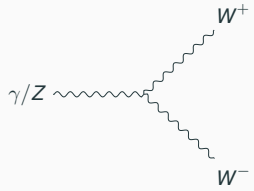
Triple Gauge Couplings: Using Optimal Observables at the Detector Level

Leonhard Reichenbach
CERN

LCWS
2026-11-11

Triple Gauge Couplings (TGC)

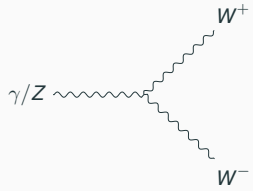
- SM Lagrangian contains interaction:



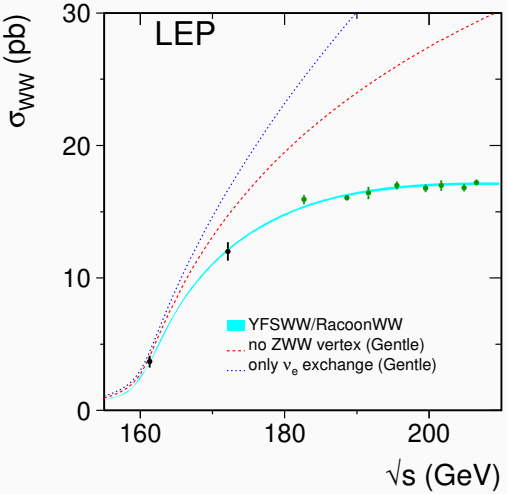
- Regularises $e^+e^- \to W^+W^-$ cross-section

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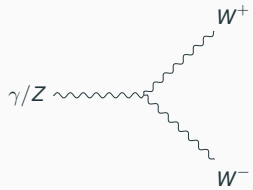


- Regularises $e^+e^- \to W^+W^-$ cross-section
- Observed and compatible with SM

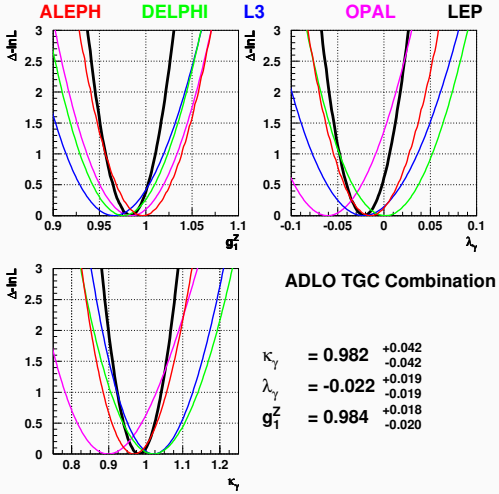


Triple Gauge Couplings (TGC)

- SM Lagrangian contains interaction:



- Regularises $e^+e^- \to W^+W^-$ cross-section
- Observed and compatible with SM
- Dim.-6 SMEFT: 3 additional operators
- LEP parametrisation: g_1^Z, κ_γ, λ_γ
- *Anomalous* triple gauge couplings (aTGC)



