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Title: Searching for New Physics at the Intensity Frontier at the EIC: Project Visit

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# Searching for New Physics at the Intensity Frontier at the EIC

LDRD Project 20200775PRD4


PI: Christopher Lee
Co-PI: Emanuele Mereghetti
PD: Bin Yan
T-2


PRD Project visit, October 5, 2021

Los Alamos NATIONAL LABORATORY

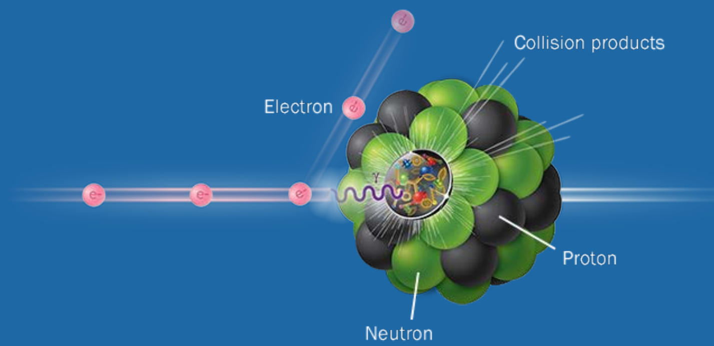


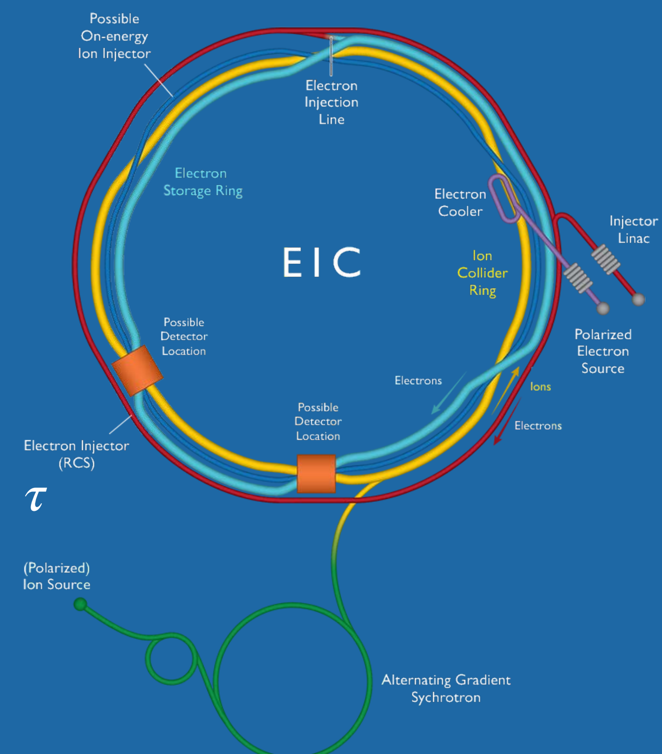
LA-UR-21-29821

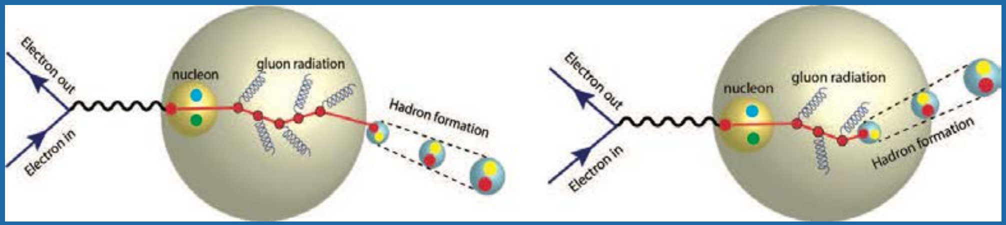
# The Electron-Ion Collider: a new frontier

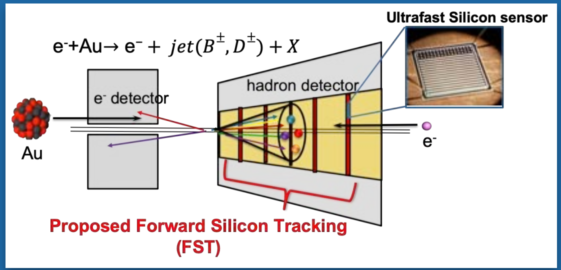
## Electron-Ion Collider: the new frontier in high-energy nuclear physics

- To be built by 2030 at BNL to be the world's most powerful microscope into proton and nuclear structure, with most intense *polarized* electron & hadron beams: *3-D tomography of the proton, new states of matter, origin of proton spin and mass.*
- LANL a leading contributor to the Jets & Heavy Quarks program at EIC, both theory and detector development.
  - Focused on probing hadronization in both cold and hot dense nuclear matter: frontiers of QCD



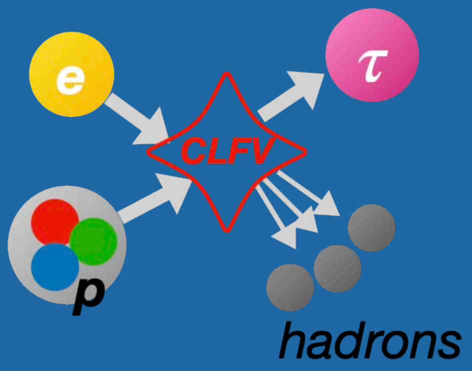



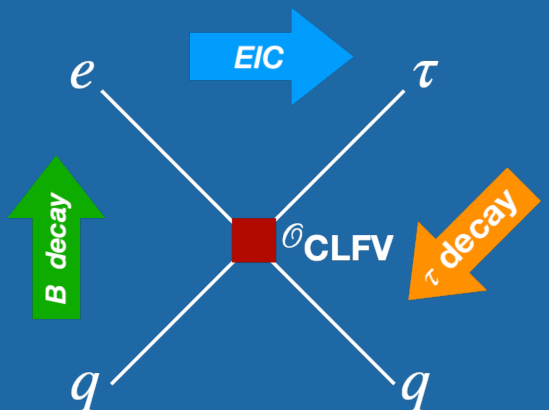

*I. Vitev, X. Li, et al.*

# The Electron-Ion Collider: a new capability

## This project:

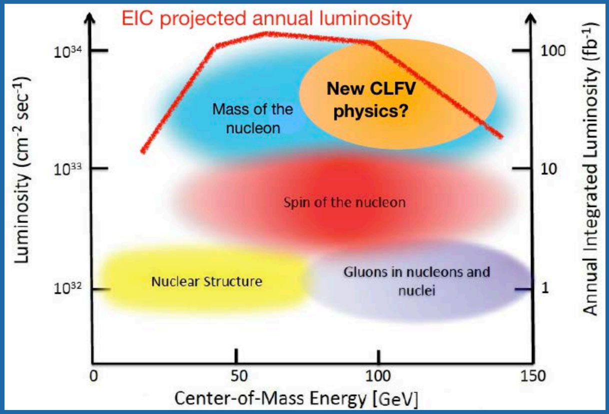
- Work towards a new capability for the EIC: ***ability to search for new physics beyond the Standard Model***
- Unprecedented luminosity to search for rare processes, in particular **charged lepton flavor violation, e.g.** $e \to \tau$
- Such CLFV interactions are generated in models of new physics that give rise to neutrino masses and mixings, and may explain origin of matter-antimatter asymmetry in early universe
  - also topics of significant investment at LANL (e.g. neutrino & neutron experiments and theory)




