Interplay of beam polarisation and systematic uncertainties in electroweak precision measurements at future e+e- colliders

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Future $e^+e^-$ Colliders and (longitudinally) Polarised Beams

- Longitudinally **polarised beams** are a special feature of **Linear $e^+e^-$ Colliders**:
  - SLC: $P(e^-) = \pm 80\%$, $P(e^+) = 0\%$
  - ILC: $P(e^-) = \pm 80\%$, $P(e^+) = \pm 30\%$ (upgrade 60%)
  - CLIC: $P(e^-) = \pm 80\%$, $P(e^+) = 0\%$

- Electroweak interactions highly sensitive to chirality of fermions: $SU(2)_L \times U(1)$
  - every cross section depends on beam polarisations
  - **with both its beams polarised, ILC is “four colliders in one”**: $P = \frac{N_R - N_L}{N_R + N_L}$

- note: future **circular Higgs factories** offer **no longitudinal beam polarisation**

General references on polarised $e^+e^-$ physics:
- arXiv:1801.02840
- Phys. Rept. 460 (2008) 131-243
Physics benefits of polarised beams

**background suppression:**
- $e^+ e^- \rightarrow WW / \nu_e \nu_e$
  - strongly P-dependent since t-channel only for $e_L^- e_R^+$

**signal enhancement:**
- Higgs production in WW fusion
- many BSM processes have strong polarisation dependence => higher S/B

**chiral analysis:**
- SM: Z and $\gamma$ differ in couplings to left- and right-handed fermions
- BSM: chiral structure unknown, needs to be determined!

**redundancy & control of systematics:**
- “wrong” polarisation yields “signal-free” control sample
- flipping *positron* polarisation controls nuisance effects on observables relying on *electron* polarisation
- essential: fast helicity reversal for both beams!
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See previous talk by Gudrid Moortgat-Pick
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The general idea
Polarisation & Systematics: what we start from

Processes and their polarisation dependence

- **s-channel**: exchange of vector particles $\Rightarrow \sigma_{LL} = \sigma_{RR} = 0$
- **t-channel $W$ or $\nu$ exchange**: $\Rightarrow \sigma_{LL} = \sigma_{RR} = \sigma_{RL} = 0$
- **t-channel $\gamma$, $Z$ or $e$ exchange**: all chiral cross sections $> 0$

Time-dependent experimental uncertainties

- originate from drifts in calibrations, changes in detector configuration, alignment, machine parameters, ...
- change _slowly_ w.r.t. to flipping of polarisation signs
- $\Rightarrow$ data sets with different polarisation signs are collected “quasi-concurrently”
- $\Rightarrow$ time-dependent systematic effects are _strongly correlated_ between such data sets!
A simplified example - consider....

.. one signal and one background process

- signal: \(s\)-channel process, e.g. \(\mu^+\mu^-\), or \(\mu^+\mu^-h\): \(\sigma_{LR}^S, \sigma_{RL}^S\)
- background: dominantly \(t\)-channel \(\nu\) exchange, e.g. \(W^+W^- \rightarrow \mu^+\nu\mu^-\nu\): \(\sigma_{LR}^B, \sigma_{RL}^B\)

... one uncertainty depending on one kinematic variable

- e.g. reconstruction efficiency for isolated \(\mu^-\): \(\epsilon(\cos\theta_{\mu^-})\)
- can change with time e.g. due to change of beam spot position, detector alignment w.r.t. machine, ..
- important: at any time and \(\cos\theta_{\mu^-}\), the efficiency is the same for each isolated muon, regardless of process or polarisation.
Target quantities and nuisance parameters

- $\sigma_{LR}^{S}, \sigma_{RL}^{S}, \sigma_{LR}^{B}, \sigma_{RL}^{B}$ (or, equivalently, $\sigma_{0}^{S}, A_{LR}^{S}, \sigma_{0}^{B}, A_{LR}^{B}$)
  - note: this assumes differential cross-sections perfectly known — in practice additional $N_{\text{shape}}$ “shape” parameters, e.g. $A_{\text{FB}}, \text{TGCs, etc.}$
- $\epsilon(i)$ in each of $n$ bins in $\cos \theta_{\mu}$
- optionally $P_{e^{-}}, P_{e^{+}}, P_{e^{-}}, P_{e^{+}}$
  - between $n+4 (+N_{\text{shape}})$ and $n+8 (+N_{\text{shape}})$ “unknowns”

