DM@ILC

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LC Days, Saclay, Nov 2013

Outline

- Introduction.
  - The ideas behind model independent search for WIMPs at ILC
  - Effective Operators
- Limits - current and projected
  - LHC
  - Direct searches
  - ILC
  - The relation between them
- Detection and parameter determination at ILC
- Conclusions and Outlook.

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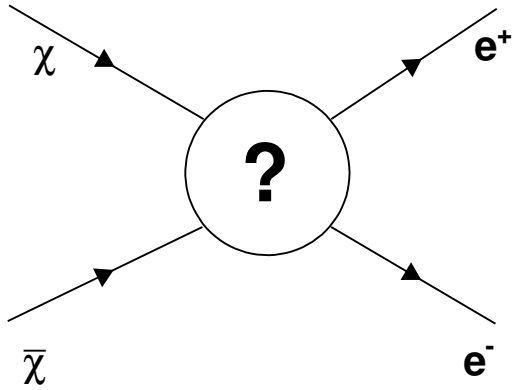
Introduction

- Cosmology $\Rightarrow$ 25% of universe = Dark Matter
- One possibility: WIMPs (χ).
- Bottom-up approach:
  - Assume only WIMP, don't rely on other new particles
  - Only know $< \sigma_v >$ for $\chi\chi \to f\bar{f}$ (Caveat: resonant or co-annihilation!)
  - Or: effective operator approach
- Direct searches for primordial WIMPs in WIMP-nucleon scattering
- Searches for direct WIMP production at collider:
  - $pp \to \chi\chi g$ or $\chi\chi\gamma$
  - $e^+e^- \to \chi\chi\gamma$

Model independent WIMP search at ILC: the idea

In models where the relic density Ω_{dm} depends on rate for $\chi\chi \to$ SM-particles, crossing-symmetry tells us what ee$\to \chi\chi$ is.



Vary

- κ_e annihilation fraction to electrons
- Lorentz structure ($1-\gamma_5$, 1 or $1+\gamma_5$).
- Dominating partial-wave of the f.s.
- WIMP spin.

$\Rightarrow$ Get sensitivity for all such scenarios.

How? χ is after all invisible ?!

Trick! Demand an ISR γ in the detector and nothing else.

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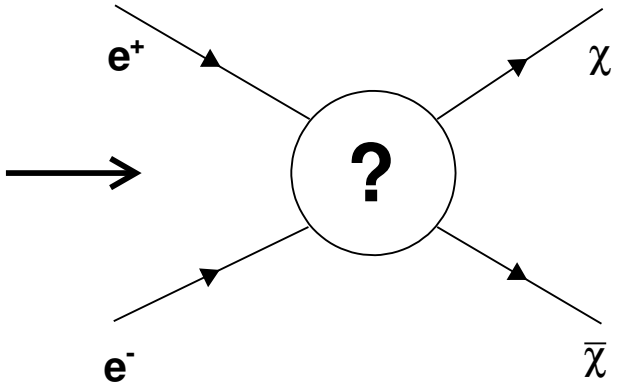

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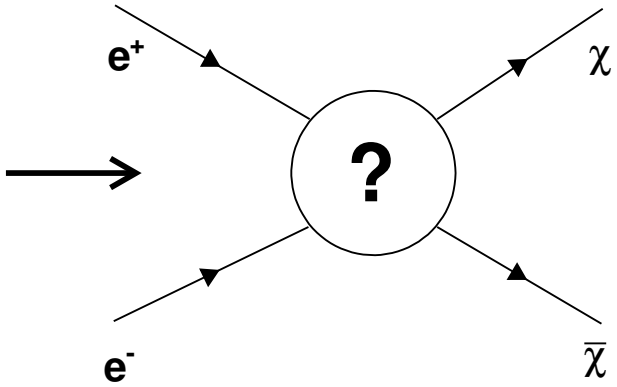

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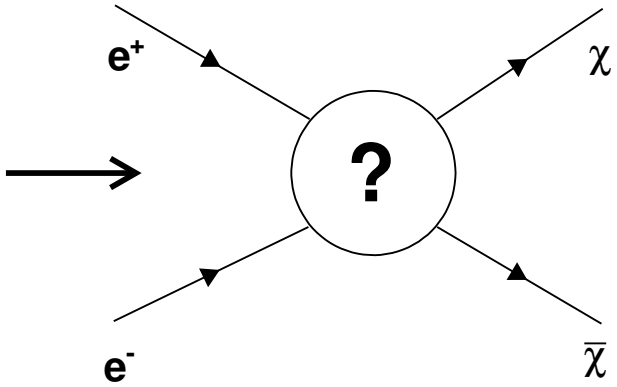

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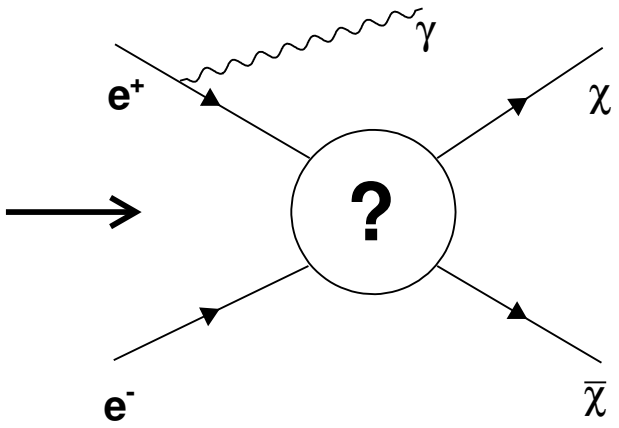

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Model independent WIMP search at ILC: the idea

Background: $ee \to \nu\nu\gamma$

- Recoil-mass peaks at M_Z
- If WIMP Lorentz-structure is different from $1 - \gamma_5$, beam-polarisation will reduce background.

Calculate the recoil mass to get M_{WIMP} from the threshold.

Vary assumptions, M_{WIMP}, polarisation $\Rightarrow$ discovery-reach and $\Delta(M_{WIMP})$.

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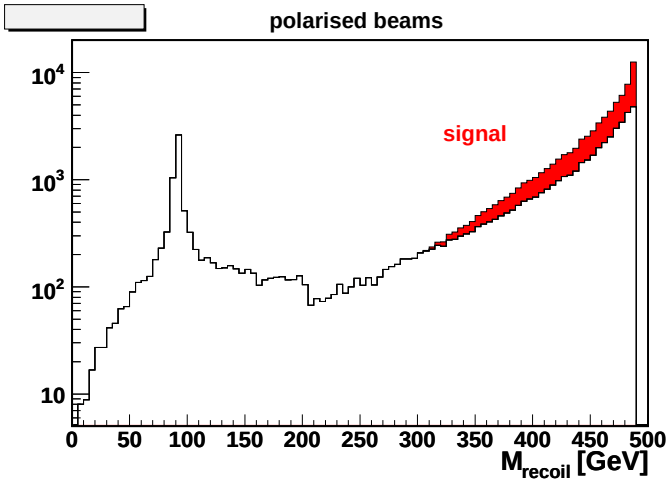

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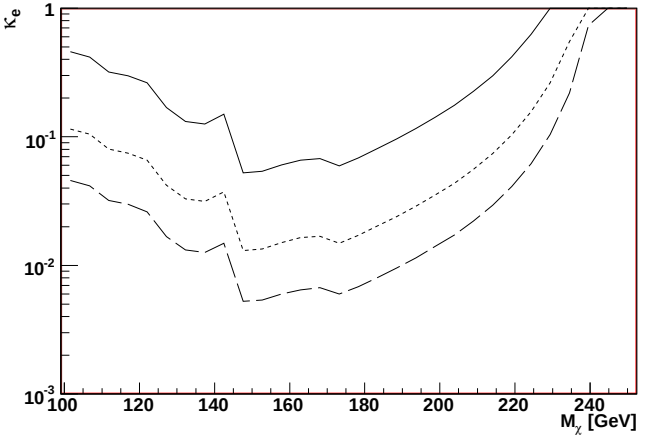

