# Bhabha scattering at the ILC

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# What is the ILC?

The International Linear Collider will be the next $e^+e^-$ collider based on superconducting technology:

- first phase: $\sqrt{s} \leq 500\,\mathrm{GeV}$
- upgrade: $\sqrt{s} \approx 1\,\mathrm{TeV}$
- luminosity $\mathcal{L} \approx 3-5 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1} \Rightarrow\sim 300-500\ \mathrm{fb}^{-1}/\mathrm{year}$
- polarised electron beams (P = 80-90%) and, as an option, polarised positron beams (P = 40-60%).
- GigaZ option: $10^9$ events at the Z pole with polarised beams
- Time scale:
  - Conceptual design by end 2006
  - International Liner Collider Technical Design Report by 2007
  - Site selection and approval in 2008
  - Begin data taking: 2015

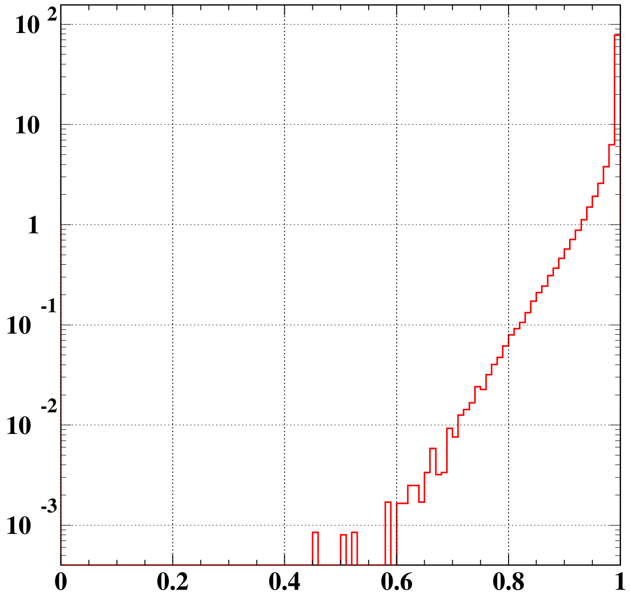
# Expected statistics at the International Linear Collider (ILC)

- few$\cdot 10^4$ $e^+e^- \to HZ$/year at $\sqrt{s} \approx 350\,\mathrm{GeV}$ $(m_\mathrm{H} \approx 120\,\mathrm{GeV})$
- $10^5$ $e^+e^- \to t\bar{t}$/year at $\sqrt{s} \approx 350\,\mathrm{GeV}$
- $5 \cdot 10^5$ $e^+e^- \to q\bar{q}$/year at $\sqrt{s} \approx 500\,\mathrm{GeV}$ (no rad. ret)
- $10^5$ $e^+e^- \to \mu^+\mu^-$/year at $\sqrt{s} \approx 500\,\mathrm{GeV}$ (no rad. ret)
- $10^6$ $e^+e^- \to W^+W^-$/year at $\sqrt{s} = 500 - 1000\,\mathrm{GeV}$
- $10^9$ $e^+e^- \to Z$/year at $\sqrt{s} \approx 91\,\mathrm{GeV}$

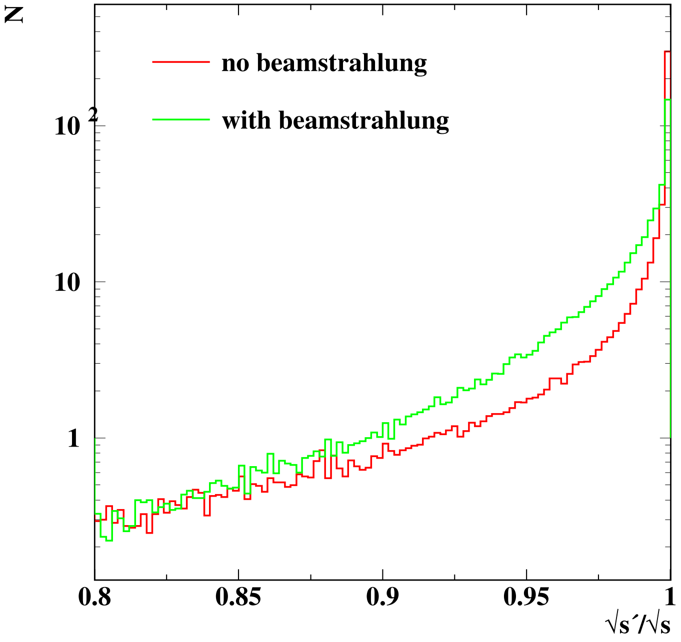
# New problem at the ILC: beamstrahlung

- Beams at IP are extremely collimated with many electrons/bunch
  → very high charge density
  ⇒ Electrons of one bunch radiate against the coherent field of the other bunch (Beamstrahlung)
- Average energy loss for colliding $e^+e^-$-pairs at 500 GeV: $\sim 1.5\%$
- For continuum processes beamstrahlung comparable to ISR, however with shorter tails
- Beamstrahlung has to be included in every generator!

