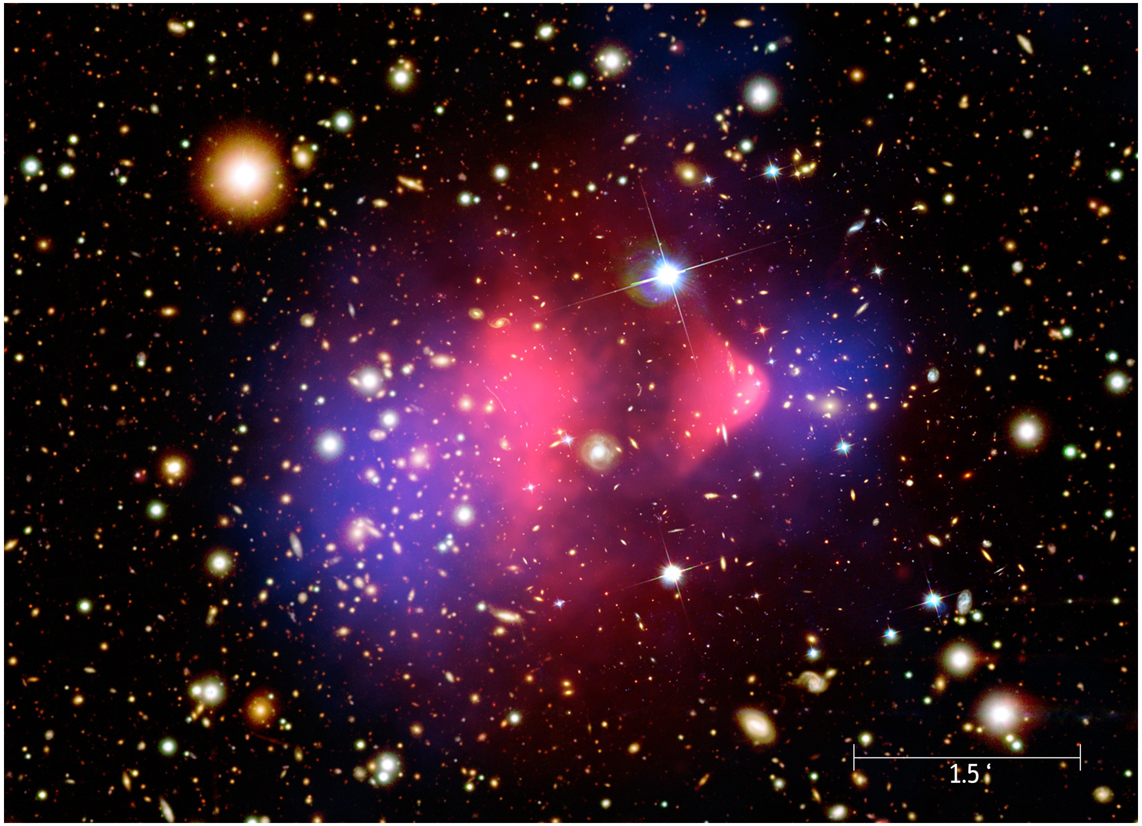
WIMPs at the ILC:
Effective Operator Approach @ 250 - 1000 GeV



Moritz Habermehl
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of the Helmholtz Alliance
“Physics at the Terascale”

HELMHOLTZ
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DESY

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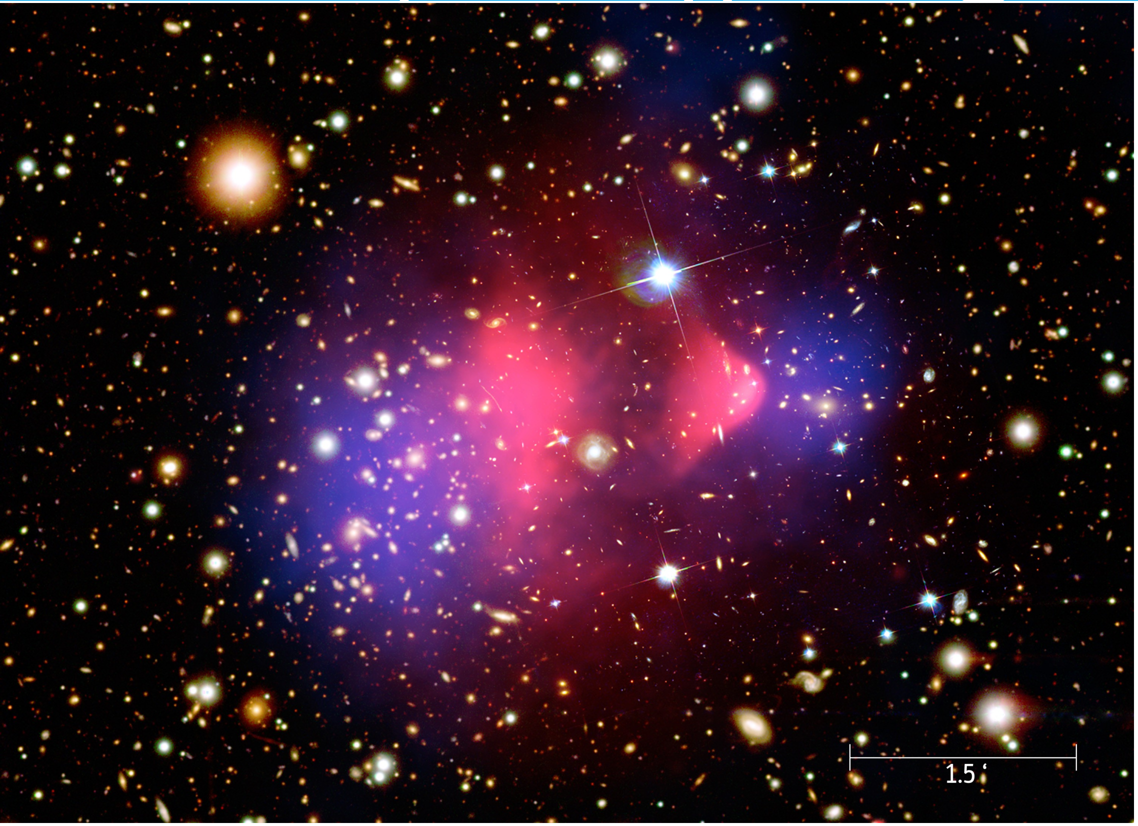


Outline:

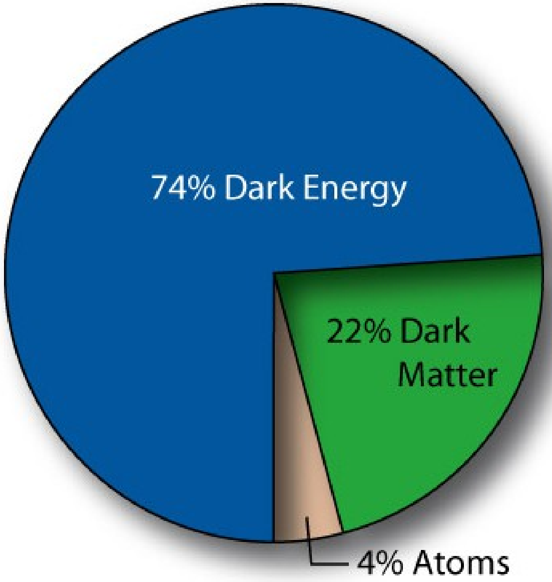
I. Introduction
   - Existing analysis @ 500 GeV
   - Effective operator approach

II. Extrapolation to different center-of-mass energies

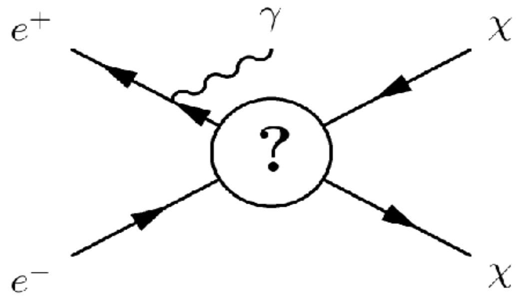
III. Summary and outlook

I. Motivation

- Weakly Interacting Massive Particles (WIMPs, χ):
  Dark Matter candidate
  - Direct search
  - Indirect search
  - **Collider search**



- Idea: SM particles $\rightarrow$ χ pair production
- Mono-X: tag particle (gluon, **photon**,...)
- Initial state radiation (ISR) $\rightarrow$ quasi model independent



