

# NA64++

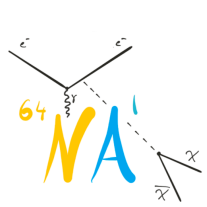
S.N. Gninenko  
INR, Moscow  
(for the NA64 Collaboration)

## Outline

- searches with  $e^-$
- searches with  $\mu^-$
- summary

# 2018 setup at the CERN SPS, H4 beam-line



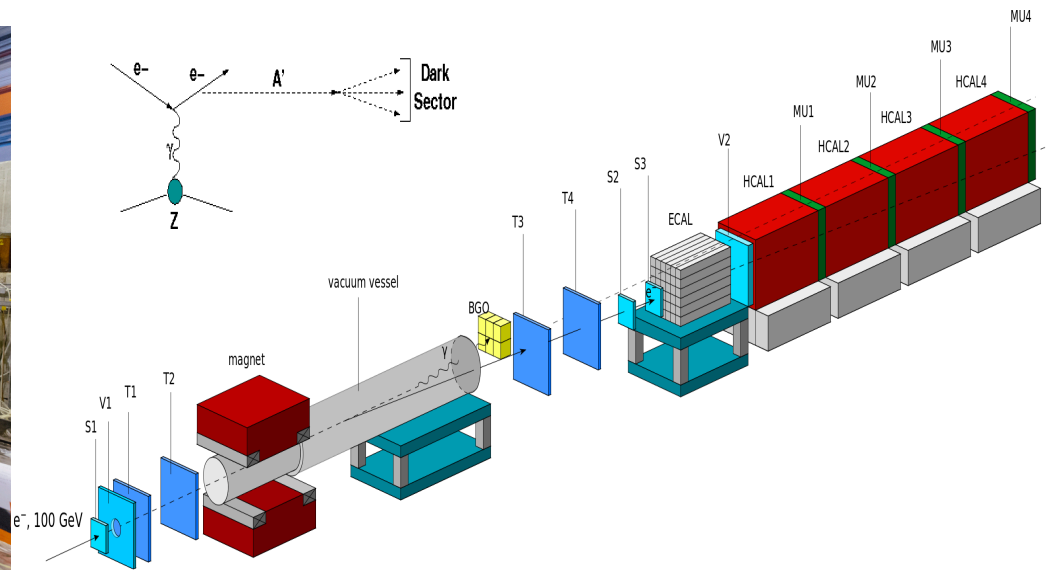
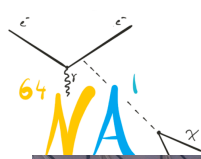


## New results with electrons

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- $A' \rightarrow$  invisible decays and sub-GeV DM
- $A' \rightarrow e+e-$  decays
- ${}^8\text{Be}^*$  anomaly

# Search for $A'$ ->invisible decays at the CERN SPS



## Main components :

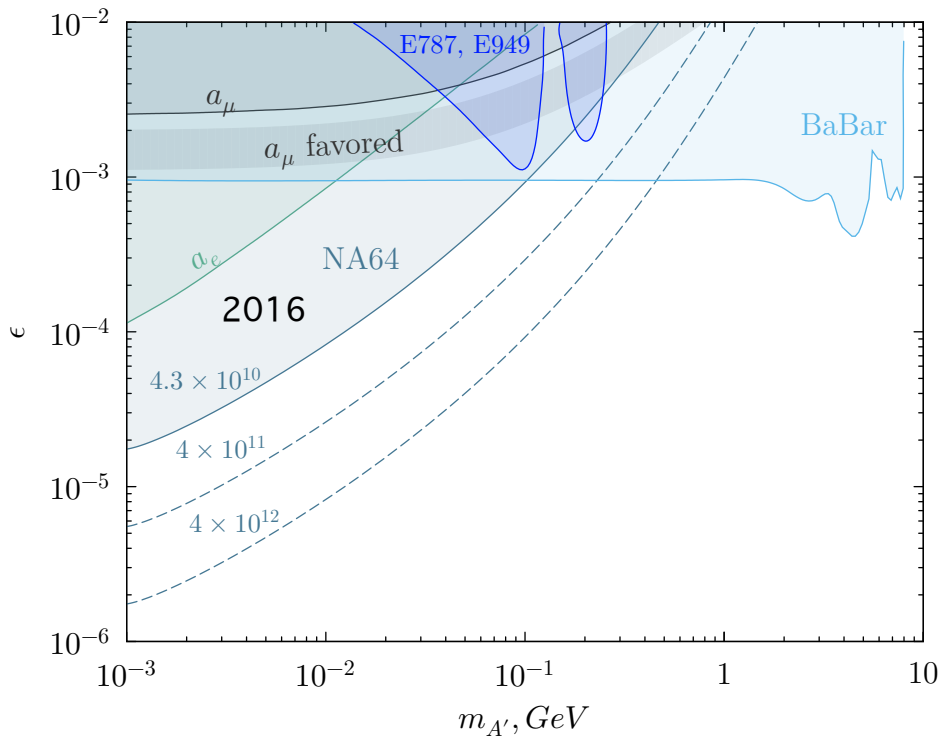
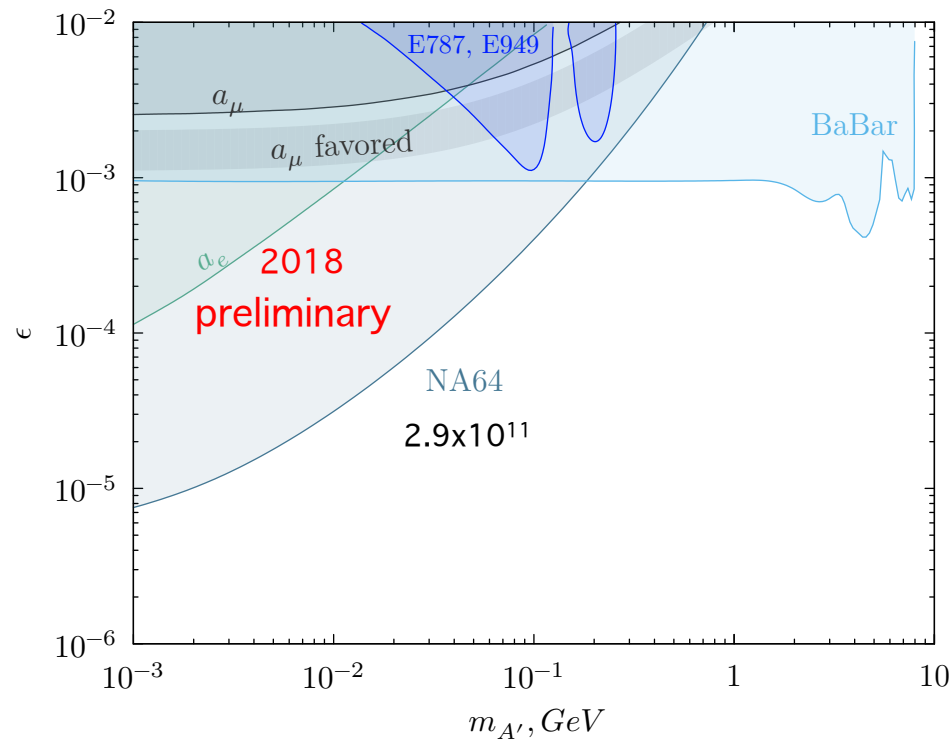
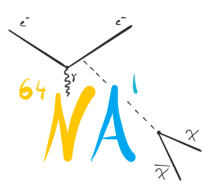
- clean 100 GeV e- beam
- e- tagging: tracker+SRD
- fully hermetic ECAL+HCAL

## Signature:

- in: 100 GeV e- track
- out:  $E_{ECAL} < E_0$  shower in ECAL
- no energy in Veto and HCAL

NA64 was designed to search for new physics in missing-energy events with  $e^-$ ,  $\mu$ ,  $\pi$ ,  $K$ ,  $p$  beams. The 2021 run is approved, as well as preparation of a new area at H4 which would be used by NA64

