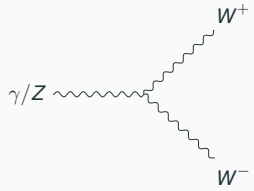
# Triple Gauge Couplings: Using Optimal Observables at the Detector Level

Leonhard Reichenbach
CERN

LCWS
2026-11-11

# Triple Gauge Couplings (TGC)

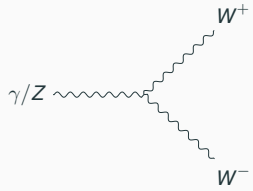
- SM Lagrangian contains interaction:



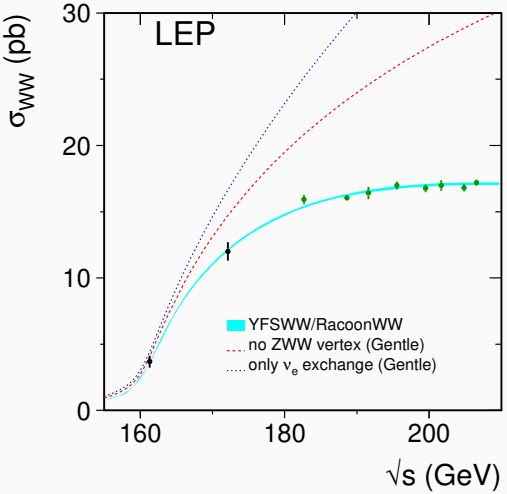

- Regularises $e^+e^- \to W^+W^-$ cross-section

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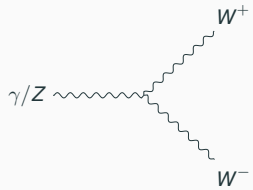



- Regularises $e^+e^- \to W^+W^-$ cross-section
- Observed and compatible with SM

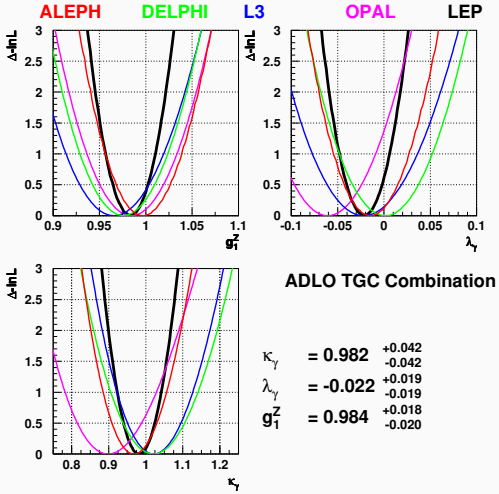


# Triple Gauge Couplings (TGC)

- 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: $g_1^Z$, $\kappa_\gamma$, $\lambda_\gamma$
- *Anomalous* triple gauge couplings (aTGC)




**ADLO TGC Combination**

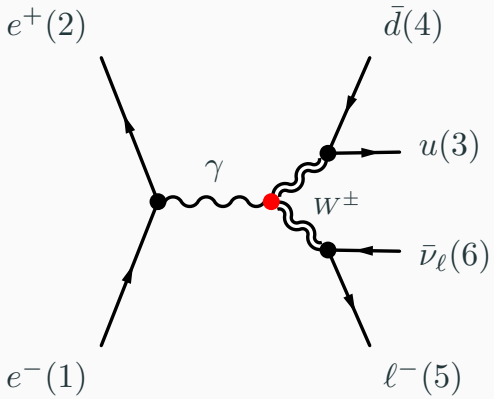
$\kappa_\gamma$ = 0.982 $^{+0.042}_{-0.042}$

