NA64: new results and prospects

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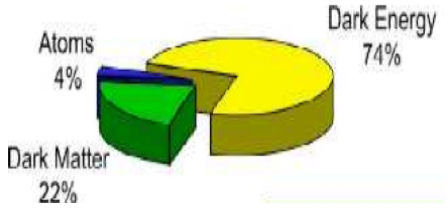
Outline

- Motivation
- NA64 overview
- Results with e^- : A´->inv, LDM, X, A´-> ee, ^{8}Be anomaly
- Plans for μ^- : S_μ Z_μ and (g-2)μ, high mass A´and LDM
- Summary

What makes up most of the Universe's mass?

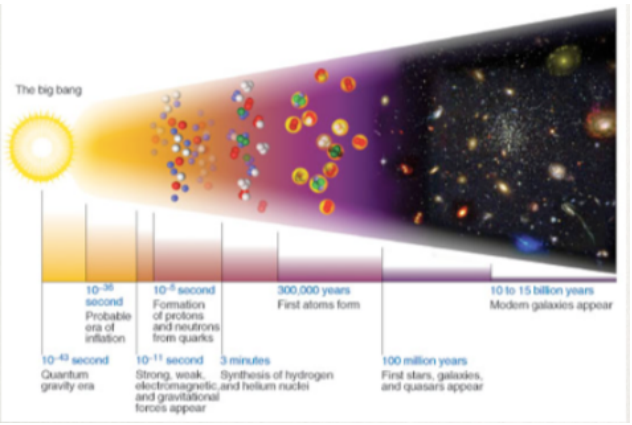


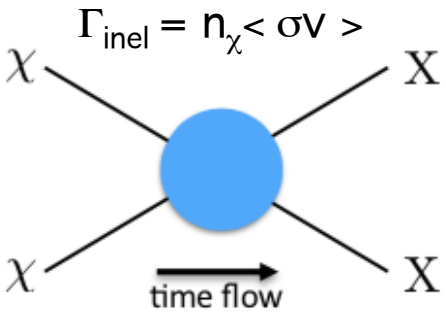
One of possible answers:

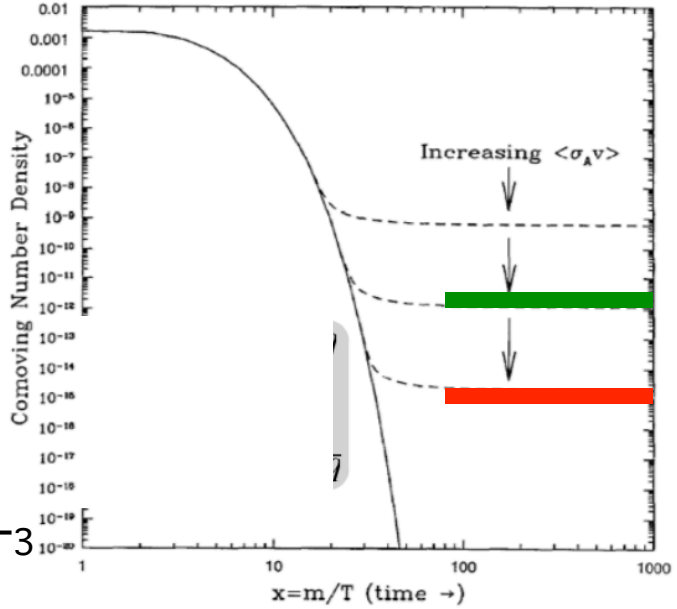
light, sub-GeV scale DM from Dark Sector (DS).

Dark sector consists of particles and fields which are singlets with respect to the gauge group of the SM and interacts with visible matter presumably only via gravity.

Thermal Dark Matter



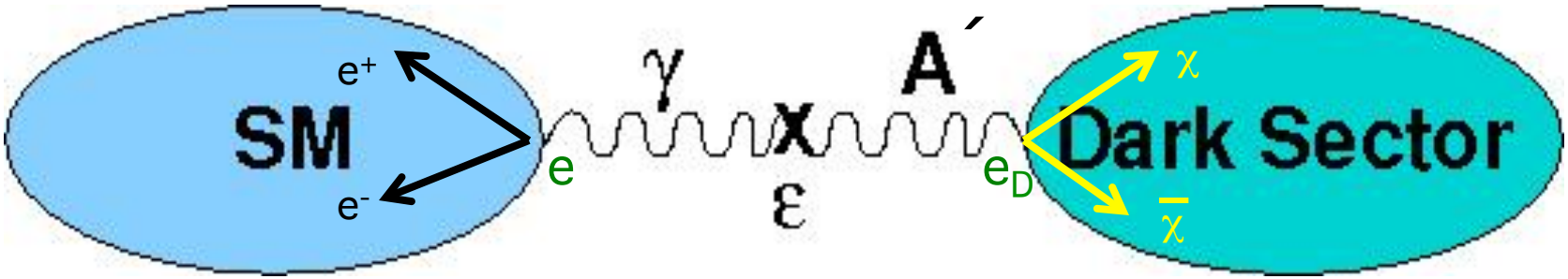




- For $T >> m_\chi$, $\chi\chi$-SM ann. is in equilibrium, $n_\chi \sim T^3$
- Hubble expansion, T & n_χ decrease
- For $T < m_\chi$ $\chi\chi$-SM annih. gets suppressed, $n_\chi \sim T^{3/2} e^{-m\chi/T}$
- Finally $\chi\chi$-SM annih. stops, n_χ~ frozen in time $\Gamma_{inel} = n_\chi < \sigma v > \sim H$
- $< \sigma v > \cong 3 \times 10^{-26}$ cm^3/s $\cong$ (1/20 TeV)^2
- If DM is in sub-GeV range it must be SM neutral
- Thermal freeze-out motivate new interaction to mediate DM-SM annihilation. New force in addition to gravity is required!

Vector portal to Dark Sector

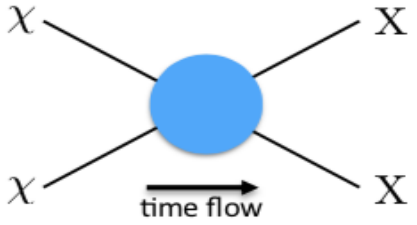
Okun, Holdom' 86 ..



- new massless (mirror DS) or massive dark photon with γ–A´ kinetic mixing: $\Delta L=\varepsilon/2\ F^{\mu\nu}A'_{\mu\nu}$
- GUT prediction for the size of the γ-A´ mixing strength ($\varepsilon<<1$):
  1-loop: $\varepsilon \sim 10^{-4} - 10^{-2}$; 2 loops: $\varepsilon \sim 10^{-5} - 10^{-3}$, $m_{A'} \sim \varepsilon^{1/2} M_Z$
- A´ decays:

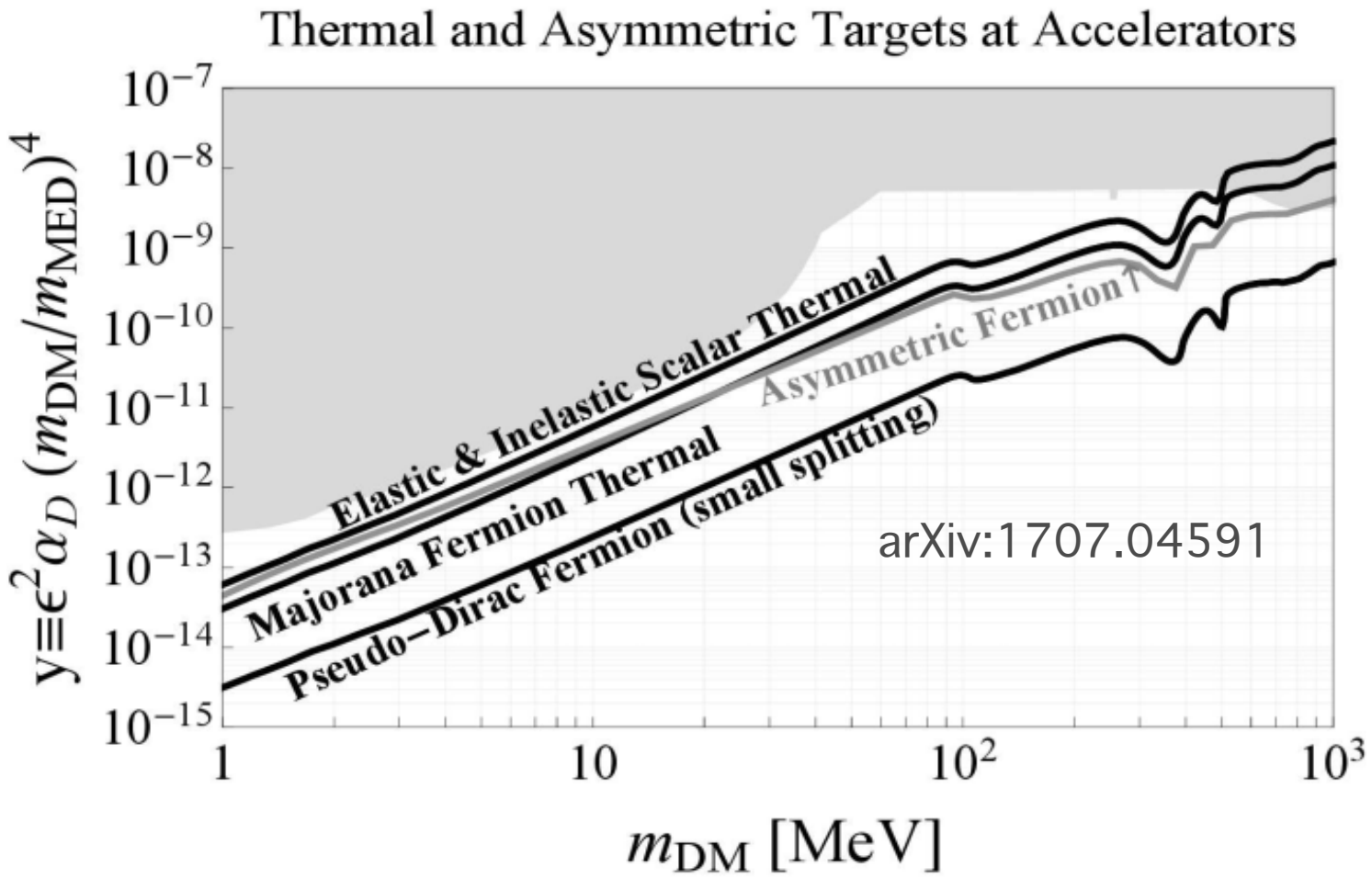
- $m_{A'}<2m_\chi$: visible decays into SM, A´→ e^+e^-, $\mu^+\mu^-$, hadrons,..
- $m_{A'}>2m_\chi$: invisible decays into DM: A´→ $\chi\chi$, $\alpha_D >> \varepsilon$, $\alpha_D=e_D^2/4\pi$

- Cross section for χ–DM annihilation:
  $\Gamma_{inel} = n_\chi < \sigma v >$
  $\sigma v \approx [\alpha_D\, \varepsilon^2 (m_\chi/m_{A'})^4]\ \alpha/m_\chi^2 = y\ \alpha/m_\chi^2$;



$y=[\alpha_D\, \varepsilon^2 (m_\chi/m_{A'})^4]$ - useful variable to compare exp. sensitivities

Sub-GeV Thermal DM scenarios



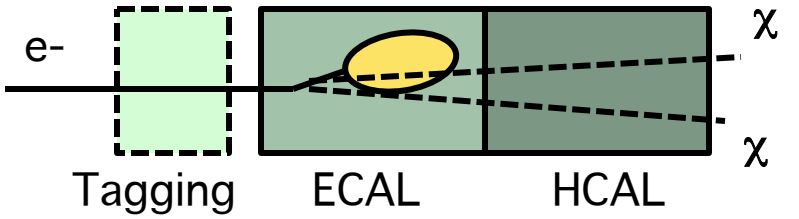
- light DM candidates χ : scalars, Majorana, pseudo-Dirac fermions.
- $(\varepsilon, \alpha_D, m_\chi, m_A)$ parameter space: target for accelerator experiments

Two approaches to probe LDM at fixed-target exp.

- Bremsstrahlung, e.g. $e^- Z \rightarrow e^- Z A'$, $\sigma \sim Z^2\varepsilon^2/m_{A'}^2$
- $\pi^0, \eta, \eta' \ldots \rightarrow \gamma A'$, $A' \rightarrow \chi\chi$, ee, $\mu\mu$, ..

