Determining Triple Gauge Couplings at Future e^+e^- Higgs Factories using Optimal Observables

Leonhard Reichenbach

University of Bonn

Promotionskolloquium
2026-09-01

With funding from the:

Federal Ministry of Research, Technology and Space

Agenda

Determining Triple Gauge Couplings at Future e^+e^- Higgs Factories using Optimal Observables

1. A short particle physics introduction.

Agenda

Determining Triple Gauge Couplings at Future e^+e^- Higgs Factories using Optimal Observables

1. A short particle physics introduction.
2. How (and why) to study the future?

Agenda

Determining Triple Gauge Couplings at Future e^+e^- Higgs Factories using Optimal Observables

1. A short particle physics introduction.
2. How (and why) to study the future?
3. Why are we looking at Triple Gauge Couplings, and what are they?

Agenda

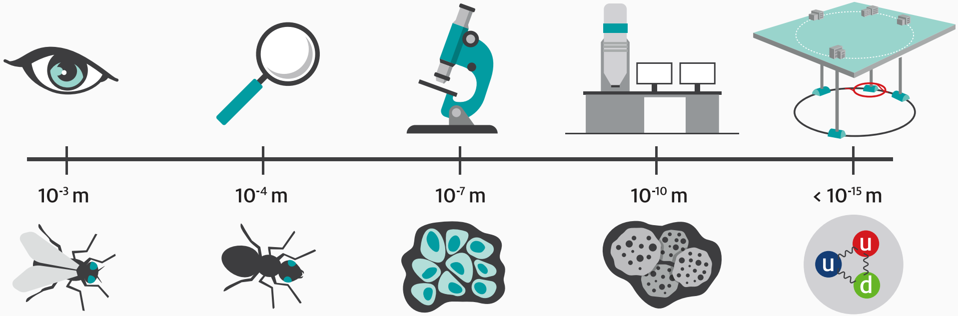
Determining Triple Gauge Couplings at Future e^+e^- Higgs Factories using Optimal Observables

1. A short particle physics introduction.
2. How (and why) to study the future?
3. Why are we looking at Triple Gauge Couplings, and what are they?
4. A selection of results, and how Optimal Observables were used to obtain them.

Matter and the Universe

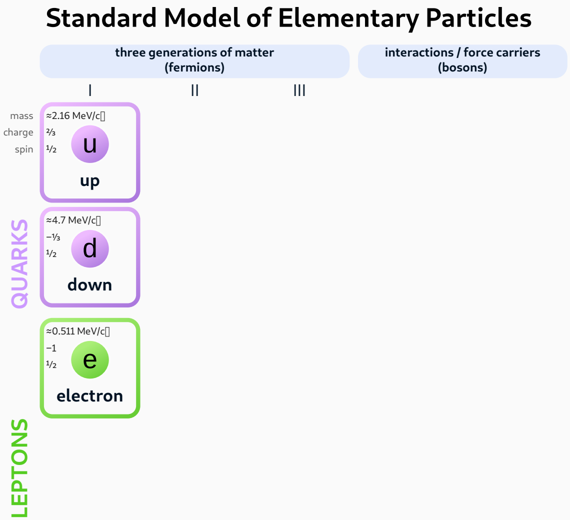
What are the building blocks of our world?

- Build larger and larger microscopes to look at smaller and smaller things
- Shine a “light” at an object and study the reflection
- Result: discovered multiple generations of fundamental particles



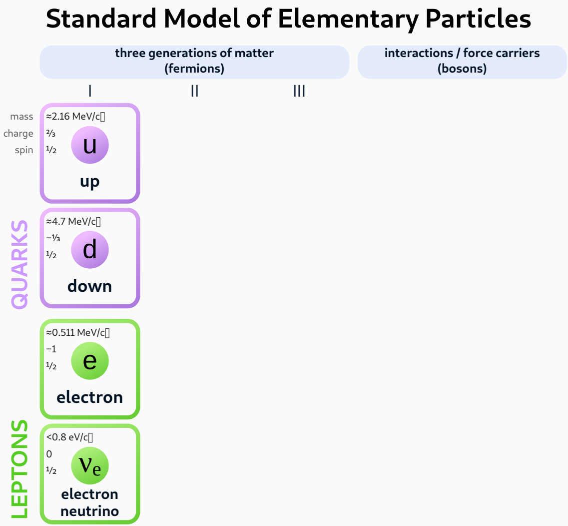
[Netzwerk Teilchenwelt]

Particles and Forces



The Standard Model (SM) contains:

- Building blocks of matter

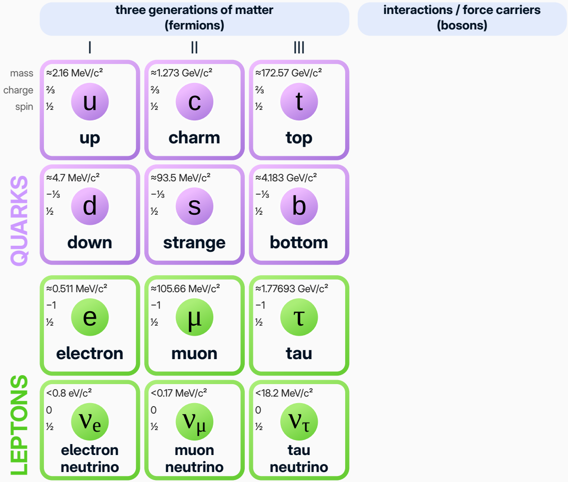


The Standard Model (SM) contains:

- Building blocks of matter

Particles and Forces

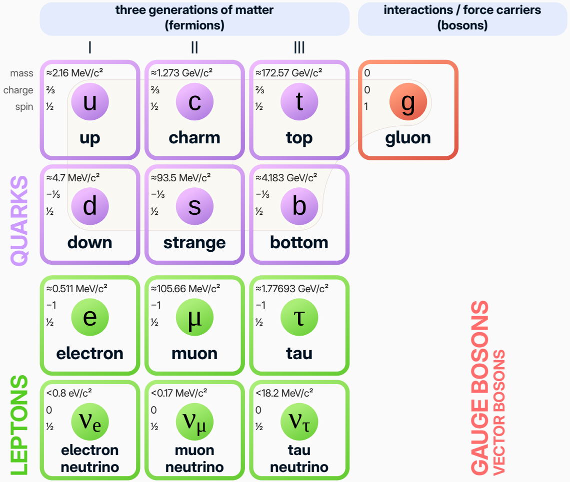
Standard Model of Elementary Particles



The Standard Model (SM) contains:

- Building blocks of matter

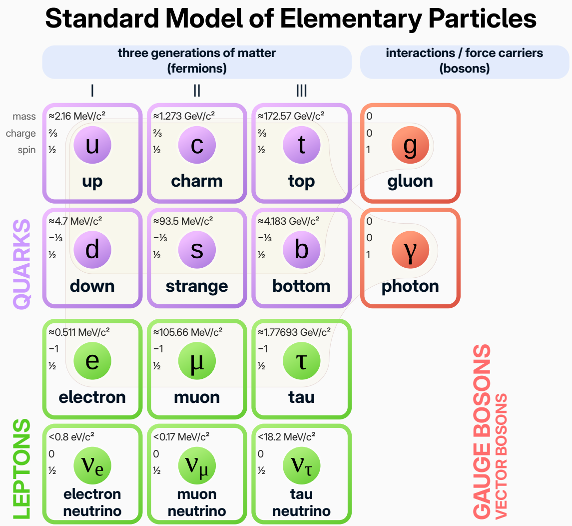
Standard Model of Elementary Particles



The Standard Model (SM) contains:

- Building blocks of matter
- 3 of 4 known forces

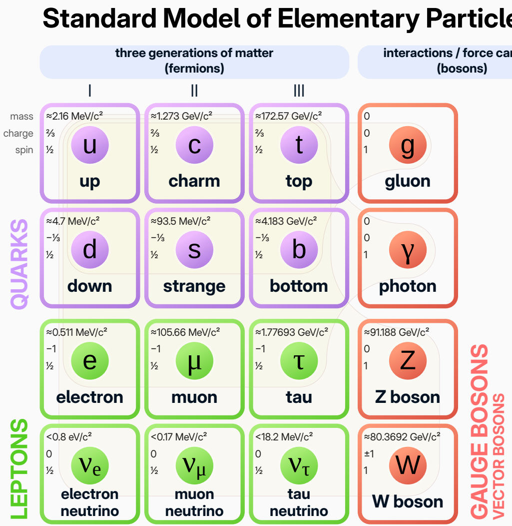
Particles and Forces



The Standard Model (SM) contains:

- Building blocks of matter
- 3 of 4 known forces

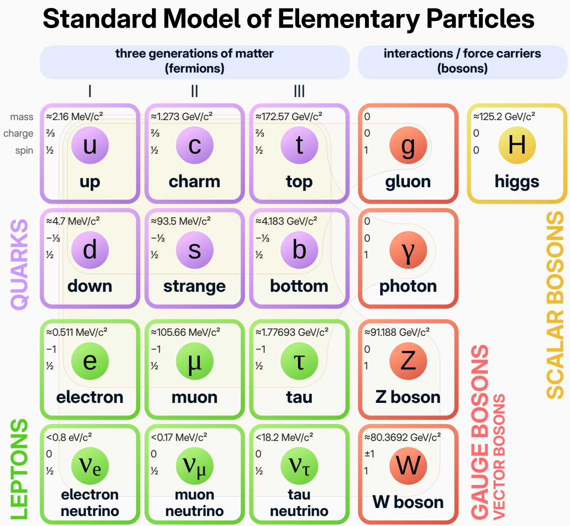
Particles and Forces



The Standard Model (SM) contains:

- Building blocks of matter
- 3 of 4 known forces

Particles and Forces



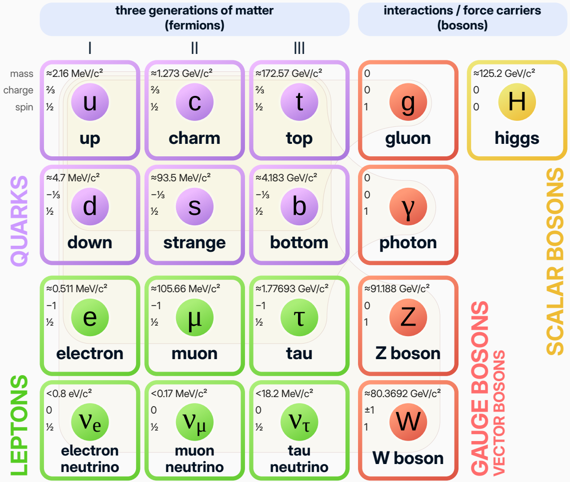
The Standard Model (SM) contains:

- Building blocks of matter
- 3 of 4 known forces
- A mechanism to give mass to particles

But misses:

Particles and Forces

Standard Model of Elementary Particles



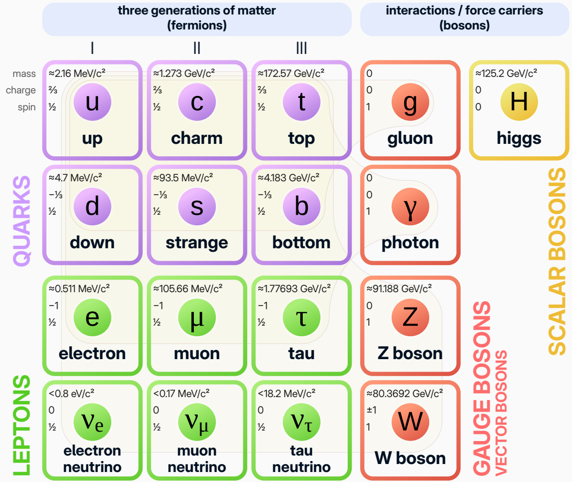
The Standard Model (SM) contains:

- Building blocks of matter
- 3 of 4 known forces
- A mechanism to give mass to particles

But misses:

- Gravity, neutrino masses, dark matter
- “Reasons” for
  - Particle masses
  - Number of generations
  - Mixing angles/matrices

Standard Model of Elementary Particles



The Standard Model (SM) contains:

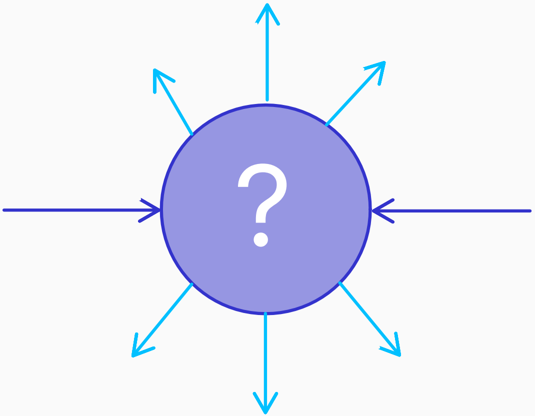
- Building blocks of matter
- 3 of 4 known forces
- A mechanism to give mass to particles

But misses:

- Gravity, neutrino masses, dark matter
- “Reasons” for
  - Particle masses
  - Number of generations
  - Mixing angles/matrices
- There should be something better!

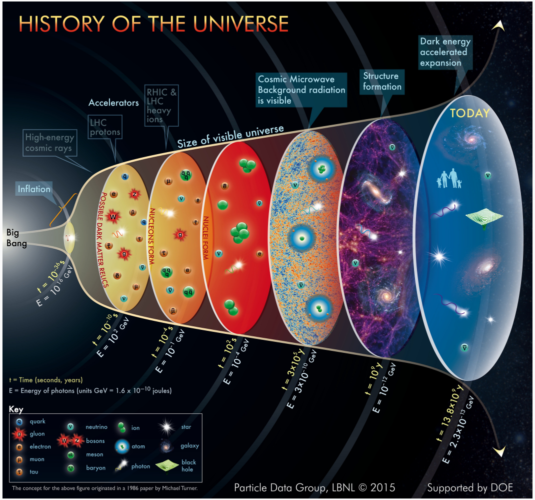
Collider Experiments

- Not quite a microscope
- “Light” and studied object are identical
- “Hard” collisions create new particles



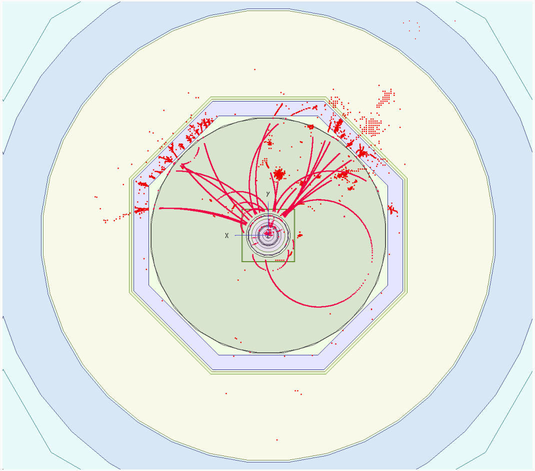
Collider Experiments

- Not quite a microscope
- “Light” and studied object are identical
- “Hard” collisions create new particles
- Conditions similar to the early universe



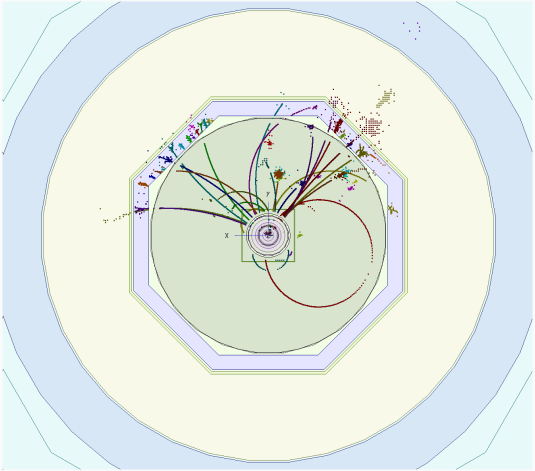
Collider Experiments

- Not quite a microscope
- “Light” and studied object are identical
- “Hard” collisions create new particles
- Conditions similar to the early universe
- Unstable particle decay after collision
- Decay products leave hits in detector



