Discoveries through ILC Precision Measurements

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The LHC Early Phase for the ILC

Fermilab, April 12 - 14, 2007

Outline

Various studies on ILC physics including search reaches and sensitivities to physics BSM exist and have been updated with new scenarios

(see TDR's, Snowmass Reports, LHC/ILC report 2004, POWER report,…)

No concurrent operation of LHC and ILC

➔ How could the ILC complete the LHC discovery results?

- precision at the ILC
- sensitivities and search reaches in the light of LHC

Baseline ILC Machine

- Physics between 200 GeV and 500 GeV, upgrade 1TeV
- Luminosity:

Running year zero for commissioning

Year 1-4: $L_{int} = 500\ fb^{-1}$:

1. year 10% → $L_{int} \approx 50\ fb^{-1}$
2. year 30% → $L_{int} \approx 150\ fb^{-1}$
3. year 60% → $L_{int} \approx 300\ fb^{-1}$
4. year 100% → $L_{int} \approx 500\ fb^{-1}$

expected statistics:

few 10^4	ee→HZ at 350 GeV (mH≈120 GeV)
~10^5	ee→ tt at 350 GeV
~$5\cdot10^5$ ($1\cdot10^5$)	**ee → qq (μμ) at 500 GeV**
~10^6	ee → WW at 500 GeV

→ statistical uncertainties at per-mille level !!

→Need high precision measurements of lumi, energy and polarisation

→ e+ polarization will help

ILC operation after LHC running

- Discovery of Higgs boson ?? (see Higgs WG)
  → implication for new physics models
- SM, top physics
- SUSY signals obtained ?
- New resonances discovered ⇔ but what is it??
  - Determination of mass, couplings, widths, spin
  - Consistency checks

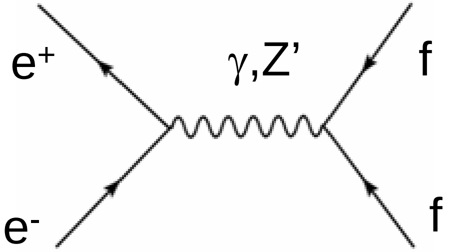
➔ establish new models and theories

Advantage ILC:

- Precision: well defined energy, high lumi, well-known initial state, excellent particle ID, clear event signatures
- Angular distribution
- Polarization of e-, e+ ⇔ helicity informations

New resonances lead to new s- and/or t-channel contributions
➔ ILC is the ideal facility to measure this

Fermion-Pair Production

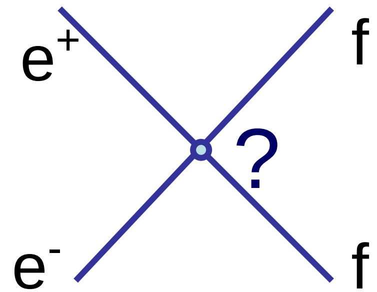


Observables:

σ, A_{FB}, A_{LR}, A_{FB}^{pol}

$$\frac{d\sigma}{d\cos\vartheta} = \sigma_{tot}\left[\left(1 - P^{+}P^{-}\right)\left\{\frac{3}{8}\left(1+\cos^{2}\vartheta\right) + 2A_{FB}\cos\vartheta\right\}\right]$$
$$+\sigma_{tot}\left[\left(P^{+} - P^{-}\right)\left\{\frac{3}{8}\left(1+\cos^{2}\vartheta\right)A_{LR} + 2A_{LR}^{pol}\cos\vartheta\right\}\right]$$

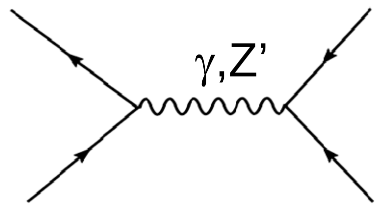
Contact terms: effective parameterization of physics BSM at 'low' energies
→ interference and loop contributions

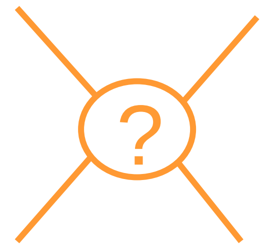


Fermion-Pair Production

$$\frac{d\sigma}{d\cos\Omega} = \sum_{i,j=L,R} \rho_{ij} \left|Q_{ij}\right|^2$$

$$\rho_{LL,RR} = \left(1+\cos^2\theta\right)$$
$$\rho_{LR,RL} = \left(1-\cos^2\theta\right)$$

$|Q|^2 \sim |$ 

$+$ 

$|^2$

$$\sim \frac{\eta_{ij}\cdot s}{\Lambda^2}$$

$$\sigma_{tot}^{f} \sim {Q_{LL}^{ef}}^2 + {Q_{LR}^{ef}}^2 + {Q_{RR}^{ef}}^2 + {Q_{RL}^{ef}}^2$$
$$\sigma_{tot}^{f} A_{FB}^{f} \sim {Q_{LL}^{ef}}^2 - {Q_{LR}^{ef}}^2 + {Q_{RR}^{ef}}^2 - {Q_{RL}^{ef}}^2$$
$$\sigma_{tot}^{f} A_{LR}^{f} \sim {Q_{LL}^{ef}}^2 + {Q_{LR}^{ef}}^2 - {Q_{RR}^{ef}}^2 - {Q_{RL}^{ef}}^2$$
$$\sigma_{tot}^{f} A_{FB}^{pol} \sim {Q_{LL}^{ef}}^2 - {Q_{LR}^{ef}}^2 - {Q_{RR}^{ef}}^2 + {Q_{RL}^{ef}}^2$$

