Charged Lepton Flavor Violation

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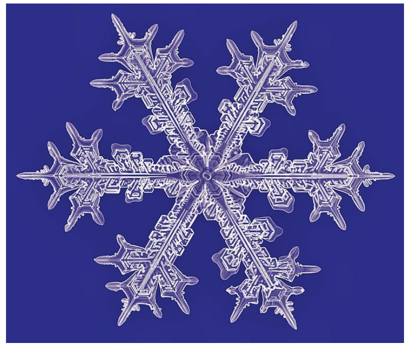
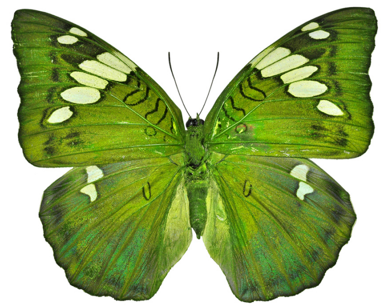
Outline

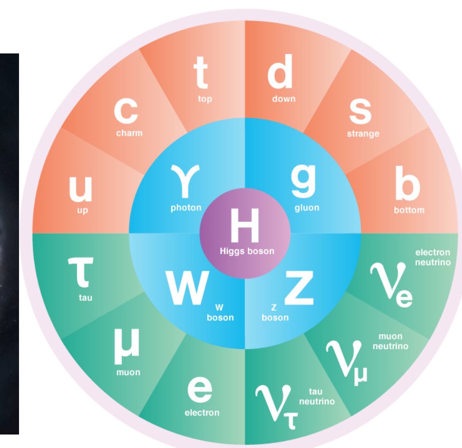
- Introduction
- Why CLFV ?
- CLFV in BSM physics
- CLFV at Hall-C CEBAF
- Conclusions

