Probing of lepton flavour violation in the NA64 experiment

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on behalf of the NA64 Collaboration

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introduction

Lepton conversion (or lepton flavor violation) is a transition among μ, e, τ that doesn't conserve lepton family number

But family number is not a fundamental symmetry

- quark family number is violated in weak decays in the CKM matrix
- neutrino oscillations (PMNS matrix) are violation in neutral leptons

- but charged lepton mixing does not occur in the Standard Model.

Charged Lepton Flavor Violation (CLFV) is heavy suppressed in the SM $l_a \to l_b < 10^{-55}$

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- quark family number is violated in weak decays in the CKM matrix
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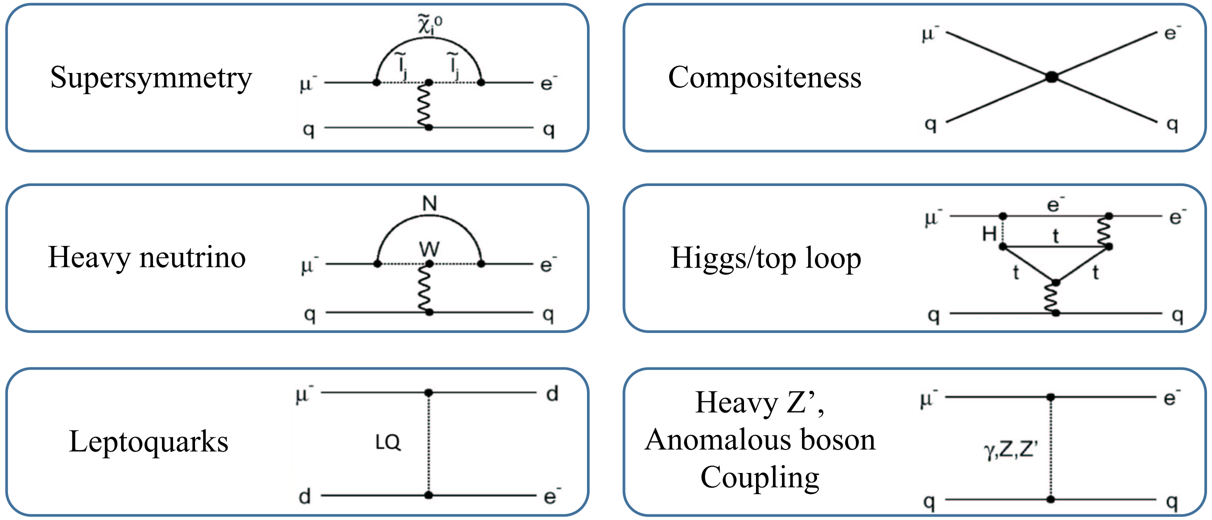
Opportunity for New Physics !!!

introduction

Various BSM models that predict CLFV



R. Bernstein.arxiv.org/abs/1307.5787v3 (2014)
Y. Kuno and Y. Okada,arXiv:hep-ph/9909265
M. Raidal et al.,arXiv:0801.1826

Major experimental searches:

- $\mu \rightarrow e$ decays or transitions
- $\tau \rightarrow l$ decays
- heavy particle decaying into LFV final states

