Recent results of the NA64 experiment at the CERN SPS.

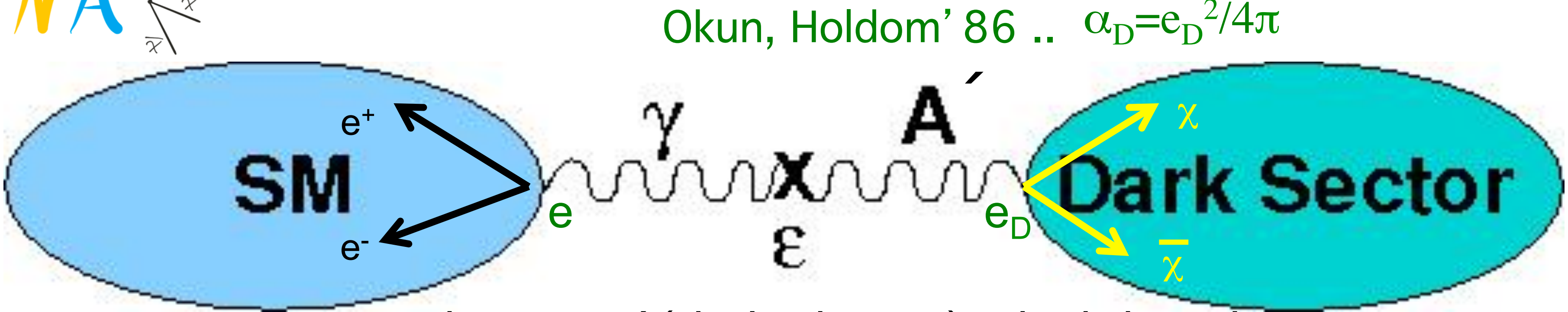
Mikhail Kirsanov INR RAS (Moscow)
(on behalf of the NA64 collaboration)

PhiPsi19
February 2019 Novosibirsk

Outline

- Motivation
- The NA64 experiment
- Runs NA64
- Simulation of the Dark Matter production
- Analysis of the data
- Results on A' in invisible mode
- Plans for the invisible mode
- Visible mode: X-boson, motivation
- Event selection, efficiency, backgrounds
- Results on the X-boson search
- Conclusion, near and more distant plans of NA64

Vector portal to Dark Sector

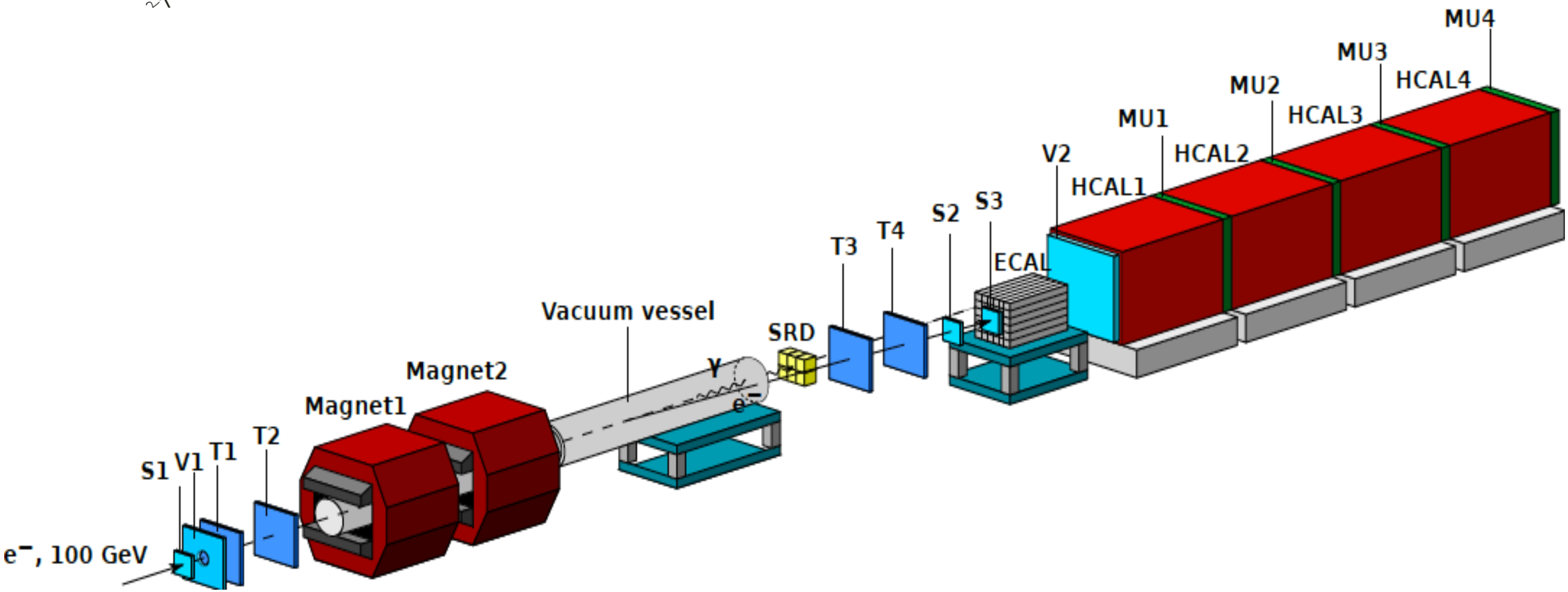


- new massive boson A´ (dark photon) which has kinetic mixing with ordinary photon: $\Delta L = \varepsilon/2\ F^{\mu\nu}A'_{\mu\nu}$
- Production: A´ - bremsstrahlung $e^- Z \to e^- Z A'$, $\sigma \sim Z^2\varepsilon^2/m_{A'}^2$
- Decays:
  - Visible: $A' \to e^+e^-, \mu^+\mu^-$, hadrons,..
  - Invisible: $A' \to \chi\bar{\chi}$ if $m_{A'} > 2m_\chi$ assuming $\alpha_{DM} \sim \alpha >> \varepsilon$. Can explain $(g-2)_\mu$, astrophys. observations
    - Cross section for χ–DM annihilation: $\sigma v \sim \underbrace{[\alpha_{DM}\,\varepsilon^2 (m_\chi/m_{A'})^4]}_{y}\ \alpha/m_\chi^2$

Thermal dark matter

- Assume that in the early Universe dark matter is in equilibrium with the SM matter. At some temperature the dark matter decouples
- DM density today tells us about annihilation cross-section. Correct DM density corresponds to $\langle\sigma_{an}v\rangle \sim O(1)$ pbn
- The most popular models of dark matter χ:
    - Scalar dark matter
    - Majorana dark matter
    - Pseudo Dirac dark matter

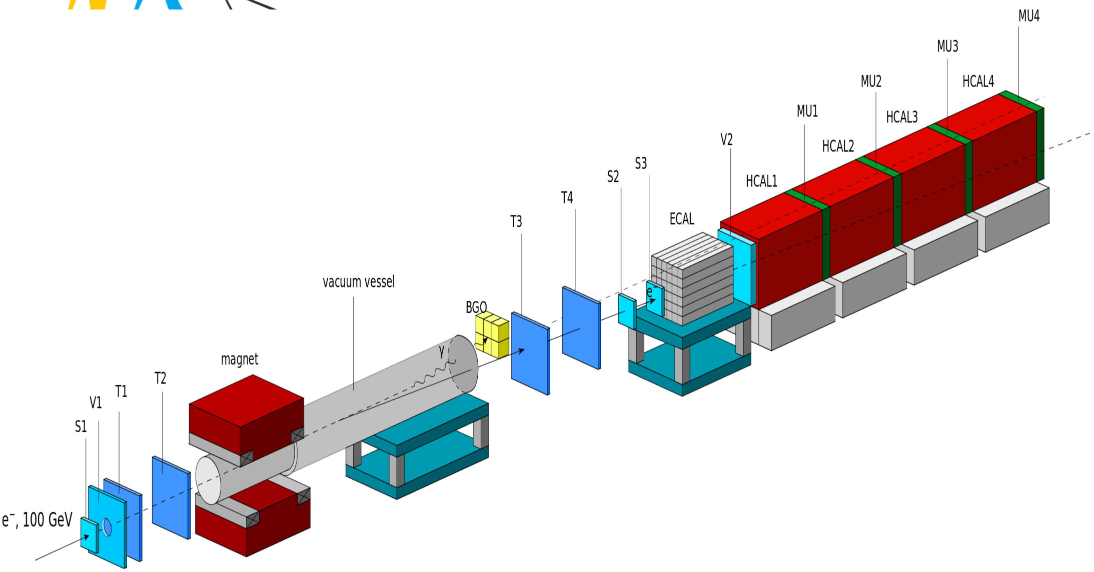
NA64 experiment setup (invisible mode)