Introduction



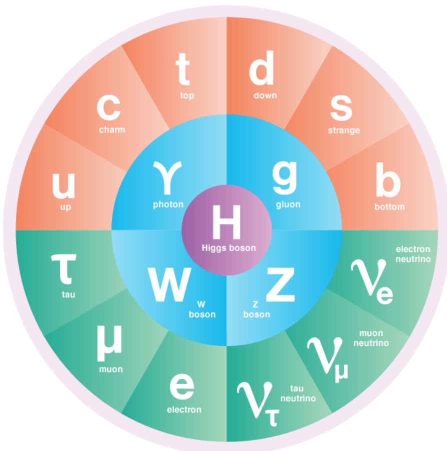


Symmetry



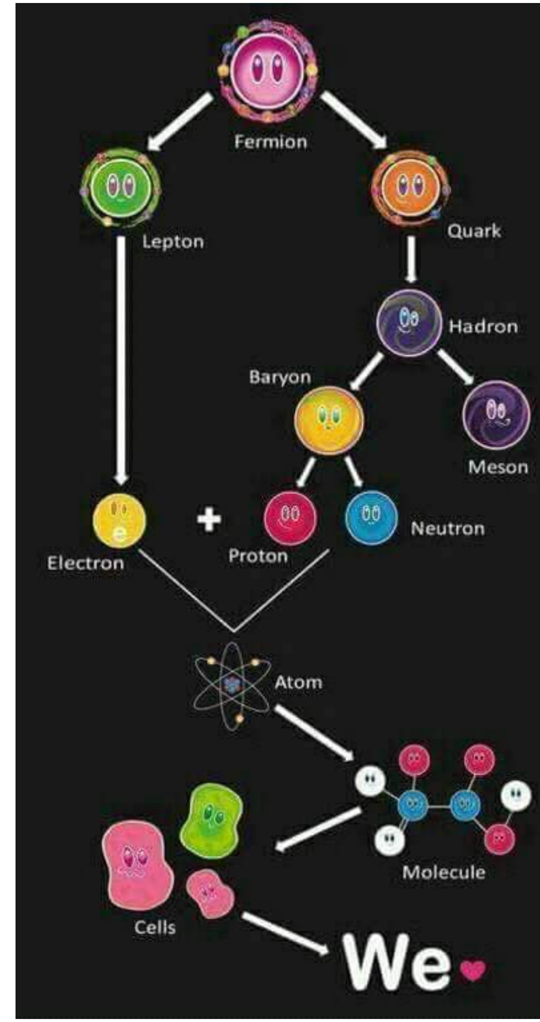
Random pictures from Google

The Standard Model



- What is a fundamental symmetry?
- What are conserved quantities in the fundamental interactions?
- SM contains no explanation for the symmetry between quark and lepton sectors:
  - -mass hierarchy
  - -the number of generations.

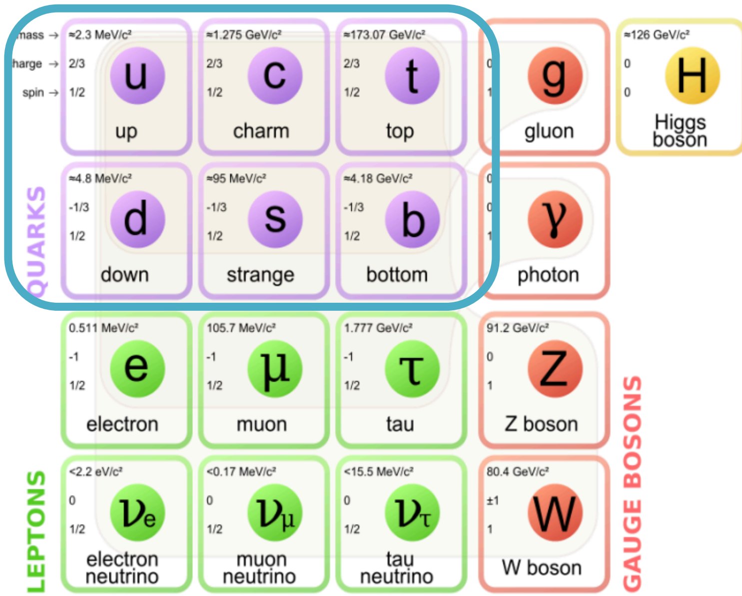
-Flavor is not a conserved quantity in fundamental interactions: Flavor mixing



"Physics page", FB

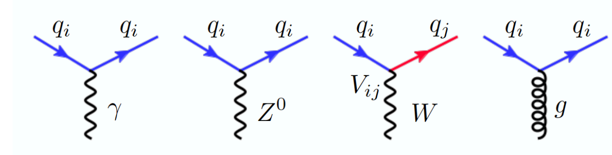
Flavors in quark sectors

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$



In the quark sector:

The flavor changing neutral currents (FCNCs) are forbidden in the standard model (SM) at tree level (require a loop process involving a virtual W exchange).



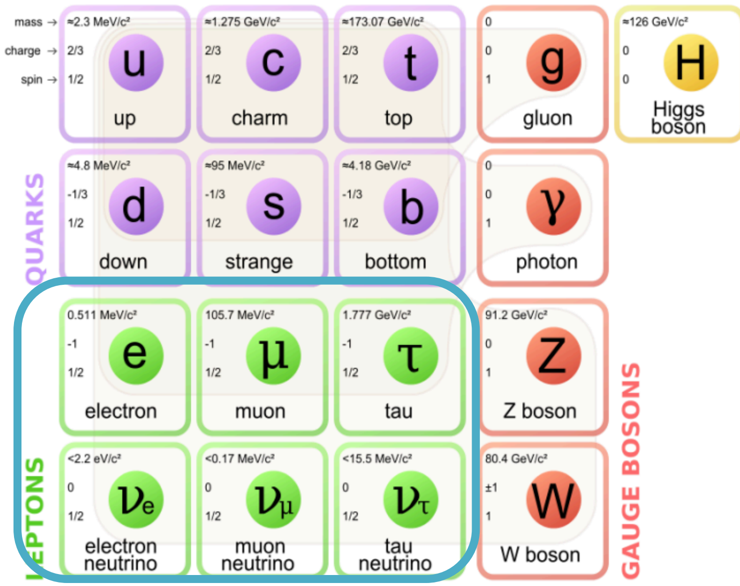
- Family number is not a symmetry in SM: quark family number is violated in weak decays in the CKM matrix
- Flavor mixing in the standard model quark sector is well established, through processes like K^0–$\overline{K}^0$ oscillations, B_d–$\overline{B}_d$ mixing etc.

