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Indirect constraints on the mass of a heavy Z' boson of the $U(1)_{L_\mu - L_\tau}$ model at a future muon collider with polarized beams

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SM Problems and Z' Motivation

***SM — a low-energy limit** of a more fundamental theory?*

Open problems of the SM:

- ***Baryon asymmetry** of the Universe*
- ***Mass hierarchy problem***
- ***Dark matter and energy***
- ***Neutrino masses** and their origin*
- ***Phenomenological nature:** 18+ free parameters, three generations of fermions without explanation, lack of strong CP violation*

Current status of Z' search

*Direct searches by CMS (Run 3: 13.6 TeV, 283 fb^{-1}) and ATLAS (Run 3: 13.6 TeV, 165 fb^{-1}) at LHC excluded $M_{Z'} > 5.55$ TeV and $M_{Z'} > 5.20$ TeV for the benchmark SSM model respectively (**ICHEP-2026, Preliminary**).*

*Precision LEP data at the Z-pole constrain the Z–Z' mixing angle: $\theta_{Z\text{-}Z'} \lesssim (1\text{–}3) \times 10^{-3}$ (**arXiv:0906.2435**).*

*Lack of indications of "new" physics → further progress requires **indirect searches at high-energy lepton colliders**.*

BSM extensions predicting Z' bosons:

- *Extensions based on **large gauge groups** ($SU(5)$, $SO(10)$, E_6) or **additional $U(1)'$ symmetries** naturally predict additional neutral gauge bosons, denoted as Z' (**arXiv:9805494**, **arXiv:0801.1345**).*
- *Z' bosons **play an important role in dark matter phenomenology**, acting as portals connecting SM particles to the hidden sector (**arXiv:2407.00969**, **arXiv:2509.12192**).*

The $U(1)_{L_\mu - L_\tau}$ Model

Key aspects (arXiv:2101.04956v1):

- The model is **anomaly-free** without introducing exotic fermions;
- Since the $(g-2)_\mu$ anomaly lost its status as an indication of "new" physics (**arXiv:2506.03069**), the **necessity of a light Z′** disappeared, which opens up the possibility to explore the **heavy sector** (masses of the order of TeV) within the standard formulation;
- Within the model, **Z′ does not interact with electrons and quarks at the tree level**. The interaction with electrons arises only at the loop level (suppressed as $\sim 10^{-6}$)..

Standard formulation:

Within the model, the interaction of the Z' boson with leptons is described by the lagrangian

$$\mathcal{L} \supset g' \left(\overline{\ell_{\mathrm{L}}} Q' \gamma^\mu \ell_{\mathrm{L}} + \overline{E_{\mathrm{R}}} Q' \gamma^\mu E_{\mathrm{R}} \right) Z'_\mu,$$

where g' is the gauge coupling constant, $\ell \equiv (\nu, E)^{\mathrm{T}}$ is the lepton doublet, and $Q' = diag(0, 1, -1)$ is the charge matrix in the flavor basis (e, μ, τ).

Couplings of Z′ to μ and τ:

From the Q' matrix, it follows that the left and right couplings are equal to:

$$g^L_{Z'}(\mu) = g^R_{Z'}(\mu) = g',$$
$$g^L_{Z'}(\tau) = g^R_{Z'}(\tau) = -g'.$$

This yields a purely vector-like interaction. As benchmark scenarios, we choose $g' = e$ and $g' = e/3$.

