Is there a case for muon detection?

Davide .Boscherini
(INFN-Bologna)

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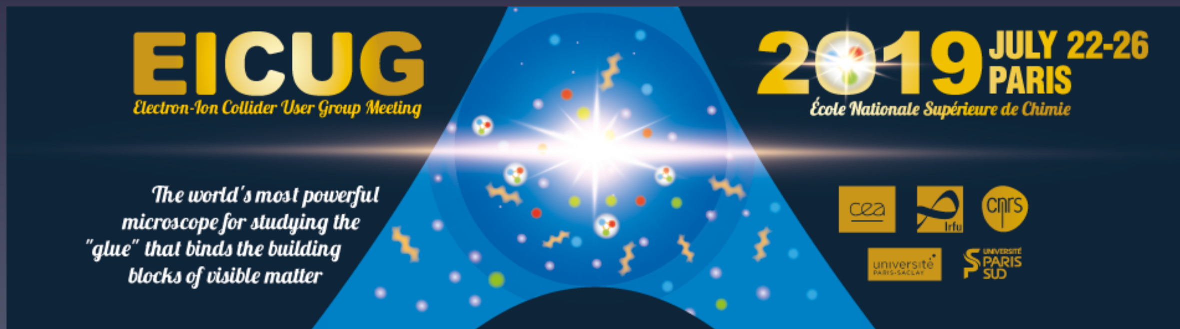
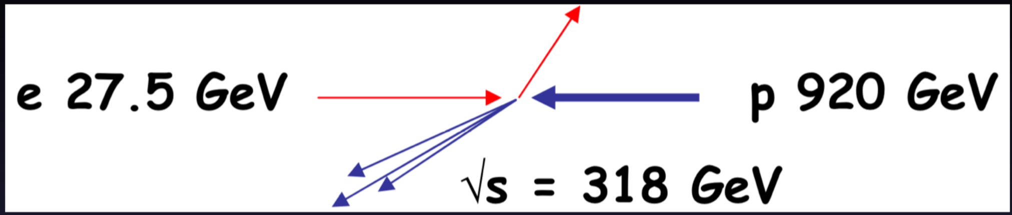


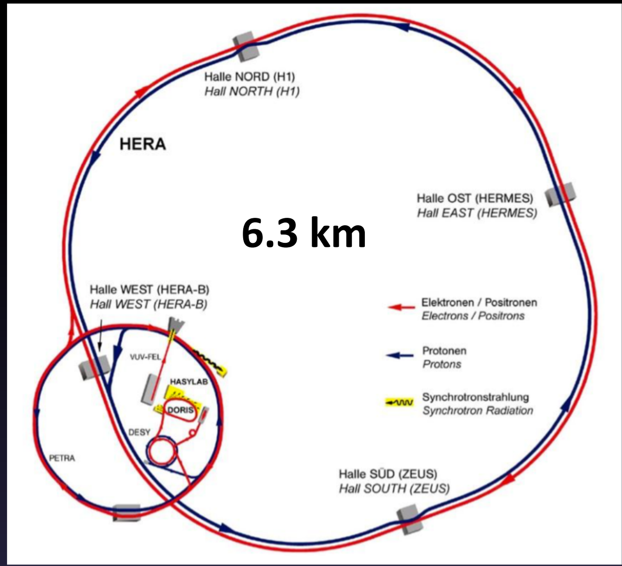
Introduction

- Looking at analysis performed at HERA
  where muon reconstruction is necessary
  aiming to identify possible case studies for EIC

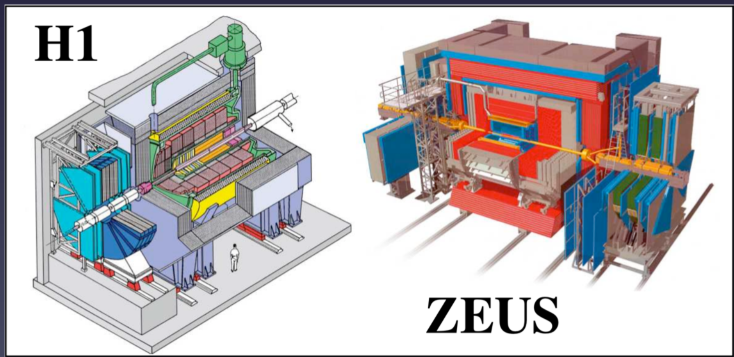
HERA collider

- Lepton-proton collider: HERA @ DESY
  $27.5\ GeV\ e^{+/-}\ \rightarrow\leftarrow\ p\ 920\ GeV;\ \sqrt{s} = 318\ GeV$

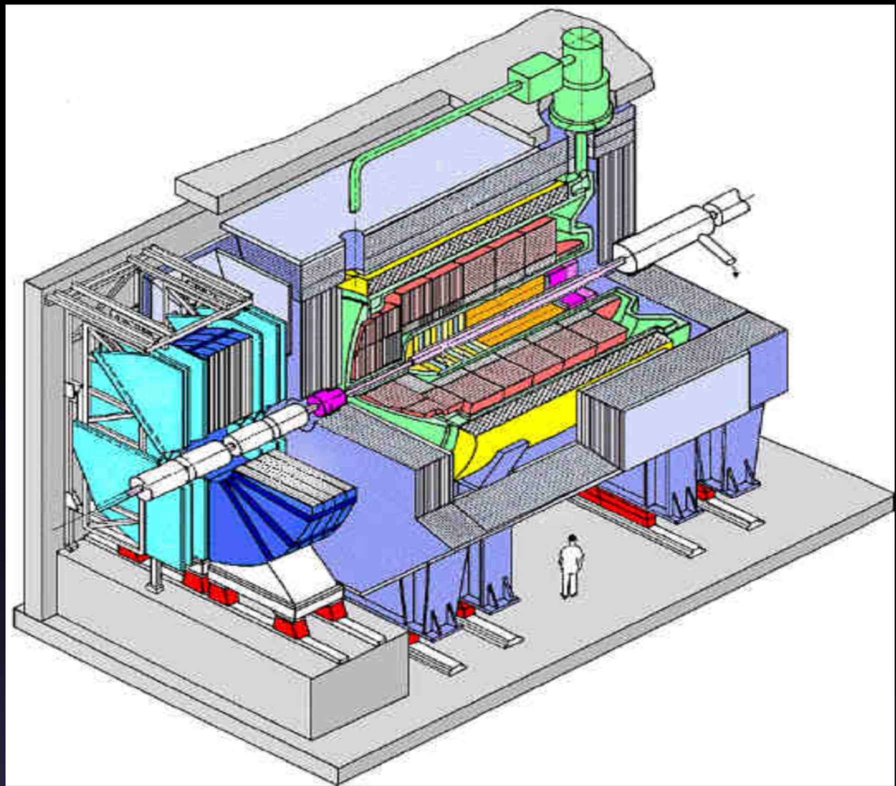




- **H1, ZEUS**
  Data taking periods
  - HERA-I (1992-2000) $\sim 130\ pb^{-1}$
  - HERA-II (2003-2007) $\sim 380\ pb^{-1}$
  Total integrated luminosity:
  ~ 0.5 fb^{-1}/experiment



H1 detector

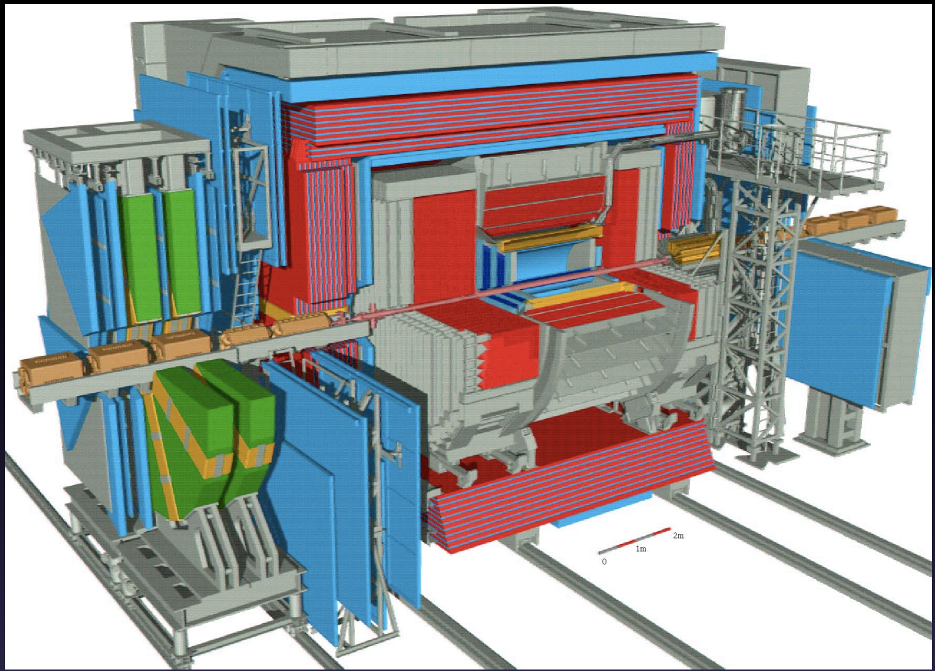


Muon Detectors
- Forward Spectrometer
  $3° < \theta < 17°$
  $24\% < \sigma(p)/p < 36\%$
- LSTs
  $6° < \theta < 172°$
  $\sigma(p)/p \simeq 35\%$

Tracker
- Forward Tracking:
  $7° < \theta < 25°$
- Central Tracking:
  $25° < \theta < 155°$
  $\sigma(p)/p^2 < 0.01\ GeV^{-1}$
- Backward Proportional Chamber:
  $155° < \theta < 175°$

