# CHARGED TRIPLE GAUGE COUPLINGS AT PRESENT AND FUTURE COLLIDERS

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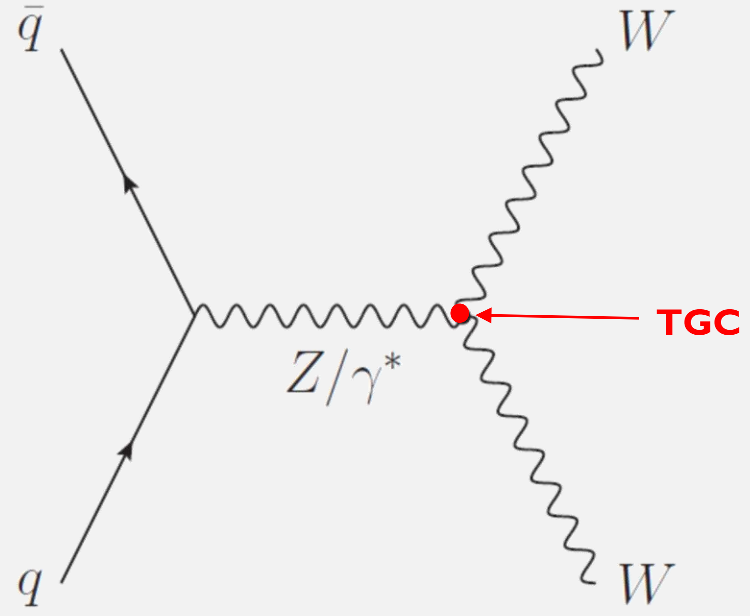
# What is a charged Triple Gauge Coupling?

- Non-Abelian self-coupling of the two $W$s with a $Z/\gamma$

- The (charged) TGC is probed in di-boson production at colliders.



# Why the Triple Gauge Coupling?

- The Standard Model (SM) is expected to be completed (dark matter, neutrino masses…)

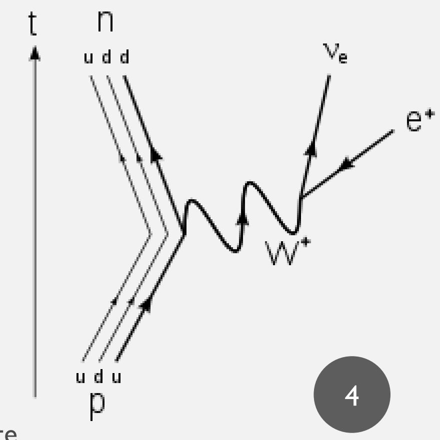
- The high-energy behaviour of the $WW$ cross-section and the angular distributions of the $WW$ decay products could be affected by new physics phenomena at higher (with respect to the actual $13\ \mathrm{TeV}$) centre-of-mass energies.

# Effective Lagrangians

- Not enough information to provide a fundamental description of properties of a system.
- Parameterization of the corresponding effects by introducing new interactions with coefficients to be determined phenomenologically.

- Familiar example: the $\beta$-decay Fermi coupling constant:

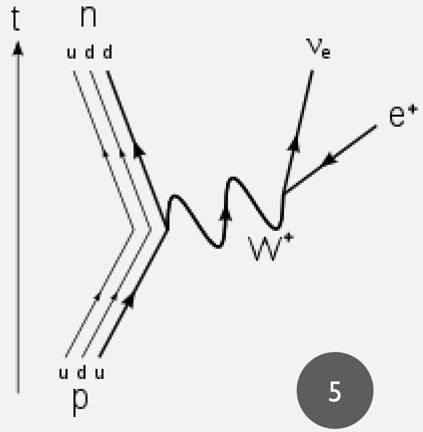
$$\mathcal{L}_{\beta} = \mathrm{G_F}(\bar{u}_{\mathrm{p}}\gamma_{\mu}u_{\mathrm{n}})(\bar{u}_{\mathrm{e}}\gamma^{\mu}u_{\nu_e})$$



# Effective Lagrangians

- The Lagrangian of a 4D field has dimensionality $[\mathcal{L}] = [\text{energy}]^{+4}$
- Fermionic fields have dimensionality $[\Psi] = [\text{energy}]^{+3/2}$
- In order to conserve the energy density of the lagrangian, the coefficient has to assume a dimension $\mathrm{G_F} \propto [\text{energy}]^{-2}$

$$\underbrace{\mathcal{L}_\beta}^{\mathbf{4}} = \overbrace{\mathrm{G_F}}^{\mathbf{-2}}(\overbrace{\bar{u}_\mathrm{p}}^{\frac{3}{2}}\gamma_\mu \overbrace{u_\mathrm{n}}^{\frac{3}{2}})(\overbrace{\bar{u}_\mathrm{e}}^{\frac{3}{2}}\gamma^\mu \overbrace{u_{\nu_e}}^{\frac{3}{2}})$$

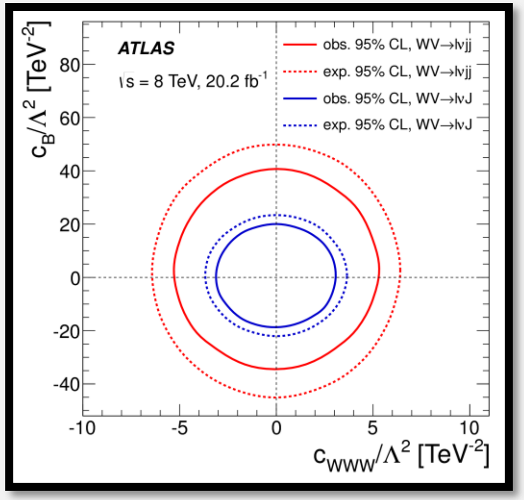


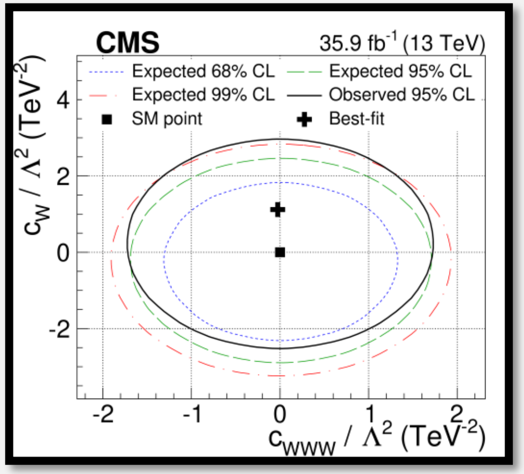
# The TGC Effective Field Theory Lagrangian

$$\mathcal{L}_{\mathrm{EFT}}^{TGC} = \mathcal{L}_{\mathrm{SM}} + \sum_{\substack{d>4 \\ \text{even}}} \sum_{i} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i$$

a=anomalous, or not described completely by the SM

- Dimension-six operators can give rise to aTGCs
- Dimension-eight operators can give rise to aQGCs



