



Charged Lepton Flavor Violation with high Luminosity facilities

Physics Program with High Luminosity Facilities,
Jefferson Lab, October 5–9, 2026

Yulia Furletova (JLAB)

Outline

- Introduction. Why CLFV ?
- Overview of CLFV searches
- CLFV with future facilities
 - EIC
 - SOLID
 - μ CLAS12
- Conclusions

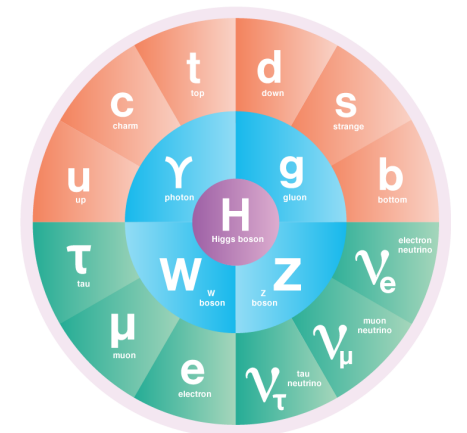
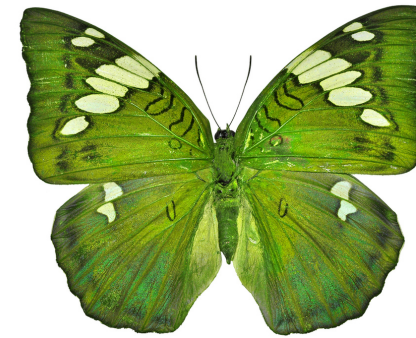
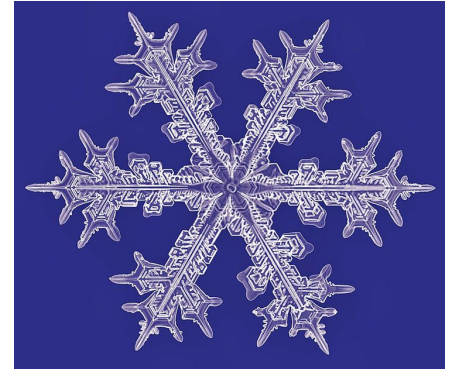
Thanks to
Sonny Mantry
Vardan Khachatryan
Zhiwen Zhao

Introduction. Symmetry

Symmetry is one of the organizing principles of physics - from the smallest scales to the largest structures of the Universe.

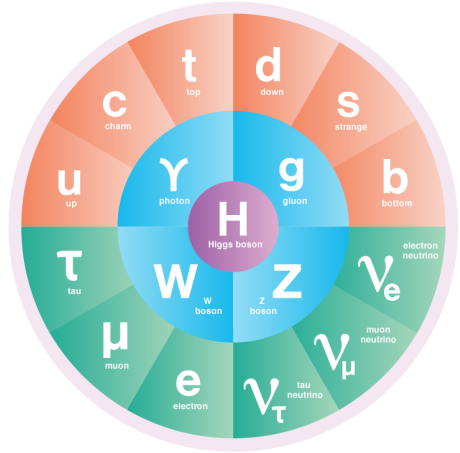
At large scales, symmetries appear in condensed matter, planetary systems, galaxies

At the microscopic scale, gauge symmetries provide the foundation of the Standard Model and determine how quarks and leptons interact.



pictures from Google

The Standard Model

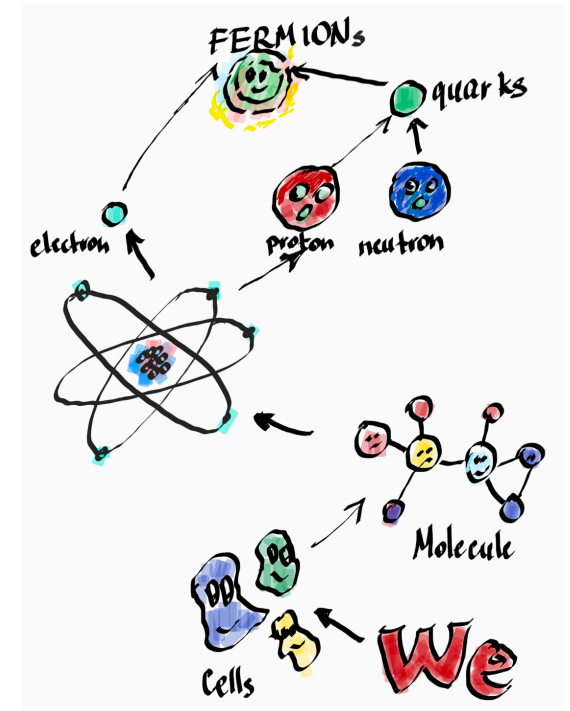


- Sometimes symmetries that look fundamental are only **approximate symmetries**.
- Small violations observed in an "obvious" symmetry can **reveal deeper physics**.

- What is a fundamental symmetry?
- What are conserved quantities in the fundamental interactions?
- Standard Model contains **no explanation for the symmetry between quark and lepton sectors (fermions)**:
 - the mass hierarchy
 - the number of generations.
- **Flavor (a type of quarks or leptons)** is **not a conserved quantity in fundamental interactions** (weak force) : Flavor mixing

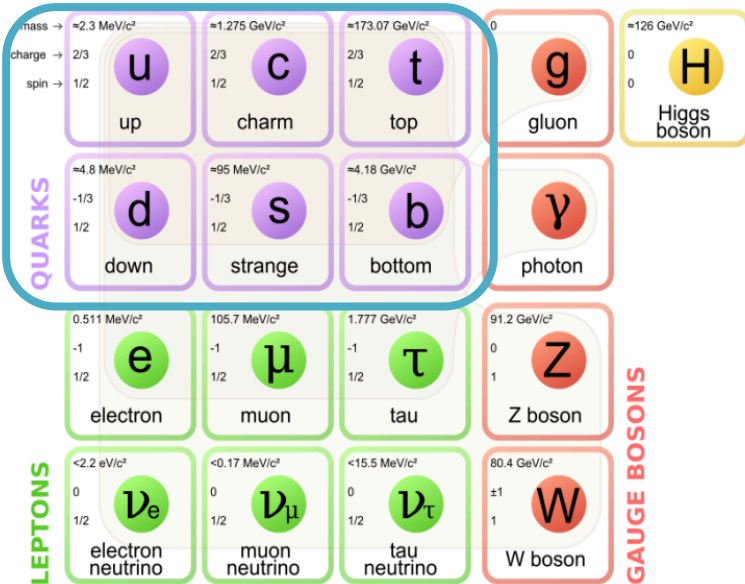
We are fermions :-)

Definition of a **Particle physicist** -
"it is an ability of quarks and gluons to think about quarks and gluons".

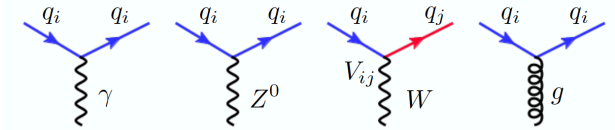


Flavor Mixing in the quark sector

In the quark sector: $\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$



- Flavor mixing is an established feature of the Standard Model in the quark sector
- The flavor changing neutral currents (FCNCs) are forbidden in the standard model (SM) at tree level (requires a virtual W exchange).
- Family number** is not a symmetry in the SM: a quark family number is violated in weak decays in the CKM matrix
- Flavor mixing** in the Standard Model quark sector **is well established**, through processes like $K^0-\bar{K}^0$ oscillations, $B^0-\bar{B}^0$ mixing etc.



The quark mixing is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$J_\mu^{cc} = (\bar{u}, \bar{c}, \bar{t})_L \gamma_\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \approx \begin{pmatrix} 0.97 & 0.22 & 0.0037 \\ 0.22 & 0.97 & 0.042 \\ 0.094 & 0.040 & 1.0 \end{pmatrix}$$

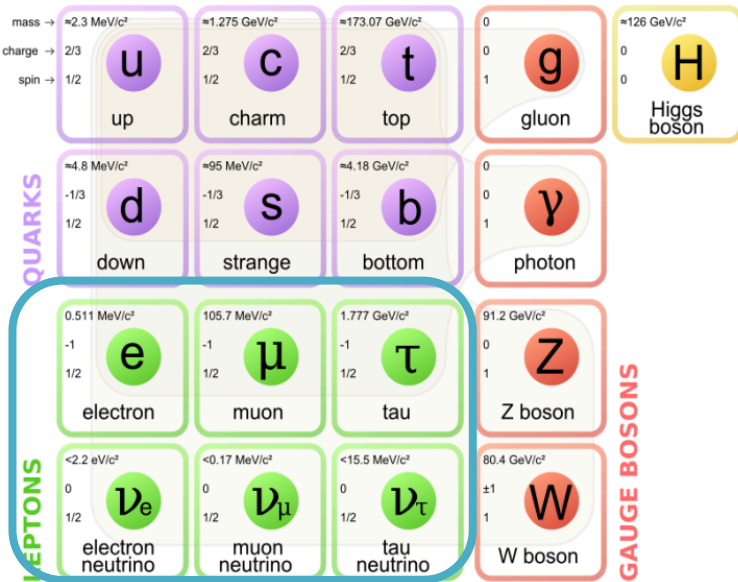
The hierarchy of CKM matrix elements shows that some flavor transitions are strongly suppressed, while others are relatively large

What about lepton sector?