Muon Collider (MuC) Among Future Colliders

Future colliders with $\sqrt{s} \sim$ TeV

Name	$\sqrt{s}$, TeV	$\mathcal{L}_{\rm int}$, ab^{-1}	Pol., %
HL-LHC (pp)	14	3	—
HE-LHC (pp)	27	15	—
FCC-hh (pp)	100	30	—
ILC (e^+e^-)	1	8	30/80
CLIC (e^+e^-)	3	5	0/80
μTRISTAN (μ^+e^-)	1	1	80/70
μTRISTAN ($\mu^+\mu^+$)	2	1	80/80
MuC3 ($\mu^+\mu^-$)	**3**	**1**	30/30
MuC6 ($\mu^+\mu^-$)	**6**	**4**	
MuC10 ($\mu^+\mu^-$)	**10**	**10**	

MuC project: **arXiv:2203.07261**;

Detailed detector and beam-induced background modeling: **arXiv:2203.07964**;

Detector geometry (MDI): coverage $|\eta| < 2.5$ (angles $10^\circ < \theta < 170^\circ$) $\rightarrow$ accessible range $z \equiv \cos\theta \in [-0.985, 0.985]$, divided into 20 bins.

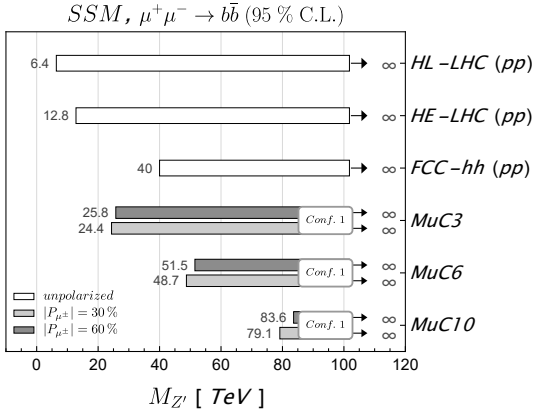
Advantages of MuC:

- **Synchrotron radiation losses are suppressed** by 2×10^9 compared to ILC and CLIC $\rightarrow$ ring scheme and higher energies;
- **Absence of beamstrahlung**;
- Possibility of **longitudinal beam polarization**.

Why MuC specifically for $U(1)_{L_\mu - L_\tau}$?

- **ILC and CLIC are "blind" to this model** due to the absence of tree-level Z' interaction with electrons.
- MuC is an **ideal facility** to study this sector in the process $\mu^+\mu^- \rightarrow \tau^+\tau^-$ (detection efficiency $\epsilon_\tau \approx 70\%$).

Potential of MuC: Comparison with Hadron Colliders



Lower bounds on the Z' mass in the benchmark SSM for MuC stages and future hadron colliders (appear in Phys. Part. Nucl. Lett., Vol. 23., No. 6)

- *Hadron colliders (HL-LHC, HE-LHC and FCC-hh) aim at **direct resonance searches**;*
- *Lepton colliders (ILC, CLIC, and MuC) aim at **indirect searches**: the region of **virtual exchange**, where the interference contribution dominates;*
- *The sensitivity of the indirect search at MuC3 is 2 times higher than the direct search potential at HE-LHC (27 TeV);*
- *Already at the MuC6 stage, indirect constraints exceed the direct discovery reach of FCC-hh (100 TeV);*
- *The sensitivity of the indirect search at MuC10 is 2 times higher than the direct search potential at FCC-hh (100 TeV);*
- ***Hadron and lepton colliders complement each other**: the former for direct resonance searches, the latter for exploring large scales through interference.*

Goals and Objectives of the Study

Goals:

- ***Obtain indirect constraints on the mass of the heavy Z' boson within the $U(1)_{L_\mu - L_\tau}$ model*** *in the process $\mu^+\mu^- \to \tau^+\tau^-$ at MuC.*
- ***Assess the impact of longitudinal beam polarization*** *on the search strategy.*
- *Demonstrate how longitudinal beam polarization can be used to* ***identify this model*** *— distinguishing it from other extensions that preserve lepton universality — should any deviation from the SM be observed.*

Objectives:

1. *Apply the methodology of linear parameterization of the Z' contribution and the extraction of helicity parameters $(q^{Z'}_{LL}, q^{Z'}_{RR})$ using beam polarization for the $\mu^+\mu^- \to \tau^+\tau^-$ process;*
2. *Obtain model-independent confidence regions in the $(q^{Z'}_{LL}, q^{Z'}_{RR})$ plane for the MuC3, MuC6, and MuC10 stages (95% C.L.);*
3. *Plot the $U(1)_{L_\mu - L_\tau}$ model trajectories on the obtained regions and compare them with other models;*
4. *Based on the intersection of the trajectories with the confidence regions, obtain lower bounds on the $M_{Z'}$ mass for the $U(1)_{L_\mu - L_\tau}$ model (95% C.L.).*

Parameterization of the Z' contribution to the cross section

The differential cross section is expressed as the ***SM contribution plus the deviation caused by Z'****:*

$$\frac{d\sigma^{Z'}}{dz}(P_{\mu^+},P_{\mu^-}) = C_f\frac{\pi\alpha^2_{\rm e.m.}}{2s}\frac{(1-P_{\mu^-}P_{\mu^+})}{4}\Big[(1-z)^2Q_1^{Z'}+(1+z)^2Q_2^{Z'}\Big]$$

where $Q_1^{Z'} = p^- q_{LR}^{Z'} + p^+ q_{RL}^{Z'}$, $Q_2^{Z'} = p^- q_{LL}^{Z'} + p^+ q_{RR}^{Z'}$ $(p^\pm = 1 \pm P_{\rm eff},\ P_{\rm eff} = (P_{\mu^-} - P_{\mu^+})/(1 - P_{\mu^-}P_{\mu^+}))$.

The helicity parameters $q_{\alpha\beta}^{Z'}$ contain interference and quadratic contributions *depending on the Z' parameters:*

$$q_{\alpha\beta}^{Z'} = \underbrace{2\,Re[(\mathcal{A}_{\alpha\beta}^{SM})^*\mathcal{A}_{\alpha\beta}^{Z'}]}_{\propto s/M_{Z'}^2} + \underbrace{|\mathcal{A}_{\alpha\beta}^{Z'}|^2}_{\propto s^2/M_{Z'}^4}$$

Reduced amplitudes $\mathcal{A}_{\alpha\beta}$:

$$\mathcal{A}_{\alpha\beta}^{SM} = \sum_{V=\gamma,Z}\frac{G_V^{\alpha\beta}(\mu,\tau)}{e^2}R_V, \qquad \mathcal{A}_{\alpha\beta}^{Z'} = \frac{G_{Z'}^{\alpha\beta}(\mu,\tau)}{e^2}R_{Z'},$$

$$\text{where} \quad G_V^{\alpha\beta}(\mu,\tau) = g_V^\alpha(\mu)g_V^\beta(\tau), \quad R_V = \frac{s}{s-M_V^2+iM_V\Gamma_V}.$$

Here, $G_V^{\alpha\beta}$ is the product of the left and right couplings of boson V to the μ and τ, and R_V is the dimensionless propagator containing the mass (M_V) and width (Γ_V) of the boson.

Methodology: Asimov data set and statistical analysis

We use the ***"Asimov data set" (arXiv:1007.1727), which assumes full agreement of future data with the SM*** *in all 20 bins over* $z = \cos\theta$.

Quadratic form of χ^2***:*** *As a result of the linear parameterization, the* χ^2 *function can be written in a quadratic form:*

$$\chi^2 = (Q^{Z'})^T V_Q^{-1} Q^{Z'},$$

where $Q^{Z'} \equiv (Q_1^{Z'}, Q_2^{Z'})^T$ *is the parameter vector,* V_Q *is the parameter covariance matrix* ($F_Q = V_Q^{-1}$). *The confidence ellipse in the* $Q^{Z'}$ *space is defined by* $\chi^2 \leq \chi^2_{\rm crit}$, *where* $\chi^2_{\rm crit} = 3.84$ *for 95% C.L.*

Fisher Matrix: *The elements of the Fisher information matrix* (F_Q) *can be expressed as:*

$$(F_Q)_{ij} = \sum_{k=1}^{20} \frac{A_k^{(i)} A_k^{(j)}}{(\delta\sigma_k^{SM})^2},$$

where $\delta\sigma_k^{SM}$ *is the total SM cross-section uncertainty in the k-th bin (stat. error + syst. error), and* $A_k^{(i)}$ *are the coefficients in the k-th bin* ($\sigma_k^{Z'} = \sum A_k^{(i)} Q_i^{Z'}$).

