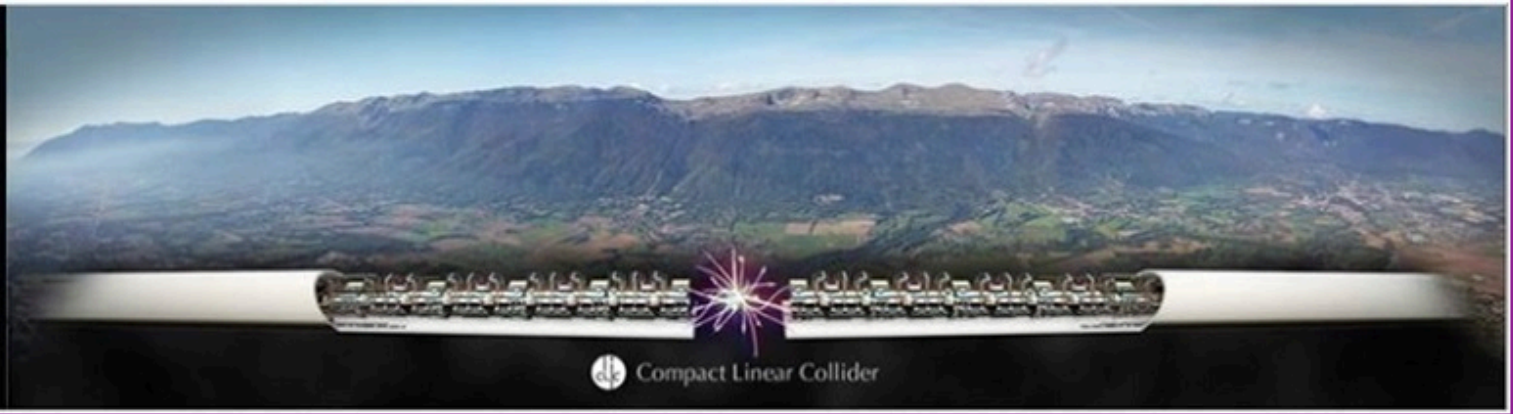



CLIC Workshop 2016

CERN 18-22 January 2016

# Single-photon processes at e+e- colliders

**Jan Kalinowski**
**University of Warsaw**

FACULTY OF PHYSICS
UNIVERSITY OF WARSAW

# Motivation

Great expectations for New Physics at the LHC, but no direct evidence (yet?)

Outstanding questions remain + various BSM hints (DM, neutrinos,...)

A plausible scenario:

- all colored particles very heavy
- a few light EW particles, nearly mass-degenerate
- even charged states difficult to detect due to soft decay products

A future e+e- collider with:

- clean environment
- fixed CM frame
- polarized beams

can cope with such a difficult scenario via

$$e^+e^- \to \gamma \bar{X} X \to \gamma + E^{miss}$$

Linssen ea 2012
Behnke ea 2013,
Moortgat-Pick es 2015
Fujii ea 2015
Levy (CLICdp) 2015
……

# Motivation

Processes $e^+e^- \to \gamma + E^{miss}$ have been exploited in the past:

- counting neutrino families
- anomalous gauge couplings
- search for invisible states like lightest neutralino

Question: can we reveal the nature of events from the observed photon?

Here we exploit $e^+e^- \to \gamma + E^{miss}$ to full extent possible

- not only to detect X-pair production,
- but also determine the spin
- and the coupling structure

see also Bartels, Berggren,List 1206.6639

# Outline:

- Three benchmark scenarios – adopted from the MSSM

  → higgsino, wino and slepton

- ISR and FSR
- Photon energy distributions
- Discovery limits for invisible states
- Spin determination
- Beam polarisation ⇔ scenario discrimination

based on:
S.Y. Choi, T. Han, J.K., K. Rolbiecki and X. Wang
PRD 92(2015)095006 [arXiv:1503.08538]
+ an update for ILC-2 and CLIC

# Higgsino Scenario – $H_{1/2}$

- realised when $\mu \ll$ other SUSY parameters

a pair of spin ½ higgsino doublets

$$\tilde{H}_d = [\tilde{H}^0_{dL}, \tilde{H}^-_{dL}] \quad and \quad \tilde{H}_u = [\tilde{H}^+_{uL}, \tilde{H}^0_{uL}]$$

➔ 1 Dirac chargino + 1 Dirac neutralino

$$\mu\left(\overline{\tilde{H}^-_{uR}}\tilde{H}^-_{dL} + \overline{\tilde{H}^+_{dR}}\tilde{H}^+_{uL}\right) - \mu\left(\overline{\tilde{H}^0_{uR}}\tilde{H}^0_{dL} + \overline{\tilde{H}^0_{dR}}\tilde{H}^0_{uL}\right) \quad \Rightarrow \quad \mu\,\overline{\chi^-_H}\,\chi^-_H + \mu\,\overline{\chi^0_H}\,\chi^0_H$$

with pure vector-type interactions with EW gauge bosons

$$\mathcal{L}^H_{V\chi\chi} = e\,\overline{\chi^-_H}\gamma^\mu\chi^-_H\,A_\mu + e\,\frac{(1/2 - s^2_W)}{c_W s_W}\,\overline{\chi^-_H}\gamma^\mu\chi^-_H\,Z_\mu$$

$$-\frac{1}{2}\,\frac{e}{c_W s_W}\,\overline{\chi^0_H}\gamma^\mu\chi^0_H\,Z_\mu - \frac{e}{\sqrt{2}s_W}(\overline{\chi^0_H}\gamma^\mu\chi^-_H\,W^+_\mu + \text{h.c.})$$

# Wino Scenario - $W_{1/2}$

- realised when $M_2 \ll$ other SUSY parameters

a triplet of spin ½ wino states

$$\tilde{W} = [\tilde{W}_L^+, \tilde{W}_L^0, \tilde{W}_L^-]$$

➔ 1 Dirac chargino + 1 Majorana neutralino

$$M_2\,(\overline{\tilde{W}_R^+}\tilde{W}_L^+ + \overline{\tilde{W}_R^0}\tilde{W}_L^0 + \overline{\tilde{W}_R^-}\tilde{W}_L^-) \quad \Rightarrow \quad M_2\,\overline{\chi_W^-}\,\chi_W^- + \frac{1}{2}\,M_2\,\overline{\chi_W^0}\,\chi_W^0$$

which interact with EW gauge bosons as

$$\mathcal{L}_{V\chi\chi}^W = e\,\overline{\chi_W^-}\gamma^\mu\chi_W^-\,A_\mu + e\,\frac{(1-s_W^2)}{c_W\,s_W}\,\overline{\chi_W^-}\gamma^\mu\chi_W^-\,Z_\mu - \frac{e}{s_W}\left(\overline{\chi_W^-}\gamma^\mu\chi_W^0\,W_\mu^- + \text{h.c.}\right)$$

