Charged Lepton Flavor Violation

Yulia Furletova (JLAB)

Outline

- Introduction
- Why CLFV ?
- CLFV in BSM physics
- CLFV with DDVCS
- Conclusions

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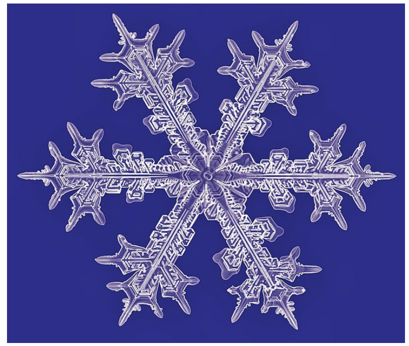
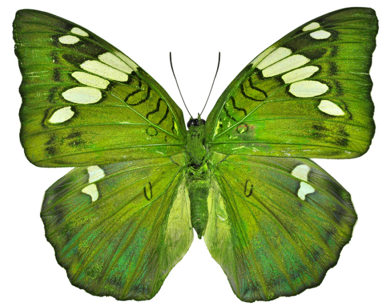
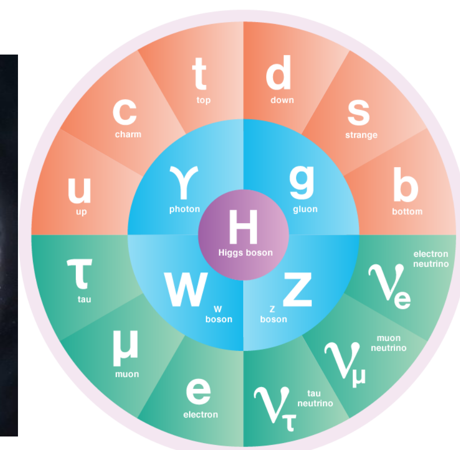
Introduction





Symmetry



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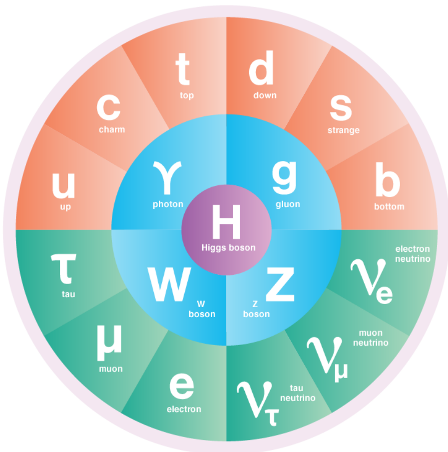
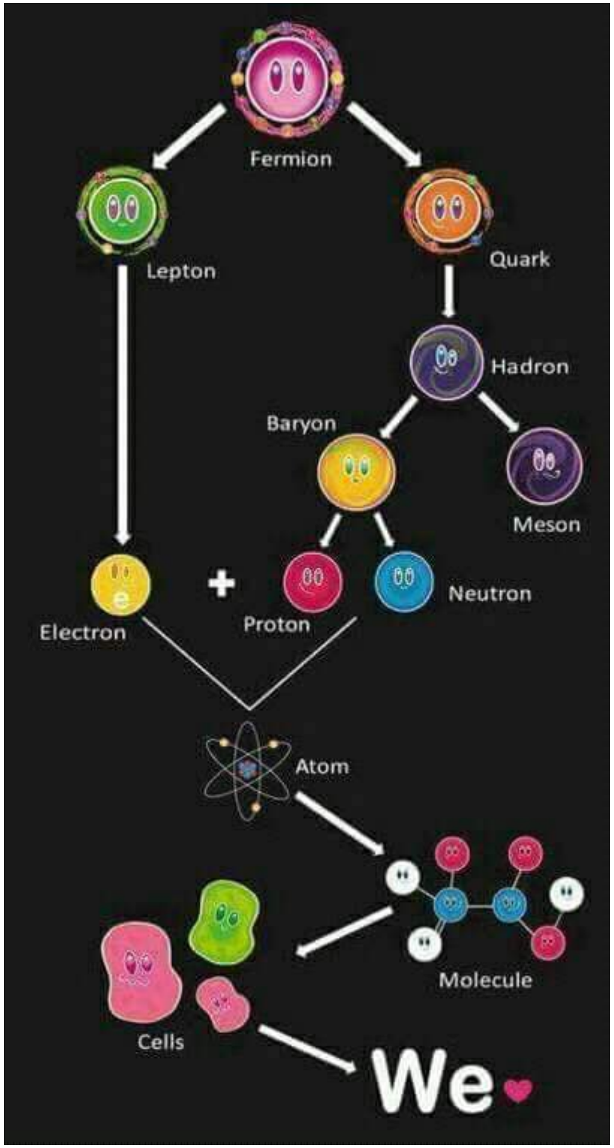
Random pictures from Google

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.