# New results and projections for $\gamma$ - $A'$ mixing

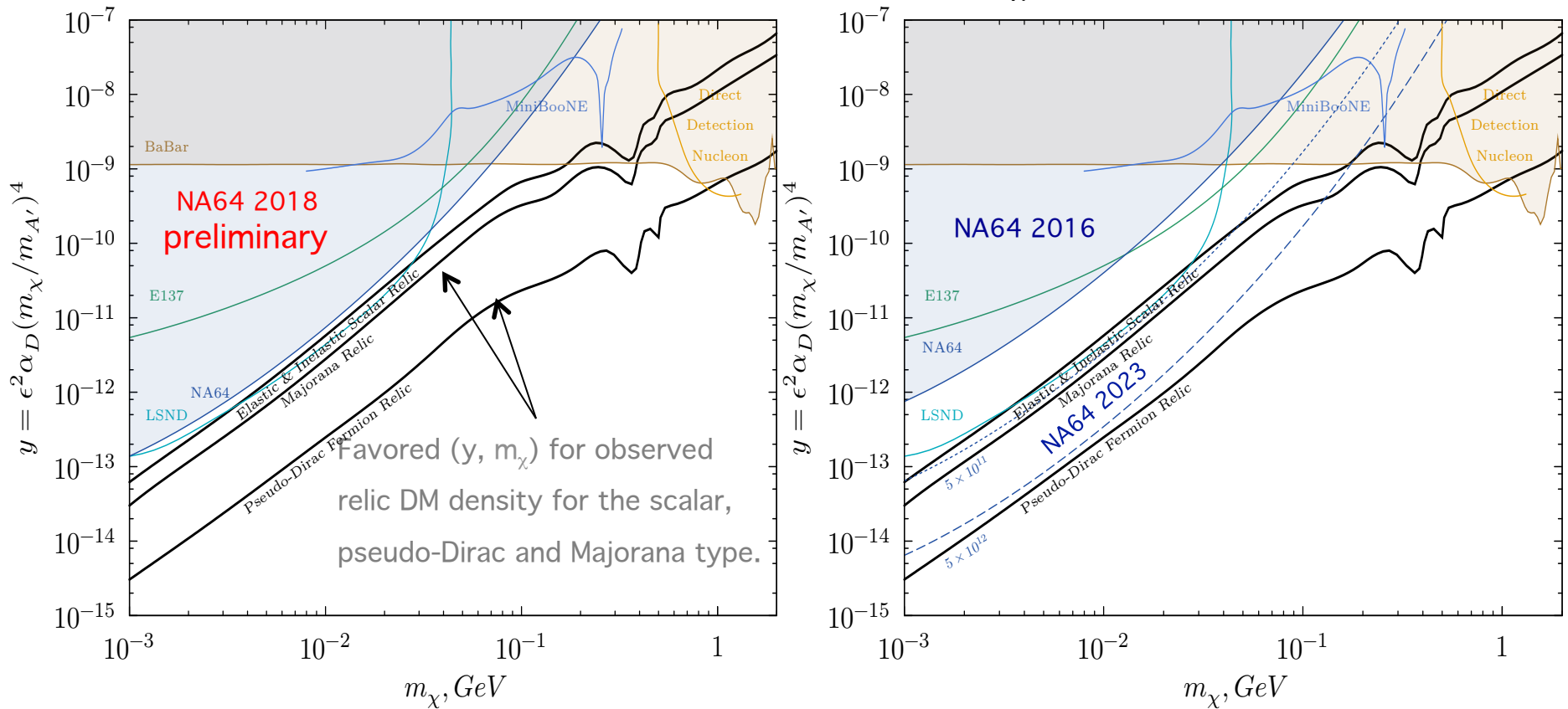


Plans to accumulate  $\sim (4-5) \times 10^{12}$  EOT after LS2

# New results and projection for sub-GeV thermal DM (I)

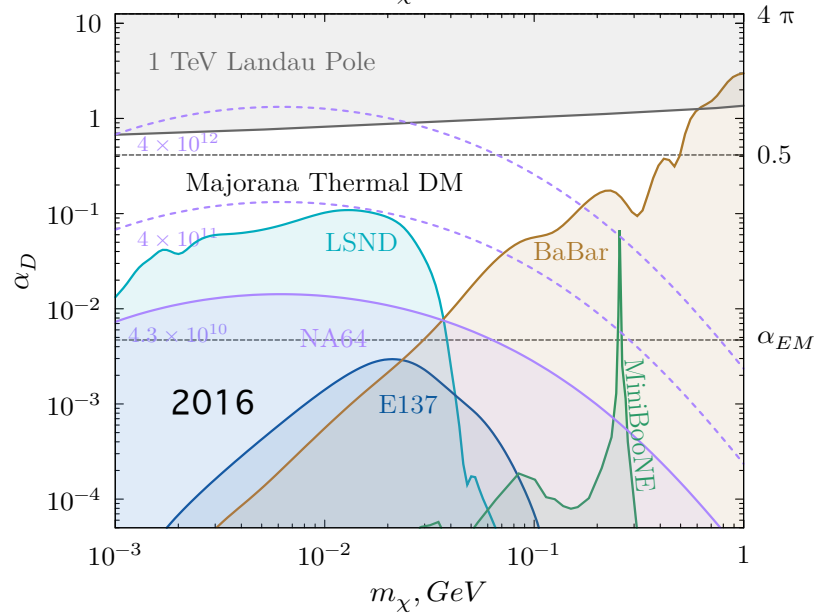
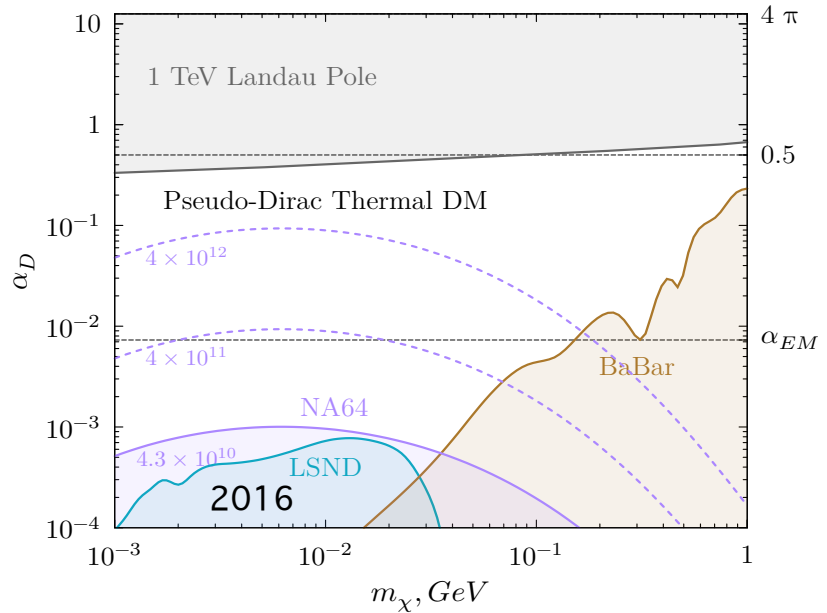
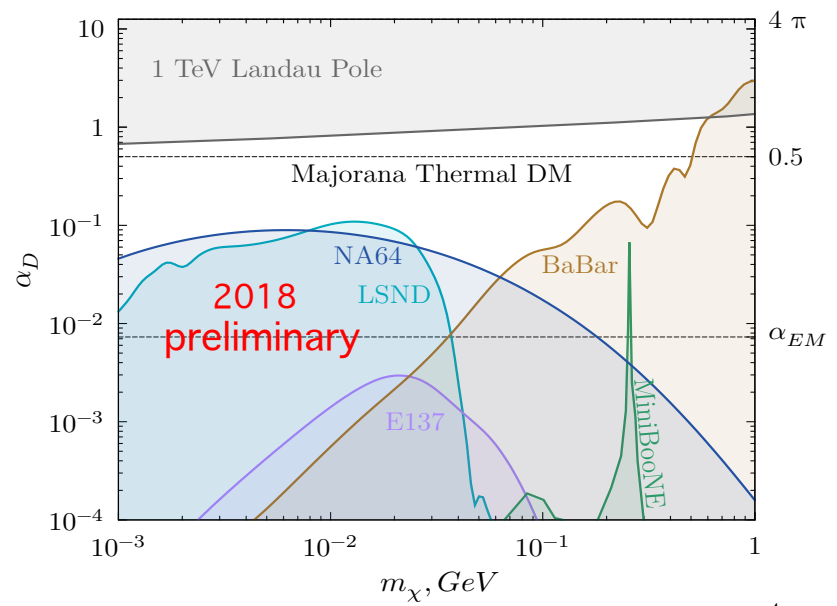
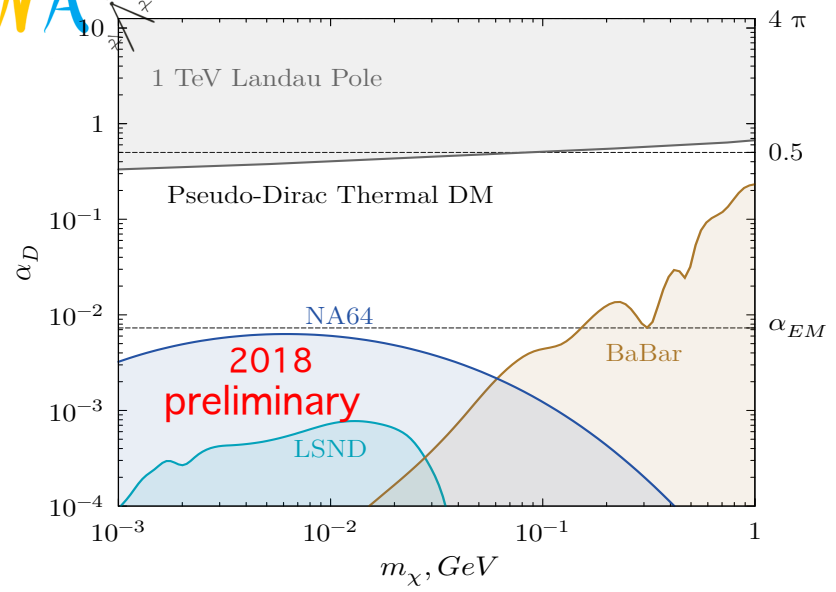
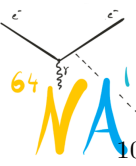