Bounds on the mass of the Z′ boson:

Fixing the model makes the parameters functions of mass only, $Q^{Z'}(M_{Z'})$, *forming a one-dimensional trajectory in the parameter space.*

- *The* ***lower bound is determined by the intersection*** *of the model trajectory with the confidence ellipse;*
- *The* ***upper bound is unrestricted****: at the center of the ellipse* $M_{Z'} \to \infty$ ($Q^{Z'} \to 0$), *which corresponds to full agreement with the SM.*

The Role of Longitudinal Beam Polarization

In the $U(1)_{L_\mu - L_\tau}$ model, the interaction is ***purely vector-like****: $g^L_{Z'} = g^R_{Z'}$, hence $q^{Z'}_{LL} = q^{Z'}_{RR}$.*

Why is polarization needed then?

- *To* ***prove the vector nature*** *of the new current ($q^{Z'}_{LL} = q^{Z'}_{RR}$);*
- *To distinguish the $U(1)_{L_\mu - L_\tau}$ model from others where $g^L_{Z'} \neq g^R_{Z'}$.*

Extraction of helicity parameters:

Combining two sessions a and b *with different polarizations allows the transition from $Q^{Z'}_2$ to $q^{Z'}_{LL}$ and $q^{Z'}_{RR}$ (and from $Q^{Z'}_1$ to $q^{Z'}_{LR}$ and $q^{Z'}_{RL}$ respectively):*

$$\begin{pmatrix} q^{Z'}_{LL} \\ q^{Z'}_{RR} \end{pmatrix} = M^{-1}_{ab} \begin{pmatrix} Q^{Z'}_2(a) \\ Q^{Z'}_2(b) \end{pmatrix} \quad M_{ab} = \begin{pmatrix} p^-_a & p^+_a \\ p^-_b & p^+_b \end{pmatrix}, \quad p^\pm = 1 \pm P_{\text{eff}}.$$

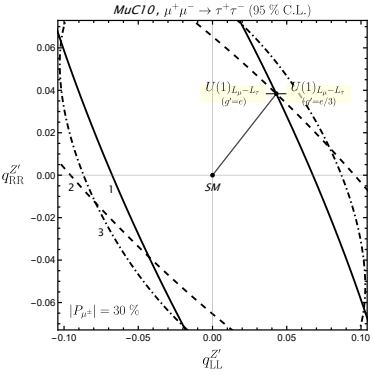
Minimizing correlation:

The correlation $\rho(q^{Z'}_{LL}, q^{Z'}_{RR})$ is minimal at the maximum difference between $P^{(a)}_{\text{eff}}$ and $P^{(b)}_{\text{eff}}$, which is achieved with ***opposite signs*** *of polarizations: $P_{\mu^-} = -P_{\mu^+}$. For ideal beam polarizations, $\rho(q^{Z'}_{LL}, q^{Z'}_{RR}) = 0$.*

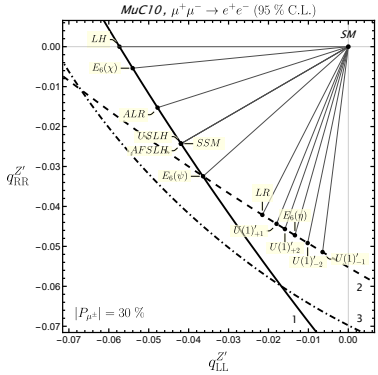
Considered configurations:

Conf. 1:	***Conf. 2:***	***Conf. 3:***
$\{0,0\}$ *and* $\{-P_{\mu^-}, +P_{\mu^+}\}$	$\{0,0\}$ *and* $\{+P_{\mu^-}, -P_{\mu^+}\}$	$\{+P_{\mu^-}, -P_{\mu^+}\}$ *and* $\{-P_{\mu^-}, +P_{\mu^+}\}$

Confidence Regions and Model Trajectories



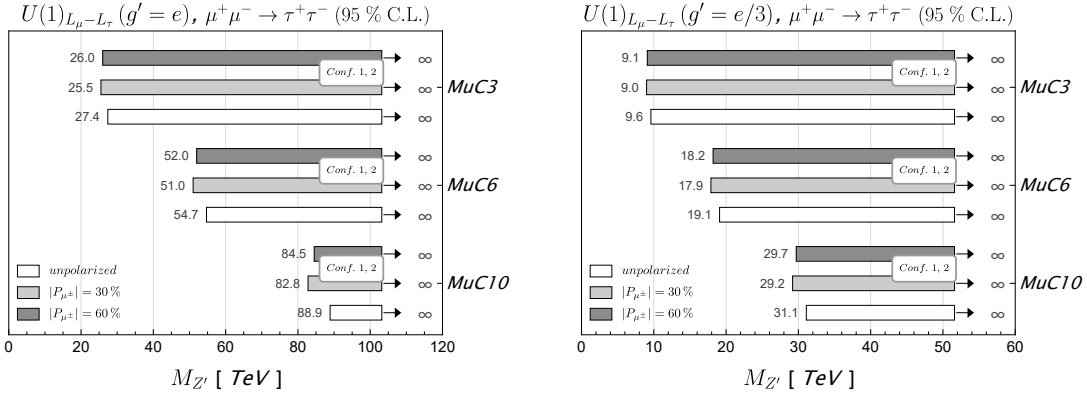
The $U(1)_{L_\mu - L_\tau}$ model with lepton universality violation



Other popular models preserving lepton universality (appear in Phys. Part. Nucl. Lett., Vol. 23., No. 6)

Key observation: *The opposite signs of the μ and τ charges in $U(1)_{L_\mu - L_\tau}$ change the sign of the interference term ($q^{Z'}_{LL}$ and $q^{Z'}_{RR}$ are positive). This fundamentally distinguishes this model from others ($q^{Z'}_{LL}$ and $q^{Z'}_{RR}$ are negative). This extraction allows us to experimentally confirm the purely vector nature of the new interaction and prove the equality of the left and right couplings.*

Lower Bounds on the Mass of the Z' Boson



Lower bounds on the mass of the Z' boson in the $U(1)_{L_\mu - L_\tau}$ model for the three MuC stages

Key observation: *The advantage of the unpolarized session (by 4–8%) is explained by the absence of helicity asymmetry in the model ($g^L_{Z'} = g^R_{Z'}$). However, the use of polarization and the developed methodology is justified from the point of view of model identification.*

Conclusion

1. *The sensitivity of MuC to the heavy Z' boson of the $U(1)_{L_\mu - L_\tau}$ model in the $\mu^+\mu^- \to \tau^+\tau^-$ process has been investigated.*
2. *It is established that* ***MuC has a unique potential for exploring this model****, allowing indirect constraints on the mass of the Z' boson up to tens of TeV depending on the strength of the Z' interaction with μ and τ leptons (g' values).*
3. *It is shown that the model trajectory in the space of helicity parameters is localized in the* ***first quadrant****, which is its most important distinguishing feature and indicates lepton universality violation.*
4. ***The use of longitudinal beam polarization****, although it does not improve the lower mass bounds, is* ***necessary for the identification of the $U(1)_{L_\mu - L_\tau}$ model****.*

Thank you for your attention!

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