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

What about lepton sector?

Lepton Flavor

In the lepton sector: $\begin{pmatrix}\nu_e \\ e\end{pmatrix} \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix} \begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}$



- 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.

- 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…

Pontecorvo–Maki–Nakagawa–Sakata matrix (PMNS)

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

What about charged leptons ?

Charged LFV

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

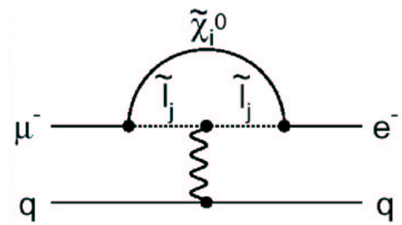
$$\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$$

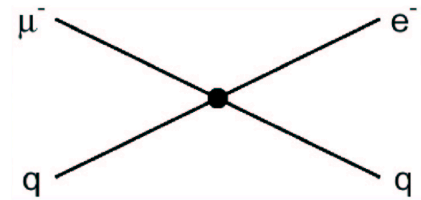
Example of CLFV: neutrinoless muon decay $\mu^- \rightarrow e^- \gamma$

Opportunity for New Physics !!!

Various BSM models that predict CLFV

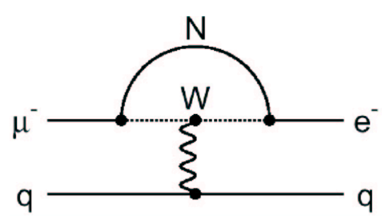
Supersymmetry