Liquid Argon Calorimeter
- Angular coverage:
  $4° < \theta < 153°$
- Thickness:
  $20 - 30\ X_0\ (em), 5 - 8\ \lambda_I\ (had)$
- Energy Resolution (em, had):
  $\sigma(E)/E = 12\%/\sqrt{E(GeV)} \oplus 1\%$
  $\sigma(E)/E = 50\%/\sqrt{E(GeV)} \oplus 2\%$

ZEUS detector



Muon Detectors

- Forward Spectrometer
  $6° < \theta < 32°$
  $\sigma(p)/p < 25\%$ up to $p = 100\ GeV$
- Barrel-Rear Detector
  $35° < \theta < 160°$
  $\sigma(p)/p = 30 - 50\%$ for $p < 50\ GeV$

Uranium Calorimeter

- Angular coverage:
  $2.5° < \theta < 178.4°$
- Thickness:
  $20 - 25\ X_0\ (em), 4 - 7\ \lambda_I\ (had)$
- Energy Resolution (em, had):
  $\sigma(E)/E = 18\%/\sqrt{E(GeV)} \oplus 2\%$
  $\sigma(E)/E = 35\%/\sqrt{E(GeV)} \oplus 1\%$

Central Tracking Detector

- Angular coverage:
  $15° < \theta < 164°$
- Momentum resolution:
  $\sigma(p_T)/p_T = 0.58\%\ p_T(GeV) \oplus 0.65\% \oplus 0.14\%/p_T$

Lepton Flavor Violation search

F. D. Aaron *et al.* [H1 Collaboration], *Search for lepton flavour violation at HERA*
***Phys. Lett. B* 701 (2011) 20 [arXiv:1103.4938]**

411 pb^{-1}

S. Chekanov *et al.* [ZEUS Collaboration], *Search for lepton-flavor violation at HERA*
Eur.Phys.J. C44 (2005) 463-479

130 pb^{-1}

- Discovery of neutrino oscillations
  → lepton flavor not conserved in fundamental interactions

- Can lepton flavor non-conservation be observed with charged leptons?
  → search for charged lepton flavor violation

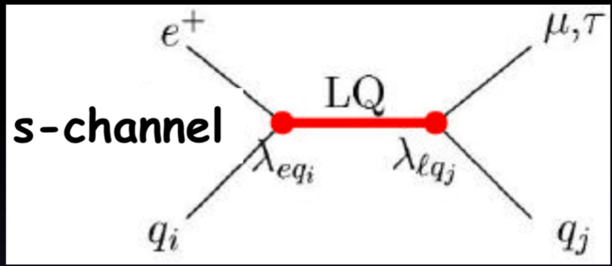
- LFV searches performed in lepton-hadron interactions:
  e ➔ μ, τ or μ ➔ τ transitions in **low energy experiments**
  e ➔ μ, τ transitions at **HERA**

- Electron-proton collider ideal place to study LFV

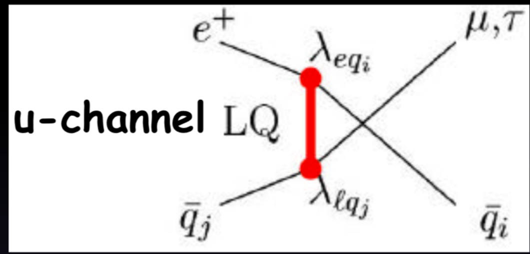
- LFV could be mediated by lepto-quarks (LQ) or R_p-violating squarks

LFV mediated by LQs

If a LQ couples to different leptons → LFV process could be possible

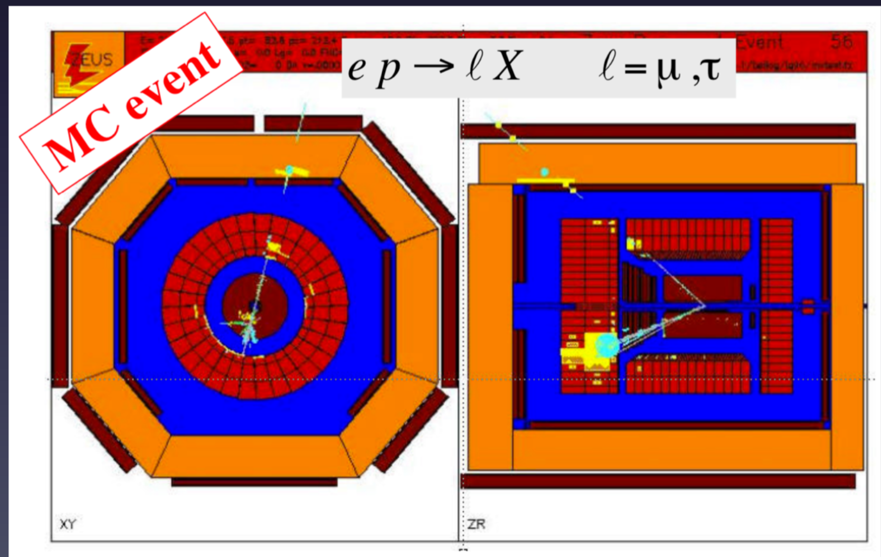


resonant production



LQ exchange

Event signature similar to SM NC DIS
with a ***μ*** or ***τ*** replacing the scattered electron



Introduction to LQs

Phenomenological model by *Buchmüller, Rückl, Wyler* - **Phys. Lett. B191 (1987) 442**

- Colour triplet bosons, with fractional charge and both lepton and baryon number
- Invariance under the SM symmetry groups $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
- Coupling to either left-handed or right-handed leptons, not both
- Resulting in 14 LQ types
  7 scalar S_I^χ and 7 vector V_I^χ
  isospin $I = 0, ½, 1$; helicity $\chi = L, R$
  classified according to their quantum numbers (see next table)
- Fermion number $F = | L + 3B | = 0\ or\ 2$
  $F = 0\ (2)$ LQs: larger sensitivity in $e^{+(-)}p$ interactions,
  depending on involvement of valence quarks
- If LQ couples to different leptons → LFV

LQ classification

LQ types in the BRW model:

Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ	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	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
S_0^R	0	2	$-1/3$	$e^-_R u_R \to \ell^- u$	λ_R	1	V_0^R	1	0	$+2/3$	$e^+_L d_R \to \ell^+ d$	λ_R	1
$\tilde{S}_0^R$	0	2	$-4/3$	$e^-_R d_R \to \ell^- d$	λ_R	1	$\tilde{V}_0^R$	1	0	$+5/3$	$e^+_L u_R \to \ell^+ u$	λ_R	1
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^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
$V_{1/2}^L$	1	2	$-4/3$	$e^-_L d_R \to \ell^- d$	λ_L	1	$S_{1/2}^L$	0	0	$+5/3$	$e^+_R u_R \to \ell^+ u$	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	$S_{1/2}^R$	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
$\tilde{V}_{1/2}^L$	1	2	$-1/3$	$e^-_L u_R \to \ell^- u$	λ_L	1	$\tilde{S}_{1/2}^L$	0	0	$+2/3$	$e^+_R d_R \to \ell^+ d$	λ_L	1

LFV search strategy

Two regions considered:

- $M_{LQ} < \sqrt{s}$ → narrow width approximation $\sigma_{NWA} \propto \lambda^2{}_{eq_1} Br_{lq_j}$
  dominated by s-channel resonance production

- $M_{LQ} \gg \sqrt{s}$ → contact interaction approximation $\sigma_{CI} \propto \frac{\lambda_{eq_i} \lambda_{eq_j}}{M_{LQ}^2}$
  both u- and s-channel contribute

HERA much more competitive in the τ-channel since the limits from low-energy experiments are much weaker respect to the μ-channel

LFV event selection

Topology looked for: muon + jet

- $P_T^{\mu} > 8\ GeV,\ 10° < \vartheta_\mu < 120°$
- 1 muon required, riduce di-muon events
- $P_T^{CAL} > 25\ GeV,$ energy imbalance reduce NC background
- isolation of muon from closest track and closest jet
- azimuthal difference between muon and hadronic system $> 170°$
- longitudinal energy imbalance $\mathrm{E} - P_Z \equiv \sum(E_i - P_{Z_i}) > 40\ GeV,$
  remove events with undetected particles
  $(E - Pz\ =\ 2Ee\ =\ 55\ GeV)$ when all particles are detected

