# Focus Point Phenomenology

## "LCC2" Benchmark studies

## Linear Collider Cosmology Connection


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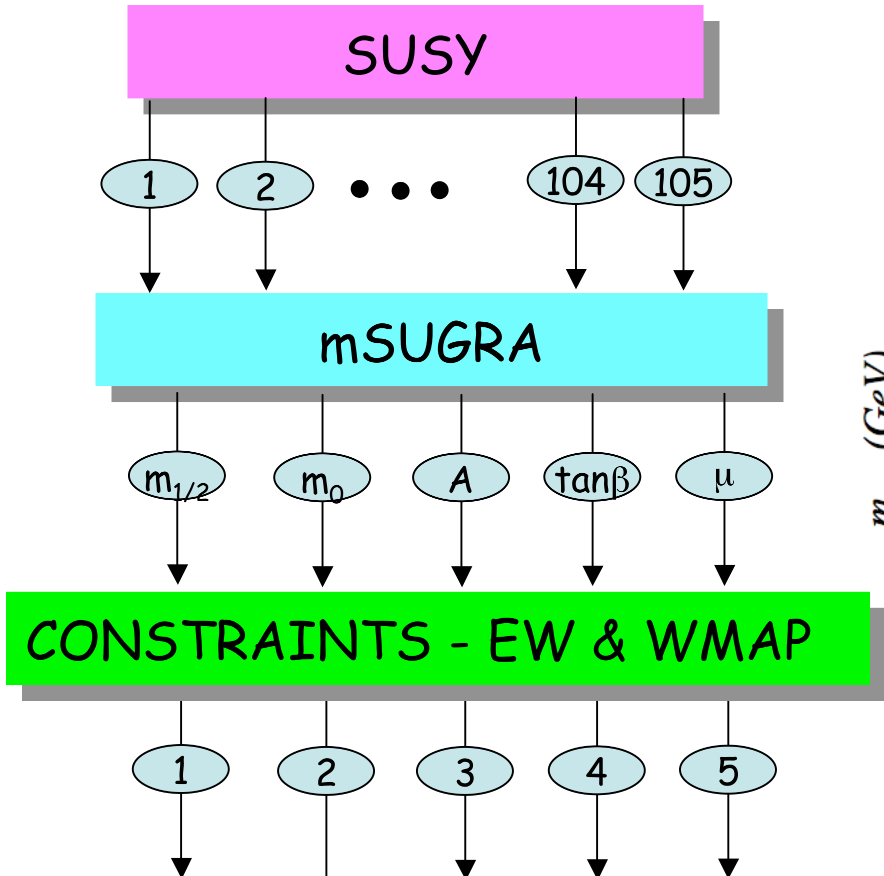
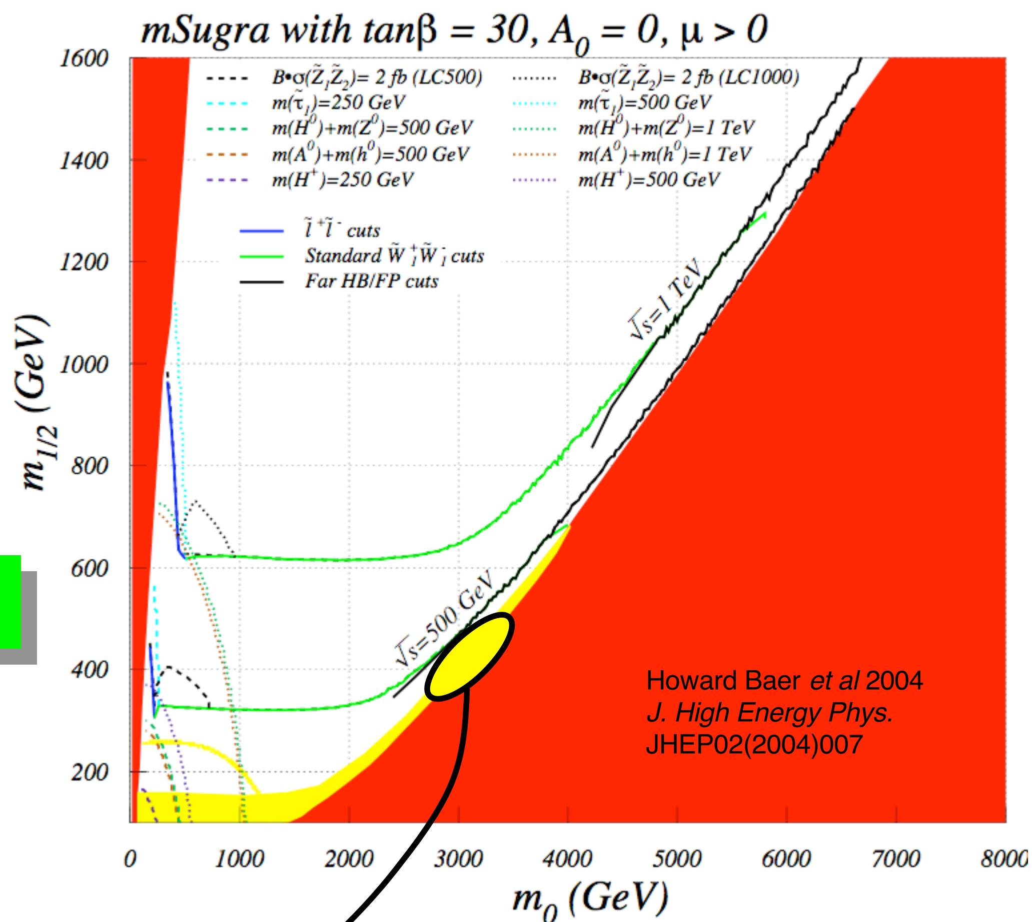
# Focus Point Benchmark LCC-2




| | |
|---|---|
| $m_0$ = 3280 | $m_{1/2}$ = 300 |
| A = 0 | tanβ = 10 |
| sgn(μ) = + | ($m_t$ = 175) |

# Cosmological Connections

ILC Experiment

↓

$\sigma_L, \quad \sigma_R, \quad d\Gamma/dM, \quad d\Gamma/dE, \ldots$

↓

$m_+, \quad m_0, \quad \zeta = (v_+^2 - a_+^2)/(v_+^2 + a_+^2), \quad v_0^2 + a_0^2, \ldots$

↓

$M1, \quad M2, \quad A, \quad \tan\beta, \quad \mu, \ldots$

↓

$\Omega_{cdm} h^2$

↑

WMAP, Planck,...

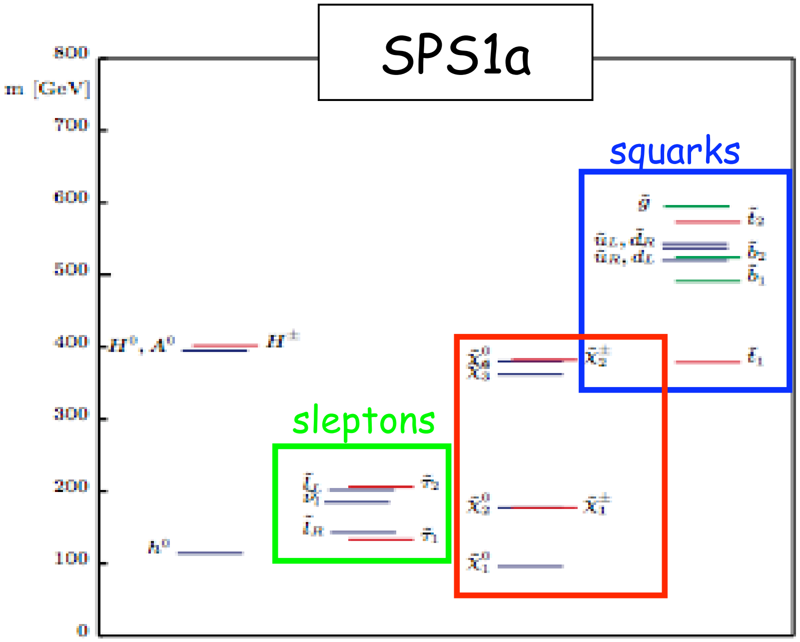
# Detector Benchmarking

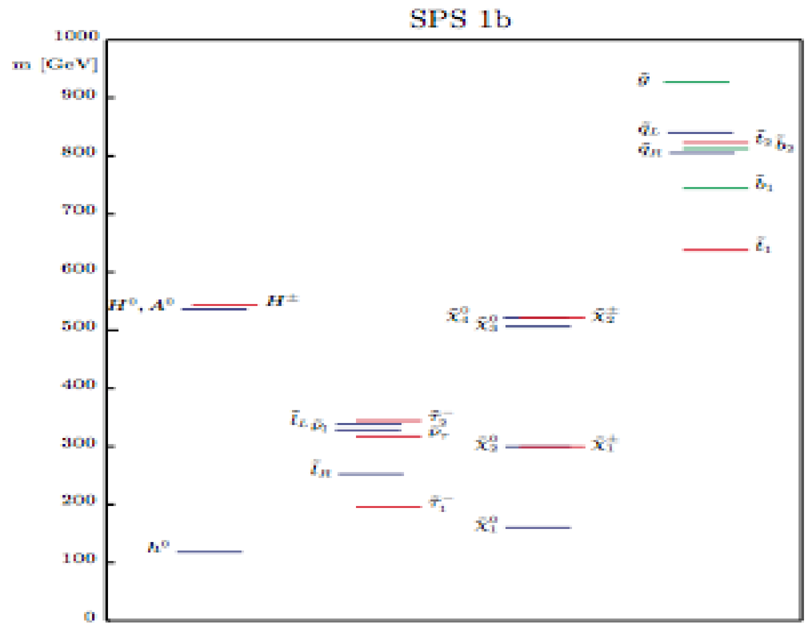
Tim Barklow's List

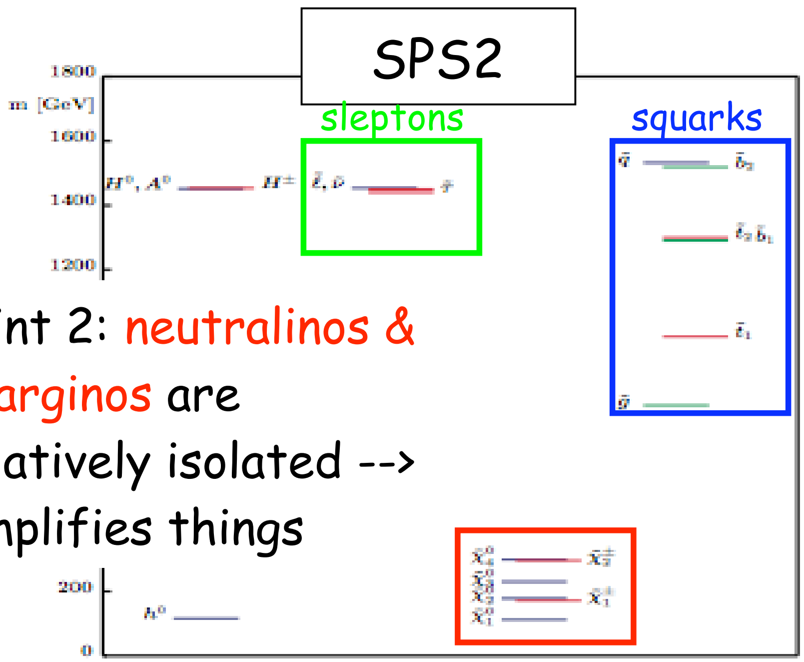
Table II: Benchmark reactions for the evaluation of ILC detectors

