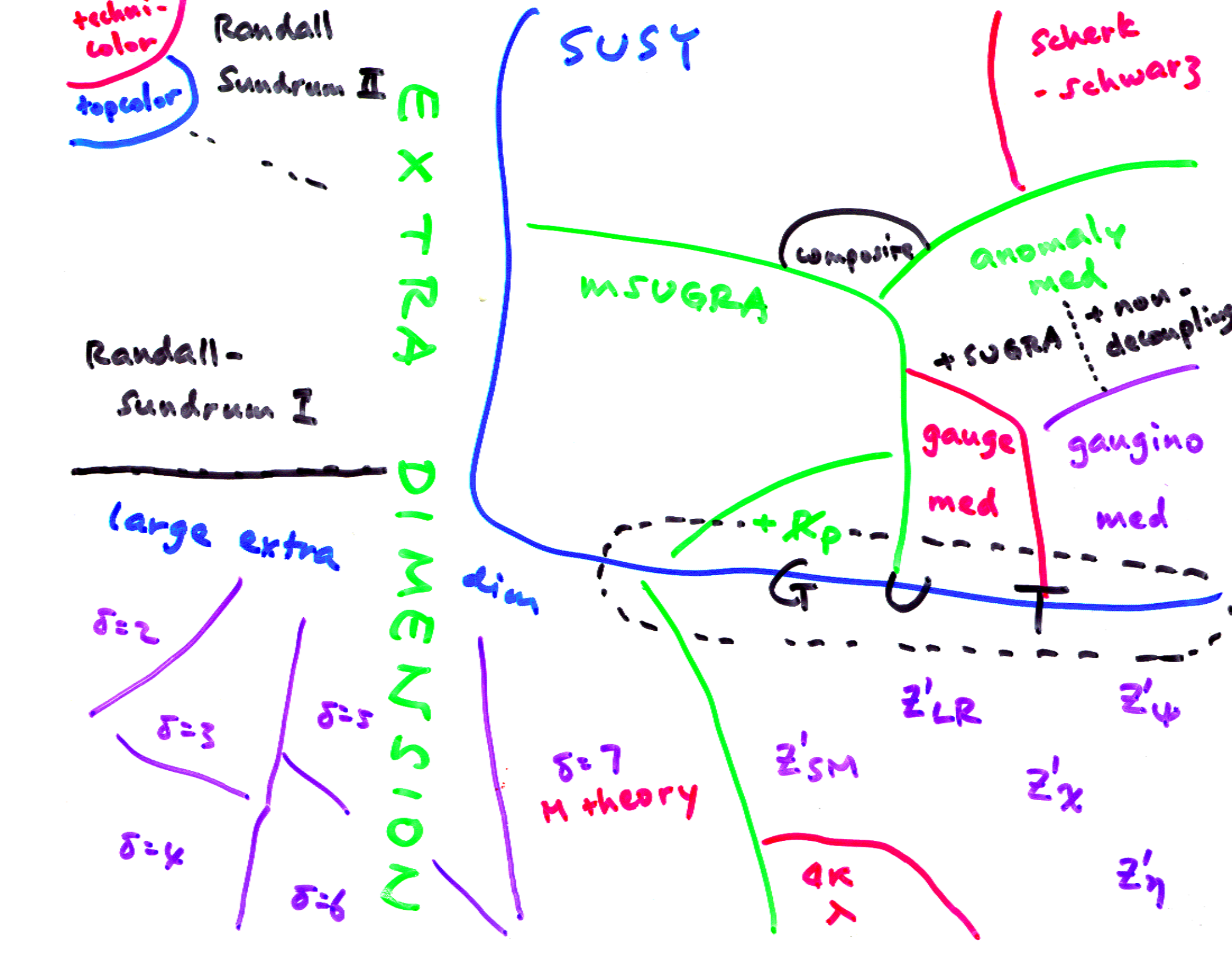
e^+e^- LC : post-LHC machine

By the time a LC turns on,
we will know beyond SM signals
from LHC w/ many precision data

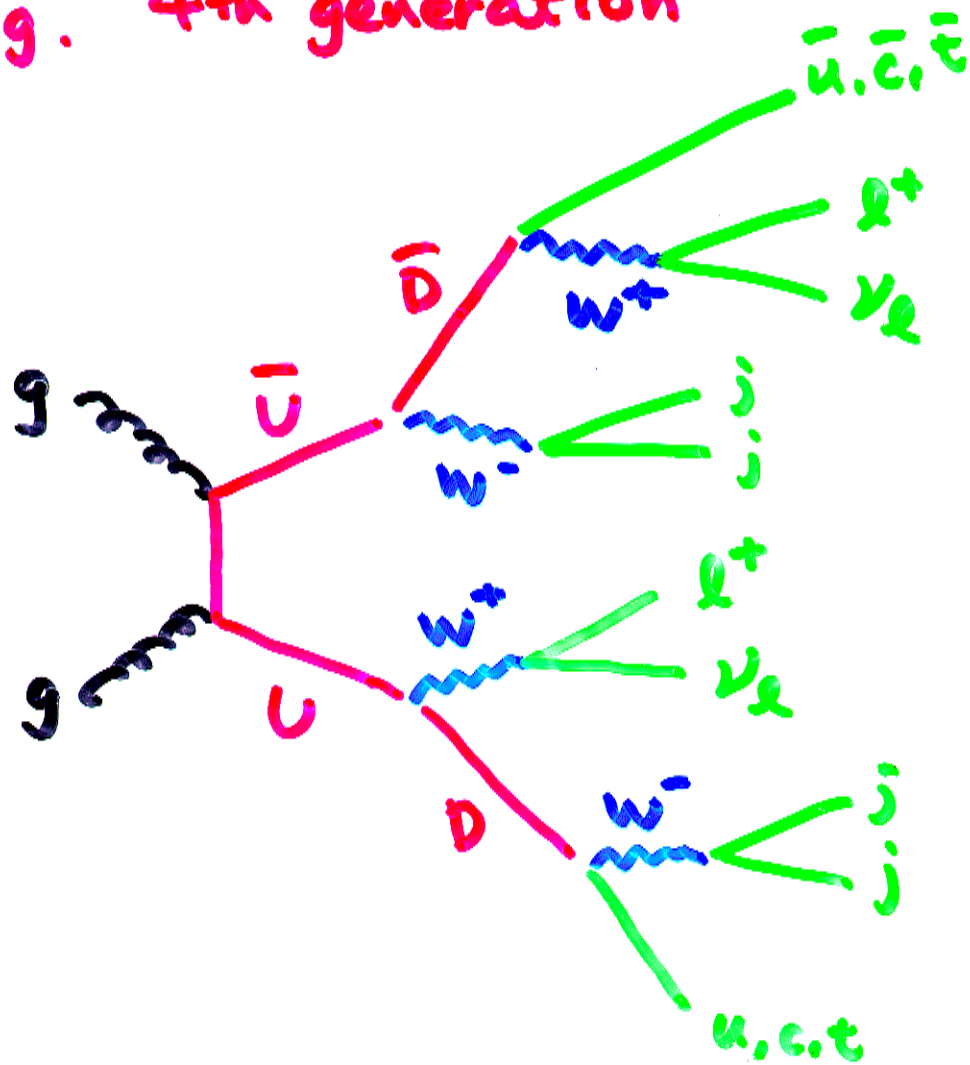
what's the point of a LC?

we can tell our grandchildren
what our generation of physicists
discovered about Mother Nature
with absolute confidence
by combining LHC + LC data


techni-color
topcolor
Randall Sundrum II
Randall-Sundrum I
EXTRA DIMENSION
SUSY
Scherk-schwarz
composite
anomaly med
+ SUGRA
+ non-decoupling
mSUGRA
gauge med
gaugino med
+ Rp
G
large extra dim
δ=2
δ=3
δ=4
δ=5
δ=6
δ=7 M theory
Z'LR
Z'SM
Z'χ
Z'ψ
Z'η
4K
λ