$$\alpha_D = 0.1, m_{A'} = 3m_\chi$$

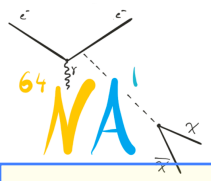


- Sensitivity of a beam-dump  $\sim \epsilon^4 \alpha_D$ , NA64  $\sim \epsilon^2$
- Bounds from LSND, SLAC, MiniBooNE for  $\sim 10^{22}$ ,  $10^{19}$ ,  $10^{20}$  POT
- NA64 can cover significant area with  $\sim$  a few  $10^{12}$  EOT

# New results and projection for sub-GeV thermal DM (II)



# $^8\text{Be}^*$ anomaly: a new light X boson?



PRL 116, 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

## Observation of Anomalous Internal Pair Creation in $^8\text{Be}$ : A Possible Indication of a Light, Neutral Boson

A. J. Krasznahorkay, M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tomyi, and Zs. Vajta

Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

T. J. Ketel

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(Received 7 April 2015; published 26 January 2016)

$^7\text{Li}(p, \gamma)^8\text{Be}$ ,  $M_X = 16.7 \text{ MeV}$

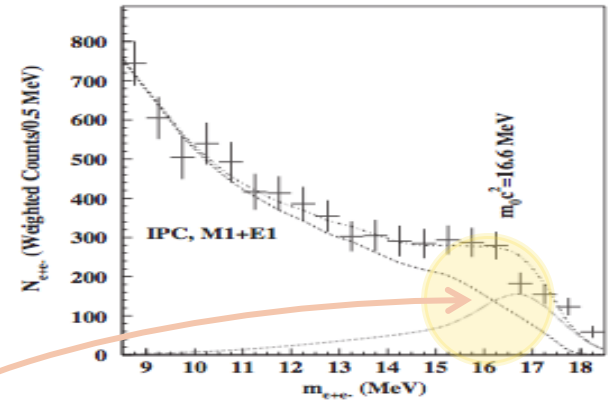
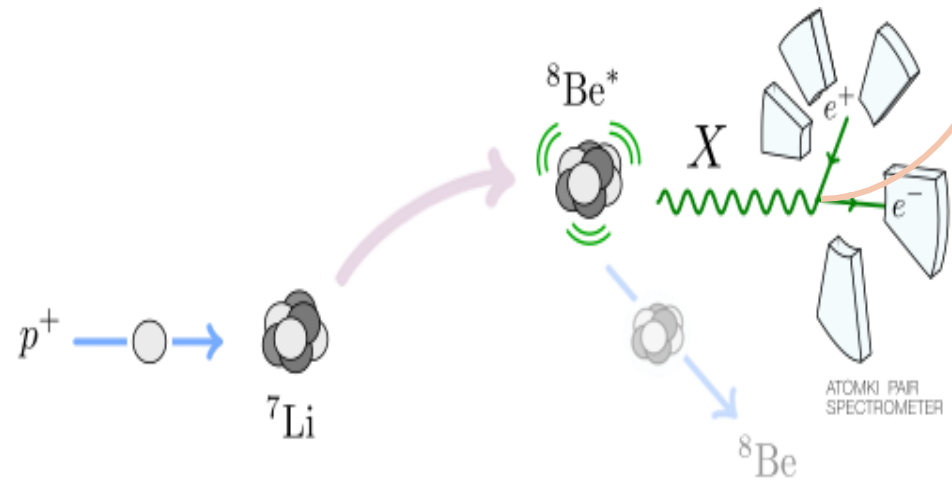
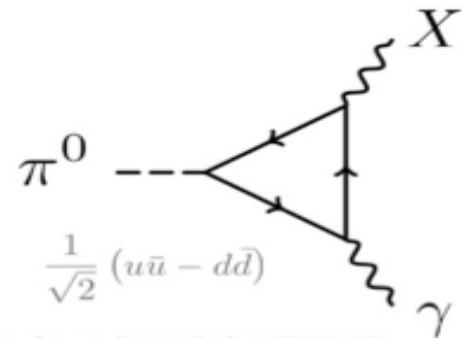


FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in  $^8\text{Be}$ .



X cannot be  $A'$  due to constraints from  $\pi^0 \rightarrow X\gamma$  decay:



Feng et al, 2016

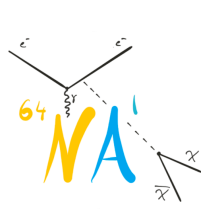
$$2 \times 10^{-4} < \epsilon_e < 1.4 \times 10^{-3}$$

$$\Gamma(\pi^0 \rightarrow X\gamma) \sim (\epsilon_u q_u - \epsilon_d q_d)^2 \sim 0$$