➔ $\chi_W^0$ does not couple to Z

# Slepton Scenario – $L_0$

- realised when $m_{\tilde{l}_L} \ll$ other SUSY parameters

a doublet of spin 0 sleptons

$$\tilde{L} = [\tilde{\nu}_\ell, \tilde{\ell}_L^-]$$

momentum-dependent interaction with EW gauge bosons

$$\mathcal{L}^L_{V\tilde{\ell}_L\tilde{\ell}_L} = e\,\tilde{\ell}_L^+ \overleftrightarrow{\partial}_\mu \tilde{\ell}_L^-\, A^\mu + e\,\frac{(1/2 - s_W^2)}{c_W s_W}\,\tilde{\ell}_L^+ \overleftrightarrow{\partial}_\mu \tilde{\ell}_L^-\, Z^\mu - \frac{e}{2c_W s_W}\,\tilde{\nu}_\ell^* \overleftrightarrow{\partial}_\mu \tilde{\nu}_\ell\, Z^\mu - \frac{e}{\sqrt{2}s_W}\left(\tilde{\nu}_\ell^* \overleftrightarrow{\partial}_\mu \tilde{\ell}_L^-\, W^{+\mu} + \mathrm{h.c.}\right)$$

additional quartic contact interaction

$$\mathcal{L}^L_{\gamma Z \tilde{\ell}_L^- \tilde{\ell}_L^-} = e^2 \tilde{\ell}_L^+ \tilde{\ell}_L^- A_\mu A^\mu + 2e^2 \frac{(1/2 - s_W^2)}{c_W s_W} \tilde{\ell}_L^+ \tilde{\ell}_L^- A_\mu Z^\mu$$

changes threshold behavior

# Radiatively-induced mass difference

although degenerate at tree level, radiative corrections split by a calculable amount

$$\Delta m_H = m_{\chi_H^\pm} - m_{\chi_H^0} = \frac{\alpha}{4\pi}\mu\left[f(m_Z/\mu) - f(0)\right]$$

$$\Delta m_W = m_{\chi_W^\pm} - m_{\chi_W^0} = \frac{\alpha}{4\pi s_W^2} M_2\left[f(m_W/M_2) - c_W^2 f(m_Z/M_2) - s_W^2 f(0)\right]$$

$$f(a) = 2\int_0^1 dx\,(1+x)\ln\left[x^2 + (1-x)a^2\right]$$

asymptotic values for $\mu, M_2 \gg m_Z$

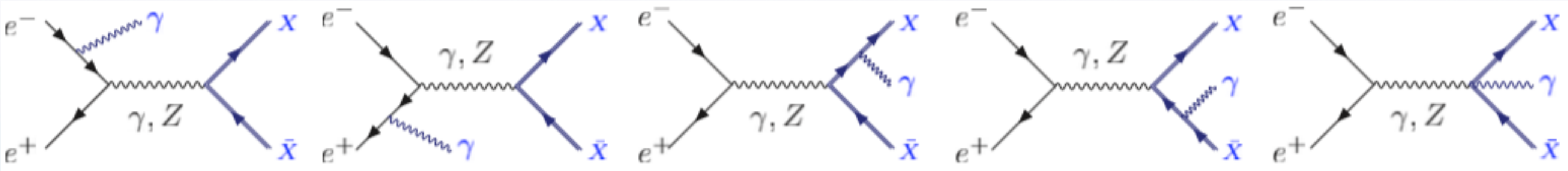
$$\Delta m_H \simeq 355\ MeV, \quad \Delta m_W \simeq 165\ MeV$$

for sleptons the mass splitting $\sim \dfrac{\alpha}{4\pi} M_Z$

D-term splitting =0 for tanβ=1

# Single-photon processes at e+e- colliders

We want to exploit fully the photon in $e^+e^- \to \gamma \bar{X} X$




universal ISR

$\chi^{\pm}_H, \chi^{\pm}_W, \chi^0_H, \tilde{l}^{\pm}_L, \tilde{\nu}_L$

process-dependent FSR

$\chi^{\pm}_H, \chi^{\pm}_W$

unique

$\tilde{l}^{\pm}_L$

- the ISR and FSR are separately gauge invariant and do not interfere
- in most analyses so far the FSR has been ignored

# Initial state radiation

The ISR effect can be expressed in a factorised form

$$\frac{d\sigma(e^+e^- \to \gamma X\bar{X})_{\rm ISR}}{dx_\gamma \, d\cos\theta_\gamma} = \mathcal{R}(s; x_\gamma, \cos\theta_\gamma) \times \sigma^{X\bar{X}}(q^2)$$

$$x_\gamma = 2E_\gamma/\sqrt{s}$$

$$q^2 = (1 - x_\gamma)s$$

$$\beta_q = \sqrt{1 - 4m_X^2/q^2}$$

with the universal ISR radiator $\mathcal{R}$

and the $X\bar{X}$ production cross section at the reduced CM energy

$$\sigma^{X\bar{X}}(q^2) = \frac{2\pi\alpha^2}{3q^2}\beta_q \mathcal{P}(X; P_-, P_+; q^2) \begin{cases} \beta_q^2 & \text{for spin-0} \\ 2(3-\beta_q^2) & \text{for spin-1/2} \end{cases}$$

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P-wave

S-wave

At threshold, when $x_\gamma \to x_\gamma^{max} = 1 - 4m_X^2/s$ , the X speed $\beta_q \to 0$

# Final state radiation

The FSR can be decomposed as

$$\frac{d\sigma(e^+e^- \to \gamma X\bar{X})_{\rm FSR}}{dx_\gamma \, d\cos\theta_\gamma} = \mathcal{F}(s; x_\gamma, \cos\theta_\gamma) \times \sigma^{X\bar{X}}(s)$$

but unlike ISR, the FSR radiator

$$\mathcal{F}(s; x_\gamma, \cos\theta_\gamma) \; = \; \tfrac{3}{8} \, \left[(1+\cos^2\theta_\gamma)\mathcal{F}_1^X(s; x_\gamma) + (1 - 3\cos^2\theta_\gamma)\mathcal{F}_2^X(s; x_\gamma)\right]$$

is not universal: depends on the spin of X

In the soft photon limit, and after integrating over $\cos\theta_\gamma$

it approaches a well known universal form

$$\mathcal{F}(s; x_\gamma) \; \to \; \frac{\alpha}{\pi}\frac{1}{x_\gamma}\left[(1+\beta_s^2)L(\beta_s) - 2\right] \quad \text{as} \quad x_\gamma \to 0$$

$$L(\beta_q) = \frac{1}{\beta_q} \ln \frac{1+\beta_q}{1-\beta_q}$$

# Final state radiation

On the other hand, at threshold $\beta_q \to 0$

- the radiator function $\mathcal{F}_2^X$ behaves

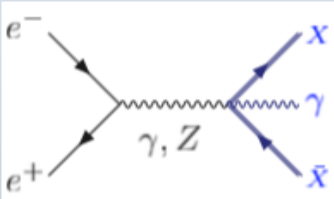
$\mathcal{F}_2^X \sim \beta_q^3$ i.e. P-wave for both spin 0 and 1/2

- but the other radiator function $\mathcal{F}_1^X$ behaves differently

$$\mathcal{F}_1^X(s; x_\gamma) \quad \to \quad \frac{\alpha}{\pi}\beta_q \begin{cases} 2/\beta_s & \text{for spin-0} \\ 2\beta_s/(3-\beta_s^2) & \text{for spin-1/2} \end{cases}$$

i.e. S-wave for both spin 0 and 1/2

this is due to a quartic coupling appearing in




Question: does it jeopardize spin determination of charged states?