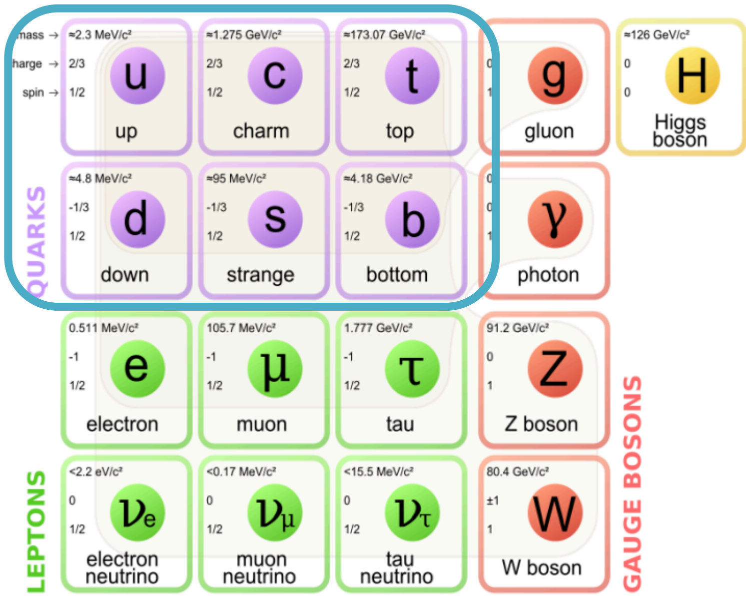
-Flavor is not a conserved quantity in fundamental interactions: Flavor mixing



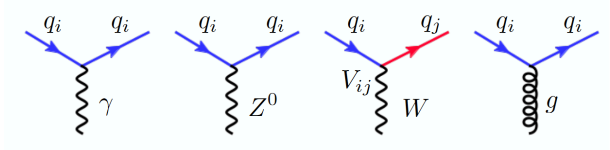
"Physics page", FB

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).

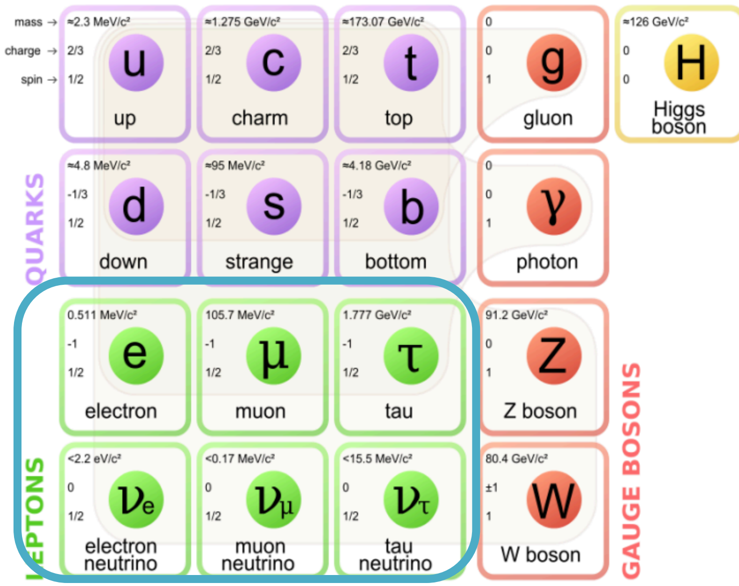


- Family number is not a symmetry in SM: quark family number is violated in weak decays in the CKM matrix
- Flavor mixing in the standard model quark sector is well established, through processes like K^0–$\overline{K}^0$ oscillations, B_0–$\overline{B}_0$ mixing etc.

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

What about lepton sector?

Lepton Flavor



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

- 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)

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

What about charged leptons ?

Charged LFV

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

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

Example of lepton flavor conservation is a muon decay

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

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

Opportunity for New Physics !!!

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 ·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)
$CR(\mu - e, \mathrm{Au})$	7.0×10^{-13} (SINDRUM II 2006)	
$CR(\mu - e, \mathrm{Ti})$	4.3×10^{-12} (SINDRUM II 2004)	10^{-18} PRISM (J-PARC)
$CR(\mu - e, \mathrm{Al})$		3.1×10^{-15} COMET-I (J-PARC)

CLFV search $e\to\mu$

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

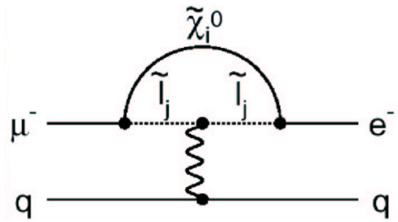
Conclusion: "We strongly urge our experimental colleagues to consider performing such an experiment".

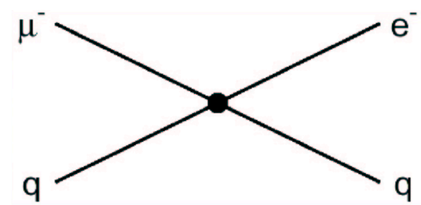
Complementary search ($e \to \mu$) using a high luminosity environments at JLAB CEBAF:

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

Various BSM models that predict CLFV

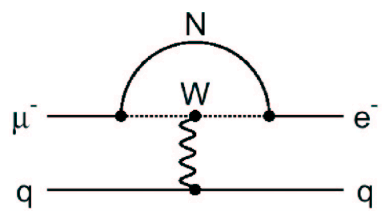
Supersymmetry

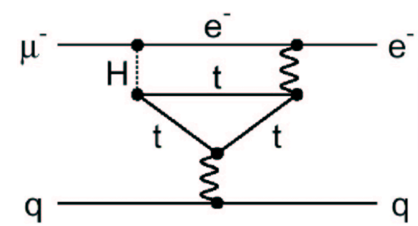




Compositeness

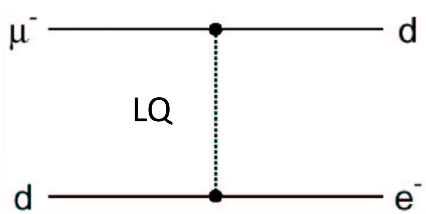
Heavy neutrino

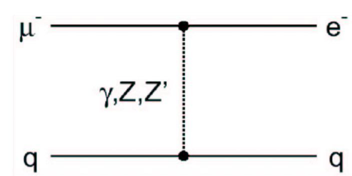




Higgs/top loops

Leptoquarks





Heavy Z', Anomalous boson Coupling

time

Leptoquarks

·Leptoquark is a color triplet **boson** (appear in many SM extensions)