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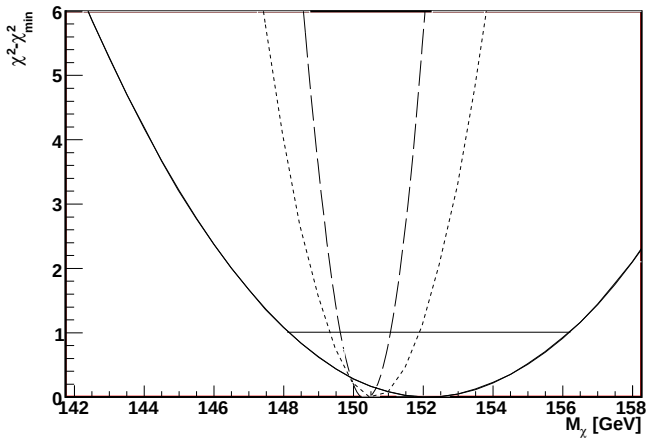

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Effective Operator Approach: Full model space

- Assume *fermion* / vector / scalar WIMP
- Plus heavy mediator particle:
  - Scalar / vector / axial-vector / ...
  - s-channel / t-channel / loop!
- Integrate mediator out
  → "contact interation"
  scale Λ (or M_*)

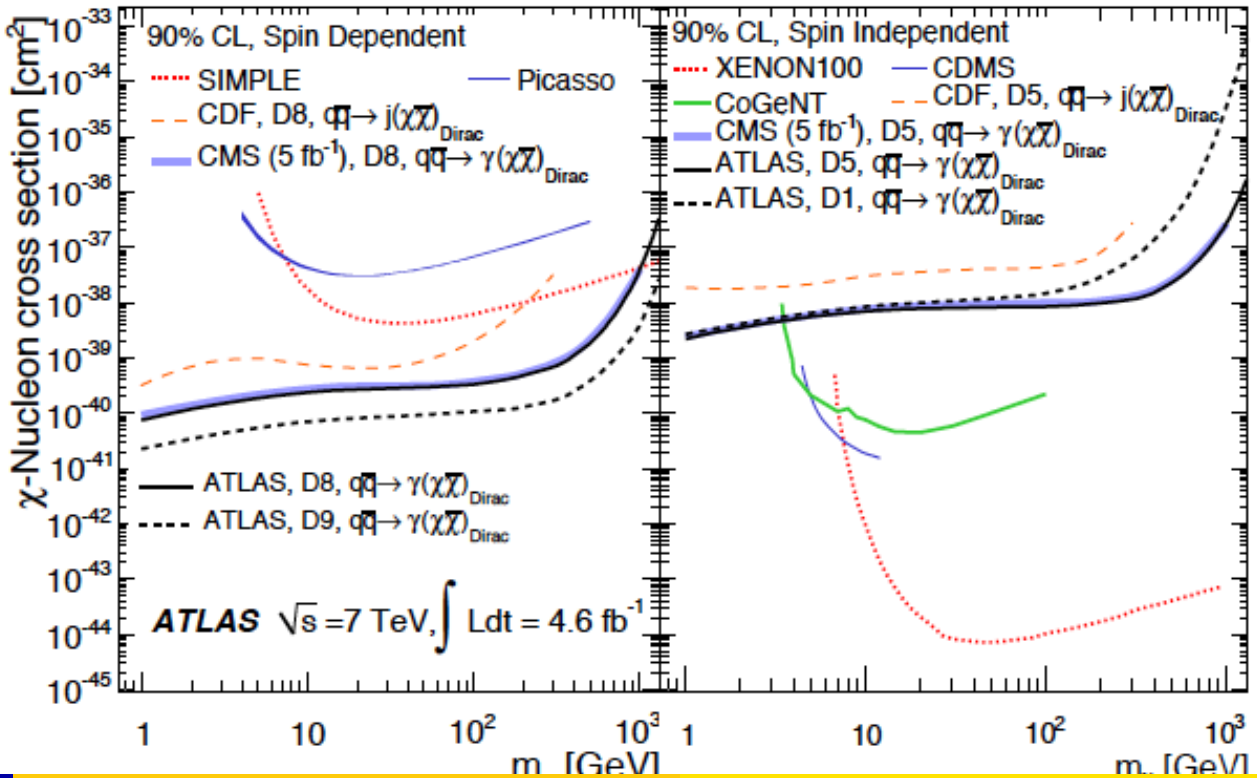
$$\mathcal{O}_V = (\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell)\,, \quad \text{(vector)}$$
$$\mathcal{O}_S = (\bar{\chi}\chi)(\bar{\ell}\ell)\,, \quad \text{(scalar, } s-\text{channel)}$$
$$\mathcal{O}_A = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma^5\ell)\,, \quad \text{(axial}-\text{vector)}$$
$$\mathcal{O}_t = (\bar{\chi}\ell)(\bar{\ell}\chi)\,, \quad \text{(scalar, } t-\text{channel)}.$$

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

LHC and direct searches

- Direct crossing relation: Both probe WIMP-nucleon interaction
- Hence: Unique relation LHC (ex: ATLAS mono-photon search) $\leftrightarrow$ direct searches
- Translation from pp $\rightarrow \chi\chi$ to WIMP-nucleon cross-section depends on assumed operator.

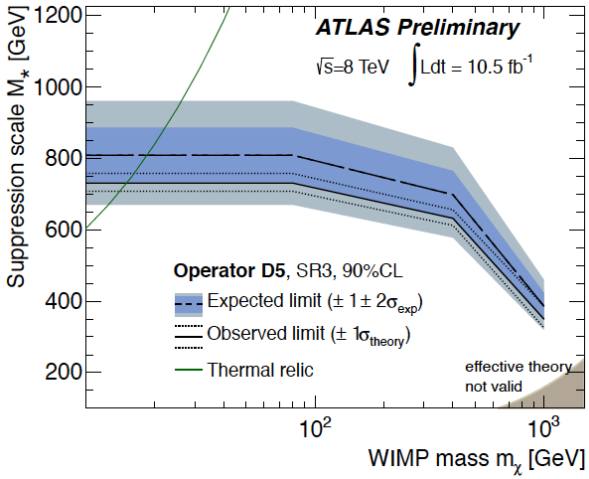
- D1: scalar, s-channel
- D5: vector
- D8: axial vector
- D9: magnetic moment