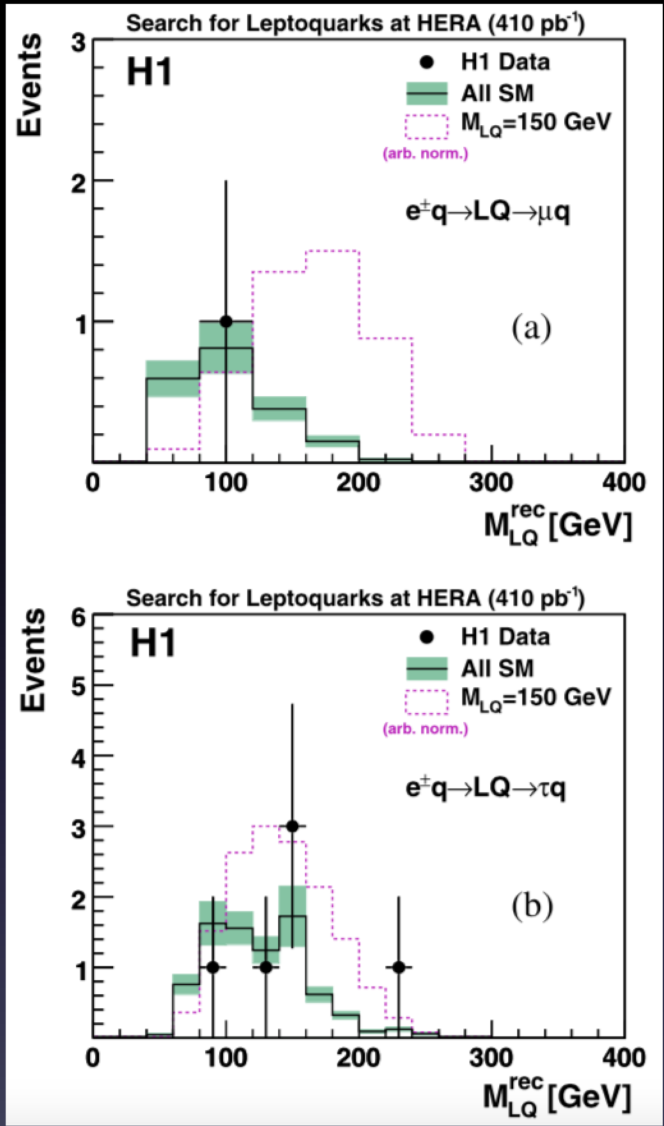
Selection efficiency:
75% - 65% for $M_{LQ} = 150 - 300\ GeV$

LFV selection results

Reconstructed leptoquark mass in the search for events of type:

ep → μ*X*

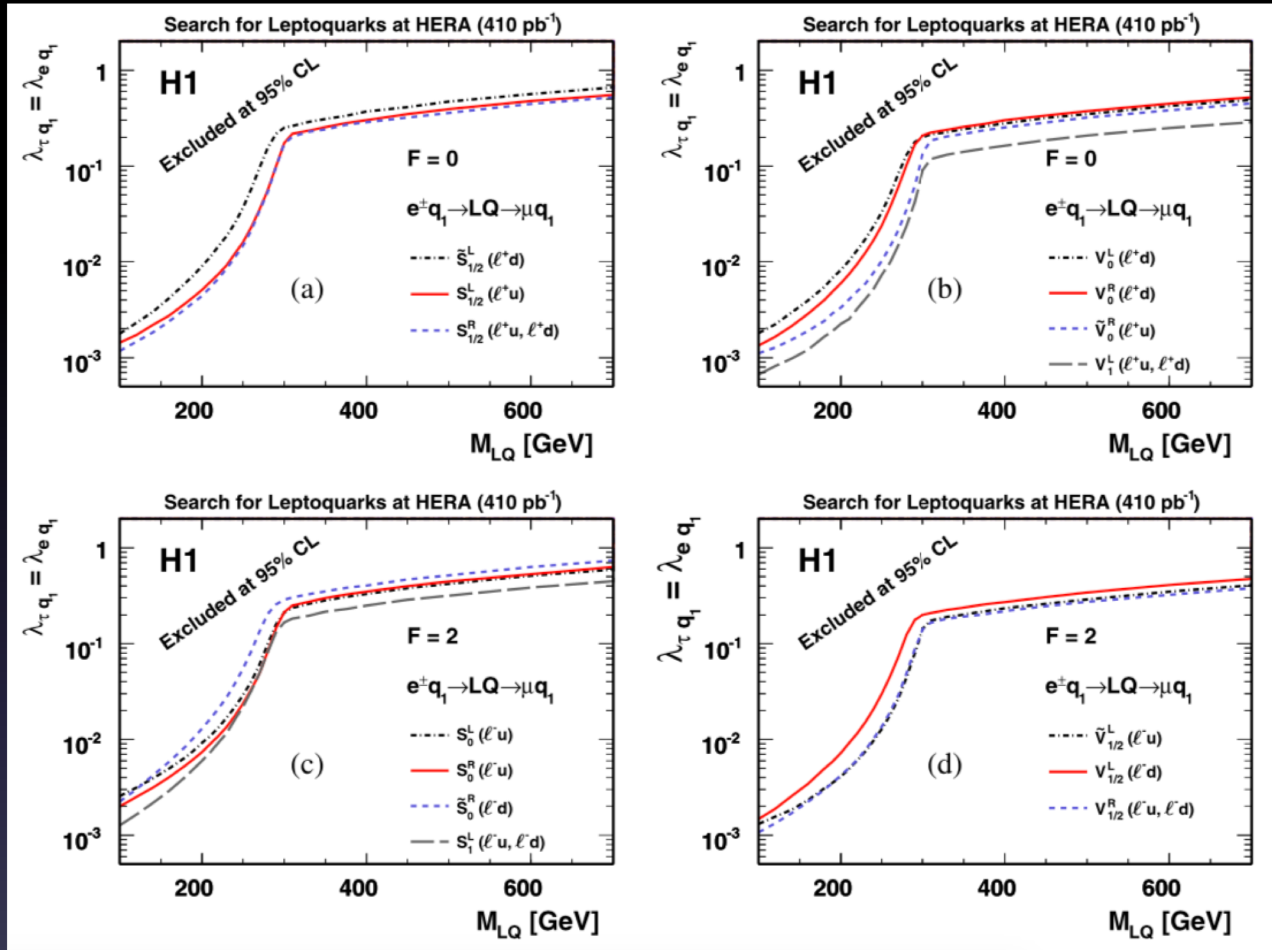
ep → τ *X*



No signal observed → set limits on couplings

LFV limit settings

95% confidence level upper limits on the coupling $\lambda_{\mu q}$ of all 14 LQ types to a muon–quark pair as a function of the LQ mass



Low-mass LQs: limits on resonant production

Near the kinematic limit of 319 GeV the limit turns smoothly into a limit on the virtual effects of both an off-shell *s*-channel LQ process and a *u*-channel LQ exchange

Limits on high-mass LQs ($ep \to \mu X$, F=0)

At masses $M_{LQ} \gg \sqrt{s}$ the two processes contract to an effective four-fermion interaction, where the cross section is proportional to $\left(\frac{\lambda_{eq_i}\,\lambda_{\mu q_j}}{M_{LQ}^2}\right)^2$

→ limits at 95% CL on $\frac{\lambda_{eq_i}\,\lambda_{\mu q_j}}{M_{LQ}^2}$ for $ep \to \mu X$, F=0 LQs

Limits from H1 are compared with the most stringent results from low energy experiments

In yellow:
HERA limits are most stringent

$ep \to \mu X$ — **H1** — $F = 0$

Upper exclusion limits on $\lambda_{eq_i}\lambda_{\mu q_j}/M_{LQ}^2$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL

$q_i q_j$	$S^L_{1/2}$ $e^-\bar{U}$ e^+U	$S^R_{1/2}$ $e^-\bar{U}, e^-\bar{D}$ e^+U, e^+D	$\tilde{S}^L_{1/2}$ $e^-\bar{D}$ e^+D	V^L_0 $e^-\bar{D}$ e^+D	V^R_0 $e^-\bar{D}$ e^+D	$\tilde{V}^R_0$ $e^-\bar{U}$ e^+U	V^L_1 $e^-\bar{U}, e^-\bar{D}$ e^+U, e^+D
1 1	$\mu N \to eN$ 5.2×10^{-5} **0.6**	$\mu N \to eN$ 2.6×10^{-5} **0.6**	$\mu N \to eN$ 5.2×10^{-5} **0.9**	$\mu N \to eN$ 2.6×10^{-5} **0.5**	$\mu N \to eN$ 2.6×10^{-5} **0.6**	$\mu N \to eN$ 2.6×10^{-5} **0.4**	$\mu N \to eN$ 0.8×10^{-5} **0.2**
1 2	$D \to \mu\bar{e}$ 0.8 **0.7**	$K \to \mu\bar{e}$ 2×10^{-5} **0.5**	$K \to \mu\bar{e}$ 2×10^{-5} **0.9**	$K \to \mu\bar{e}$ 1×10^{-5} **0.6**	$K \to \mu\bar{e}$ 1×10^{-5} **0.7**	$D \to \mu\bar{e}$ 0.4 **0.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.2**
1 3	*	$B \to \mu\bar{e}$ 0.08 **1.0**	$B \to \mu\bar{e}$ 0.08 **0.9**	$B \to \mu\bar{e}$ 0.04 **0.7**	$B \to \mu\bar{e}$ 0.04 **0.8**	*	$B \to \mu\bar{e}$ 0.04 **0.7**
2 1	$D \to \mu\bar{e}$ 0.8 **1.4**	$K \to \mu\bar{e}$ 2×10^{-5} **1.2**	$K \to \mu\bar{e}$ 2×10^{-5} **1.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.6**	$K \to \mu\bar{e}$ 1×10^{-5} **0.7**	$D \to \mu\bar{e}$ 0.4 **0.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.2**
2 2	$\mu N \to eN$ 9.2×10^{-4} **2.4**	$\mu N \to eN$ 1.3×10^{-3} **1.7**	$\mu N \to eN$ 3×10^{-3} **1.9**	$\mu N \to eN$ 1.5×10^{-3} **1.0**	$\mu N \to eN$ 1.5×10^{-3} **1.1**	$\mu N \to eN$ 4.6×10^{-4} **1.4**	$\mu N \to eN$ 2.7×10^{-4} **0.5**
2 3	*	$B \to \bar{\mu}eK$ 2.0×10^{-3} **2.3**	$B \to \bar{\mu}eK$ 2.0×10^{-3} **2.1**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.4**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.5**	*	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.4**
3 1	*	$B \to \mu\bar{e}$ 0.08 **2.1**	$B \to \mu\bar{e}$ 0.08 **1.9**	V_{ub} 0.14 **0.6**	$B \to \mu\bar{e}$ 0.04 **0.7**	*	V_{ub} 0.14 **0.6**
3 2	*	$B \to \bar{\mu}eK$ 2.0×10^{-3} **3.2**	$B \to \bar{\mu}eK$ 2.0×10^{-3} **2.8**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.1**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.2**	*	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.1**
3 3	*	$\mu N \to eN$ 1.3×10^{-3} **3.8**	$\mu N \to eN$ 3×10^{-3} **3.4**	$\mu N \to eN$ 1.5×10^{-3} **1.7**	$\mu N \to eN$ 1.5×10^{-3} **1.9**	*	$\mu N \to eN$ 2.7×10^{-4} **1.7**