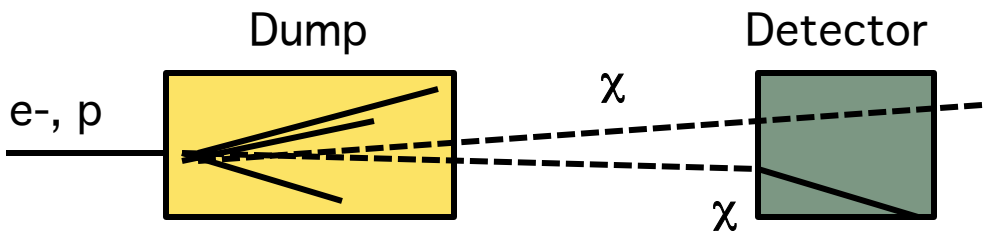
Missing energy/momentum

NA64e (active dump)

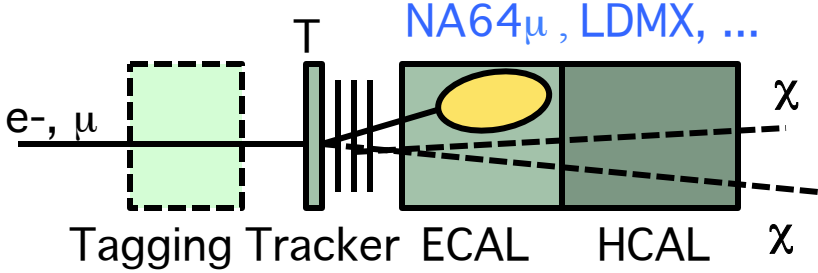


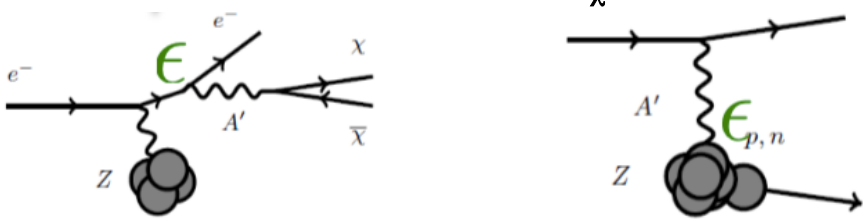
Beam dump

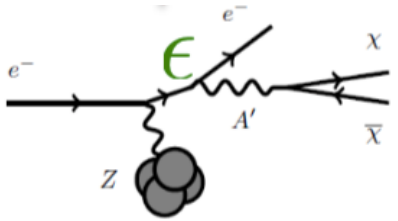
BDX, NA62D, SeaQuest,...



NA64μ , LDMX, ...







$n_S \sim \alpha_D \varepsilon^4 n_{pot}$

$n_S \sim \varepsilon^2 n_{eot}$

NA64e at the CERN SPS

NA64 is designed to search for new, in particular Dark Sector physics in missing energy events. Broad research program with e-, μ, π, K, and p beams at the CERN SPS (PBC'16–19).

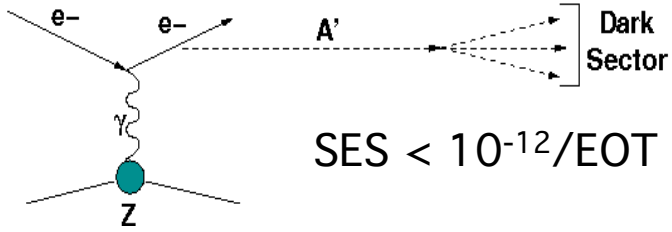
History:

- **December 2013:** proposal P348 to SPSC
- **April 2014:** recommended for tests
- **April 2014-March 2015:** design, production, delivery at CERN.
- **October 2015:** feasibility test run+upgrade
- **March 2016:** approved as NA64 experiment at the CERN SPS

Main goals for searching in 2016 - 2018 runs:

- Invisible A´ as an explanation of $(g\text{-}2)_\mu$
- A´ mediator of LDM production in invisible decay mode
- New X(17) boson from the ^{8}Be anomaly, A´->e+e- decays

Searches for A´->invisible decays: NA64e@CERN SPS



SES < 10^{-12}/EOT

Signature:

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

S.Andreas et al., arXiv: 1312.3309
S.G., PRD(2014)

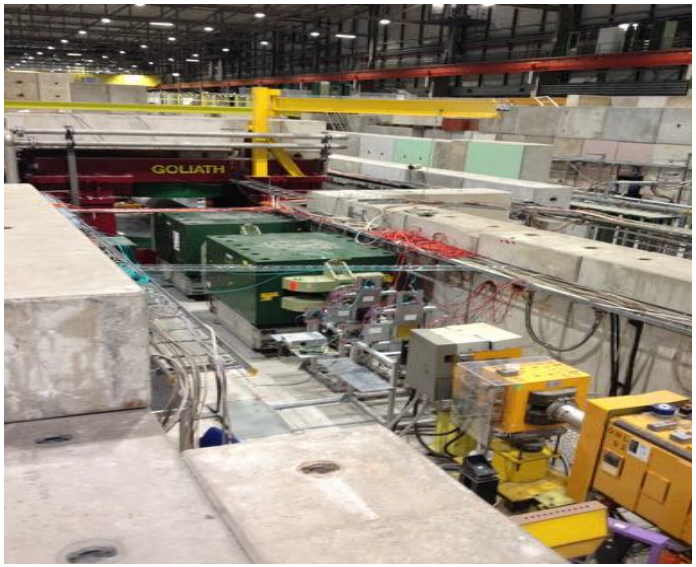
Main components :

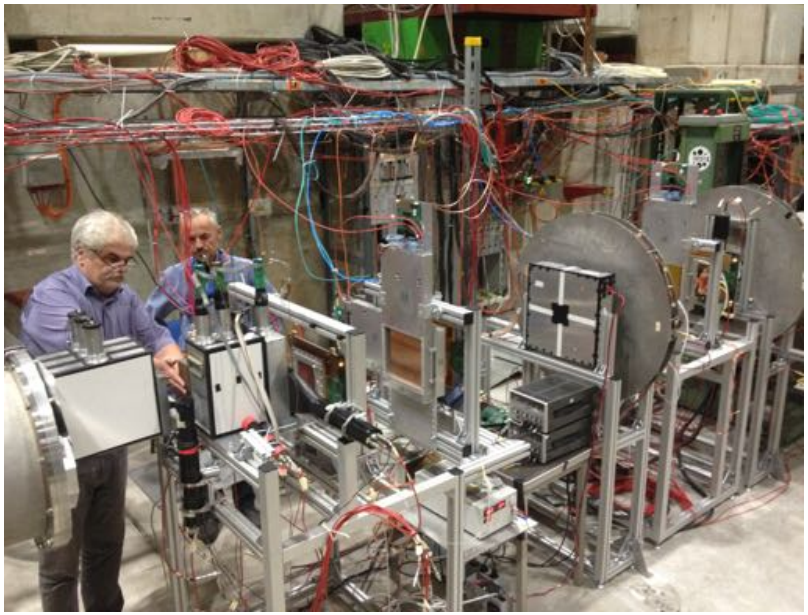
- clean 100 GeV e- beam
- e- tagging system: tracker+SRD
- 4π fully hermetic ECAL+ HCAL

Background:

- e- from μ, π, K decays in flight
- e- from interactions in beamline
- energy leak from ECAL+HCAL

2018 run





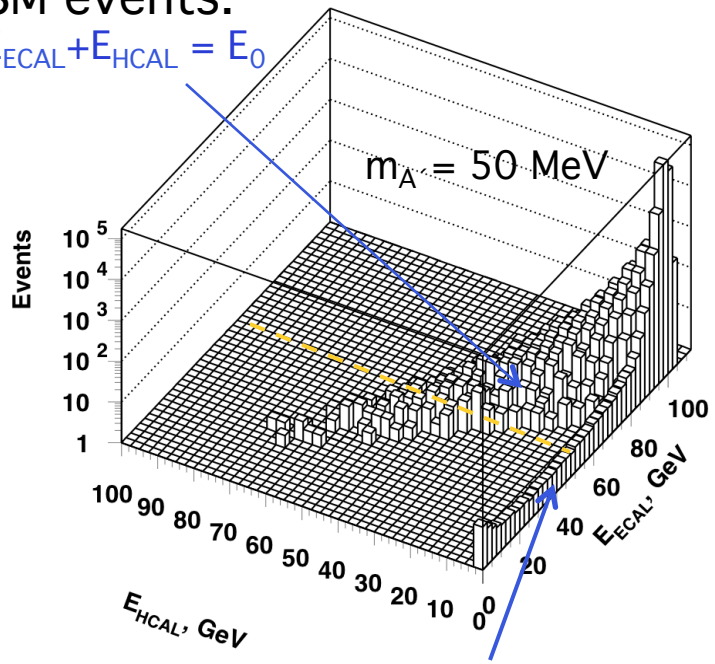
1.

Simulations of eZ->eZA´; A´-> invisible

SG, Kirsanov,Krasnikov, Kirpichnikov, PRD(2016)

SM events:

$E_{ECAL}+E_{HCAL} = E_0$



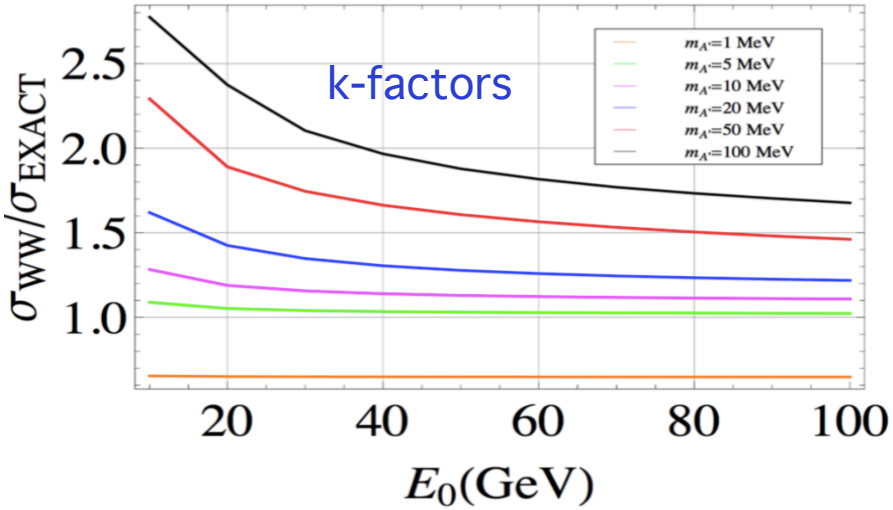
A´ events:

$E_{ECAL}<E_0$; $E_{HCAL}=0$

ETL vs WW cross sections:
Strong reduction for $m_{A'} > m_{A'}$

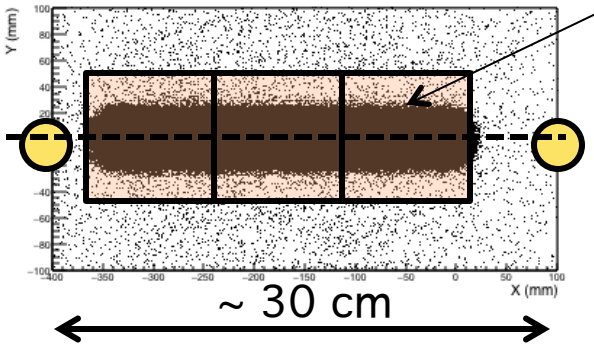
- GEANT4+code for A´ emission in the process of e-m shower development
- WW approximation for σ(e⁻Z->e⁻ZA´) (Bjorken et al.'09)
- Corrections (k-factors) to WW from exact tree-level (ETL) calculations: large for higher A´ masses
- The shape of WW and ETL differential cross sections is quite similar: strongly peaked at x= $E_{A'}/E_0$ ~1.

arXiV:1712.05706

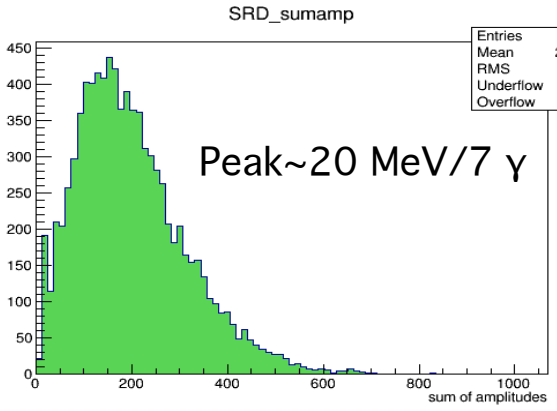


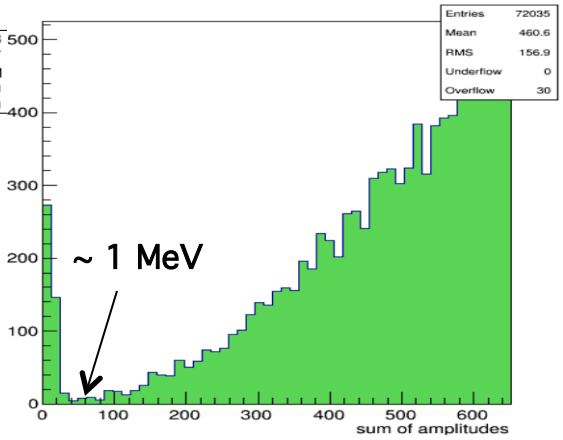
Electron tagging with synchrotron radiation (SR)

Deflected beam position



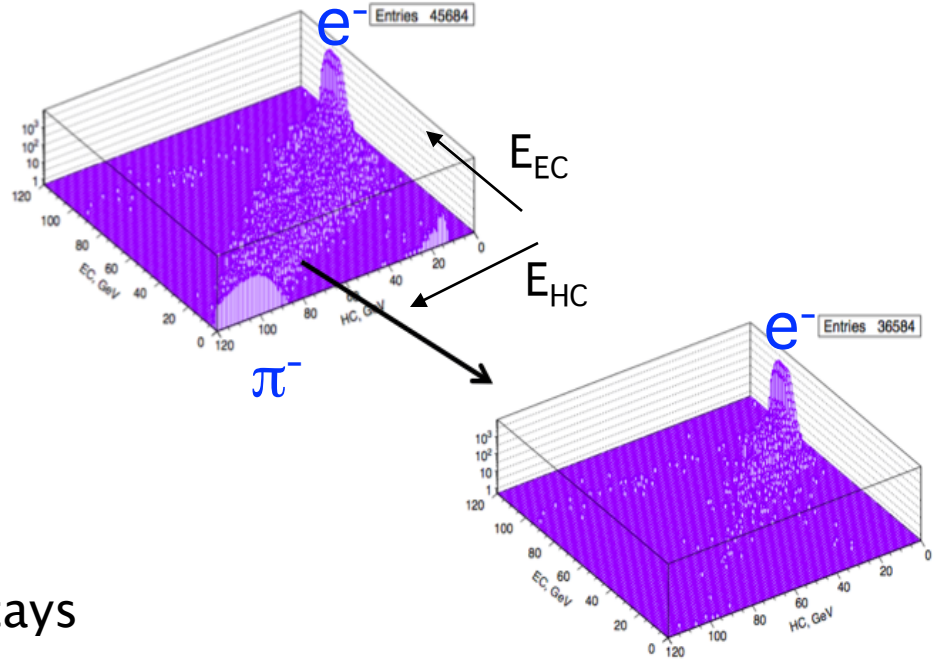
SRD: PbSc, 200 layers
0.08 mm Pb+1mm Sc





Amount of detected SR energy, γ's:
$\Delta E \sim E_0^3/m^4$, $\langle E\gamma \rangle \sim$ 2 MeV, $\langle N\gamma \rangle \sim$ 30

2017 run: Pb-Sc with transv. segmentat+green-extanded PMT
Tuning halo.