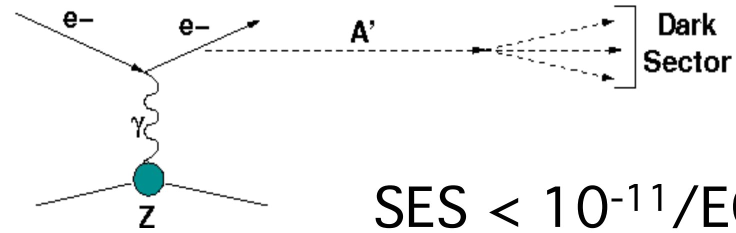


~50 researchers from 12 institutes
Proposed in 2014, first test runs in 2015

NA64 experiment setup

Search for A´->invisible decays at CERN SPS





SES < 10^{-11}/EOT

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

Signature:

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

Main components :

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

Background:

- μ, π, K decays in flight
- upstream interactions
- Tail < 50 GeV in the e- beam
- Energy leak from ECAL+HCAL

Summary of the NA64 runs

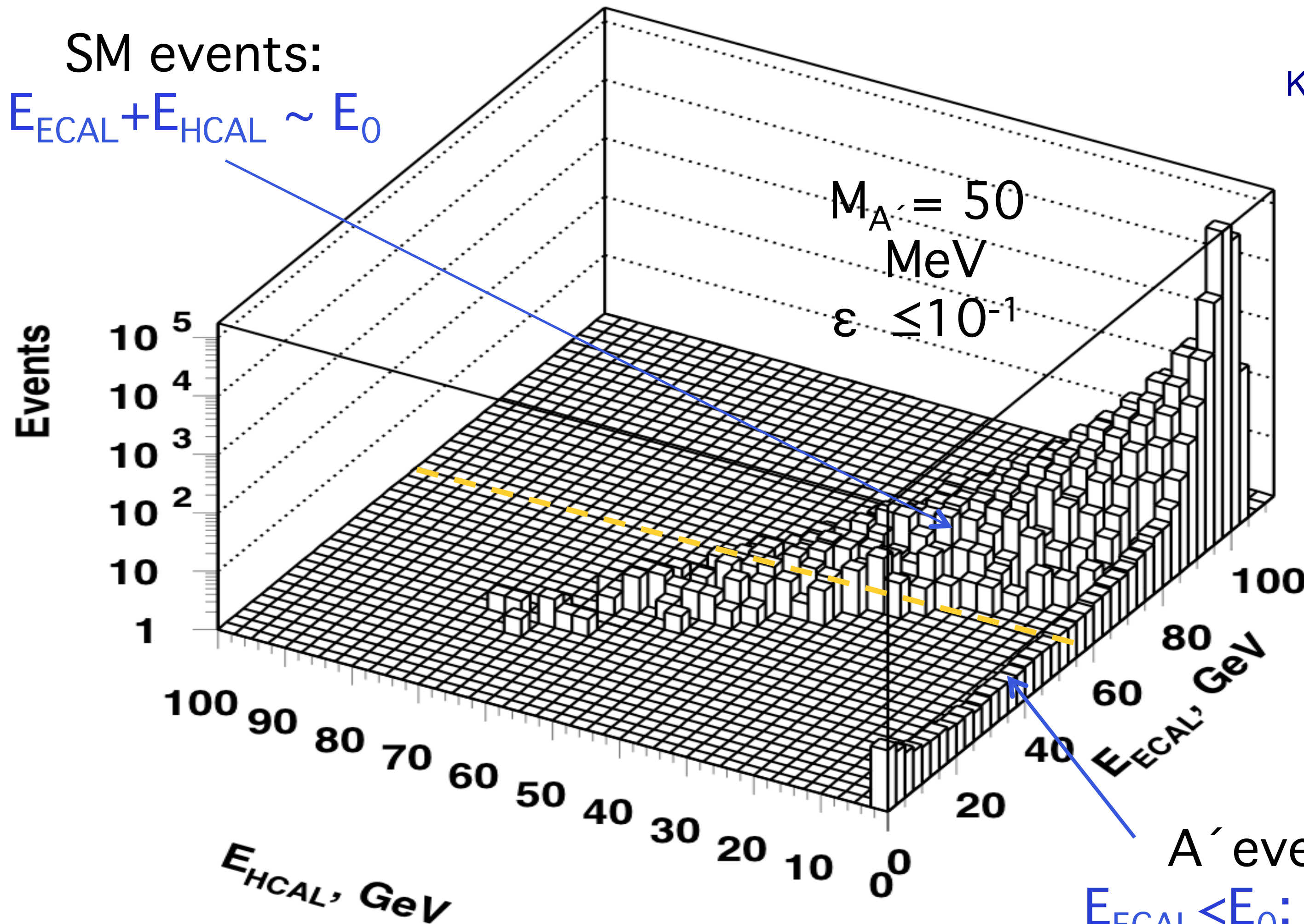
- **Invisible mode configuration, first run 12.10-09.11 2016**
  - **Subrun1 2016 EOT ~ $2x10^{10}$, S_0 rate $1.5÷2.2x10^6$;**
  - **Subrun2 2016 EOT ~ $1.5x10^{10}$, S_0 rate $2.4÷3.2x10^6$;**
  - **Subrun3 2016 EOT ~ $1.0x10^{10}$, S_0 rate $4.6÷5.0x10^6$; ~0.6 day**
  - **Run 2017 EOT ~ $5.4x10^{10}$, S_0 rate $4÷6x10^6$**
  - **Run 2018 EOT ~ $1.9x10^{11}$, S_0 rate $6÷8x10^6$**
  - **Total number ~ 2.89 $x10^{11}$ eot**

- **Visible mode configuration first run 22.09-01.10 2017**
  - **Subrun 1 WCAL 40X0 EOT ~ $2.4x10^{10}$, S_0 rate ~$3x10^6$**
  - **Subrun 2 WCAL 30X0 EOT ~ $3x10^{10}$, S_0 rate $4-5x10^6$**
  - **Run 2018 S4 in WCAL EOT ~ $3x10^{10}$, beam 150 GeV**
  - **Total EOT ~ $8.4x10^{10}$**

Simulation of eZ->eZA´; A´-> invisible @ BG

GEANT4 + code for A´emission in the process of e-m shower development. σ($e^-Z \to e^-ZA´$) from Bjorken et al. 2009

Gninenko, Kirsanov, Krasnikov, Kirpichnikov PRD(2016)