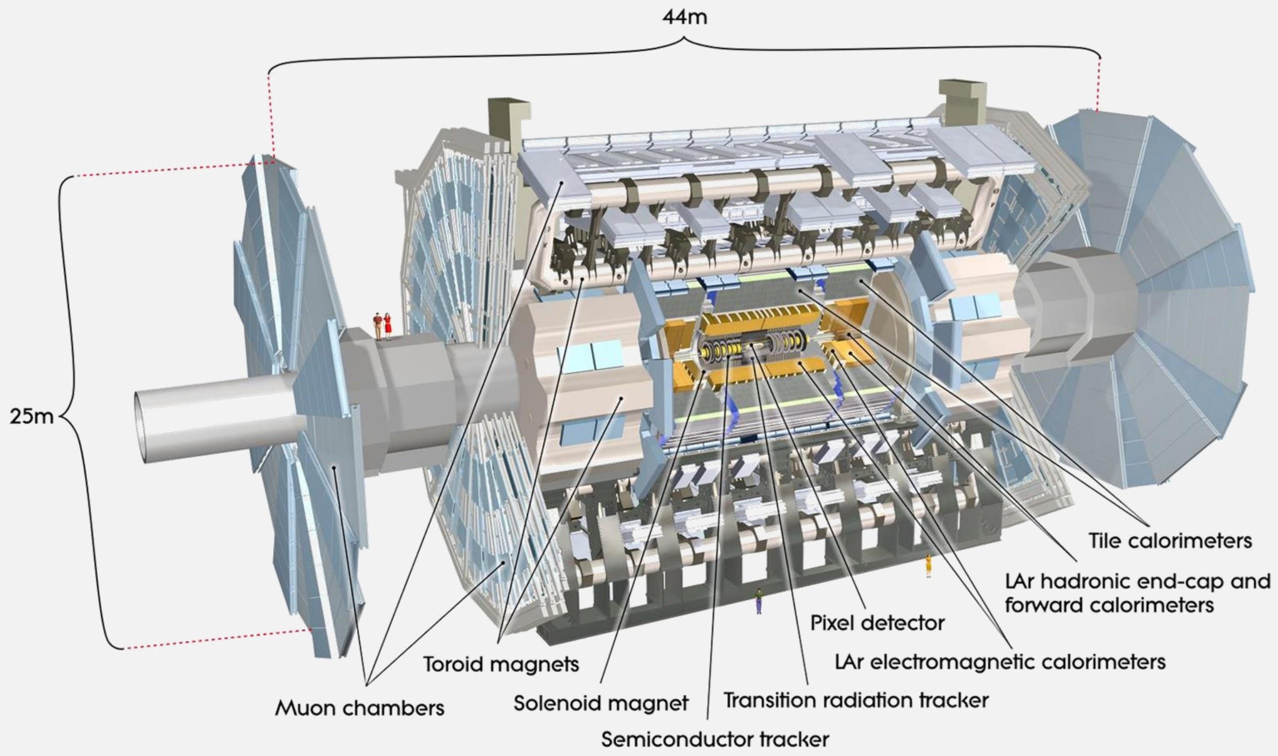



# PRESENT AND FUTURE COLLIDERS

# LHC

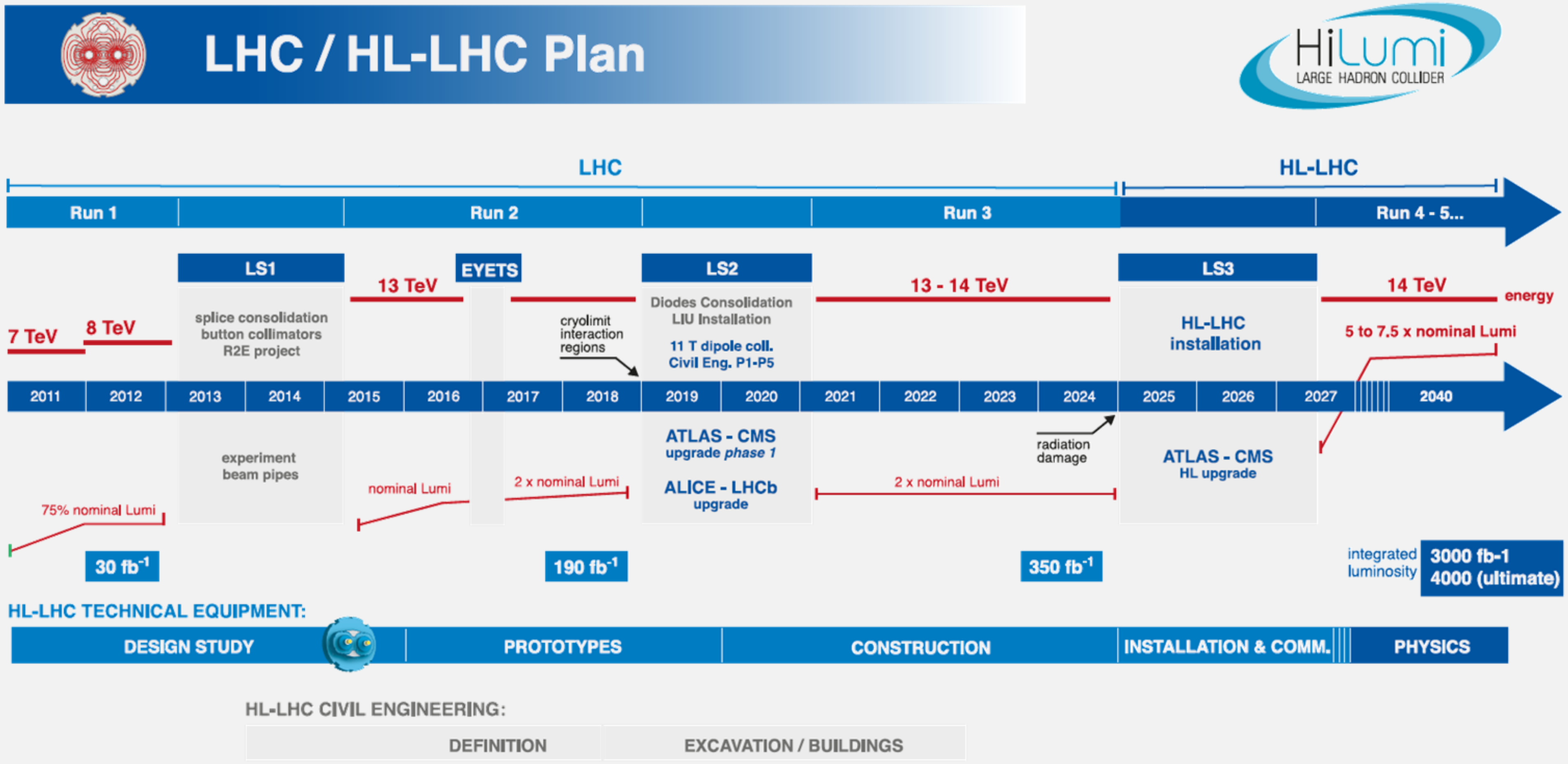
## THE ATLAS DETECTOR

- Multi-purpose cylindrical detector
- Tracker system
- EM + hadronic calorimeters
- Muon detecting system