In the lepton sector:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Lepton Flavor violation (LFV): Neutrinos



- Nature allows flavor mixing in both quarks and leptons- but the patterns are dramatically different. Understanding this difference may be the key to understanding the origin of flavors

- A **Lepton Flavor Violation** (LFV) is a transition between e, μ, τ sectors that doesn't conserve lepton family number
- Evidence of LFV: neutrinos oscillate**
Neutrinos have a (small) mass and mix.
- Neutrino oscillations show that a neutrino produced as one flavor can later be detected as another

- Many experiments (MINOS, K2K, Super-K , etc) at particle accelerators independently observed muon neutrino disappearance over several hundred km long baselines. OPERA observed a presence of tau in muon neutrino beam.... T2K, NOvA...

What about charged leptons ?

Pontecorvo–Maki–Nakagawa–Sakata matrix (PMNS)

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

In the lepton sector:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

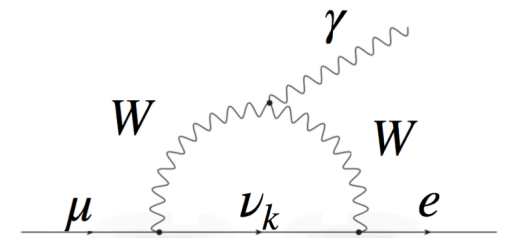
Charged Lepton Flavor violation (CLFV)

In the charged lepton sector Lepton Flavor Violation is **heavy suppressed** in the Standard Model

$$l_\alpha \rightarrow l_\beta < 10^{-54}$$

Example of **lepton flavor conservation** is a muon decay $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$

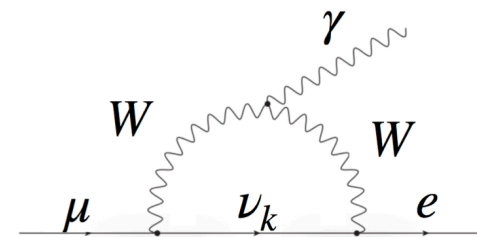
Example of **charged lepton flavor violation (CLFV)**: neutrinoless muon decay $\mu^- \rightarrow e^- \gamma$



Opportunity for New Physics !!!

Strongest present limits on $\mu \rightarrow e$, $\tau \rightarrow e$, $\tau \rightarrow \mu$

- Many searches for a physics Beyond the Standard Model.
- CLFV can be investigated both through **rare lepton decays/processes** and through **lepton-hadron scattering**
- The strongest limit comes from MEG-II $\mu^- \rightarrow e^- \gamma$



Process	Current limit	Experiment	Facility	Target sensitivity
$\mu \rightarrow e \gamma$	1.5×10^{-13}	MEG II	PSI, Switzerland	$\sim 6 \times 10^{-14}$
$\mu \rightarrow 3e$	1.0×10^{-12}	Mu3e	PSI, Switzerland	$\sim 10^{-16}$
$\mu N \rightarrow e N$	7×10^{-13} (Au)	Mu2e	Fermilab, USA	$\sim 10^{-16}$
$\mu N \rightarrow e N$	7×10^{-13} (Au)	COMET	J-PARC, Japan	$\sim 10^{-16} - 10^{-17}$
$\mu N \rightarrow e N$	7×10^{-13} (Au)	PRISM/PRIME	J-PARC, Japan	$\sim 10^{-18}$ (long-term goal)
$\tau \rightarrow \ell \gamma$	$\sim (3 - 4) \times 10^{-8}$	Belle II	KEK, Japan	$\sim 10^{-9}$
$\tau \rightarrow 3\ell$	$\sim 10^{-8}$	Belle II	KEK, Japan	$\sim 10^{-10}$

CLFV search $e \rightarrow \mu$

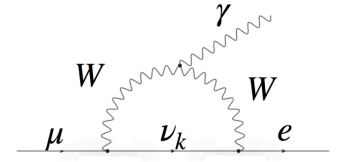
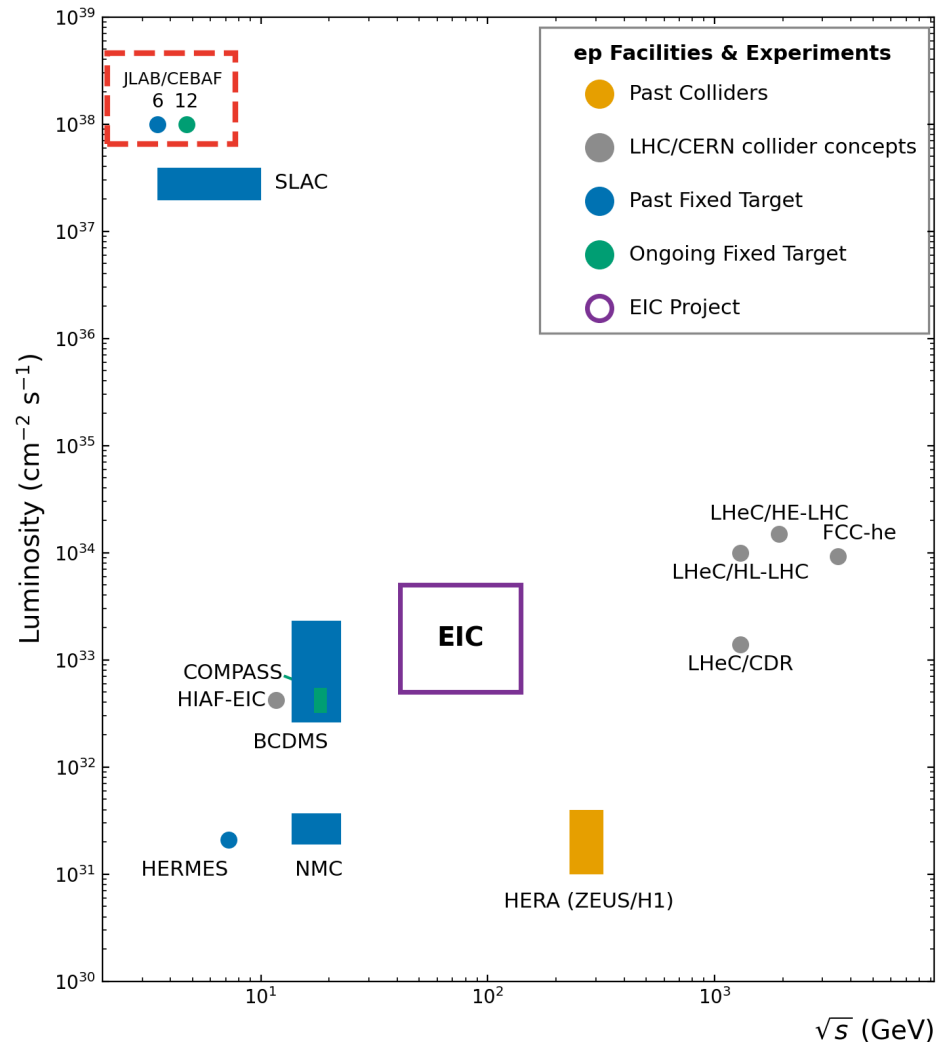
[T.Blazek](#), [S.F.King](#) "Electron to Muon Conversion in Electron-Nucleus Scattering as a Probe of Supersymmetry", [arXiv:hep-ph/0408157](#)

Estimated limit from $\mu \rightarrow e \gamma$ $\text{BR}(\mu \rightarrow e \gamma) \leq 10^{-11} \rightarrow \sigma(e + N \rightarrow \mu + N) \leq 10^{-8} \text{fb}$.

Conclusion: "We strongly urge our experimental colleagues to consider performing such an experiment".