Below a resonance:

- sensitivity to contribution to each helicity amplitude
- flavor sensitive

Interpretation of contact terms

The puzzle of model distinction

$$\frac{\eta_{ij}}{\Lambda^2} \Rightarrow \frac{g_i^X g_j^X}{s - m_X^2}$$

- Leptoquark, squark, sneutrino exchange

$$\frac{\eta_{LL}^{ef}}{\Lambda_{LL}^2} \cdot \frac{\eta_{RR}^{ef}}{\Lambda_{RR}^2} \neq \frac{\eta_{LR}^{ef}}{\Lambda_{LR}^2} \cdot \frac{\eta_{RL}^{ef}}{\Lambda_{RL}^2}$$

- New gauge bosons (Z')

$$\frac{\eta_{LL}^{ef}}{\Lambda_{LL}^2} \cdot \frac{\eta_{RR}^{ef}}{\Lambda_{RR}^2} = \frac{\eta_{LR}^{ef}}{\Lambda_{LR}^2} \cdot \frac{\eta_{RL}^{ef}}{\Lambda_{RL}^2} = \frac{g_L^e}{M_{Z'}} \cdot \frac{g_L^f}{M_{Z'}} \cdot \frac{g_R^e}{M_{Z'}} \cdot \frac{g_R^f}{M_{Z'}}$$

- KK excitation of gauge bosons

Parameterization

$$\mathbf{V} \equiv 2\sum_{\vec{n}} \left(\frac{\mathbf{g}_{\vec{n}}^2}{\mathbf{g}^2} \right) \frac{\mathbf{m}_W^2}{\vec{n}^2 \mathbf{M}_C^2}$$

$$\frac{\eta_{ij}}{\Lambda^2} \Rightarrow \left(Q_e Q_f + g_i^e g_j^f \right) \frac{\pi}{3M_C^2}$$

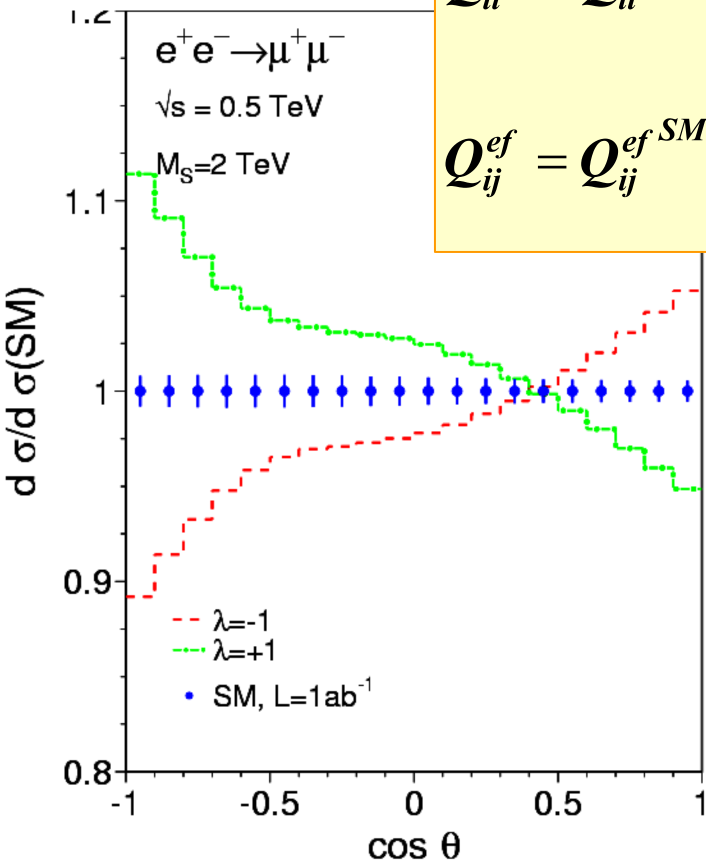
Virtual graviton exchange in $e^+e^- \rightarrow f\bar{f}$

