A Model-Independent Signature for WIMPs at the ILC

Maxim Perelstein (Cornell)
in collaboration with
Andreas Birkedal (U. of Florida)
Konstantin Matchev (U. of Florida)

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Dark Matter Puzzle:

- About 25% of the energy in the universe is dark, non-relativistic matter
- Non-particle explanations unlikely
- χ has to be stable (or at least $\tau \geq 10$ bln. years)
- χ cannot have strong interactions (otherwise $p\chi$ exotic nuclei) or electric charge (dark)
- χ cannot be a Standard Model neutrino (free streaming)
- Have to invent (at least one) new particle

WIMP: a Perfect Fit

- χ's interact with the SM matter via weak forces (or a new interaction of similar strength/range)
- χ is massive (mass >> 1 MeV) ⇒ χ's are in thermal equilibrium with the SM matter as long as T>M(χ): $n_\chi \sigma v > H$
- When T<M(χ), $n_\chi \propto \exp(-M/T)$(Boltzmann suppression) and χ's decouple
- Energy density of χ's today: $\rho_\chi \approx \dfrac{T_0^3}{M_{\rm pl}\sigma} \sim \rho_c$

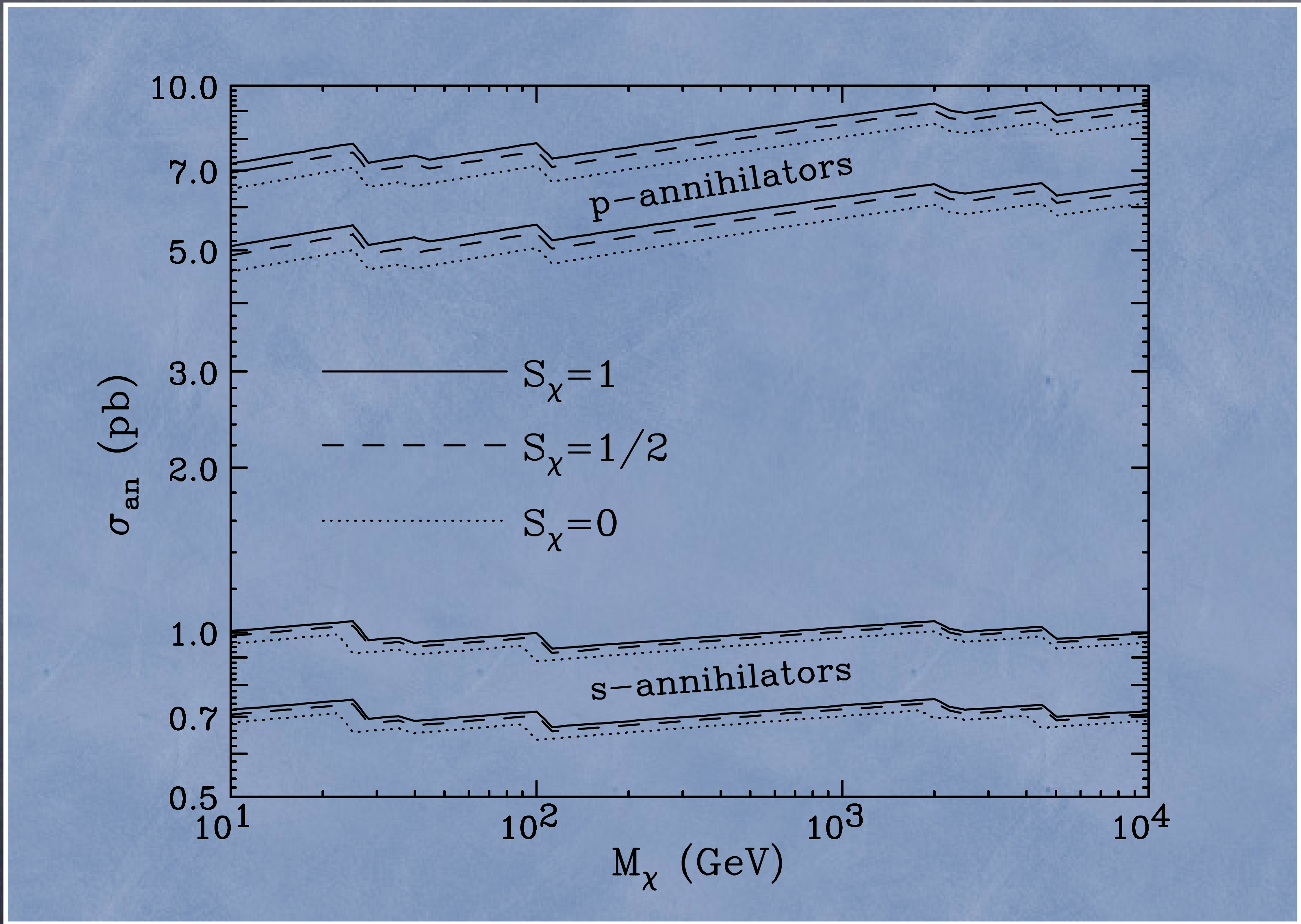
Assumptions:

- Assume generic mass spectrum (no resonances, no coannihilations)
- At the time of χ decoupling, the only important reactions are $\chi\chi \leftrightarrow X_i \bar{X}_j$, where X_i is SM
- For non-relativistic WIMPs, can be expanded as:

$$\sigma_i v = \sigma_i^{(0)} + \sigma_i^{(1)} v^2 + \ldots$$

- Dominated by either s-wave or p-wave
- Define $$\sigma_{\rm an} = \sum_i \sigma_i^{J_0}$$

Ω_{dm} determines σ_{an}



2σ constraint using $\Omega_{dm}h^2$=0.112±0.009 (WMAP)

From Cosmology to Colliders

- Cosmology provides a precise, model-independent measurement of $\sigma_{\rm an}$
- Idea: use this information to predict χ production rate at a collider!
- Step 1: Detailed Balancing (DB)

$$\frac{\sigma(\chi\chi \to e^+e^-)}{\sigma(e^+e^- \to \chi\chi)} = 2\frac{v_e^2(2S_e+1)^2}{v_\chi^2(2S_\chi+1)^2}$$

- Define annihilation fraction: $\kappa_e = \sigma^{J_0}_{e^+e^-}/\sigma_{\rm an}$

Tagging and Factorization

- Obtain a prediction:

$$\sigma(e^+e^- \to \chi\chi) = \frac{2^{2(J_0+1)}}{(2S_\chi+1)^2}\,\kappa_i \sigma_{\rm an}\left(1-\frac{4M_\chi^2}{s}\right)^{1/2+J_0}$$

- This is unobservable (like $e^+e^- \to \nu\bar{\nu}$)
- Consider instead $e^+e^- \to \chi\chi + \gamma$
- Step 2: Use soft/collinear factorization:

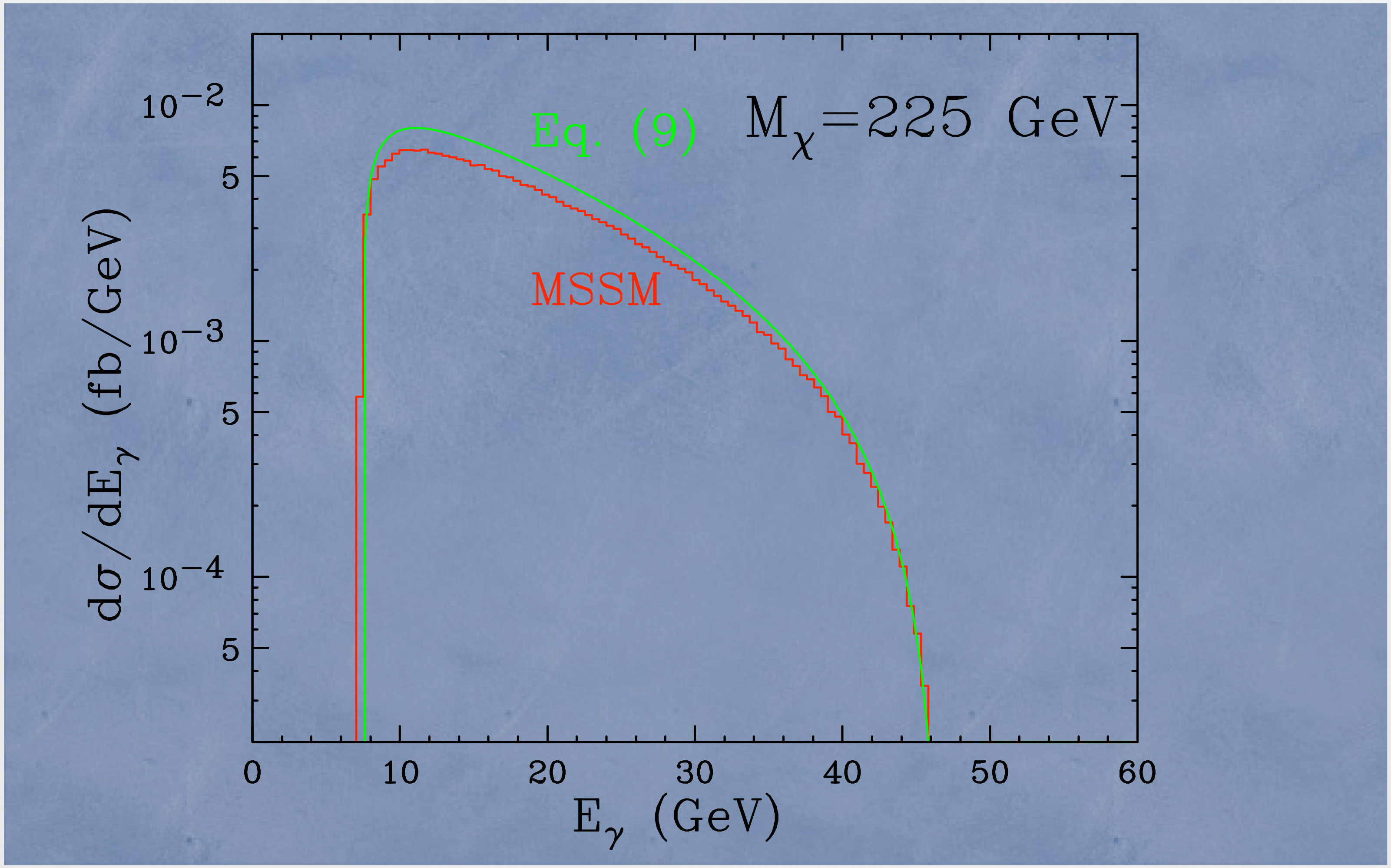
$$\frac{d\sigma(e^+e^- \to 2\chi+\gamma)}{dx\, d\cos\theta} \approx \mathcal{F}(x,\cos\theta)\hat{\sigma}(e^+e^- \to 2\chi)$$

$$\mathcal{F}(x,\cos\theta) = \frac{\alpha}{\pi}\,\frac{1+(1-x)^2}{x}\,\frac{1}{\sin^2\theta}, \qquad x = 2E_\gamma/\sqrt{s}$$

Potential Problems:

- DB+CF results in a model-independent prediction for an observable quantity
- Rates are $\propto \kappa_e$ ⇨ no lower bound
- However many models predict $\kappa_e \sim 0.2 - 0.3$
- Only works for NR ⇨ WIMPs close to threshold
- Collinear photons are unobservable: cuts on E_T^γ and $\sin\theta$ are necessary to eliminate backgrounds (e.g. Bhabha)
- Compare the rates (integrated with realistic cuts) obtained by an exact calculation in a chosen model (MSSM) to the DB+CF results with matching parameters ($\kappa_e, M_\chi, S_\chi, J_0$)