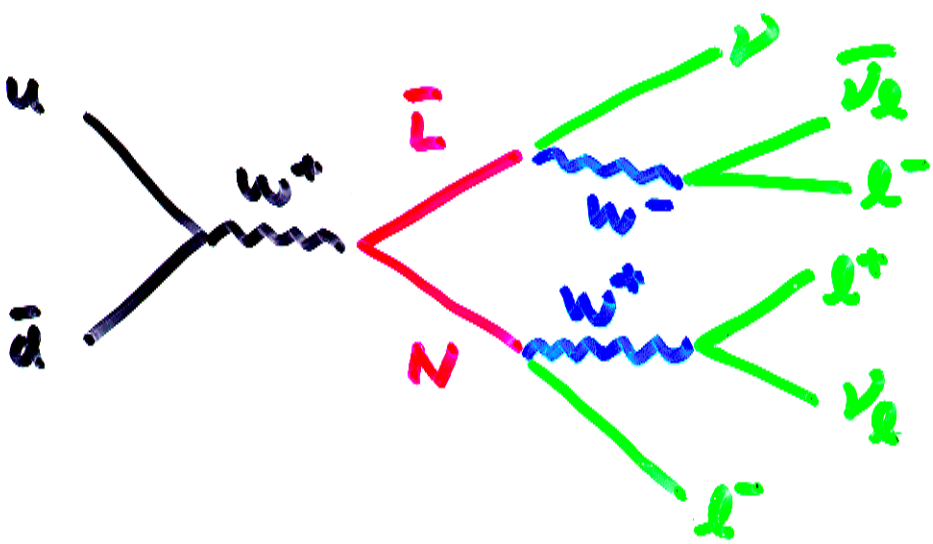

NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
SUSY
effective SUSY
NMSSM
NNMSSM
MSSM
un-unified SM
axigluon
monopole
milli-charged
fractionally charged
sterile ν
heavy Majorana ν
shadow matter
mirror symmetry
milli-weak
superweak
Weinberg's 3HD
vector-like family
4th gen
5th gen
6th gen
triplet Higgs
Type I
Type II
spontaneous CP
doubly charged Higgs
axion
familon
Majoron
NGB
pseudo NGB
hypercolor
supercolor
techni-GIM
extended TC
composite Higgs
bosonic TC
TC-TC
heterotic
matrix
contact int.
composite W/Z
worm-hole
Extra dim.
strings

e.g. 4th generation



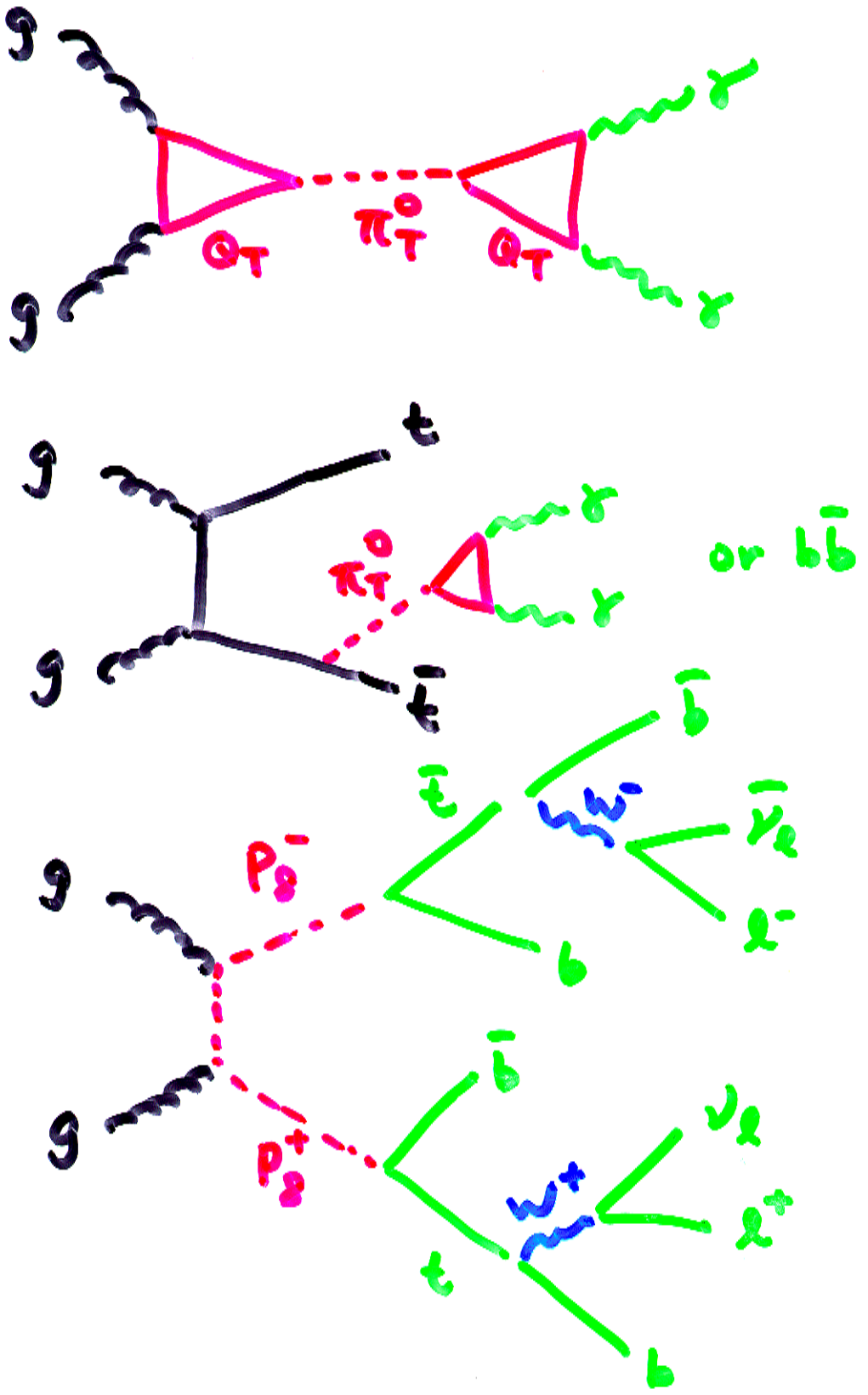
jets
$\not{E}_T$

like-sign dileptons



trilepton

e.g. technicolor



it is conceivable that

LHC can exclude these specific hypotheses

However, what we want is to go from

New York Times' level

"Missing Half Of The World Found"

"We All Have Partners"

to

Halliday - Resnik level

We have uncovered in this century
that we are only a part of
the supersymmetric world where
every single particle in Nature
has its own partner...

Challenging task for both LHC + LC!

Remember,

High-energy Community is

"the best constructive skeptics"

e.g. beautiful data from Superk

$\Rightarrow$ neutrino oscillation

but

neutrino decay?

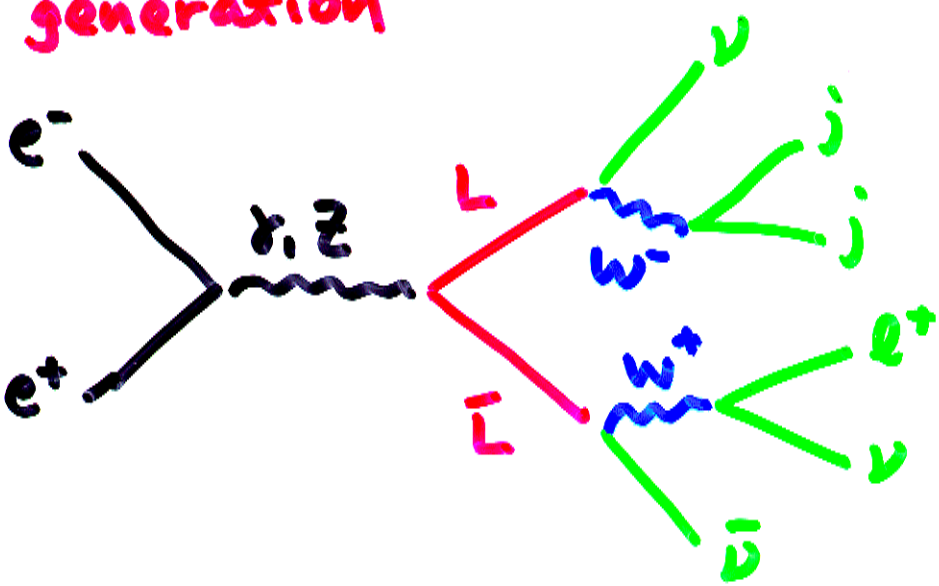
decoherence?

non-universal gravity?

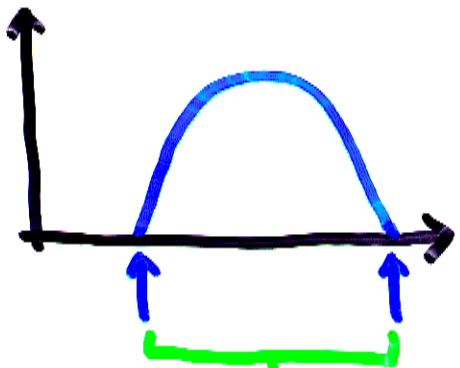
flavor-changing four-Fermi?

we need to pin down supersymmetry

4th generation



$\simeq$ chargino



$\rightarrow m_L , m_\nu = 0$

or $m_{\chi_1^+}, m_{\chi_1^0} \neq 0$

$\sigma_F (e_L^- e^+)$ $\sigma_B (e_L^- e^+)$

$\sigma_F (e_R^- e^+)$ $\sigma_B (e_R^- e^+)$

$\Rightarrow (I_3)_L , (I_3)_R , Y_L , Y_R$

complications:

t-channel diagram

do we know the spin of "L"?