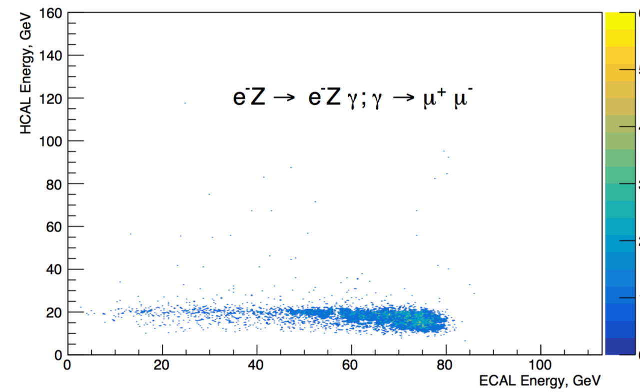
Simulation of eZ->eZA´

- The signal process events are simulated using simplified Weizsaecker – Williams (WW) approximation (Bjorken et al., 2009)
- For the total cross section we use the full matrix element calculations (arXiV:1712.05706 [hep-ph]) through the K-factors applied to the WW cross sections
- These K-factors can be as small as 1/15 at $M_A \sim 1$ GeV
- The differential cross section (essentially the distribution of the energy fraction transferred to A’) from WW is used. The difference is small because both WW and exact are strongly peaked near 1. The A’ spectrum is determined mainly by the EM shower development

Reconstruction: key moments

- Synchrotron Radiation detectors (SRD) made as lead – scintillator sandwiches suppress pions and other particles heavier than electrons that are present in the beam by a factor of 10^{-5}
- The shower profile in ECAL is compared to the profile of true electrons in order to further suppress wrong particles.
- Micromegas track detectors are used to reconstruct the momentum of electron before the ECAL in order to suppress small fraction of soft electrons from interactions on beam line elements.

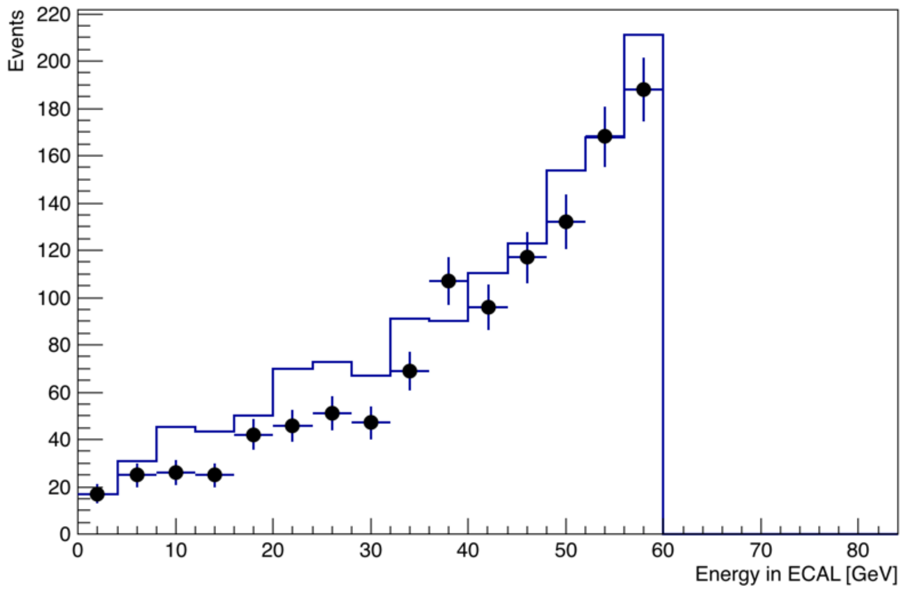
Dimuon production as a reference process

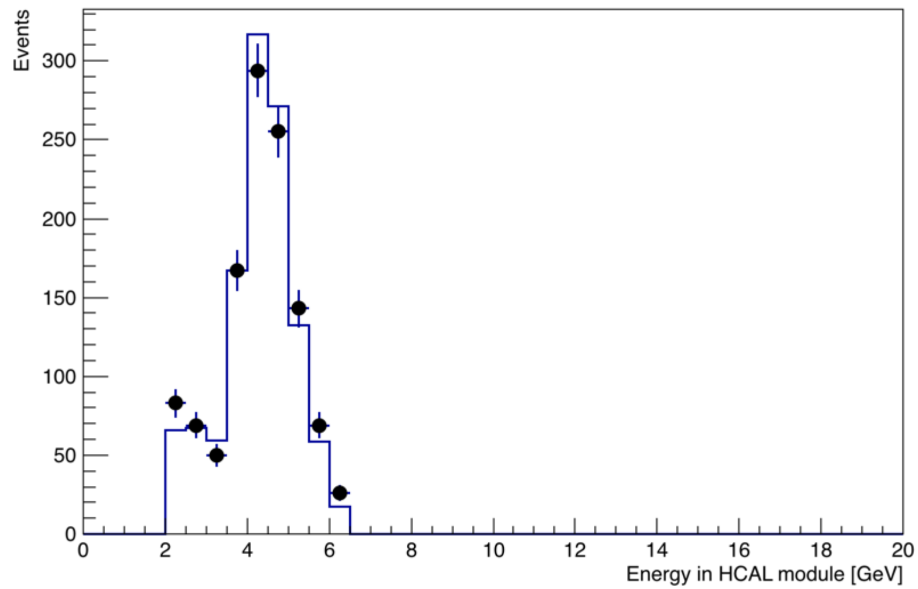


- There is an excellent reference process: gamma to muons conversion. It is rather rare and has many similarities with our signal
- Several 10^4 dimuon pairs with both muons reaching all HCAL modules are registered in the 2016 runs
- The process is available in GEANT4, off by default
- We bias the cross section in GEANT4 by a factor of 200 in order to have good statistics with reasonable CPU time.
- Reasonable agreement DATA - MC