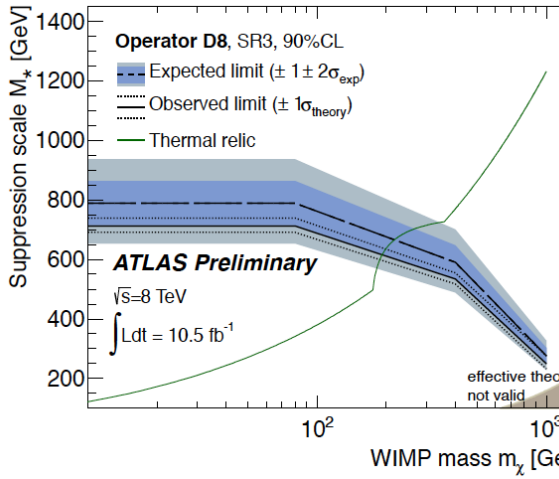


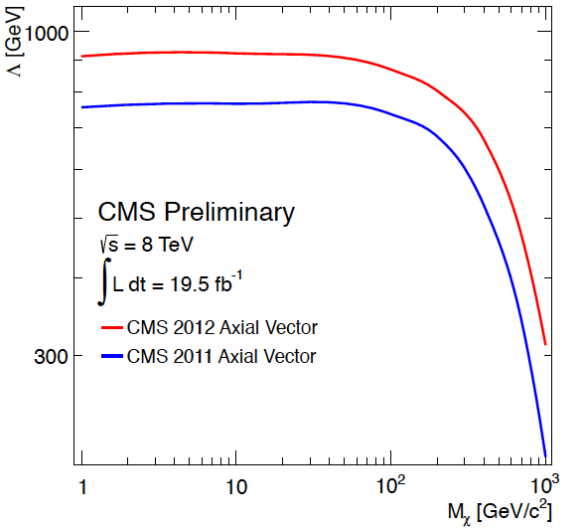
LHC: Limits on Λ

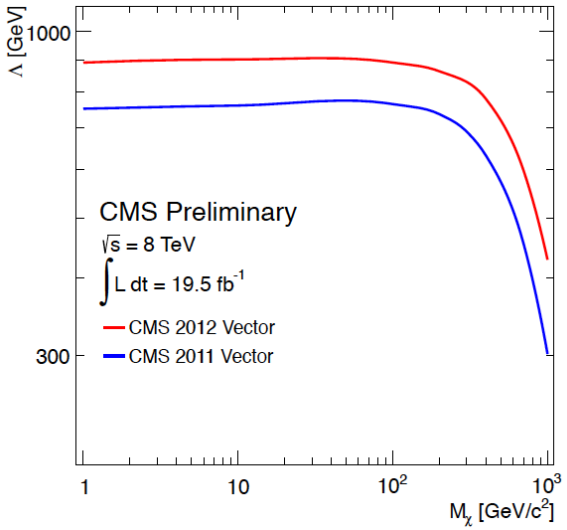
Eg mono-jet search:

- Vector / Axial vector limits 900 GeV for light WIMPs
- Note:
  - at 90% CL
  - Scalar limits 3x weaker
  - "Thermal relic" line assumes 100% annihilation to qq via this operator
  - $7 \rightarrow 8$ TeV & $5 \rightarrow 20$ fb^{-1} $\rightarrow$ 150 GeV increase of limit







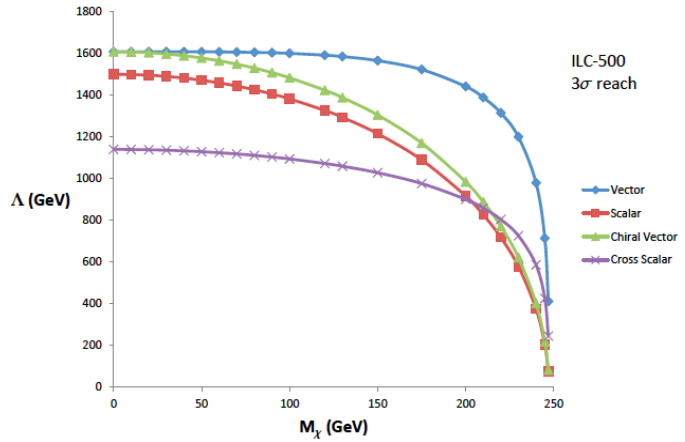


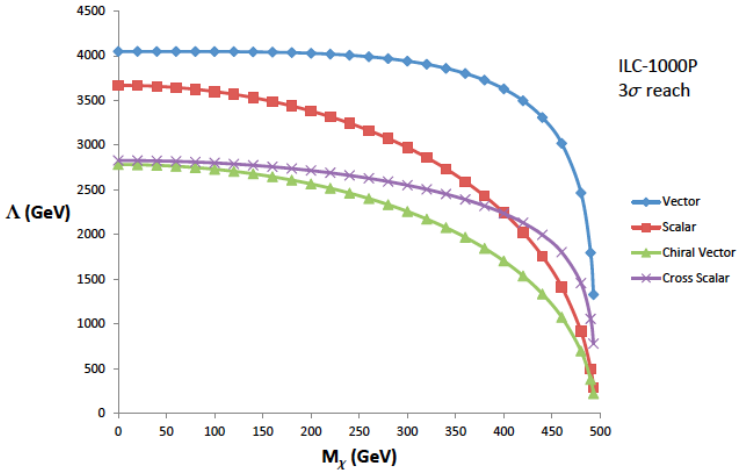
ILC: theoretician projection on Λ limits

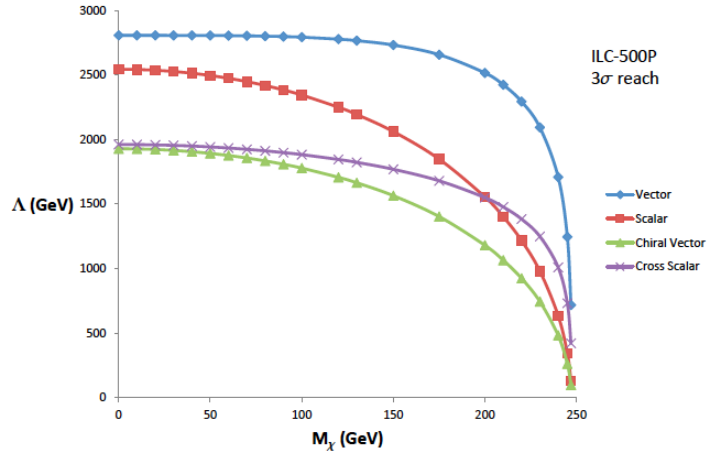
Monophoton search:

- 3σ observation reach (99.x% CL)
- Polarised case P(e^-,e^+) = (+80%,-50%): improves by ~factor 2
- Reach up to 3-4 TeV, far beyond E_{CM}

From 1211.4008, Chae & Perelstein





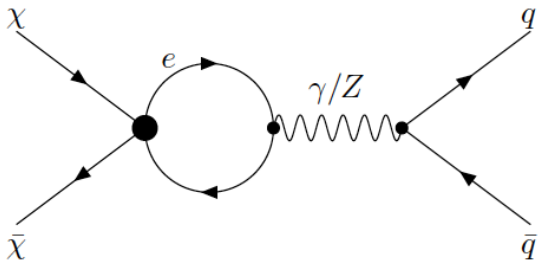


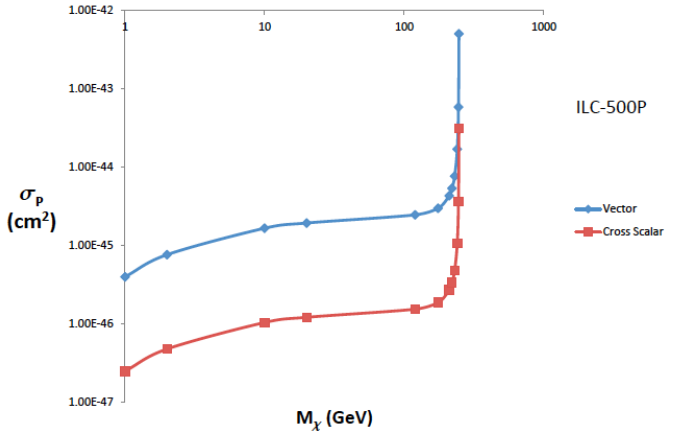
Relation e^+e^-, pp, χN

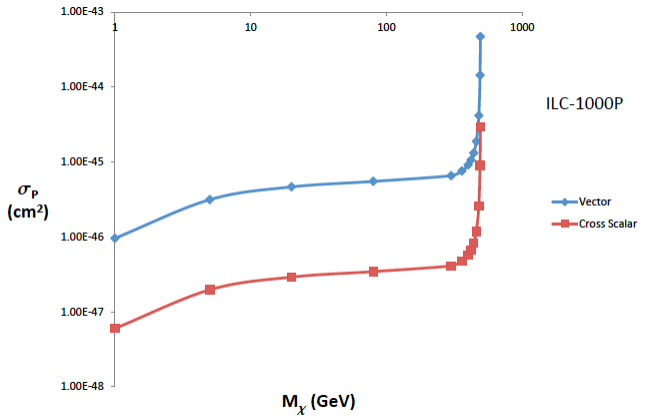
- LC probes WIMP – *lepton* interaction
- Relation to WIMP – nucleon interaction highly model-dependent
- Is suppression scale the same for quarks and leptons?
- A priori not!
  - Ex: t-channel exchange of "$\tilde{q}/\tilde{l}$"
  - Direct couplings vs loop couplings
  - $\Rightarrow$ LC provides orthogonal and independent information, regardless whether LHC discovers or just excludes