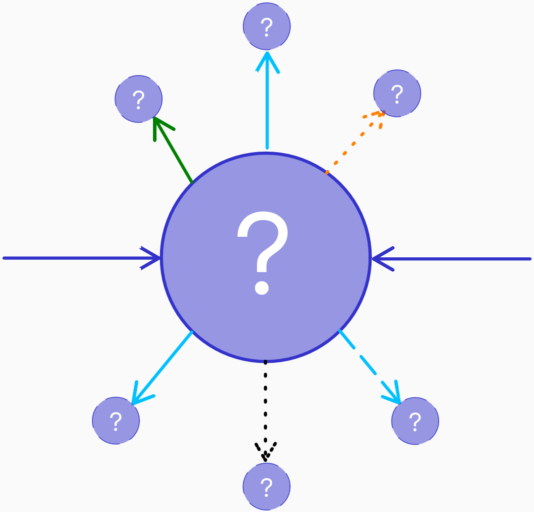
Collider Experiments

- Not quite a microscope
- “Light” and studied object are identical
- “Hard” collisions create new particles
- Conditions similar to the early universe
- Unstable particle decay after collision
- Decay products leave hits in detector
- Need to be clustered and identified



Collider Experiments

- Not quite a microscope
- “Light” and studied object are identical
- “Hard” collisions create new particles
- Conditions similar to the early universe
- Unstable particle decay after collision
- Decay products leave hits in detector
- Need to be clustered and identified
- Collision results have randomness
- Need to collect many collisions to compare against predicted distributions



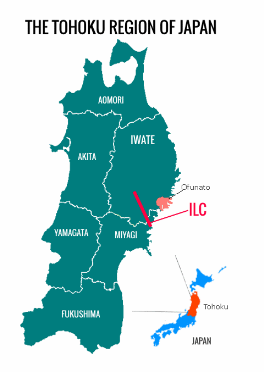
The Future of Particle Physics

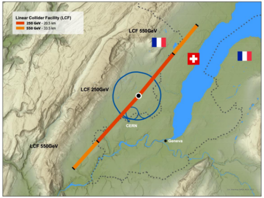
Current State of the Field

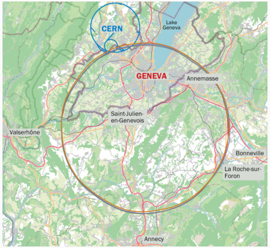
- The LHC found the Higgs
- But no further fundamental particles

Current State of the Field

- The LHC found the Higgs
- But no further fundamental particles
- Next step: precision Higgs and SM studies
- Higgs factories: ILC, LCF, FCC-ee, etc.
- e^+e^- collider, ZH production ($\sim 250\,\mathrm{GeV}$)
- Unlikely to operate before the late 40s

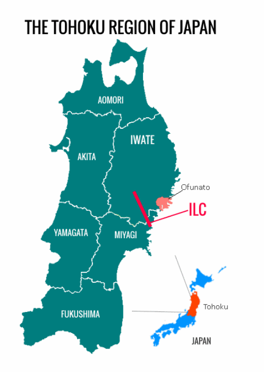


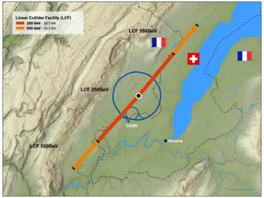


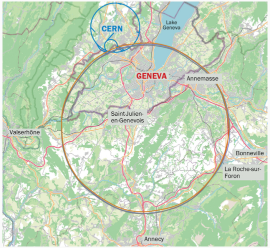


Current State of the Field

- The LHC found the Higgs
- But no further fundamental particles
- Next step: precision Higgs and SM studies
- Higgs factories: ILC, LCF, FCC-ee, etc.
- e^+e^- collider, ZH production ($\sim 250\,\text{GeV}$)
- Unlikely to operate before the late 40s
- How to systematically study the full SM?
- How to compare project performances?







SMEFT: the Solution?

- Standard Model Effective Field Theory
- Idea: consistent maximal extension of SM
- Add *all* independent operators of higher mass dimension
- Captures effects of higher-scale particles
- Historical example: Fermi interaction
- Large but finite number of operators

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

- 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)

Future Detectors

- Higgs factory 20+ years away

Future Detectors

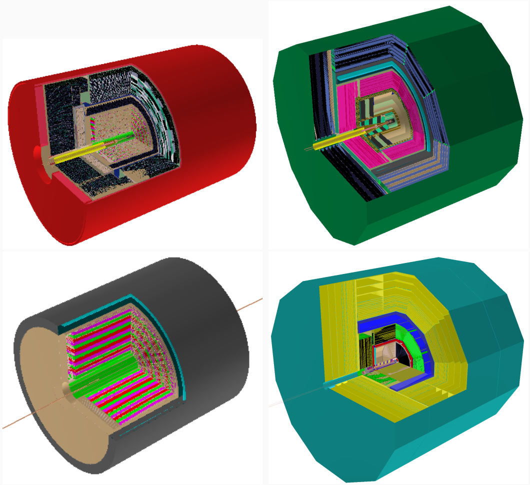
- Higgs factory 20+ years away
- Detectors themselves are cutting-edge research products!
- ATLAS ITk: 18 years from LOI to OP?
- Specifications need to be determined now

Future Detectors

- Higgs factory 20+ years away
- Detectors themselves are cutting-edge research products!
- ATLAS ITk: 18 years from LOI to OP?
- Specifications need to be determined now
- Cost $\sim$0.5–1 GCHF
- Massive (cost) optimisation pressure

Future Detectors

- Higgs factory 20+ years away
- Detectors themselves are cutting-edge research products!
- ATLAS ITk: 18 years from LOI to OP?
- Specifications need to be determined now
- Cost $\sim$0.5–1 GCHF
- Massive (cost) optimisation pressure
- How to evaluate their performance. . .
- . . . before they are built?
- Study “digital twin” of the experiment



4 of 6 FCC-ee detector concepts

Motivation

Aim of This Work

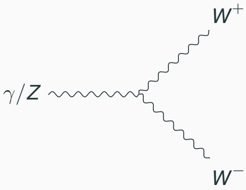
Develop a benchmark analysis using Key4hep, studying TGC at future Higgs factories

- to compare the impacts of various detector/reconstruction effects
- to validate performance assumptions from theory-only projections
- to study differences between different Higgs factories
- in a SMEFT-compatible way that makes “optimal” use of the available information

Here: using the ILD detector as an example, but the analysis is portable

Triple Gauge Couplings (TGC)

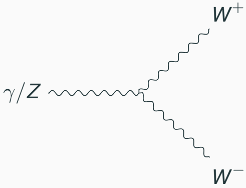
- SM Lagrangian contains interaction:



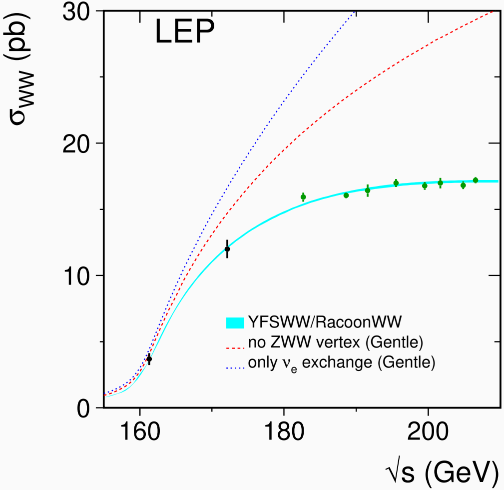
- Regularises $e^+e^- \to W^+W^-$ cross-section

Triple Gauge Couplings (TGC)

- SM Lagrangian contains interaction:

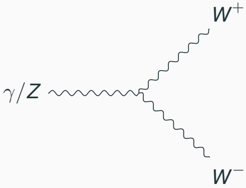


- Regularises $e^+e^- \to W^+W^-$ cross-section
- Observed and compatible with SM

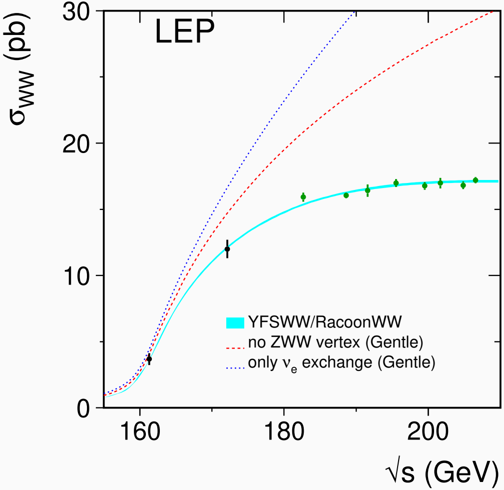


Triple Gauge Couplings (TGC)