***SMEFT connecting different experiments***

- Analyze EIC discovery potential using most general framework of BSM physics: SM Effective Field Theory (SMEFT)
- Develop best strategies to identify $\tau$ decay products, measurements on associated hadrons with least SM background and best discriminating power for different CLFV mechanisms



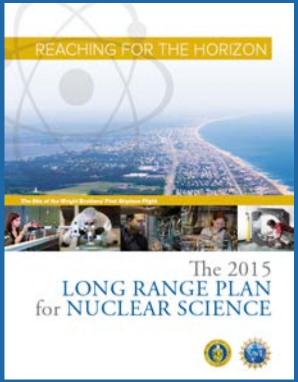
# EIC physics timeline

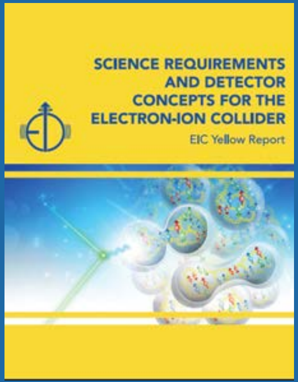
## The time to influence the EIC physics program and detector design & development is now:

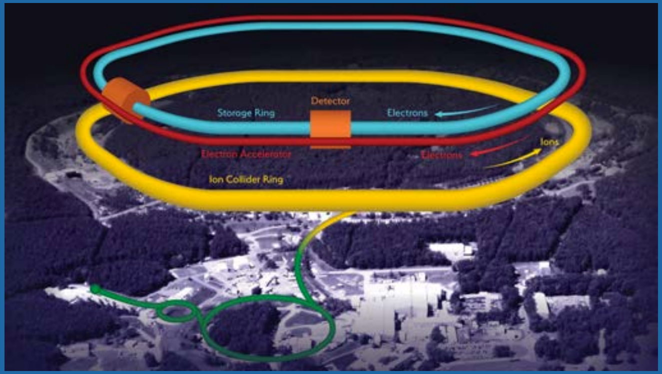
| 2015 | 2020 | 2021 | 2022 | 2023 | 2024 | 2030 |
|---|---|---|---|---|---|---|
| *NSAC Long-Range Plan: “EIC top priority for new construction”* | *CD-0: Mission-Need Approval* | *Yellow Report/ CD-1* | *Preliminary detector designs/CD-2* | *Detailed detector designs/CD-3* | *Next NSAC LRP* | *EIC construction complete* |

***This PRD Project***

***Era of EIC Discoveries***




- LANL T and P-Div teams authored several sections of the YR on jets & heavy quarks
- This project’s paper on CLFV at EIC was cited in the YR section on electroweak & BSM physics, which is not yet heavily developed and has room to grow

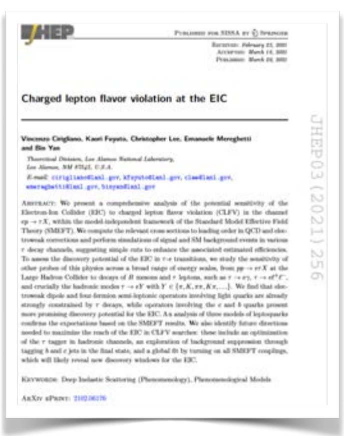
# Goals & Accomplishments of this project

## Original proposal goals:

- Propose and compute observables that can distinguish CLFV signal from SM backgrounds
  - Use SMEFT and QCD theory and Monte Carlo simulation packages for QCD showering, hadronization, and detector effects
- Use SMEFT to compare EIC sensitivity to CLFV to other types of searches where same interactions may produce CLFV effects, e.g. *B* decays, $\tau$ decays
- Discovering BSM physics @ EIC would be one of its most exciting and transformational outcomes possible.

## Achieved:

- Published 108-page paper in Journal of High-Energy Physics, was immediately accepted for publication


JHEP

Charged lepton flavor violation at the EIC

Vincenzo Cirigliano, Kaori Fuyuto, Christopher Lee, Emanuele Mereghetti and Bin Yan

JHEP03(2021)256

V. Cirigliano, K. Fuyuto, C. Lee, E. Mereghetti, **B. Yan,** JHEP 03 (2021) 156

- Most comprehensive study of CLFV in SMEFT to date, most complete comparison of all available & projected experimental constraints
- **Key outcome:** EIC may have superior sensitivity to CLFV operators probing **heavy quark** content of proton or final-state jets ⇒ synergy with QCD jets & heavy quark program
- Based so far only on leading-order QCD perturbation theory, however.

# Goals & Accomplishments of this project

## Extended goals into 2nd year (FY22):

- Compute next-to-leading order corrections in QCD which may be important in mixing different SMEFT operator contributions to CLFV processes
- Explore sensitivity of EIC (at leading order in QCD) to **lepton-number-violating** (LNV) processes such as $e^- + p \to \tau^+ + X$ which are connected to nature of neutrino masses (Majorana or Dirac) also to be tested in double beta decay experiments
- Explore other ways to test boundaries of SM physics with the EIC

## Achieved so far:

- Postdoc Bin Yan wrote Letter with external collaborators, accepted in Phys. Lett. B, proposing measurements at the EIC that can measure precisely the coupling of *Z* bosons to heavy *b* quarks for possible signs of new physics beyond the SM and possibly resolve the anomaly in these couplings measured at the LEP and SLC $e^+e^-$ colliders

  B. Yan, Z. Yu, C.-P. Yuan, *The anomalous $Zb\bar{b}$ coupling at HERA and the EIC*, Phys. Lett. B, in press (2021)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Physics Letters B
Contents lists available at ScienceDirect
www.elsevier.com/locate/physletb

The anomalous $Zb\bar{b}$ couplings at the HERA and EIC

Bin Yan[a], Zhite Yu[b], C.-P. Yuan[b]

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ABSTRACT
To resolve the long-standing discrepancy between the precision measurement of bottom quark forward-backward asymmetry at LEP/SLC and the Standard Model prediction, we propose a novel method to probe the $Zb\bar{b}$ coupling by measuring the single-spin asymmetry $A_e^b$ of the polarized lepton cross section in neutral current DIS processes with a $b$-tagged jet at HERA and EIC. Depending on the tagging efficiency of the final state $b$-jet, the measurement of $A_e^b$ at HERA can already partially break the degeneracy found in the anomalous $Zb\bar{b}$ coupling, as implied by the LEP and SLC precision electroweak data. In the first year run of the EIC, the measurement of $A_e^b$ can already break the degeneracy, due to its much larger luminosity and higher electron beam polarization. With enough integrated luminosity collected at the EIC, it is possible to either verify or exclude the LEP data and resolve the $A_{FB}^b$ puzzle. We also discuss the complementary roles between the proposed $A_e^b$ measurement at EIC and the measurement of $gg \to Zh$ cross section at the HL-LHC in constraining the anomalous $Zb\bar{b}$ coupling.


