Probing anomalous $WW\gamma$ triple gauge bosons coupling at the LHeC

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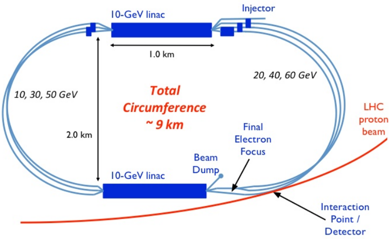
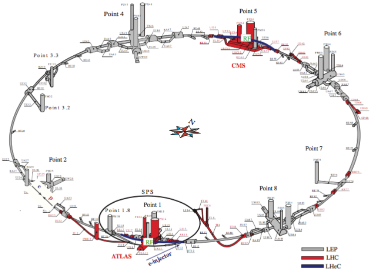
High energy collider and LHeC

- hh: LHC, Tevatron, FCC-hh, SppC
- e^+e^-: LEP, CEPC, ILC, CLIC, FCC-ee/TLEP
- he(DIS): HERA, LHeC, FCC-eh

- Large Hadron electron Collider(LHeC):
  - based on the current 7 TeV proton beam of the LHC by adding one electron beam of 60–140 GeV
  - Electron beam options: “linac-ring (LR)”, “ring-ring (RR)”



(a) LR



(b) RR

Figure 1: Layout of the LHeC

- Advantages of LHeC:
  1. Higgs factory $\rightarrow$ VBF production
     - precision measurement of Higgs couplings and properties
     - corrections of the VVh via Higgs self coupling
  2. Help LHC for precision measurement $\rightarrow$ forward detector and small QCD backgrounds
     - Precise PDFs(large x region)
     - electro-weak vertex
     - b quark Yukawa coupling
  3. search NP $\rightarrow$ cleaner backgrounds
     - SUSY, DM
     - Anomalous couplngs
  4. Economic proposal

- Triple Gauge Bosons Coupling(TGCs):
  1. TGC is important for electro-weak theory
  2. WW pair and single Z/γ production
  3. cross section analysis

Single W production, W polarization, LHeC

Effective Lagrangian

$$\begin{aligned}\mathcal{L}_{TGC}/g_{WWV} \quad = \quad & ig_{1,V}(W^+_{\mu\nu}W^-_{\mu}V_{\nu} - W^-_{\mu\nu}W^+_{\mu}V_{\nu}) + i\kappa_V W^+_{\mu}W^-_{\nu}V_{\mu\nu} + \frac{i\lambda_V}{M_W^2}W^+_{\mu\nu}W^-_{\nu\rho}V_{\rho\mu} \\ & + g_5^V\epsilon_{\mu\nu\rho\sigma}(W^+_{\mu}\overleftrightarrow{\partial}_{\rho}W^-_{\nu})V_{\sigma} - g_4^V W^+_{\mu}W^-_{\nu}(\partial_{\mu}V_{\nu} + \partial_{\nu}V_{\mu}) \\ & + i\tilde{\kappa}_V W^+_{\mu}W^-_{\nu}\tilde{V}_{\mu\nu} + \frac{i\tilde{\lambda}_V}{M_W^2}W^+_{\lambda\mu}W^-_{\mu\nu}\tilde{V}_{\nu\lambda}\end{aligned}$$

- g_4^V: C and CP violation, P conservation;
- g_5^V: C and P violation, CP conservation;
- $\tilde{\kappa}_V$ and $\tilde{\lambda}_V$: P and CP violation, C conservation;
- $g_{1,V}$,κ_V and λ_V: C, P and CP conservation.

$$g_{1,\gamma} = 1,\ \lambda_\gamma = \lambda_Z,\ \Delta\kappa_Z = \Delta g_{1,Z} - \tan^2\theta_W\Delta\kappa_\gamma$$

Only 3 independent aTGCs parameters(CP conservation): $\Delta g_{1,Z}$, $\Delta\kappa_\gamma$ and λ_γ.

Constraints

- Experiment

aTGC	LEP	CMS, 8 TeV	ATLAS, 8 TeV	SM
Δg_Z	[-0.054, 0.021]	[-0.0087, 0.024]	[-0.021, 0.024]	0
$\Delta\kappa_\gamma$	[-0.099, 0.066]	[-0.044, 0.063]	[-0.061, 0.064]	0
λ_γ	[-0.059, 0.017]	[-0.011, 0.011]	[-0.013, 0.013]	0

Table 1: 95% C.L. limits on $\Delta\kappa_\gamma$ and λ_γ at LEP and LHC. These bounds are from single parameter fittings. LHC measurement of WW/WZ pair production in semi-leptonic decay channel with an integrated luminosity of 19 ab^{-1}(CMS) and 20.2 ab^{-1}(ALTAS) give the above abounds.

