Something out of nothing:

Dark matter observation and mass determination in photon + missing energy events at the ILC

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Work in progress with:

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Dark matter - WIMP

- Cosmological observations $\longrightarrow$ 20% of the energy density of Universe is due to non-relativistic, non-baryonic dark matter.
- WIMP most attractive candidate.
  - Mass $\longrightarrow$ 10 GeV – 1 TeV
  - Interactions strength $\longrightarrow$ weak interactions of Standard Model.
- Have a relic abundance of the correct order of magnitude to account for the observed dark matter.
- Many BSM extensions contain suitable candidates for WIMP.
  - SUSY – LSP ?
  - UED – LKP ?
  - ....
  - ....

Dark matter at collider

- Can we produce DM (χ) in collider?
  - We are in correct energy range
  - Expect "missing energy" signature
- Can we quantify these process : $X_i + \bar{X}_i \to \chi + \chi$

  $(X_i = q, \ell, g, W, Z, \gamma, h)$
  - In a model independent way?
  - Using the known cosmological abundance of WIMP $\to$ governed by scattering $\chi + \chi \to X_i + \bar{X}_i$
- We need inverse relation for any prediction @ collider

Relic density

- At early times, the DM particles are in thermal equilibrium with the SM particles : $\chi\chi \Longleftrightarrow X_i \bar{X}_i$
- Freeze-out of thermal relics is described by the Boltzmann equation
  $\frac{dn_\chi}{dt} = -3Hn_\chi - <\sigma_A v> (n_\chi^2 - n_{eq}^2)$
- Total DM annihilation cross-section (σ_A) can be expanded:
  $\sigma_A v = \sum_i \sigma(\chi + \chi \to X_i + \bar{X}_i) v = a + bv^2 + \mathcal{O}(v^4)$
- Approximate Relic density : $\Omega h^2 = 0.08 \frac{1pb}{a+(3b-0.75a)x_F}$
  - $x_F = T_F/M_\chi \sim 0.04$
  - T_F the freeze-out temperature.

Relic density

- WMAP: The present amount of dark matter
  $\sigma_{DM} h^2 = 0.111^{+0.011}_{-0.015}$ *WMAP Coll. '06*
  $\longrightarrow$ *WIMP annihilation cross-section*

- *Two classes of DM candidates:*
  - $a = b$: *"s-annihilators"*
  - $a < bx_F << b$: *"p-annihilators".*

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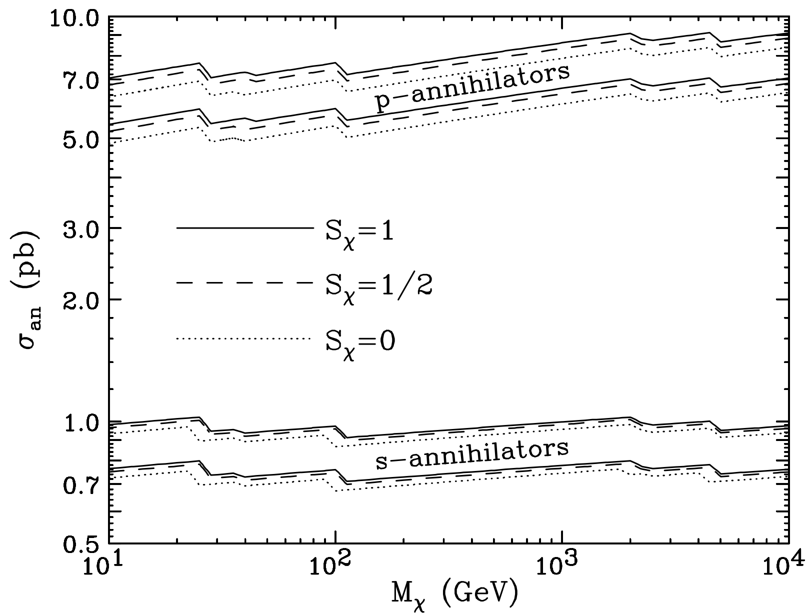