Relating e^+e^- to Direct Searches

- Will be model-dependent!
- Most conservative, ie minimal “unavoidable” X-Nucleon cross-section:
  - Assume no tree-level coupling to quarks
  - Leaves us with loop contributions
- Direct searches need sensitivity of ~ $10^{-46..47}$ cm^2 to rule out model-indenpently lepton-WIMP couplings observable at ILC







Searching for WIMPS at ILC

(Thesis of C. Bartels)

WIMP Dark Matter properties

- Masses of 0.1–1 TeV.
- In thermal equilibrium with SM soup after inflation.
- Weak interactions naturally give observed relic density.
- In SUSY with conserved R-Parity: LSP: $\tilde{\chi}_1^0$ or $\tilde{G}$.
- Here: no model assumptions.

Pair production at ILC

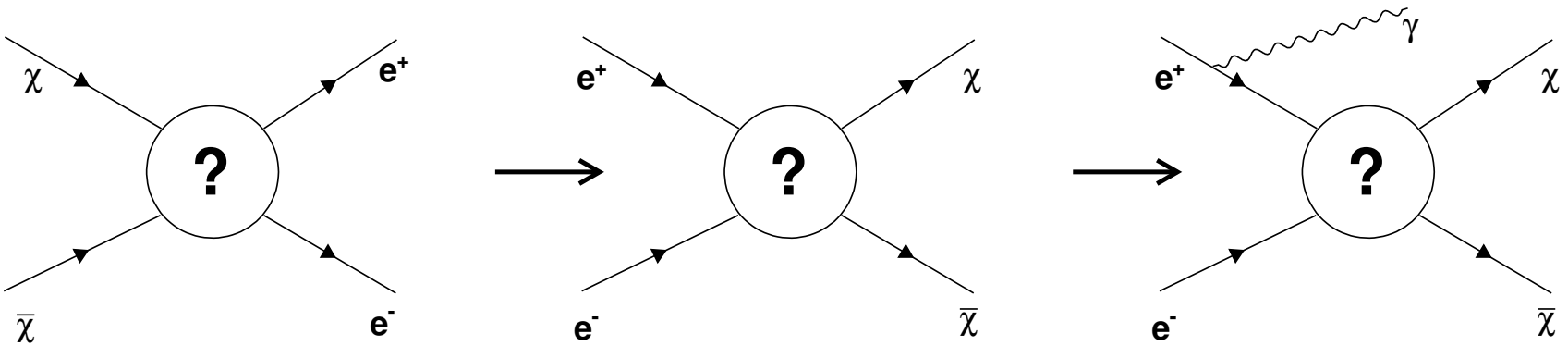
- $e^+e^- \to \chi\chi$, WIMPs not detected.
- Detection via ISR: $e^+e^- \to \chi\chi\gamma$.
- Missing $\not{E}$.
- Dominant background: $e^+e^- \to \nu\nu(N)\gamma$.

Search for WIMPS

Birkedal *et al.* [hep-ph/0403004]

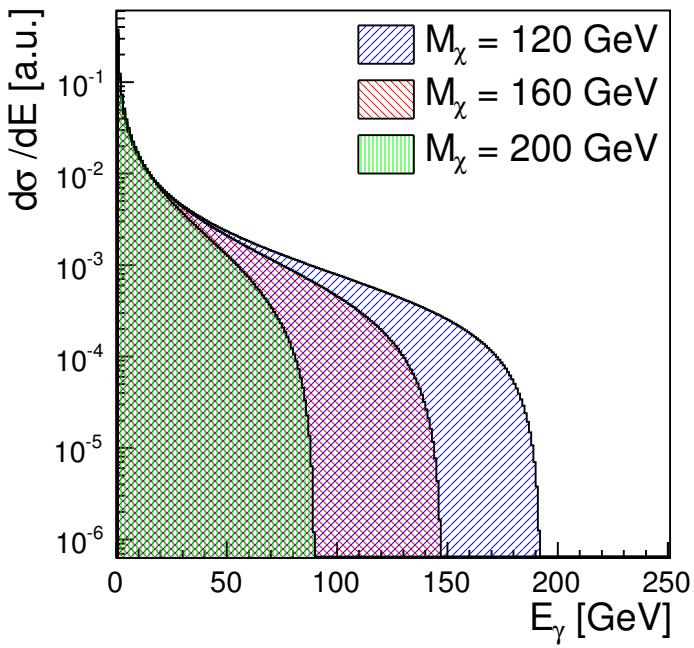
Model independence

- Assume only one DM candidate, no co-annihilation.
- Constrain WIMP pair annihilation XSec from observation.
- Crossing Symmetry (annihilation $\Rightarrow$ production).
- ISR.



Model Independent Production Cross Section

Mass dependent signal cut-off.

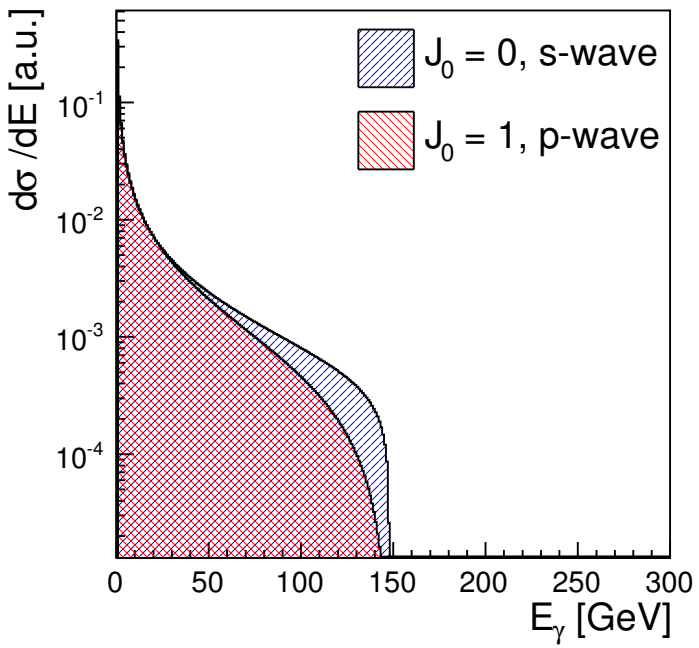


Parameters:

- $\kappa_e(P_e, P_p)$: Helicity dependent annihilation fraction to e^+e^-.
- S_χ: Spin, scale factor.
- M_χ, $J_0 \rightarrow$ shape, J_0 dominant partial wave.

Model Independent Production Cross Section

Signal shape at threshold provides information on partial wave (s- or p-wave).