| | Process and Final states | Energy (TeV) | Observables | Target Accuracy | Detector Challenge | Notes |
|---|---|---|---|---|---|---|
| *Higgs* | $ee \to Z^0h^0 \to \ell^+\ell^-X$ | 0.35 | $M_{recoil}$, $\sigma_{Zh}$, $BR_{bb}$ | [illegible]$_{Zh}$ = 2.5%, $\delta BR_{bb} = 1\%$ | T | {1} |
| | $ee \to Z^0h^0, h^0 \to b\bar{b}/c\bar{c}/\tau\tau$ | 0.35 | Jet flavour [illegible] | [illegible]$_h$=40 MeV, $\delta(\sigma_{Zh} \times BR)$=1%/7%/5% | V | {2} |
| | $ee \to Z^0h^0, h^0 \to WW^*$ | 0.35 | M[illegible] | [illegible]$(\sigma_{Zh} \times BR_{WW^*})$=5% | C | {3} |
| | $ee \to Z^0h^0/h^0\nu\bar{\nu}, h^0 \to \gamma\gamma$ | 1.0 | [illegible] | $\delta(\sigma_{Zh} \times BR_{\gamma\gamma})$=5% | C | {4} |
| | $ee \to Z^0h^0, h^0\nu\bar{\nu}, h \to \mu^+\mu$[illegible] | [illegible] | [illegible] | $5\sigma$ Evidence for $m_h$ = 120 GeV | T | {5} |
| | $ee \to Z^0h^0, h^0 \to invisible$ | [illegible] | [illegible]$_{qqE}$ | $5\sigma$ Evidence for $BR_{invisible}$=2.5% | C | {6} |
| | $ee \to h^0\nu\bar{\nu}$ | 0.5 | $\sigma_{bb\nu\nu}$, $M_{bb}$ | $\delta(\sigma_{\nu\nu h} \times BR_{bb}) = 1\%$ | C | {7} |
| | $ee \to t\bar{t}h^0$ | 1.0 | $\sigma_{tth}$ | $\delta g_{tth}$=5% | C | {8} |
| | $ee \to Z^0h^0h^0,\ h^0h^0\nu\bar{\nu}$ | 0.5/1.0 | $\sigma_{Zhh}$, $\sigma_{\nu\nu hh}$, $M_{hh}$ | $\delta g_{hhh}$=20/10% | C | {9} |
| *SSB* | $ee \to W^+W^-$ | 0.5 | | $\Delta\kappa_\gamma, \lambda_\gamma = 2 \cdot 10^{-4}$ | V | {10} |
| | $ee \to W^+W^-\nu\bar{\nu}/Z^0Z^0\nu\bar{\nu}$ | 1.0 | $\sigma$ | $\Lambda_{*4}, \Lambda_{*5}$ = 3 TeV | C | {11} |
| *SUSY* | $ee \to \tilde{e}^+_R\tilde{e}^-_R$ (Point 1) | 0.5 | $E_e$ | $\delta m_{\tilde{\chi}^0_1}$=50 MeV | T | {12} |
| | $ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1,\ \tilde{\chi}^+_1\tilde{\chi}^-_1$ (Point 1) | 0.5 | $E_\pi$, $E_{2\pi}$, $E_{3\pi}$ | $\delta(m_{\tilde{\tau}_1} - m_{\tilde{\chi}^0_1})$=200 MeV | T | {13} |
| | $ee \to \tilde{t}_1\tilde{t}_1$ (Point 1) | 1.0 | | $\delta m_{\tilde{t}_1}$=2 GeV | | {14} |
| *-CDM* | $ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1,\ \tilde{\chi}^+_1\tilde{\chi}^-_1$ (Point 3) | 0.5 | | $\delta m_{\tilde{\tau}_1}$=1 GeV, $\delta m_{\tilde{\chi}^0_1}$=500 MeV | F | {15} |
| | $ee \to \tilde{\chi}^0_2\tilde{\chi}^0_3,\ \tilde{\chi}^+_1\tilde{\chi}^-_1$ (Point 2) | 0.5 | $M_{jj}$ in $jj\not{E}$, $M_{\ell\ell}$ in $jj\ell\ell\not{E}$ | $\delta\sigma_{\chi 2\chi 3}$ = 4%, $\delta(m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1})$= 500 MeV | C | {16} |
| | $ee \to \tilde{\chi}^+_1\tilde{\chi}^-_1/\tilde{\chi}^0_2\tilde{\chi}^0_3$ (Point 5) | 0.5/1.0 | $ZZ\not{E}$, $WW\not{E}$ | $\delta\sigma_{\tilde{\chi}\tilde{\chi}}$=10%, $\delta m_{\tilde{\chi}^0_3}$ [illegible] $_{\tilde{\chi}^0_1}$=2 GeV | C | {17} |
| | $ee \to H^0A^0 \to b\bar{b}b\bar{b}$ (Point 4) | 1.0 | Mass constrained $M_{bb}$ | $\delta m_A$=1 GeV | C | {18} |
| *-alternative SUSY breaking* | $ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1$ (Point 6) | 0.5 | Heavy stable particle | $\delta m_{\tilde{\tau}_1}$ | T | {19} |
| | $\tilde{\chi}^0_1 \to \gamma + \not{E}$ (Point 7) | 0.5 | Non-pointing $\gamma$ | $\delta c\tau$=10% | C | {20} |
| | $\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 + \pi^\pm_{soft}$ (Point 8) | 0.5 | Soft $\pi^\pm$ above $\gamma\gamma$ bkgd | $5\sigma$ Evidence for $\Delta\tilde{m}$=0.2-2 GeV | F | {21} |
| *Precision SM* | $ee \to t\bar{t} \to 6\ jets$ | 1.0 | | $5\sigma$ Sensitivity for $(g-2)_t/2 \le 10^{-3}$ | V | {22} |
| | $ee \to f\bar{f}\ (f = e, \mu, \tau; b, c)$ | 1.0 | $\sigma_{f\bar{f}}$, $A_{FB}$, $A_{LR}$ | $5\sigma$ Sensitivity to $M(Z_{LR})$ = 7 TeV | V | {23} |
| *New Physics* | $ee \to \gamma G$ (ADD) | 1.0 | $\sigma(\gamma + \not{E})$ | $5\sigma$ Sensitivity | C | {24} |
| | $ee \to KK \to f\bar{f}$ (RS) | 1.0 | | | T | {25} |
| *Energy/Lumi Meas.* | $ee \to ee_{fwd}$ | 0.3/1.0 | | $\delta m_{top}$=50 MeV | T | {26} |
| | $ee \to Z^0\gamma$ | 0.5/1.0 | | | T | {27} |

# *Snowmass Points and Slopes* Benchmarks



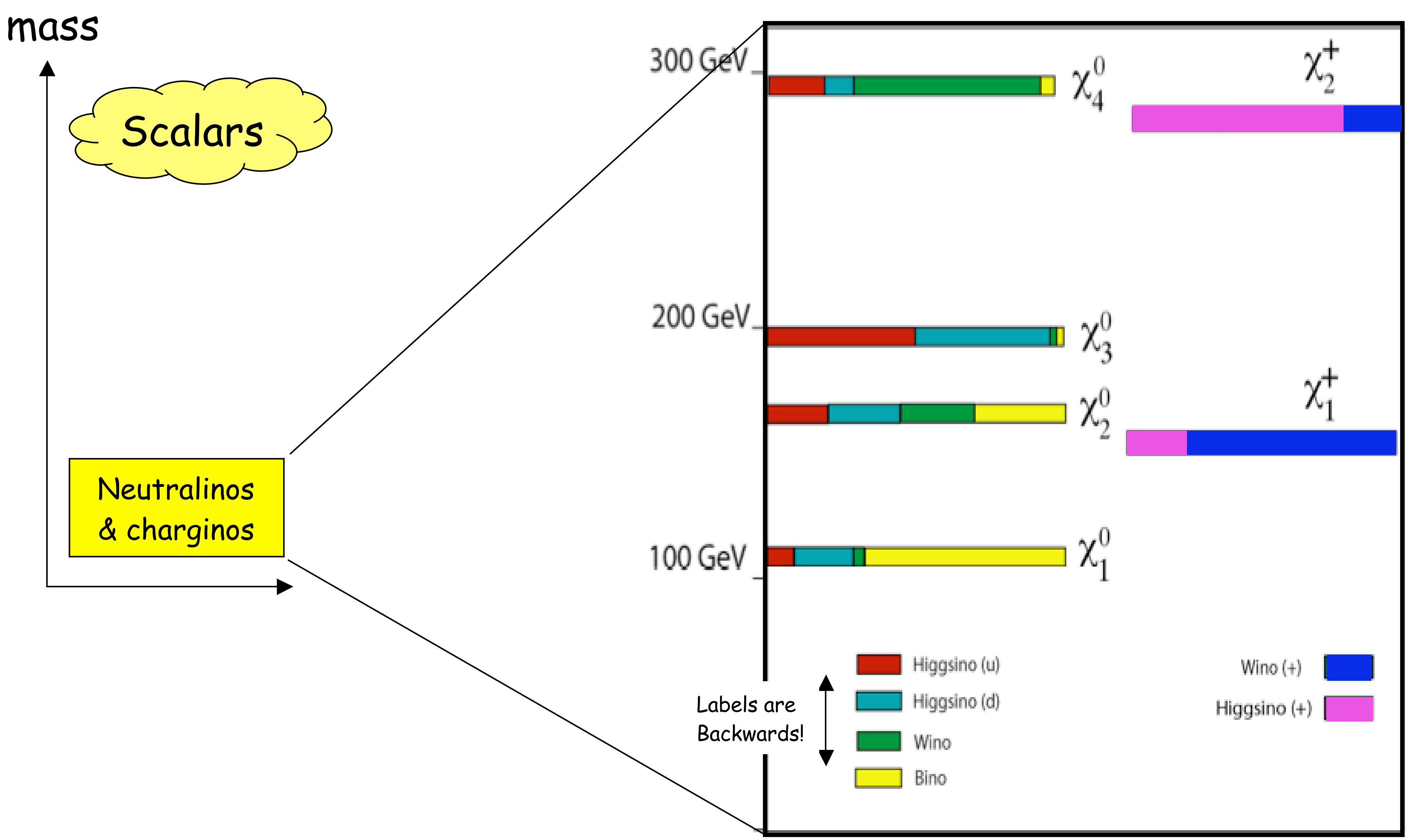




Point 2: neutralinos & charginos are relatively isolated --> simplifies things

Since the scalars are heavy in this scenario, they decouple.

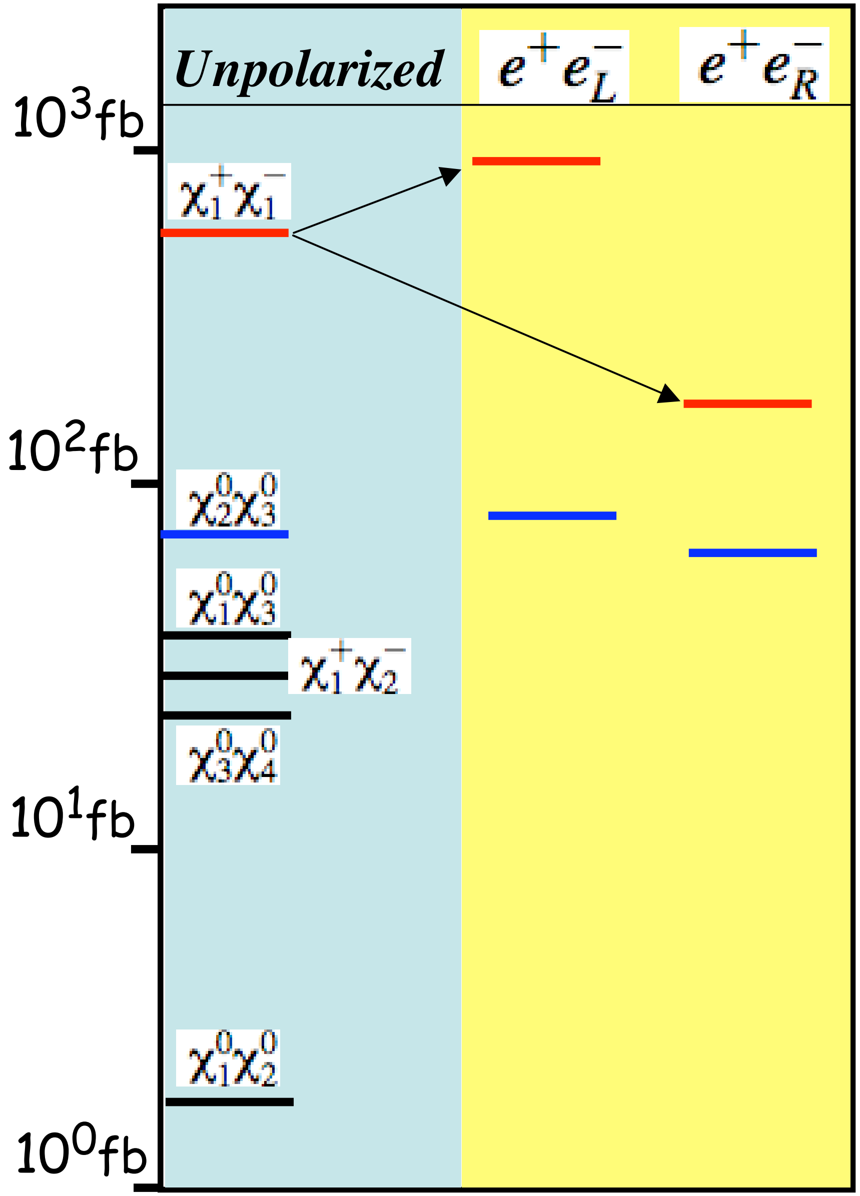
As a result, neutralino and chargino production and decay mechanisms are rather simple, with usually only one contributing amplitude.