experimental searches

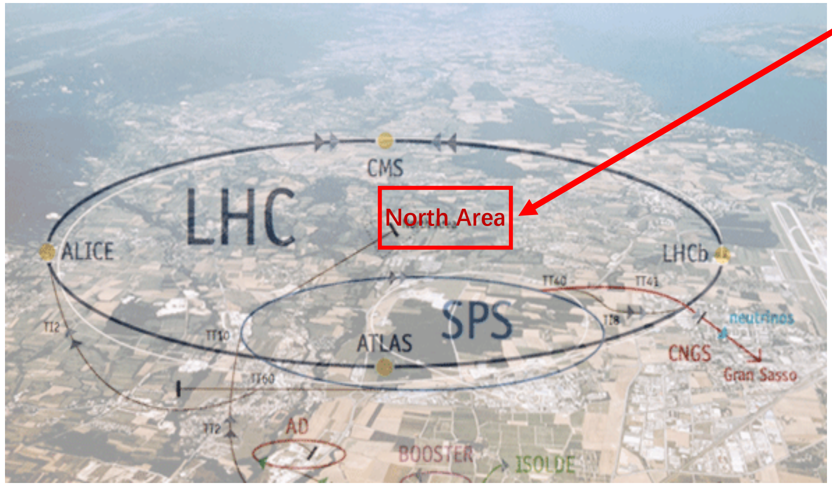
NA64

Process	Current upper limits of BR	Future sensitivity
$\mu \to e\gamma$ $\mu \to \bar{e}ee$ $\mu N \to eN$	4.2×10^{-13} MEG (2016) 1×10^{-12} SINDRUM (1988) 7×10^{-13} SINDRUM-II (2006)	10^{-14} MEGII 10^{-16} Mu3e $10^{-16} \to 10^{-18}$ COMET, Mu2e
$eN \to \tau X$ $\mu N \to \tau X$	ZEUS	10^{-13} NA64 10^{-12} NA64
$\tau \to l\gamma$ $\tau \to l\bar{l}l$ $\tau \to \mu\bar{e}e$ $(e\bar{\mu}\mu)$ $\tau \to l\rho^0$ …	3.3×10^{-8} BaBar (2010) $< 2 \times 10^{-8}$ Belle (2010) 1.8 $(2.7) \times 10^{-8}$ Belle (2010) 1.2×10^{-8} Belle (2011)	10^{-9} 4×10^{-9} 3.5×10^{-9} BelleII 10^{-9} BelleII
$K^0 \to \mu^\pm e^\mp$ $B^0 \to \tau^\pm \mu^\mp$ $J/\psi \to e\mu$ …	4.7×10^{-12} BNL E871 (1998) 1.4×10^{-5} LHCb (2019) 1.5×10^{-7} BESIII (2013)	
$Z^0 \to \mu e$ $Z^0 \to \tau e$ $Z^0 \to \tau\mu$ $H \to \mu e$ $H \to \tau e$ $H \to \tau\mu$	7.5×10^{-7} ATLAS (2014) 9.8×10^{-6} OPAL (1995) 1.2×10^{-5} DELPHI (1997) 6.1×10^{-5} ATLAS (2019) 2.2×10^{-3} CMS (2021) 1.5×10^{-3} CMS (2021)	 2.1×10^{-4} 2.4×10^{-4} 2.3×10^{-4} ILC

M. Ardu, G. Pezzullo, Universe 8, 299 (2022)

NA64 experiment

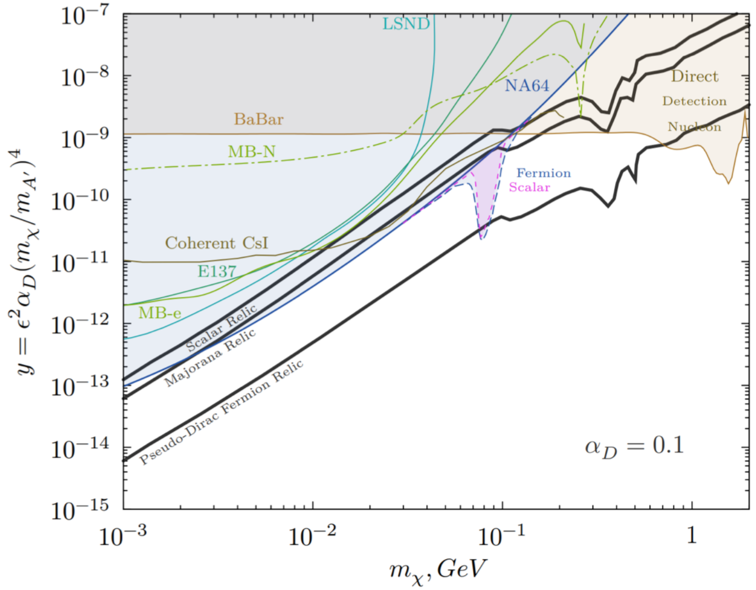
NA64



Motivation: search for new physics beyond the SM

Realization: combine the active beam dump and missing energy techniques to search for rare events