# HL-LHC

## COLLIDER OVERVIEW

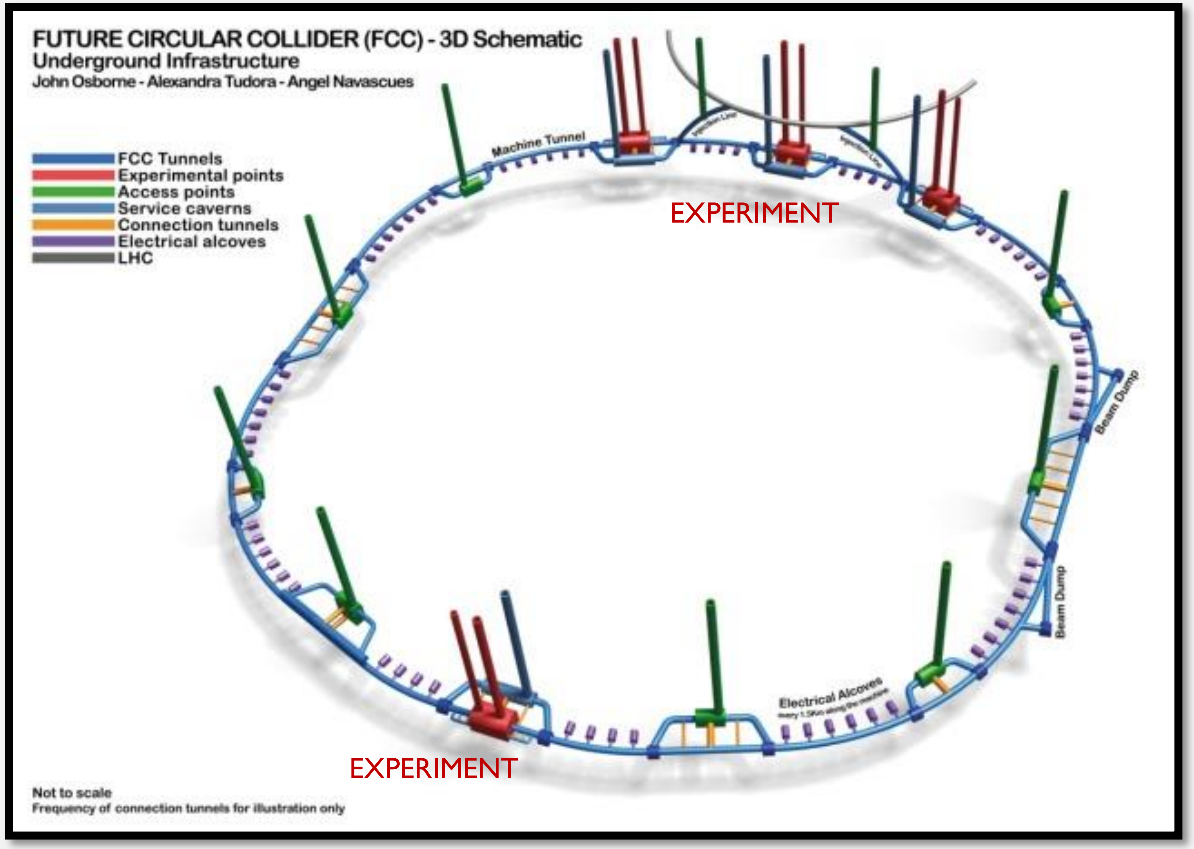


# FCC-ee

## COLLIDER OVERVIEW

- 97.75 km circumference ring
- Centre of mass energy of collisions:
  - $Z$-pole (91 GeV)
  - $W^+W^-$ production threshold (160 GeV)
  - $ZH$ production threshold (240 GeV)
  - $t\bar{t}$ production threshold (365 GeV)
- Total integrated luminosity: 167 $\mathrm{ab}^{-1}$

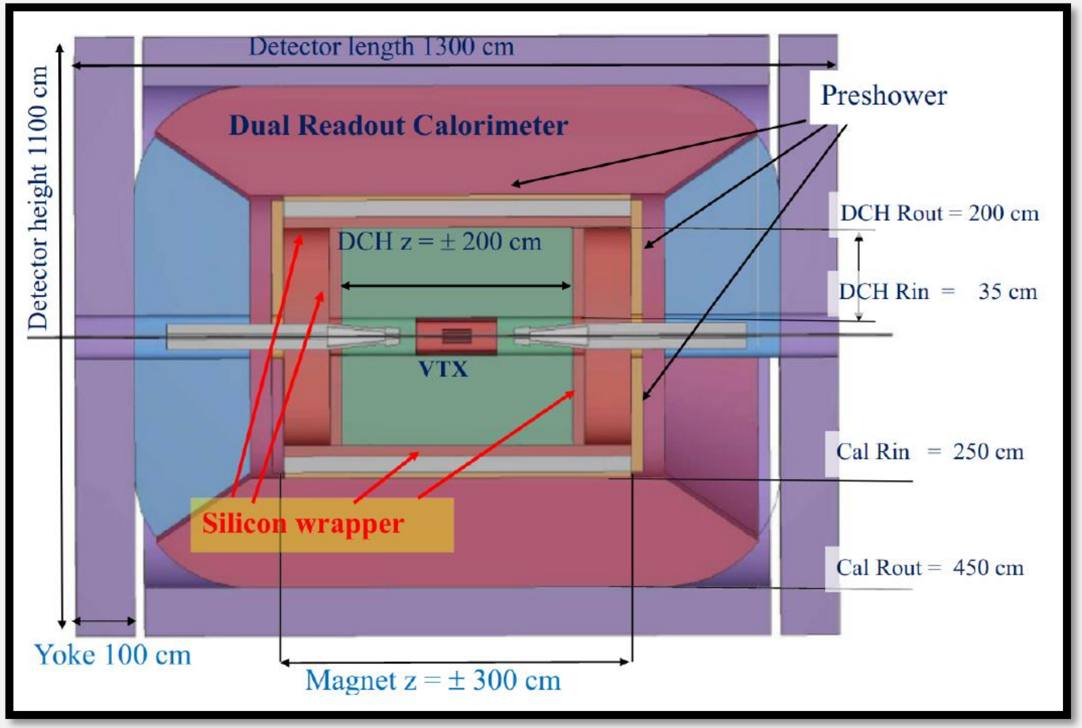
| Working point | Luminosity ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) | Tot. lum./year ($\mathrm{ab}^{-1}$)/year | Goal ($\mathrm{ab}^{-1}$) | Run time (years) |
|---|---|---|---|---|
| Z first two years | 100 | 24 | 150 | 4 |
| Z other years | 200 | 48 | | |
| W | 25 | 6 | 10 | 1–2 |
| H | 7.0 | 1.7 | 5 | 3 |
| RF reconfiguration | | | | 1 |
| $t\bar{t}$ 350 GeV (first year) | 0.8 | 0.20 | 0.2 | 1 |
| $t\bar{t}$ 365 GeV | 1.4 | 0.34 | 1.5 | 4 |