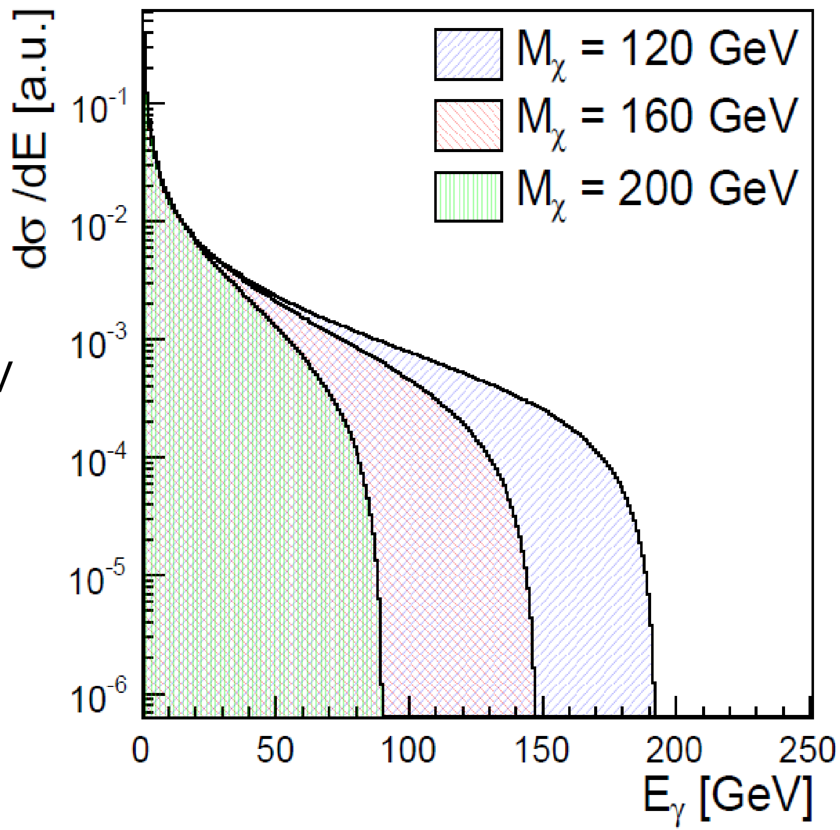
- Signal: single (hard) photon and missing energy: $\gamma + \not{E}$

WIMPs at the ILC: Observables

- Free parameters of χ: mass, spin, type of coupling
- Only observables: photon: energy, theta
  - Energy: characteristic endpoint

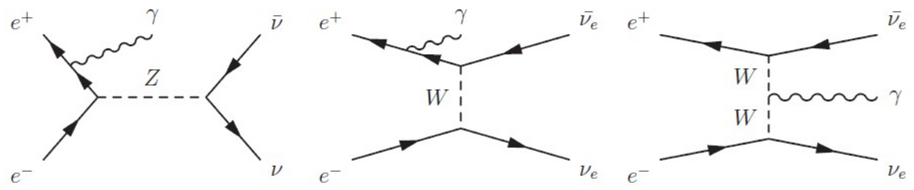
$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{4M_\chi^2}{s}\right)$$

500 GeV



WIMPs at the ILC: Background

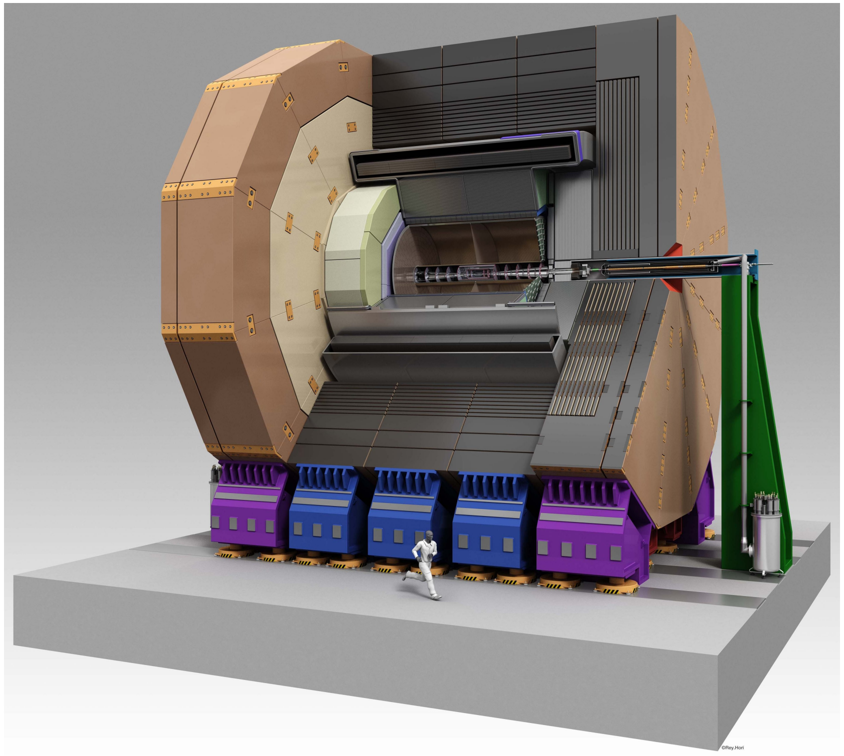
- Irreducible background
  - Impossible to distinguish from signal on an event-by-event basis
  - Neutrino pair production ($e^+e^- \rightarrow \nu\nu\gamma$)



- Reducible background
  - Main contribution: radiative Bhabha scattering ($e^+e^- \rightarrow e^+e^-\gamma$) ($e^+$ and e^- undetected at low θ)

Status of status within ILD

- Existing full simulation
- Christoph Bartels (arXiv1206.6639 , DESY-THESIS-2011-034)
- $\sqrt{s}$ = 500 GeV



Status of studies within ILD: effective operator approach

- 2013/2014: Reinterpretation: **effective operator approach**
- Done by Andrii Chaus
- Effective operator approach
  - Heavy mediator particles
  - Described by small number of operator coefficents
  - Λ = energy scale of new physics

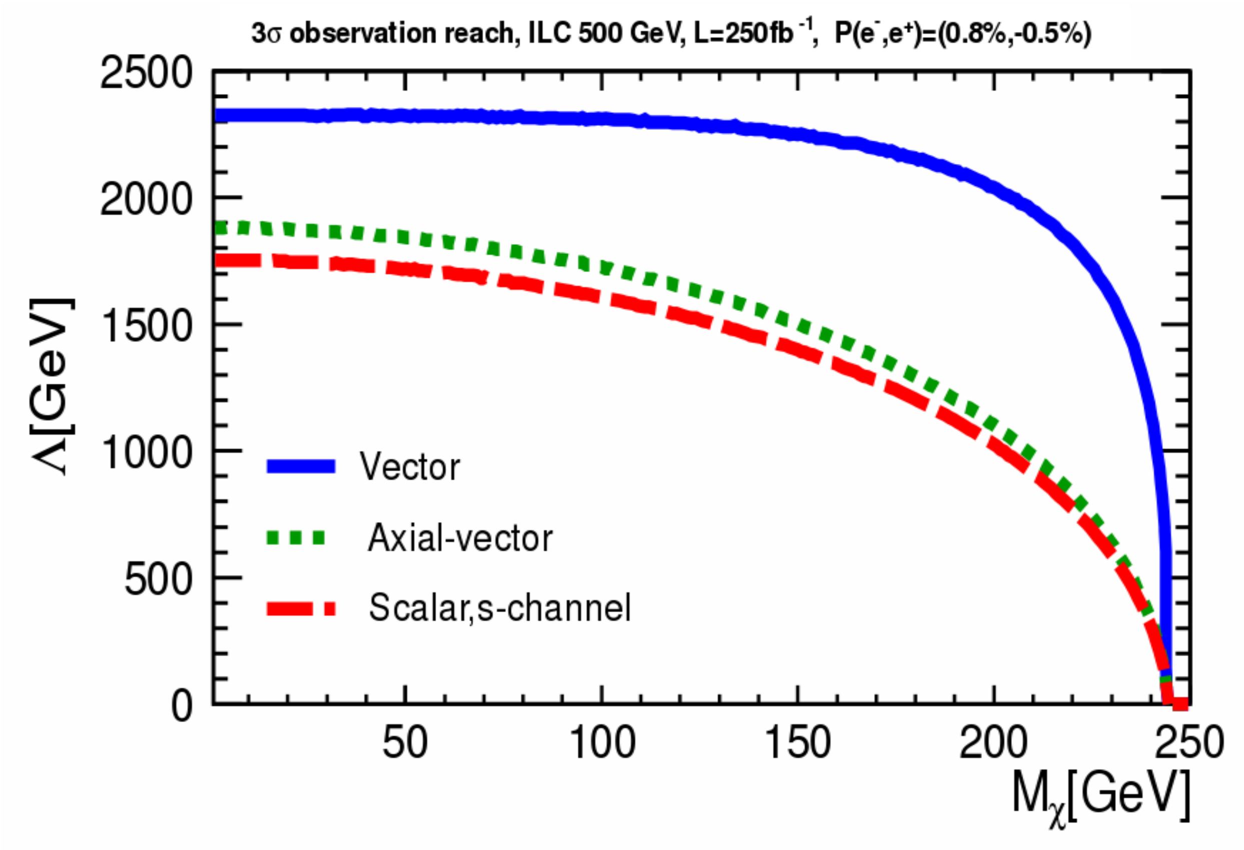
$$\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