Normalised $e^-$ spectrum



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



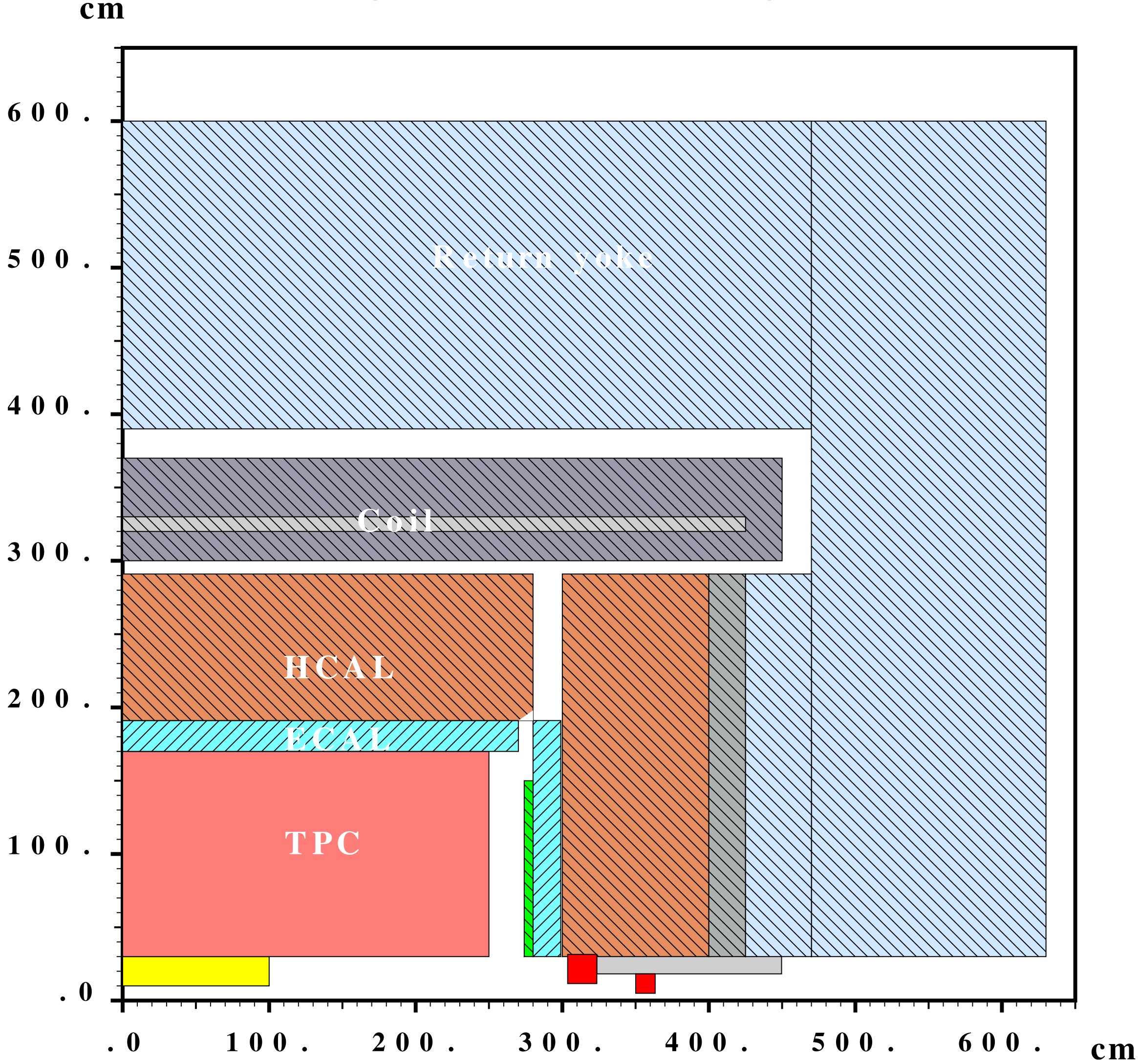
# The Detector at the ILC

The concept for a large detector with gaseous tracking

Hermetic detector with full tracking and calorimetry above $\theta = 7°$

Efficient electron identification in the full tracking range