Complementary search ($e \rightarrow \mu$)

Past, existing and proposed DIS facilities



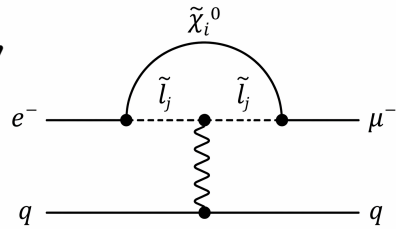
- Rare process. High luminosity is a key!
- Different CLFV processes probe different combinations of new-physics couplings
- Complementary search with ($e \rightarrow \mu$)
- together they can reveal the underlying mechanism

Process	Current limit	Experiment	Facility	Target sensitivity
$\mu \rightarrow e \gamma$	1.5×10^{-13}	MEG II	PSI, Switzerland	$\sim 6 \times 10^{-14}$
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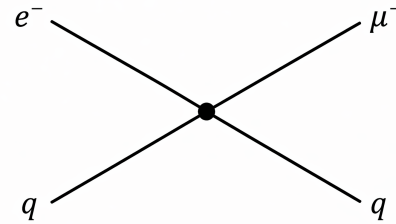
Various BSM models that predict CLFV

- eN facilities are complementary to $\mu+N \rightarrow e+N$ experiments ($\mu+N$: low energy conversion, stopped muon+Nucleus)
- $e+N \rightarrow \mu+N$ DIS scattering directly probes lepton-quark flavor-changing interactions at high momentum transfer
- Comparing the two could help disentangle the underlying CLFV mechanism (sensitivity to scalar, vector, dipole or other effective interactions)

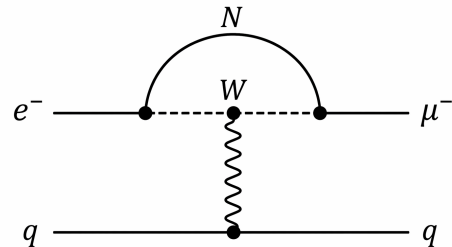
Supersymmetry



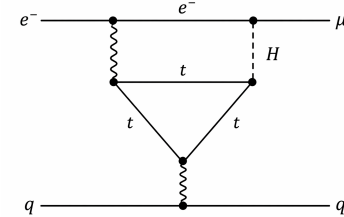
Compositeness



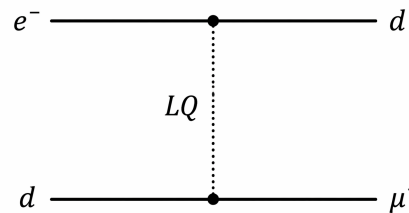
Heavy neutrino



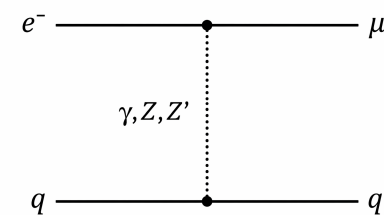
Higgs/top loops



Leptoquarks

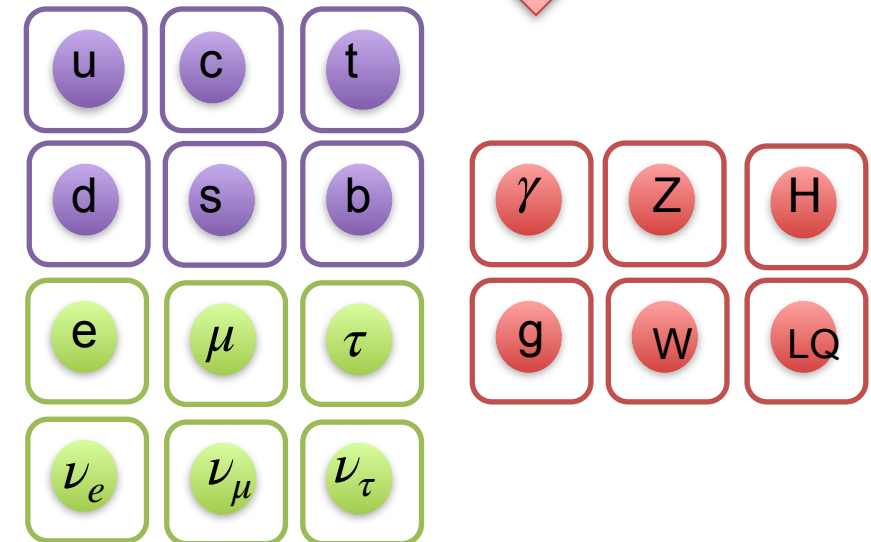
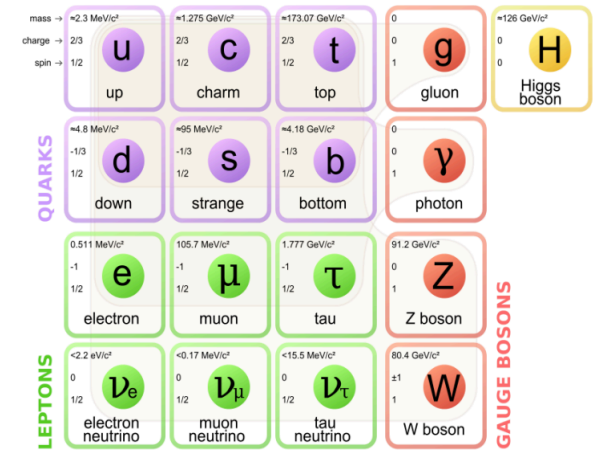


Heavy Z' ,
Anomalous boson
Coupling



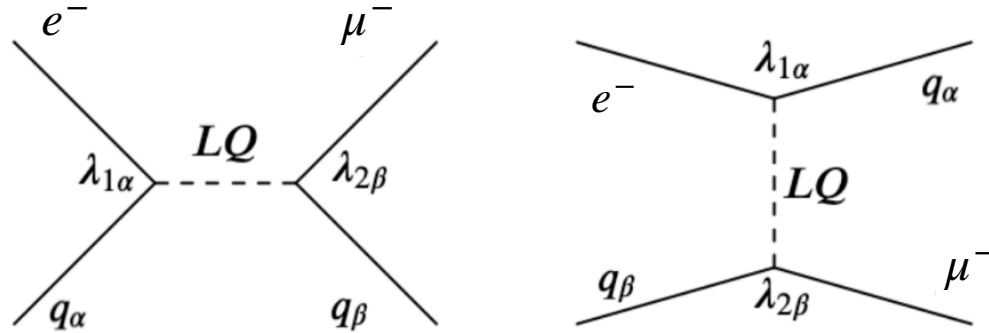
Leptoquarks

- **Leptoquarks** provide a particularly **direct mechanism** for CLFV in lepton-hadron scattering
- Leptoquark is a hypothetical color triplet **boson** (appear in many SM extensions)
- **It provides a symmetry** between electron and quark sectors: It carries both lepton and quark quantum numbers.
- **Flavor is not conserved**, but
- **Fermion number** $F = 3B + L$ ($F = 0, F = 2$) is to be conserved
- LQs model are explored in Buchmüller-Rückl-Wyler (BRW) framework under $SU(3) \times SU(2) \times U(1)$:
- 14 different LQ types (7 scalars, 7 vectors) .
- LQ couple to both leptons and quarks and carry $SU(3)$ color, fractional electric charge, baryon (B) and lepton (L) number



CLFV ($e \rightarrow \mu$)

$e^- N \rightarrow \mu^- X$ CLFV process mediated by the tree-level exchange of LQ states in the s- and u- channels.



$$\sigma_{F=0}^{e^- p} = \sum_{\alpha, \beta} \frac{s}{32\pi} \left[\frac{\lambda_{1\alpha} \lambda_{2\beta}}{M_{LQ}^2} \right]^2 \left\{ \int dx \int dy x \bar{q}_\alpha(x, xs) f(y) + \int dx \int dy x q_\beta(x, -u) g(y) \right\},$$

$$\sigma_{|F|=2}^{e^- p} = \sum_{\alpha, \beta} \frac{s}{32\pi} \left[\frac{\lambda_{1\alpha} \lambda_{2\beta}}{M_{LQ}^2} \right]^2 \left\{ \int dx \int dy x q_\alpha(x, xs) f(y) + \int dx \int dy x \bar{q}_\beta(x, -u) g(y) \right\},$$