angular dependent modification of helicity amplitudes

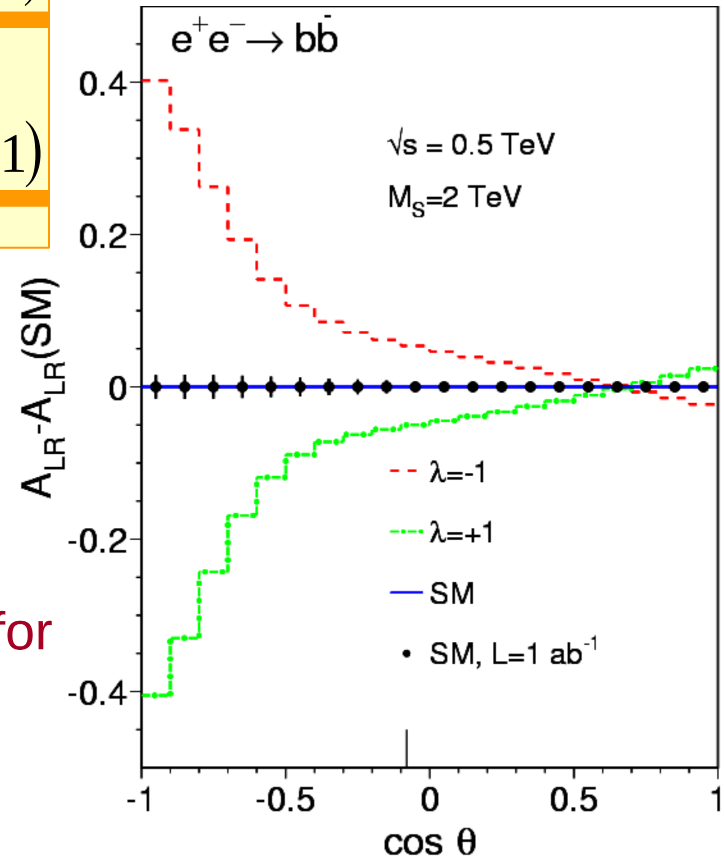
(long. Polarization: P(e-)=80%, P(e+)=60%)

$$Q_{ii}^{ef} = Q_{ii}^{ef\,SM} - \frac{\lambda \cdot s^2}{4\pi\alpha M_S^4}\left(2\cos\theta - 1\right)$$

$$Q_{ij}^{ef} = Q_{ij}^{ef\,SM} - \frac{\lambda \cdot s^2}{4\pi\alpha M_S^4}\left(2\cos\theta + 1\right)$$



ILC: sensitivity for $M_S < 10\sqrt{s}$



Famous Example: Z'

Is the ILC sensitive enough ??

LHC:

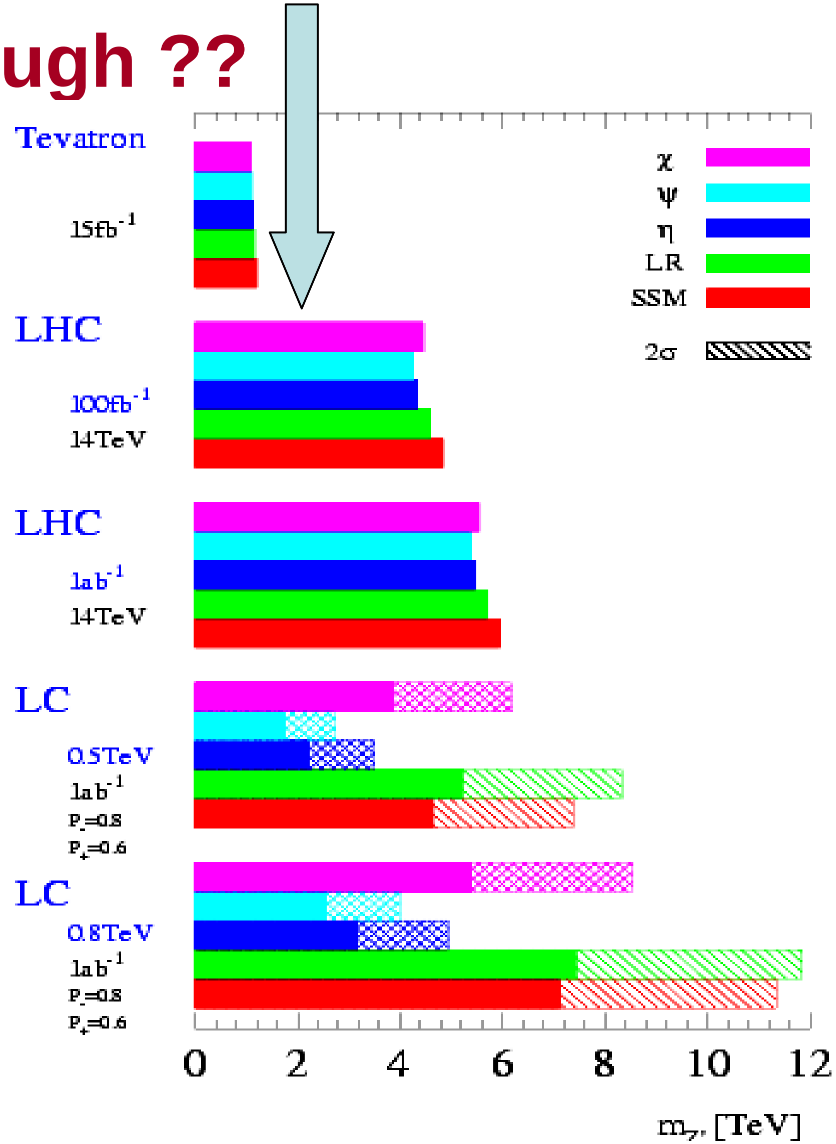
Z' discovery reaches

(100/fb: model distinction

for $M_{Z'} < 2.5$TeV)

