Proposal to Search for Dark Sector Particles weakly coupled to the muon with NA64μ

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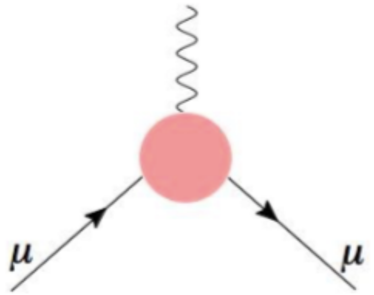
(for the NA64 Collaboration)

Outline

- g_μ-2 anomaly, sub-GeV Dark Matter
- NA64μ detector
- Expected results
- Complementarity of NA64e and NA64μ
- Summary

The muon anomalous magnetic moment (a_μ)

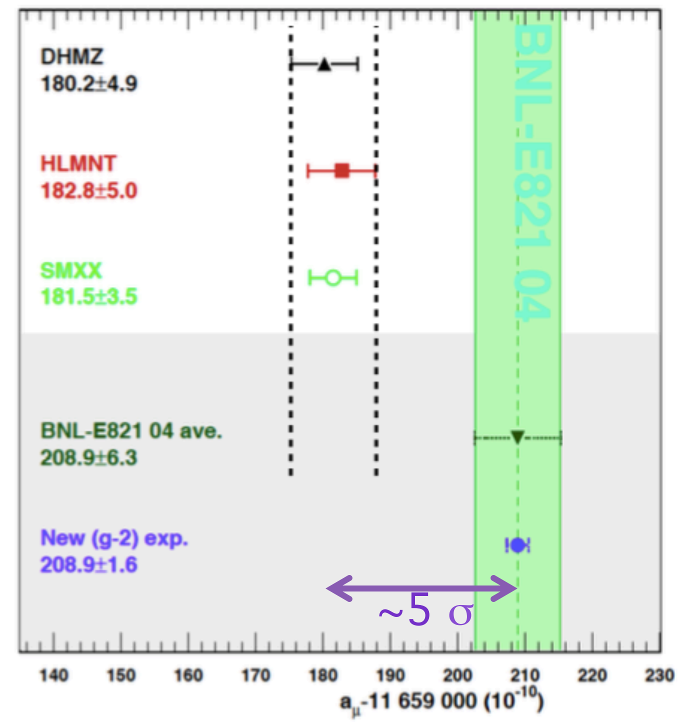
$\mu \sim g_\mu \sim (1+a_\mu)$, $a_\mu=(g_\mu-2)/2=F_2(0)$



$$= (-i\,e)\,\bar{u}(p')\left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2)\right]u(p)$$

τ lepton	$-0.052 < a_\tau < 0.013$	exp.	
	$a_\tau = 1.17721(5)\,10^{-3}$	SM	
muon:	$10^{11}\,a_\mu = 116592089\,(63)$	exp.	(3.6 σ)
	$116591803\,(49)$	SM	
electron:	$10^{14}\,a_e = 115965218091\,(26)$	exp.	
	$115965218173\,(77)$	SM	

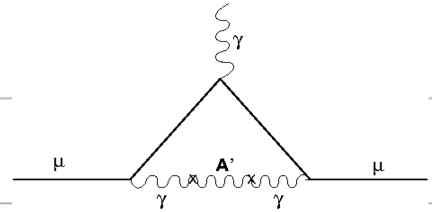
a_μ Th/Exp



- SM : loop QED, EW, QCD contributions to a_μ
- BMS: sensitive probe of New physics
- E989 at FNAL: new result with statistics of E821 in 2019. If confirmed =>~5 σ anomaly

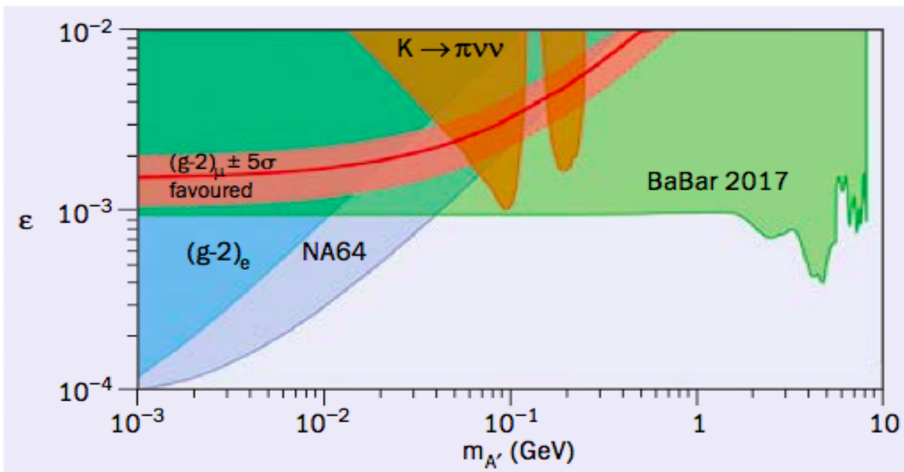
The A´explanation of g_μ-2 anomaly is ruled out

- BaBar $e^+ e^- \to \gamma A'$; $A' \to$ invisible
- NA64 $e^- Z \to e^- Z A'$; $A' \to$ invisible



CERN Courier April 2017

News



Regions of the dark-photon parameter space (mixing strength versus mass) excluded by BaBar (green) compared with the previous constraints. The new analysis rules out dark-photon coupling as the explanation for the muon (g-2) anomaly and places stringent constraints on dark-sector models.

of Caltech, who has worked on dark-photon models. "In contrast to massless dark photons, which are analogous to ordinary photons, this experiment constrains a slightly different idea of dark force-carrying particles that are associated with a broken symmetry, which therefore get a mass and then can decay. They are more like 'dark Z bosons' than dark photons."

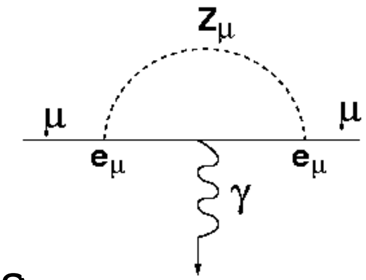
Further reading

BaBar Collaboration 2017 arXiv:1702.03327.
NA64 Collaboration 2017 *Phys. Rev. Lett.* **118** 011802.

The A´coupled to e^- is excluded, but could it be coupled predominantly to muon (recall ν_μ ...)? What about the theory?

Solution to $(g\text{-}2)_\mu$ anomaly: Z_μ of $L_\mu - L_\tau$

- <u>Remarkable fact:</u> out of $U(1)_{Le}$, $U(1)_{L\mu}$, $U(1)_{L\tau}$ global symmetries in the SM models one of $L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$ differences could be gauge. No changing in the structure of the SM: no new fermions, still 3 generations and anomaly-free renormalizable theory (R. Foot (1991))



- New massive boson Z_μ from broken $U(1)'_{L\mu - L\tau}$ coupled predominantly to μ and τ
  $M_{Z\mu}$ could be in sub-GeV range, $Z_\mu \to \mu^+\mu^-$ or $Z_\mu \to \nu\nu$ for $M_{Z\mu} < 2\, m_\mu$

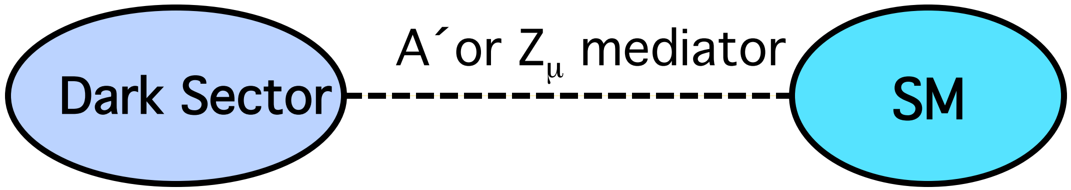
<u>Large recent literature</u>

- explanation of $(g\text{-}2)_\mu$
- mediator of new force, sub-GeV DM
- Impact on ν-physics, mixing matrix
- astophysical observation (EDGES 21-cm anomaly, IceCube cosmic ν, ..)
- ….

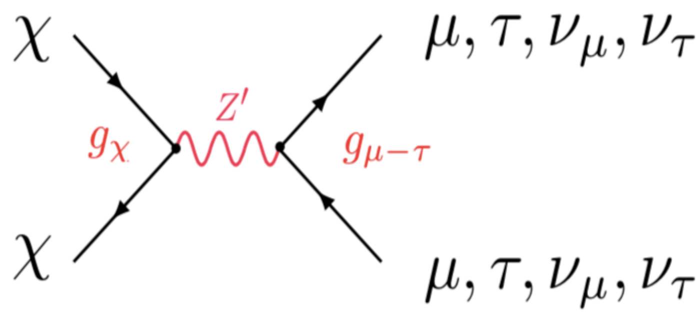
<u>New ideas for NA64μ-like experiment</u>