if  $2\epsilon_u = -\epsilon_d \rightarrow$  **protophobic X**

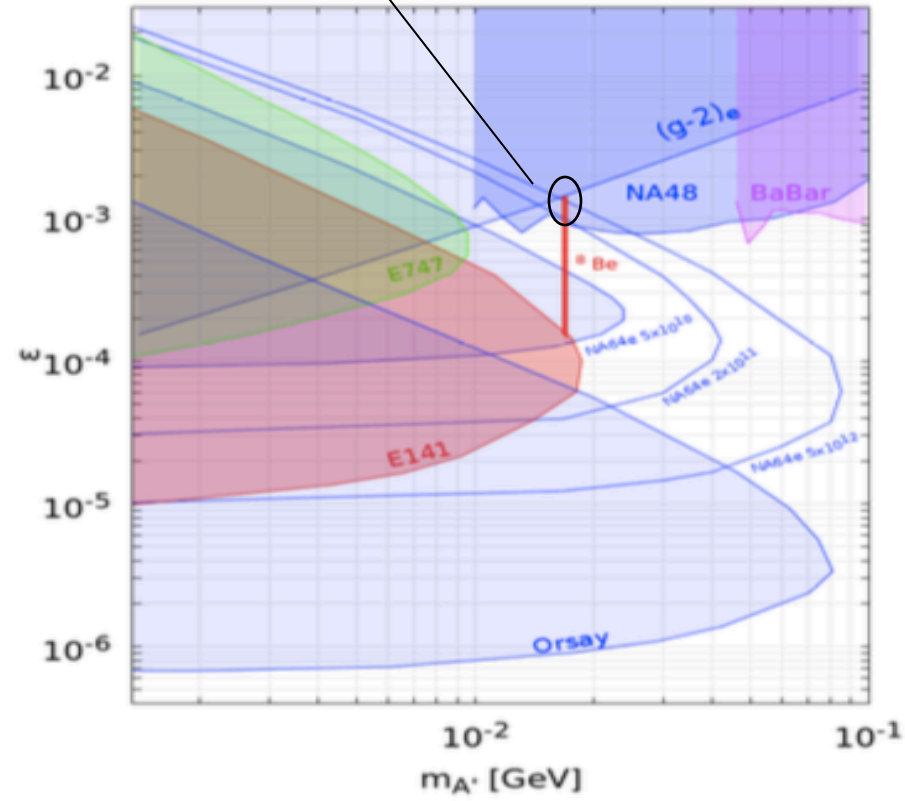
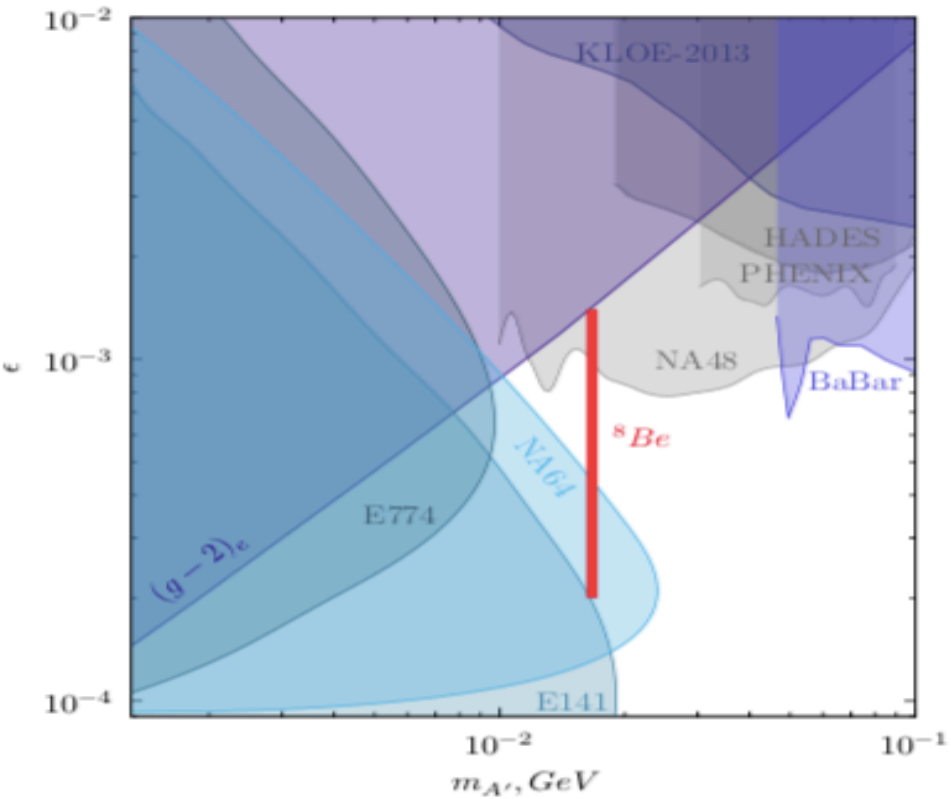


# First results and projections for $X, A' \rightarrow e^+e^-$

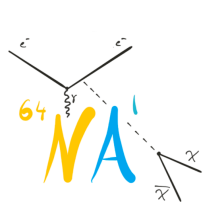


Could be covered by using Si pixels in 2021

NA64 PRL(2018)



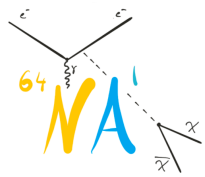
2017  $\rightarrow \sim 5 \times 10^{10}$  EOT at 100 GeV  
 2018  $\rightarrow \sim 5 \times 10^{10}$  EOT at 150 GeV



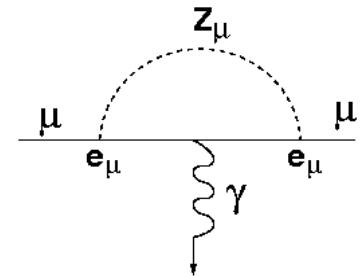
# New results and plans with muons

- $(g-2)_\mu$  and search for the  $L_\mu - L_\tau$   $Z'$
- Complementarity of measurements with  $e^-$  and  $\mu$
- Search for the  $A'$ 's with muons

# Muon $g-2$ anomaly



- E989 at FNAL: New result with statistics of E821 in 2019.  
If confirmed anomaly  $\rightarrow \sim 5 \sigma$  assuming the same Exp/Th central values
- $(g-2)_\mu$  explanation:  $Z'$  (e.g.  $A'$ ) with universal coupling is ruled out
- Still possible explanation: **new light states weakly coupled predominantly to muon (S or V)**
- E.g. : New massive boson  $Z_\mu$  from broken  $U(1)'_{L_\mu - L_\tau}$  coupled predominantly to  $\mu$  and  $\tau$   
 $M_{Z_\mu}$  could be in sub-GeV range  $Z_\mu \rightarrow \nu\nu$  for  $M_{Z_\mu} < 2 m_\mu$



- explanation of  $(g-2)_\mu$
  - mediator of new force, sub-GeV TDM
  - Impact on  $\nu$ -physics, astophys. observation (21 cm anomaly) ....
- New ideas for NA64 $_\mu$ -like experiment
- $L_\mu - L_\tau$   $Z_\mu$   $M^3$ @FNAL, arXiv:1804.03144
  - Leptophilic TDM, arXiv:1807.03790
  - Light scalars of DS, arXiv:1701.07437

# NA64 $\mu$ proposal to the SPSC (Jan'19)



PREPARED FOR SUBMISSION TO SPSC

## Proposal for an experiment to search for dark sector particles weakly coupled to muon at the SPS

D. Banerjee<sup>k</sup>, J. Bernhard<sup>d</sup>, V.E. Burtsev<sup>j</sup>, A.G. Chumakov<sup>j</sup>, P. Crivelli<sup>m</sup>, E. Depero<sup>m</sup>, A.V. Dermenev<sup>c</sup>, S.V. Donskov<sup>i</sup>, R. Dusaev<sup>j</sup>, T. Enik<sup>b</sup>, V. Frolov<sup>b</sup>, A. Gardikiotis<sup>b</sup>, S.N. Gninenko<sup>c</sup>, M. Hösger<sup>c</sup>, A. Karneyev<sup>c</sup>, G.D. Kekelidze<sup>b</sup>, B. Ketzer<sup>a</sup>, D. Kirpichnikov<sup>c</sup>, M.M. Kirsanov<sup>c</sup>, S. Kovalenko<sup>j</sup>, L.V. Kravchuk<sup>c</sup>, V.A. Kramarenko<sup>b,s</sup>, N.V. Krasnikov<sup>c</sup>, S.V. Kuleshov<sup>j</sup>, V.E. Lyubovitskij<sup>j,l</sup>, V.M. Lysan<sup>b</sup>, V.A. Matveev<sup>b</sup>, Yu.V. Mikhailov<sup>i</sup>, L. Molina-Bueno<sup>m</sup>, D.V. Peshekhonov<sup>b</sup>, V.A. Polyakov<sup>i</sup>, B. Radics<sup>m</sup>, A. Rubbia<sup>m</sup>, V. Samoylenko<sup>j</sup>, D. Shchukin<sup>j</sup>, V.O. Tikhomirov<sup>j</sup>, D.A. Tlisov<sup>c</sup>, A.N. Toropin<sup>c</sup>, A. Yu. Trifonov<sup>j</sup>, P. Ulloa<sup>l</sup>, B.I. Vasilishin<sup>j</sup>, B.M. Veit<sup>d</sup>, P.V. Volkov<sup>b,s</sup>, and V.Yu. Volkov<sup>s</sup>