$\lambda_\gamma$ = -0.022 $^{+0.019}_{-0.019}$

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

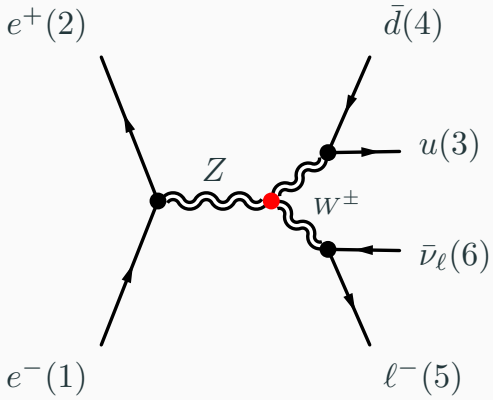
# TGC in WW at $e^+e^-$

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



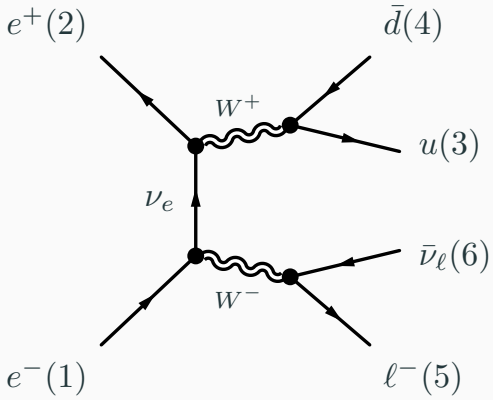
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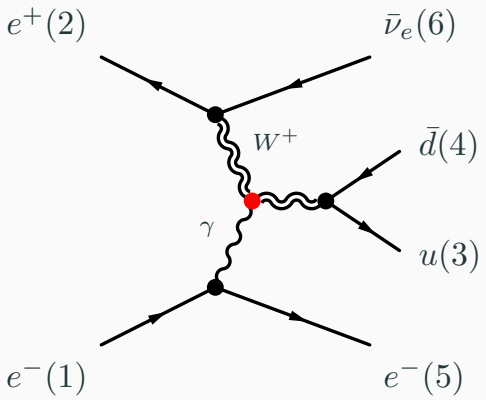
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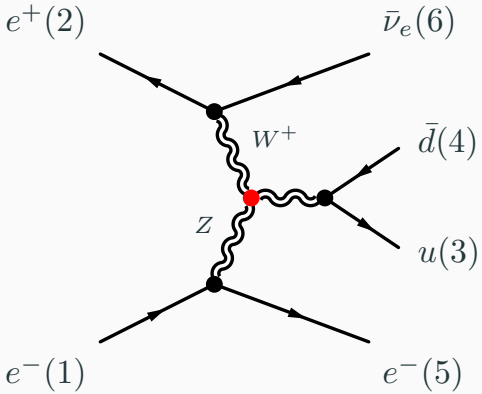
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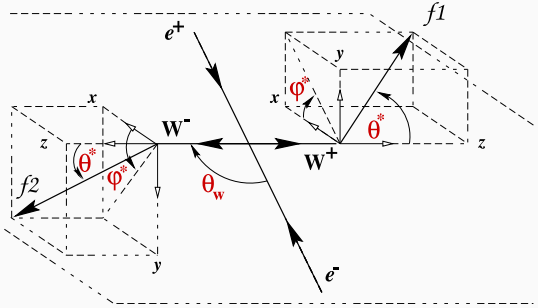
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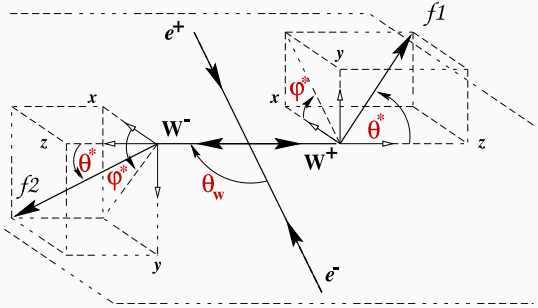
- Change in the couplings
  $\rightarrow$ change in WW-pol. fractions
- Information in W production and decay angles (and their correlations!)
- $m_{\ell\nu}$, $m_{jj}$ also relevant
- Not so easy to perform a binned template fit in 5 or more dimensions...
- Workarounds: uncorrelated 1D fits, 3D fit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