# Focus Point Spectrum

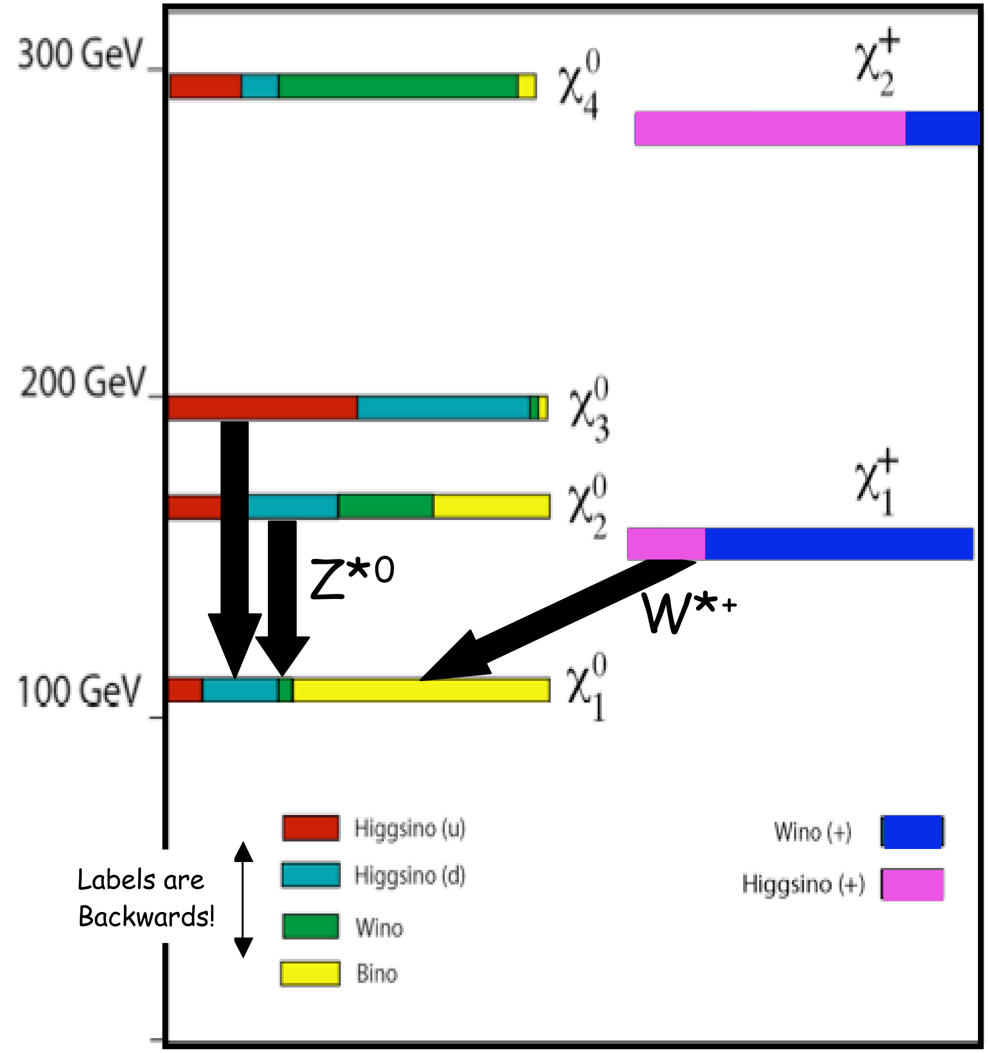



Spectrum computed by ISAJET

# Production and Decay



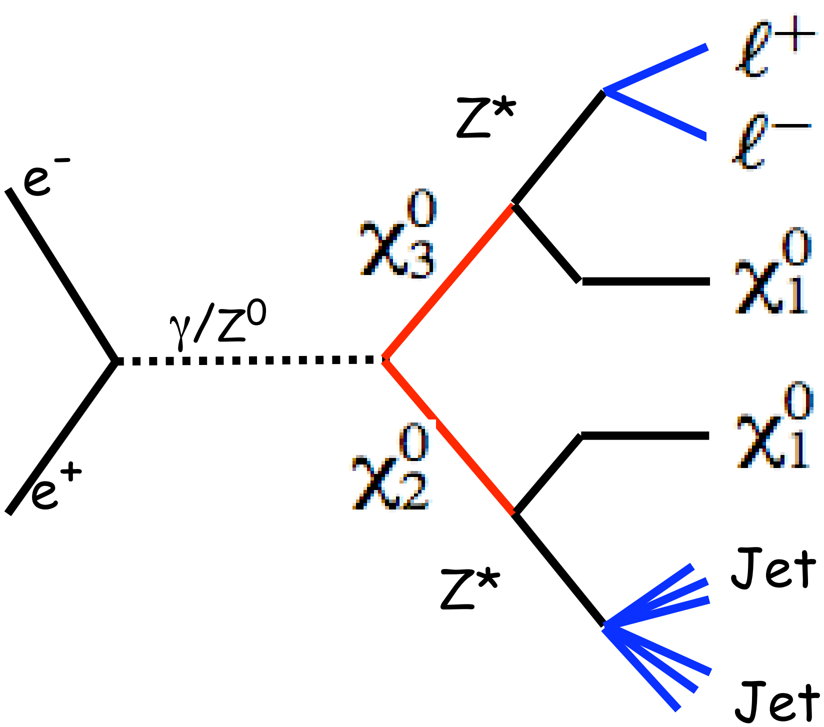

Cross sections computed by ISAJET




Single channel decay mechanism is a feature of this benchmark point.

# Studies Presented at LCWS-05

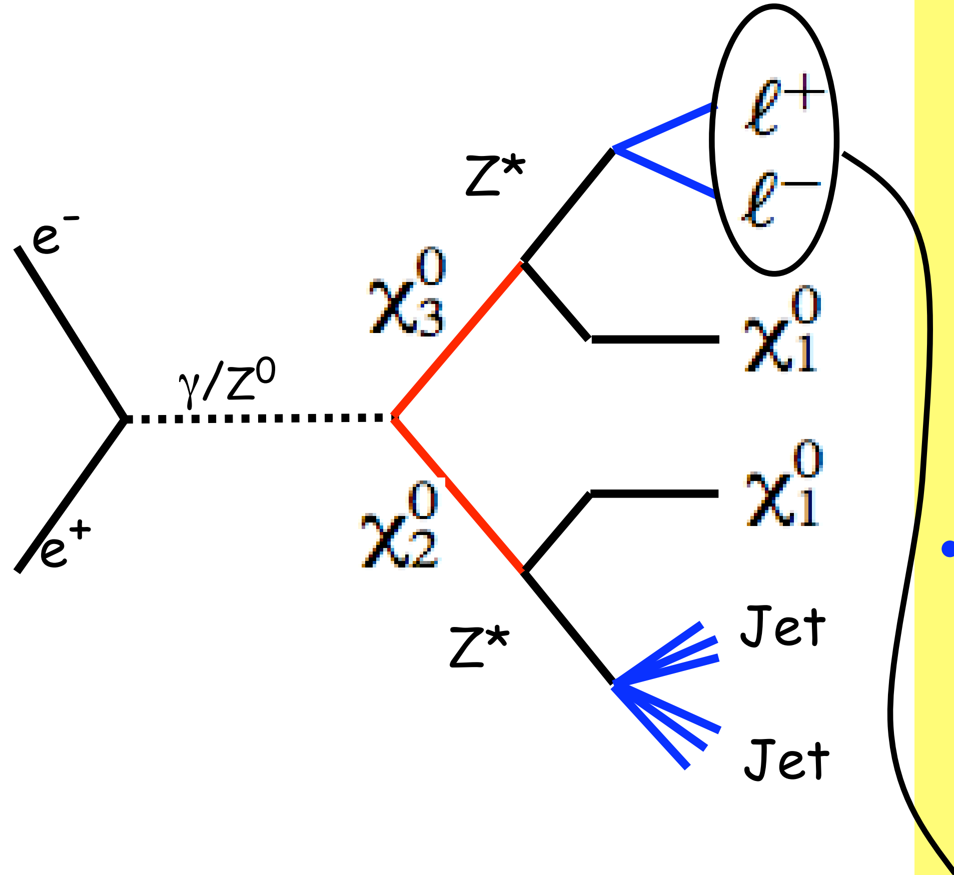
$$e^+e^- \rightarrow \chi_2^0 \chi_3^0$$




- Talks:
  - Richard Gray
    - hep-ex/0507008
  - Andreas Birkedal
    - hep-ph/0507214

# Studies Presented at LCWS-05

$$e^+e^- \rightarrow \chi_2^0\chi_3^0$$




- Talks:
  - Richard Gray
    - hep-ex/0507008
  - Andreas Birkedal
    - hep-ph/0507214
- Results (500fb$^{-1}$):

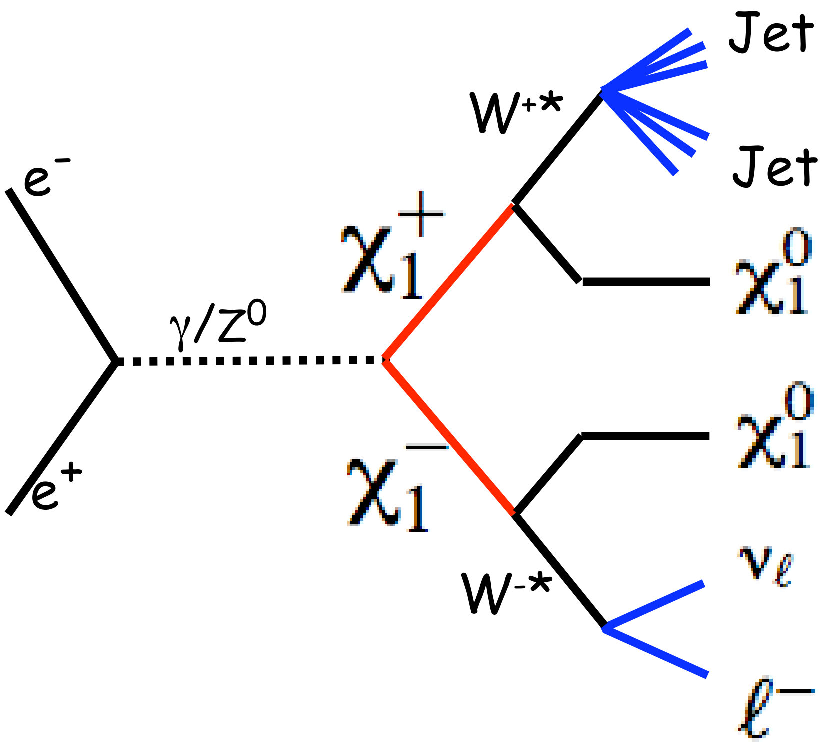
$$m(\chi_3^0) - m(\chi_1^0) = 82.3 \pm 0.2$$

$$m(\chi_2^0) - m(\chi_1^0) = 58.8 \pm 0.3$$

$$m(\chi_1^0) = 108.3 \pm 1.0$$

$$\frac{\varepsilon_2\varepsilon_3}{\varepsilon_1} = +- \qquad (13\sigma)$$

# Mode du jour: $e^+e^- \rightarrow \chi_1^+\chi_1^-$



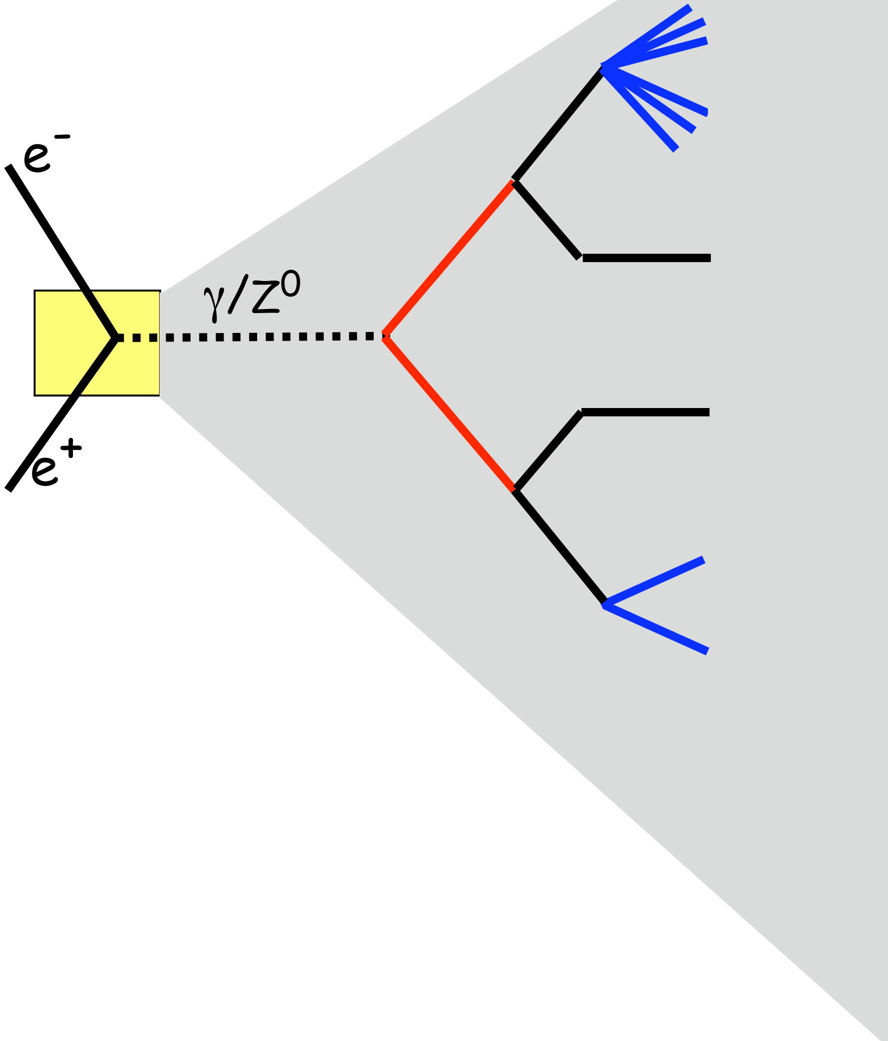

- poorer resolution
- More missing energy
- Fewer visible leptons

But:

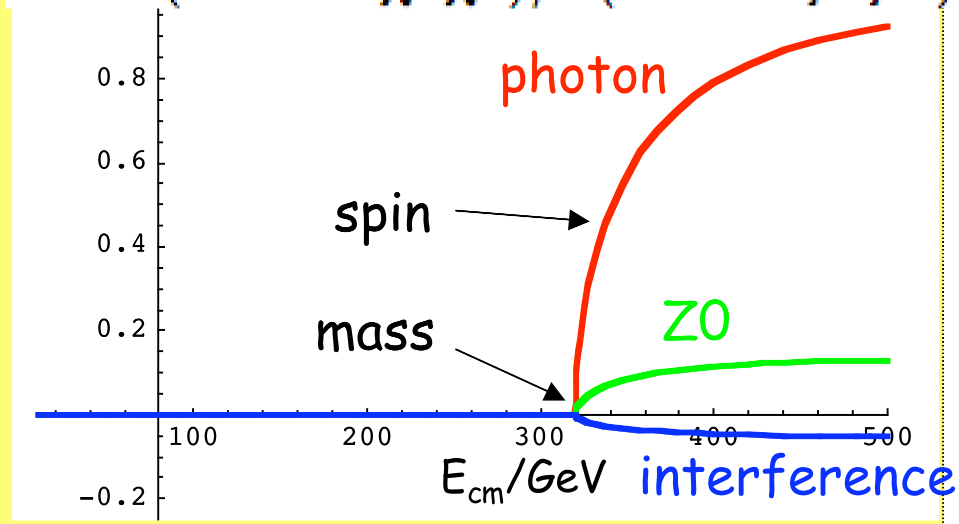
- much larger cross section
- lepton sign tags chargino (maybe useful later?)