ILC:

Z' sensitivity (2σ and 5σ)

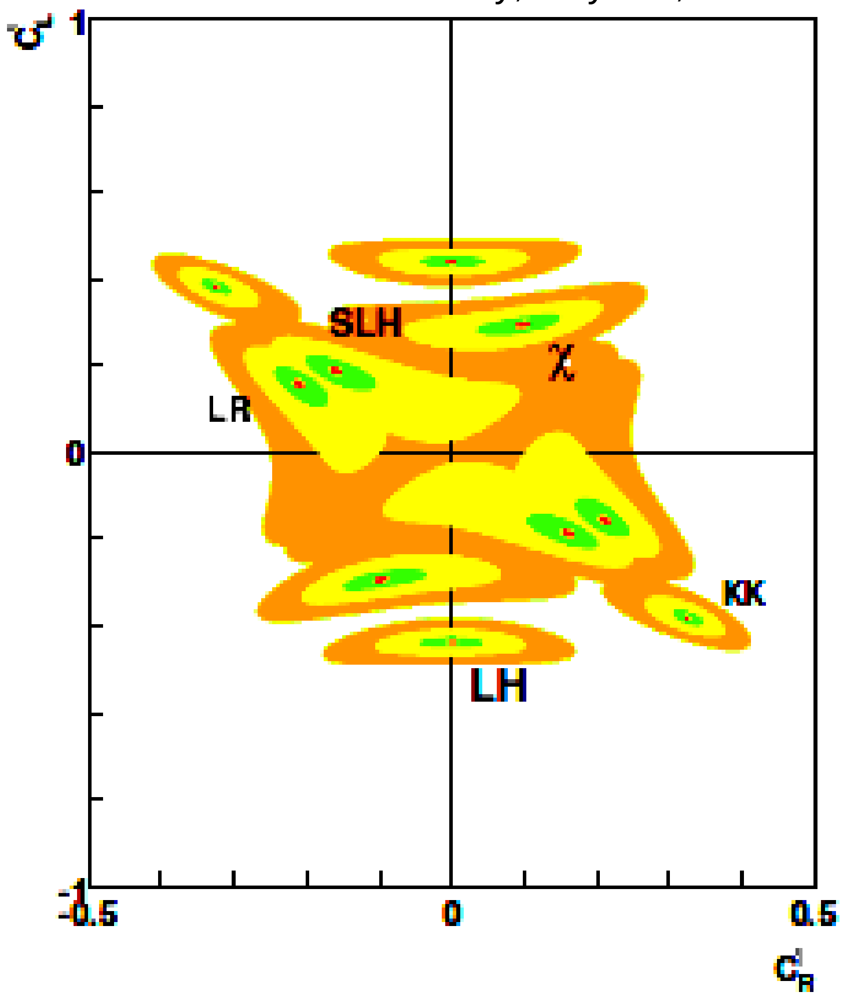


Assumptions:

- $\mathcal{L}_{int} = 1ab^{-1}, \quad \Delta\mathcal{L}_{int} = 0.2\%$
- $P_- = 0.8, \quad P_+ = 0.6, \quad \Delta P_- = \Delta P_+ = 0.5\%$
- Δsys(lept)=0.2%, Δsys(had)=0.1%