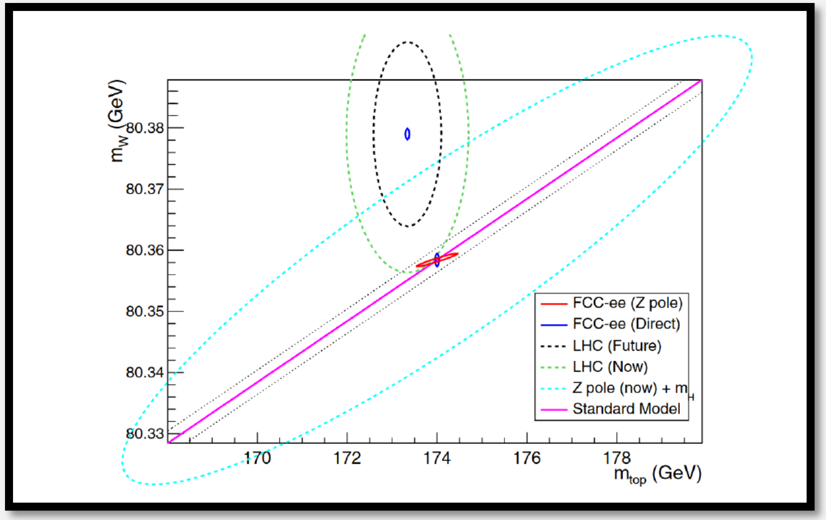


# FCC-ee

## THE IDEA DETECTOR

- High precision measurements: silicon detectors (ALICE insipired)
- High granularity tracking system
- Calorimeter sensitive to both scintillation and Čerenkov light
- Magnet system (ATLAS inspired)



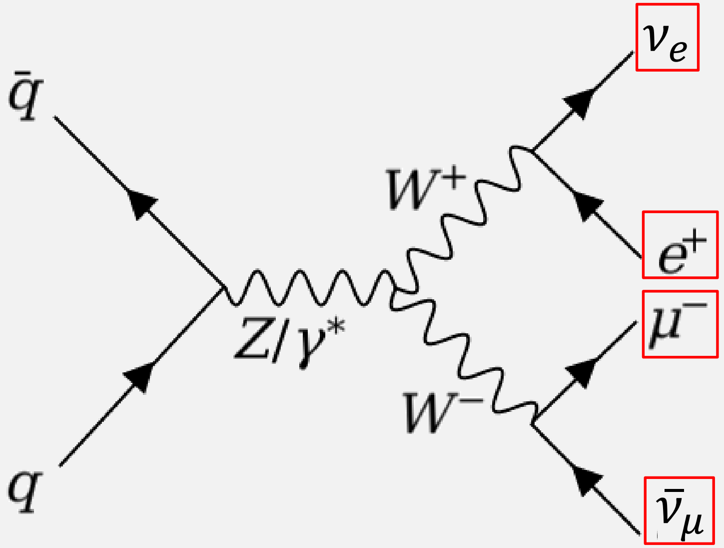
# $c_{WWW}$ LIMIT EXTRACTION

# $c_{WWW}$ LIMIT AT LHC

SIGNAL REGION DEFINITION

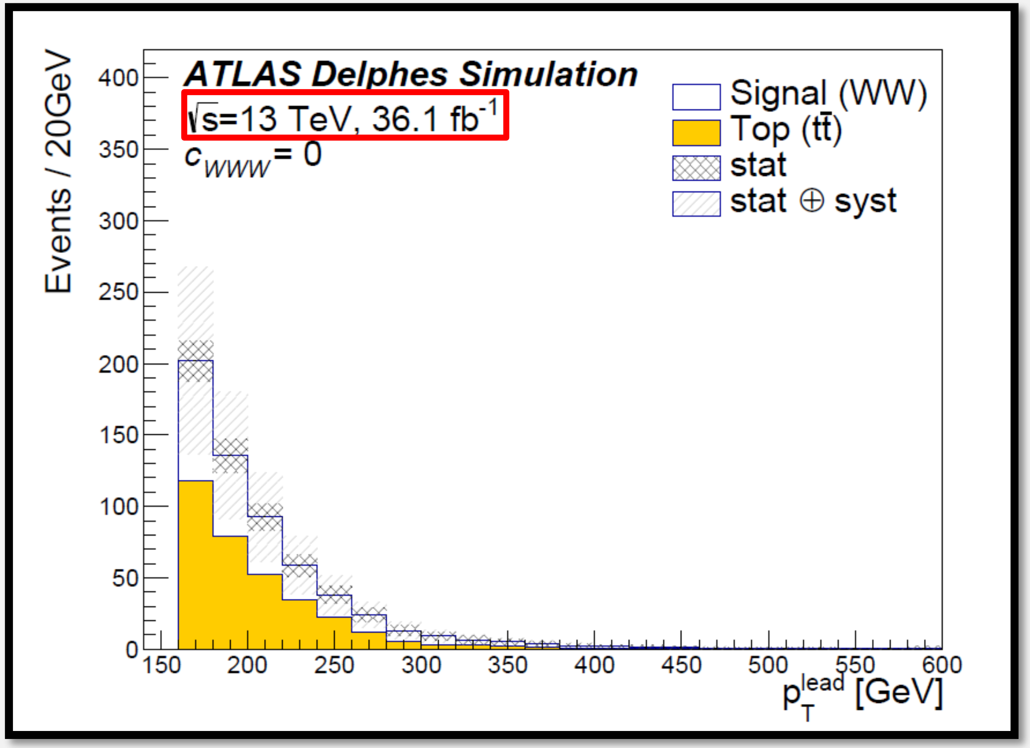
Selection cuts on final state particles: Eur. Phys. J. C 79 (2019) 884

| Selection requirement | Selection Value |
|---|---|
| $p_T^\ell$ | >27 GeV |
| $\eta^\ell$ | $\lvert\eta^e\rvert < 2.47$ (excluding $1.37 < \lvert\eta^e\rvert < 1.52$)<br>$\lvert\eta^\mu\rvert < 2.5$ |
| Number of $b$-tagged jets ($p_T > 20$ GeV, $\lvert\eta\rvert < 2.5$) | 0 |
| Number of jets ($p_T > 35$ GeV, $\lvert\eta\rvert < 4.5$) | 0 |
| $E_T^{miss}$ | >20GeV |
| $p_T^{e\mu}$ | >30GeV |
| $m^{e\mu}$ | >55GeV |



