

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

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Based on Kento Asai, Koichi Hamaguchi, Natsumi Nagata, Shih-Yen Tseng,  
and JW arXiv[2109.10093]

# MUonE & Muon g-2

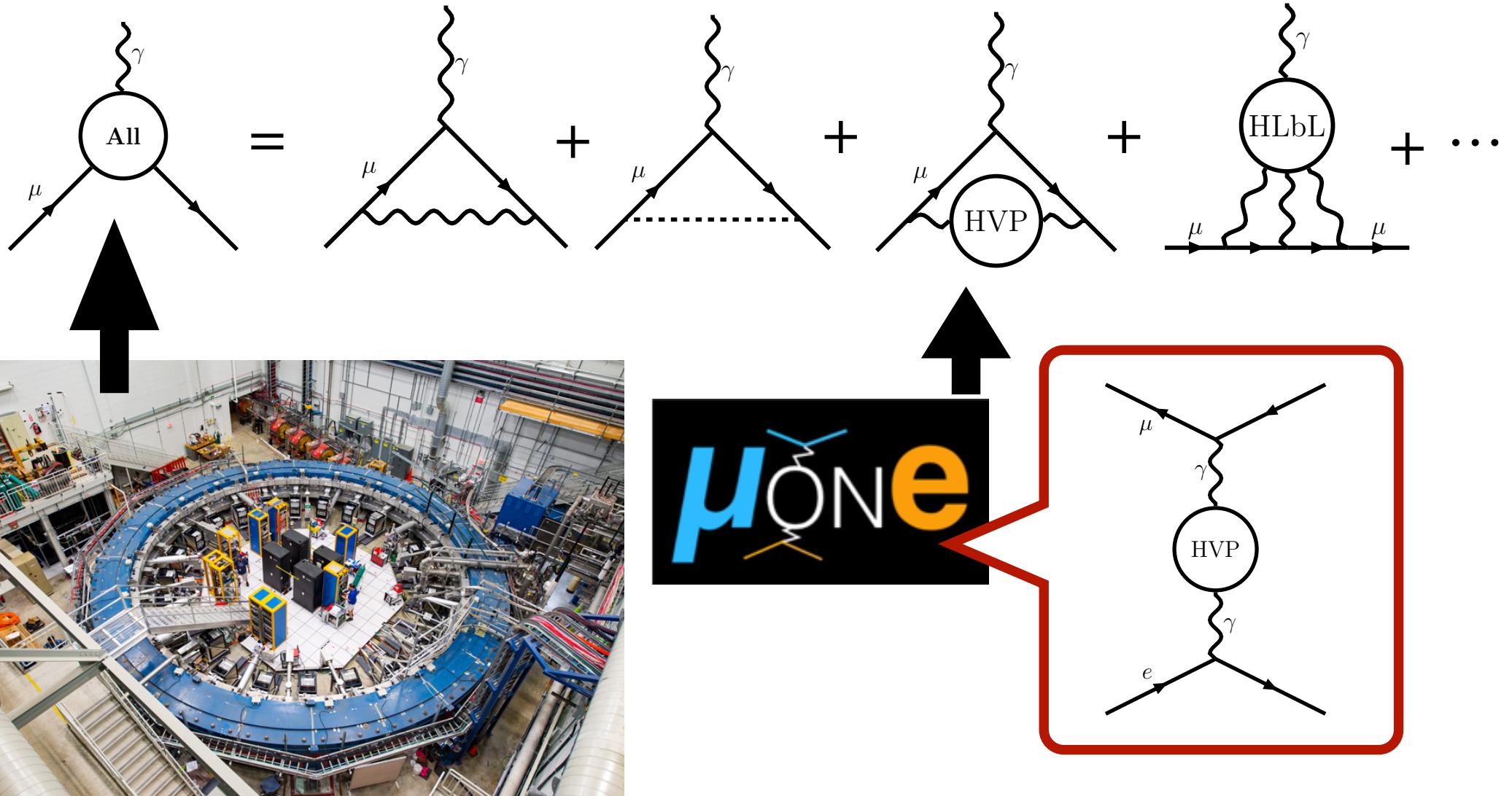


photo from Fermilab Muon g-2 web page

# MUonE & Muon g-2

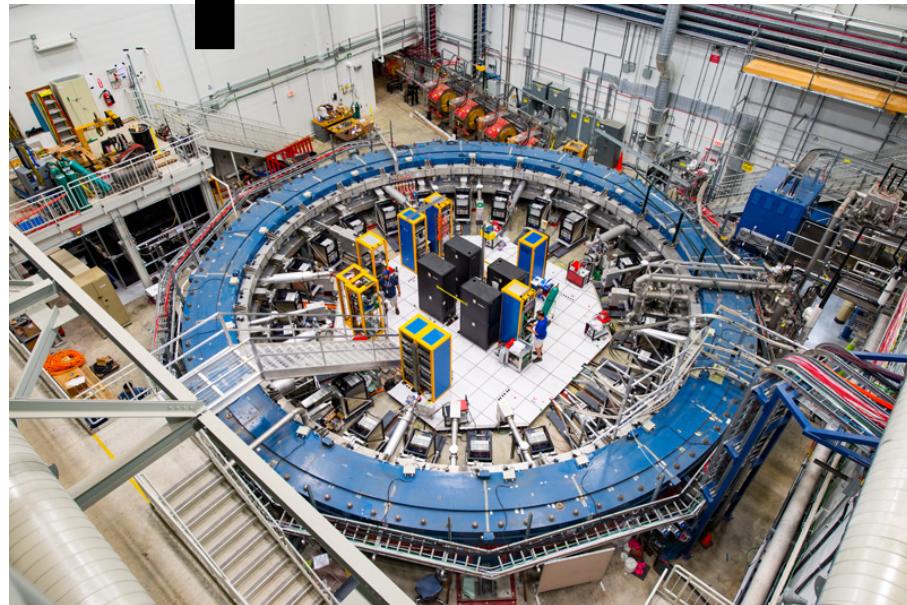
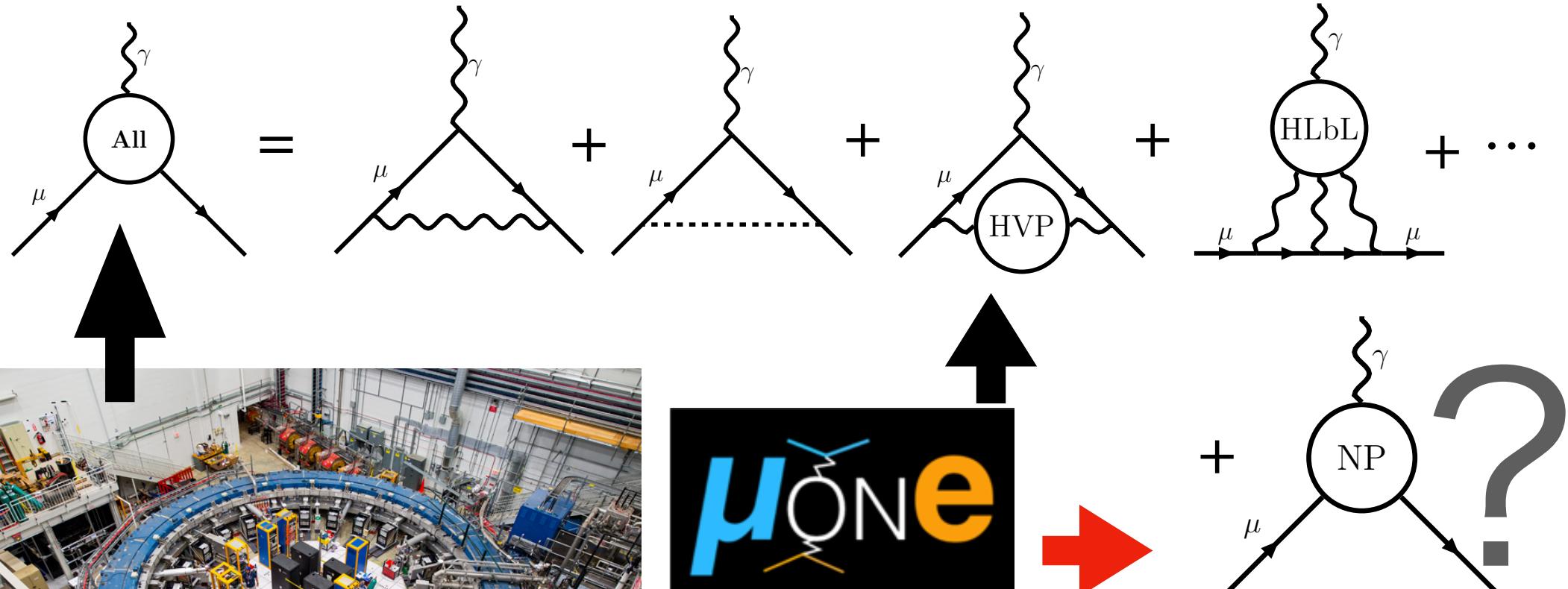


photo from Fermilab Muon g-2 web page



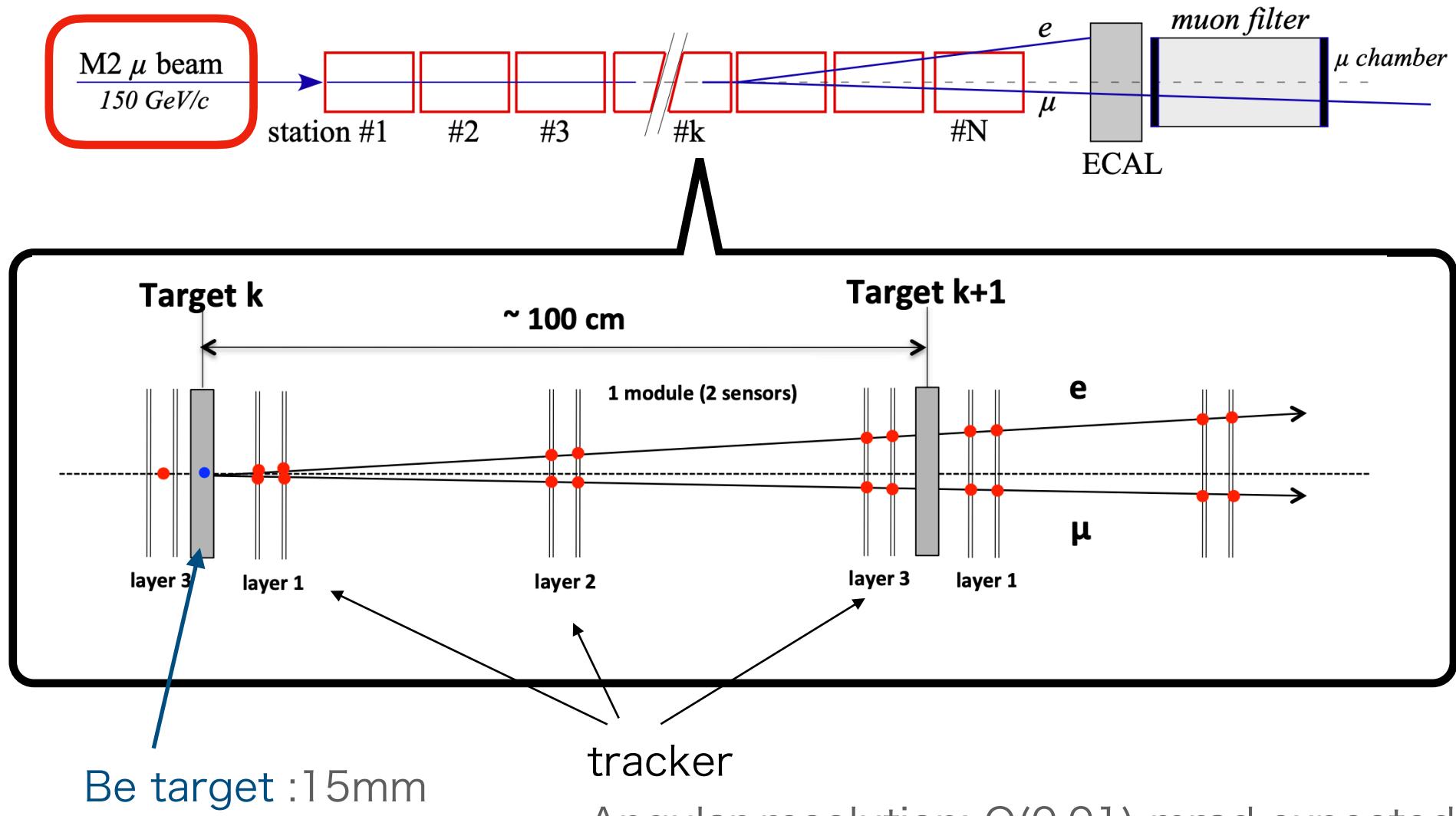
Can we search  
the BSM physics in MUonE?  
→ Focus on  $U(1)_{\mu-\tau}$  gauge boson

# Outline

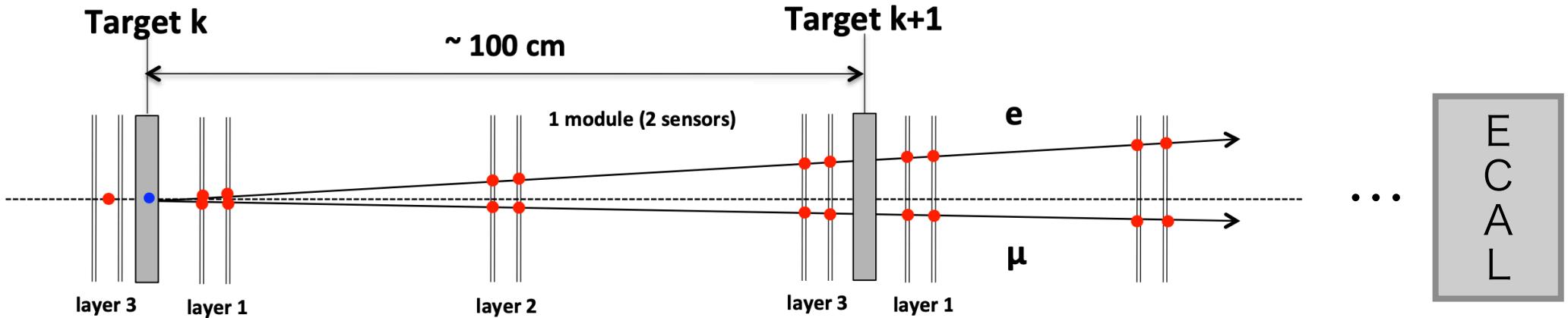
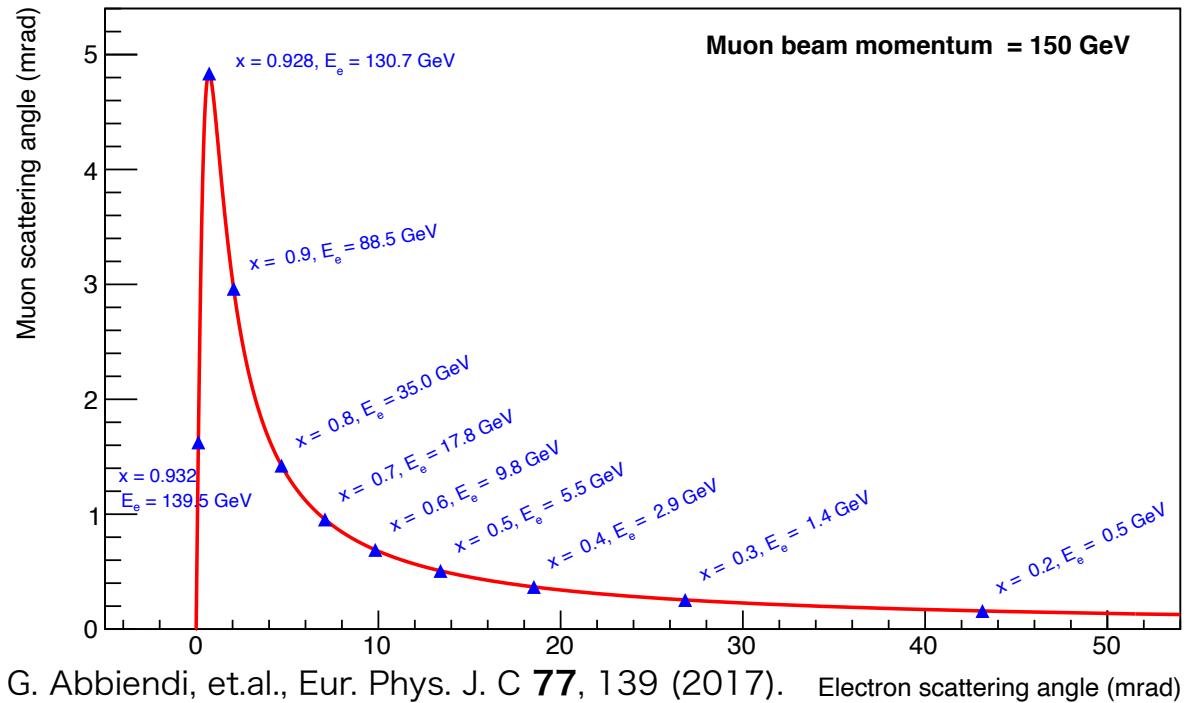
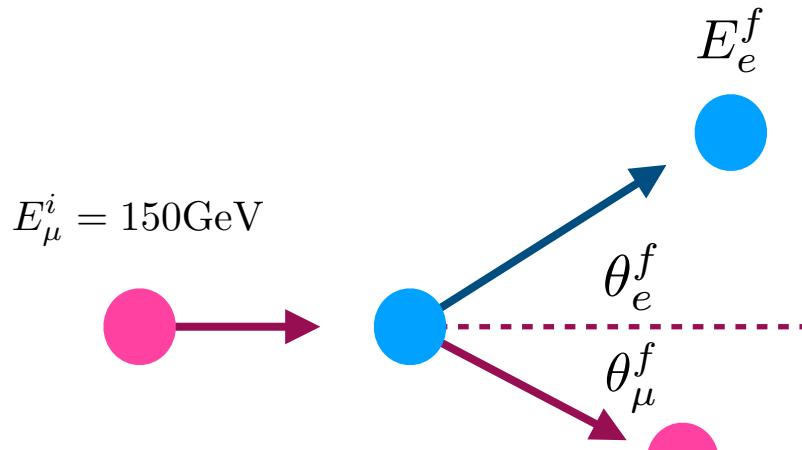
- ✓ Introduction
- ▶ MUonE experiment
- ▶  $U(1)_{\mu-\tau}$  gauge symmetry
- ▶ New Physics at MUonE

# MUonE setup

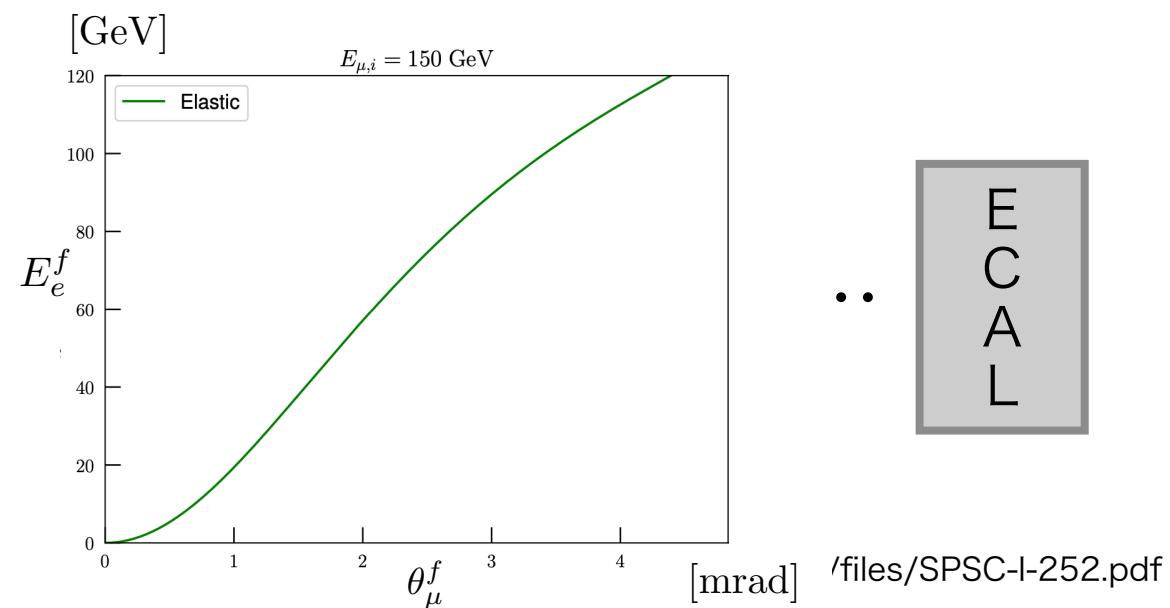
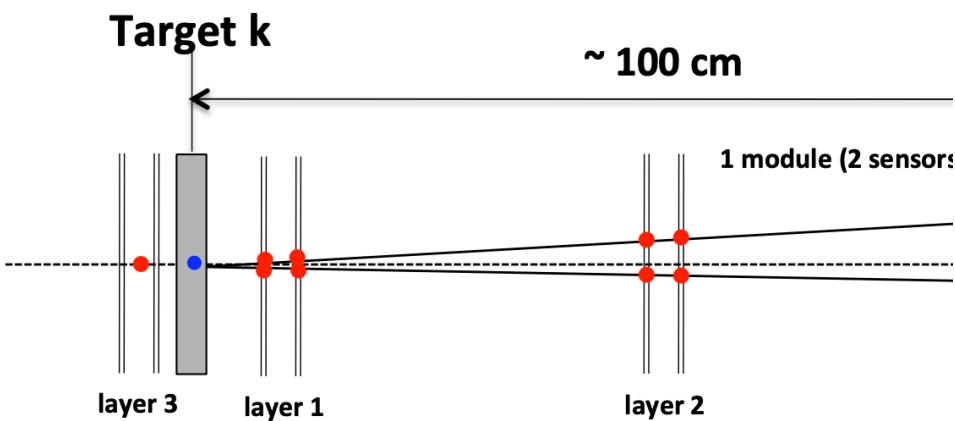
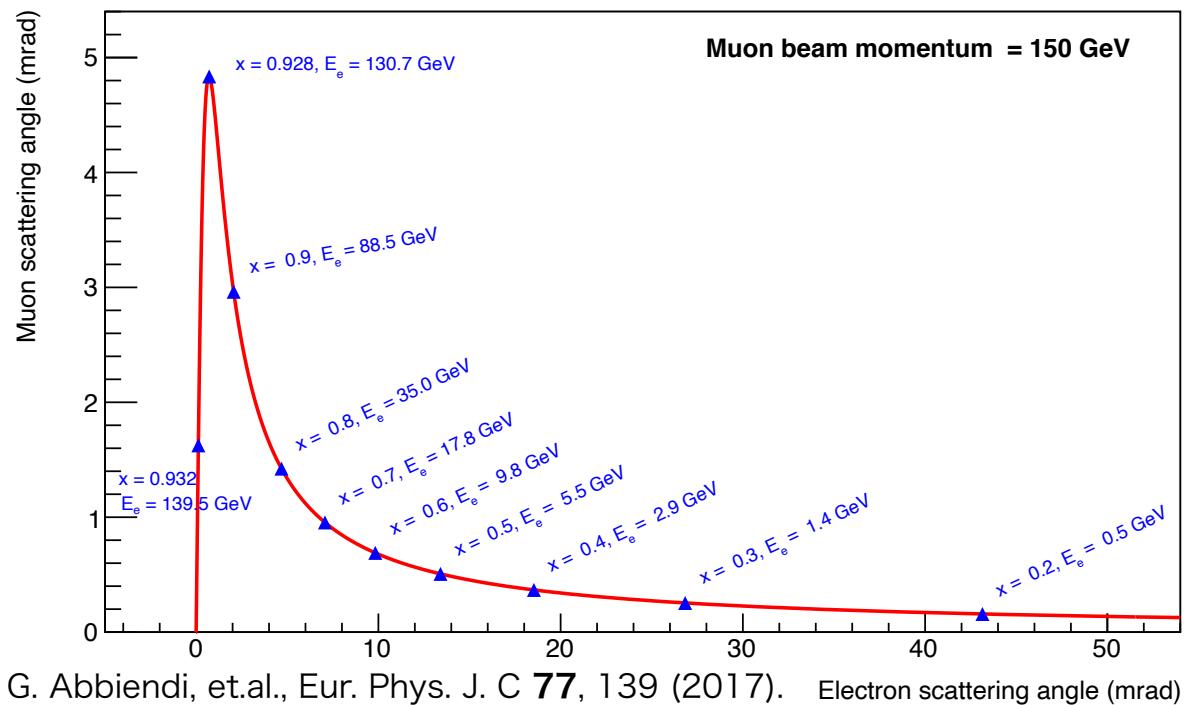
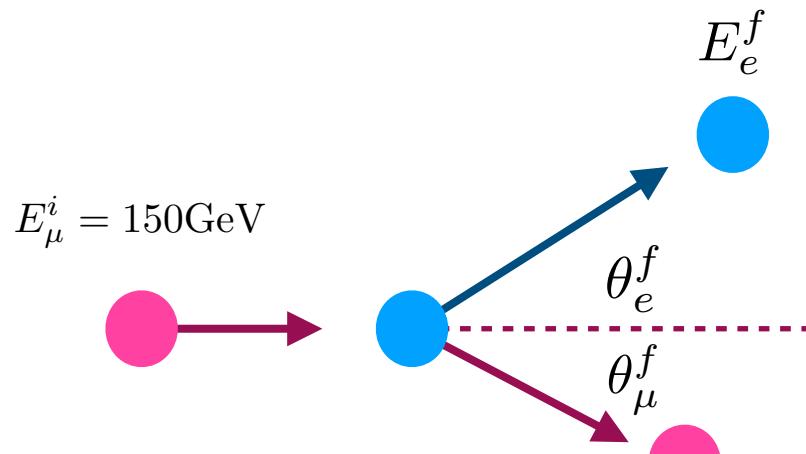
$$\mathcal{L} = 15[\text{fb}^{-1}]$$