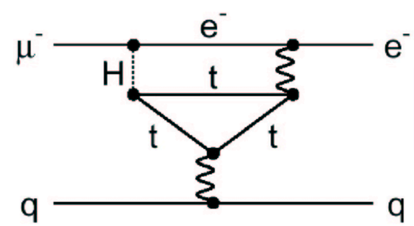




Compositeness

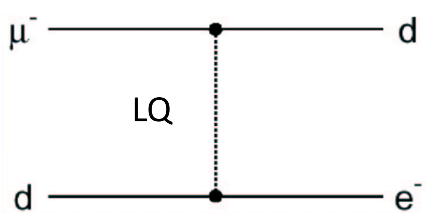
Heavy neutrino

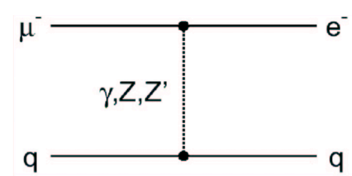




Higgs/top loops

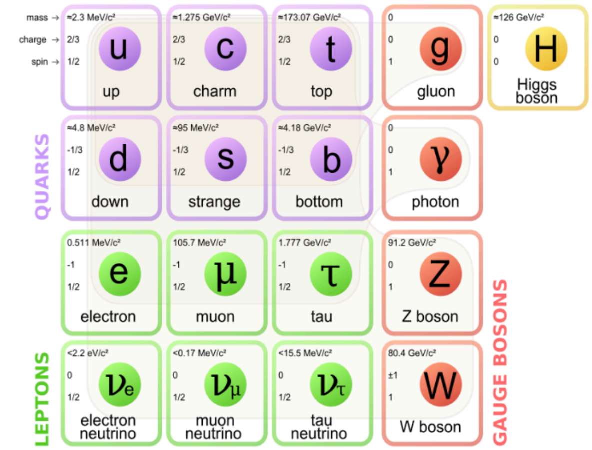
Leptoquarks



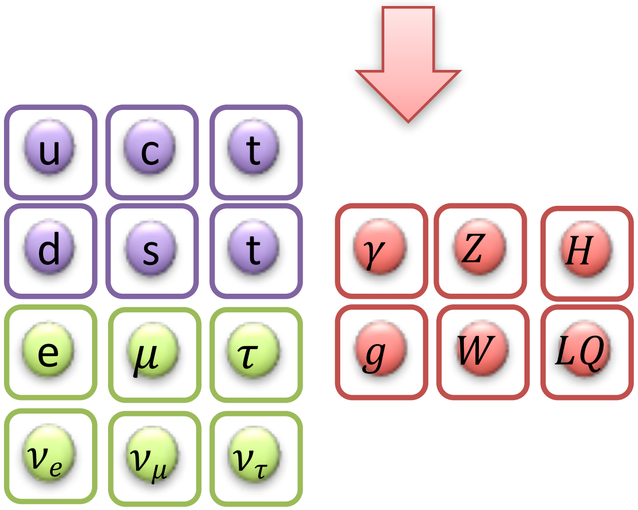


Heavy Z',
Anomalous boson
Coupling

Leptoquarks



- Leptoquark is a color triplet boson (appear in many SM extensions)
- Symmetry between electron and quark sectors.
- 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)xSU(2)xU(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



Leptoquarks at ep/eA experiments

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

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

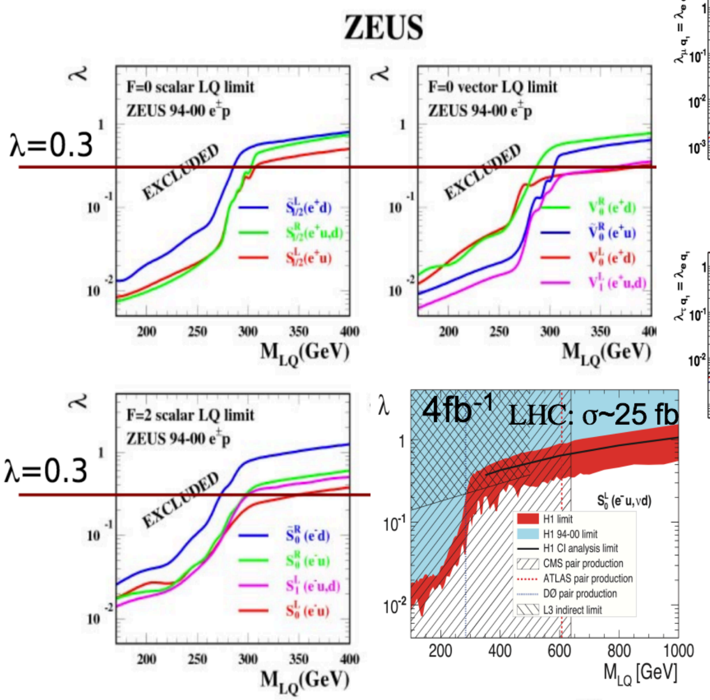
2 generation
eq -> LQ -> μqX
eq -> LQ -> ν_μqX

3 generation
eq -> LQ -> τqX
eq -> LQ -> ν_τqX

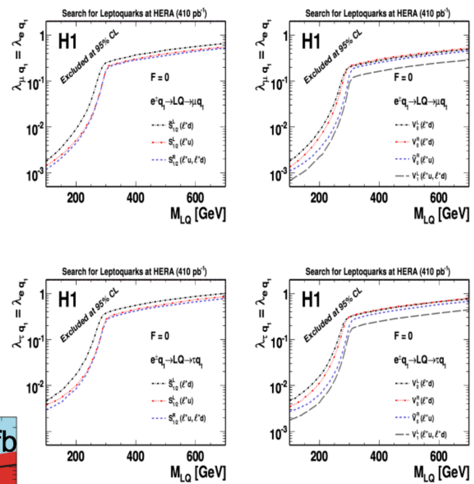
CLFV

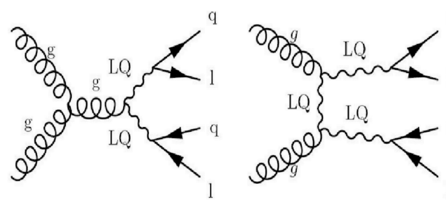
Leptoquark limits at ep, ee and pp colliders