Leptoquarks at ep/eA experiments

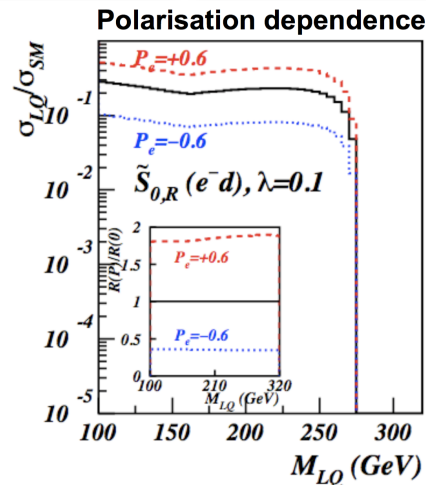
e^-p

Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
S_0^L	0	2	-1/3	$e_L^- u_L \rightarrow \begin{cases} \ell^- u \\ \nu_\ell d \end{cases}$	$\begin{matrix} \lambda_L \\ -\lambda_L \end{matrix}$	$\begin{matrix} 1/2 \\ 1/2 \end{matrix}$
S_0^R	0	2	-1/3	$e_R^- u_R \rightarrow \ell^- u$	λ_R	1
$\tilde{S}_0^R$	0	2	-4/3	$e_R^- d_R \rightarrow \ell^- d$	λ_R	1
S_1^L	0	2	-1/3	$e_L^- u_L \rightarrow \begin{cases} \ell^- u \\ \nu_\ell d \end{cases}$	$\begin{matrix} -\lambda_L \\ -\lambda_L \end{matrix}$	$\begin{matrix} 1/2 \\ 1/2 \end{matrix}$
			-4/3	$e_L^- d_L \rightarrow \ell^- d$	$-\sqrt{2}\lambda_L$	1
$V_{1/2}^L$	1	2	-4/3	$e_L^- d_R \rightarrow \ell^- d$	λ_L	1
$V_{1/2}^R$	1	2	-1/3	$e_R^- u_L \rightarrow \ell^- u$	λ_R	1
			-4/3	$e_R^- d_L \rightarrow \ell^- d$	λ_R	1
$\tilde{V}_{1/2}^L$	1	2	-1/3	$e_L^- u_R \rightarrow \ell^- u$	λ_L	1

e^+p

Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
V_0^L	1	0	+2/3	$e_R^+ d_L \rightarrow \begin{cases} \ell^+ d \\ \bar{\nu}_\ell u \end{cases}$	$\begin{matrix} \lambda_L \\ \lambda_L \end{matrix}$	$\begin{matrix} 1/2 \\ 1/2 \end{matrix}$
V_0^R	1	0	+2/3	$e_L^+ d_R \rightarrow \ell^+ d$	λ_R	1
$\tilde{V}_0^R$	1	0	+5/3	$e_L^+ u_R \rightarrow \ell^+ u$	λ_R	1
V_1^L	1	0	+2/3	$e_R^+ d_L \rightarrow \begin{cases} \ell^+ d \\ \bar{\nu}_\ell u \end{cases}$	$\begin{matrix} -\lambda_L \\ \lambda_L \end{matrix}$	$\begin{matrix} 1/2 \\ 1/2 \end{matrix}$
			+5/3	$e_R^+ u_L \rightarrow \ell^+ u$	$\sqrt{2}\lambda_L$	1
$S_{1/2}^L$	0	0	+5/3	$e_R^+ u_R \rightarrow \ell^+ u$	λ_L	1
$S_{1/2}^R$	0	0	+2/3	$e_L^+ d_L \rightarrow \ell^+ d$	$-\lambda_R$	1
			+5/3	$e_L^+ u_L \rightarrow \ell^+ u$	λ_R	1
$\tilde{S}_{1/2}^L$	0	0	+2/3	$e_R^+ d_R \rightarrow \ell^+ d$	λ_L	1

- Electron and positron beams probe different types of Leptoquarks
 - electron-proton collisions, mainly $F=2$ LQs are produced
 - positron-proton collisions, mainly $F=0$ LQs are produced
- u vs d targets
- Polarization



1 generation

$eq \rightarrow LQ \rightarrow eqX$
 $eq \rightarrow LQ \rightarrow \nu_e qX$

LFC

2 generation

$eq \rightarrow LQ \rightarrow \mu qX$
 $eq \rightarrow LQ \rightarrow \nu_\mu qX$

3 generation

$eq \rightarrow LQ \rightarrow \tau qX$
 $eq \rightarrow LQ \rightarrow \nu_\tau qX$

CLFV

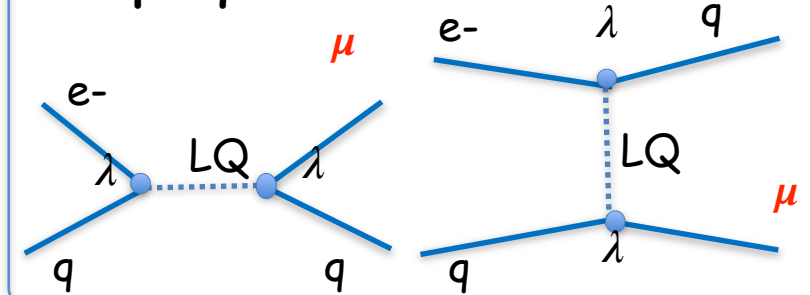
CLFV ($e \rightarrow \mu$)

- A CLFV signature via Leptoquark or via Parity Violating SUSY is **similar to DIS** :

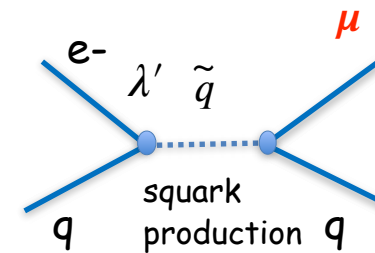
one isolated high P_T lepton + hadronic final state.

- Different flavor of lepton (**muon**) instead of DIS-electron in the final state.
- No scattered electron (!!!)
- Muon and hadronic system approximately back-to-back in the transverse plane (collider kinematics)
- Single-muon trigger
- Need good muon identification and muon background suppression

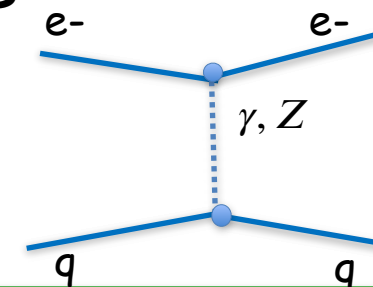
Leptoquarks



SUSY via Rp violating decay



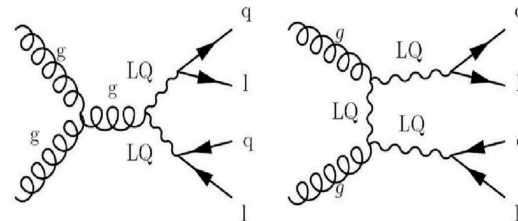
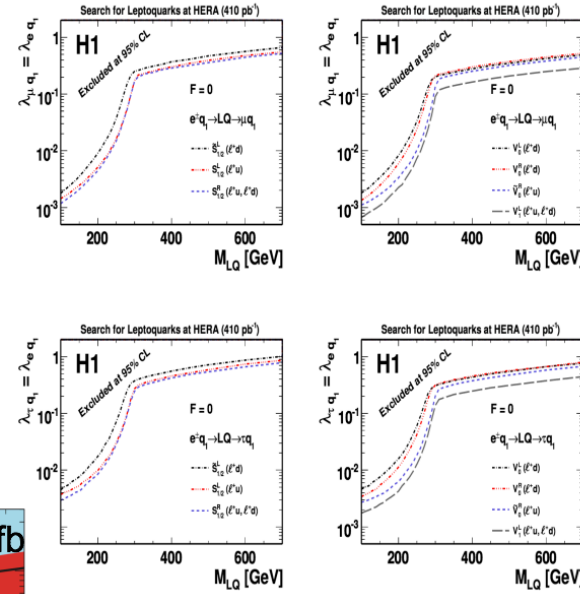
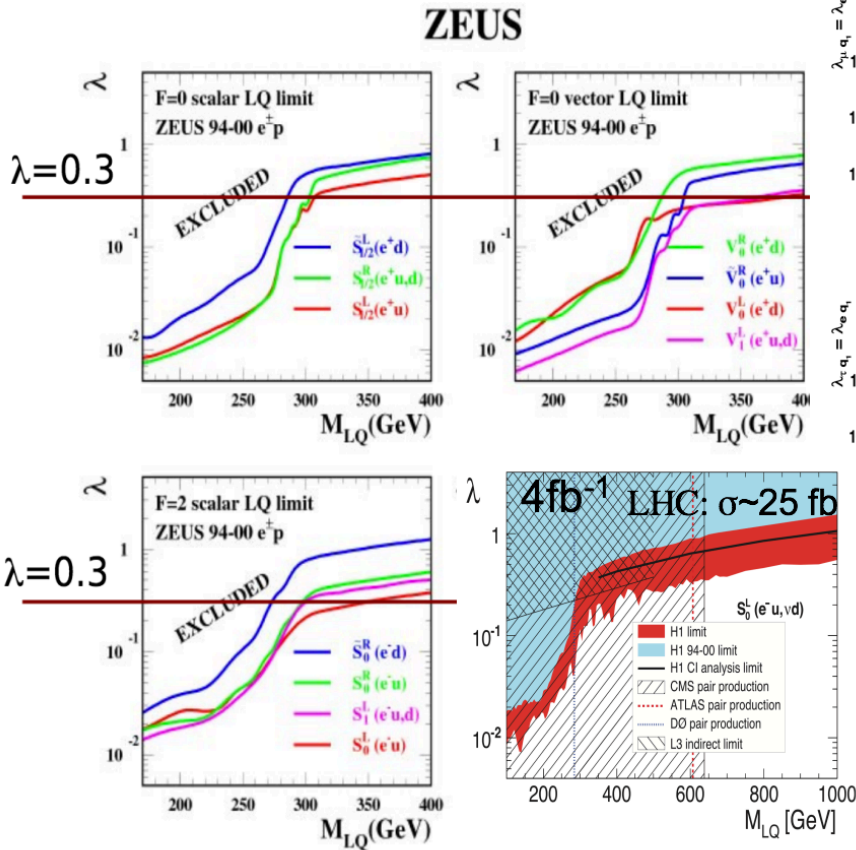
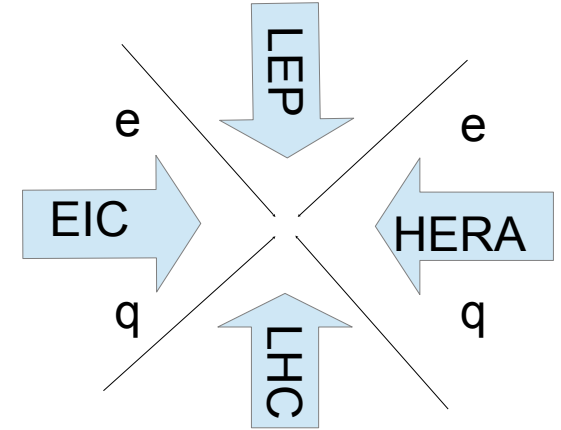
DIS