Unambiguous charge identification in the full tracking range



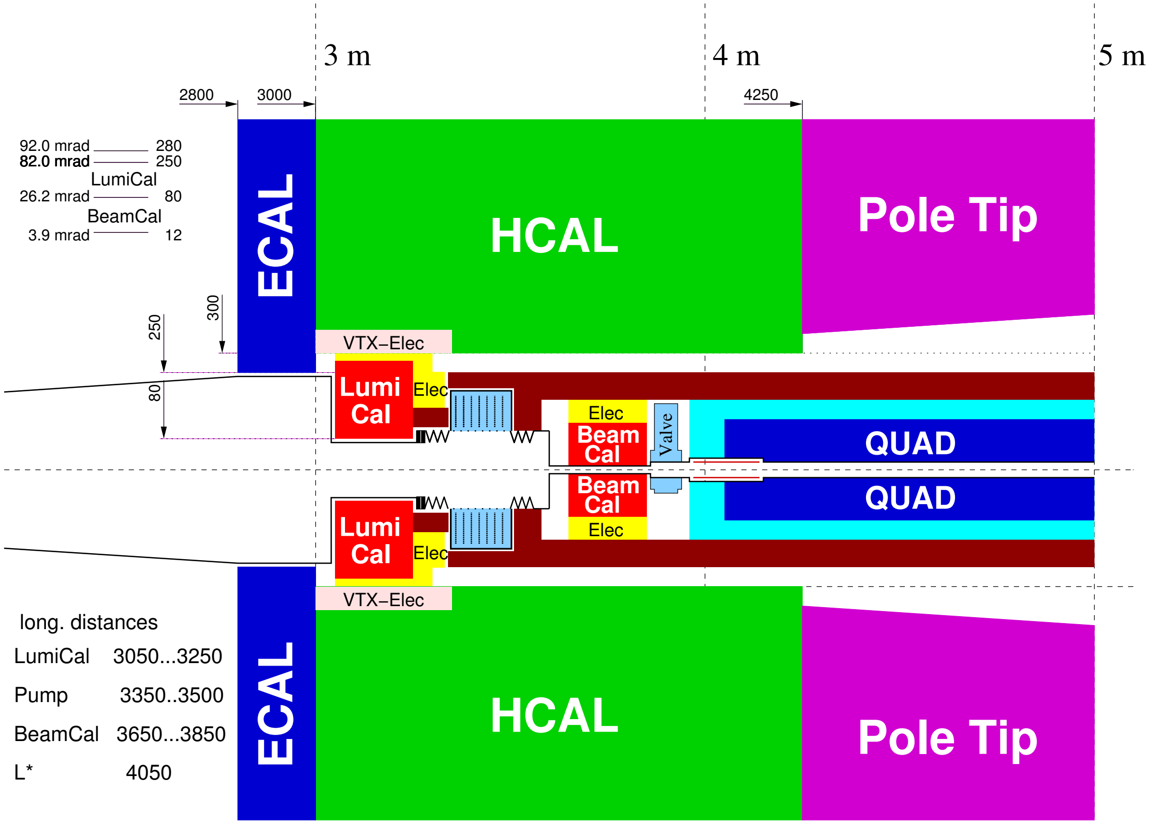
# The forward region of the detector

## BeamCal

- $4\,\text{mrad} < \theta < 25\text{mrad}$
- huge background from beam-beam interactions
- can only be used for machine tuning and $\gamma\gamma$ veto