WW production and decay angles

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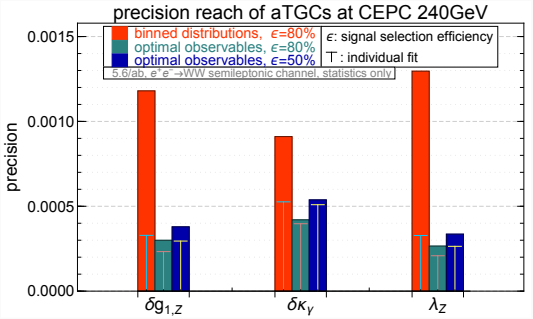
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- and Optimal observables (OO)




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)




Comparison of binned fit to OO at CEPC

Taken from **1907.04311**

# Optimal Observables (OO)

- OO: matrix-element-based “most-sensitive” 1D-projection for a parameter
- One observable $\mathcal{O}_i$ per parameter $\theta_i$ 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: $g_1^Z$, $\kappa_\gamma$, $\lambda_\gamma$
  - 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 $\theta$ by the derivative

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

  where $\theta_0$ is the nominal value
- Templates for the mean values are obtained via reweighting and linearly parametrised
- The $\chi^2$-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
- Selection results are in the backup

## MiniDST

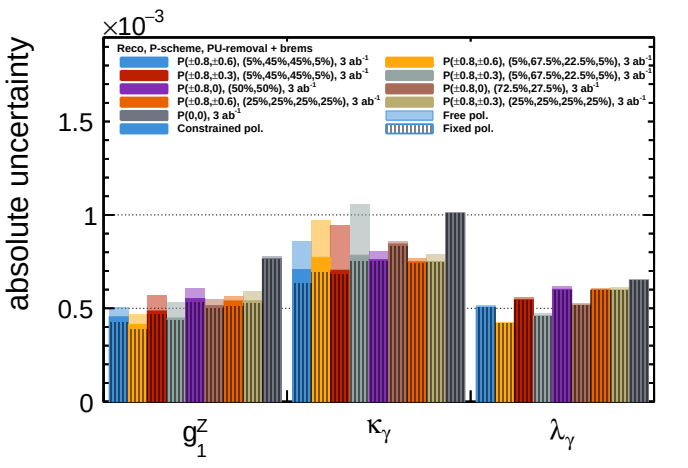
- “analysis-ready” format
- tagged isolated particles
- pre-defined jets

## 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)

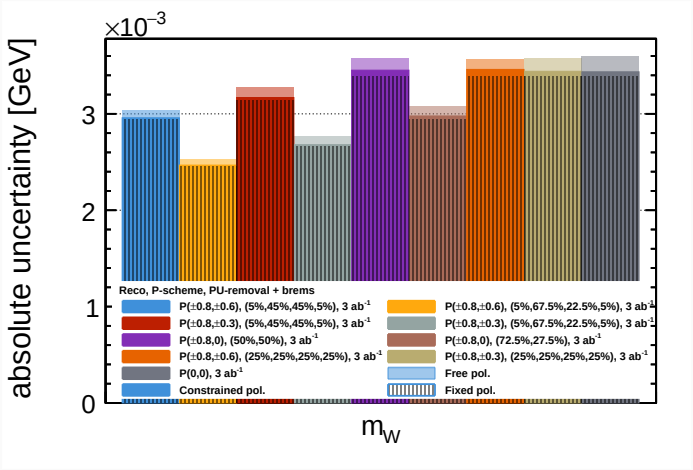
# Effect of Longitudinally Polarised Beams

- Varied polarisation strength and luminosity fraction
- Two effects:
  - More Ws per $fb^{-1}$
  - Separation of LR and RL
- Knowledge of polarisation:
  - Freely floating (light)
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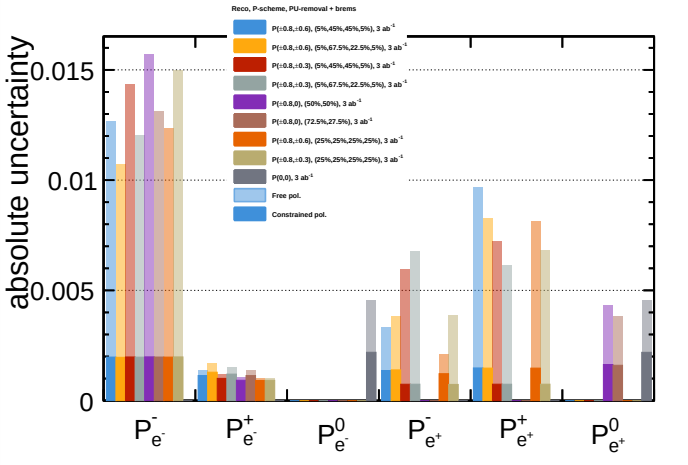
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# In-situ polarisation fit

- 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
- Should probably also be split into correlated/uncorrelated components...