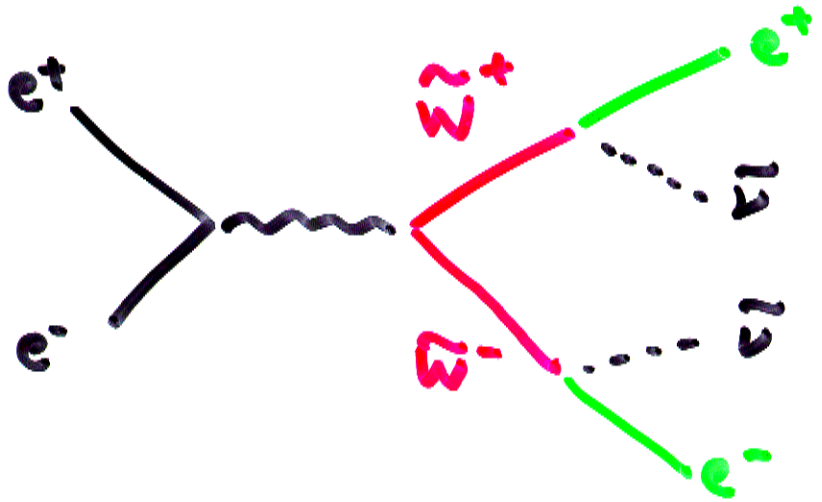
Even within SUSY

SuperK → $m_\nu \neq 0$

$\exists \nu_R$

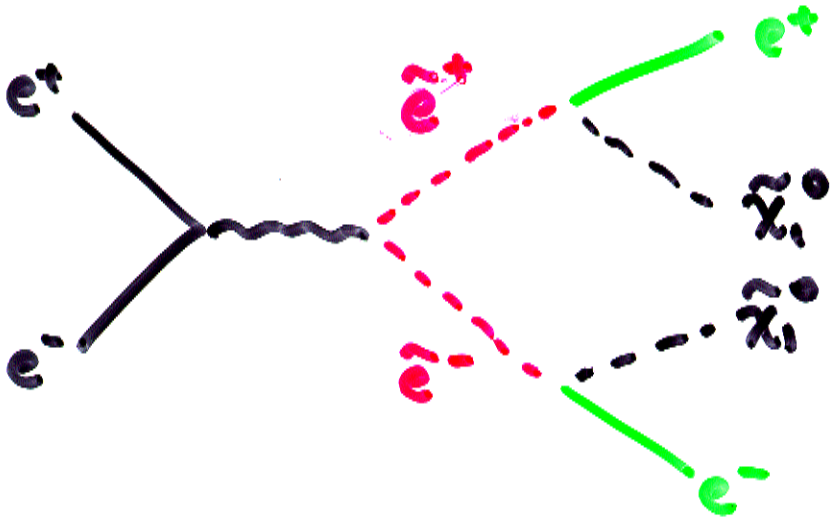
Arkani-Hamed, Hall, HM, Smith, Weiner

then also $\tilde{\nu}_R$ ← maybe LSP



acoplanar electrons

cf



acoplanar electrons

4 body phase space: 8 variables
2 leptons: 6, mass constraints: 2

} can solve kinematics up to a 2-fold ambiguity

Study as many observables as possible!

① threshold behavior

$$\sigma(\tilde{e}_R^+ \tilde{e}_R^-) \propto \beta^3$$

$$\sigma(\tilde{W}^+ \tilde{W}^-) \propto \beta$$

however,

$$\sigma(\tilde{e}_R^\pm \tilde{e}_L^\mp) \propto \beta$$

② angular distribution

$$d\sigma(\tilde{e}^+ \tilde{e}^-) \propto \sin^2\theta \, d\cos\theta$$

$$d\sigma(\tilde{W}^+ \tilde{W}^-) \propto (1+\cos^2\theta) \, d\cos\theta$$

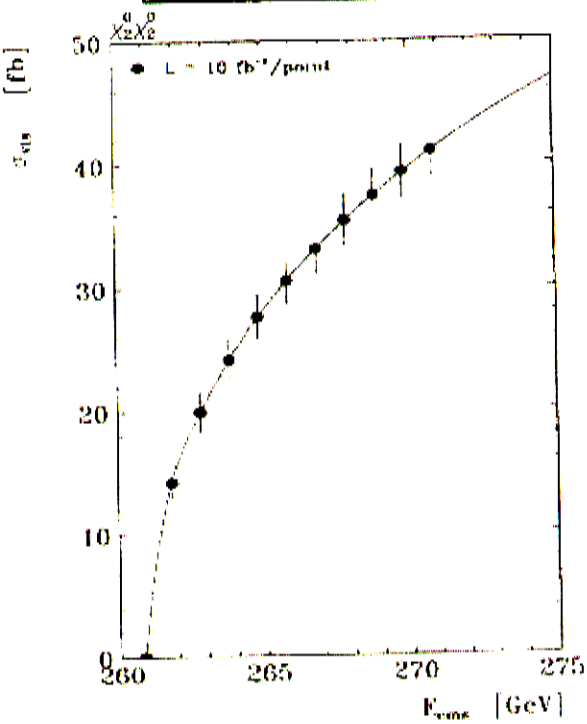
actually,

⇒ can change $d\sigma/d\cos\theta$

③ decay angle distribution = $d\sigma/dE_\ell$

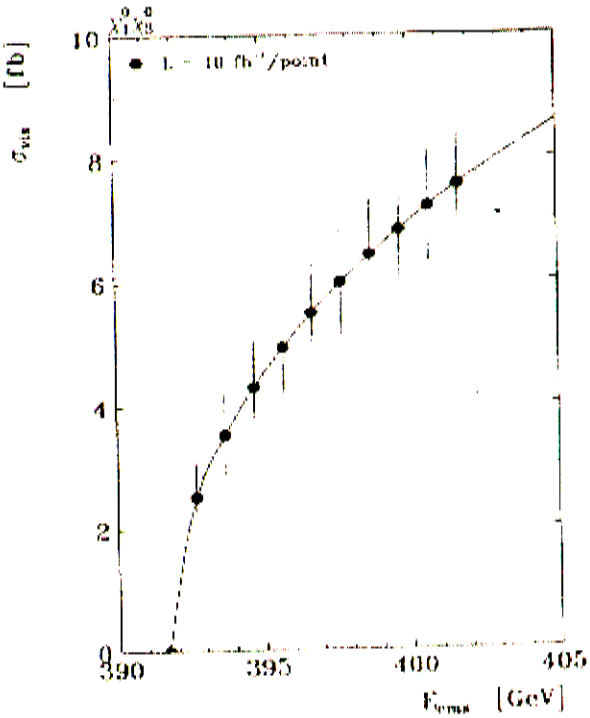
close to threshold, $\tilde{W}^\pm$ decay isotropically

