Lepton flavor violation study in the NA64 experiment

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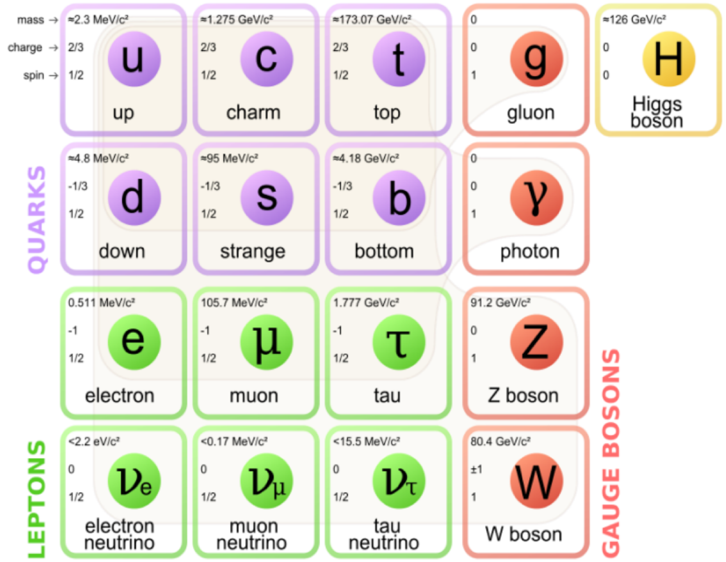
on behalf of the NA64 Collaboration

21st Lomonosov Conference, 30.08.2023

introduction



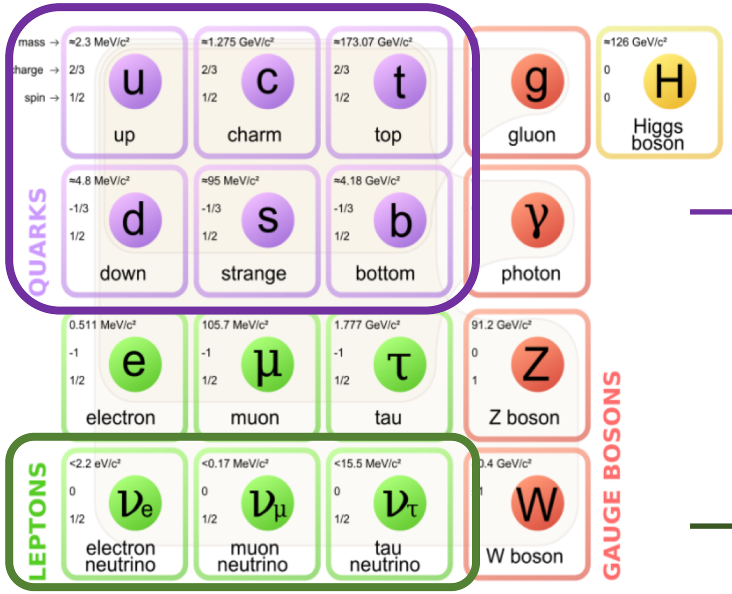
Standard Model (SM) describes the fundamental particles of matter and all their interactions.

but these phenomena are not explained:

- gravity
- dark matter
- dark energy
- neutrino masses
- matter-antimatter asymmetry

new physics Beyond the SM (BSM)

introduction



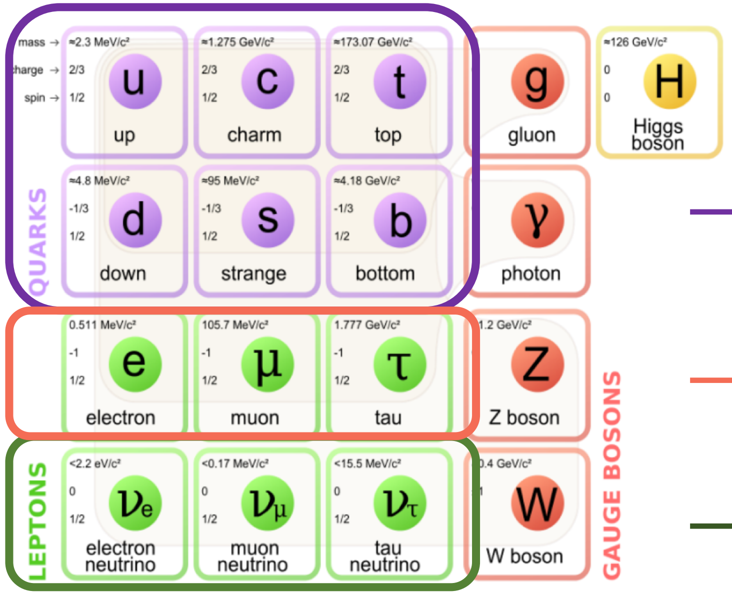
In the Standard Model lepton flavor is conserved