Birkedal, Matchev, Perelstein. '04

WIMP production cross-section

- Forward and backward WIMP production are related by detailed balancing:
  $$\frac{\sigma(\chi+\chi\to X_i+\bar{X}_i)}{\sigma(X_i+\bar{X}_i\to\chi+\chi)} = 2.\frac{v_X^2(2S_X+1)^2}{v_\chi^2(2S_\chi+1)^2}$$
- Annihilation fraction: $\kappa_i = \frac{\sigma_i^{(J_0)}}{\sigma_{tot}}, \quad \sum_i \kappa_i = 1$
- Model-independent prediction of the WIMP production rate
  $$\sigma(X_i+\bar{X}_i\to\chi+\chi) = 2^{2(J_0-1)}\kappa_i\sigma_{an}\frac{v_\chi^2(2S_X+1)^2}{v_X^2(2S_\chi+1)^2}\left(1-\frac{4M_\chi^2}{s}\right)^{1/2+J_0}$$
  - Unknown parameters : κ_i, M_χ, S_χ, J_0
- But this is useless – We need at least one detectable particle to trigger.
  - Tag the known initial state with a soft photon ..
    $e^+e^- \to 2\chi+\gamma$

WIMP production cross-section

- Soft/collinear photon factorization:

$$\frac{d\sigma(e+e-\to 2\chi+\gamma)}{dx d\cos\theta} = \frac{\alpha}{\pi}\frac{1+(1-x)^2}{x}\frac{1}{\sin\theta^2}\hat{\sigma}(e+e-\to 2\chi)$$

  - $x = 2E_\gamma/\sqrt{s}$
  - $\hat{\sigma}$ calculated at $\hat{s} = (1-x)s$
  - Applicable when $E_\gamma << \sqrt{s} - M_\chi$