- L_μ-L_τ Z_μ M[3]@FNAL, arXiv:1804.03144
- Leptophilic LDM, arXiv:1807.03790
- Light scalars of DS, arXiv:1701.07437

sub-GeV Dark Matter and A´or Z_μ mediator

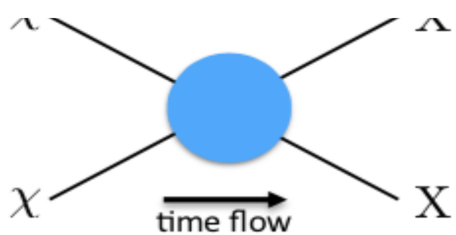


Similar to a dark photon A´, the Z_μ could be a muonic dark photon mediator



LDM candidates χ

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



Kahn,Krnjaic, Tran, Whitbeck 1804.03144

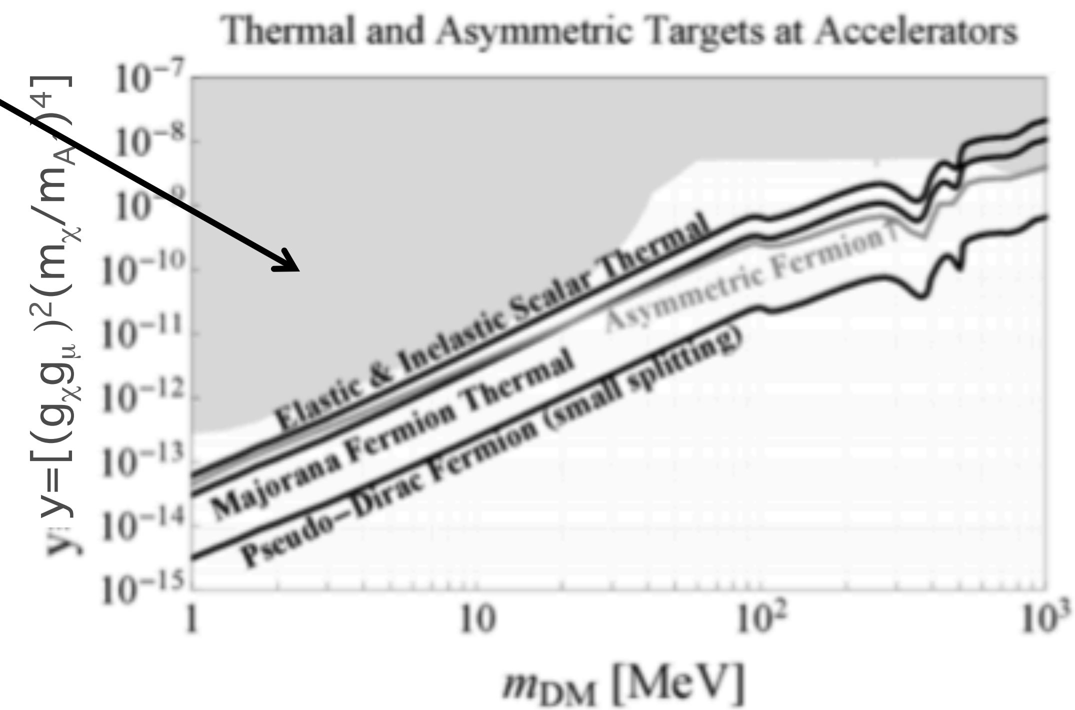
- free parameters m_χ, $m_{Z\mu}$, g_χ, g_μ, the dark coupling is assumed to be $\alpha_{e\text{-}m} < \alpha_D < \alpha_S$
- Z_μ decays:

- $m_{Z\mu} < 2m_\chi$-decays into SM, $Z_\mu \to \nu\nu, \mu^+\mu^-, \tau^+\tau^-$
- $m_{Z\mu} > 2m_\chi$- invisible decays into DM: $Z_\mu \to \chi\chi, \nu\nu$, $\alpha_D >> \alpha_{SM}$, $\alpha_D = g_\chi^2/4\pi$, $\alpha_{SM} = g_\mu^2/4\pi$

- Cross section for χ–DM annihilation:
  $\Gamma_{inel} = n_\chi < \sigma v >$
  $\sigma v \approx [(g_\chi g_\mu)^2 (m_\chi/m_{A'})^4]/m_\chi^2 = y/m_\chi^2$;
  $y = [(g_\chi g_\mu)^2 (m_\chi/m_{A'})^4]$ - useful variable to compare exp. sensitivities

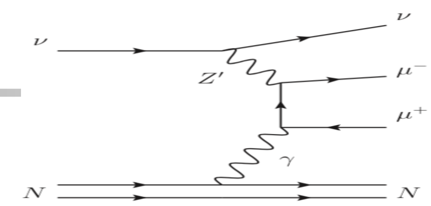
Sub-GeV DM scenarios

The $(g_\chi, g_\mu, m_\chi, m_{Z'})$ parameter space –
a clear sharp target for fixed-target experiments.



Strong motivations to search for A´ and Z_μ in a near future

Constraints on Z_μ of $L_\mu - L_\tau$



- Muon pair-production by neutrinos in CCFR

VOLUME 66, NUMBER 24 PHYSICAL REVIEW LETTERS 17 JUNE 1991

Neutrino Tridents and *W-Z* Interference

S. R. Mishra,[a] S. A. Rabinowitz, C. Arroyo, K. T. Bachmann,[b] R. E. Blair,[c] C. Foudas,[d] B. J. King,

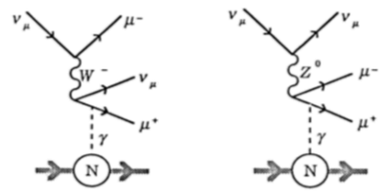


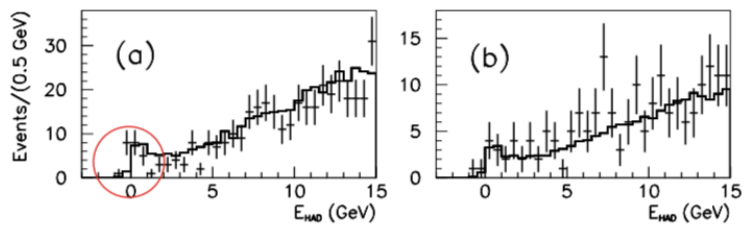
FIG. 1. Feynman diagram showing the neutrino trident production in ν_μ-A scattering via the W and the Z channels.

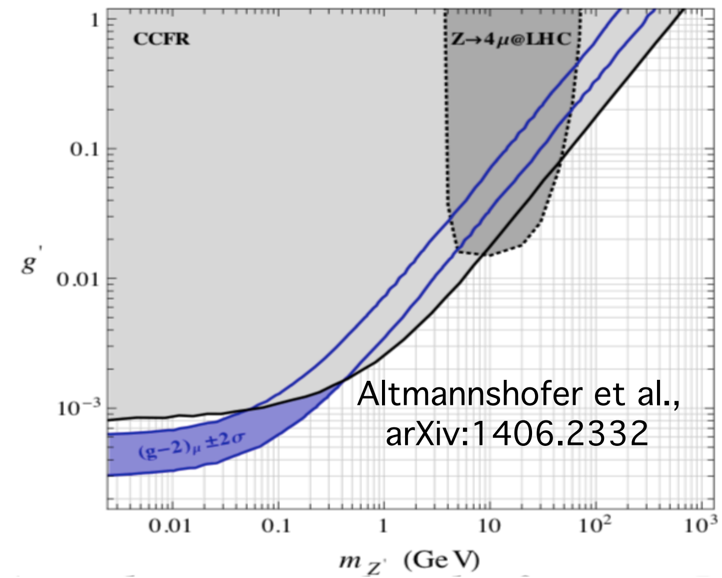
$$\sigma_{\nu N}(\mathrm{CC}) = (0.680 \pm 0.015) E_\nu \times 10^{-38}\ \mathrm{cm}^2/\mathrm{GeV},$$

$$\sigma(\nu\ \mathrm{trident}) = (4.7 \pm 1.6) E_\nu \times 10^{-42}\ \frac{\mathrm{cm}^2}{\mathrm{Fe\ nucleus}}$$

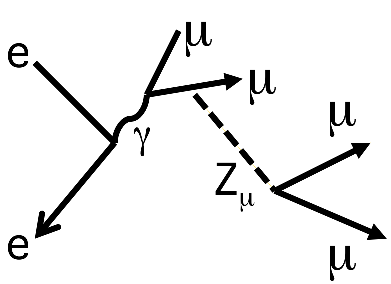
at $\langle E_\nu \rangle = 160$ GeV.

NuTeV results:

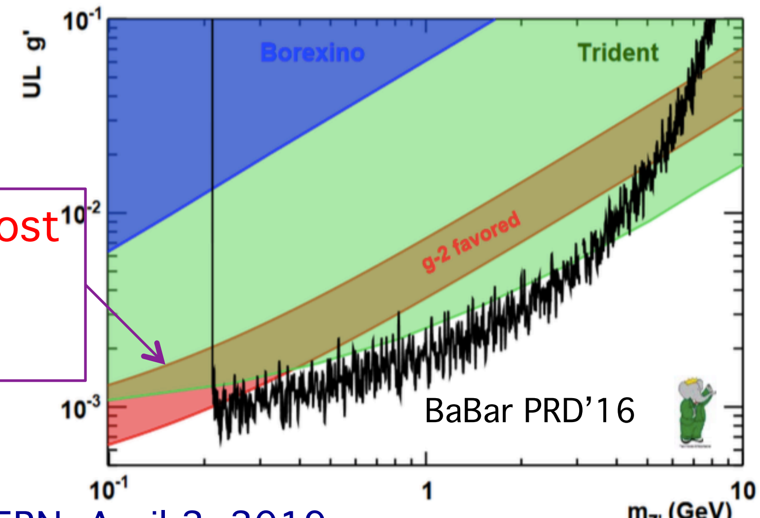




- BaBar searches for $e^+e^- \to 4\mu$

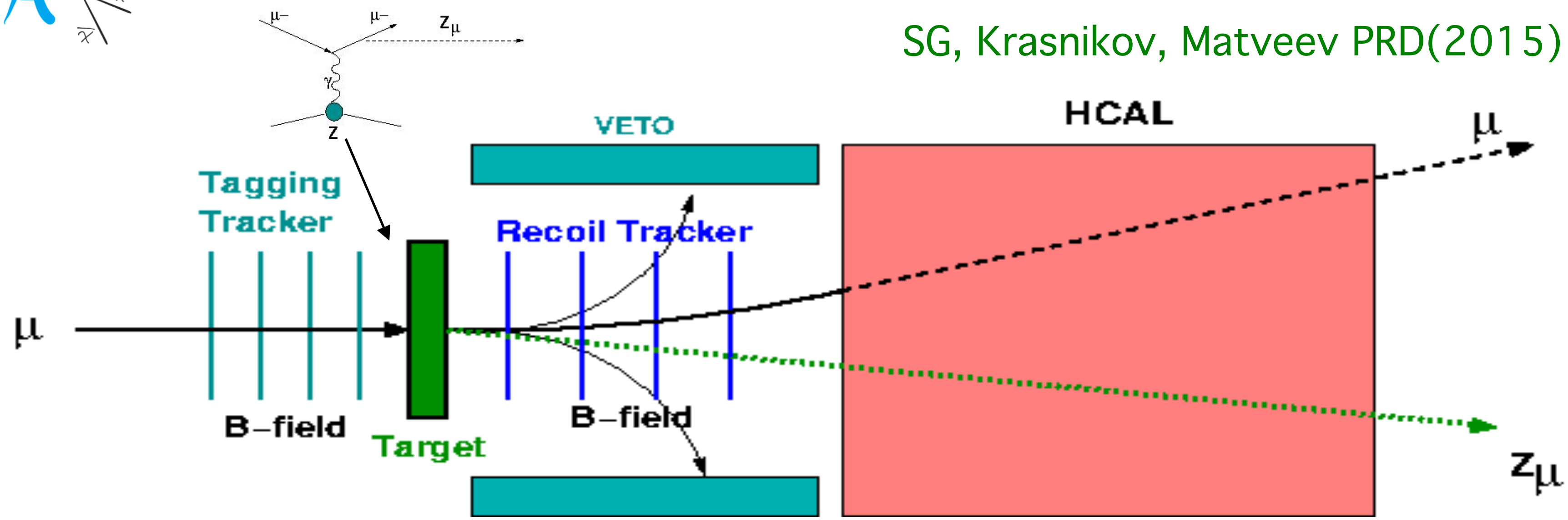


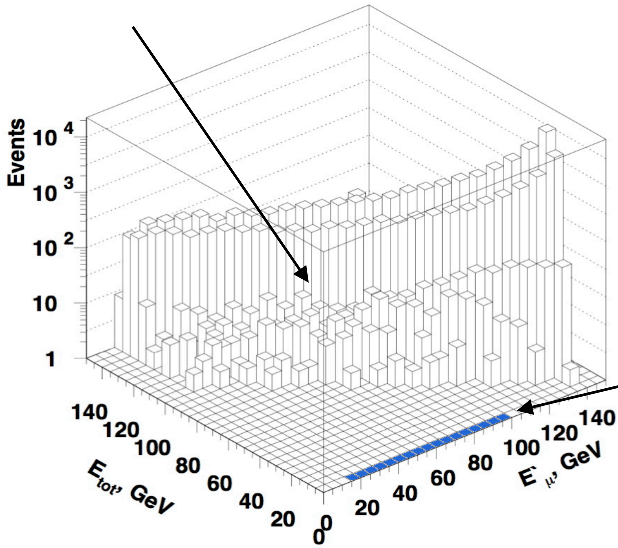
The region $M_{Z\mu} < 2\, m_\mu$ Is most difficult to constrain:
$Z_\mu \to \nu\nu$ decays are invisible



NA64μ method: search for Z_μ -> inv in E_{miss}-events

SG, Krasnikov, Matveev PRD(2015)





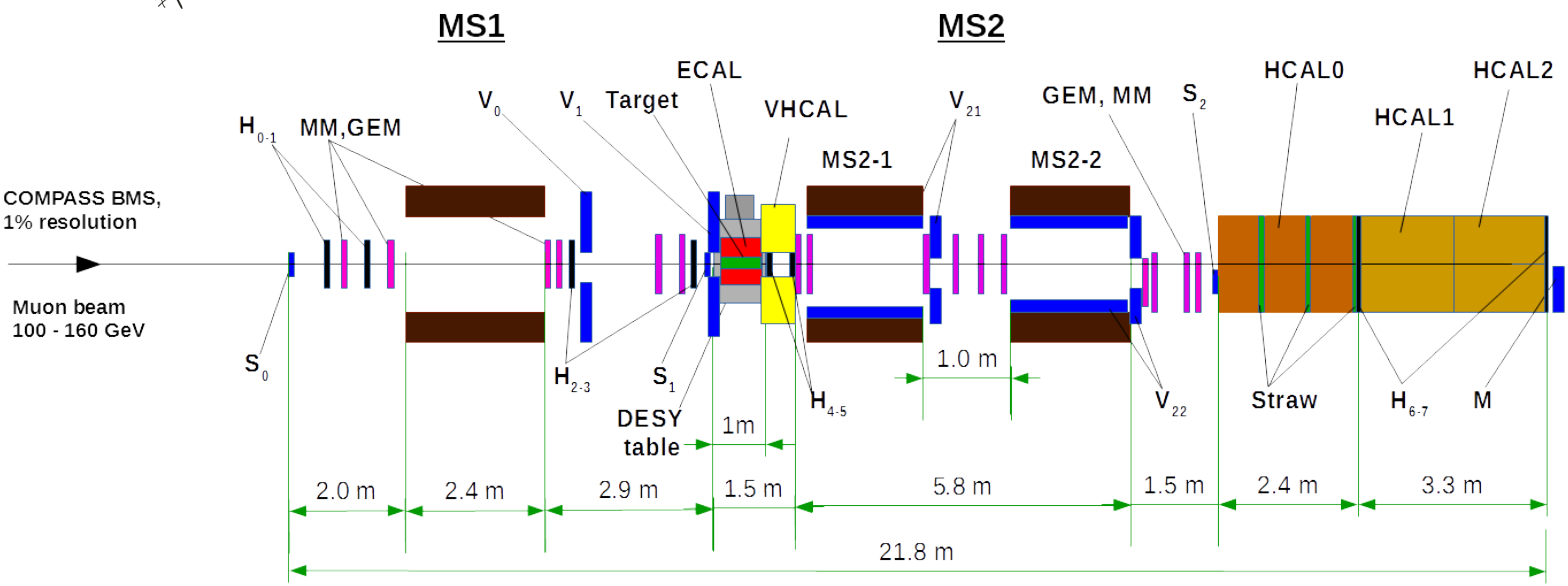
Processes under consideration:

- $\mu Z \to \mu Z\ Z_\mu$; $Z_\mu \to \nu\nu$ – vector case
- $\mu Z \to \mu Z\ a_\mu$; $a_\mu \to$ inv - scalar a_μ, ALPs
- $\mu Z \to \mu Z\ q\bar{q}$ - milliQ particles
- $\mu Z \to \tau Z+..$; $\tau \to \mu\nu\nu$ – LFV μ-τ conversion

Common signature in ($E_{\mu'}$; E_{tot}) plane

- in: 160 GeV μ- track
- out: < 80–100 GeV μ- track
- no energy in the ECAL, Veto, HCAL
- Sensitivity ~ g_μ^2, SES ≤ 10^{-10}

The NA64μ detector



Main components :

- 160 GeV μ- beam, $I_\mu \sim 10^7 \mu$/spill.
- in μ tagging: BMS+MS1(MBPL+tracker)
- out μ tagging: MS2 (2MBPL+tracker)
- 4π-hermetic ECAL, VHCAL, Veto, HCAL
- Location upstream of COMPASS (PBC EHN2 WG)

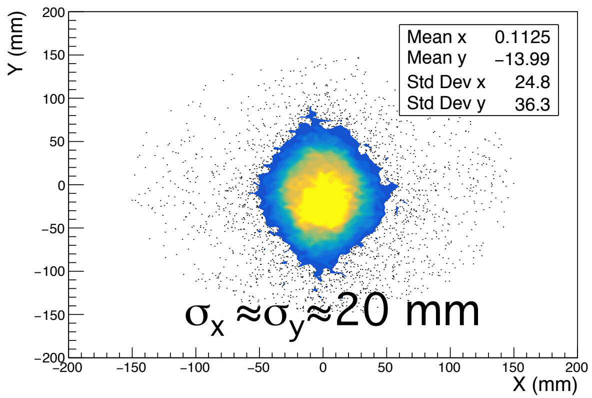
Signature:

- in: 160 GeV μ- track
- out: < 80–100 GeV μ- track
- no energy in the ECAL,Veto,HCAL...
- Sensitivity ~ g_μ^2, SES ≤ 10^{-10}

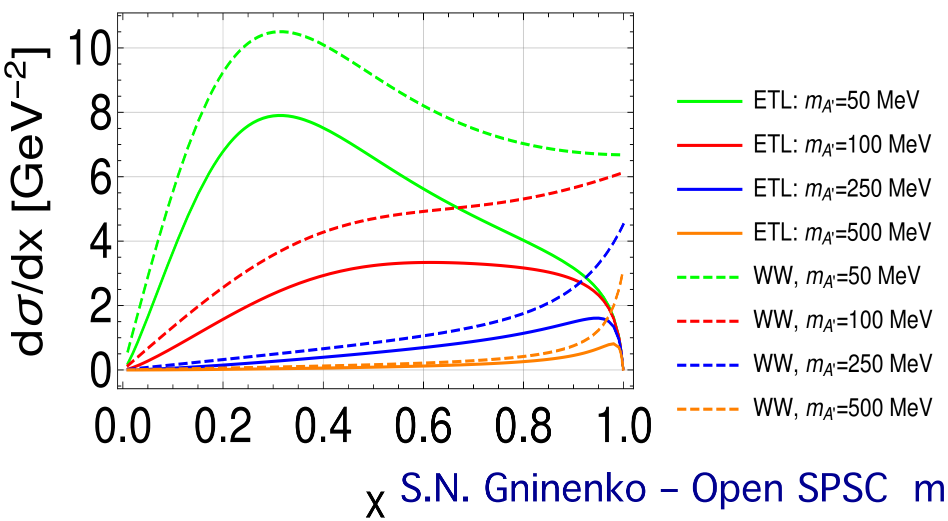
Simulations

- Incoming μ-beam: HALO, D.Banerjee, J.Bernhard (EN-EA-LE)
- $\mu Z \to \mu Z \, Z_\mu$: NA64 code,Geant4
- Sensitivity: ETL cross-sections

