Probing the $L_\mu - L_\tau$ Gauge Boson at the MUonE Experiment

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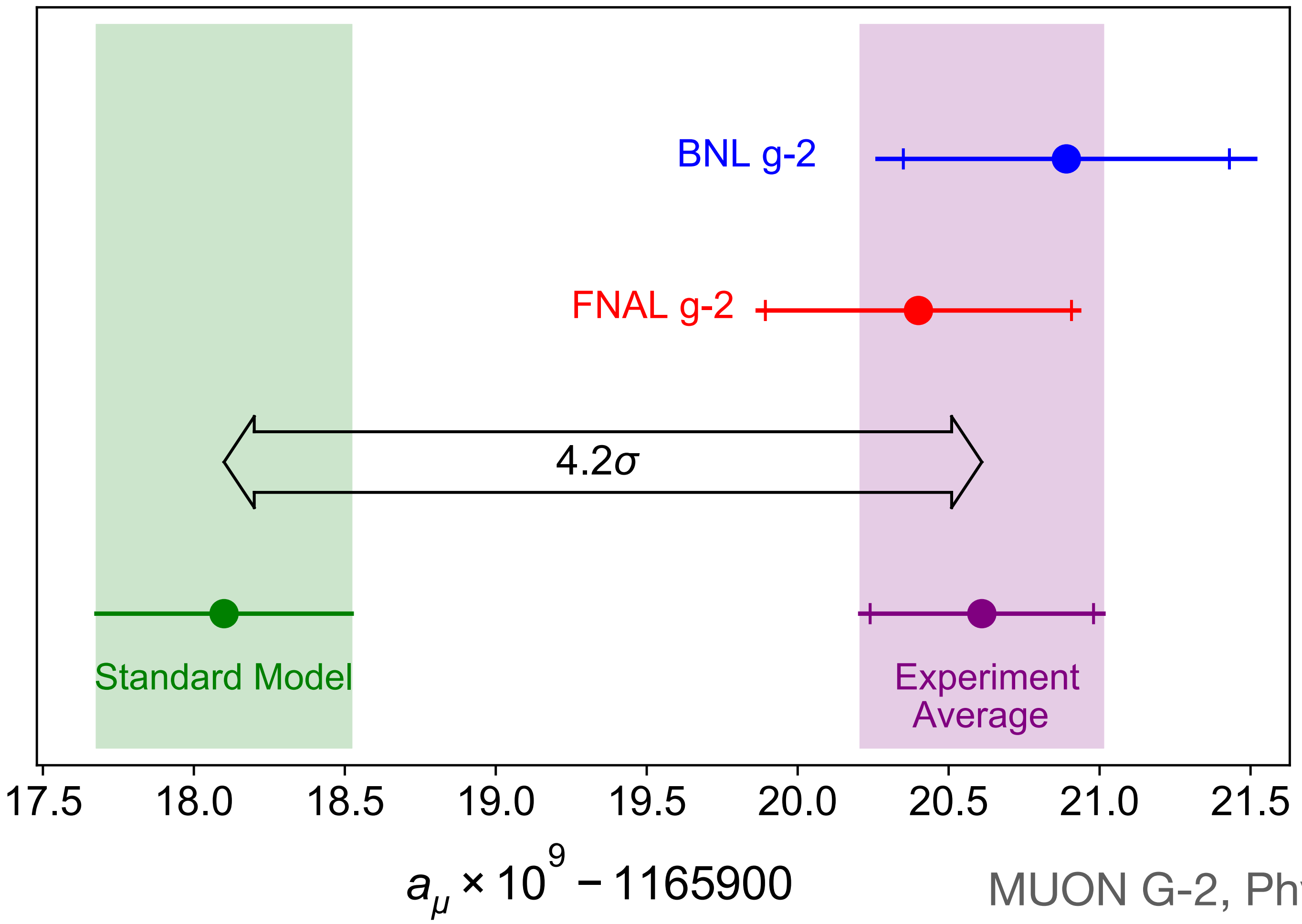
Based on K. Asai, K. Hamaguchi, N. Nagata, S. Tseng, J. Wada, arXiv:2109.10093.

Muon g-2: latest result

Recently, a new result for the measurement of the muon anomalous magnetic moment was reported:



Previous result

New result

MUON G-2, Phys. Rev. Lett. **126**, 141801 (2021).

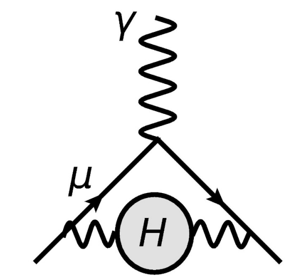
- $a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11}$
- $a_\mu(\mathrm{SM}) = 116\,591\,810(43) \times 10^{-11}$

$$\Delta a_\mu = 251(59) \times 10^{-11}$$

White Paper: T. Aoyama, et.al., Phys. Rept. **887**, 1 (2020).

4.2σ discrepancy

Hadronic Vacuum Polarization



Two different strategies to evaluate the HVP:

- Data-driven dispersive method   Adopted in WP
- Lattice simulation

The latest lattice results differ from the WP value.

e.g.) $$a_\mu(\mathrm{HVP;\ BMW}) = 7075(55) \times 10^{-11}$$

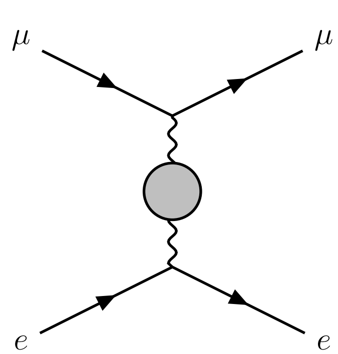
S. Borsanyi, et.al., Nature **593**, 51 (2021).

Cf.) $a_\mu(\mathrm{HVP;\ WP}) = 6845(40) \times 10^{-11}$

An alternative way to determine this contribution using the elastic scattering $\mu e \to \mu e$.

G. Abbiendi, et.al., Eur. Phys. J. C **77**, 139 (2017).

See also C. Carloni Calame, et. al., Phys. Lett. B **746**, 325 (2015).



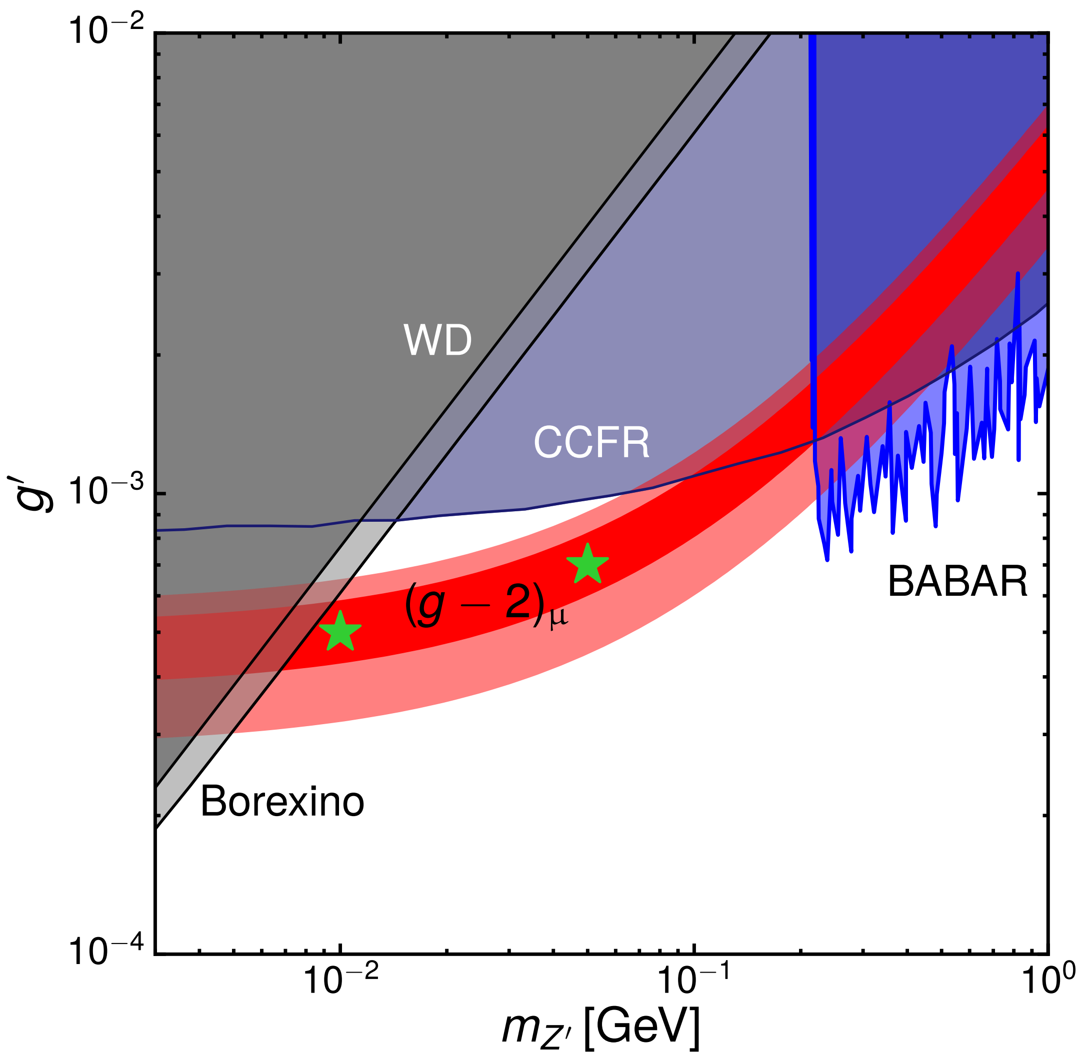
MUonE experiment

Our proposal

The MUonE experiment can also search for new physics.