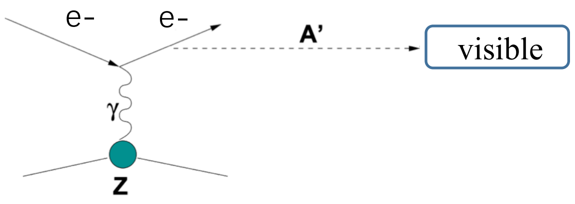
- **NA64e** (since 2015)
  100 GeV e-beam
- **NA64μ** (since 2021)
  160 GeV μ-beam
- **NA64h**
  ~100 GeV h-beam

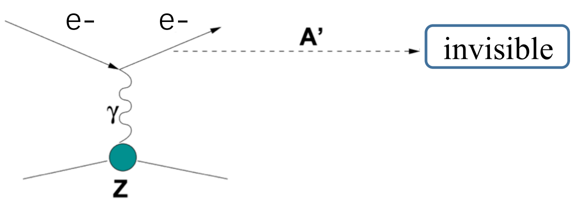


Yu. Andreev et al. [NA64 Collaboration] arXiv:2307.02404 (2023)

NA64 experiment: physics goals

target: lead ECAL



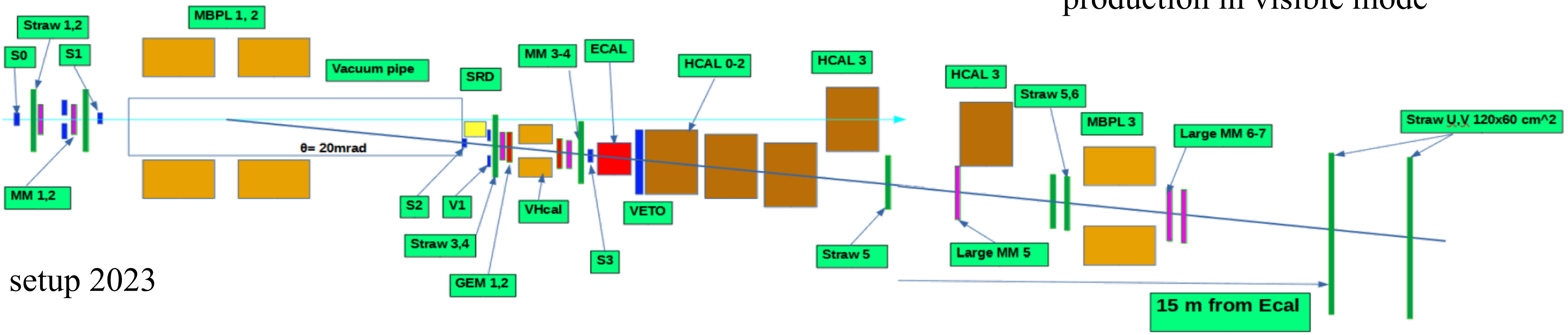


NA64e

- Thermal sub-GeV Dark Matter (LDM)
- axions, ALP, S → γ γ decays
- S, P, V, and A dark portal particles, their invisible, visible, semi-visible decays
- Light B-L Z′
- ATOMKI anomaly: X17 (P, V, A′) → e+e- decays
- MilliQ particles, etc…
- Lepton Flavor Violation in $e \to \tau$ and $e \to \mu$ conversion

A. Andreas et al. [NA64 Collaboration]. CERN-SPSC-2013-034; SPSC-P-348 (2013)
Yu. Andreev et al. [NA64 Collaboration] Phys.Rev.Lett. 129 (2022) 16, 161801
Phys. Rev. Lett. 125, 081801 (2020)