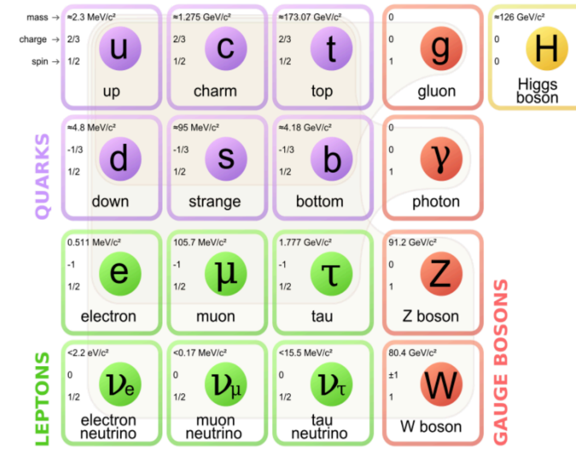
·Symmetry between electron and quark sectors.

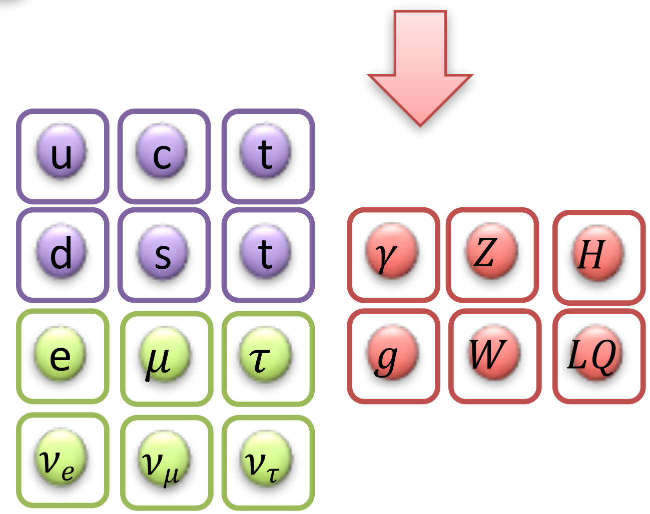
·Flavor is not conserved, but

·Fermion number $F= 3B+L$ ($F= 0$, $F= 2$) is to be conserved

·LQs model are explored in Buchmüller-Rückl-Wyler (BRW) framework under $SU(3)\times SU(2)\times U(1)$:
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





Leptoquarks at ep/eA experiments

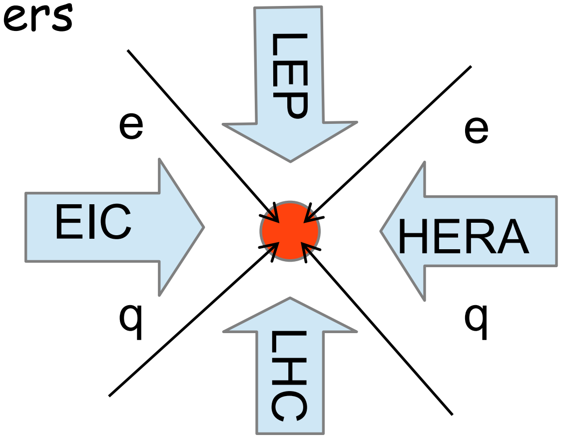
Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
S_0^L	0	2	$-1/3$	$e_L^- u_L \to \ell^- u$	λ_L	$1/2$
				$e_L^- u_L \to \nu_\ell d$	$-\lambda_L$	$1/2$
S_0^R	0	2	$-1/3$	$e_R^- u_R \to \ell^- u$	λ_R	1
$\tilde{S}_0^R$	0	2	$-4/3$	$e_R^- d_R \to \ell^- d$	λ_R	1
S_1^L	0	2	$-1/3$	$e_L^- u_L \to \ell^- u$	$-\lambda_L$	$1/2$
				$e_L^- u_L \to \nu_\ell d$	$-\lambda_L$	$1/2$
			$-4/3$	$e_L^- d_L \to \ell^- d$	$-\sqrt{2}\lambda_L$	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	$-1/3$	$e_R^- u_L \to \ell^- u$	λ_R	1
			$-4/3$	$e_R^- d_L \to \ell^- d$	λ_R	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	$+2/3$	$e_R^+ d_L \to \ell^+ d$	λ_L	$1/2$
				$e_R^+ d_L \to \bar{\nu}_\ell u$	λ_L	$1/2$
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	$+2/3$	$e_R^+ d_L \to \ell^+ d$	$-\lambda_L$	$1/2$
				$e_R^+ d_L \to \bar{\nu}_\ell u$	λ_L	$1/2$
			$+5/3$	$e_R^+ u_L \to \ell^+ u$	$\sqrt{2}\lambda_L$	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	$+2/3$	$e_L^+ d_L \to \ell^+ d$	$-\lambda_R$	1
			$+5/3$	$e_L^+ u_L \to \ell^+ u$	λ_R	1
$\tilde{S}_{1/2}^L$	0	0	$+2/3$	$e_R^+ d_R \to \ell^+ d$	λ_L	1