## LumiCal

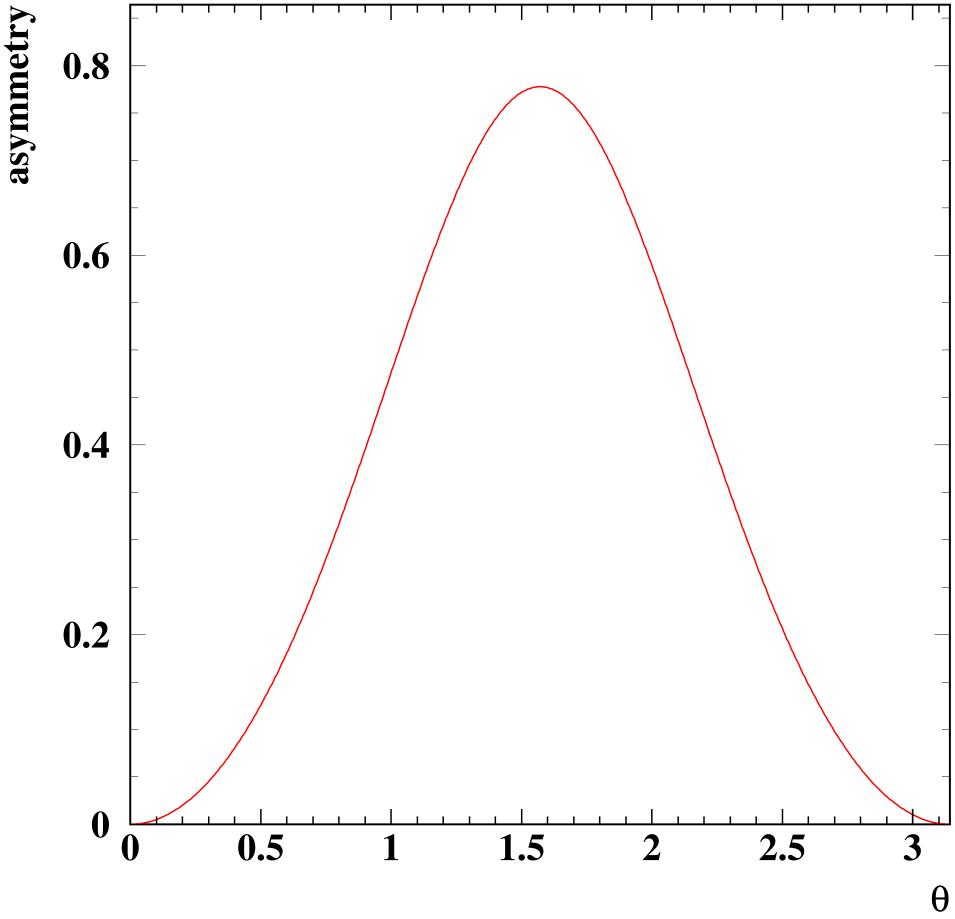
- $25\,\text{mrad} < \theta < 80\text{mrad}$
- almost no background
- will be used for a precision luminosity measurement



# Bhabha scattering and polarisation

- At ILC both beams can be polarised
- Even for pure QED there is a cross section asymmetry between parallel and antiparallel beams proportional to $\mathcal{P}_{e^+}\mathcal{P}_{e^-}$ (ILC: $\mathcal{P}_{e^+}\mathcal{P}_{e^-} \sim 0.5$)
- This asymmetry is huge in the centre and small but sizable in the forward region
- Polarisation of both beams has to be included in the calculations and the generators

$A = \frac{\sigma(\rightrightarrows)-\sigma(\leftrightarrows)}{\sigma(\rightrightarrows)+\sigma(\leftrightarrows)}$ as a function of $\theta$ for QED only



# The Luminosity Measurement at ILC

What precision do we need?

Luminosity precision is determined by statistics of interesting processes

- $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-}$: $\sim 10\,\mathrm{pb}$ at $\sqrt{s} = 340\,\mathrm{GeV}$ scaling with $1/\mathrm{s}$
  ➡ $\mathcal{O}(10^6)$ events ➡need $10^{-3}$ precision

- $\mathrm{e^+e^-} \rightarrow \mathrm{f\bar{f}}$: $\sim 5\,\mathrm{pb}$ at $\sqrt{s} = 340\,\mathrm{GeV}$ scaling with $1/\mathrm{s}$
  ➡ $\mathcal{O}(10^6)$ events ➡need $10^{-3}$ precision

- GigaZ: aim for $10^9$ hadronic Z decays. Relevant physics quantities (except $N_\nu$) need also leptonic decays (10% of hadronic decays)
  ➡ need $10^{-4}$ precision