ADLO TGC Combination

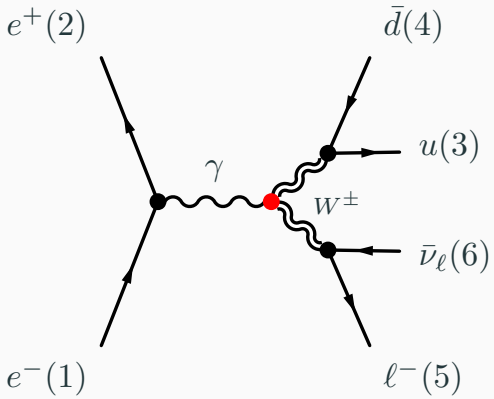
κ_γ = 0.982 $^{+0.042}_{-0.042}$

λ_γ = -0.022 $^{+0.019}_{-0.019}$

g_1^Z = 0.984 $^{+0.018}_{-0.020}$

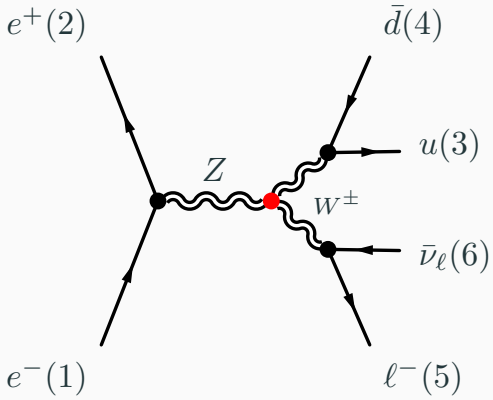
TGC in WW at e^+e^-

- "Golden-channel": semi-leptonic
  - Only one neutrino
  - No colour reconnection
  - $\sigma(\ell\nu qq) > 2\,\text{pb}$ at ZH energies
- 2 TGC-sensitive *s*-channel diagrams



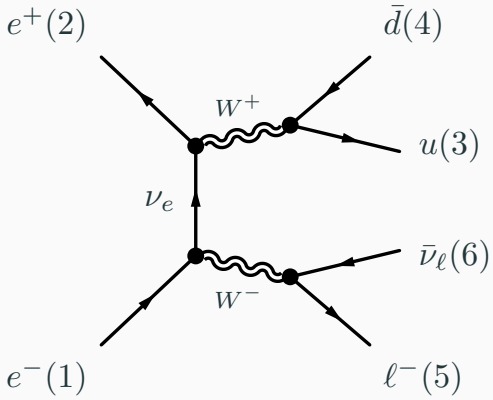
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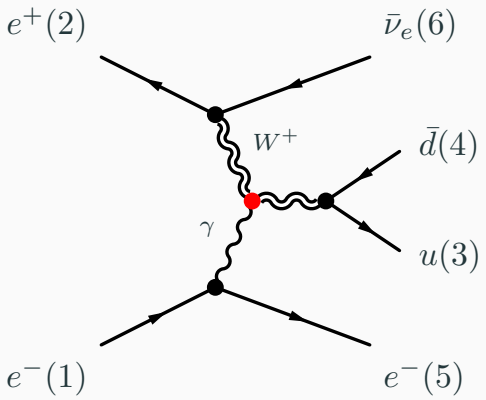
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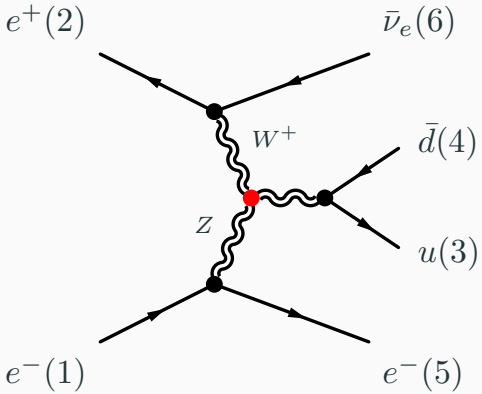
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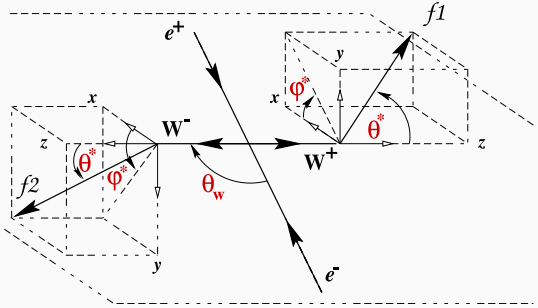
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aTGC determination in e^+e^-