Entrance beam



Cross sections

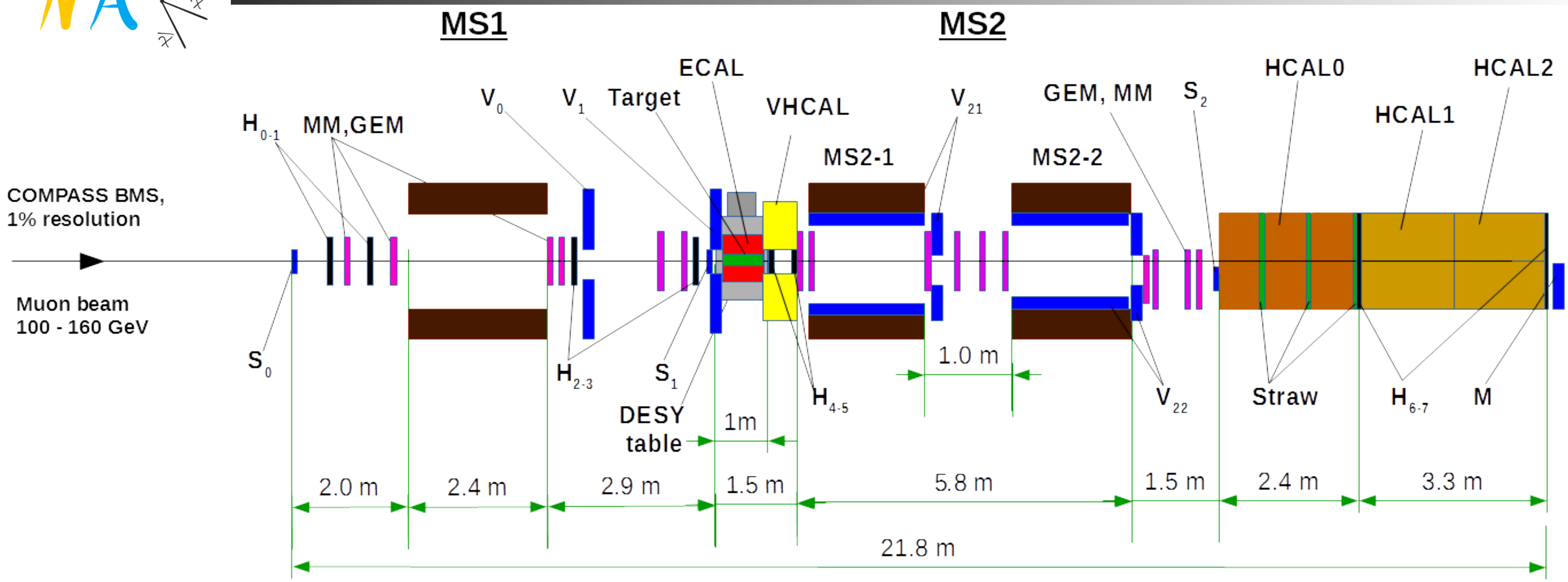


Signal acceptance

Number of Magnets		1 MBPL		2 MBPL	
		SC2 X<-60mm	SC2 X<-70mm	SC2 X<-120mm	SC2 X<-130mm
Muon realistic beam 100 GeV (100000)	Signal [MA = 10 MeV]	73% (56%)	60% (46%)	100% (50%)	99% (50%)
	Signal [MA = 100 MeV]	80% (57%)	66% (47%)	100% (45%)	99% (45%)
	Signal [MA = 1000 MeV]	86% (40%)	76% (36%)	100% (17%)	99% (17%)
	Primary beam	0.08%	0.03%	0.2%	0.06%

Number of Magnets		1 MBPL		2 MBPL	
		SC2 X<-40mm	SC2 X<-50mm	SC2 X<-80mm	SC2 X<-90mm
Muon realistic beam 160 GeV (100000)	Signal [MA = 10 MeV]	73% (69%)	57% (54%)	99% (94%)	96% (91%)
	Signal [MA = 100 MeV]	76% (67%)	63% (55%)	99% (54%)	97% (53%)
	Signal [MA = 1000 MeV]	86% (50%)	75% (44%)	99% (28%)	98% (28%)
	Primary beam	0.3%	0.02%	0.2%	0.05%

Background study

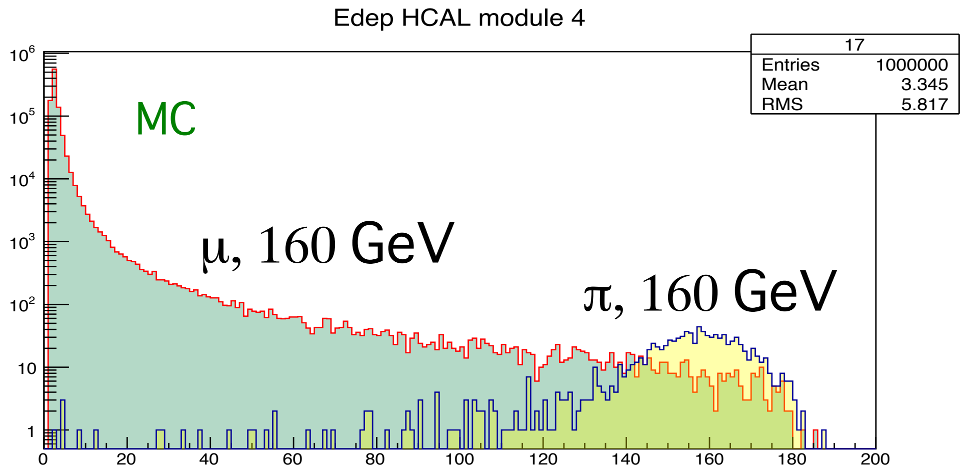


- π , K -> $\mu\nu$ decays: $E_\mu < E_\pi$
- Detector hermeticity: energy leak
- Mis-measurements of $P^{\mu}_{in,out}$ momentum:

Q1: What is the probability for a tagged incoming μ to be a <~80–100 GeV μ?
Q2: What is the probability for a passing beam μ to be reconstructed as a <100 GeV μ?

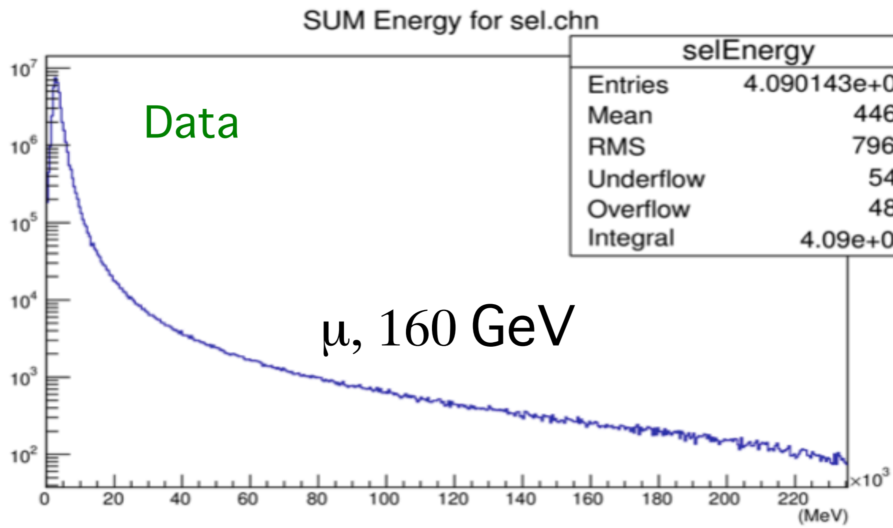
- Physical background (tridents, EW processes, ..): small

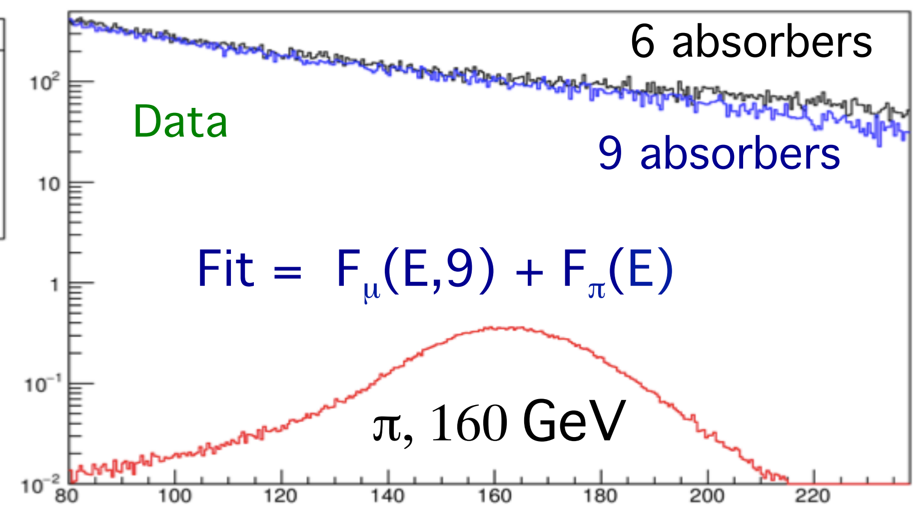
Measurements of π,K contamination in the M2 beam



COMPASS October'17

- empty LiH target
- HCAL calibration, π^- 160 GeV
- Statistics ~ 5×10^8 MOT
- Sensitivity (rough)estimate: $\pi/\mu \sim 6\times10^{-5}/(n_{MOT}/10^6)^{0.5}$