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

- Information from shape of $E\gamma$

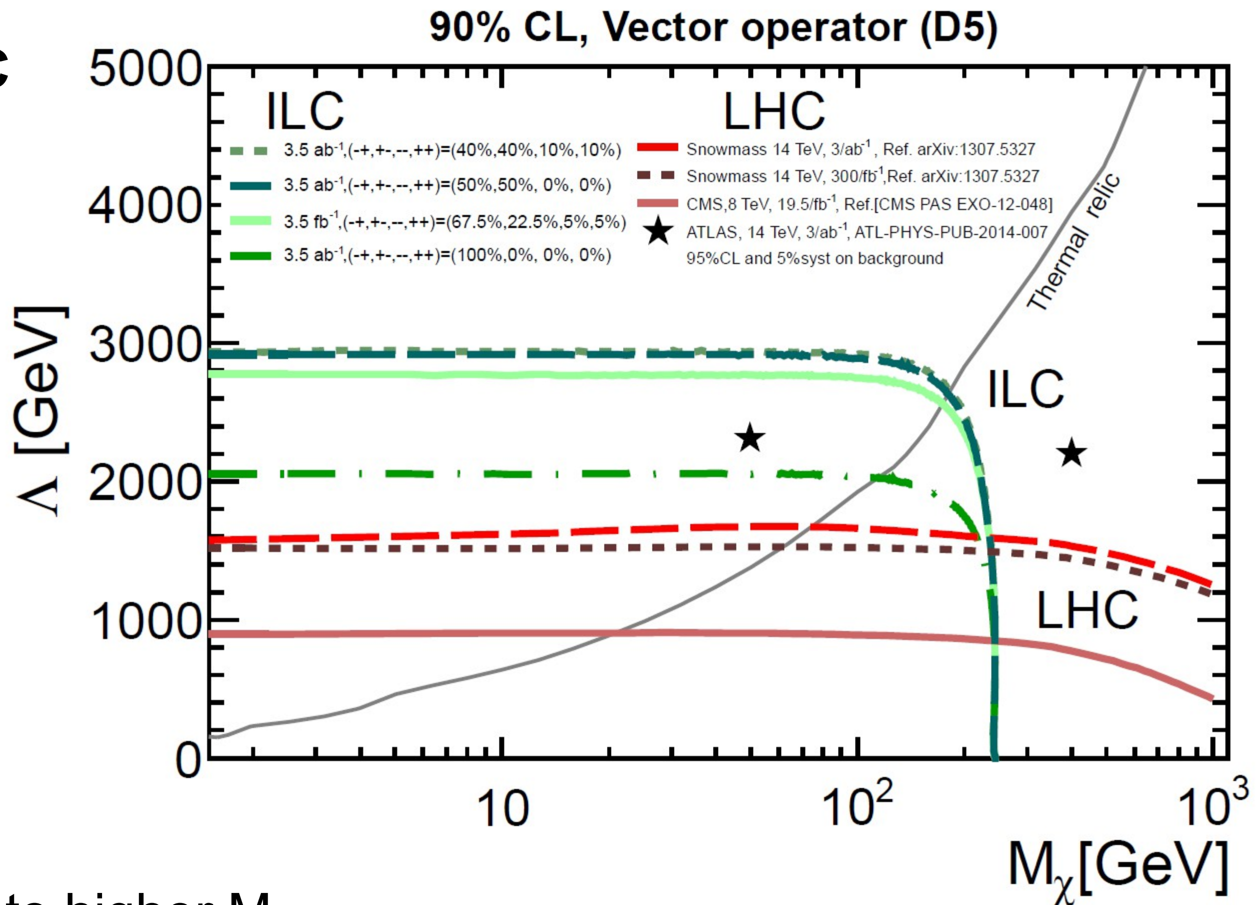
Status of studies within ILD: effective operator approach

- Λ^{reach} at 500 GeV
- for $M\chi << \sqrt{s}/2$: Λ^{reach} independent of $M\chi$



Status of studies within ILD: effective operator approach

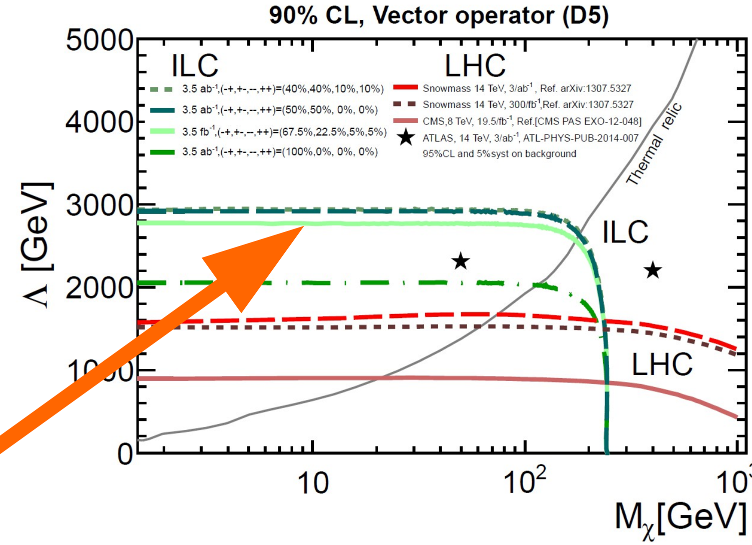
- **Comparison to LHC**



- LHC: more sensitive to higher M_χ
- ILC: more sensitive to higher Λ values

II. Extrapolation

- Extrapolation of results @ 500 GeV to other (any) √s



Idea:

1) Take existing value from full sim. Λ_0^{reach}

   Mχ << √s/2 (e.g. 10 GeV)

2) Find approximative formula: $\Lambda^{reach} \propto F(\sqrt{s}, L)$

   a) signal

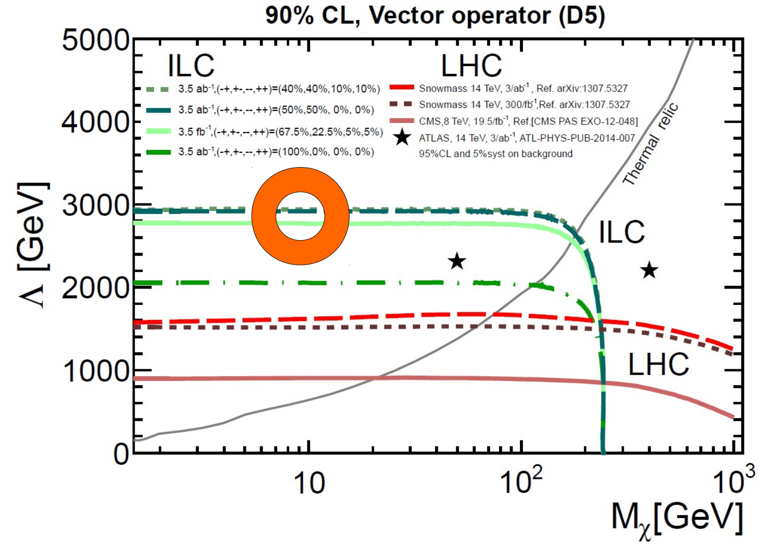
   b) background

3) Scaling Λ^{reach}:

$$\Lambda^{reach} = \Lambda_0^{reach} \frac{F(\sqrt{s}, L)}{F(\sqrt{s_0}, L_0)}$$

Extraplation: 1) Take existing value Λ^{reach}

- Starting point: $\Lambda^{reach,fullsim}$ for a specific...
  - √s = 500 GeV (fixed)
  - integrated luminosity (L)
  - Polarization configuration
  - Significance
- Gives: Λ^{reach} with
  - same Pol, Sig
  - any √s and L
- Main assumption: factorisation of
  - shape information
  - polarisation dependence