but

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix} = \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix}$$

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

introduction



In the Standard Model lepton flavor is conserved

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$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix} = \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix}$$

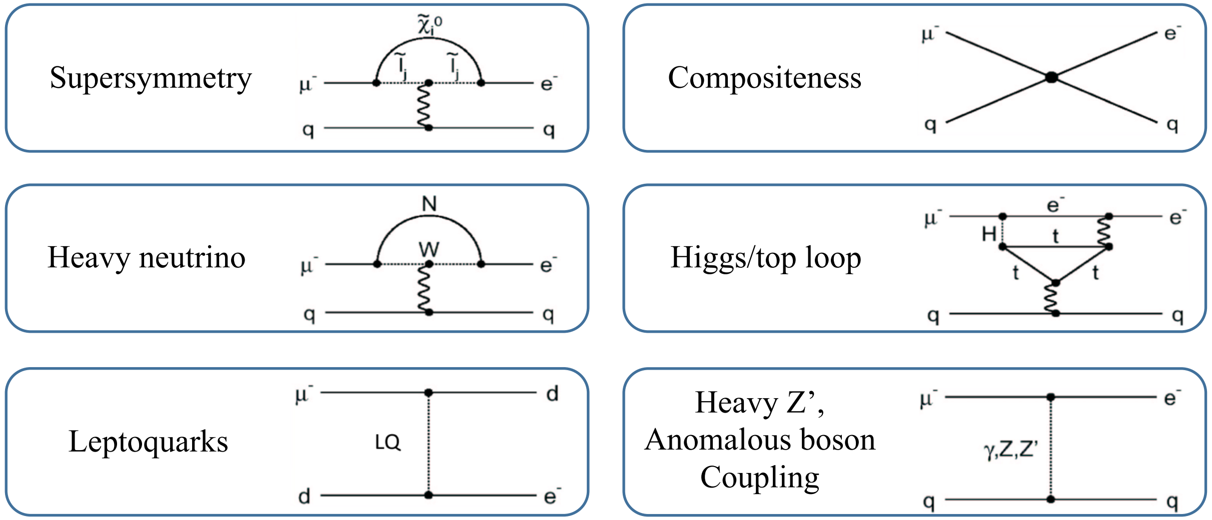
???

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

charged lepton flavor violation $l_a \rightarrow l_b$

In the charged lepton sector Lepton Flavor Violation is heavy suppressed in the SM $l_a \rightarrow l_b < 10^{-55}$

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



Various BSM models that predict CLFV

Example of CLFV:

$\mu^- \rightarrow e^- \gamma$ neutrinoless muon decay

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

experimental searches

$\mu^- + (A, Z) \to e^- + (A, Z)$ - COMET (J-PARC)

$\mu^- + N \to e^- + N$ – MECO (BNL)

$\mu \to e\gamma$ – MEG II (PSI)

$\mu \to e\bar{e}e$ – Mu3e (PSI)

$\mu \to e$ – Mu2e (Fermilab)

$e + p \to \tau + \mathcal{X}$ – ZEUS (DESY)

…

$e(\mu) + (A, Z) \to \tau + \mathcal{X}$

$e(\mu) + (A, Z) \to \mu(e) + \mathcal{X}$

NA64 (CERN)