1. Introduction

The bottom quark forward-backward asymmetry ($A_{FB}^b$) at the Z-pole measured at the Large Electron-Positron collider (LEP) exhibits a long-standing discrepancy with the Standard Model (SM) prediction by a significance around $2.1\sigma$ [1]. Though the observed discrepancy could be caused by statistical fluctuation or some subtle systematic errors in the experiment, it could be an evidence of new physics (NP) beyond the SM. Many global analyses have been carried out in the literature to include also the other experimental data sensitive to the $Zb\bar{b}$ coupling, such as the measurement of the branching fraction ($R_b$) of $Z \to b\bar{b}$ in the inclusive hadronic decay of $Z$ at LEP, and the left-right forward-backward asymmetry ($A_b$) of $b$ production at the Stanford Linear Collider (SLC) experiment with longitudinally polarized electron beam. A class of popular NP models to interpret these precision data is to introduce an anomalous right-handed $Zb\bar{b}$ coupling, while keeping the left-handed $Zb\bar{b}$ coupling about the same as the SM [2–5]. Such a condition can be fulfilled for any theory with an underlying approximate custodial symmetry [3]. However, it is well known that combining the $R_b$ and $A_{FB}^b$, $A_b$ measurements at the Z-pole does not uniquely determine the $Zb\bar{b}$ coupling, but leads to 4 degenerate solutions [2]. The LEP $A_{FB}^b$ measurement off the Z-pole offers a way to break that degeneracy, but not completely, due to the low event rate, with still two possible solutions left [2]. To break this degeneracy, more events off the Z-pole should be accumulated in a future lepton collider, such as CEPC, ILC, CLIC and FCC-ee [6–8].

While still in wait for a next-generation lepton collider, we shall also seek for other opportunities that exist in the present or near future to break the above-mentioned degeneracy by, for example, probing exclusively the vector or axial-vector component of the $Zb\bar{b}$ coupling, as well as to confirm or exclude the discrepancy between the $A_{FB}^b$ measurement and the SM. In a recent paper, we proposed to resolve this puzzle through the precision measurement of $gg \to Zh$ scattering at the Large Hadron Collider (LHC) [9], which is sensitive to the axial-vector component of the $Zb\bar{b}$ coupling. We showed that the high-luminosity LHC (HL-LHC) can not only break the degeneracy, but also verify or exclude the anomalous $Zb\bar{b}$ coupling observed at LEP through measuring the $Zh$ production rate, and this conclusion is not sensitive to possible NP contribution induced by top quark or Higgs boson anomalous couplings in the loop [9].

In this paper we propose a novel method for directly measuring the vector, as opposed to the axial-vector, component of the $Zb\bar{b}$ coupling, to be carried out at lepton-hadron colliders, such as HERA and the upcoming Electron-Ion Collider (EIC). The observable we propose to probe the $Zb\bar{b}$ coupling is the single-spin asymmetry (SSA) $A_e^b$ of the polarized lepton-proton cross section in neutral current deeply-inelastic scattering (DIS) processes with one $b$-tagged jet in the final state [10].

# Postdoc Development

## Background:

- Dr. Bin Yan comes with high recommendations from PhD program at Peking University and postdoc at Michigan State
- Supported FY20 by DOE-funded projects on Nuclear Theory in T-2 and Early Career Award of C. Lee on Precision QCD
  - Bin is collaborating on large project to determine strong coupling in QCD to high precision using data from LEP $e^+e^-$ collider at CERN.
- Won Director’s Postdoctoral Fellowship for FY21-22 to work on new physics at EIC
  - In FY22 continues to be partially supported by DOE projects on QCD

## Breadth:

- Has engaged with other colleagues in T-2 to achieve goals of this PRD project: V. Cirigliano & K. Fuyuto
- Maintained active external collaborations with existing and new collaborators on perturbative QCD, tests of SM and BSM particles and couplings at LHC, EIC, and new linear ($e^+e^-$) colliders
  - 6 papers published or submitted to peer-reviewed journals outside of this PRD project
  - Over 20 invited talks (mostly virtual during Covid) all over the world

# Postdoc Development

## Future prospects:

- Follow-on proposal: our work on CLFV @ EIC motivated and comprised a major component of a proposal to DOE's call early this year for proposal on ML/AI applications for EIC or other future colliders. (*unfortunately not funded)*
  - NMC-supported collaboration with NMSU to carry forward some exploratory research to strengthen proposal for next call
- The outcome of this PRD research also strengthens a potential ER proposal building on this topic for FY23, to expand LANL's expertise and leadership on jets & heavy quarks at EIC to a BSM physics program
- Bin has been invited to interview for faculty positions at several universities:
  - Beijing Normal U.
    U. Regensburg
    BeiHang U.
    NanKai U.
    Beijing Institute of Technology
  - Awaiting outcome, and new opportunities to apply this Fall/Winter

# Searching for New Physics at the Intensity Frontier at the EIC

Bin Yan
Los Alamos National Laboratory

V. Cirigliano, K. Fuyuto, C. Lee, E. Mereghetti and Bin Yan, JHEP 03 (2021) 256

Bin Yan, Zhite Yu and C.-P. Yuan, arxiv 2107.02134 (Accepted by PLB)

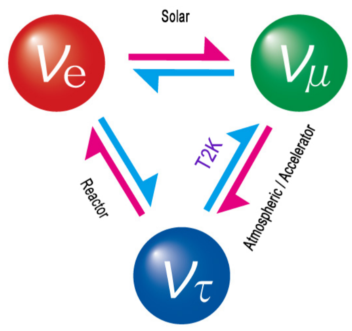
# Charged Lepton Flavor Violation @ EIC

V. Cirigliano, K. Fuyuto, C. Lee, E. Mereghetti and Bin Yan, JHEP 03 (2021) 256

# Charged Lepton Flavor Violation

Lepton Flavor is not conserved:

Neutrino Oscillations

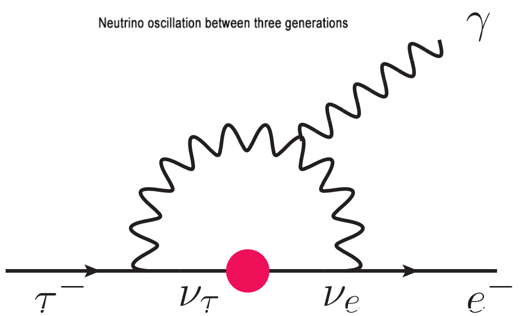



Neutrino oscillation between three generations

## Charged Lepton Flavor Violation (CLFV):

$$BR \sim \left(\frac{m_\nu}{m_W}\right)^2 \sim 10^{-44}$$

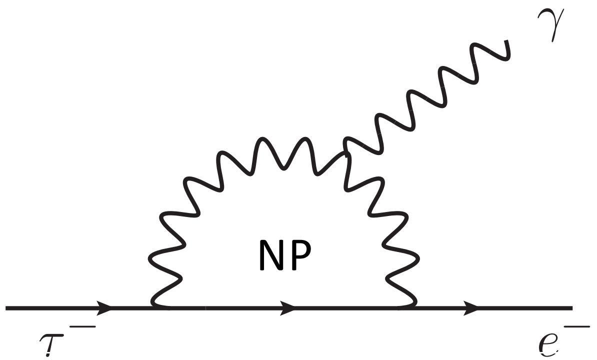
S. Petcov, '77; W. Marciano and A. Sanda, '77