# 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

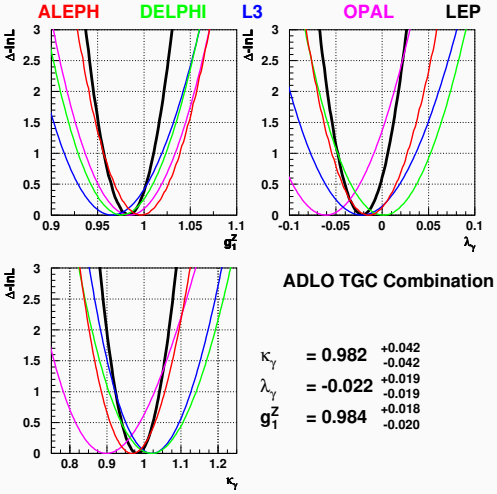
$$\mathcal{L}_{\text{SMEFT,d6}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}$$

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

**SMEFT provides:**

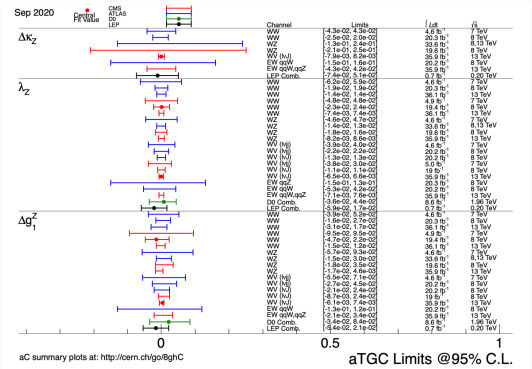
- A framework to systematically study deviations from the Standard Model
- An intermediate representation between theory and experiment
- A way to compare experimental coverage? (hotly debated)

# Past and Future aTGC Results



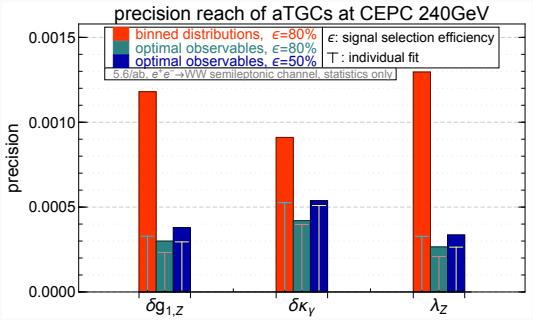

- LEP: a few percent uncertainty

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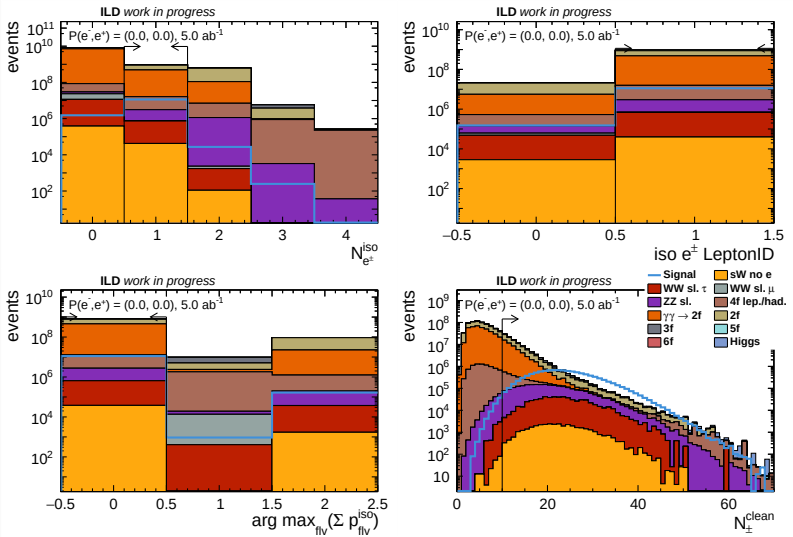