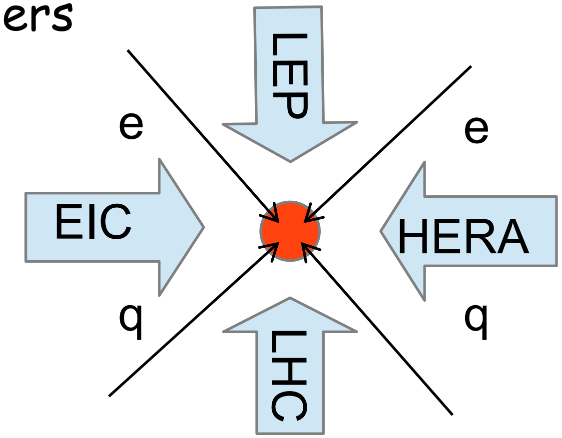
LQ->eq



LQ->μq and LQ-> τq





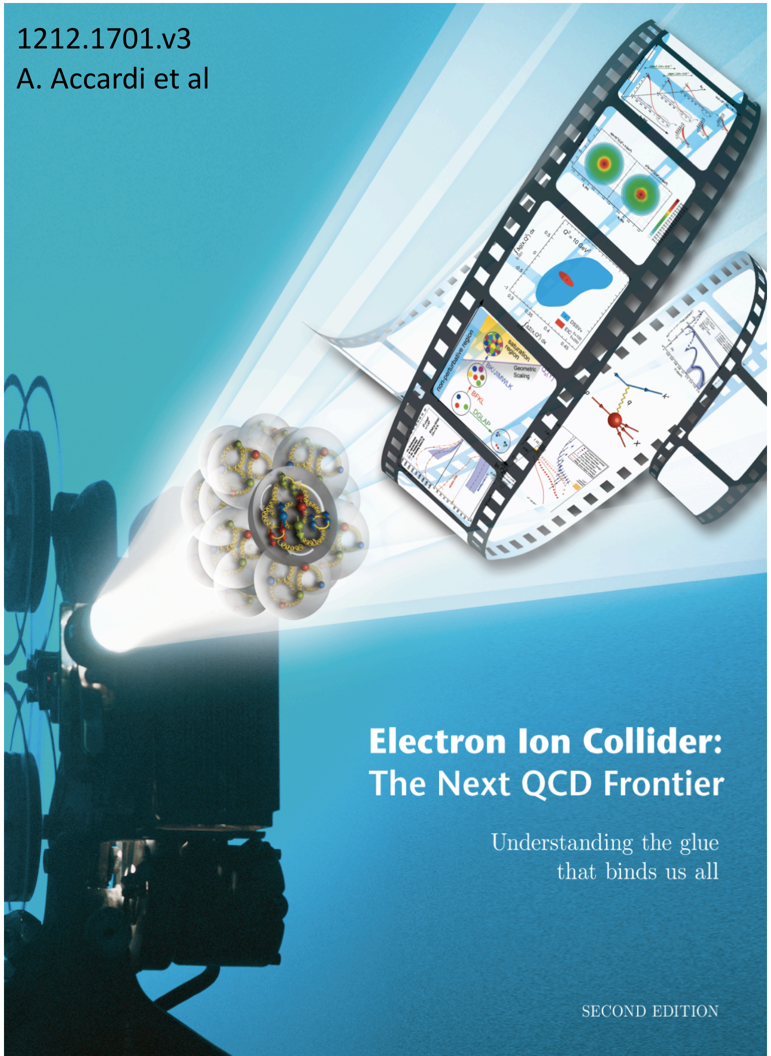


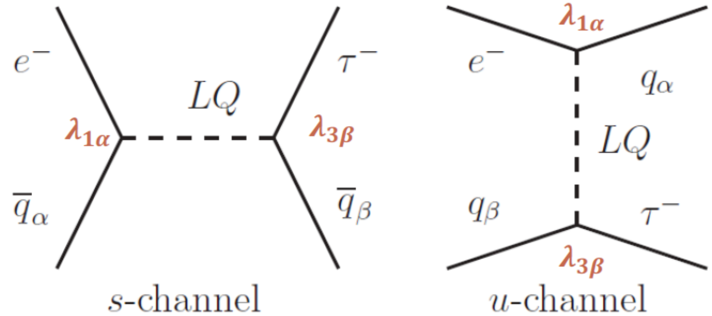
- LEP (ee):contact interactions (indirect constrains from e^+e^--> qq)
- LHC/TEVATRON (pp): pair production (λ independent)
- HERA/EIC (ep): single LQ production M<√s, contact interaction M>√s

HERA: L~10^{30-31}cm^{-2}s^{-1} (0.5 fb^{-1})
EIC: L~10^{34}cm^{-2}s^{-1} (>50 fb^{-1})