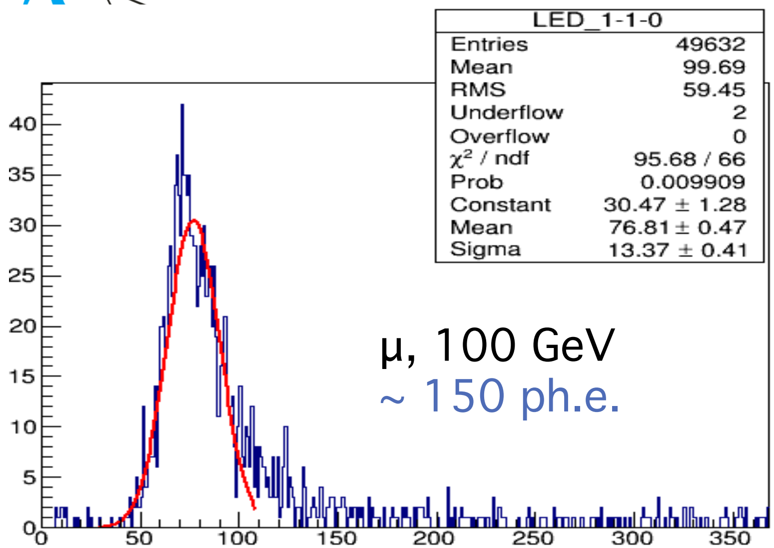


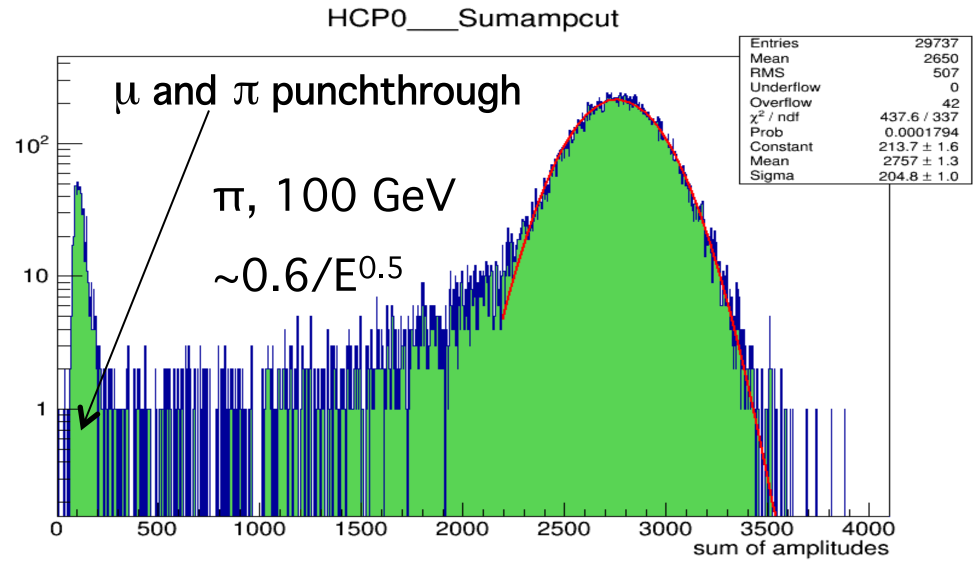


Preliminary results: $\pi,K/\mu = (9.7\pm1.4)\times10^{-5}$ (6 absorbers)

Background from $\pi,K \to \mu\nu$ decays is expected to be small (prelim.)

HCAL longitudinal hermeticity: punchthrough

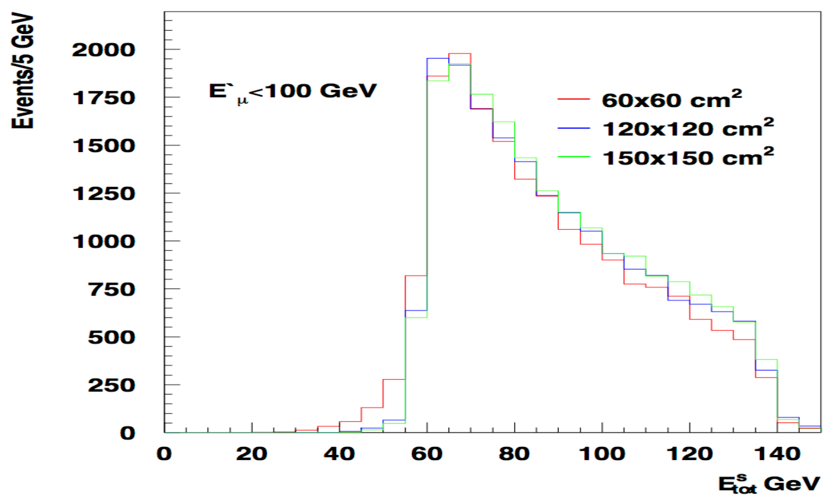


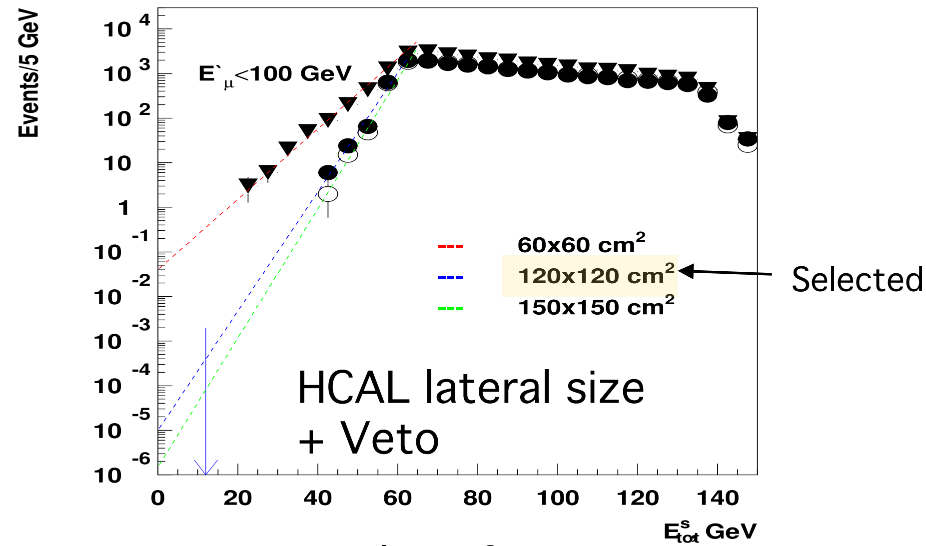


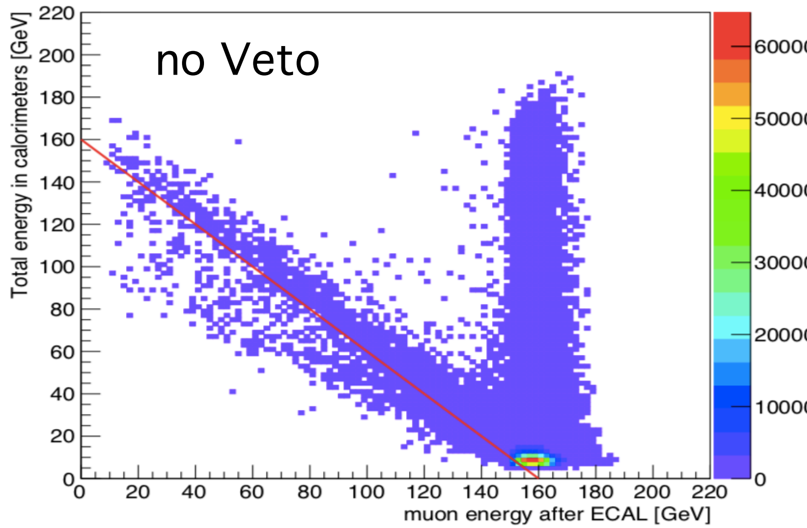
- Crucial number $<N_{ph.e.}>$/MIP ~ 150–200 ph.e. (target~100 ph.e.)
- $\sigma/E \approx 0.56/E^{0.5} + 0.02$, negligible background from the leak to signal box
- HCAL module hermeticity. π–punchthrough level ~ $3\text{x}10^{-3}$ in agreement with MC. Neutrals are estimated from MC.
- Large transverse h-shower fluctuations (NOMAD)

No source of a significant background is identified

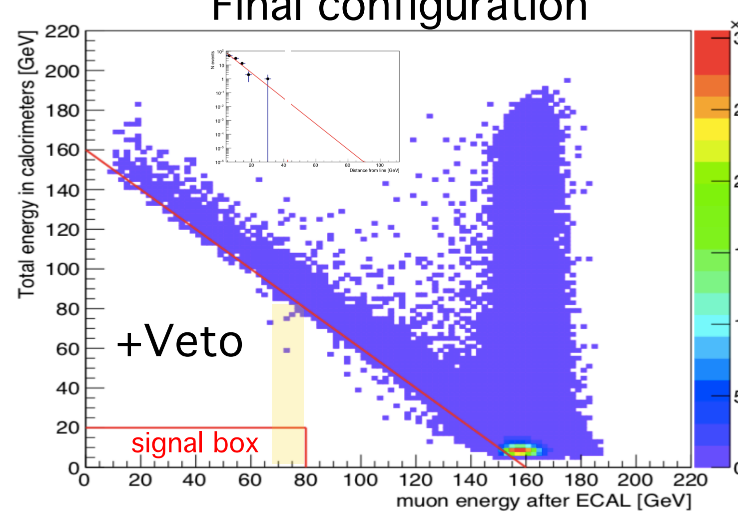
Hermeticity: VHCAL, Veto and HCAL lateral size







Final configuration



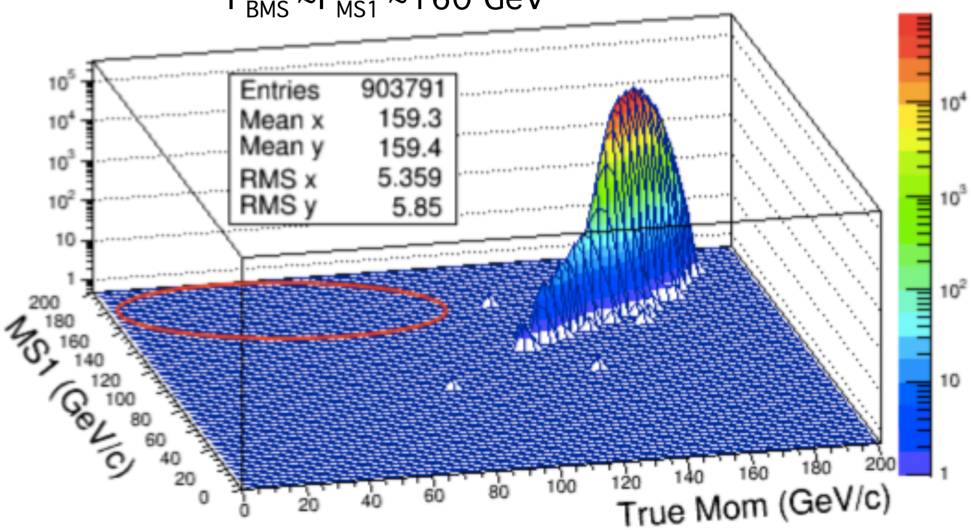
Estimate from the background extrapolation to the signal region: $\leq 10^{-11}$

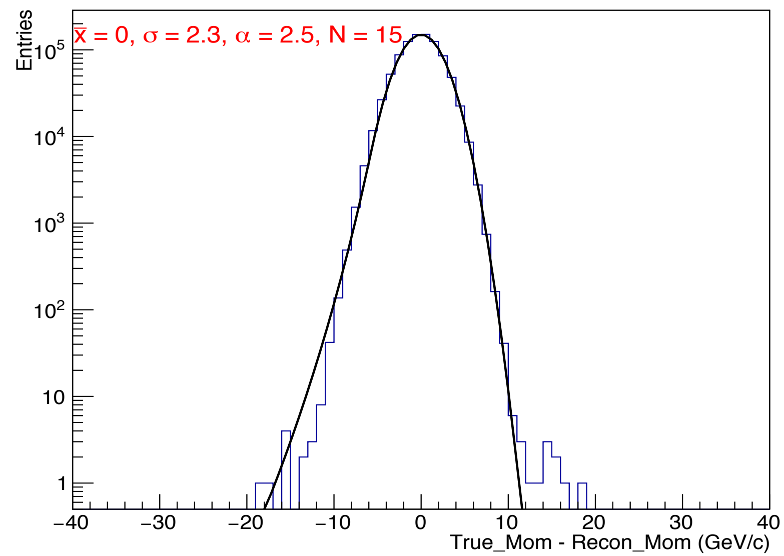
Mis-measurement of incoming muons

Q1: What is the probability for a tagged incoming μ to be a < 80 GeV μ?