Process	Current bound on BR	Future Sensitivity
$\mu \to e\gamma$	$< 4.2 \times 10^{-13}$ MEG	10^{-14} MEGII
$\mu \to \bar{e}ee$	$< 1.0 \times 10^{-12}$ SINDRUM	10^{-16} Mu3e
$\mu A \to eA$	$< 7 \times 10^{-13}$ SINDRUMII	$10^{-16} \to 10^{-18}$ COMET, Mu2e
$\tau \to l\gamma$	$< 3.3 \times 10^{-8}$	$3 \times 10^{-9}(e), 10^{-9}(\mu)$
$\tau \to e\bar{e}e$	$< 2.7 \times 10^{-8}$	5×10^{-9}
$\tau \to \mu\bar{\mu}\mu$	$< 2.1 \times 10^{-8}$	4×10^{-9}
$\tau \to \mu\bar{e}e, e\bar{\mu}\mu$	$< 1.8, 2.7 \times 10^{-8}$ Belle	$3, 5 \times 10^{-9}$ BelleII
…	…	…
$\tau \to l\pi^0$	$< 8.0 \times 10^{-8}$	4×10^{-9}
$\tau \to l\eta$	$< 6.5 \times 10^{-8}$	7×10^{-9}
$\tau \to l\rho$	$< 1.2 \times 10^{-8}$ Belle	10^{-9} BelleII
$K^0 \to \mu^\pm e^\mp$	$< 4.7 \times 10^{-12}$	
$B^0_d \to \tau^\pm \mu^\mp$	$< 1.2 \times 10^{-5}$ LHCb	$\sim 10^{-6}$?
…	…	…
$h \to e^\pm \mu^\mp$	$< 6.1 \times 10^{-5}$ Atlas	2.1×10^{-5}
$h \to e^\pm \tau^\mp$	$< 2.2 \times 10^{-3}$ CMS	2.4×10^{-4}
$h \to \tau^\pm \mu^\mp$	$< 1.5 \times 10^{-3}$ CMS	2.3×10^{-4} ILC
$Z \to e^\pm \mu^\mp$	$< 7.5 \times 10^{-7}$ Atlas	
$Z \to l^\pm \tau^\mp$	$< 10^{-7}$ Atlas	