# Production

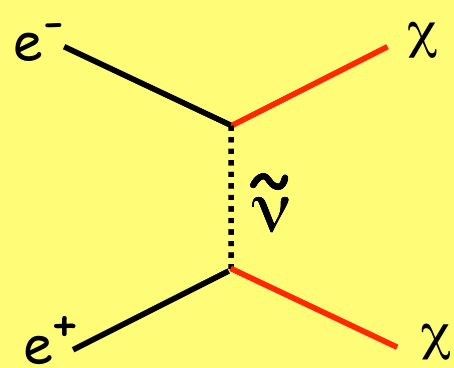
$$e^+e^- \to \chi_1^+\chi_1^-$$




$$R \equiv \sigma(e^+e^- \to \chi^+\chi^-)/\sigma(e^+e^- \to \mu^+\mu^-)$$

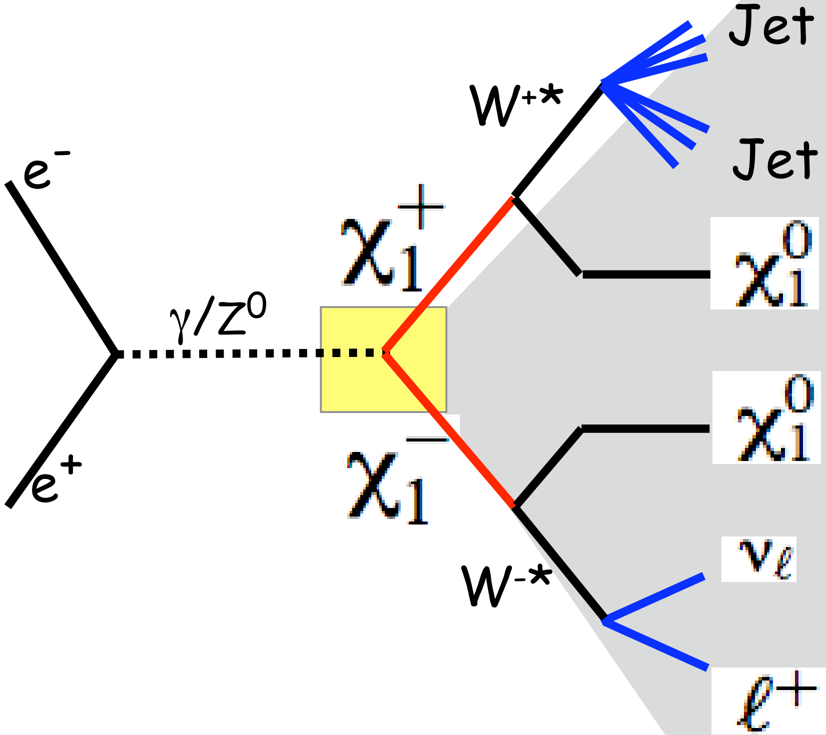



Note that possible t-channel term is suppressed in *this* benchmark point (large sneutrino mass):




$$\sim \frac{1}{t - M_{\tilde{\nu}}^2}$$

# Production: *The $\chi_1^+\chi_1^-(Z^0,\gamma)$ vertex*




Yield: $\sigma$

$$\frac{ig}{2\cos\theta_W}\gamma^\mu\left[O'^L_{11}(1-\gamma_5)+O'^R_{11}(1+\gamma_5)\right]$$

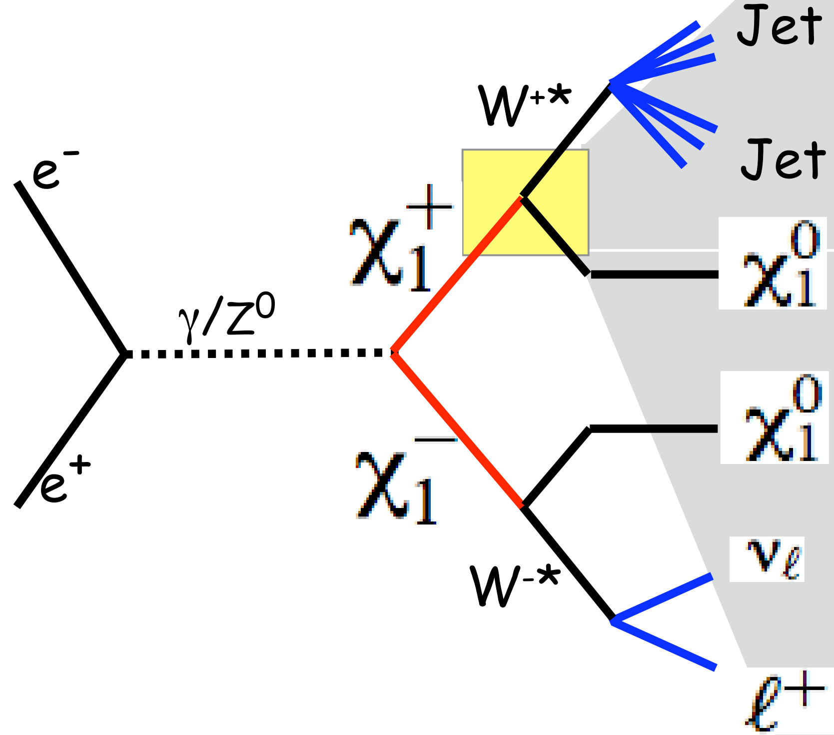
$M_2$, $\mu$, $\tan\beta$

(a) for photon coupling, R=L

(b) for Z0 coupling R≠L, but in this case (R-L)/(R+L) ~ -0.09. Afb is small.

(C) $\chi$+– wino and higgsino components couple differently; results in significant beam polarization dependence.

# Decay: *The* $\chi_1^+\chi_1^0 W^{*+}$ *vertex*




Kinematic distributions
$d\Gamma/dM$, $d\Gamma/dE$

↓

$$\frac{ig}{2}\left[O_{11}^{L}(1-\gamma_5)+O_{11}^{R}(1+\gamma_5)\right]$$

↓

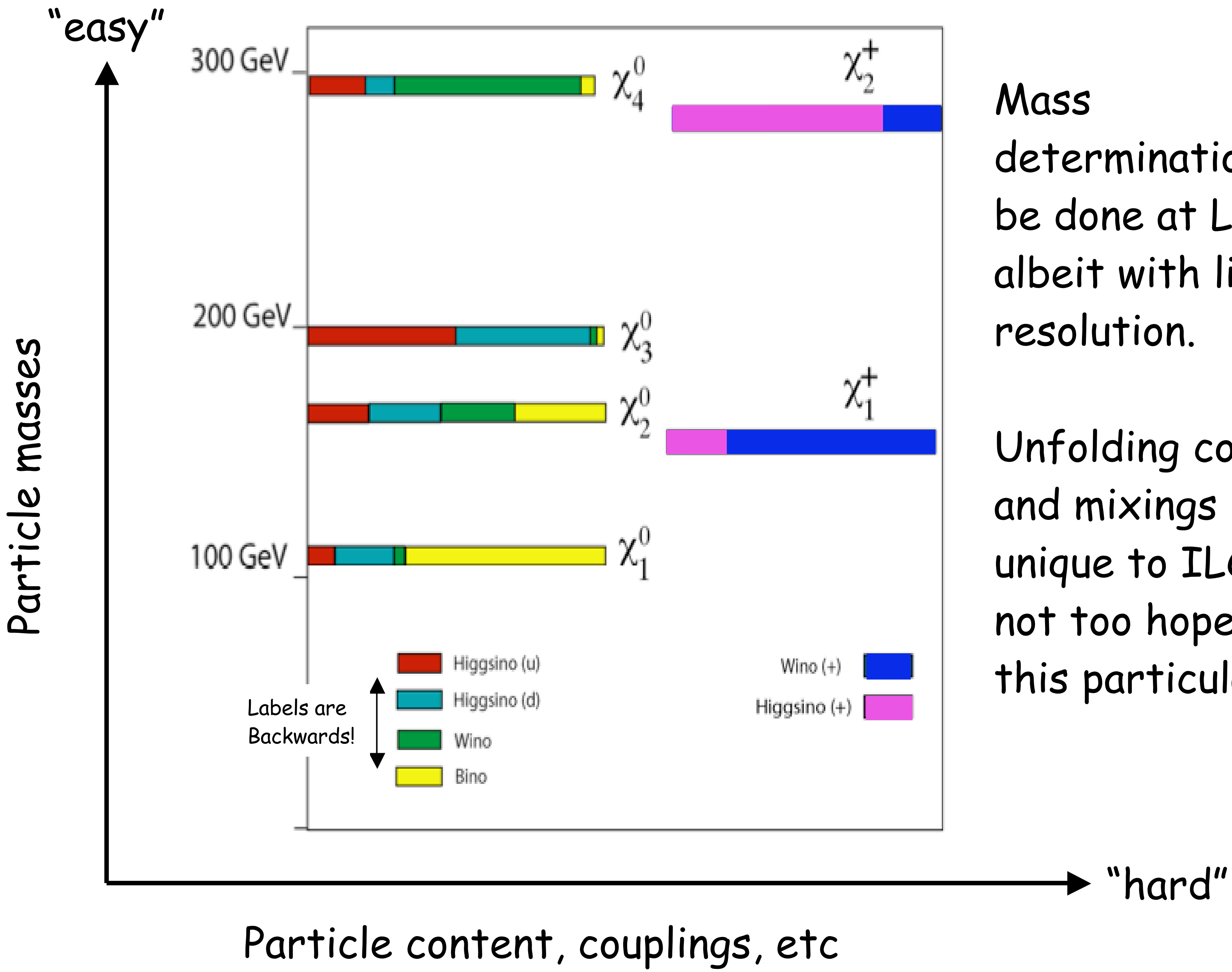
$M_1$ , $M_2$, $\mu$, $\tan\beta$

---

For future study:
If the $\chi$+- is polarized, $d\Gamma/d\cos\theta^*$ could be interesting. (Use lepton tag to separate $\chi$+ , $\chi$- , measure $d\Gamma/dE$.)

(R-L)/(R+L) ~ -0.06

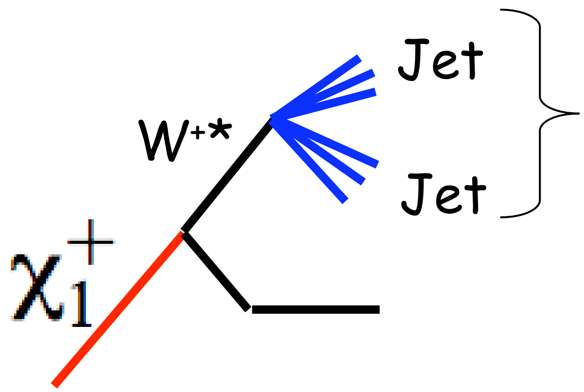
# Couplings are hard. Spectroscopy is easier.