Signature: missing energy or SM particles pair production in visible mode



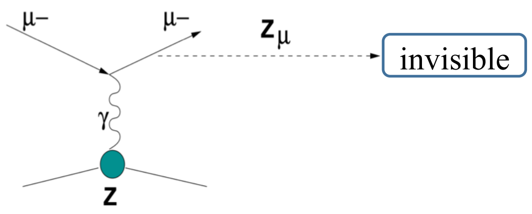
setup 2023

NA64 experiment: physics goals

target: lead ECAL

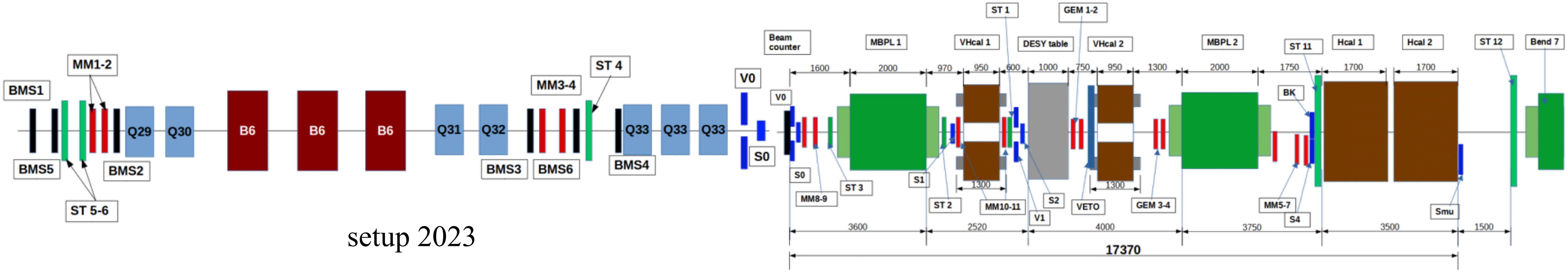
NA64μ

- Z_μ – light boson coupled to the muon, as a remaining low mass explanation of the $(g\text{-}2)_\mu$ (the muon anomaly)
- LDM interacting with the Standard Matter via a new gauge vector-boson mediator Z_μ
- Scalar, Axion Like Particles coupled to the muon
- Lepton Flavor Violation in $\mu \to \tau$ and $\mu \to e$ conversion



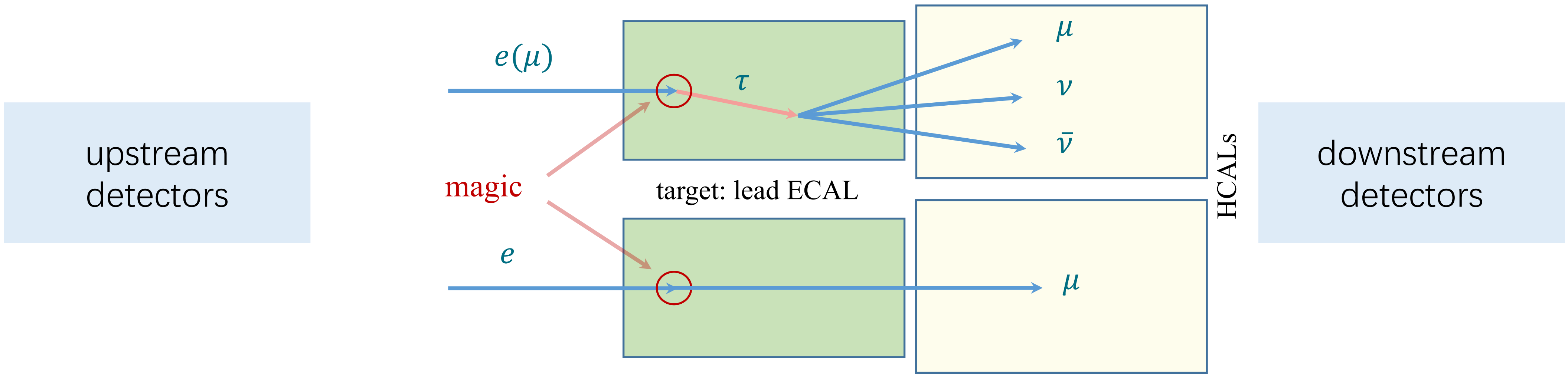
Signature: missing energy and momentum

S. Gninenko et al. PLB796, 117 (2019)
D. Banerjee et al. [NA64 Collaboration]. CERN-SPSC-2019-002 / SPSC-P-359, January 14, 2019.