# $c_{WWW}$ LIMIT AT LHC

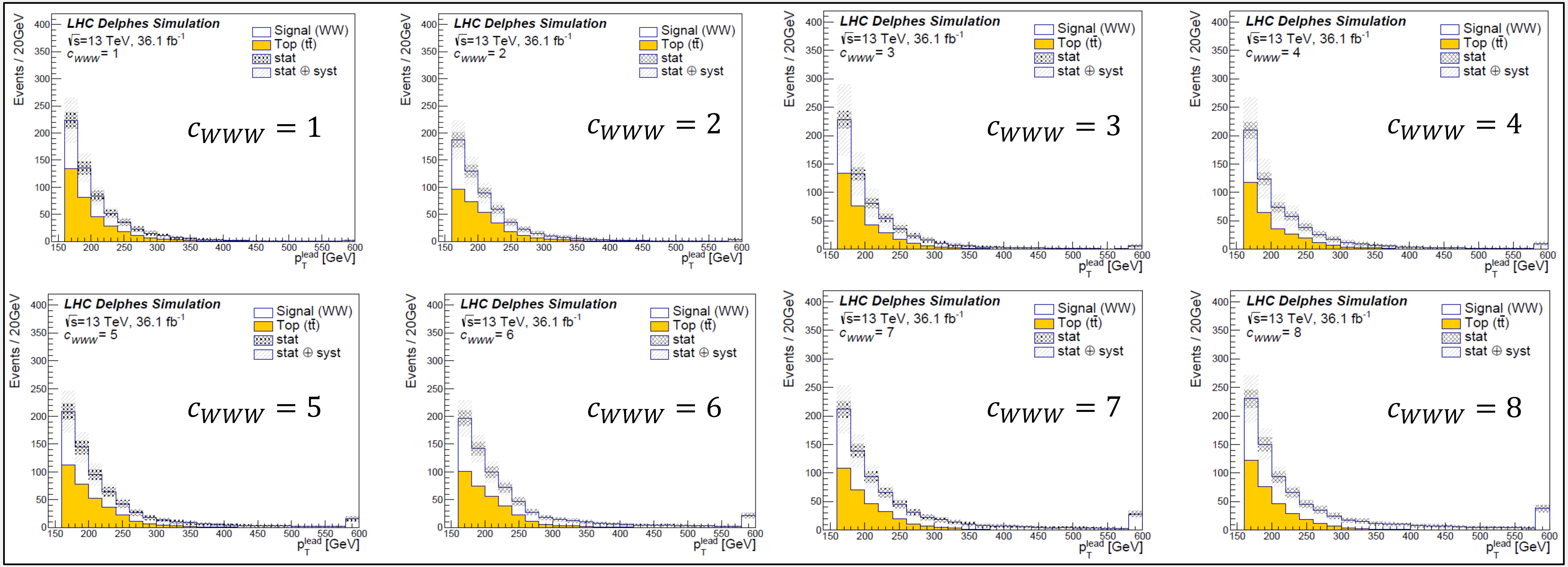
## KINEMATIC DISTRIBUTIONS




Optimised bin and range $p_T^{lead}$ distribution

# $c_{WWW}$ LIMIT AT LHC

EFT coefficient dependence

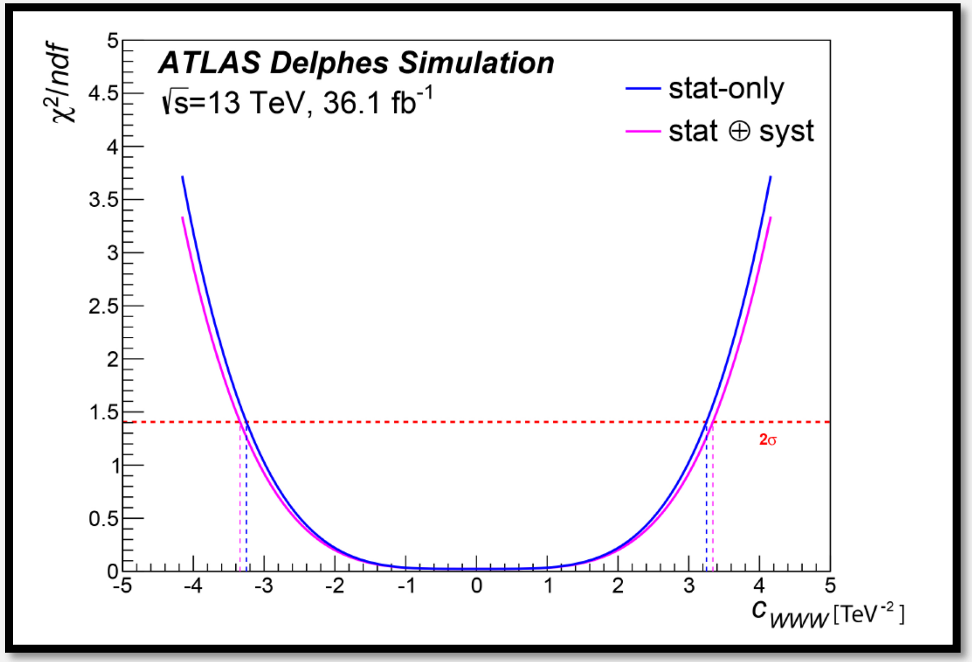


# $c_{WWW}$ LIMIT AT LHC

## 95% CL LIMIT EXTRACTION

- Systematic uncertainty affecting interval size:

| Uncertainty source | Uncertainty on interval size [%] |
|---|---|
| $b$-tagging | 3.2 |
| pileup | 1.5 |
| top-quark background modelling | 1.1 |
| Jet energy scale | <1 |
| Total | 3.8 |