DB+CF vs. Exact: Photon Spectra, $e^+e^- \to \chi_1\chi_1\gamma$



$p_T^\gamma > 7.5\ \mathrm{GeV}, \sin\theta > 0.1$

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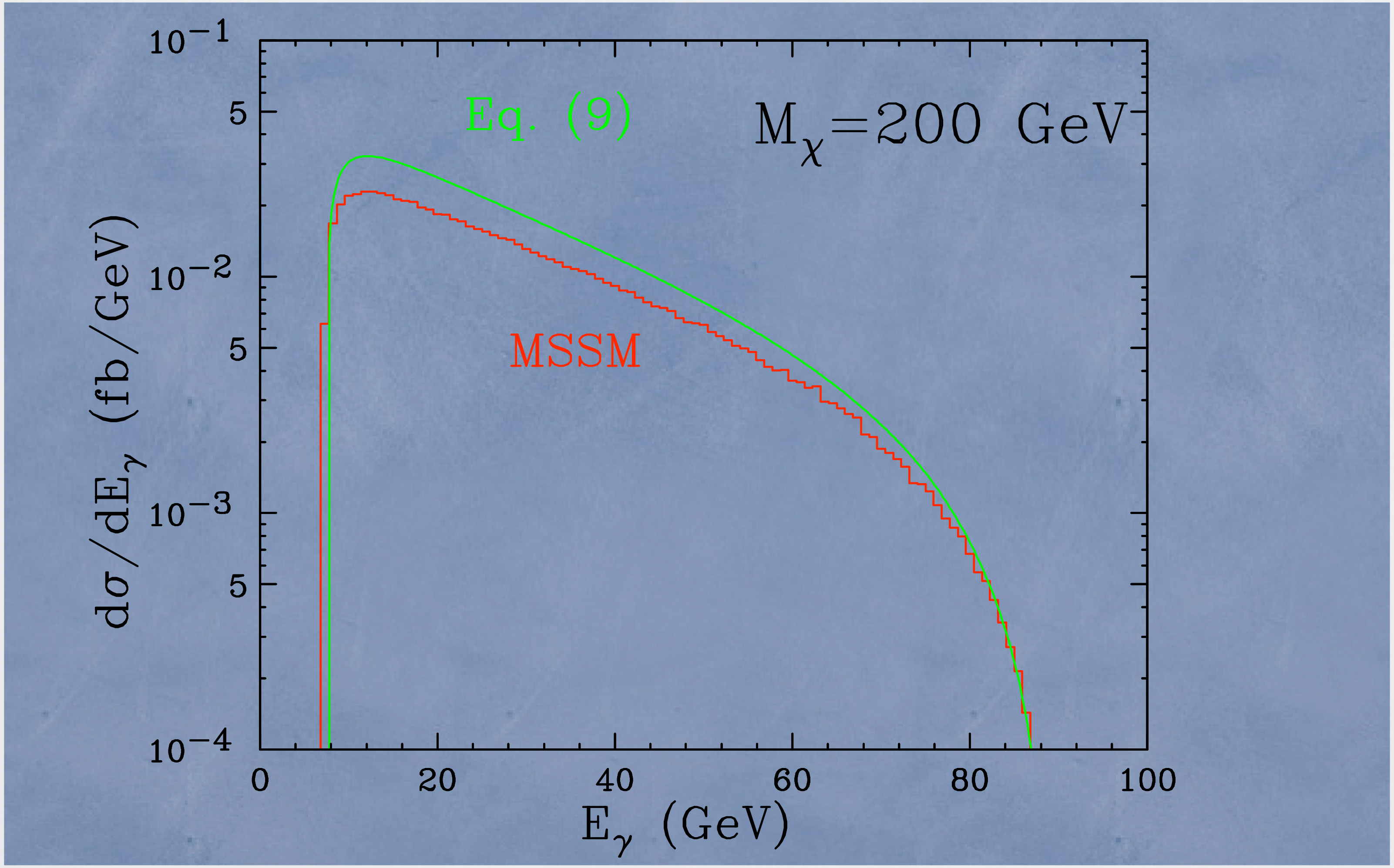