This is a very simple example designed to illustrate the basic mechanisms!
Observables (still in our simple example)

for each data set:

- event count in bin $i$

$$\frac{dN(i)}{d\cos\theta_{\mu^-}} = f_{LR}\sigma_{LR}^S \frac{d\sigma_{LR}^S(i)}{d\cos\theta_{\mu^-}} \epsilon(i) + f_{RL}\sigma_{RL}^S \frac{d\sigma_{LR}^S(i)}{d\cos\theta_{\mu^-}} \epsilon(i)$$  \hspace{1cm} (1)

$$+ f_{LR}\sigma_{LR}^B \frac{d\sigma_{LR}^B(i)}{d\cos\theta_{\mu^-}} \epsilon(i) + f_{RL}\sigma_{RL}^B \frac{d\sigma_{LR}^B(i)}{d\cos\theta_{\mu^-}} \epsilon(i)$$ \hspace{1cm} (2)

- $f$’s depend on polarisation values:

$$f_{LR} = (1 - P_{e-})(1 + P_{e+}) \times \mathcal{L}, \quad f_{RL} = (1 + P_{e-})(1 - P_{e+}) \times \mathcal{L}$$

- $\frac{d\sigma(i)}{d\cos\theta_{\mu^-}}$ denotes differential cross section in bin $i$; normalised to $\int = 1$ (shape only)

$\Rightarrow$ $n, 2n$ or $4n$ “observables” for one, two or four data sets
The unpolarised case (still in our simple example)

\[ P(e^-, e^+) = (0,0): \]

\[
\frac{dN(i)}{d \cos \theta_{\mu^-}} = (\sigma^S_0 \frac{d\sigma^S_0(i)}{d \cos \theta_{\mu^-}} + \sigma^B_0 \frac{d\sigma^B_0(i)}{d \cos \theta_{\mu^-}}) \cdot \epsilon(i) \cdot \mathcal{L} \tag{3}
\]

- \( n \) observables vs \( n+2+N_{\text{shape}} \) unknowns \( \Rightarrow \) no overconstraining (even for \( N_{\text{shape}} = 0! \))
- \( \epsilon(i) \) and \( \sigma^B_0 \) need to be known from other measurements / control samples / MC
- or systematic effect (\( \mu \) efficiency) needs to be described with much less parameters than 1 per bin
Polarised beams (still in our simple example)

\[ P(e^-, e^+) = (\pm 80\%, 0), \ N_{\text{shape}}=0: \]

- assume polarisations known: \( 2n \) observables vs \( n+4 \) unknowns
  \( \Rightarrow \) overconstraining with more than 4 bins
- polarisations as nuisance parameters: \( 2n \) observables vs \( n+8 \) unknowns
  \( \Rightarrow \) overconstraining with more than 8 bins
- this can still be combined with additional knowledge from other measurements / control samples / MC

\[ P(e^-, e^+) = (\pm 80\%, \pm 30\%), \ N_{\text{shape}}=0: \]

- assume polarisations known: \( 4n \) observables vs \( n+4 \) unknowns
  \( \Rightarrow \) overconstraining with at least 2 bins
- polarisations as nuisance parameters: \( 4n \) observables vs \( n+8 \) unknowns
  \( \Rightarrow \) overconstraining with more than 2 bins
- again, this can still be combined with additional knowledge from other measurements / control samples / MC
What about “common modes”?

- A global bias in efficiency can mathematically not be distinguished from a global bias in all polarised cross sections.

- How likely is it that all polarised cross sections of all processes (in reality combine many more than 2!) are off from the SM in exactly the same way?

  - in a global fit: include a-priori knowledge from theory as additional constraint with reasonable uncertainty.
  - compensating $\mu$ efficiency by changing all cross sections will give $\chi^2$ penalty for each included process.
Add a “reducible” background, e.g. with non-prompt $\mu$'s:

- determine in addition fake rates $\epsilon_f(i)$
  note: this is a brute-force approach, assuming one independent parameter for “fakes” for each bin, for the sake of the argument.