Limits on high-mass LQs ($ep \to \mu X$, F=2)

Limits at 95% CL on $\frac{\lambda_{eq_i}\ \lambda_{\mu q_j}}{M_{LQ}^2}$

for $ep \to \mu X$, F=2 LQs

$ep \to \mu X$			**H1**				$F = 2$
Upper exclusion limits on $\lambda_{eq_i}\lambda_{\mu q_j}/M_{LQ}^2$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL							
$q_i q_j$	S_0^L $\ell^- U$ $\ell^+ \bar{U}$	S_0^R $\ell^- U$ $\ell^+ \bar{U}$	$\tilde{S}_0^R$ $\ell^- D$ $\ell^+ \bar{D}$	S_1^L $\ell^- U, \ell^- D$ $\ell^+ \bar{U}, \ell^+ \bar{D}$	$V_{1/2}^L$ $\ell^- D$ $\ell^+ \bar{D}$	$V_{1/2}^R$ $\ell^- U, \ell^- D$ $\ell^+ \bar{U}, \ell^+ \bar{D}$	$\tilde{V}_{1/2}^L$ $\ell^- U$ $\ell^+ \bar{U}$
1 1	$\mu N \to eN$ 5.2×10^{-5} **0.7**	$\mu N \to eN$ 5.2×10^{-5} **0.8**	$\mu N \to eN$ 5.2×10^{-5} **1.1**	$\mu N \to eN$ 1.7×10^{-5} **0.4**	$\mu N \to eN$ 2.6×10^{-5} **0.5**	$\mu N \to eN$ 1.3×10^{-5} **0.3**	$\mu N \to eN$ 2.6×10^{-5} **0.3**
1 2	$K \to \pi\nu\bar{\nu}$ 1×10^{-3} **0.8**	$D \to \mu\bar{e}$ 0.8 **0.9**	$K \to \mu\bar{e}$ 2×10^{-5} **1.2**	$K \to \mu\bar{e}$ 1×10^{-5} **0.4**	$K \to \mu\bar{e}$ 1×10^{-5} **0.8**	$K \to \mu\bar{e}$ 1×10^{-5} **0.5**	$D \to \mu\bar{e}$ 0.4 **0.6**
1 3	*	*	$B \to \mu\bar{e}$ 0.08 **1.3**	V_{ub} 0.3 **0.6**	$B \to \mu\bar{e}$ 0.04 **0.9**	$B \to \mu\bar{e}$ 0.04 **1.0**	*
2 1	$K \to \pi\nu\bar{\nu}$ 1×10^{-3} **1.2**	$D \to \mu\bar{e}$ 0.8 **1.2**	$K \to \mu\bar{e}$ 2×10^{-5} **1.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.6**	$K \to \mu\bar{e}$ 1×10^{-5} **0.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.3**	$D \to \mu\bar{e}$ 0.4 **0.4**
2 2	$\mu N \to eN$ 9.2×10^{-4} **2.4**	$\mu N \to eN$ 9.2×10^{-3} **2.7**	$\mu N \to eN$ 3×10^{-3} **2.1**	$\mu N \to eN$ 2.5×10^{-3} **0.9**	$\mu N \to eN$ 1.5×10^{-3} **1.0**	$\mu N \to eN$ 6.7×10^{-4} **0.9**	$\mu N \to eN$ 4.6×10^{-4} **1.2**
2 3	*	*	$B \to \bar{\mu}eK$ 2.0×10^{-3} **2.3**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.0**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.4**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.5**	*
3 1	*	*	$B \to \mu\bar{e}$ 0.08 **1.8**	$B \to \mu\bar{e}$ 0.08 **0.8**	$B \to \mu\bar{e}$ 0.04 **0.5**	$B \to \mu\bar{e}$ 0.04 **0.5**	*
3 2	*	*	$B \to \bar{\mu}eK$ 2.0×10^{-3} **3.2**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.4**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.1**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.2**	*
3 3	*	*	$\mu N \to eN$ 3×10^{-3} **3.8**	$\mu N \to eN$ 2.5×10^{-3} **1.7**	$\mu N \to eN$ 1.5×10^{-3} **1.7**	$\mu N \to eN$ 6.7×10^{-4} **1.9**	*

Limits on high-mass LQs ($ep \to \tau X$, F=0,2)

Limits at 95% CL on $\frac{\lambda_{eq_i}\,\lambda_{\mu q_j}}{M_{LQ}^2}$ for $ep \to \tau X$

$ep \to \tau X$			**H1**				$F = 2$
Upper exclusion limits on $\lambda_{eq_i}\lambda_{\tau q_j}/M_{LQ}^2$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL							
$q_i q_j$	S_0^L $\ell^- U$ $\ell^+ \bar{U}$	S_0^R $\ell^- U$ $\ell^+ \bar{U}$	$\tilde{S}_0^R$ $\ell^- D$ $\ell^+ \bar{D}$	S_1^L $\ell^- U, \ell^- D$ $\ell^+ \bar{U}, \ell^+ \bar{D}$	$V_{1/2}^L$ $\ell^- D$ $\ell^+ \bar{D}$	$V_{1/2}^R$ $\ell^- U, \ell^- D$ $\ell^+ \bar{U}, \ell^+ \bar{D}$	$\tilde{V}_{1/2}^L$ $\ell^- U$ $\ell^+ \bar{U}$
1 1	G_F 0.3 **1.6**	$\tau \to \pi e$ 0.06 **1.8**	$\tau \to \pi e$ 0.06 **2.6**	$\tau \to \pi e$ 0.01 **1.0**	$\tau \to \pi e$ 0.03 **1.1**	$\tau \to \pi e$ 0.01 **0.7**	$\tau \to \pi e$ 0.03 **0.8**
1 2	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **1.9**	**2.1**	$\tau \to Ke$ 0.04 **2.9**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.1**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.9**	$\tau \to Ke$ 0.02 **1.3**	**1.5**
1 3	*	*	$B \to \tau\bar{e}$ 0.07 **3.0**	V_{ub} 0.3 **1.3**	$B \to \tau\bar{e}$ 0.03 **2.2**	$B \to \tau\bar{e}$ 0.03 **2.4**	*
2 1	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **2.7**	**2.7**	$\tau \to Ke$ 0.04 **3.5**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.4**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.2**	$\tau \to Ke$ 0.02 **0.7**	**0.9**
2 2	$\tau \to 3e$ 0.6 **6.3**	$\tau \to 3e$ 0.6 **6.8**	$\tau \to 3e$ 1.8 **5.4**	$\tau \to 3e$ 1.5 **2.3**	$\tau \to 3e$ 0.9 **2.7**	$\tau \to 3e$ 0.5 **2.2**	$\tau \to 3e$ 0.3 **3.4**
2 3	*	*	$B \to \bar{\tau}eX$ 14.0 **5.8**	$B \to \bar{\tau}eX$ 7.2 **2.7**	$B \to \bar{\tau}eX$ 7.2 **3.6**	$B \to \bar{\tau}eX$ 7.2 **4.0**	*
3 1	*	*	$B \to \tau\bar{e}$ 0.07 **4.0**	$B \to \tau\bar{e}$ 0.03 **2.0**	$B \to \tau\bar{e}$ 0.03 **1.2**	$B \to \tau\bar{e}$ 0.03 **1.3**	*
3 2	*	*	$B \to \bar{\tau}eX$ 14.0 **7.9**	$B \to \bar{\tau}eX$ 7.2 **3.7**	$B \to \bar{\tau}eX$ 7.2 **2.9**	$B \to \bar{\tau}eX$ 7.2 **3.1**	*
3 3	*	*	$\tau \to 3e$ 1.8 **10.1**	$\tau \to 3e$ 1.5 **4.6**	$\tau \to 3e$ 0.9 **4.7**	$\tau \to 3e$ 0.5 **4.9**	*