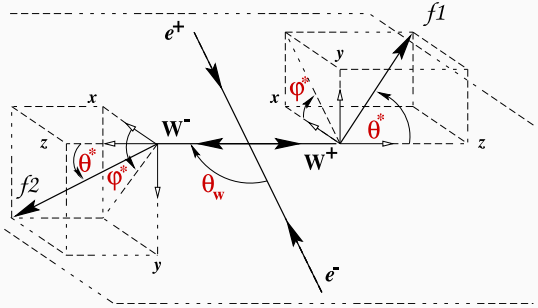
- Change in the couplings
  $\rightarrow$ change in WW-pol. fractions
- Information in W production and decay angles (and their correlations!)
- $m_{\ell\nu}$, m_{jj} also relevant
- Not so easy to perform a binned template fit in 5 or more dimensions...
- Workarounds: uncorrelated 1D fits, 3D fit ignoring hadronic W



WW production and decay angles

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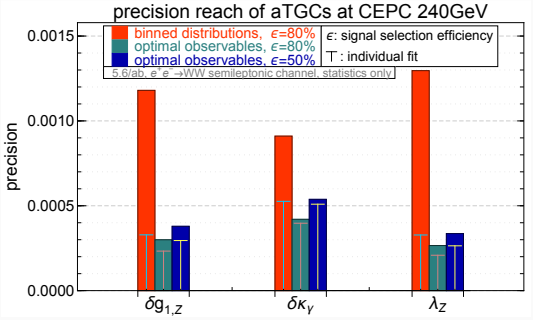
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- and Optimal observables (OO)



WW production and decay angles

Other aTGC studies for future colliders

- Already studied for TESLA during LEP times (M. Diehl, W. Menges)
- At the ILC focus changed to aTGC as nuisance parameters to the in-situ beam-polarisation determination (I. Marchesini, R. Karl, J. Beyer)
- Optimal observables (OO) supposed to massively improve performance
- ILC/ILD analyses: binned fits in 3D (also some theory-only OO)
- Also studied for CEPC (1D fits, OO)



Optimal Observables (OO)

- OO: matrix-element-based “most-sensitive” 1D-projection for a parameter
- One observable $\mathcal{O}_i$ per parameter θ_i of the differential cross-section $\mathrm{d}\sigma/\mathrm{d}\phi$

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- Identical performance to $\hat{\theta}_i$ given perfect reconstruction
- Relies solely on shape information in this formulation (but can be extended)

OO fit setup

- Signal-only fit as in the theory-level studies, due to too low background statistics after selection
- Parameters:
  - aTGC: g_1^Z, κ_γ, λ_γ
  - SM: m_W
  - Polarisations: $P_{e^-}^{+,-,0}$, $P_{e^+}^{+,-,0}$
- One polarisation parameter per beam and polarisation direction
- Simultaneous fit of multiple polarisation configurations/“runs”
- Polarisation parameters are shared across runs (assuming fast helicity reversal)

- Approximate optimal observable for each parameter θ by the derivative

$$\mathcal{O}_\theta(\phi) = \left.\frac{\mathrm{d}|\mathcal{M}(\phi;\theta)|^2}{\mathrm{d}\theta}\right|_{\theta=\theta_0}$$

  where θ_0 is the nominal value
- Templates for the mean values are obtained via reweighting and linearly parametrised
- The χ^2-fit is performed as a maximum likelihood fit of the multivariate normal distribution and optionally combined with an external Gaussian constraint of the beam polarisation

Used Samples

- ILD 2020 mass production for 250 GeV ILC conditions
- WHIZARD+Pythia6 $\rightarrow$DD4hep/Geant4 $\rightarrow$Marlin
- Full set of Standard Model processes
- Subset of statistics converted to miniDST
- Files converted from LCIO into EDM4hep file format
- Includes WW-categorisation for potential combinations
- Used for signal definition and respected by selection