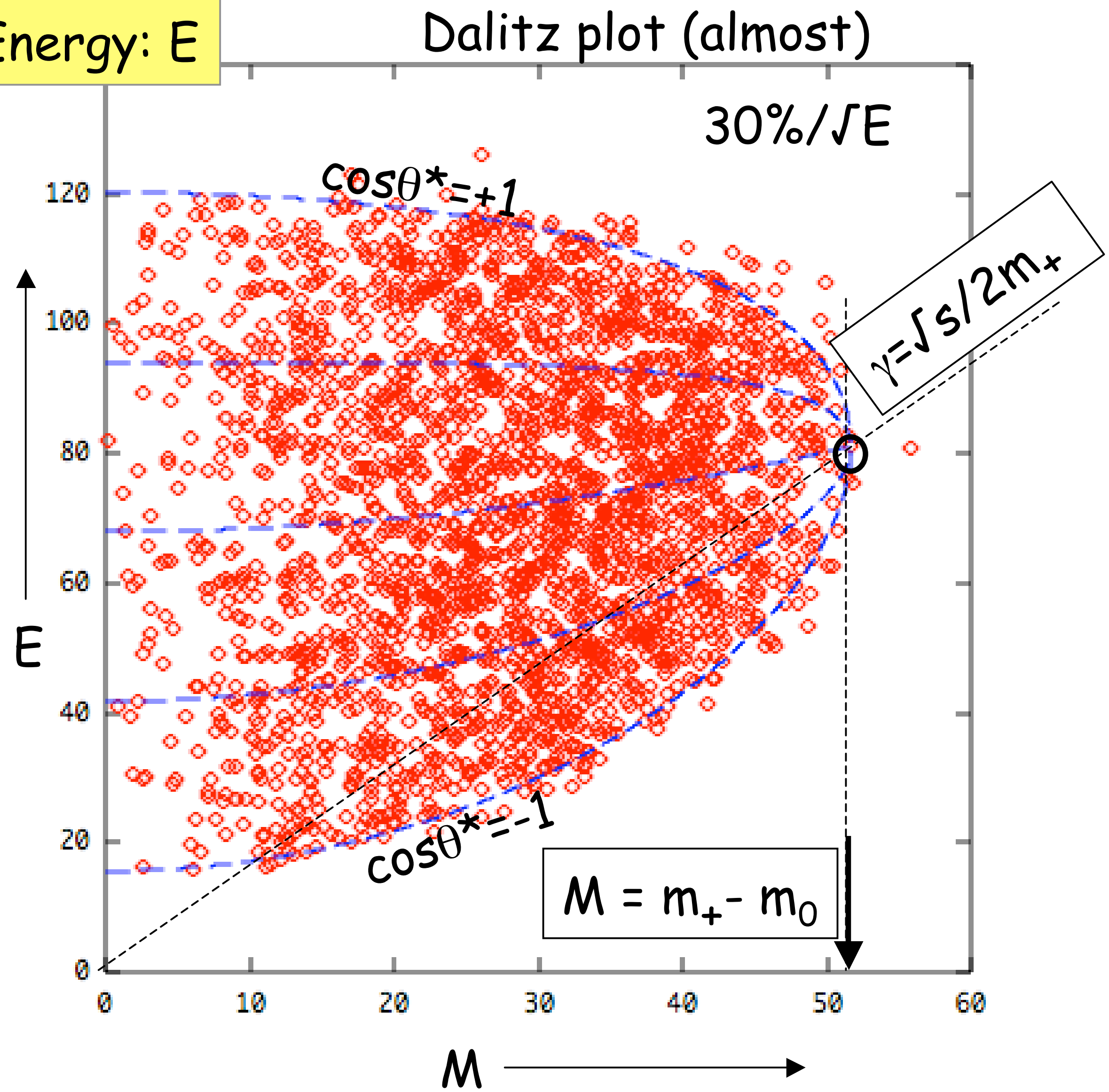

Mass determinations can be done at LHC - albeit with limited resolution.

Unfolding couplings and mixings is unique to ILC. But not too hopeful in this particular case.

# Kinematics of the hadronic system




Mass: M
Energy: E




For given M, just 2-body decay:

$$\chi_1^+ \rightarrow W^* \chi_1^0$$

$m_+ \quad M \quad m_0$

$$E^* = \frac{M^2 + m_+^2 - m_0^2}{2m_+}$$

$$P^* = \sqrt{E^{*2} - M^2}$$

# $d\Gamma/dM$

Andreas Birkedal calculated:

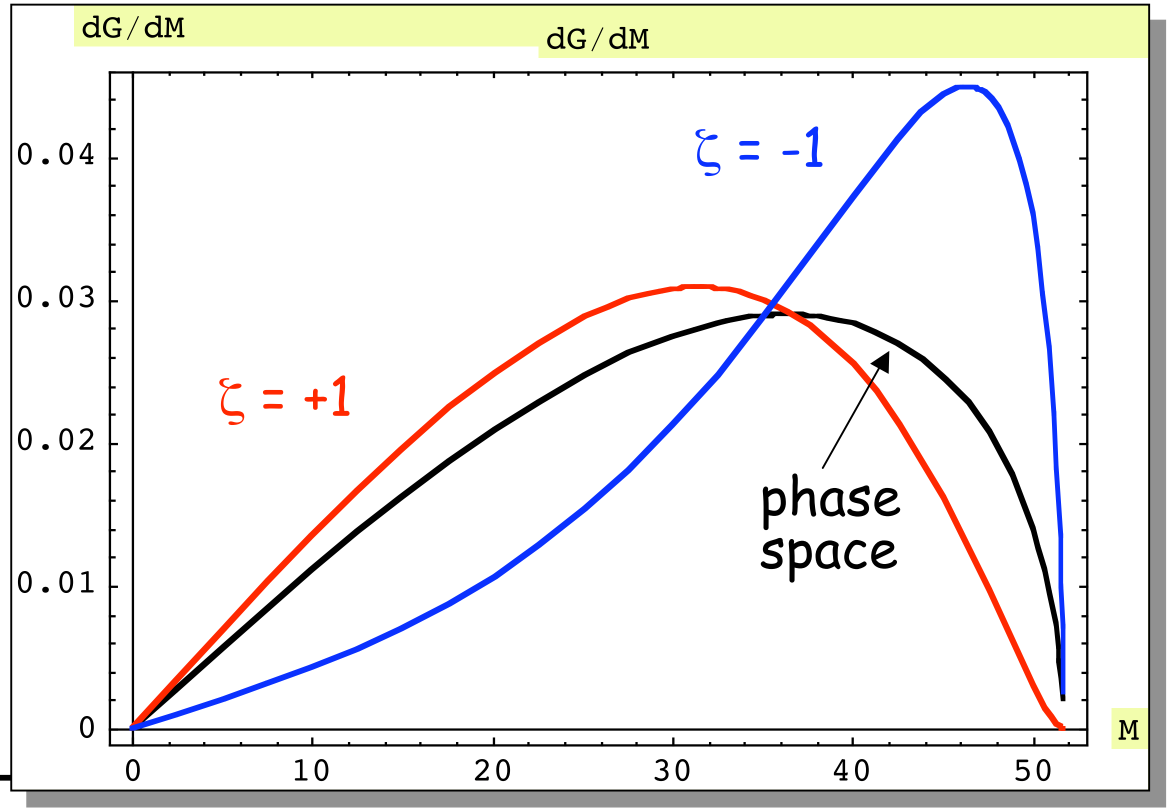
(generic for F -> $f\bar{f}'$ F')

$$\frac{d\Gamma}{dM} \sim \frac{M P^*}{m_+^2 (M^2 - m_W^2)^2} \times \left[m_0^4 + m_+^4 + M^2 m_+^2 - 2M^4 + m_0^2(M^2 - 2m_+^2) - 6\zeta M^2 m_0 m_+\right]$$

Note: $\zeta$ is asymmetry in vector & axial-vector couplings at $\chi^+ W^{*+} \chi^0$ vertex:

$$\zeta \equiv \frac{v_+^2 - a_+^2}{v_+^2 + a_+^2}$$

- Dependence:
  - Strong: $m_+ - m_0$
  - Medium: $\zeta$
  - Weak: $m_+ + m_0$



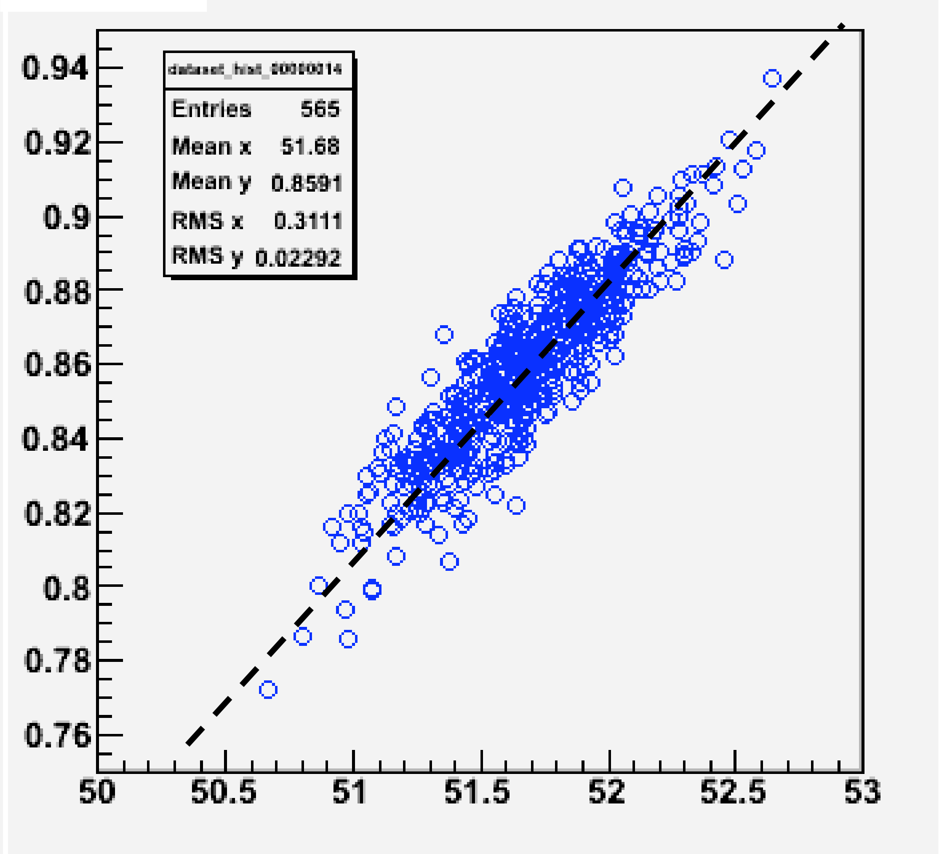

Fit yields $m_+ - m_0$ and $\zeta$

....and they are strongly (+) correlated

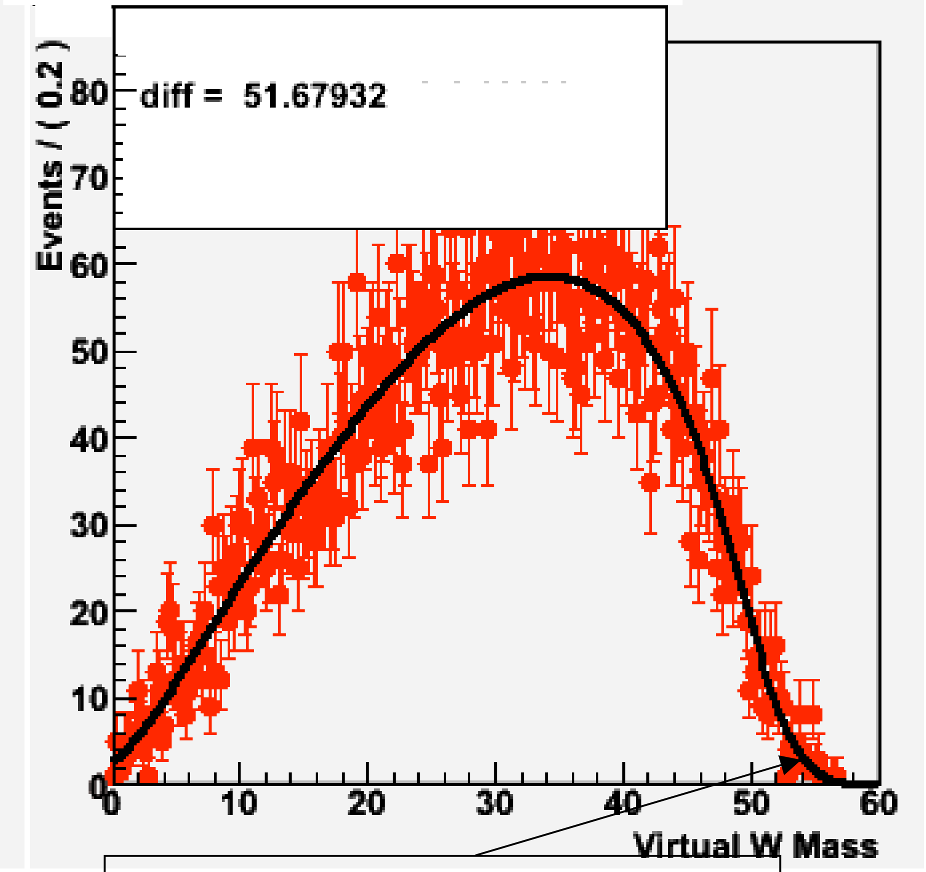
# Example: toy expts fitting to d$\Gamma$/dM

Generate ~500 toy expts, fit to formula.

$\zeta$ versus $m_+ - m_0$

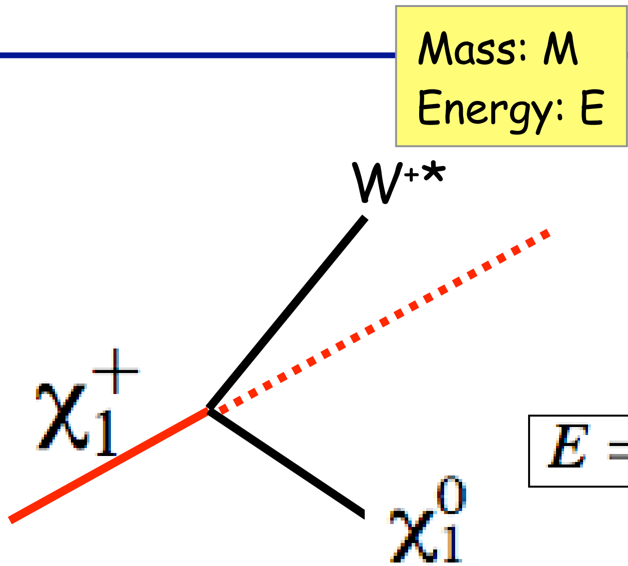



Sample fit




Shape includes resolution smearing

# $d\Gamma/dE$




E,P of W* in $\chi$+ rest frame
(functions of $M, m_+, m_0$)

$$E = \gamma(E^* + \beta P^* \cos\theta^*)$$

$$\frac{d\Gamma}{d\cos\theta^*} = ???$$

Lorentz boost of $\chi$+ ($\gamma = \sqrt{s}/2m_+$ )

- Thus for a given M, $d\Gamma/dE$ measures the angular distribution $d\Gamma/\cos\theta^*$.