# MUonE kinematics



# MUonE kinematics



# Outline

- ✓ Introduction
- ✓ MUonE experiment
- ▶  $U(1)_{\mu-\tau}$  gauge symmetry
- ▶ New Physics at MUonE

# $U(1)_{\mu-\tau}$ gauge symmetry

$$\mathcal{L} = -\frac{1}{4} F'^{\alpha\beta} F'_{\alpha\beta} + \frac{1}{2} m_{Z'}^2 Z'_\alpha Z'^\alpha + g' Z'_\alpha \sum_\psi Q_\psi \bar{\psi} \gamma^\alpha \psi$$

- ▶ No electron direct interaction
- ▶ Gauge anomaly free
- ▶ Related to the neutrino sector  
e.g. Neutrino oscillations, Leptogenesis...

Asai, Hamaguchi, Nagata, 1705.00419

Asai, Hamaguchi, Nagata, Tseng 2005.01039

R. Foot, Mod. Phys. Lett. **A6** 527–530 (1991).

X. G. He, et.al., Phys. Rev. D **43**, 22 (1991).

X. G. He, et.al., Phys. Rev. D **44** 2118–2132 (1991).

R. Foot, Mod. et.al., Phys. Rev. D **50** 4571–4580 (1994).

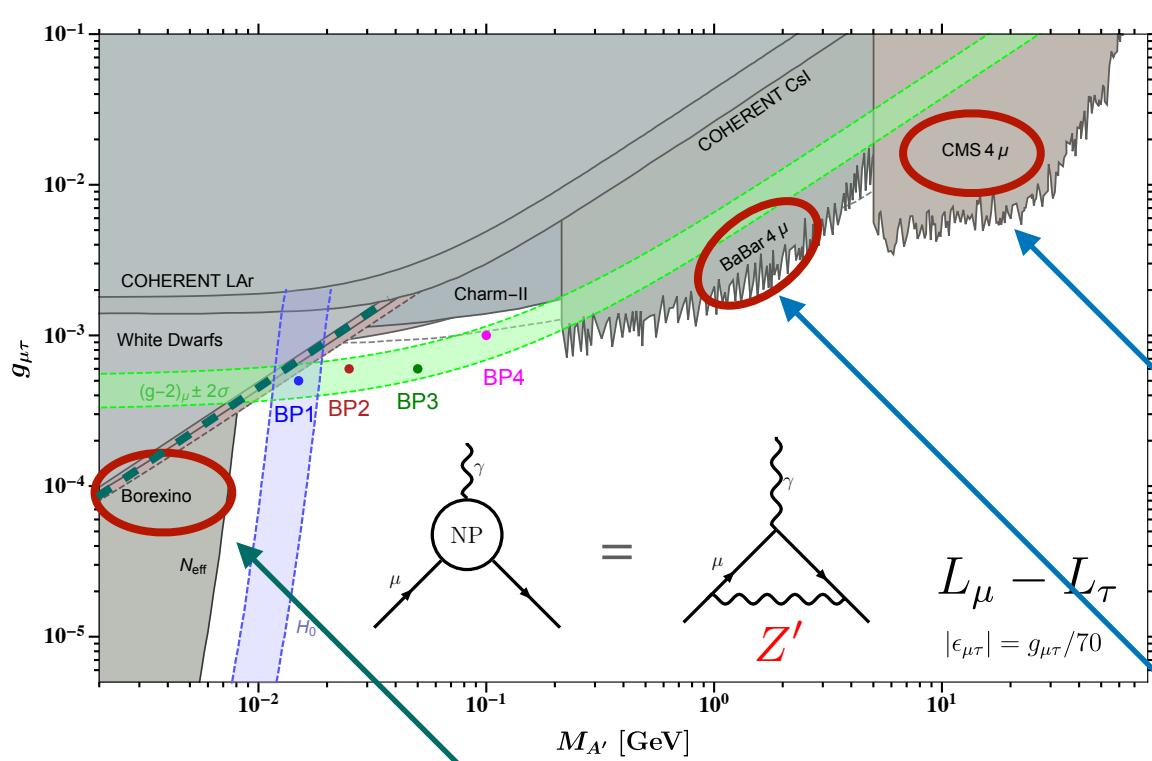
mass →	$\approx 2.3 \text{ MeV}/c^2$	u	c	t	g	H
charge →	2/3	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1/2	1	0
	up	charm	top	gluon	photon	Higgs boson
QUARKS						
mass →	$\approx 4.8 \text{ MeV}/c^2$	d	s	b	$\gamma$	
charge →	-1/3	-1/3	-1/3	-1/3	0	0
spin →	1/2	1/2	1/2	1/2	1	1
	down	strange	bottom	photon		
LEPTONS						
mass →	$0.511 \text{ MeV}/c^2$	e	$\mu$	$\tau$	Z	
charge →	-1	-1	+1	-1	0	0
spin →	1/2	1/2	1/2	1/2	1	1
	electron	muon	tau	Z boson		
GAUGE BOSONS						
mass →	$<2.2 \text{ eV}/c^2$	$\nu_e$	$\nu_\mu$	$\nu_\tau$	W	
charge →	0	0	+1	-1	$\pm 1$	
spin →	1/2	1/2	0	1/2	1	1
	electron neutrino	muon neutrino	tau neutrino	W boson		

QUANTUM DIARIES

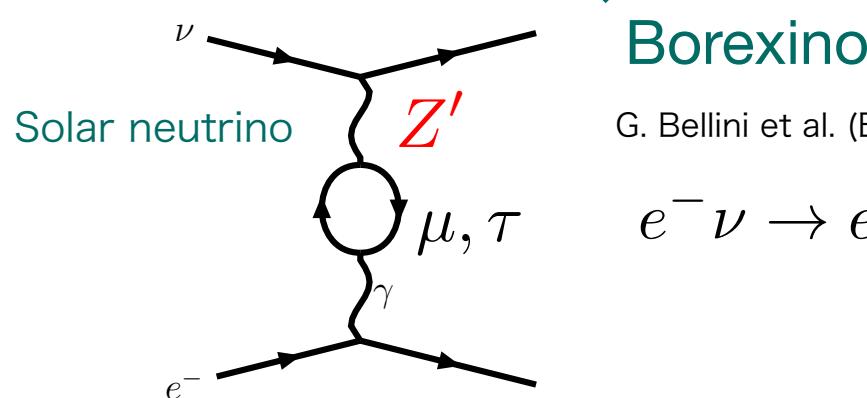
<https://www.quantumdiaries.org/2014/03/14/the-standard-model-a-beautiful-but-flawed-theory/>

$+Z'$

# Constraint

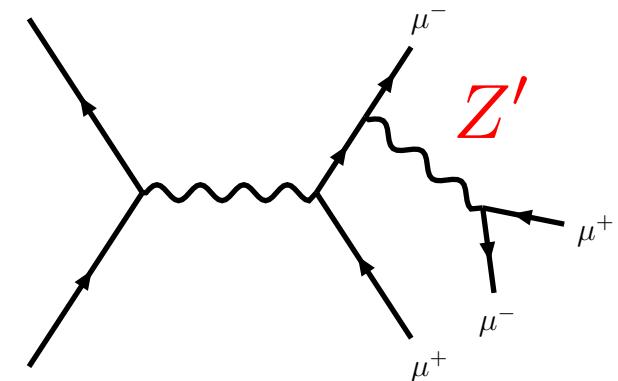


D.W.P. Amaral, et.al., Eur. Phys. J. C **81**, 861 (2021).



G. Bellini et al. (Borexino), Phys. Rev. Lett. 107, 141302 (2011)

$$e^- \nu \rightarrow e^- \nu$$



**CMS**

A. Sirunyan, et al. (CMS) Phys. Lett. B **792**, 345 (2019).  
 $q\bar{q} \rightarrow \mu^-\mu^+ Z' \rightarrow \mu^-\mu^+\mu^-\mu^+$

**BaBar**

J. P. Lees et al. (BaBar), Phys. Rev. D **94**, 011102 (2016),

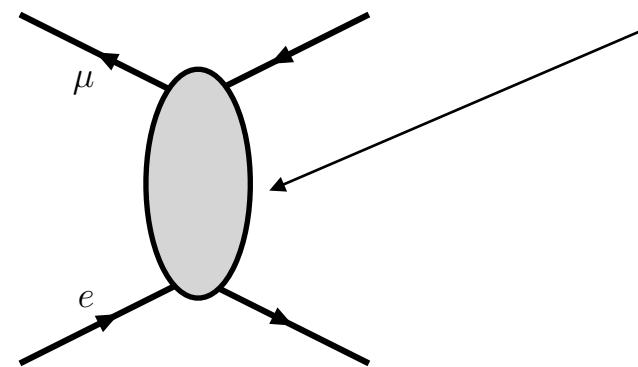
$$e^- e^+ \rightarrow \mu^-\mu^+ Z' \rightarrow \mu^-\mu^+\mu^-\mu^+$$

# Outline

- ✓ Introduction
- ✓ MUonE experiment
- ✓  $U(1)_{\mu-\tau}$  gauge symmetry
- ▶ New Physics at MUonE

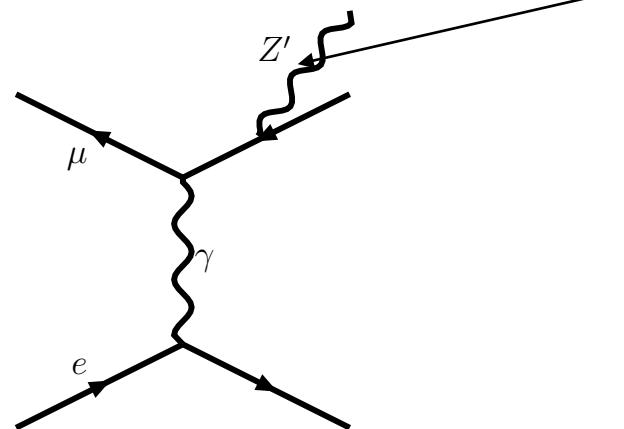
# New Physics at MUonE

- $\mu e \rightarrow \mu e$  scattering



New physics can affect the elastic scattering.

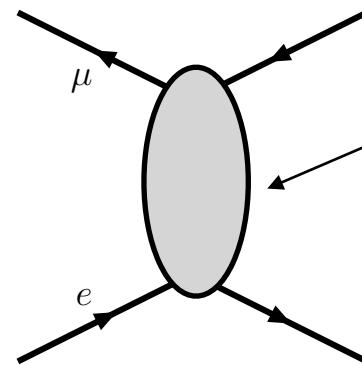
- $\mu e \rightarrow \mu e Z'$



If NP exist, We may be able to search the direct production of  $Z'$  at MUonE.

# New Physics at MUonE

- ▶  $\mu e \rightarrow \mu e$  scattering



New physics can affect  
the elastic scattering.

There are some previous researches.

e.g. Heavy NP

A. Masiero, et.al., Phys. Rev. D **102**, 075013 (2020)

dark photon

A. Masiero, et.al., Phys. Rev. D **102**, 075013 (2020)

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

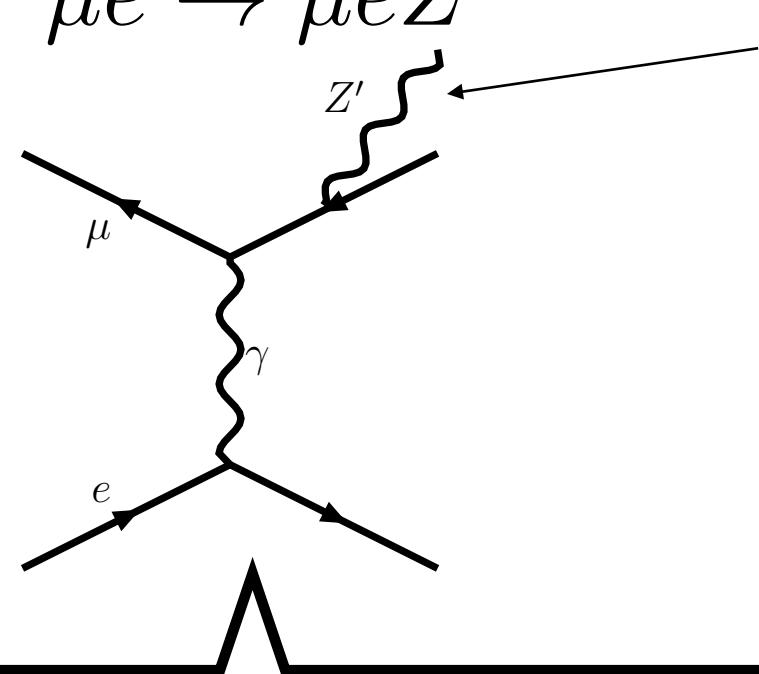
P. B. Dev, JHEP **05**, 053 (2020)

The possible NP effects in  $\mu e \rightarrow \mu e$  scattering  
are expected to **lie below MUonE's sensitivity**.

(with existing experimental bounds taken into account)

# New Physics at MUonE

- ▶  $\mu e \rightarrow \mu e Z'$



If NP exist, We may able to search the direct production of  $Z'$  at MUonE.

In this context,  
there was no previous research.

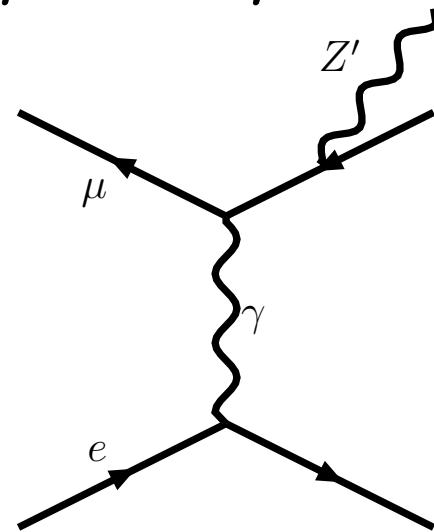
Our proposal:

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

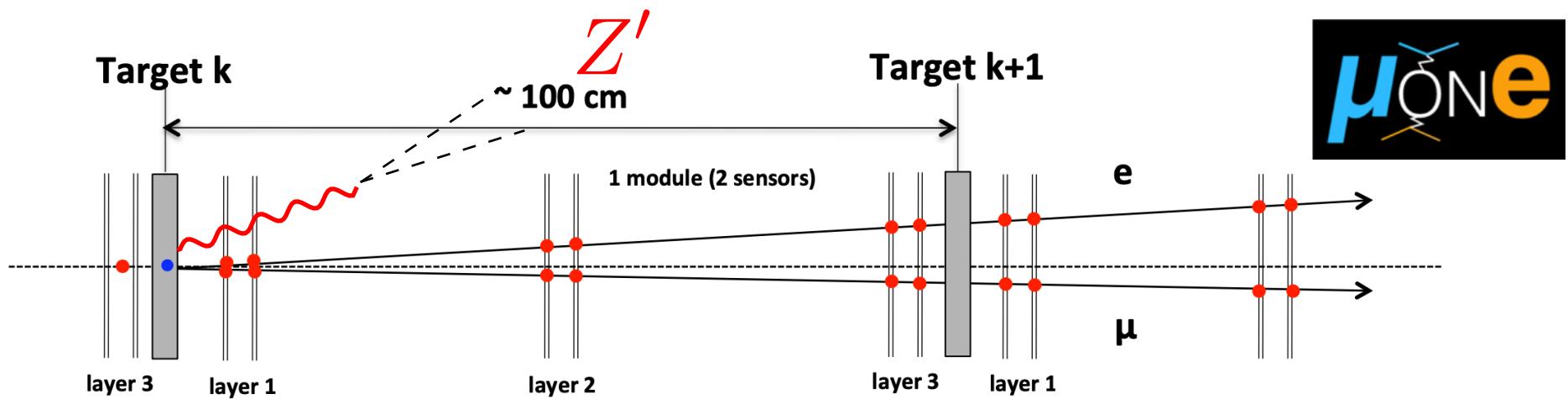
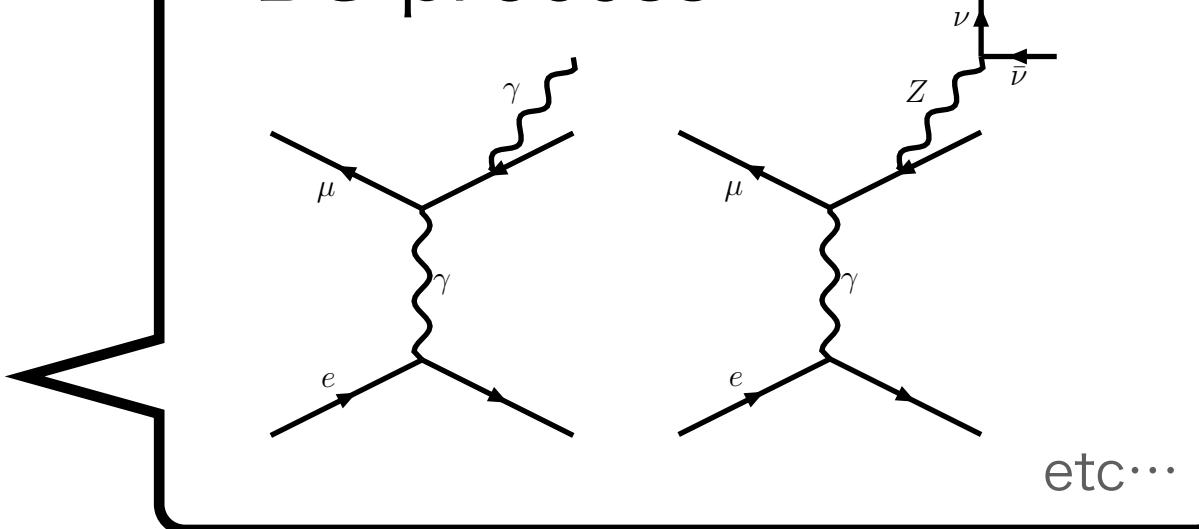
Kento Asai, Koichi Hamaguchi, Natsumi Nagata, Shih-Yen Tseng,  
and JW arXiv[2109.10093]

# Signal & Background

►  $\mu e \rightarrow \mu e Z' \rightarrow \mu e \nu \bar{\nu}$



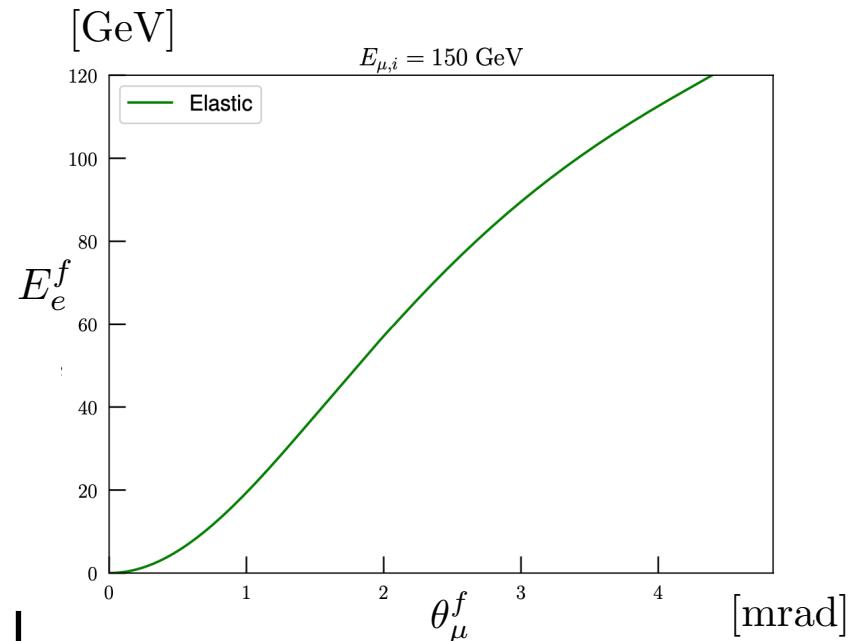
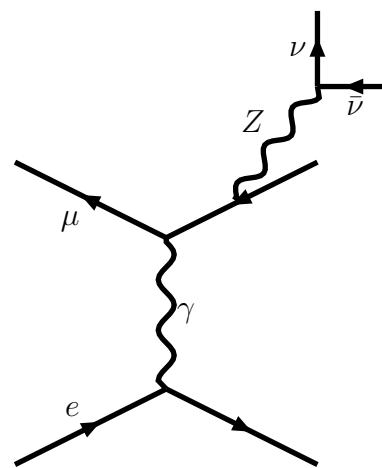
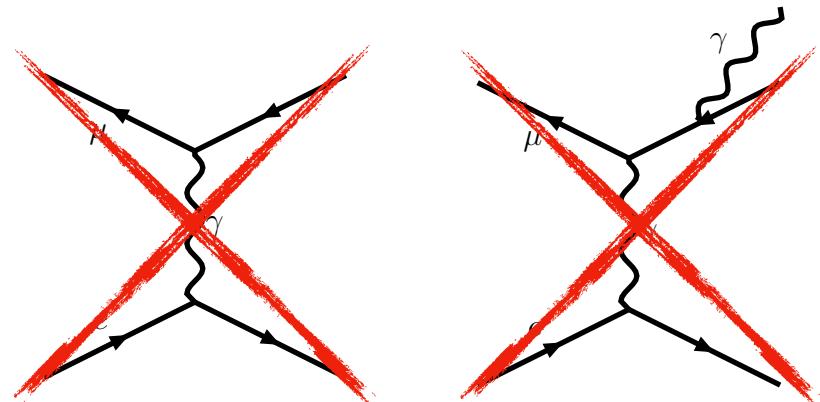
BG process