# $\mathrm{e}^+\mathrm{e}^- \longrightarrow \mathrm{f\bar{f}}$

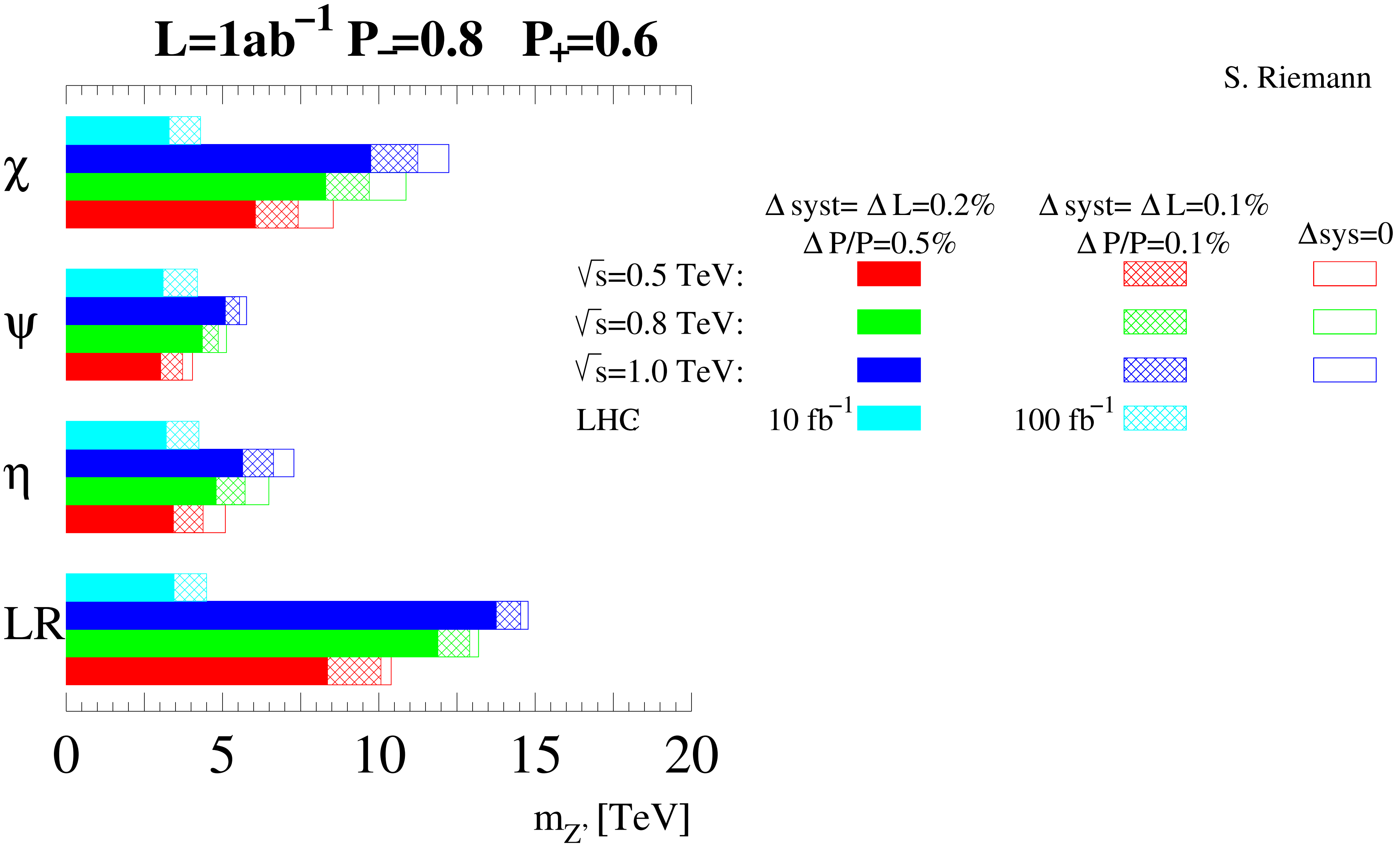
$\mathrm{e}^+\mathrm{e}^- \longrightarrow \mathrm{f\bar{f}}$ is sensitive to physics at very high scales (compositness, Z', extra space dimensions)

Sensitivity is mainly via interference with Standard Model amplitude
➠ $\propto 1/M^2$

All observables (cross section, left-right asymmetry, forward-backward asymmetry) are important

Systematic errors (e.g. luminosity) effect results significantly

# Z' limits in different models



# GigaZ

GigaZ $= 10^9$ Z at $\sqrt{s} \approx m_{\mathrm{Z}}$

Main aim: $\sin^2\theta^l_{eff}$ determination ➠ no $\mathcal{L}$ dependence

Important additional information from “lineshape” parameters $\Gamma_{\mathrm{Z}}$, $\sigma_0^{\mathrm{had}}$, $R_l$

Interesting information is obtained from combination of these parameters:

$$\sigma_0^{\mathrm{had}} = \frac{12\pi}{m_Z}\frac{\Gamma_e\Gamma_{\mathrm{had}}}{\Gamma_Z^2}$$