$L_\mu - L_\tau$ gauge boson

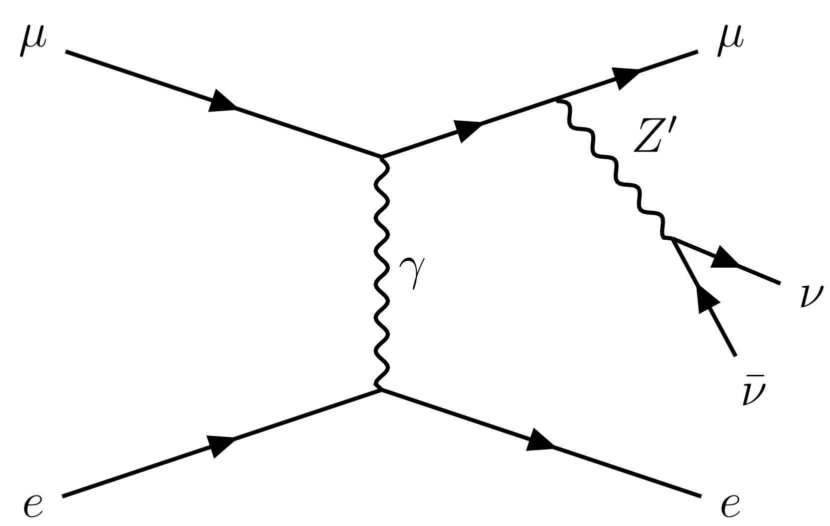
K. Asai, K. Hamaguchi, N. Nagata, S. Tseng, J. Wada, arXiv:2109.10093.



A. Kamada, K. Kaneta, K. Yanagi, H. Yu, JHEP **1806**, 117 (2018).

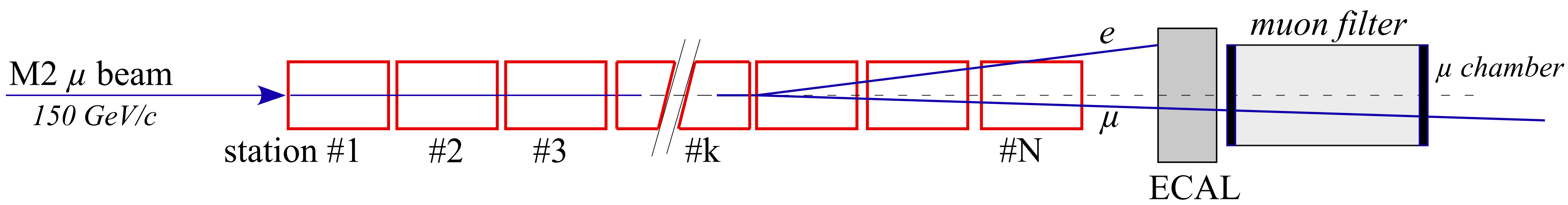
$L_\mu - L_\tau$ gauge model

- Motivated by the muon g−2 discrepancy.
- Z’ decays only into neutrinos.

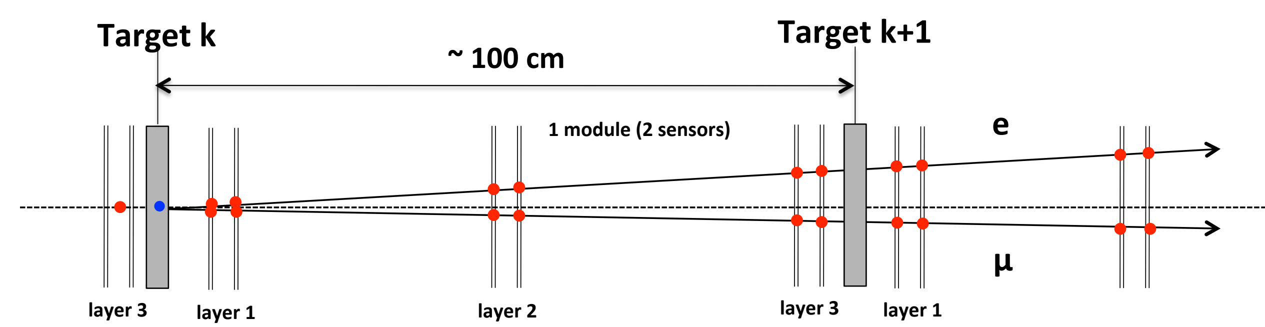


MUonE setup

Letter of Intent: The MUonE Project



- 150 GeV muon beam @ CERN
- Target: electrons in Be



- Consists of 40 identical stations:
  - 15 mm thick Be target
  - Tracking sensors (Si strips) Angular resolution: O(0.01) mrad.
- Electromagnetic calorimeter (ECAL)

  Energy resolution: $\lesssim 10\,\%$
- Muon chamber

MUonE kinematics

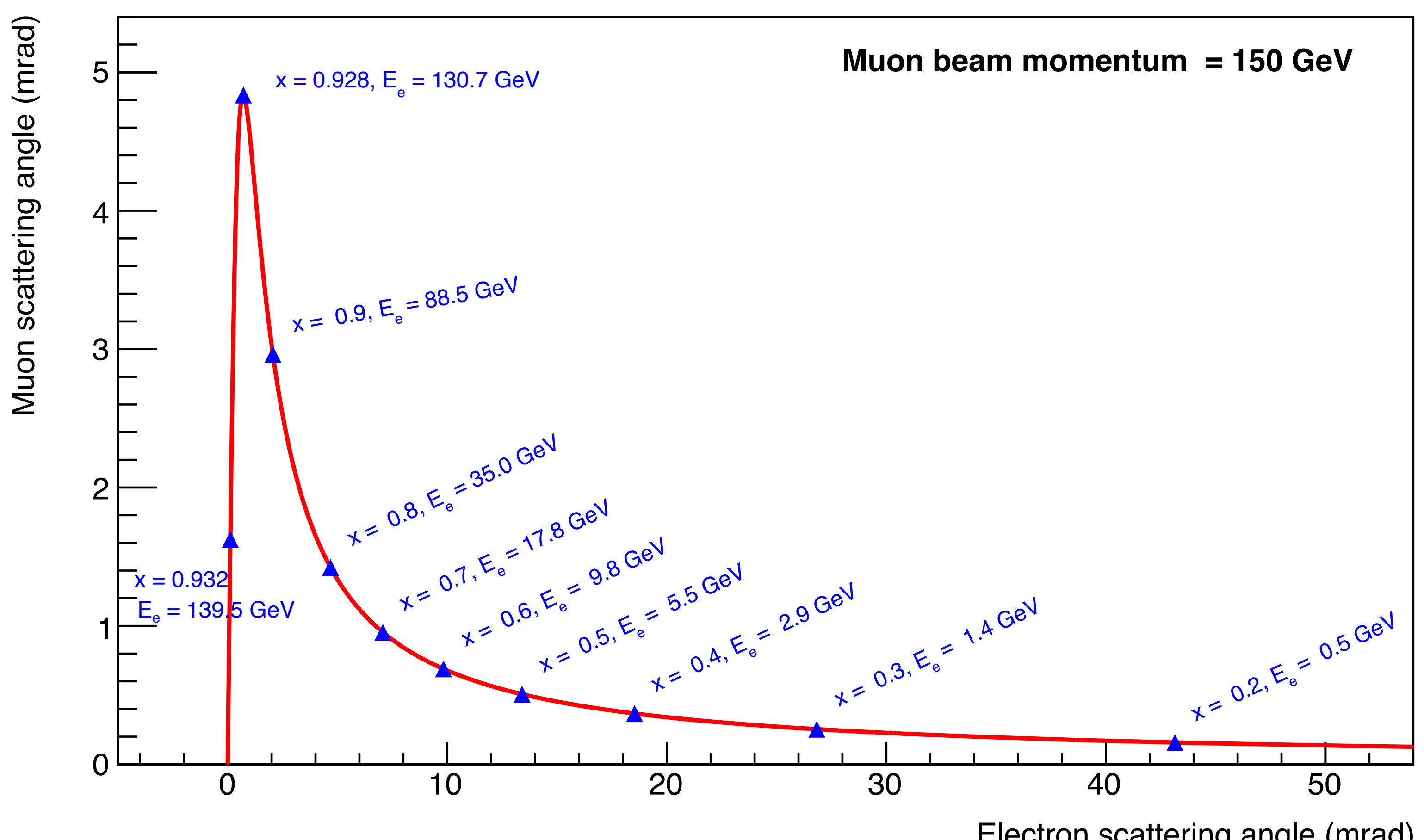
The primary target of MUonE is the elastic scattering process:

$$\mu e \rightarrow \mu e$$

150 GeV At rest

$$\sqrt{s} \simeq 406 \text{ MeV}$$

Energies and scattering angles of the final state electron and muon are determined as one parameter functions.