Leptonic Z' Couplings at ILC

Godfrey, Kalyniak, Reuter



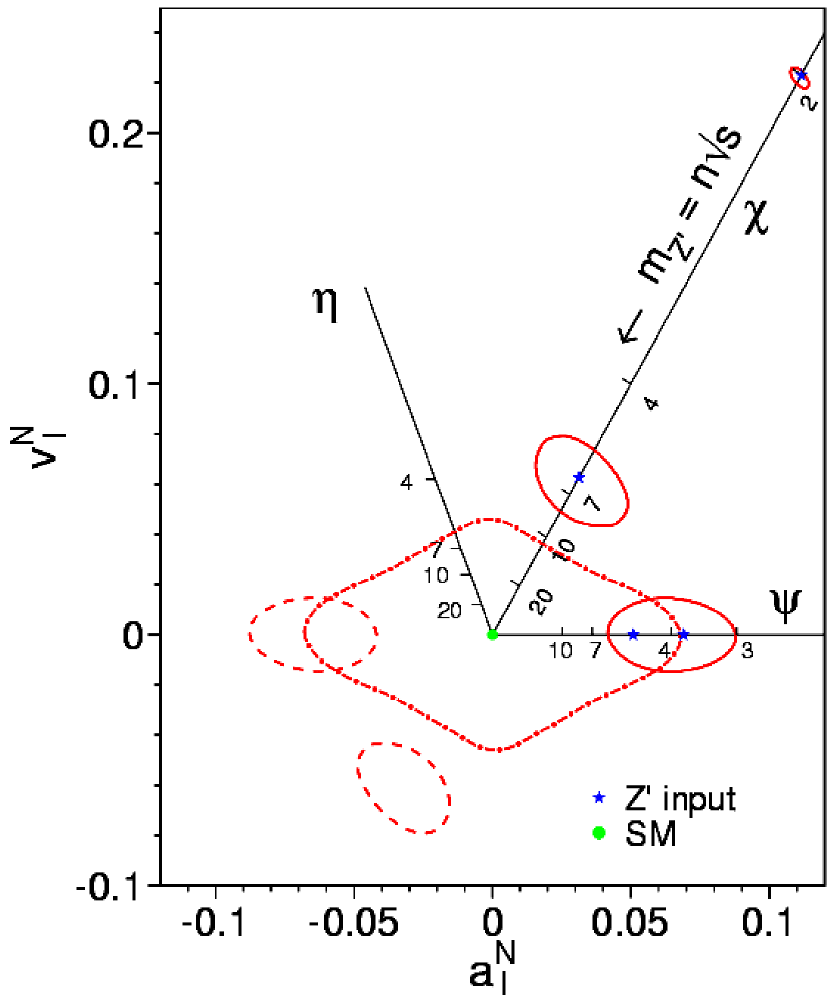
$M_{Z'}$ = 1,2,3,4 TeV
E_{cm} = 500 GeV
L = 1/ab

Good model distinction:
$M_{Z'} < 4\sqrt{s}$

In some cases sensitivity up to $M_{Z'} \sim 8\sqrt{s}$

Z’ model distinction at ILC

$e^+e^- \to l^+l^-$



$$a_N^f = a_f' \sqrt{\frac{s}{s - m_{Z'}^2}} \qquad v_N^f = v_f' \sqrt{\frac{s}{s - m_{Z'}^2}}$$

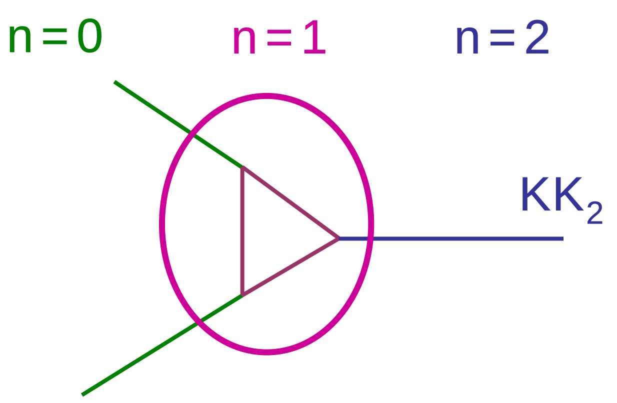
If no Z’ information from LHC:
Z’ model distinction for
$m_{Z'} < 4 \div 8\sqrt{s}$

L_{int}=1ab-1 (±0.2%)
P-=0.8 (±0.5%)
P+=0.6 (±0.5%)
δ_{sys}^l=0.2%
δ_{sys}^b=0.5%

UED KK signals (indirect search)

