Dark Matter: Colliders (and Direct Detection)

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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)

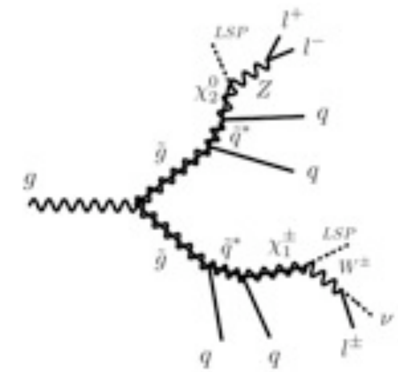
- χ is massive (1 GeV - 10 TeV range) ⇒ χ's are in thermal equilibrium with the SM matter as long as T>M(χ): $n_\chi \sigma v > H$

- When T<M(χ), $n_\chi \propto \exp(-M/T)$ (Boltzmann suppression) and χ's decouple

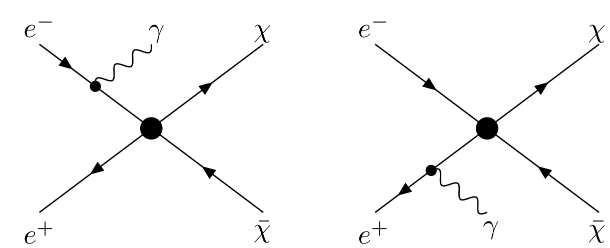
- Energy density of χ's today: $\rho_\chi \approx \frac{T_0^3}{M_{\rm pl}\sigma} \sim \rho_c$

WIMPs at Colliders

- Much of the reasonable mass range for WIMPs is within reach of the LHC and ILC/CLIC
- Two basic ways to produce WIMPs at colliders:
    - In decay of heavier exotic particles: for example



    - Direct production: for example

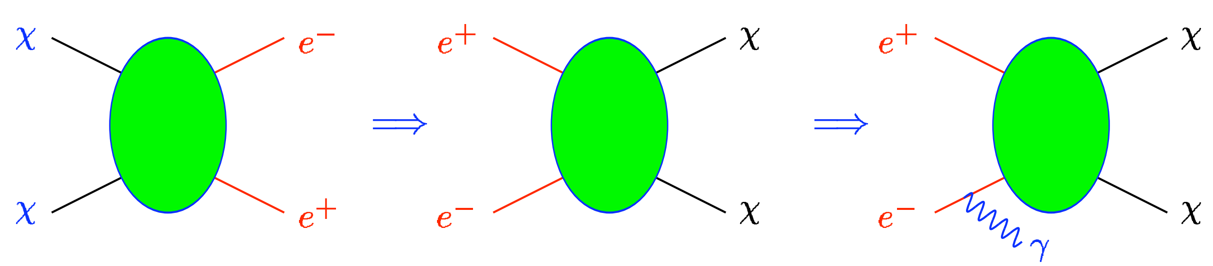


- Production in decay can dominate (e.g. if decaying particle is colored → high rate) but is more model-dependent (assumptions beyond WIMP!)
- Strong LHC bounds on colored exotic states decaying to MET+SM shrinking parameter space for observing WIMPs in decays...
- Direct production is less model-dependent, and is not yet strongly constrained. Will be my focus in this talk.

Predicting WIMP Signatures: "Model-Independent" Approach

- Many particle physics models contain WIMPs: SUSY, Extra Dimensions, Little Higgs, etc.
- Direct (radiative) WIMP production can be described within a model-independent formalism [Birkedal, Matchev, MP, hep-ph/0403004]

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



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

Assumptions:

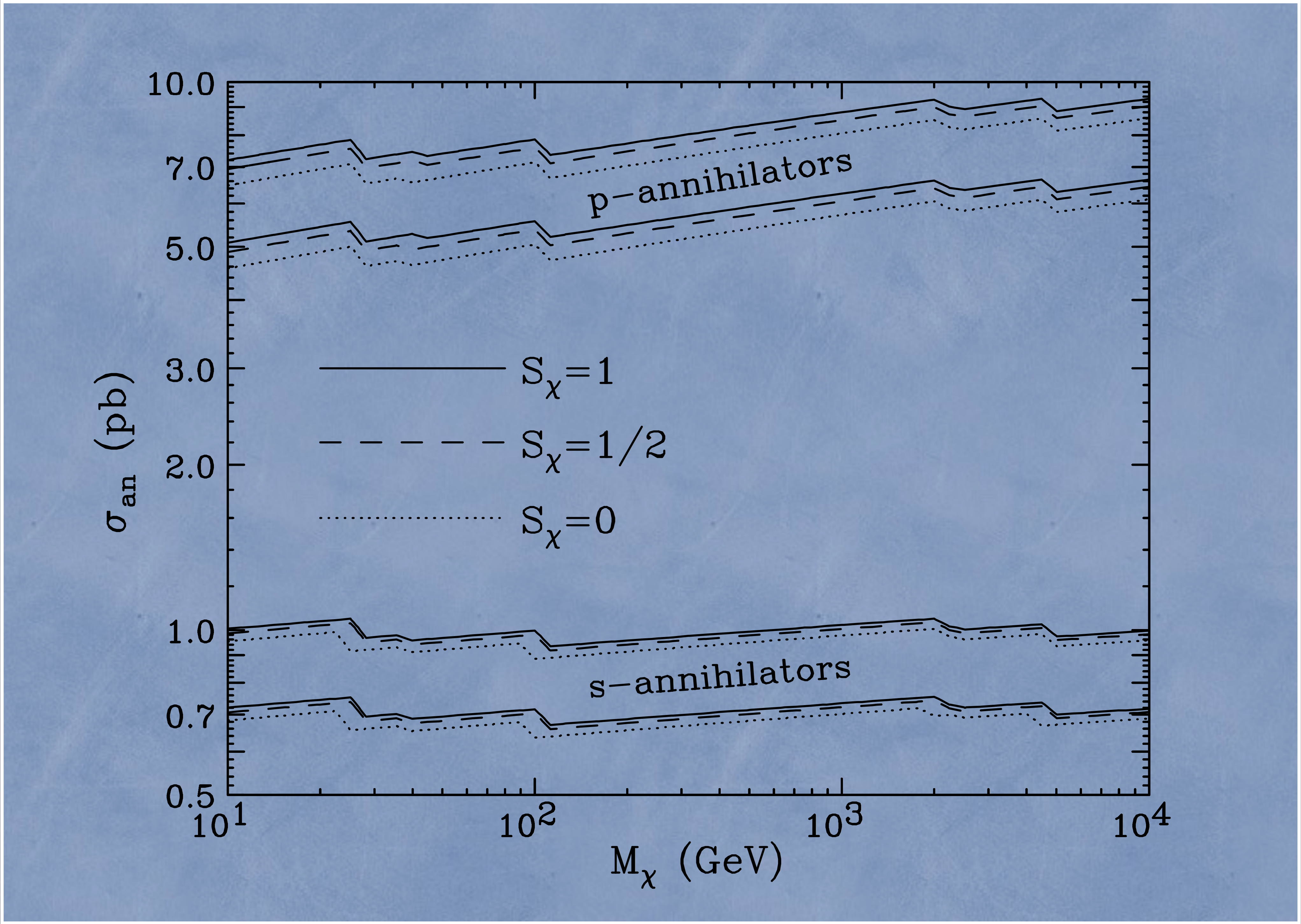
- Assume generic mass spectrum (no resonances, no coannihilations)
- At the time of χ decoupling, the only important reactions are $\chi\chi \leftrightarrow X_i \bar{X}_j$, where X_i is SM
- For non-relativistic WIMPs, can be expanded as:

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

- Dominated by either s-wave or p-wave
- Define

$$\sigma_{\mathrm{an}} = \sum_i \sigma_i^{J_0}$$

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:

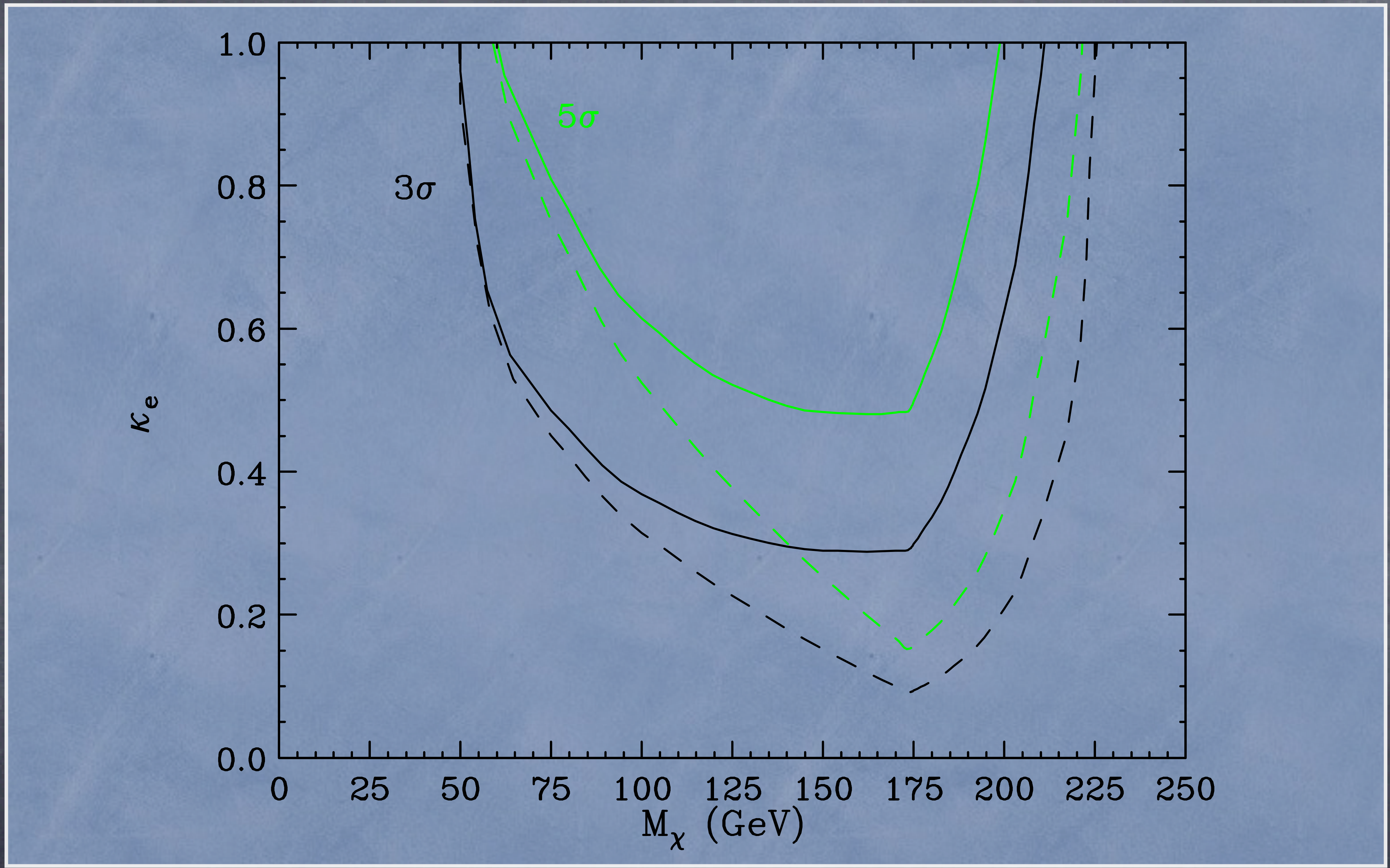
$$\frac{d\sigma(e^+e^- \to 2\chi+\gamma)}{dx\, d\cos\theta} \approx \mathcal{F}(x,\cos\theta)\hat{\sigma}(e^+e^- \to 2\chi)$$