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

CLFV at EIC (e->μ,e->τ)





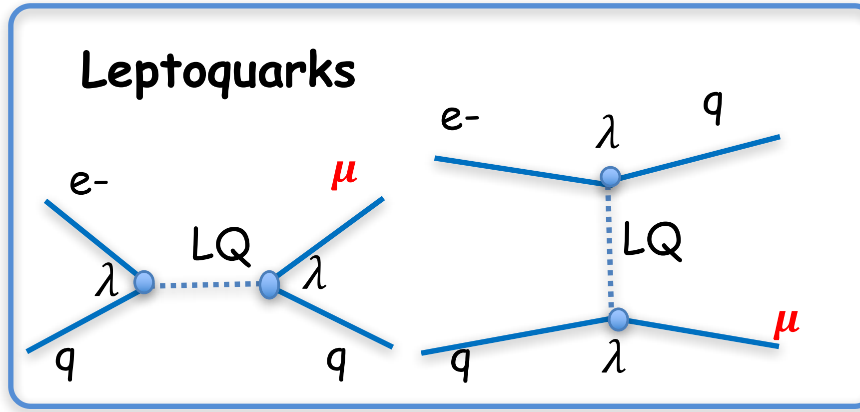
- Cross-section for $ep \to \tau X$ takes the form:

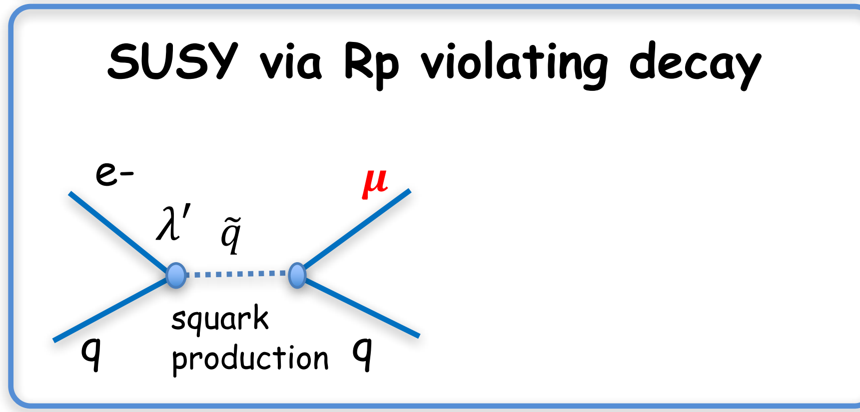
$$\sigma_{F=0} = \sum_{\alpha,\beta} \frac{s}{32\pi} \left[\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2} \right]^2 \left\{ \int dxdy \; x\bar{q}_\alpha(x, xs)\, f(y) + \int dxdy \; xq_\beta(x, -u)\, g(y) \right\}$$