2) Find approximative formula $\Lambda^{reach}(\sqrt{s},L)$
a) signal

- Signal:
  - cross section $\sigma_s(\Lambda,\sqrt{s})$
  - e.g.: vector type, for $M_\chi \ll \sqrt{s}/2$:

$$\frac{d^2\sigma}{dz\,d\cos\theta} \approx \frac{\alpha}{12\pi^2}\frac{s}{\Lambda^4}\frac{1}{z\sin^2\theta}(1-z)[4(1-z)+z^2(1+\cos^2\theta)]$$

$$z = \frac{2E_\gamma}{\sqrt{s}}$$

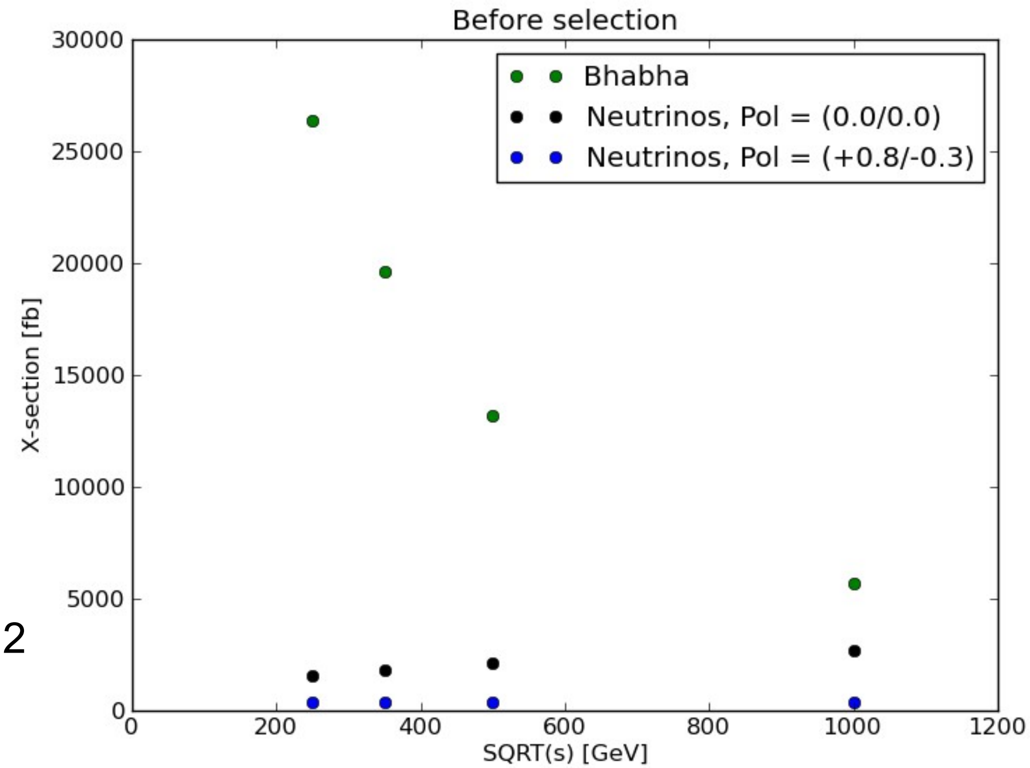
arXiv1211.4008

- First approximation $\boldsymbol{\sigma_s \sim s/\Lambda^4}$
- Effect of z-terms tested => negligible

2) Find approximative formula $\Lambda^{reach}(\sqrt{s},L)$
b) background

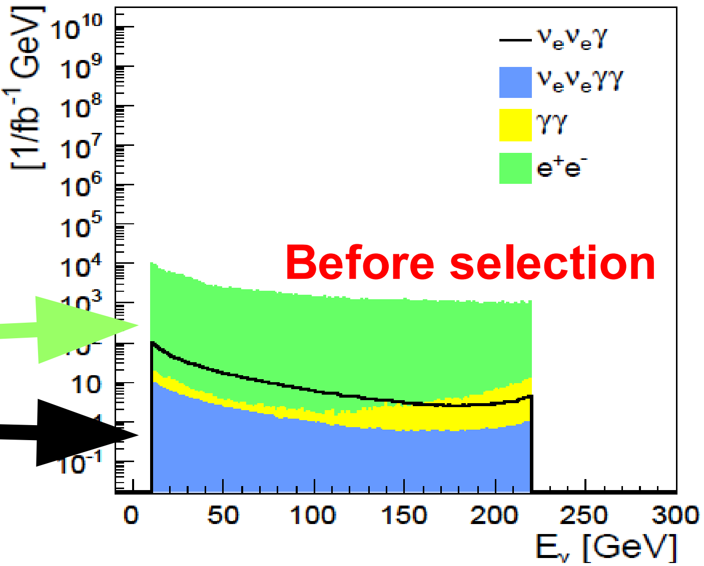
- $e^+e^- \rightarrow \nu\nu\gamma$
- $e^+e^- \rightarrow e^+e^-\gamma$

- Cross sections
  - Event generator: Whizard 2.2.2
  - @ 250, 350, 500,1000 GeV
  - |P| = (0.8/0.3)

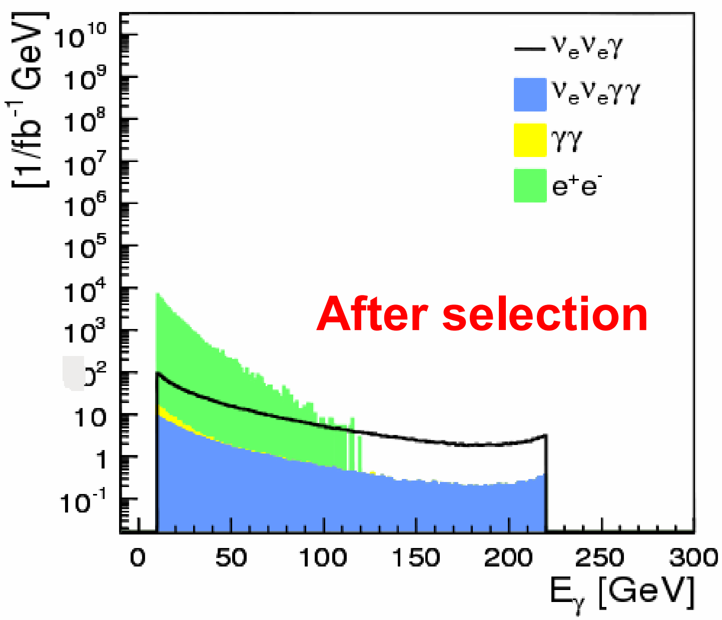


2) Find approximative formula $\Lambda^{reach}(\sqrt{s},L)$
b) background

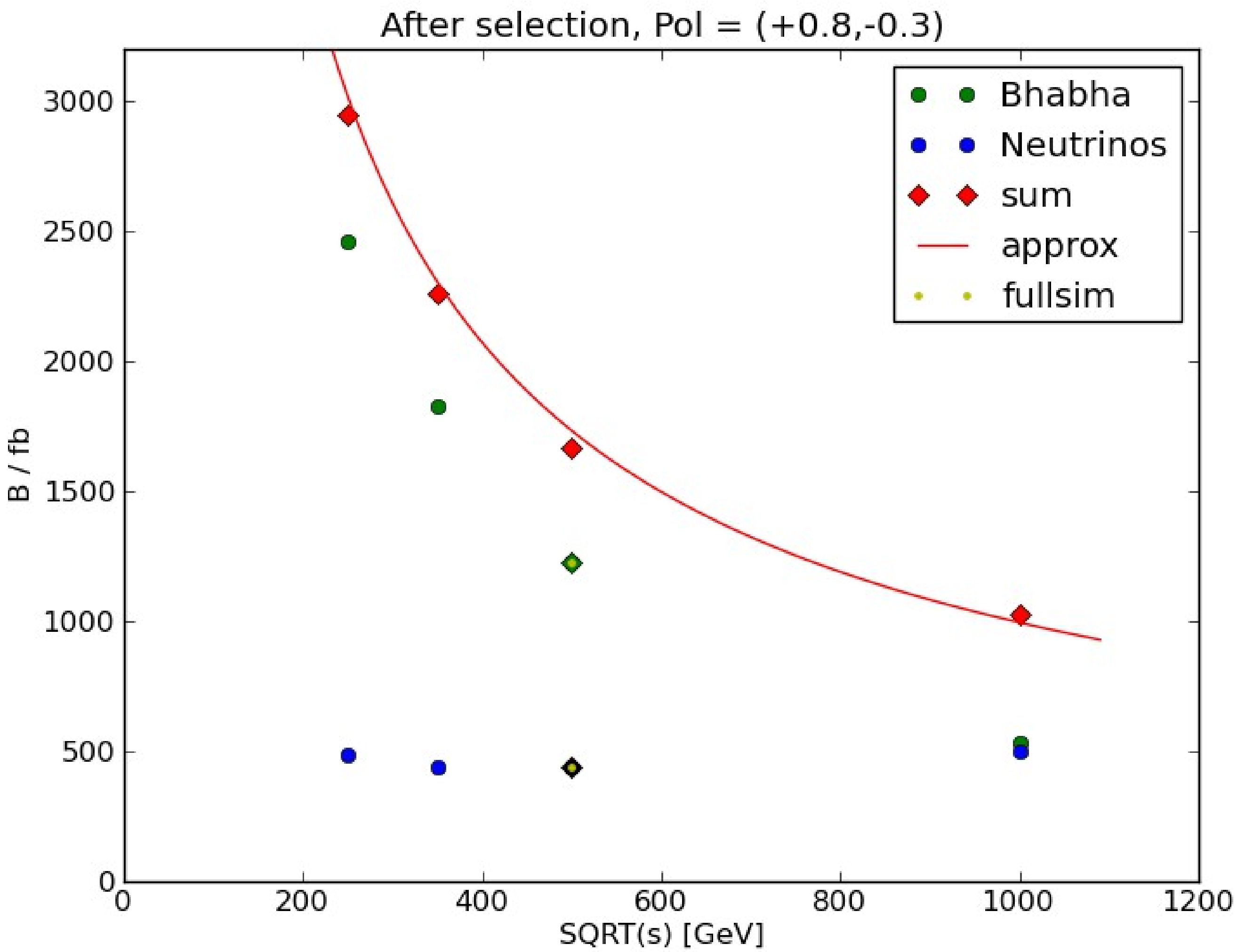
- For efficiency: need full detector simulation
- Assume efficiency is independent of √s
- Full simulation @ 500 GeV:
  - Bhabha scattering: ~ 0.3%
  - Neutrinos: ~ 90%