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

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

Detector-Level Studies

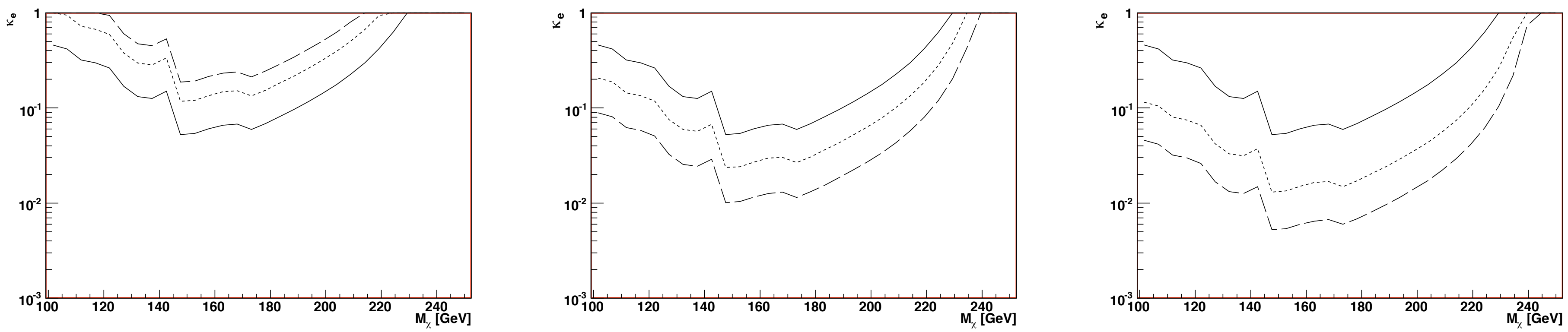
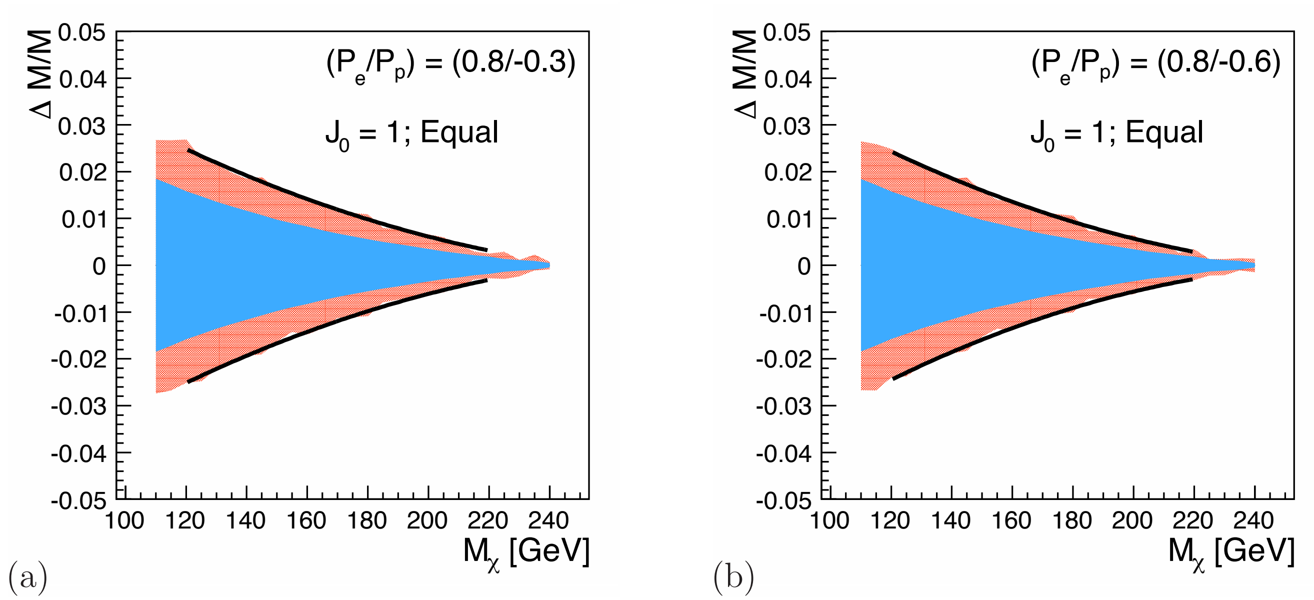


Figure 4: 3σ observation reach of the ILC for a Spin-$\frac{1}{2}$ WIMP in terms of WIMP mass and κ_e for three different assumptions on the chirality of the electron-WIMP coupling, see text. Full line: $P_{e^-} = P_{e^+} = 0$, dotted line: $P_{e^-} = 0.8, P_{e^+} = 0$, dashed line : $P_{e^-} = 0.8, P_{e^+} = 0.6$. Regions above the curves are accessible.

[Bartels, List, 0709.2629]

Reach down to $\kappa_e \sim 10^{-2}$!



[Bartels, Berggren, List, 1206.6639]

Percent-level mass measurement!

Alternative: Effective Operator Approach

- The formalism I just reviewed makes no reference to a Lagrangian
- Alternative: Model DM-SM couplings with effective operators in a Lagrangian [Beltran et. al. 1002.4137; Goodman et. al. 1005.1286; Bai, Fox, Harnik, 1005.3797; Fox et. al. 1109.4398]
- Example: Spin-1/2 Dirac WIMP, some of the possible electron-DM couplings are