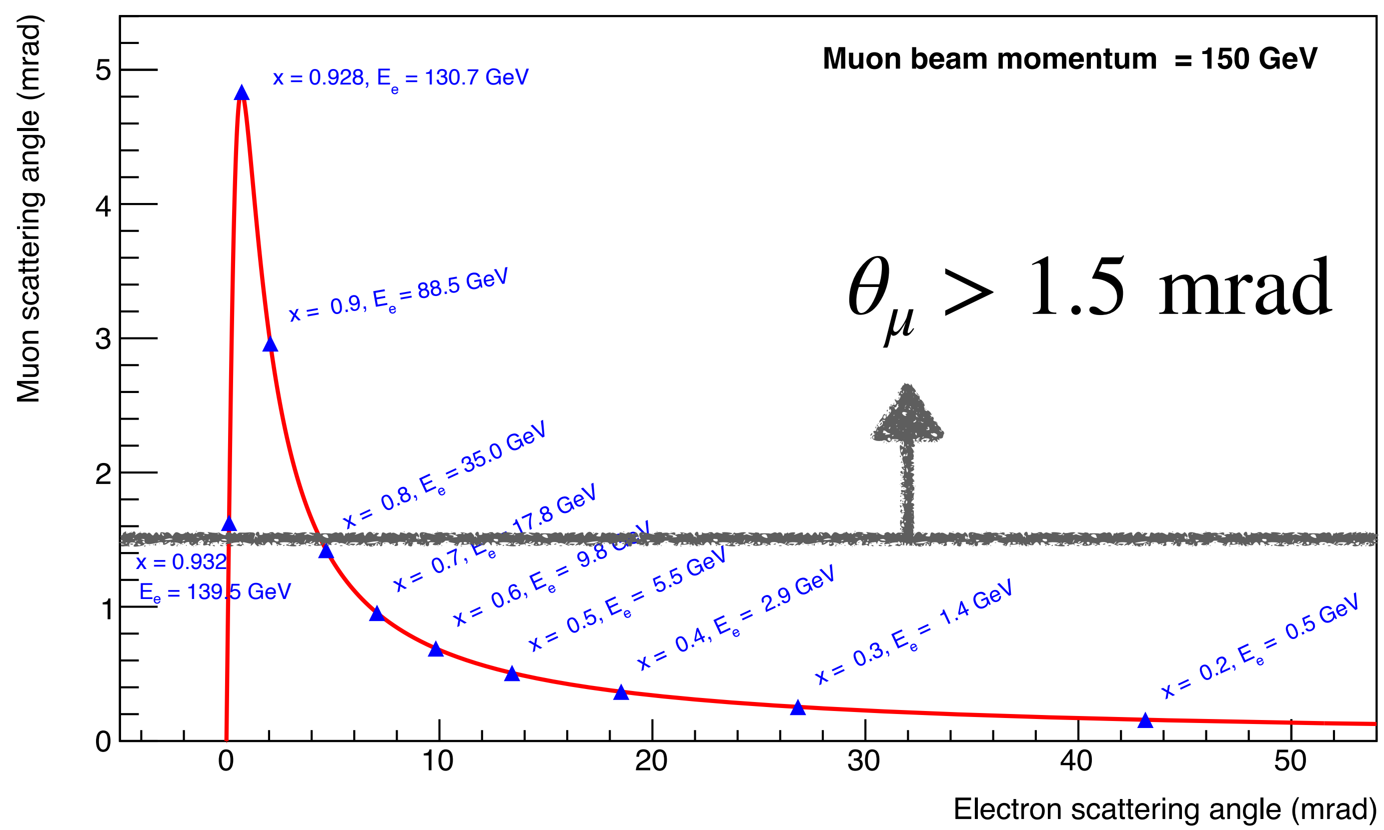
Larger θ_e

→ Smaller E_e

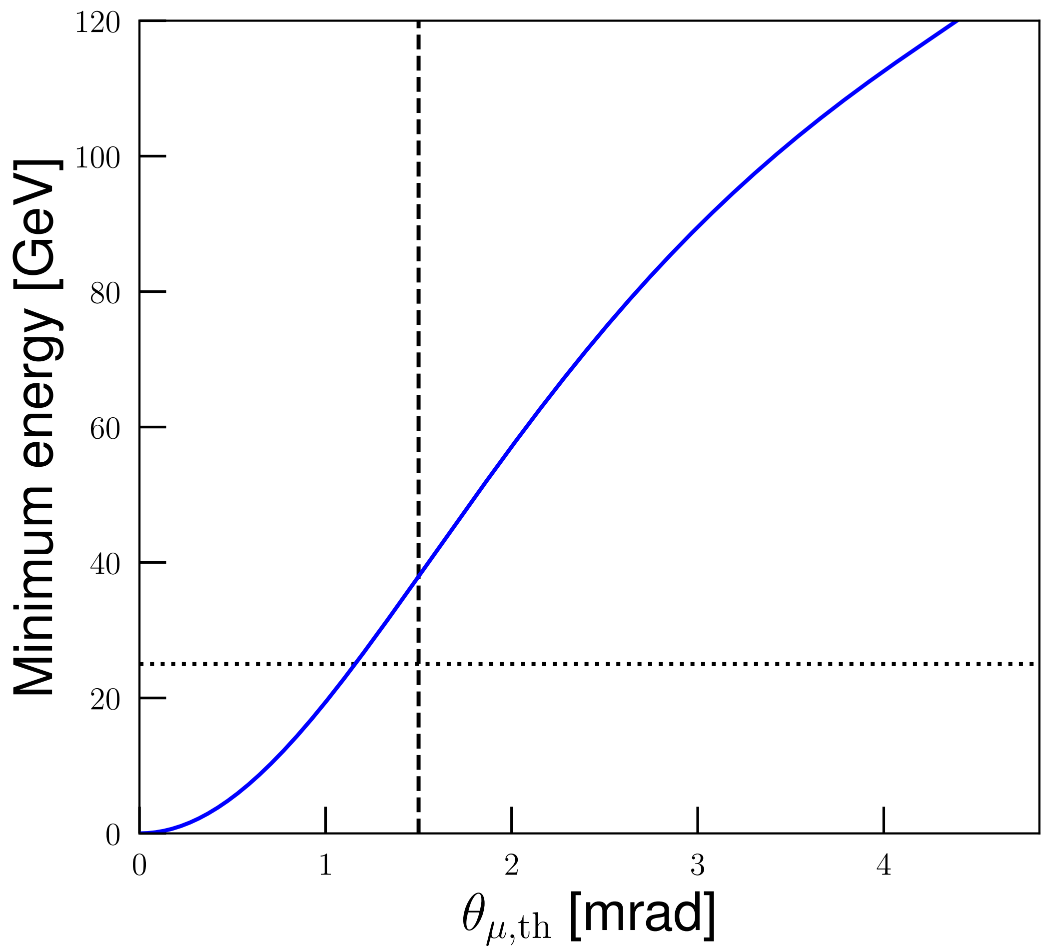
G. Abbiendi, et.al., Eur. Phys. J. C **77**, 139 (2017).

MUonE kinematics

A threshold on θ_μ selects large E_e events for $e\mu \to e\mu, e\mu\gamma$.

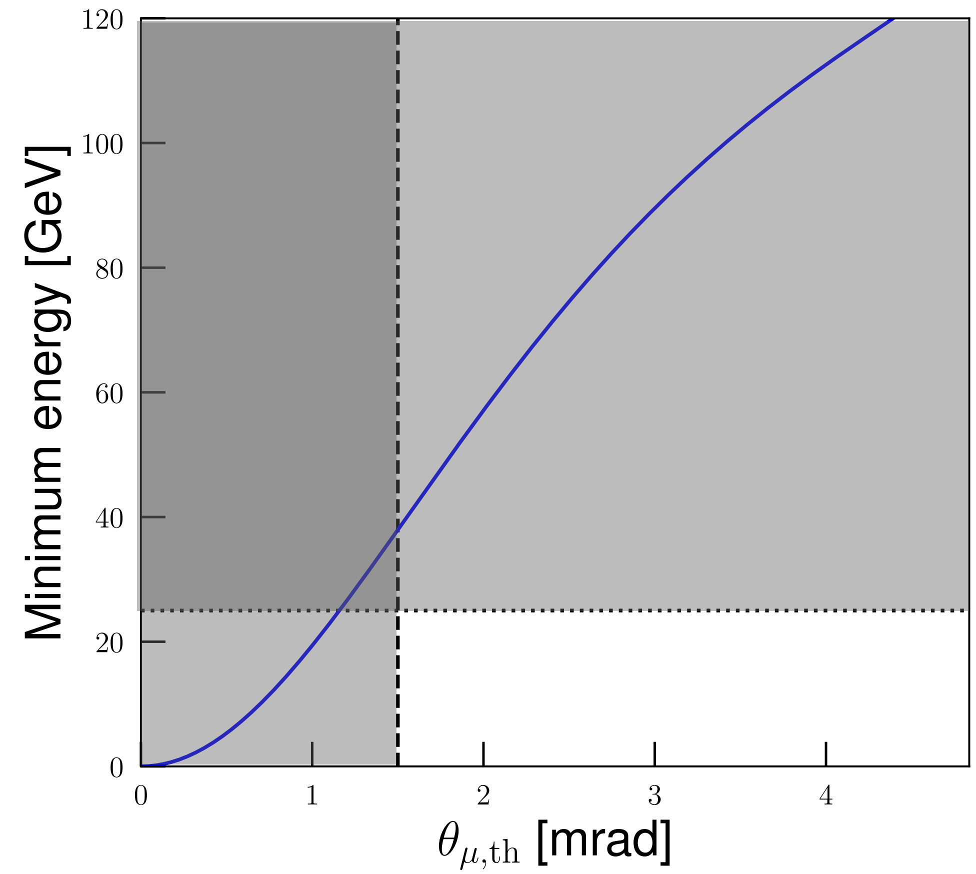


G. Abbiendi, et.al., Eur. Phys. J. C **77**, 139 (2017).



- For $e\mu \to e\mu$, $\theta_\mu > 1.5$ mrad → $E_e \gtrsim 38$ GeV
- For $e\mu \to e\mu\gamma$, $\theta_\mu > 1.5$ mrad → $E_e + E_\gamma \gtrsim 38$ GeV

Search strategy



Selection criteria

- $\theta_\mu > 1.5$ mrad
- $1\ \mathrm{GeV} < E_e < 25\ \mathrm{GeV}$
- Photon veto

➡ Both $\mu e \to \mu e$ and $\mu e \to \mu e \gamma$ can safely be removed.