Dimuon reconstruction

HCAL module 3





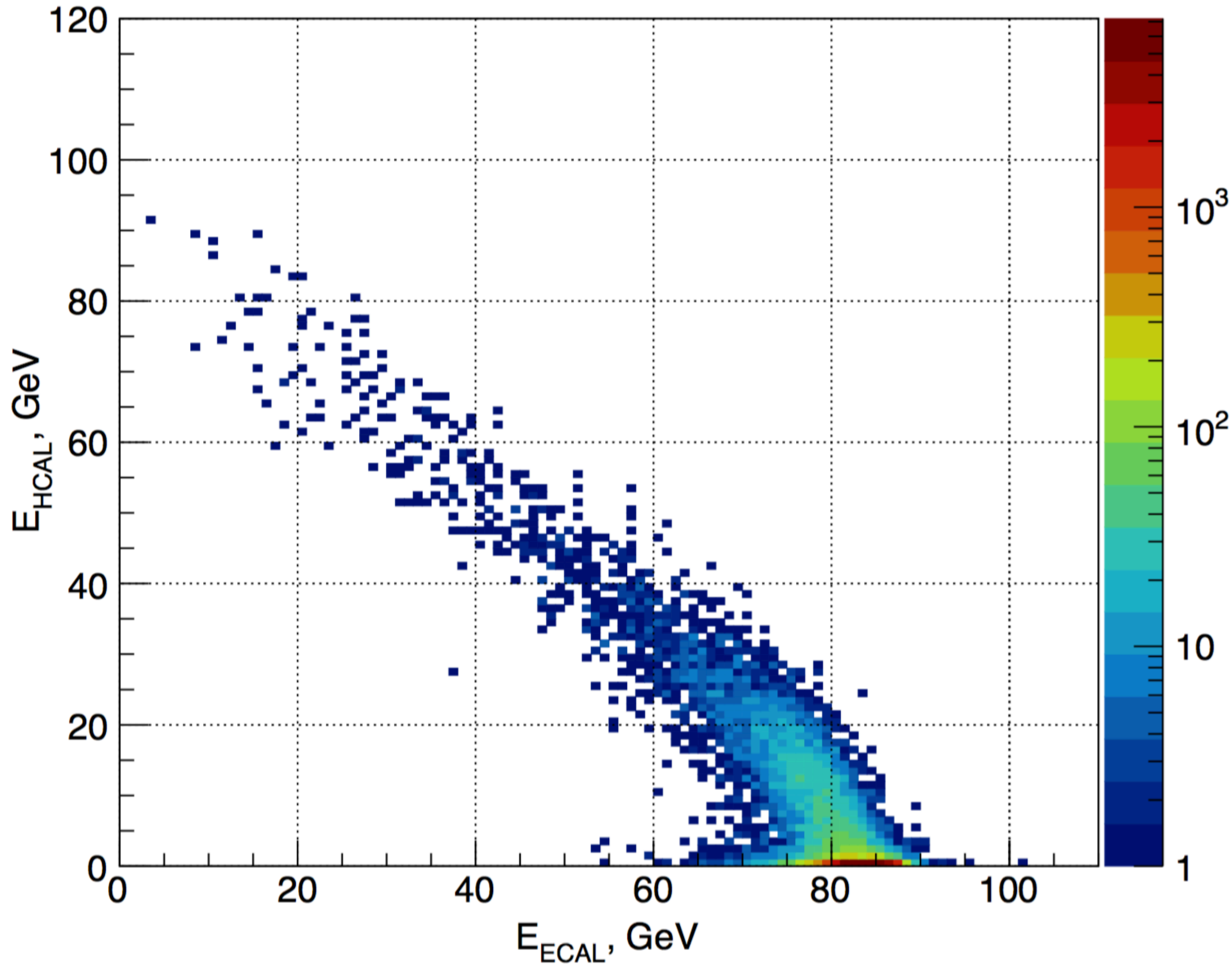
Dimuons selection: $E_{ECAL} < 60$ GeV

$2.5 < E_{HCAL1} < 6.35$

$2 < E_{HCAL3} < 6.35$

Left plot: number of dimuons in DATA ~ 0.92 of MC prediction, slightly smaller at high intensity -> efficiency correction

Background

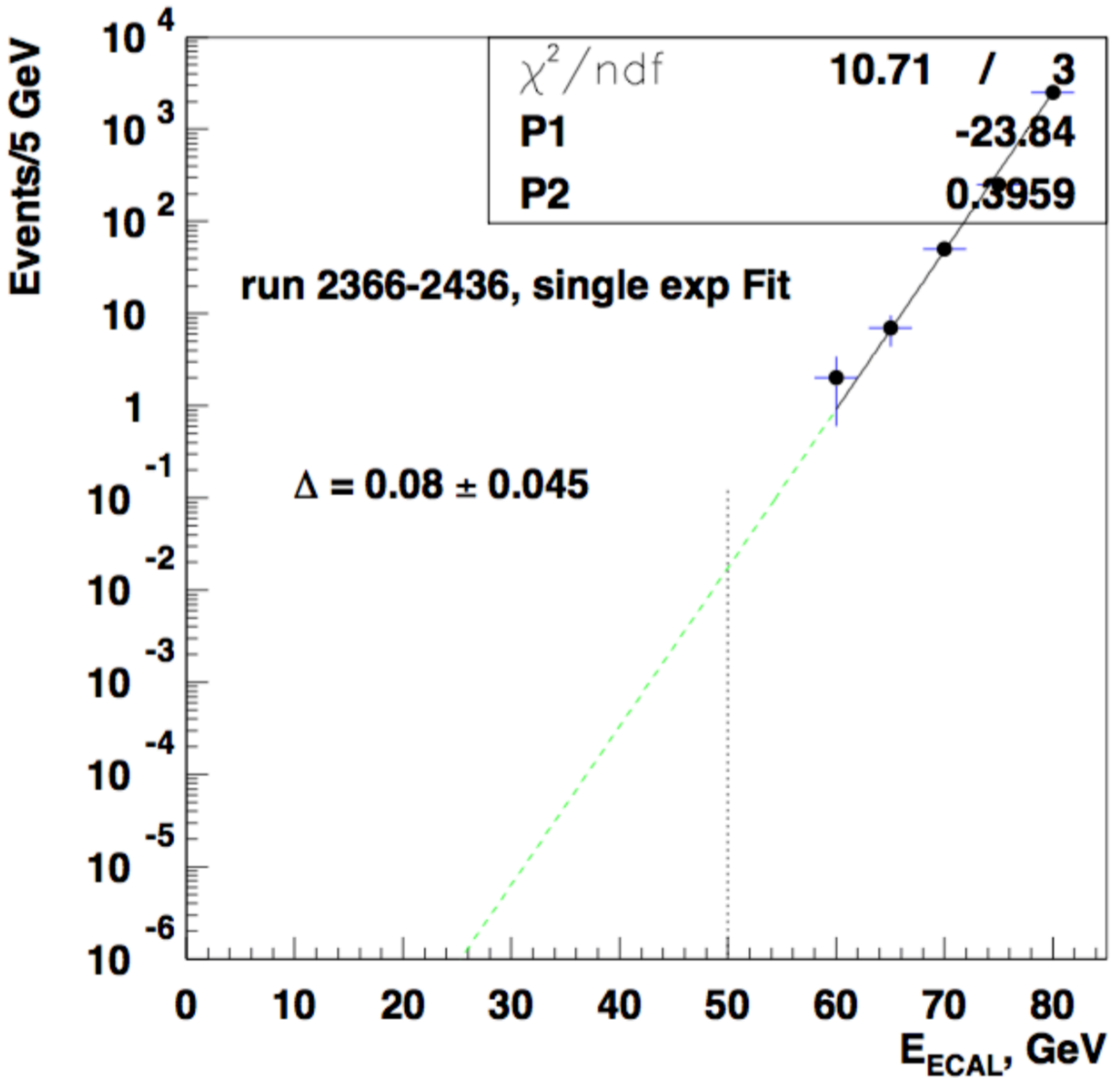


120
100
80
60
40
20
0
0
20
40
60
80
100
E_{HCAL}, GeV
E_{ECAL}, GeV
10^3
10^2
10
1

Background

- As mentioned above, the sources of background are decays in flight and various impurities of the beam (softer electrons etc.)
- The BG from decays was estimated by biasing the life times in GEANT4
- The second BG is higher and difficult to simulate. We estimated it using extrapolation from the “side bin” , i.e. from what we see beside our “signal box” preliminarily defined as “$E_{ECAL} < 50$ GeV”
- In the 2018 run additional BG from the interactions in the material of the tracker started to be important. Estimated by biasing cross sections. Suppressed by additional cuts on the multiplicity in MM and energy profile in HCAL