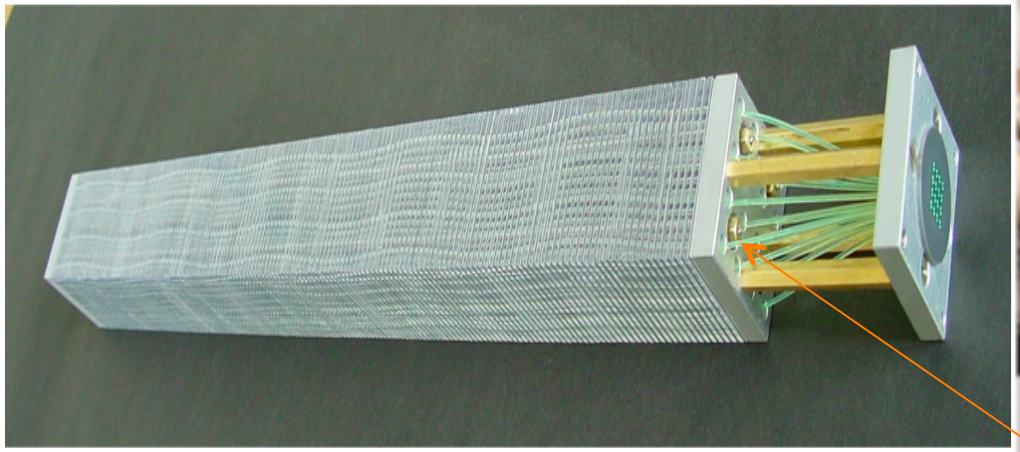


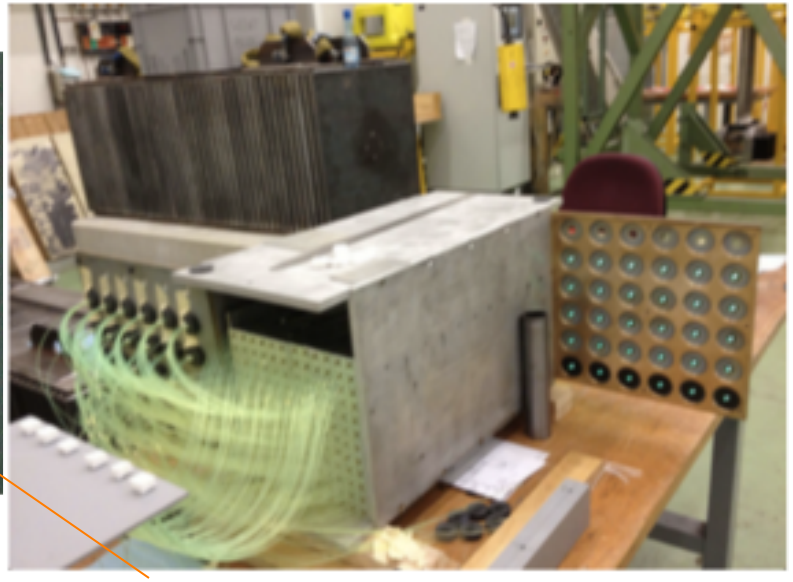
SRD selection:

- $1 < SRD_i < 80$ MeV
- All SRD_i in time within ±2 ns
- $\varepsilon_{SRD} > 0.95$, $\pi/e \sim 10^{-6}$
- SRD π rejection ~10^4 NIMA(2017)
- Background estimate from π, K.. decays

Active dump: shashlik ECAL

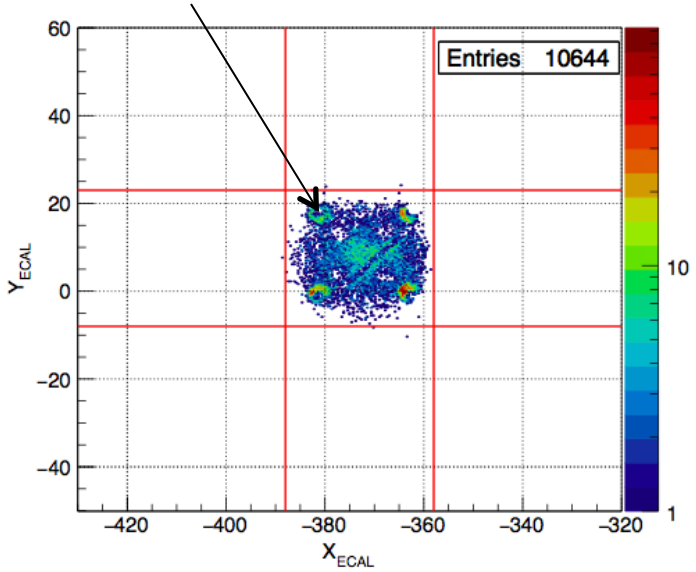
ECAL cell



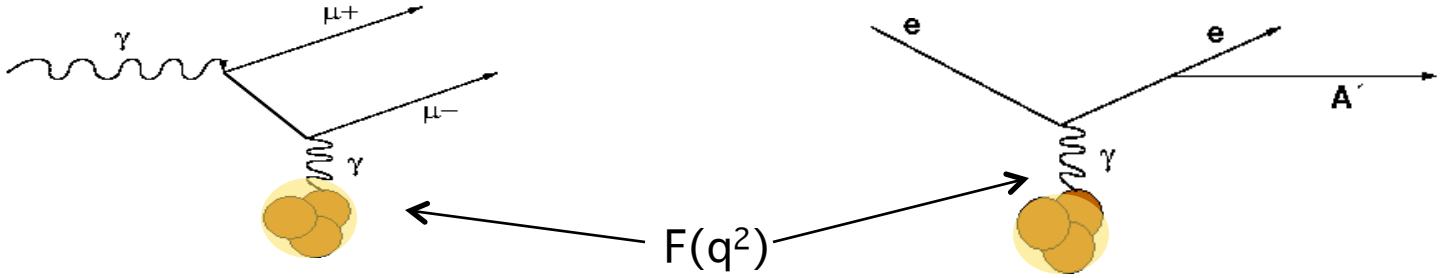


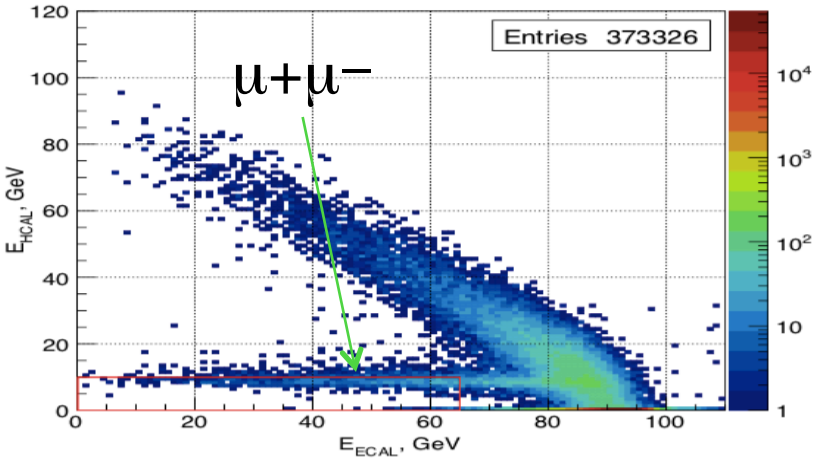
- Dump: rad.-hard, tight, fast, hodoscopic, good energy resolution
- Readout WLS fibers go in a spiral to avoid E-leak and dead zones
- Transverse X-Y scan showed non-uniformity in vicinity of fibers $\delta E/E < 2$ %
- Variation of ECAL energy in vicinity of rods $\delta E/E < 10$ %
- Resolution $\delta E/E \sim 0.1/E^{0.5}$, δX, $\delta Y \sim 1-5$mm
- Hermeticity scan: no potential source of background is found

e,γ punchthroughs

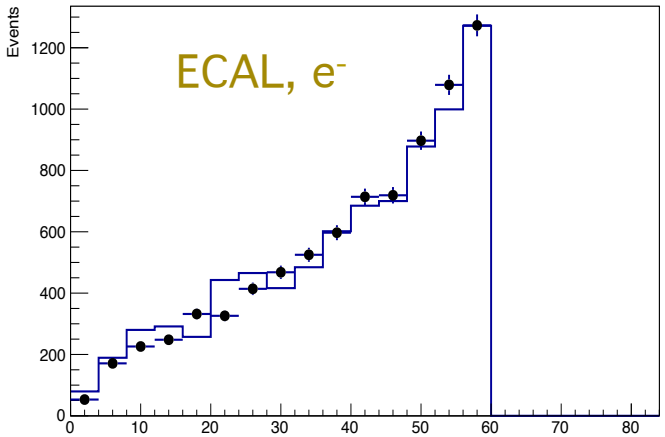


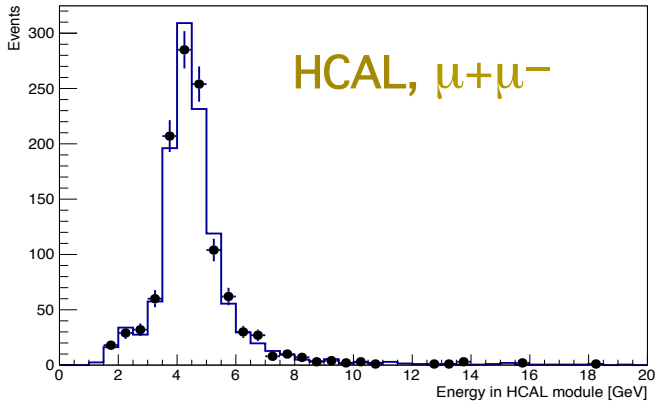
Gauge: dimuon production in eZ->eZγ, γ->μ⁺μ⁻





Dimuon Data vs MC

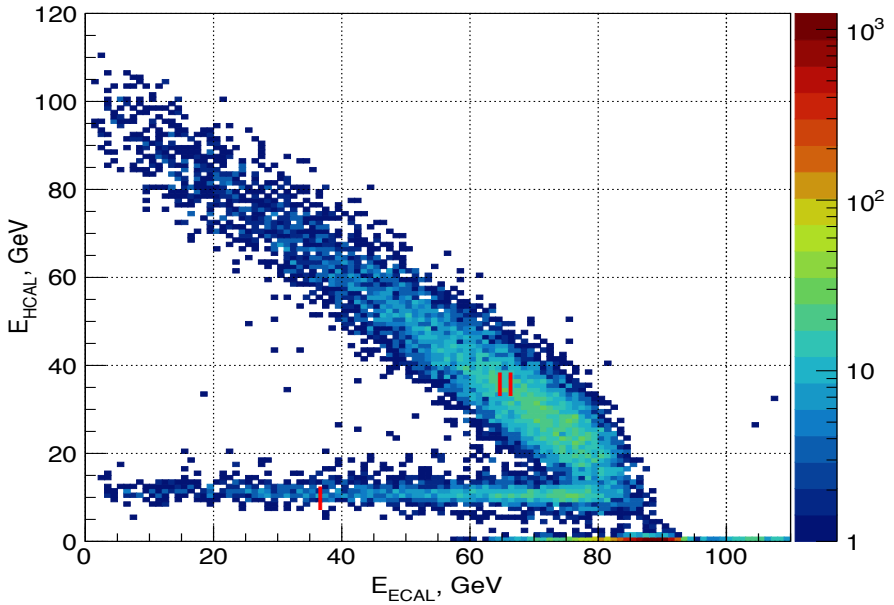




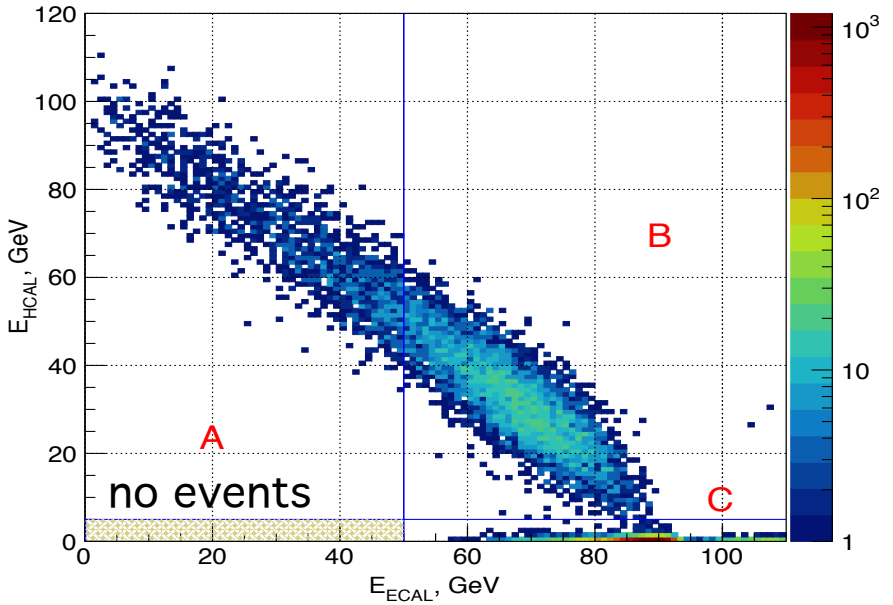
Rare QED reference process~10^{-5}/EOT

- similar to the A´ production
- same region of $q^2 \sim m^2_{A'}/E \sim m^2_{\mu\mu}/E$
- cross check of A´ yield, systematic error
- background prediction from data
- cross check of overall efficiency