- $$B(\sqrt{s},L) = B^{fullsim}(1\,fb^{-1})\frac{\sigma_b(\sqrt{s})}{\sigma_b(500)}L$$



2) Find approximative formula $\Lambda^{reach}(\sqrt{s},L)$
b) background



Approximaton "by eye": $B \propto \left(\frac{1}{\sqrt{s}}\right)^{0.8} \cdot L$

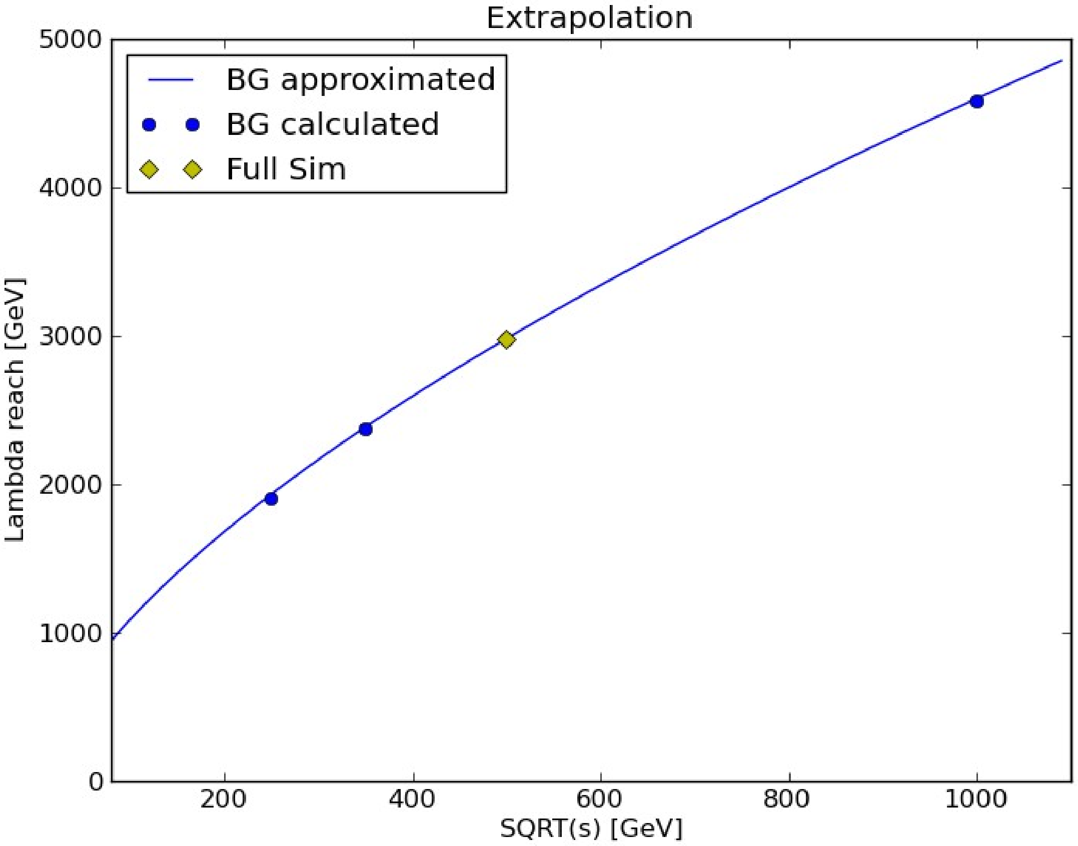
3) Scaling Λ^{reach}

- What we want to get: $$\Lambda^{reach} = \Lambda_0^{reach} \frac{F(\sqrt{s}, L)}{F(\sqrt{s_0}, L_0)}$$
- relation of signal and background (confidence level) $$N_s^{CL} = k\sqrt{B}$$
- approximation for signal (2a): $$\sigma_s \propto \frac{s}{\Lambda^4} \quad , \quad N = \sigma L$$
- plugging in: $$\Lambda^{reach} \propto \sqrt[4]{\frac{s L}{N_S^{CL}}} = \sqrt[4]{\frac{s L}{k\sqrt{B}}}$$
- approximation for background (2b): $$B \propto \left(\frac{1}{\sqrt{s}}\right)^{0.8} \cdot L$$
- finally: $$\Lambda^{reach} = \Lambda_0^{reach} \cdot \sqrt[4]{\frac{s \cdot L}{s_0 \cdot L_0}} \cdot \sqrt[8]{\frac{L_0}{L}} \left(\frac{\sqrt{s_0}}{\sqrt{s}}\right)^{0.8}$$

Scaling Λ^{reach}

- $$\Lambda^{reach} = \Lambda_0^{reach} \cdot \sqrt[4]{\frac{s \cdot L}{s_0 \cdot L_0}} \cdot \sqrt[8]{\frac{L_0}{L}} \left(\frac{\sqrt{s_0}}{\sqrt{s}}\right)^{0.8}$$

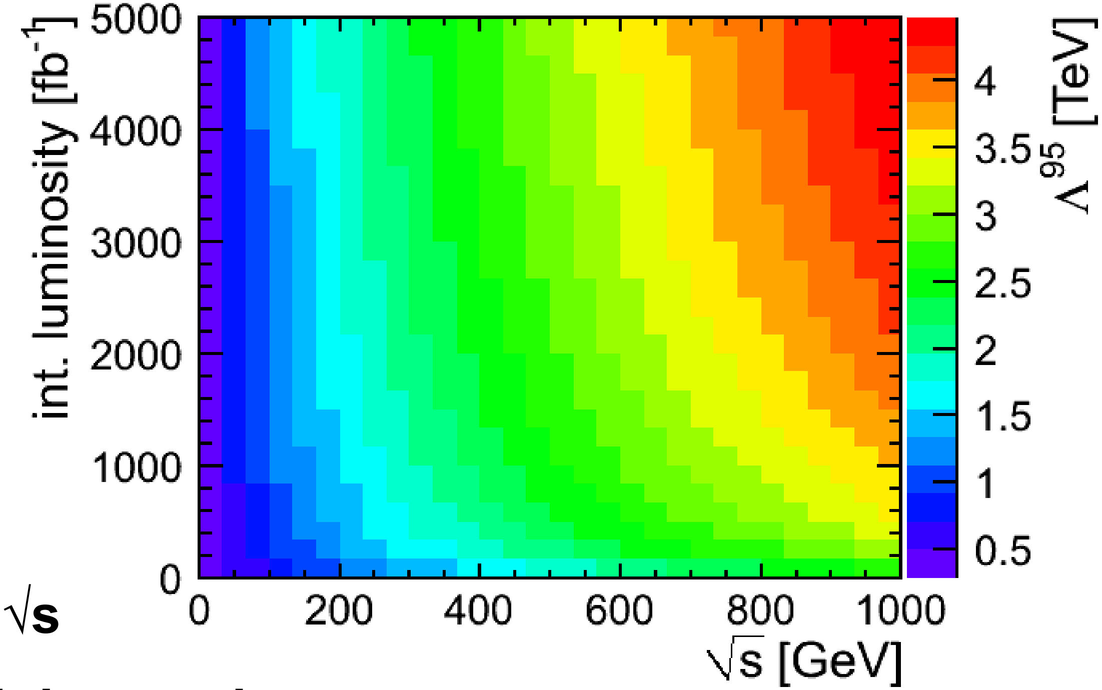
- Λ^{reach} for M_χ = 10 GeV
  - as function of √s
  - What about L ?