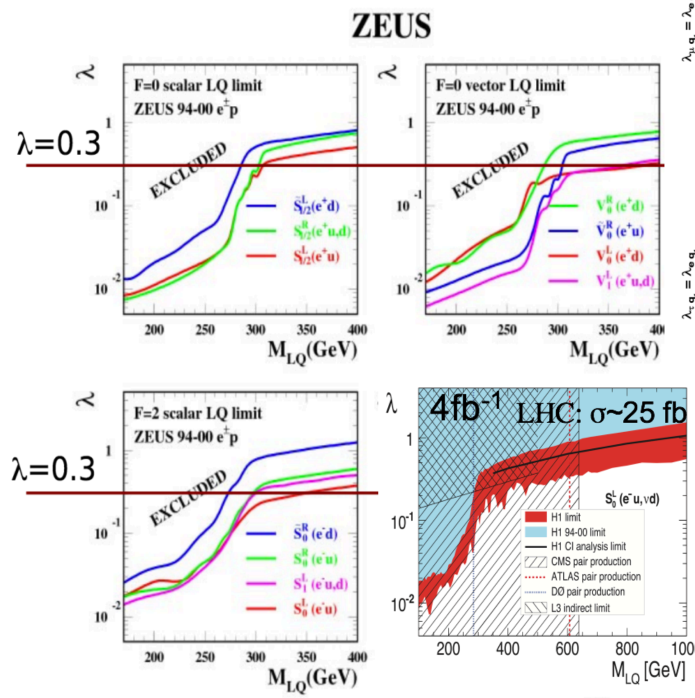
- Electron and positron beams probe different types of Leptoquarks
  - -electron-proton collisions, mainly F=2 LQs are produced
  - -positron-proton collisions, mainly F=0 LQs are produced
- u vs d targets
- Polarization

1 generation	eq -> LQ -> eqX eq -> LQ -> ν_eqX	LFC
2 generation	eq -> LQ -> μqX eq -> LQ -> ν_μqX	CLFV
3 generation	eq -> LQ -> τqX eq -> LQ -> ν_τqX	

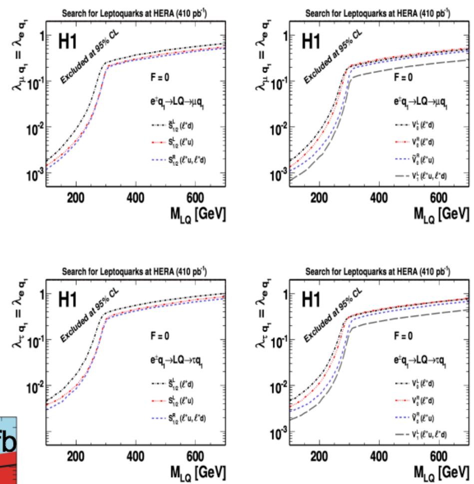
Leptoquark limits at ep, ee and pp colliders

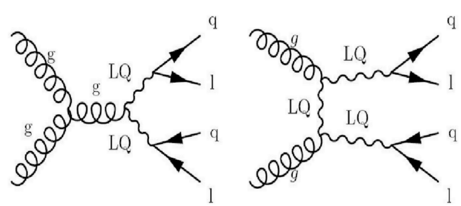


LQ->eq



LQ->μq and LQ-> τq





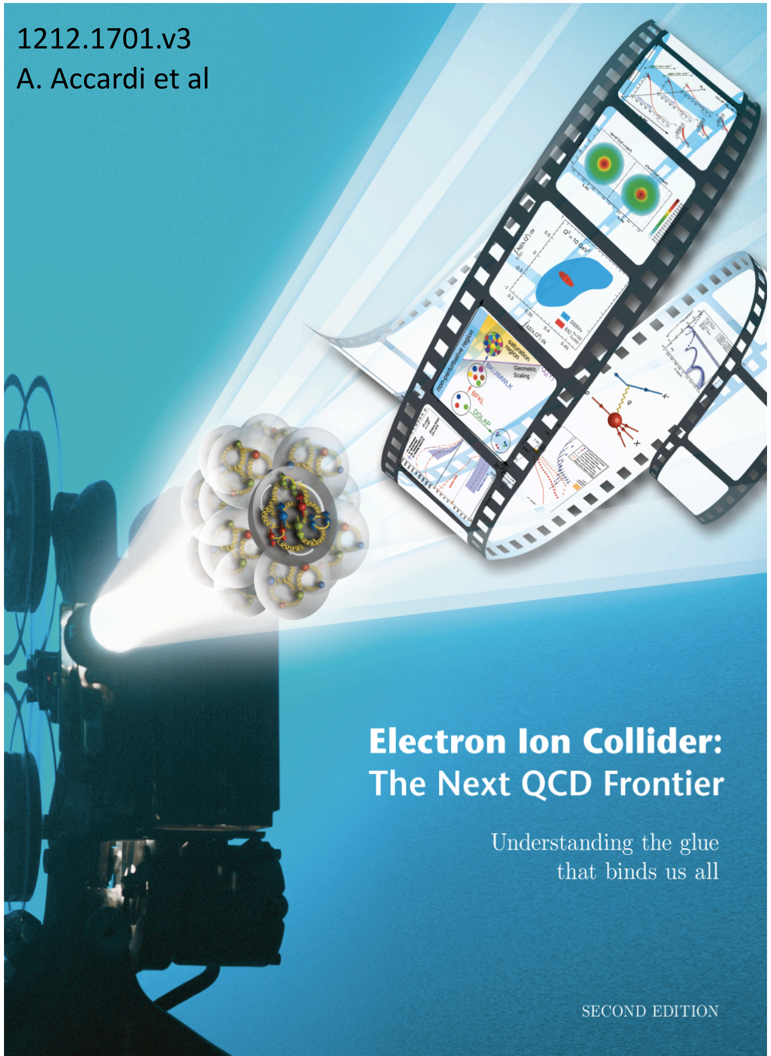
- LEP (ee):contact interactions (indirect constrains from e^+e^--> qq)
- LHC/TEVATRON (pp): pair production (λ independent)
- HERA/EIC (ep): single LQ production M<√s, contact interaction M>√s