### The NA64 Collaboration<sup>1</sup>

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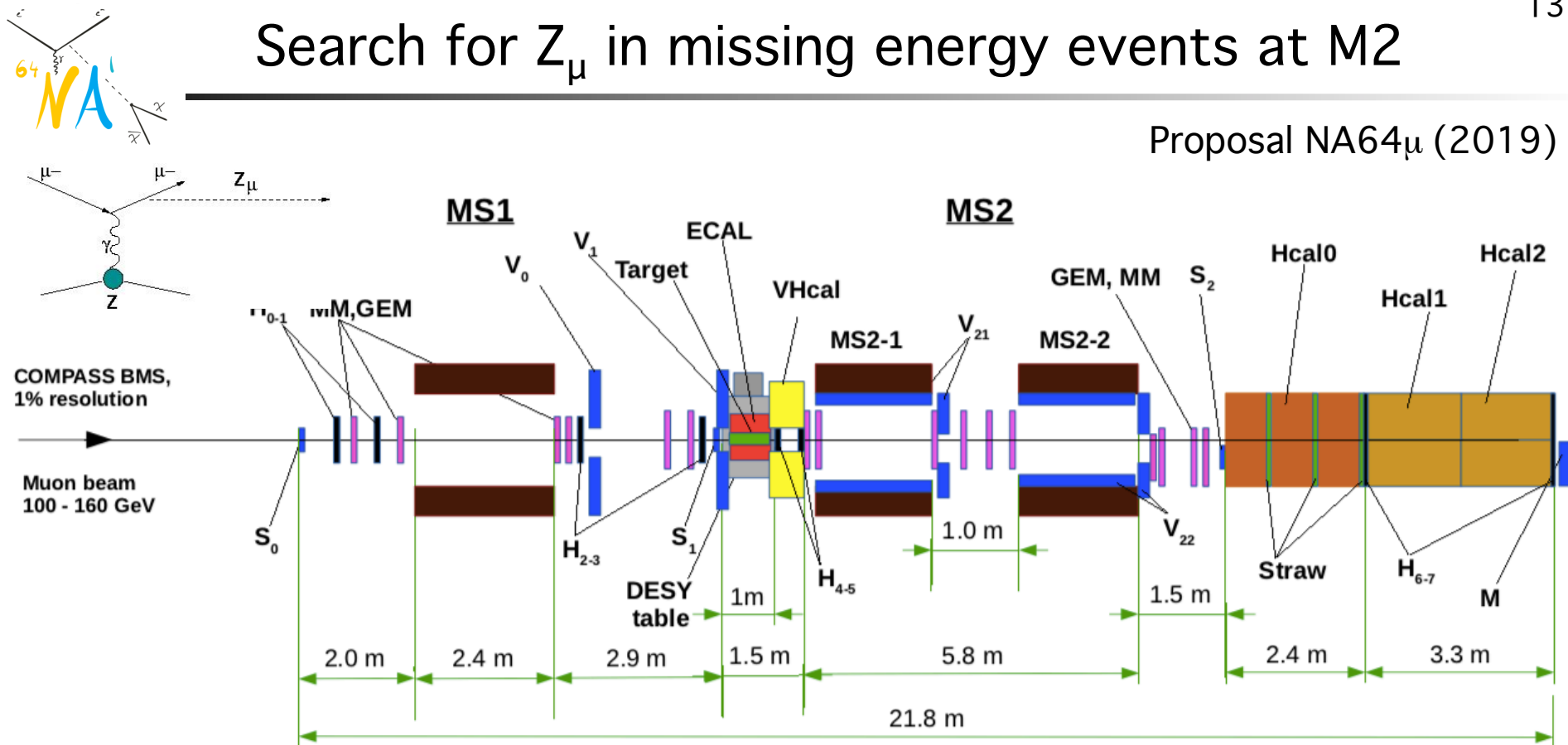
<sup>k</sup>ETH Zürich, Institute for Particle Physics, CH-8093 Zürich, Switzerland

January 7, 2019

<sup>1</sup><http://webna64.cern.ch>

# Search for $Z_\mu$ in missing energy events at M2

Proposal NA64 $_\mu$  (2019)



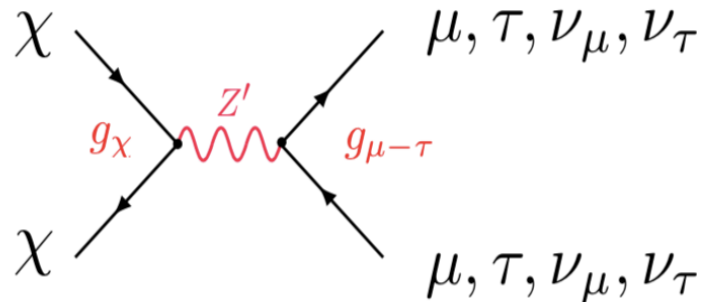
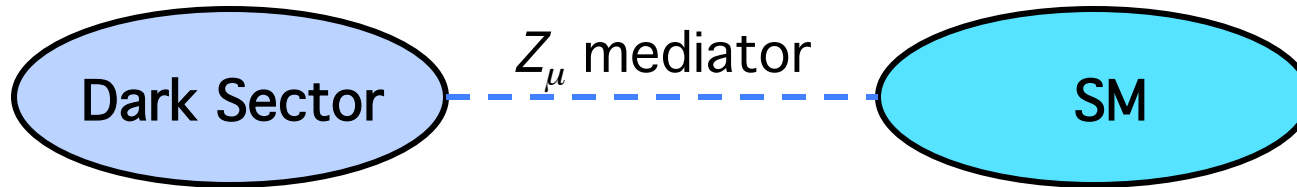
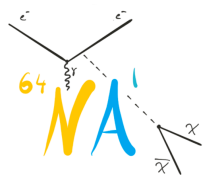
## Main components :

- 100–160 GeV  $\mu^-$  beam,  $I_\mu \sim 10^7 \mu^-/\text{spill}$ .
- in  $\mu$  tagging: BMS+MS1 (MBPL+tracker)
- out  $\mu$  tagging: MS2 (2MBPL+tracker)
- $4\pi$  fully hermetic ECAL+Veto+ HCAL

## Signature:

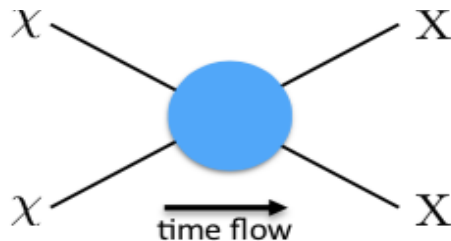
- in: 150 GeV  $\mu^-$  track
- out:  $< 100$  GeV  $\mu^-$  track
- no energy in the ECAL, Veto, HCAL
- Sensitivity  $\sim g_\mu^2$

# $L_\mu$ - $L_\tau$ Charged Dark Matter and $Z_\mu$ mediator



Kahn, Krnjaic, Tran, Whitbeck 1804.03144

$$J_\chi^\mu = g_\chi \times \begin{cases} i\chi^* \partial_\mu \chi + h.c. & \text{Complex Scalar} \\ \bar{\chi}_1 \gamma^\mu \chi_2 + h.c. & \text{Pseudo-Dirac Fermion} \\ \frac{1}{2} \bar{\chi} \gamma^\mu \gamma^5 \chi & \text{Majorana Fermion} \\ \bar{\chi} \gamma^\mu \chi & \text{Dirac Fermion} \end{cases}$$