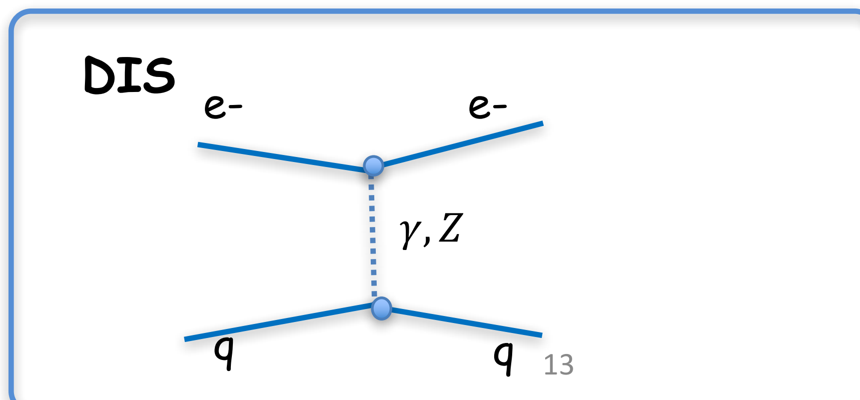
$$f(y) = \begin{cases} 1/2 & \text{(scalar)} \\ 2(1-y)^2 & \text{(vector)} \end{cases}, \quad g(y) = \begin{cases} (1-y)^2/2 & \text{(scalar)} \\ 2 & \text{(vector)} \end{cases}$$

CLFV (e->μ)

- A CLFV signature via Leptoquark or Parity Violating SUSY is similar to DIS but with muon instead of electron in the final state.
- Searches at HERA and LHC







Strongest present limits on μ->e, τ->e, τ->μ

Many searches for a physics Beyond the Standard Model, example

$$\mu^- \to e^- \gamma$$

Current limit (MEG) : Br < 4.2 $\cdot 10^{-13}$

LFV transitions	LFV Present Bounds (90%CL)	Future Sensitivities
$BR(\mu \to e\gamma)$	4.2×10^{-13} (MEG 2016)	4×10^{-14} (MEG-II)
$BR(\tau \to e\gamma)$	3.3×10^{-8} (BABAR 2010)	10^{-9} (BELLE-II)
$BR(\tau \to \mu\gamma)$	4.4×10^{-8} (BABAR 2010)	10^{-9} (BELLE-II)
$BR(\mu \to eee)$	1.0×10^{-12} (SINDRUM 1988)	10^{-16} Mu3E (PSI)
$BR(\tau \to eee)$	2.7×10^{-8} (BELLE 2010)	$10^{-9,-10}$ (BELLE-II)
$BR(\tau \to \mu\mu\mu)$	2.1×10^{-8} (BELLE 2010)	$10^{-9,-10}$ (BELLE-II)
$BR(\tau \to \mu\eta)$	2.3×10^{-8} (BELLE 2010)	$10^{-9,-10}$ (BELLE-II)
$CR(\mu - e, Au)$	7.0×10^{-13} (SINDRUM II 2006)	
$CR(\mu - e, Ti)$	4.3×10^{-12} (SINDRUM II 2004)	10^{-18} PRISM (J-PARC)
$CR(\mu - e, Al)$		3.1×10^{-15} COMET-I (J-PARC)

