

PKMuon software and a case study on CLFV

PKMuon 软件及 CLFV 案例研究

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Based primarily on: [arXiv:2410.20323](https://arxiv.org/abs/2410.20323)

^{*}<https://lyazj.github.io/pkmuon-site/categories/activities/> and [1–4]

Outline

- 1 PKMuon 软件框架
- 2 PKMuon CLFV 案例研究
- 3 总结、参考文献和备用页面

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- 1 PKMuon 软件框架
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PKMuon detector simulation framework

PKMuon 探测器模拟框架

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PKMuon

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PKMuon Collaboration

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3 followers

China

<https://iyazj.github.io/pkmuon-site/>

seeson@pku.edu.cn

PKMUON_G4sim

Public

Forked from yuxdPKU/PKMUON_G4sim

Geant4-based simulation of PKMUON

● C++

Earliest edition

Phys. Rev. D 110, 016017 (2024)

pkmuon-site-src

Public

Forked from iyazj/pkmuon-site-src

source code of PKMUON site

● Stylus

Collaboration Website

PKMUON_2024

Public

PKMuon software 2024

● C++

☆ 2

Current edition

General, extensible, human-friendly

arXiv:2410.20323 (2024)

mudet

Public

Muon detector simulation

● C++

Minimal detector implementations

clfv

Public

CLFV simulation study

● C++

Extension: provides CLFV processes

DMG4

Public

[Adaption] Simulation of Dark Matter production with Geant4

● C++

Extension: provides DM processes

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PKMuon detector simulation framework

PKMuon 探测器模拟框架

PKMuon / PKMUON_2024

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Philosophy: maximal reuse and minimal adaption above the base

midpoint 13 Branches 2 Tags

Go to file Add file <> Code About

Switch branches/tags

Find or create a branch...

Branches Tags

Common code, geometry, data...

Branch	Description	Last Commit
main	(default)	Clean code except geometry 9 months ago
clfv	Derived for beam-CLFV	Clean code except geometry 9 months ago
clfv-cry	Derived for cosmic-CLFV	Update 2 months ago
cry	Derived for cosmic rays	Update clfv last month
dm-cry	Derived for cosmic-DM	Update layout configs 3 days ago
dmg4	Derived for various DMs	Squash commits to clfv 5 months ago
✓ midpoint	Derived for cosmic-dark-Z'	Add more spec 9 months ago
midpoint-debug		Switch to new RPC 3 days ago
new	Derived for new RPCs	Squash recent commits to merge 6 months ago
ref		Update submodule urls last month

View all branches

**Convenient sync
Integrated via submodule**

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About

PKMuon software 2024

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- 1 watching
- 0 forks
- Report repository

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2 tags

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Packages

No packages published

Publish your first package

Contributors 4

PKMuon detector simulation framework

PKMuon 探测器模拟框架

Files

main

Go to file

DM_step1

DM_step2

analysis

config

layout.yaml

layout_al.yaml

layout_pb.yaml

material_schema.yaml

rpc.yaml

rpc_material.yaml

rpc_readout.yaml

volume_schema.yaml

include

spec

src

ActionInitialization.cc

DetectorConstruction.cc

EventAction.cc

GeometryConfig.cc

GpsPrimaryGeneratorAction.cc

PKMUON_2024 / config / rpc.yaml

Open the link for more details

166 lines (143 loc) · 2.81 KB

Code Blame

64

- rpc_gas

65

material: rpc_gas

66

67

rpc_electrode_pair:

68

solid: bottom_up

69

components:

70

- rpc_electrode

71

- rpc_electric

72

- rpc_electrode

73

material: rpc_gas

74

75

rpc_electrode_pair_0:

76

solid: rotation

77

components: [rpc_electrode_pair]

78

79

rpc_electrode_pair_1:

80

solid: rotation

81

components: [rpc_electrode_pair, [x, 180 deg]]

82

83

rpc_mainbody:

84

solid: bottom_up

85

components:

86

- rpc_x_readout_board # external

87

- rpc_insulating_filem

88

- rpc_electrode_pair_0

89

- rpc_insulating_filem

90

- rpc_gas

91

- rpc_t_readout_board # external

92

- rpc_gas

93

- rpc_insulating_filem

94

- rpc_electrode_pair_1

95

- rpc_insulating_filem

96

- rpc_y_readout_board # external

97

material: rpc_gas

98

GEANT := GEometry AND Tracking

Abstraction: Multiple geometrical operations supported

Modulization: Accepts external definitions (elsewhere)