MiniDST

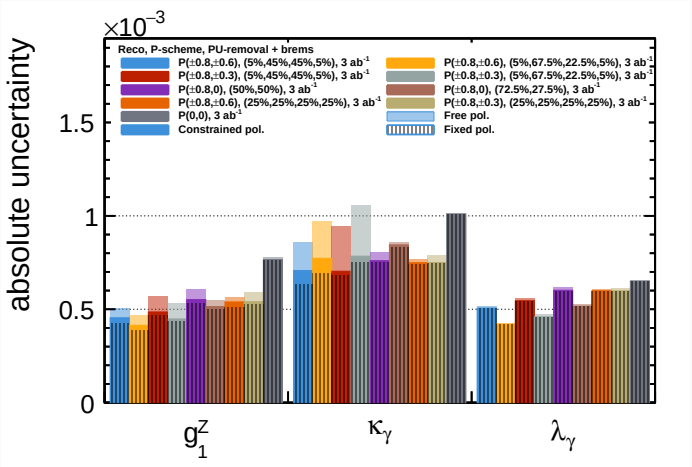
- “analysis-ready” format
- tagged isolated particles
- pre-defined jets

WW-categorisation

- Separates WW into different decay modes: leptonic, semi-leptonic, hadronic
- Semi-leptonic split by flavour and electron polar angle
- Definitions developed by a previous student (A. Silva)

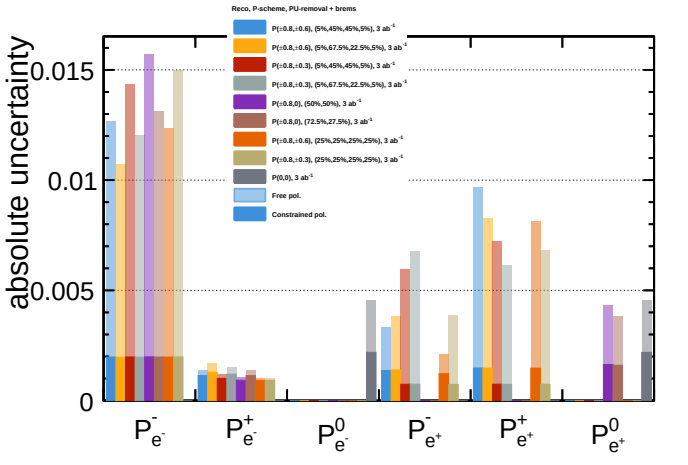
Effect of Longitudinally Polarised Beams

- Varied polarisation strength and luminosity fraction
- Knowledge of polarisation:
  - Freely floating (light)
  - Constrained (solid)
  - Fixed (hatched)
- Adds real information, not just *s*-channel statistics
- Opposite behaviour of g_1^Z &λ_γ vs. κ_γ
- Polarisation knowledge matters for aTGC



In-situ polarisation fit

- Same variations as last slide
- Knowledge of polarisation:
  - Freely floating (light)
  - Constrained (solid)
  - Fixed (hatched)
- Could be improved by adding further channels and information on the total rate



Outlook/Potential improvements

- Fit framework needs some cleanup and extension to consider also event counts (needed to include background)
  - Should also improve the polarisation determination
- In principle easily extendable to more parameters to build full SMEFT likelihoods and consider more systematics in situ
- The calculation of the matrix elements is slow and inefficient at the moment and the interface to the O'Mega matrix elements very brittle

Summary

- Optimal observables work really well also for fits on reconstruction-level data
- It is possible to use them to simultaneously determine nuisance parameters like the beam polarisations
- With some more work it should be possible to make the OO calculation and fit framework easily usable also for other analyses

This work has been sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 13E18CHA).