Leptoquark limits at ep, ee and pp colliders

LQ $\rightarrow e q$

LQ $\rightarrow \mu q$ and LQ $\rightarrow \tau q$



For $M_{LQ} < \sqrt{s}$: s-channel resonant
For $M_{LQ} > \sqrt{s}$: exchange - contact interaction

•LEP (ee):contact interactions (indirect
constrains from $e^+e^- \rightarrow qq$)

•LHC/TEVATRON (pp): pair production (λ
independent)

•HERA/EIC (ep): **single LQ production** $M < \sqrt{s}$,
contact interaction $M > \sqrt{s}$

For leptoquark Yukawa coupling $\lambda = 0.1$, the ZEUS bounds on the first-generation leptoquarks range from 248 to 290 GeV

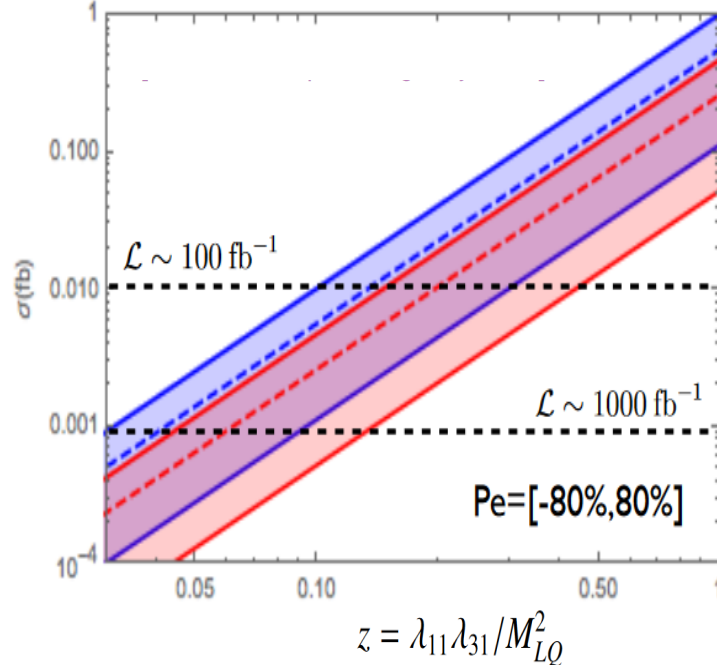
CLFV at EIC ($e \rightarrow \mu$, $e \rightarrow \tau$)

- Cross-section for $ep \rightarrow \tau X$ takes the form:

$$\sigma_{F=0} = \sum_{\alpha, \beta} \frac{s}{32\pi} \left[\frac{\lambda_{1\alpha} \lambda_{3\beta}}{M_{LQ}^2} \right]^2 \left\{ \int dx dy x \bar{q}_{\alpha}(x, xs) f(y) + \int dx dy x q_{\beta}(x, -u) g(y) \right\}$$

$$f(y) = \begin{cases} 1/2 & (\text{scalar}) \\ 2(1-y)^2 & (\text{vector}) \end{cases}, \quad g(y) = \begin{cases} (1-y)^2/2 & (\text{scalar}) \\ 2 & (\text{vector}) \end{cases}$$

Yulia Furletova and Sonny Mantry



$$z = \lambda_{11} \lambda_{31} / M_{LQ}^2$$

The blue (red) dotted line gives the unpolarized, $Pe = 0$

<https://doi.org/10.1063/1.5040210>

- Tau vertex displaced at cm level
- 3-prong tau jet; decay topology important for τ jet ID
- 1-prong: recovering higher branching ratios; but background control is much more demanding

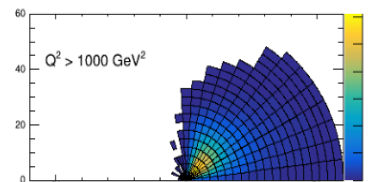
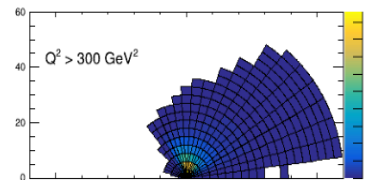
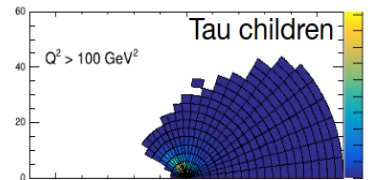
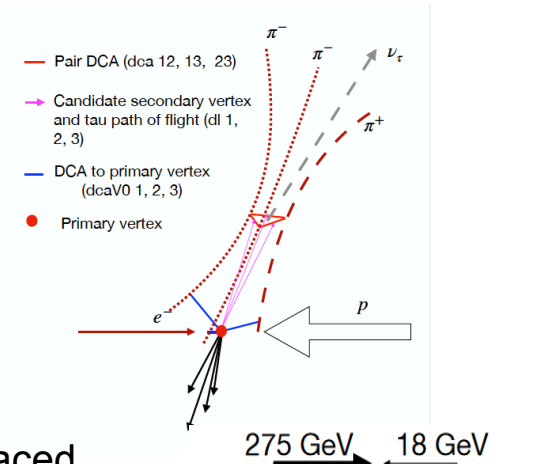
- Isolated tau, Pt balance with q-jet.
- Tau-Jet identification (narrow cone, displaced vertex)
- Precise measurements of vertex (tau vertex displacements 200 to 3000 microns)

- Sensitivities to the CLFV(1,3) would be enhanced with positron beams (can search for specific LQ)

- Current limits set by HERA sitting at sensitivities of a few fb

→ The high luminosity of the EIC will gain us 2 orders of magnitude, compared to HERA

Jinlong Zhang



Angle for theta, radius for momentum

Complementary search ($e \rightarrow \mu$) using a high
luminosity environments at JLAB/CEBAF:

$$e+N \rightarrow \mu+N$$

CLFV ($e \rightarrow \mu$)