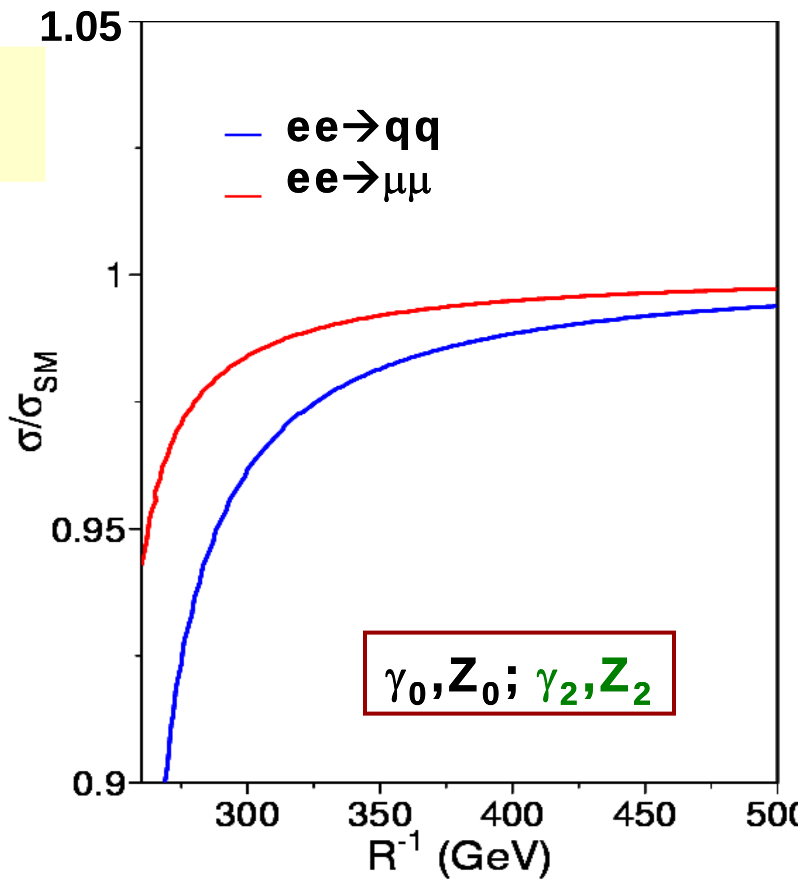
Direct production at ILC is unlikely

KK-number conservation ➔



$\gamma_2,\ Z_2 \rightarrow f_0 f_0$

effective couplings much smaller than SM couplings



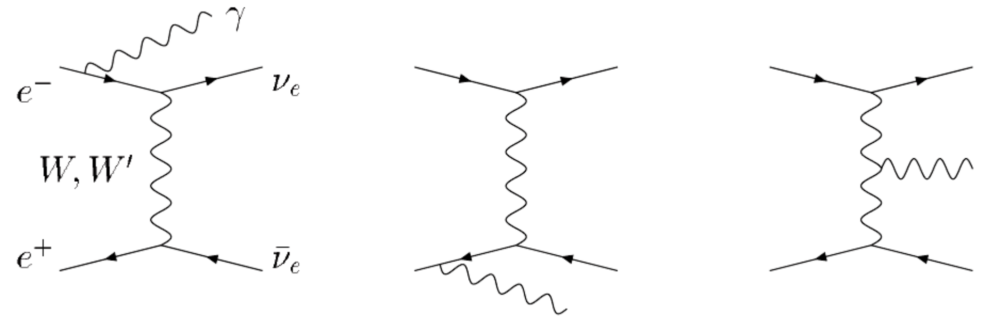
2nd level KK bosons can be excluded at 95% C.L. for LR=20

$\gamma_2,\ Z_2 < 2\sqrt{s}$

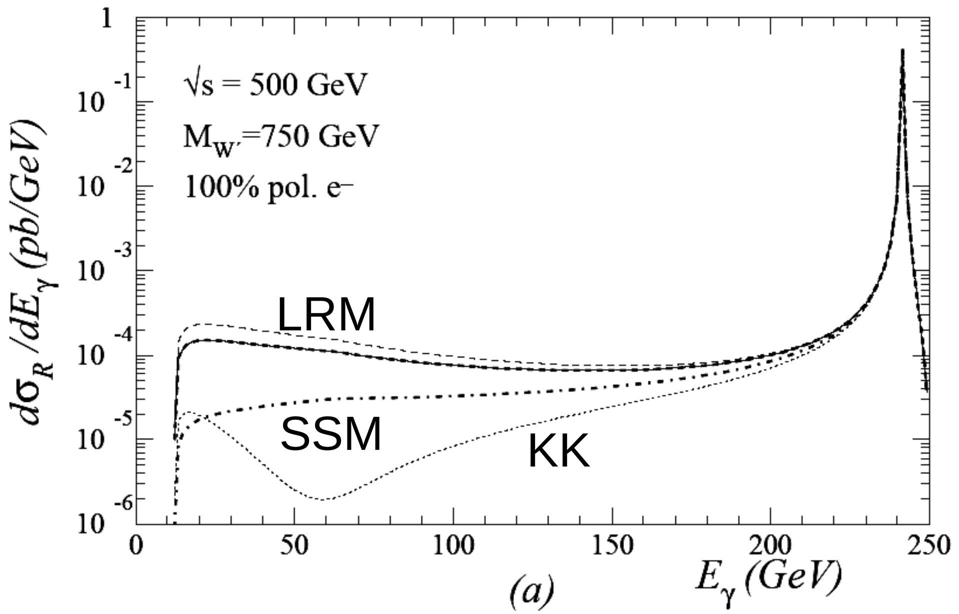
Search for W'

$e^+e^- \rightarrow \nu \bar{\nu} \gamma$

Godfrey, Kalyniak, Kamal, Leike



$d\sigma/dE_\gamma$ depends on W' model → sensitivity to W':



ILC, 500GeV, 500/fb:

$M_{W'}$ <1.7TeV (SSM,KK)

<0.6TeV (LRM)

Without systematic error factor ~2.5 more sensitive

If W' discovered at LHC
→ W' Couplings

Scaling of sensitivity to contact terms

Scaling with energy and luminosity

$$\left(\frac{\sigma-\sigma_{SM}}{\delta\sigma}\right)^2 \le \chi^2_{CL}$$

$$\left(\frac{\sigma-\sigma_{SM}}{\delta\sigma}\right)^2 \approx L\cdot s\cdot(\sigma-\sigma_{SM})^2 \propto L\cdot s\cdot T^2_{contact}$$

- $T_{contact} = \frac{\eta_{ij}}{\Lambda^2};\ \frac{g_i g_j}{M_X^2}$ $\Longrightarrow$ $\Lambda, M_X \sim (s\cdot L)^{1/4}$
  - reduction of statistical uncertainty by factor 2 needs 4·L and improves sensitivity by factor 1.4
  - Double energy increases sensitivity factor ~1.4
- $T_{contact} = \frac{\lambda\cdot s}{M_S^4}$ $\Longrightarrow$ $M_S \sim (s^3\cdot L)^{1/8}$