Other background sources

- Multiple scattering associated with $\mu e \to \mu e$

  Kink/branch of tracks

- Muon-nuclear scattering

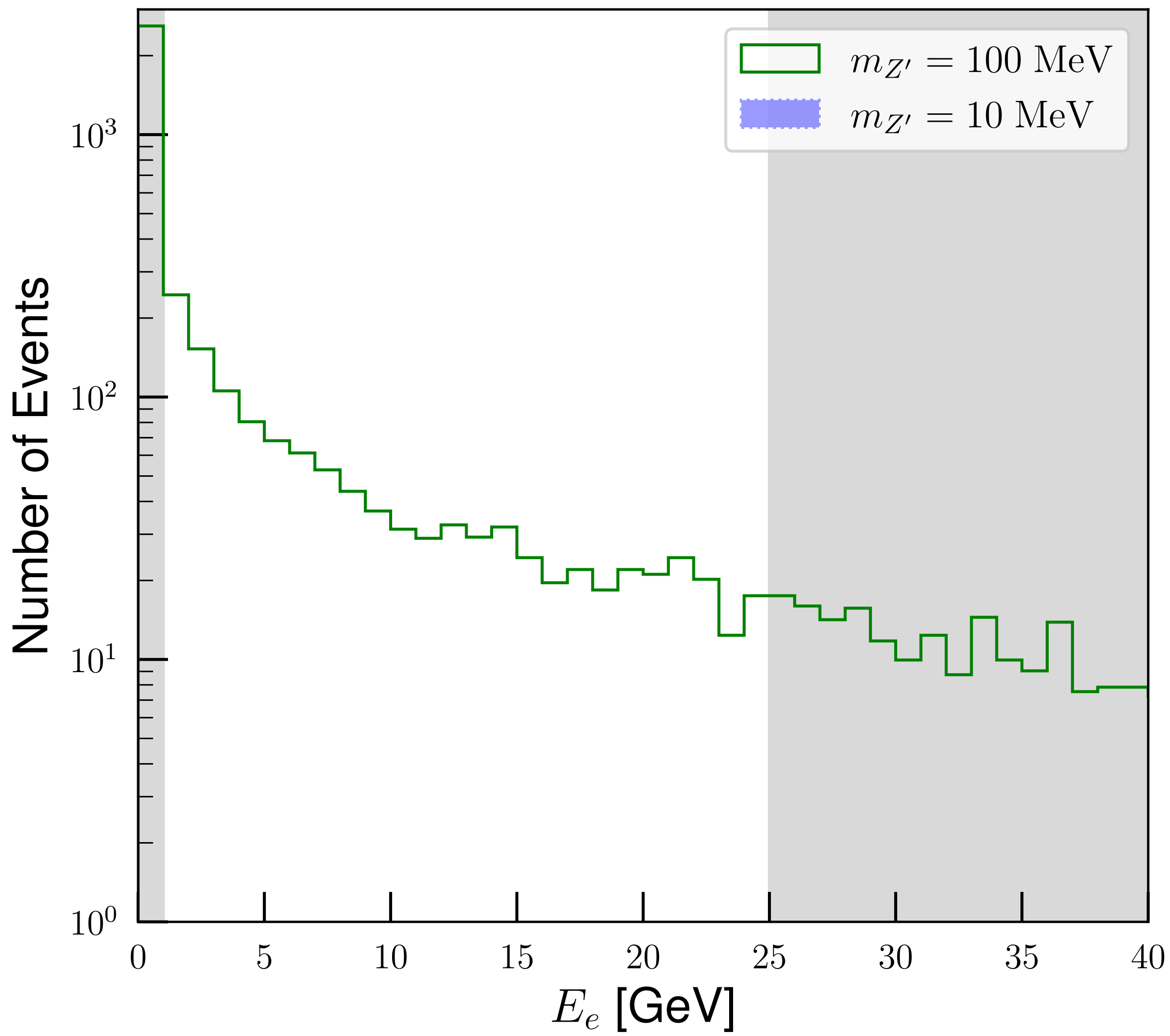
  Track multiplicity

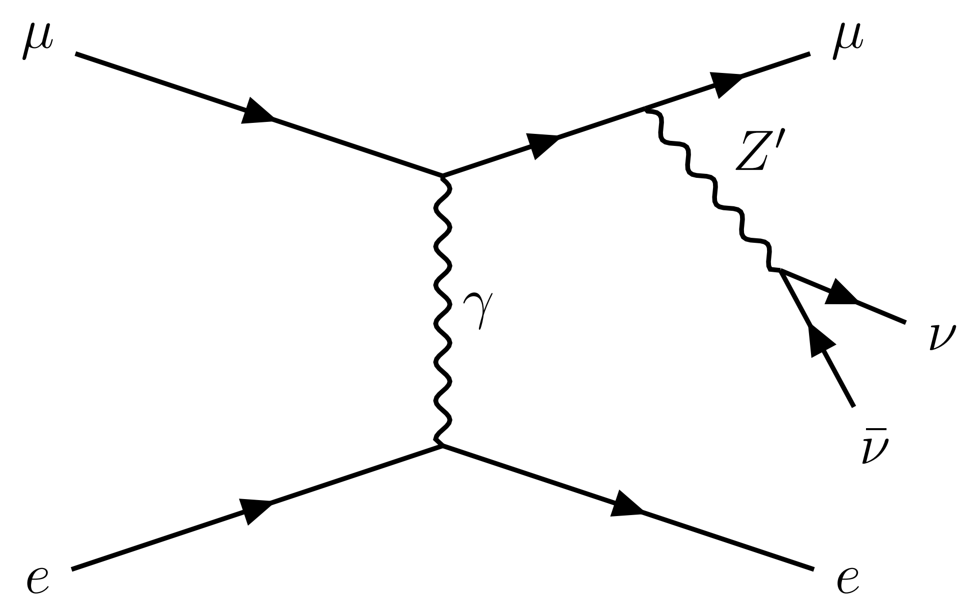
Strongly depend on the experimental setup

- EW processes: $\mu e \to \mu e \nu \bar{\nu}$

Negligibly small number of events ($\sim 10^{-4}$)