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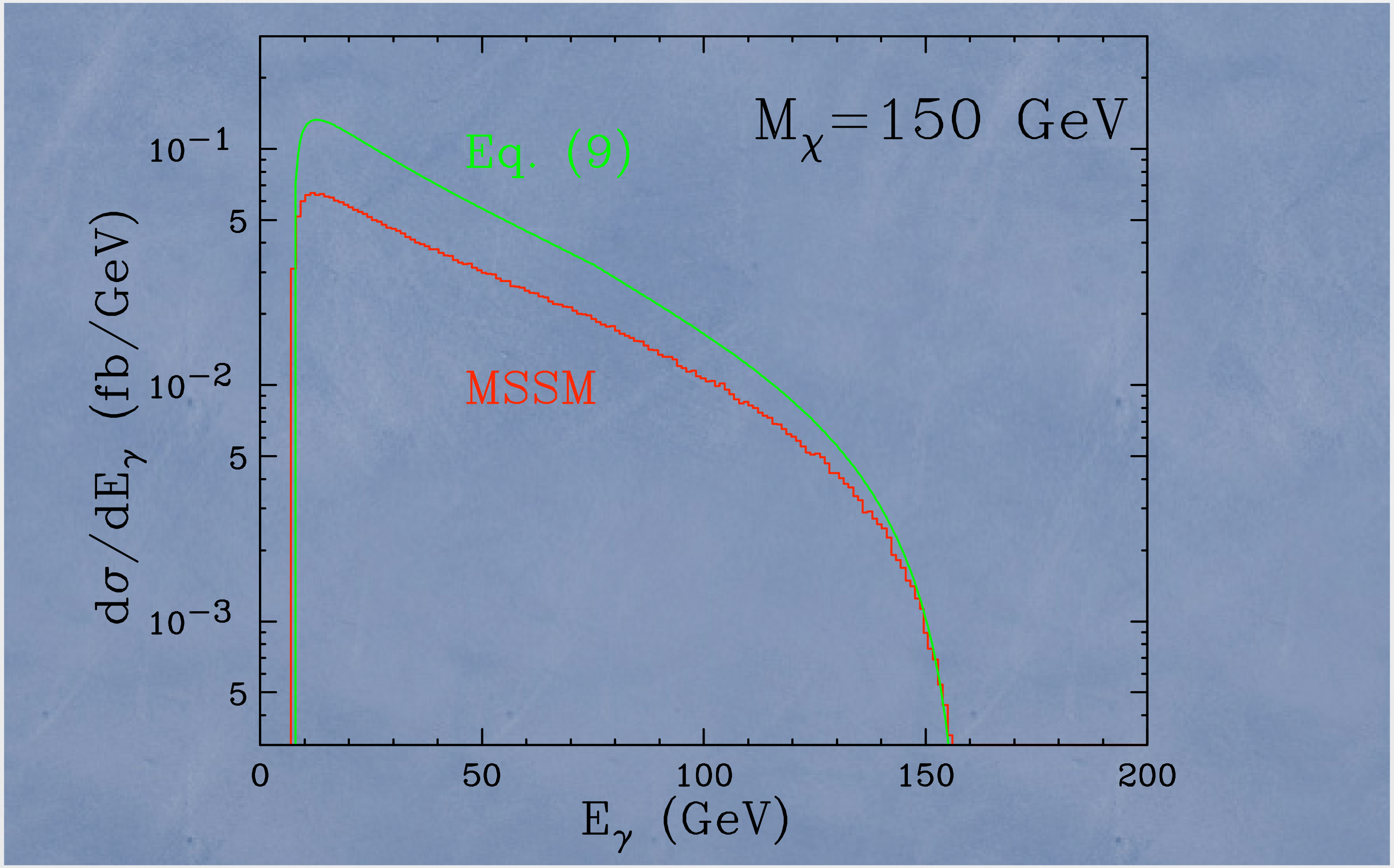