A. CLFV is sensitive to the NP

B. CLFV could be related to the neutrino mass generation mechanism;

   Tree level or Loop level

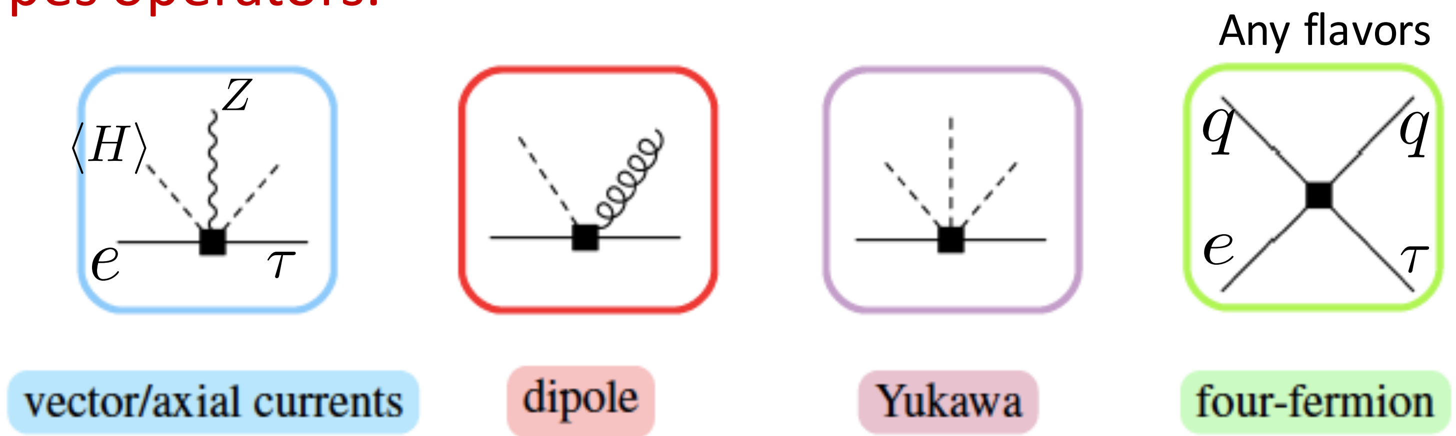



For example: Two loop neutrino mass model

QHC, SLC, E. Ma, Bin Yan, DMZ, PLB779 (2018)430-435

# CLFV and EFT

Four types operators:




For example:

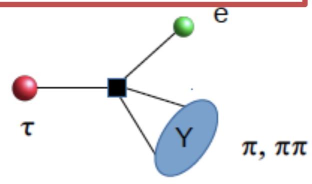
$$\mathcal{L} = -\frac{g}{2c_W} Z_\mu \left[ \left( c_{L\varphi}^{(1)} + c_{L\varphi}^{(3)} \right)_{\tau e} \bar{\tau}_L \gamma^\mu e_L + c_{e\varphi} \bar{\tau}_R \gamma^\mu e_R \right]$$
$$- \frac{e}{2v} [\Gamma_\gamma^e]_{\tau e} \bar{\tau}_L \sigma^{\mu\nu} e_R F_{\mu\nu} - \frac{g}{2c_W v} [\Gamma_Z^e]_{\tau e} \bar{\tau}_L \sigma^{\mu\nu} e_R Z_{\mu\nu}$$

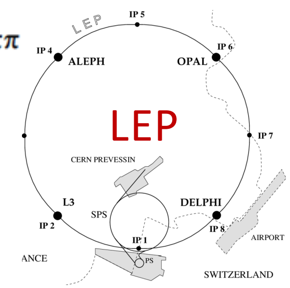
Four-fermion operatrors:
we assume the generic quark flavor structures

$$[C_{Ld}]_{\tau e} = \begin{pmatrix} [C_{Ld}]_{dd} & [C_{Ld}]_{ds} & [C_{Ld}]_{db} \\ [C_{Ld}]_{sd} & [C_{Ld}]_{ss} & [C_{Ld}]_{sb} \\ [C_{Ld}]_{bd} & [C_{Ld}]_{bs} & [C_{Ld}]_{bb} \end{pmatrix}$$