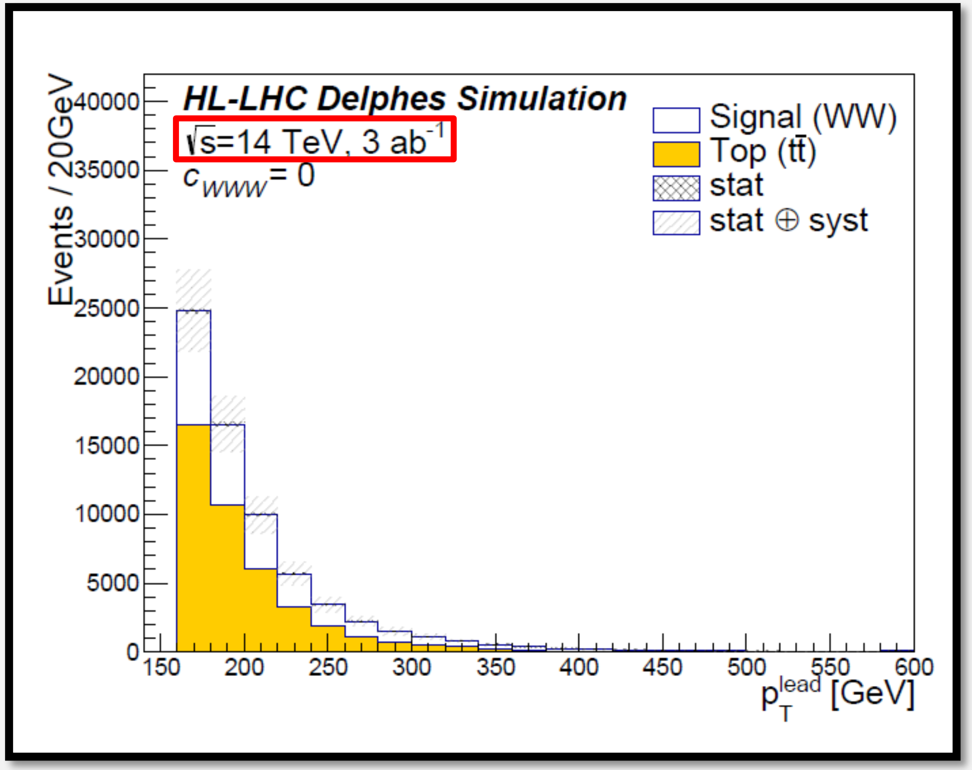



- Limit extraction result:
  - $c_{WWW} \in [-3.3, 3.3]\ \mathrm{TeV}^{-2}$

# $c_{WWW}$ LIMIT AT HL-LHC

## KINEMATIC DISTRIBUTIONS

- Increased centre-of mass energy of collisions
- Increased integrated luminosity
- Same event selection of LHC analysis
- $14\ \mathrm{TeV}, 365\ \mathrm{ab}^{-1}$




Optimised bin and range $p_T^{lead}$ distribution

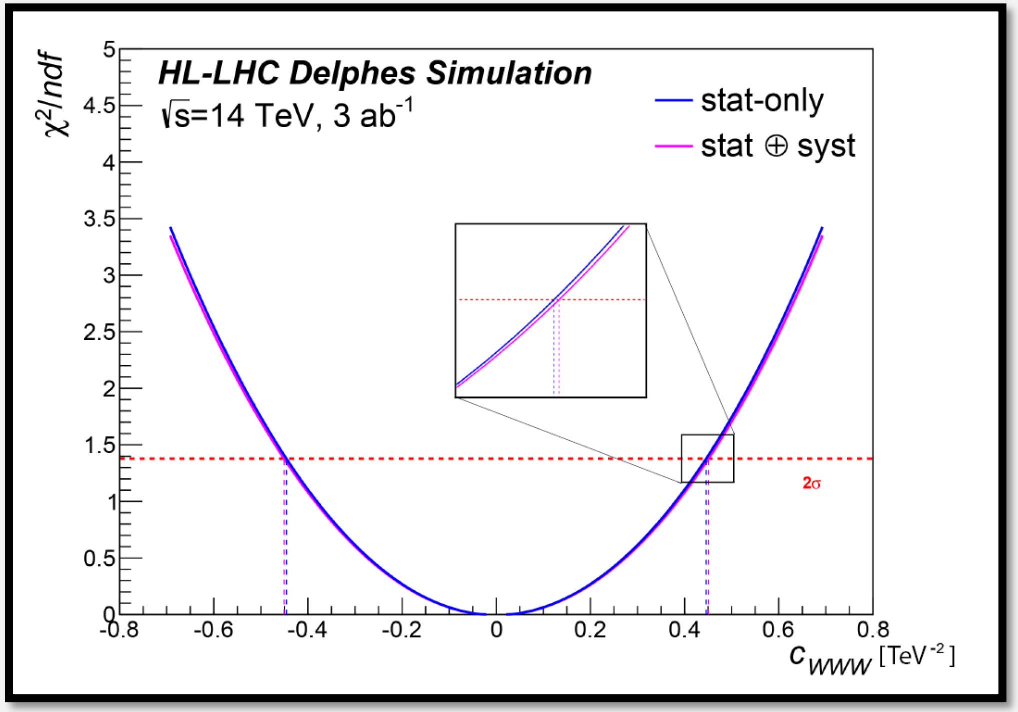
# $c_{WWW}$ LIMIT AT HL-LHC

## 95% CL LIMIT EXTRACTION

- Systematic uncertainty affecting interval size:

| Uncertainty source | Uncertainty on interval size [%] |
|---|---|
| $b$-tagging | 1.4 |
| pileup | 1.2 |
| top-quark background modelling | 1.1 |
| Jet energy scale | <1 |
| Total | 2.3 |

- Limit extraction result:
  - $c_{WWW} \in [-0.45, 0.45]\ \mathrm{TeV}^{-2}$

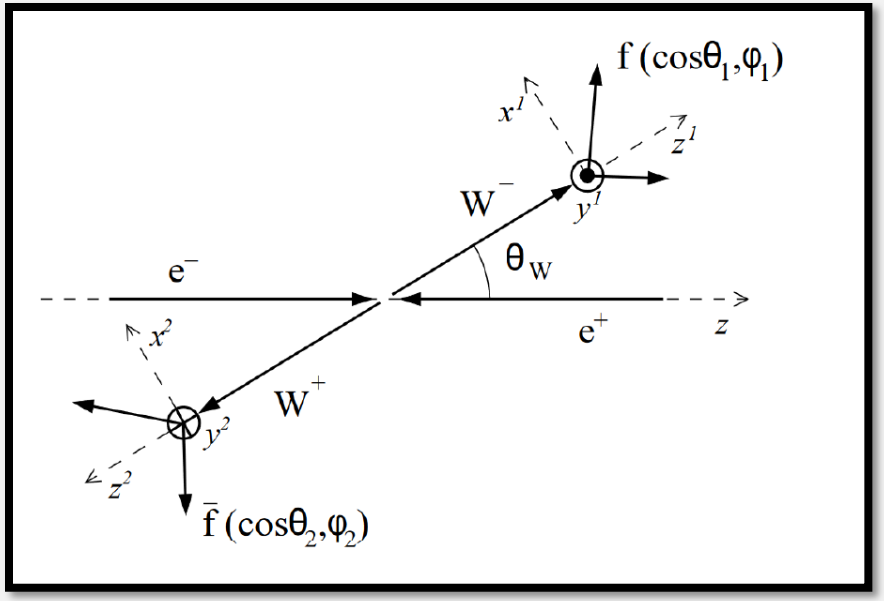


# $c_{WWW}$ LIMIT AT FCC-ee

## EVENTS PRODUCTION

365 GeV $e^+e^-$ collisions, 1.5 $\mathrm{ab}^{-1}$

- $e^+e^- \to W^+W^-$ events.
- No generator level cuts.
- Constant background, yielding $\sim$ 1.8% of the total distribution.
- Kinematic variable selected: $\cos\theta_W$.



# $c_{WWW}$ LIMIT AT FCC-ee

## SIGNAL REGION DEFINITION

Selection cuts on leptonic final state particles: arXiv.org/abs/hep-ex/0308067v1

D1 Both jets must contain at least one charged track and have $|\cos\theta| < 0.96$; at least one jet must satisfy $< 0.90$.