$ep \to \tau X$			**H1**				$F = 0$
Upper exclusion limits on $\lambda_{eq_i}\lambda_{\tau q_j}/M_{LQ}^2$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL							
$q_i q_j$	$S_{1/2}^L$ $\ell^- \bar{U}$ $\ell^+ U$	$S_{1/2}^R$ $\ell^- \bar{U}, \ell^- \bar{D}$ $\ell^+ U, \ell^+ D$	$\tilde{S}_{1/2}^L$ $\ell^- \bar{D}$ $\ell^+ D$	V_0^L $\ell^- \bar{D}$ $\ell^+ D$	V_0^R $\ell^- \bar{D}$ $\ell^+ D$	$\tilde{V}_0^R$ $\ell^- \bar{U}$ $\ell^+ U$	V_1^L $\ell^- \bar{U}, \ell^- \bar{D}$ $\ell^+ U, \ell^+ D$
1 1	$\tau \to \pi e$ 0.06 **1.4**	$\tau \to \pi e$ 0.03 **1.2**	$\tau \to \pi e$ 0.06 **2.2**	$\tau \to \pi e$ 0.03 **1.2**	$\tau \to \pi e$ 0.03 **1.3**	$\tau \to \pi e$ 0.03 **0.9**	$\tau \to \pi e$ 0.005 **0.4**
1 2	**1.5**	$\tau \to Ke$ 0.04 **1.2**	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **2.2**	$\tau \to Ke$ 0.02 **1.5**	$\tau \to Ke$ 0.02 **1.6**	**1.2**	$K \to \pi\nu\bar{\nu}$ 1.5×10^{-4} **0.5**
1 3	*	$B \to \tau\bar{e}$ 0.07 **2.2**	$B \to \tau\bar{e}$ 0.07 **2.2**	$B \to \tau\bar{e}$ 0.03 **1.8**	$B \to \tau\bar{e}$ 0.03 **1.8**	*	$B \to \tau\bar{e}$ 0.03 **1.8**
2 1	**3.4**	$\tau \to Ke$ 0.04 **2.8**	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **3.9**	$\tau \to Ke$ 0.02 **1.5**	$\tau \to Ke$ 0.02 **1.6**	**1.2**	$K \to \pi\nu\bar{\nu}$ 1.5×10^{-4} **0.5**
2 2	$\tau \to 3e$ 0.6 **6.4**	$\tau \to 3e$ 0.9 **4.2**	$\tau \to 3e$ 1.8 **5.0**	$\tau \to 3e$ 0.9 **2.7**	$\tau \to 3e$ 0.9 **2.8**	$\tau \to 3e$ 0.3 **3.5**	$\tau \to 3e$ 0.2 **1.4**
2 3	*	$B \to \tau\bar{e}X$ 14.0 **5.8**	$B \to \tau\bar{e}X$ 14.0 **5.6**	$B \to \tau\bar{e}X$ 7.2 **3.6**	$B \to \tau\bar{e}X$ 7.2 **4.0**	*	$B \to \tau\bar{e}X$ 7.2 **3.6**
3 1	*	$B \to \tau\bar{e}$ 0.07 **5.3**	$B \to \tau\bar{e}$ 0.07 **4.8**	V_{ub} 0.14 **1.5**	$B \to \tau\bar{e}$ 0.03 **1.7**	*	V_{ub} 0.14 **1.5**
3 2	*	$B \to \tau\bar{e}X$ 14.0 **7.9**	$B \to \tau\bar{e}X$ 14.0 **7.6**	$B \to \tau\bar{e}X$ 7.2 **2.9**	$B \to \tau\bar{e}X$ 7.2 **3.1**	*	$B \to \tau\bar{e}X$ 7.2 **2.9**
3 3	*	$\tau \to 3e$ 0.9 **10.1**	$\tau \to 3e$ 1.8 **9.1**	$\tau \to 3e$ 0.9 **4.7**	$\tau \to 3e$ 0.9 **4.9**	*	$\tau \to 3e$ 0.2 **4.7**

HERA limits much more competitive … but not the focus of todays talk

Limits on LQ mass

- For a coupling of electromagnetic strength, $\lambda = \sqrt{4\pi\alpha_{em}} = 0.3$:

  LFV leptoquarks decaying to a muon–quark or a tau–quark pair are excluded at 95% confidence level up to M_{LQ} of **712 GeV** and **479 GeV**, respectively

HERA-EIC comparison

$\sqrt{s_{HERA}} = 318\ GeV$; assuming $\sqrt{s_{EIC}} = 100\ GeV$

- **Cross section** for LQ production at HERA in HMA:

$$\sigma_{HMA}(eq_i \to \ell q_j, e\bar{q}_i \to \ell \bar{q}_j) = \frac{s}{32\pi}\left[\frac{\lambda_{eq_i}\ \lambda_{eq_j}}{M^2_{LQ_{F=2}}}\right]^2 \left[\int dx\, dy\, x q_i(x,\hat{s})\ f(y) + \int dx\, dy\, x\bar{q}_j(x,u)\ g(y)\right]$$

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

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

- **Center-of-mass energy**

Since $\sigma_{HMA} \propto s$ → $\left(\frac{s_{HERA}}{s_{EIC}}\right)^2 = \left(\frac{318}{100}\right)^2 \sim 10$ → EIC 10x disadvantaged wrt HERA

→ 10x HERA luminosity needed to recover the same sensistivity

- **Luminosity**

Limits on high-mass LQs are expressed in terms of $\frac{\lambda_{eq_i}\ \lambda_{\mu q_j}}{M^2_{LQ}}$ and $\sigma_{HMA} \propto \left(\frac{\lambda_{eq_i}\ \lambda_{\mu q_j}}{M^2_{LQ}}\right)^2$

→ limits $\propto \sqrt{\int \mathcal{L}\, dt}$

If $\int \mathcal{L}_{EIC}\, dt \sim 10^3 \int \mathcal{L}_{HERA}\, dt$ → EIC limits 10x better than HERA limits

LQ cross-sections at EIC and HERA

Cross sections from LQgenEP for two LQ types and two different masses

- coupling assumed of electro-magnetic strength ($\lambda = 0.3$)
- CTEQ4L pdfs have been used
- **EIC** colliding beams: Ee=10 GeV → ← Ep=250 GeV

LQ type	M_{LQ} [TeV]	σ_{EIC} [fb]	σ_{HERA} [fb]	$\frac{\sigma_{HERA}}{\sigma_{EIC}}$
$S^L_{1/2}$	1.0	0.0338	0.345	10.2
$S^L_{1/2}$	0.5	0.548	6.39	11.7
$\tilde{V}^R_0$	1.0	0.0483	0.523	10.8
$\tilde{V}^R_0$	0.5	0.787	9.50	12.1

factor ~10, as expected

Thanks!

L.Bellagamba, *LQGENEP: a leptoquark generator for ep scattering*
Computer Physics Communications 141 (2001) 83–97

High-mass LQ limits: EIC contribution?

$ep \to \mu X$ **H1** $F = 0$

Upper exclusion limits on $\lambda_{eq_i}\lambda_{\mu q_j}/M^2_{LQ}$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL

$q_i q_j$	$S^L_{1/2}$ $\ell^-\bar{U}$ ℓ^+U	$S^R_{1/2}$ $\ell^-\bar{U}, \ell^-\bar{D}$ ℓ^+U, ℓ^+D	$\tilde{S}^L_{1/2}$ $\ell^-\bar{D}$ ℓ^+D	V^L_0 $\ell^-\bar{D}$ ℓ^+D	V^R_0 $\ell^-\bar{D}$ ℓ^+D	$\tilde{V}^R_0$ $\ell^-\bar{U}$ ℓ^+U	V^L_1 $\ell^-\bar{U}, \ell^-\bar{D}$ ℓ^+U, ℓ^+D
1 1	$\mu N \to eN$ 5.2×10^{-5} **0.6**	$\mu N \to eN$ 2.6×10^{-5} **0.6**	$\mu N \to eN$ 5.2×10^{-5} **0.9**	$\mu N \to eN$ 2.6×10^{-5} **0.5**	$\mu N \to eN$ 2.6×10^{-5} **0.6**	$\mu N \to eN$ 2.6×10^{-5} **0.4**	$\mu N \to eN$ 0.8×10^{-5} **0.2**
1 2	$D \to \mu\bar{e}$ 0.8 **0.7**	$K \to \mu\bar{e}$ 2×10^{-5} **0.5**	$K \to \mu\bar{e}$ 2×10^{-5} **0.9**	$K \to \mu\bar{e}$ 1×10^{-5} **0.6**	$K \to \mu\bar{e}$ 1×10^{-5} **0.7**	$D \to \mu\bar{e}$ 0.4 **0.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.2**
1 3	*	$B \to \mu\bar{e}$ 0.08 **1.0**	$B \to \mu\bar{e}$ 0.08 **0.9**	$B \to \mu\bar{e}$ 0.04 **0.7**	$B \to \mu\bar{e}$ 0.04 **0.8**	*	$B \to \mu\bar{e}$ 0.04 **0.7**
2 1	$D \to \mu\bar{e}$ 0.8 **1.4**	$K \to \mu\bar{e}$ 2×10^{-5} **1.2**	$K \to \mu\bar{e}$ 2×10^{-5} **1.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.6**	$K \to \mu\bar{e}$ 1×10^{-5} **0.7**	$D \to \mu\bar{e}$ 0.4 **0.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.2**
2 2	$\mu N \to eN$ 9.2×10^{-4} **2.4**	$\mu N \to eN$ 1.3×10^{-3} **1.7**	$\mu N \to eN$ 3×10^{-3} **1.9**	$\mu N \to eN$ 1.5×10^{-3} **1.0**	$\mu N \to eN$ 1.5×10^{-3} **1.1**	$\mu N \to eN$ 4.6×10^{-4} **1.4**	$\mu N \to eN$ 2.7×10^{-4} **0.5**
2 3	*	$B \to \bar{\mu}eK$ 2.0×10^{-3} **2.3**	$B \to \bar{\mu}eK$ 2.0×10^{-3} **2.1**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.4**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.5**	*	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.4**
3 1	*	$B \to \mu\bar{e}$ 0.08 **2.1**	$B \to \mu\bar{e}$ 0.08 **1.9**	V_{ub} 0.14 **0.6**	$B \to \mu\bar{e}$ 0.04 **0.7**	*	V_{ub} 0.14 **0.6**
3 2	*	$B \to \bar{\mu}eK$ 2.0×10^{-3} **3.2**	$B \to \bar{\mu}eK$ 2.0×10^{-3} **2.8**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.1**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.2**	*	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.1**
3 3	*	$\mu N \to eN$ 1.3×10^{-3} **3.8**	$\mu N \to eN$ 3×10^{-3} **3.4**	$\mu N \to eN$ 1.5×10^{-3} **1.7**	$\mu N \to eN$ 1.5×10^{-3} **1.9**	*	$\mu N \to eN$ 2.7×10^{-4} **1.7**