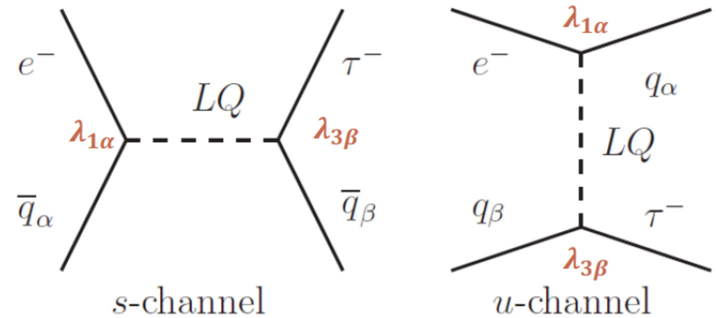
For leptoquark Yukawa coupling λ = 0.1, the ZEUS bounds on the first-generation leptoquarks range from 248 to 290 GeV

HERA: L~10^{30-31}cm^{-2}s^{-1} (0.5 fb^{-1})
EIC: L~10^{34}cm^{-2}s^{-1} (>50 fb^{-1})
JLAB: L >10^{38}cm^{-2}s^{-1}

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

1212.1701.v3
A. Accardi et al



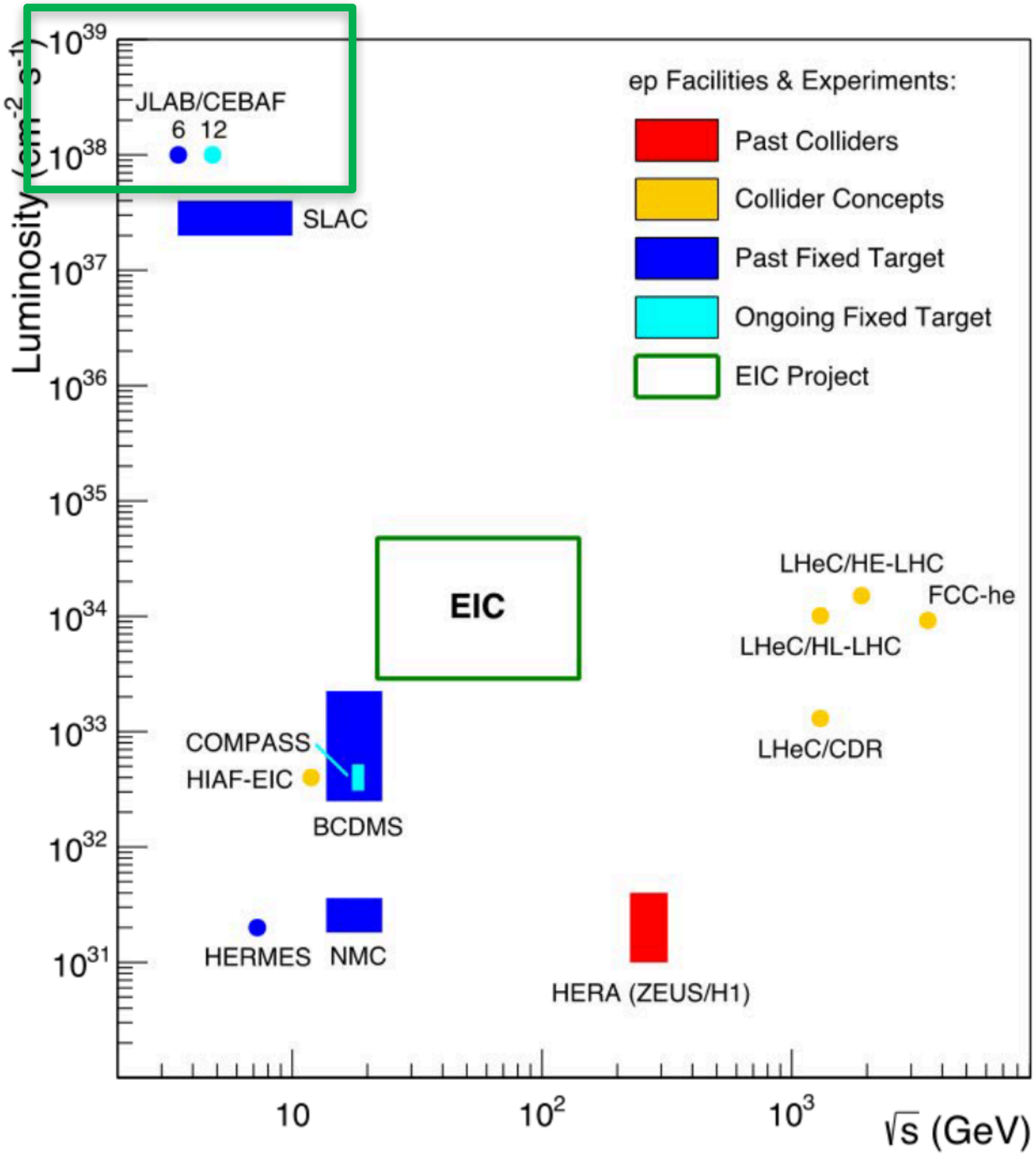


- Cross-section for $ep \to \tau X$ takes the form:

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

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

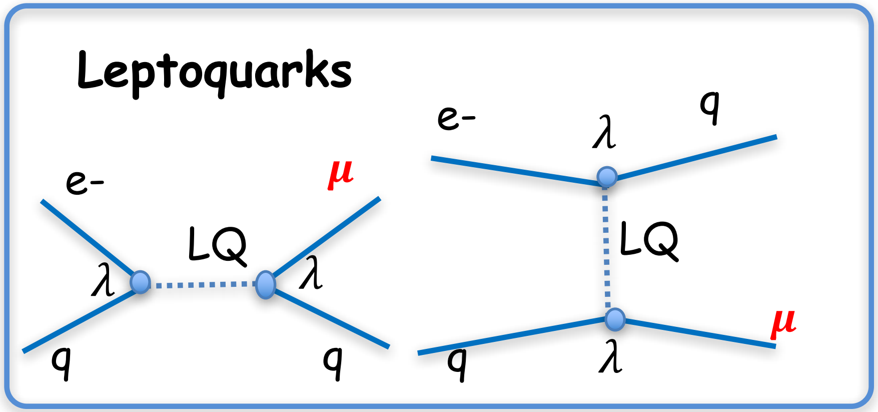
Past, existing and proposed DIS facilities

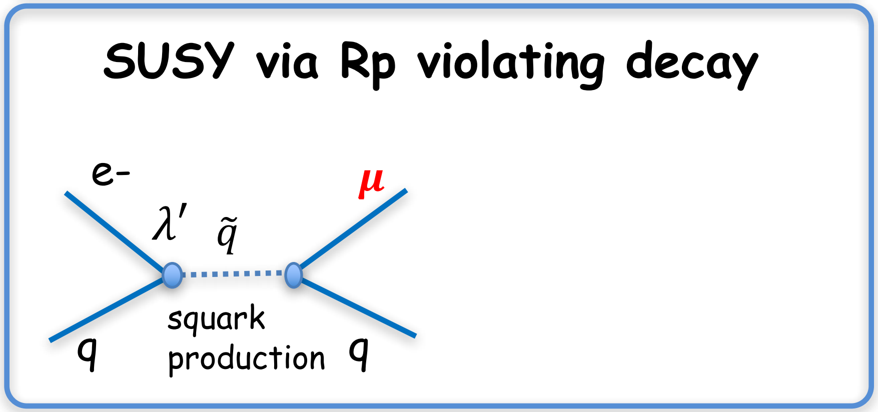


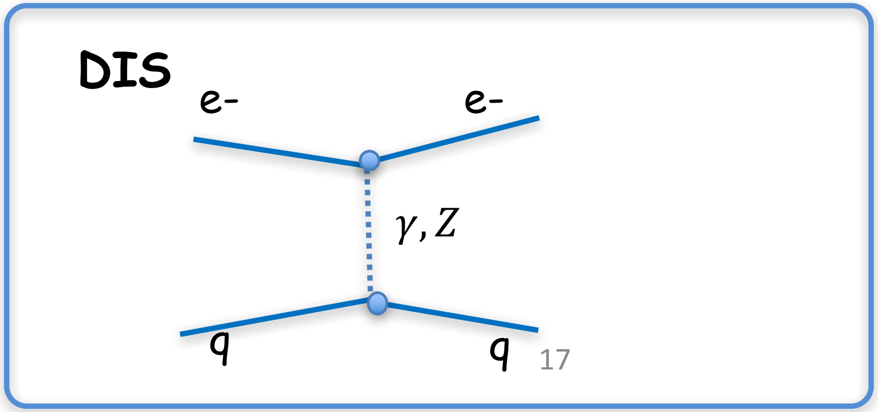
From luminosity point of view, JLAB is a unique ep/eA facility in the world!

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.
- Need muon identification





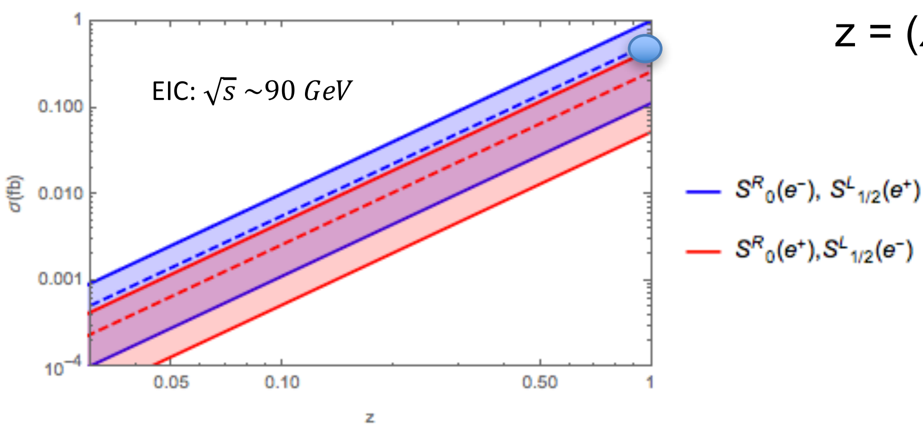


CLFV (e->μ)