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

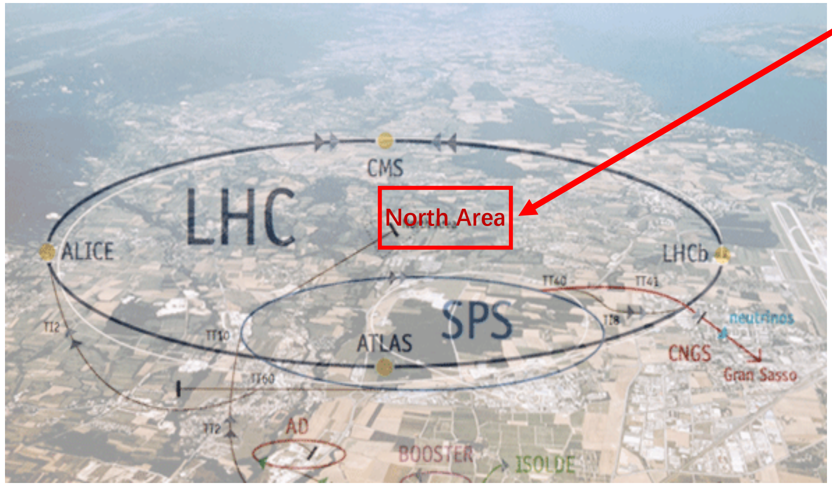
NA64 experiment

NA64e
100 GeV e-beam

NA64μ
160 GeV μ-beam

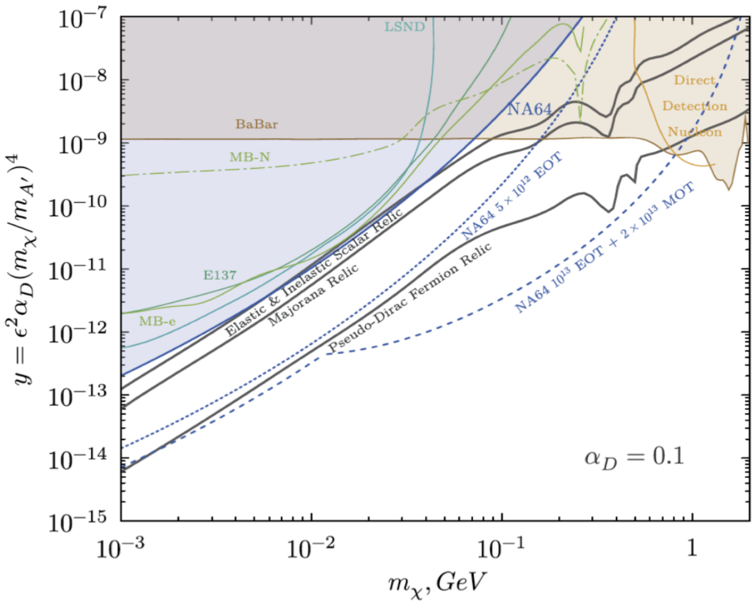
NA64h
~100 GeV h-beam

NA64



Motivation: search of new physics beyond the SM

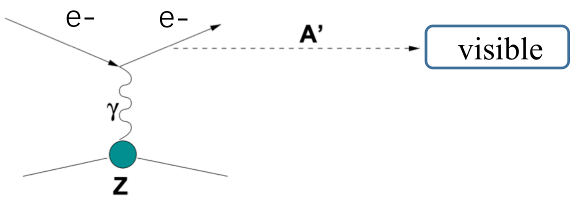
Realization: combine the active beam dump and missing energy techniques to search for rare events