# Strategy

## Selection criteria

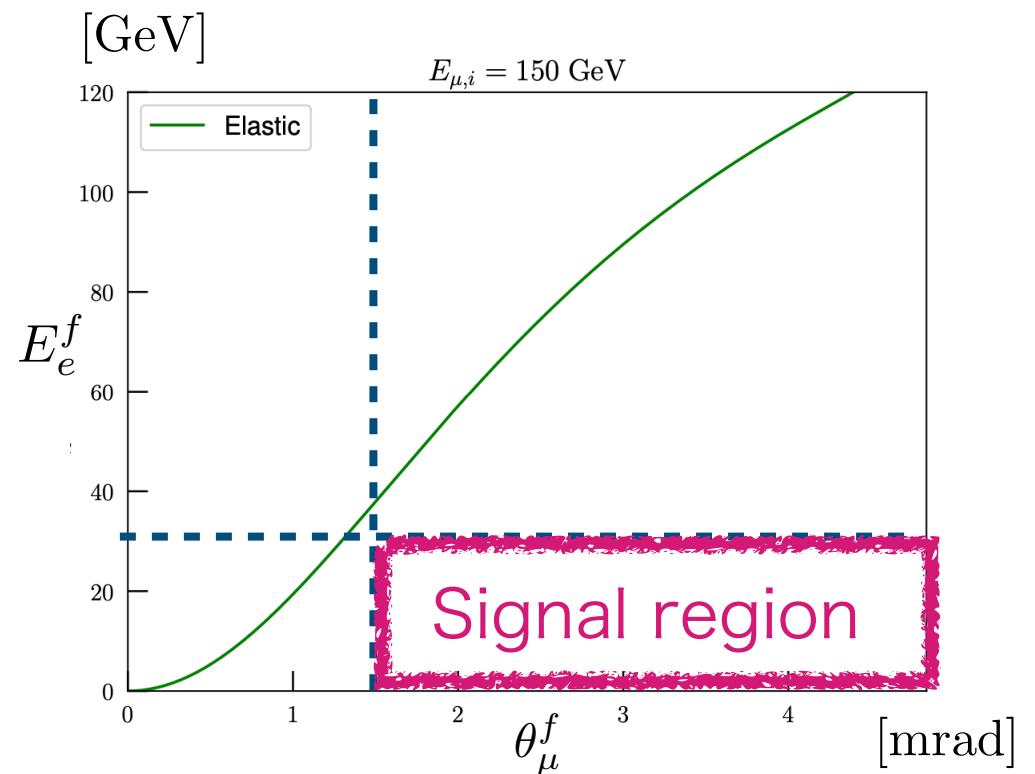
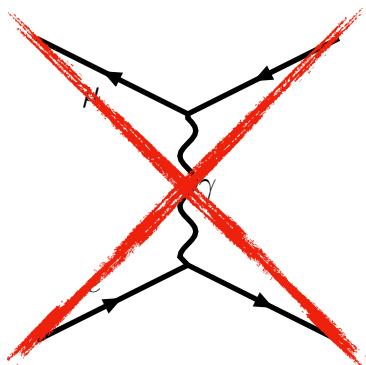
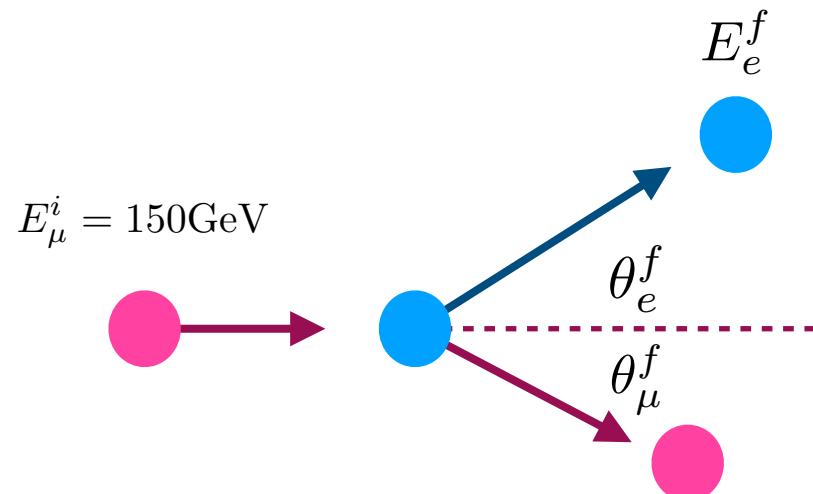
- ▶ Muon scattering angle :  $\theta_\mu^f$
- ▶ Energy of the electron :  $E_e^f$
- ▶ Photon veto



Monte Carlo  
simulations

Removed by kinematics + Photon veto

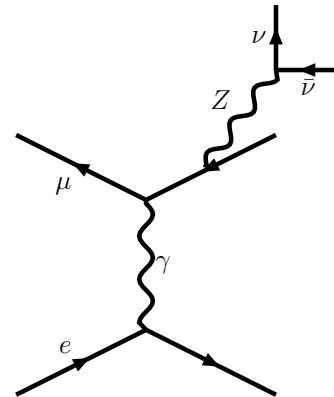
# Strategy



- ▶  $\theta_\mu^f \geq 1.5 \text{ [mrad]}$
- ▶  $E_e^f \leq 25 \text{ [GeV]}$

# Other Backgrounds

- ▶ EW process: e.g.  $\mu e \rightarrow \mu e Z^* \rightarrow \mu e \nu \bar{\nu}$



MC simulation

►  $O(10^{-4})$  events

Negligibly small

FeynRules & MadGraph5 \_aMC@NLO

N. D. Christensen and C. Duhr,  
Comput. Phys. Comm. **180**, 1614 (2009)

A. Alloul, et.al., Comput. Phys. Commun. **185**, 2250 (2014)

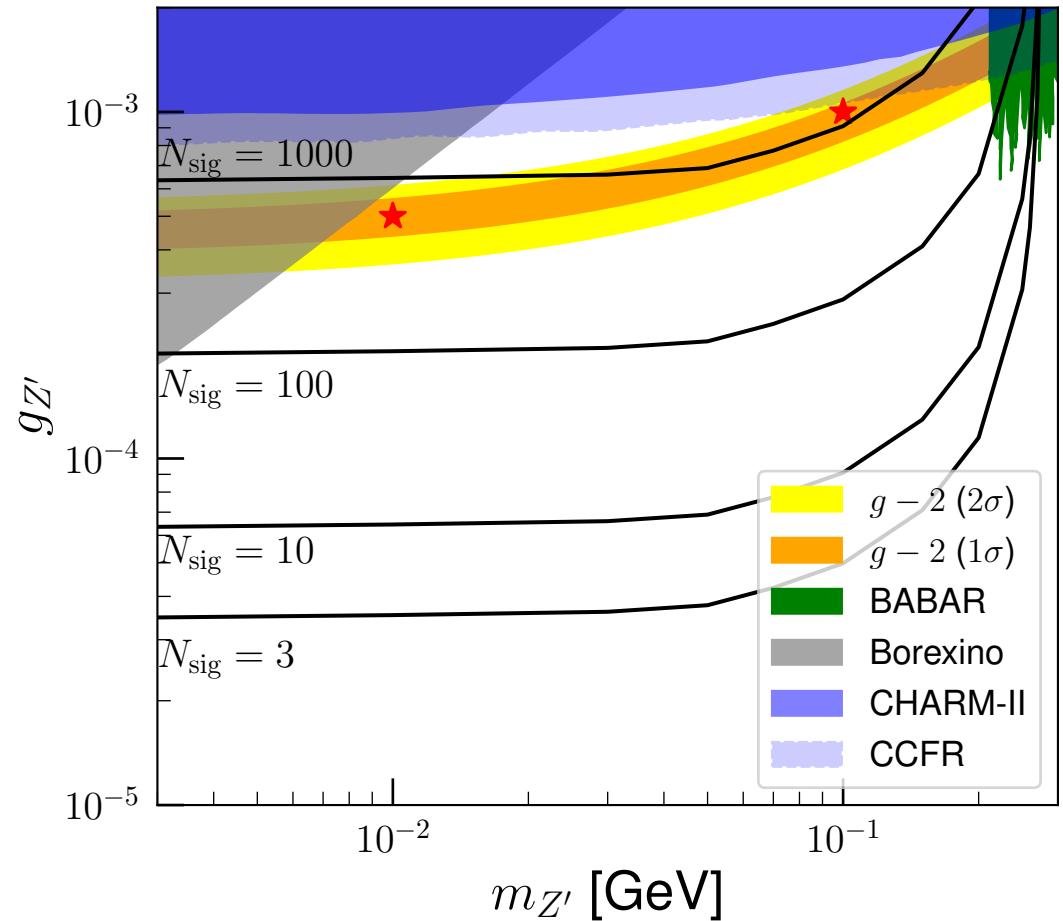
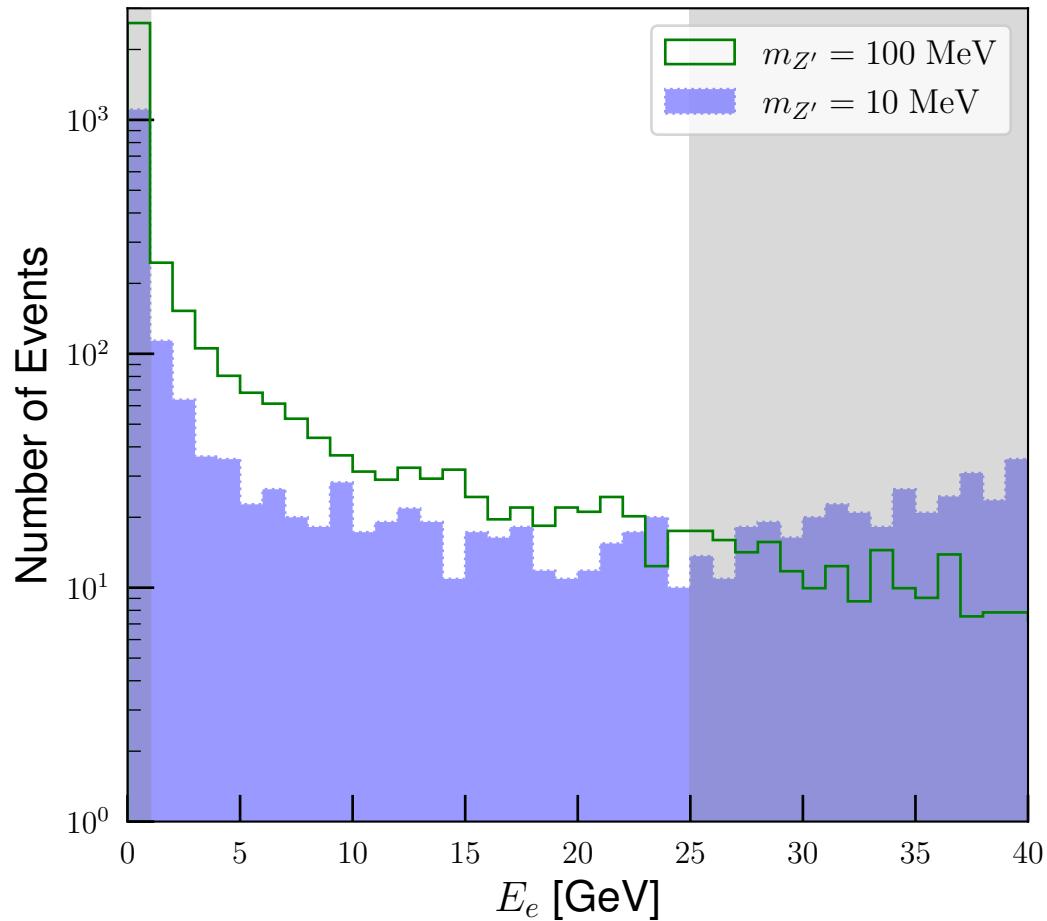
J. Alwall, et.al., JHEP **07**, 079 (2014)

- ▶ multiple scattering
- ➔ Kink/branch of the track
- ▶ nuclear scattering
- ➔ Track multiplicity



These effects strongly depend  
on the experimental setup  
(not fully fixed yet).

# Results



# Summary

- The MUonE collaboration intends to assess the HVP contribution to the muon g-2 via elastic  $\mu$ -e scattering.
- We showed that the  $L\mu-L\tau$  gauge boson  $Z'$  can be searched for at the MUonE experiment by imposing kinematical cuts on  $\theta_\mu^f$  and  $E_e^f$
- Our result shows that the MUonE experiment is also sensitive to the new physics and therefore it can serve a double purpose.



# Back up

# MUonE & Muon g-2

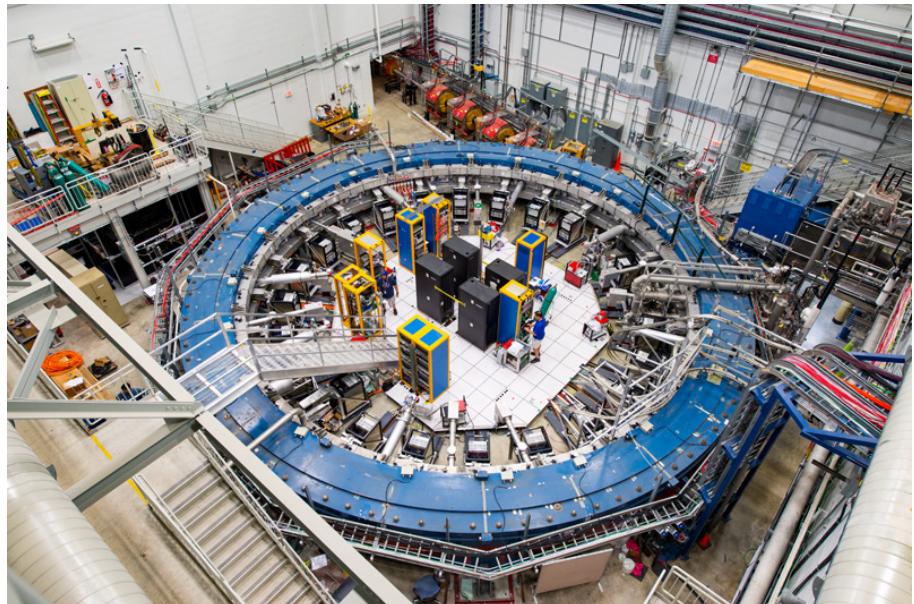
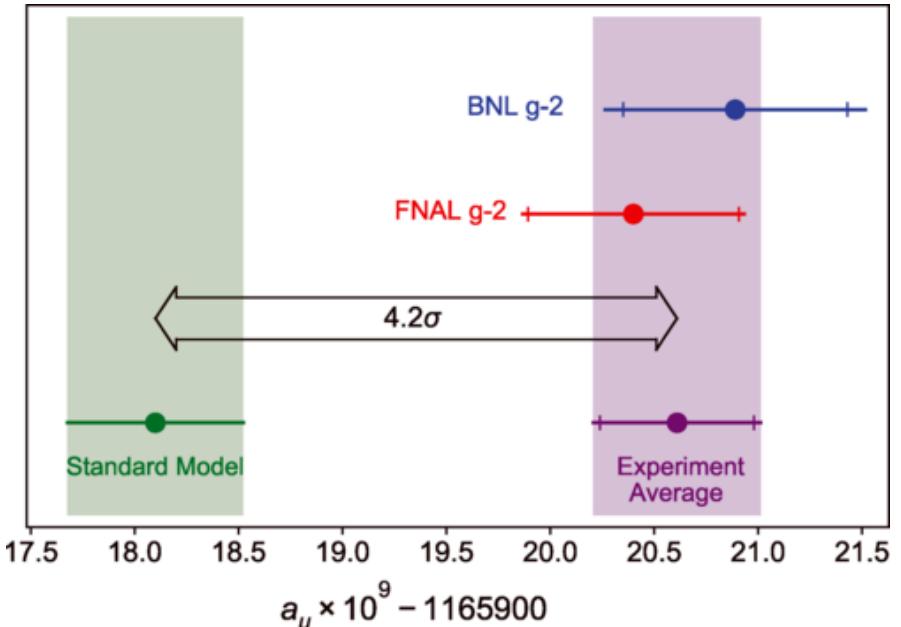
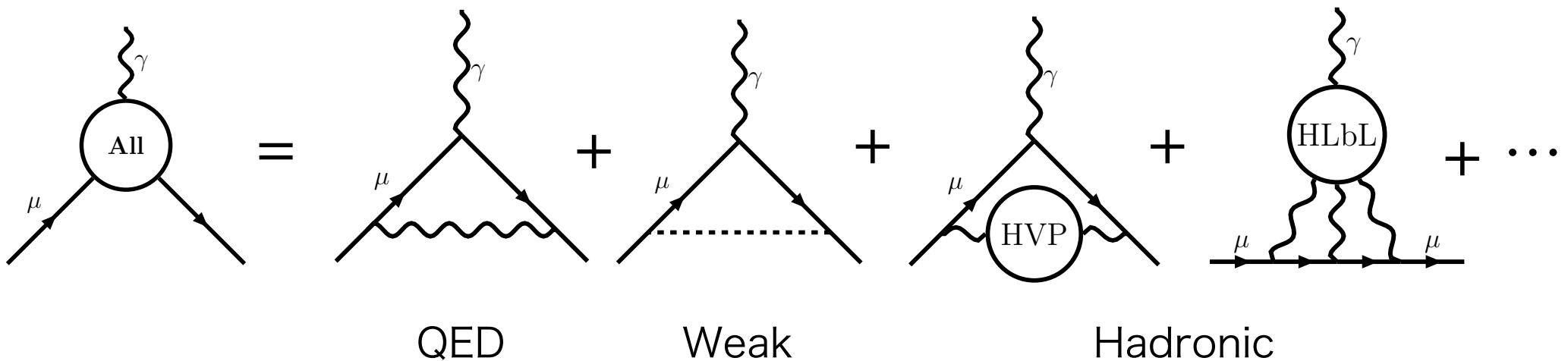


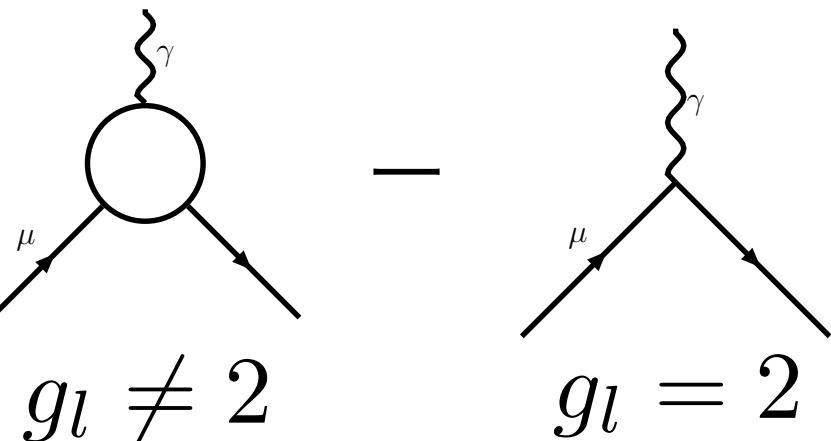
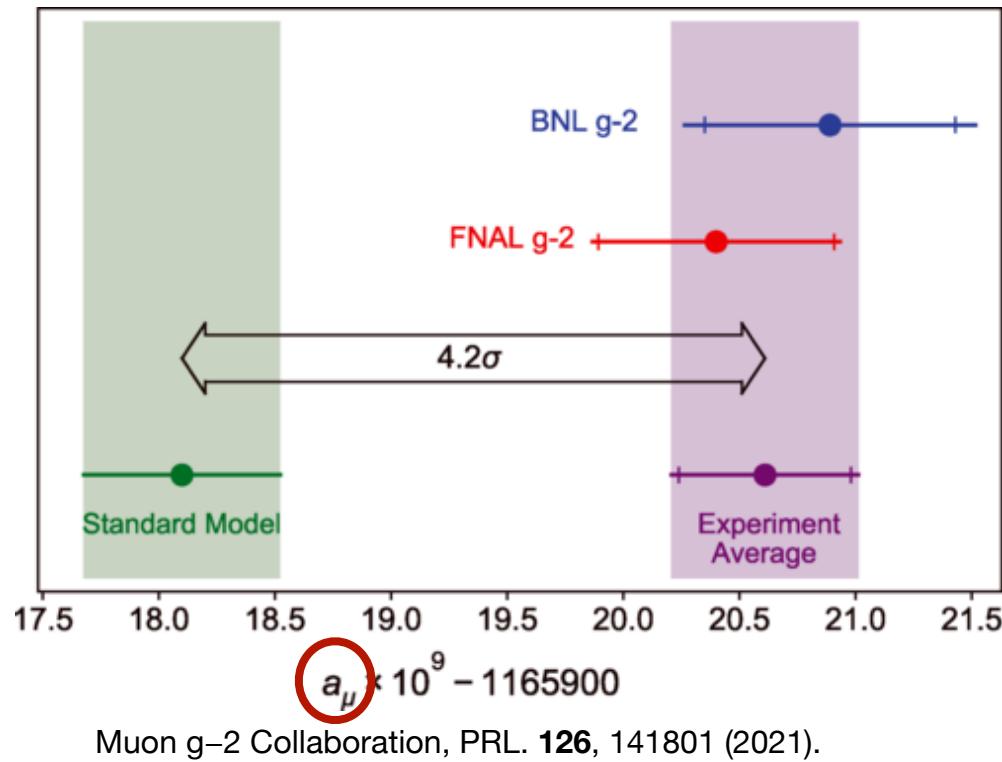
photo from Fermilab Muon g-2 web page



Muon g-2 Collaboration, PRL. **126**, 141801 (2021).