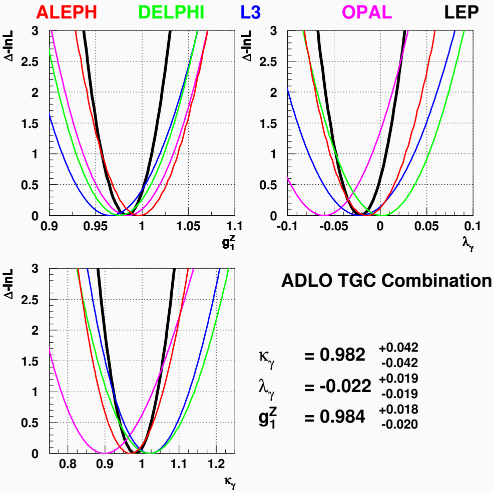
- SM Lagrangian contains interaction:



- 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)



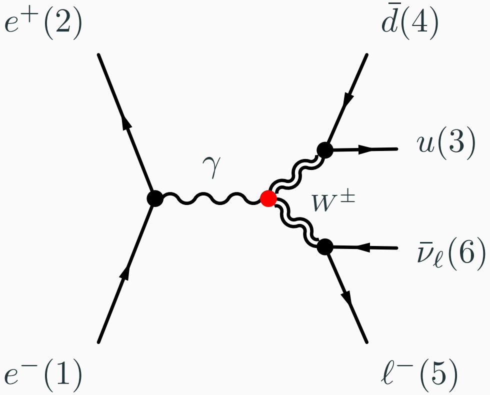
Past and Future aTGC Results



- 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

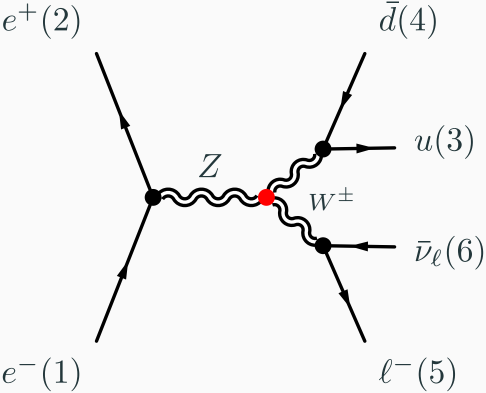
WW at e^+e^-

- "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



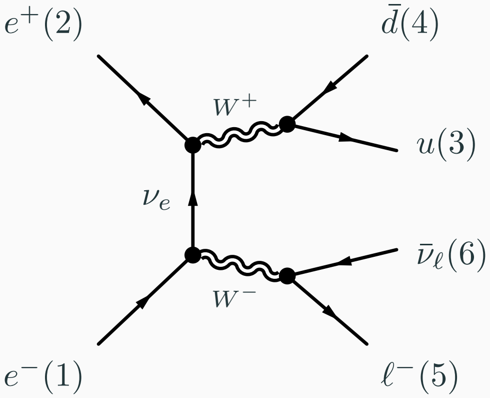
WW at e^+e^-

- "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



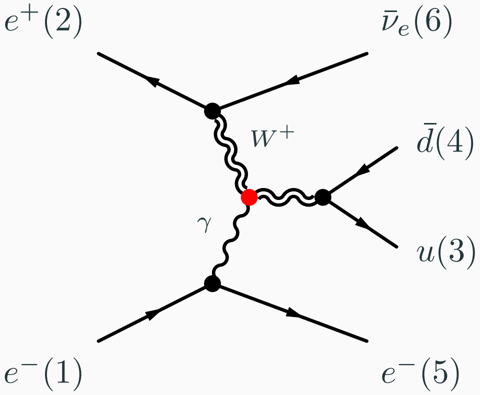
WW at e^+e^-

- “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
- Large insensitive *t*-channel diagram



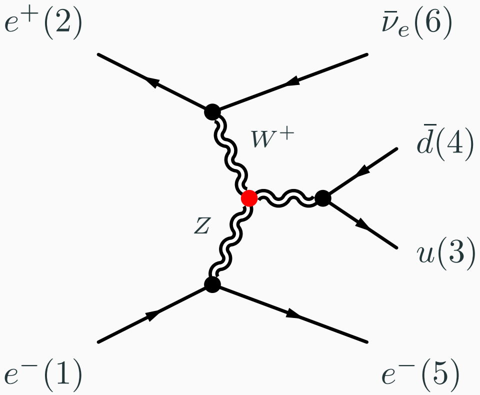
WW at e^+e^-

- “Golden-channel”: semi-leptonic
  - Only one neutrino
  - No colour reconnection
  - $\sigma(\ell\nu qq) > 2\,\mathrm{pb}$ at ZH energies
- 2 TGC-sensitive *s*-channel diagrams
- Large insensitive *t*-channel diagram
- Additional single-W production in $e\nu qq$



WW at e^+e^-

- "Golden-channel": semi-leptonic
  - Only one neutrino
  - No colour reconnection
  - $\sigma(\ell\nu qq) > 2\,\mathrm{pb}$ at ZH energies
- 2 TGC-sensitive *s*-channel diagrams
- Large insensitive *t*-channel diagram
- Additional single-W production in $e\nu qq$

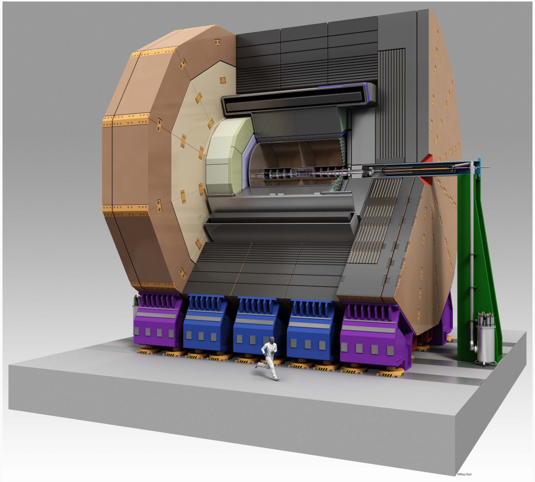


The Triple Gauge Couplings Analysis

Studied Example Detector

The International Large Detector (ILD)

- Optimised for “particle flow”
- Low mass gaseous tracker (TPC)
- Silicon vertex detector and wrapper
- Less than 0.15 X_0 in the barrel (ATLAS 0.5–2, ITk: 0.5–1)
- Highly granular calorimeters
- Calorimeters inside the solenoid
- Used well-studied ILC model
- FCC-ee model is still WIP



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

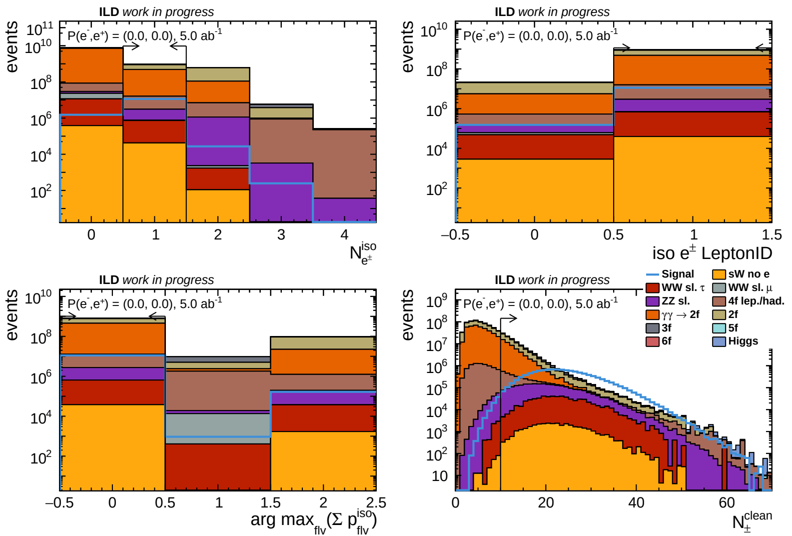
MiniDST

- "analysis-ready" format
- tagged isolated particles
- pre-defined jets

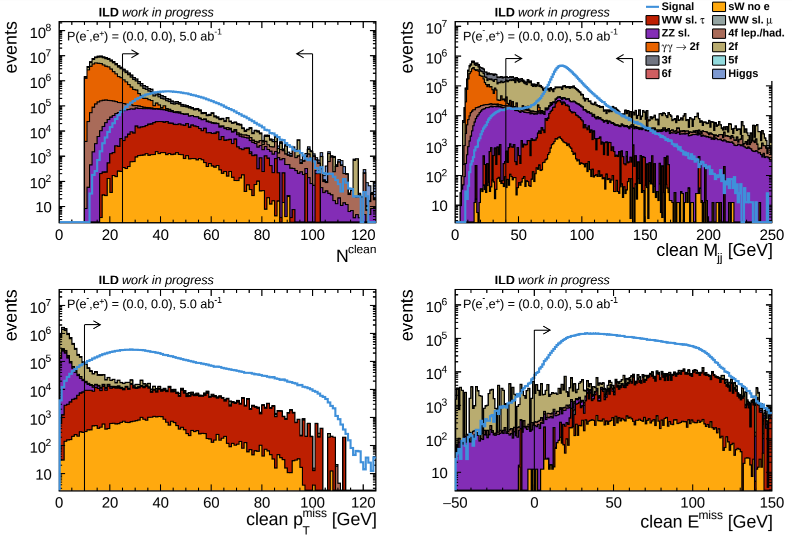
WW-categorisation

- 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)