Combined results 2016–2018, 2.84x10^{11} EOT



Signal box: E_{EC} < 50 GeV, HCAL<1 GeV



selection criteria	efficiency
incoming e- selection	2016(18)
S_i ,tracker hits in time	0.98(0.95)
SRD_i in-time, SR range	0.98(0.95)
no large Θ_{in}angle tracks	0.95(-)
p momentum in range	0.80(0.83)

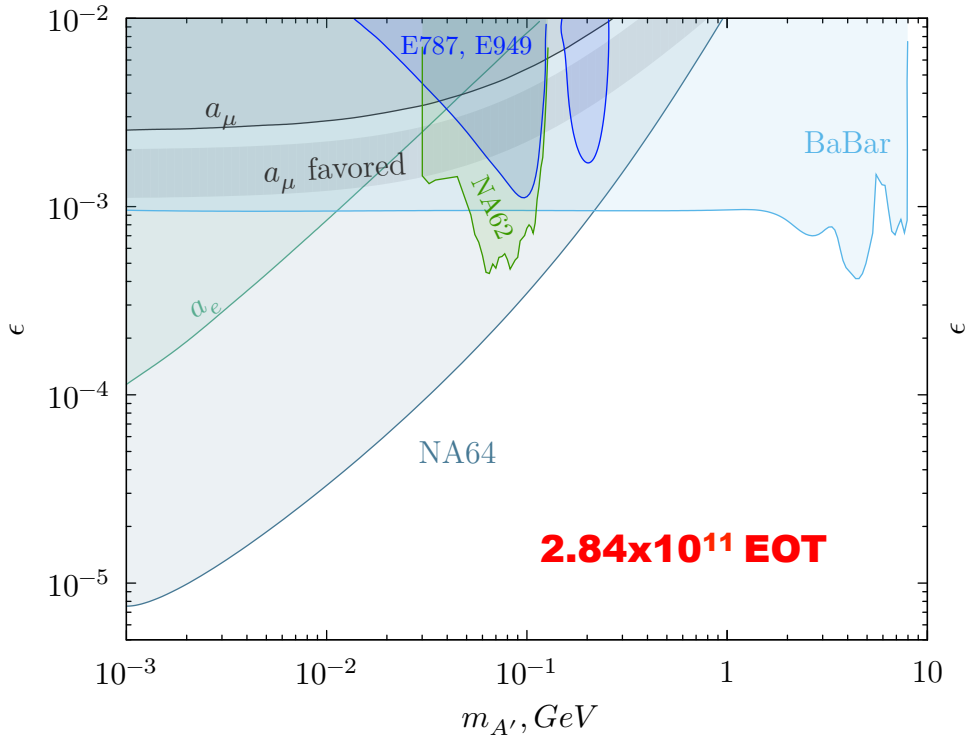
A´ signal, $m_{A'}$~ 20 MeV	
Yield ε_{EC}, ECAL<50 GeV	$m_{A'}$ dep.
ε_{PS} , PS > 0.3 GeV	0.94(0.91)
ε_{SH}, ECAL in time	
+ shower shape	0.96(0.92)
ε_V ,Veto < MIP	0.97(0.93)
ε_{HC}, HCAL<1 GeV	0.96(0.94)

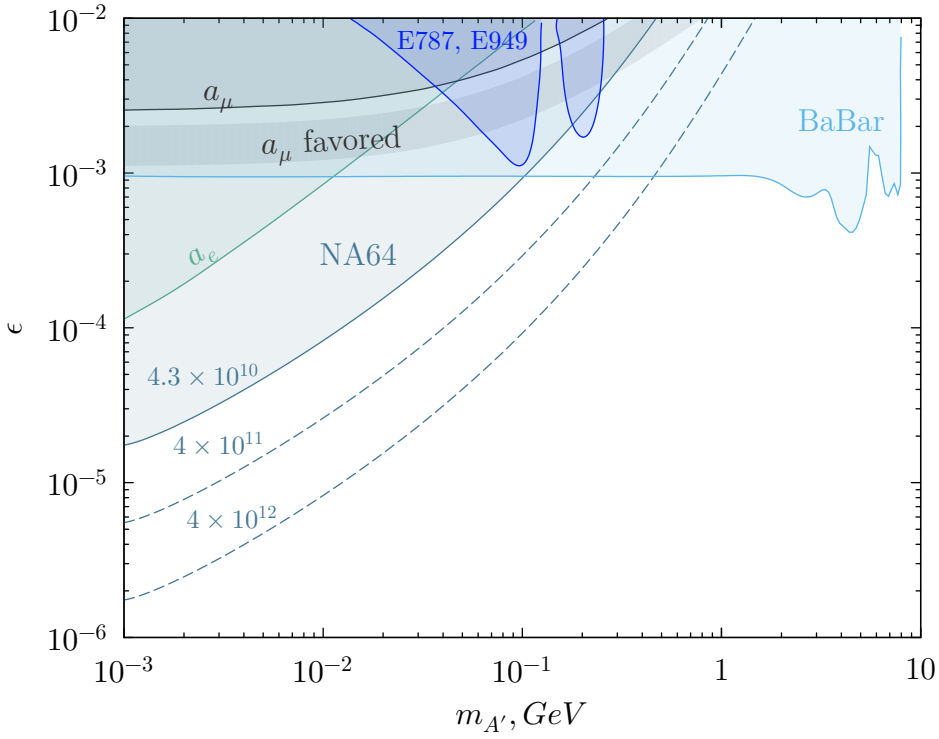
The overall A´ efficiency for $m_{A'}$ ~ 0.001 – 0.3 GeV and I_e ~(1.5–9.0)x10^{6}e/spill

$\varepsilon_{A'}$~0.69±0.09–0.55±0.07(2016) => 0.53± 0.09 to 0.48±0.08(2018)

Combined results 2016–2018 and projections for ε

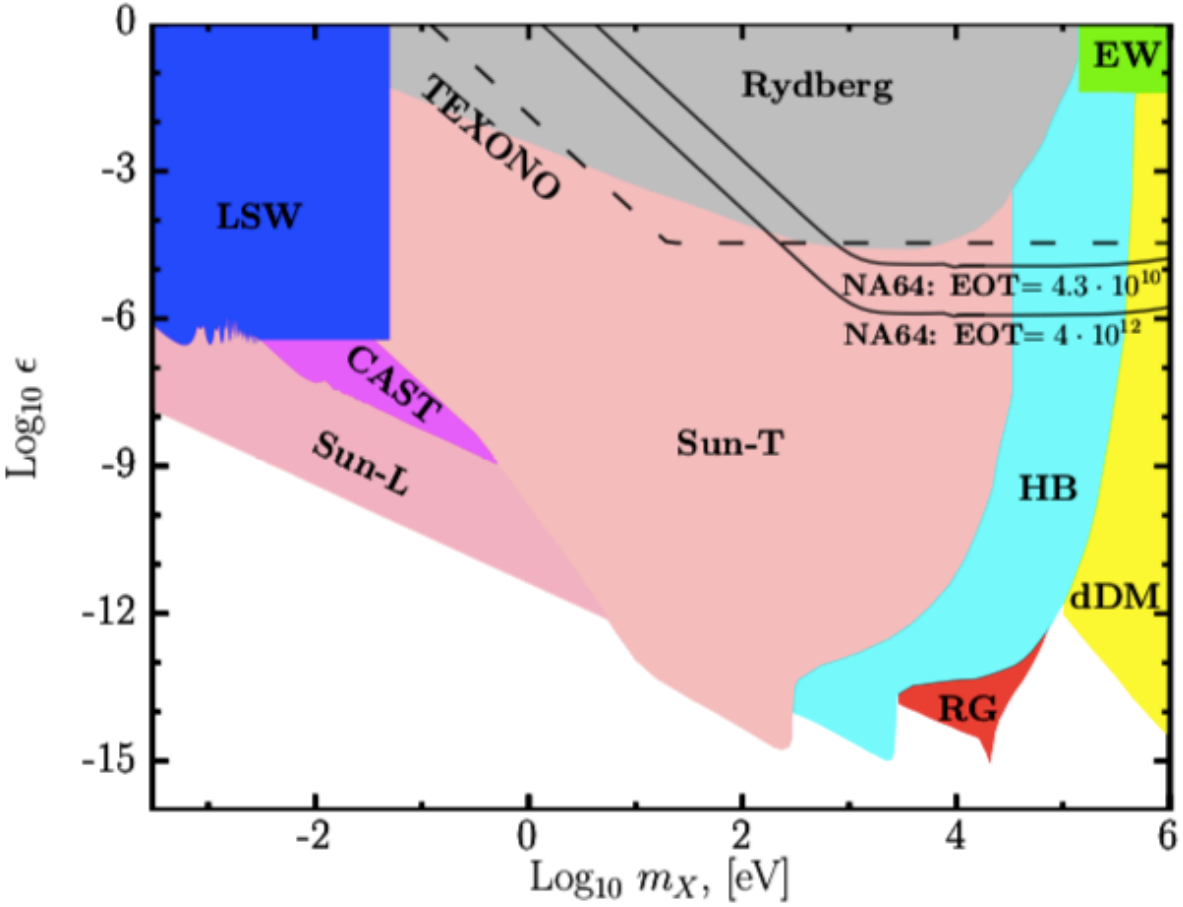
arXive:1906.00176





- The search is background free
- Plans to accumulate > 5x10^{12} EOT after LS2
- A possible source of background – upstream e- interactions in the beamline. Currently under study.