$ep \to \mu X$ **H1** $F = 2$

Upper exclusion limits on $\lambda_{eq_i}\lambda_{\mu q_j}/M^2_{LQ}$ (TeV^{-2}) for lepton flavour violating leptoquarks at 95% CL

$q_i q_j$	S^L_0 ℓ^-U $\ell^+\bar{U}$	S^R_0 ℓ^-U $\ell^+\bar{U}$	$\tilde{S}^R_0$ ℓ^-D $\ell^+\bar{D}$	S^L_1 ℓ^-U, ℓ^-D $\ell^+\bar{U}, \ell^+\bar{D}$	$V^L_{1/2}$ ℓ^-D $\ell^+\bar{D}$	$V^R_{1/2}$ ℓ^-U, ℓ^-D $\ell^+\bar{U}, \ell^+\bar{D}$	$\tilde{V}^L_{1/2}$ ℓ^-U $\ell^+\bar{U}$
1 1	$\mu N \to eN$ 5.2×10^{-5} **0.7**	$\mu N \to eN$ 5.2×10^{-5} **0.8**	$\mu N \to eN$ 5.2×10^{-5} **1.1**	$\mu N \to eN$ 1.7×10^{-5} **0.4**	$\mu N \to eN$ 2.6×10^{-5} **0.5**	$\mu N \to eN$ 1.3×10^{-5} **0.3**	$\mu N \to eN$ 2.6×10^{-5} **0.3**
1 2	$K \to \pi\nu\bar{\nu}$ 1×10^{-3} **0.8**	$D \to \mu\bar{e}$ 0.8 **0.9**	$K \to \mu\bar{e}$ 2×10^{-5} **1.2**	$K \to \mu\bar{e}$ 1×10^{-5} **0.4**	$K \to \mu\bar{e}$ 1×10^{-5} **0.8**	$K \to \mu\bar{e}$ 1×10^{-5} **0.5**	$D \to \mu\bar{e}$ 0.4 **0.6**
1 3	*	*	$B \to \mu\bar{e}$ 0.08 **1.3**	V_{ub} 0.3 **0.6**	$B \to \mu\bar{e}$ 0.04 **0.9**	$B \to \mu\bar{e}$ 0.04 **1.0**	*
2 1	$K \to \pi\nu\bar{\nu}$ 1×10^{-3} **1.2**	$D \to \mu\bar{e}$ 0.8 **1.2**	$K \to \mu\bar{e}$ 2×10^{-5} **1.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.6**	$K \to \mu\bar{e}$ 1×10^{-5} **0.5**	$K \to \mu\bar{e}$ 1×10^{-5} **0.3**	$D \to \mu\bar{e}$ 0.4 **0.4**
2 2	$\mu N \to eN$ 9.2×10^{-4} **2.4**	$\mu N \to eN$ 9.2×10^{-3} **2.7**	$\mu N \to eN$ 3×10^{-3} **2.1**	$\mu N \to eN$ 2.5×10^{-3} **0.9**	$\mu N \to eN$ 1.5×10^{-3} **1.0**	$\mu N \to eN$ 6.7×10^{-4} **0.9**	$\mu N \to eN$ 4.6×10^{-4} **1.2**
2 3	*	*	$B \to \bar{\mu}eK$ 2.0×10^{-3} **2.3**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.0**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.4**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.5**	*
3 1	*	*	$B \to \mu\bar{e}$ 0.08 **1.8**	$B \to \mu\bar{e}$ 0.08 **0.8**	$B \to \mu\bar{e}$ 0.04 **0.5**	$B \to \mu\bar{e}$ 0.04 **0.5**	*
3 2	*	*	$B \to \bar{\mu}eK$ 2.0×10^{-3} **3.2**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.4**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.1**	$B \to \bar{\mu}eK$ 1.0×10^{-3} **1.2**	*
3 3	*	*	$\mu N \to eN$ 3×10^{-3} **3.8**	$\mu N \to eN$ 2.5×10^{-3} **1.7**	$\mu N \to eN$ 1.5×10^{-3} **1.7**	$\mu N \to eN$ 6.7×10^{-4} **1.9**	*

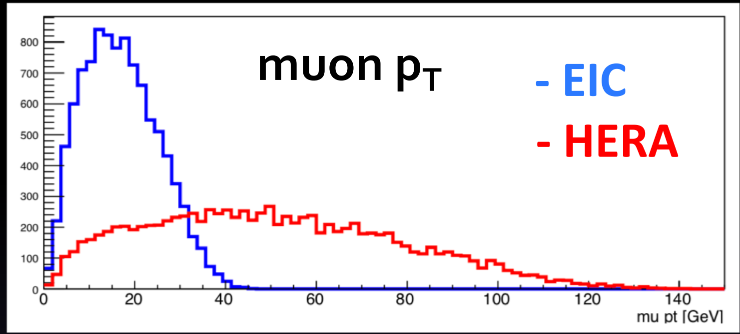
(red box) Limit which could be improved at EIC

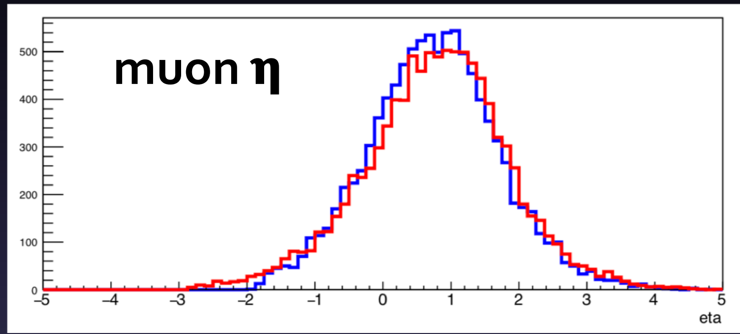
Is kinematics of LQ production at EIC compatible with detector capabilities?

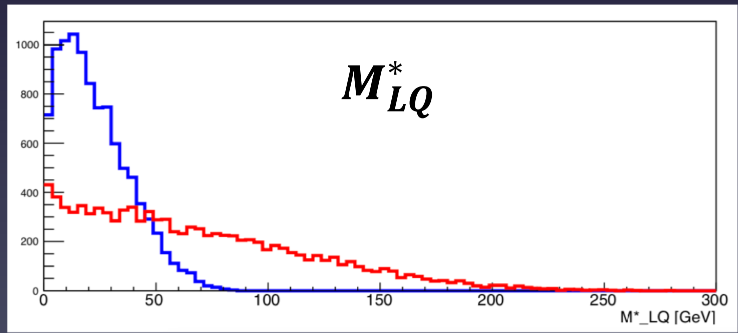
LQ kinematics at EIC

LQgenEP events for $S^{L}_{1/2}$ with $M_{LQ} = 1\ TeV$

- **HERA**: Ee=27.5 GeV → ← Ep=920 GeV
- **EIC**: Ee=10 GeV → ← Ep=250 GeV



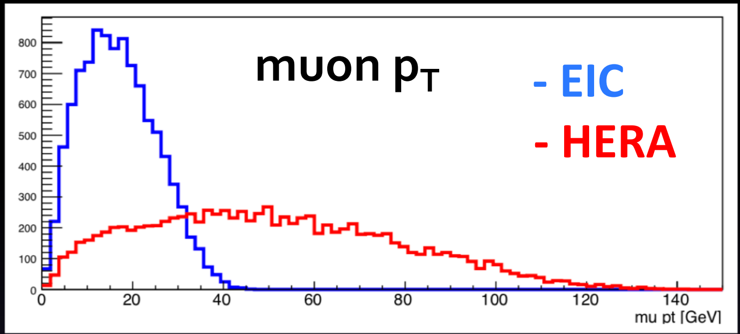


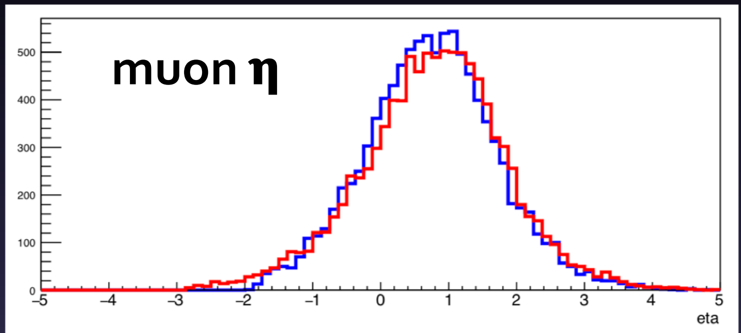


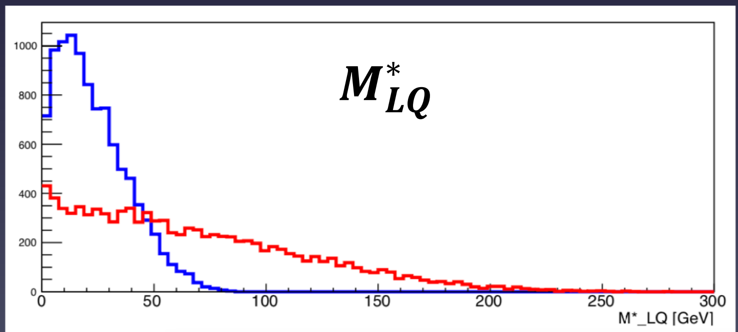
- softer spectrum in muon transverse momentum
- similar muon pseudo-rapidity distribution
- virtual LQ mass ($= \sqrt{xs}$)