Decorrelated from the code; human-friendly; error-repelling

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CLFV and recent studies

CLFV 和近期研究

CLFV (Charged Lepton Flavor Violation):

- Strongly suppressed due to the tiny neutrino masses in the Standard Model (SM): $\text{BR}(\mu \rightarrow e\gamma) \sim 10^{-54} - 10^{-55}$
- Can be significantly enhanced in various BSM models

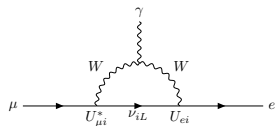


FIG. SM $\mu \rightarrow e\gamma$ decay process

Dedicated low-energy muon experiments, such as $\mu \rightarrow e\gamma$, set limits on $\lambda_{ee}\lambda_{e\mu}$ and $\lambda_{e\mu}\lambda_{\mu\mu}$ coherently according to Ref. [5] as

$$\Gamma(\mu \rightarrow e\gamma) = \frac{\alpha G_F^2 m_\mu^3 M_Z^4 \left(\sin^2 \theta_W \left(\sin^2 \theta_W - 1/2 \right) \right)^2}{4\pi^4 M_{Z'}^4},$$

$$\left(\lambda_{ee}\lambda_{e\mu}m_e + \lambda_{e\mu}\lambda_{\mu\mu}m_\mu + \lambda_{e\tau}\lambda_{\tau\mu}m_\tau + \dots \right)^2,$$

The gray part involving τ and BSM contributions is not considered in previous works.

Strong interference and cancellation between the terms shown or omitted are possible, allowing the existence of terms with very large modulus, highlighting the necessity to probe each term individually.

Theoretical model and simulation setup

理论模型和模拟设定

The $U(1)$ Z' CLFV model:

- Has the same gauge coupling and chiral strength as the SM Z boson except for allowing CLFV quantified by

$$\lambda = \begin{pmatrix} \lambda_{ee} & \lambda_{e\mu} & \lambda_{e\tau} \\ \lambda_{\mu e} & \lambda_{\mu\mu} & \lambda_{\mu\tau} \\ \lambda_{\tau e} & \lambda_{\tau\mu} & \lambda_{\tau\tau} \end{pmatrix},$$

relative to SM, with the diagonal elements equal to 1 and the off-diagonal expected to be near 0

The PKMuon detectors for $\mu^+ e^- \rightarrow \mu^+ \mu^-$ measurements:

- Applies to cosmic-ray and artificial muons
- Cost-effective: no magnetic/calorimeter, giving 2 average momentum directions for each track, without magnitudes
- 3 RPCs per group to suppress muon decay products
- A scintillator PID system downstream RPCs to reject (ionization/bremsstrahlung) electrons (not plotted)
- Generalizable (from DM detection) to other experiments

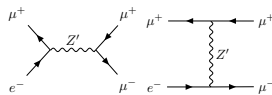


FIG. $U(1)$ Z' -mediated CLFV processes

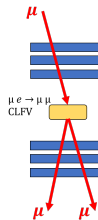
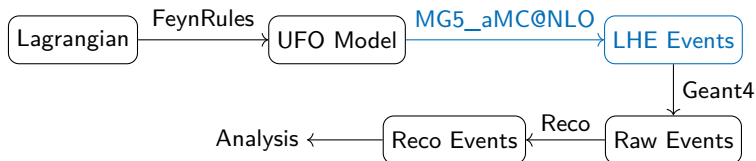


FIG. PKMuon RPC tracker for CLFV measurements

Efficient new physics modeling

高效产生 CLFV 事例



LHE events for arbitrary new physics can be efficiently and conveniently generated through FeynRules and [MG5_aMC@NLO](#)

- For various Z' masses and incoming muon energies (incoming muon energies should be varied for muons passing the first 3 RPC layers)
- However, efficient only for *bunch of* (at least $\sim 10^4$) events per mass/energy setup

Our speeding-up solution to avoid event-by-event launch of [MG5_aMC@NLO](#)

Pre-acquire the cross section and kinematic distributions for interpolation.