Preliminary results for the sub-MeV A´ mass range



TEXONO:
arXiv:1804.10777

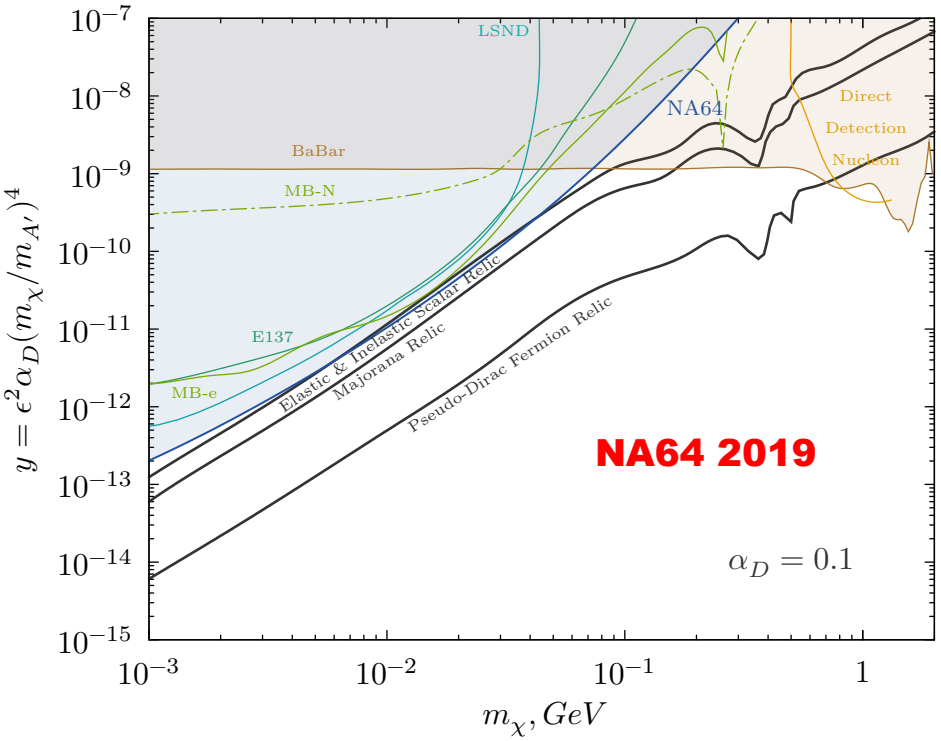
NA64:
arXiv:1812.02719

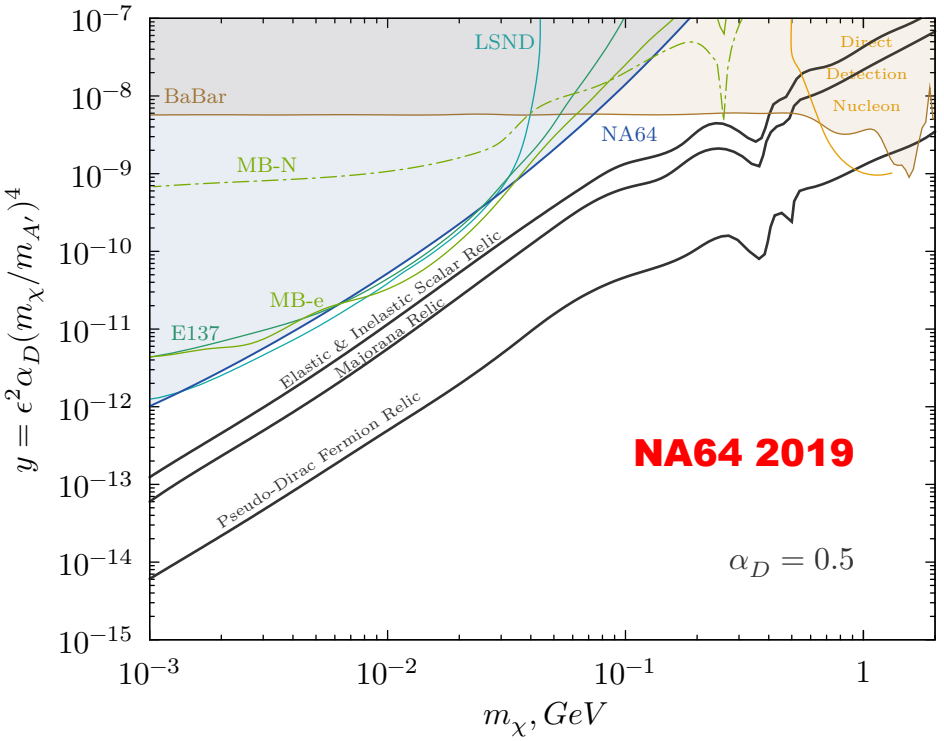
Simulations for eV–MeV A´ mass range including dumping of γ-A´ oscillations in the target under development

Combined results 2016–2018 for LDM (I)

$m_{A'} = 3m_{\chi}$

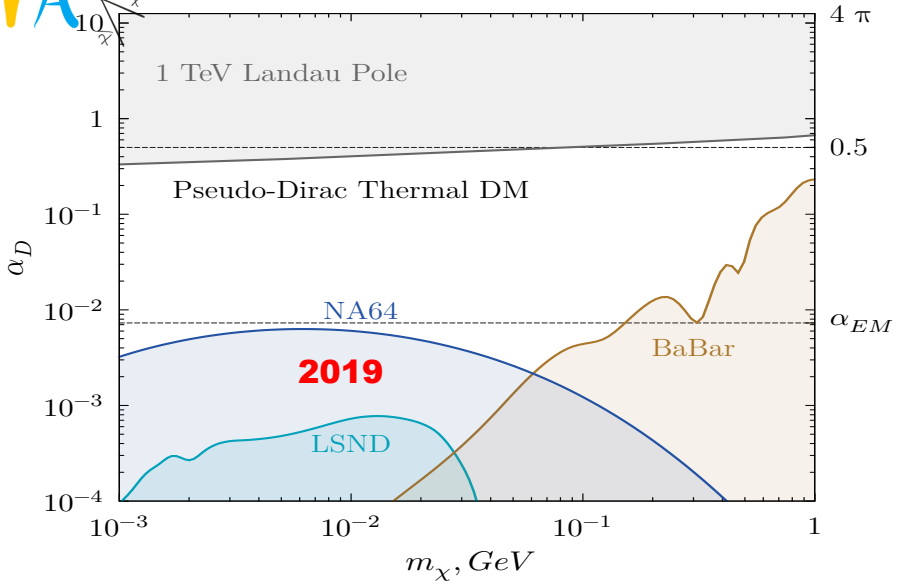
arXive:1906.00176

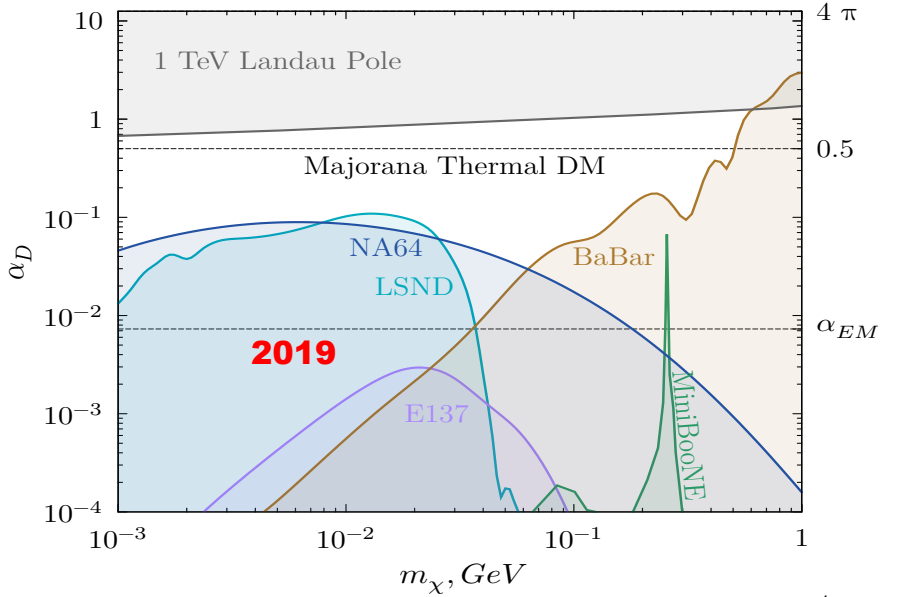


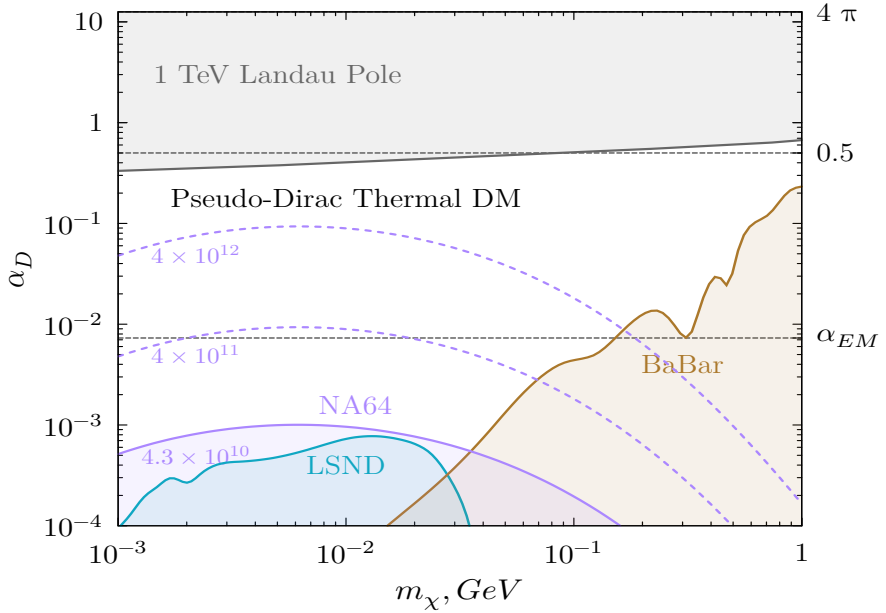


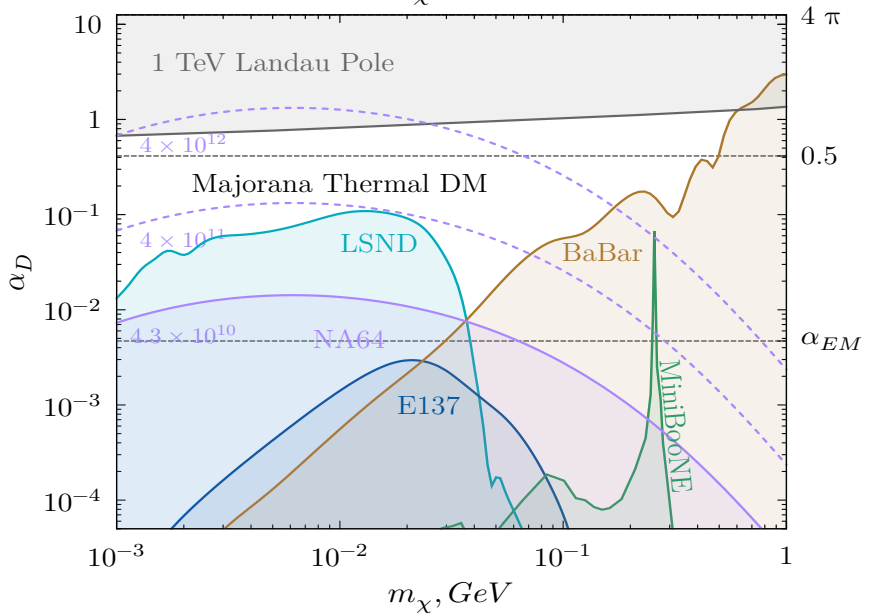
The most stringent constraints on the γ-A′ mixing strength and parameter space for the scalar and fermionic dark matter in the mass range < ~0.5 GeV. The power of the active beam dump + missing energy approach for the dark matter search.

2016–2018 results and projection for LDM DM (II)









$^8Be^*$ 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}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. Tornyi, and Zs. Vajta
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(Received 7 April 2015; published 26 January 2016)

^{7}Li(p, γ)^{8}Be, M $_X$ =16.7 MeV

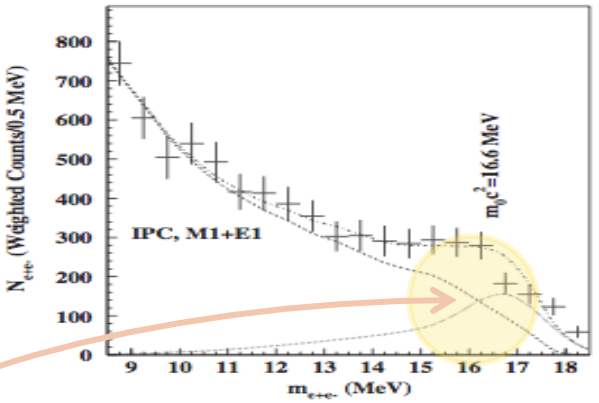
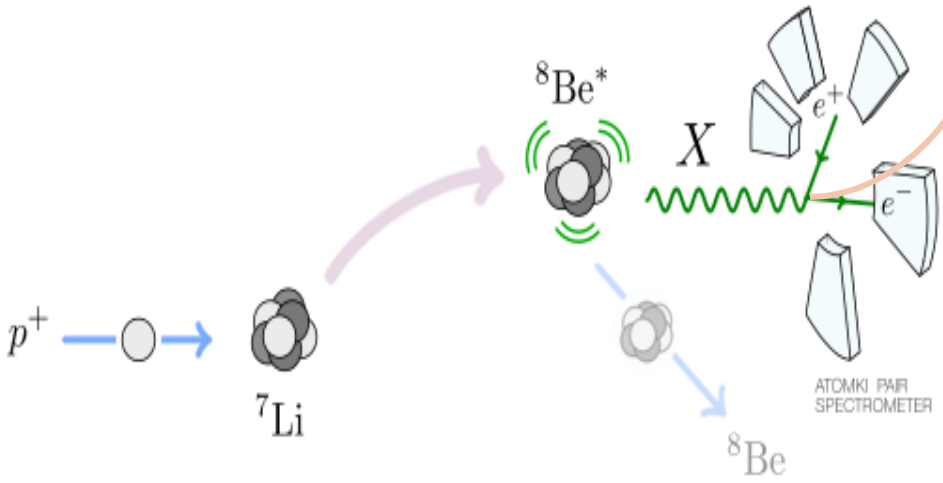


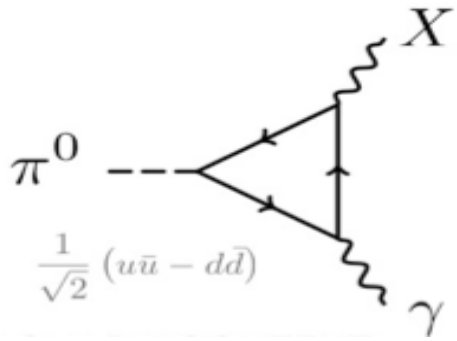
FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.