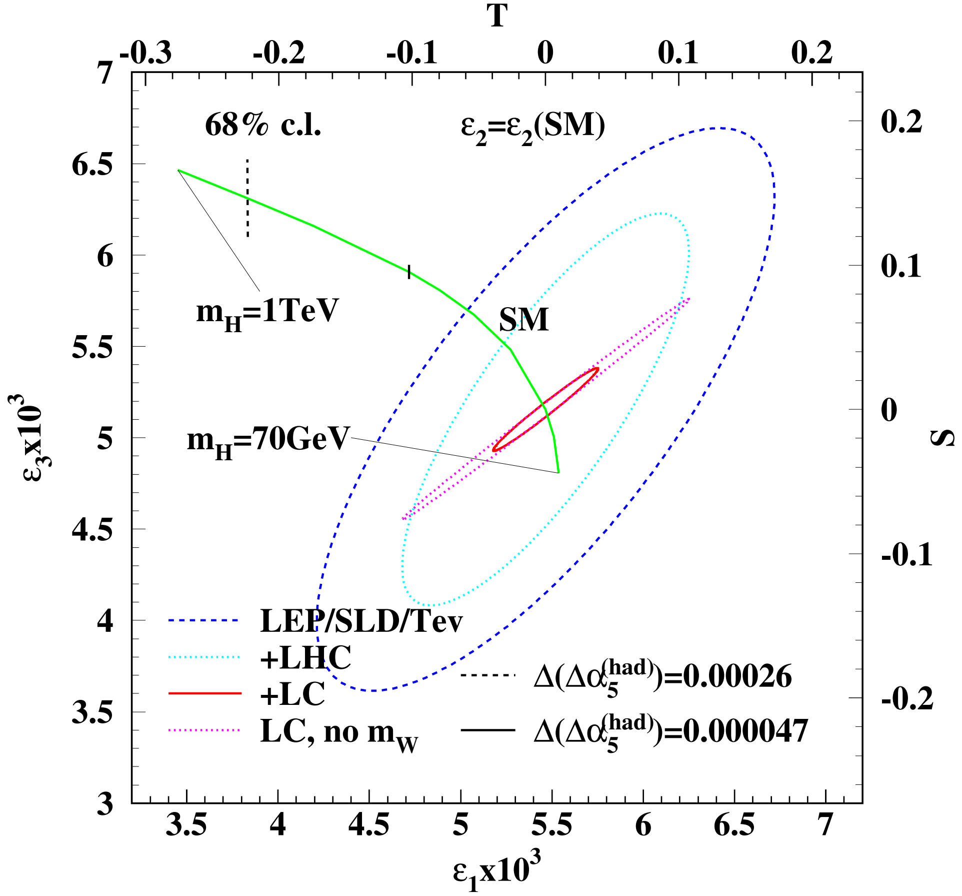
$$R_l = \frac{\Gamma_{\mathrm{had}}}{\Gamma_l}$$

$\Rightarrow$ need all parameters with about the same accuracy

- $\Gamma_Z$: difficult to estimate (beam energy, beamstrahlung, beamspread) but $\Delta\Gamma_Z = 1\,\mathrm{MeV}$ ($\Delta\Gamma_Z/\Gamma_Z = 4\cdot 10^{-4}$) seems realistic
- $R_l$: $\Delta R_l/R_l = 10^{-4}$ from lepton statistics

➠ need lumi error (exp+theo) $\Delta\mathcal{L}/\mathcal{L} \sim 2\cdot 10^{-4}$

Gain of GigaZ:



- small axis: $\sin^2\theta^l_{eff}$
  $\Rightarrow$ no luminosity dependence
- large axis: $m_W$ if $\varepsilon_2 = U = SM$, otherwise $\Gamma_l$
  $\Rightarrow$ luminosity precision essential
  Important in interpretations outside SM!

# The Luminometer (current planning)

- Calorimeter with high granularity
- No tracking in front

➠ Will do "calorimetric measurement", i.e. no separation of nearby electron and photon

- $25\,\text{mrad} < \theta < 80\text{mrad}$
- All similar to LEP

# Theoretical uncertainties

- Uncertainty was $\Delta\mathcal{L} = 0.05\%$ at LEP
- Sufficient for high energy, if constant with $\sqrt{s}$
- Definitely too large at GigaZ

## Polarisation effects

- Asymmetry $3 \cdot 10^{-4}$ at 25 mrad and $3 \cdot 10^{-3}$ at 80 mrad ($\mathcal{P}_{e^+}\mathcal{P}_{e^-} = 1$)
- Marginal effect at for high energy precision
- Relevant for GigaZ
- Polarisation affects also asymmetries where luminosity normally cancels:
  - 0.1% asymmetry affects $A_{\mathrm{LR}}$ at GigaZ by $0.36 \cdot 10^{-4} = 1.2\sigma$ using the Blondel scheme
  - also at high energy the beam polarisation can be measured with the Blondel scheme
  - 0.1% asymmetry affects the measured asymmetry by $0.5 \cdot 10^{-3} = 0.5\sigma$