$e_L^- e_R^+ \to \chi_2^0 \chi_2^0$



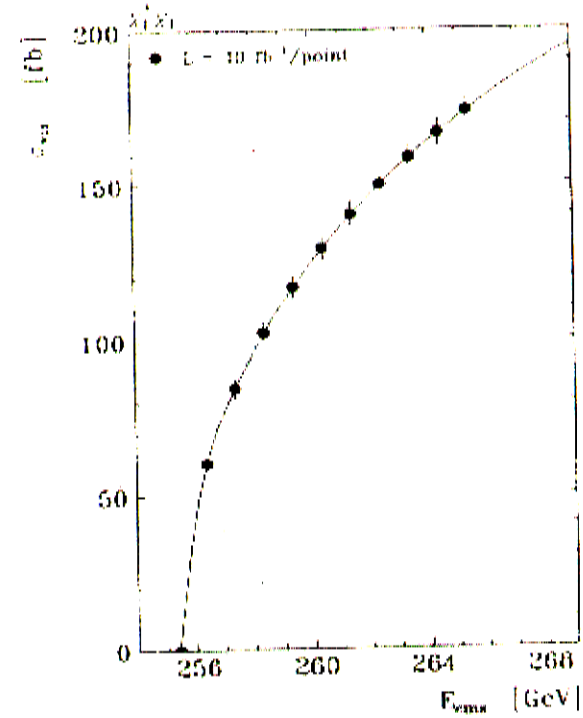
$m_{\chi_2^0} = 130.3 \pm 0.07$ GeV

$e_L^- e_R^+ \to \chi_1^0 \chi_3^0$



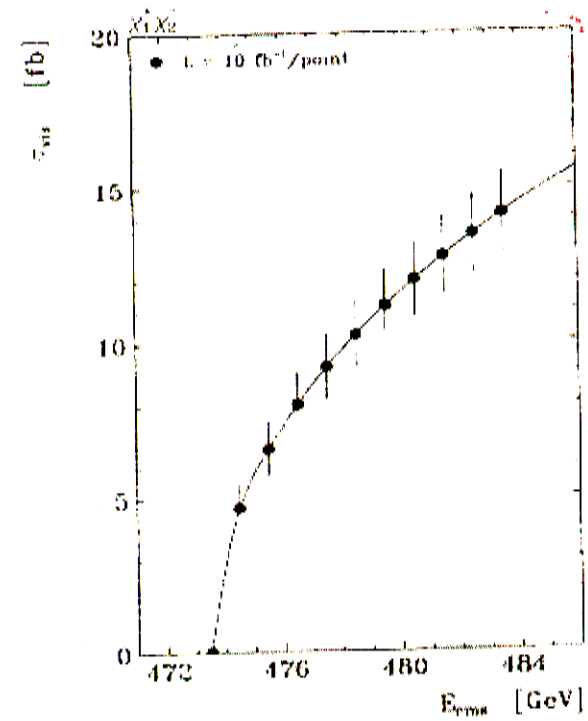
$m_{\chi_3^0} = 319.8 \pm 0.30$ GeV

$e_L^- e_R^+ \to \chi_1^- \chi_1^+$



$m_{\chi_1^\pm} = 127.7 \pm 0.04$ GeV

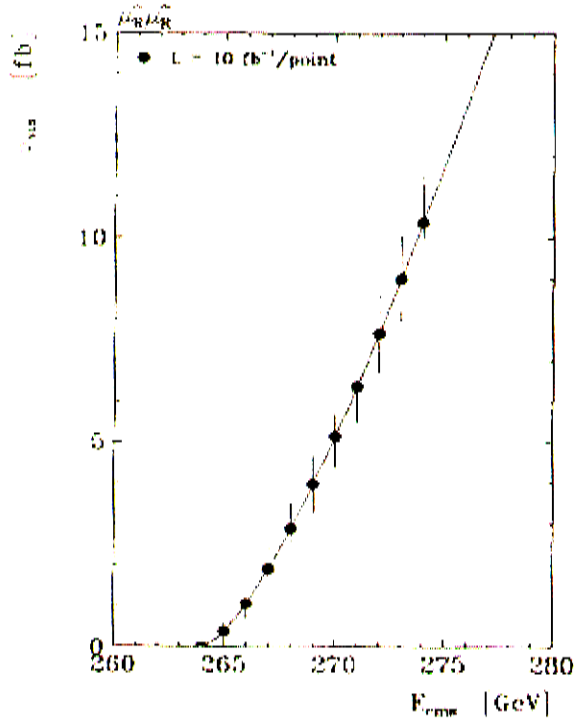
$e_L^- e_R^+ \to \chi_1^\mp \chi_2^\pm$

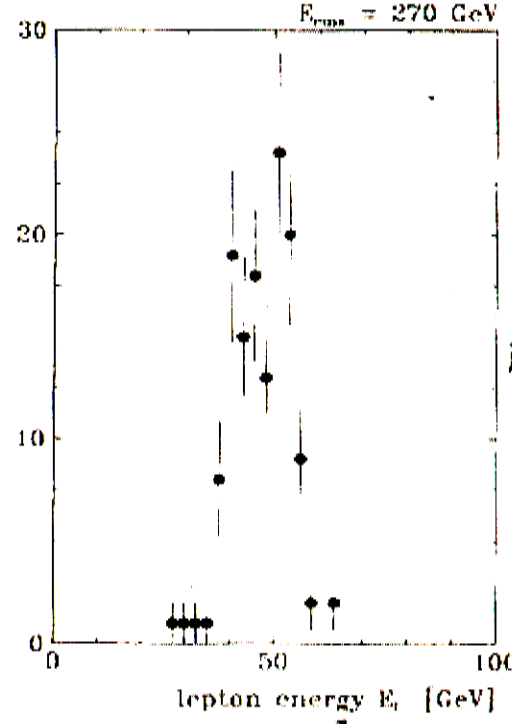


$m_{\chi_2^\pm} = 345.8 \pm 0.25$ GeV

Threshold Scans

$$e^-_R e^+_L \to \tilde{\mu}_R \tilde{\mu}_R$$



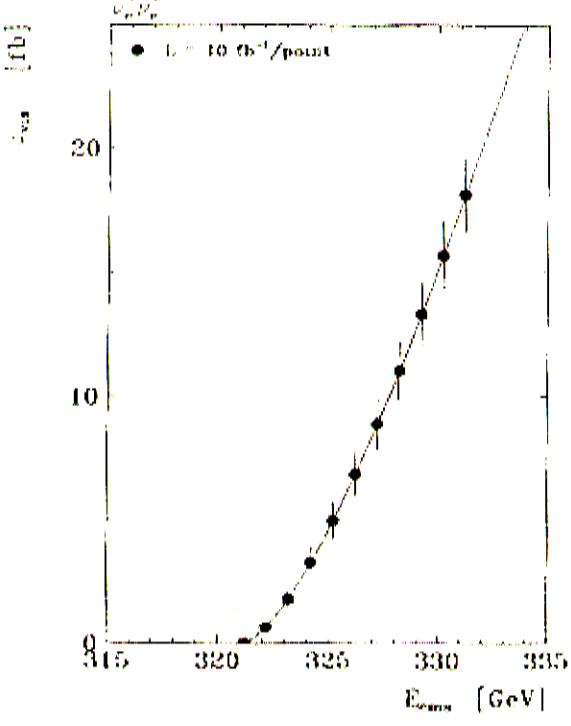


$\sqrt{s}_{fit} + 5$ GeV

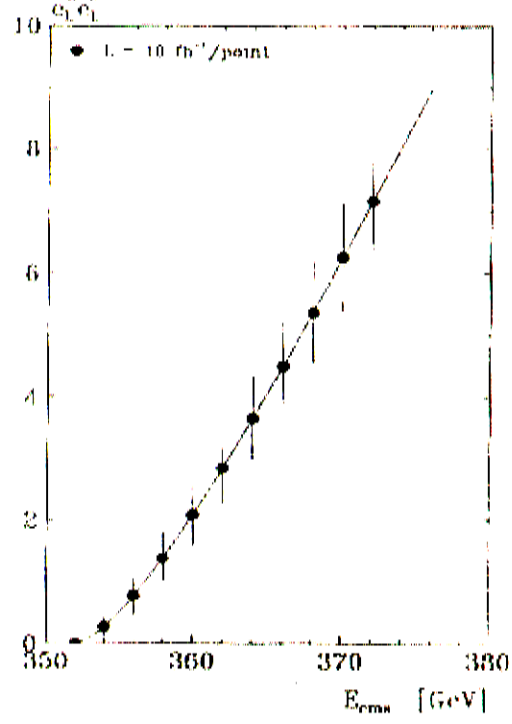
$m_{\tilde{\mu}_R} = 132.0 \pm 0.08$ GeV