# Muon g-2



Magnetic moment

$$H = -\vec{\mu}_l \cdot \vec{B}$$

$$\vec{\mu}_l = g_l \frac{e}{2m_l} \vec{S}$$

QFT correction

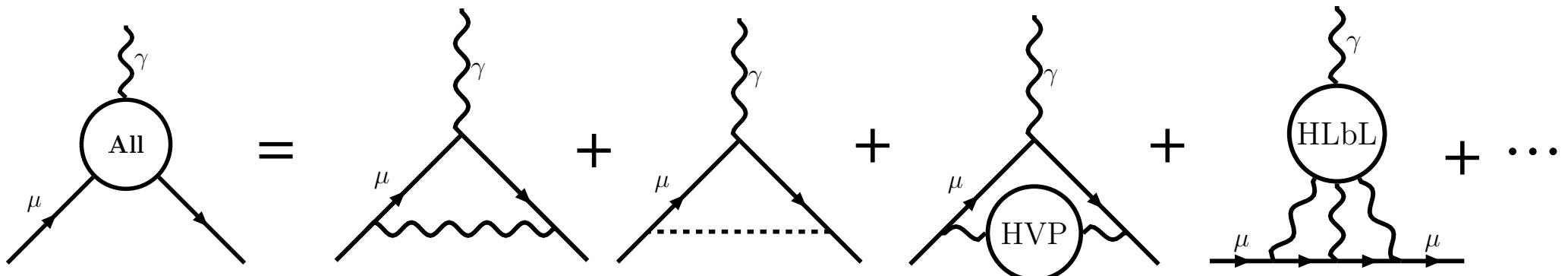
$$a_l = \frac{g_l - 2}{2}$$

Observation value

# Muon g-2

Contribution	Section	Equation	Value $\times 10^{11}$	References
Experiment (E821)		Eq. (8.13)	116 592 089(63)	Ref. [1]
HVP LO ( $e^+e^-$ )	Sec. 2.3.7	Eq. (2.33)	6931(40)	Refs. [2–7]
HVP NLO ( $e^+e^-$ )	Sec. 2.3.8	Eq. (2.34)	-98.3(7)	Ref. [7]
HVP NNLO ( $e^+e^-$ )	Sec. 2.3.8	Eq. (2.35)	12.4(1)	Ref. [8]
HVP LO (lattice, $udsc$ )	Sec. 3.5.1	Eq. (3.49)	7116(184)	Refs. [9–17]
HLbL (phenomenology)	Sec. 4.9.4	Eq. (4.92)	92(19)	Refs. [18–30]
HLbL NLO (phenomenology)	Sec. 4.8	Eq. (4.91)	2(1)	Ref. [31]
HLbL (lattice, $uds$ )	Sec. 5.7	Eq. (5.49)	79(35)	Ref. [32]
HLbL (phenomenology + lattice)	Sec. 8	Eq. (8.10)	90(17)	Refs. [18–30, 32]
QED	Sec. 6.5	Eq. (6.30)	116 584 718.931(104)	Refs. [33, 34]
Electroweak	Sec. 7.4	Eq. (7.16)	153.6(1.0)	Refs. [35, 36]
HVP ( $e^+e^-$ , LO + NLO + NNLO)	Sec. 8	Eq. (8.5)	6845(40)	Refs. [2–8]
HLbL (phenomenology + lattice + NLO)	Sec. 8	Eq. (8.11)	92(18)	Refs. [18–32]
Total SM Value	Sec. 8	Eq. (8.12)	<u>116 591 810(43)</u>	Refs. [2–8, 18–24, 31–36]
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	Sec. 8	Eq. (8.14)	279(76)	

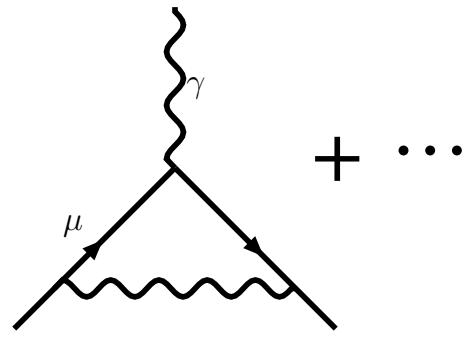
“White Paper” T. Aoyama, et.al., Phys. Rept. **887**, 1 (2020)



# Muon g-2

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

## ► QED



$$a_\mu(QED) = 116584718.931(104) \times 10^{-11}$$

Smallest error

Up to 5 loops !

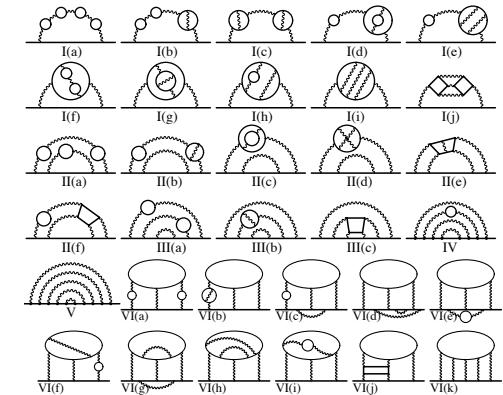
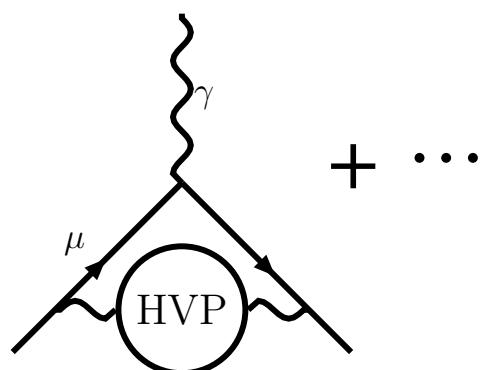


Fig. from 1205.5370

## ► HVP



$$a_\mu(HVP) = 6845(40) \times 10^{-11}$$

Largest error

(mainly coming from LO)

Using dispersion relation  
& experimental data

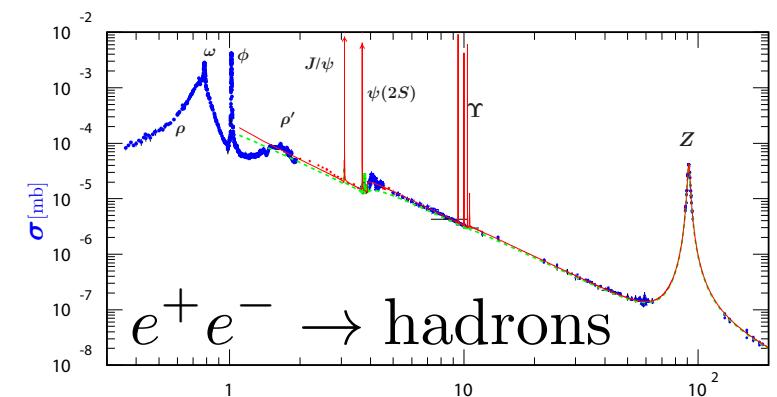
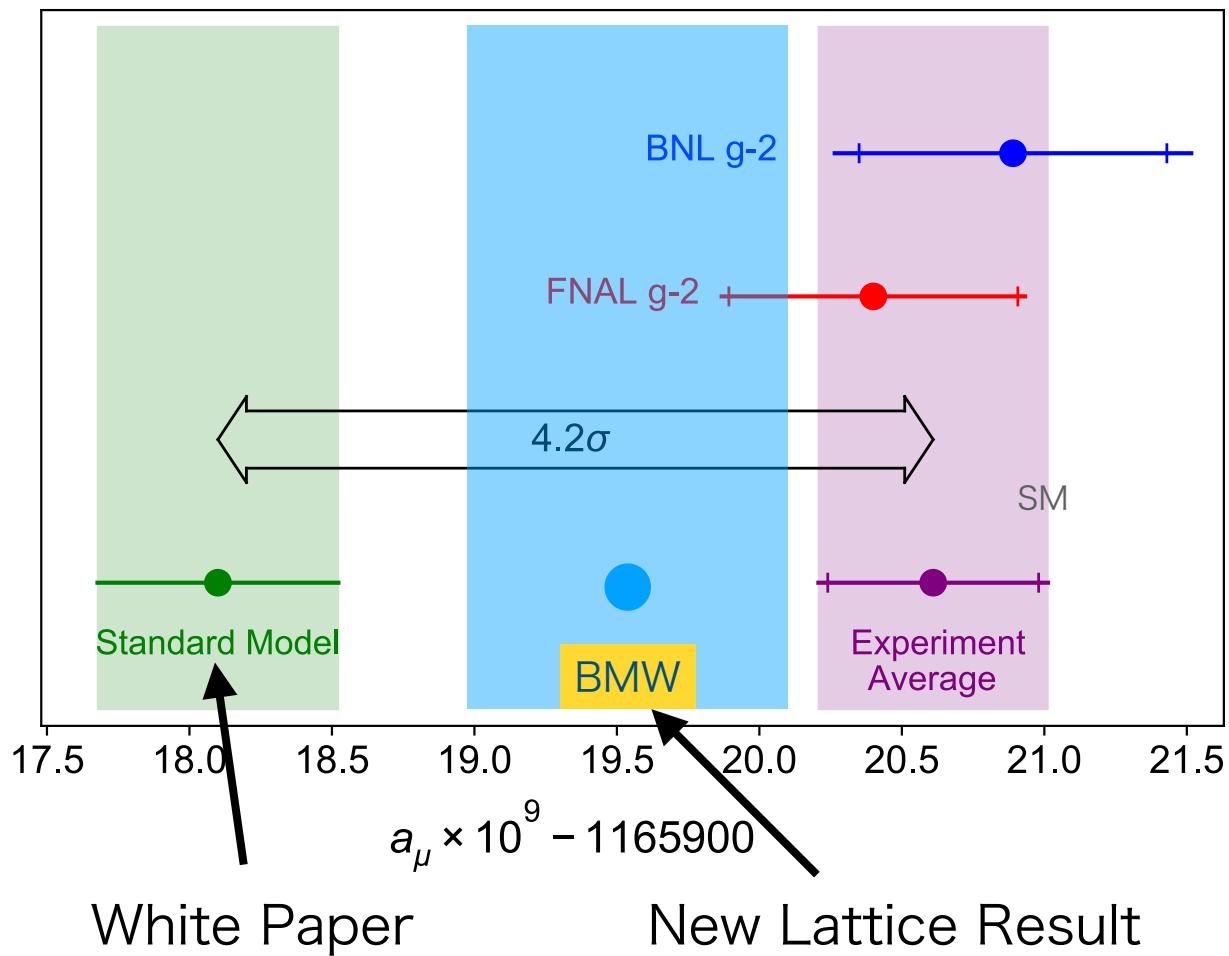


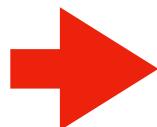
Fig. from PDG

# BMW (another tension)



Muon g-2 Collaboration, PRL. **126**, 141801 (2021).

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



HVP is problematic but important

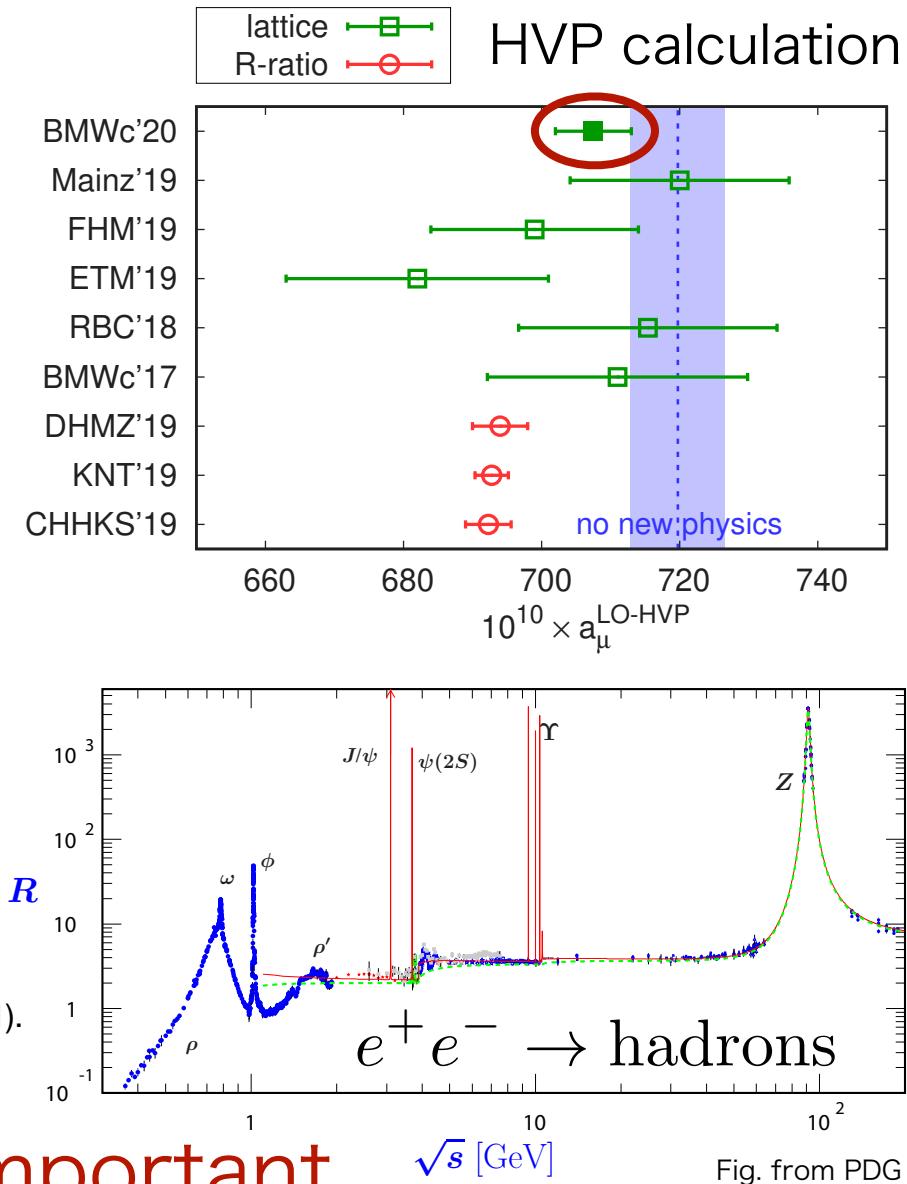
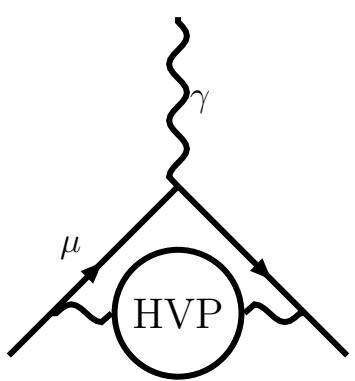


Fig. from PDG

# How to calculate HVP?

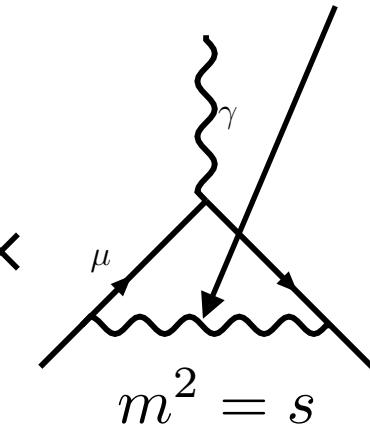
There are two methods.



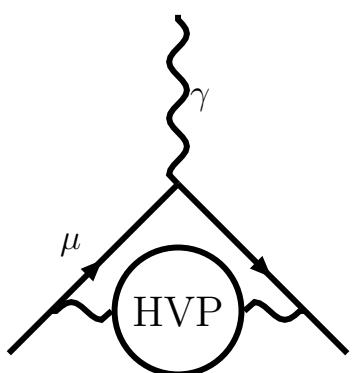
$$\leftarrow \int_{m_\pi^2}^{\infty} \frac{ds}{s} \text{Im} \left( \begin{array}{c} \text{HVP} \\ \text{s} \end{array} \right)$$

s-channel

Massive gauge boson



S. J. Brodsky and E. de Rafael, Phys. Rev. **168**, 1620 (1968).  
M. Gourdin and E. de Rafael, Nucl. Phys. B **10** 667-674 (1969)



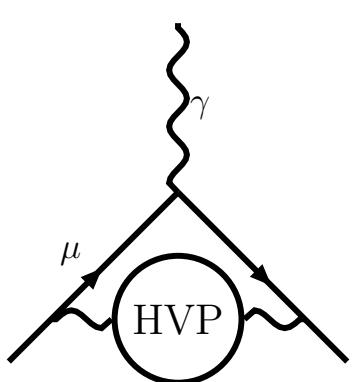
$$\leftarrow \int_0^1 dx (1-x) \left( \begin{array}{c} \text{HVP} \\ t(x) \end{array} \right)$$
$$t(x) = -\frac{x^2}{1-x} m_\mu^2 < 0$$

t-channel

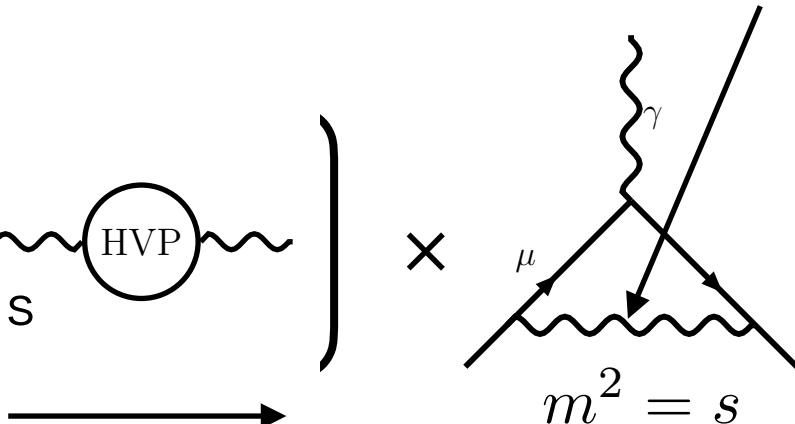
B. E. Lautrup, et.al., Phys. Rep. **3**, 193 (1972)

# How to calculate HVP?

There are two methods.



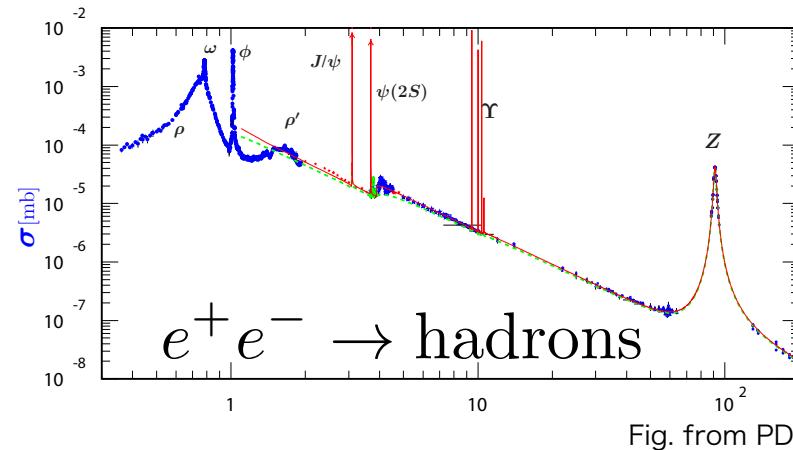
$$\leftarrow \int_{m_\pi^2}^{\infty} \frac{ds}{s} \text{Im} \left( \begin{array}{c} \text{HVP} \\ s \end{array} \right)$$



S. J. Brodsky and E. de Rafael, Phys. Rev. **168**, 1620 (1968).  
M. Gourdin and E. de Rafael, Nucl. Phys. B **10** 667-674 (1969)

In White Paper,  
the authors use this method.

$$\text{Im} \left( \begin{array}{c} \text{HVP} \\ \vdash \end{array} \right) = -\frac{s}{e^2} \left| \begin{array}{c} e^+ \\ e^- \end{array} \right. \left| \begin{array}{c} e^+ \\ e^- \end{array} \right. \right|^2$$



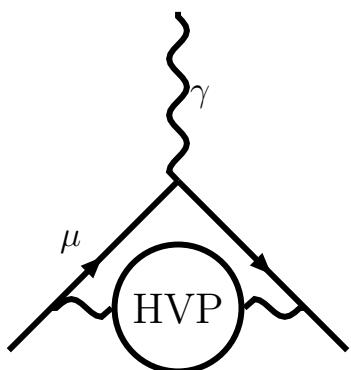
# How to calculate HVP?

There are two methods.

We can rewrite VP in terms of the effective coupling constant.

$$\alpha_{\text{eff}}(q^2) = \frac{\alpha}{1 - \Delta\alpha(q^2)} \quad \Delta\alpha \equiv \Pi(q^2) - \Pi(0)$$

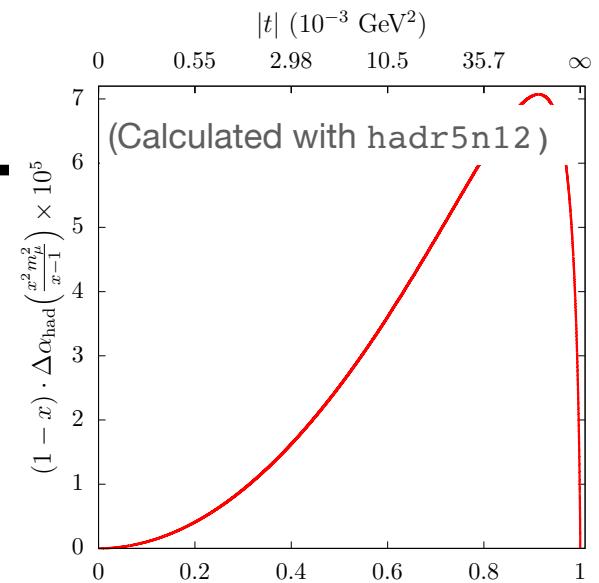
Observation value



$$\leftarrow \int_0^1 dx (1-x) \left( \text{HVP} \right) t(x)$$

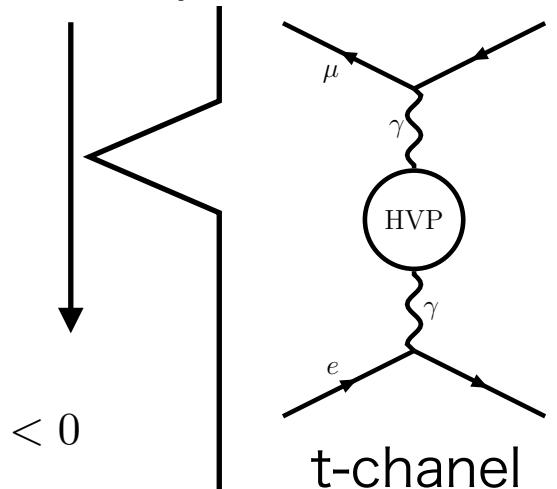
$t(x) = -\frac{x^2}{1-x} m_\mu^2 < 0$

B. E. Lautrup, et.al., Phys. Rep. **3**, 193 (1972)



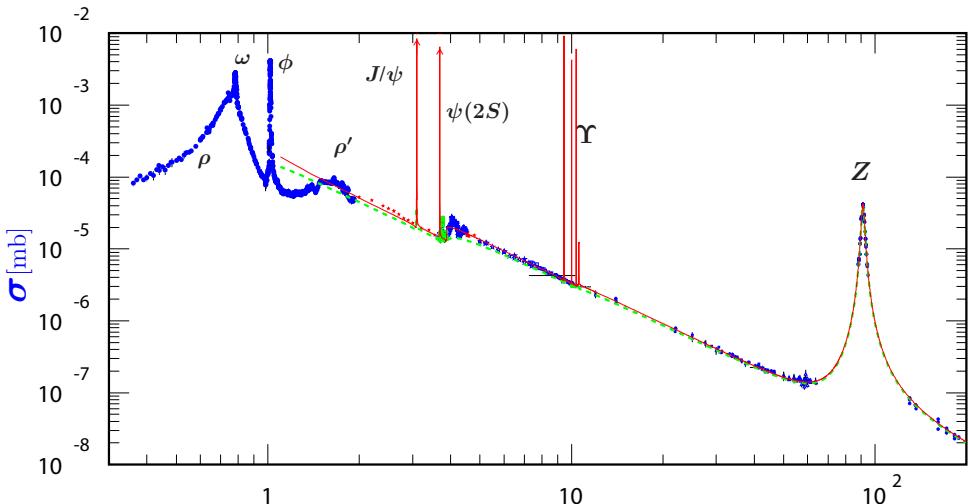
C. M. Carloni Calame, et.al.,  
Phys.Lett.B **746** 325-329 (2015).