Scaling Λ^{reach}

- $$\Lambda^{reach} = \Lambda_0^{reach} \cdot \sqrt[4]{\frac{s \cdot L}{s_0 \cdot L_0}} \cdot \sqrt[8]{\frac{L_0}{L}\left(\frac{\sqrt{s_0}}{\sqrt{s}}\right)^{0.8}}$$

- Λ^{reach} as function of √s and L



- **Λ^{reach} saturates for given √s**
- **Prefered run scenario: high energies asap**

Summary

- Full simulation @ 500 GeV

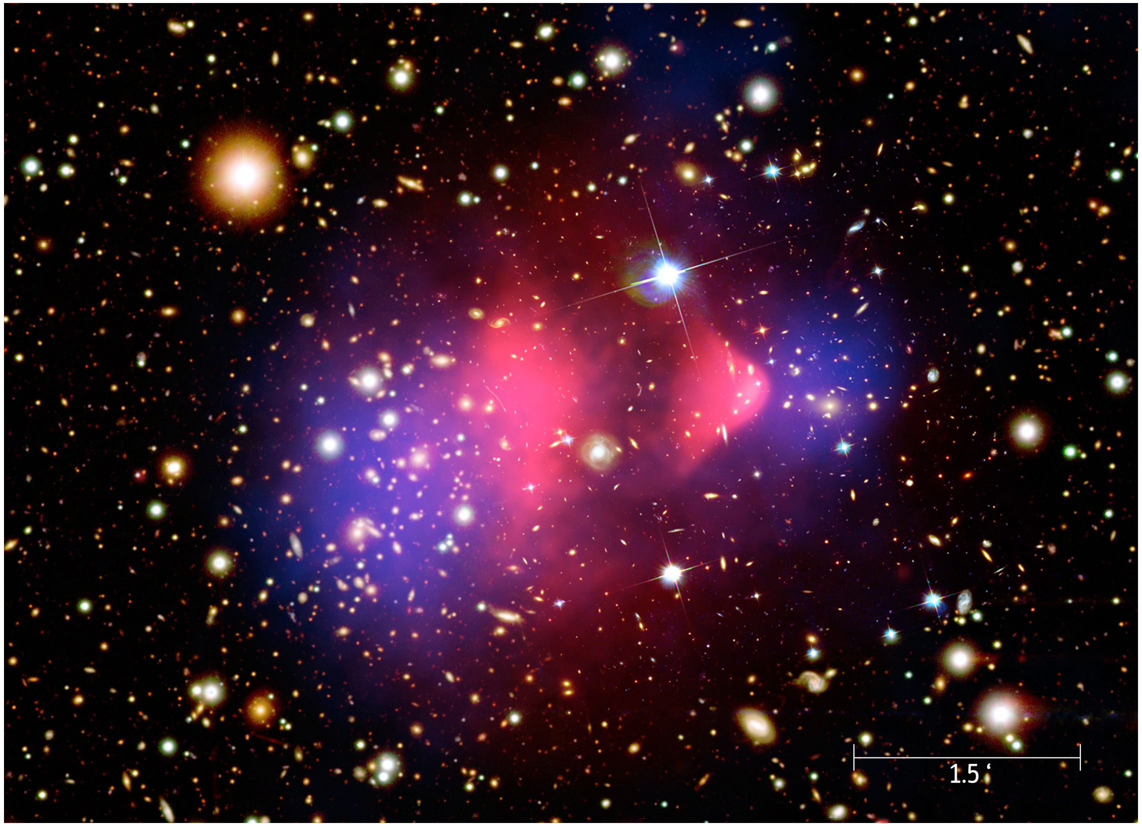
- Effective operator approach
  - ILC: higher Λ^{reach} (for smaller M_χ)
  - LHC: higher M_χ (but smaller Λ^{reach})

  → **complementary**

- Extrapolation to arbitrary center-of-mass energies and int. luminosities

- Higher center-of-mass energies better than high integrated luminosities

Thank you



Backup

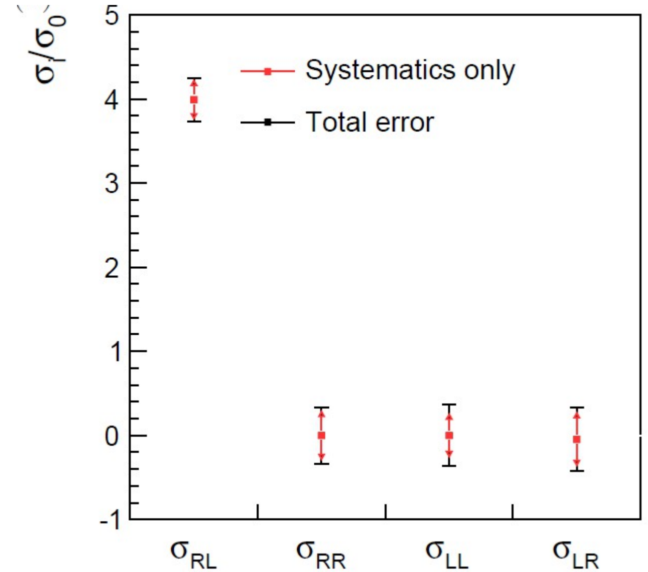
Status of studies within ILD: full simulation

- Christoph Bartels (arXiv1206.6639 , DESY-THESIS-2011-034)
- $\sqrt{s}$ = 500 GeV
- stdhep:
  - Whizard 1.96
  - Beam parameters: RDR
  - No matching of matrix element γ and ISR
- ilcsoft v01-06
- Detector models:
  - LDC_PrimeSc_02
  - ILD_00

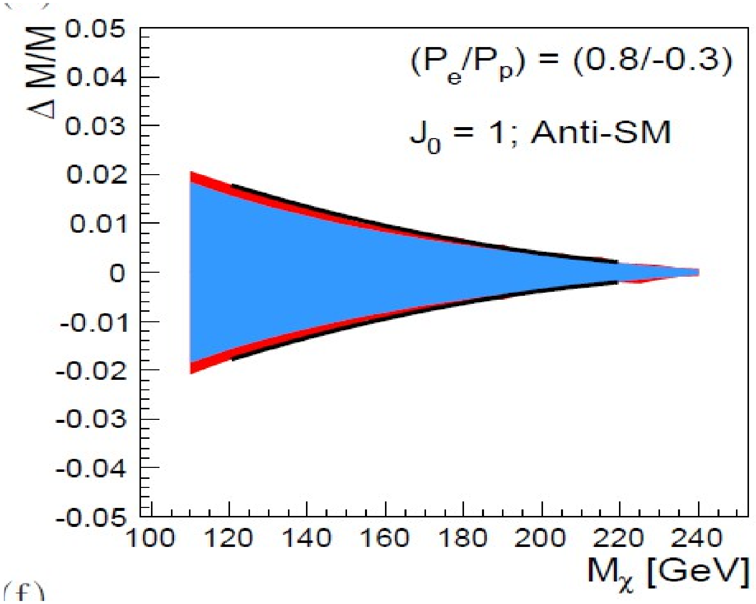
M_χ = 150 GeV
$|P|$ = (0.8/0.3)
$\delta P/P$ = 0.25%
L = 500 fb^{-1}

Status of studies within ILD: existing full simulation

- Christoph Bartels (arXiv1206.6639 , DESY-THESIS-2011-034)
- √s = 500 GeV
- Interpretation: cosmological approach
  - e.g.: "**Anti-SM**" scenario