- Unitarity ($\sqrt{\hat{s}} \sim \Lambda$)
  - $ff' \to VV'$: $|\Delta\kappa_\gamma| \leq 1.86/\Lambda^2$ and $|\lambda_\gamma| \leq 0.99/\Lambda^2$. The cutoff scale Λ is larger than 3 TeV for aTGC sensitivity better than $\mathcal{O}(0.1)$.
  - $VV' \to VV'$: $\Lambda \sim$ TeV。

Phenomenology

Triple gauge couplings could be measured via single γ/Z and W production directly at the LHeC. We choose single W production:

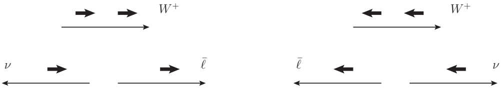
$$e^- p \to e^- W^{\pm} j.$$

We focus on the muonic decay subchannel which provides additional information on W polarization as a handle:

$$e^- + p \to e^- + j + W^{\pm} \to e^- + j + \mu^{\pm} + \nu_{\mu} \ .$$

There are two kinematic variables chosen to estimate aTGC sensitivities:

- $\theta_{\mu W}$: $\theta_{\mu W}$ is the angle between the W boson and the μ^+ defined in W boson CM frame(contains W polarization information).
- $\Delta\phi_{ej}$: the azimuthal angle $\Delta\phi_{ej}$ is defined on the ej plane in Lab frame.



(a) right-hand W^+ (b) left-hand W^+

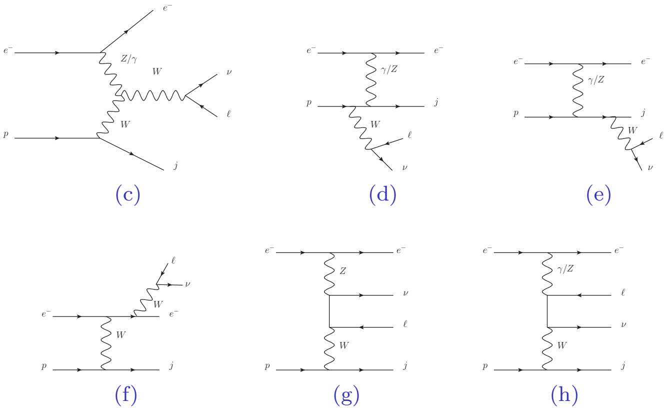


Figure 2: The Feynman diagrams of $e^- p \to e^- \mu^+ \nu_\mu j$ process

In principle, the $e^- p \to e^- W^\pm j$ process contains both diagrams with the WWZ vertex and diagrams with the $WW\gamma$ vertex, which interfere with each other. However, due to large suppression from the Z boson mass, the results are insensitive to WWZ couplings. Therefore, we only use the results in this study as a direct constraint on the anomalous $WW\gamma$ vertex.

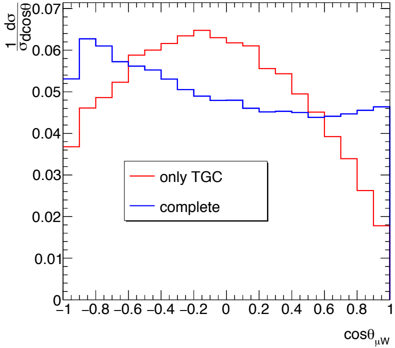
Only (c) contains TGC vertex (longitudinal polarized W dominates) $\Rightarrow$ unitarity violation

(d)–(h) are included $\Rightarrow$ large cancellation between the longitudinal components $\Rightarrow$ unitarity restoration

Spontaneously symmetry breaking
↓
Longitudinal polarization contribution
↓
Unitarity problem

⇔

Gauge completeness
↓
Unitarity restoration



TGC is related to the polarization information. We can choose some kinematic observables containing W polarization information to probe aTGC contributions!!