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



# Time-like vs Space-like

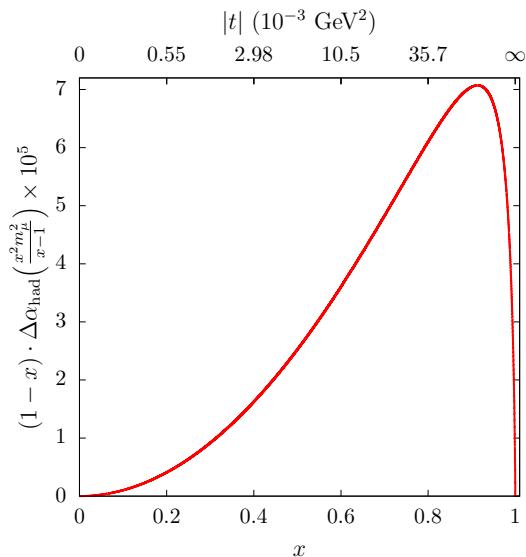
Time-like data ( $s > 0$ )



Complicated structure  
(Source of uncertainty )

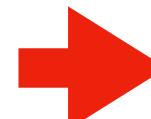
Fig. from PDG

Space-like data ( $t < 0$ )



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

integrand function is a smooth function  
: no resonances



# HVP error

$$a_\mu(HVP) = 6845(40) \times 10^{-11}$$

$$\sqrt{28^2 + 28^2 + 7^2} \simeq 40$$

$$a_\mu^{\text{HVP,LO}} = 6931(28)_{\text{stat}}(28)_{\text{sys}}(7)_{\text{DV+QCD}} \times 10^{-11}$$

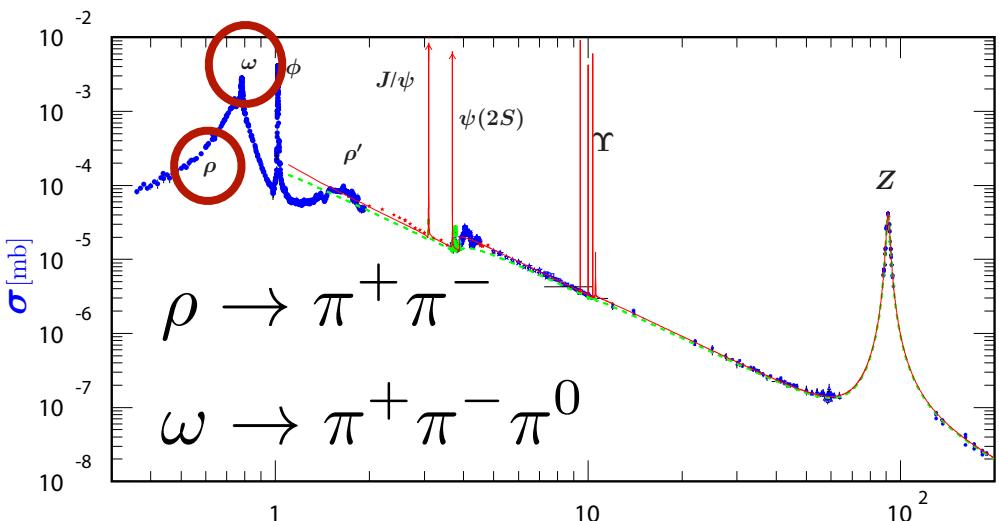
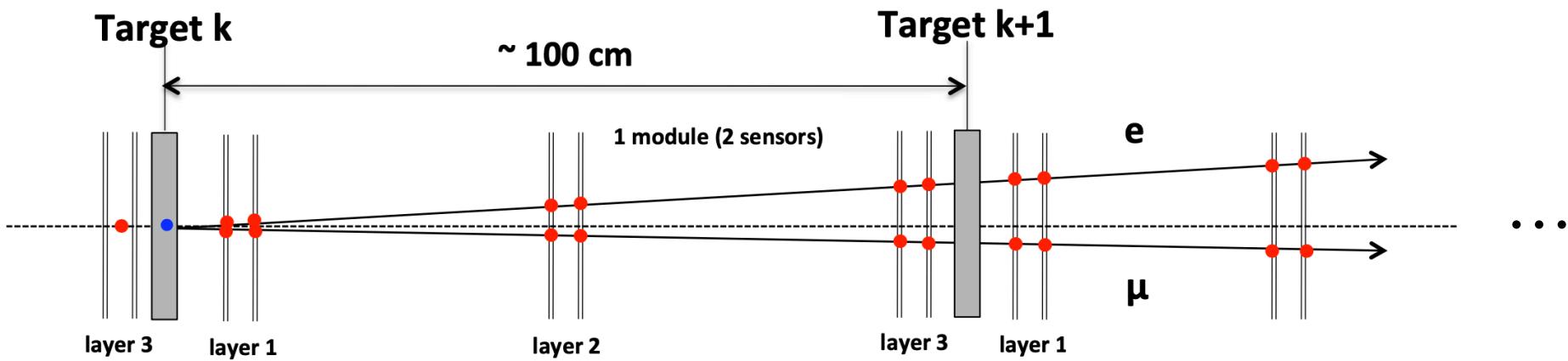
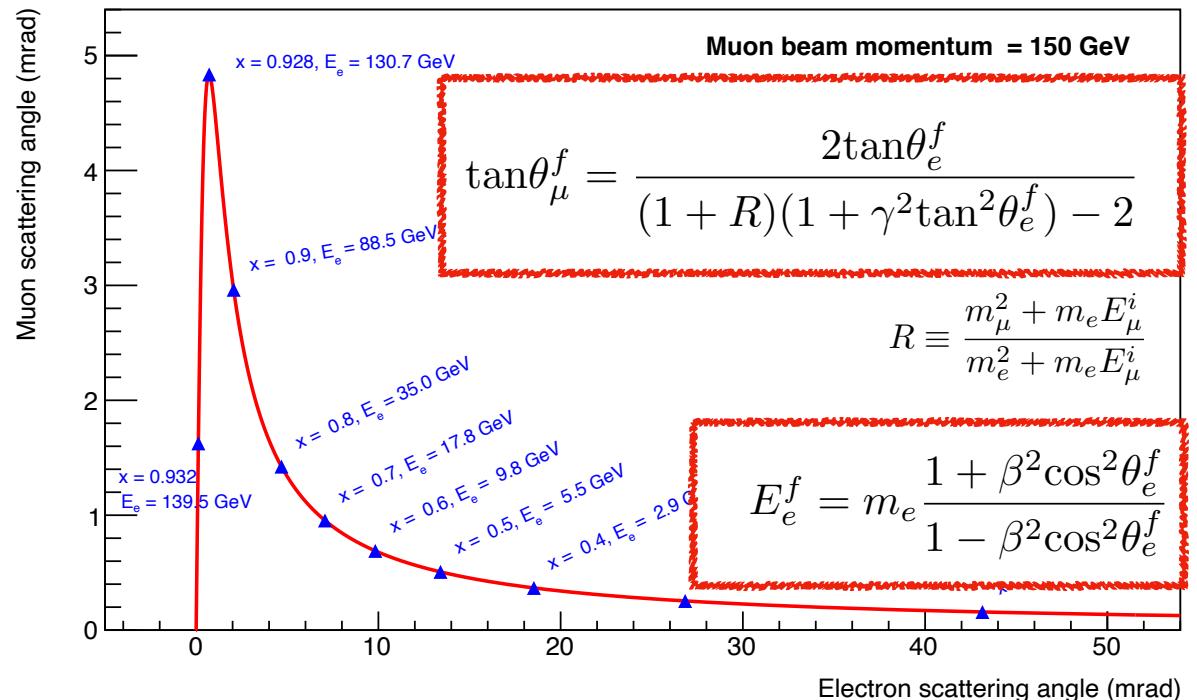
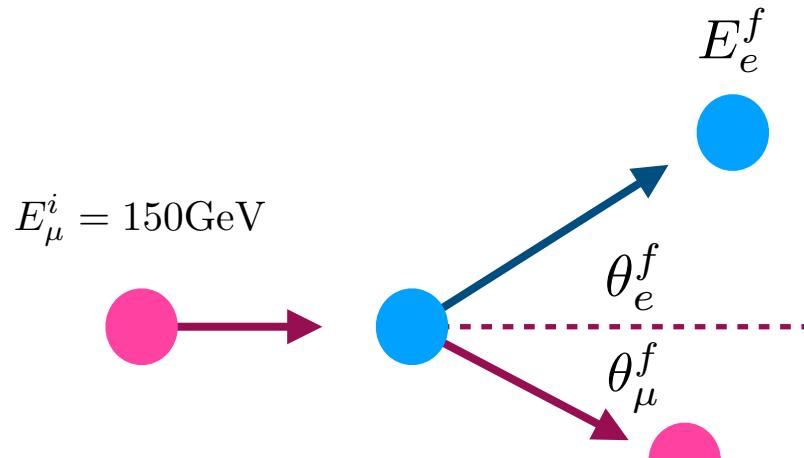


Fig. from PDG

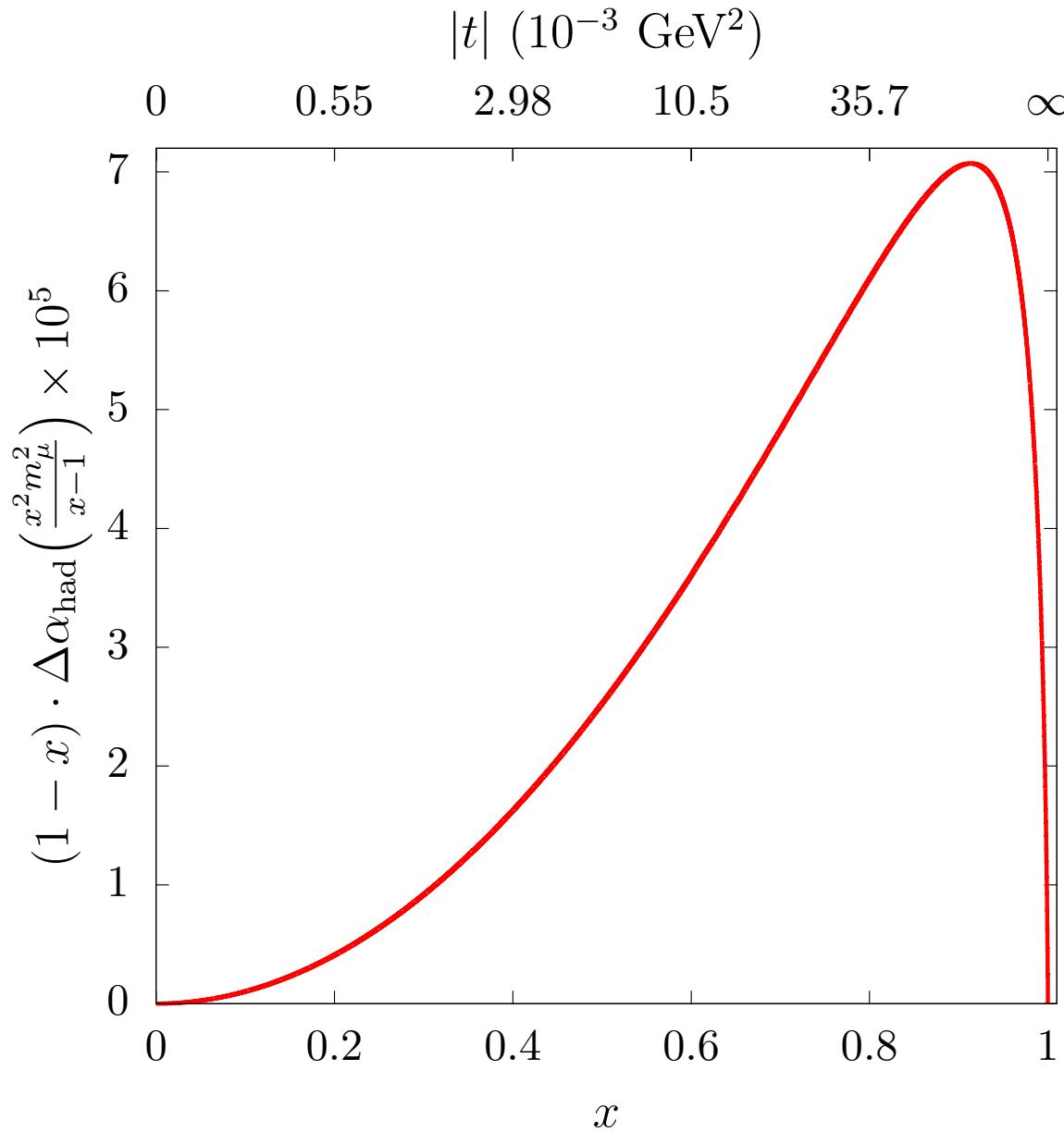
Statistic error mainly come from  $2\pi$  and  $3\pi$  channels.

Largest systematic error comes from  $2\pi$  channel.

# MUonE kinematics



# MUonE kinematics



$$E_e^f = m_e \frac{1 + \beta^2 \cos^2 \theta_e^f}{1 - \beta^2 \cos^2 \theta_e^f}$$

→ 1 <  $E_e^f < 139.8$  [GeV]

Low energy cut: Not fixed yet

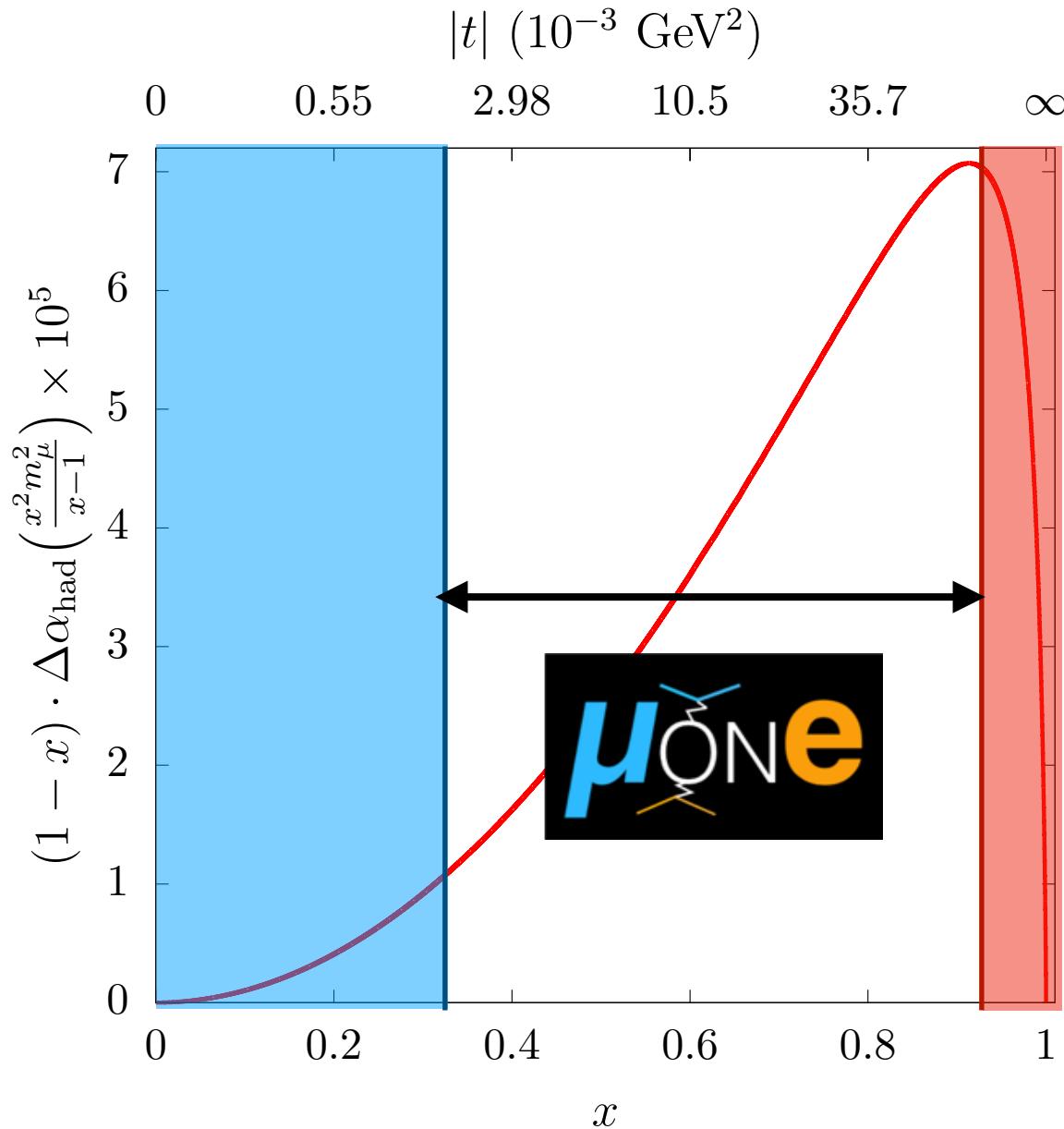
$$t = 2m_e^2 - 2m_e E_e^f$$

→  $-0.143 < t < -0.001$  [GeV]<sup>2</sup>

$$t(x) = -\frac{x^2}{1-x} m_\mu^2 < 0$$

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

# MUonE kinematics



$$E_e^f = m_e \frac{1 + \beta^2 \cos^2 \theta_e^f}{1 - \beta^2 \cos^2 \theta_e^f}$$

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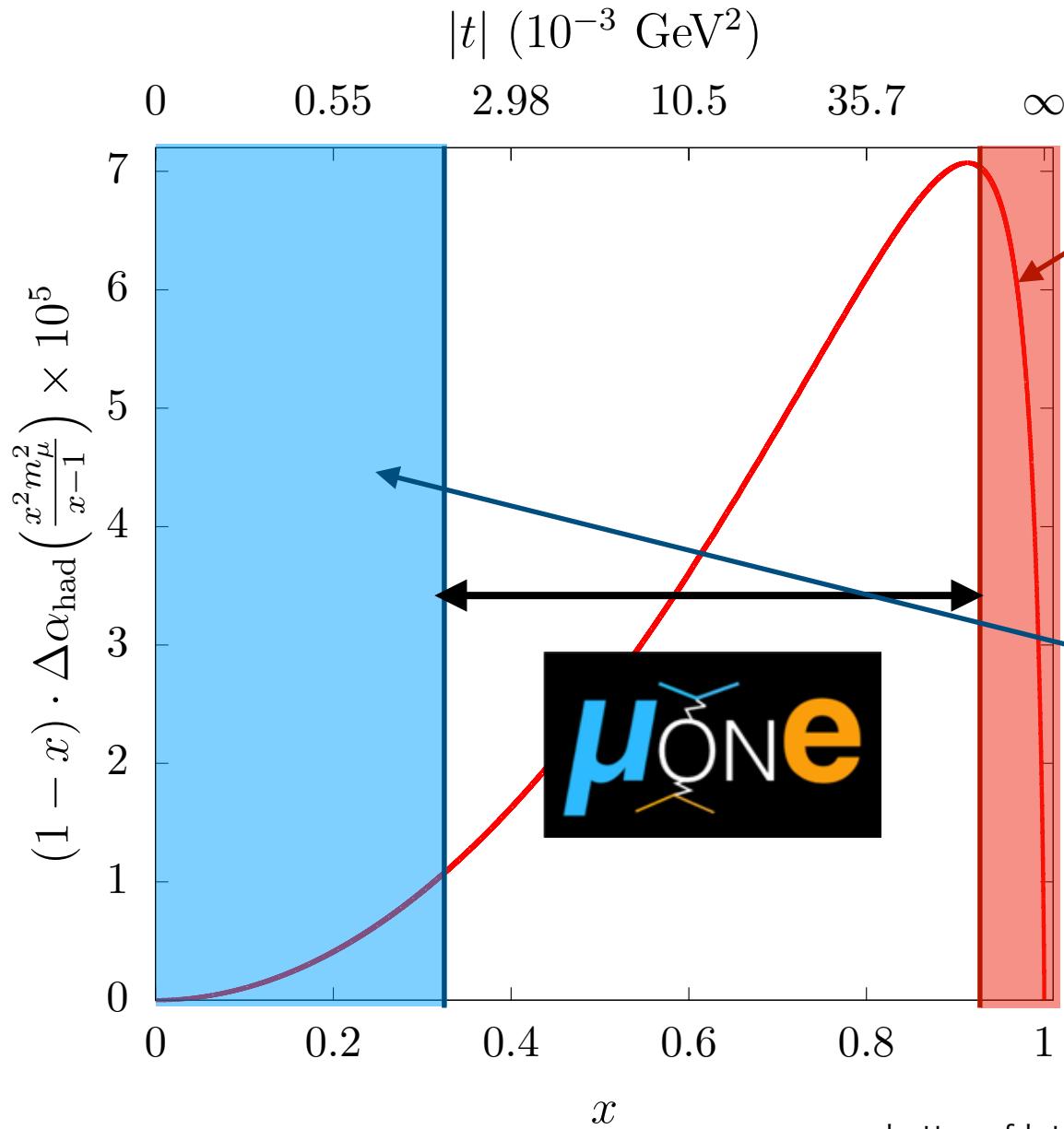
$$t = 2m_e^2 - 2m_e E_e^f$$

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

# MUonE kinematics



In this red region,  
we can use

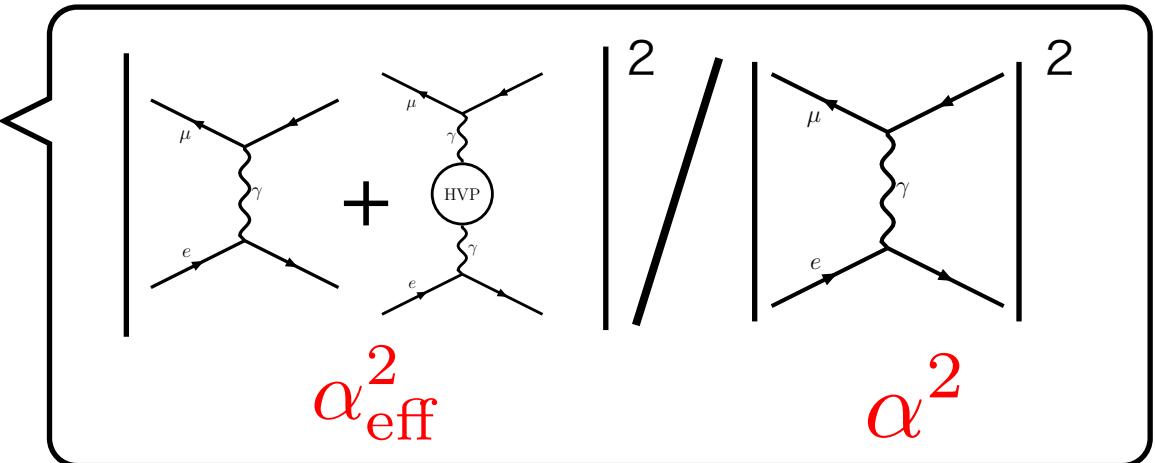
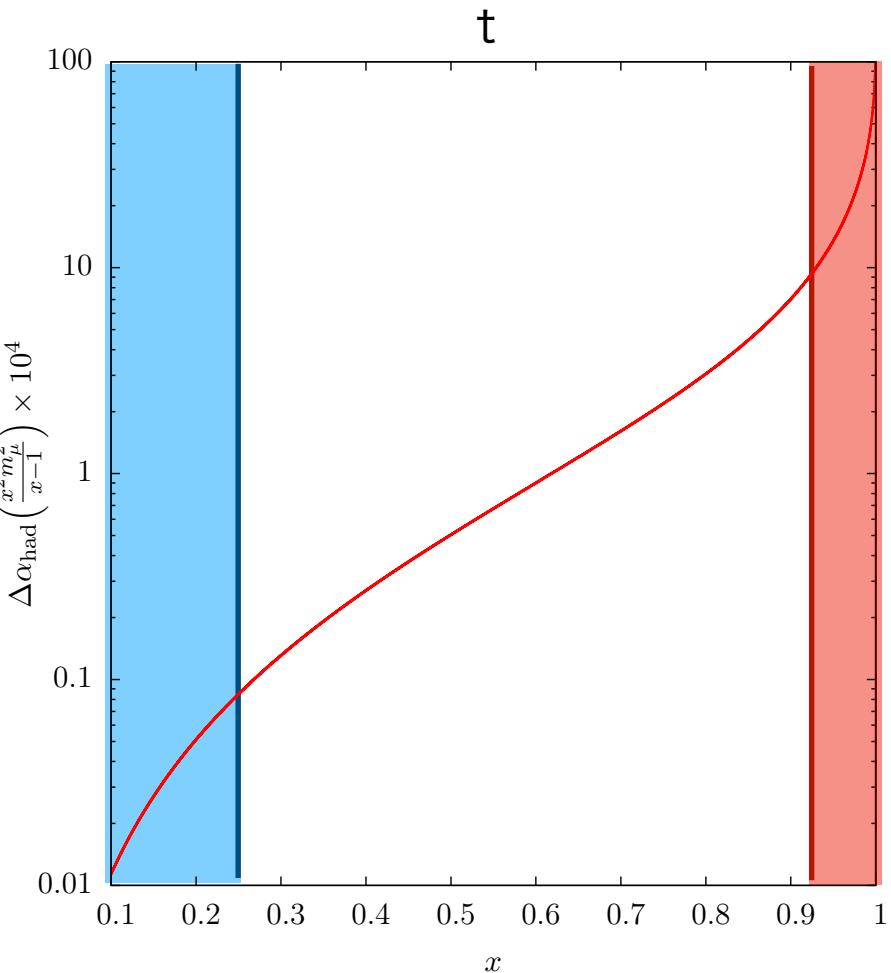
- Perturbative QCD
- Lattice QCD
- Time-like data

In this blue region,  
we assume the fitting  
function.