(ADD model)

- Low cms energy cannot be 'compensated' with luminosity

Scaling of sensitivity to contact terms

Scaling with polarization

$$\chi^2 \geq \left(\frac{\sigma - \sigma_{SM}}{\delta\sigma} \right)^2 \approx L \cdot s \cdot (\sigma - \sigma_{SM})^2 \propto L \cdot s \cdot T_{contact}^2$$

- Polarization of both beams increases lumi

$$\Lambda \sim \left(1 + P^+ P^-\right)^{1/4}$$

- If polarization-dependent observables (A_{LR}) dominate the sensitivity →

$$\Lambda \sim \sqrt{P_{eff}} = \left(\frac{P^+ - P^-}{1 - P^+ P^-} \right)^{1/2}$$

Extrapolation LEP2 (200GeV)➔ ILC (0.5 TeV, 500/fb):

Λ(ILC) ≈ 7.5 ·Λ(LEP2) but: systematic uncertainties

Summary

Physics case has been studied for many models
→ ILC complements LHC physics results

- Precision measurement
  - independent observables → high resolution power
  - top quark production ⇔ new physics

- Measurements at energies 200-500 GeV, later 1TeV
  - This energy scan supports extrapolations (‘lever arm’) to effects at higher energies and constrains physics models.

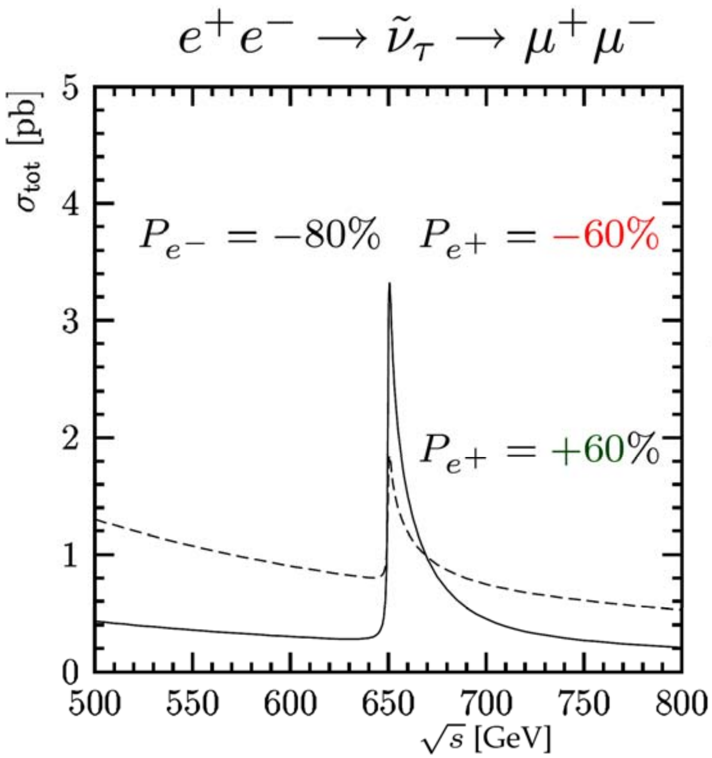
To be done:

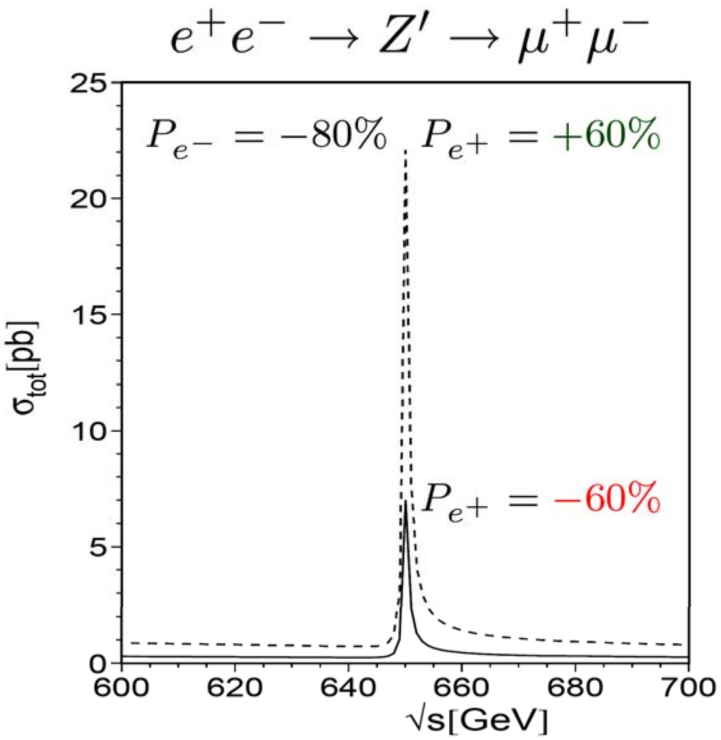
- Take realistic LHC results at a realistic LHC/ILC time scale and figure out the remaining unknowns
- Include realistic ILC detector developments into studies