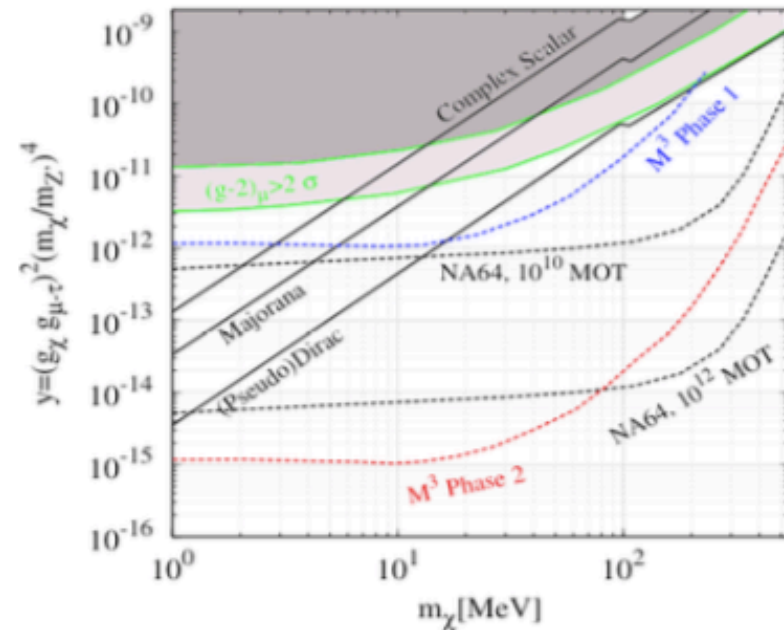
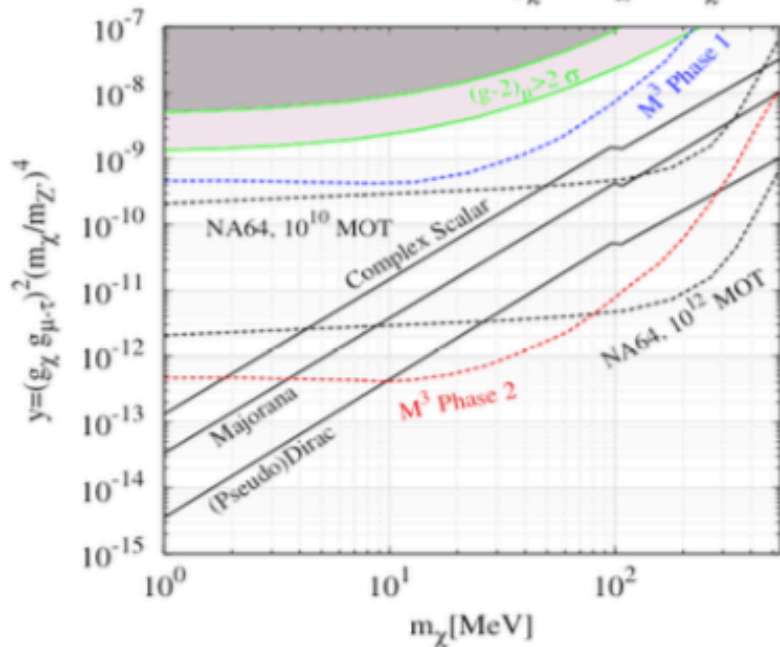
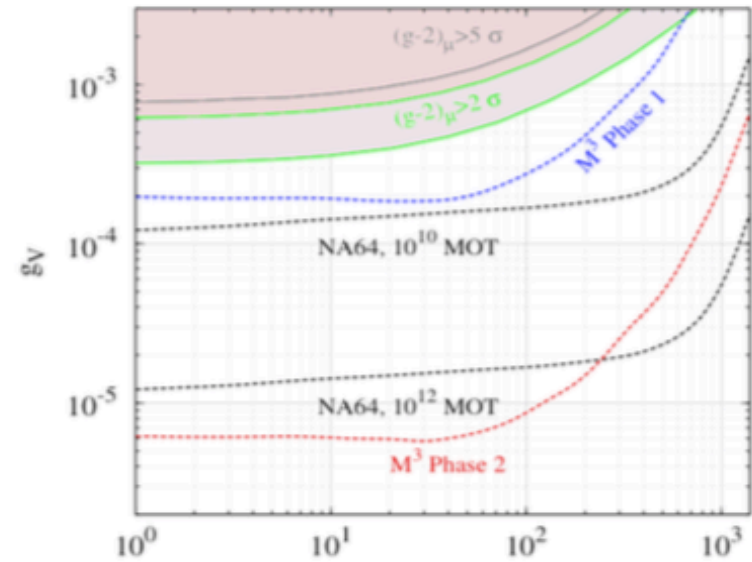
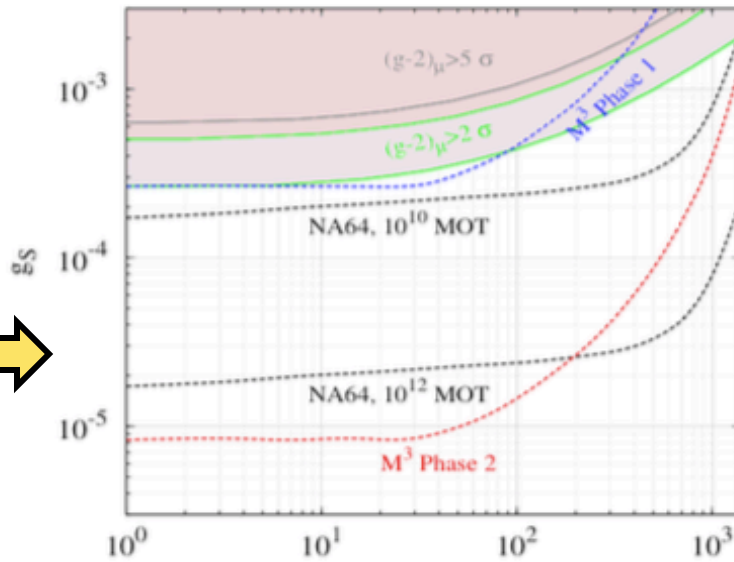
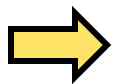
- free parameters  $m_\chi, m_{Z_\mu}, g_\chi, g_\mu$
- $Z_\mu$  decays:
  - $m_{Z_\mu} < 2m_\chi$  - decays into SM,  $Z_\mu \rightarrow \nu\nu, \mu^+\mu^-, \tau^+\tau^-$
  - $m_{Z_\mu} > 2m_\chi$  - invisible decays into DM:  $Z_\mu \rightarrow \chi\chi, \nu\nu$ ,  $\alpha_D \gg \alpha_{SM}$ ,  $\alpha_D = g_\chi^2/4\pi$ ,  $\alpha_{SM} = g_\mu^2/4\pi$
- Cross section for  $\chi$ -DM annihilation:
 
$$\Gamma_{\text{inel}} = n_\chi \langle \sigma v \rangle$$

$$\sigma v \approx [(g_\chi g_\mu)^2 (m_\chi/m_{A'})^4] / m_\chi^2 = y/m_\chi^2;$$

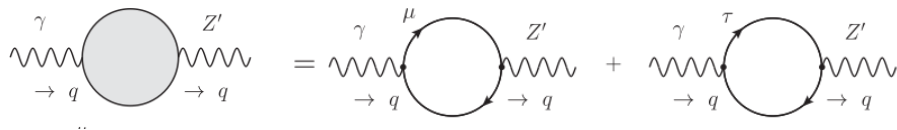
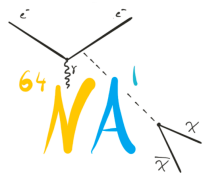
$$y = [(g_\chi g_\mu)^2 (m_\chi/m_{A'})^4] -$$
 useful variable to compare FTE sensitivities