Signal production and event selection

We focus on $e^- p \to e^- \mu^+ \nu_\mu j$ subchannel:

1. $\ell = e^+$: Additional backgrounds–neutral bosons decay to $e^+ e^-$ pair;
2. $\ell = e^-$: The mistagging rate between the electron from W boson decay and the scattered beam electron is 7%, if we assume the electron from W decay takes the smaller rapidity value. On the other hand, neutral current deep inelastic scattering events in the e^- channel are potential sources of backgrounds as well.
3. $\ell = \mu^-$: Its signal production rate would be smaller than in the μ^- channel because of the parton distribution of proton (uud) at the e−p collider. However it's potential to be combined. Thus among all the leptonic channels, we expect the μ^+ channel to be more sensitive to aTGCs than others。
4. W hadronic decay channel: We need to consider $e^- + 3j$ with a 30.53 pb production cross section as the final state, which is approximately two orders over the leptonic decay channel because of huge QCD processes. After setting kinematic cuts to reduce QCD backgrounds, the cross section is still (pb) level despairing to probe tiny aTGC contributions.

Signal production and event selection

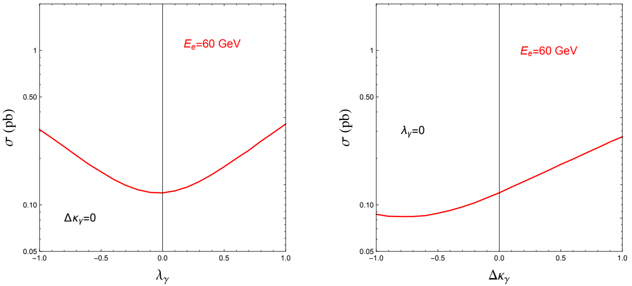
$E_e = 60$ GeV, $E_P = 7$ TeV@LHeC

- events generator and cross section calculation: *MadGraph*5v2.4.2(including off-shell W boson contributions)
- parton shower and hadronization: *Pythia*6.420
- detector simulation: *Delphes*3.3.0

basic cut:

- $|\eta_{\ell,j}| < 5$
- $\Delta R_{\ell\ell} > 0.4$
- $\Delta R_{\ell j} > 0.4$
- $P_{T\ell} > 10$ GeV
- $P_{Tj} > 20$ GeV

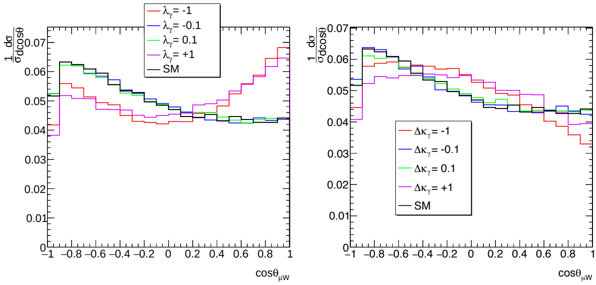
SM: $\sigma_{tot} = 0.120$ pb



(a) (b)

- $\Delta\kappa_\gamma$: interference term is dominant.
- λ_γ: interference term is overshadowed by the contribution purely coming from the 6-dimension anomalous term when $\sqrt{\hat{s}} \geq 500$ GeV.

Kinematic differential distributions

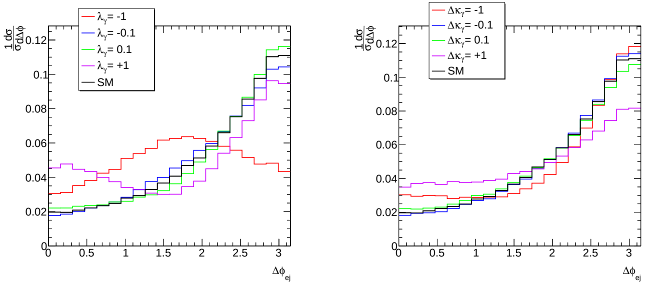


(c) $\Delta\kappa_\gamma = 0$ (d) $\lambda_\gamma = 0$

Figure 3: The normalized $\theta_{\mu W}$ distributions varying with λ_γ(left panel) and $\Delta\kappa_\gamma$ (right panel) respectively for $E_e = 60$GeV

- $\lambda_\gamma \Rightarrow$ transverse polarization component $\Rightarrow \cos\theta_{\mu W} = -1 \rightarrow +1$
- $\Delta\kappa_\gamma \Rightarrow$ longitudinal polarization component $\Rightarrow \cos\theta_{\mu W} = -1 \rightarrow 0$

The result is consistent with the semiquantitive description of the $e^- p \rightarrow e^- \mu^+ \nu_\mu j$ process with the helicity technique.