- $P(e^-, e^+) = (\pm 80\%, 0)$: $2n$ observables vs $2n+8+N_{\text{shape}}$ unknowns $\Rightarrow$ never overconstrained
  $\Rightarrow$ need additional control regions

- $P(e^-, e^+) = (\pm 80\%, \pm 30\%)$: $4n$ observables vs $2n+8+N_{\text{shape}}$ unknowns $\Rightarrow$ overconstrained when more than $4+N_{\text{shape}}/2$ bins
  $\Rightarrow$ data sets with different polarisations – thus different S/B – act as “control samples” here.
For all time-dependent effects, more data taken at another time (a month later, a year later, ...) does not help anymore, because the exact change with time can only be determined with limited precision.

In the long-term average, the “jitter” of time-dependent systematic effects leads to a finite minimum of the systematic uncertainties.

Concurrently taken data sets with different polarisation will push this minimum further down.
A full analysis example - mono-photon WIMP search

- Large background from SM $\nu\bar{\nu}\gamma$
- Limit calculation by fractional event counting, weight optimisation includes systematic uncertainties
- Many systematic uncertainties included (luminosity, polarisation, beam energy spectrum, photon efficiency etc pp) in lower plot
- assumed to be correlated to a large degree between data sets with different polarisations

⇒ Combination of several data sets “H20 pol mix” is significantly more robust against systematics than individual data sets!

Here: only global scaling systematics, no shape-dependency
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More details later in talk by Filip Zarnecki
Towards a combined analyses of ee-\textgreater{}2f and ee-\textgreater{}4f including systematic uncertainties
Physics processes & parameters

- $E_{CM} = 250$ GeV, $L=2$ ab$^{-1}$, $P(e^-, e^+)$=(±80%,±30%), (±80%,0%), (0%,0%)
- nuisance parameters: polarisations, luminosity, with constraints from polarimeters & lumi measurement

- ee$\to$2f example process: ee$\to$µµ
  - observable: $\cos \theta^*$ in restframe;
    separated into “high-$Q^2$” and “return to Z”
  - physics parameters:
    - polarised: $\sigma_0$, $A_\mu$; $\epsilon_\mu$ ($Z/\gamma$ interference), $k_{L/R}$ (ISR)
    - unpolarised: $\sigma_0$, $A_{FB,0}$; $k_0$
      $\Rightarrow$ $Z/\gamma$ interference and initial/final state asymmetries collapse to one parameter (all linear in $\cos \theta^*$)

- ee$\to$4f example process: ee$\to$WW$\to$µνqq
  - observables: production angle $\cos \theta_W$, decay angles $\cos \theta_i^*$, $\cos \phi_i^*$
    [separated into $\mu^+$ and $\mu^-$ as preparation for evqq including single-W]
  - physics parameters: $\sigma_0(W)$, $A_{LR}(W)$, 3 charged TGCs
Which experimental systematics to test?

**ALEPH**

Table 13. Exclusive $\mu^+\mu^-$ selection: examples of relative systematic uncertainties (in %) for the 1994 (1995) peak points

| Source                                      | 1993  | 1994  | 1995  |
|---------------------------------------------|-------|-------|-------|
| Acceptance                                  | 0.9 – | 1.5   | 0.4 – | 1.7 – | 2.4   |
| Selection cuts                              | 1.3   | 1.3   | 1.4 – | 2.2   |
| Trigger                                     | 0.6   | 0.6   | 0.5 – | 0.7   |
| Resonant background                         | 0.3   | 0.3   | 0.3   |
| Total scale                                 | 3.2 – | 3.4   | 3.1   | 3.9 – | 4.6   |
| $e^+e^- \rightarrow e^+e^- \mu^+\mu^-$     | [pb]  | [pb]  | [pb]  |
| Cosmic rays                                  | 0.3   | 0.3   | 0.3   |
| Total absolute                               | 0.3   | 0.3   | 0.3   |

**L3**

First test of systematic effect: $\mu$ acceptance

**OPAL**

Table 8. Contributions to the systematic uncertainty on the cross section $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ Except for the contribution from Monte Carlo statistics, all errors are fully correlated among the data sets yielding a correlated scale error of $\Delta\sigma = 3.1\%$ for 1993–94 data. For the 1995 data this error is estimated to be $3.6\%$ and it is taken to be fully correlated with the other years.