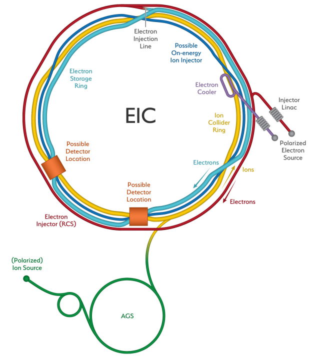
# Charged Lepton Flavor Violation

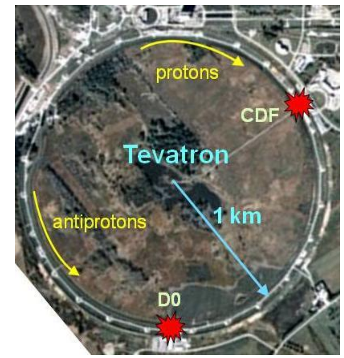
Focus on tau lepton



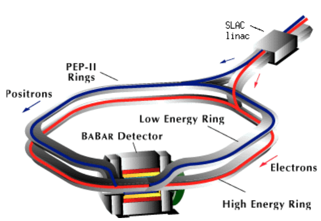

EIC

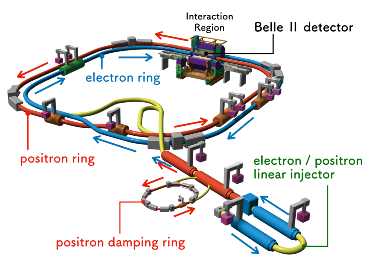


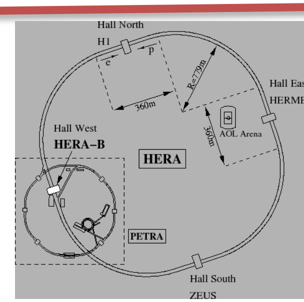




Low energy observables

High energy observables

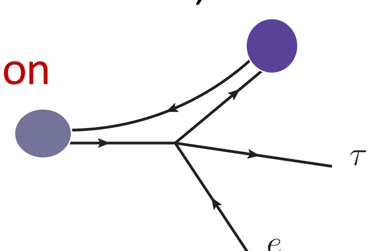


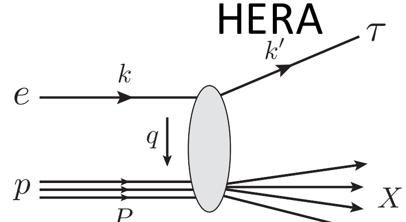




Babar, Belle II

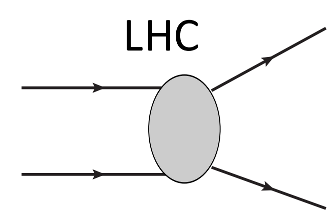
Meson



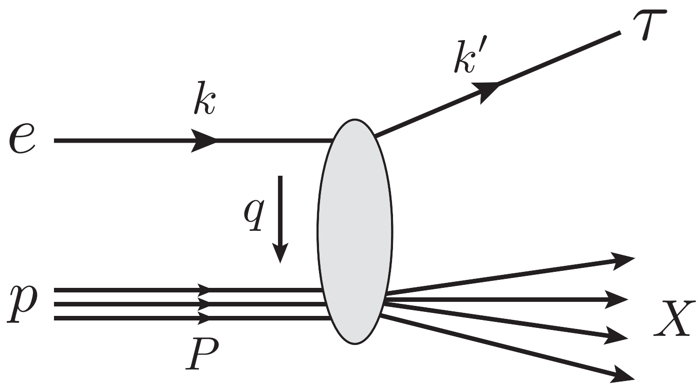

HERA




LHC



# Collider analysis @ EIC

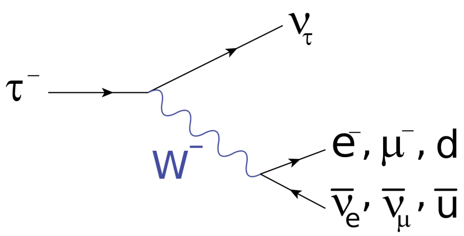



Signal: $E_e = 20\ \mathrm{GeV}, \quad E_p = 250\ \mathrm{GeV}$

$$(1) e^- p \to \tau^- X \to e^- \bar{\nu}_e \nu_\tau X;$$

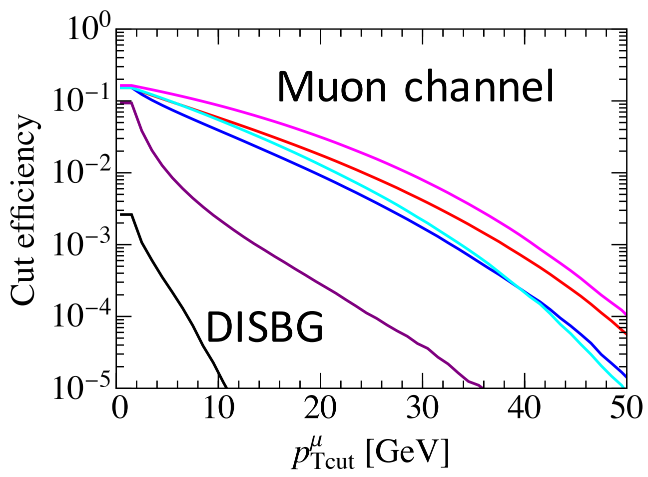
$$(2) e^- p \to \tau^- X \to \mu^- \bar{\nu}_\mu \nu_\tau X;$$

$$(3) e^- p \to \tau^- X \to \nu_\tau\, X_h\, X$$




Background: SM DIS production

The electron and hadronic decay channels would be challenge due to the large backgrounds;




Based on Pythia8+Delphes

$$p_T^\mu > 10\ \mathrm{GeV}, \quad p_T^{j1} > 20\ \mathrm{GeV}$$

$$\not{E}_T > 15\ \mathrm{GeV}, \quad |\eta_{\mu,j1}| < 3.$$

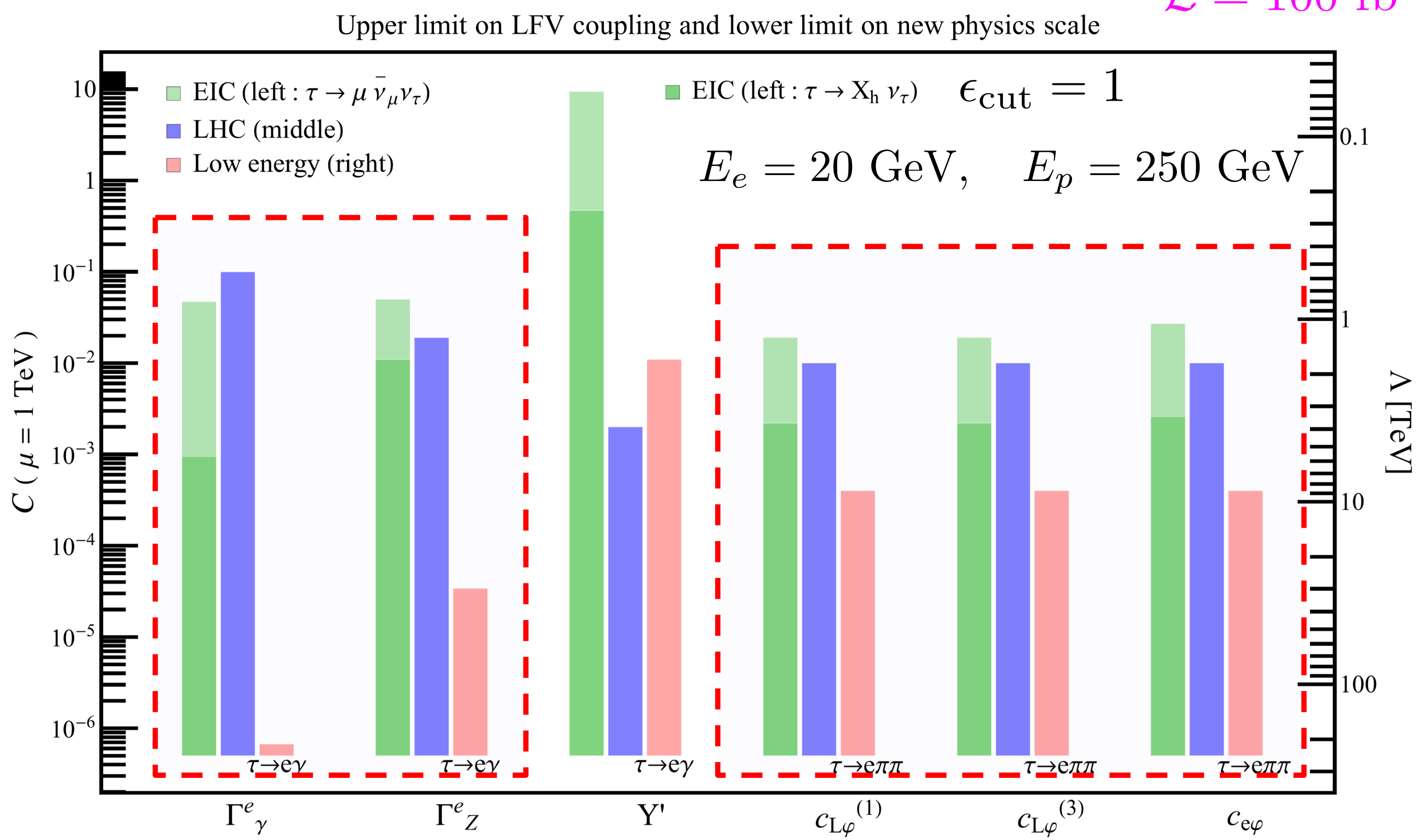
Background free process

# The sensitivity of CLFV

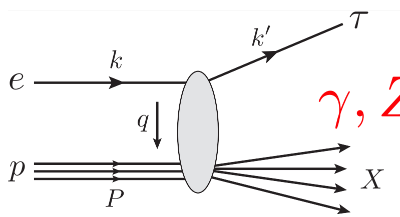
Dipole, Yukawa and Vector/Axial vector current