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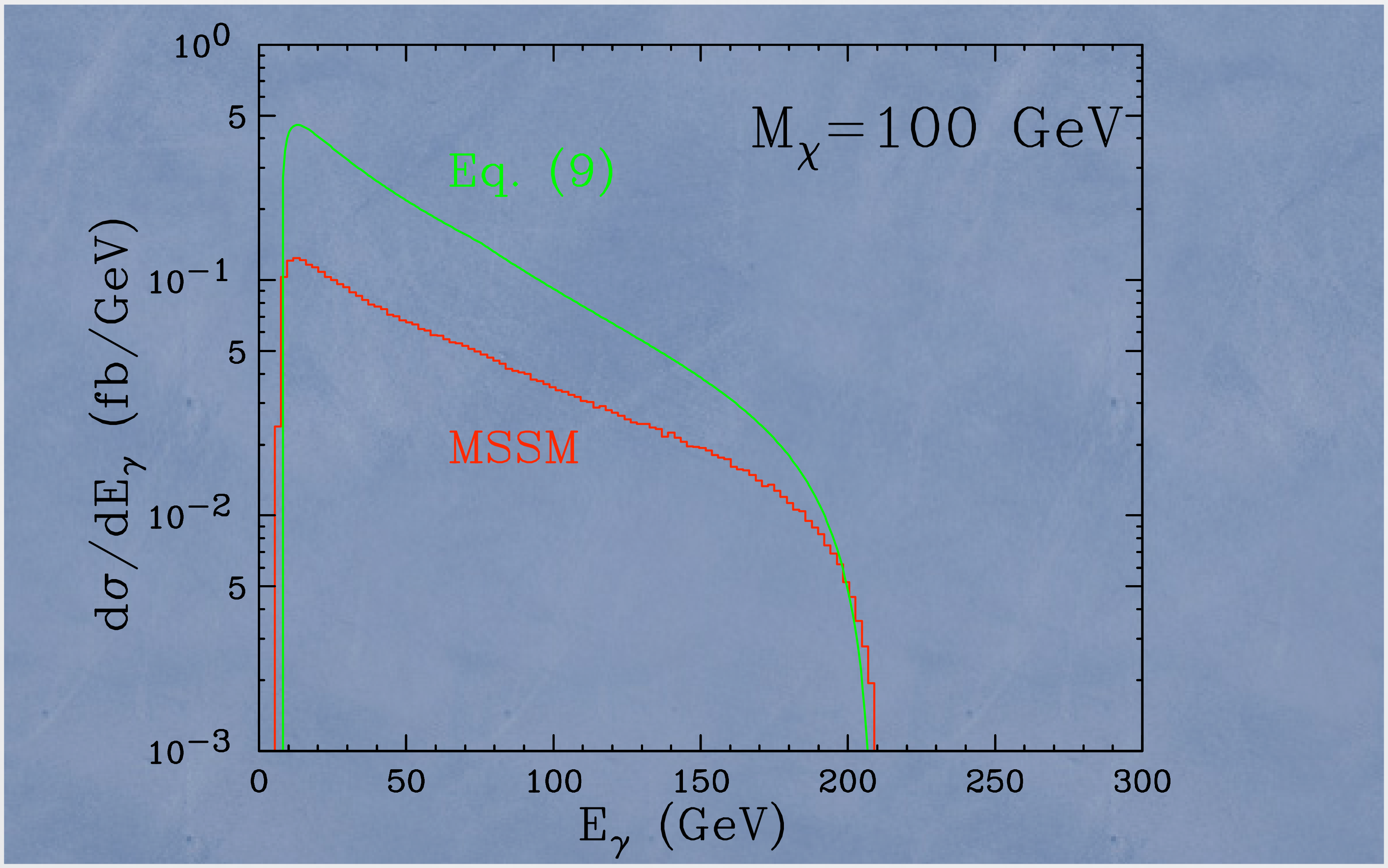