setup 2023

lepton conversion at NA64



Signature for $l\tau$ conversion: SM tau's decay production and missing energy

Event selection criteria* for *e*-beam:

- ECAL < 50 GeV
- VETO < 1 MIP
- HCAL0 < 1 GeV
- HCAL1, HCAL2 < MIP
- ECAL Shower Profile $\chi^2 < \chi^2_{cut}$ (χ^2_{cut} from 4 to 8)

*used for A' searching

Signature for $e\mu$ conversion: single muon production and missing energy

The criteria for selecting events for the μ-beam have not yet been determined, but:

- ECAL < 80 GeV

lepton conversion at NA64

Effective Lagrangian for $l + q_i \rightarrow l' + q_f$ process

$$\mathcal{L} = \frac{\text{couplings}}{\Lambda^{n}}$$

→ mass scale of new physics

$$\mathcal{L}_{\ell\tau} = \sum_{I,if,XY} \left(\Lambda^{\ell\tau}_{I_{if},XY}\right)^{-2} \mathcal{O}^{\ell\tau}_{I_{if},XY} + \text{H.c.}$$

$l = e, \mu$
I = S, V, T operators
i, f = u, d, c, b, t initial and final states
X,Y = L, R chiralities

with different operators

$$\begin{aligned}
\mathbf{S}-\text{type:} \quad & \mathcal{O}^{\ell\tau}_{S_{if},XY} = (\bar{\tau} P_X l)(\bar{q}_f P_Y q_i)\,, \\
\mathbf{V}-\text{type:} \quad & \mathcal{O}^{\ell\tau}_{V_{if},XY} = (\bar{\tau} \gamma^{\mu} P_X l)(\bar{q}_f \gamma_{\mu} P_Y q_i)\,, \\
\mathbf{T}-\text{type:} \quad & \mathcal{O}^{\ell\tau}_{T_{if},XX} = (\bar{\tau} \sigma^{\mu\nu} P_X l)(\bar{q}_f \sigma_{\mu\nu} P_X q_i)
\end{aligned}$$

S. Gninenko et al. Phys. Rev. D 98, 015007 (2018)

lepton conversion at NA64

Total cross section of the $l \to \tau$ conversion on a nucleus

A - atomic number
Z - mass number
$l = e, \mu$
$m_l = 0$

$$\sigma(\ell + (A, Z) \to \tau + X) \; = \; Z\,\sigma(\ell + p \to \tau + X) + (A - Z)\,\sigma(\ell + n \to \tau + X)$$

For nucleon $N = p,\ n$

$$\sigma(\ell + N \to \tau + X) \; = \; \sum_{if} \int_0^1 dx \int_0^1 dy \left[\frac{d^2\hat{\sigma}}{dxdy}(\ell + q_i \to \tau + q_f)\, q_i^N(x, Q^2) + \frac{d^2\hat{\sigma}}{dxdy}(\ell + \bar{q}_f \to \tau + \bar{q}_i)\, \bar{q}_f^N(x, Q^2) \right]$$

where

$$\frac{d^2\hat{\sigma}}{dxdy}(\ell + q_i \to \tau + q_f) \; = \; \sum_{I,XY} \frac{1}{\left(\Lambda^{\ell\tau}_{I_{if},XY}\right)^4} \frac{\hat{s} f_{I,XY}(y)}{64\pi}$$

$$\frac{d^2\hat{\sigma}}{dxdy}(\ell + \bar{q}_f \to \tau + \bar{q}_i) \; = \; \sum_{I,XY} \frac{1}{\left(\Lambda^{\ell\tau}_{I_{if},XY}\right)^4} \frac{\hat{s} g_{I,XY}(y)}{64\pi}$$