Distribution of E_e of signal events





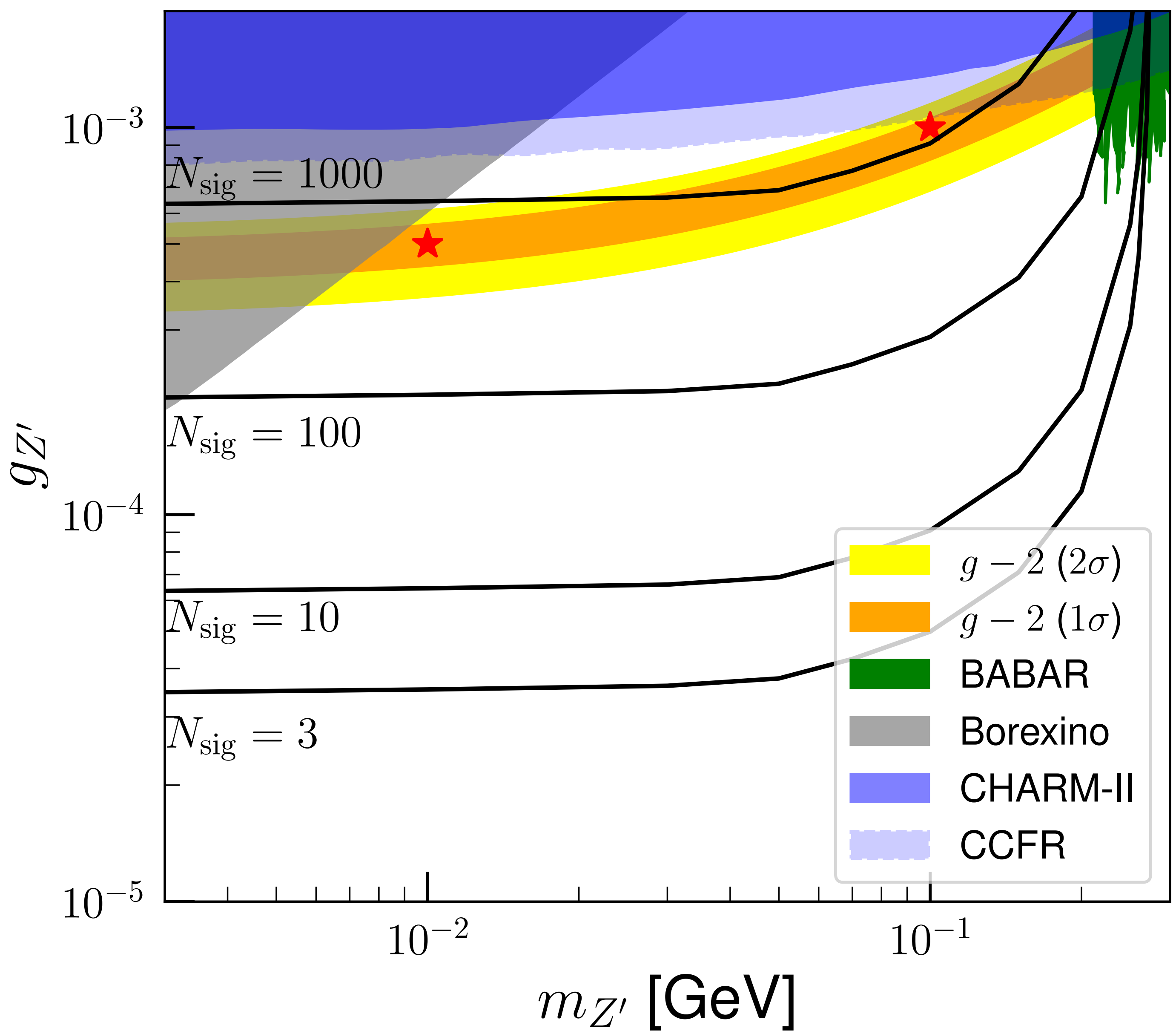
- FeynRules
- MadGraph5

Integrated luminosity: $15\ \mathrm{fb}^{-1}$

- $m_{Z'} = 100\ \mathrm{MeV}, g_{Z'} = 10^{-3}$ ➡ $N_{\mathrm{sig}} \simeq 1200$
- $m_{Z'} = 10\ \mathrm{MeV}, g_{Z'} = 5 \times 10^{-4}$ ➡ $N_{\mathrm{sig}} \simeq 600$

K. Asai, K. Hamaguchi, N. Nagata, S. Tseng, J. Wada, arXiv:2109.10093.

Number of signal events



Integrated luminosity: $15\ \mathrm{fb}^{-1}$

We expect $\sim 10^3$ signal events in the muon g–2 favored region.

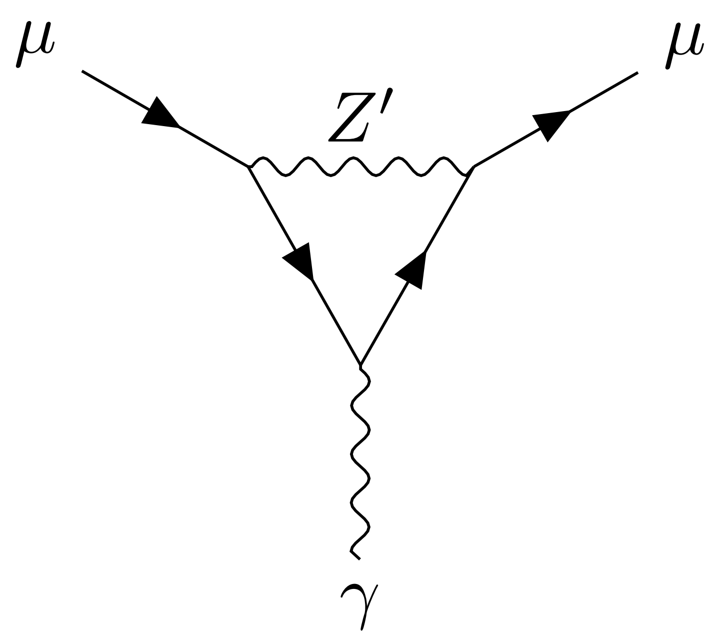
K. Asai, K. Hamaguchi, N. Nagata, S. Tseng, J. Wada, arXiv:2109.10093.

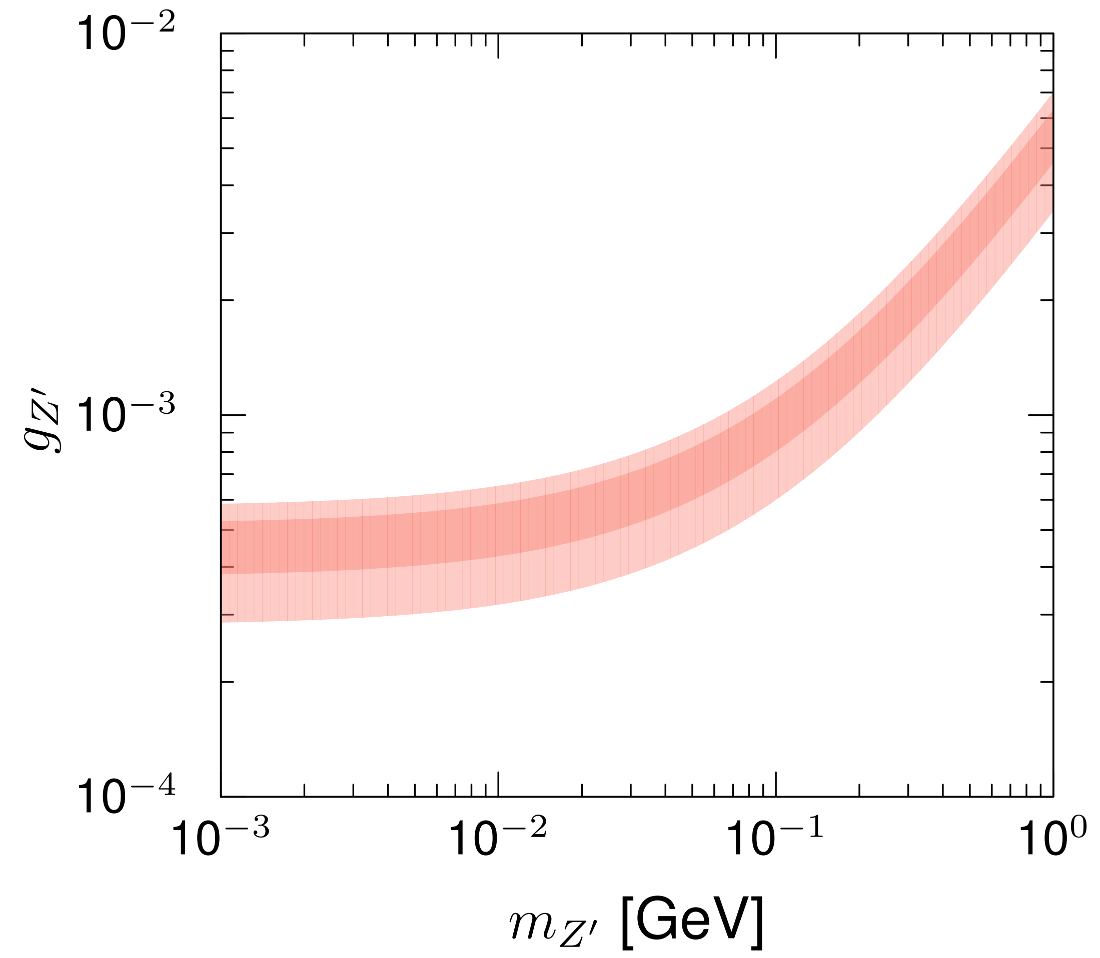
Summary

- The MUonE experiment will provide a new way to measure the hadron contribution to the muon g–2.
- We proposed that this MUonE experiment could be used to probe the $L_\mu - L_\tau$ gauge boson.
- The muon g–2 favored parameter region can fully be explored without introducing additional devices.