Feng et al, 2016

$2\times10^{-4} < \varepsilon_e < 1.4\times10^{-3}$

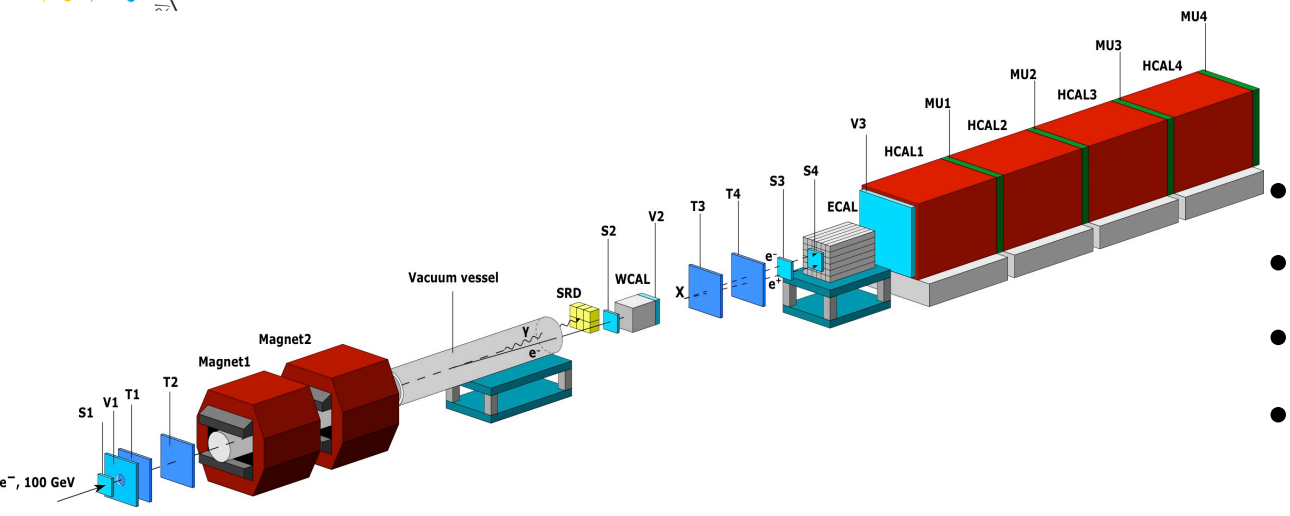
X cannot be A´due to constraints from π^0->Xγ decay:



$\Gamma(\pi^0\text{->}X\gamma)\sim(\varepsilon_u q_u-\varepsilon_d q_d)^2 \sim 0$

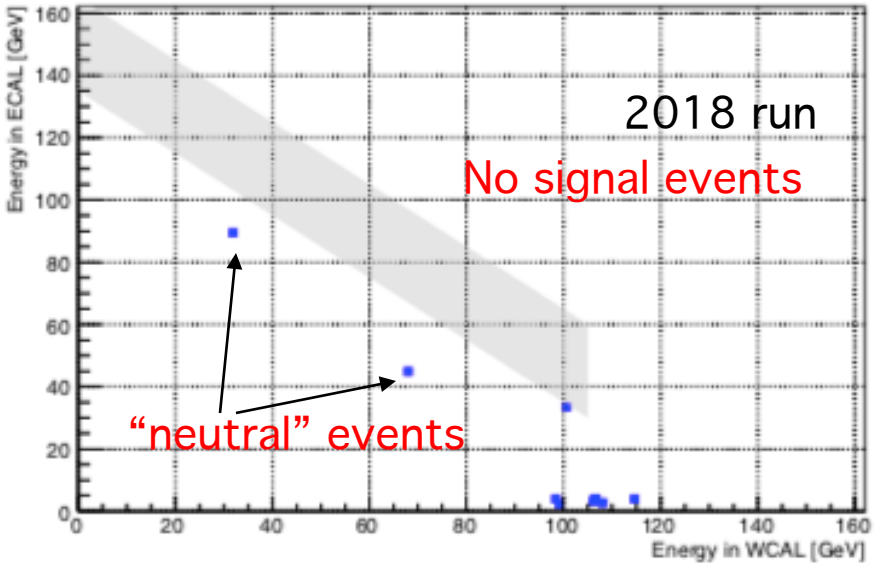
if $2\varepsilon_u=-\varepsilon_d$ -> protophobic X

Search for the a->γγ, X(16.7), A´-> e^+e^-, invisible decays



Main components :

- clean 100 GeV e- beam
- e- tagging: tracker+SRD
- active dump WCAL
- ECAL, HCAL

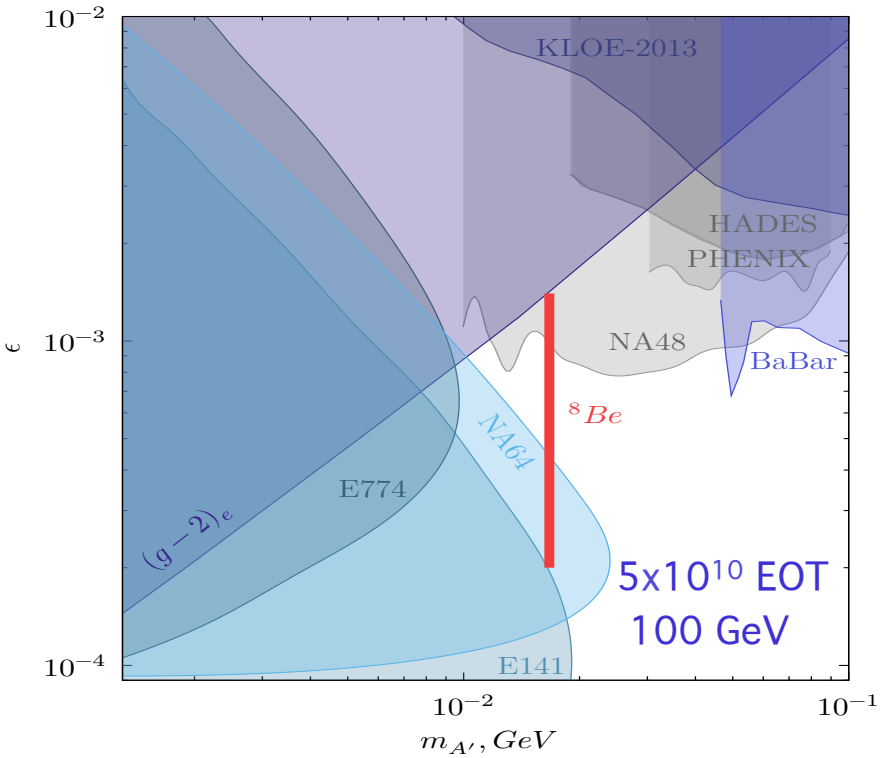


Signature:

- 100 GeV incoming e- track
- Single shower in WCAL
- Double or single shower in ECAL
- $E_{WCAL}+E_{ECAL}=E_0$
- no energy in Veto and HCAL

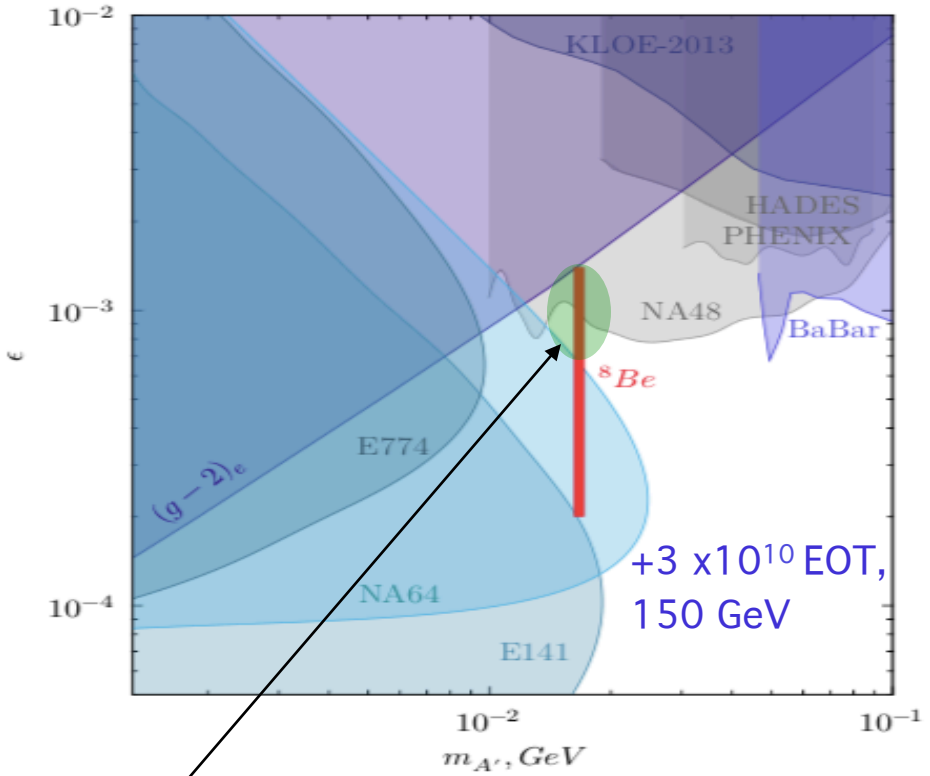
Results for X, A´→ e^+e, with the main focus on X

NA64 2017, PRL(2018)



$1.3\times10^{-4} < \varepsilon_e < 4.2\times10^{-3}$

Combined NA64 2017+2018



$1.2\times10^{-4} < \varepsilon_e < 6.8\times10^{-3}$

Sensitivity is defined by the WCAL dump length. Attempt to make it shorter by optimizing the WCAL structure: Xs carry away most of the energy, while the recoil e- is soft.

NA64μ at the CERN SPS

NA64μ is designed

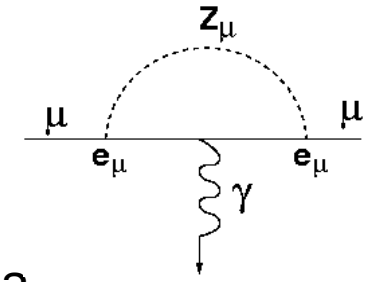
- to search for new S,V states coupled predominantly to muon and test of $(g-2)_\mu$ anomaly in missing energy events from μZ interaction
- to improve NA64e senstivity to LDM in the mass range $m_{A'} >> m_e$.

Status:

- **April 2019:** Proposal to SPSC, CERN-SPSC-2019-002/SPSC-P-359
- **Currently:** Under discussions for M2 beam sharing between COMPASS, MUonE, NA64μ
- **End of 2019:** expected decision on the pilot run at M2 after LS2

Remaining low mass solution to $(g-2)_\mu$: Z_μ of $L_\mu - L_\tau$

- Remarkable fact: out of $U(1)_{Le}$, $U(1)_{L\mu}$, $U(1)_{L\tau}$ global symmetries in the SM models one of L_e-L_μ, L_e-L_τ, $L_\mu-L_\tau$ differences could be gauge. The same 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, $Z_\mu \rightarrow \mu^+\mu^-$ or $Z_\mu \rightarrow \nu\nu$ for $M_{Z\mu}<2\ m_\mu$

Large recent literature

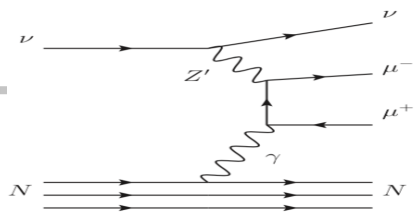
- explanation of $(g-2)_\mu$
- mediator of new force, sub-GeV DM
- Impact on ν-physics, mixing matrix
- astophysical observation (EDGES 21-cm anomaly, IceCube cosmic ν, ..)
- ….

New ideas for NA64μ-like experiment

- L_μ-L_τ Z_μ M³@FNAL, arXiv:1804.03144
- Leptophilic LDM, arXiv:1807.03790
- Light scalars of DS, arXiv:1701.07437

E989 at FNAL: new result with statistics of E821 in 2019. If confirmed =>~5 σ anomaly

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,

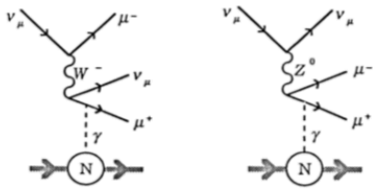


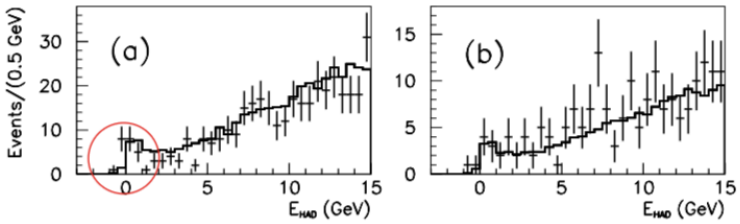
FIG. 1. Feynman diagram showing the neutrino trident production in ν_μ-A scattering via the W and the Z channels.