$q_i^N(x, Q^2)$ - quark PDF
$\bar{q}_i^N(x, Q^2)$ - antiquark PDF
$x = \; Q^2/(q \cdot P)$ - Bjorken variable
$y = (q \cdot P)/(k \cdot P)$ - inelasticity
$f_{I,XY}(y)$ and $g_{I,XY}(y)$ - matrix elements of the operators

S. Gninenko et al. Phys. Rev. D 98, 015007 (2018)

lepton conversion at NA64

$$\sigma(\ell + (A,Z) \to \tau + X) = \sum_{I,if,XY} \frac{Q^A_{I_{if,XY}}}{\Lambda^4_{I_{if,XY}}}$$

with
$$Q^A_{I_{if,XY}} = \frac{s}{64\pi} \int_0^1 dx \int_0^1 dy \left[x\, f_{I,XY}(y)\, q_i^A(x, sxy) + x\, g_{I,XY}(y)\, \bar{q}_f^A(x, sxy) \right]$$

where
$$u^A(x,Q^2) = Zu^p(x,Q^2) + (A-Z)d^p(x,Q^2)\,,$$
$$d^A(x,Q^2) = Zd^p(x,Q^2) + (A-Z)u^p(x,Q^2)\,,$$
$$u^A(x,Q^2) + d^A(x,Q^2) = A\left(u^p(x,Q^2) + d^p(x,Q^2)\right),$$
$$\bar{u}^A(x,Q^2) = A\bar{u}^p(x,Q^2)\,,$$
$$\bar{d}^A(x,Q^2) = A\bar{d}^p(x,Q^2)\,,$$
$$s^A(x,Q^2) = \bar{s}^A(x,Q^2) = As^p(x,Q^2)\,,$$
$$c^A(x,Q^2) = \bar{c}^A(x,Q^2) = Ac^p(x,Q^2)\,,$$
$$b^A(x,Q^2) = \bar{b}^A(x,Q^2) = Ab^p(x,Q^2)$$

S. Gninenko et al. Phys. Rev. D 98, 015007 (2018)

lepton conversion at NA64

$$R_{\ell\tau} = \frac{\sigma(\ell + A \to \tau + X)}{\sigma(\ell + A \to \ell + X)}$$

where $\sigma(\ell + A \to \ell + X) \approx \sigma_{BS}(\ell + A \to \ell + X)$

$$R_{\ell\tau} \sim 10^{-13} - 10^{-12}$$

Limits on the LFV scales for Pb target:

S — operators: $\Lambda^{e\tau} \geq 0.04 - 0.19$ TeV, $\Lambda^{\mu\tau} \geq 0.56 - 2.45$ TeV,

V — operators: $\Lambda^{e\tau} \geq 0.05 - 0.35$ TeV, $\Lambda^{\mu\tau} \geq 0.78 - 4.46$ TeV,