Polarized cross sections σ_{ij}/σ_0

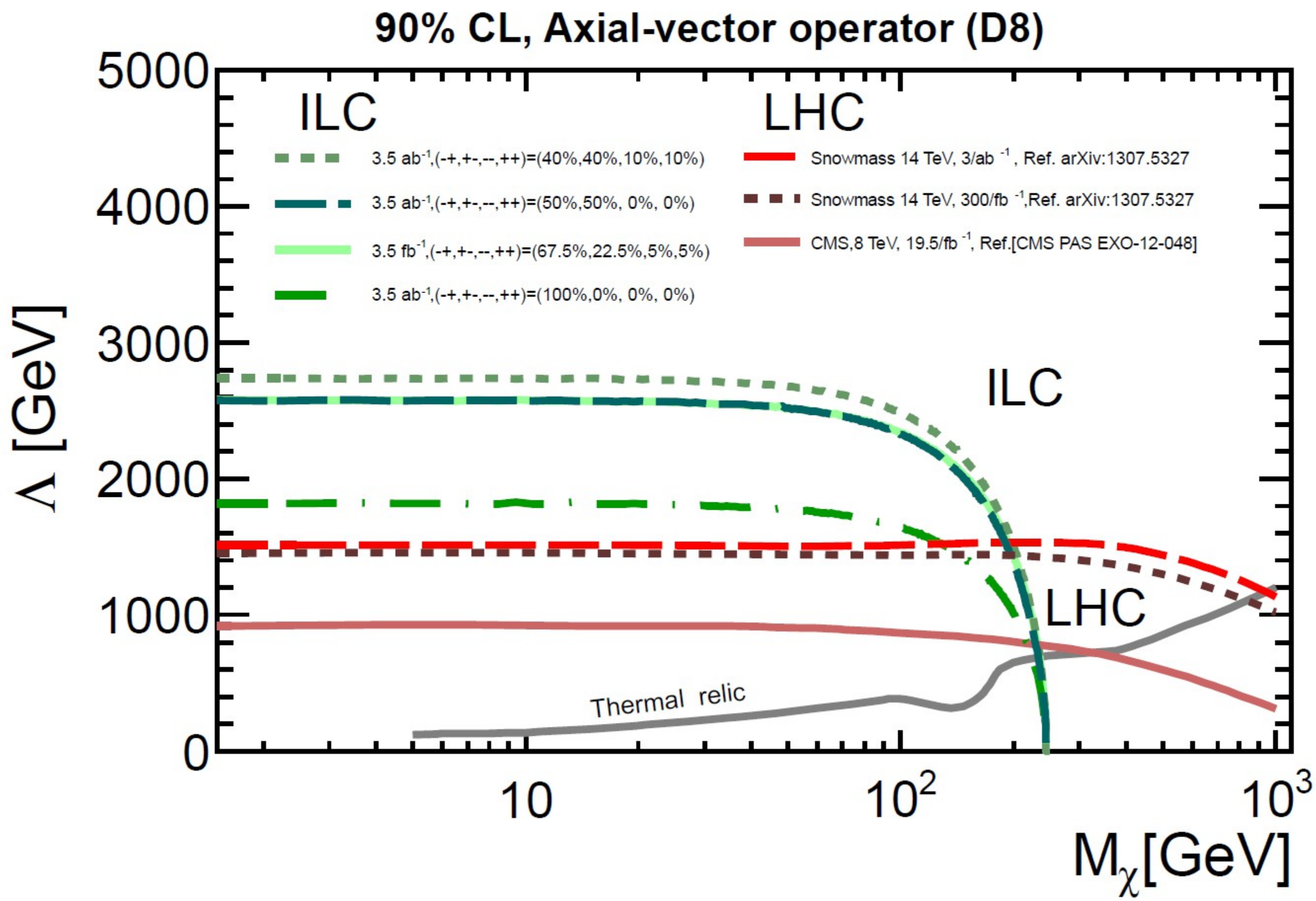


Relative error ΔM/M

Whizard 2.2.2

- “hard” photon in matrix element
- Additional: 2 photons from initial state radiation
- Signal definition:
  - E_{min} = 10 GeV
  - E_{max} < Z-return
  - $|\cos\theta| < 0.98$
  - Bhabha: additional: $M_{inv,ij}$ > 4 GeV (ij: incoming and final state particles)