WIMP production cross-section

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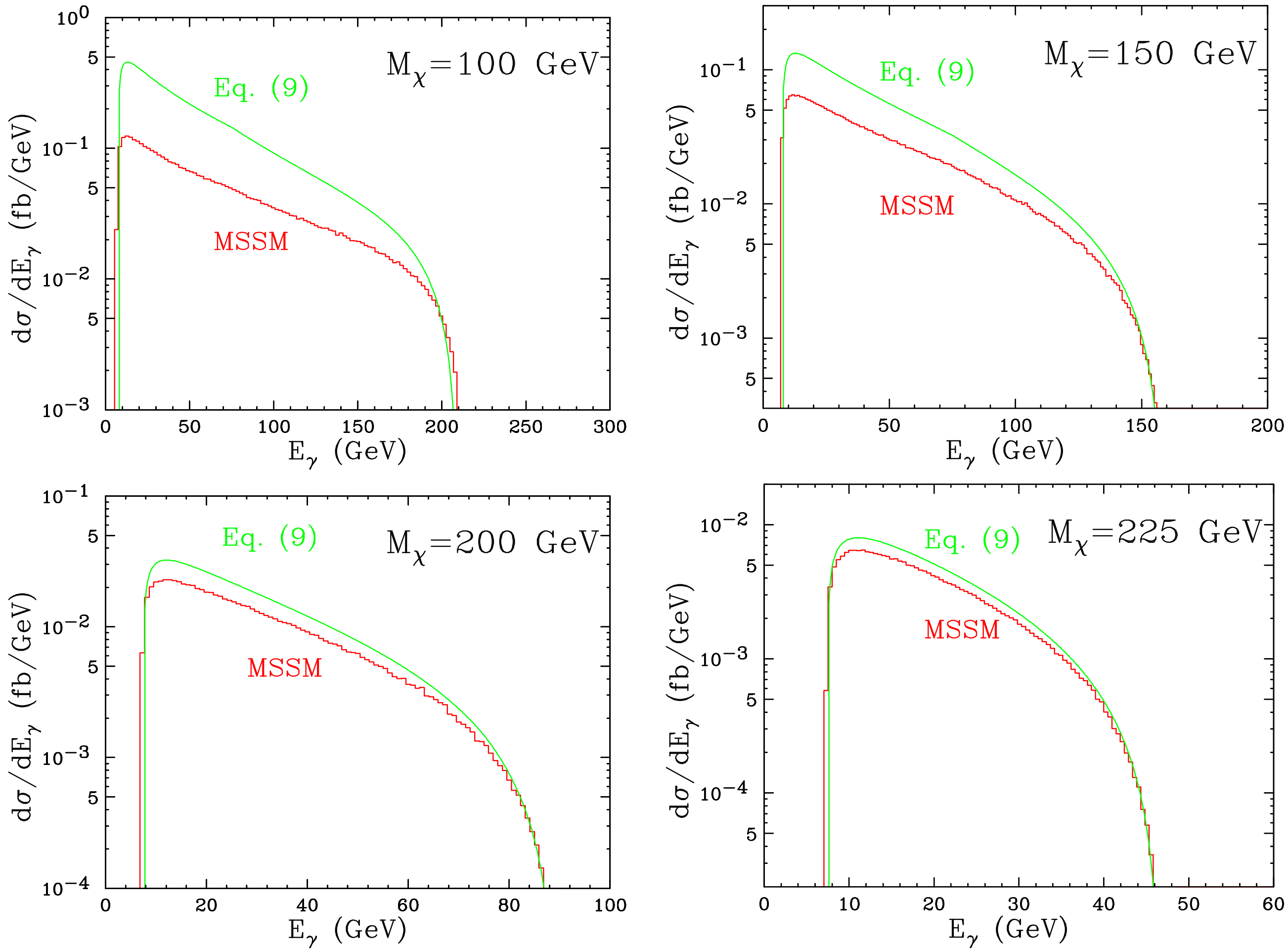
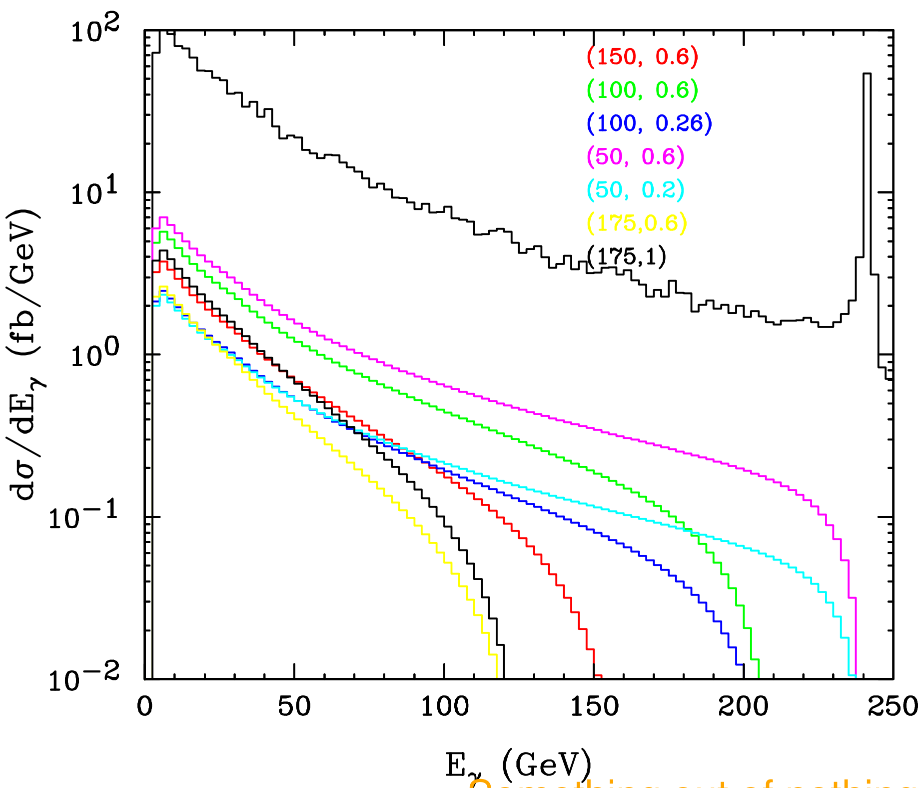