Efficient new physics modeling

高效产生 CLFV 事例

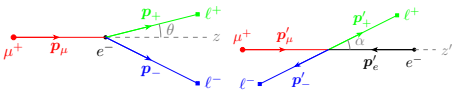


FIG. Lab and COM frame event display

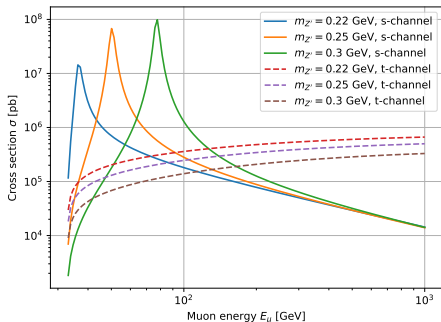
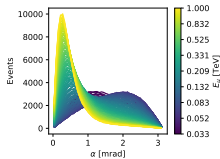
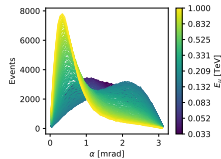


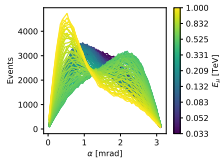
FIG. s - and t -channel cross sections



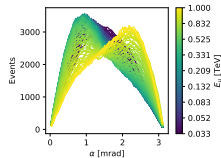
(a) $m_{Z'} = 0.22$ GeV



(b) $m_{Z'} = 0.30$ GeV



(c) $m_{Z'} = 0.50$ GeV



(d) $m_{Z'} = 0.80$ GeV

FIG. $\mu^+ e^- \rightarrow \mu^+ \mu^-$ event distributions in the COM frame with varying incident E_μ .

Efficient new physics modeling

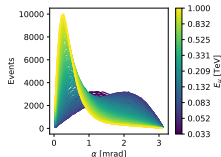
高效产生 CLFV 事例

Algorithm: Efficient $\mu^+e^- \rightarrow \ell^+\ell^-$ event generation

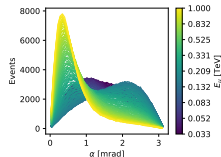
```

function GENERATEMUELL( $E_\mu, \vec{p}_\mu, m_\ell$ )
   $E_{\mu 1}, E_{\mu 2}, \sigma_1, \sigma_2, H_1, H_2 \leftarrow$ 
  ADJACENTGRIDPOINTS( $E_\mu$ );
  if  $E_\mu$  is out of the grid range then
    return no  $\mu^+e^- \rightarrow \ell^+\ell^-$  happens;
  end if
   $w_1 \leftarrow \frac{E_\mu - E_{\mu 2}}{E_{\mu 1} - E_{\mu 2}}, w_2 \leftarrow \frac{E_{\mu 1} - E_\mu}{E_{\mu 1} - E_{\mu 2}};$ 
   $\sigma \leftarrow w_1 \sigma_1 + w_2 \sigma_2;$  // cross section
  if RANDOM(0, 1) <  $w_1$  then
     $\alpha \leftarrow H_1.SAMPLE();$  // polar angle
  else
     $\alpha \leftarrow H_2.SAMPLE();$ 
  end if
   $\phi \leftarrow \text{RANDOM}(0, 2\pi);$  // azimuthal angle
   $E', p', \gamma, \beta \leftarrow \text{KINEMATICS}(E_\mu, m_\ell);$ 
   $p_{x+} \leftarrow p' \sin \alpha \cos \phi, p_{y+} \leftarrow p' \sin \alpha \sin \phi;$ 
   $p_{z+} \leftarrow \gamma (p' \cos \alpha + \beta E' / 2);$ 
   $\vec{p}_+ \leftarrow \text{THREEVECTOR}(p_{x+}, p_{y+}, p_{z+});$ 
   $\vec{p}_+ \leftarrow \vec{p}_+. \text{ROTATEZAXISTo}(\vec{p}_\mu);$ 
   $\vec{p}_- \leftarrow \vec{p}_\mu - \vec{p}_+;$ 
  return  $\sigma, \vec{p}_+, \vec{p}_-;$ 
end function

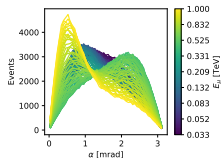
```



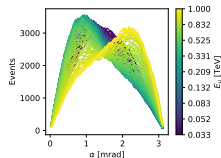
(a) $m_{Z'} = 0.22$ GeV



(b) $m_{Z'} = 0.30$ GeV



(c) $m_{Z'} = 0.50$ GeV

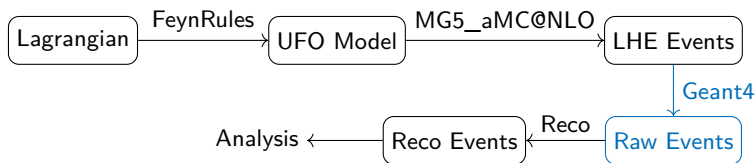


(d) $m_{Z'} = 0.80$ GeV

FIG. $\mu^+e^- \rightarrow \mu^+\mu^-$ event distributions in the COM frame with varying incident E_μ .