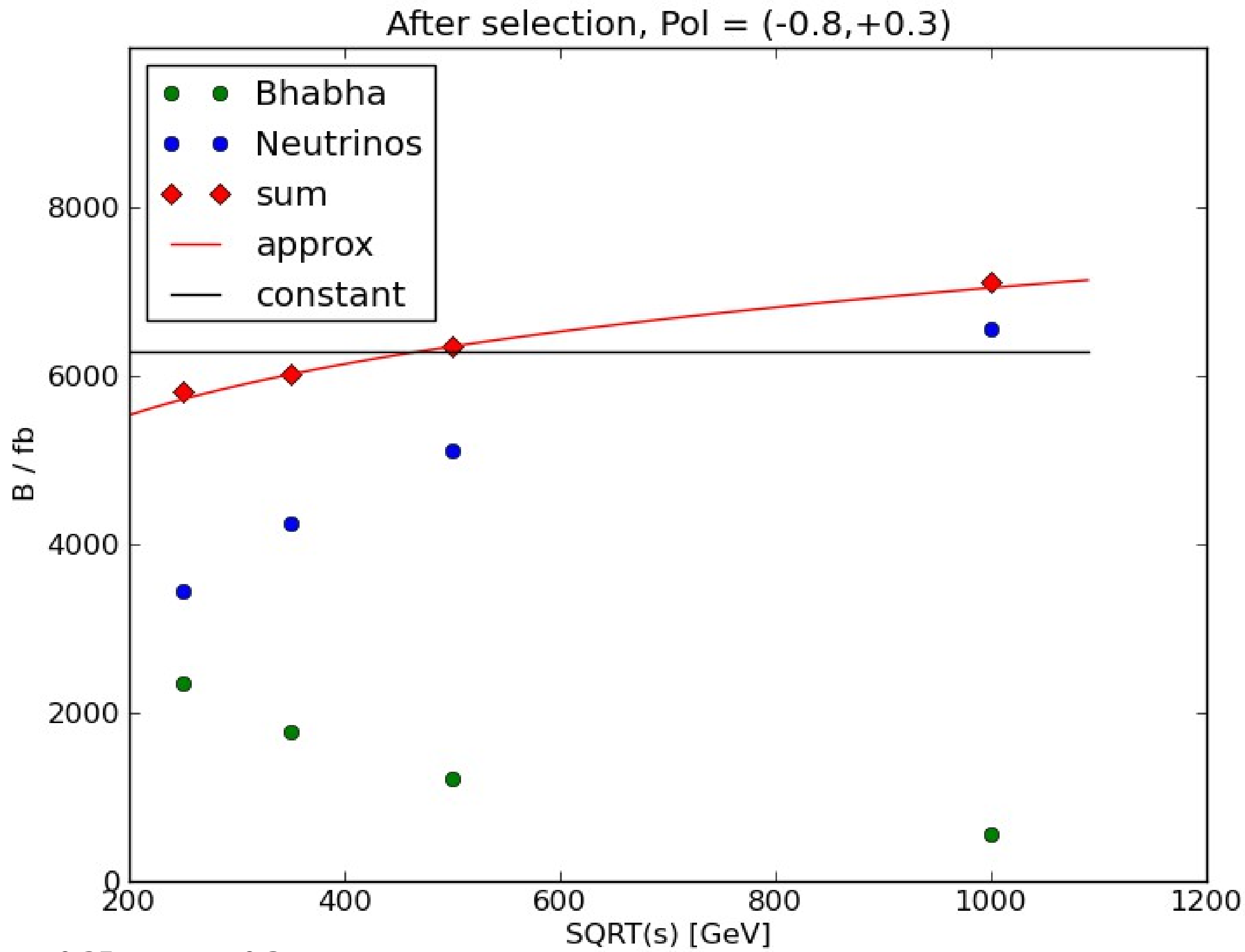
Axial vector



2) Find approximative formula $\Lambda^{reach}(\sqrt{s},L)$
b) background

$$B \propto (\sqrt{s})^{0.15} \cdot L$$

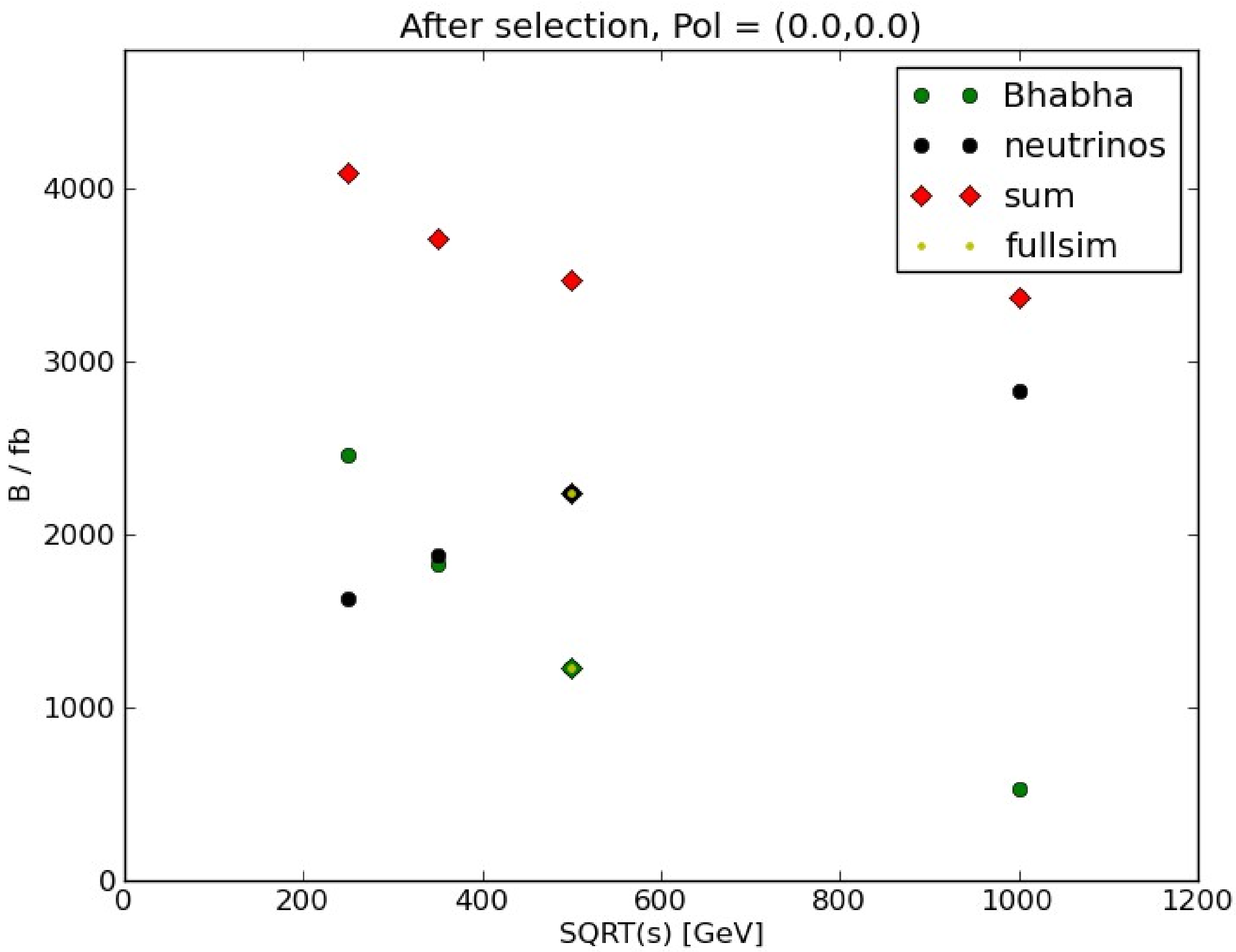
$$\Rightarrow \quad B \propto L$$



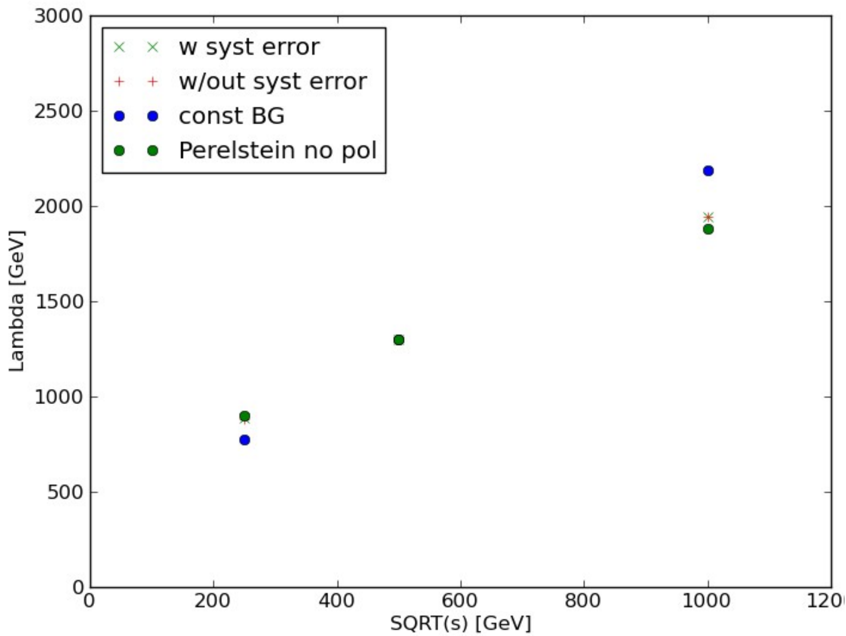
$$\Lambda^{reach} = \Lambda_0^{reach} \cdot \sqrt[8]{\frac{L}{L_0}} \cdot \left(\left(\frac{s}{s_0}\right)^{0.25} + \left(\frac{s}{s_0}\right)^{0.3} \right)$$

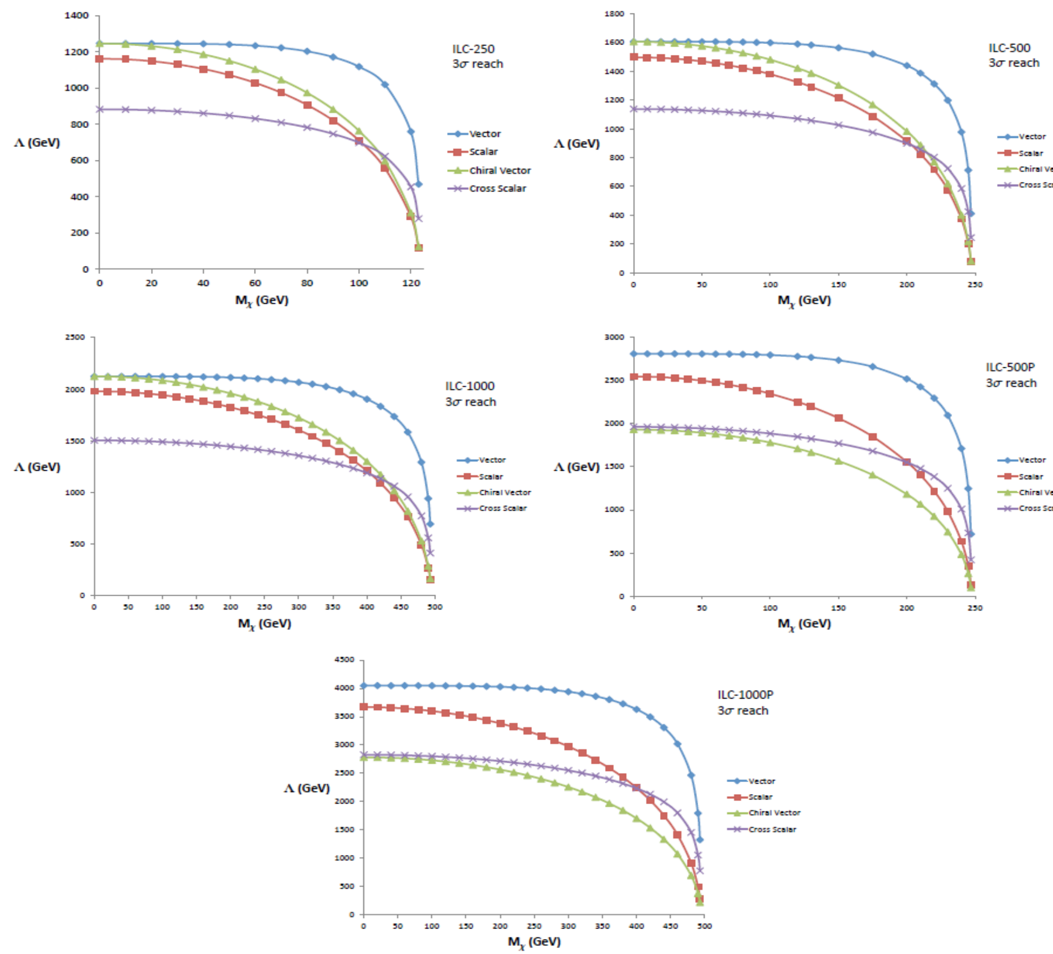
2) Find approximative formula $\Lambda^{reach}(\sqrt{s},L)$
b) background

- Unpolarized beams



Perelstein





$$\frac{d^2\sigma}{dz\,d\cos\theta} = \frac{\alpha}{12\pi^2}\,\frac{s}{\Lambda^4}\,\frac{1}{z\sin^2\theta}\sqrt{\frac{1-z-4\mu^2}{1-z}}\,\left(1-z+2\mu^2\right)\left[4(1-z)+z^2(1+\cos^2\theta)\right]$$