Birkedal, Matchev, Perelstein. '04

WIMP signal at a 500 GeV ILC

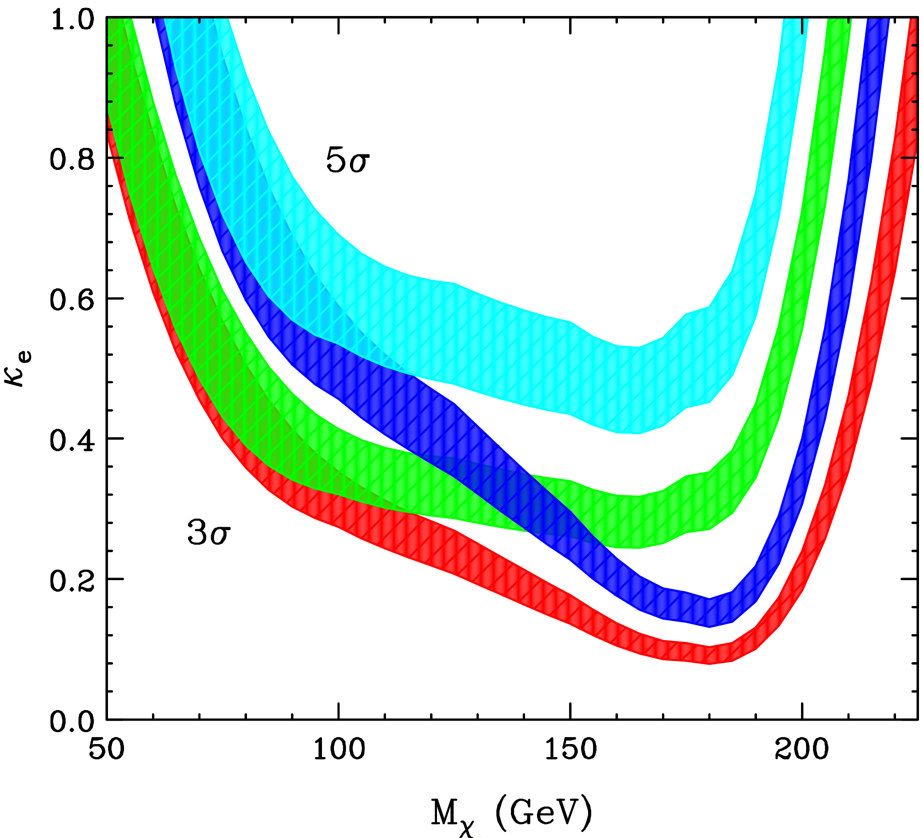
- We look at the signal for 500 GeV ILC and $\mathcal{L} = 500 fb^{-1}$
- Main irreducible background from $e^+e^- \to \nu\bar{\nu}\gamma$
- Background from $e^+e^- \to e^+e^-\gamma$ can be eliminated using lower cut on the $p_{T,\gamma}$
- Photon energy distribution for Signal and Background:



- For p-annihilator WIMP
- Signal in terms of (M_χ, κ_e)