S. Mantry,
Y.Furletova

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

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



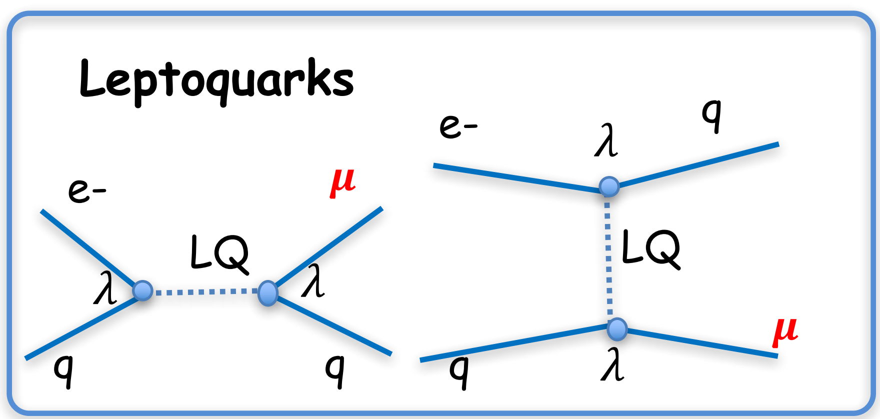
z = $(\lambda_{11}\lambda_{21}/M^2_{LQ})/(\lambda_{11}\lambda_{21}/M^2_{LQ})$ {HERA LIMIT}

For JLAB12 :
s : ~x 10^{-2}
PDFs : x 10^{-1}

But luminosity > x10^7 higher

Luminosity:

HERA: L~10^{30-31}cm^{-2}s^{-1} (0.5 fb^{-1})
EIC: L~10^{34}cm^{-2}s^{-1} (>50 fb^{-1})
JLAB: L >10^{38}cm^{-2}s^{-1}



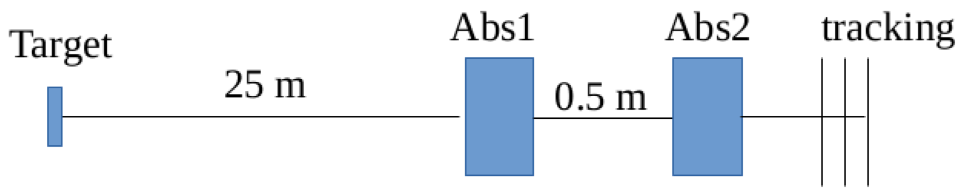
Muon identification

Vardan Khachatryan

W
X_0 = 0.35 cm (radiation length)
λ = 9.95 cm (hadron interaction length)