(a) $\Delta\kappa_\gamma = 0$ (b) $\lambda_\gamma = 0$

Figure 4: The normalized $\Delta\phi_{ej}$ distributions varying with λ_γ(left panel) and $\Delta\kappa_\gamma$ (right panel) respectively for $E_e = 60$GeV

- $\lambda_\gamma = +1$: two peak $\Rightarrow$ e^- and j move in the same or opposite direction on the azimuthal plane.
- $\lambda_\gamma = -1$: one peak $\sim \pi/2 \Rightarrow e^-$ and j are orthogonal on the azimuthal plane.

Reconstruction

Nontrivial!

1. one invisible neutrino in the final state
2. the unknown collision energy in the initial state(the unknown Bjorken x)

Three reconstruction methods:

- 1. use the W boson invariant mass and massless neutrino:
  - problem: two solutions for the invisible neutrino.
- 2. use energy and z-direction momentum conservation conditions:
  Splitting the final states into two parts: the invisible neutrino with $p^{\mu}_{\nu_\mu}$ and the others(e^-, μ^+ and jet) with $p^{\mu}_{e' j\mu}$

$$p^z_{\nu_\mu} = \frac{(2E_e - E_{e' j\mu} - p^z_{e' j\mu})^2 - (p^T_{\nu_\mu})^2}{2(2E_e - E_{e' j\mu} - p^z_{e' j\mu})}$$

  - advantage: only single accurate solution for the invisible neutrino.

- 3. use the recoil mass M_X:

  The final states could be separated into two parts: scattered electron-jet system with $p^{\mu}_{e'j}$ and all remaining particles with p^{μ}_X called recoil system. Computing the invariant mass square of the recoil system M^2_X:

$$M^2_X = \hat{s} + M^2_{e'j} - 2E_{e'j}(E_q + E_e) + 2p^z_{e'j}(E_e - E_q).$$

  Since the process we study get large contribution from on-shell W channels, we could simply choose W boson itself as the recoil system and get a relation of Bjorken x with the known input:

$$x = \frac{M^2_W - M^2_{e'j} + 2E_e(E_{e'j} - p^z_{e'j})}{2E_P(2E_e - E_{e'j} - p^z_{e'j})}.$$

  It is easy to solve the accurate z-direction momentum of the invisible neutrino:

$$p^z_{\nu_\mu} = E_e - xE_P - p^z_{e'} - p^z_j$$

  - advantage: restore z-direction momentum conservation condition.
  - problem: there are some deviations due to off-shell contributions.

The recoil mass method works well for events with an on-shell W , but leads to certain deviation for other off-shell contributions.

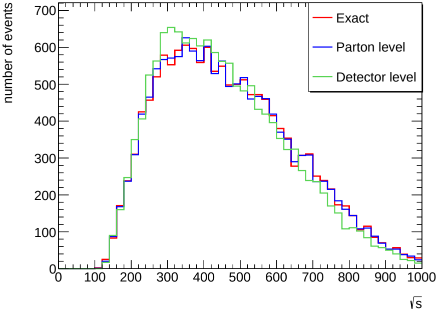
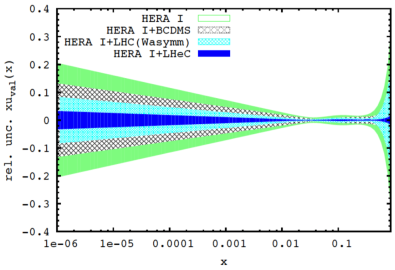


Figure 5: Comparison of partonic collision energy $\sqrt{\hat{s}}$ distributions of exact value(red), parton level value(blue) and detector level value(green)

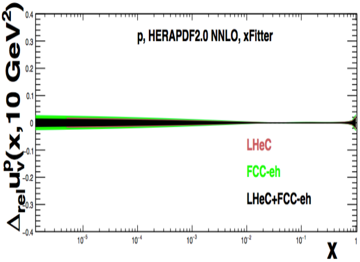
The reconstructed partonic collision energy distributions are shown here confirming the validity of the recoil mass method!