With funding from the:

Federal Ministry
of Research, Technology
and Space

Standard Model Effective Field Theory (SMEFT)

- Structure of new physics unknown
- Model higher scale particles with higher dimensional operators (Fermi interaction)
- Number of independent operators finite at a given mass-dimension cutoff
- Idea: consistent maximal extension of SM
- Already 2499 operators at dim.-6...
- Interesting relations emerge e.g. between Higgs and EW gauge couplings

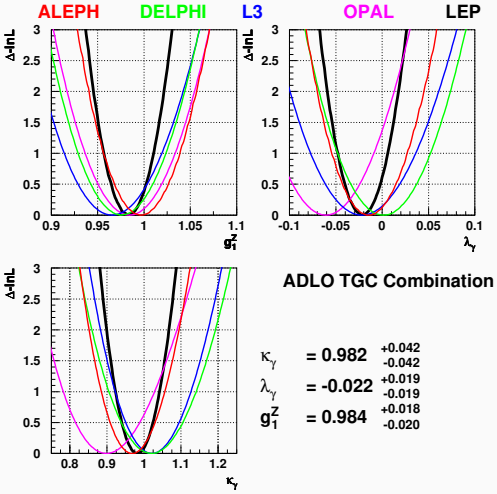
$$\mathcal{L}_{\text{SMEFT,d6}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}$$

- Λ: energy scale
- $c_i^{(6)}$: Wilson coefficients
- Cut off after a fixed dimension, usually 6

SMEFT provides:

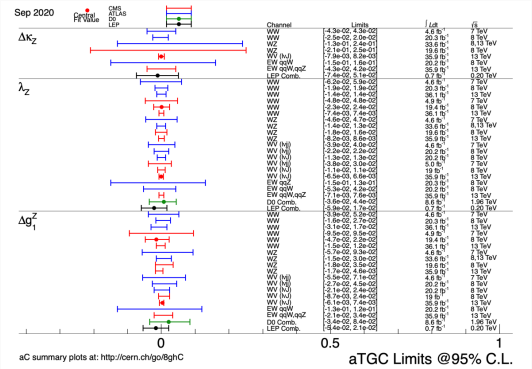
- A framework to systematically study deviations from the Standard Model
- An intermediate representation between theory and experiment
- A way to compare experimental coverage? (hotly debated)