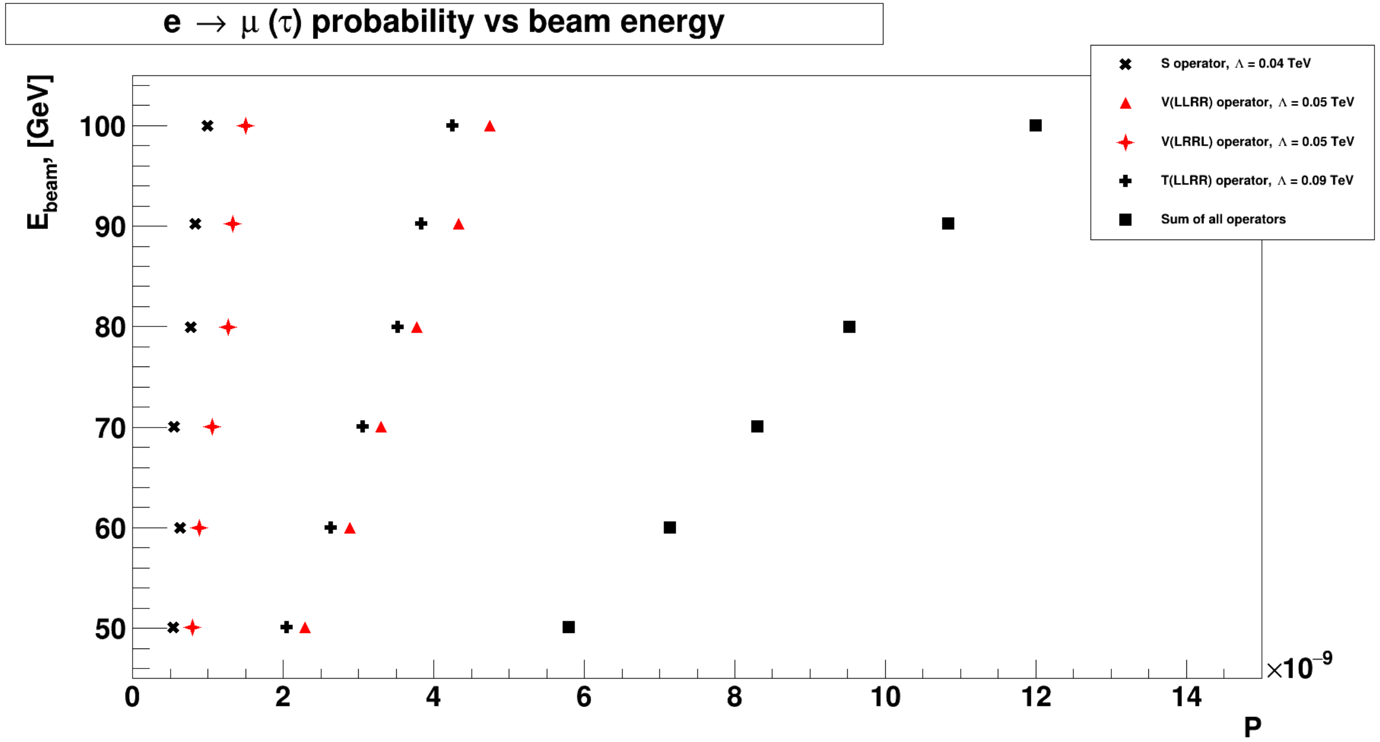
T — operators: $\Lambda^{e\tau} \geq 0.09 - 0.63$ TeV, $\Lambda^{\mu\tau} \geq 1.45 - 8.01$ TeV.

$\Lambda^{e\tau}_{\text{ZEUS}} \geq 0.41 - 1.86$ TeV sum of all operators (based on leptoquarks)