| Source                                    | 1993   | 1994   | 1995   |
|-------------------------------------------|--------|--------|--------|
| Acceptance                                | 2.7    | 2.7    | 3.2    |
| Selection cuts                            | 1.3    | 1.3    | 1.4 – 2.2 |
| Trigger                                   | 0.6    | 0.6    | 0.5 – 0.7 |
| Resonant background                       | 0.3    | 0.3    | 0.3    |
| Total scale                               | 3.2 – 3.4 | 3.1   | 3.9 – 4.6 |
| $e^+e^- \rightarrow e^+e^- \mu^+\mu^-$    | [pb]   | [pb]   | [pb]   |
| Cosmic rays                               | 0.3    | 0.3    | 0.3    |
| Total absolute                            | 0.3    | 0.3    | 0.3    |

Table 6: Summary of the correction factors, $F$, and their relative systematic errors, $\Delta F/F$, for the peak–peak cross-section measurements. These numbers, when multiplied by the number of events actually selected, give the number of signal events which would have been observed in the ideal acceptance described in Table 2. The effects tracking biases, track multiplicity cuts and muon identification, are, in principle, simulated by the Monte Carlo. The quoted corrections were introduced to take into account the observed discrepancies between the data and Monte Carlo for these effects. The error correlation matrix is given in Table 10.
Parametrising the muon acceptance for an ILC detector

ILD tracking down to:

Simplified picture: Event passes if all μ’s inside box

Fit parameters: Δc, Δw

notabene: according to previous considerations, an acceptance described by 2 parameters can be determined in all cases - only a first conceptual step here

also: all inputs on generator-level…
Nuisance parameters from combined ee-$\rightarrow$\(\mu\mu\) & ee-$\rightarrow$$\mu\nu qq$ fit

full bars: $\sigma_0$(WW), $A_{LR}$(WW) fixed - dash-dotted bars: all free

![Graph showing nuisance parameters and external constraints](image-url)
Nuisance parameters from combined ee→μμ & ee→μνqq fit

full bars: $\sigma_0(WW)$, $A_{LR}(WW)$ fixed - dash-dotted bars: all free

- (80%, 30%)$^{\text{ww}}$, 2ab$^{-1}$
- (0%, 0%), 2ab$^{-1}$
- (80%, 30%), 2ab$^{-1}$
- (0%, 0%), 10ab$^{-1}$
- (80%, 0%), 2ab$^{-1}$

$P_{e^-}, P_{e^+}$, $L$

Acceptance parameters:
- $\sigma$, $A_{LR}$ free
- $\sigma$, $A_{LR}$ free

External constraints determined at $10^{-5}$ level, mainly from 2f

Rel. (Abs.) Uncertainty [1E-4]
Nuisance parameters from combined ee->μμ & ee->μνqqq fit

full bars: $\sigma_0$(WW), $A_{LR}$(WW) fixed - dash-dotted bars: all free

if one $\sigma_0$ were known better than lumi measurement, luminosity could be better constrained => academic ?
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full bars: \( \sigma_0(WW) \), \( A_{LR}(WW) \) fixed - dash-dotted bars: all free

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polarisations determined to 0.05…0.2%, almost exclusively from WW
Nuisance parameters from combined ee→µµ & ee→µνqq fit

full bars: $\sigma_0$(WW), $A_{LR}$(WW) fixed - dash-dotted bars: all free

- $(P_{e^-}, P_{e^+}, L)$
  - $(80\%, 30\%){}^{\mu\nu}/P_{e^-}$, 2ab$^{-1}$
  - $(0\%, 0\%), 2ab^{-1}$
  - $(80\%, 30\%), 2ab^{-1}$
  - $(0\%, 0\%), 10ab^{-1}$
  - $(80\%, 0\%), 2ab^{-1}$
  - $L$ fixed

- $\sigma_0$ free
- $\sigma_0$ & $A_{LR}$ free

- Acceptance parameters determined at $10^{-5}$ level, mainly from $2f$

- Polarisations determined to 0.05...0.2%, almost exclusively from WW

if one $\sigma_0$ were known better than lumi measurement, luminosity could be better constrained

$\Rightarrow$ academic?

external constraints

acceptance parameters determined at $10^{-5}$ level, mainly from $2f$ x10
Nuisance parameters from combined ee->µµ & ee->µνqq fit

full bars: \( \sigma_0(WW), A_{LR}(WW) \) fixed - dash-dotted bars: all free

- **External constraints**
  - (80%, 30%)\(^{\text{w/P}}\), 2ab\(^{-1}\)
  - (0%, 0%), 2ab\(^{-1}\)
  - (80%, 30%), 2ab\(^{-1}\)
  - (0%, 0%), 10ab\(^{-1}\)
  - L fixed