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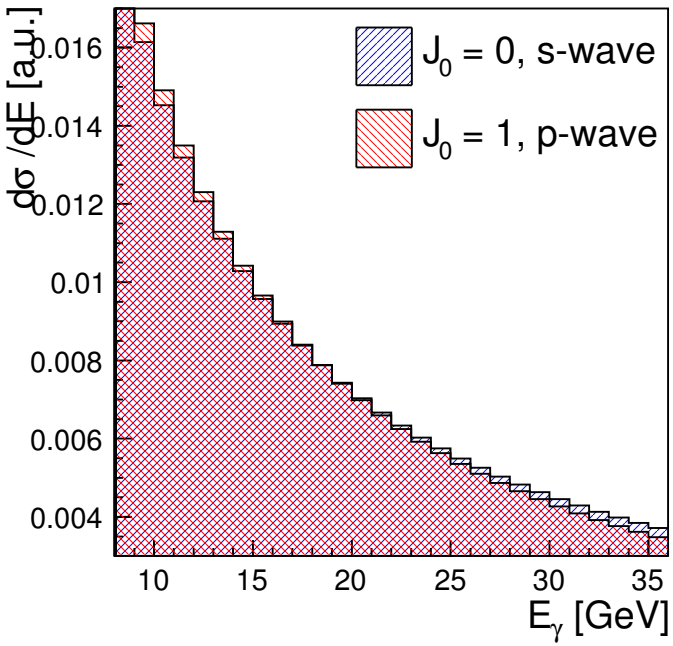
Model Independent Production Cross Section

Crossover for s-wave and p-wave signal with same cross section.
($\Rightarrow$ important later)



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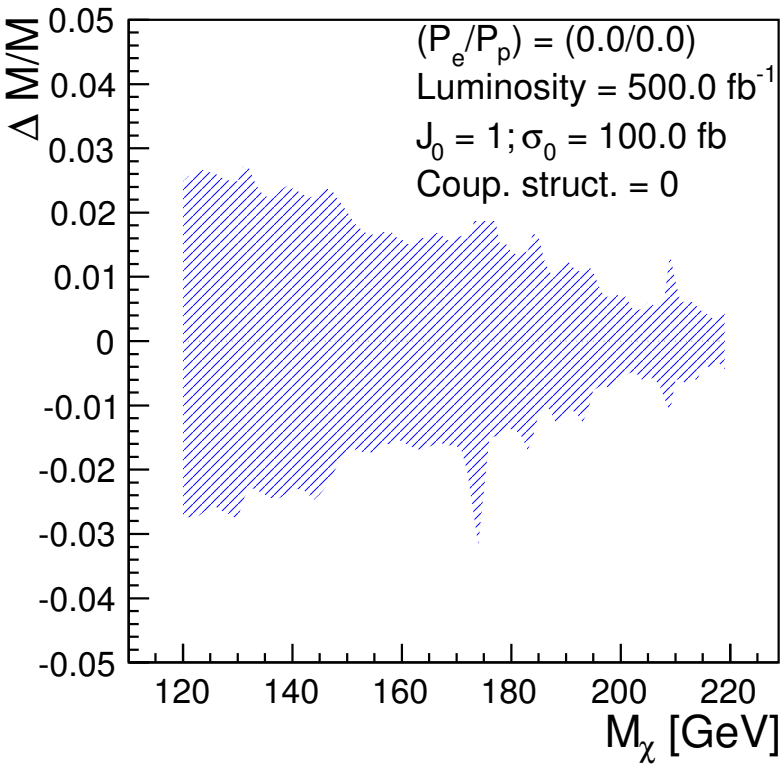
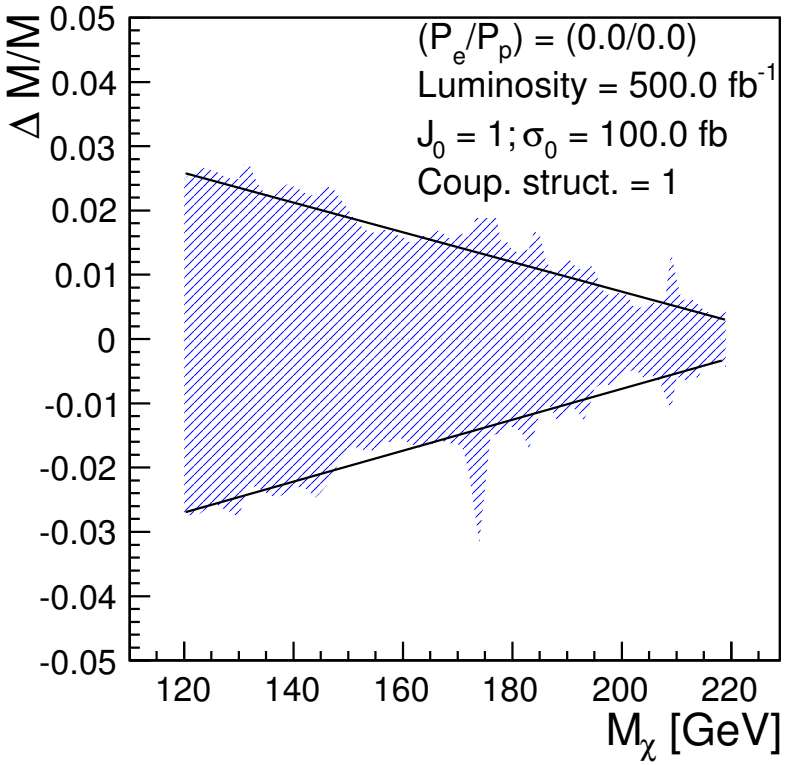
Mass Determination, $P_{e^-} = 0\%$ $P_{e^+} = 0\%$





$\sigma_{RR} = \sigma_{LL} = \sigma_{LR} = \sigma_{RL}$

- $\Delta M/M$ from $\sim 2.5\%$ at $M = 120$ to 0.5% at $M = 220$.

$\sigma_{LR} = \sigma_{RL}; \sigma_{RR} = \sigma_{LL} = 0$

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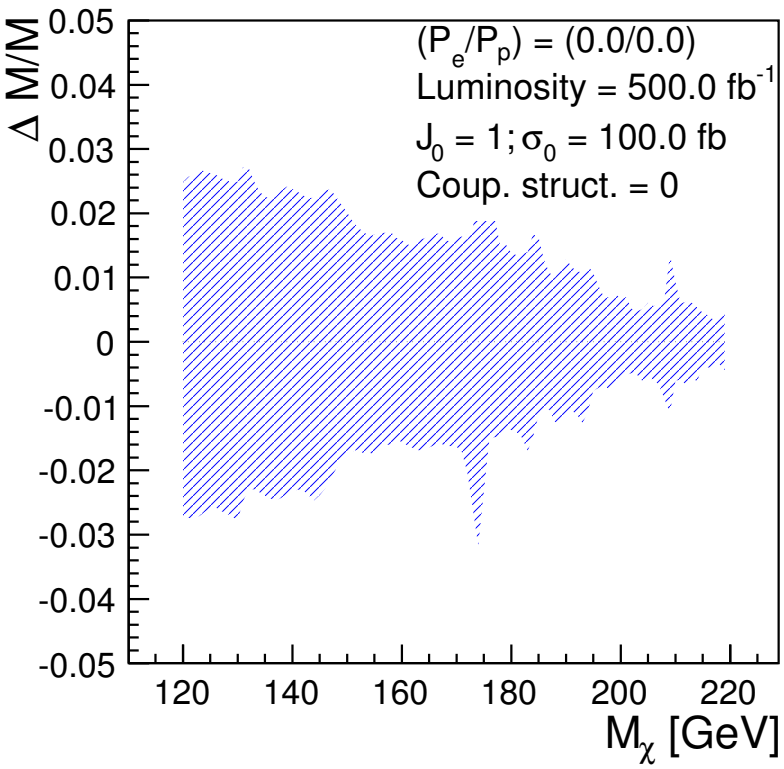