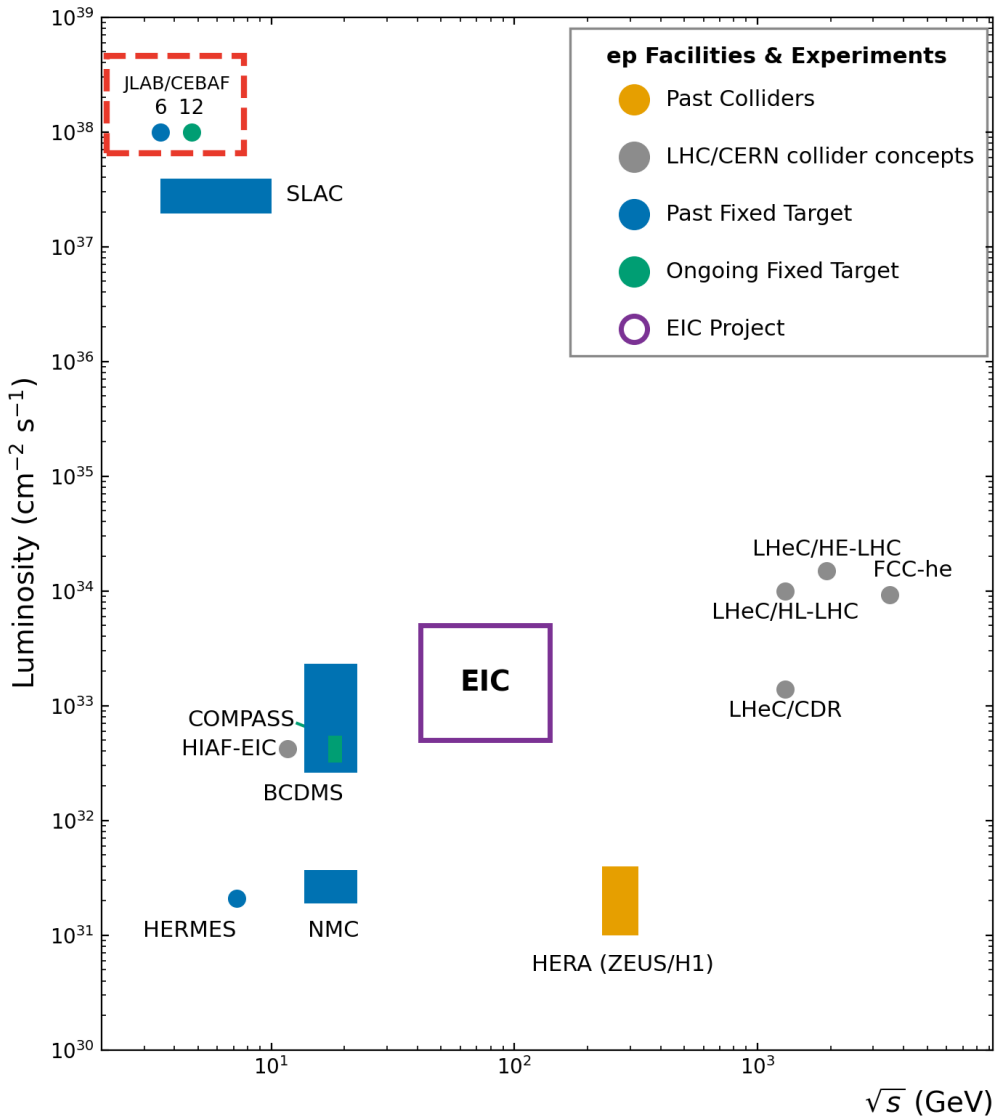
An experimental program with high duty-cycle polarized and unpolarized positron beams at Jefferson Lab

=> (chapter) Charged lepton flavor violation

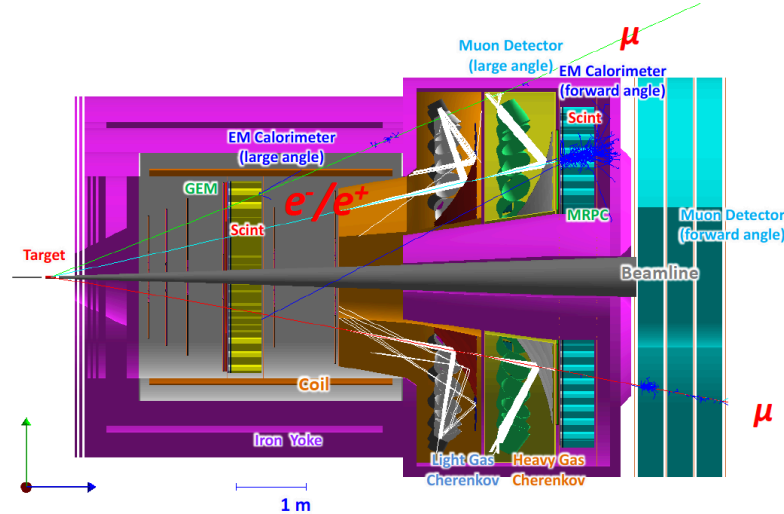
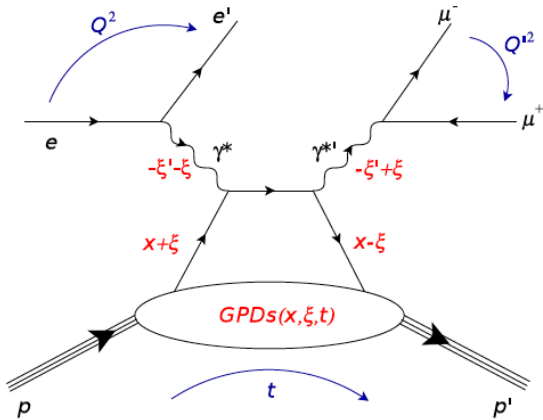
<https://arxiv.org/pdf/2007.15081>

$$z = (\lambda_{11}\lambda_{21}/M_{LQ}^2)/(\lambda_{11}\lambda_{21}/M_{LQ}^2)_{\text{HERA LIMIT}}$$

	HERA	EIC	JLAB/CEBAF
center-of-mass (s)	~ 320	$\times 10^{-1}$	$\times 10^{-2}$
PDFs			$\times 10^{-1}$
Luminosity	10^{31}	$\times 10^2 - 10^3$	$\times 10^7 - 10^8$
Ions/Nuclear beam	p	p/A	p/A
positron beams	e+ / e-	e-	e- (possible upgrade e+ ?)
Polarization	only e	e- and p/A	e- and p/A

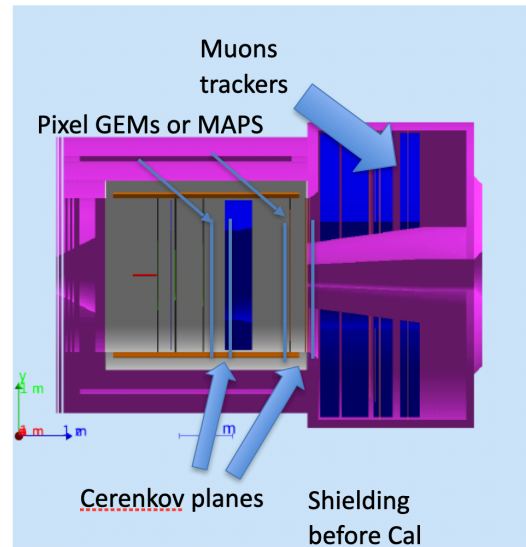


SOLID J/Psi setup and Dedicated possible DDVCS setup



- GEM-Tracker
- EMCAL
- Muon chambers

- Data could be taken concurrently with J/Psi experiment
- High luminosity $\sim 10^{37} \text{ cm}^{-2}\text{s}^{-1}$ (corrected for acceptance)
- 70% for one muon detection efficiency



- Future dedicated experiments
- Target in magnet to contain low energy background
- Optimized new setup with more planes and pixel readout GEM or MAPS
- Optimized high granularity Cerenkov (Hadron Blind Detector type or using pixelized MCP PMTs)
- Giving up calorimeter resolution with shielding for radiation hardness, rely on tracking for momentum measurement

High luminosity at least $10^{38} \text{ cm}^{-2}\text{s}^{-1}$
(35 uA on 15 cm LH2 target)

Could reach $5 \cdot 10^{38} \text{ cm}^{-2}\text{s}^{-1}$

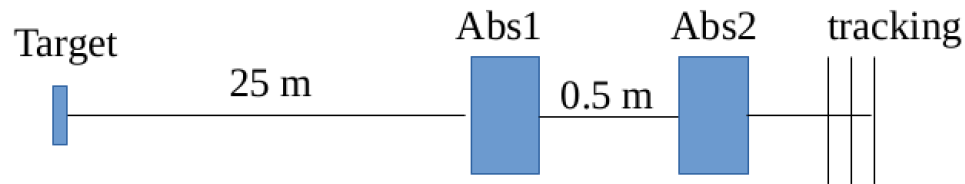
(60 uA on 40 cm target limited by detectors rate capability under study)

Muon identification

Vardan Khachatryan

- Single-muon trigger (no electrons)
- Minimize muon background
 - main sources of muon background
 - pion decays $\pi^+ \rightarrow \mu^+ + \nu_\mu$ or $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
 - cosmic