# Effects of ISR and FSR for charged pairs

In general FSR much smaller than ISR
because photon radiated by heavy X

$$\mathcal{R}_{\mathrm{FI}}(x_\gamma) = \frac{d\sigma(e^+e^- \to \gamma X\bar{X})_{\mathrm{FSR}}/dx_\gamma}{d\sigma(e^+e^- \to \gamma X\bar{X})_{\mathrm{ISR}}/dx_\gamma}.$$

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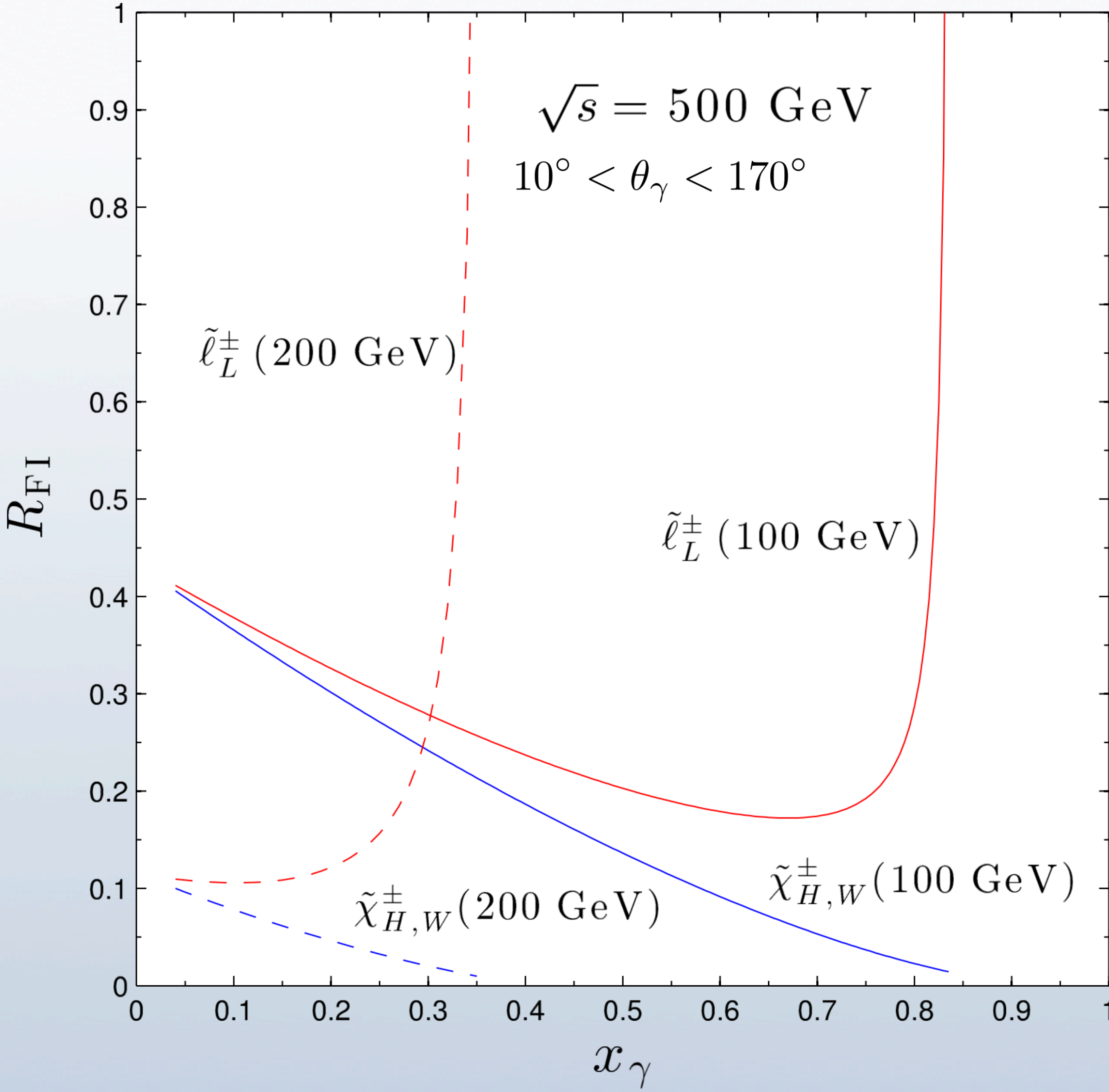
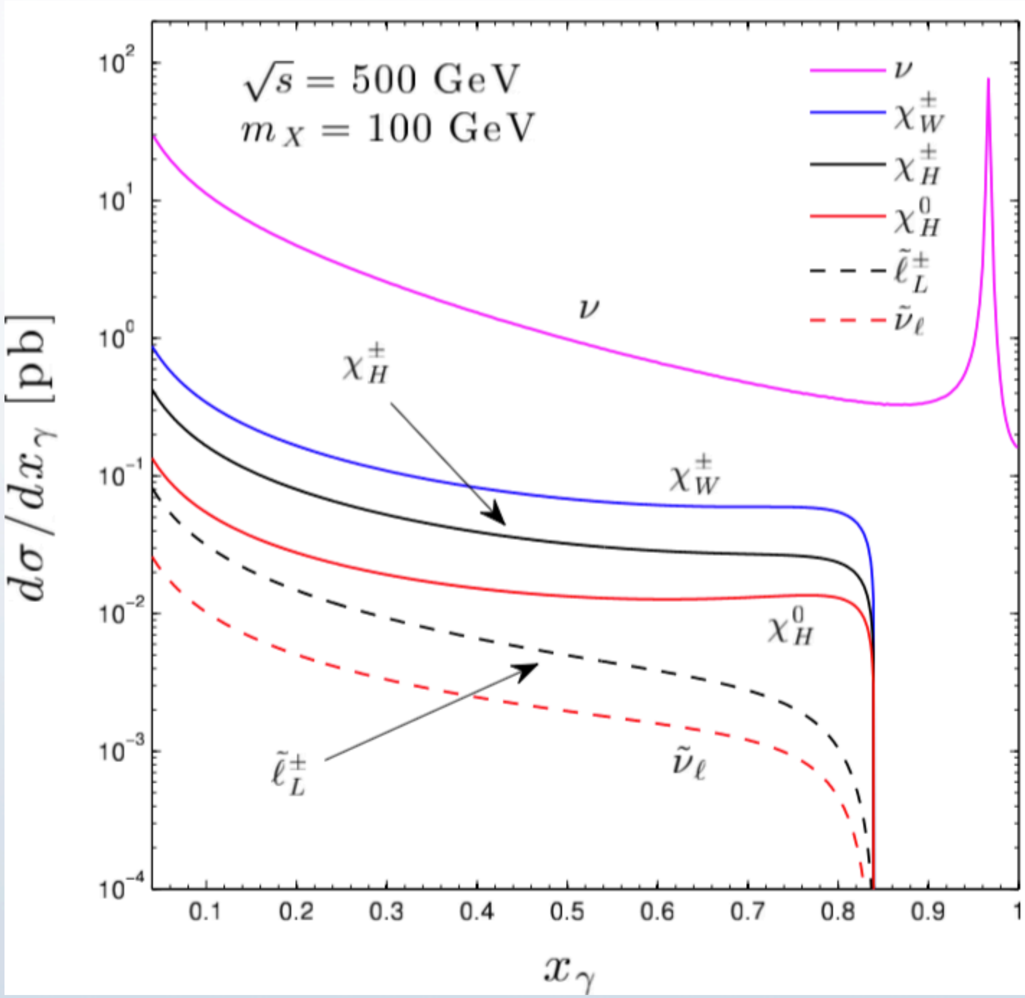
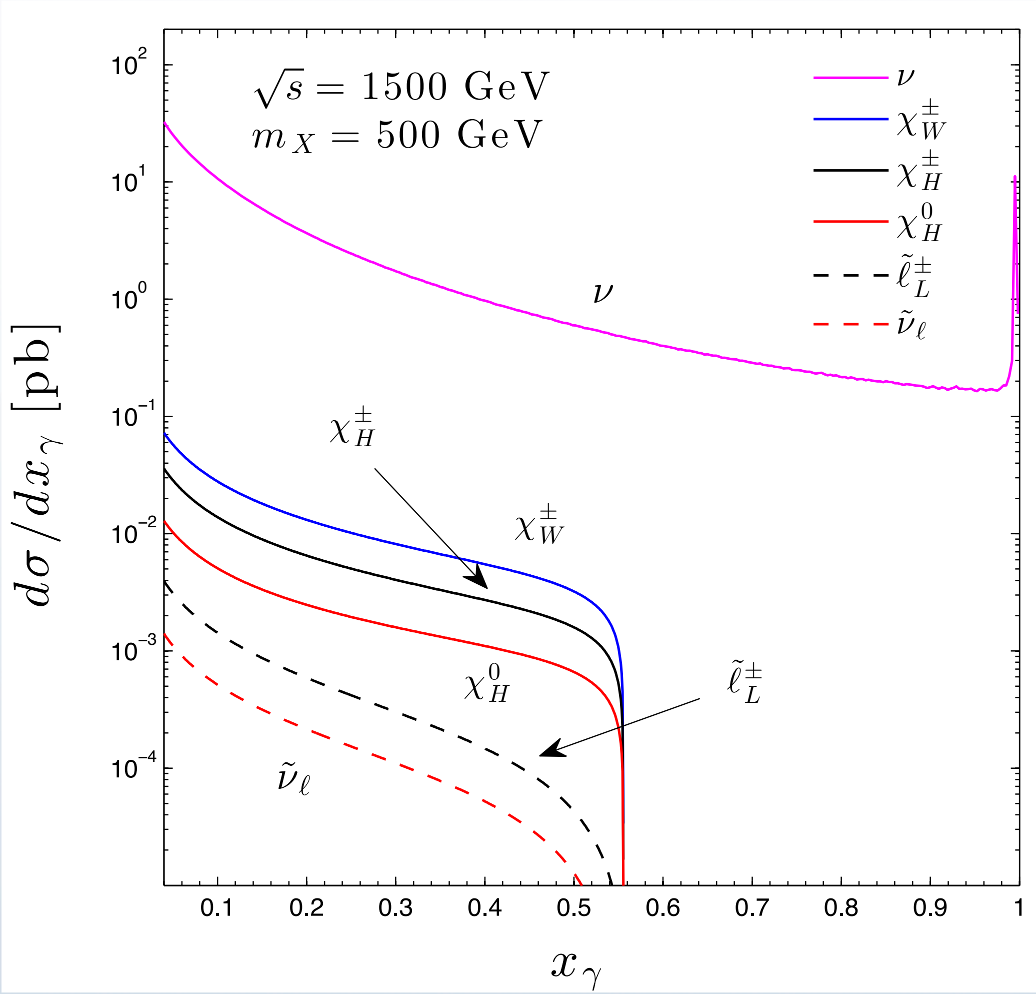
In contrast to spin ½ chargino case,