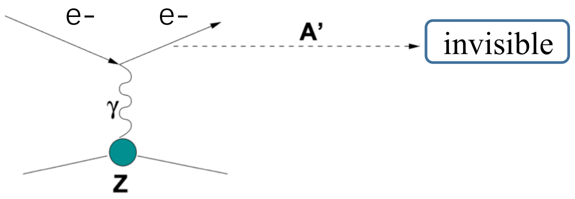


S. Gninenko et al. PLB796, 117 (2019)

NA64 experiment: physics goals

target: lead ECAL



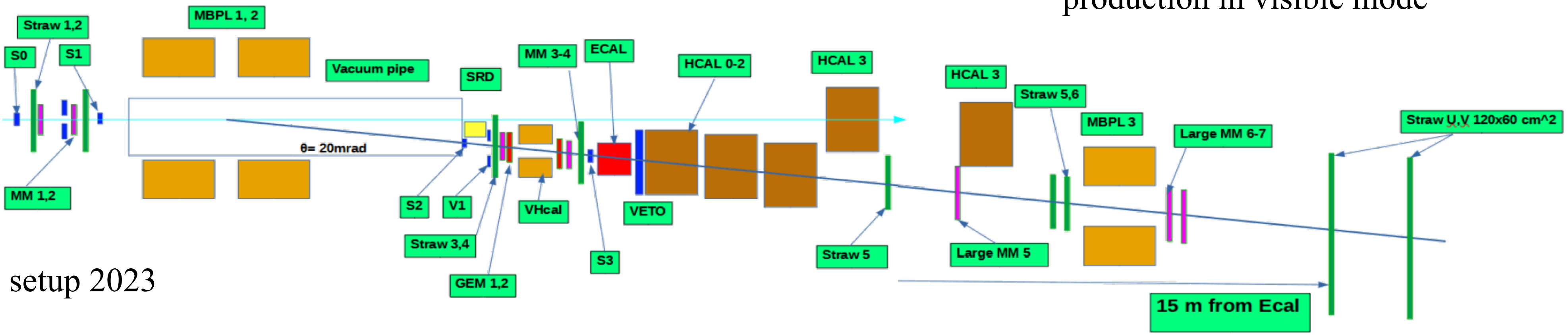


NA64e

- 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



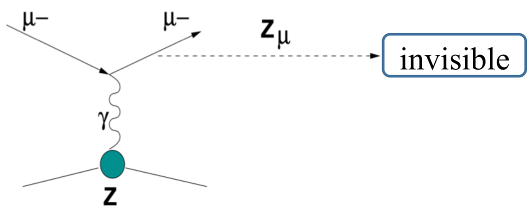
setup 2023

NA64 experiment: physics goals

target: lead ECAL

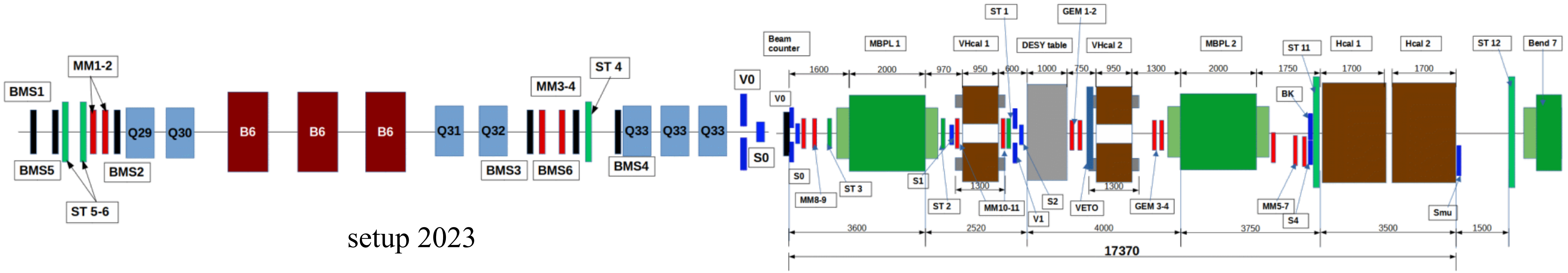
NA64μ

- 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



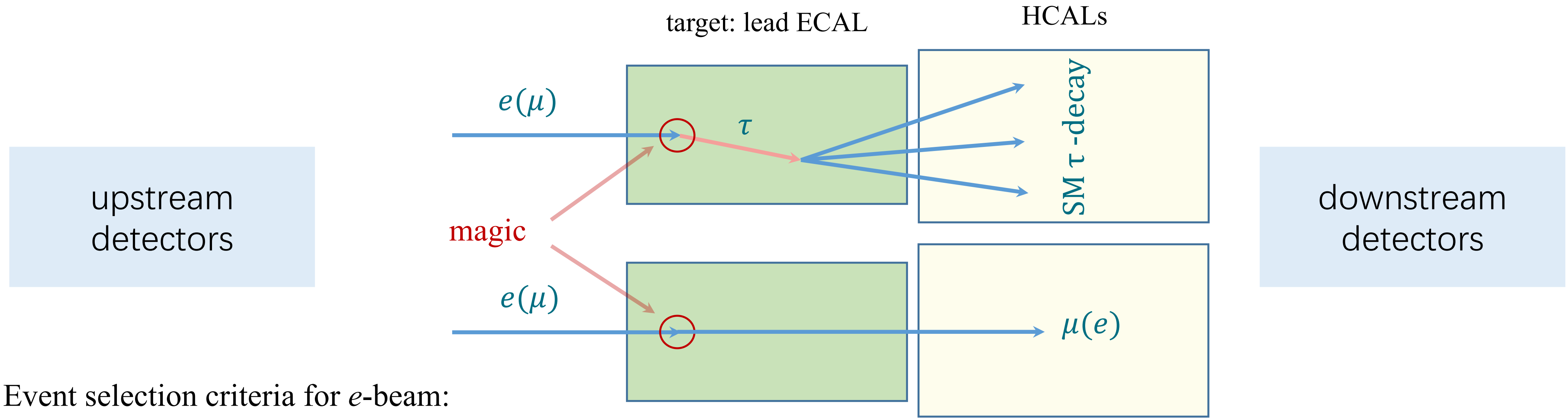
Signature: missing energy and momentum

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

NA64 experiment: CLFV



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)

Signature for $l\tau$ conversion: SM tau's decay production
Signature for $e\mu$ conversion: single muon production