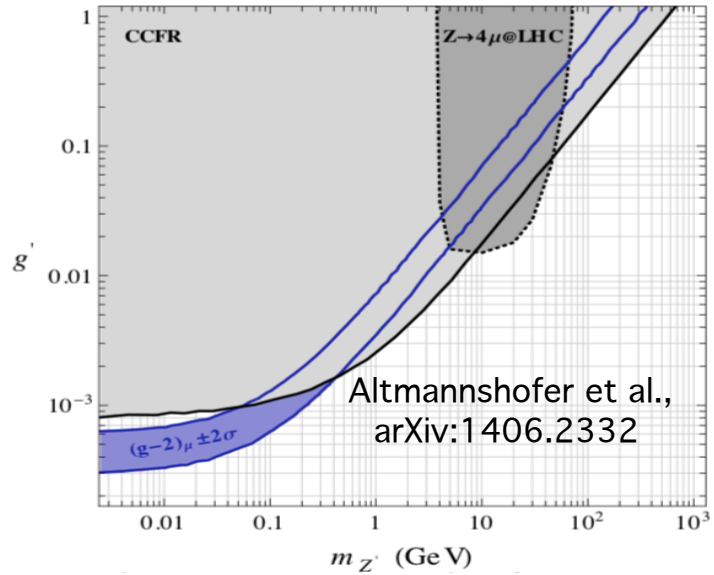
$$\sigma_{\nu N}(\mathrm{CC}) = (0.680 \pm 0.015) E_\nu \times 10^{-38}\ \mathrm{cm}^2/\mathrm{GeV},$$

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

$$\mathrm{at}\ \langle E_\nu \rangle = 160\ \mathrm{GeV}.$$

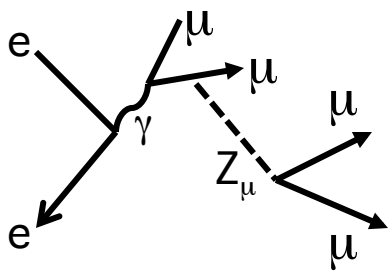
NuTeV results:



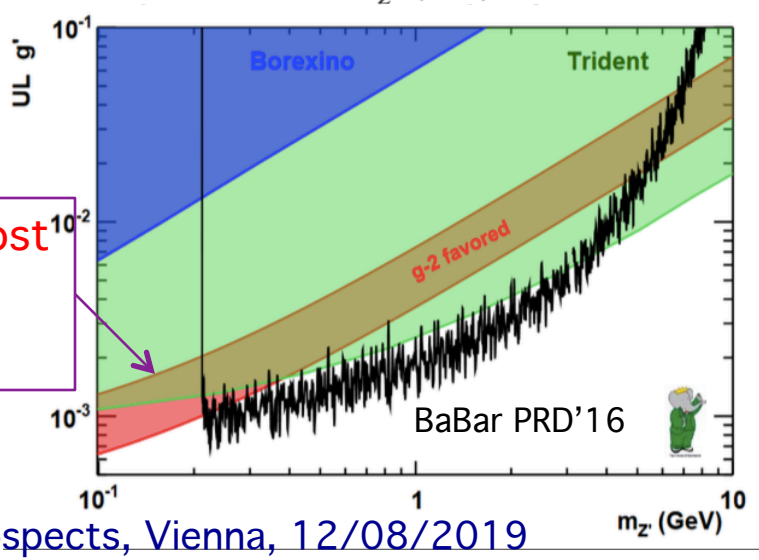


Altmannshofer et al., arXiv:1406.2332

- BaBar searches for e^+e^- -> 4μ

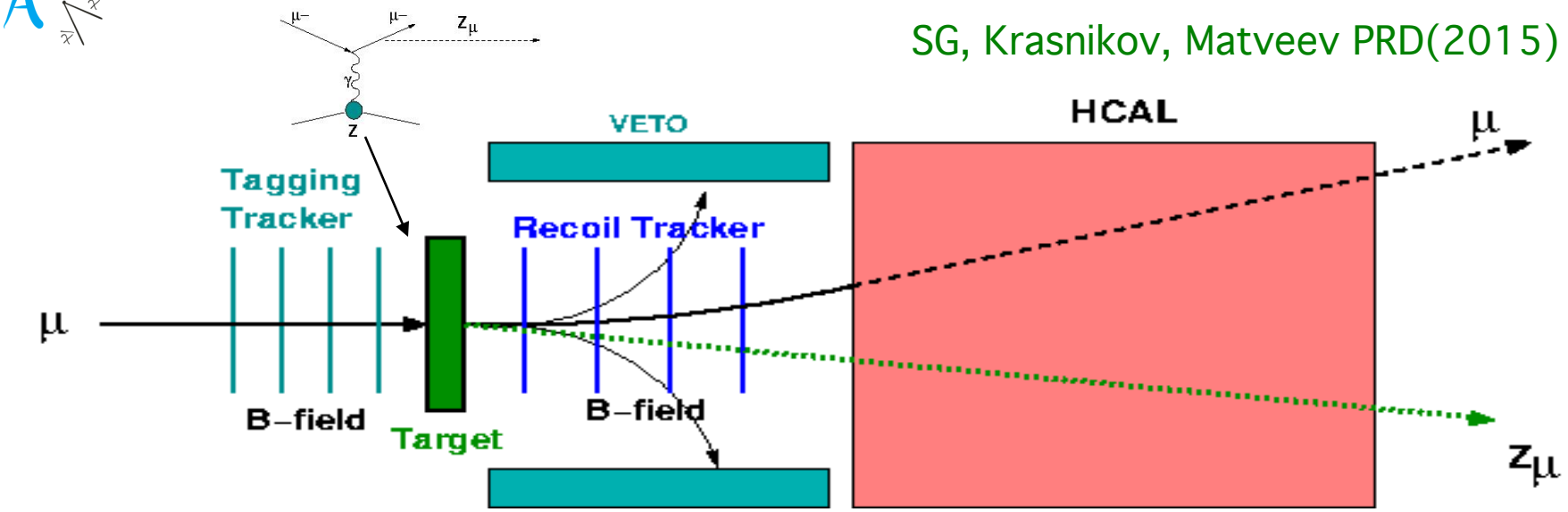


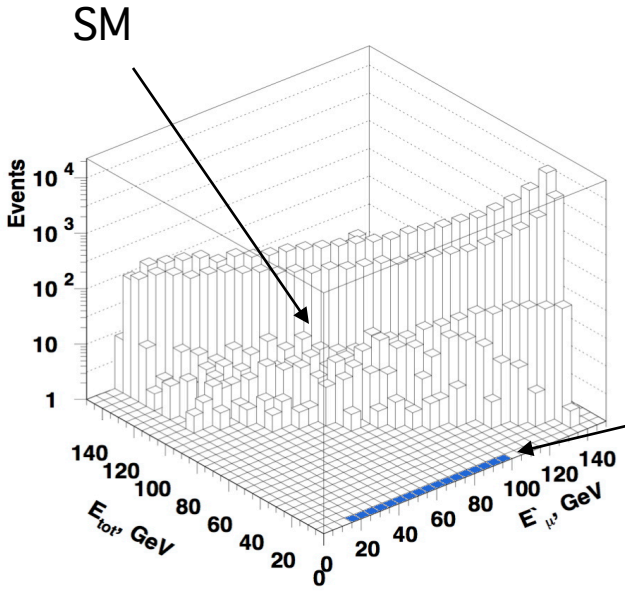
The region $M_{Z\mu} < 2\ m_\mu$ Is most difficult to constrain:
$Z_\mu \rightarrow \nu\nu$ decays are invisible



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

SG, Krasnikov, Matveev PRD(2015)





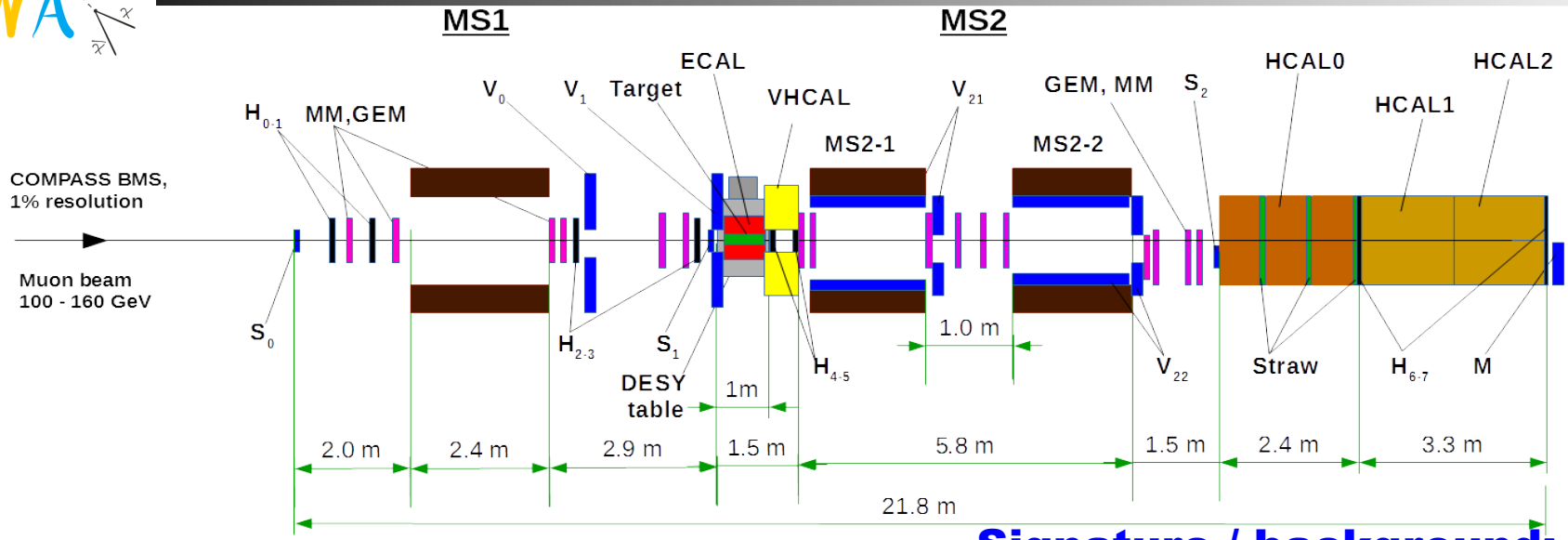
Processes under consideration:

- μZ->μZ Z_μ; Z_μ -> νν – vector case
- μZ->μZ a_μ ; a_μ -> inv - scalar a_μ, ALPs
- μZ->μZ $q\bar{q}$ - milliQ particles
- μZ -> τZ+..; τ->μνν – 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



Signature / background:

- in: 160 GeV μ- track
- out: < 80–100 GeV μ- track
- no energy in ECAL,Veto,HCAL
- Sensitivity ~ g_μ^2, SES ≤ 10^{-13}

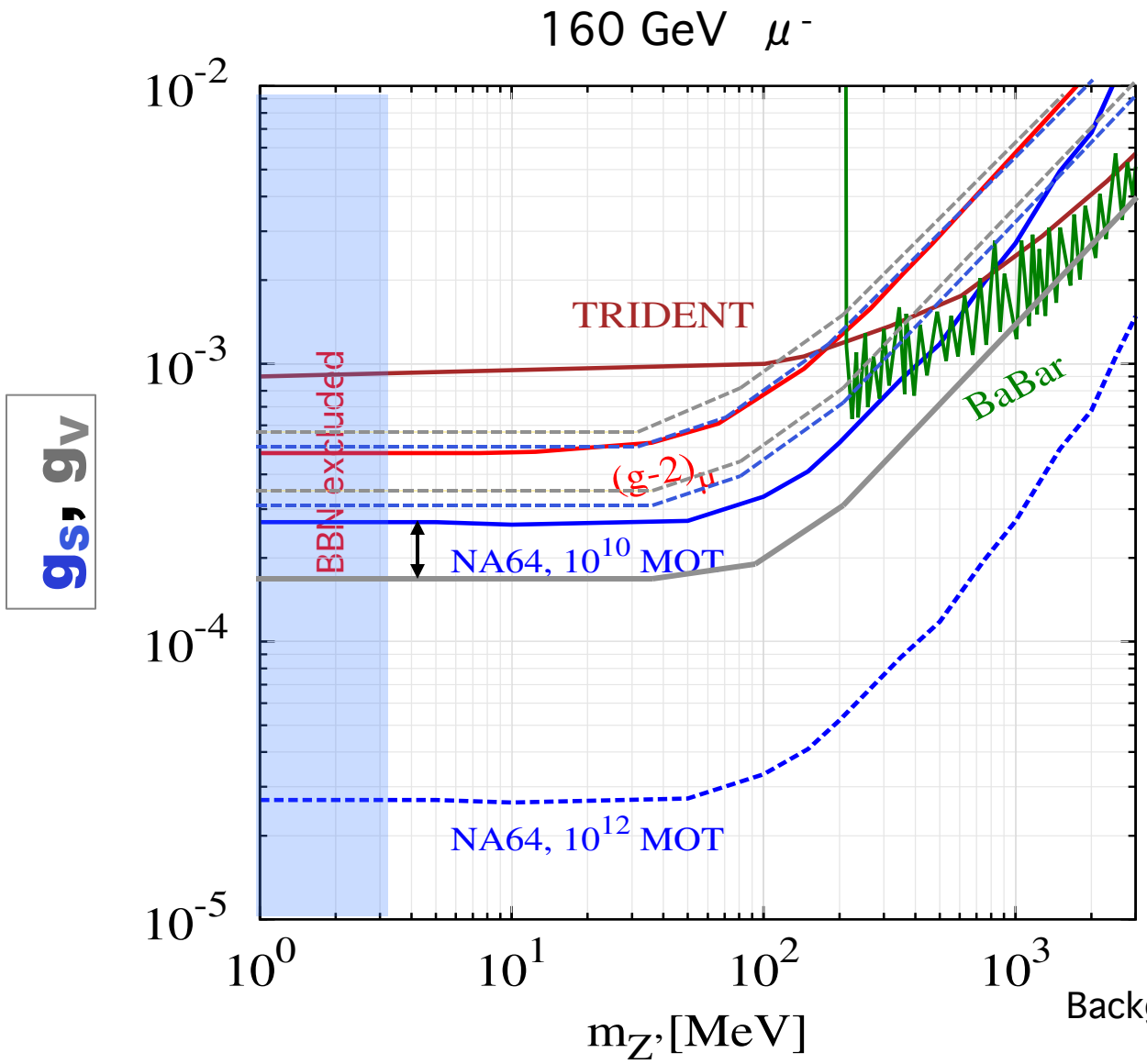
Main components :

- 160 GeV μ- beam, ~10^8μ/spill.
- in μ tagging: BMS+MS1
- out μ tagging: MS2
- 4π-hermetic system: ECAL+VHCAL+Veto+HCAL

✧ π , K -> μν decays: $E_\mu < E_\pi$
✧ Detector hermeticity
✧ Mis-measurements of $P^\mu_{in,out}$
✧ Physical background

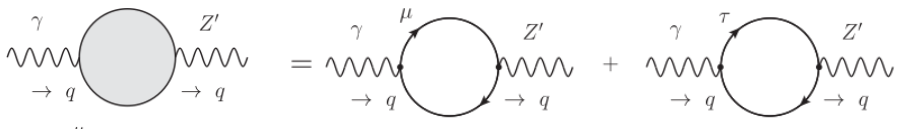
Total expected: < 10^{-11}/MOT

Expected sensitivity



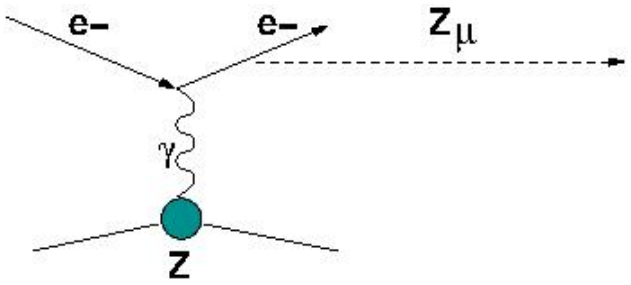
Background-free case.