Backup

Muon g-2

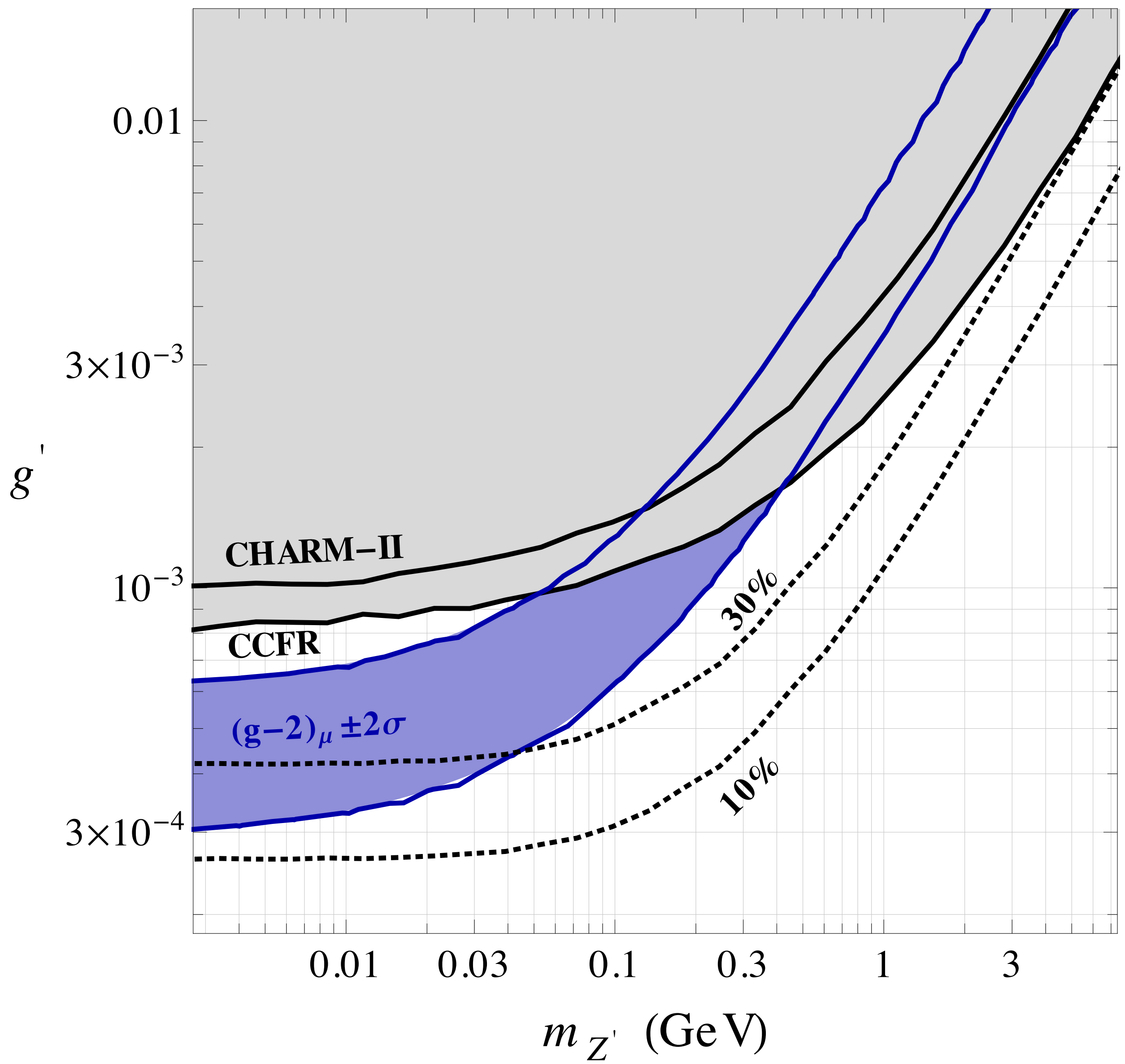


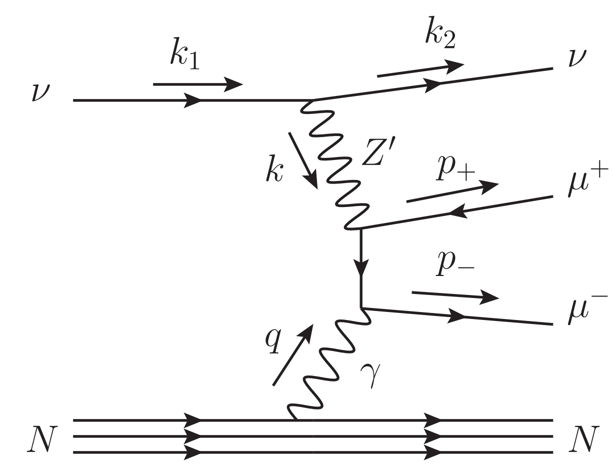


$$\delta a_\mu = \frac{g_{Z'}^2}{8\pi^2} \int_0^1 dx \frac{2m_\mu^2 x^2 (1-x)}{x^2 m_\mu^2 + (1-x) m_{A'}^2}$$

Neutrino trident production

W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin, Phys. Rev. Lett. **113**, 091801 (2014).





CCFR (1991)

$$\sigma_{\rm CCFR}/\sigma_{\rm SM} = 0.82 \pm 0.28$$

CHARM-II (1990)

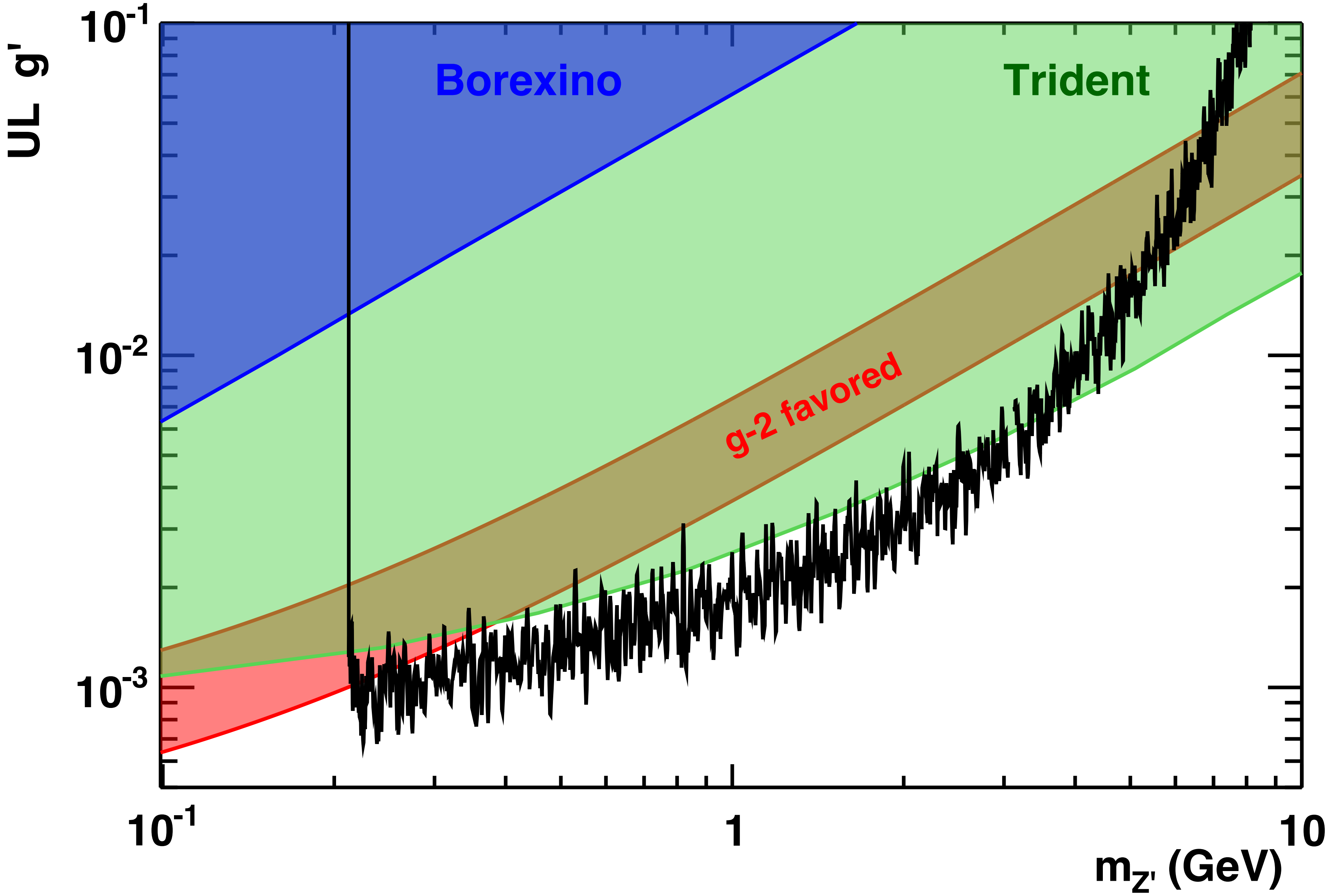
$$\sigma_{\rm CHARM-II}/\sigma_{\rm SM} = 1.58 \pm 0.57$$

····· 10 (30)% accuracy measurement with 5 GeV neutrino scattering on argon.

Z' mass larger than 400 MeV has been excluded.

BABAR constraint

$$e^+e^- \to \mu^+\mu^- Z' \ , \quad Z' \to \mu^+\mu^-$$



BABAR, Phys. Rev. **D94**, 011102 (2016).