BACKUP

Polarized initial states: $e^+e^- \rightarrow \mu^+\mu^-$

R-parity violating SUSY (spin-0) or Z' (spin-1) ?





enhancement for $e^+(L)e^-(L)$ enhancement for $e^+(L)e^-(R)$

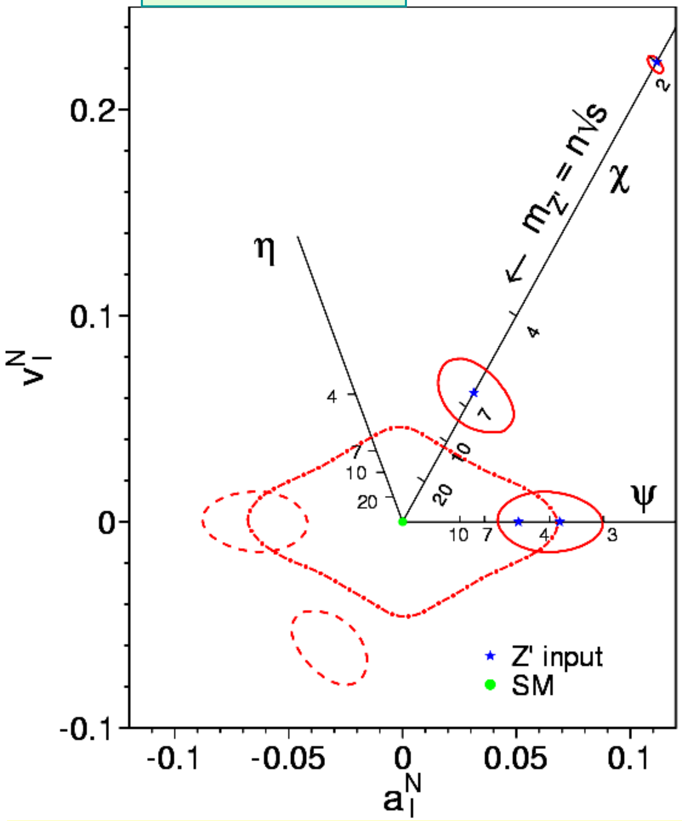
(see also POWER report)

➔ polarisation improves sensitivity substantially

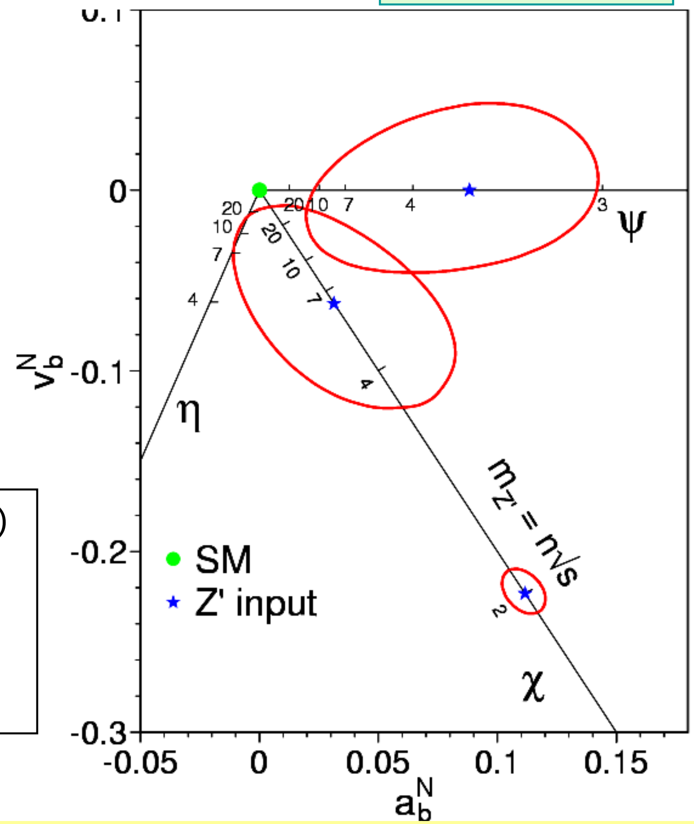
Z’ model distinction at ILC

$$a_N^f = a'_f \sqrt{\frac{s}{s - m_{Z'}^2}} \qquad v_N^f = v'_f \sqrt{\frac{s}{s - m_{Z'}^2}}$$

$e^+e^- \rightarrow l^+l^-$



$e^+e^- \rightarrow bb$



L_{int} = 1ab-1 (±0.2%)
P- = 0.8 (±0.5%)
P+ = 0.6 (±0.5%)
$\delta_{sys}{}^l$ = 0.2%
$\delta_{sys}{}^b$ = 0.5%

If no Z’ information from LHC ➔ distinction up to $m_{Z'}$ ~4÷8√s