# Reconstruction of the Luminosity Spectrum

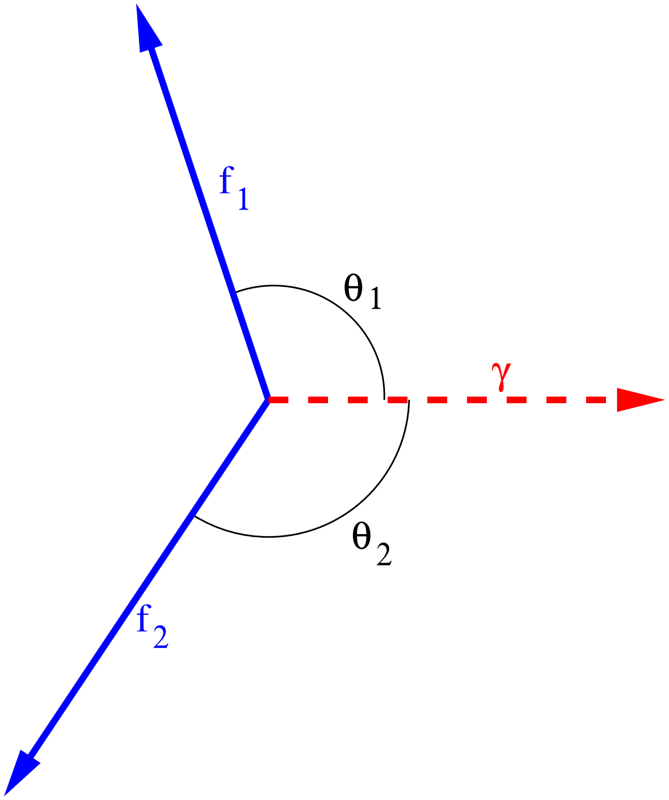
- Since the beam parameters will not be known to with high precision the spectrum of beamstrahlung has to be measured from data
- The energy loss of the outgoing beam is much larger than for the colliding particles
- For this reason the luminosity spectrum has to be measured from annihilation data
- Since one is interested in a $< 10^{-4}$ precision this cannot be done with calorimeters
- Method of choice: Bhabha acolinearity in the forward region:
  - very simple final state
  - very high cross section

# The acolinearity method

- Assume only one photon is radiated
  ➟ $\sqrt{s'}$ can be calculated from fermion angles only

$$\frac{\sqrt{s'}}{\sqrt{s}} = \sqrt{\frac{\sin\theta_1 + \sin\theta_2 + \sin(\theta_1+\theta_2)}{\sin\theta_1 + \sin\theta_2 - \sin(\theta_1+\theta_2)}}$$

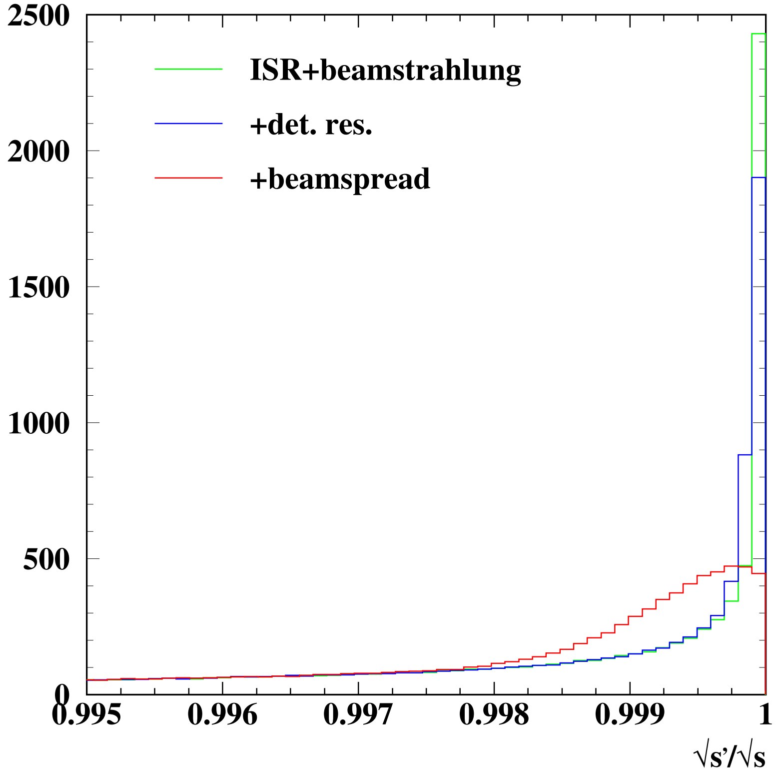
- The radiation in both directions can be unfolded in the fit
- This requires the knowledge of correlations
- ISR/FSR has to be known from theory



# Requirements from theory

- Experimental $\theta$ resolution: $\delta\theta = 2 \cdot 10^{-5}$ resulting in an $\sqrt{s'}$ resolution of about $10^{-4}$
- A possible photon energy cutoff in the generator therefore has be be blow $k/E_b = 10^{-4}$
- This resolution is needed to disentangle beamstrahlung and beam energy spread
- Statistical error is $\Delta(\sqrt{s'}/\sqrt{s}) = 10^{-5}$ for $100 \ \mathrm{fb}^{-1}$

Reconstructed $\sqrt{s'}/\sqrt{s}$ spectra



- The radiation has to be precise on this level
- The acolinearity method uses the charged tracks only
  ➠ need to have an exact description of FSR and ISR/FSR interference