S. Chekanov et al. (ZEUS Collaboration), Phys. Rev. D 65, 092004 (2002)

probability of lepton conversion

accumulated around 10^{12} EOT



The probability of $e - \mu(\tau)$ conversion as a function of electron energy

82 **Pb** Lead 207.2 ***e - beam***

$\Lambda_S^{e\tau} = 0.04$ TeV,

$\Lambda_V^{e\tau} = 0.05$ TeV,

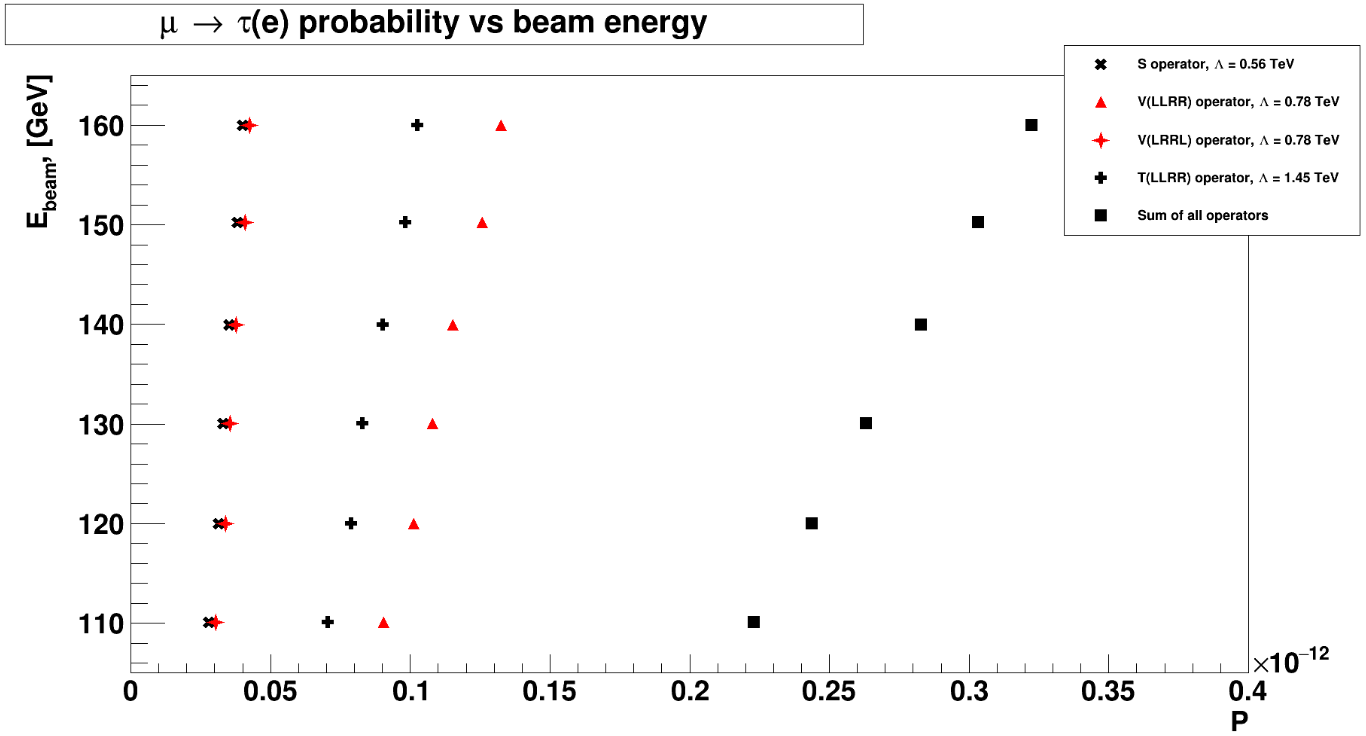
$\Lambda_T^{e\tau} = 0.09$ TeV

Sensitivity estimation for the Vector operators:

- expected sensitivity to Λ is 0.13 TeV
- ~100 events

probability of lepton conversion

accumulated around 10^{11} MOT



The probability of $\mu - e(\tau)$ conversion as a function of muon energy

82 **Pb** Lead 207.2 ***μ - beam***

$$\Lambda_S^{\mu\tau} = 0.56 \text{ TeV},$$
$$\Lambda_V^{\mu\tau} = 0.78 \text{ TeV},$$
$$\Lambda_T^{\mu\tau} = 1.45 \text{ TeV}$$

Sensitivity estimation for the Vector operators:

- sensitivity to Λ is 0.095 TeV (for the run 2022 with $2x10^{10}$ MOT)
- < 1event

summary

Search for charged lepton conversion is another opportunity to explore new physics.

The study of lepton conversion was started on the NA64 experiment. The probability of observing the process in the experiment on the current statistics was studied.

- With an accumulated statistics about 100 conversion events are expected for a vector interaction on an electron beam.

- For the μ – beam less than 1 event is expected for the current statistics. It is difficult to use the NA64mu analysis for this conversion. Analysis strategy needs to change.

Thanks!

Acknowledgements

NA64 Collaboration in particular **M. Kirsanov, A. Zhevlakov and A. Ivanov**