# MUonE strategy

$$\left( \frac{d\sigma_{\text{had}}}{dt} / \frac{d\sigma_0}{dt} \right) \simeq 1 + 2\Delta\alpha_{\text{had}}$$

$$\alpha_{\text{eff}} = \frac{\alpha}{1 - \Delta\alpha}$$



Divide “t” into bins labeled by “i” and determine  $\Delta\alpha_{\text{had}}$  bin by bin

$$\sigma_i \equiv \int_i dt \frac{d\sigma}{dt}(t) \quad \begin{array}{l} \sigma: \text{full cross section} \\ i: \text{the } i\text{-th } t\text{-bin} \end{array}$$

$$\sigma_i = \underline{\sigma_{0,i}} [1 + 2\Delta\alpha_{\text{had},i} + \overline{\delta_{\text{SM},i}}]$$

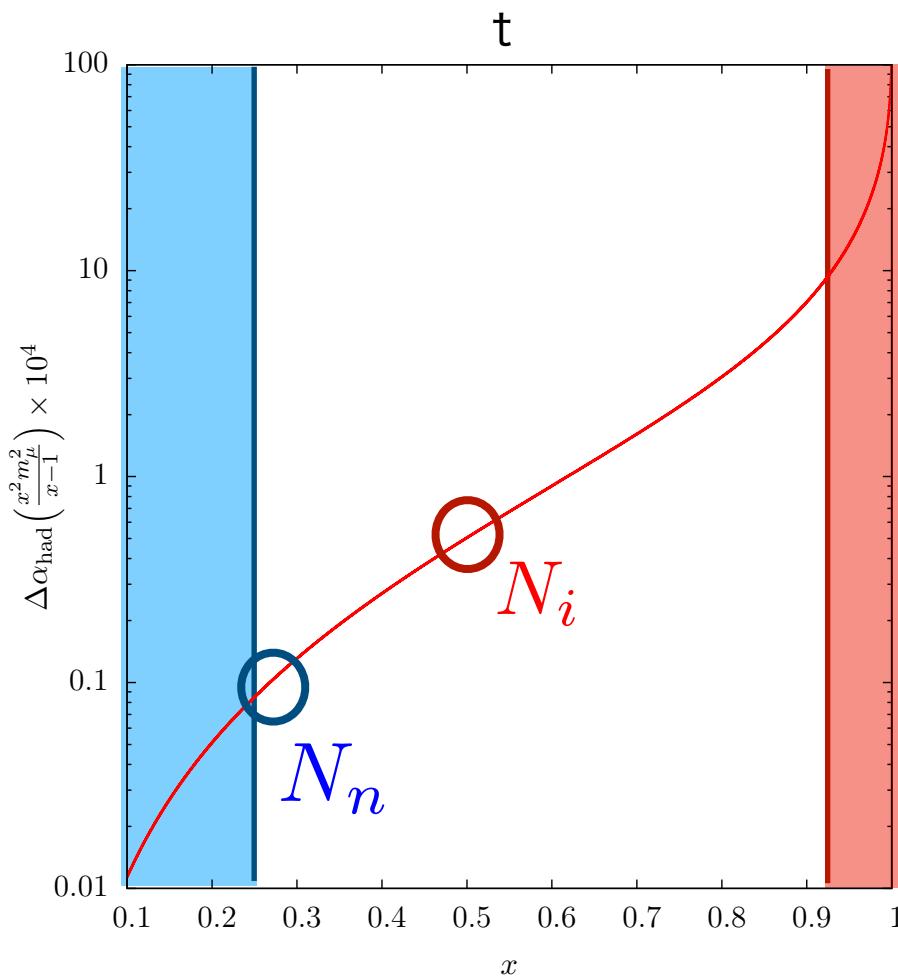
Computable

# MUonE strategy

Observation value:  
event number  $N_i$



We can extract the information  
of  $\Delta\alpha_{\text{had}}$  from  $N_i/N_n$   
(Independent on the luminosity)



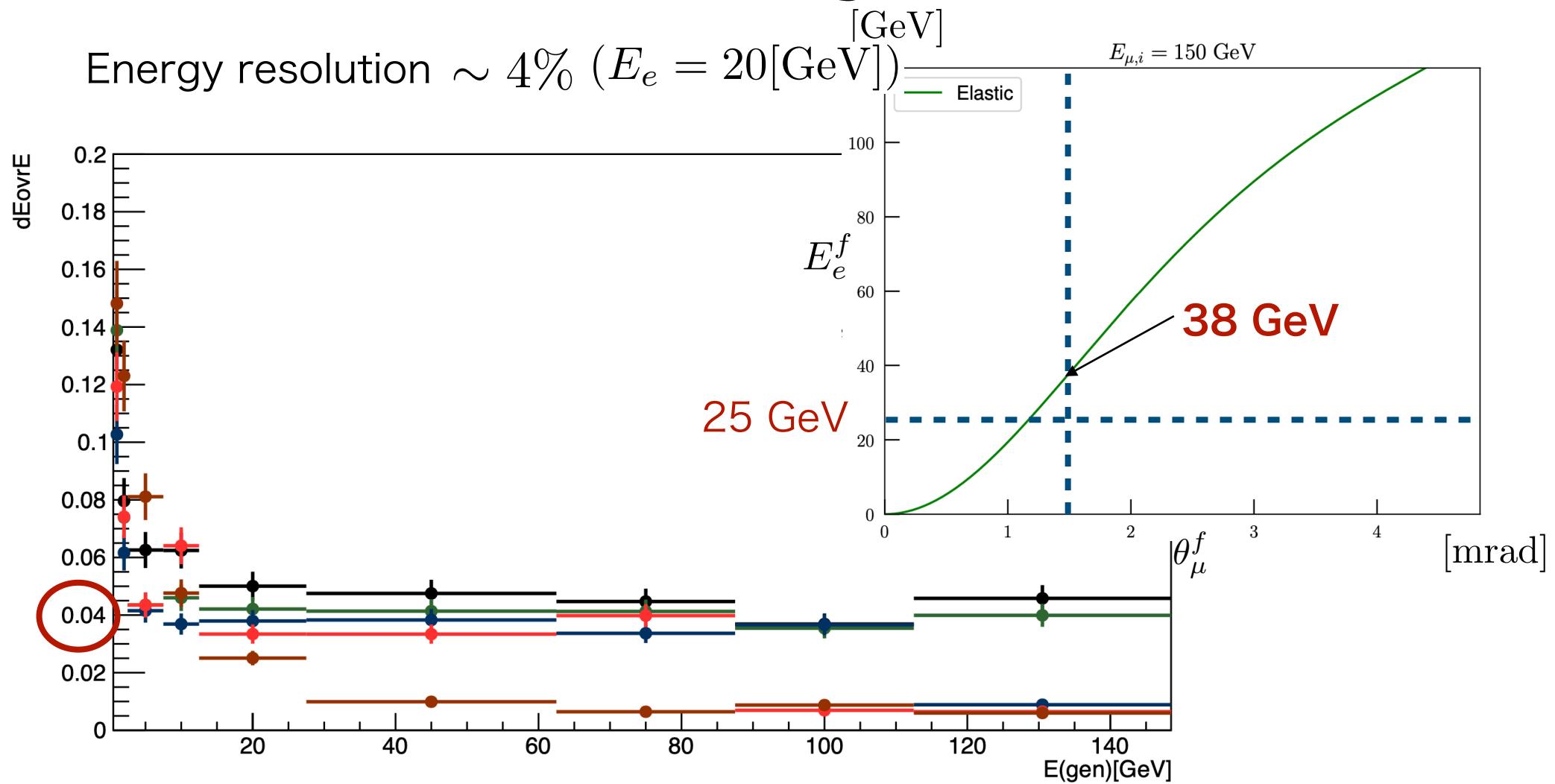
$$\frac{N_i}{N_n} \simeq \frac{\sigma_{0,i}}{\sigma_{0,n}} [1 + 2(\Delta\alpha_{\text{had},i} - \Delta\alpha_{\text{had},n})]$$

Computable +  $\delta_{SM,i} - \delta_{SM,n}$

Computable

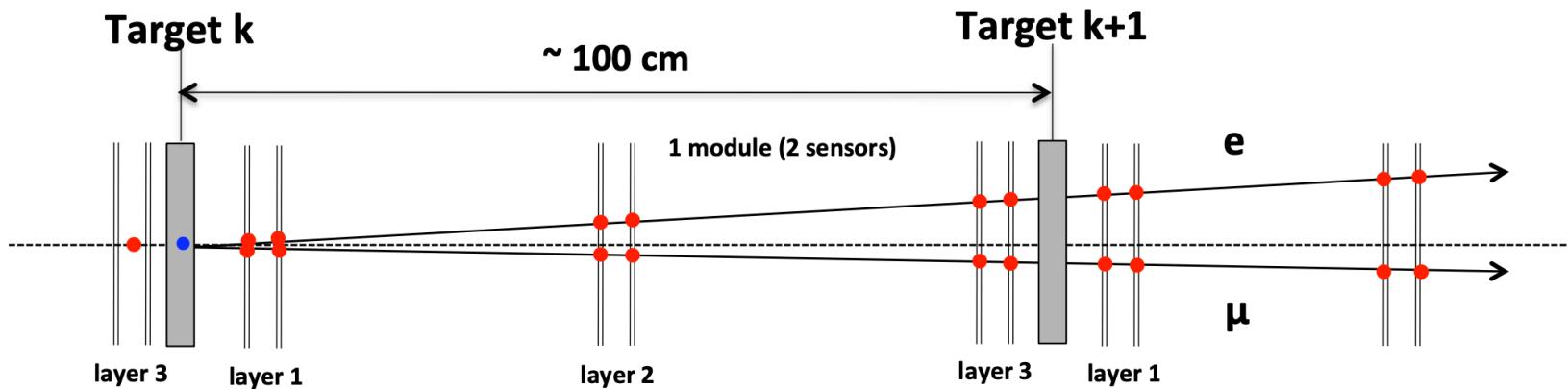
$\Delta\alpha_{\text{had},n}$  can be determined by  
the time-like data.

# MUonE sensitivity

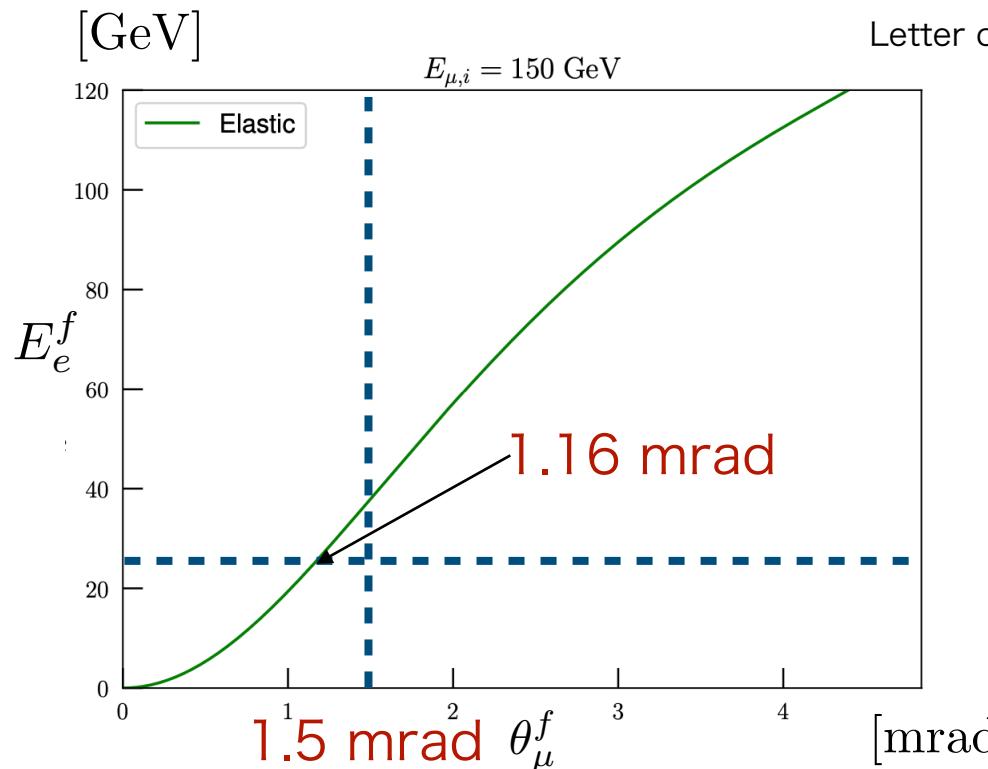


**Fig. 10:** Rms width of the  $\delta_E$  distributions as a function of the electron energy, for electrons produced in the 1st (black), 5th (green), 10th (blue), 15th (red), and 20th (maroon) target. In the final apparatus, these stations correspond to 21st, 25th, 30th, 35th, and 40th.

# MUonE sensitivity



tracker: Angular resolution:  $O(0.01)$  mrad expected

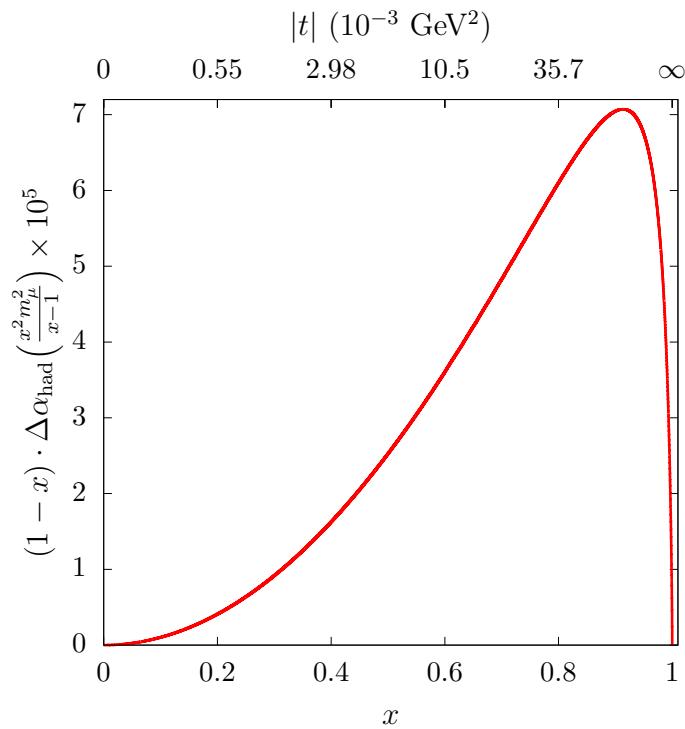


Letter of Intent: <https://cds.cern.ch/record/2677471/files/SPSC-I-252.pdf>

# MUonE uncertainties

Expected statistical accuracy of  $a_\mu^{\text{HVP}}$ : 0.3 %

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



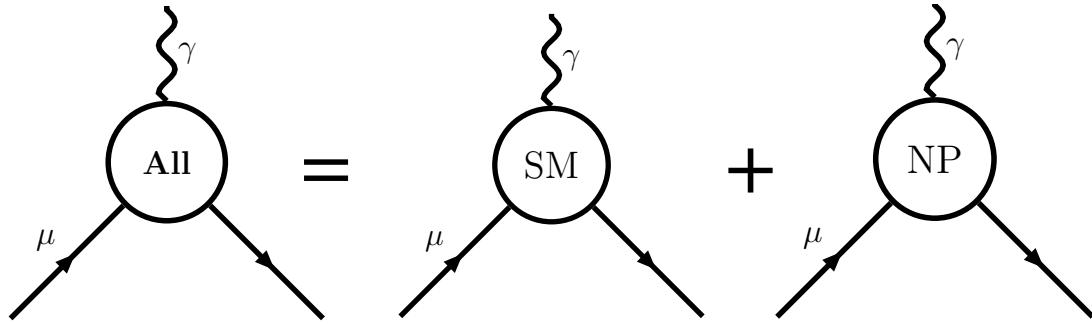
# MUonE(M2) beam status

- ▶ The typical maximal intensity for a beam energy of 160 GeV is  $5 \times 10^7 \mu^+/\text{s}$  for a SPS spill with  $10^{13}$  protons on target.
- ▶ momentum resolution :  $\sim 0.9\%$  for a 160 GeV/c incoming beam from simulation (using bending magnets)

# MUonE schedule

- ▶ Letter of Intent submitted in 2019.
- ▶ Test run of 3 weeks is planned at the end of the running period of 2021.
- ▶ Start data taking in 2022 with half the apparatus.
- ▶ Data taking with the complete apparatus  
in 2023 and 2024. → 2026-2028?

# BSM scale



$$\begin{aligned} a_\mu^{\text{Exp}} - a_\mu^{\text{SM}} \\ = (25.1 \pm 5.9) \times 10^{-10} \end{aligned}$$

Muon g-2 Collaboration, PRL. **126**, 141801 (2021).

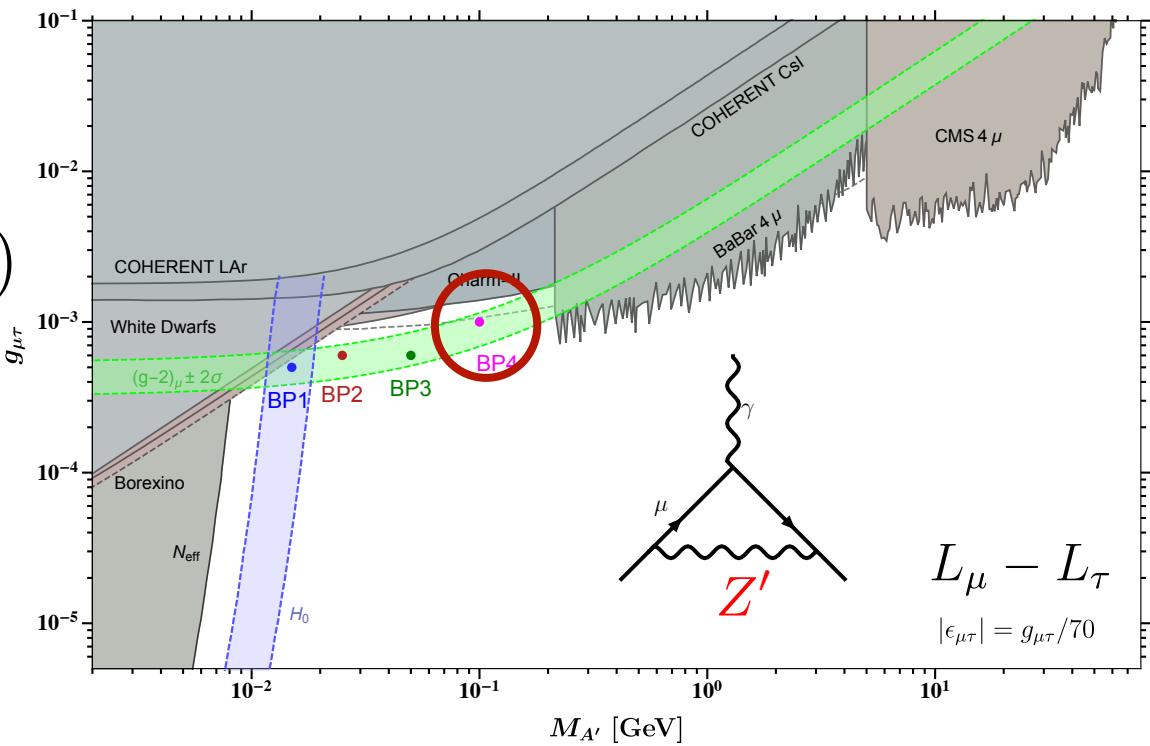
Naive estimate

$$a_\mu^X = \frac{g_X^2}{16\pi^2} \frac{m_\mu^2}{M_X^2} \quad (m_\mu \lesssim m_X)$$

→  $M_X \sim g_X \times 100 \text{ GeV}$

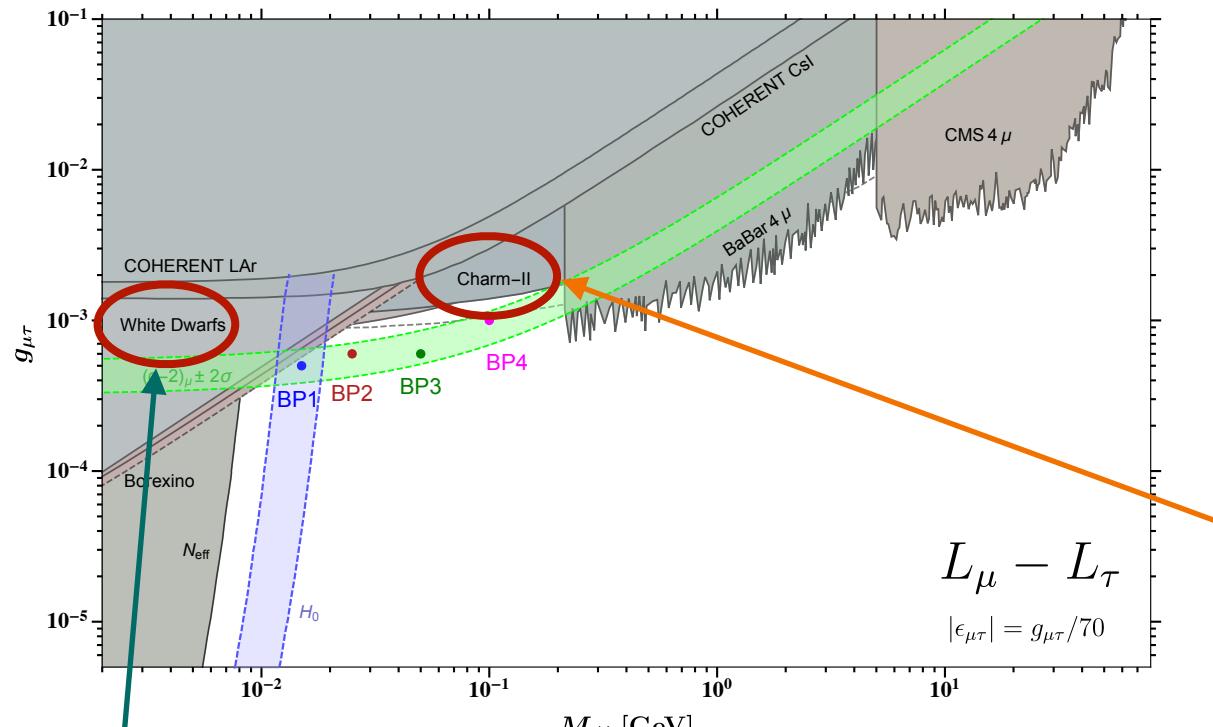
e.g.  $g_X \sim O(10^{-3})$ ,

$M_X \sim O(100) \text{ MeV}$



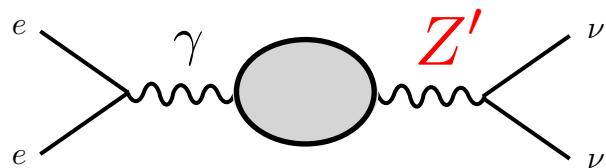
D.W.P. Amaral, et.al., Eur. Phys. J. C **81**, 861 (2021).