Simulation of incoming muons: BMS vs MS1

$P_{BMS} \sim P_{MS1} \sim 160$ GeV





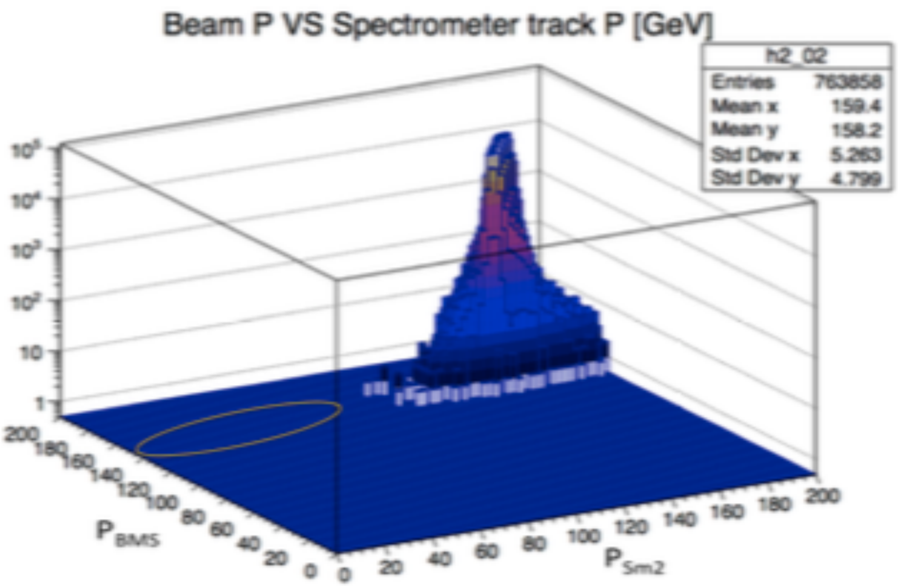
$\Delta = P_{TRUE} - P_{RECO}$, GeV

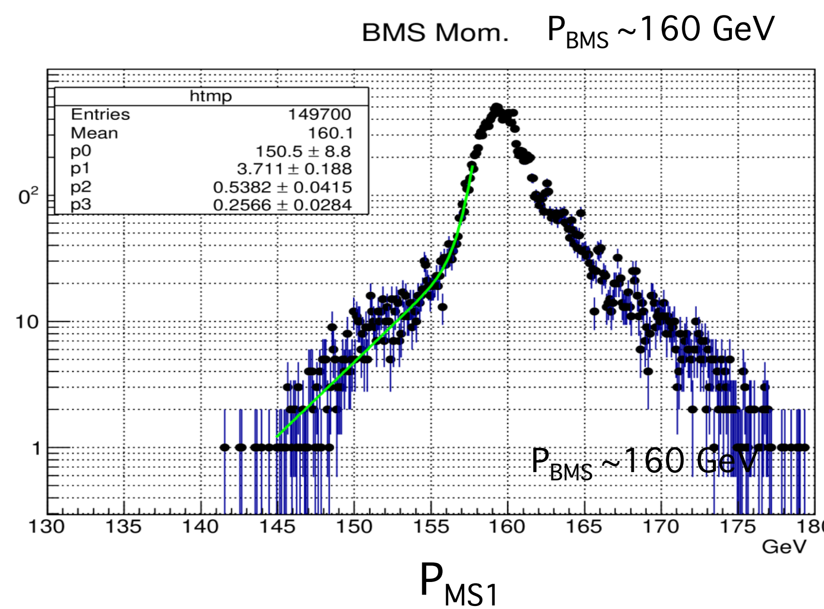
Probability estimate from the extrapolation: P_{in} (Δ < 80 GeV) < 10^{-11}

Mis-measurement of passing beam muons

Q2: What is the probability for a passing beam μ to be reconstructed as a < 80 GeV μ?

COMPASS data sample: BMS vs SM2 track reconstruction





Probability estimate from the extrapolation: P_{out} (80 GeV) < 10^{-11}

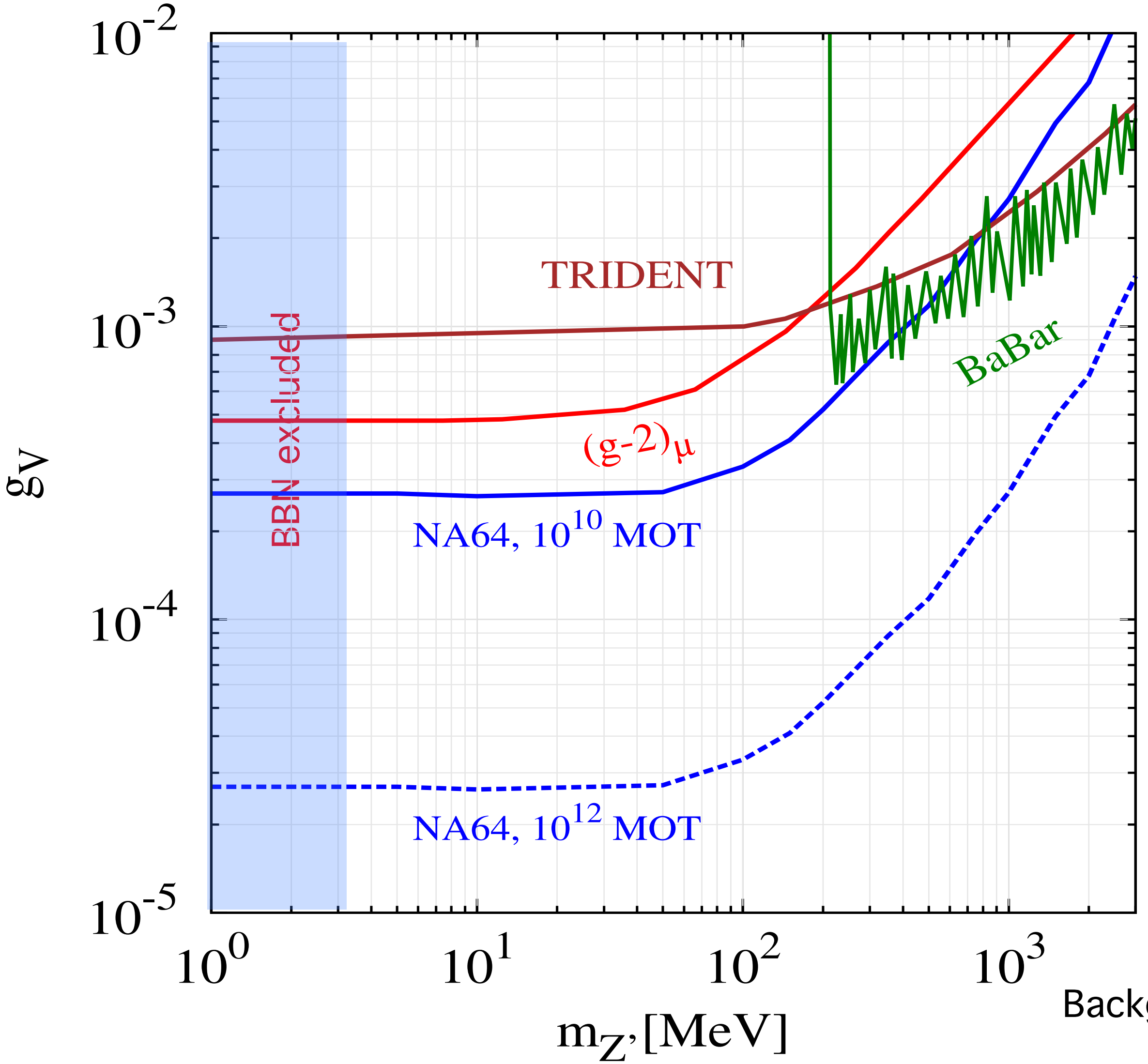
Background summary

Table 1. Expected contributions to the total level of background from different background sources estimated for a beam energy of 160 GeV (see text for details).

