Model-independent WIMP Characterization
Using ISR

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Dark Matter at the ILC?

- **WIMP properties:**
  - Electrically neutral
  - Stable $\Rightarrow$ new conserved quantum number
  - Cold, i.e. non-relativistic
  - Cross sections $\mathcal{O}(100\,\text{fb})$
  - Massive $M \sim 100\,\text{GeV}$

- Well known initial state $\Rightarrow$ precision physics
- Longitudinal polarized beams: $P_{e^-} = 80\%$ and $P_{e^+} \geq 30\%$
- Machine Parameters: RDR, SB-2009 impact beam energy spectrum
Direct WIMP Production in $e^+e^-$-Collisions

Model-independent WIMP pair production (Birkedal et al.):

- Annihilation cross section determined by relic DM abundance
- Annihilation and production cross sections related by detailed balancing
- $\Rightarrow e^+e^- \rightarrow \chi\chi$, invisible in collider experiment, use ISR

- Search for high $p_T$ photons balancing invisible WIMP system
- Model dependent interpretation (SUSY) $\rightarrow$ O. Kittel tomorrow
Neutrino pair production $e^+ e^- \rightarrow \nu\nu\gamma$

- Irreducible
- Large production cross section
- Polarization dependent

⇒ Precise event reconstruction, excellent $\delta P / P$

Other: Multi-photon, radiative Bhabha scattering
Analysis Strategy I

- Observables: Photon energy $E_\gamma$ (and polar angle $\Theta_\gamma$)
- Measure from ISR spectrum
- Cross sections, Coupling structure, Mass, Partial wave

Threshold energy ⇔ missing mass, threshold behaviour ⇔ partial wave
Achievable precision, influence of polarization measurement?
Analysis Strategy II

- Large WIMP parameter space
  - Select irreducible $e^+e^- \rightarrow \nu\nu\gamma$ background
  - Reweight $\nu\nu\gamma$ events with $\frac{\sigma(\chi\chi\gamma)}{\sigma(\nu\nu\gamma)}$
- Large backgrounds: $S/B \approx O(10^{-3})$
  - Include photon in matrix element
  - Full detector simulation
  - Photon reconstruction
- Precise background prediction required
  - Parametrization of independent background sample
  - Generate signal prediction from parametrization

![Signal and Background Comparison](chart.png)
Reconstruction algorithm tends to split electromagnetic clusters
- Photons: no tracking information, fracturing not recovered
- Merge photon candidates with cone based method
- Optimize cone opening angle w.r.t. purity and efficiency
- Small amount of fracturing remaining at high photon energies
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Reconstruction algorithm tends to split electromagnetic clusters
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Merge photon candidates with cone based method
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Small amount of fracturing remaining at high photon energies
Selection of single high $p_T$ photons

- **Signal definition:**
  - $10 \text{ GeV} < E_\gamma < 220 \text{ GeV}$, $|\cos \Theta_\gamma| < 0.98$
  - Low energy ISR, massless $Z$ final state
  - Tracking and calorimetric acceptance

- **Maximal exclusive visible energy**
  - $E_{vis} - E_\gamma < 20 \text{ GeV}$
  - Reject multi-photon final states
  - Reject hadronic and leptonic final states

- **Tag electrons in forward calorimeters**
  - Reduce abundant Bhabha background

- **Veto high $p_T$ tracks**
  - $p_T < 3 \text{ GeV}$
  - Reject hadronic and leptonic final states
Selection Efficiencies

\[ \nu\nu\gamma \quad \Rightarrow \quad \chi\chi\gamma \]

- Selection efficiency of \( \nu\nu\gamma \) background energy dependent
- Reduced efficiency due to remaining cluster fracturing at high \( E_\gamma \)
- Signal photon spectrum mass dependent
- P-wave WIMP spectrum peaked sharper at low \( E_\gamma \)
Selection Efficiencies

\[ \nu\nu\gamma \quad \Rightarrow \quad \chi\chi\gamma \]

- Selection efficiency of \( \nu\nu\gamma \) background energy dependent
- Reduced efficiency due to remaining cluster fracturing at high \( E_\gamma \)
- Signal photon spectrum mass dependent
- P-wave WIMP spectrum peaked sharper at low \( E_\gamma \)
- WIMP selection efficiency mass dependent \( \epsilon > 90\% \)
Cross Section and Coupling Structure

\[ \sigma = \mathcal{F}(\sigma_{RR}, \sigma_{LL}, \sigma_{RL}, \sigma_{LR}; P_{e^-}, P_{e^+}) \]

Fully polarized cross sections \(\Leftrightarrow\) Coupling structure of WIMP interactions

- Study three scenarios:
  - "Equal": \(\sigma_{RR} = \sigma_{LL} = \sigma_{RL} = \sigma_{LR}\)
  - "Helicity": \(\sigma_{RL} = \sigma_{LR}\)
  - "Anti-SM": \(\sigma_{RL}\)

- Requires four measurements with polarized beams:
  - 200 fb\(^{-1}\) with \((+|P_{e^-}|; -|P_{e^+}|)\),
  - 200 fb\(^{-1}\) with \((-|P_{e^-}|; +|P_{e^+}|)\),
  - 50 fb\(^{-1}\) with \((+|P_{e^-}|; +|P_{e^+}|)\),
  - 50 fb\(^{-1}\) with \((-|P_{e^-}|; -|P_{e^+}|)\).