$\mathcal{R}_{\rm FI}(x_\gamma)$ for spin 0 blows up near threshold



# Signal vs. SM background




To suppress the background:

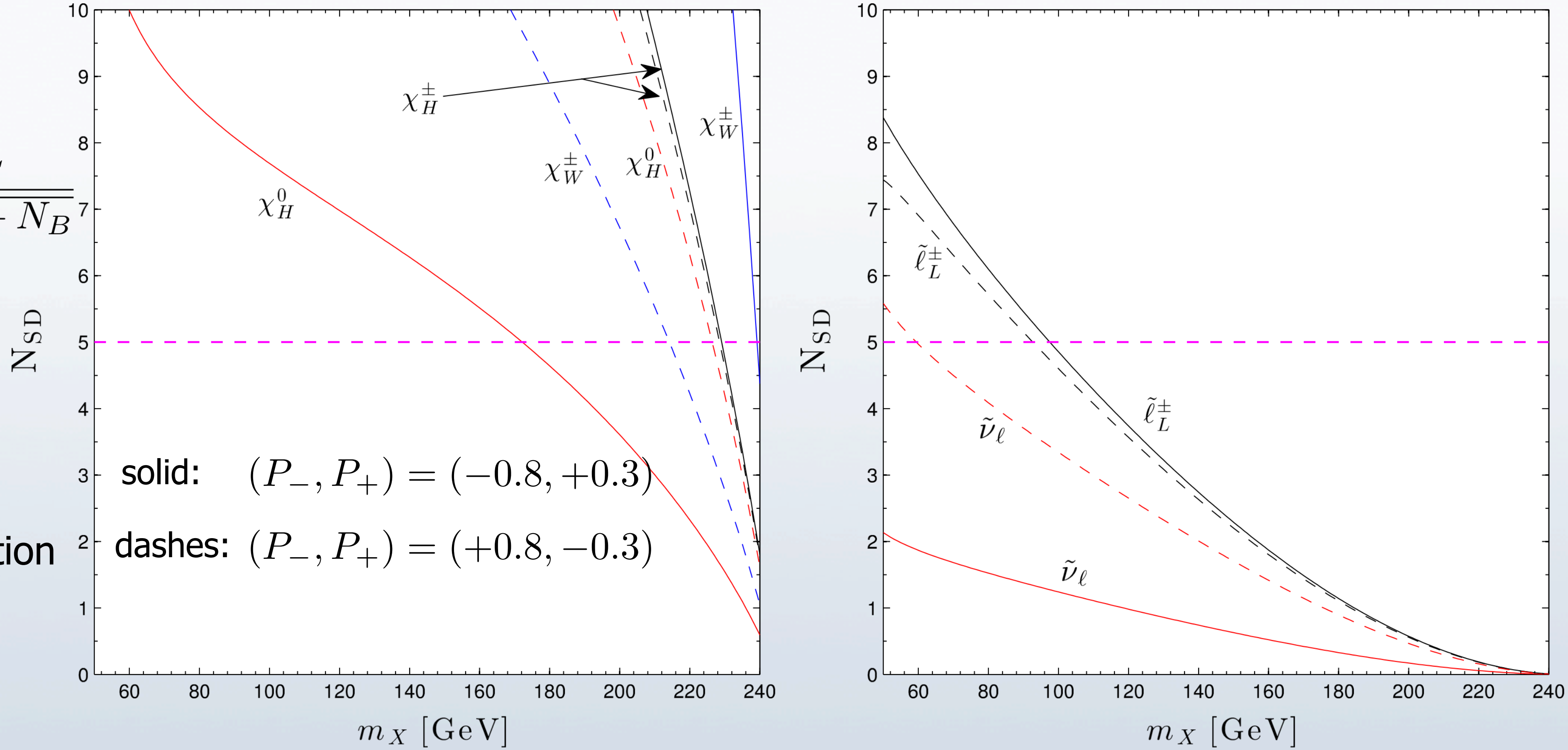
- cut on the photon recoil mass
- use polarized beams

# Statistical significance of signal: ILC $\mathcal{L} = 0.5\ \mathrm{ab}^{-1}$

$$N_{SD} = \frac{N_S}{\sqrt{N_S + N_B}}$$

sensitive to:

- beam polarization
- scenario type




e.g. for m_X=100 GeV

| | $(P_-, P_+)$ | $(-0.8, +0.3)$ | $(+0.8, -0.3)$ |
|---|---|---|---|
| | $\sigma(\gamma\nu\bar{\nu})$ | 6230 fb | 400 fb |
| number of signal events for 5σ significance: | $N_S$ | 8840 ev. | 2250 ev. |