# Other constraints

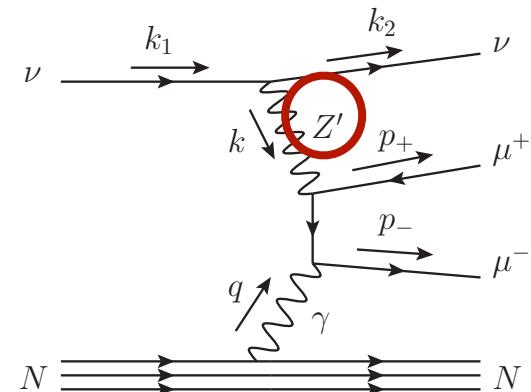


## White dwarf cooling

M. Bauer, et.al., JHEP **07**, 094 (2018)



## neutrino-trident process



W. Altmannshofer, et.al., PRL. **113**, 091801 (2014)

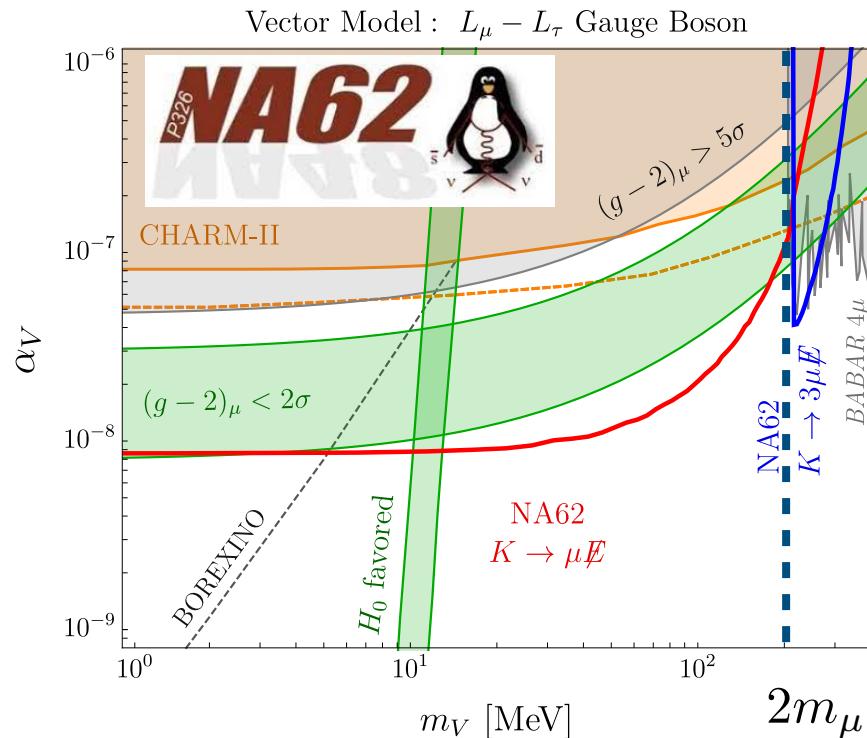
**CHARM-II**

D. Geiregat et al. (CHARM-II),  
Phys. Lett. B 245, 271 (1990).

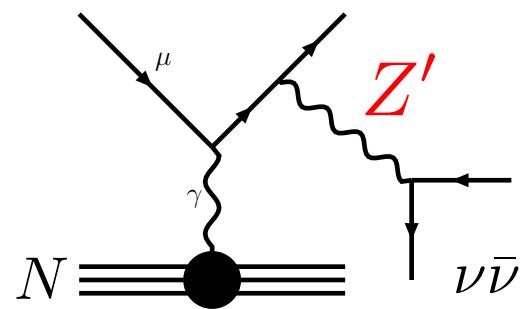
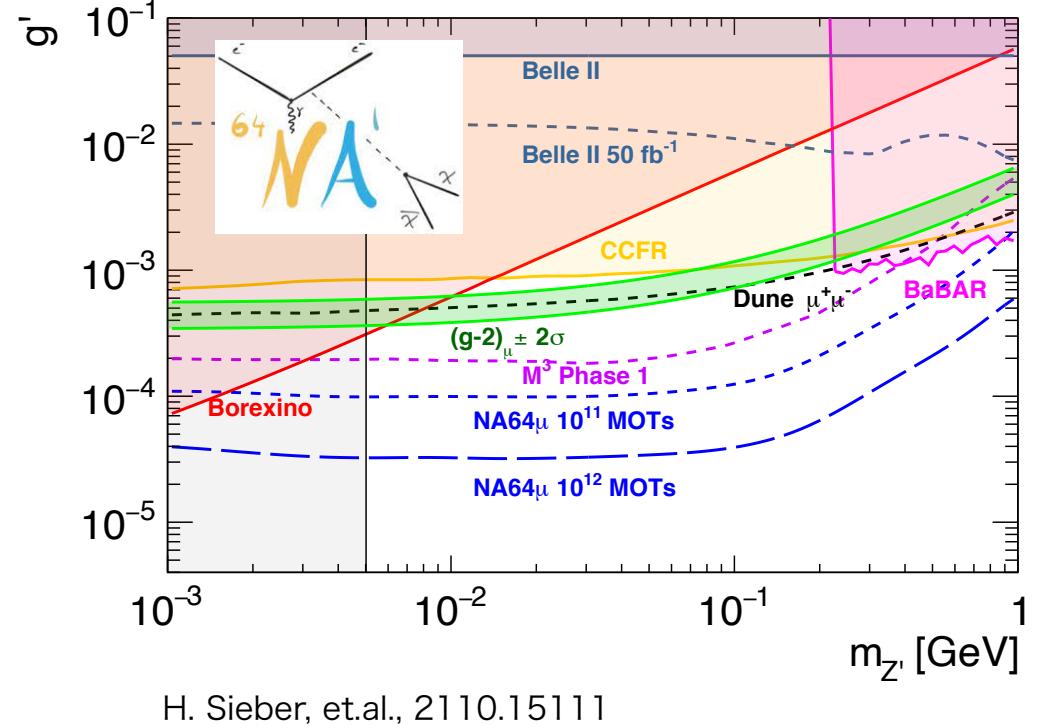
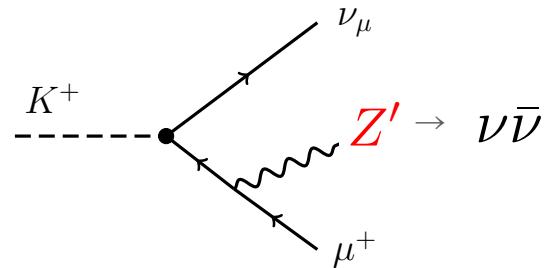
**CCFR**

S. R. Mishra et al. (CCFR),  
Phys. Rev. Lett. 66, 3117 (1991).

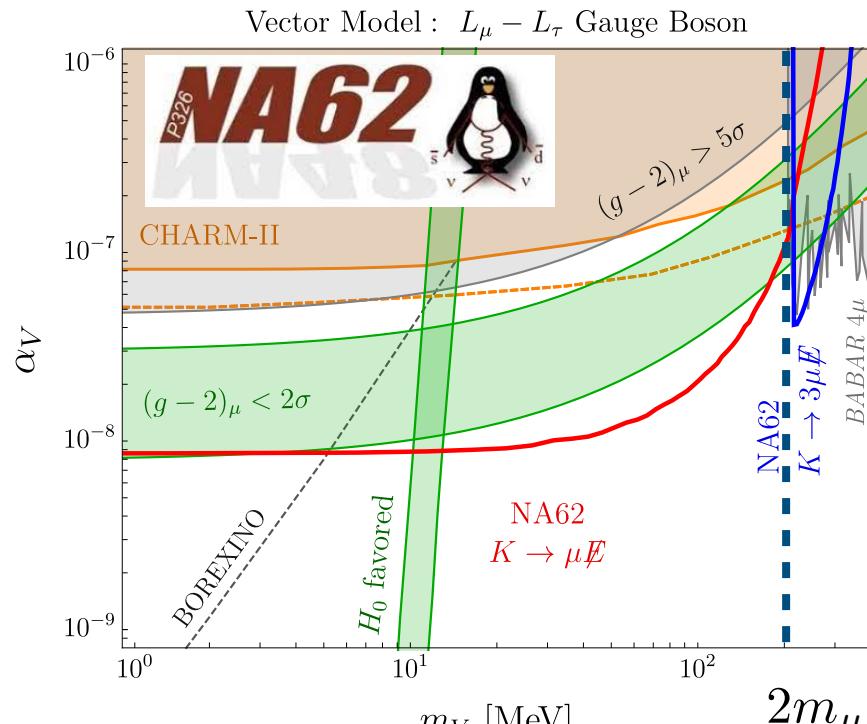
# Fate of g-2 region



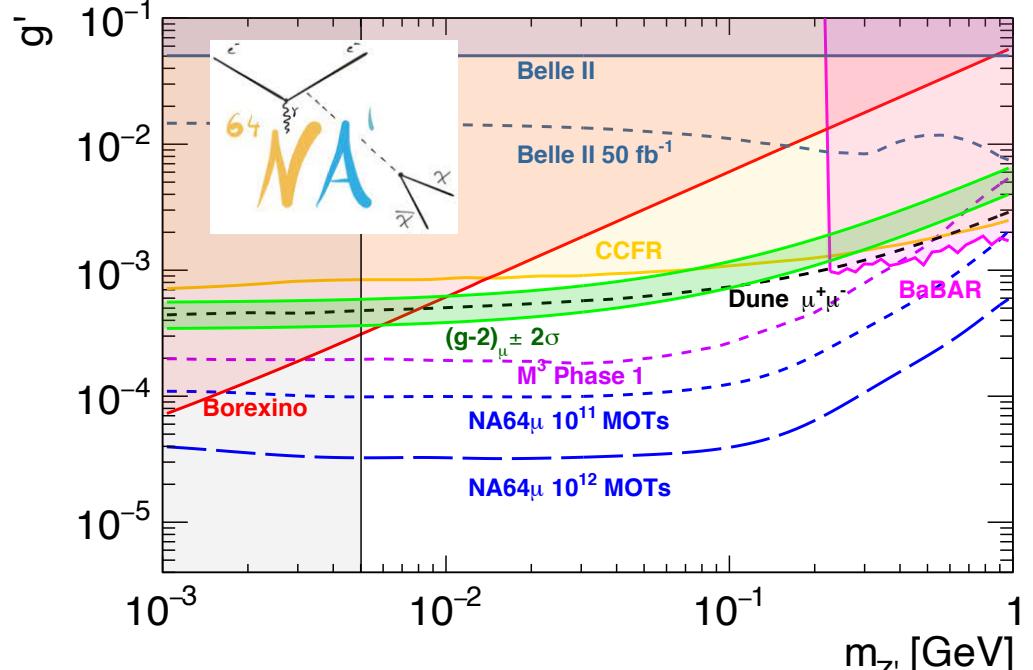
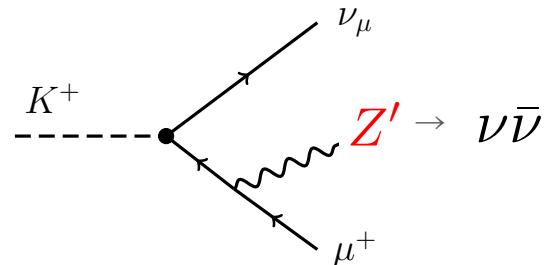
G. Krnjaic, et.al., PRL. **124**, 041802 (2020)



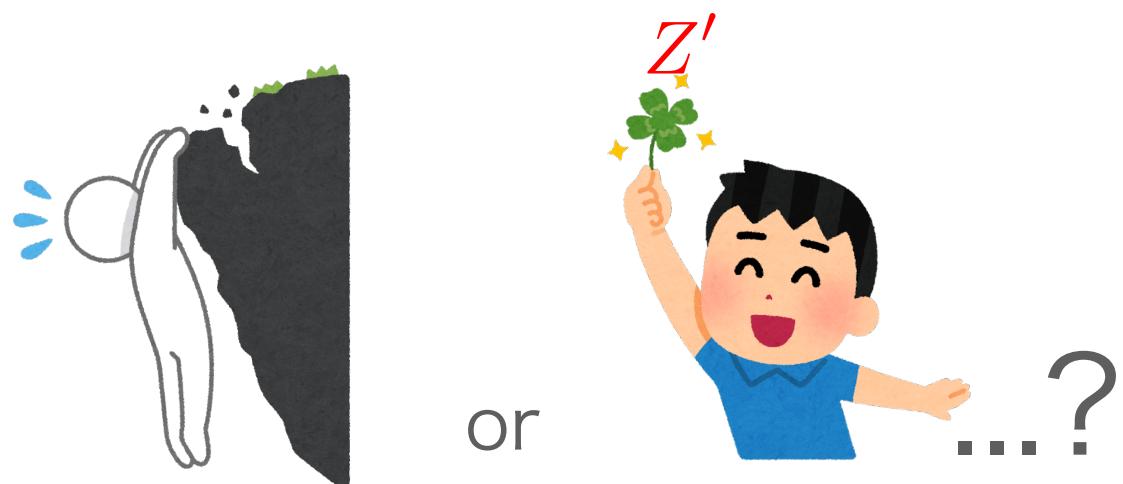
# Fate of g-2 region



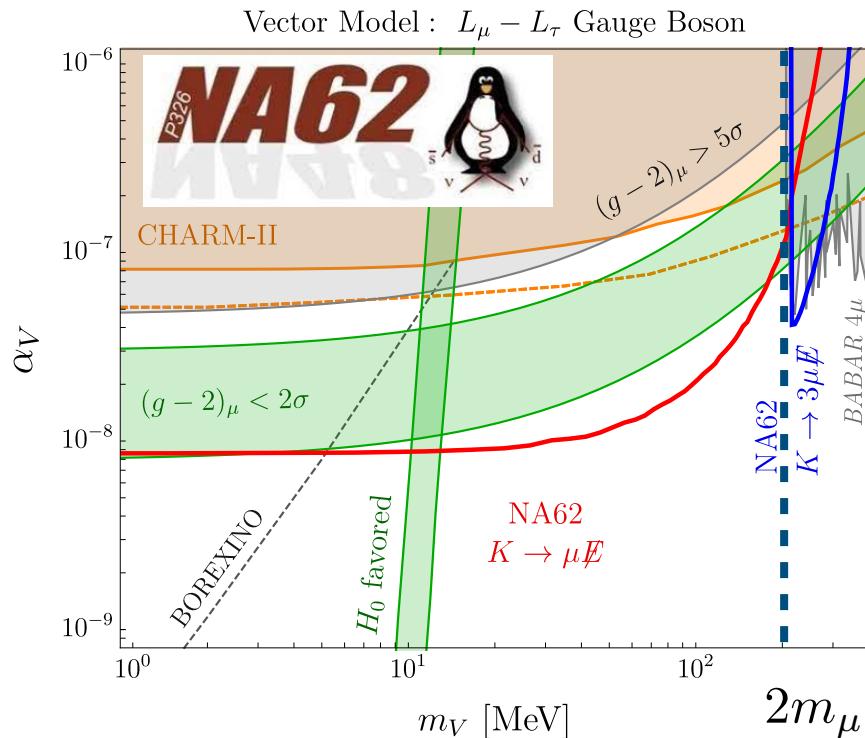
G. Krnjaic, et.al., PRL. **124**, 041802 (2020)



H. Sieber, et.al., 2110.15111



# Fate of g-2 region



G. Krnjaic, et.al., PRL. **124**, 041802 (2020)

The author assumed  
the full NA62 luminosity  
 $N_{K^+} \approx 10^{13}$

## NA62 schedule

- Run1: 2016-2018
- Run2: 2021-2024

2021 NA62 Status Report to the CERN SPSC

cf)

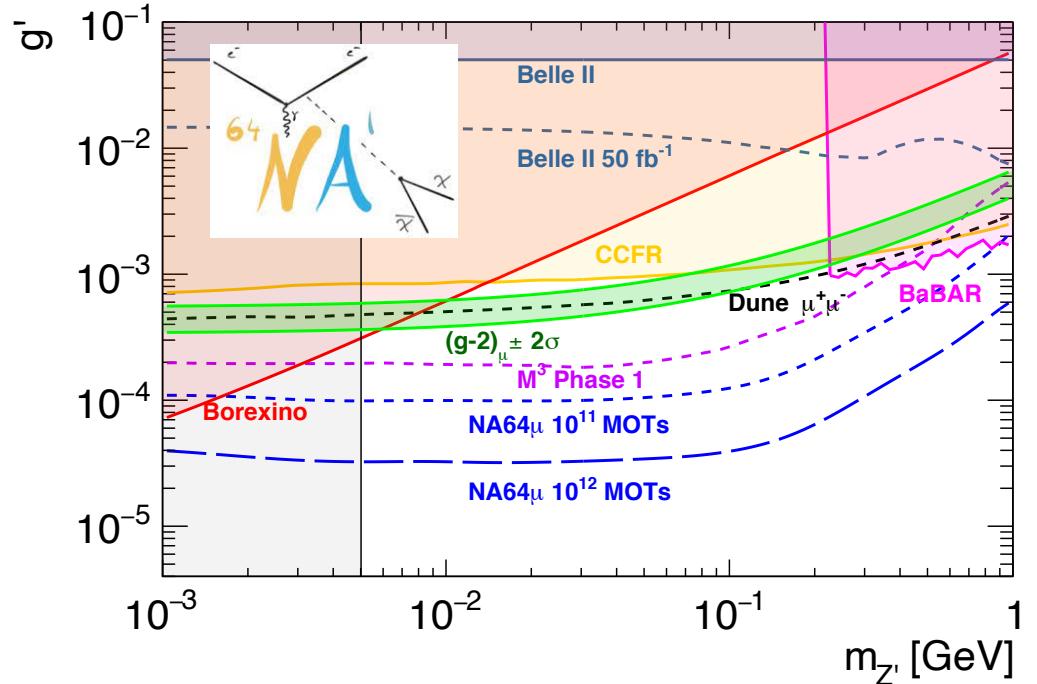
$$\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \sim 10^{-11}$$

# Fate of g-2 region

NA64 $\mu$  schedule

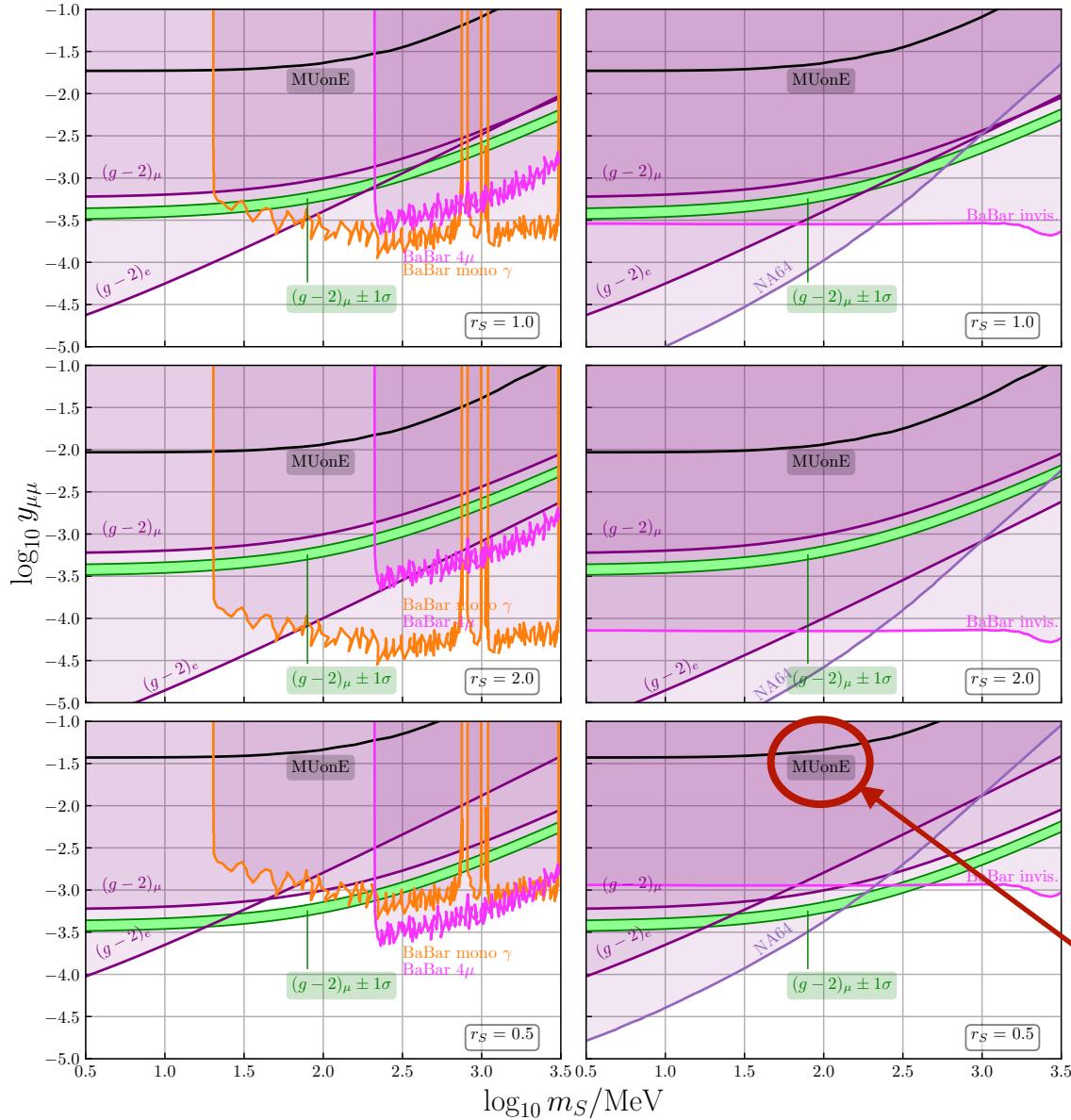
- ▶ Test run: 2021
  - ▶ Run1: 2022,  $10^{11}$  MOT
- Final goal:  $10^{13}$  MOT