Past and Future aTGC Results



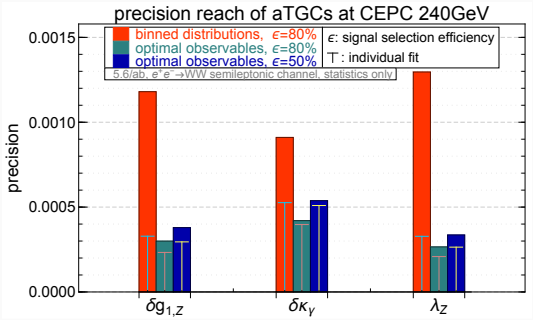
- LEP: a few percent uncertainty

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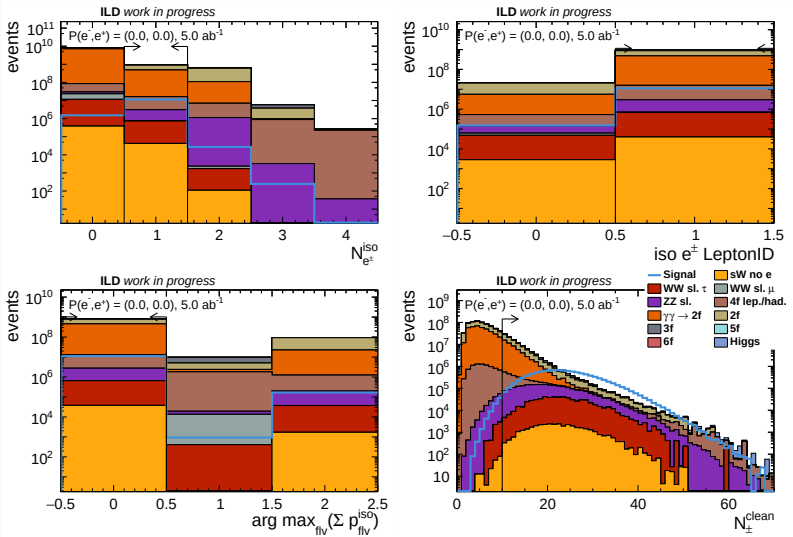
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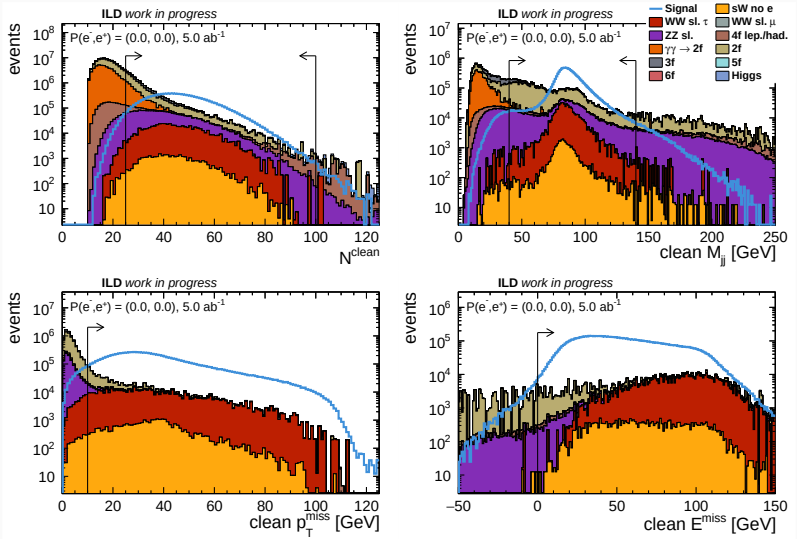


- LEP: a few percent uncertainty
- LHC: few 10^{-3} in dedicated aTGC search
- But some issues regarding interpretability
- Expect a few 10^{-4} at Higgs factories from theory-only studies with assumed selection efficiencies and other extrapolations

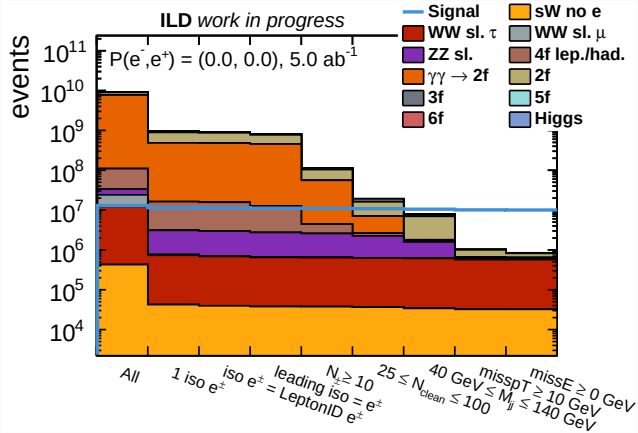
Selection results



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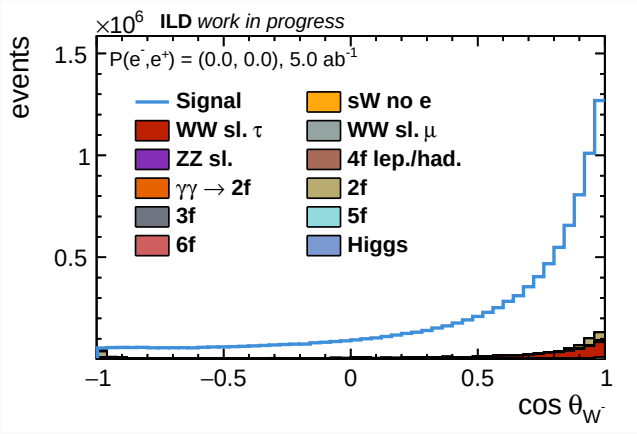


Selection results



- Reduces background to 8 %
- 77 % signal efficiency
- Fits optimistic expectation

Selection results



- Reduces background to 8 %
- 77 % signal efficiency
- Fits optimistic expectation
- Some issues from signal definition
- τ background irreducible on detector level
- `2f` background very small
- Continue signal-only from here