Detector simulation

含本底的探测器模拟



Background-included signal detection simulated by Geant4 11.2.2:

- $\mu^+e^- \rightarrow \ell^+\ell^-$: subclasses `G4VDiscreteProcess`
- Simulated upon physics list `FTFP_BERT`
- Signal (or background) definition: whether (or not) CLFV happens
- Signal rate is scaled to 10^{-3} to 10^{-2} to balance precision and efficiency
- Allows a step length up to 10^{-3} times MFP assuring granularity

Detector simulation

含本底的探测器模拟

The PKMuon RPC tracking detectors:

- 3 RPCs/group $\times$ 2 groups
- minor/major distance as 200/500 mm
- 2D pixel readout (0.7 mm Exp., 0.5 mm MC)
- trigger as 1 MeV (1/2 mean muon Edep.)

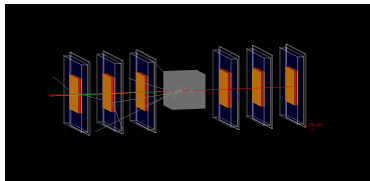


FIG. $\mu^+e^- \rightarrow \mu^+\mu^-$ event display

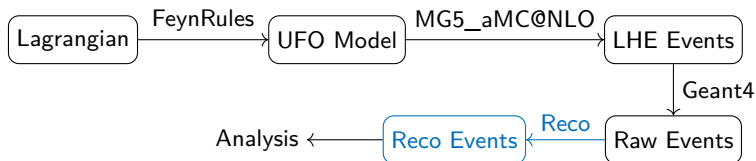
CLFV *can* happen outside the target, but those events are unintended for measurements and will be filtered out by event selection.

The parameters here and the target selection are to be optimized.

Since the measurement is insensitive to the focusing of the incoming muon beam, the beam is considered to be monochromatic, impinging perpendicularly to the detector and distributed uniformly over the area of the RPC module.

Event reconstruction and selection

事例重建和选择

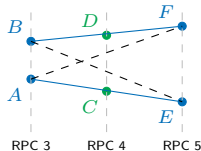


Pre-requirements:

- Comparing none/perfect electron rejection
- #hits on RPCs 0–5: [1, 1, 1, 2, 2, 2]

Reconstruction of 2 outgoing tracks:

- **Step 1/3:** match hits on RPC 3 and 5
 - expecting 2 tracks diverge from a single point
 - i.e. minimizing the sum of the 2 resulting track lengths
 - e.g. $BF + AE < BE + AF$
- **Step 2/3:** add hits on RPC 4, minimizing total χ^2 error
- **Step 3/3:** Recompute (fit) spatial lines BDF and ACE



Event reconstruction and selection

事例重建和选择

Event distribution:

- key signal feature: 3 highly collimated tracks (in: 0; out: 1, 2)
- distributed discretely due to limited detector granularity
- signal and background remain largely separated

Event selection:

- $\chi^2 \leq 6$
- $\max_{i \neq j} \langle \vec{p}_i, \vec{p}_j \rangle \leq 0.003$

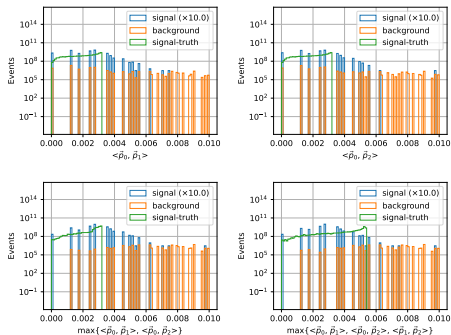
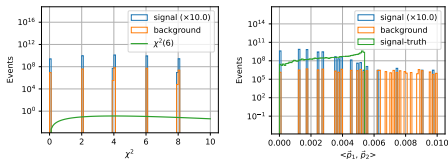


FIG. Event distributions for $E_\mu = 50.2$ GeV, $m_{Z'} = 0.25$ GeV, and $\lambda_{e\mu}$ scaled to 10. The target is a 30 mm thick aluminum block. The yields are normalized to 3×10^{13} muons on target, corresponding to a one-year run.