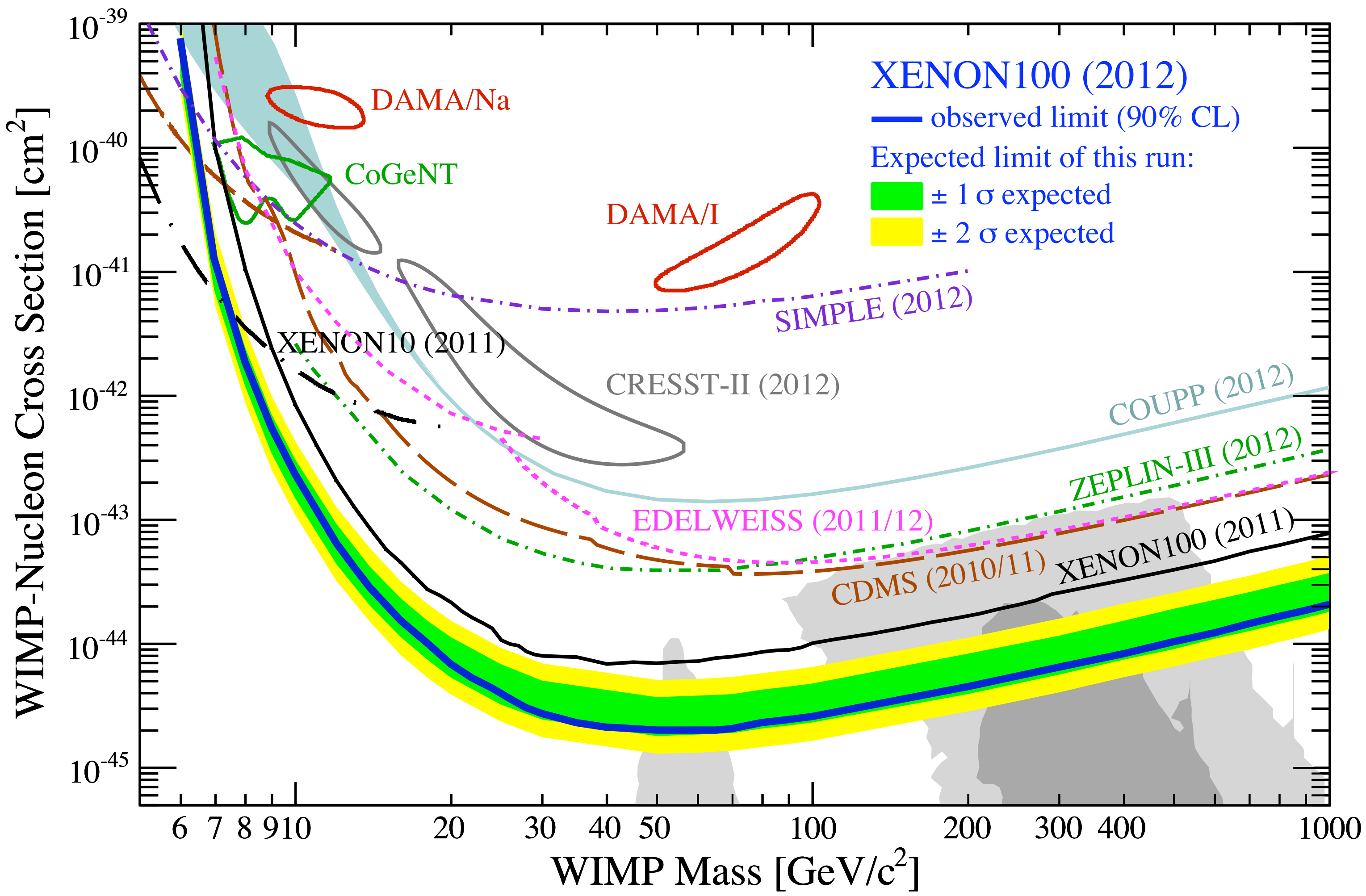
$$\mathcal{O}_V = (\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell)\,, \qquad \mathcal{O}_A = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma^5\ell)\,,$$

$$\mathcal{O}_S = (\bar{\chi}\chi)(\bar{\ell}\ell)\,, \qquad \mathcal{O}_t = (\bar{\chi}\ell)(\bar{\ell}\chi)\,,$$

- Parameterizes the effect of heavy particles mediating WIMP-DM interactions (e.g. t-channel selectrons in the MSSM), in a model-independent way
- Works if the scale Λ is above the energy scale of the experiment
- Does not require NR WIMPs - broader kinematic validity
- Applicable to more processes - e.g. $q\chi$ elastic scattering (direct detection!)

Direct Detection Status

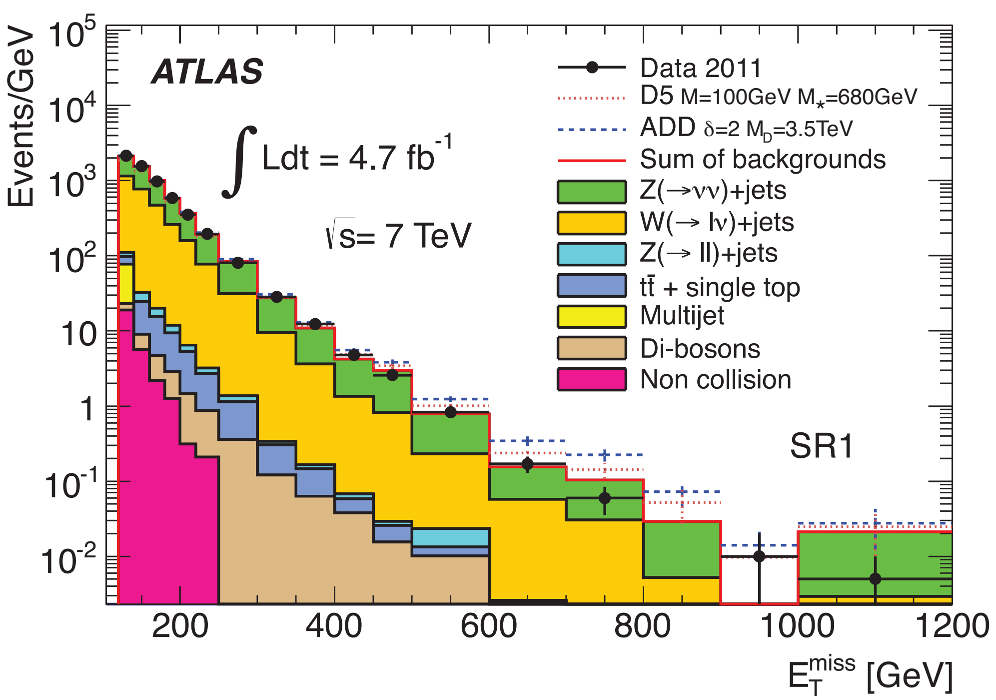
[XENON100, 1207.5988]

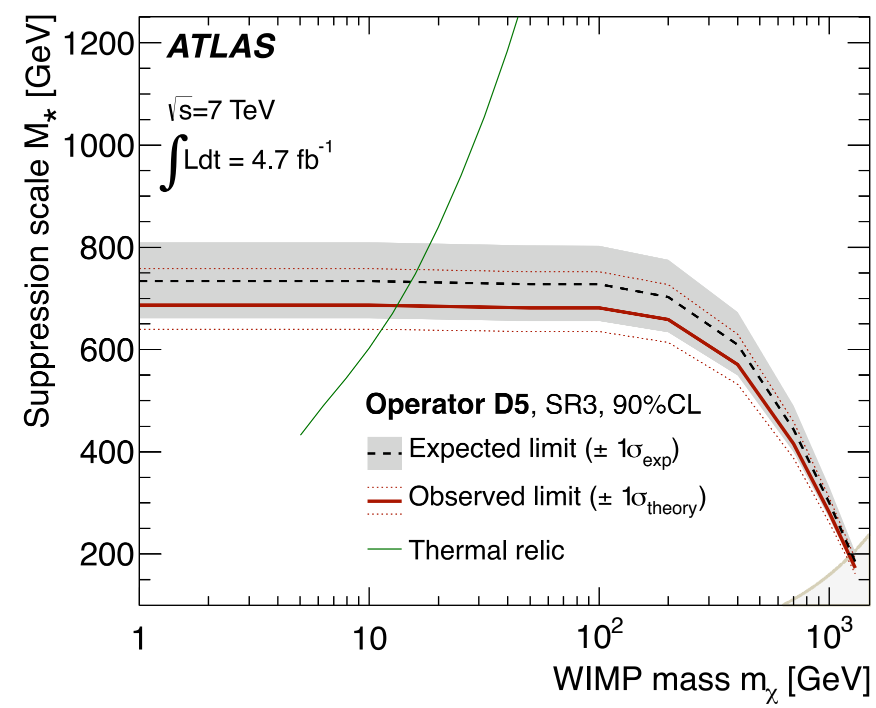


LHC Limits

[ATLAS, 1210.4491; see also CMS, 1206.5663]