- This distribution depends on m+, m0,... as well as $R_+$, $L_+$ couplings and degree of $\chi$+ polarization...

# $d\Gamma/dE$

If $d\Gamma/\cos\theta^*$ is symmetric, then $\langle\cos\theta^*\rangle = 0$.

- We can ensure symmetry of $d\Gamma/\cos\theta^*$ by ignoring opposite-side-lepton sign -- so we do not distinguish $\chi$+, $\chi$-
- Alternatively, $d\Gamma/\cos\theta^*$ may be flat (eg if $\chi$+ is unpolarized... which it basically is, it turns out).

Assuming $\langle\cos\theta^*\rangle = 0$, we find:

$$\langle E\rangle = \langle\gamma\rangle E^* = a + bM^2$$

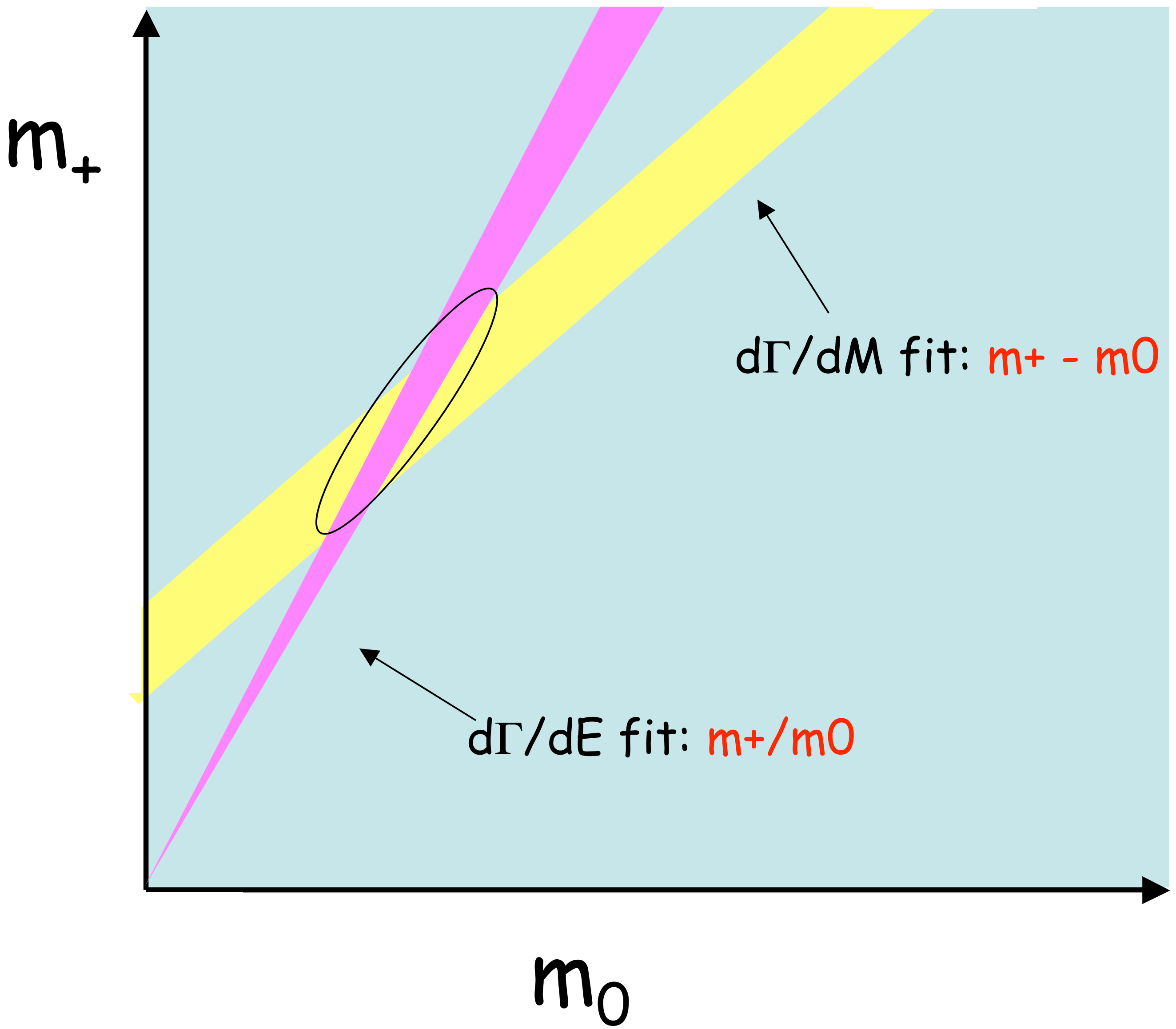
$$a = \frac{\sqrt{s}}{4}\left(1 - \left(\frac{m_0}{m_+}\right)^2\right)$$

$$b = \frac{\sqrt{s}}{4m_+^2}$$

Mainly sensitive to the *ratio* $m_+/m_0$

Note: in ISAJET $d\Gamma/\cos\theta^*$ = flat.

# Simultaneous fit for $d\Gamma/dM$ & $d\Gamma/dE$



# Simulation Details

ISAJET 7.69 → stdhep → LCDROOT: FASTMC (SDMar01) → root → SUEZ

Lumi = 500 $fb^{-1}$:

250$fb^{-1}$ e- pol = +95%,

250$fb^{-1}$ e- pol = -95%

Note: "95%" means $\frac{R-L}{R+L} = 0.90$

Analysis (to be described):

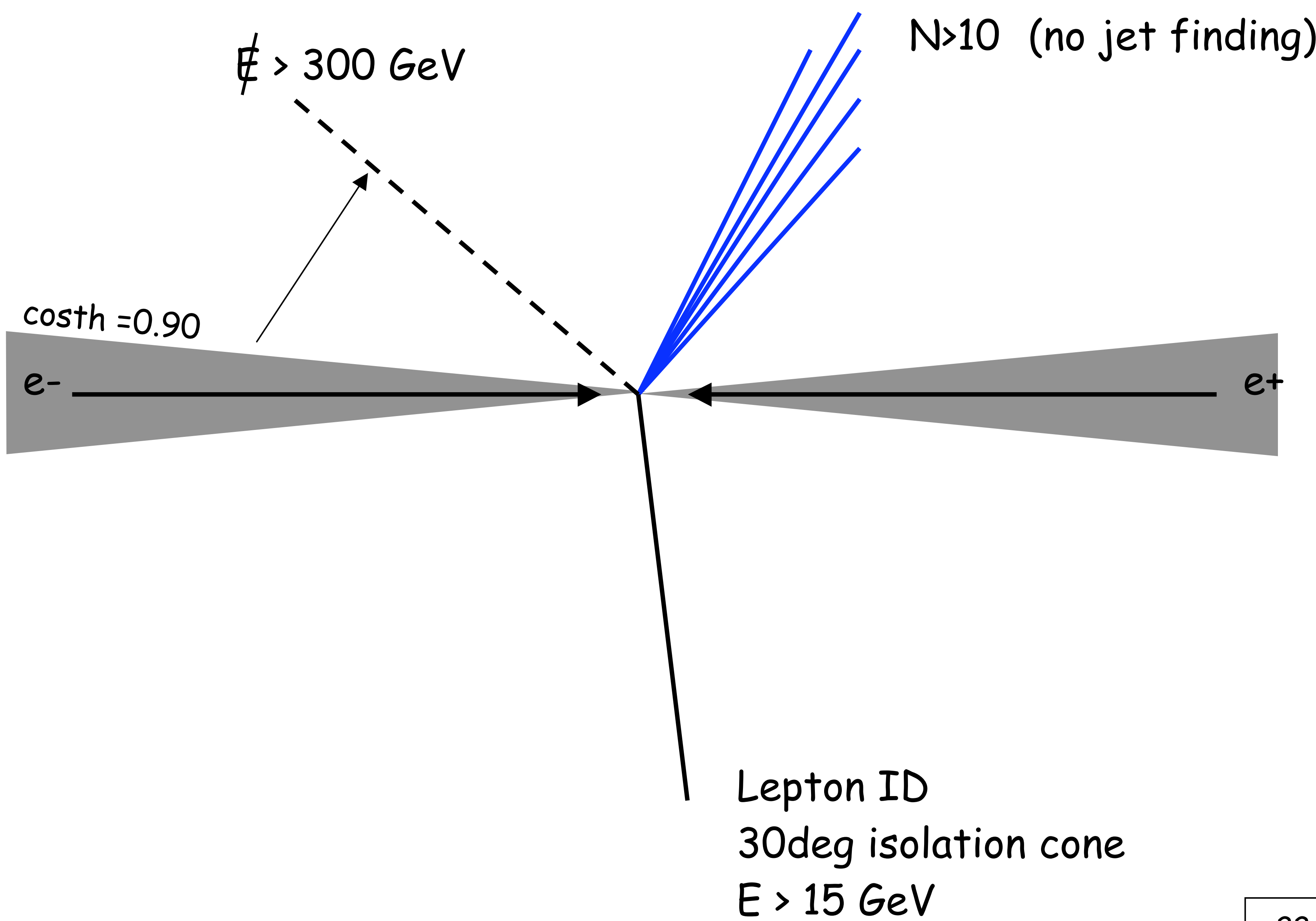
reconstruction eff = 36%

W* branching ratios = 15%

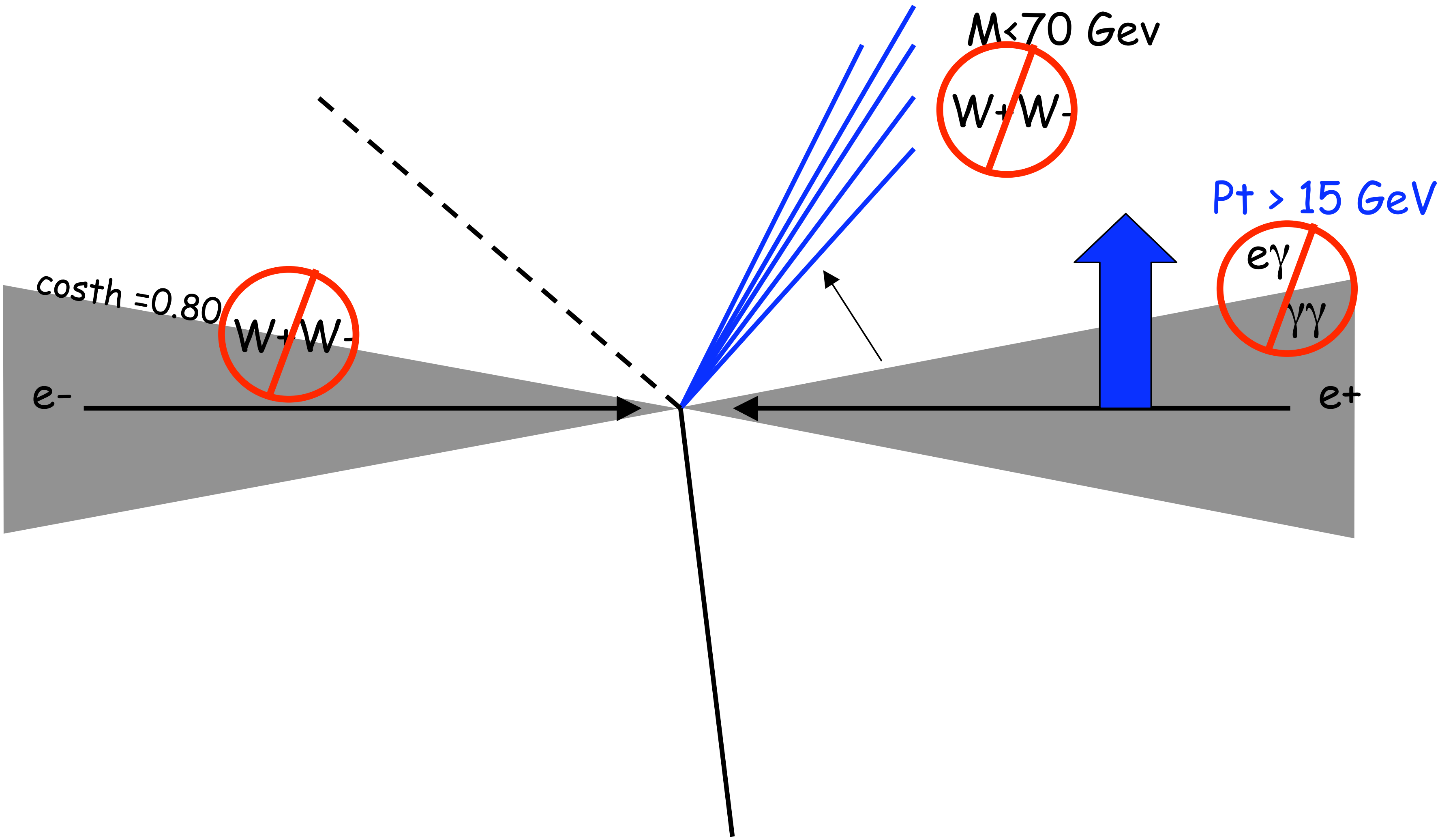
Signal yield = (500fb-1) $\left(\begin{matrix} 940\text{fb} \\ 120\text{fb} \end{matrix}\right)$ (0.36x0.15) = $\begin{matrix} 12000 \text{ evts} & e^-_L \\ 1500 \text{ evts} & e^-_R \end{matrix}$