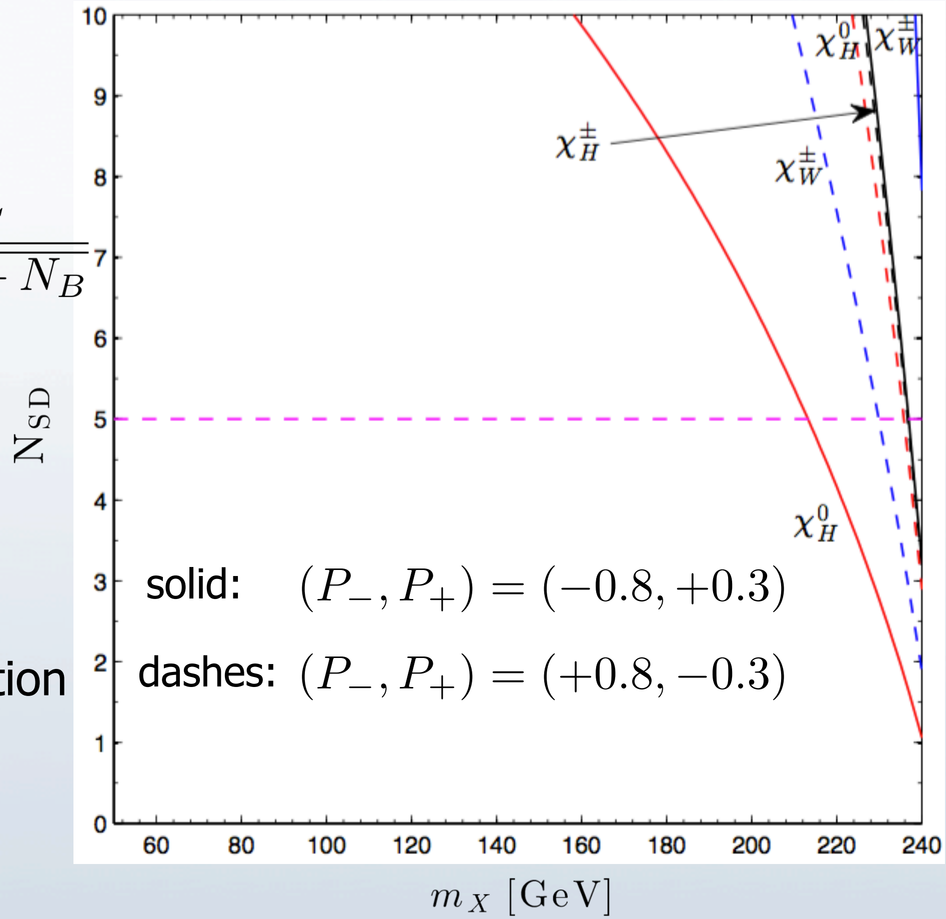
# Statistical significance of signal: ILC-2

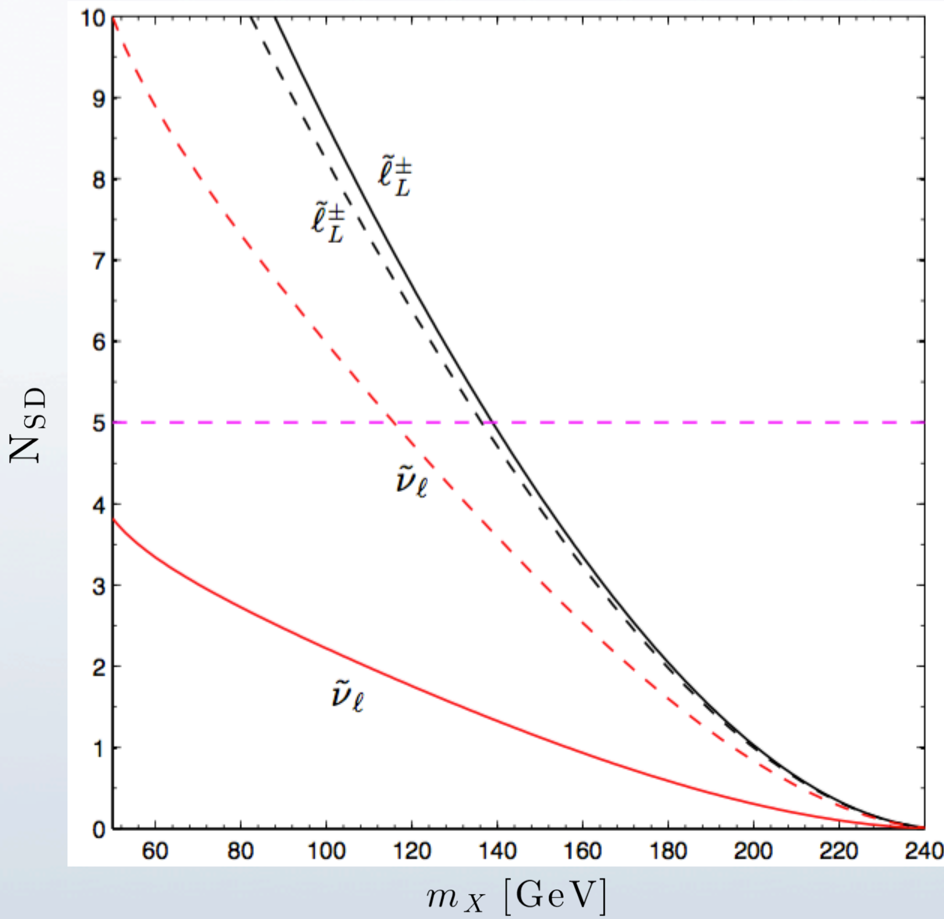
$\mathcal{L} = 1.6\ \text{ab}^{-1}$

$$N_{SD} = \frac{N_S}{\sqrt{N_S + N_B}}$$

sensitive to:

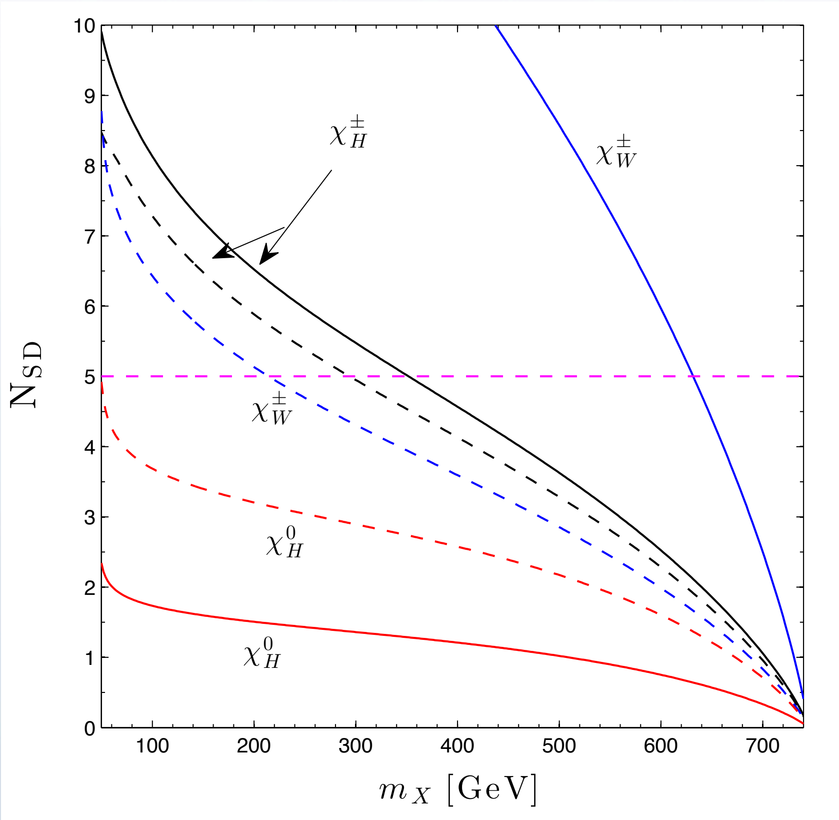
- beam polarization
- scenario type



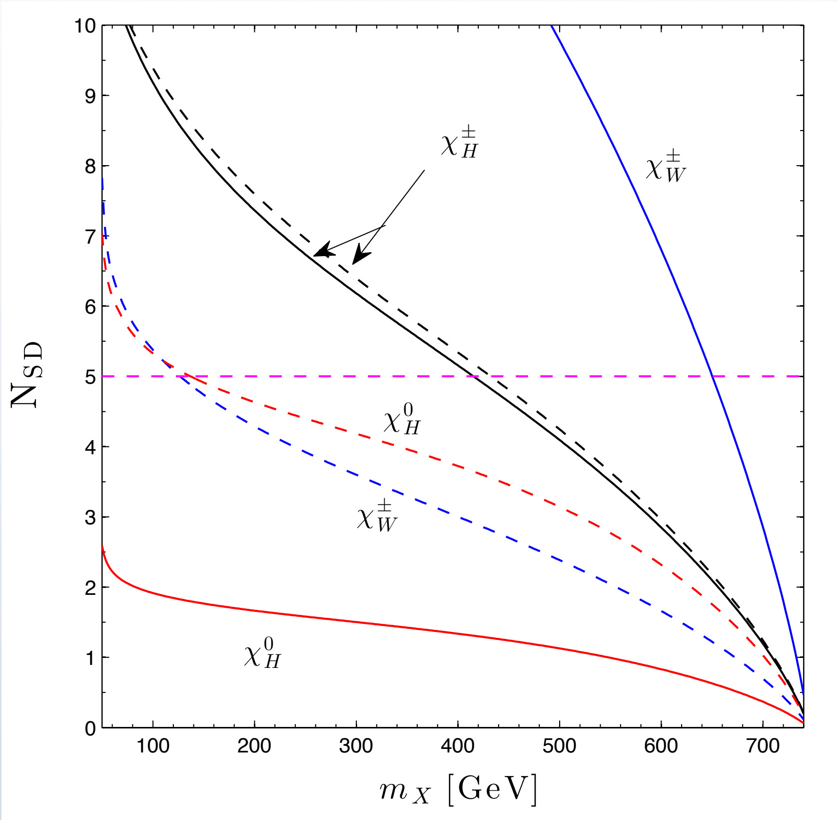



# Statistical significance of signal: CLIC $\mathcal{L} = 1.5\ \mathrm{ab}^{-1}$

only e- polarised




both beams polarised




solid: $(P_-, P_+) = (-0.8, 0.0)$

dashes: $(P_-, P_+) = (+0.8, 0.0)$

solid $(P_-, P_+) = (-0.8, +0.3)$

dashes $(P_-, P_+) = (+0.8, -0.3)$

# Spin determination

threshold behavior:

for neutrals:

S-wave for spin ½

P-wave for spin 0

for charged the FSR:

S-wave for both spin 0 and ½

does it geopardise the spin determination?

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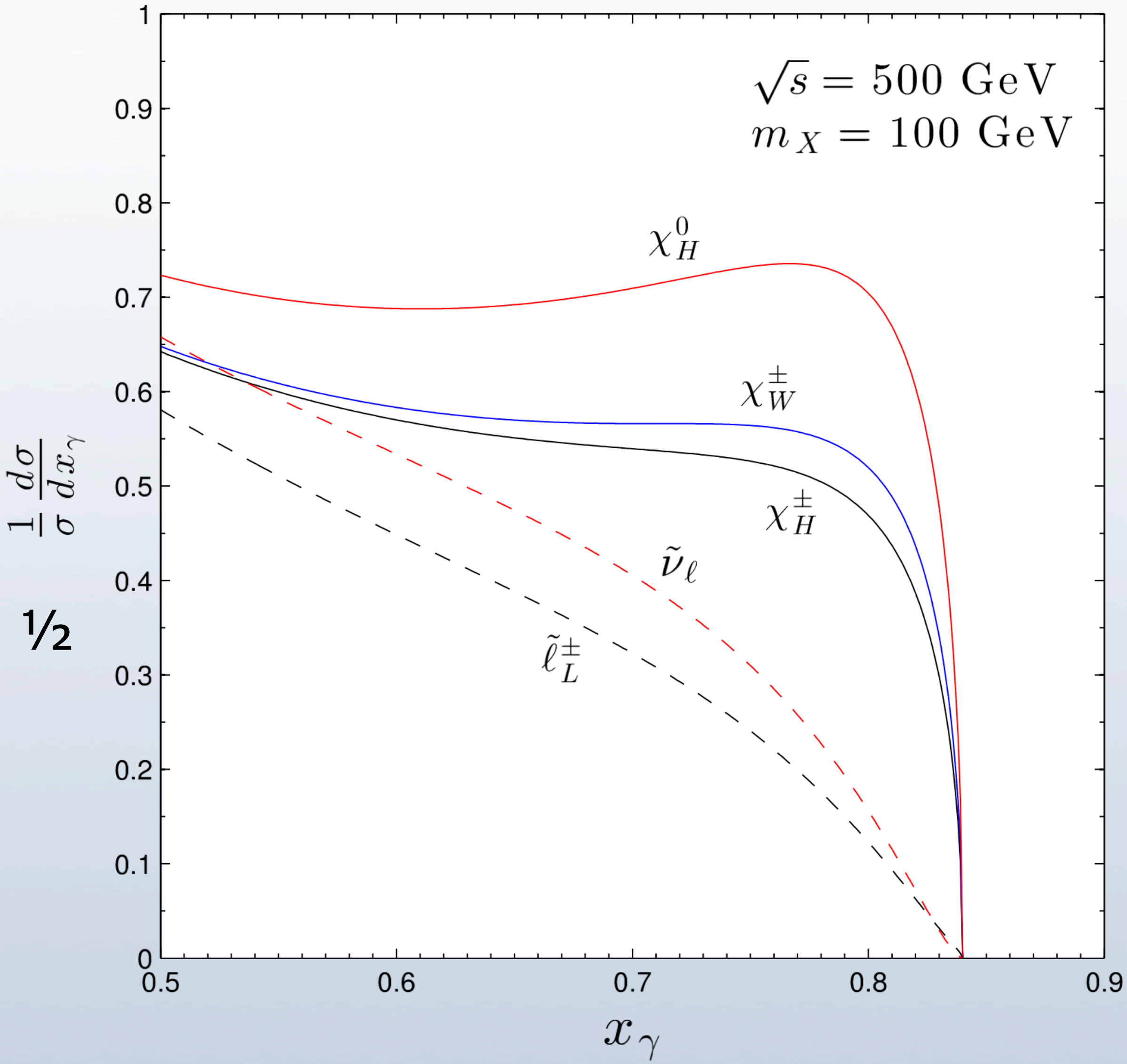
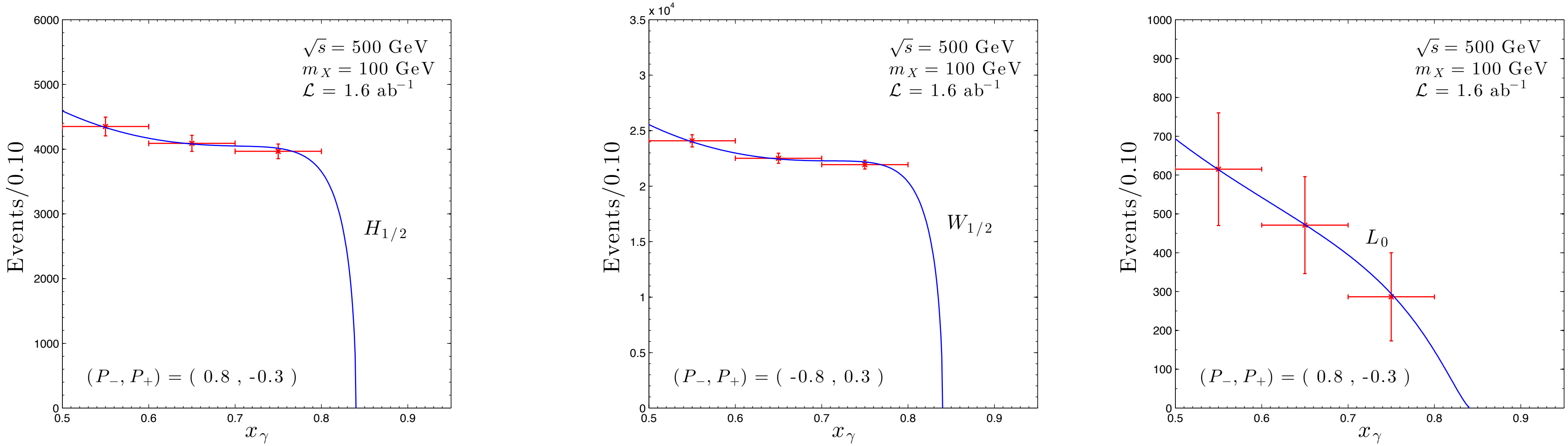