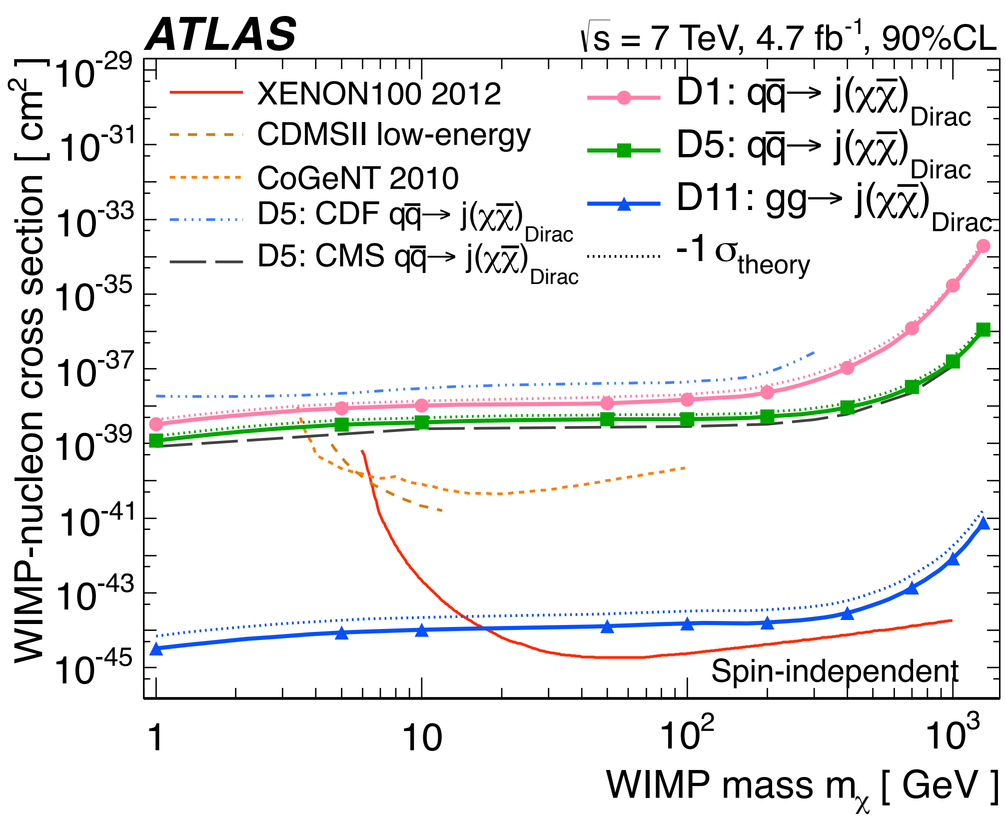
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

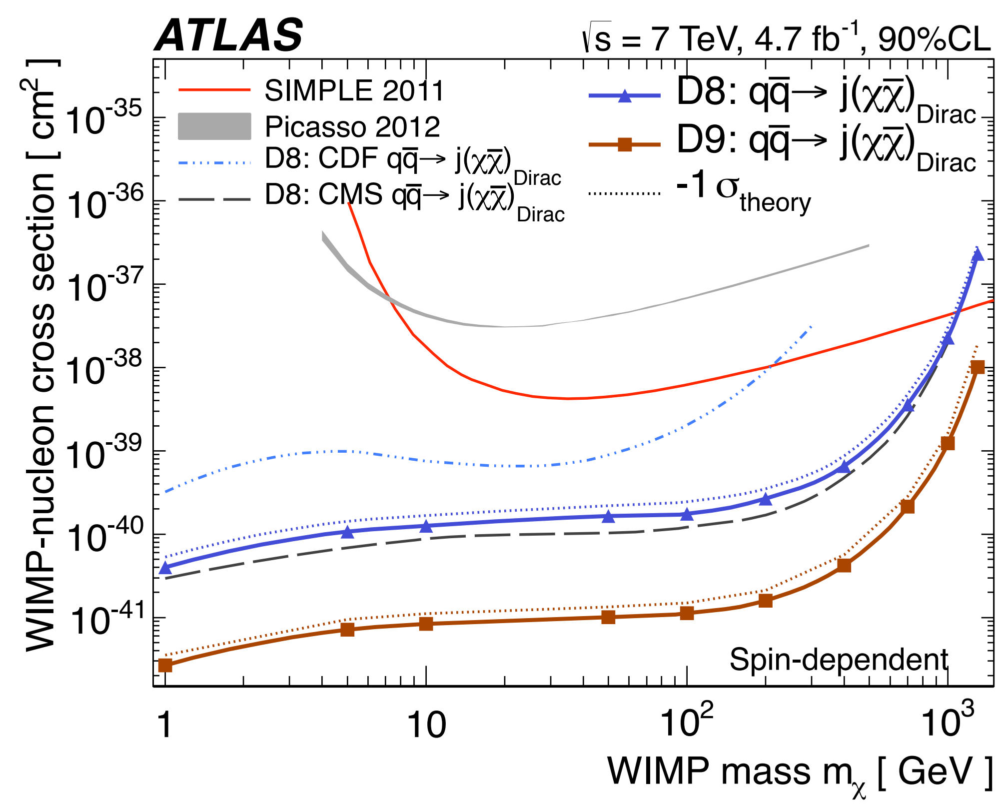




LHC vs. Direct Detection

[ATLAS, 1210.4491; see also CMS, 1206.5663]