Source of background	Expected level
Impurity of incoming muons	$\lesssim 10^{-11}$
Impurity of outqoing muons	$\lesssim 10^{-11}$
pion contamination (9 absorber case)	$\lesssim 10^{-12}$
kaon contamination (9 absorber case)	$\lesssim 10^{-11}$
HCAL lateral nonhermeticity	
- single-MBPL case	$\lesssim 10^{-11}$
- two- MBPL case with additional VHCAL	$\lesssim 10^{-11}$
μ induced reactions in the target	$\lesssim 10^{-13}$
μ trident events	$\lesssim 10^{-12}$
Total (preliminary)	
- single-MBPL case	$\lesssim 10^{-11}$
- two- MBPL case	$\lesssim 10^{-11}$

Expected sensitivity

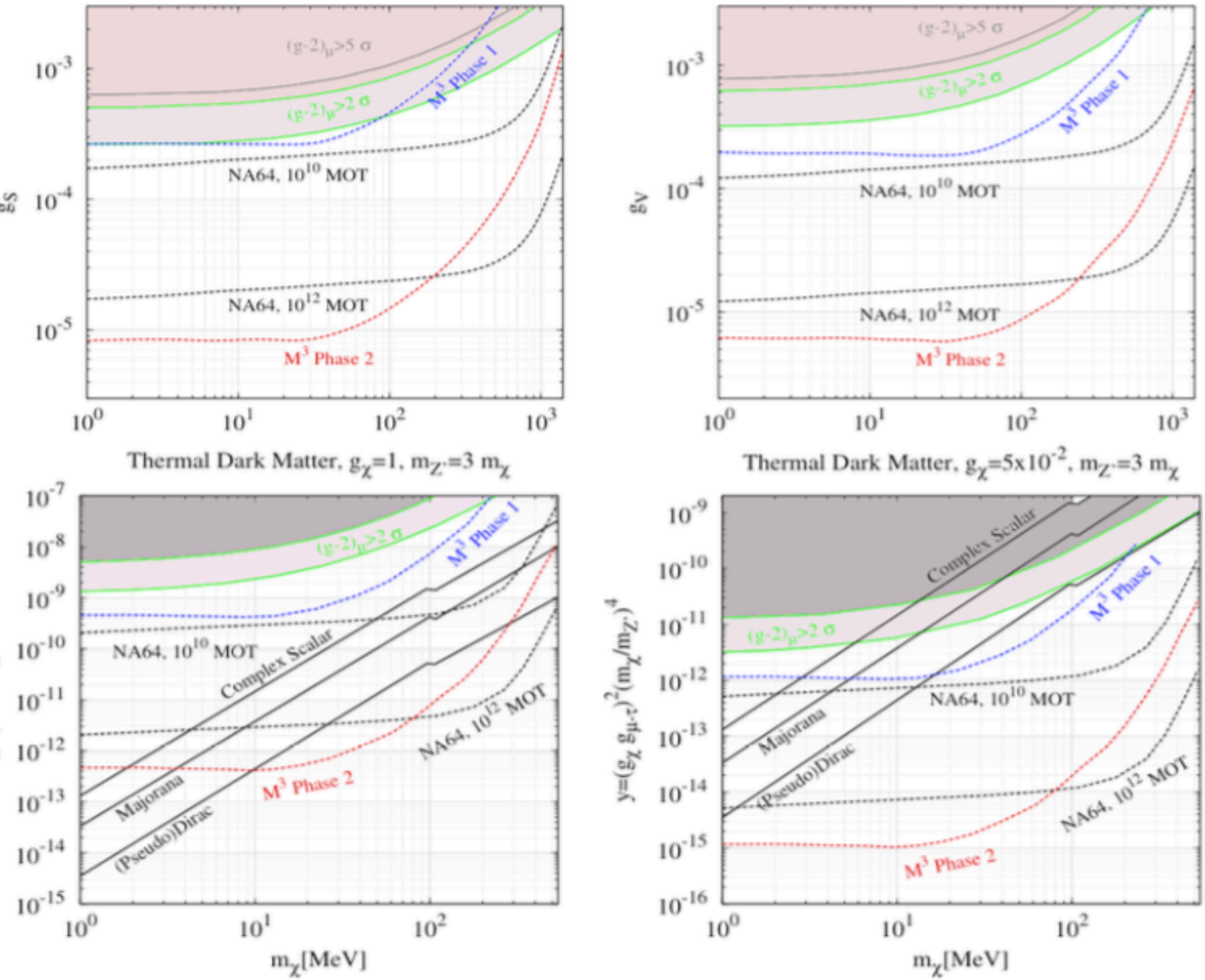
160 GeV μ⁻



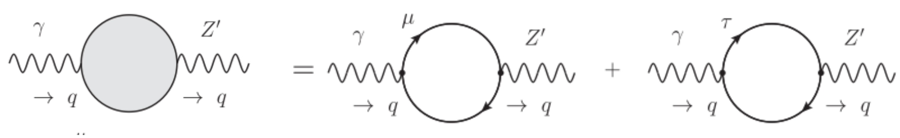
Background-free case.

DM sensitivities of NA64μ and M³@FNAL

NA64 need just <~ 10^{11}
to probe muon g-2 region

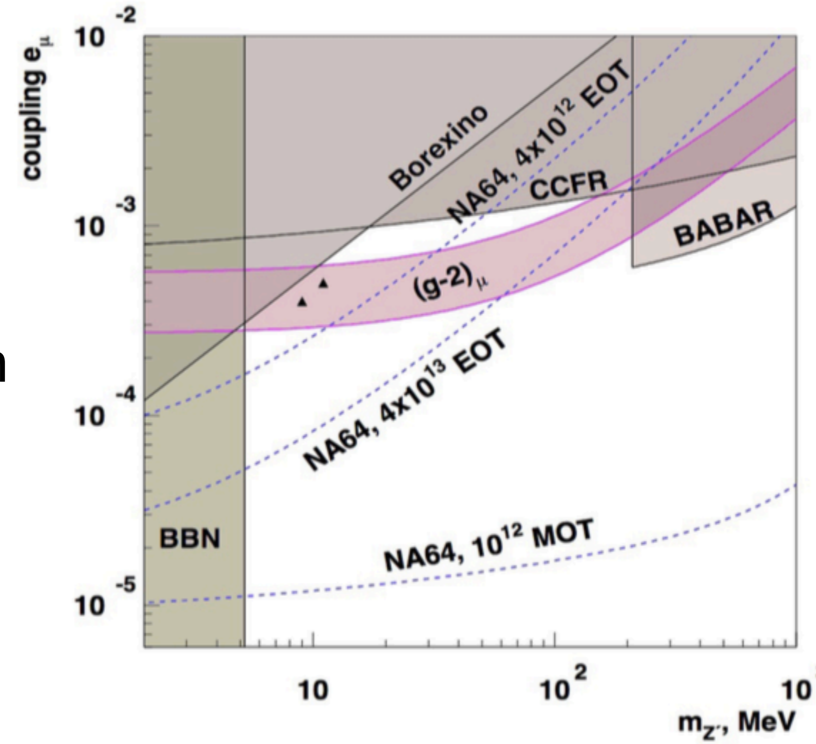


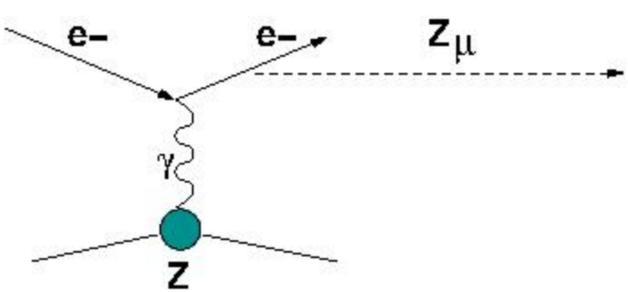
Complementarity of e and μ searches (I): $\gamma - Z_\mu$ mixing



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

in $e^- Z \to e^- Z Z_\mu$; $Z_\mu \to$ invisible
(similar to A´)





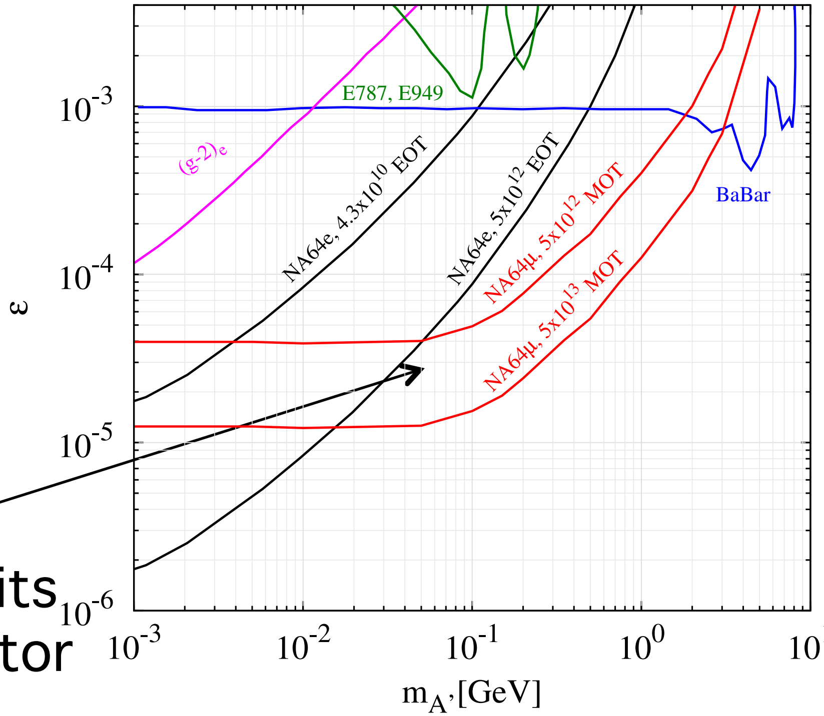
Complementarity of NA64e and NA64μ: if Z_μ is observed in NA64μ it should be seen in NA64e

SG, N.Krasnikov,1801.10448

Complementarity of e and μ searches (II): the A´case

arXiv:1903.07899

- For $e(\mu) + Z \to e(\mu) + Z + A'$, $E \gg m_\mu$
  $N_{A'} \sim N_{e,\mu}\, \varepsilon^2 m_e^2/m_{A'}^2$
  Cr-sec is suppressed for $m_{A'} >\sim m_\mu$
- The μ case: an enhancement $\sim 10^2$ occurs from the ratio t_μ/t_e of the effective target lengths for μ and e^-
  The $t_e \sim X_0$ while for the μ case it is $t_\mu \sim t_{tag} \gg X_0$
- NA64μ can significantly improve limits for A´ mass ~ 0.1- 1 GeV, by a factor $\sim 10^2$ for ε^2, y and α_D (next slide)