LQ kinematics at EIC vs M_{LQ}

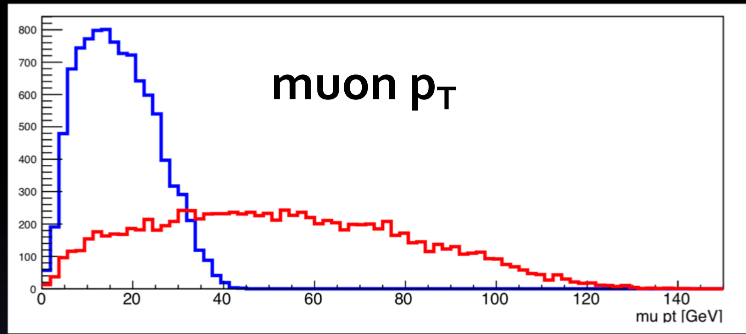
$S^{L}_{1/2}$ M_{LQ} = 1 TeV

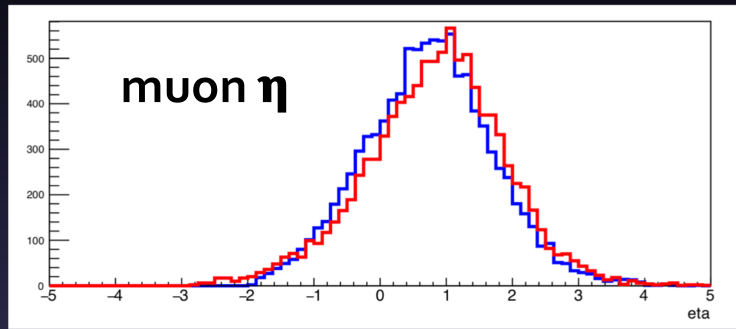


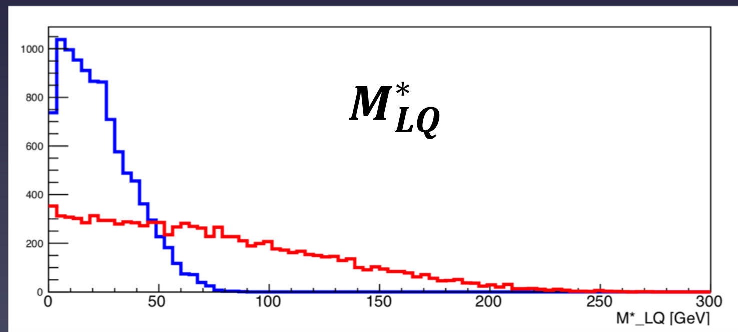




$S^{L}_{1/2}$ M_{LQ} = 0.5 TeV





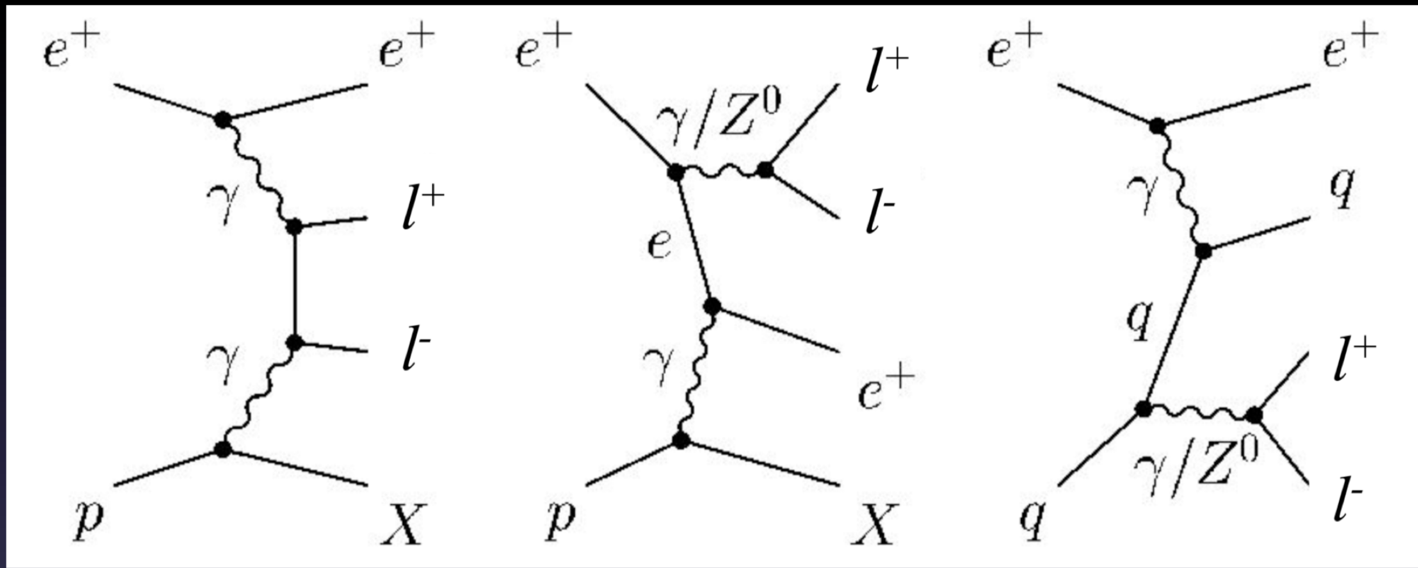


No significant variation with M_{LQ}

Multi-lepton production at HERA

H1 and ZEUS Coll., Multi-Leptons with High Transverse Momentum at HERA
JHEP 10(2009)013

In ep interaction multi-lepton production is dominated by the $\gamma\gamma$ processs



QED process with very precise prediction from the Standard Model

Low cross-section at high mass, high pt → look for new phenomena

Multi-lepton analysis steps

- QED process, precise SM prediction, modelled by GRAPE(*)
  $ep \rightarrow e\mu^+\mu^- X$ and $ep \rightarrow ee^+e^- X$ are simulated

- Events with only two leptons ($\mu\mu$, $e\mu$ or ee) are observed if the scattered electron or one lepton of the pair is not detected

- Main SM background:
  - NC-DIS, QED Compton for multi-electron events
  - very low background for multi-muon events

- Examine events using the mass of the two highest P_T leptons, $\boldsymbol{M}_{12}$,
  and the sum of the transverse momentum of all leptons, $\boldsymbol{\Sigma P_T}$

(*) T.Abe, GRAPE-Dilepton A generator for dilepton production in *ep* collisions
Computer Physics Communications 136 (2001) 126–147

Event selection

- Two leptons with
  - $P_T > 10\ GeV$
  - $P_T > 5\ GeV$

- Additional leptons:
  - $E > 5\ GeV$ for electrons, $P_T > 2\ GeV$ for muons

- All leptons isolated wrt each other by at least 0.5 units in $\eta - \phi$ plane

- Subsamples of ee and μμ events are selected requiring $E - P_Z < 45$
  in order to measure the $\gamma\gamma \rightarrow ee$ and $\gamma\gamma \rightarrow \mu\mu$ photoproduction cross section

- Efficency for electrons: 80-95%
- Efficiency for muons: 55-90%   depending on region and experiment

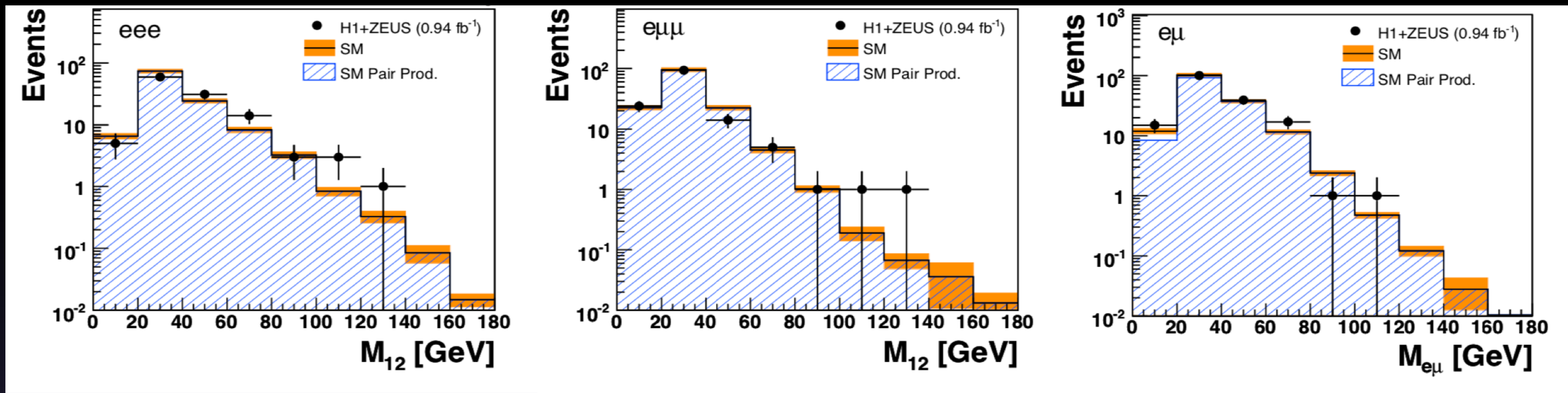
Selected events

Summary of selected events for the different topologies
for the H1+ZEUS combined analysis