W	Cu	Fe
$X_0 = 0.35$ cm (radiation length)	$X_0 = 1.44$ cm	$X_0 = 1.76$ cm
$\lambda = 9.95$ cm (hadron interaction length)	$\lambda = 15.32$ cm	$\lambda = 16.8$ cm

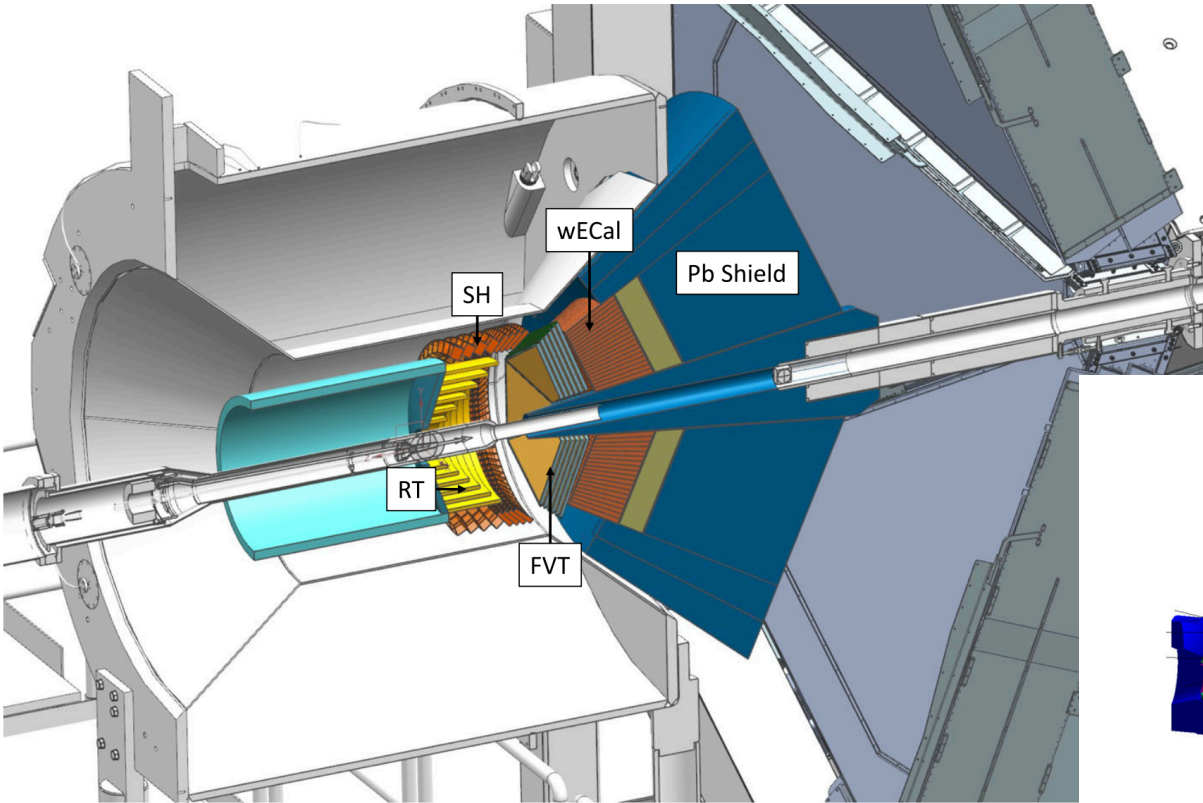


With one 30cm tungsten absorber (W): 1-10 % of pions will be identified as muons

Need more abs/tracking sections

Need to reduce distance or place tracking close to target (vertex detector)

Muon identification with μCLAS12



• https://www.jlab.org/exp_prog/proposals/25/PR12-25-001.pdf

- Single muon trigger
- Good muon identification
- Good **primary vertex reconstruction for muons** (helps to reduce a background)

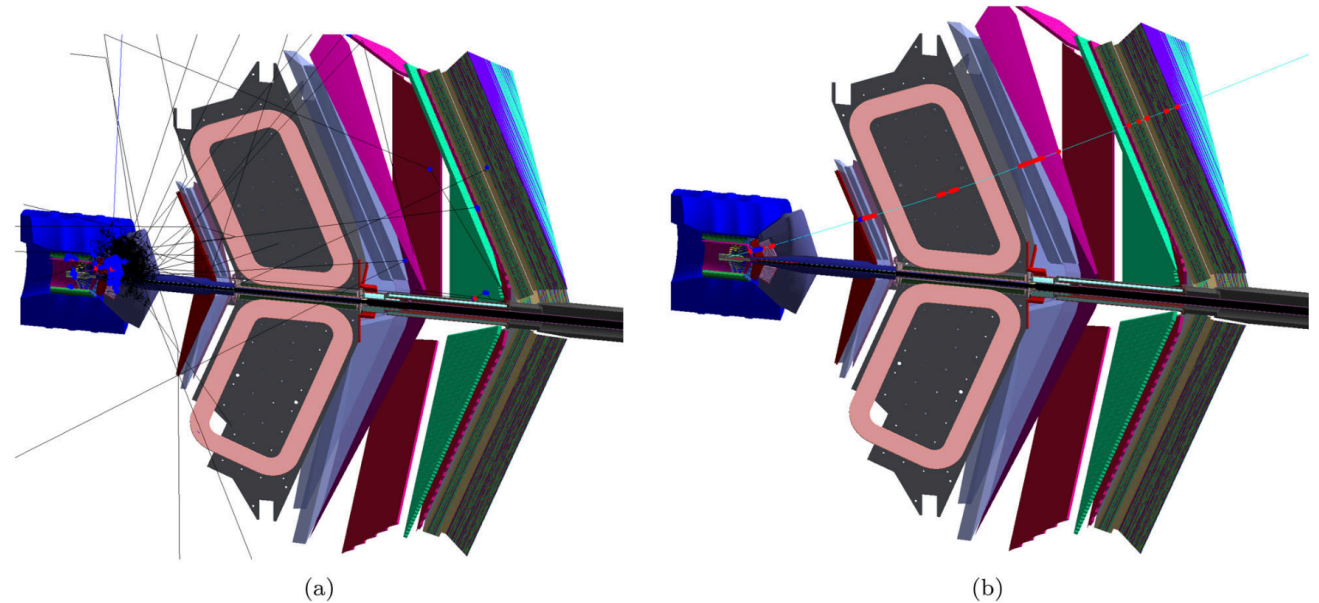
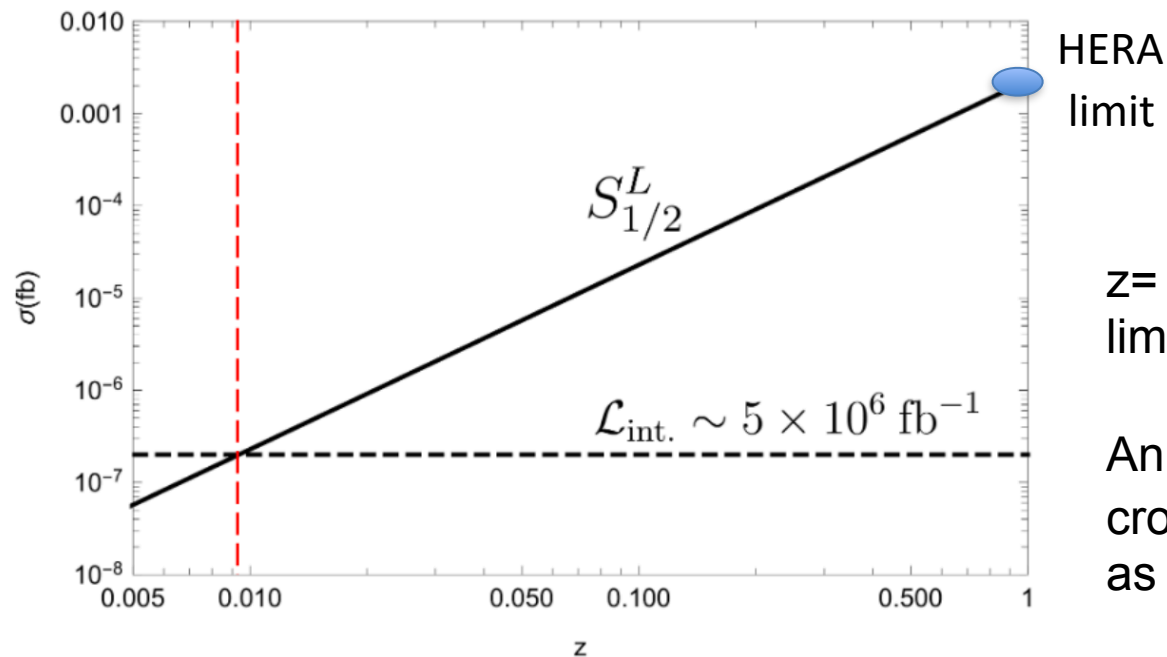