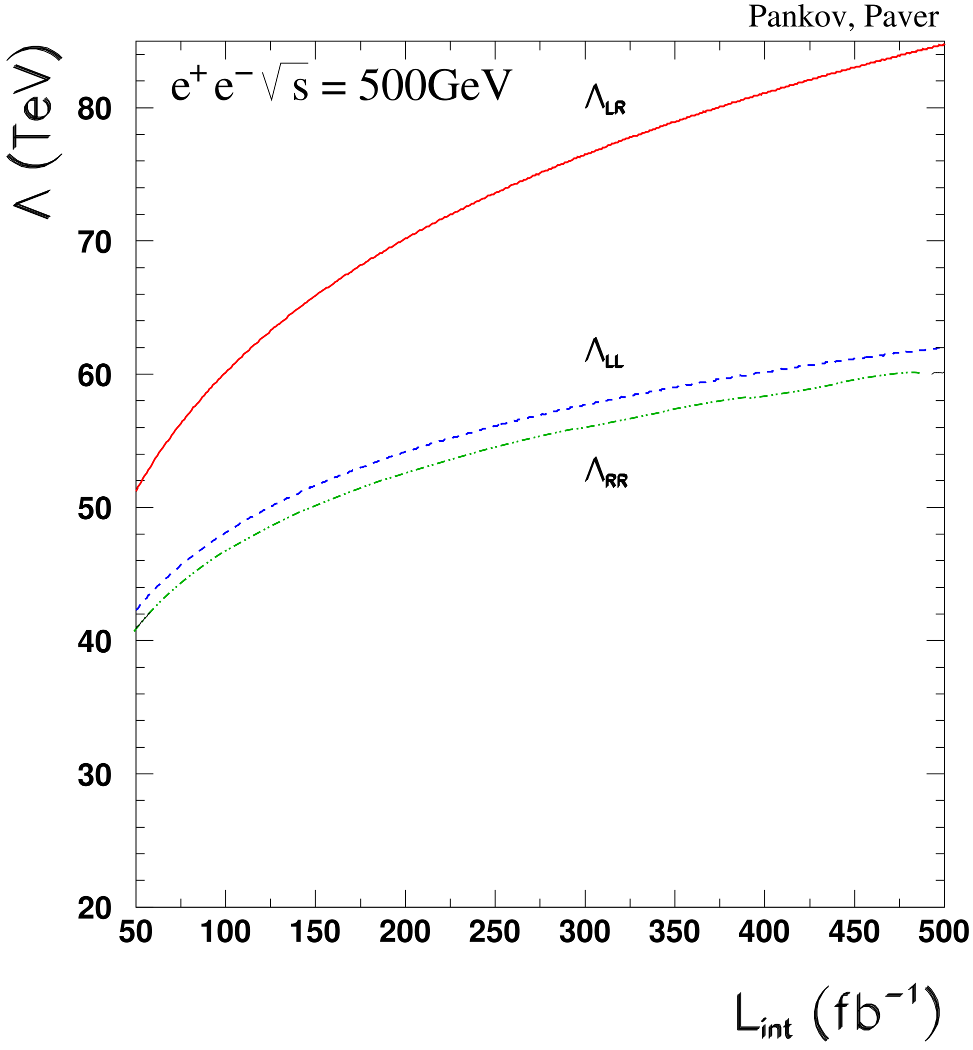
# Physics with large angle Bhabhas at the ILC

- Large angle Bhabha scattering can be used as a general probe for new physics
- The most general description of this are contact interactions
- $\mathcal{O}(10^5)$ events per year are expected requiring the corresponding theoretical uncertainty
- Polarisation is very important to distinguish between the different helicity structures
- As a unique feature of Bhabha scattering the J=0 state can isolate the t-channel for vector currents and scalar s-channel exchange

# Results

- Contact interaction limits of $\Lambda > 60 - 80\,\mathrm{TeV}$ can be reached, depending on the helicity structure ($\sqrt{s} = 500\,\mathrm{GeV}$, $\mathcal{L} = 500\ \mathrm{fb}^{-1}$)
- These limits are better than and complementary to muons
- In principle similar limits can be reached for $e^-e^-$, do we have Moller scattering under control theoretically?

Contact interaction limits from Bhabha scattering



# Conclusions

- Bhabha scattering is needed at the ILC for technical measurements (luminosity, luminosity spectrum) and for physics

- The required precision is up to $10^{-4}$

- A few new technical requirements are needed to use the theory predictions at the ILC:
  - beamstrahlung
  - polarisation of both beams
  - non calorimetric measurements

- The 2-loop calculations are definitely a huge step towards these goals