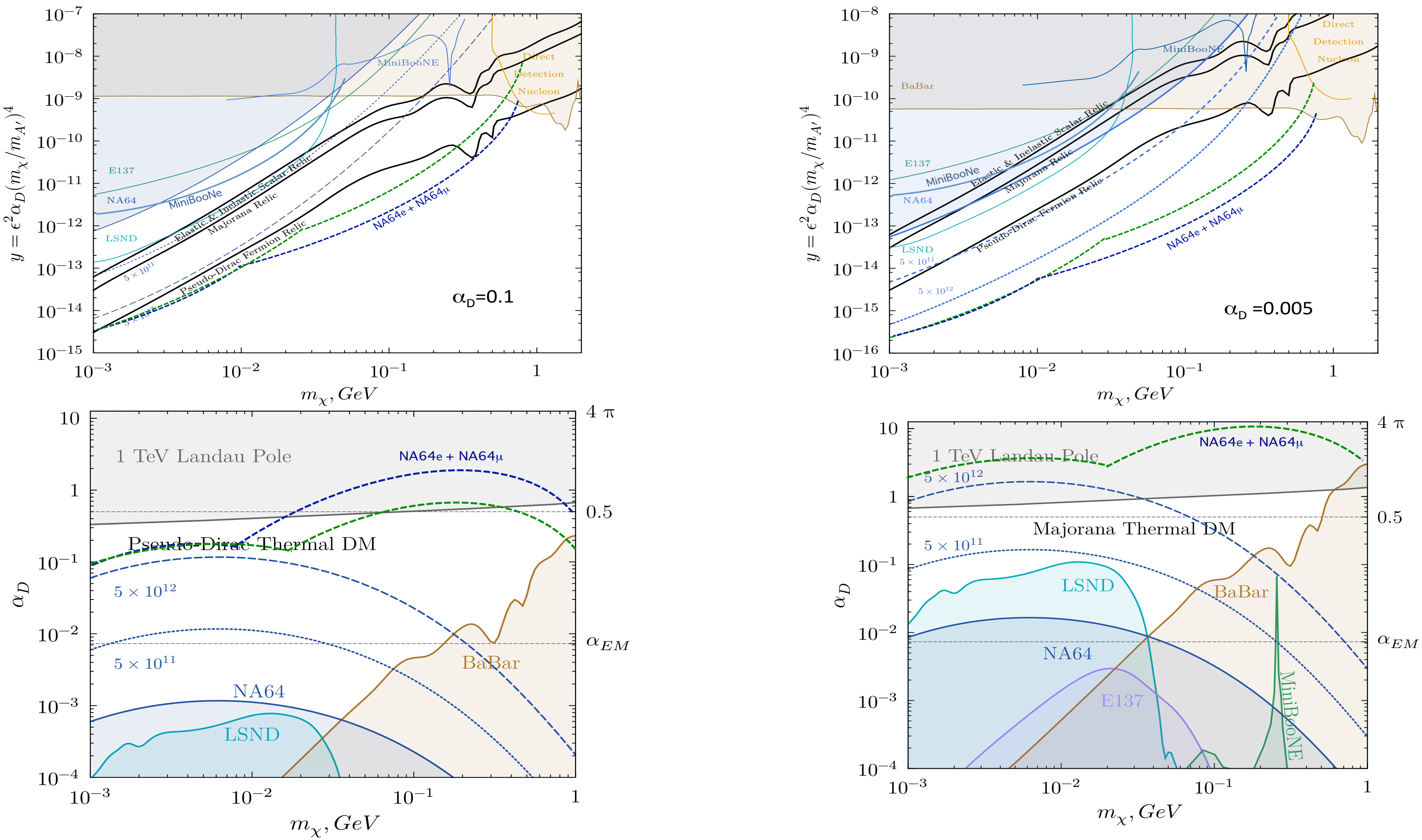


These new oservations significantly strengthen motivation for the experimental search of the A´and Z_μ portals with M2 muon beam

Combined NA64e and NA64μ results: sub-GeV DM

10^{13} EOT (NA64e)+10^{13} MOT (NA64μ)

10^{13} EOT (NA64e)+2x10^{13} MOT (NA64μ)



Summary

The existence of the M2 beam-line at CERN provides unique opportunity to explore new physics in the muon sector.

We propose to take this possibility by using NA64μ as a sensitive probe of Dark Sector physics.

NA64μ' s research program complementing NA64e's includes:

- Test of the remaining explanation of the g_μ-2 anomaly
- Searching for invisible decays of DM mediators, full coverage of the remaining parameter space of the most interesting LDM models
- Test of a variety of other models: milliQ, ALPs, LVF μ - τ conversion... and possibly additional Dark Sector signatures

It has been reported and widely discussed at PBC BSM

To ensure timely delivery of the high quality physics results we propose a two-steps plan (in collaboration with PBC EHN2 WG):

Phase I: g_μ-2
pilot run 2021or 2022,
1st physics run 2023,
~$10^7 \mu$ /spill, ~10^{11} MOT

Phase II: Dark Sector
physics run 2024 =>
~$5x10^7 \mu$ /spill, ~10^{13} MOT

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SPSC
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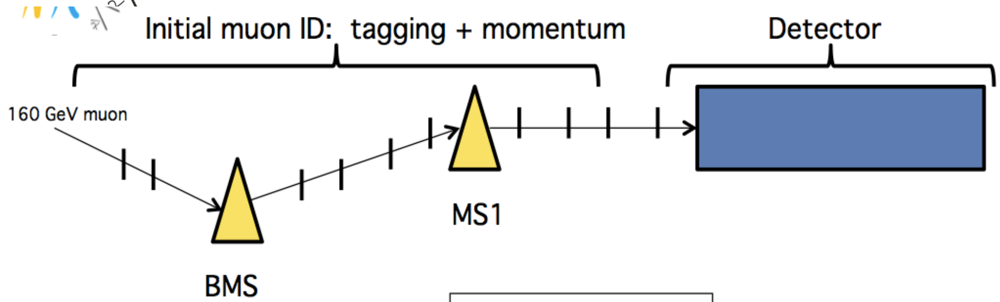
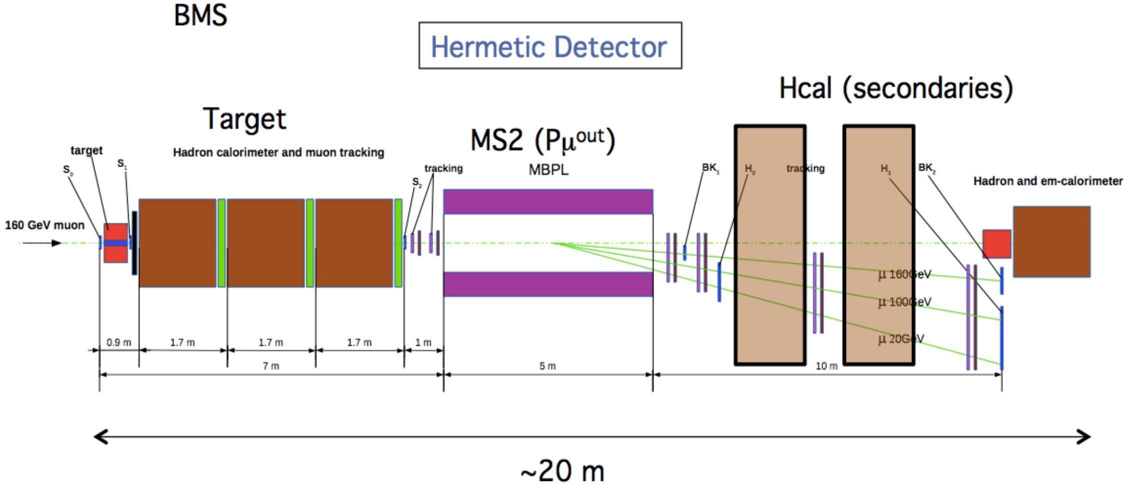
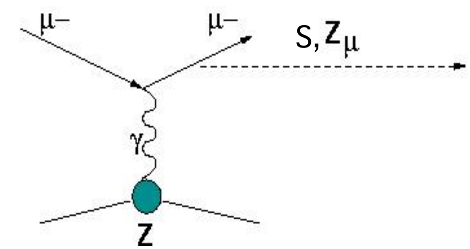
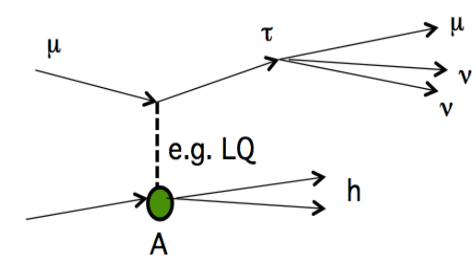
Back up

Search for $Z_{\mu\tau}$ in missing energy events with M2 beam









Main components :

- clean, mono-energ. 160 GeV μ- beam
- in μ tagging: MM/GEM tracker
- out μ tagging: GEM/Straw tracker
- 4π fully hermetic detector

Signature:

- in: 160 GeV μ- track
- out: < 100 GeV μ- track
- no energy in the ECAL, Veto, HCAL
- Sensitivity ~ g_Z^2

Summary of plans

NA64e

- Detector upgrade, and assembly H4B
- 2021 Run: A´,^{8}Be* anomaly, ALPs
- 2021–23 run:
  - ✧ ~5x10^{12} EOT
  - ✧ to cover the sub-GeV DM param. space
  - ✧ to clarify the origin of the ^{8}Be* anomaly

NA64μ

- 2021–22 M2 pilot run
- Phase I : test $(g\text{-}2)_\mu$ ~10^{11} MOT, short-term
- Phase II : S_μ, Z_μ, A´, LDM milliQ with ~10^{13} MOT

NA64++ provisional time schedule

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

e^-, H4 →	$(g\text{-}2)_\mu$, 8Be, Dark Sector	LS2	8Be, Dark Sector	LS3	Dark Sector
μ^-, M2 →	Proposal, Preparation		g_μ-2, Dark sector, μ-τ	LS3	Dark sector, μ-τ
π^-, K^-, H2-H8,T9 →	Proposal		$\pi^0,\eta,\eta',K_L \to inv$	LS3	$\pi^0,\eta,\eta',K_S,K_L \to inv$