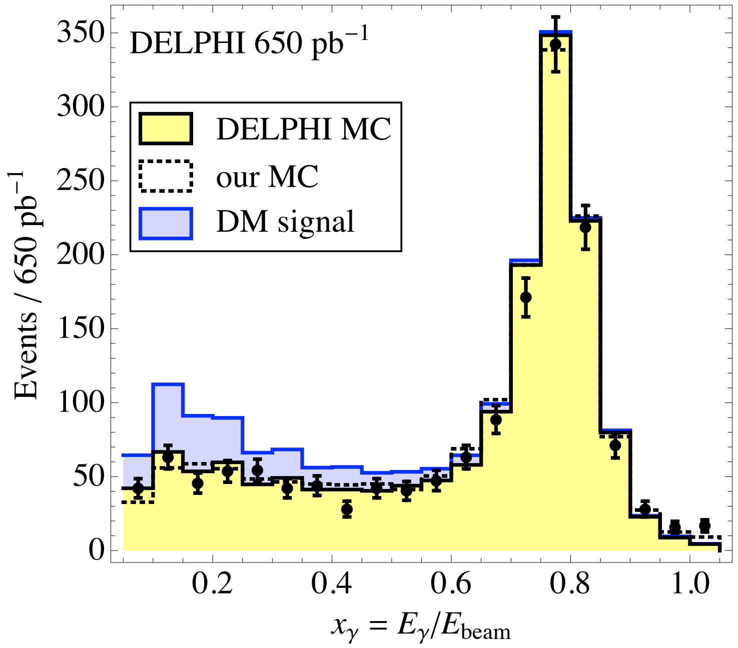
Collider Searches are more sensitive in two regimes:

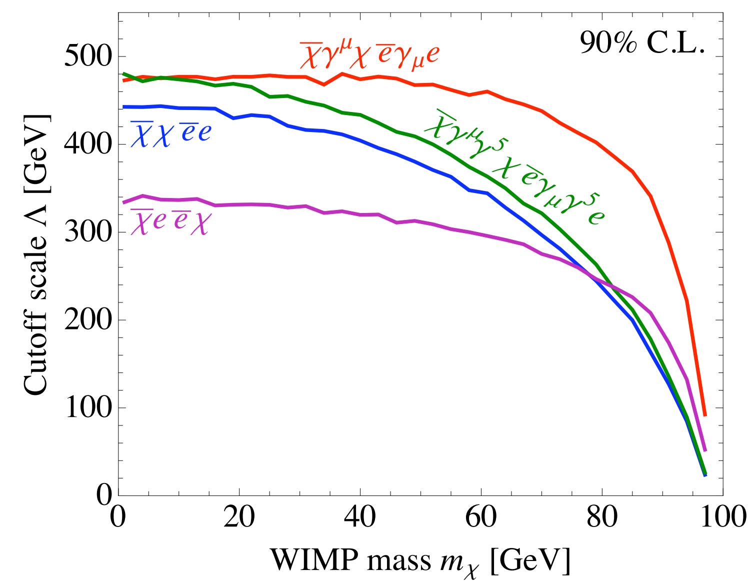
Low WIMP mass (<10 GeV)

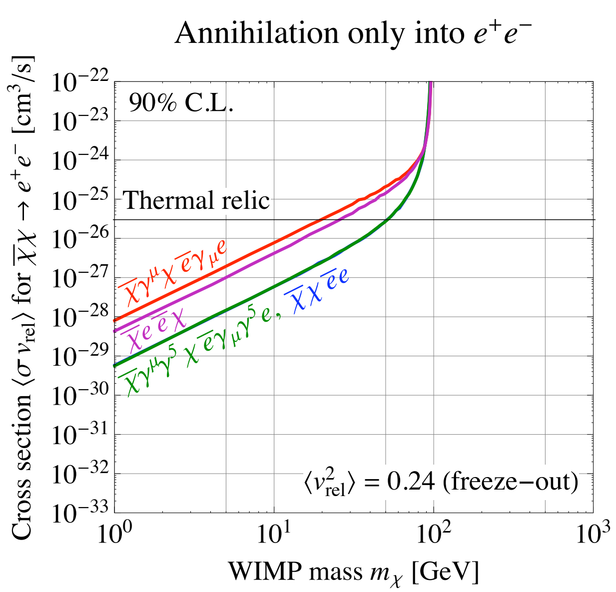
Coupling via Spin-Dep. operators

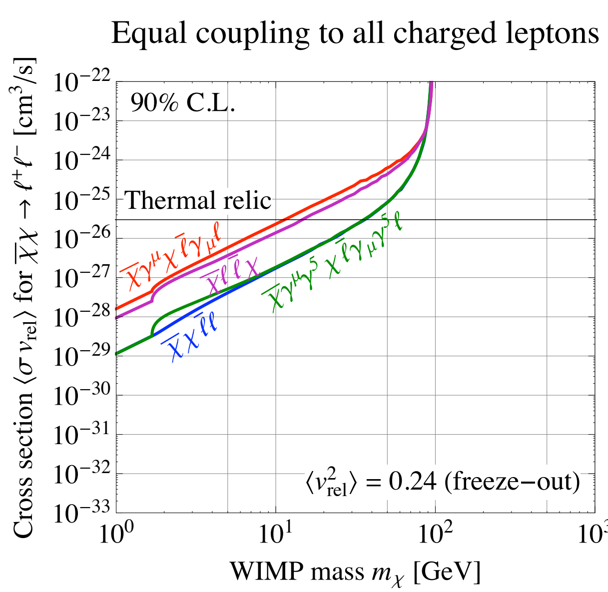
LEP-2 Limits

[Fox, Harnik, Kopp, Tsai, 1103.0240]