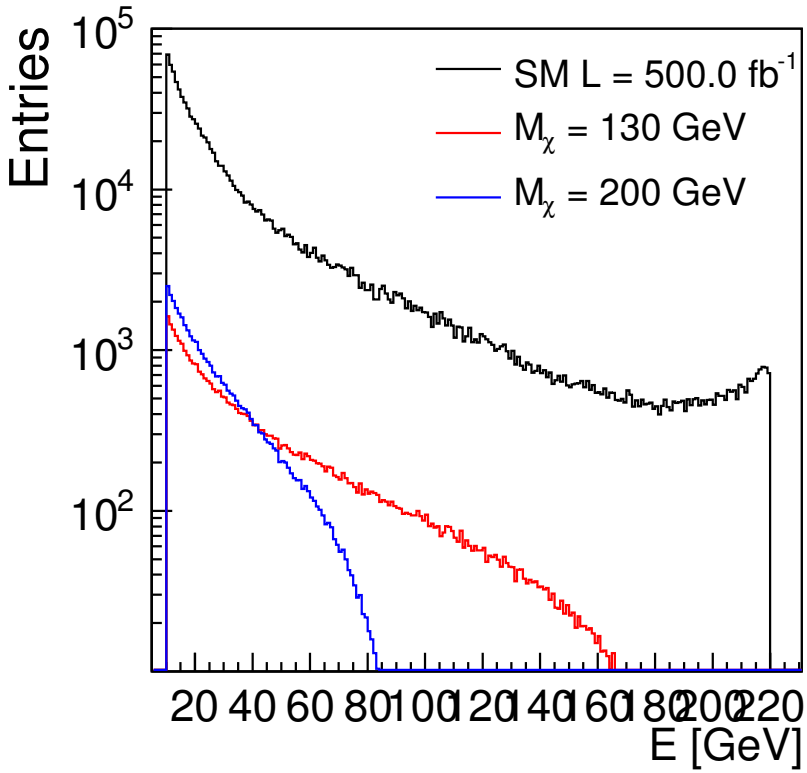

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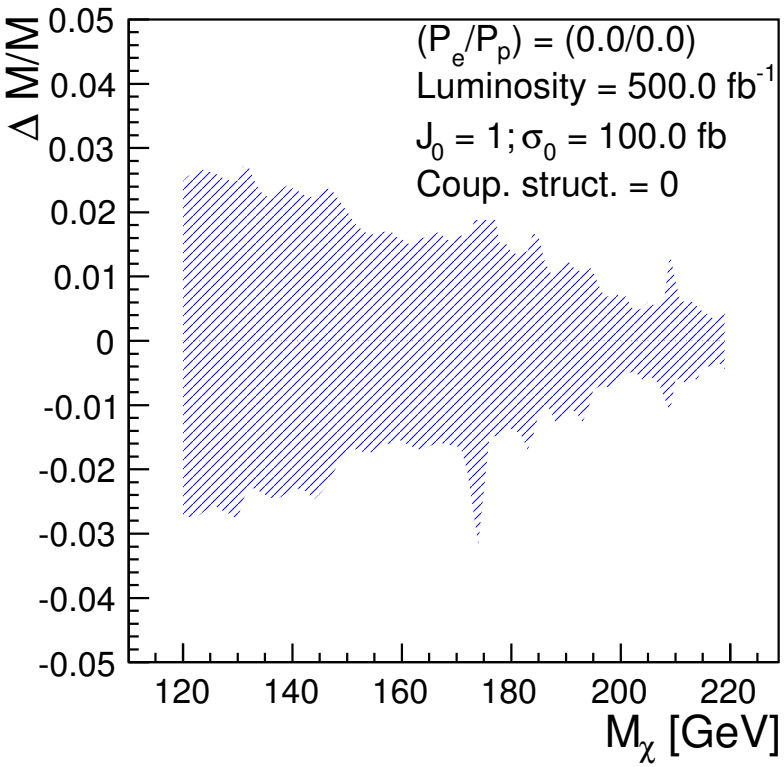