$\mathcal{L} = 100$ fb^{-1}/10 *pt*

$$e^-_L e^+_R \to \tilde{\nu}_e \tilde{\nu}_e$$



$$e^-_L e^+_R \to \tilde{e}_L \tilde{e}_L$$



$m_{\tilde{\nu}_e} = 160.6 \pm 0.07$ GeV

$m_{\tilde{e}_L} = 176.0 \pm 0.18$ GeV

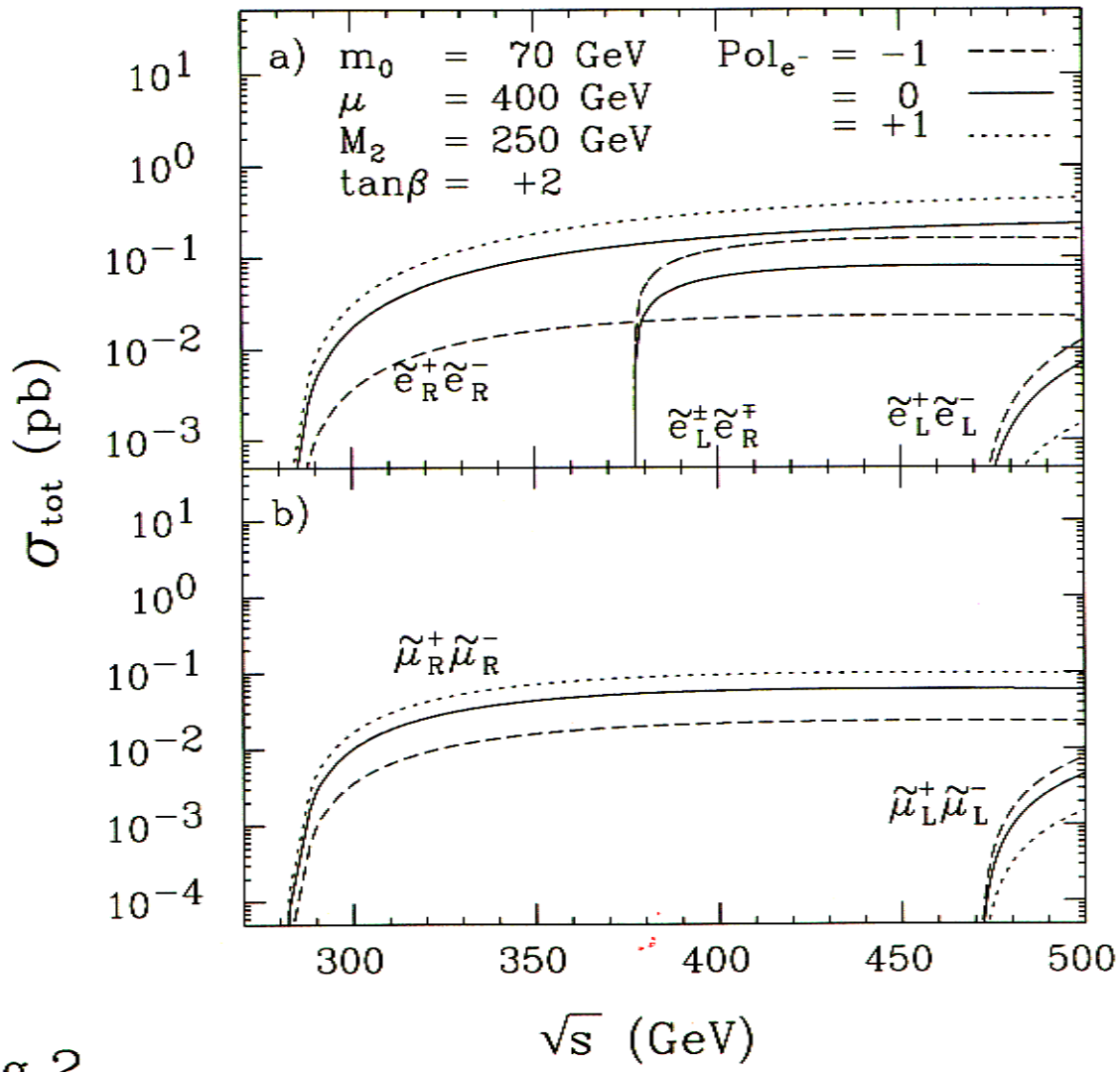


Fig.2

Tsukamoto, Fujii, HM, Yamaguchi, Okada

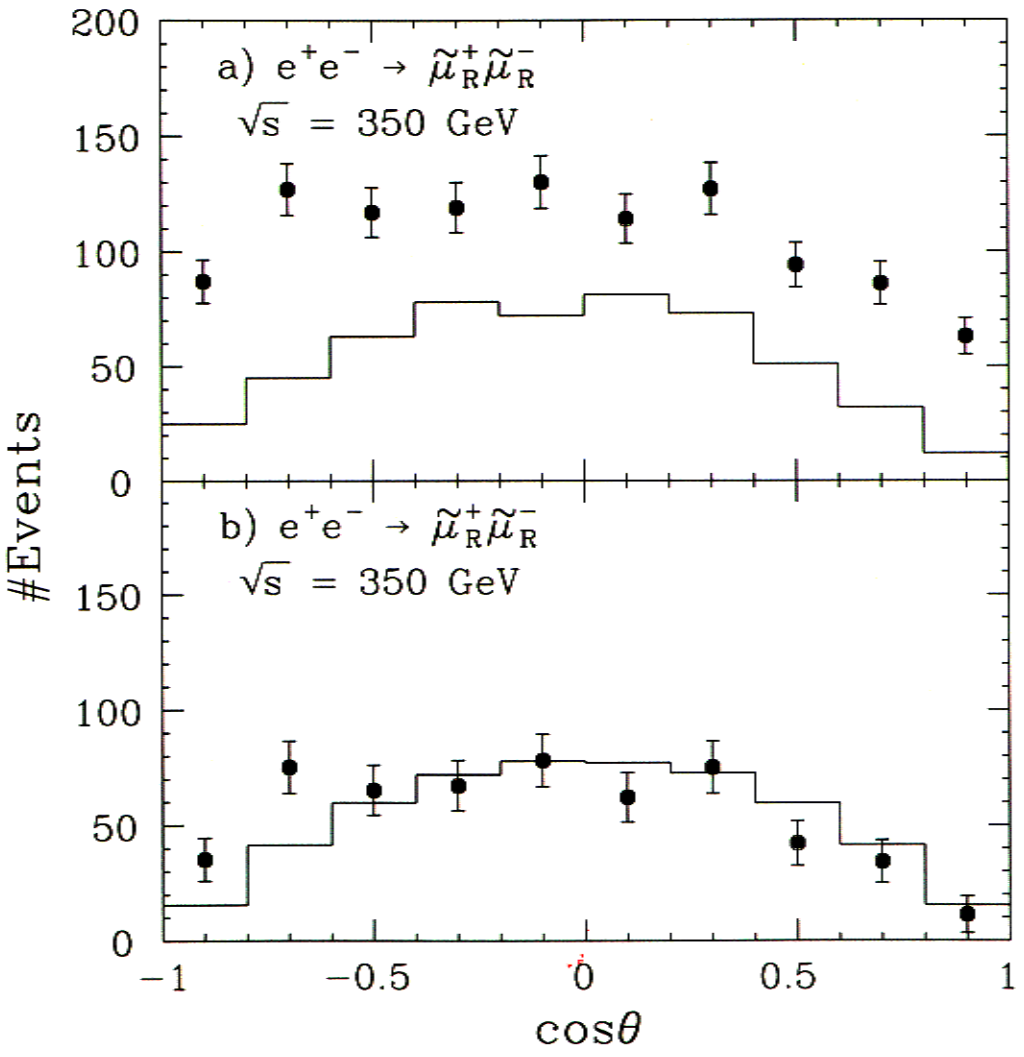
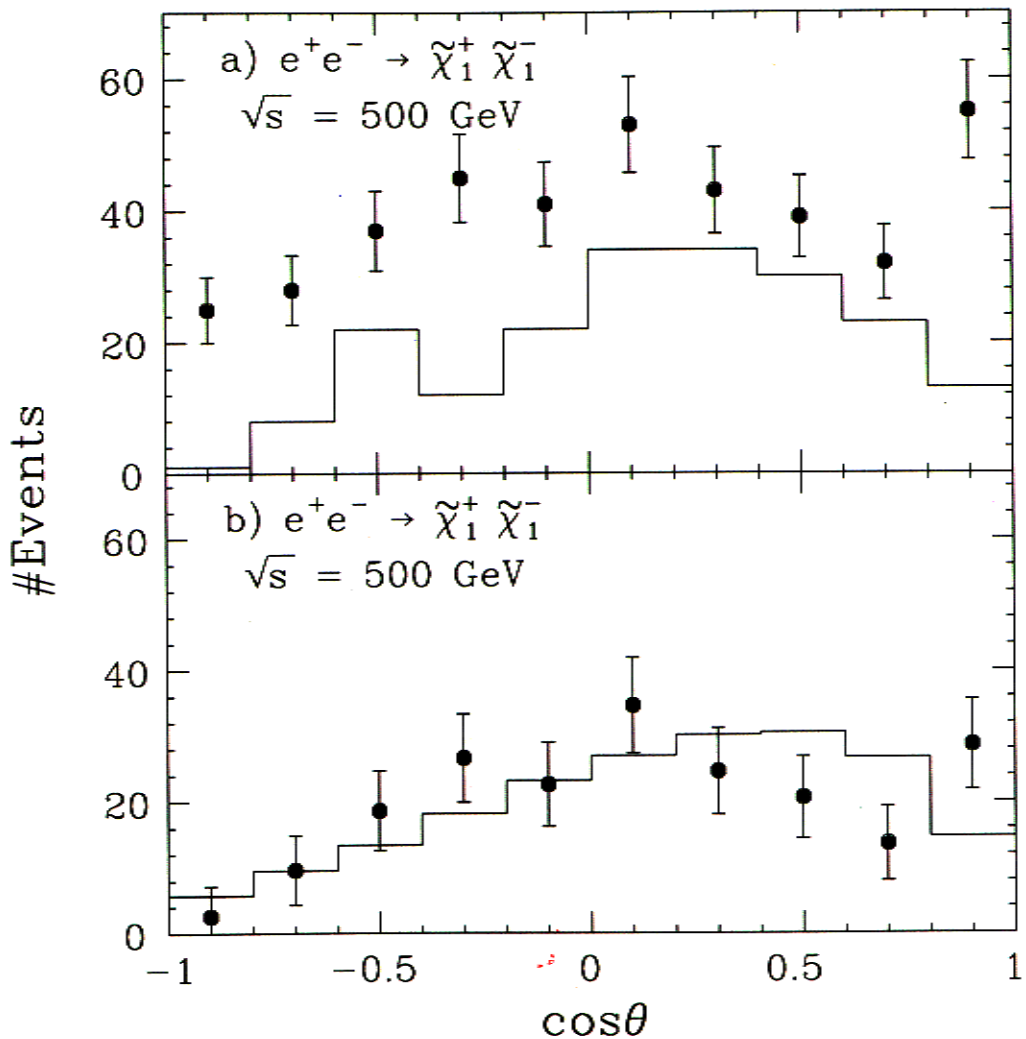