Background: example of extrapolation

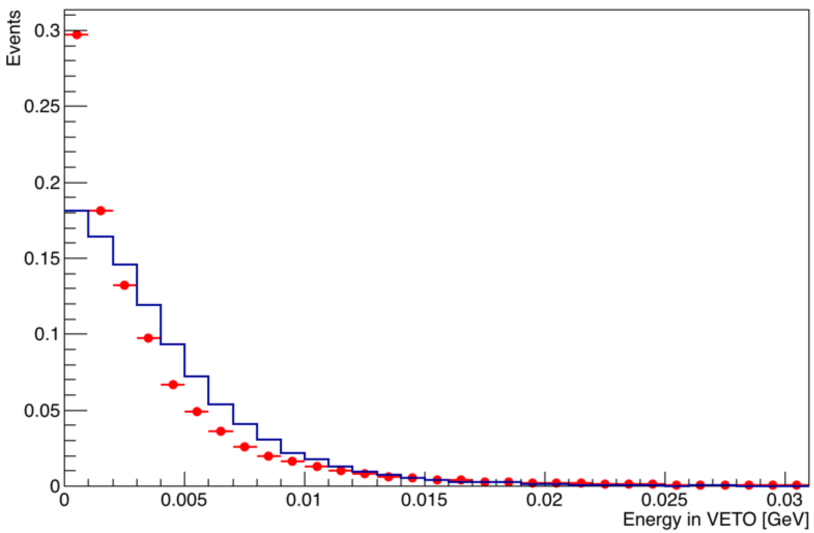


Total predicted background ~0.17

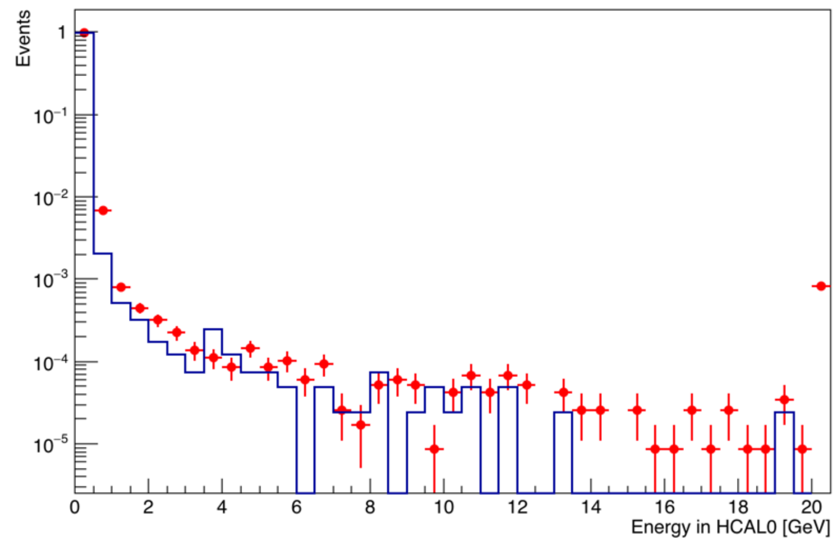
Analysis: efficiency corrections and uncertainties

Efficiency type	Method	Efficiency	uncertainty
Trigger and SRD selection, DAQ	Dimuons analysis	0.91	10%
VETO cut	Comparison MC - data in calib. runs	1	5%
HCAL cut	Comparison MC - data in calib. runs	0.99	5%

Veto: cut at 0.01 GeV



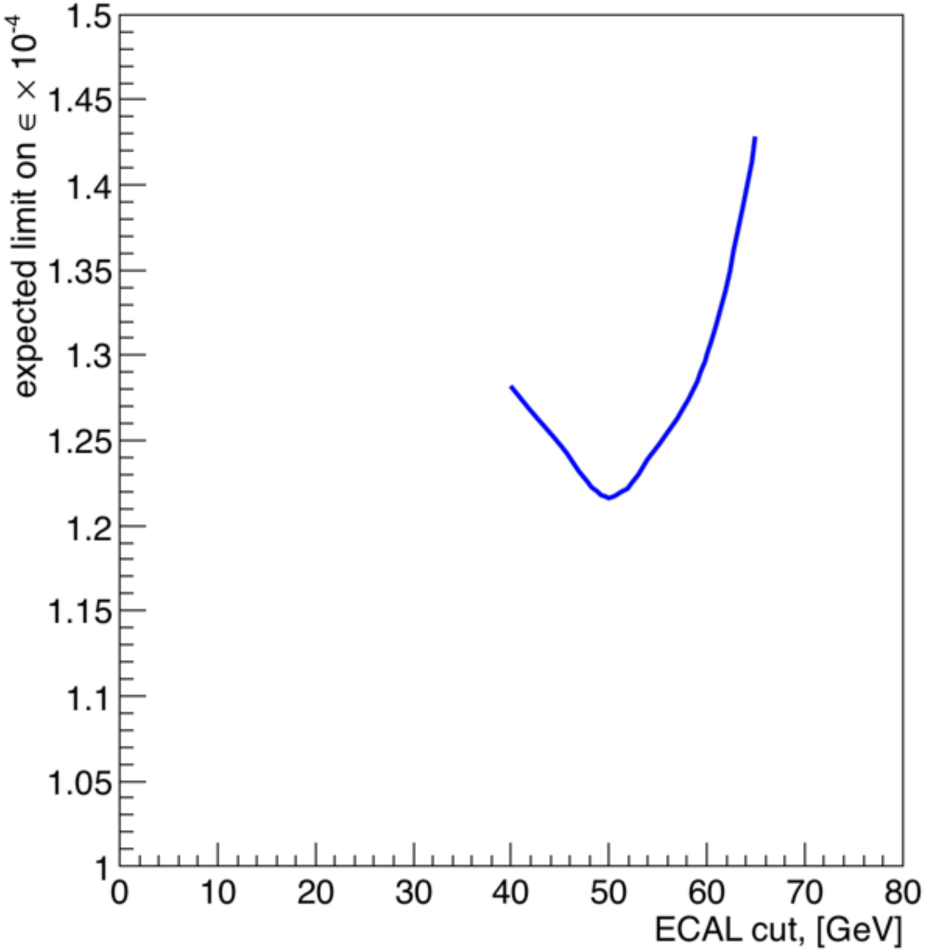
HCAL0: cut at 1 GeV



Analysis

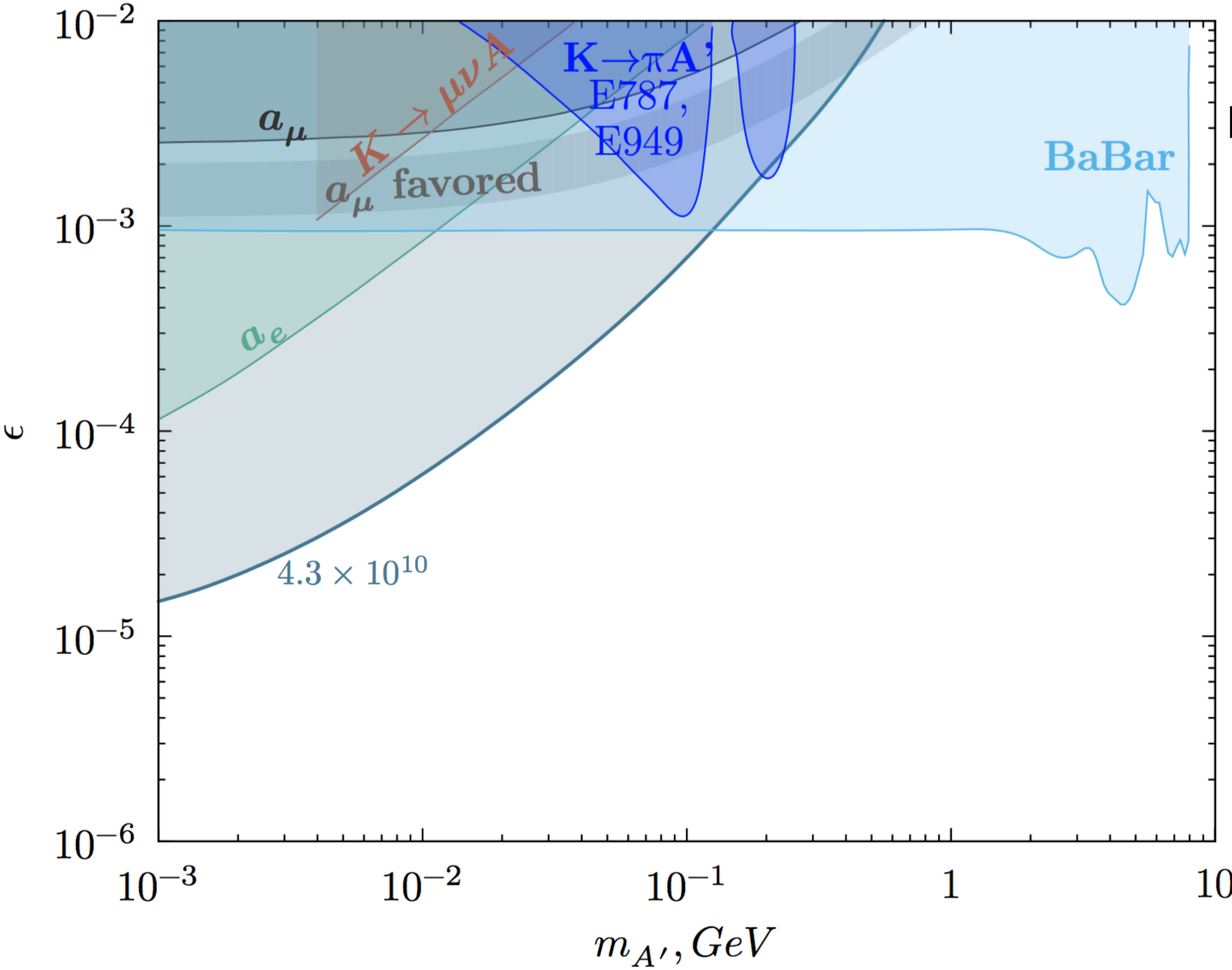
- Data collected in the automn 2016 run are divided in 3 bins: low, medium and high intensity
- For each bin the background, efficiency corrections and their uncertainties are estimated
- The expected sensitivity was calculated with ProfileLikelihood method
- The limits are calculated with CL_S method