Backgrounds: WW, ZZ, tt + generic (1 $ab^{-1}$ from Tim Barklow)

# Signal Selection

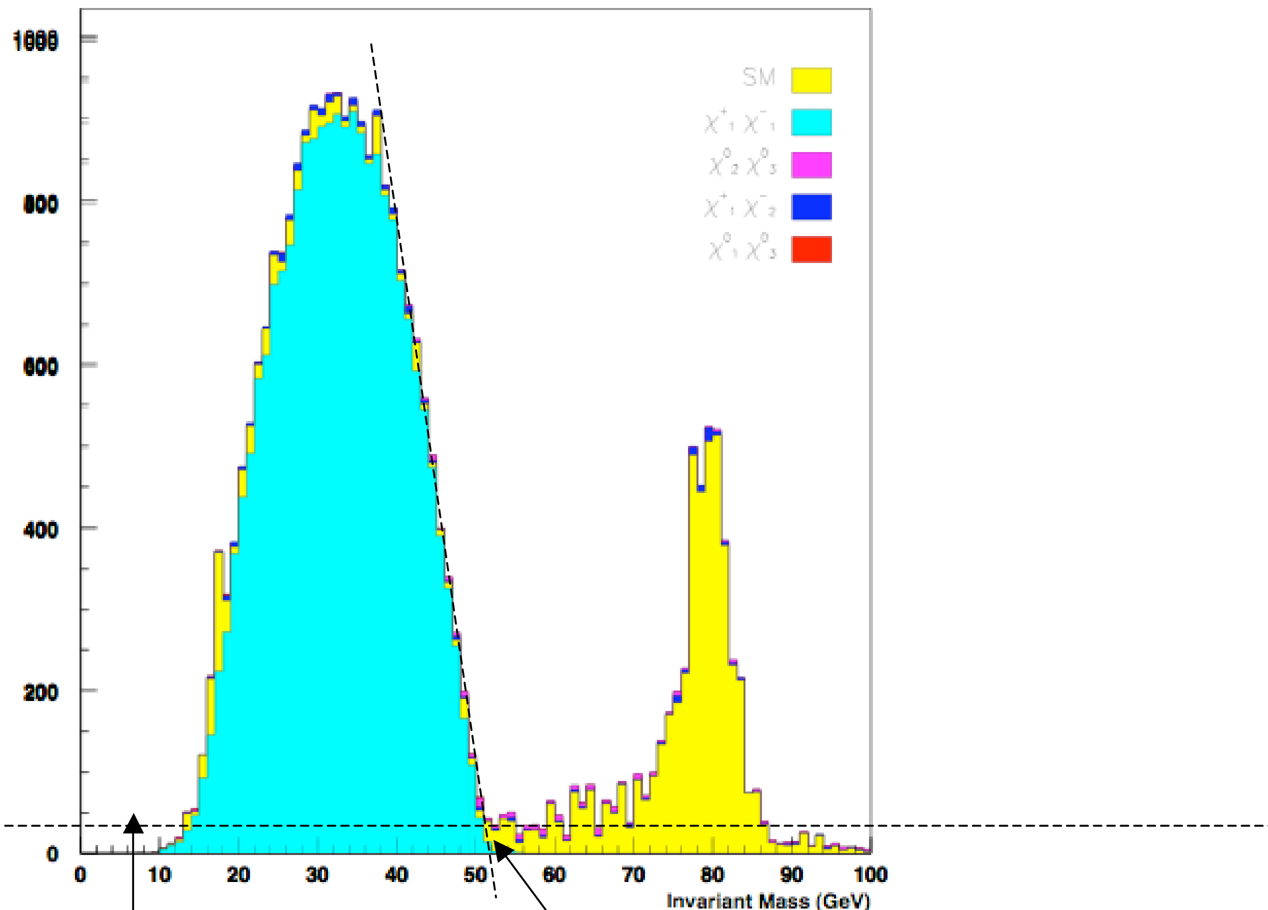


# Background Suppression



# Signal and Backgrounds

dΓ/dM, 500 fb-1



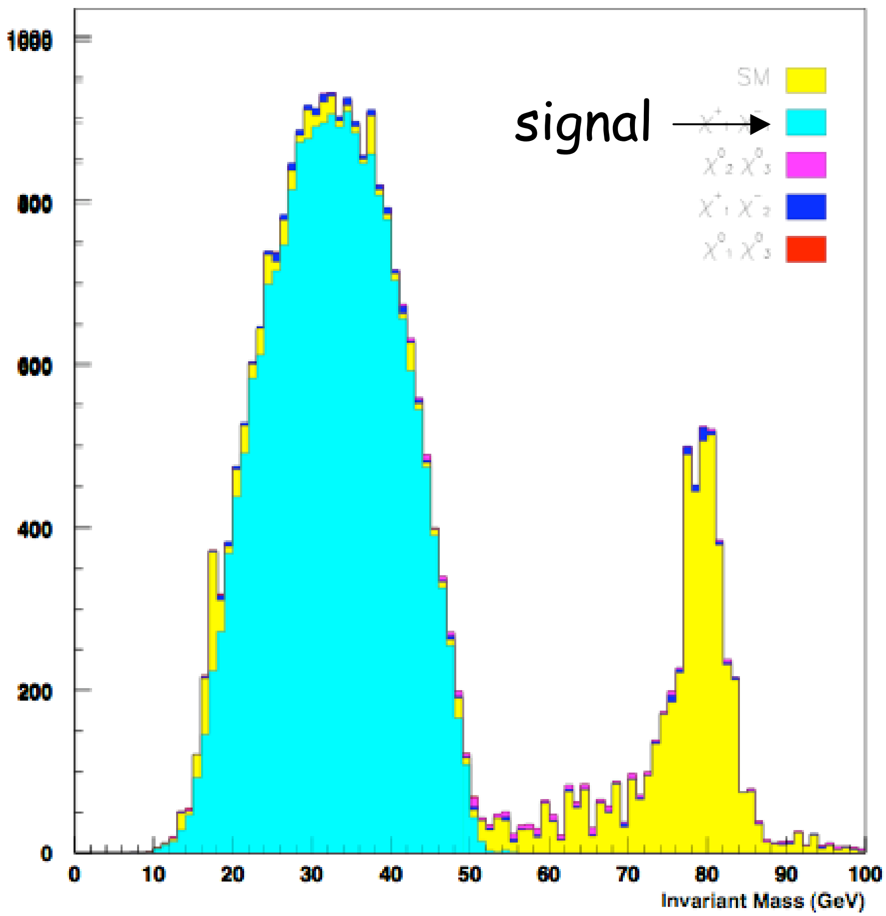

Cuts kill this region

Kinematic endpoint at $M = m_+ - m_0 = 51.7$ GeV

# Detector Resolution Matters!

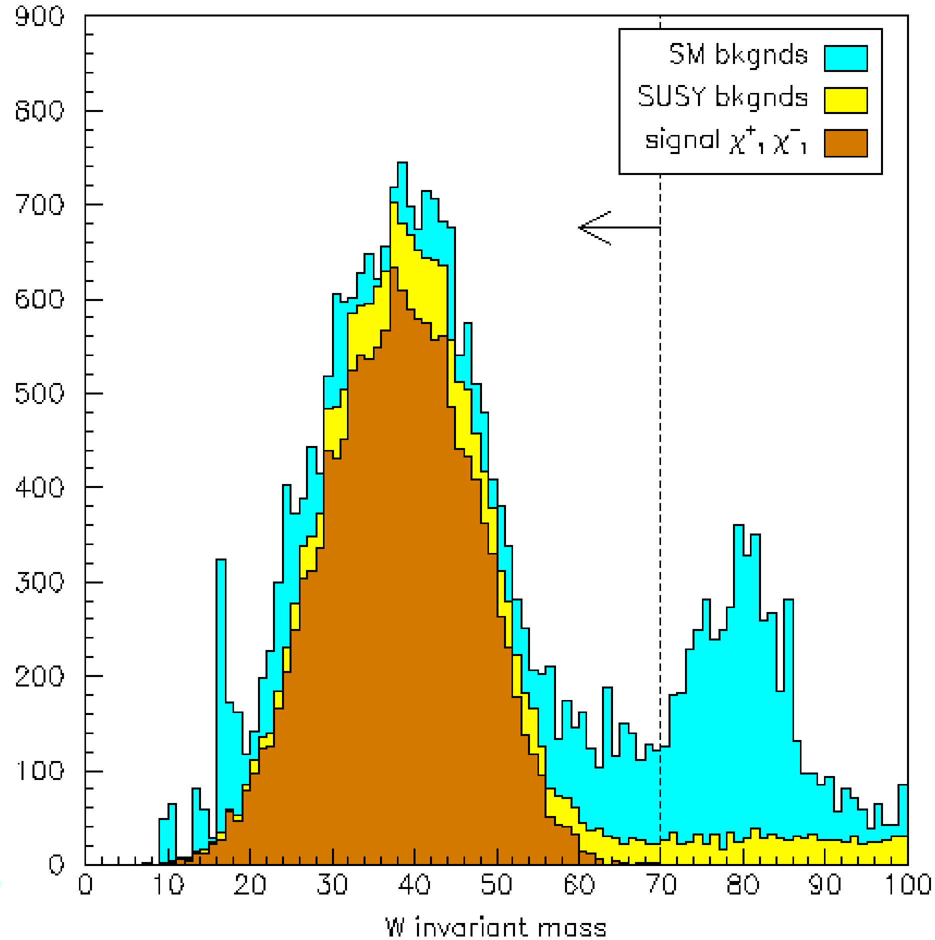
(oops - colors mean different things in these two plots!)

Analysis "A"




$$\frac{\sigma_E}{E} \sim \frac{0.15}{\sqrt{E}}$$

Analysis "B"




$$\frac{\sigma_E}{E} \sim \frac{0.8}{\sqrt{E}}$$

# Yields, $\sigma_L$, $\sigma_R$

Counting events in FASTMC with Analysis "B"

| | left-pol. | right-pol. |
|---|---|---|
| Signal ($\chi_1^+\chi_1^- \to e^\pm jj(g)$) | 12421 | 1592 |
| SUSY backgrounds (including $\chi_1^+\chi_1^-$ to other modes) | 1751 | 480 |
| Standard Model backgrounds | 3170 | 1209 |
| Cross-section measurement | $940 \pm 10$ fb | $119 \pm 4.3$ fb |

~1% on total cross section (or $\sigma_L$);
~4% on $\sigma_R$.

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = 0.78 \pm 0.01$$

Note: this polarization asymmetry is due to lopsided chargino content. $e^-_R e^+_L$ only couples to (small) higgsino component of chargino. Thus the cross section measurement alone probes mixing.

# Simultaneous fit for $d\Gamma/dM$ & $d\Gamma/dE$

Explore further with toy MC -- flexible, fast

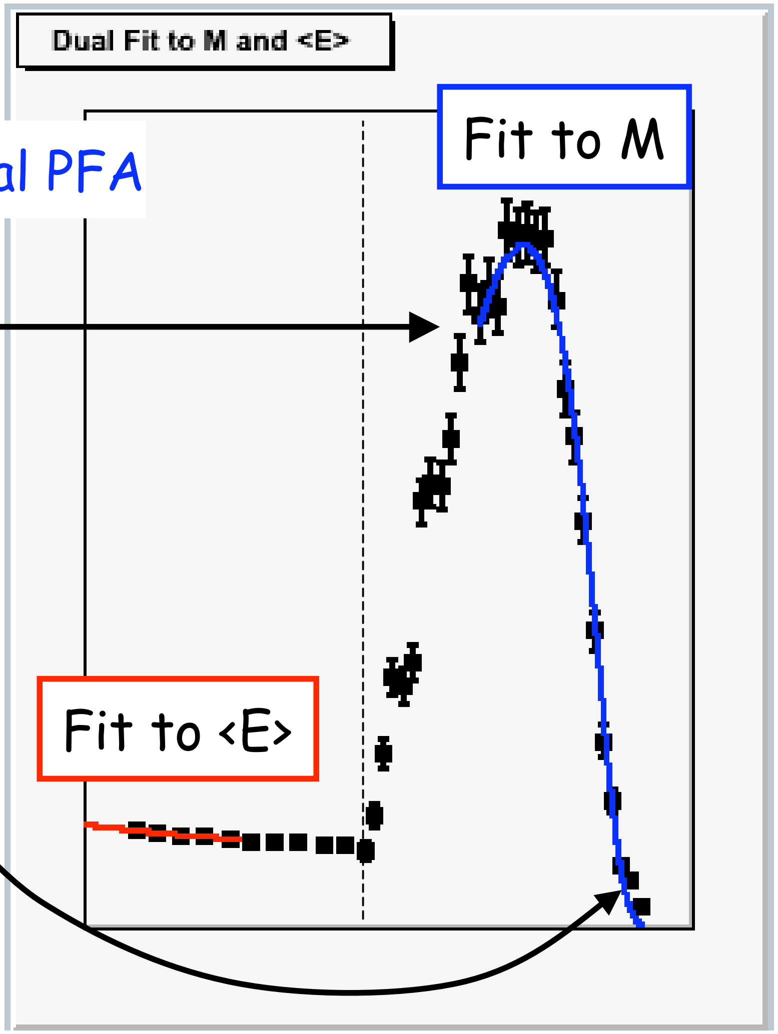
- 250 toy experiments
- generate 10k events in each expt:
  - $d\Gamma/dM$ - Andreas' formula; $\zeta$=0.86
  - $d\Gamma/dE$ flat
- E,M smeared by $\sigma_E$=30%/√E --> optimal PFA
- Restrict fit to M>25GeV:
  - ISAJET/FASTMC:
  - - low mass range is sculpted
  - - not understood yet.
  - - main impact on fit is reduced statistics (64%)

-Fit includes resolution smearing

Sensitive - get it right!!