NA64 Status Report 2021



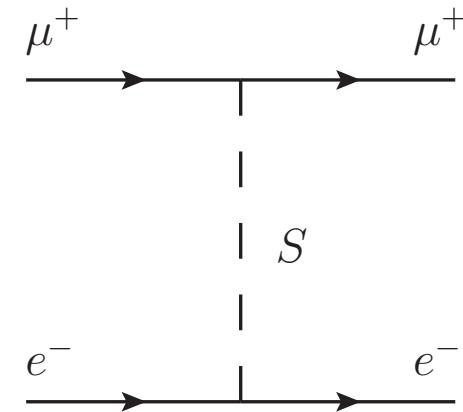
H. Sieber, et.al., 2110.15111

# Light scaler



$$\mathcal{L} = S(y_{ee}\bar{e}e + y_{\mu\mu}\bar{\mu}\mu)$$

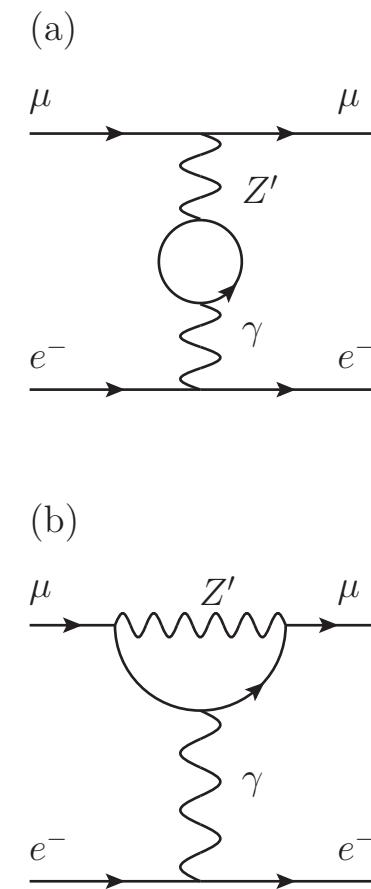
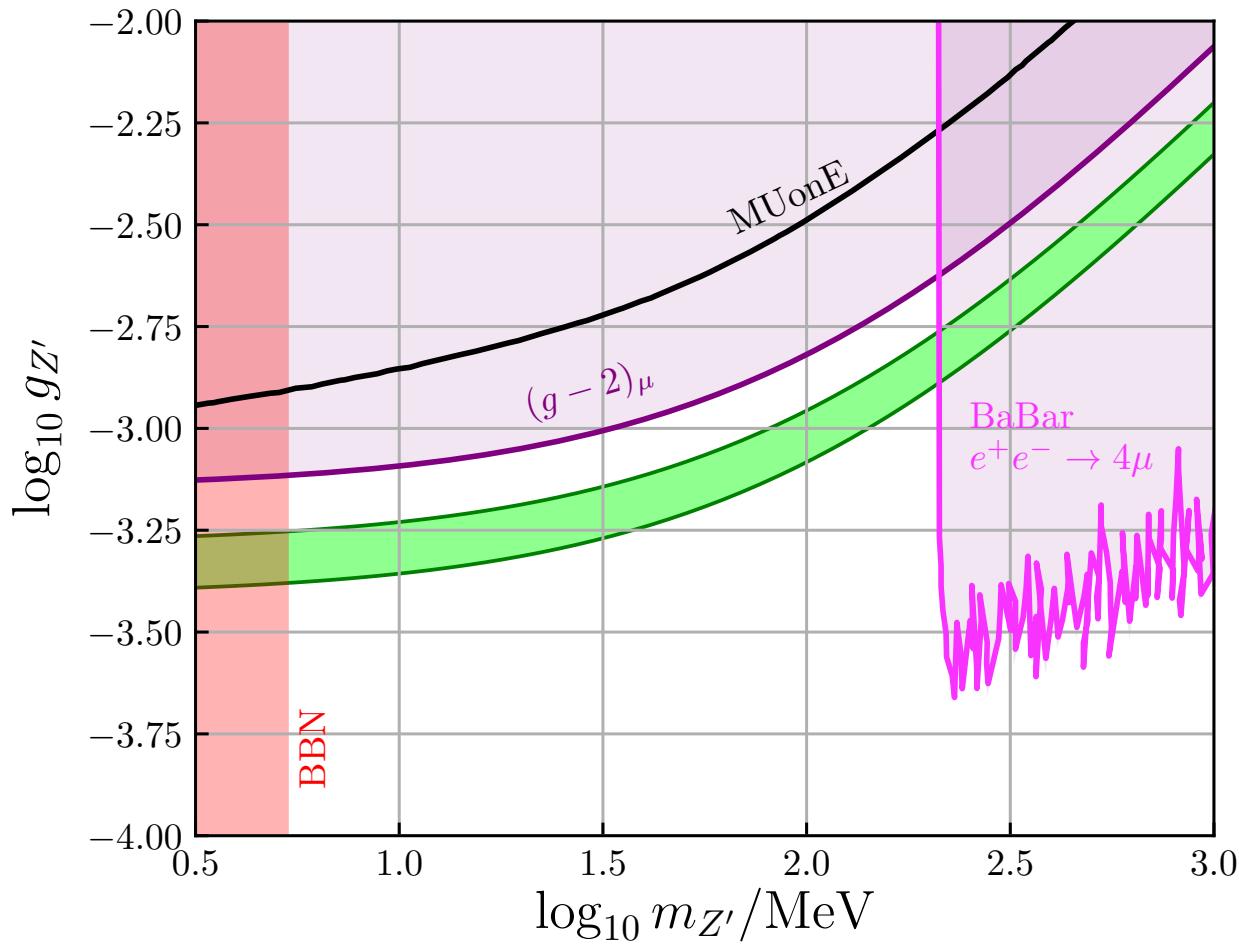
*t*-channel



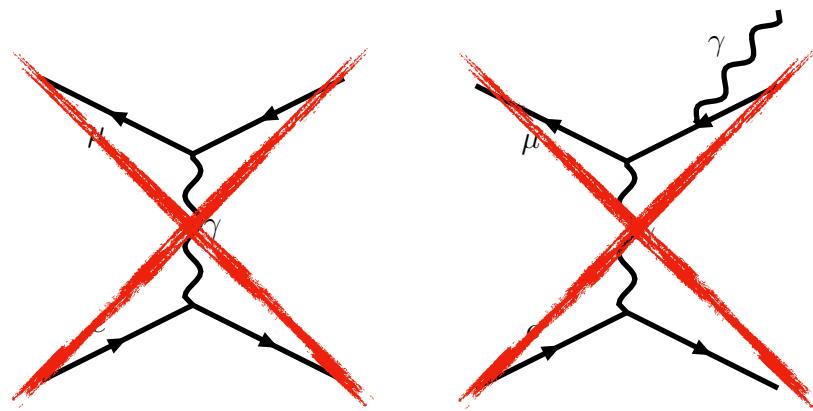
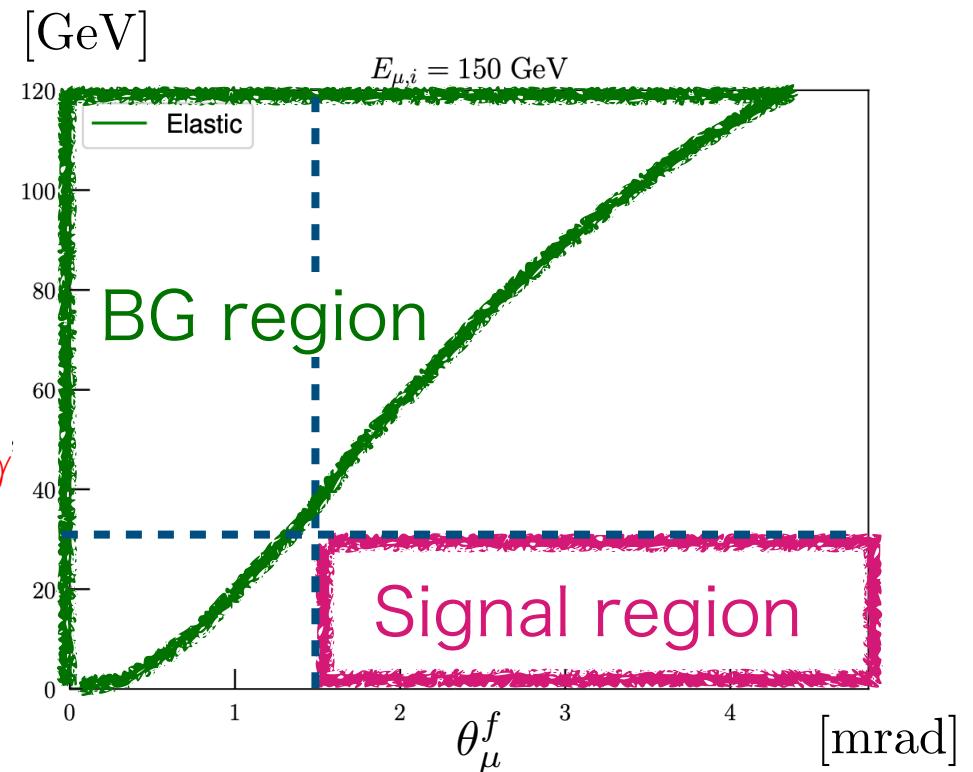
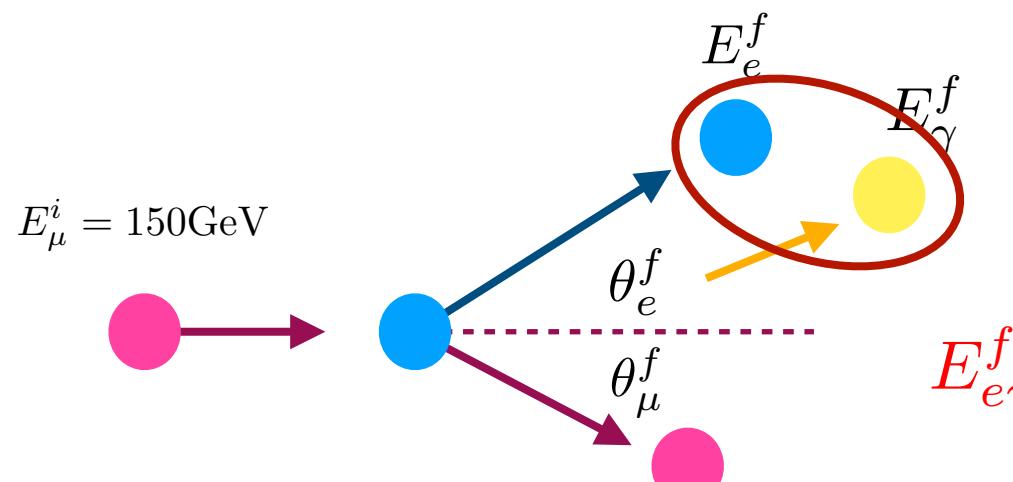
$$r_S \equiv \sqrt{\frac{y_{ee}}{y_{\mu\mu}}}$$



# $U(1)_{\mu-\tau}$ gauge symmetry

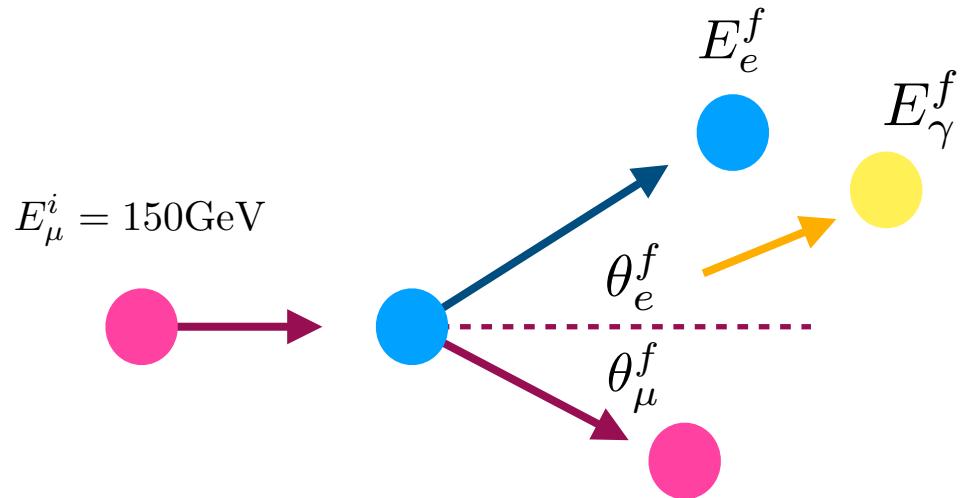


# Strategy



- ▶  $\theta_\mu^f \geq 1.5\text{ [mrad]}$
- ▶  $E_e^f \leq 25\text{ [GeV]} \quad E_{e\gamma}^f \equiv E_e^f + E_\gamma^f$
- $E_{e\gamma}^f$  is minimum when  $E_\gamma^f \rightarrow 0$

# Minimum value of $E_{e\gamma}^f$



$$E_{e\gamma}^f \equiv E_e^f + E_\gamma^f$$

$$m_{e\gamma}^2 \equiv (p_e^f + p_\gamma^f)^2$$

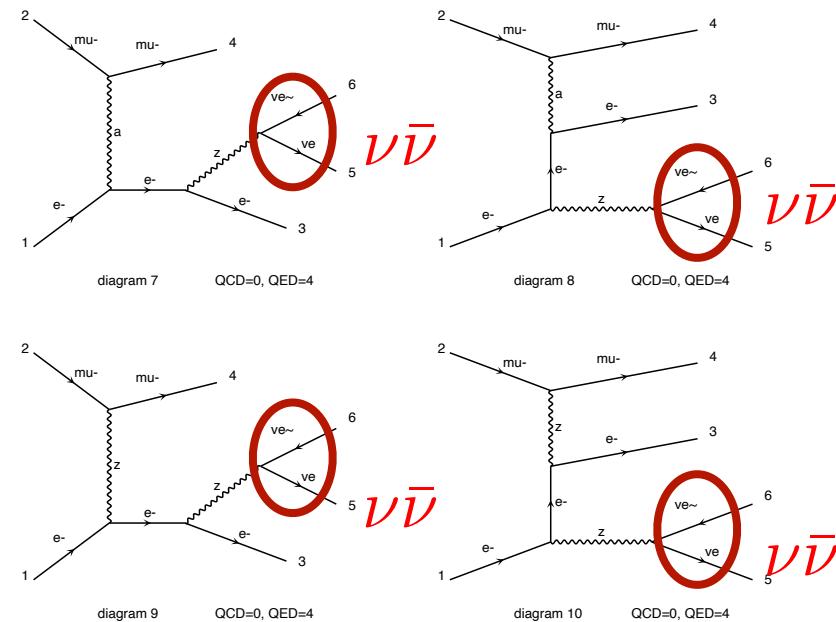
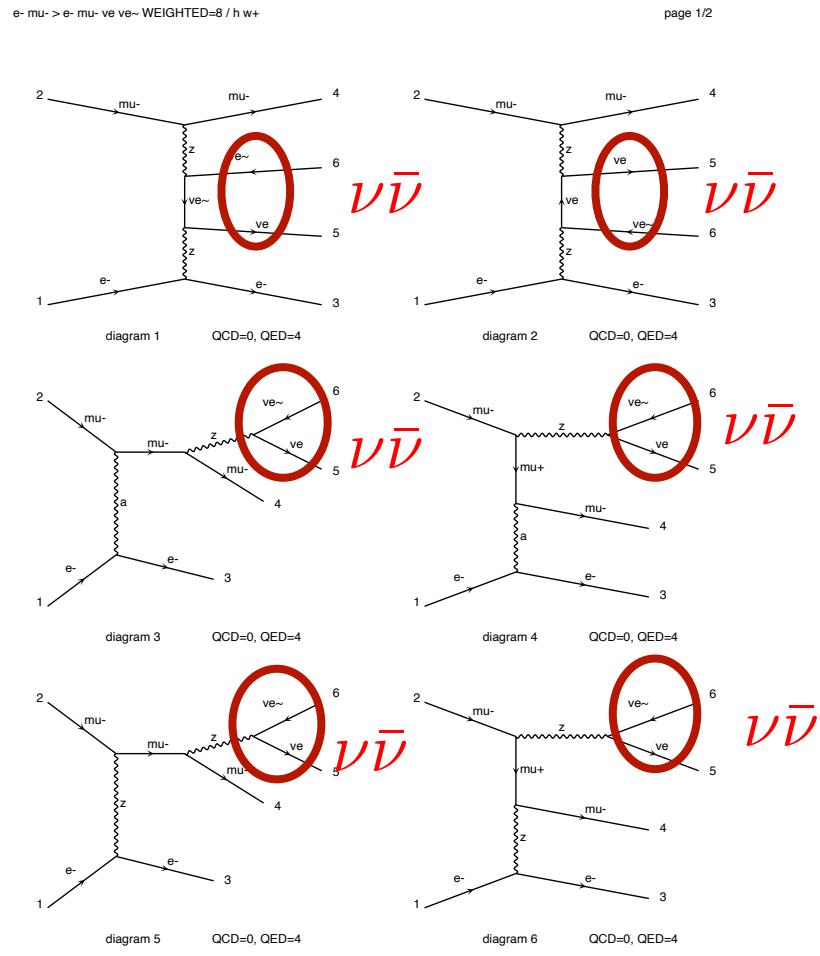
$$\begin{aligned} m_{e\gamma}^2 &= (p_e^f + p_\gamma^f + p_\mu^f - p_\mu^f)^2 & E_{\mu,CM}^f + E_{e\gamma,CM}^f &= E_{CM}^f \\ &= s + m_\mu^2 - 2\sqrt{s}E_{\mu,CM}^f \end{aligned}$$

$m_{e\gamma}^2$  is minimum  $\Leftrightarrow E_\mu^f$  is maximum  $\Leftrightarrow E_{e\gamma}^f$  is minimum

$m_{e\gamma}^2 \geq m_e^2$   $E_{e\gamma}^f$  is minimum when  $E_\gamma^f \rightarrow 0$

# EW background

- ▶ EW process      e.g.  $e^- \mu^- \rightarrow e^- \mu^- \nu e \bar{\nu} / h w^+$



FeynRules & MadGraph5 \_aMC@NLO

N. D. Christensen and C. Duhr,  
Comput. Phys. Com- mun. **180**, 1614 (2009)

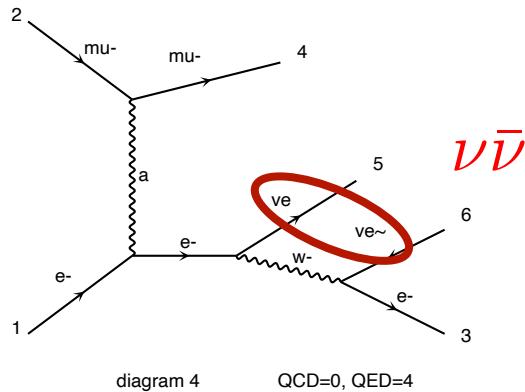
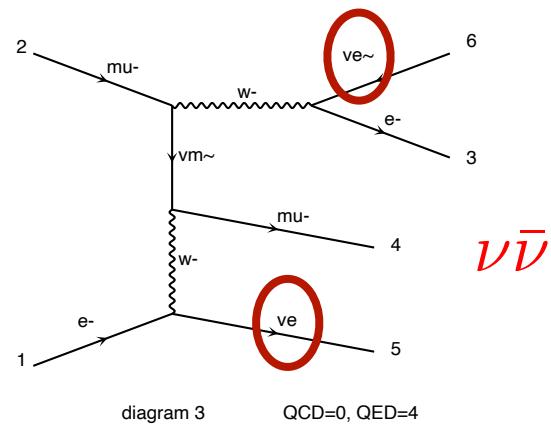
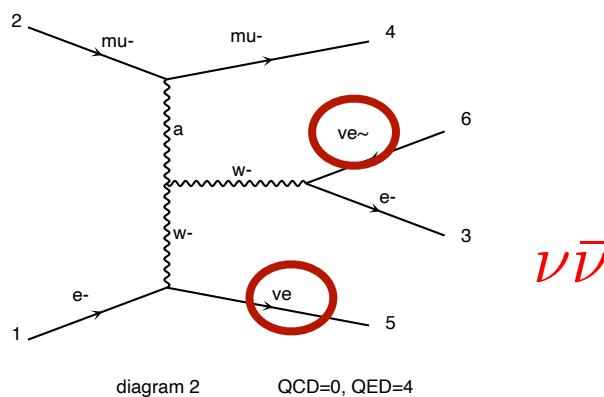
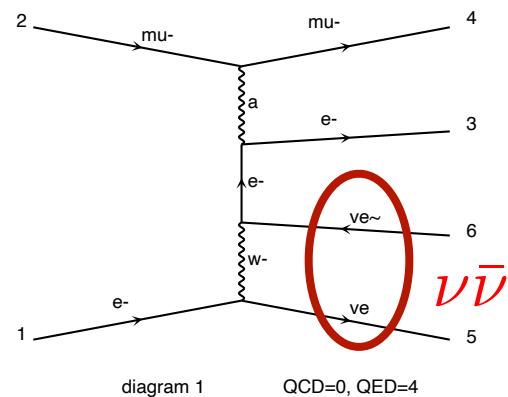
A. Alloul, et.al., Comput. Phys. Commun. **185**, 2250 (2014)  
J. Alwall, et.al., JHEP **07**, 079 (2014)

# EW background

- ▶ EW process      e.g.  $e^- \mu^- \rightarrow e^- \mu^- \nu e \bar{\nu} e^- / h z$

$e^- \mu^- \rightarrow e^- \mu^- \nu e \bar{\nu}$  WEIGHTED=8 / h z

page 1/1



$\nu \bar{\nu}$

FeynRules & MadGraph5 \_aMC@NLO

N. D. Christensen and C. Duhr,  
Comput. Phys. Com- mun. **180**, 1614 (2009)  
A. Alloul, et.al., Comput. Phys. Commun. **185**, 2250 (2014)  
J. Alwall, et.al., JHEP **07**, 079 (2014)