- **Acceptance parameters**
  - determined at 10\(^{-5}\) level, mainly from 2f
  - \( \sigma_0 \) free
  - \( \sigma_0 \) & \( A_{LR} \) free

- **Polarisations**
  - determined to 0.05…0.2%, almost exclusively from WW

- If one \( \sigma_0 \) were known better than lumi measurement, luminosity could be better constrained => academic?
Nuisance parameters from combined $ee\rightarrow\mu\mu$ & $ee\rightarrow\mu\nuqq$ fit

full bars: $\sigma_0(WW)$, $A_{LR}(WW)$ fixed - dash-dotted bars: all free

Note: more polarisation parameters for polarised beams (obviously) — but each of them better constrained than $P=0$! — and better than polarimeter measurements alone
2f parameters - return-to-Z  (very similar picture for high-E)
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without positron polarisation, $A_e$ precision directly limited by polarimeter precision!
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with positron polarisation, $A_e$ precision $\sim 7 \times 10^{-4}$ from $\mu \mu$ alone

no polarisation: $A_{FB,0}$ limited by disentangling $Z/\gamma$ interference

10 $ab^{-1}$: same level as $A_e$ and $A_\mu$ with 2$ab^{-1}$ polarised
WW cross section and left-right asymmetry
WW cross section and left-right asymmetry

\( (P_{e^-}, P_{e^+}), L \)

\( (80\%, 30\%)^{\mu^\prime/\mu^0}, 2ab^{-1} \)

\( (80\%, 30\%), 2ab^{-1} \)

\( (80\%, 0\%), 2ab^{-1} \)

\( (0\%, 0\%), 2ab^{-1} \)

\( (0\%, 0\%), 10ab^{-1} \)

\( L \text{ fixed} \)

\( \sigma_0 \text{ free} \)

\( \sigma_0 & A_{LR} \text{ free} \)

\( \mu \text{ acc. fixed} \)

\( P & \mu \text{ acc. fixed} \)

\( \text{only } P_0 \text{ fixed} \)

\( A_{LR} \text{ free} \)

A\(_{LR}(WW)\) determined to 0.015\% with polarised beams or 10 \( ab^{-1} \)
\( \sigma_0(\text{WW}) \) determined to 0.03% with polarised beams or to 0.045% with 10 ab\(^{-1}\)

\( A_{\text{LR}}(\text{WW}) \) determined to 0.015% with polarised beams or 10 ab\(^{-1}\)
**WW - charged triple gauge couplings - previous studies**

- **I. Marchesini, 500 GeV**
  - full Geant4-based simulation of ILD
  - free pars: 3 cTGCs, polarisations
    => i.e. $\sigma_0(WW)$, $A_{LR}(WW)$ fixed
- **R. Karl, extrapolation to 250 GeV**

![Detail View of the ILC Precision](image)

**Figure 2.10:** Comparison of the TGC extrapolation for 2 ab$^{-1}$ at 250 GeV and 350 GeV and the full H-20 running scenario. The same systematic uncertainty as in tab. 2.4 was used.

Up to here, all extrapolations were based on the full simulation study [63]. This, however, does not include all possibilities, since it was restricted to $W$-pair production in the semi-leptonic channel, with a binned 3-dimensional angle distribution to determine the precision on $a_{\text{TGC}}$. It can be expected that this precision can be improved, as was performed at LEP (e.g. at ALEPH [55, 67]), by:
- including e.g. the fully hadronic channel
- taking into account all five sensitive angles (production angle of one of a $W$ boson together with the decay angles of both $W$ bosons, as illustrated in chap. 9.1)
- using an unbinned fit or the technique of optimal observables, as introduced in chap. 10.2.1

A study estimated at parton-level that the precision on $g_1 Z_1$ improves by a factor of 2.4 and on the other two couplings by a factor of 1.9 [68]. Thereby, the study found that the improvement with regards to an unbinned fit or the technique of optimal observables are equivalent. Taking these improvements into account, the extrapolated $a_{\text{TGC}}$ precision of

$\begin{align*}
\sigma_0(WW),
A_{LR}(WW) \text{ fixed}
\end{align*}$

expect $8..10 \times 10^{-4}$ at 250 GeV

$WW \rightarrow evqq$ & $\mu vqq$,
detector effects somewhat pessimistic,
$\sigma_0(WW), A_{LR}(WW)$ fixed
WW - charged triple gauge couplings - this study