Kinetic mixing

In general, there is a kinetic mixing between U(1)$_Y$ and U(1)':

$$\mathcal{L}_{\rm mix} = \frac{\epsilon}{2} B_{\mu\nu} F'^{\mu\nu}$$

B. Holdom, Phys. Lett. **B166**, 196 (1986).

We may forbid this using a discrete symmetry:

$$\mu \leftrightarrow \tau \ , \quad B_\mu \leftrightarrow B_\mu \ , \quad A'_\mu \leftrightarrow -A'_\mu$$

R. Foot, X. G. He, H. Lew, and R. R. Volkas, Phys. Rev. **D50**, 4571 (1994).

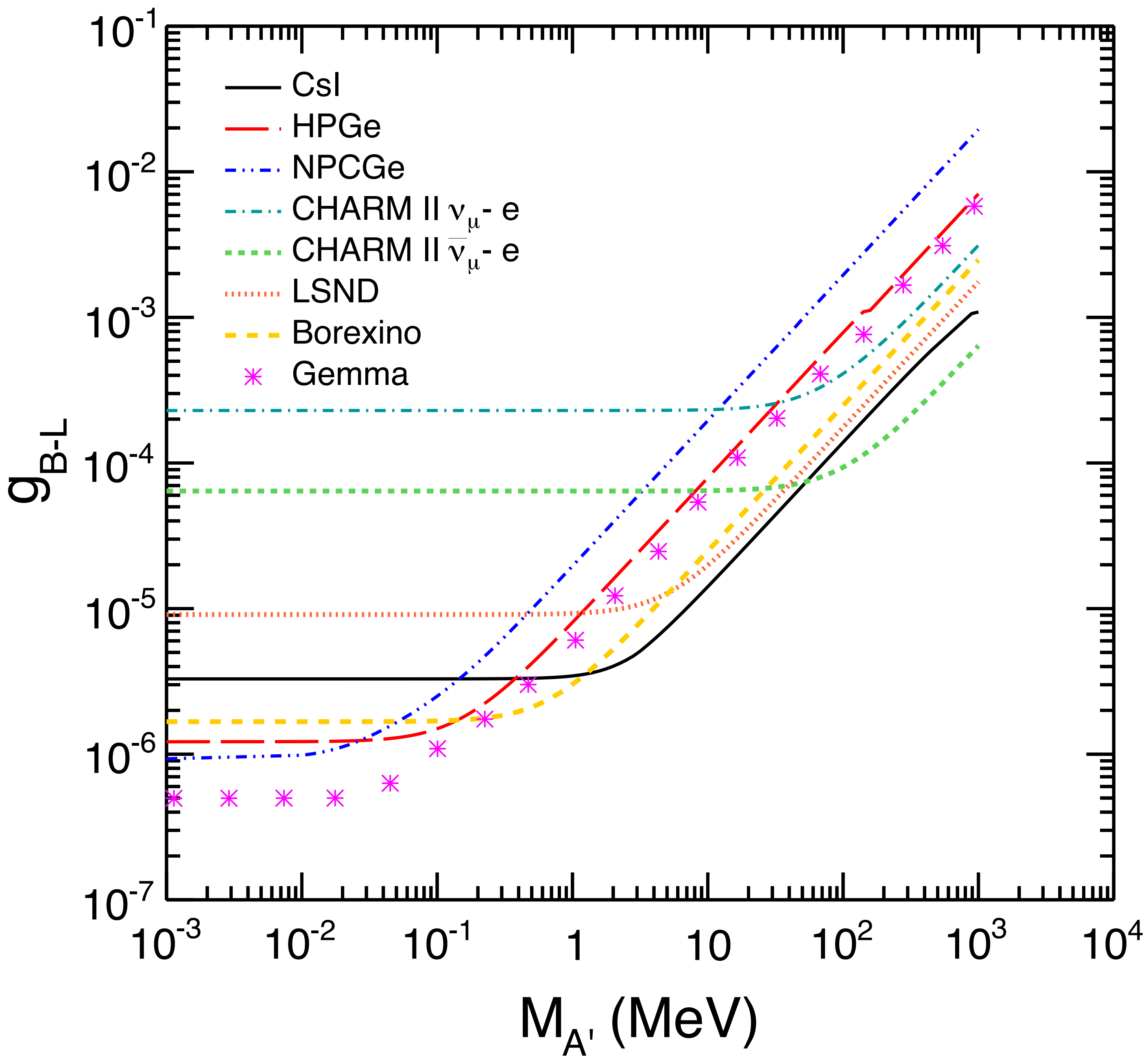
This symmetry is broken by the μ and τ masses, and thus the kinetic mixing is induced at loop level.

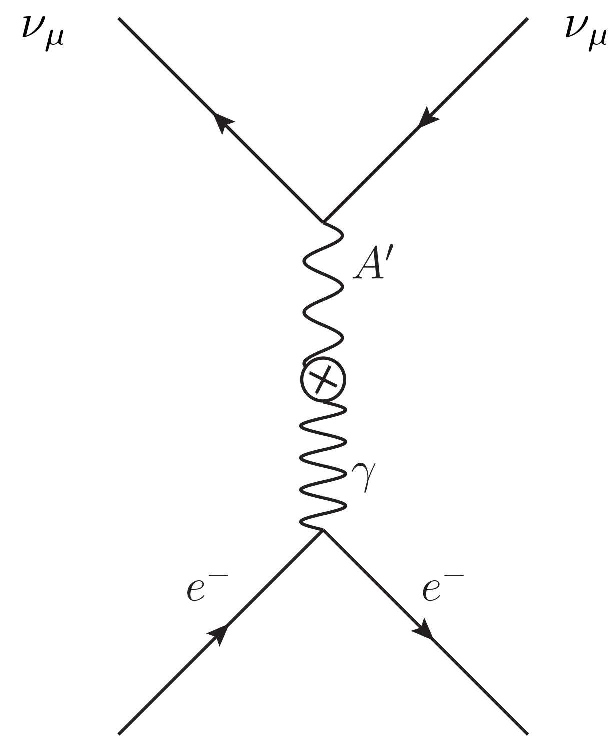
$$\epsilon = \frac{8}{3} \frac{e g_{Z'}}{16\pi^2} \ln\left(\frac{m_\tau}{m_\mu}\right)$$

(in the limit of low momenta)

Neutrino electron scattering

Neutrino-electron scattering occurs via kinetic mixing.

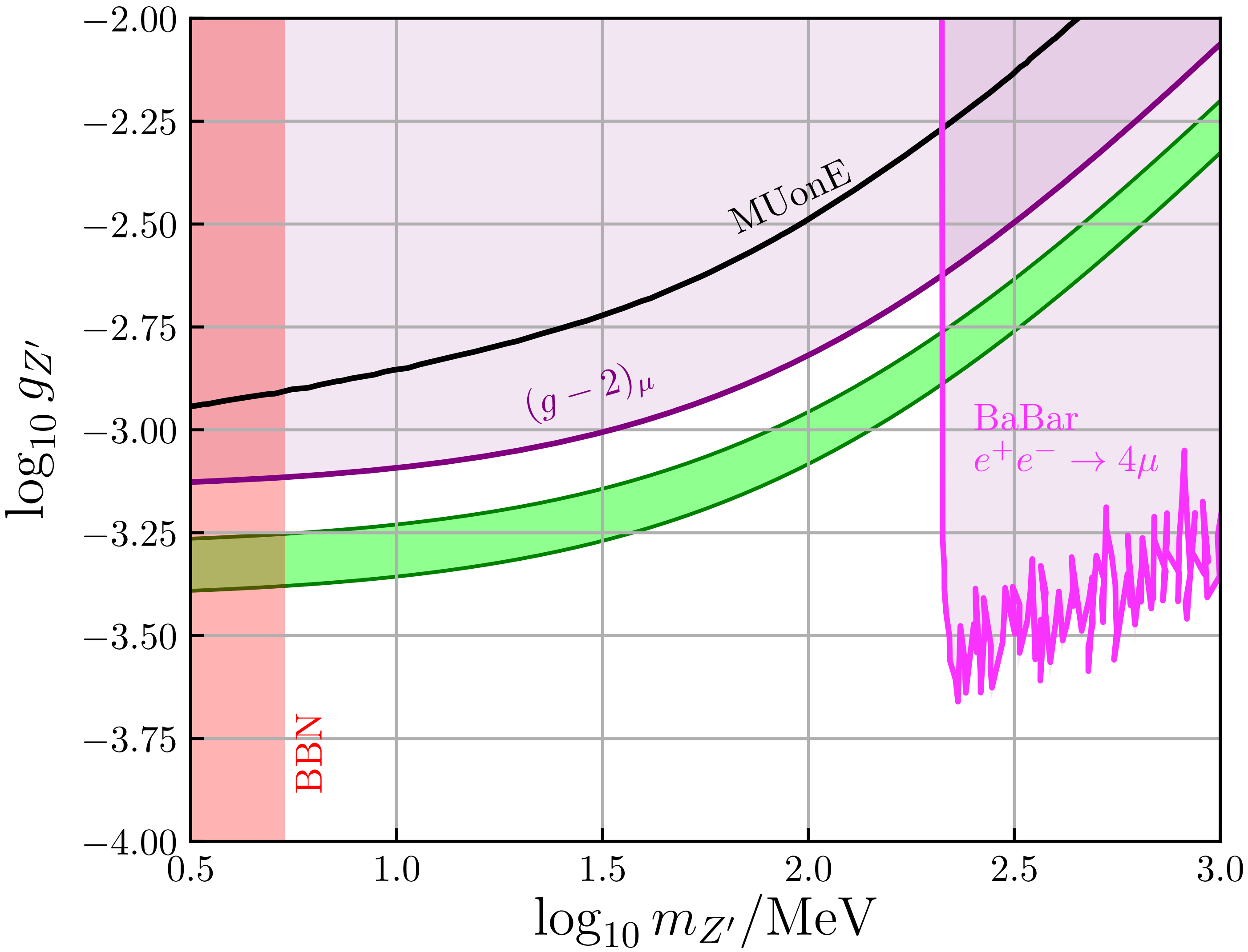


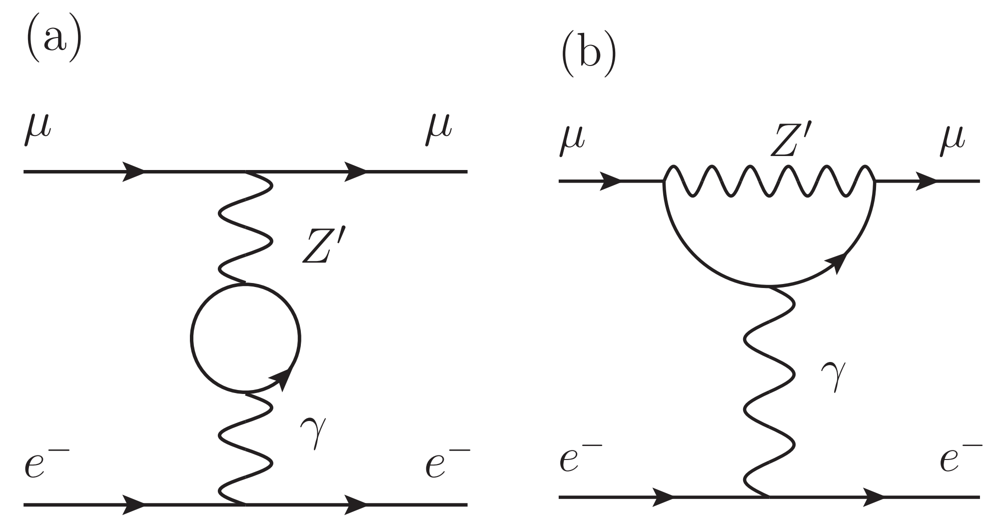


CHARM II and Borexino are sensitive to ν_μ-e scattering.