# Sensitivities of NA64 $_{\mu}$ and M $^3$ @FNAL to $g_S, g_V, y$

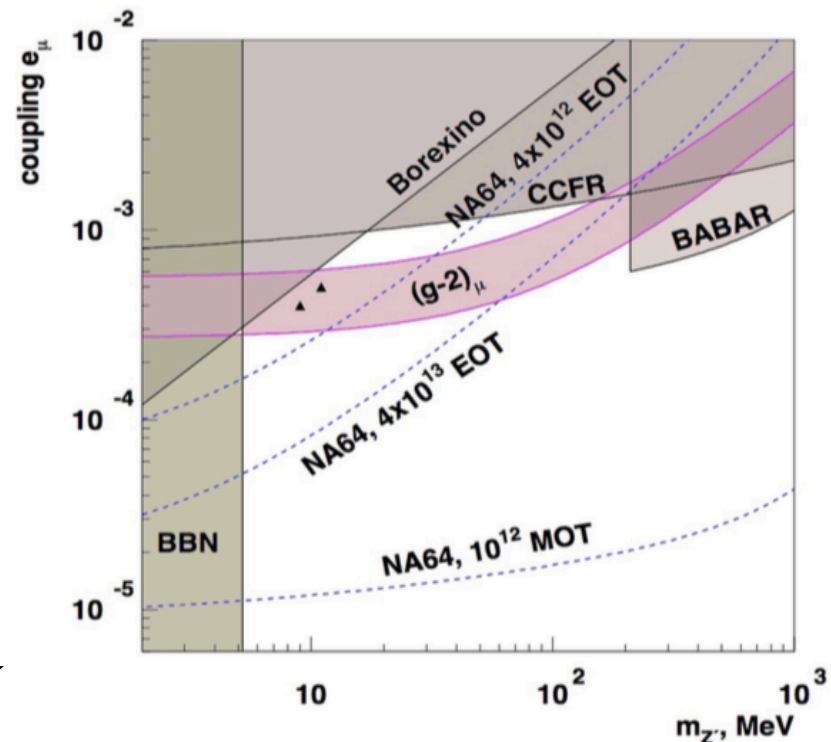
NA64 need just  $\sim 10^{10}$ - $10^{11}$   
to probe muon g-2 region



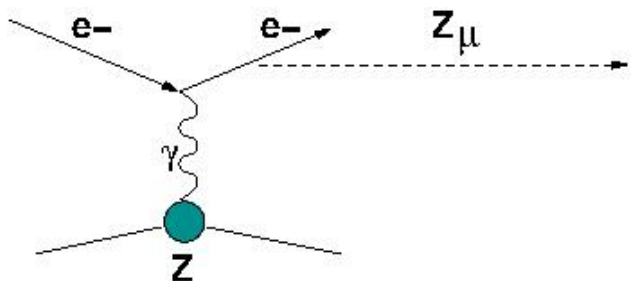
# $\gamma - Z_\mu$ kinetic mixing



- kinetic mixing  $\gamma - Z_\mu$
- mixing  $\epsilon \sim 3eg_\mu/16\pi^2 \ln(m_\tau/m_\mu)$
- $m_{Z'} < m_\mu$ :  $g_\mu = 4.8 \times 10^{-4}, \epsilon = 6.8 \times 10^{-6}$
- **Loophole:** search for  $Z_\mu$  with e- beams



$e - Z \rightarrow e - Z Z_\mu$ ;  $Z_\mu \rightarrow$  invisible similar to  $A'$



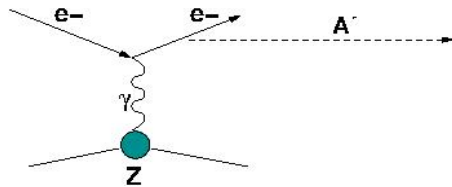
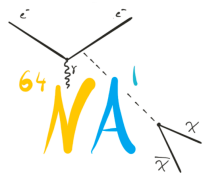
Complementarity of NA64e and NA64 $\mu$ :  
if  $Z_\mu$  is observed in NA64 $\mu$  it should be seen in NA64e

SG, N.Krasnikov, 1801.10448

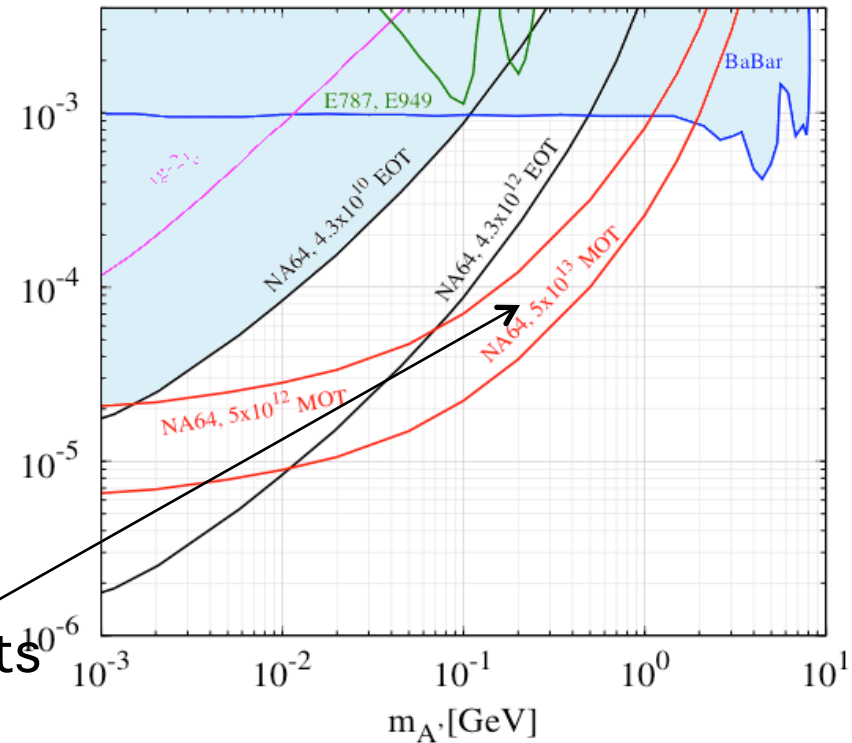
S.N. Gninenko – NA64++ – PBC Workshop, CERN, January 16–17, 2019



# Search for the $A'$ with a muon beam



- $N_{A'} \sim N_e \epsilon^2 m_e^2 / m_{A'}^2$   
Cross-section is suppressed for  $m_{A'} > \sim m_\mu$
- An enhancement factor for  $\mu \sim 10^2$  came from the ratio of the effective e- and muon target length  $t_\mu / t_e$   
The  $t_e \sim X_0$  while for the  $\mu$  case it is  $t_e \ll t_\mu$
- NA64 $_\mu$  can significantly improve limits for  $A'$  mass  $\sim 0.1 - 1$  GeV, a factor  $10^2 - 10^3$  for  $\epsilon^2$  or variables  $y$  and  $\alpha_D$  (next slide)