Analysis: optimization



The optimization confirmed the preliminary choice of the E_{ECAL} cut: 50 GeV

Published results

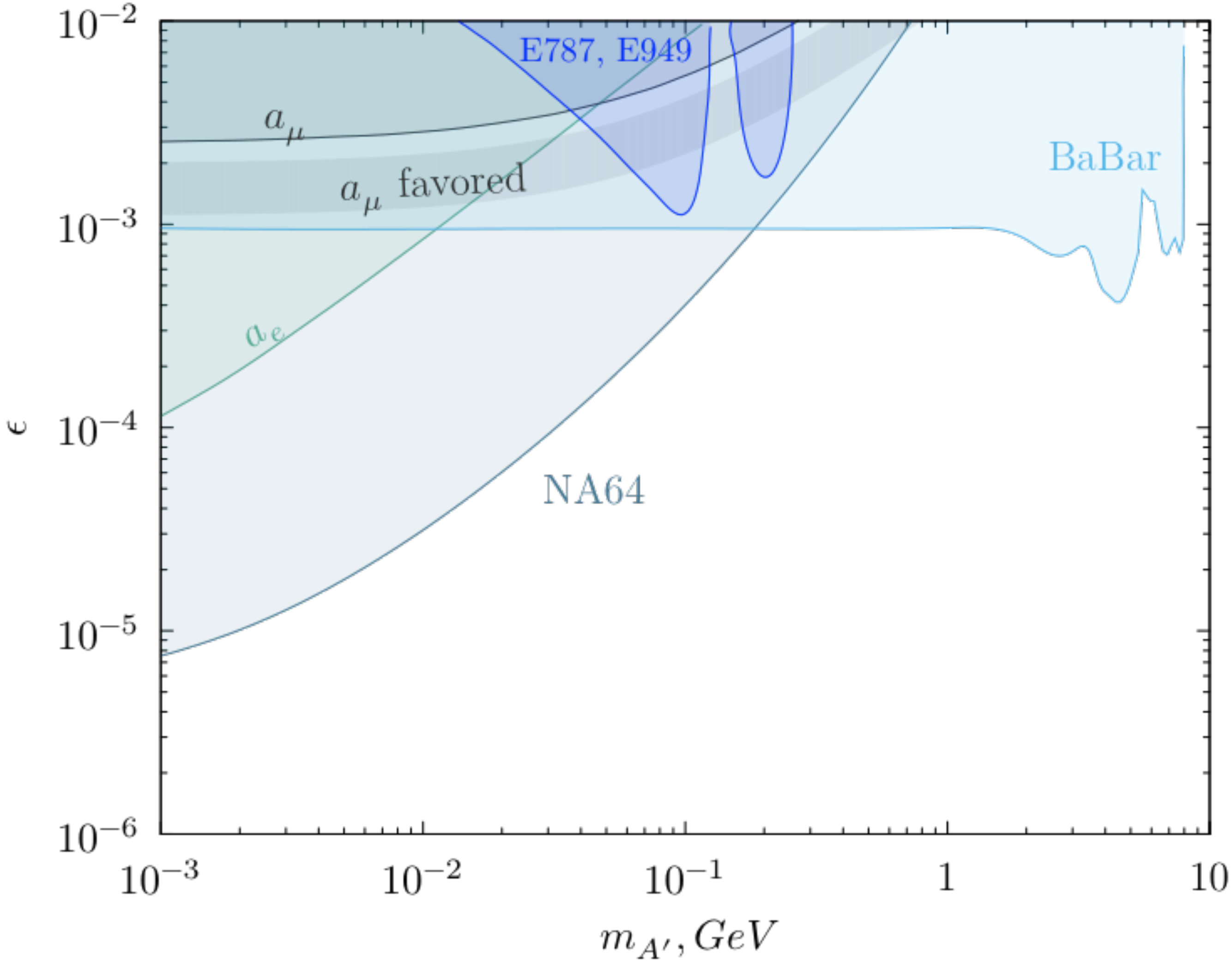


arXiV:1710.00971 [hep-ph]
Phys. Rev. D 97, 072002 (2018)