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

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

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

lepton conversion at NA64

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

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

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

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

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,

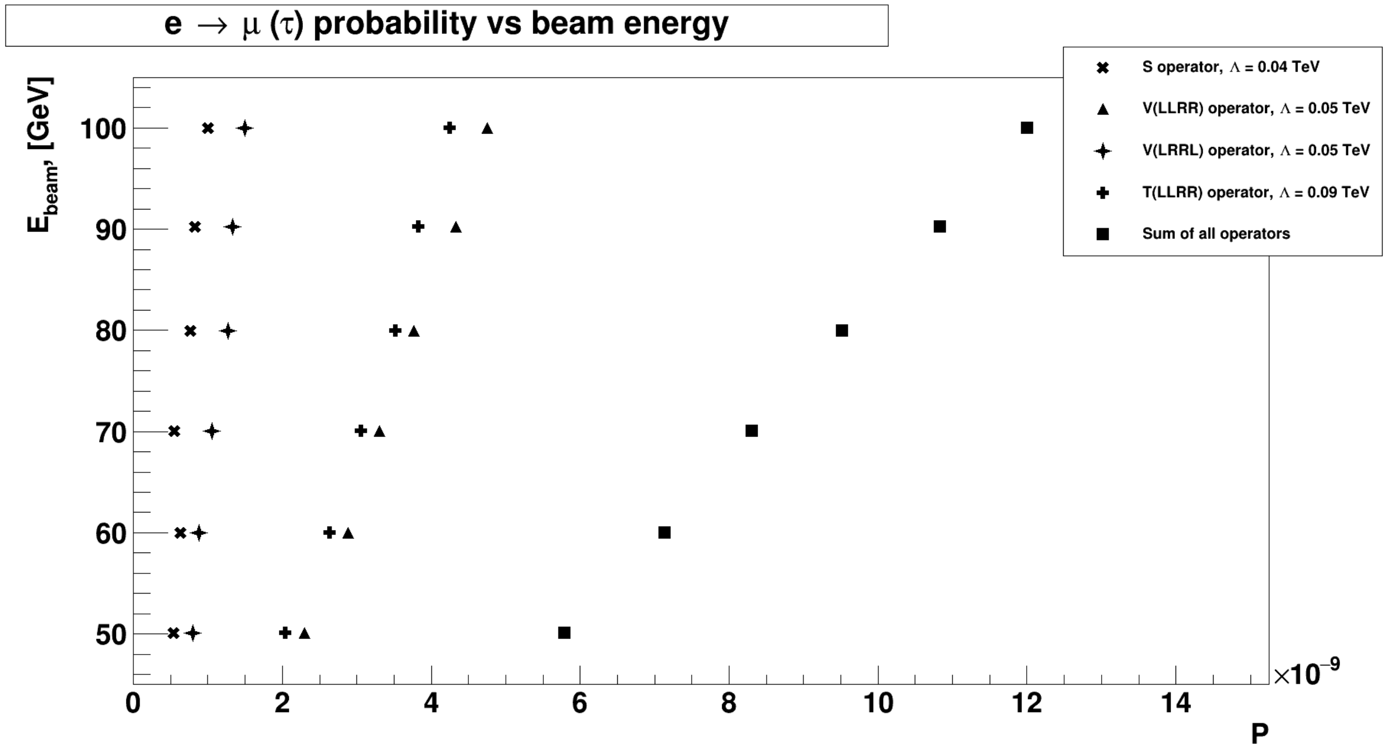
T — operators: $\Lambda^{e\tau} \geq 0.09 - 0.63$ TeV, $\Lambda^{\mu\tau} \geq 1.45 - 8.01$ TeV.

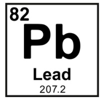
$\Lambda^{e\tau}_{\mathrm{ZEUS}} \geq 0.41 - 1.86$ TeV