WIMP signal at a 500 GeV ILC

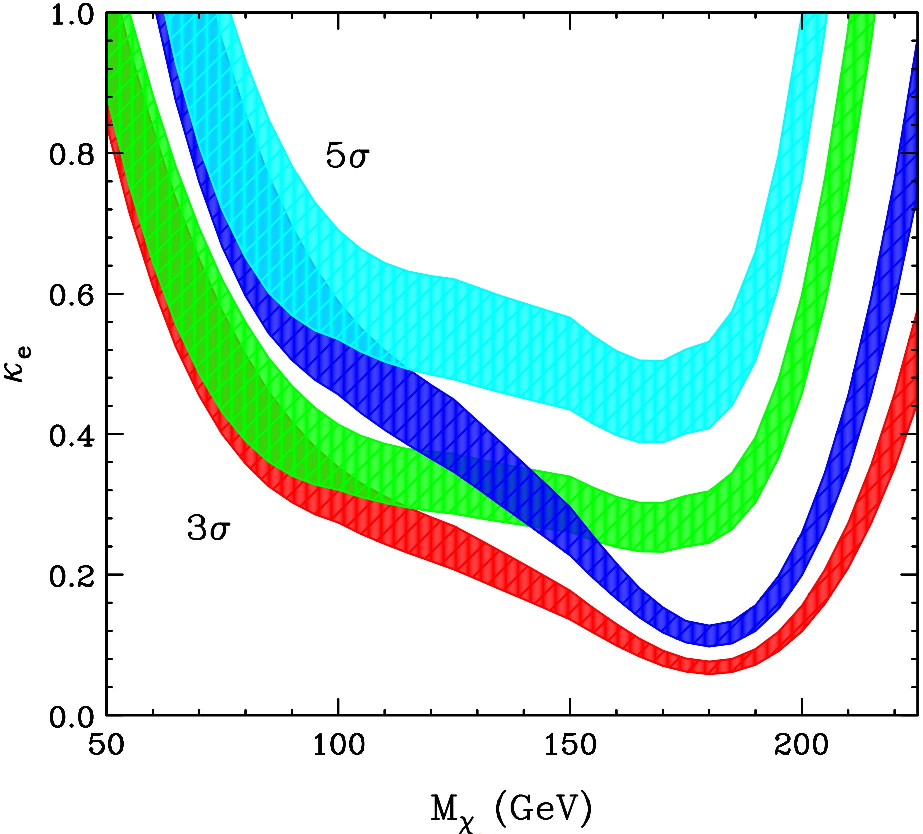
- $\sin\theta_\gamma > 0.1$
- $p_{T_\gamma} > 7.5\ GeV$ *(suppress Bhabha : mask calorimeter acceptance of 1^o)*
- χ non-relativistic and E_γ below threshold-
$\frac{\sqrt{s}}{2}\left(1-\frac{8M_\chi^2}{s}\right) \le E_\gamma \le \frac{\sqrt{s}}{2}\left(1-\frac{4M_\chi^2}{s}\right)$



- Discovery reach for $\mathcal{L} = 500 fb^{-1}$ ILC
- No polarization.
- For p-annihilator WIMP
- (red, blue) band include a systematic uncertainty of 0.3%

WIMP signal at a 500 GeV ILC

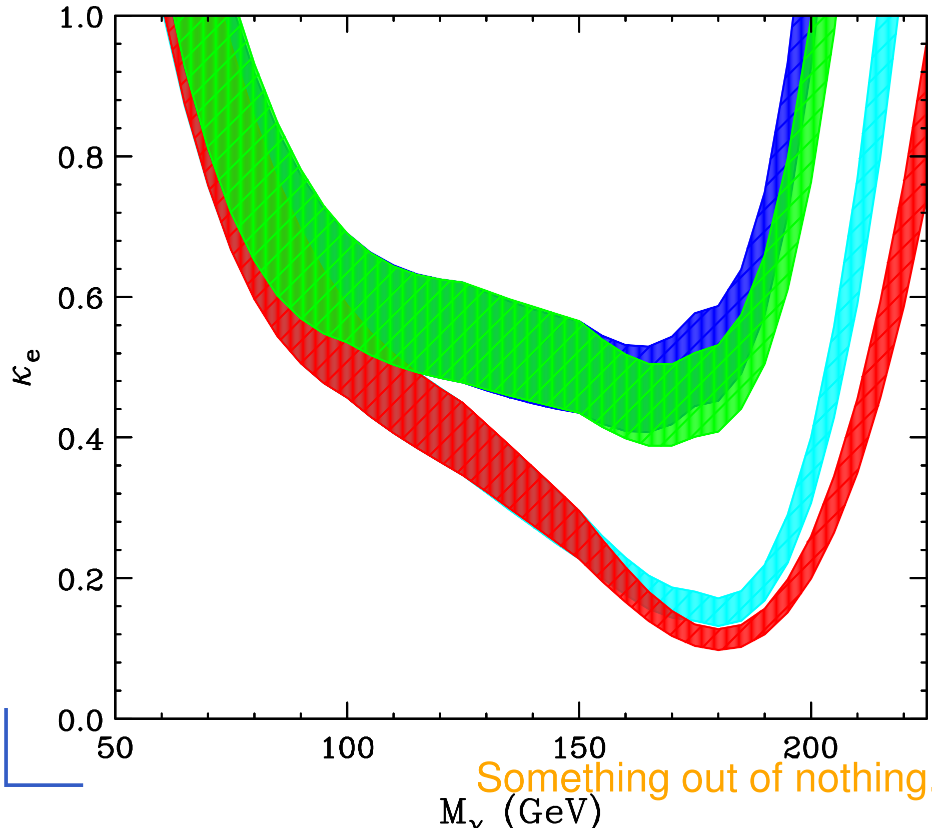
- $\sin\theta_\gamma > 0.1$
- $p_{T_\gamma} > 3.0\ GeV$ *(suppress Bhabha : BeamCAL acceptance of* 0.38^o*)*
- χ non-relativistic and E_γ below threshold-
  $$\frac{\sqrt{s}}{2}\left(1-\frac{8M_\chi^2}{s}\right) \le E_\gamma \le \frac{\sqrt{s}}{2}\left(1-\frac{4M_\chi^2}{s}\right)$$