- Assume \(\sigma_0 = 100\) fb throughout
Systematic Uncertainties

- $\delta P/P$:
  - Cross sections, coupling structure $\sigma_{\{R,L\}}$
  - 0.25% to 0.1%

- $\delta L/L$:
  - Cross sections, coupling structure $\sigma_{\{R,L\}}$
  - 0.01%

- $\delta \epsilon/\epsilon$:
  - Cross sections, coupling structure $\sigma_{\{R,L\}}$
  - 2.0%
  - Calibrate with radiative $Z$-return

- Beam energy spectrum
  - Cross sections, Partial wave, Mass
  - Estimate from signal spectra of SB2009 and RDR parameter sets

- Beam energy scale
  - Mass
  - Calibrate with radiative $Z$-return
"Equal" scenario, $P_{e^-} = +0.8$, $P_{e^+} = -0.3$, $\mathcal{L} = 50 \text{ fb}^{-1}$, $\sigma_{P_{e^-}, P_{e^+}} = 100 \text{ fb}$

| Parameter | Value  | $\delta\sigma$ [fb] |
|-----------|--------|---------------------|
| $\delta P/P$ | 0.25%  | 5.7                 |
| $\delta \epsilon/\epsilon$ | 1.73% | 1.7                 |
| $\delta \mathcal{L}/\mathcal{L}$ | 0.01% | 0.01                |
| Total     |        | 5.9                 |
**Coupling Structure**

**"Equal"**

- $|P_{e^-}| = 0.8$
- $|P_{e^+}| = 0.3$
- $\delta P/P = 0.25\%$

**"Helicity"**

**"Anti-SM"**

- Scenarios distinguishable with $\chi^2/ndf > 10 \ (p < 10^{-8})$
- $|P_{e^+}| = 0.3, \ \delta P/P = 0.25\%: \ \Delta \sigma_{\{R,L\}} = 20 \text{ fb to } 40 \text{ fb}$
### Model Independent WIMP Search

#### Coupling Structure

**"Equal"**

- Systematics only
- Total error

\[
\left| P_{e^{-}} \right| = 0.8 \quad \left| P_{e^{+}} \right| = 0.6 \quad \delta P/P = 0.25\%
\]

- Scenarios distinguishable with \( \chi^2/ndf > 10 \) (\( p < 10^{-8} \))

**"Helicity"**

- Systematics only
- Total error

**"Anti-SM"**

- Systematics only
- Total error
Coupling Structure

| $P_{e^-}$ | $P_{e^+}$ | $\delta P/P$ |
|-----------|-----------|-------------|
| 0.8       | 0.6       | 0.10%       |

- Scenarios distinguishable with $\chi^2/ndf > 10$ ($p < 10^{-8}$)
- $|P_{e^+}| = 0.3$, $\delta P/P = 0.25\%$: $\Delta \sigma_{\{R,L\}} = 20$ fb to 40 fb
- $|P_{e^+}| = 0.6$, $\delta P/P = 0.25\%$: $\Delta \sigma_{\{R,L\}} = 10$ fb to 30 fb
- $|P_{e^+}| = 0.6$, $\delta P/P = 0.10\%$: $\Delta \sigma_{\{R,L\}} = 7$ fb to 20 fb
- Combine measurements: $\Delta \sigma_0/\sigma_0 = 2\%$ to 5%
Partial Wave Determination

- $\mathcal{L} = 500 \text{ fb}^{-1}$, "Helicity" scenario
- Test template s- and p-wave spectra against data spectrum
- $\chi^2_{min}$ indicates partial wave

- $P_{e^{-}} = +0.0$
- $P_{e^{+}} = +0.0$
Partial Wave Determination

- $\mathcal{L} = 500 \text{ fb}^{-1}$, "Helicity" scenario
- Test template s- and p-wave spectra against data spectrum
- $\chi^2_{min}$ indicates partial wave
- Partial wave determination requires polarized beams
Mass Measurement

- **Equal**
  - \((P_e/P_p) = (0.8/0.0)\)
  - \(J_0 = 1; \text{Equal}\)

- **Helicity**
  - \((P_e/P_p) = (0.8/0.0)\)
  - \(J_0 = 1; \text{Helicity}\)

- **Anti-SM**
  - \((P_e/P_p) = (0.8/0.0)\)
  - \(J_0 = 1; \text{Anti-SM}\)

- \(\mathcal{L} = 500 \text{ fb}^{-1}\), p-wave WIMPs, \(\sigma_0 = 100 \text{ fb}\)
- Relative errors mass dependent: \(\Delta M/M = 0.5\% \text{ to } 2.5\%\)
- Scenario dependent increase in precision for polarized beams
- Systematic errors: Luminosity spectrum, beam energy scale
**Mass Measurement**

- $\mathcal{L} = 500 \text{ fb}^{-1}$, p-wave WIMPs, $\sigma_0 = 100 \text{ fb}$
- Relative errors mass dependent: $\Delta M/M = 0.5\%$ to $2.5\%$
- Scenario dependent increase in precision for polarized beams
- Systematic errors: Luminosity spectrum, beam energy scale
Conclusion

- Model independent WIMP search by detection of high $p_T$ photons
- Structure of studied coupling scenarios distinguishable
- Unpolarized cross section $\sigma_0$ determined to 2% to 5%
- Dominant uncertainty: Polarization measurement

- Partial wave can be determined with polarized beams
- Masses determined to $\leq 2.5$
- Dominant uncertainty: Beam energy spectrum

- Increased precision on Polarization measurement $\rightarrow$ factor two reduction of systematic errors
- Study of e.g. SUSY scenarios where only $\tilde{\chi}_1^0$ accessible (see O. Kittel tomorrow)