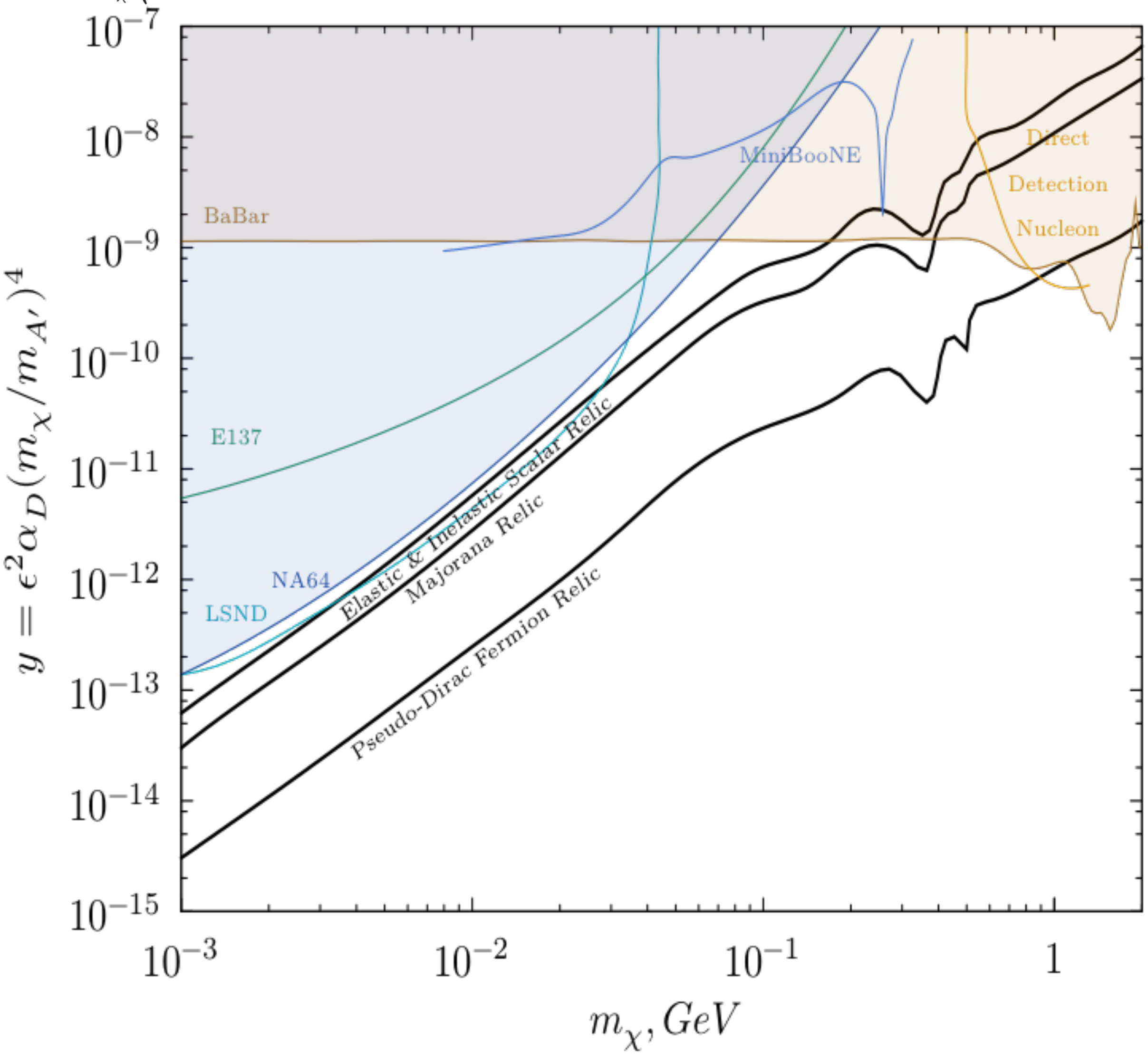
Full data set analysis

- The analysis of the 2017 and 2018 data in invisible mode is not yet finished, it is in advanced stage
- The sensitivity is estimated, it is shown in the next slide

Sensitivity with the full data set $2.89 \cdot 10^{11}$ EOT



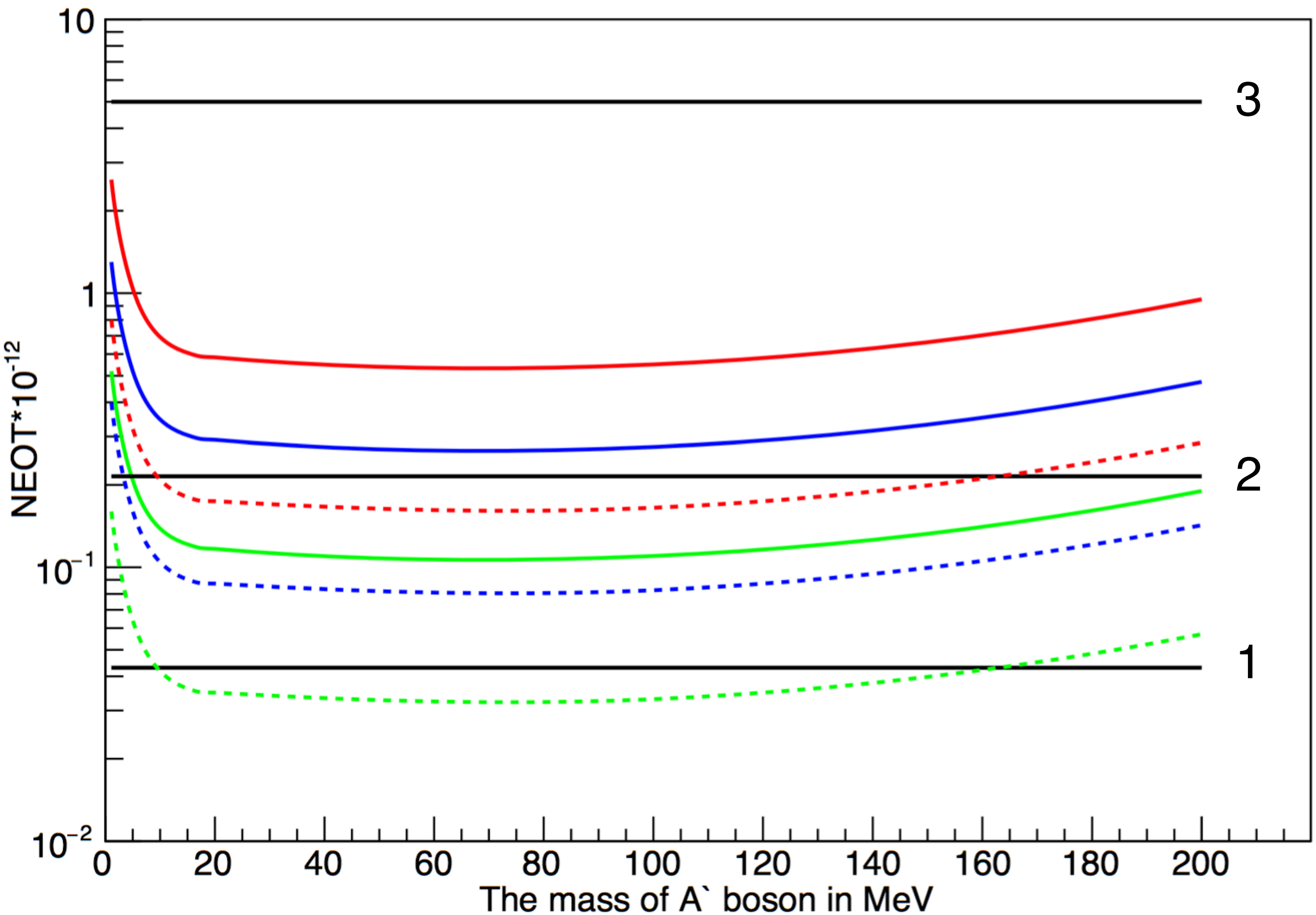
Sensitivity to y and some popular sub-GeV Dark Matter models



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

For $\alpha_D < 0.1$ we start to cover the scalar case

Sensitivity to some popular sub-GeV Dark Matter models



Scalar DM

Red, blue, green solid:
$\alpha_D = 0.1, 0.05, 0.02,$
$m_{A'} = 2.5 m_\chi$

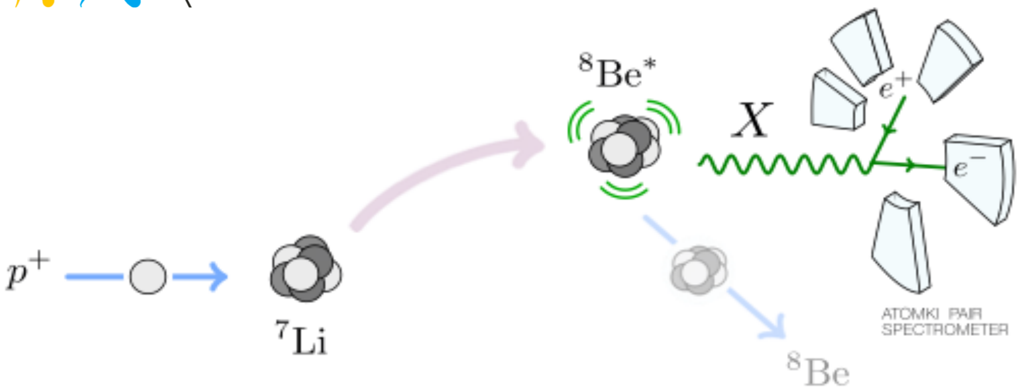
Red, blue, green dashed:
$\alpha_D = 0.1, 0.05, 0.02,$
$m_{A'} = 3 m_\chi$

1 – published result
2 – stat. up to 2018
3 – plans for 2021+

Search for a new X-boson and Dark Photons decaying to e^+e^-

ATOMKI ^{8}Be* anomaly: a new 17 MeV gauge boson?