$\mathcal{L} = 100\ \text{fb}^{-1}$

Coefficients




New Physics Scale




$\gamma, Z, h$

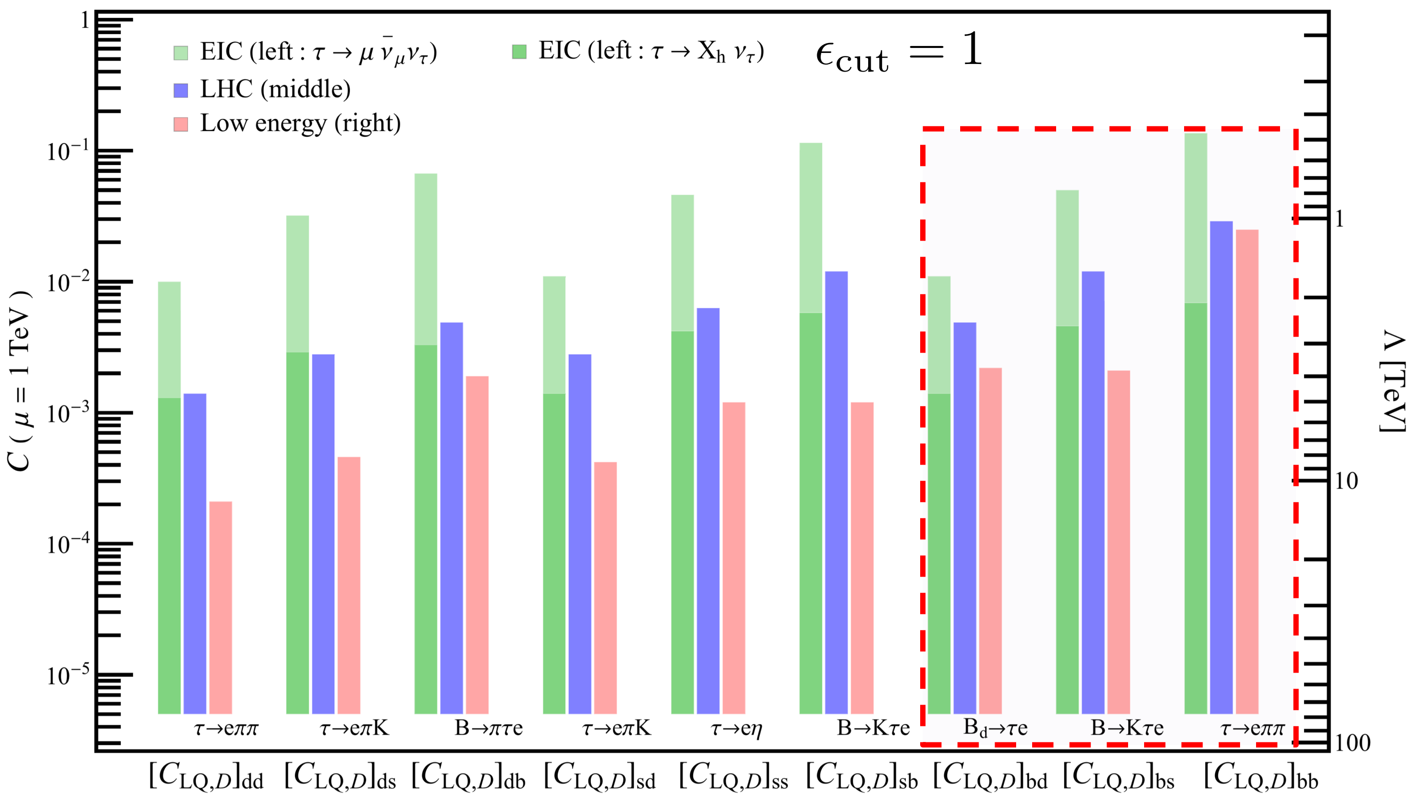
**EIC is comparable to LHC limits**

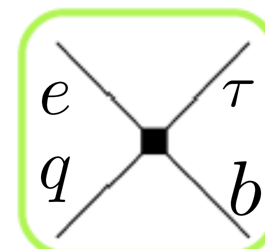
# The sensitivity of CLFV

Four-Fermion operators

$\mathcal{L} = 100\ \text{fb}^{-1}$

Upper limit on LFV coupling and lower limit on new physics scale



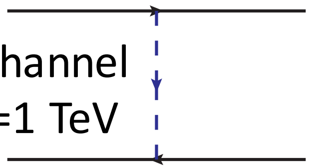

four-fermion

**The limits for the heavy quark components at the EIC are comparable to the LHC and low energy data**

# The sensitivity of CLFV

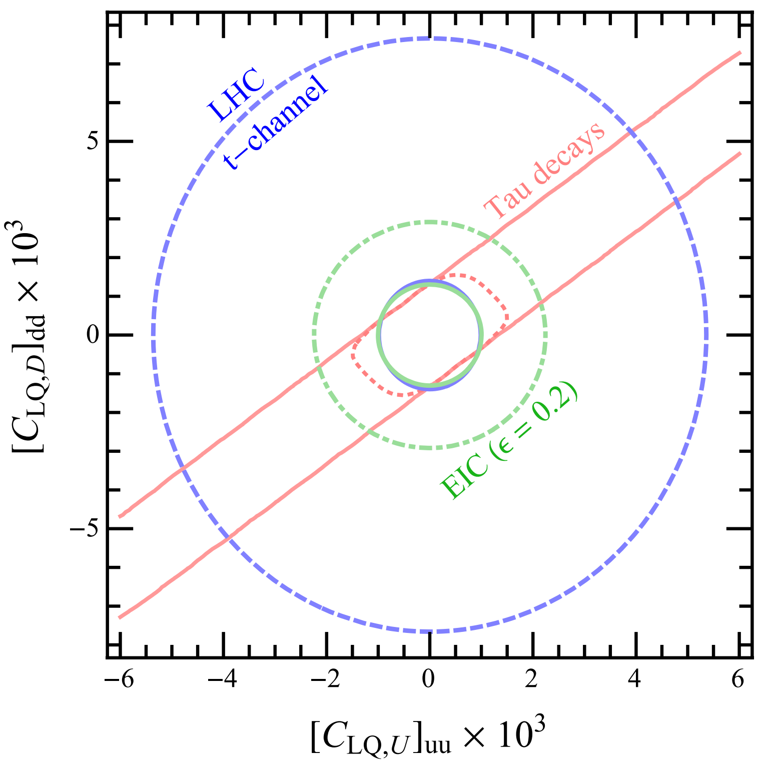
Global analysis:

t-channel
M=1 TeV

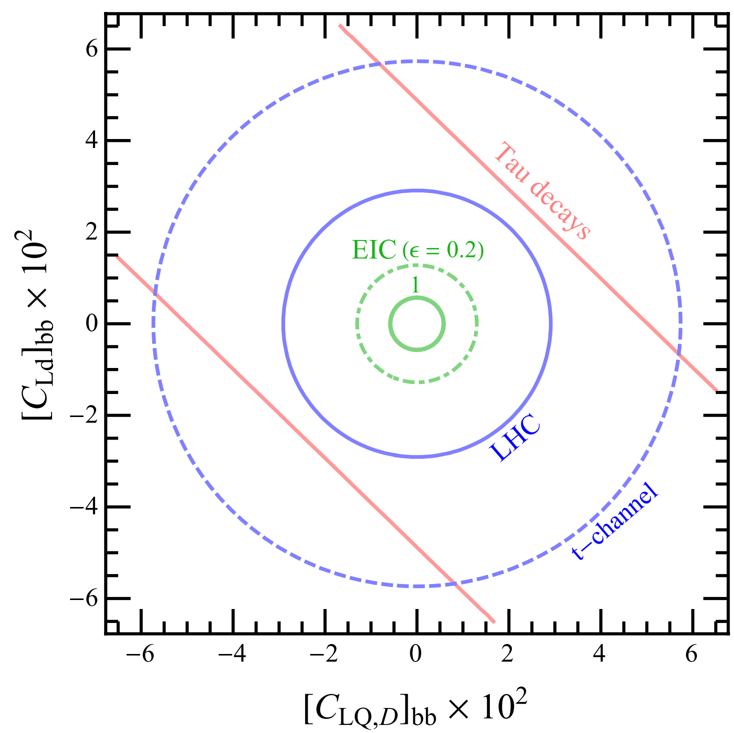


| Scenario | Operators |
|---|---|
| A | $c_{L\varphi}^{(1,3)}$, $[C_{LQ,U}]_{uu}$, $[C_{LQ,D}]_{dd,ss}$, $[C_{Lu}]_{uu}$, $[C_{Ld}]_{dd,ss}$ |
| B | $c_{L\varphi}^{(1,3)}$, $[C_{LQ,D}]_{dd,ss,bb}$, $[C_{Ld}]_{dd,ss,bb}$ |

Scenario A



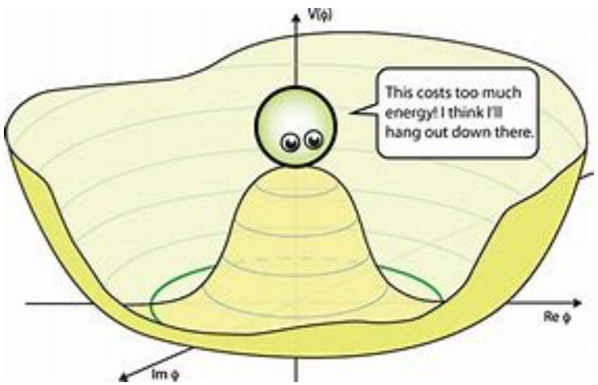

Scenario B



# The anomalous Zbb couplings @ EIC

Bin Yan, Zhite Yu and C.-P. Yuan, arxiv 2107.02134 (Accepted by PLB)

# Z boson couplings

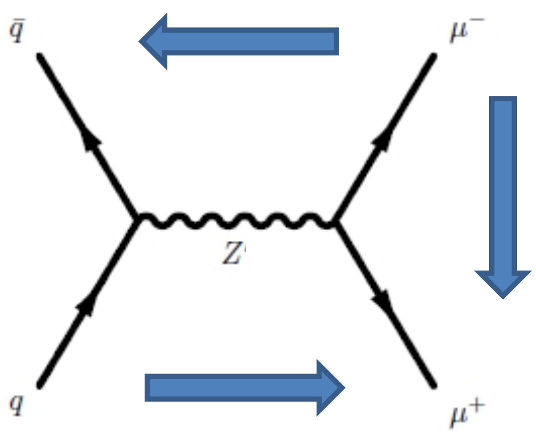



Electroweak symmetry breaking

⇩

Massive gauge bosons: W and Z

Lepton colliders: LEP and SLAC




ep colliders: HERA and EIC

Hadron colliders: Tevatron and LHC

Probing the Z boson couplings are very important for us to test the Standard Model

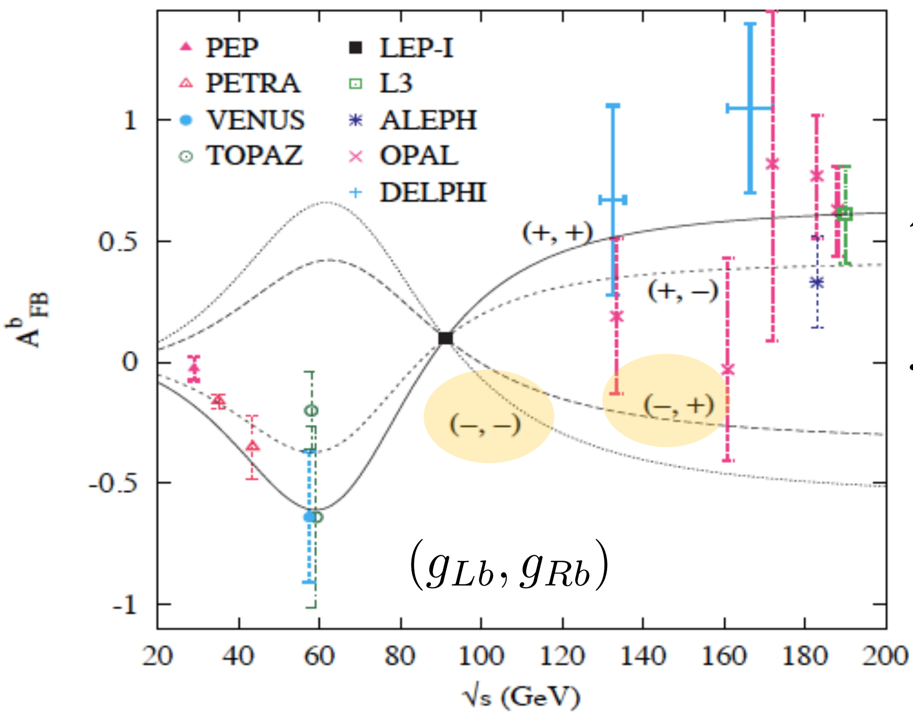
# Status of Zbb couplings

| | measured value | SM prediction |
|---|---|---|
| $R_b^0$ | $0.21629 \pm 0.00066$ | $0.21578 \pm 0.00011$ |
| $A_{\rm FB}^{0,b}$ | $0.0992 \pm 0.0016$ | $0.1032 \pm 0.0004$ |
| $\mathcal{A}_b$ | $0.923 \pm 0.020$ | $0.93463 \pm 0.00004$ |

Gfitter Group:
EPJC74 (2014)3046
PDG2020

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\sum_q \Gamma(Z \to q\bar{q})}$$

$2.1\sigma$ deviation with SM prediction




D. Choudhury, T. M. P. Tait, C.E.M. Wagner,
PRD 65(2002)053002

$$\mathcal{L} = -\frac{g}{c_W} Z_\mu (g_{Lb}\bar{b}_L\gamma^\mu b_L + g_{Rb}\bar{b}_R\gamma^\mu b_R)$$

$$g_{Lb}^{SM} = 0.42, \quad g_{Rb}^{SM} = -0.077$$

$g_{Lb} < 0$ was Excluded

$g_{Rb}$ Could be positive *or* negative

# Status of Zbb couplings

A. How to break the degeneracy of the right-handed Zbb coupling?

New experiments: CEPC (e+e- collider), etc.