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

$$e + N \to \mu + N$$

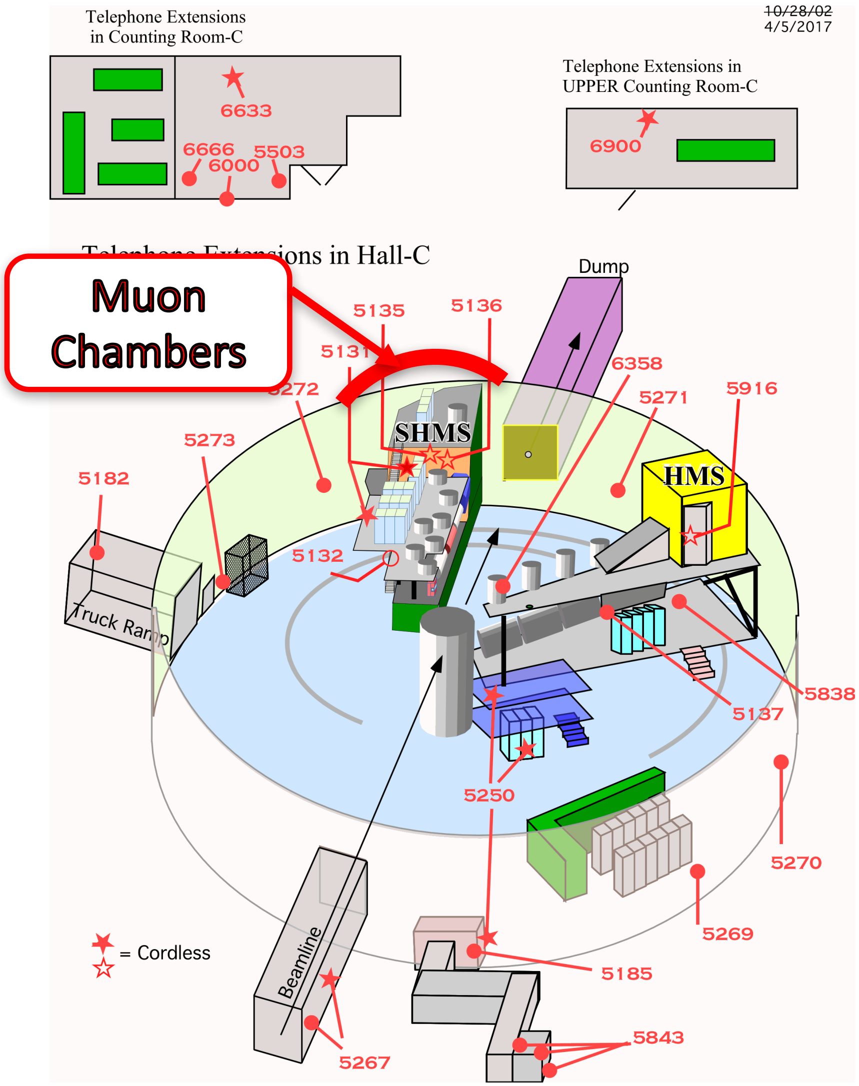
CLFV search $e\text{->}\mu$

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 $\mu^- \to e^- \gamma$ $\sigma(e + N \to \mu + N) \leq 10^{-8} fb.$

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

Hall-C

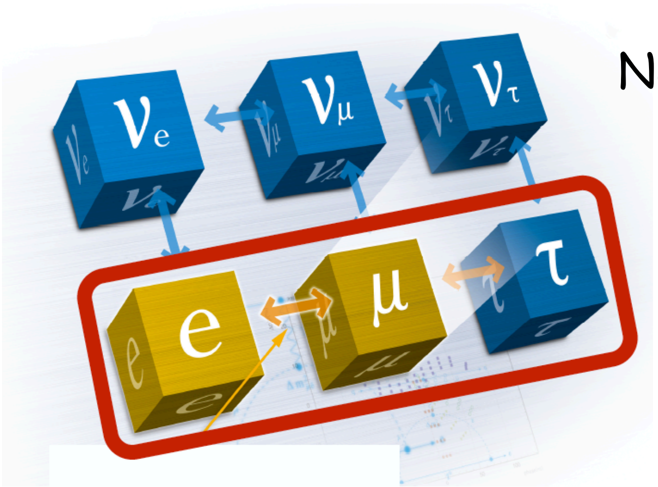


Proposal:

- A muon chamber after calorimeter and absorber ("e"-arm)
- Require a muon track to match a track in the inner/outer tracker.
- Require a "MIP" in the calorimeter
- Shielding to reduce a background

Conclusions

Quark mixing: observed



Neutrino mixing: observed.

Charged lepton mixing:
not yet observed.
Let's find it!

Backup