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

probability of lepton conversion

accumulated around 10^{12} EOT





e - beam

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

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

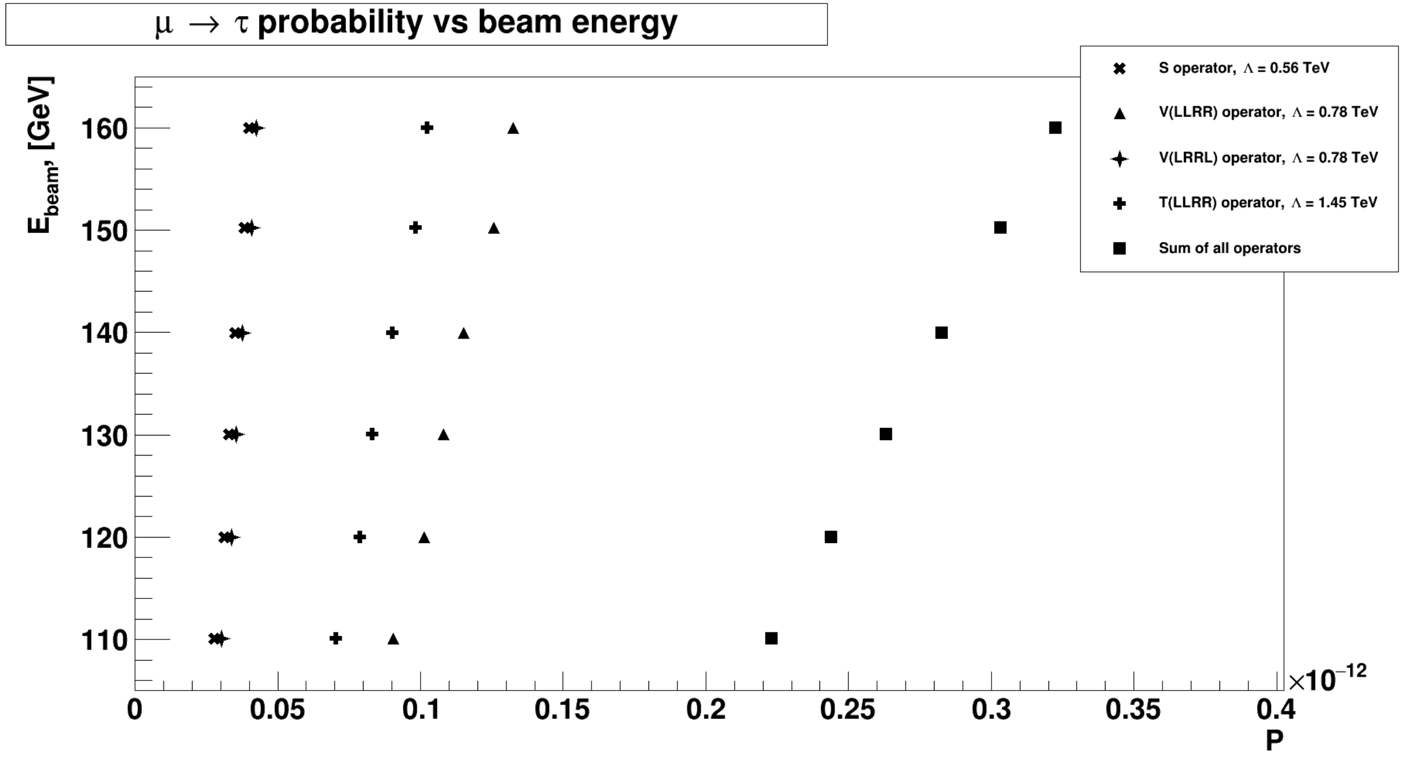
$\Lambda_T^{e\tau} = 0.09$ TeV

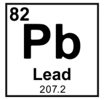
Expected sensitivity to Λ is 0.15 TeV

~100 events

probability of lepton conversion

accumulated around 10^{11} MOT





e - beam

$\Lambda_S^{\mu\tau} = 0.56$ TeV,

$\Lambda_V^{\mu\tau} = 0.78$ TeV,

$\Lambda_T^{\mu\tau} = 1.45$ TeV

sensitivity to Λ is 0.21 TeV

$<$ 1event

summary

It is possible to search $\boldsymbol{l \to \tau}$ **and** $\boldsymbol{e \leftrightarrow \mu}$ conversion at NA64.
Increasing the stats will increase the chance of the event.

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

If mixing of quarks is exists.
If mixing of neutrinos is exists.
Find the so far mixing of charged leptons.

Thanks!

Acknowledgements

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