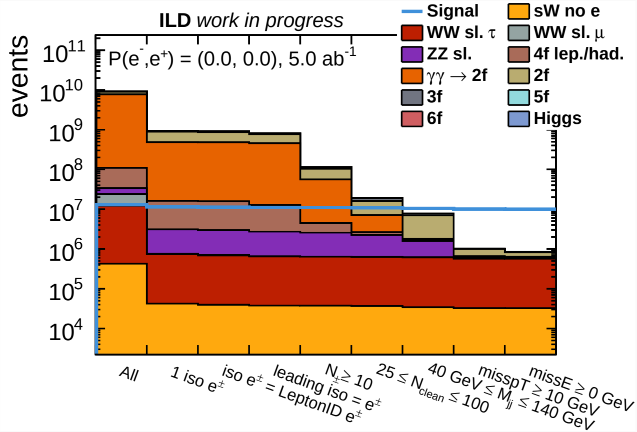
Selection results



Selection results

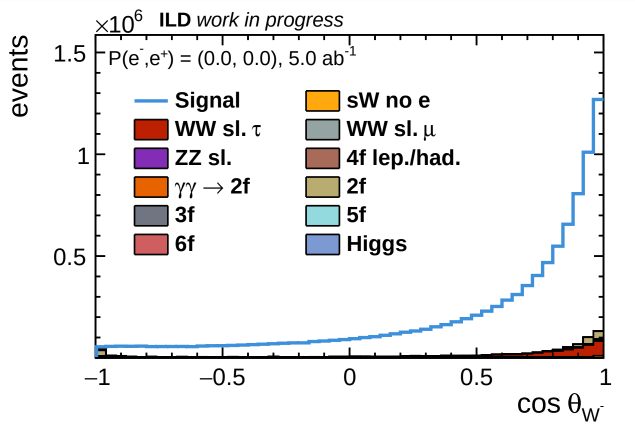


Selection results



- Reduces background to 8 %
- 77 % signal efficiency

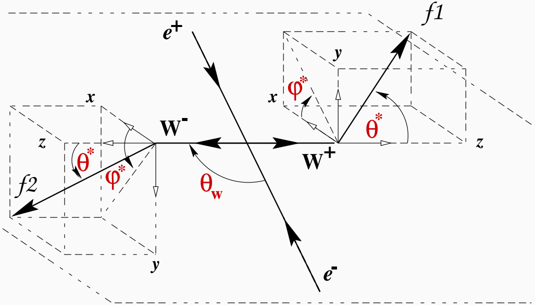
Selection results



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

Extracting the Parameters

- Full final state sensitive to TGC (W-spins)
- W production and decay angles, $m_{\ell\nu}$, m_{jj}
- More than narrow-width on-shell WW
- How to perform a fit on a 5–8 dimensions?
- Binned: too many bins
- Unbinned: too slow?
- Alternatives?



WW production and decay angles

Optimal Observables (OO)

- OO: matrix-element-based "most-sensitive" 1D-projection for a parameter
- One observable $\mathcal{O}_i$ per parameter θ_i
- Calculate mean $\overline{\mathcal{O}}_i$ and covariance matrix C_{ij} over all events

Optimal Observables (OO)

- OO: matrix-element-based “most-sensitive” 1D-projection for a parameter
- One observable $\mathcal{O}_i$ per parameter θ_i
- Calculate mean $\overline{\mathcal{O}}_i$ and covariance matrix C_{ij} over all events
- Theory: $\hat{\theta}_i = C_{ij}^{-1} \left(\overline{\mathcal{O}}_j - \mathbb{E}_0[\mathcal{O}_j]\right)$, does not work in practice

Optimal Observables (OO)

- OO: matrix-element-based “most-sensitive” 1D-projection for a parameter
- One observable $\mathcal{O}_i$ per parameter θ_i
- Calculate mean $\overline{\mathcal{O}}_i$ and covariance matrix C_{ij} over all events
- Theory: $\hat{\theta}_i = C_{ij}^{-1}\left(\overline{\mathcal{O}}_j - \mathbb{E}_0[\mathcal{O}_j]\right)$, does not work in practice
- LHC: binned template fits of $\mathcal{O}_i$, dimensionality issue reappears with more parameters

Optimal Observables (OO)

- OO: matrix-element-based “most-sensitive” 1D-projection for a parameter
- One observable $\mathcal{O}_i$ per parameter θ_i
- Calculate mean $\overline{\mathcal{O}}_i$ and covariance matrix C_{ij} over all events
- Theory: $\hat{\theta}_i = C_{ij}^{-1} \left(\overline{\mathcal{O}}_j - \mathbb{E}_0[\mathcal{O}_j]\right)$, does not work in practice
- LHC: binned template fits of $\mathcal{O}_i$, dimensionality issue reappears with more parameters
- LEP: minimise $\chi^2(\theta) = \left(\overline{\mathcal{O}}_i - \mathbb{E}[\mathcal{O}_i](\theta)\right) C_{ij}^{-1} \left(\overline{\mathcal{O}}_j - \mathbb{E}[\mathcal{O}_j](\theta)\right)$, actually works

Optimal Observables (OO)

- OO: matrix-element-based “most-sensitive” 1D-projection for a parameter
- One observable $\mathcal{O}_i$ per parameter θ_i
- Calculate mean $\overline{\mathcal{O}}_i$ and covariance matrix C_{ij} over all events
- Theory: $\hat{\theta}_i = C_{ij}^{-1} \left(\overline{\mathcal{O}}_j - \mathbb{E}_0[\mathcal{O}_j]\right)$, does not work in practice
- LHC: binned template fits of $\mathcal{O}_i$, dimensionality issue reappears with more parameters
- LEP: minimise $\chi^2(\theta) = \left(\overline{\mathcal{O}}_i - \mathbb{E}[\mathcal{O}_i](\theta)\right) C_{ij}^{-1} \left(\overline{\mathcal{O}}_j - \mathbb{E}[\mathcal{O}_j](\theta)\right)$, actually works
- Possible to construct for *any* parameter of the differential cross-section if locally linear

Optimal Observables (OO)

- OO: matrix-element-based “most-sensitive” 1D-projection for a parameter
- One observable $\mathcal{O}_i$ per parameter θ_i
- Calculate mean $\overline{\mathcal{O}}_i$ and covariance matrix C_{ij} over all events
- Theory: $\hat{\theta}_i = C_{ij}^{-1}\left(\overline{\mathcal{O}}_j - \mathbb{E}_0[\mathcal{O}_j]\right)$, does not work in practice
- LHC: binned template fits of $\mathcal{O}_i$, dimensionality issue reappears with more parameters
- LEP: minimise $\chi^2(\theta) = \left(\overline{\mathcal{O}}_i - \mathbb{E}[\mathcal{O}_i](\theta)\right) C_{ij}^{-1} \left(\overline{\mathcal{O}}_j - \mathbb{E}[\mathcal{O}_j](\theta)\right)$, actually works
- Possible to construct for *any* parameter of the differential cross-section if locally linear
- Optimality: $\hat{\theta}_i$ is a Cramér–Rao-efficient estimator
- As good as any other method can get, where the linearity condition is valid

Optimal Observables (OO)