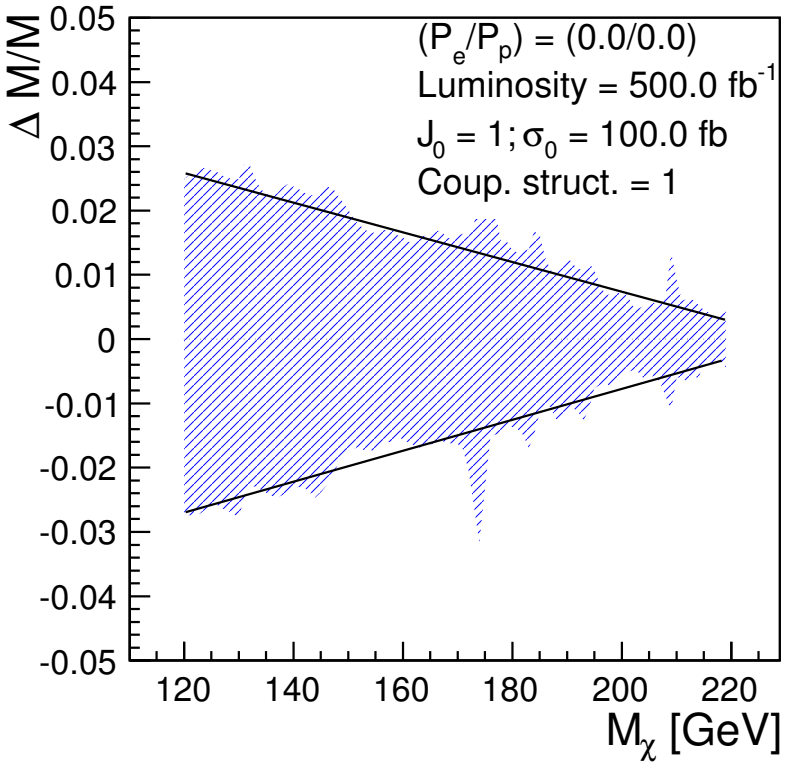

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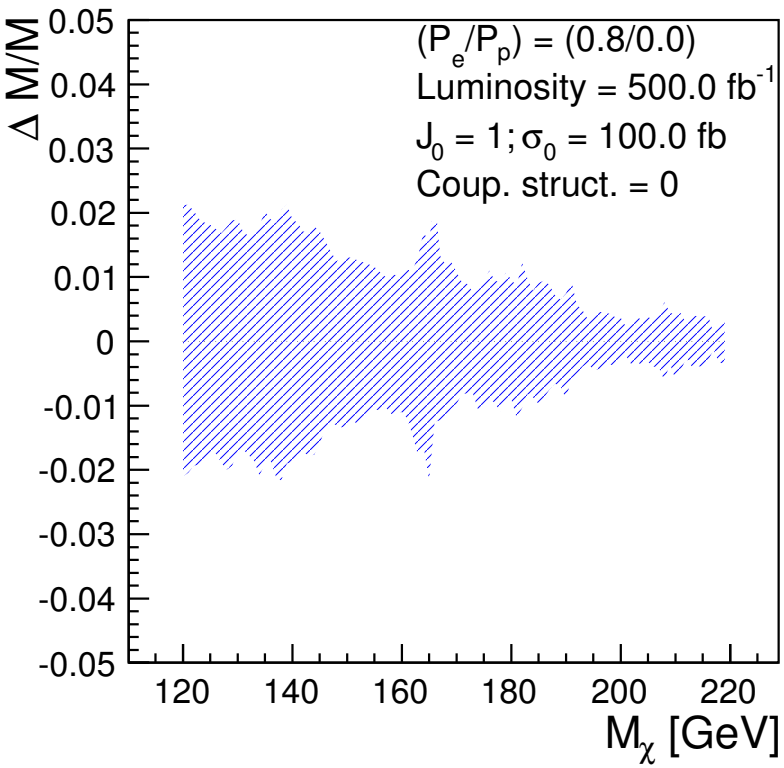
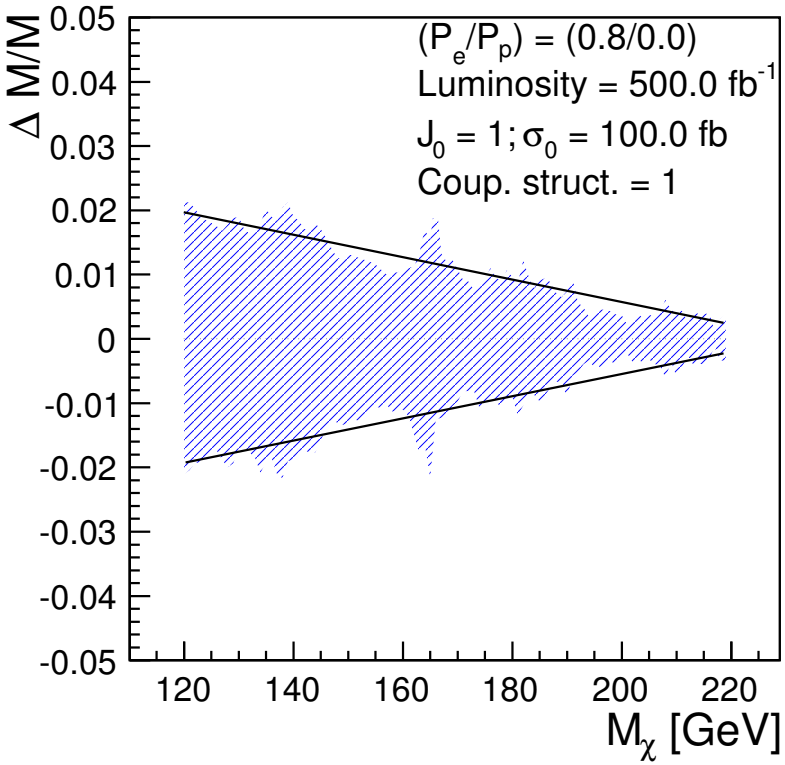
- $\Delta M/M$ from $\sim 2.5\%$ at $M = 120$ to 0.5% at $M = 220$.

Mass Determination, $P_{e^-} = 80\%$ $P_{e^+} = 0\%$





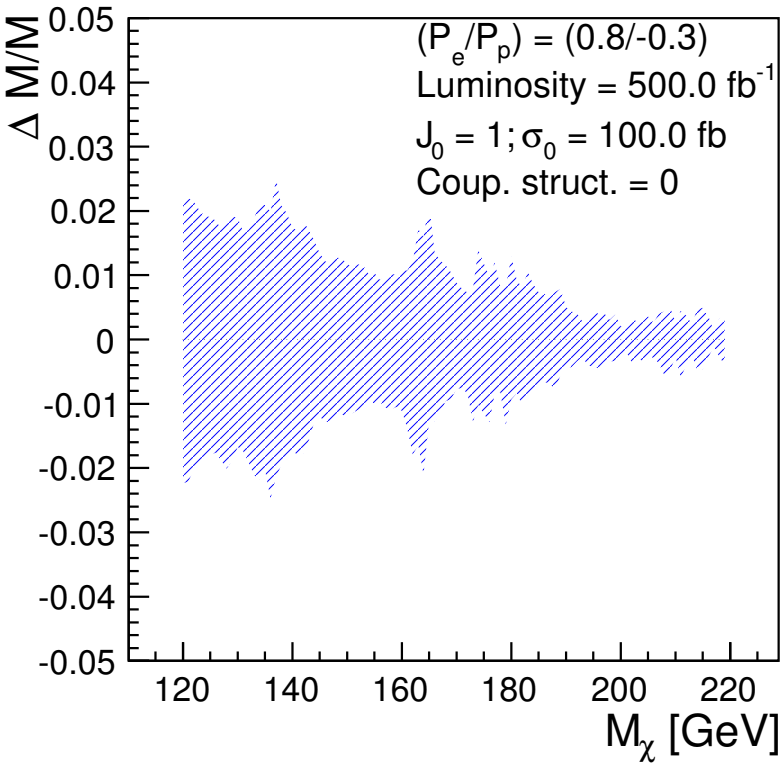
$\sigma_{RR} = \sigma_{LL} = \sigma_{LR} = \sigma_{RL}$

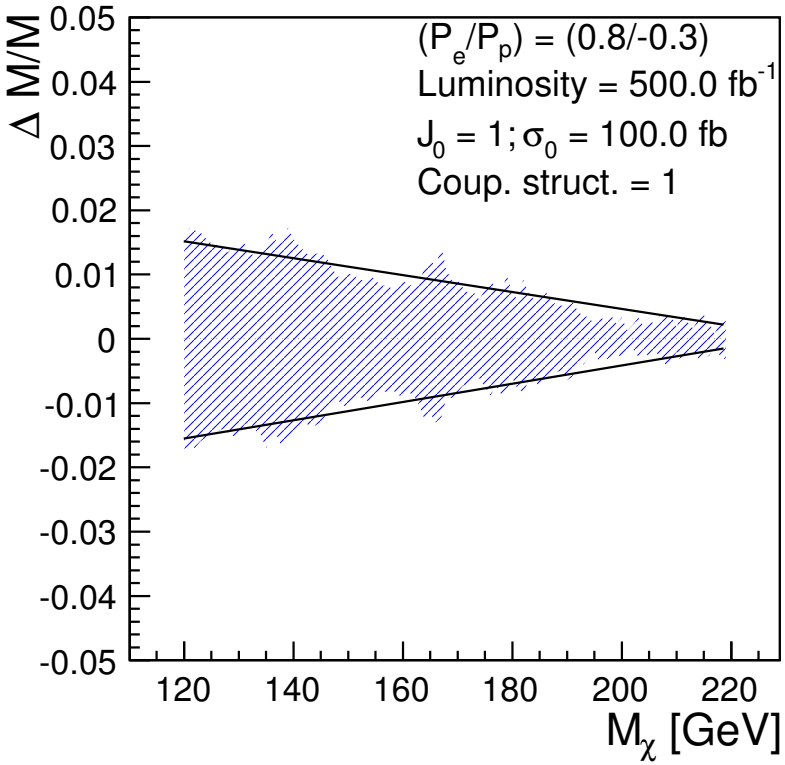
- Increased resolution
  Factor $\sim 2/3$