Cu
X_0 = 1.44 cm
λ = 15.32 cm

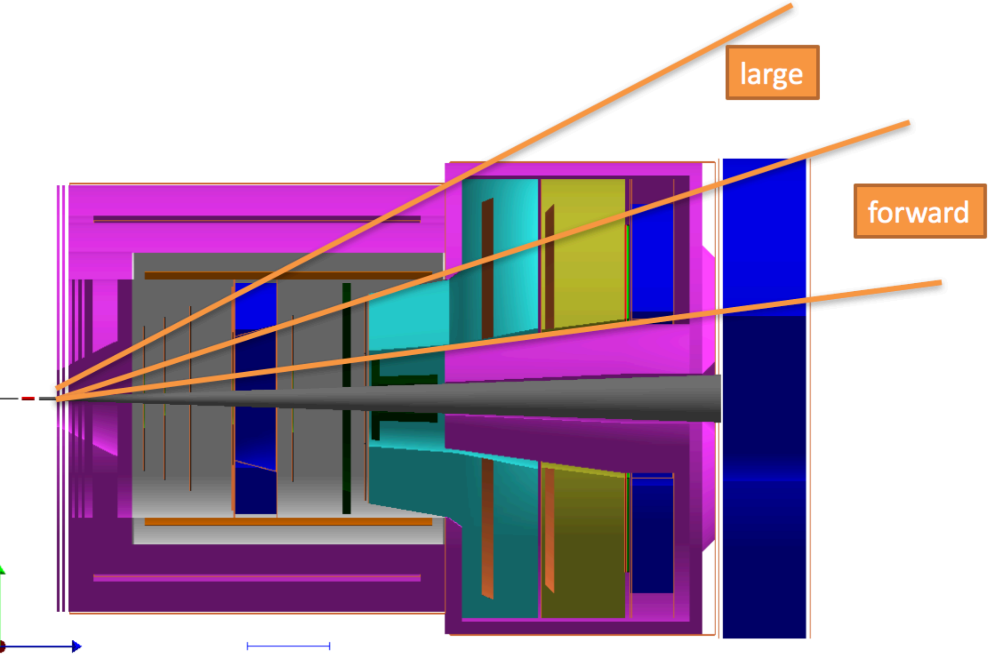
Fe
X_0 = 1.76 cm
λ = 16.8 cm



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

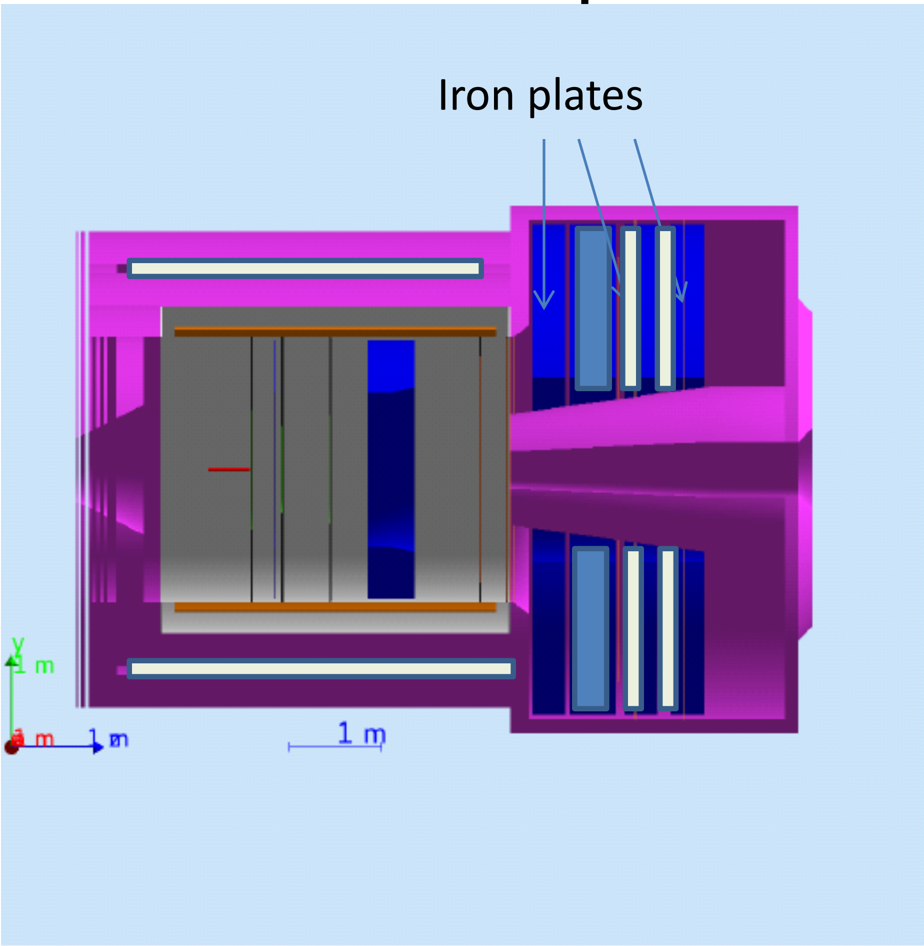
Need more abs/tracking sections
Need to reduce distance or place tracking close to target

SoLID JPsi Setup



-EMCAL
-HCAL(Absorbers)+ Muon chambers
-Vertex detector

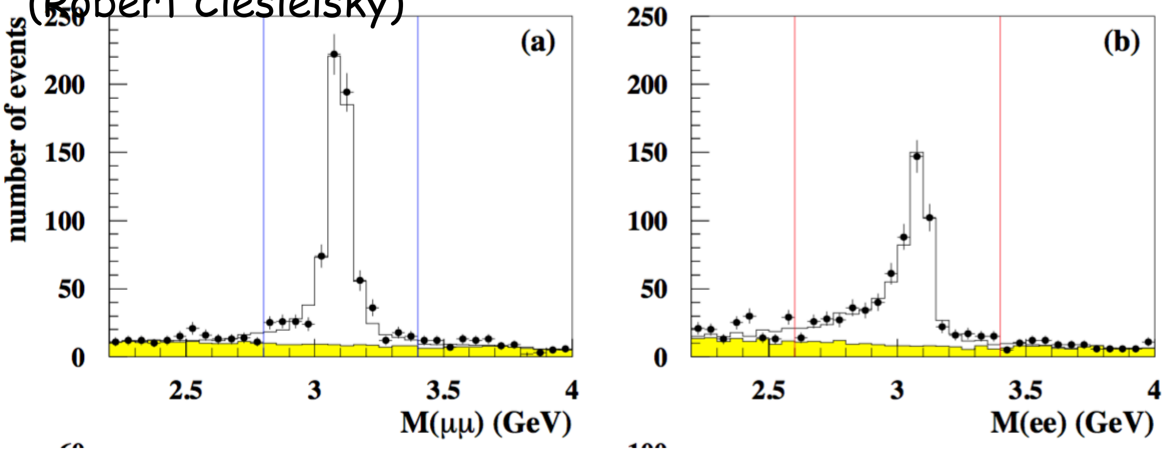
DDVCS setup



Muon identification

ZEUS/HERA data,
exclusive J/ψ
(Robert Ciesielsky)

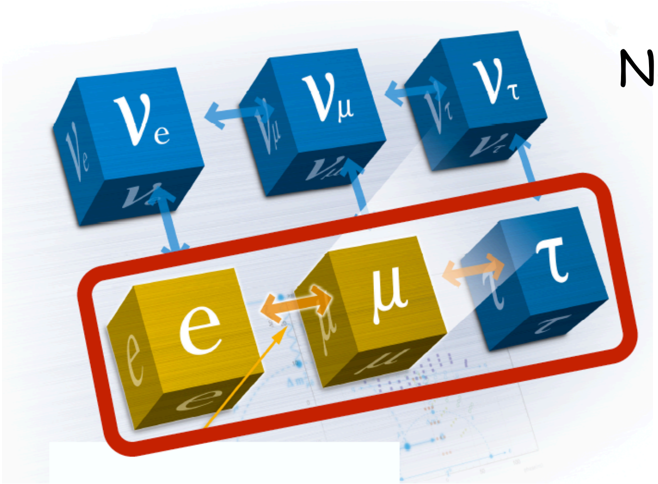
Br ($J/\psi \to \mu^+\mu^-$) ~6%



- Much cleaner sample from muon decay channel
- E_{emcal}/E_{tot} , for muons Min energy in EMCAL and HCAL
- p/E
- In addition:
  - Need instrumentation: muon chambers.
  - dE/dx, cluster counting

Conclusions

Quark mixing: observed



Neutrino mixing: observed.

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

Backup