S. Bilmis, I. Turan, T. M. Aliev, M. Daniz, L. Singh, and H. T. Wong, Phys. Rev. **D92**, 033009 (2015).

Indirect search for $L_\mu - L_\tau$

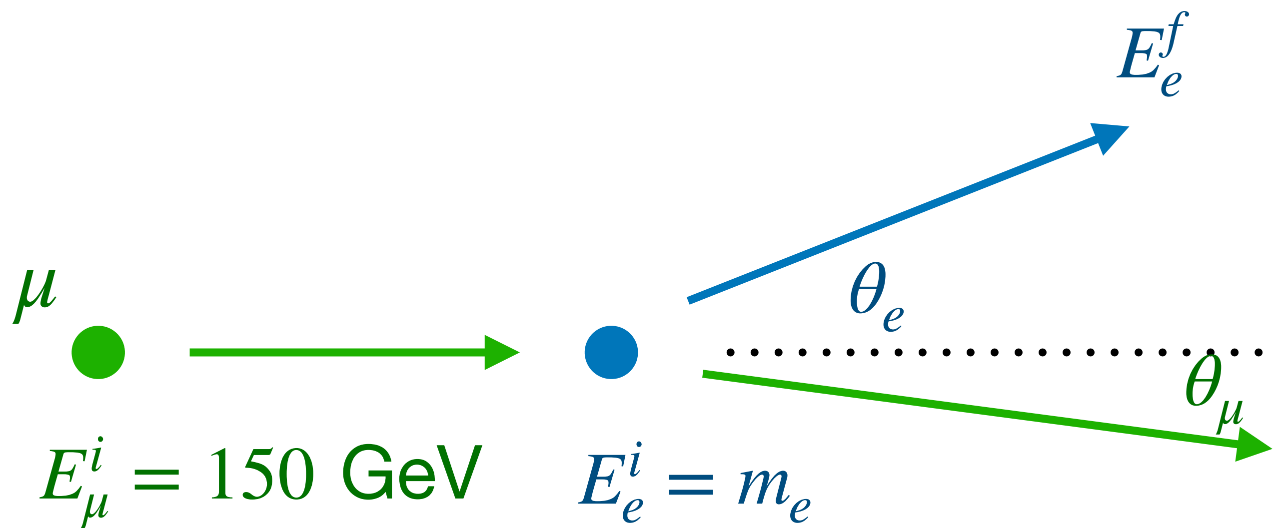




MUonE sensitive regions have already been excluded.

P. B. Dev, W. Rodejohann, X. Xu, Y. Zhang, JHEP **05**, 053 (2020) [arXiv:2002.04822].

Kinematics



Mandelstam variables

$$s = (p_\mu^i + p_e^i)^2 = m_\mu^2 + m_e^2 + 2m_e E_\mu^i$$

$\sqrt{s} \simeq 400$ MeV

$$t = (p_e^i - p_e^f)^2 = 2m_e^2 - 2m_e E_e^f$$

$$\theta_e^f = \arccos\left(\frac{E_\mu^i + m_e}{\sqrt{(E_\mu^i)^2 - m_\mu^2}}\sqrt{\frac{E_e^f - m_e}{E_e^f + m_e}}\right)$$

$$E_e^f|_{\max} \simeq \frac{2m_e (E_\mu^i)^2}{2E_\mu^i m_e + m_\mu^2} = 139.8 \text{ GeV}$$

$E_e^f = 1 - 139.8$ GeV

Low-energy cut is not fixed yet.

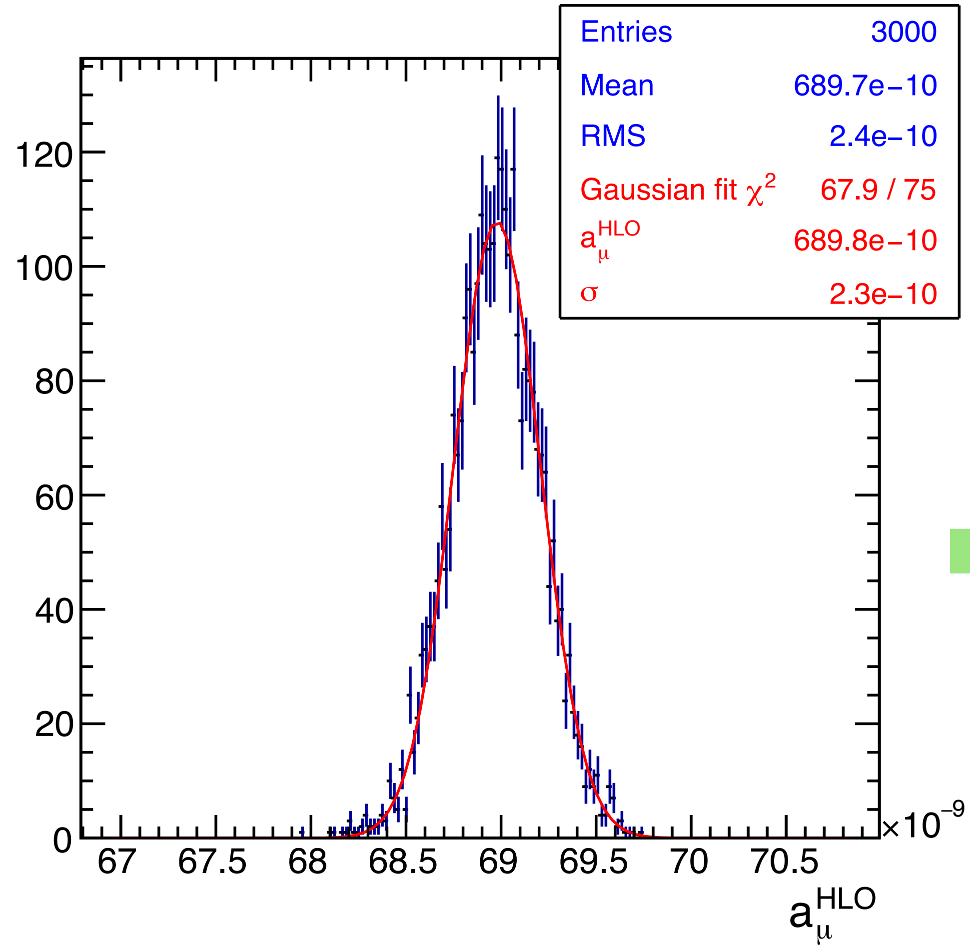
$\theta_e^f = 0 - 31.85$ mrad

Not fixed yet.

Statistics

- Muon beam rate: $\sim 1.3 \times 10^7\ \mu/\text{s}$
- 40×15 mm $= 60$ cm Be targets → $\mathcal{L} \sim 1.5 \times 10^7\ \text{nb}^{-1}$
- 2-3 years of data taking: $\sim 2 \times 10^7$ s/yr

Simulated result



- 3000 toy experiments
- Integrated luminosity: 1.5×10^7 nb^{-1}

→ $a_\mu^{(\text{HVP, LO})} = (689.8 \pm 2.3) \times 10^{-10}$

Statistical error only! True: 688.6×10^{-10}

Cf.) $a_\mu(\text{HVP; WP}) = 6845(40) \times 10^{-11}$

Systematic uncertainties

Systematic error should be controlled at the level of $\mathcal{O}(10^{-5})$!

Experiment

For instance, the following ingredients must be well controlled:

- Alignment of tracker elements
- Beam energy
- Multiple scattering
- Uniform efficiency over *t*

Should be understood at the level of O(1)%.

Theory

A Monte Carlo code at the NNLO level should be available.

For the current status, see

P. Banerjee, et.al., "Theory for muon-electron scattering @ 10ppm: A report of the MUonE theory initiative," Eur. Phys. J. C **80**, 591 (2020).

Electromagnetic calorimeter (ECAL)

Purposes

- Particle Identification
- Electron energy measurement
- Event selection (e.g., reject e + γ)

Detector material is lead tungstate ($PbWO_4$).

Similar to those used by the CMS ECAL

Final ECAL dimension will be optimized with a dedicated study.

Electron energy resolution