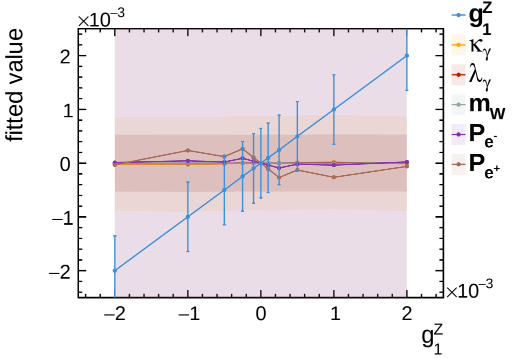
- OO: matrix-element-based “most-sensitive” 1D-projection for a parameter
- One observable $\mathcal{O}_i$ per parameter θ_i
- Calculate mean $\overline{\mathcal{O}}_i$ and covariance matrix C_{ij} over all events
- Theory: $\hat{\theta}_i = C_{ij}^{-1} \left(\overline{\mathcal{O}}_j - \mathbb{E}_0[\mathcal{O}_j]\right)$, does not work in practice
- LHC: binned template fits of $\mathcal{O}_i$, dimensionality issue reappears with more parameters
- LEP: minimise $\chi^2(\theta) = \left(\overline{\mathcal{O}}_i - \mathbb{E}[\mathcal{O}_i](\theta)\right) C_{ij}^{-1} \left(\overline{\mathcal{O}}_j - \mathbb{E}[\mathcal{O}_j](\theta)\right)$, actually works
- Possible to construct for *any* parameter of the differential cross-section if locally linear
- Optimality: $\hat{\theta}_i$ is a Cramér–Rao-efficient estimator
- As good as any other method can get, where the linearity condition is valid
- Automatically fulfilled for linear dim.-6 SMEFT!

Setup to Study Detector Effects and More

- Perform LEP-like OO-based fit of aTGCs
- Test effects of:
  - Jet recombination scheme
  - Pile-up removal
  - **Bremsstrahlungs recovery** (focus today)
- Determination of additional parameters
  - Longitudinal beam polarisation
  - Mass of the W boson
- Asimov fits to obtain uncertainties

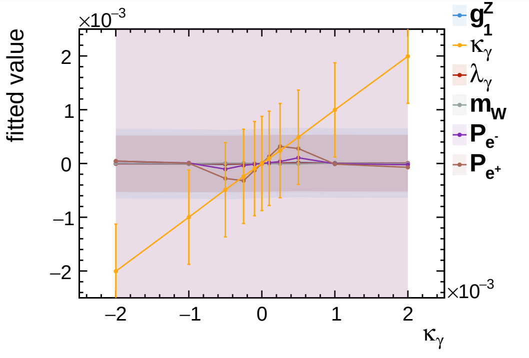
Setup to Study Detector Effects and More

- Perform LEP-like OO-based fit of aTGCs
- Test effects of:
  - Jet recombination scheme
  - Pile-up removal
  - **Bremsstrahlungs recovery** (focus today)
- Determination of additional parameters
  - Longitudinal beam polarisation
  - Mass of the W boson
- Asimov fits to obtain uncertainties
- Also performed closure tests



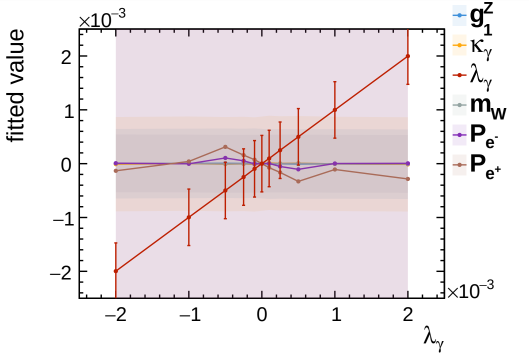
Setup to Study Detector Effects and More

- Perform LEP-like OO-based fit of aTGCs
- Test effects of:
  - Jet recombination scheme
  - Pile-up removal
  - **Bremsstrahlungs recovery** (focus today)
- Determination of additional parameters
  - Longitudinal beam polarisation
  - Mass of the W boson
- Asimov fits to obtain uncertainties
- Also performed closure tests



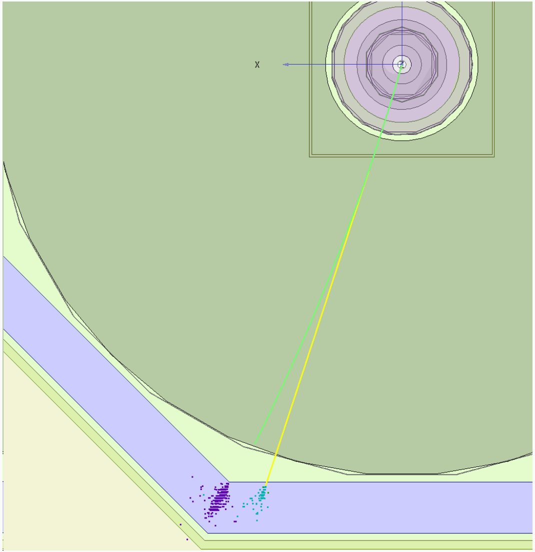
Setup to Study Detector Effects and More

- Perform LEP-like OO-based fit of aTGCs
- Test effects of:
  - Jet recombination scheme
  - Pile-up removal
  - **Bremsstrahlungs recovery** (focus today)
- Determination of additional parameters
  - Longitudinal beam polarisation
  - Mass of the W boson
- Asimov fits to obtain uncertainties
- Also performed closure tests



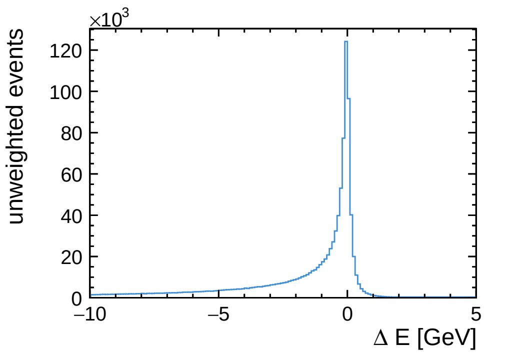
Effect of Bremsstrahlung

- Photons radiated by electron in material



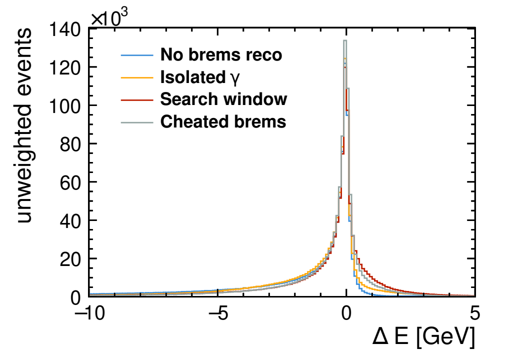
Effect of Bremsstrahlung

- Photons radiated by electron in material
- Tail in electron energy distribution



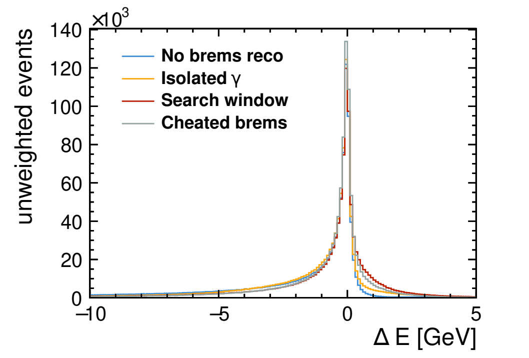
Effect of Bremsstrahlung

- Photons radiated by electron in material
- Tail in electron energy distribution
- Add back 4-momenta of reconstructed photons
  - that are isolated
  - or in a certain area
  - or truly from Bremsstrahlung



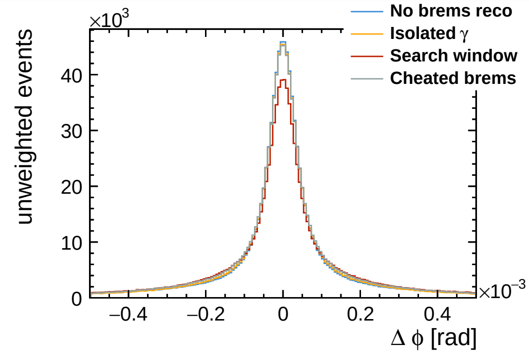
Effect of Bremsstrahlung

- Photons radiated by electron in material
- Tail in electron energy distribution
- Add back 4-momenta of reconstructed photons
  - that are isolated
  - or in a certain area
  - or truly from Bremsstrahlung
- Which method is better?