$$p_T^\gamma > 7.5\ \mathrm{GeV}, \sin\theta > 0.1$$

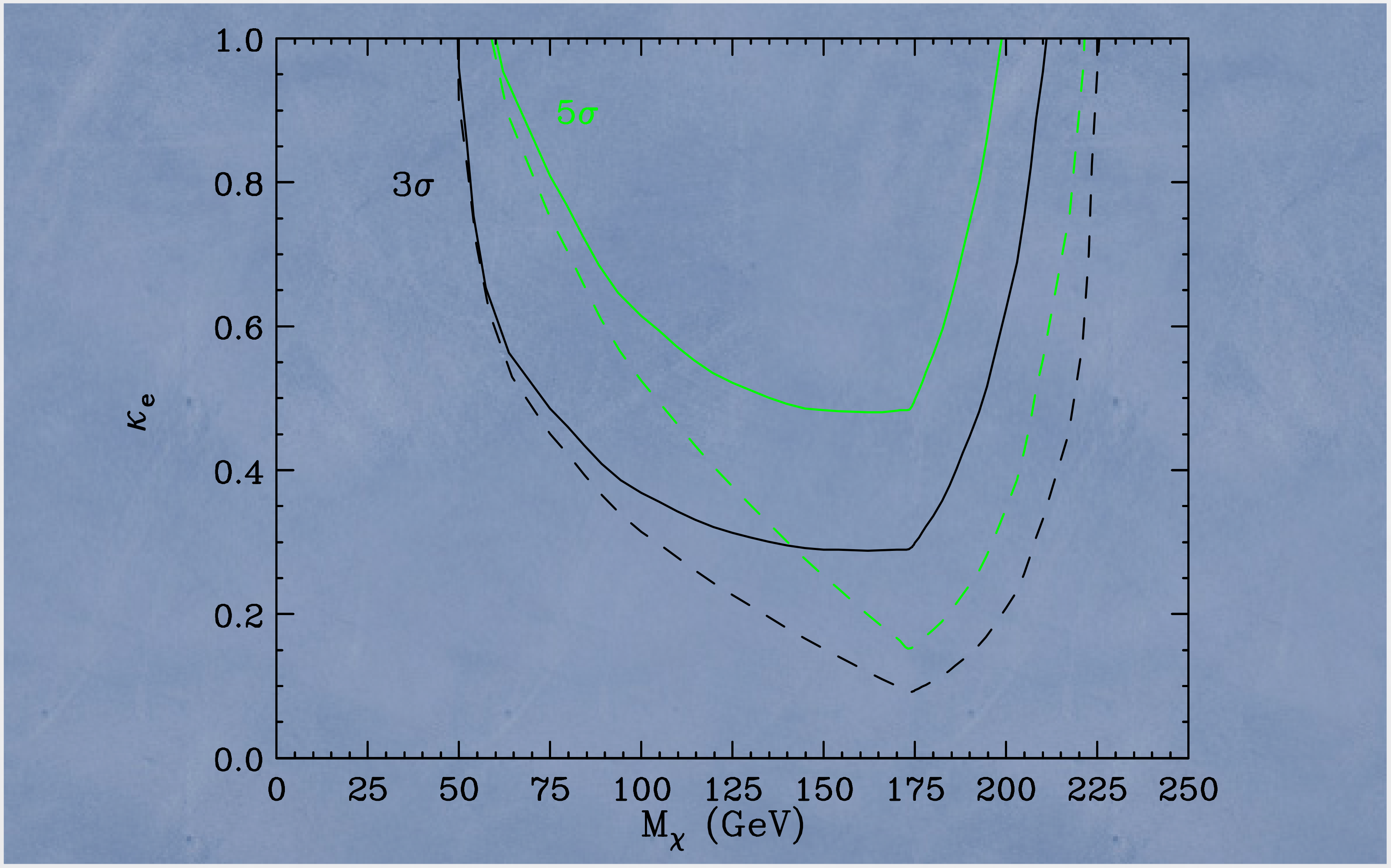
Lessons of the Comparison

- Collinear approximation works pretty well, even without an extra cut to suppress central photons!
- A lower cut on E_γ is necessary to select events with non-relativistic WIMPs

Experimental Strategy for a Model-Independent WIMP Search at the ILC

- Look for photon+missing energy events
- Impose $p_T^{\min}(\gamma)$ cut to eliminate fakes (mainly Bhabha)
- Impose $E_\gamma^{\min}$ cut to ensure non-relativistic WIMPs
- Compute and subtract the irreducible background (mainly $e^+e^- \to \nu\bar{\nu}\gamma$)
- Look for deviations from zero!

The Reach of a 500 GeV LC



Dash - stat. only ($\mathcal{L} = 500\ \mathrm{fb}^{-1}$), Solid - stat. + 0.3% syst.

Cuts: $\sin\theta > 0.1, \quad p_T^\gamma > 7.5\ \mathrm{GeV}, \ x_\gamma \in [1 - 8M_\chi^2/s, 1 - 4M_\chi^2/s]$

Comments

- Beam polarization reduces the background:

$$\sigma(e_L^- e_R^+ \to \nu\bar{\nu}\gamma) \gg \sigma(e_R^- e_L^+ \to \nu\bar{\nu}\gamma)$$

- Example: “P-symmetric WIMPs”

$$\sigma(e_L^- e_R^+ \to \chi\chi) = \sigma(e_R^- e_L^+ \to \chi\chi)$$

- Sig/Back improved by a factor of 5 for $P_- = 0.8,$ $P_+ = 0$, and a factor of 18.5 for $P_- = 0.8, P_+ = 0.6$

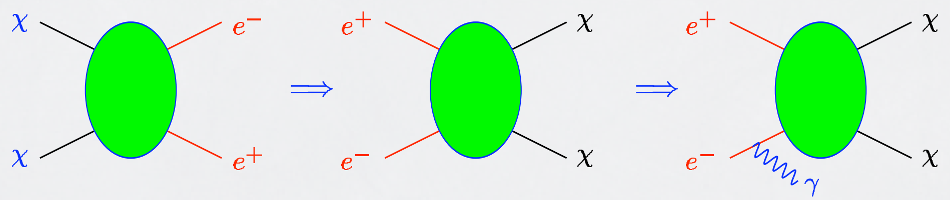
- The approach can be applied to pp collisions as well, but backgrounds are much more severe (see S. Su’s talk)

Conclusions

- Cosmology provides precise, model-independent information on the NR limit of WIMP total annihilation cross section (with mild assumptions - generic mass spectrum)
- Using detailed balancing and collinear factorization, this leads to a 1-parameter prediction of photon+missing E rates due to WIMP pair-production
- This prediction is independent of microscopic physics (SUSY, UED, LH, ...)
- Predicted rates are challenging but may be observable at the ILC

Summary: WMAP -> ILC

WMAP $\Omega_{\rm dm} \Longrightarrow$



$\Longrightarrow$ ILC $\sigma(\gamma + \not{E})$