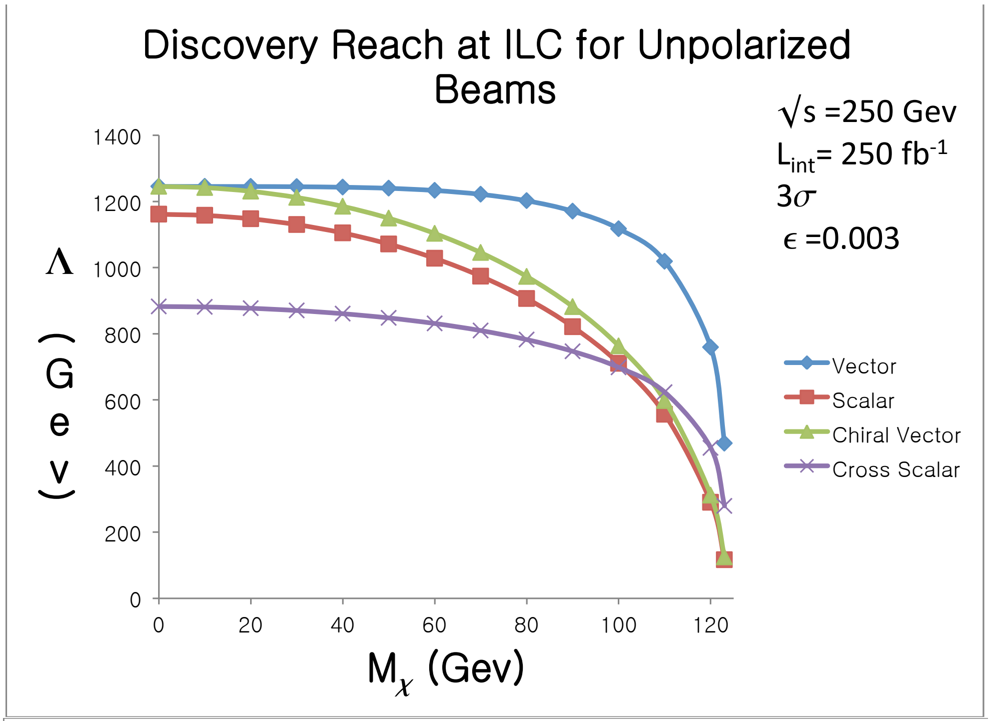


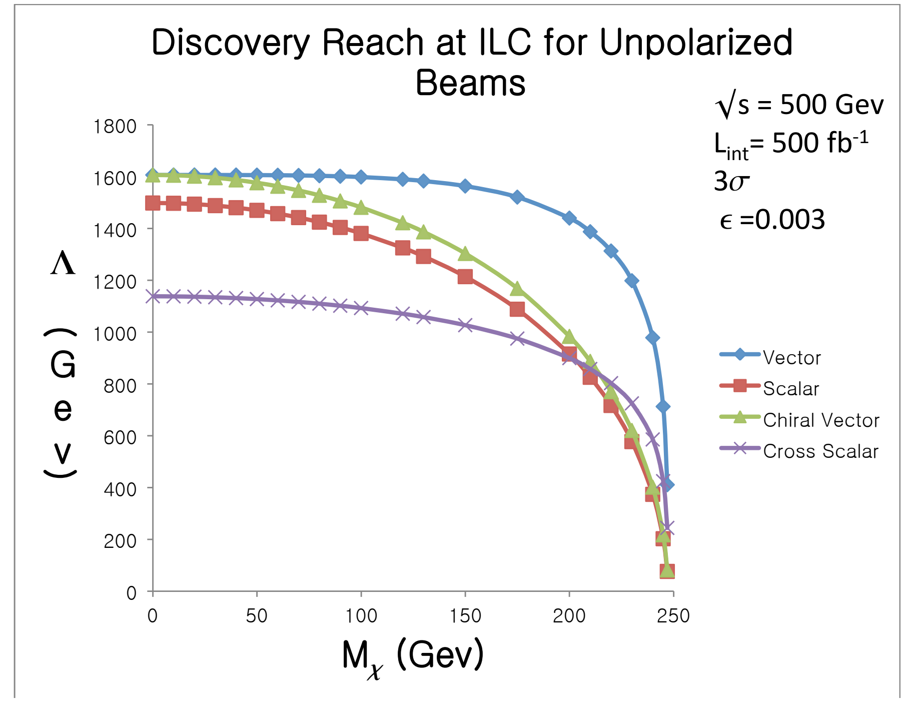
Leptophilic, thermal relic WIMP ruled out below 10-50 GeV dep. on assumptions