$\sigma_{LR} = \sigma_{RL}; \sigma_{RR} = \sigma_{LL} = 0$

- Increased resolution
  Factor $\sim 2/3$

Mass Determination, $P_{e^-} = 80\%$ $P_{e^+} = -30\%$





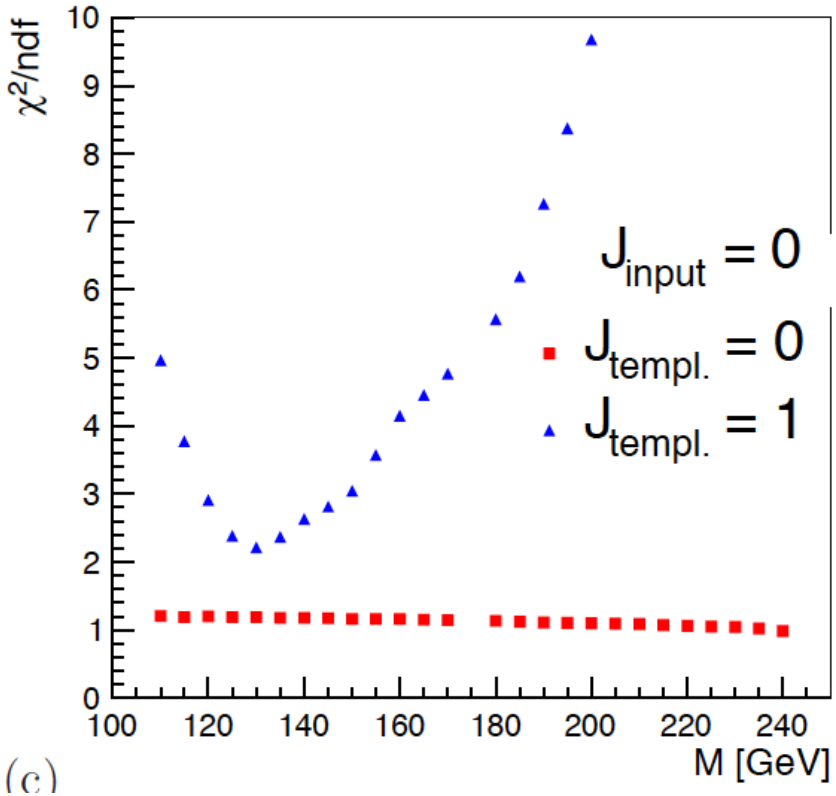
$\sigma_{RR} = \sigma_{LL} = \sigma_{LR} = \sigma_{RL}$

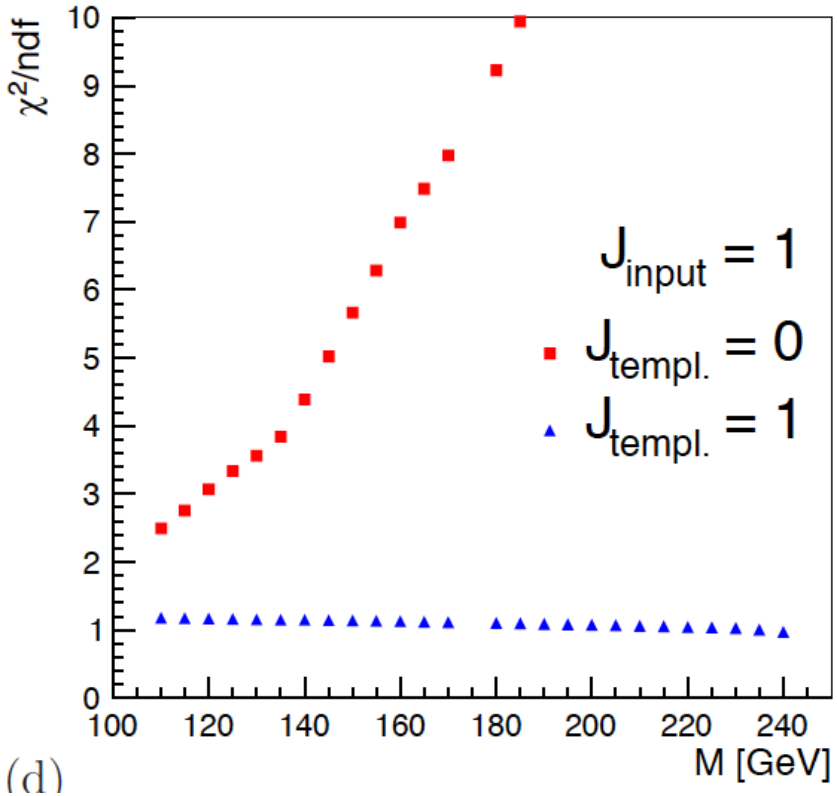
- Only small change in resolution with positron polarisation.

$\sigma_{LR} = \sigma_{RL}; \sigma_{RR} = \sigma_{LL} = 0$

- Additional resolution increase by 3/4.

Partial wave



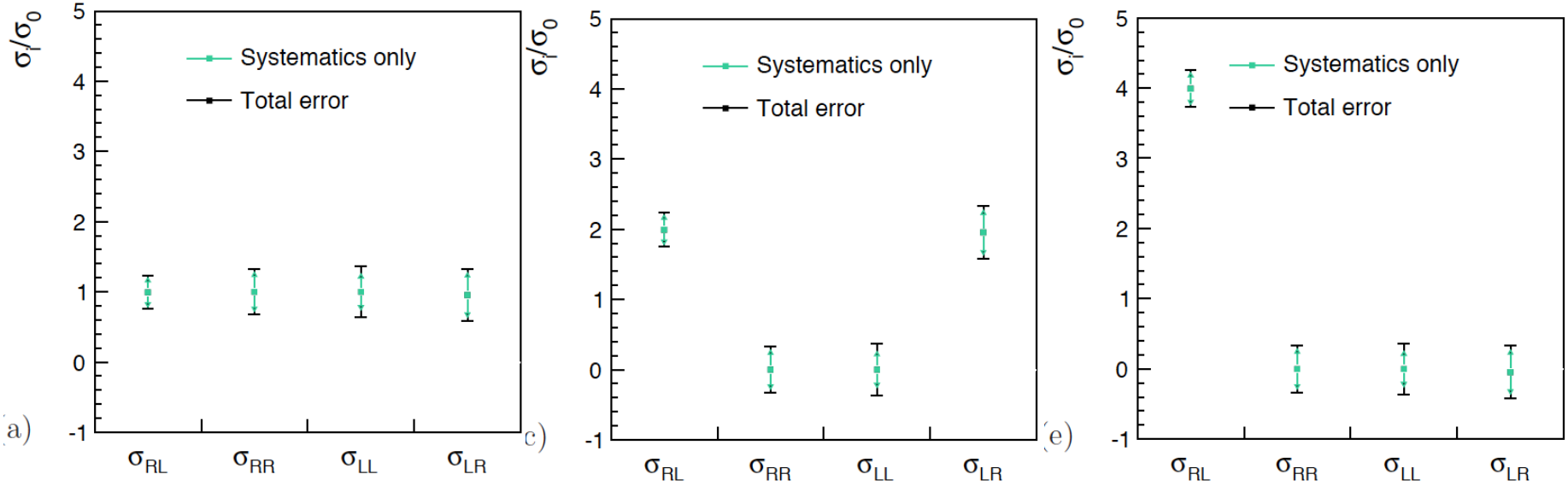


Dominant partial wave determination:

Correct hypothesis clearly favoured !

Helicity Structure of WIMP-Fermion Interaction

Measure cross-section with different beam helicities! Eg $|\mathcal{P}|$ = 80% / 30%, all four sign combinations (lumi split 200 fb^{-1} for +-/-+, 50 fb^{-1} for ++/–) NB: the more positron polarisation, the better!



Three explanatory coupling scenarios

Clear distinction possible!

Conclusions

ILC provides

- Orthogonal information to LHC and direct searches by probing WIMP-lepton interaction bottom-up, testing contact interaction scales up to 3-4 TeV
- Great opportunities for WIMP property determination (mass: 1-2%, helicity structure, spin of mediator) $\Rightarrow$ model discrimination
- Once again: The power of having both beams polarised demonstrated !
- Outlook: Extend the previous analysis to the Operator-picture:
  - Full model-space
  - Ease comparison with other searches (Direct searches, LHC)
  - On-going work (A. Chaus)

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