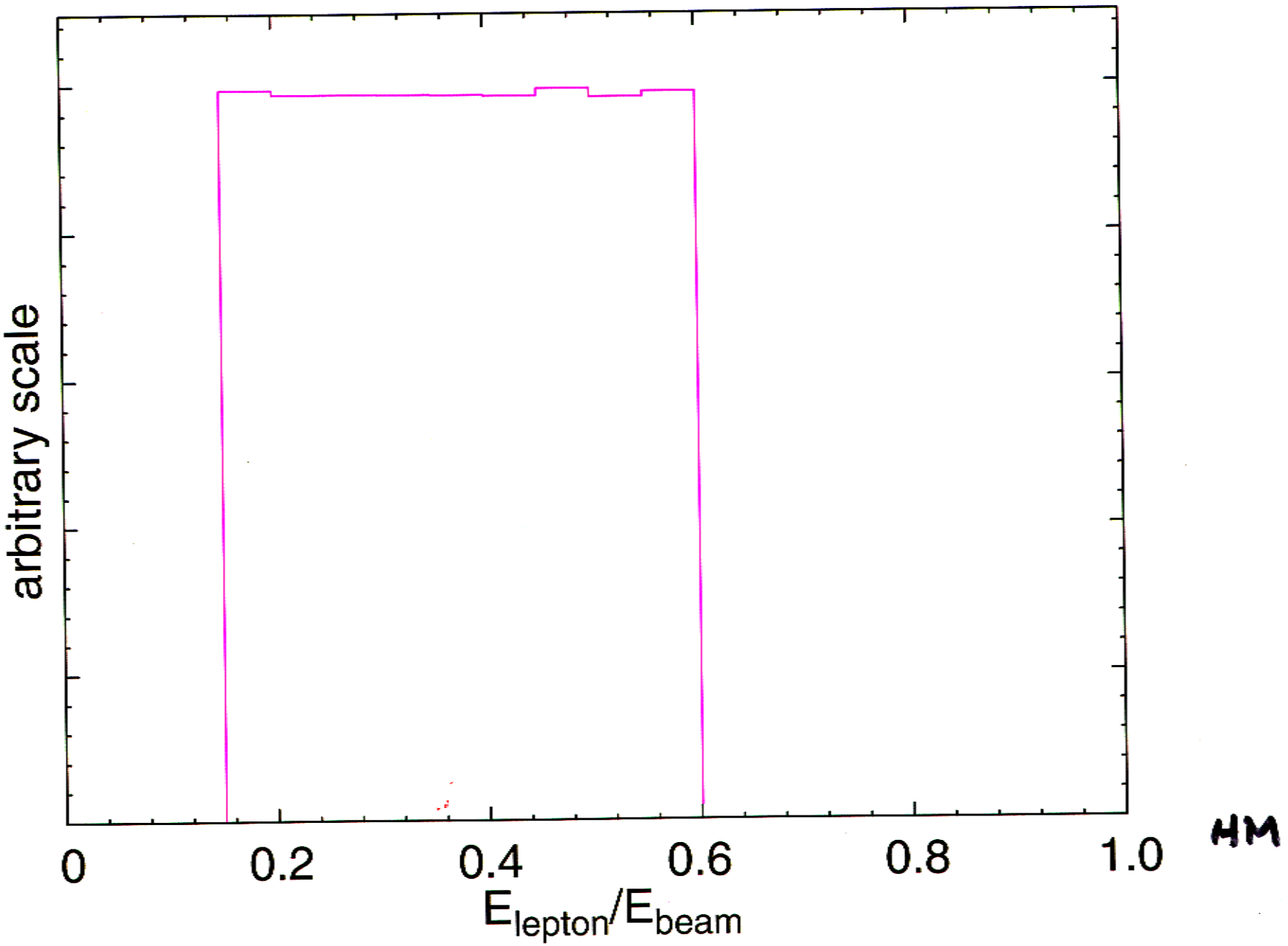
Fig.5

Tsukamoto, Fujii,
HM, Yamaguchi, Okada

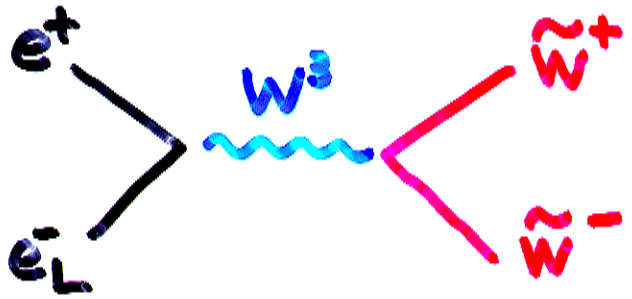


Tsukamoto, Fujii,
HM, Yamaguchi, Okada

Fig.12


arbitrary scale
0
0.2
0.4
0.6
0.8
1.0
E_lepton/E_beam
HM

TWO NEW OBSERVABLES



helicity amplitudes

$\tilde{W}^-$	$\tilde{W}^+$	$\mathcal{A}$
$-1/2$	$+1/2$	$(1+\cos\theta)$
$+1/2$	$-1/2$	$(1-\cos\theta)$
$-1/2$	$-1/2$	$\frac{m_{\tilde{W}}}{E}\sin\theta$
$+1/2$	$+1/2$	$\frac{m_{\tilde{W}}}{E}\sin\theta$

$$\begin{matrix} \cos\frac{\hat{\theta}_1}{2} e^{+i\phi_1/2} & \cos\frac{\hat{\theta}_2}{2} e^{+i\phi_2/2} \\ \sin\frac{\hat{\theta}_1}{2} e^{-i\phi_1/2} & \sin\frac{\hat{\theta}_2}{2} e^{-i\phi_2/2} \\ \cos\frac{\hat{\theta}_1}{2} e^{+i\phi_1/2} & \sin\frac{\hat{\theta}_2}{2} e^{-i\phi_2/2} \\ \sin\frac{\hat{\theta}_1}{2} e^{-i\phi_1/2} & \cos\frac{\hat{\theta}_2}{2} e^{+i\phi_2/2} \end{matrix}$$

④ correlation between

production angle Θ

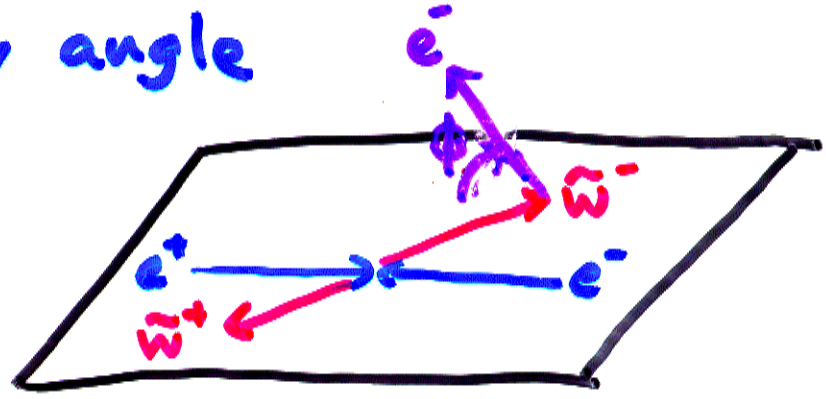
decay angles $\hat{\Theta}_1, \hat{\Theta}_2$