no, because near theshold FSR is numerically very small

# Spin determination: ILC-2

$\mathcal{L} = 1.6 \text{ ab}^{-1}$

$H_{1/2}$ $W_{1/2}$ $L_0$




statistical errors based on number of background events

difference between spin 0 and spin ½ clearly seen

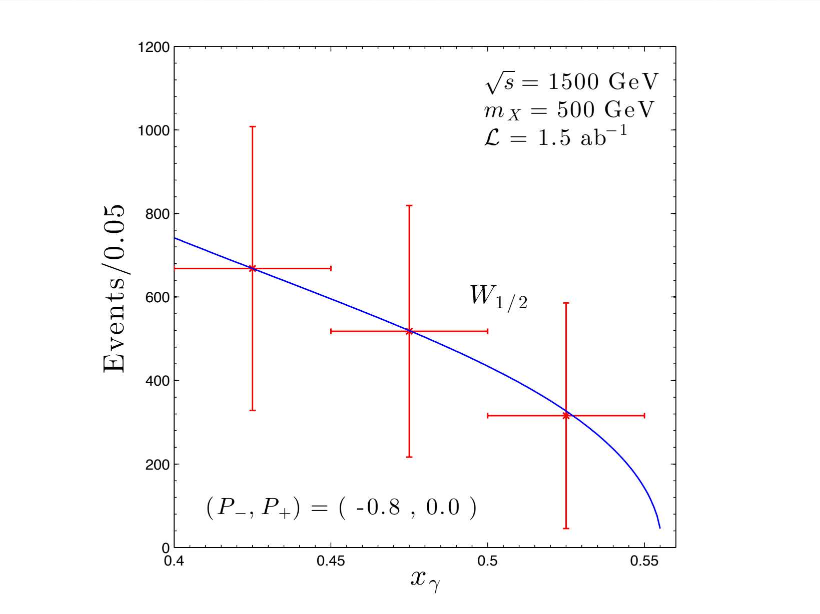
for L-scenario, dedicated study of soft decay products greatly helps