B. How to explain the LEP data?

New Physics?

Many new physics models

e.g. Custodial symmetry O(3) + heavy quark

K. Agashe, R. Contino, L. Rold, A. Pomarol, 2006'

Statistical Fluctuation or Systematic error?

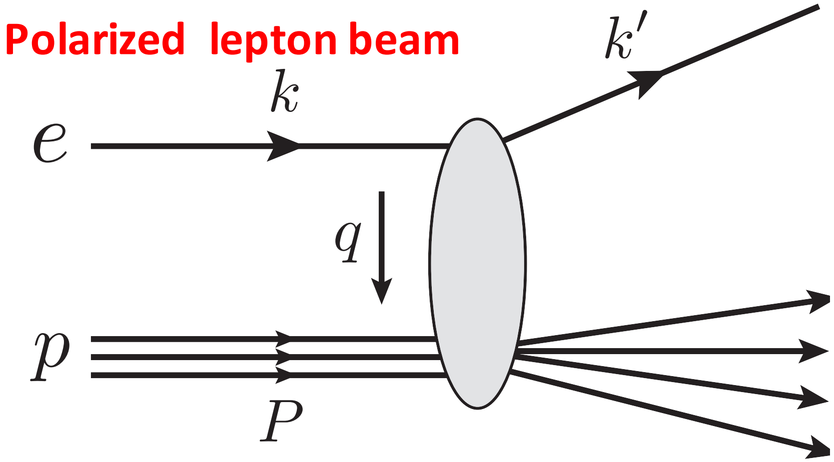
New experiments: e.g. CEPC

# So…

## Should we just wait for the next generation lepton colliders?

***<u>Any possibility from ep collider (EIC)?</u>***

# Zbb couplings @EIC




Single-Spin Asymmetry (SSA):

$$A_e^b = \frac{\sigma_{b,+}^{\rm tot} - \sigma_{b,-}^{\rm tot}}{\sigma_{b,+}^{\rm tot} + \sigma_{b,-}^{\rm tot}}$$

$+/-$: right/left-handed lepton

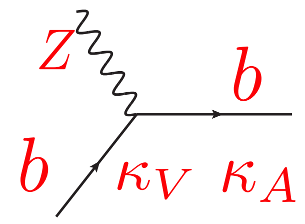
1. Photon-only diagrams will cancel in SSA
2. Leading contribution: $\gamma$-$Z$ interference
3. Only sensitive to the vector component of the Zbb coupling

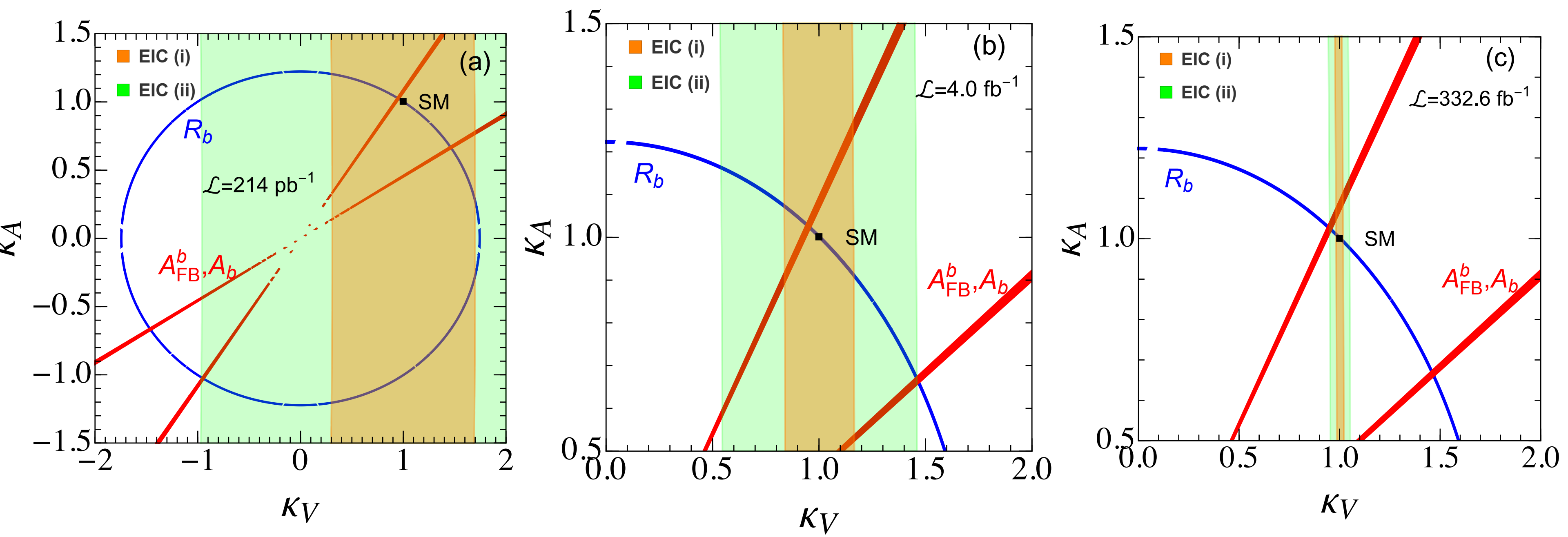
# Zbb couplings @EIC

$$E_{\mathrm{cm}} = 141\ \mathrm{GeV}, P_e = 0.7$$

$(i)\ \epsilon_q^b = 0.001, \quad \epsilon_c^b = 0.03, \quad \epsilon_b = 0.7;$

$(ii)\ \epsilon_q^b = 0.01, \quad \epsilon_c^b = 0.2, \quad \epsilon_b = 0.5.$



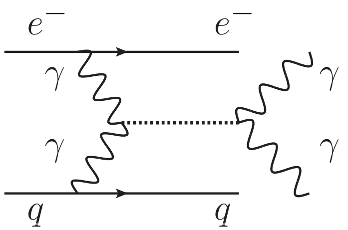




The limits for the Zbb couplings could be comparable to the LEP data

# New Physics @EIC

EIC is an important machine for the new physics searches:

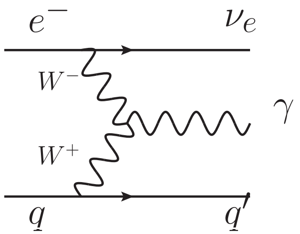
1. Lepton number violation?
2. Axion-like particle?




3. Z boson couplings?

Jet charge + single spin asymmetry observable

4. Triple gauge boson couplings?



# Conclusion

- In this PRD project Dr. Bin Yan and collaborators have exhibited the potential power of the EIC to become not only a new frontier in QCD but also in **searches for new physics beyond the SM**
    - Competitive or superior sensitivity to LHC and other searches for charged lepton flavor violation especially in interactions involving heavy quarks in proton
    - Potential sensitivity to $Z$ boson couplings to heavy $b$ quarks sufficient to resolve long-standing anomaly between LEP/SLC measurements and SM predictions
- Should motivate further investment by LANL and national nuclear physics community to strengthen ties with high-energy physics to maximize the impact of the EIC
- Establishes Dr. Yan as a leading young expert to be a future leader in this effort internationally