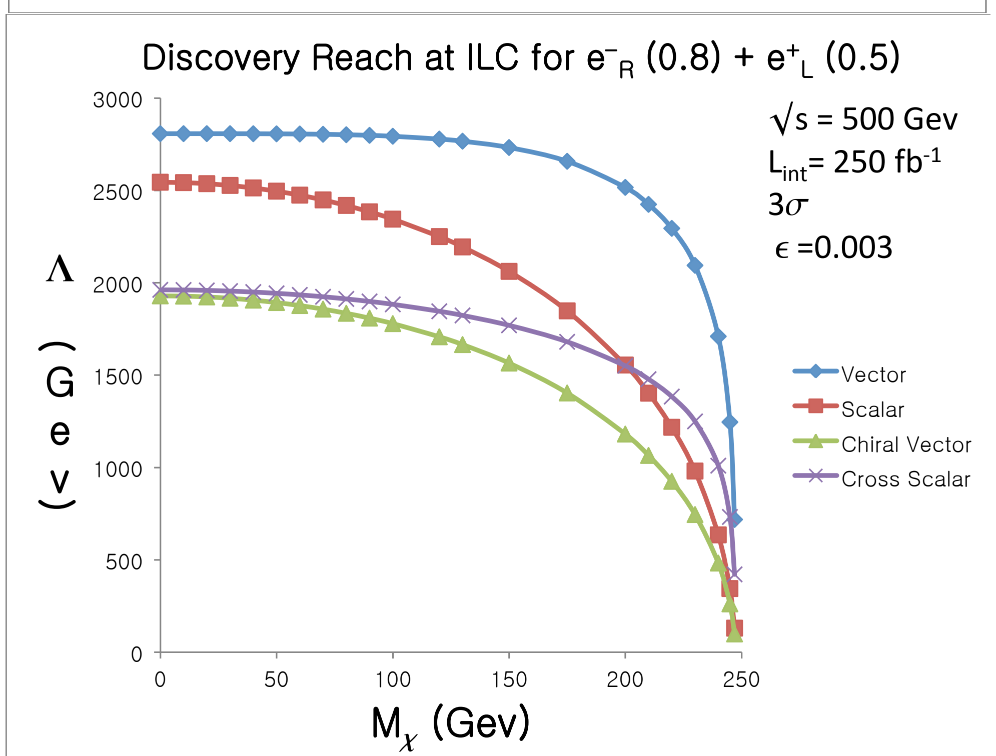
Expected ILC Limits

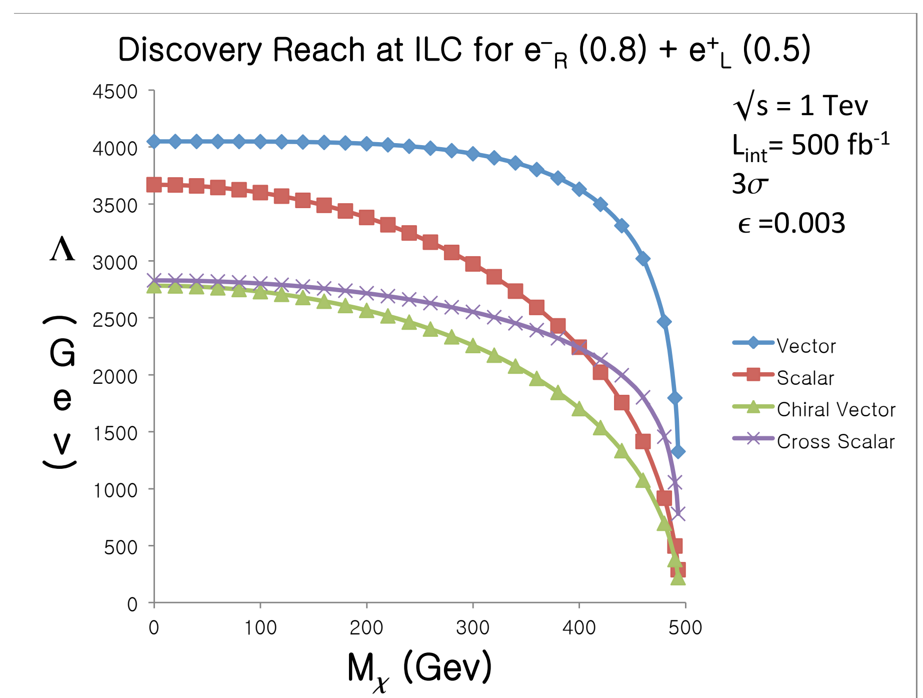
[Yoonseok Chae, MP, to appear]

PRELIMINARY!





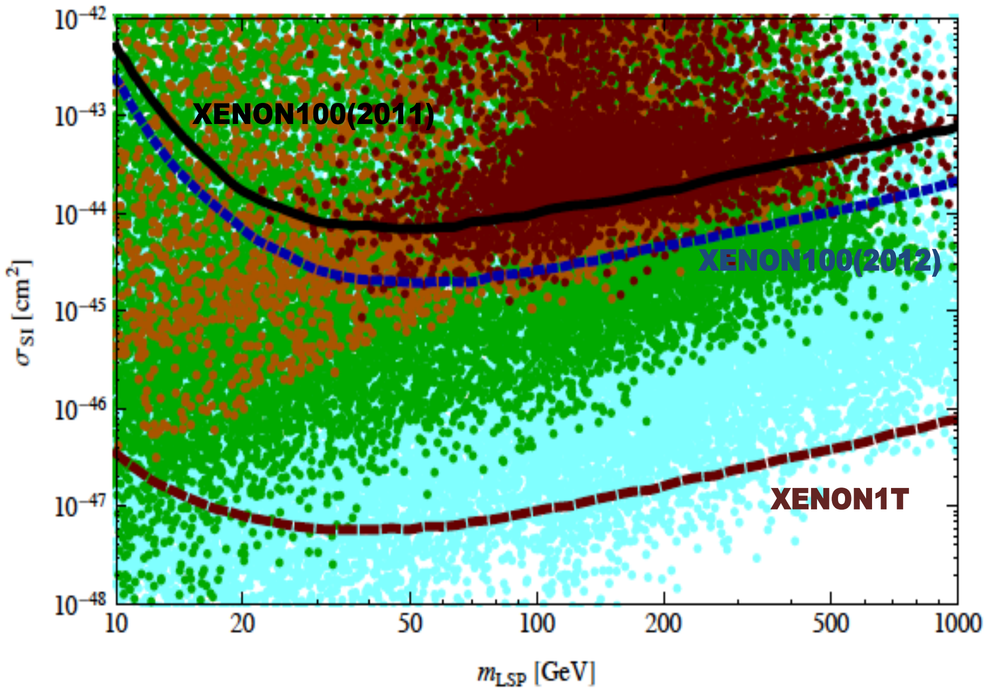




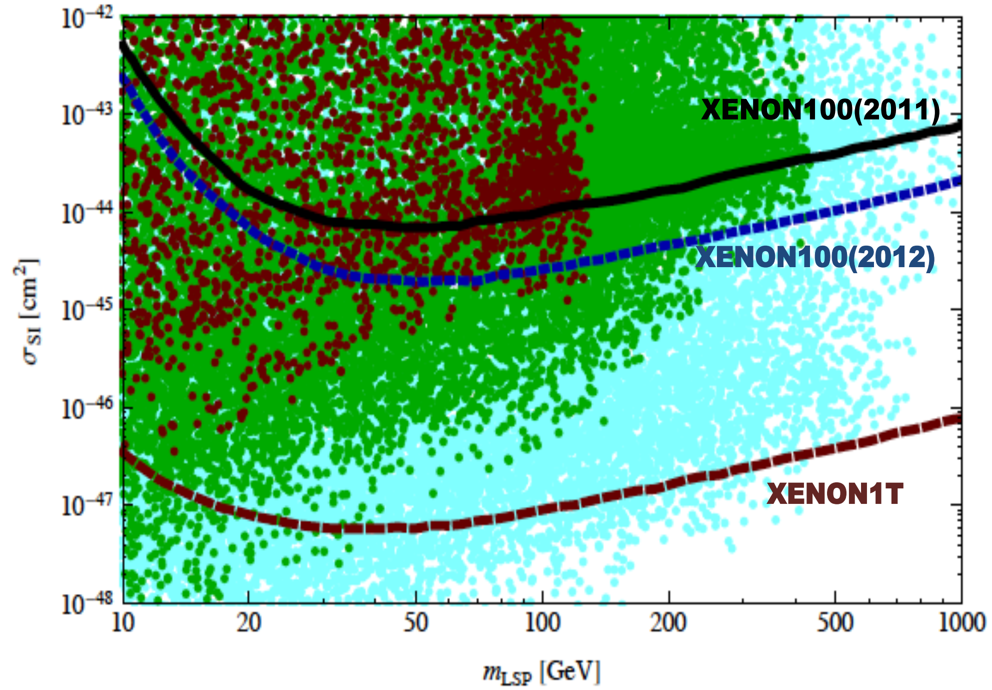
PRELIMINARY!

Direct Detection/Tuning in (N)MSSM

[Shakya, MP, 1107.5048; 1208.0833]



"Purity": fraction of the subdominant (gaugino or Higgsino) component in the LSP



Fine-tuning in EWSB (tree-level)

Tension is already developing in (N)MSSM from null result of direct detection searches!