Berggren ea 2013

# Spin determination: CLIC

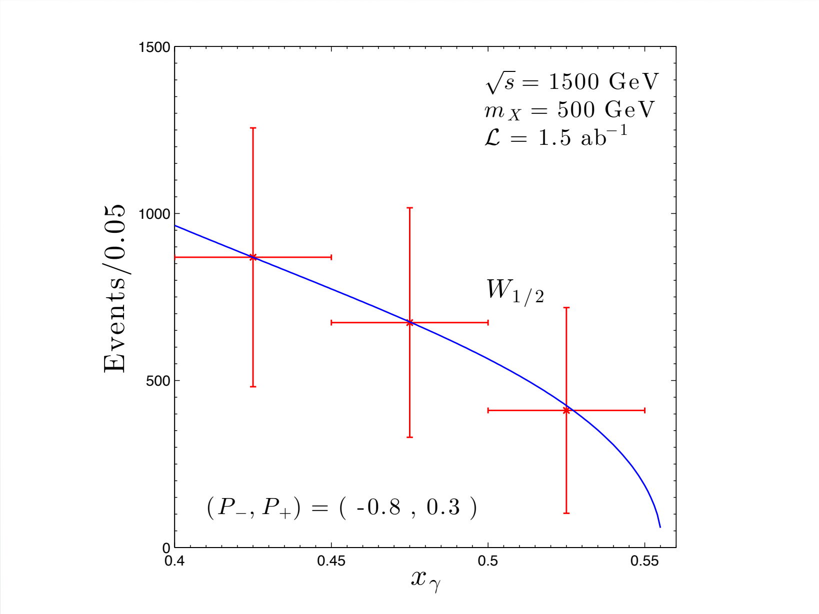
only e- polarised

$W_{1/2}$




both beams polarised

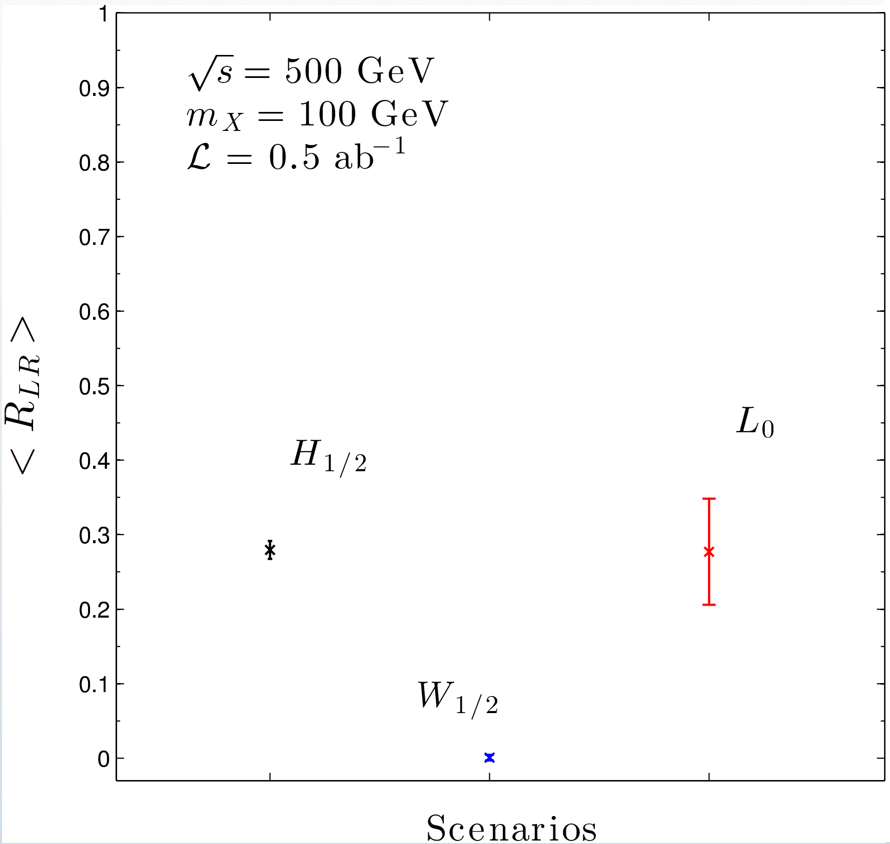
$W_{1/2}$



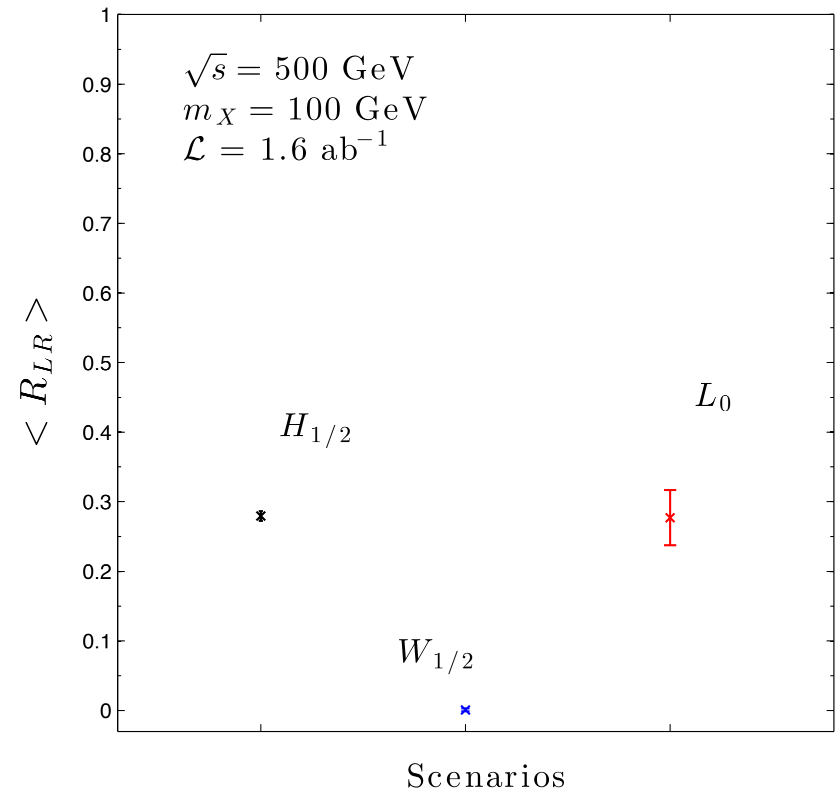

for $H_{1/2}$ and $L_0$ scenarios error bars are even larger, in particular for $L_0$

# Beam polarization ⇔ discriminating scenarios

ILC




ILC-2



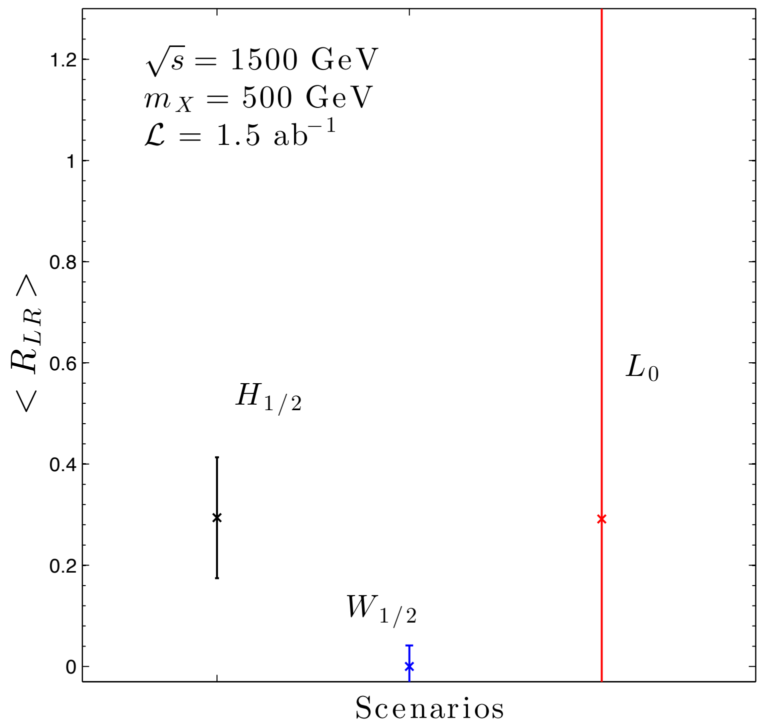

$$\mathcal{R}_{LR}(X; x_\gamma) = \frac{d\sigma(e^+e^-_R \to \gamma X\bar{X})/dx_\gamma}{d\sigma(e^+e^-_L \to \gamma X\bar{X})/dx_\gamma}$$

depends strongly on the scenario

# Beam polarization ⇔ discriminating scenarios

CLIC

only e- polarised

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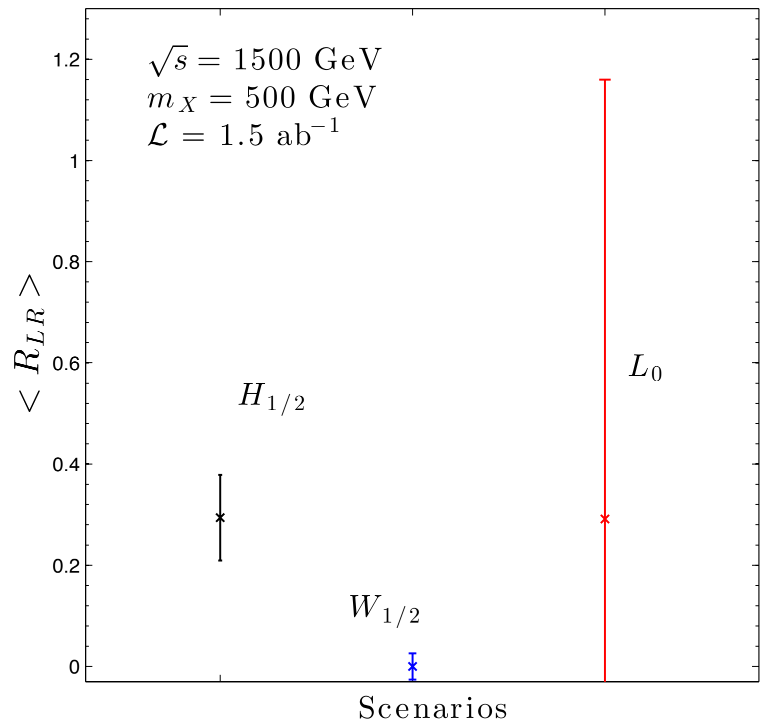


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# Conclusions

- Three scenarios $H_{1/2}$, $W_{1/2}$, $L_0$ with pairs of EW particles nearly mass-degenerate
- Both ISR and FSR analysed
- Inspite of FSR contamination, photon energy dependence near threshold allows to determin the spin
- Polarized beams are essential to discriminate among scenarios considered
- Our results demonstrate clearly the physics potential of the e+e- collider in detecting and characterizing the invisible particles

# backup slide

polarization dependent factor

$$\mathcal{P}(X;P_-,P_+;q^2) = \frac{(1+P_-)(1-P_+)}{4}\left|c_X^\gamma + c_R c_X^Z \frac{q^2}{q^2-m_Z^2}\right|^2 + \frac{(1-P_-)(1+P_+)}{4}\left|c_X^\gamma + c_L c_X^Z \frac{q^2}{q^2-m_Z^2}\right|^2$$

for spin ½

$$\mathcal{F}_1^X(s;x_\gamma) = \frac{\alpha}{\pi}\frac{1}{x_\gamma}\frac{\beta_q}{\beta_s}\left[(1+\beta_s^2-2x_\gamma)L(\beta_q) - 2(1-x_\gamma) + \frac{2x_\gamma^2}{3-\beta_s^2}[L(\beta_q)-1]\right]$$

$$\mathcal{F}_2^X(s;x_\gamma) = \frac{\alpha}{\pi}\frac{1}{x_\gamma}\frac{\beta_q}{\beta_s}\frac{2}{3-\beta_s^2}\left[2-2x_\gamma-(1-\beta_s^2)L(\beta_q)\right]$$

for spin 0

$$\mathcal{F}_1^X(s;x_\gamma) = \frac{\alpha}{\pi}\frac{1}{x_\gamma}\frac{\beta_q}{\beta_s}\left[(1+\beta_s^2-2x_\gamma)L(\beta_q) - 2(1-x_\gamma) + \frac{2x_\gamma^2}{\beta_s^2}\right]$$

$$\mathcal{F}_2^X(s;x_\gamma) = \frac{\alpha}{\pi}\frac{1}{x_\gamma}\frac{\beta_q}{\beta_s}\frac{1}{\beta_s^2}\left[(3-\beta_s^2-2x_\gamma)L(\beta_q) - 6(1-x_\gamma)\right]$$