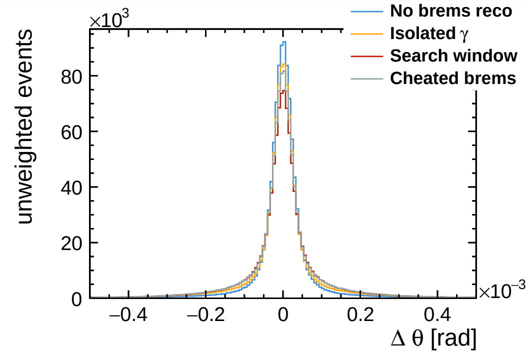
Effect of Bremsstrahlung

- Photons radiated by electron in material
- Tail in electron energy distribution
- Add back 4-momenta of reconstructed photons
  - that are isolated
  - or in a certain area
  - or truly from Bremsstrahlung
- Which method is better?
- What about the angles?



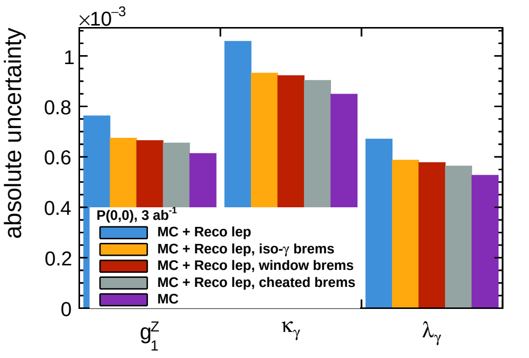
Effect of Bremsstrahlung

- Photons radiated by electron in material
- Tail in electron energy distribution
- Add back 4-momenta of reconstructed photons
    - that are isolated
    - or in a certain area
    - or truly from Bremsstrahlung
- Which method is better?
- What about the angles?



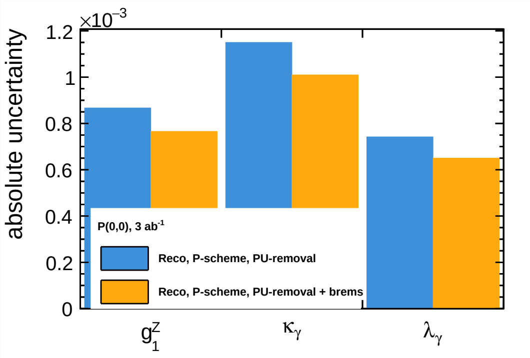
Effect of Bremsstrahlung on Final aTGC Results

- True quark vectors for jets to isolate effect
- Simple photon selections close to perfect
- Only small room for improvement left
- Better $e^{\pm}$ reconstruction not a priority (for ILD and this analysis)



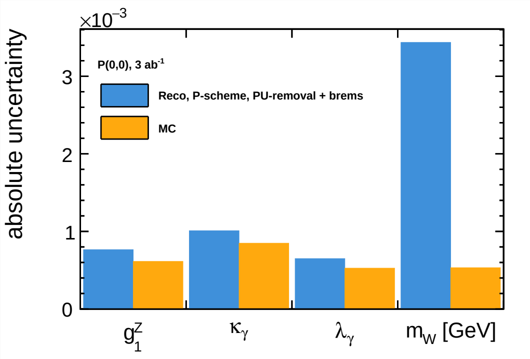
Effect of Bremsstrahlung on Final aTGC Results

- True quark vectors for jets to isolate effect
- Simple photon selections close to perfect
- Only small room for improvement left
- Better $e^{\pm}$ reconstruction not a priority (for ILD and this analysis)
- Improvement visible also with reco. jets



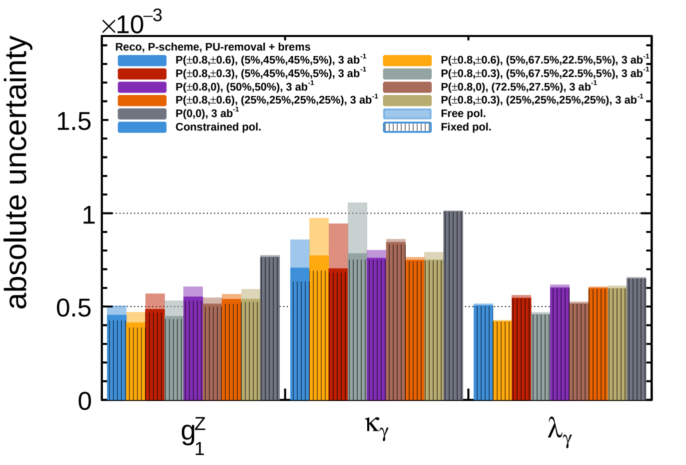
Effect of Bremsstrahlung on Final aTGC Results

- True quark vectors for jets to isolate effect
- Simple photon selections close to perfect
- Only small room for improvement left
- Better $e^{\pm}$ reconstruction not a priority (for ILD and this analysis)
- Improvement visible also with reco. jets
- Overall det./reco. “good enough” for aTGC



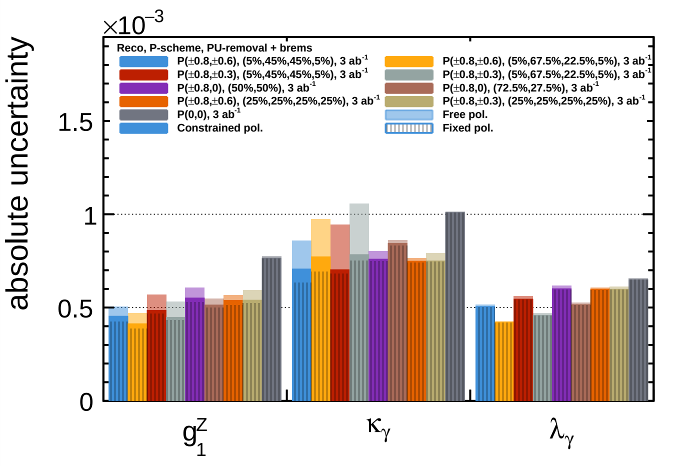
Effect of Polarised Beams

- Better than none (grey bar)
- Behaviour varies a lot
- In-situ determination not always good enough*



Effect of Polarised Beams

- Better than none (grey bar)
- Behaviour varies a lot
- In-situ determination not always good enough*
- *could likely be fixed

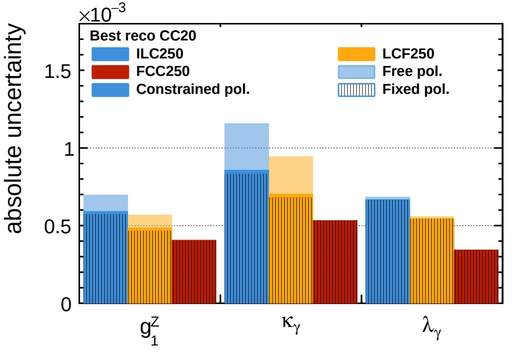


Project Comparison

- Projects differ in pol. and int. lumi.