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- LHC: few $10^{-3}$ in dedicated aTGC search
- But some issues regarding interpretability

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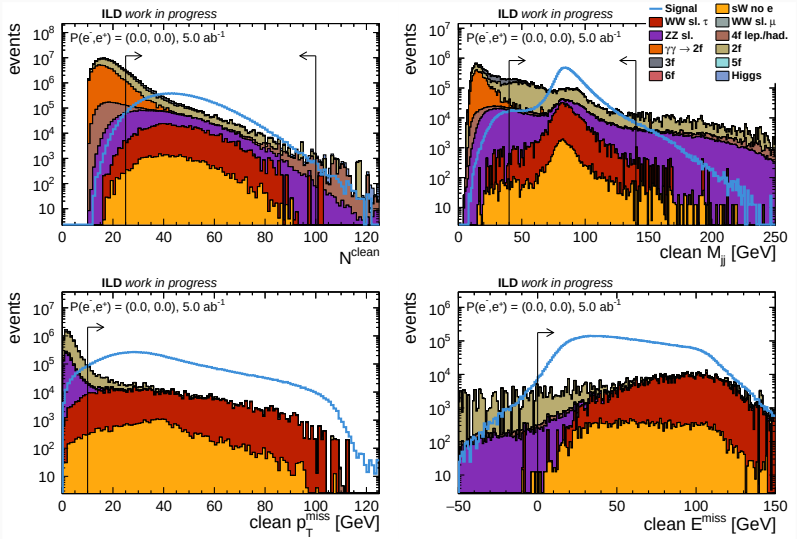



- LEP: a few percent uncertainty
- LHC: few $10^{-3}$ in dedicated aTGC search
- But some issues regarding interpretability
- Expect a few $10^{-4}$ at Higgs factories from theory-only studies with assumed selection efficiencies and other extrapolations

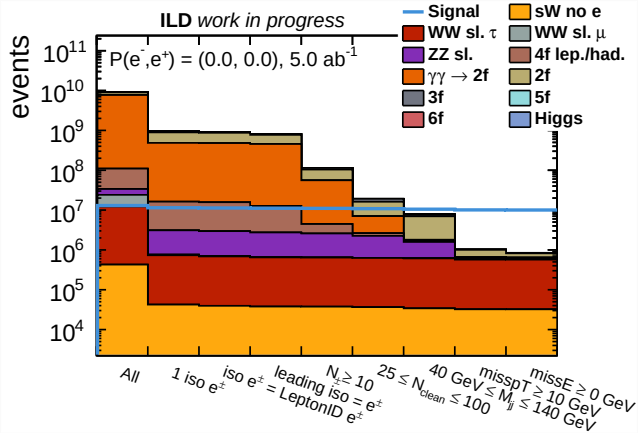
# Selection results



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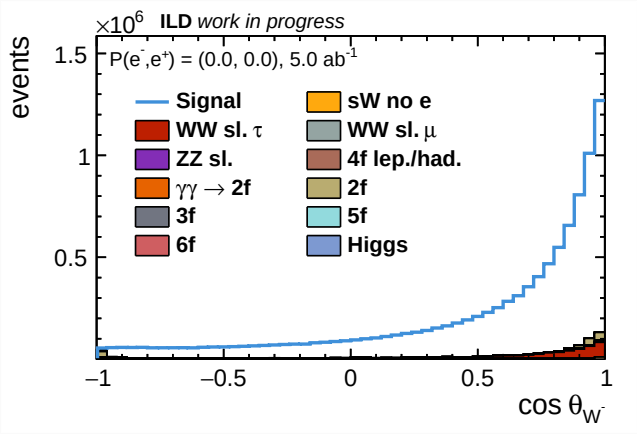


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- Reduces background to 8 %
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- Reduces background to 8 %
- 77 % signal efficiency
- Fits optimistic expectation
- Some issues from signal definition
- $\tau$ background irreducible on detector level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