Results

- theoretical error:
  PDF uncertainty 0.6%(*NNPDF23_nlo_as_0119*) ⇒ 0.15%∼0.2%@LHeC PDF
- pile-up error:
  $\not{E}_T > 20\text{GeV}$ ⇒ 87%survival probability



(a)



(b)

Figure 6: Comparison of the up valence quark distribution of different colliders.

To illustrate the feature of the two kinematic distributions proposed above, we adopt the χ^2 method for large event numbers by assuming that the best-fitting aTGC values of future data equal zero

$$\chi^2 \equiv \sum_i \left(\frac{N_i^{BSM} - N_i^{SM}}{\sqrt{N_i^{SM}}} \right)^2$$

- 10 bins， 95% C.L.
- only considering statistic uncertainty, neglecting the systematic uncertainty and theoretical uncertainty here

- Single-parameter fitting: $\mathcal{L} = 1\ ab^{-1}$

variables / parameters	μ^+ decay, $E_e = 60$ GeV		μ^+ decay, $E_e = 140$ GeV		
	$\cos\theta_{\mu^+ W^+}$	$\Delta\phi_{ej}$	$\cos\theta_{\mu^+ W^+}$	$\Delta\phi_{ej}$	SM
λ_γ	×	[-0.007, 0.0056]	×	[-0.0034, 0.0021]	0
$\Delta\kappa_\gamma$	[-0.0054, 0.006]	[-0.0043, 0.0054]	[-0.002, 0.0017]	[-0.003, 0.0021]	0

variables / parameters	μ^- decay, $E_e = 60$ GeV		μ^- decay, $E_e = 140$ GeV		
	$\cos\theta_{\mu^- W^-}$	$\Delta\phi_{ej}$	$\cos\theta_{\mu^- W^-}$	$\Delta\phi_{ej}$	SM
λ_γ	×	[-0.0092, 0.0096]	×	[-0.0031, 0.0045]	0
$\Delta\kappa_\gamma$	[-0.0073, 0.0071]	[-0.0067, 0.0075]	[-0.0016, 0.0024]	[-0.004, 0.0043]	0

Table 2: The 95% C.L. bound on aTGC λ_γ and $\Delta\kappa_\gamma$, obtained from the kinematic observables $\cos\theta_{\mu^\pm W^\pm}$ and $\Delta\phi_{ej}$ at LHeC with $E_e = 60$ and 140 GeV. The results listed are from single-parameter fitting when the other one is fixed to its SM value. The "×" in the table means this bound is no better than the ones from LEP

- Two-parameter fitting: $\mathcal{L} = 1\ ab^{-1}$

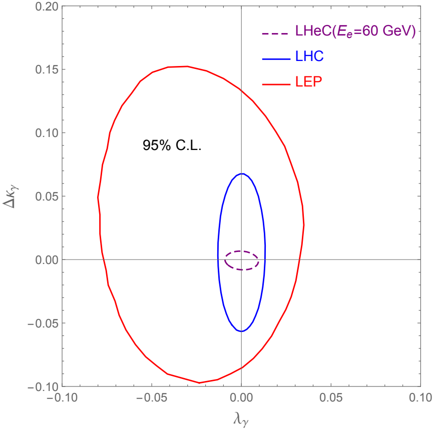


Figure 7: Two-parameter fitting results of aTGC bounds at 95% C.L. for LHeC, LHC and LEP.

The above results are all obtained via pure partonic level study. To achieve the same results in a full simulation(*Pythia* and *Delphes*), one expects about threefold integrated luminosity with 30% survival probability criteria.

Summary

- The sensitivity to λ_γ and $\Delta\kappa_\gamma$ could reach $\mathcal{O}(10^{-3})$ when $\mathcal{L} = 1\ ab^{-1}$ based on χ^2-method at parton level with the expectation of more precise PDFs at future LHeC, while in a full simulation the integrated luminosity need to be increased to 2-3 ab^{-1} to consistent the result.
- Comparing to the previous results at LEP and LHC, there is also a significant improvement in constraining aTGC parameter, particularly $\Delta\kappa_\gamma$ at LHeC.
- it is noteworthy that the kinematic methods in event reconstruction, through which one could retrieve z-direction momentum conservation condition despite of the ignorance of initial state parton and final state neutrino momentums. We believe the kinematic methods are useful for future measurements of processes with $\not{E}_T$ at this *ep* collider.
- The same result might be reached with approximately half integrated luminosity if we combined the μ^+ and μ^- channels.
- Polarization of the initial electron beam maybe help for our results


Thank You