D2 There must be at least two ECAL clusters, one of which reports an energy deposition larger than $0.5$ GeV.

D3 The acollinearity angle of the two jets must exceed $10°$.

D4 For events with the acoplanarity angle $\phi^{acop} > 60°, |\cos\theta_p^{miss}| < 0.95$. For events with $\phi^{acop} < 60°, |\cos\theta_p^{miss}| < 0.995$.

D5 Events with acollinearity angle less than $20°$ are rejected if the most energetic ECAL energy deposition exceeded $80\%$ of the beam energy.

Acoplanarity angle: $\phi_{acopl} = \pi - \phi_{12}$
Acollinearity angle: $\theta_{acol} = \pi - \theta_{12}$

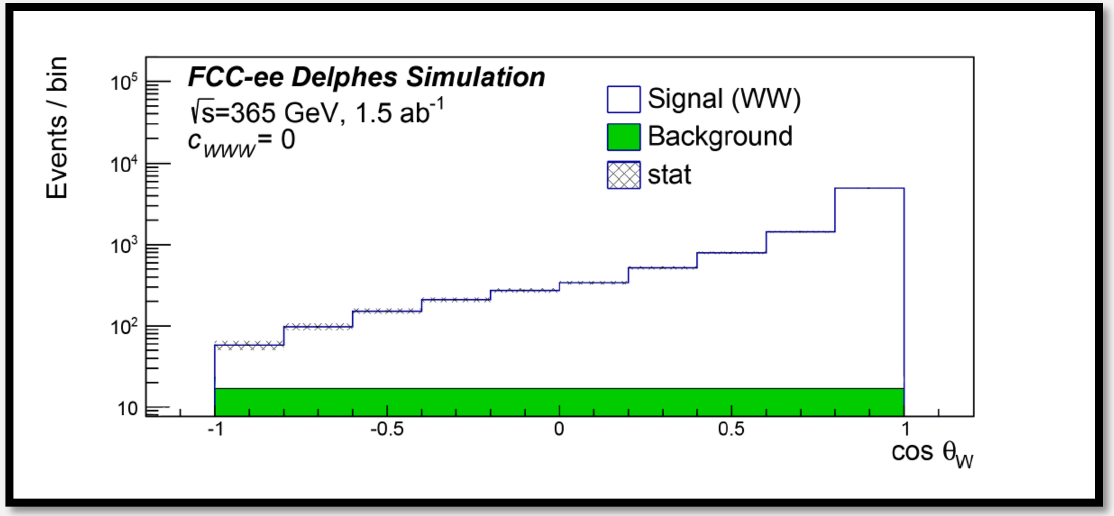
Di-jet events constitute ~ 89% of the total

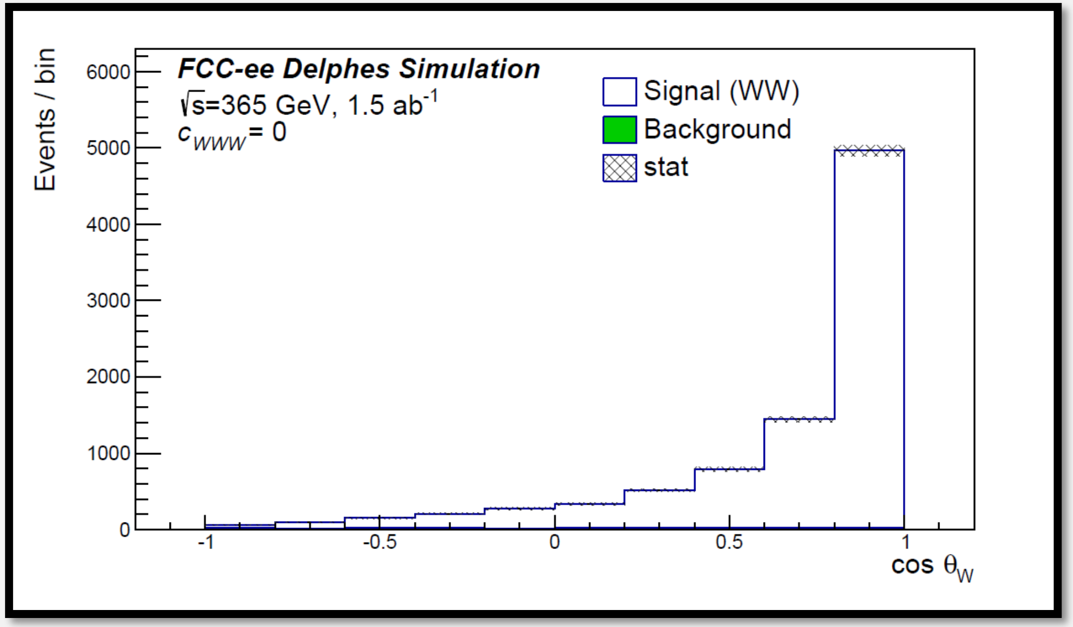
Di-jet Selection Criteria

| Selection Requirement | $WW$ production (20000 events) |
|---|---|
| $\theta_{acol} > 5°$ | 13357 |
| $p_T/\sqrt{s} > 0.05$ | 5158 |
| D1 | 1722 |
| D2 | 895 |
| D3 | 737 |
| D4 | 244 |
| D5 | 214 |