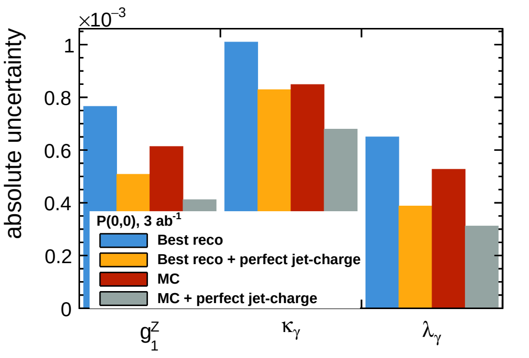
	ILC	LCF	FCC
$\int \mathcal{L}$ [ab^{-1}]	2	3	10.8
Pol.	80/30	80/30	0

- LCF250 would need to collect 4.5–7.4 ab^{-1} to match FCC250
- few 10^{-4} reached by all



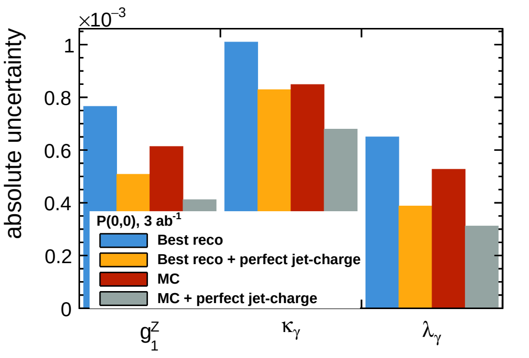
Outlook

- Integration of new flavour/charge taggers



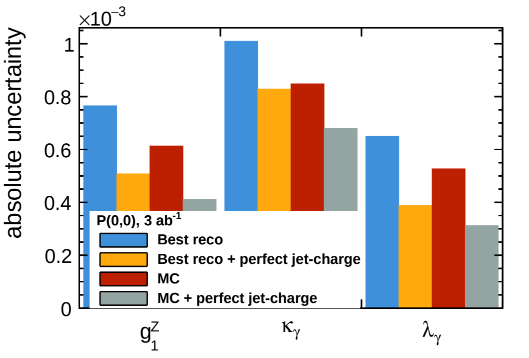
Outlook

- Integration of new flavour/charge taggers
- Including backgrounds and total rate
    - Should recover pol. performance
    - But more SMEFT operators (W BRs. etc.)
    - And additional uncertainties



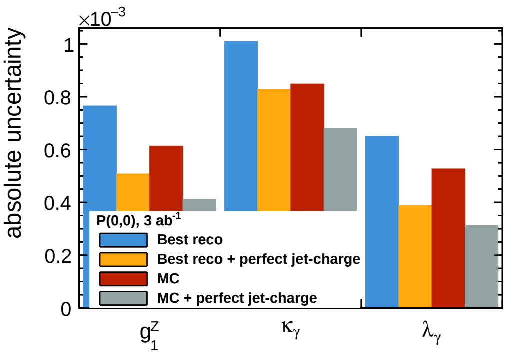
Outlook

- Integration of new flavour/charge taggers
- Including backgrounds and total rate
  - Should recover pol. performance
  - But more SMEFT operators (W BRs. etc.)
  - And additional uncertainties
- Global full-SMEFT analysis?



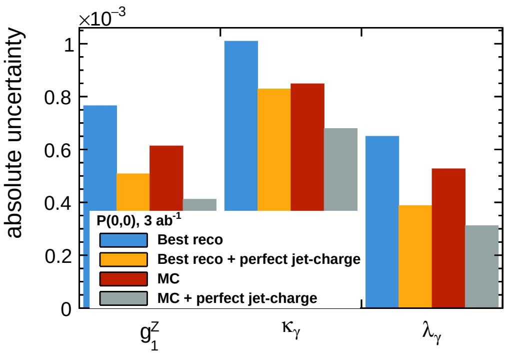
Outlook

- Integration of new flavour/charge taggers
- Including backgrounds and total rate
  - Should recover pol. performance
  - But more SMEFT operators (W BRs. etc.)
  - And additional uncertainties
- Global full-SMEFT analysis?
- Improved OO calculation (MC.-gen. dev.)



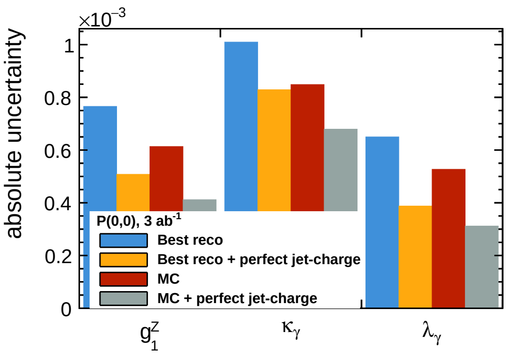
Outlook

- Integration of new flavour/charge taggers
- Including backgrounds and total rate
  - Should recover pol. performance
  - But more SMEFT operators (W BRs. etc.)
  - And additional uncertainties
- Global full-SMEFT analysis?
- Improved OO calculation (MC.-gen. dev.)
- Calibration? Theoretically possible. . .



Outlook

- Integration of new flavour/charge taggers
- Including backgrounds and total rate
    - Should recover pol. performance
    - But more SMEFT operators (W BRs. etc.)
    - And additional uncertainties
- Global full-SMEFT analysis?
- Improved OO calculation (MC.-gen. dev.)
- Calibration? Theoretically possible. . .
- Other detector concepts?



Summary

- The aTGC analysis provides a working detector benchmark and its results confirm the assumptions of theory-only studies regarding the event selection and statistical reach.
- The ILD detector concept and its existing reconstruction chain are already in a very good shape, suggesting a future aTGC determination performance close to the theoretical limits.
- The method of optimal observables seems ideally suited for future parameter-heavy analyses (e.g. SMEFT) if technical limits of the observable calculation can be overcome.

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

The Next Step? A Higgs factory!

Higgs factory

e^+e^--collider operating around the peak of the $e^+e^- \to ZH$ cross-section (240–250 GeV)

ILC

- Linear collider
- Japan
- 1 interaction point
- Longitudinal beam polarisation

LCF

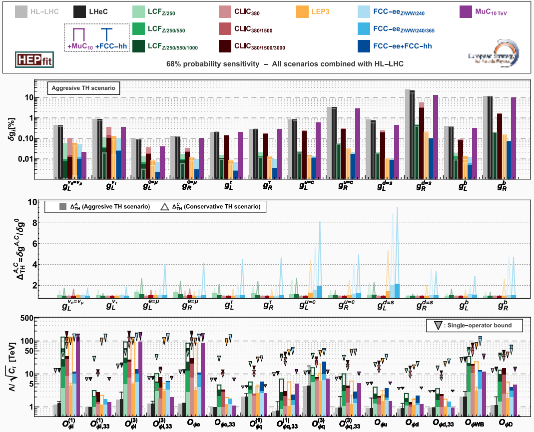
- Linear collider
- CERN
- 2 interaction points
- “ILC on steroids”

FCC-ee

- Circular collider
- CERN
- 2–4 interaction points
- Beam polarisation unlikely
- Higher luminosity

Choosing the Next Collider

- European Strategy for Particle Physics
- Partially driven by global SMEFT fit comparison between projects
- Based also on theory-only results
- 2020: e^+e^- Higgs factory highest prio.
- 2026: FCC-ee as Europe's "plan A"
- Expected begin of operation 2048+
- Do we need to know anything else?

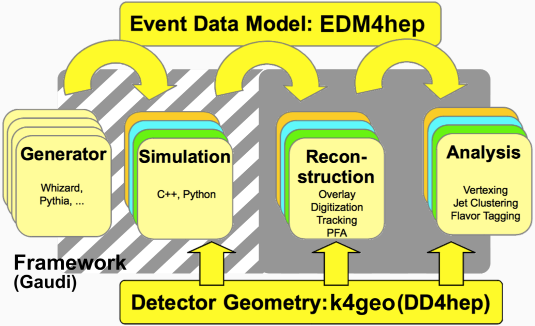


Higgs factory

e^+e^--collider operating around the peak of the $e^+e^- \to ZH$ cross-section (240–250 GeV)

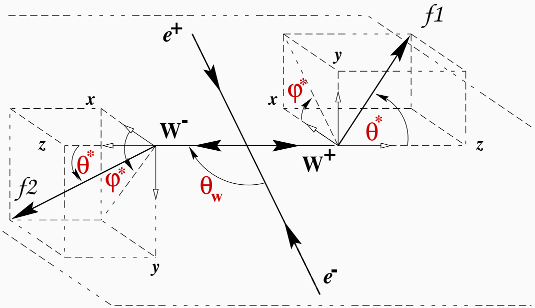
Simulation-based Studies

- Study “digital twin” of the experiment
- Need the full software chain today:
  - Event generation
  - Simulation
  - Reconstruction
  - Analysis
- Community-effort: Key4hep
- Evolution of iLCSoft



Why this Analysis?

- Millions of events “for free” at ZH
- Very efficient selection ($\gg 50\,\%$) expected
- 1ν: Fully determined event kinematics
- A bit of everything: leptons, neutrinos, jets
- Information scattered across phase-space
- Possible to perform analysis “optimally”
- Electron channel interesting for tracking



WW production and decay angles

Ideal Benchmark?

Significant reconstruction/detector performance issues are unlikely to be mitigated by future selection/analysis improvements. $\rightarrow$Issues will stay relevant.