Fig. 17 Simulation of a 6 GeV π^+ (Panel 17a) and a 6 GeV μ^+ (Panel 17b) in the μCLAS12 GEANT4 model. Nearly all pions undergo hadronic showers in the wECal, while most muons reach the FD and are reconstructed in both the DC and the ECal

CLFV ($e \rightarrow \mu$)

[arXiv:2007.15081](https://arxiv.org/abs/2007.15081) (e+@JLAB)

S. Mantry, Y. Furletova



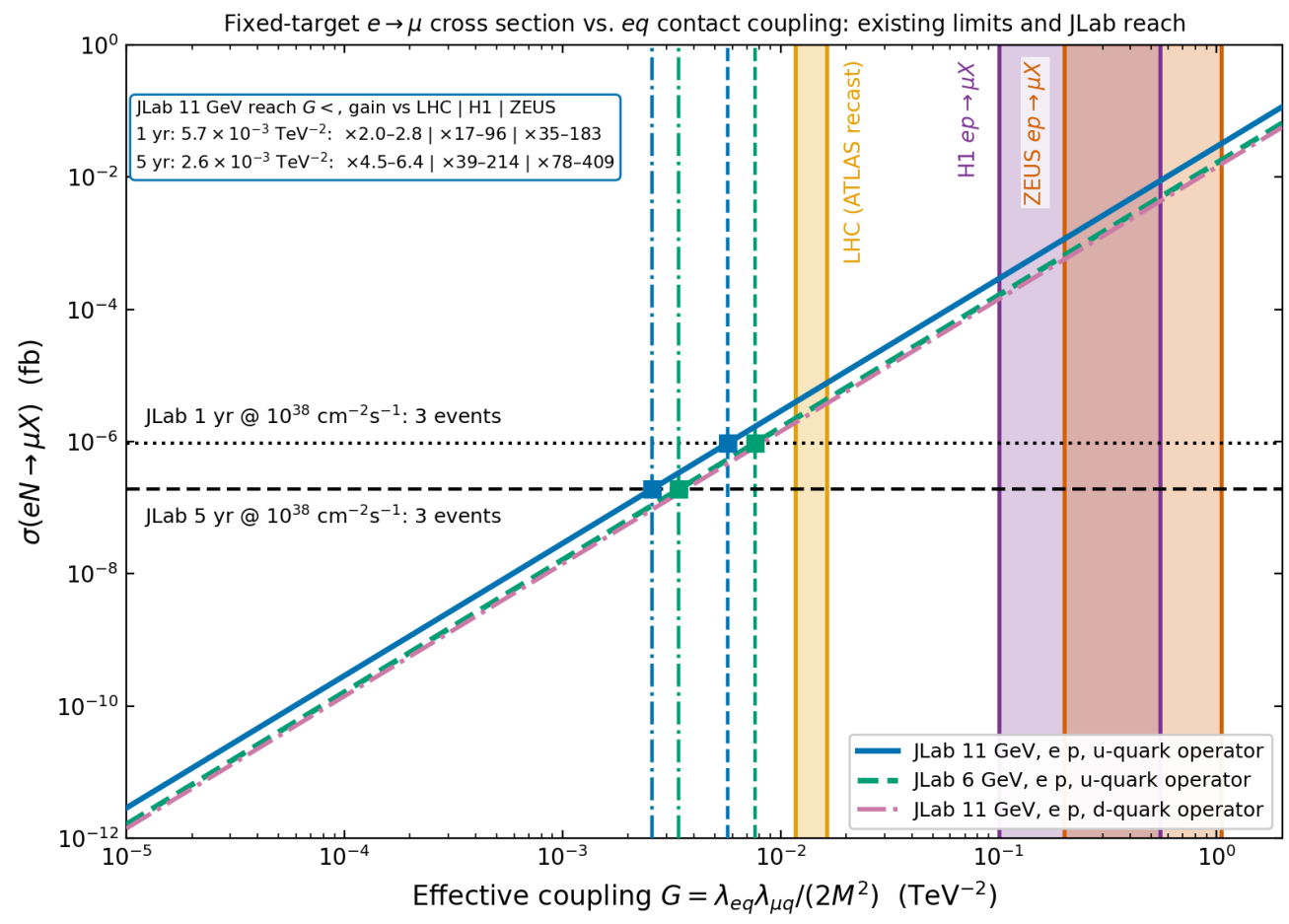
$$\chi_{\alpha\beta} \equiv \frac{\lambda_{1\alpha}\lambda_{1\beta}}{M_{LQ}^2}, \quad z \equiv \frac{\chi_{\alpha\beta}}{\chi_{\alpha\beta}^{\text{HERA}}},$$

$z = 1$ corresponds to evaluating the cross section at the HERA limit HERA $\sim 0.7 \text{ TeV}^{-2}$.

An integrated luminosity of $\mathcal{L} \sim 5 \times 10^6 \text{ fb}^{-1}$ will allow sensitivity to cross sections as small as $\sigma \sim 0.2 \times 10^{-6} \text{ fb} \sim 2 \cdot 10^{-4} \text{ ab}$ (attobarns) $\sim$ **0.2 zb (zeptobarns)**

=> Improving HERA limit by factor 100!

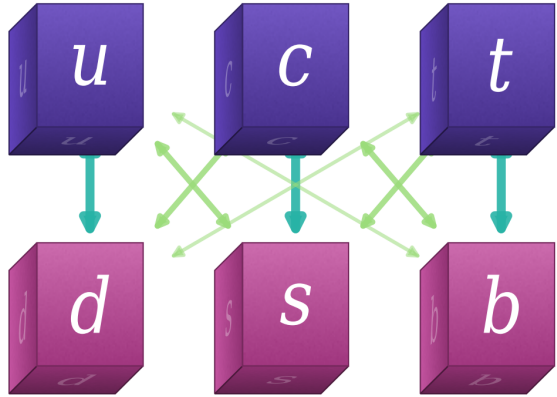
AI: CLFV ($e \rightarrow \mu$), cross-section and Effective coupling limit



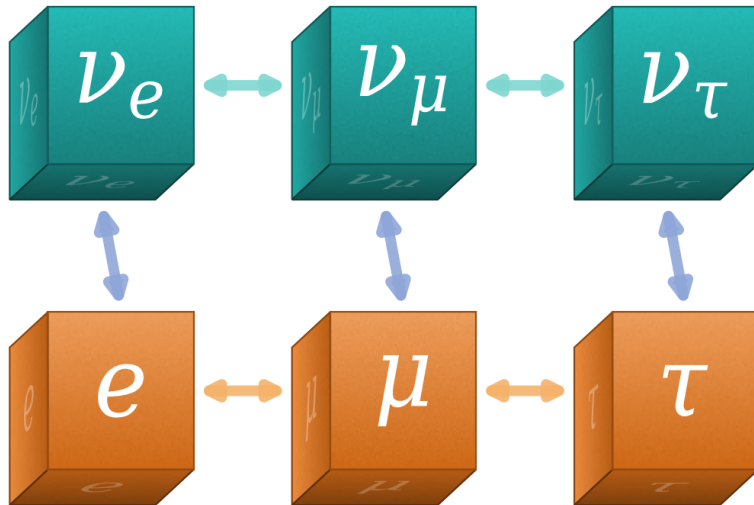
Conclusions

- CLFV is a power search for physics Beyond the Standard Model
- Existing searches (rare decays($\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$) , $\mu N \rightarrow eN$ facilities) provides extraordinary sensitivity to very small flavor-violation effects
- Complementary searches probe complementary interactions: $eN \rightarrow \mu N$ directly probes lepton-quark flavor violation interactions at high Q^2 . Leptoquarks provide a natural connection. HERA demonstrated the feasibility for CLFV at DIS searches.
- Next step is to explore with substantially higher luminosity to expand sensitivity to much smaller cross-sections and weaker lepton-quark couplings.
- CEBAF offers a very high luminosity (and potentially polarized positrons) facility for CLFV searches and can provide orders-of-magnitude stronger sensitivity, compared to previous CLFV DIS searches.
- Combined together with other CLFV facilities/experiments, such experiments could provide results in different regions of the CLFV parameter space, and therefore should be viewed as complementary rather than as competing experiments.

Conclusions



Quark mixing: **observed**



Neutrino mixing: **observed.**

Charged lepton mixing: **not yet observed.**



Let's discover it!

Backup