Multi-Leptons at HERA (0.94 fb^{-1})				
Sample	Data	SM	Pair Production (GRAPE)	NC DIS + QEDC
ee	873	895 ± 57	724 ± 41	171 ± 28
$\mu\mu$	298	320 ± 36	320 ± 36	< 0.5
$e\mu$	173	167 ± 10	152 ± 9	15 ± 3
eee	116	119 ± 7	117 ± 6	< 4
$e\mu\mu$	140	147 ± 15	147 ± 15	< 0.5
$(\gamma\gamma)_e$	284	293 ± 18	289 ± 18	4 ± 1
$(\gamma\gamma)_\mu$	235	247 ± 26	247 ± 26	< 0.5

Invariant mass distributions

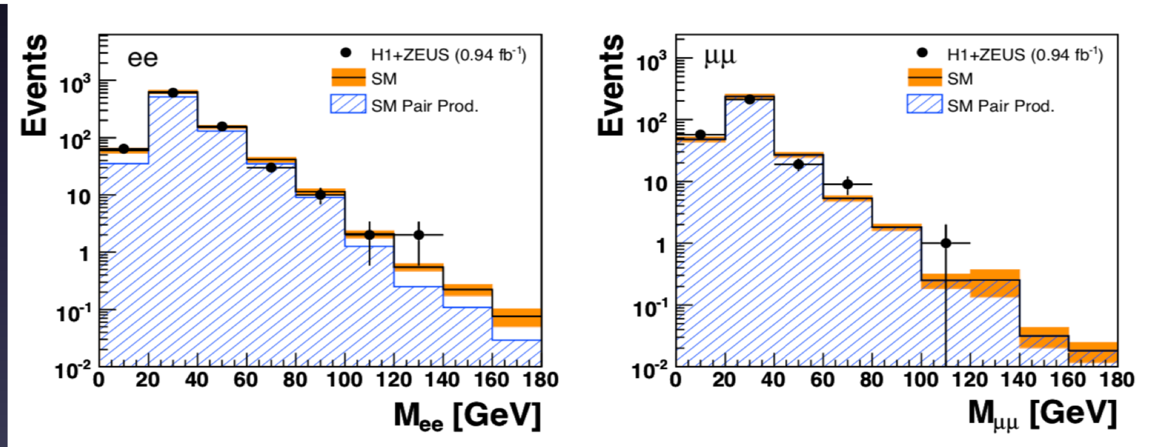
Distributions of the invariant mass M12 of the two highest P_T leptons for the different topologies



Overall good agreement with SM has been found

eμμ, μμ and eμ topologies are dominated by muon pair production

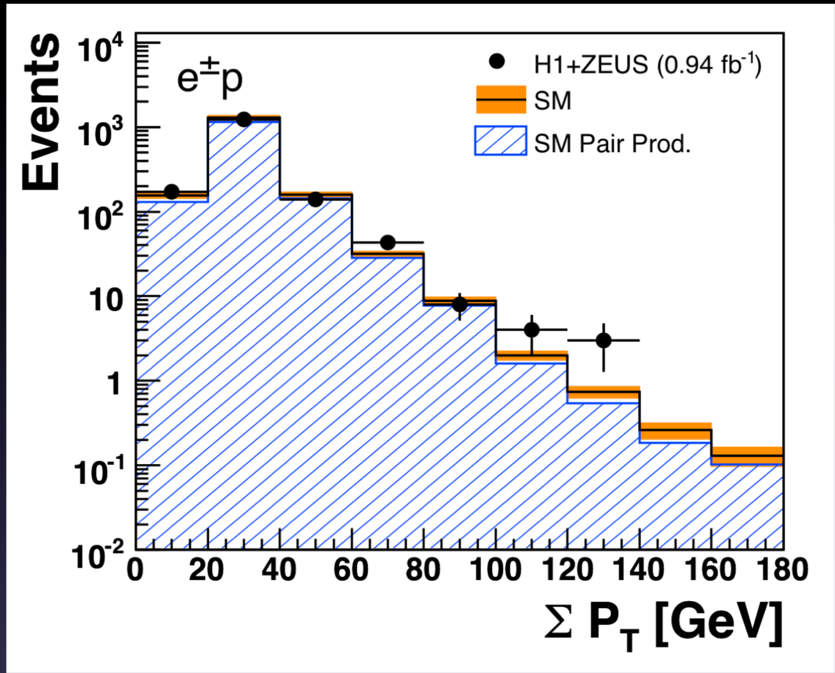
eee and ee topologies contain mainly events from electron pair production



H1 and ZEUS data combined to reach best sensitivity

Transverse momentum distribution

Distributions of the scalar sum of the transverse momenta ΣP_T of the observed multi-lepton events compared to the SM expectation



Di- lepton and tri-lepton event topologies included for all data

Good overall agreement between data and SM prediction

Photo-production cross section

In order to select lepton pair events in photoproduction,the requirement $E - P_Z < 45$ GeV is introduced, forming sub-samples of the ee and $\mu\mu$ samples

- select sample only populated with two leptons of the same flavour in the final state
- contribution from $\tau\tau$ events is found to be negligible

Cross sections evaluated for the two-photon process in the kinematic region

- Photoproduction regime: $Q^2 < 1\ GeV^2, y < 0.82$
- High transverse momentum: $P_{T_{1,2}} > 10, 5\ GeV$
- In the main body of the detectors: $20° < \theta < 150°$
- Leptons are isolated ($\Delta r > 0.5$ in the $\eta - \phi$ plane)

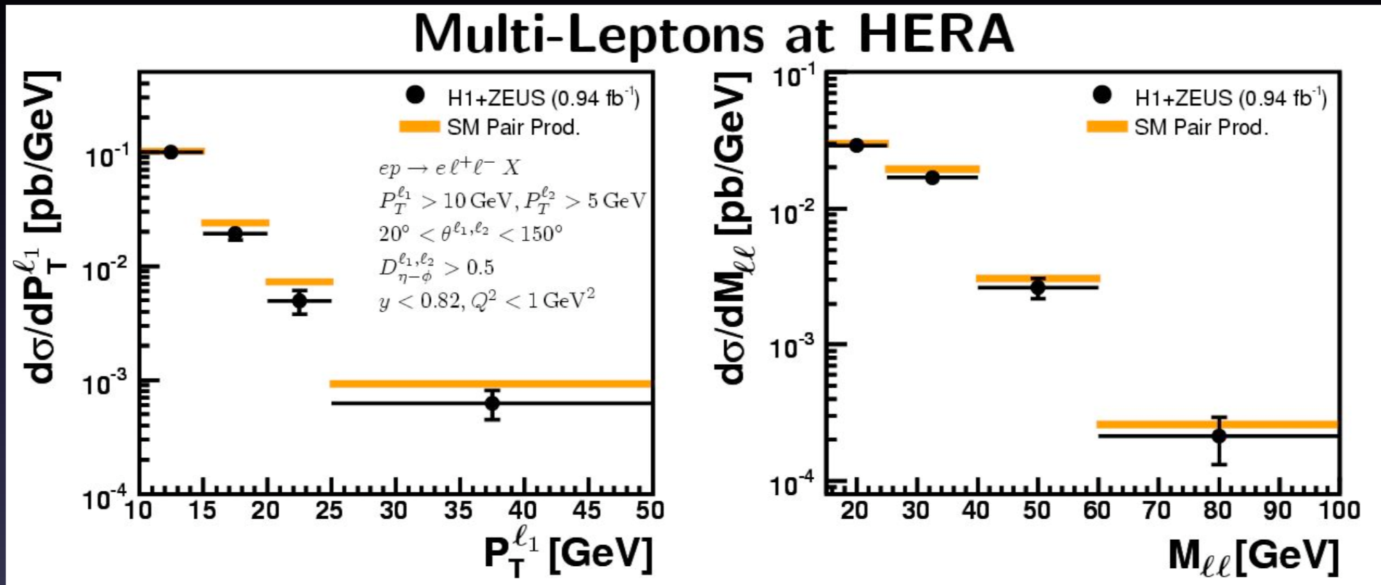
Weighted average done of electron and muon channels to form the $\gamma\gamma \rightarrow l^+ l^-$ cross section

Photo-production cross sections

Total visible and differential cross sections for electron- and muon-pair production combined in lepton-pair measurements

Differential cross sections measured as a function of

- P_T of the leading lepton
- invariant mass of the lepton pair



Total visible lepton pair production

$$\sigma(ep \to el^+l^-X) = 0.66 \pm 0.03(stat.) \pm 0.03(syst.)\, pb$$

SM expectation of 0.69 ± 0.02 pb from GRAPE in agreement (dominated by $\gamma\gamma$ collisions)

Conclusions

- HERA results presented for analyses with muons:
  - multi-lepton searches
  - LFV searches

  Not main physics target at EIC

- Multi-lepton searches has combined H1+ZEUS results

  EIC cannot reach high-pt values where interesting effects could be revealed

- LFV analysis:

  H1 results with full HERA dataset (shown)

  ZEUS has produced results on a subset (HERA-I) of data

  EIC has the potentiality to improve the HERA (and low energy experiment) results on LFV searches, i.e. provide more stringent limits on LQ production

- Heavy quark studies not considered because alternative tagging methods are available, but some benefit could come exploiting HQ semi-muonic decay