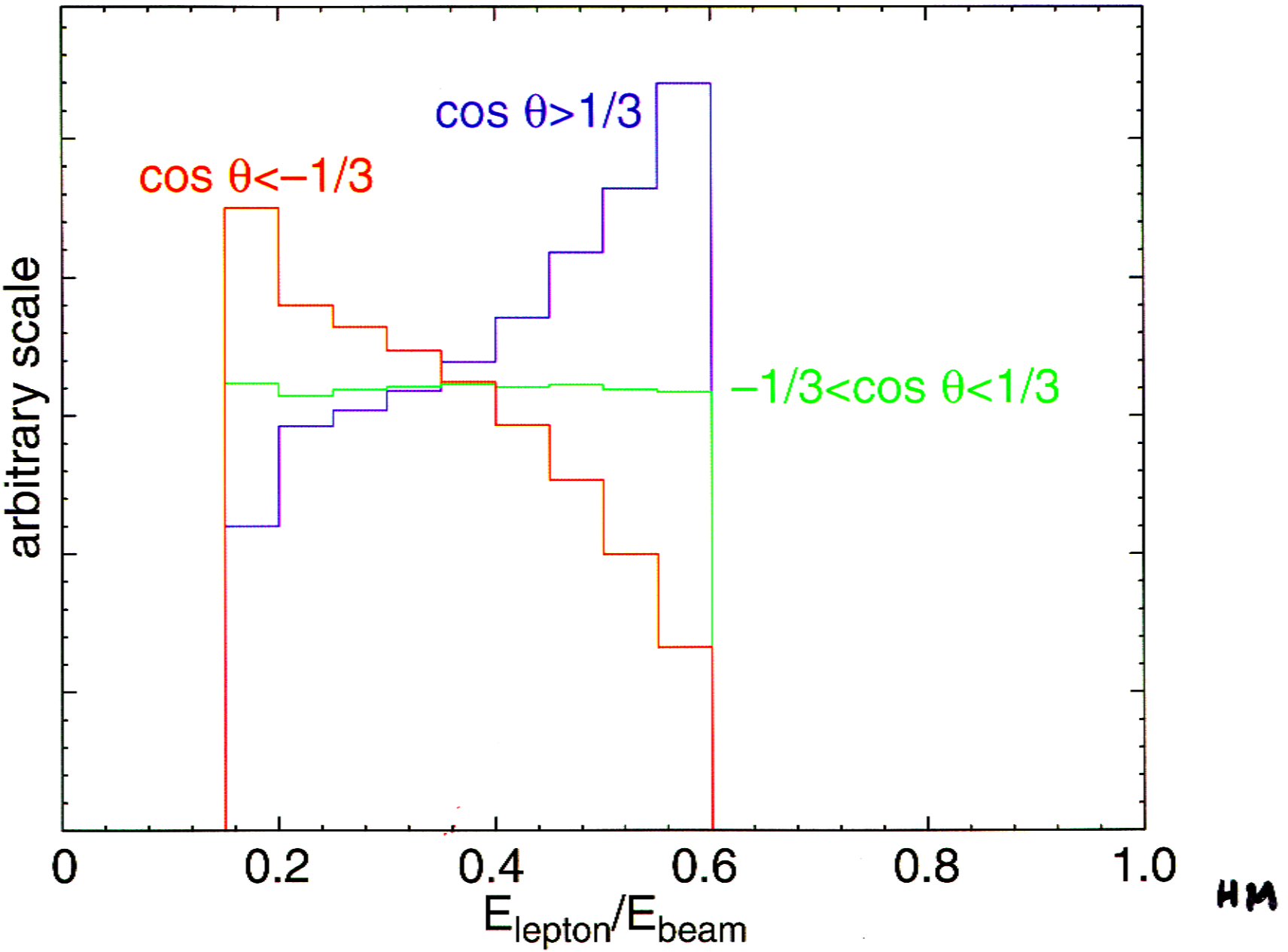
⑤ azimuthal decay angle

ϕ_1, ϕ_2

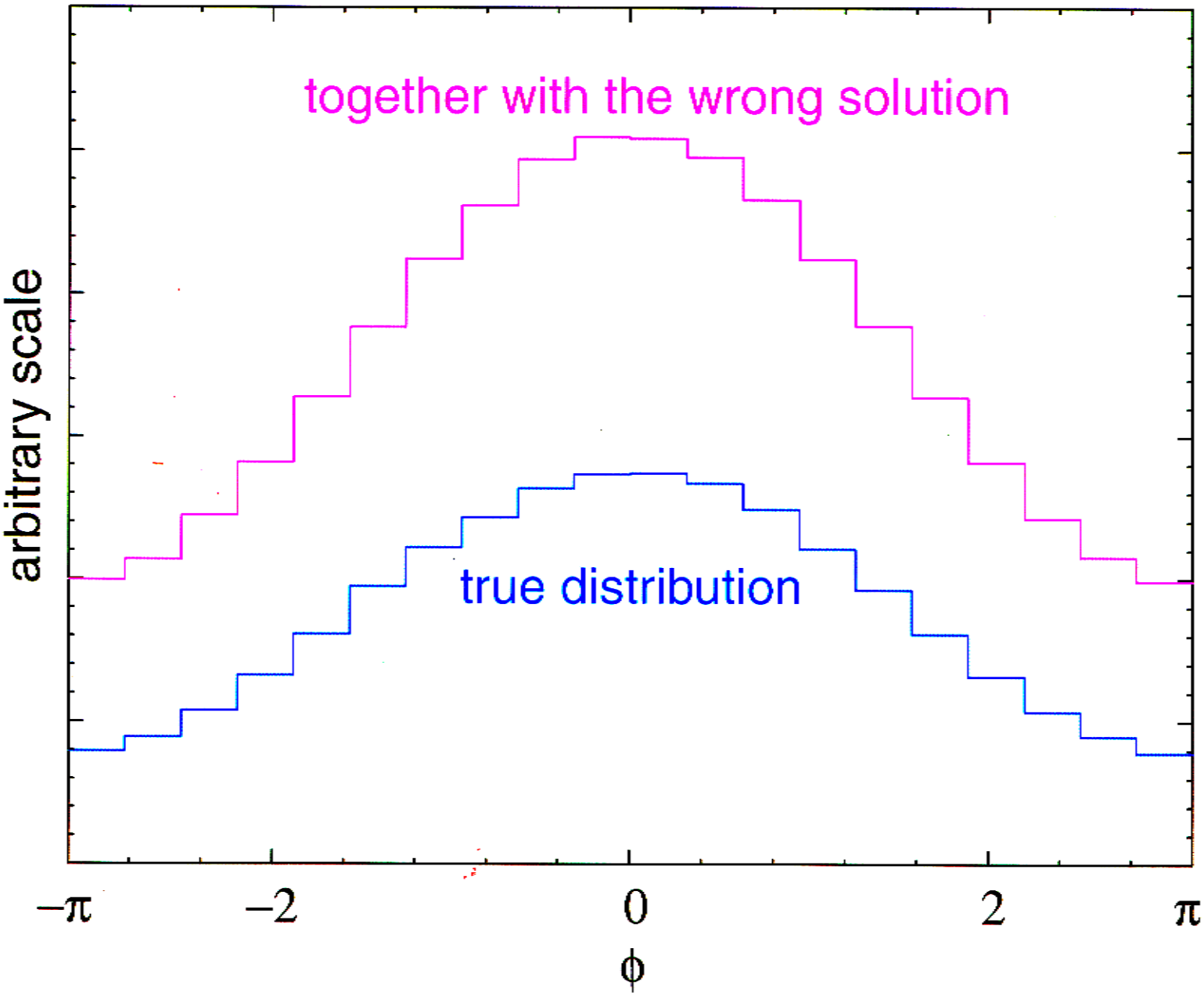
available MC

don't have this!