- Discovery reach for $\mathcal{L} = 500 fb^{-1}$ ILC
- No polarization.
- For p-annihilator WIMP
- (red, blue) band include a systematic uncertainty of 0.3%
- Revised from better beam-CAL acceptance.

WIMP signal at a 500 GeV ILC

- $\sin\theta_\gamma > 0.1$
- $p_{T_\gamma} > 3.0\ GeV$ and $7.5\ GeV$ *(suppress Bhabha : BeamCAL acceptance of 0.38^o)*
- χ non-relativistic and E_γ below threshold- $\frac{\sqrt{s}}{2}\left(1-\frac{8M_\chi^2}{s}\right) \le E_\gamma \le \frac{\sqrt{s}}{2}\left(1-\frac{4M_\chi^2}{s}\right)$



- Discovery reach for $\mathcal{L} = 500 fb^{-1}$ ILC
- No polarization.
- For p-annihilator WIMP
- (red, blue) band include a systematic uncertainty of 0.3%
- Improvement in 5σ level.

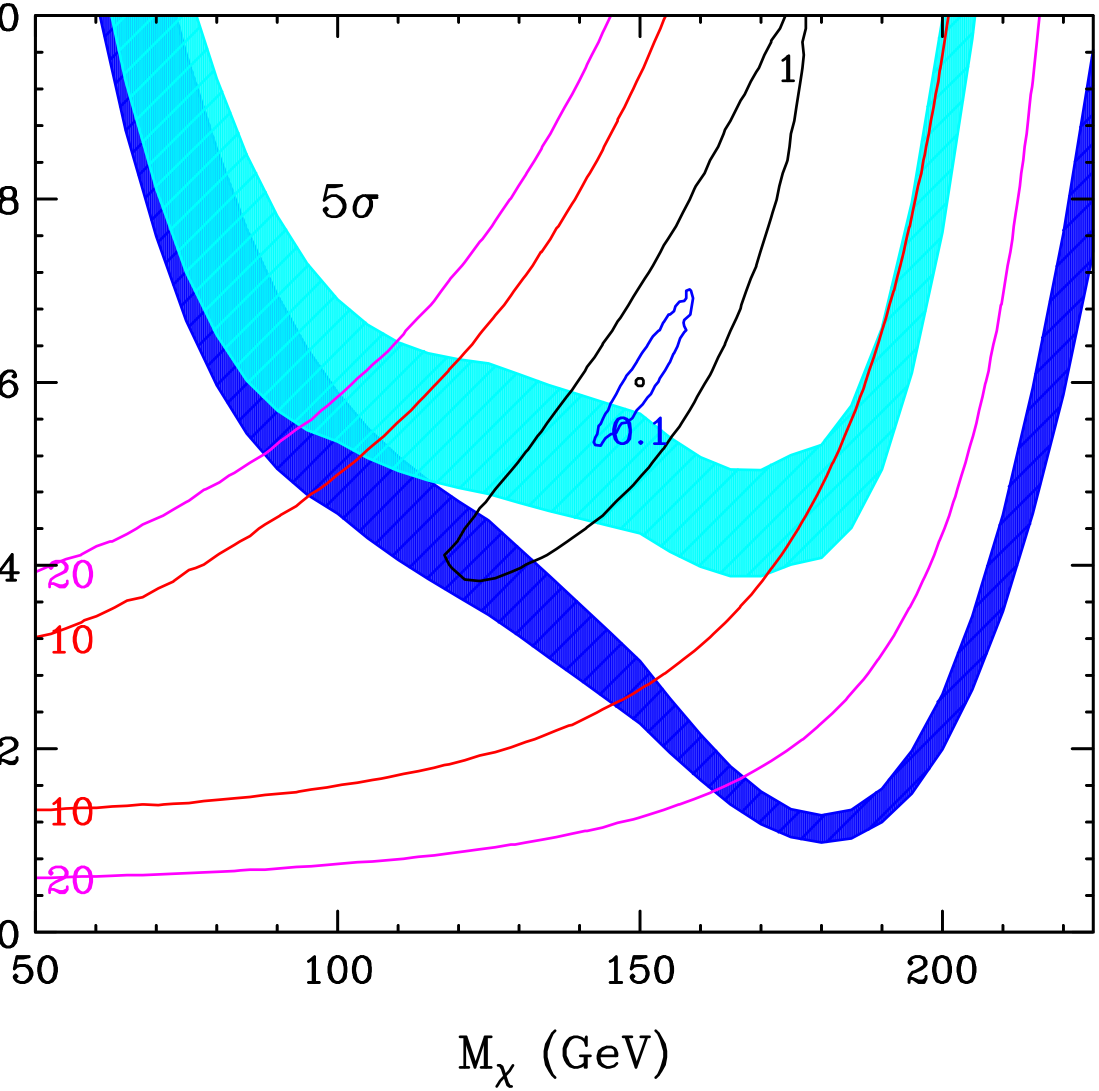
WIMP signal and mass resolution at I

- Once WIMP observed in ILC, mass measurement next step.
- Photon energy distribution can be used to reconstruct WIMP mass
- Both unpolarized case and polarized case can be considered