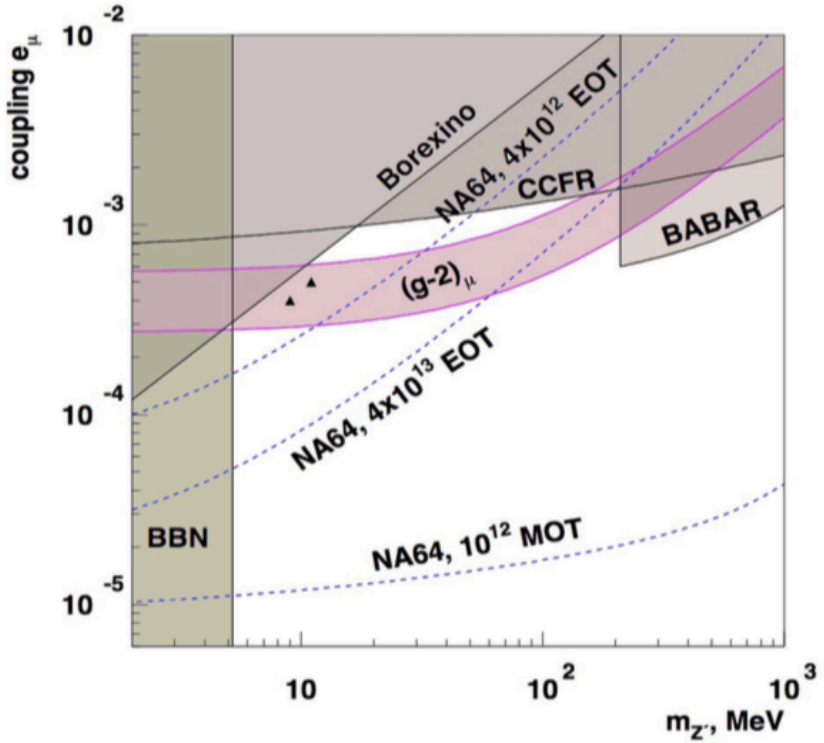
Complementarity of e and μ searches (I): γ –Z_μ mixing



- γ –Z_μ kinetic mixing
- Mixing $\varepsilon \sim 3eg_\mu/16\pi^2 \ln(m_\tau/m_\mu)$
- $m_{Z'} < m_\mu$: $g_\mu = 4.8\times10^{-4}$, $\varepsilon = 6.8\times10^{-6}$
- Loophole: search for Z_μ with e- beams

in e^- Z -> e^- Z Z_μ ; Z_μ -> invisible
(similar to A´)

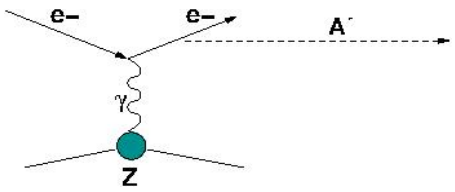




Complementarity of NA64e and NA64μ:
Z_μ < ~100 MeV should be also seen in NA64e

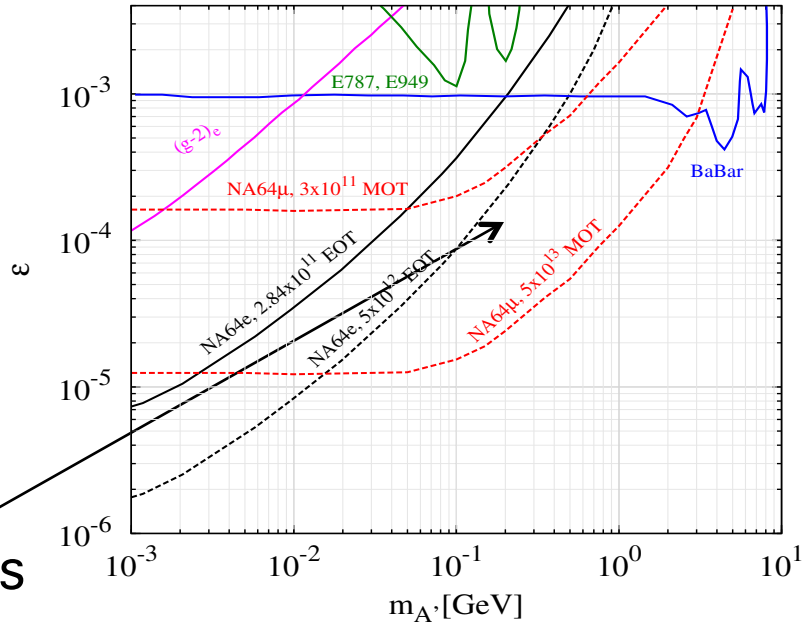
1801.10448

Search for high mass invisible A´with M2 muon beam



arXiv:1903.07899, ETL

- $N_{A'} \sim N_e\, \varepsilon^2\, m_e^2/m_{A'}^2$
  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_μ/t_e
  The $t_e \sim X_0$ while for the μ case it is $t_e << t_\mu$
- NA64μ can significantly improve limits for A´ mass ~ 0.1- 1 GeV, a factor 10^2 -10^3 for ε^2 or variables y and α_D (next slide)

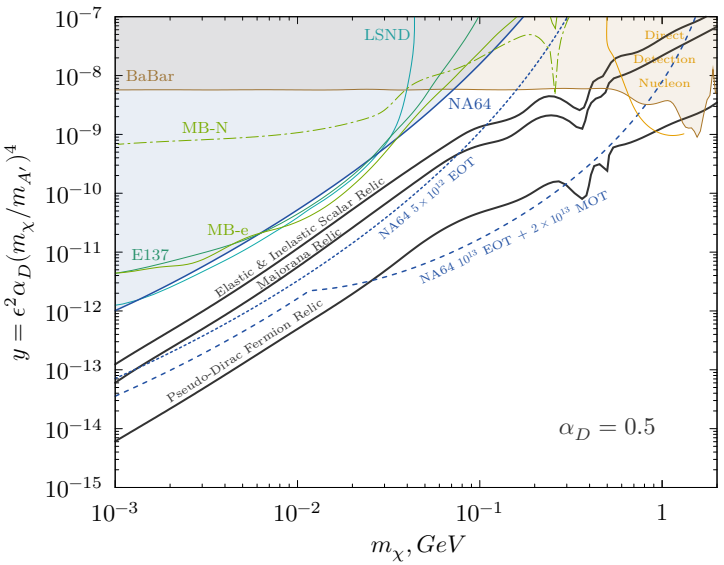


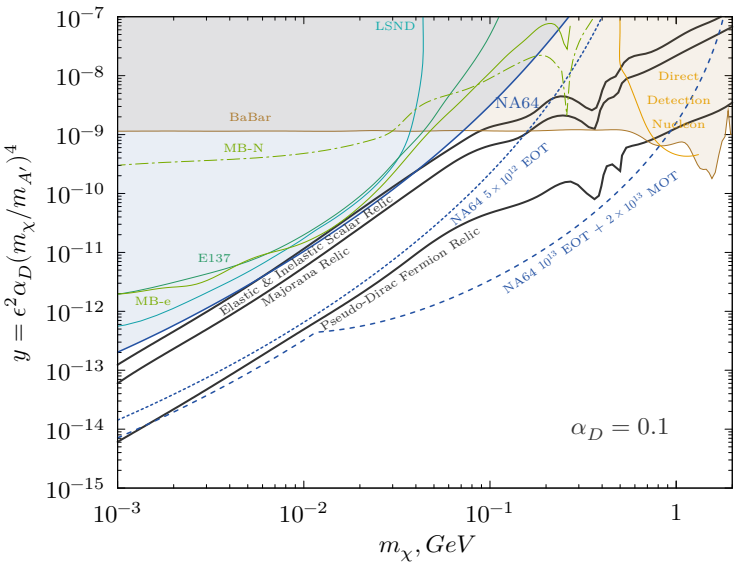
These new observations significantly strengthen motivation for the experimental search of the A´and Z_μ with M2 muon beam

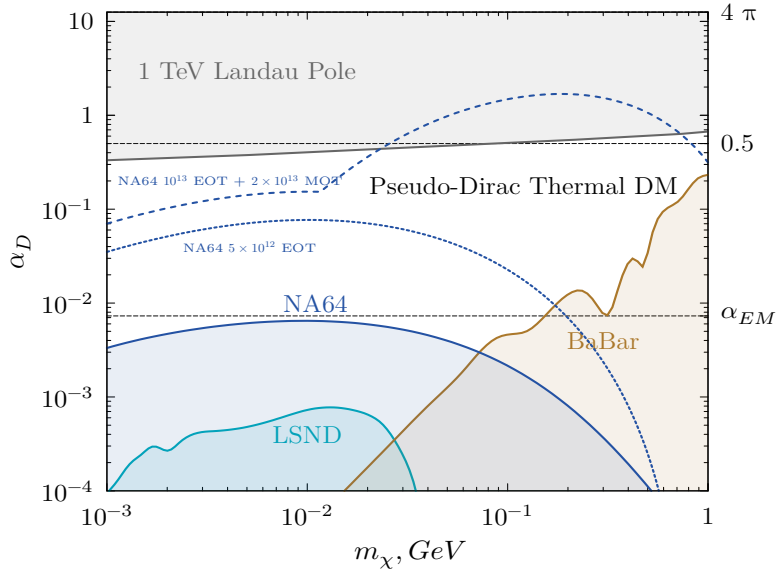
Combined probe of LDM with NA64e and NA64μ

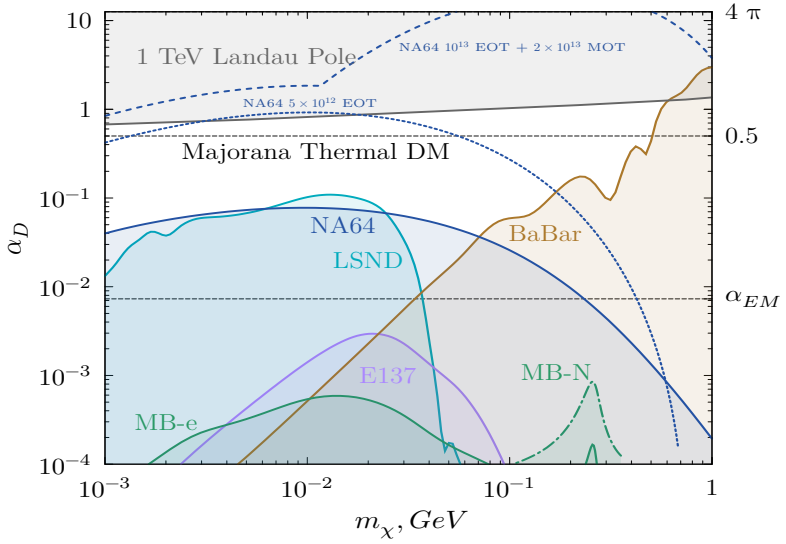
$m_{A'} = 3m_{\chi}$

arXiv:1903.07899









Summary and plans

NA64: powerful approach to search for LDM. Combined search with e and μ has great potential to probe large area of LDM parameter space

NA64e

- Detector upgrade during LS2
- 2021–24 run > ~5x10^{12} EOT
- Invisible A´,LDM,^{8}Be anomaly, ALP

NA64μ

- 2021–22 M2 pilot run
- Phase I: test g_μ-2~10^{10-11} MOT
- Phase II : ~10^{13} MOT
- S_μ, Z_μ, A´, LDM, milliQ, ALP

NA64++ provisional time schedule