- expect $8 \times 10^{-4}$ at 250 GeV

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$\sigma_0$(WW), $A_{LR}$(WW) fixed
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Expect $8 \times 10^{-4}$ at 250 GeV

$WW \rightarrow e\nu qq$ and $\mu\nu qq$,
detector effects somewhat pessimistic,
$\sigma_0(WW)$, $A_{LR}(WW)$ fixed

$\lambda$, robust against free $\sigma_0(WW)$, $A_{LR}(WW)$
WW - charged triple gauge couplings - this study

$g_1^Z$ robust against freeing $\sigma_0(WW)$
BUT: free $A_{LR}(WW)$ increases uncertainty:
  x2 polarised
  x3 unpolarised

$\lambda_\gamma$ robust against free $\sigma_0(WW)$, $A_{LR}(WW)$

expect $8 \times 10^{-4}$ at 250 GeV

WW $\to$ evqq & $\mu$qq,
detector effects somewhat pessimistic,
$\sigma_0(WW)$, $A_{LR}(WW)$ fixed
WW - charged triple gauge couplings - this study

\[ g_{1Z} \text{ robust against freeing } \sigma_0(WW) \]

**BUT**: free \( A_{LR}(WW) \) increases uncertainty:
- \( x_2 \) polarised
- \( x_3 \) unpolarised

Expect \( 8 \times 10^{-4} \) at 250 GeV

\[ WW \rightarrow e\nu qq \text{ & } \mu\nu qq, \]

Detector effects somewhat pessimistic,

\[ \sigma_0(WW), A_{LR}(WW) \text{ fixed} \]

\( \lambda, \gamma \) robust against free \( \sigma_0(WW), A_{LR}(WW) \)

Huge deterioration if \( A_{LR}(WW) \) free?
- Needs investigation!
- Inclusion of single-W processes?
- Include theory constraints / search limits (\( \nu_R \))?

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Conclusions

- role of beam polarisation for chiral analysis, signal-to-background ratio, effective luminosity at future e+e- collider well studied since years

- only more recently studied: role of beam polarisation for constraining experimental systematics

- combination of data-sets with different polarisation configurations helps significantly to reduce the impact of systematic uncertainties

- first steps have been undertaken to apply the same principles to a combined fit of ee->2f and ee->4f processes

- impact of polarisation seen in various places:

- study needs to be deepened / extended in other places to obtain complete picture, e.g. wrt role of some of the leading uncertainties in the corresponding analyses at LEP
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- impact of polarisation seen in various places:
  
  **4 polarisation sign configurations better than 2 or just 1**

- study needs to be deepened / extended in other places to obtain complete picture, e.g. wrt role of some of the leading uncertainties in the corresponding analyses at LEP
Backup
The International Linear Collider in a nutshell

- **$e^+e^-$ centre-of-mass energy**
  - first stage: 250 GeV
  - tunable
  - upgrades: 500 GeV, 1 TeV, 91 /161 GeV

- **luminosity at 250 GeV**
  - $1.35 \times 10^{34} / \text{cm}^2 / \text{s}$
  - upgrade $2.7 \times 10^{34} / \text{cm}^2 / \text{s}$

- **beam polarisation**
  - $P(e^-) \geq 80\%$
  - $P(e^+) = 30\%$, at 500 GeV upgradable to 60\%

- **total length (250 GeV)**: 20.5 km

![Diagram showing various processes like $WW$, $ZH$, $tt$, $ttH$, $vvHH$, along with energy levels 100, 250, 350, 500, and 1000 GeV.](image)

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**IlCu, Scenario H20-staged**

- $ECM = 250$ GeV
- $ECM = 350$ GeV
- $ECM = 500$ GeV

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*all up-to-date numbers in ILC ESU Document*

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*Integrated Luminosity [fb$^{-1}$]*

- $ILC, Scenario H20-staged$
  - $ECM = 250$ GeV
  - $ECM = 350$ GeV
  - $ECM = 500$ GeV

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*E$_{CM}$ / GeV*

- $Z$
- $WW$
- $ZH$
- $tt$
- $ttH$
- $vvHH$

---

*Years*

- 0
- 5
- 10
- 15
- 20