WIMP signal and mass resolution at I

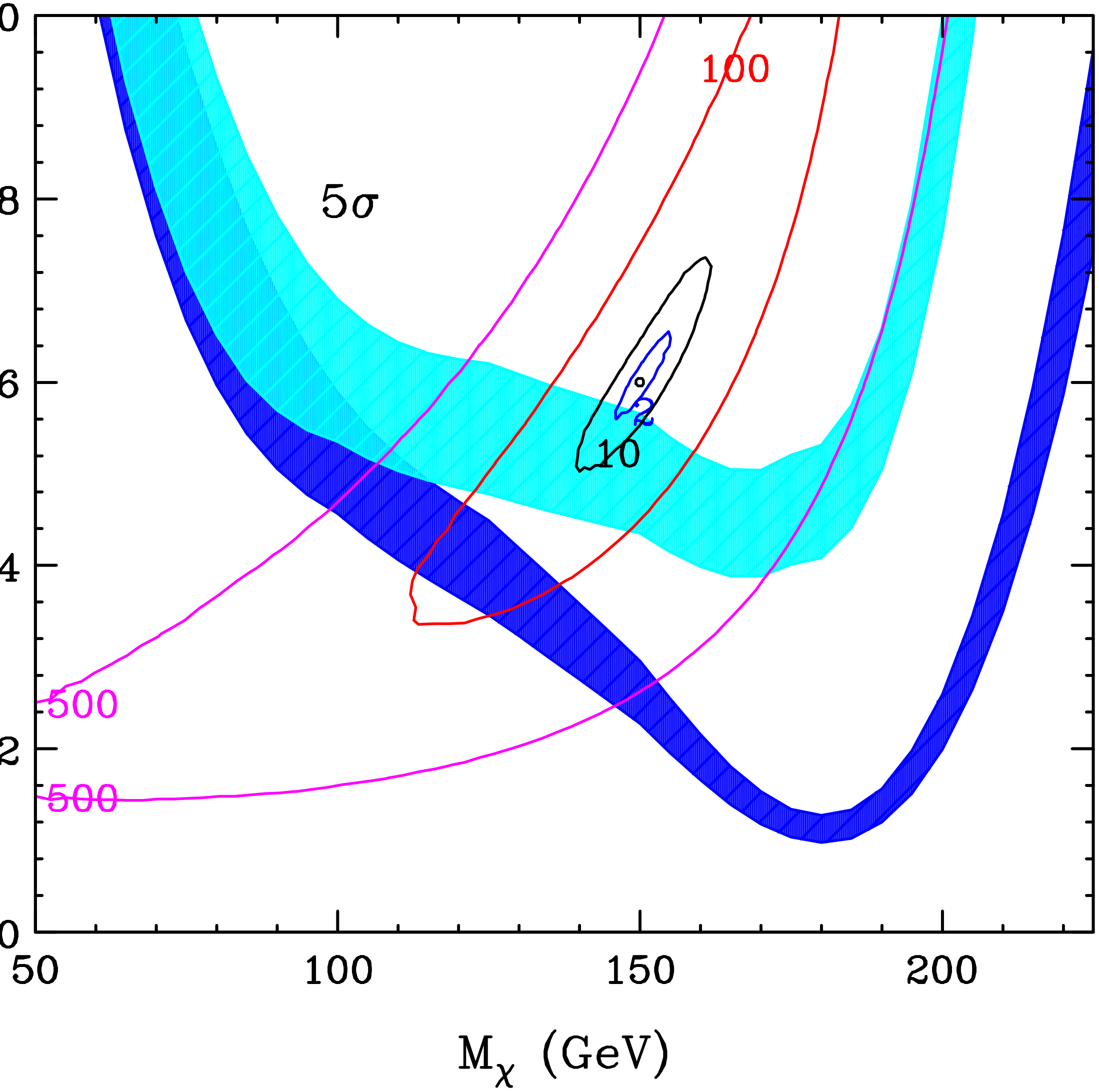
- Once WIMP observed in ILC, mass measurement next step.
- Photon energy distribution can be used to reconstruct WIMP mass
- Both unpolarized case and polarized case can be considered
- Reconstruction done scanning over the (M_χ, κ_e) parameter space and calculating χ^2.
- Our sample signal point is M_χ= 150 GEV and κ_e=0.6
- Spin $\frac{1}{2}$ and p-annihilator WIMP considered
- Smeared with energy resolution $14.4\%/\sqrt{E} + 0.5\%$

WIMP signal and mass resolution at I



- For $\mathcal{L} = 500 fb^{-1}$ ILC
- No polarization.
- For p-annihilator, Spin $\frac{1}{2}$ WIMP
- Smeared with energy resolution $14.4\%/\sqrt{E} + 0.5\%$

WIMP signal and mass resolution at I



- For $\mathcal{L} = 500 fb^{-1}$ ILC
- Polarized beam [$P_{e^-} = 0.8$(mostly right) $P_{e^+} = 0.6$(mostly left)]
- For p-annihilator, Spin $\frac{1}{2}$ WIMP
- Smeared with energy resolution $14.4\%/\sqrt{E} + 0.5\%$

Summary & Conclusions

- Model independent approach based on less assumptions over model parameters.
- ILC can efficiently resolve the mass determination of WIMP.
- Polarized beam significantly improves the result.
- Some similar analysis using recoil mass distribution indicates to measure the mass quite precisely. *Bartels, List '07*