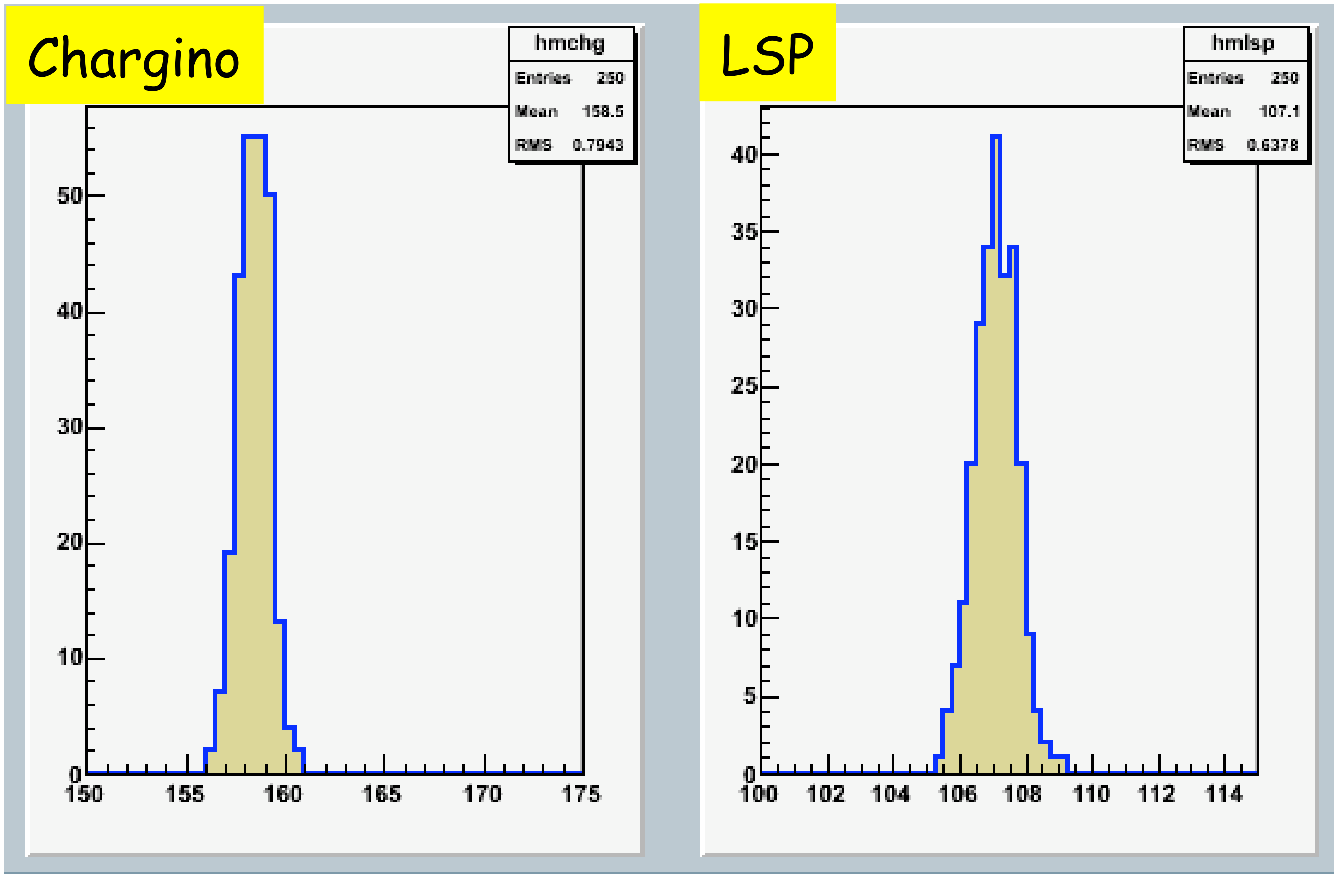
- No brem/beam-strahlung for now.

-No background for now.



# Simultaneous fit for $d\Gamma/dM$ & $d\Gamma/dE$

250 toy experiments: 10K evts, $\sigma_E$=30%/√E




$$m_+ = 158.5 \pm 0.8 \qquad m_0 = 107.1 \pm 0.6$$

(generated value: 159.4) (generated value: 107.7)

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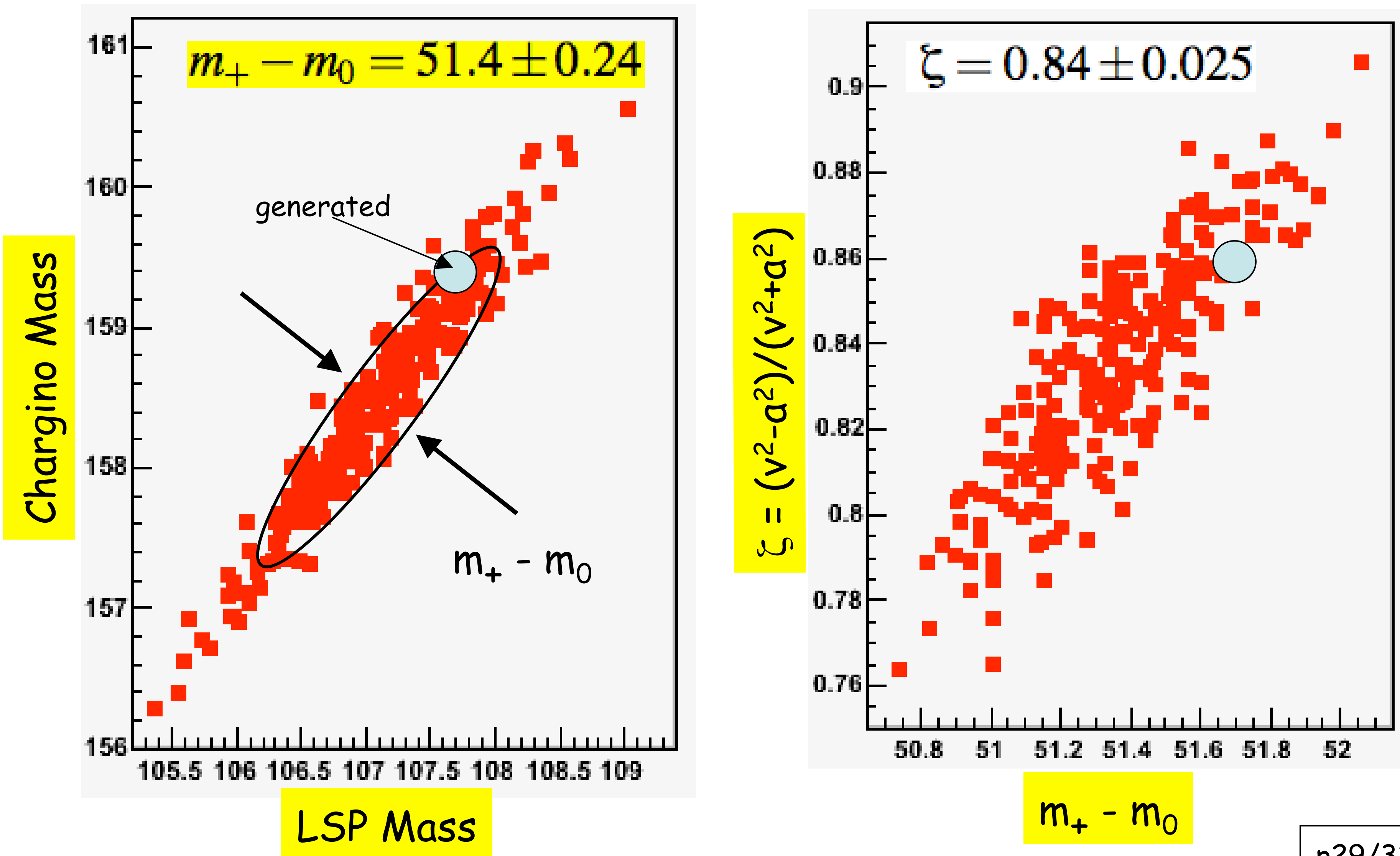


# Mass Sensitivity vs Detector Resolution

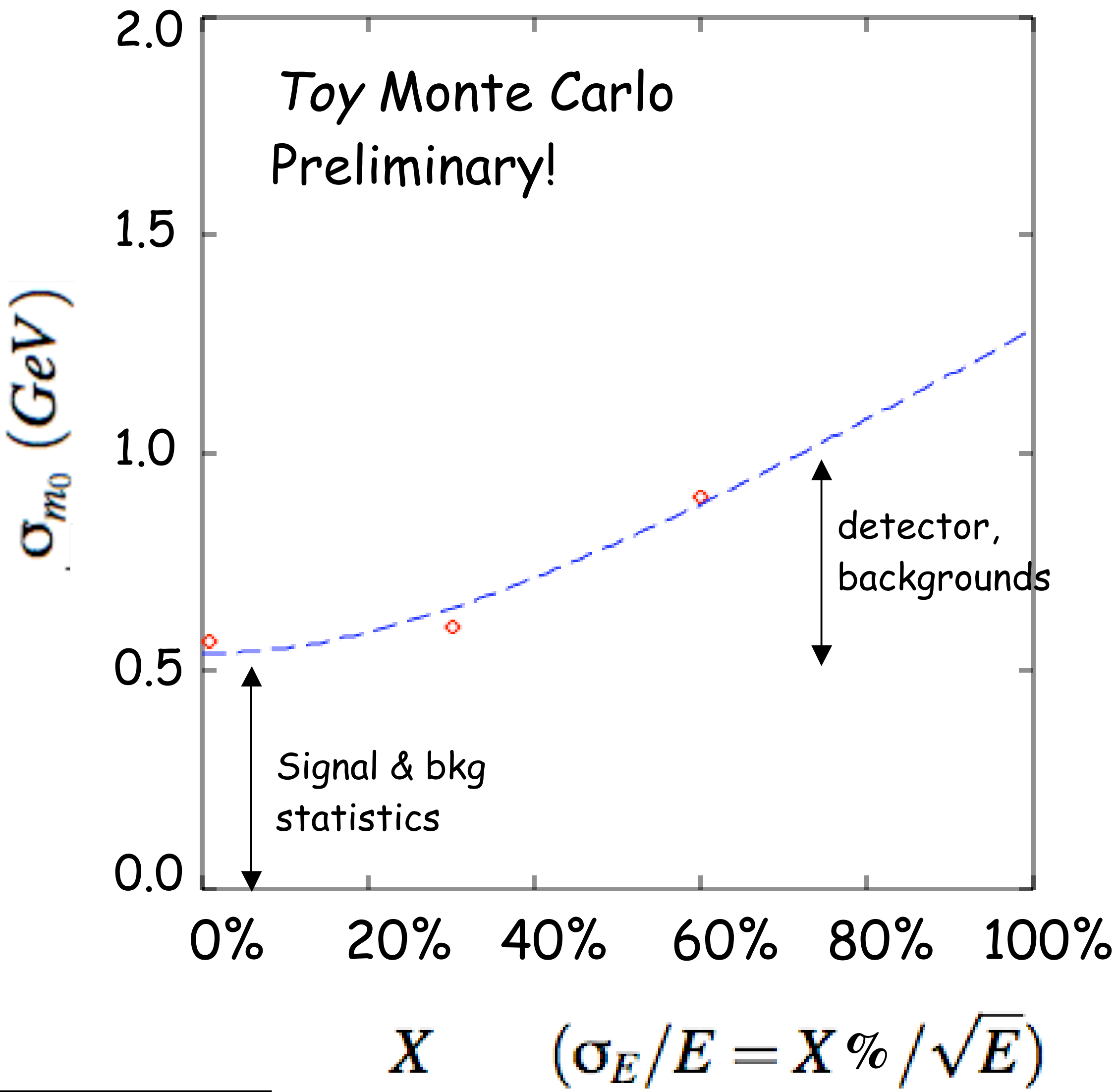
Dependence on "jet" energy resolution is somewhat mild...

CAVEATS!

1. No bkg included. Bkgs will raise the floor *and* the slope.

2. Toy Monte Carlo...

3. Preliminary!




| Res | mchg | mlsp | mdiff | zeta |
|---|---|---|---|---|
| 0% | +-0.66 | +-0.56 | +- 0.19 | +-0.020 |
| 30% | +- 0.8 | +- 0.6 | +- 0.25 | +-0.025 |
| 60% | +- 1.3 | +- 0.9 | +- 0.47 | +-0.039 |

# Other things to pursue…

- Lepton spectrum (other side of event) also contains useful kinematic info. Use it!
- Threshold production: mass, spin; fully polarized.
- Beam polarization, $A_{LR}$, $A_{LRFB}$,…
- Neutralino production needs to be revisited: purely Z0 produced; richer content. R,L couplings?? Threshold production?
- Detector benchmarking.