# $c_{WWW}$ LIMIT AT FCC-ee

## KINEMATIC DISTRIBUTIONS AND SYSTEMATIC UNCERTAINTIES




- Systematic uncertainties $\sim 10^{-4} \ll$ statistic uncertainty

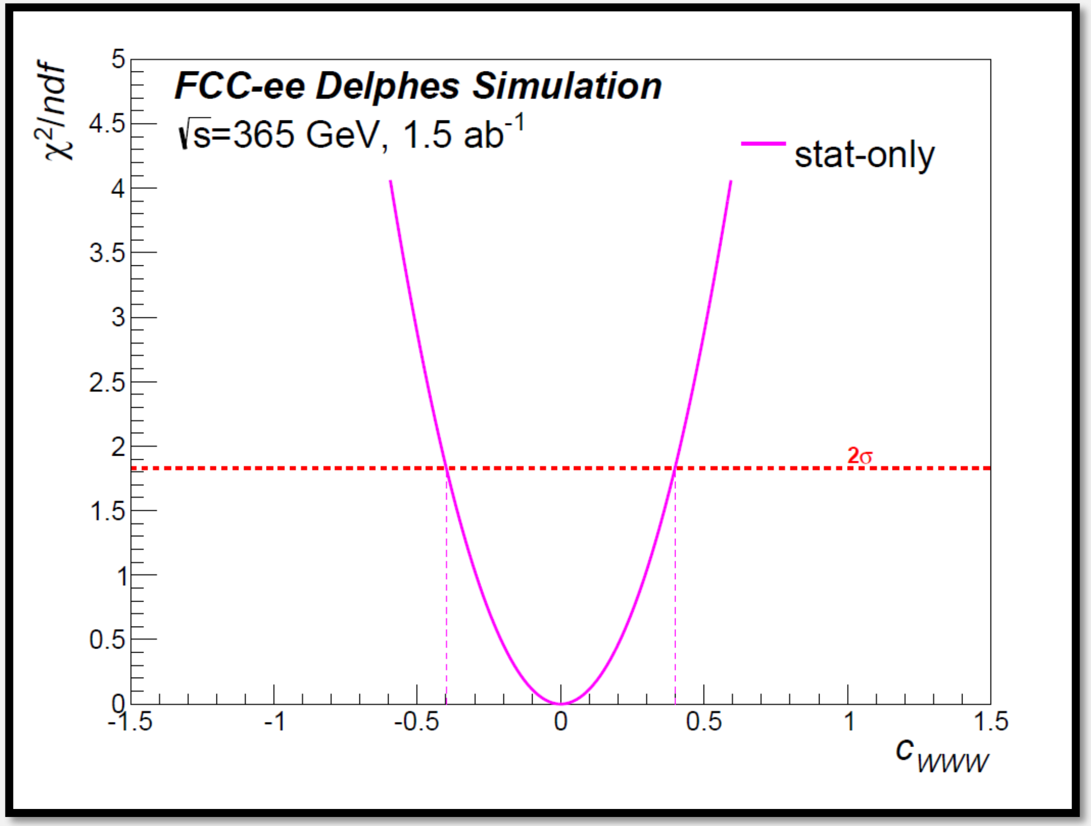
# $c_{WWW}$ LIMIT AT FCC-ee

## 95% CL LIMIT EXTRACTION

- Limit extraction result:

$$c_{WWW} \in [-0.38, 0.38]\ \mathrm{TeV}^{-2}$$

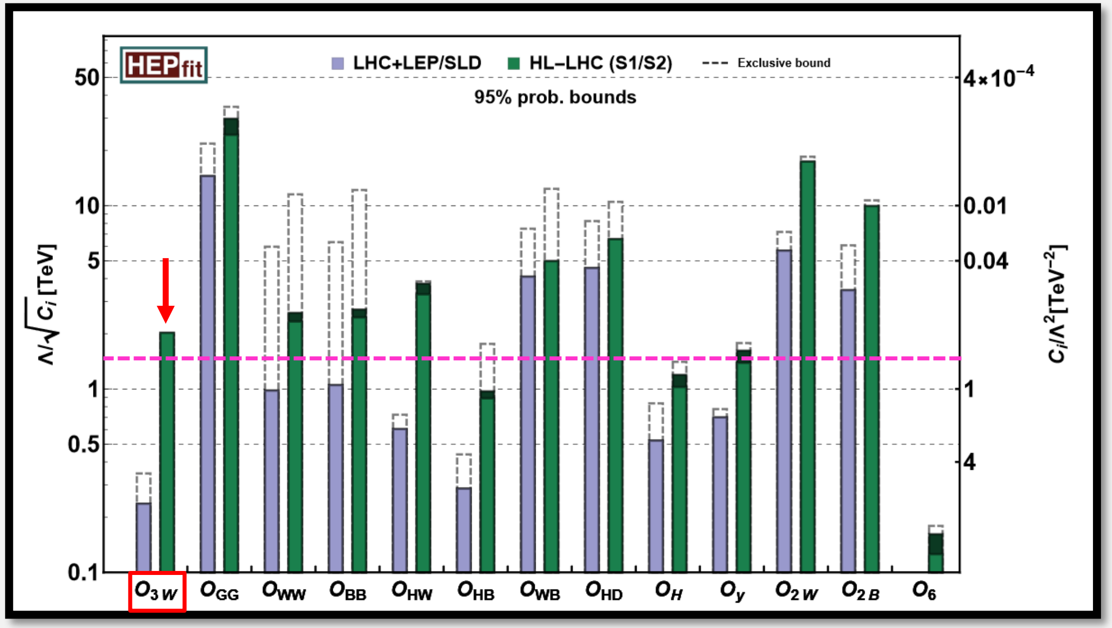
| Accelerator Complex | $c_{WWW}$ 95% CL limit [$\mathrm{TeV}^{-2}$] |
|---|---|
| LHC | [-3.3, 3.3] |
| HL-LHC | [-0.45, 0.45] |
| FCC-ee | [-0.38, 0.38] |



# RESULTS

## COMPARISON WITH LITERATURE

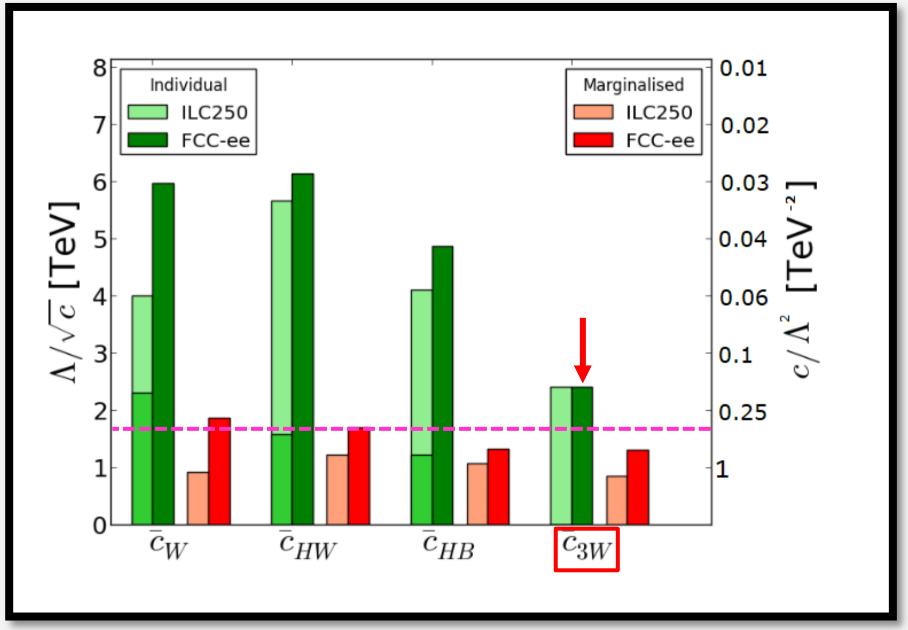
arXiv:submit/2557680




HL-LHC

14 TeV, 3 ab$^{-1}$

arXiv:1510.04561v1




FCC-ee

240 GeV, 10 ab$^{-1}$

# SUMMARY

| Accelerator Complex | $c_{WWW}$ 95% CL limit [TeV$^{-2}$] |
|---|---|
| LHC | [-3.3, 3.3] |
| HL-LHC | [-0.45, 0.45] |
| FCC-ee | [-0.38, 0.38] |

- Confidence interval narrowing
- High energy sensitivity to TGCs
- Improvement on the $c_{WWW}$ actual constraints

# THANK YOU FOR THE ATTENTION