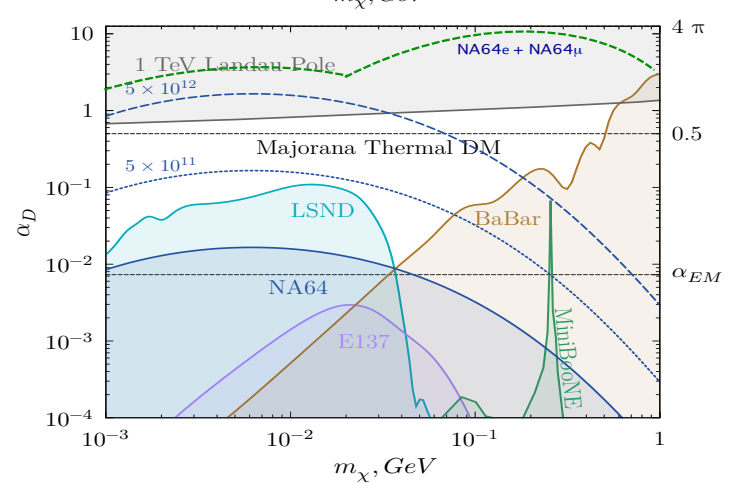
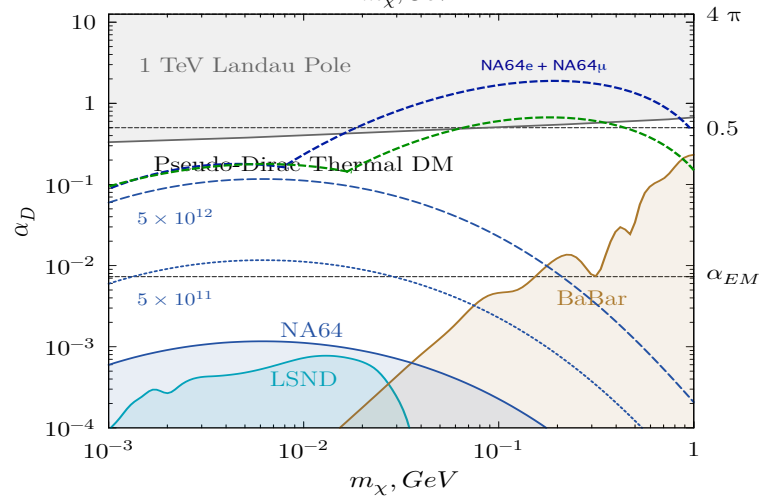
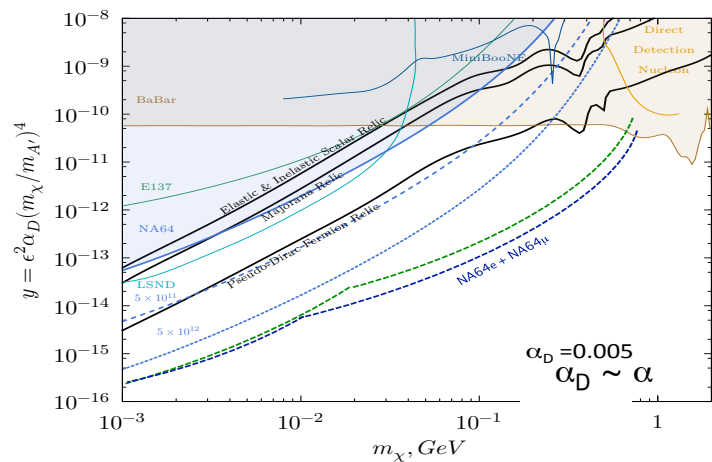
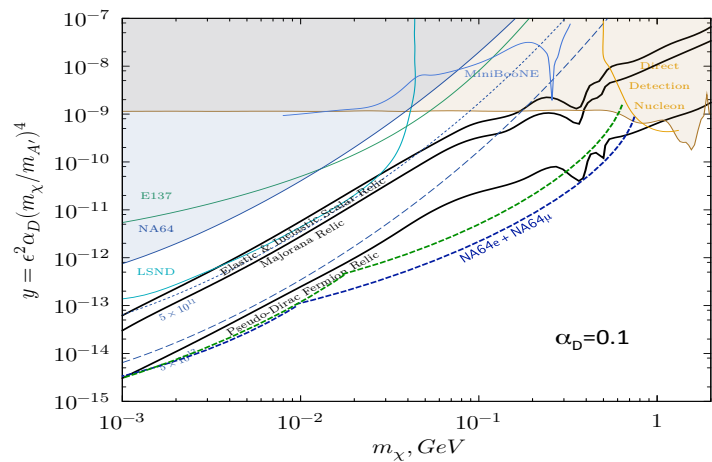


These new observations significantly strengthen motivation for the experimental search of the  $A'$  and  $Z_\mu$  portals with M2 muon beam

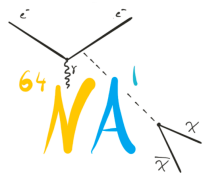


# Combined limits on sub-GeV TDM from NA64e+NA64μ

S.G., Kirpichnikov, Kirsanov, Krasnikov: arXiv:1903.07899



# Summary of plans



## NA64e

- Detector upgrade, and assembly H4B
- 2021 Run:  $A'$ ,  ${}^8\text{Be}^*$  anomaly, ALPs
- 2021–23 run:
  - ✧  $\sim 5 \times 10^{12}$  EOT
  - ✧ to cover the sub-GeV DM param. space
  - ✧ to clarify the origin of the  ${}^8\text{Be}^*$  anomaly

## NA64 $\mu$

- 2021 run at M2
- Phase I : test muon  $g-2$   
 $\sim 10^{11}$  MOT, short-term
- Phase II :  $S_\mu$ ,  $Z_\mu$ ,  $A'$ ,  
milliQ with  $\sim 10^{13}$  MOT

## NA64++ provisional time schedule

2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 |

$e^-$ , H4  $\rightarrow$  (g-2) $_\mu$ , 8Be, Dark Sector | LS2 | 8Be, Dark Sector | LS3 | Dark Sector

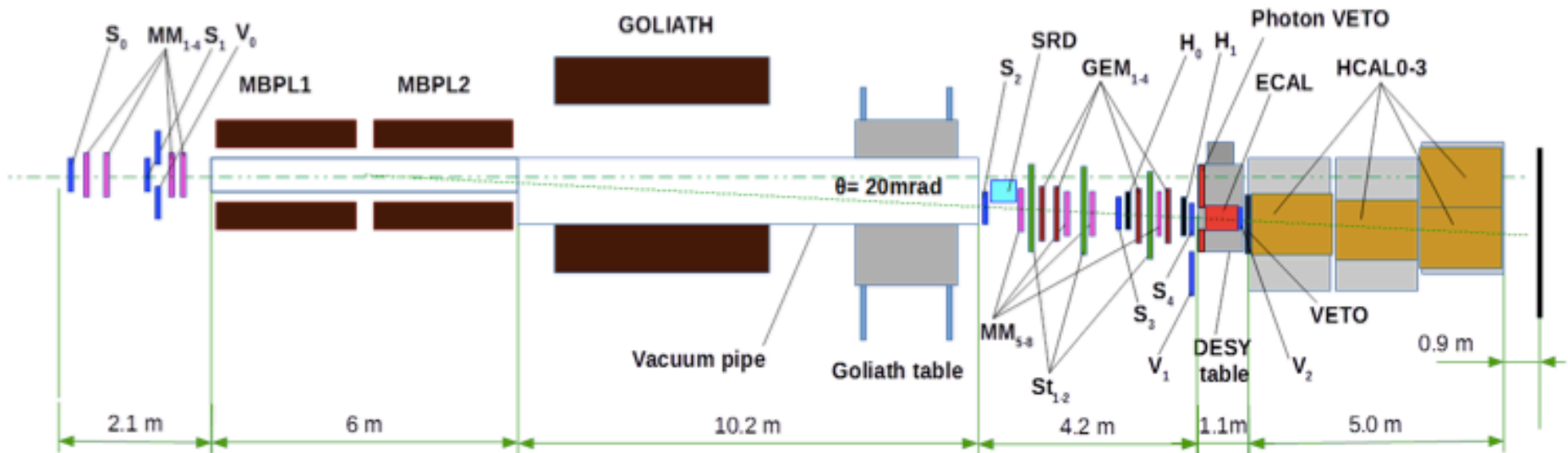
$\mu^-$ , M2  $\rightarrow$  Proposal, Preparation |  $g_\mu-2$ , Dark sector,  $\mu-\tau$  | LS3 | Dark sector,  $\mu-\tau$

$\pi^-$ ,  $K^-$ , H2-H8, T9  $\rightarrow$  Proposal |  $\pi^0, \eta, \eta', K_L \rightarrow \text{inv}$  | LS3 |  $\pi^0, \eta, \eta', K_S, K_L \rightarrow \text{inv}$

## Setup 2018

## NA64 setup for invisible mode.

## TOP VIEW



## SIDE VIEW