Results and discussion

结果和讨论

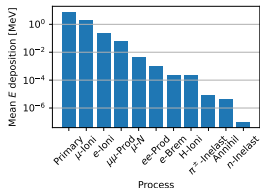


FIG. Typical background components (almost all $e!$)

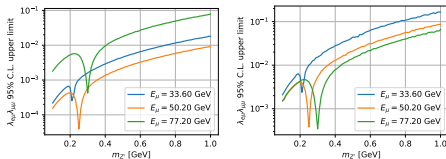
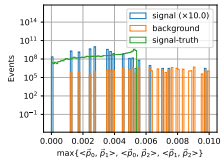
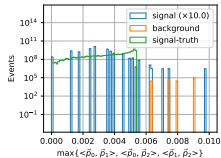


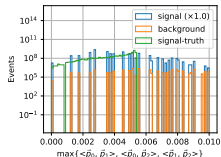
FIG. Prospected 95% ULs for 3 cm Al (L) and 8 cm Pb (R) targets, with e -veto, for a one-year run



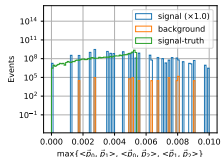
(a) 3 cm Al



(b) 3 cm Al, with e -veto



(c) 8 cm Pb



(d) 8 cm Pb, with e -veto

FIG. Event distribution before final selection

Background events are vanishing, raising requirements on a higher statistics in the future. Finer selection can also be enabled in a higher statistics.

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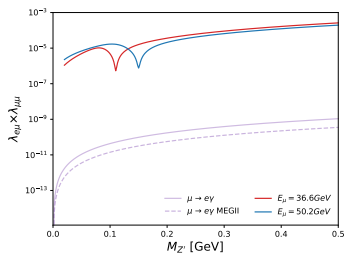
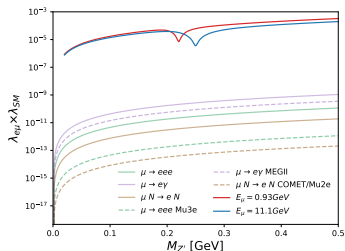
Summary

A general PKMuon detector simulation framework:

- Suitable for multiple physics processes and detector geometries
- Error-repelling and human-friendly

A case study on PKMuon CLFV experiment:

- Exclusively sensitive to $\lambda_{e\mu}\lambda_{\mu\mu}$
- A novel and generalizable efficient event generation algorithm
- $\mu^+e^- \rightarrow \mu^+\mu^-$ simulation shows the expected 95% CL UL on $\lambda_{e\mu}\lambda_{\mu\mu} \sim 10^{-5}$ with Z' mass ~ 0.25 GeV for a one-year run
- Comparable with the LHE-level simulation in Ref. [6] (lower figure on the right), but not as sensitive as $\mu \rightarrow e\gamma$



Thanks for your attention!

References I

- [1] Xudong Yu et al. Proposed Peking University muon experiment for muon tomography and dark matter search. *Phys. Rev. D*, 110(1):016017, 2024.
- [2] Leyun Gao, Zijian Wang, Cheng-en Liu, Jinning Li, Alim Ruzi, Qite Li, Chen Zhou, and Qiang Li. Probing charged lepton flavor violation in an economical muon on-target experiment. 10 2024.
- [3] Leyun Gao, Alim Ruzi, Qite Li, Chen Zhou, Liangwen Chen, Xueheng Zhang, Zhiyu Sun, and Qiang Li. Quantum state tomography with muons, 11 2024.
- [4] Leyun Gao, Alim Ruzi, Qite Li, Chen Zhou, and Qiang Li. Testing spooky action between free-traveling electron-positron pairs. 2 2025.
- [5] Paul Langacker and Michael Plumacher. Flavor changing effects in theories with a heavy Z' boson with family nonuniversal couplings. *Phys. Rev. D*, 62:013006, 2000.
- [6] Ran Ding, Jingshu Li, Meng Lu, Zhengyun You, Zijian Wang, and Qiang Li. Study of charged Lepton Flavor Violation in electron muon interactions. *JHEP*, 01:165, 2025.