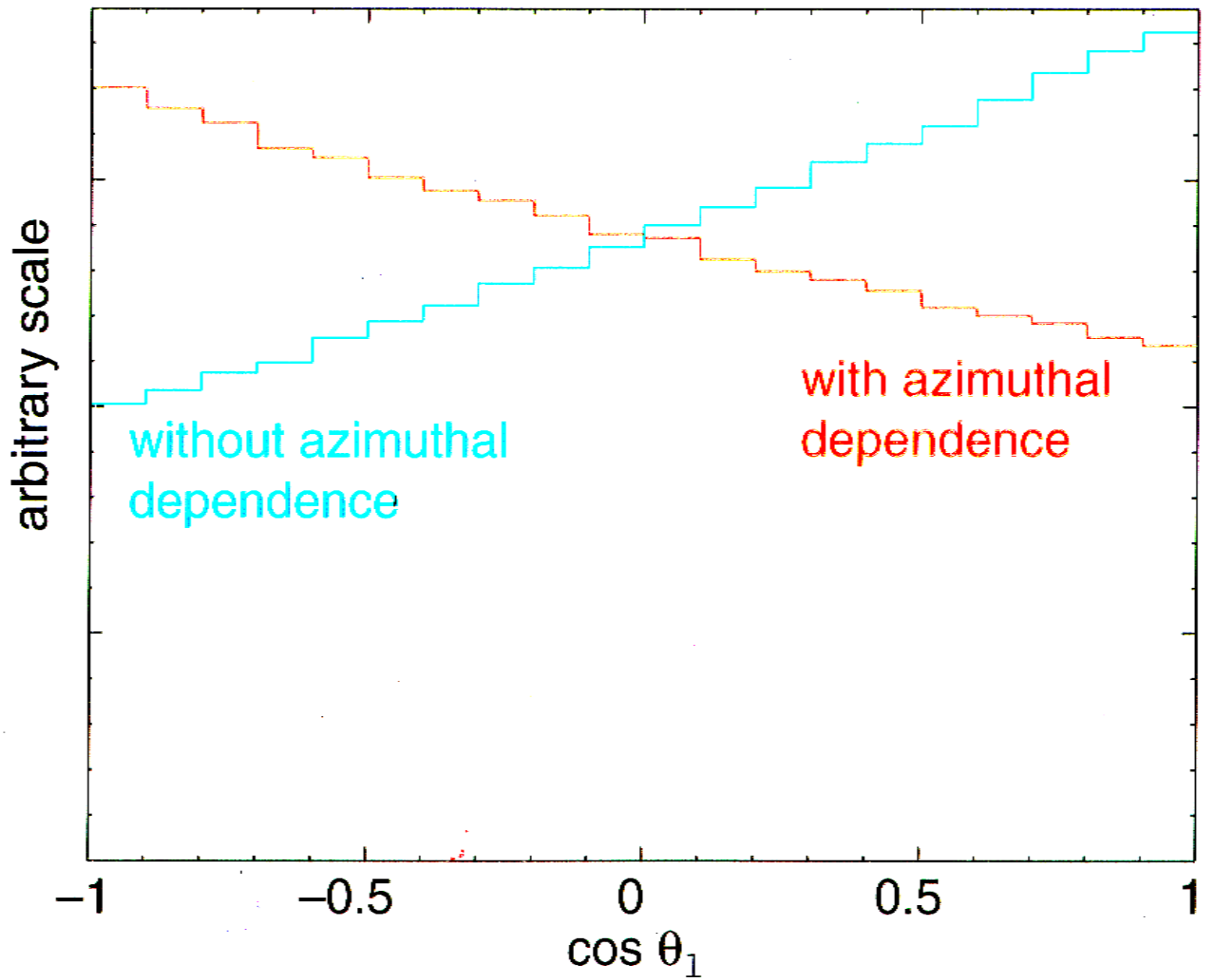


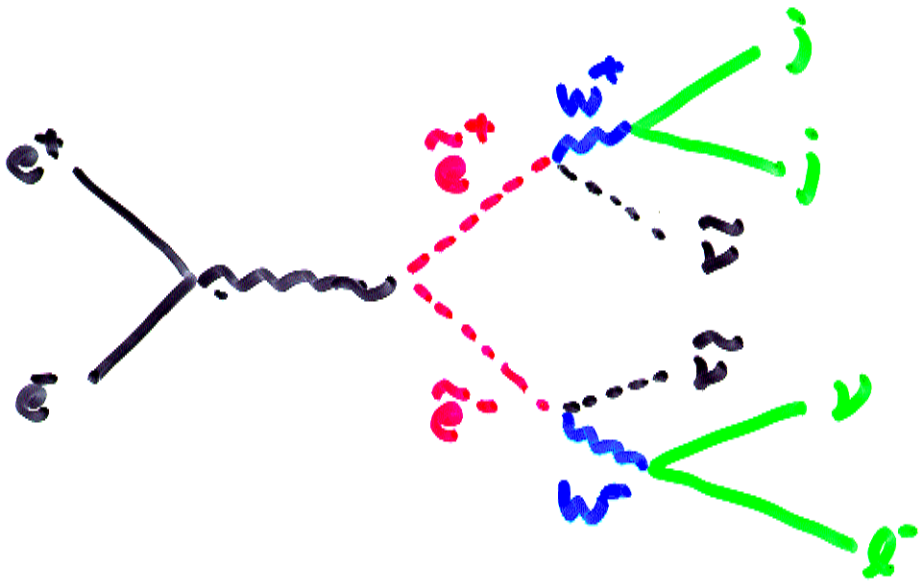

cos θ>1/3
cos θ<–1/3
–1/3<cos θ<1/3
arbitrary scale
0
0.2
0.4
0.6
0.8
1.0
E_lepton/E_beam

HM

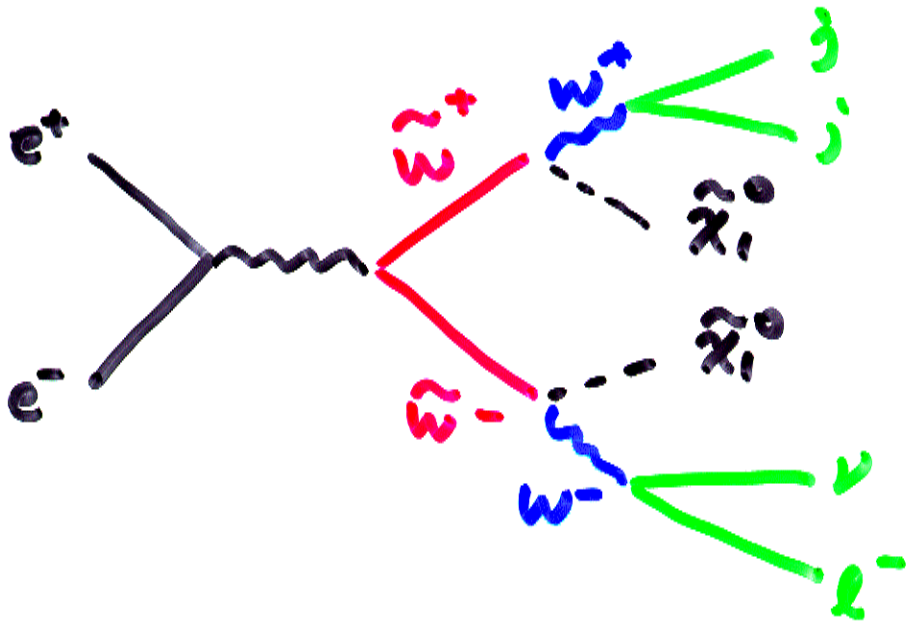

together with the wrong solution
true distribution
arbitrary scale
−π
−2
0
2
π
ϕ

HM


arbitrary scale
without azimuthal dependence
with azimuthal dependence
−1
−0.5
0
0.5
1
cos θ1



cf.



To be able to state in physics textbooks that

Nature is supersymmetric

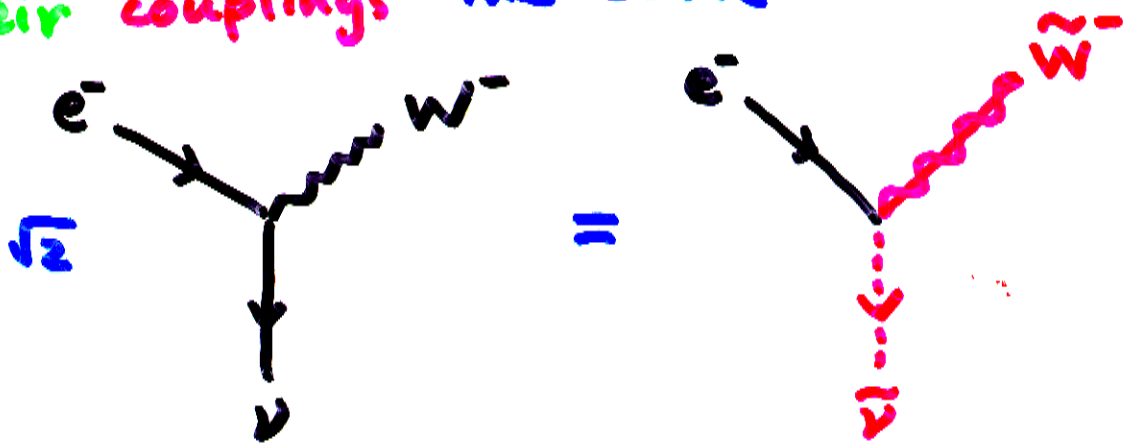
we have to show

① every particle has a partner

② their spins differ by ½

③ their gauge quantum numbers the same

④ their couplings the same



20 – 30 years program

reminiscent of hadron resonances

PDG 2014

.....

$\tilde{e}_R$ 0 $I_3 = 0$ $Y = -1$

MASS

OUR AVERAGE 212.3 ± 4.5

S = 1.5

BRANCHING FRACTION

$e^- \tilde{\chi}_1^0$ 100 %

$\tilde{e}_L$ 0 $I_3 = -\frac{1}{2}$ $Y = -\frac{1}{2}$

MASS

OUR AVERAGE 324.1 ± 8.2

BRANCHING FRACTION

$e^- \tilde{\chi}_1^0$	82 %
$e^- jj \tilde{\chi}_1^0$	3 %
$e^- \mu^+\mu^- \tilde{\chi}_1^0$	1 %
$e^- \tau^+\tau^- \tilde{\chi}_1^0$	seen

Conclusion

Even with a LC, no guarantee

that we can completely understand

the electroweak physics

but will certainly do a lot better

with a LC than without

Need one!