^{7}Li(p,γ)^{8}Be, M_X =17 MeV



Feng et al, 2016

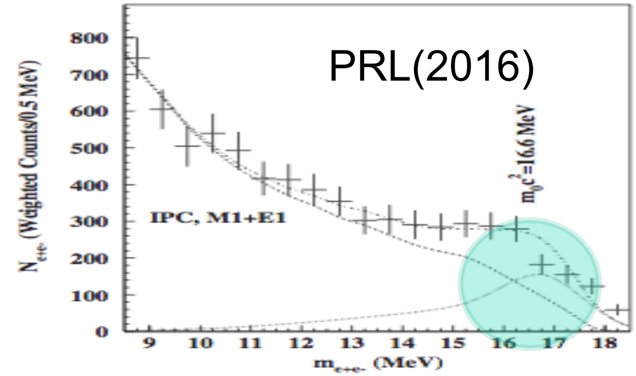
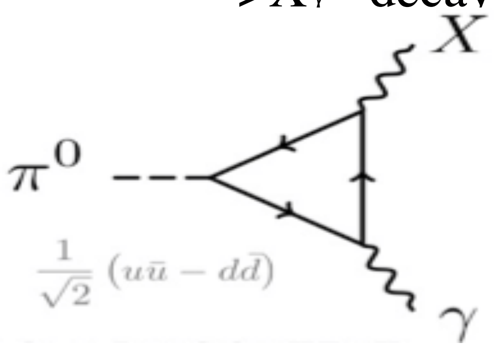
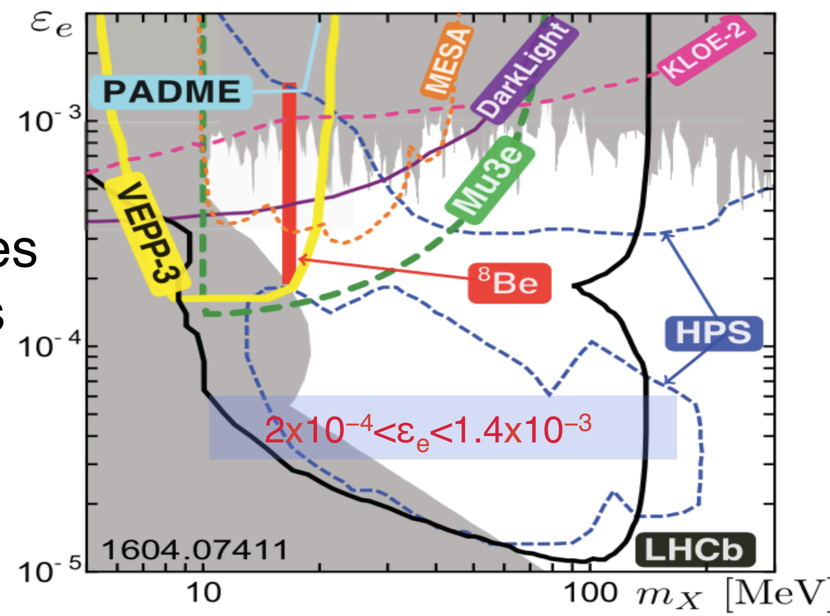


FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.

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



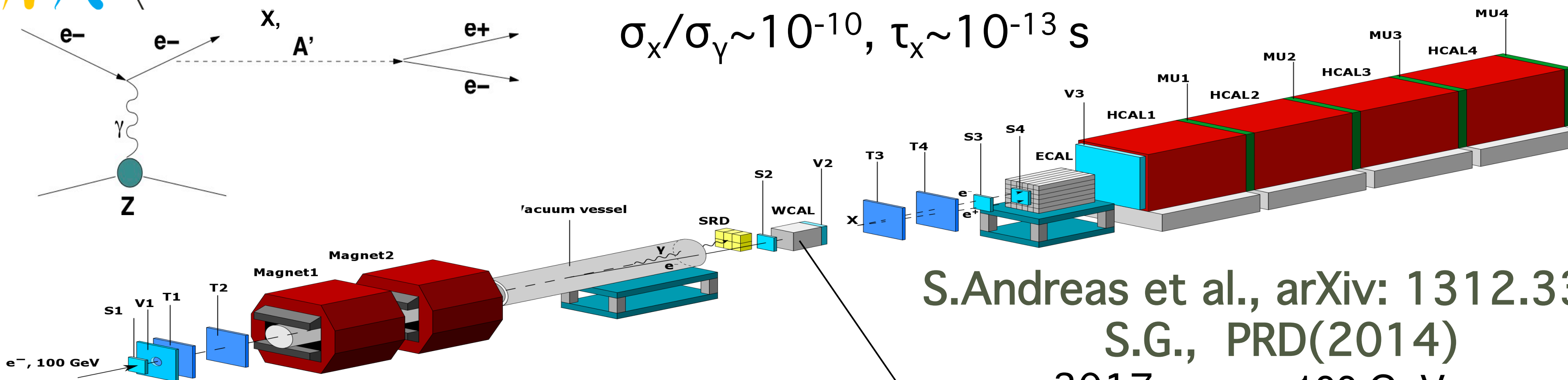
Coloured lines are projects



$\Gamma(\pi^0\to X\gamma) \sim (\varepsilon_u q_u - \varepsilon_d q_d)^2 \sim 0$

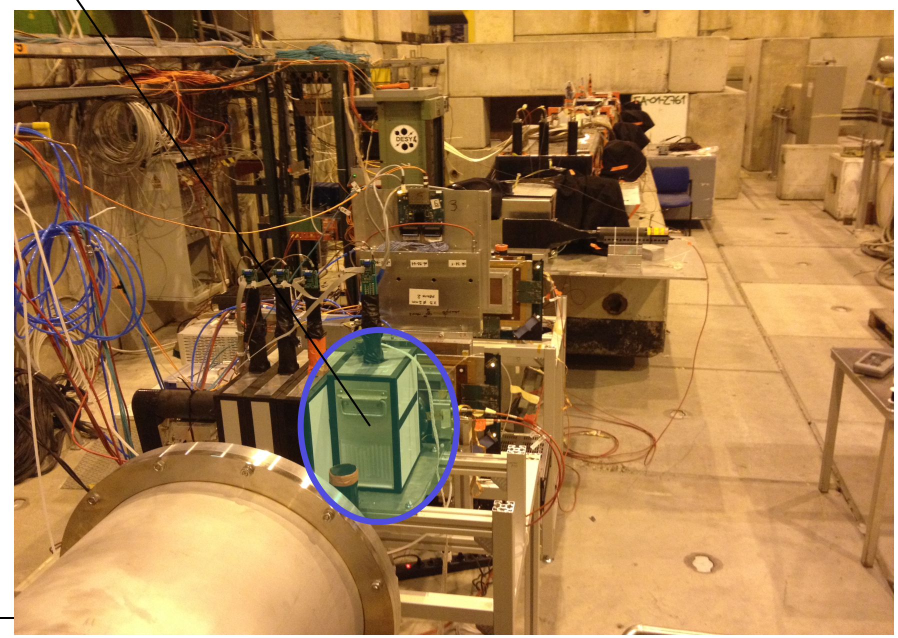
if $2\varepsilon_u = -\varepsilon_d$ -> protophobic X

Search for the X(A´)->e⁺e⁻ decays



$\sigma_X/\sigma_\gamma \sim 10^{-10}$, $\tau_X \sim 10^{-13}$ s

S.Andreas et al., arXiv: 1312.3309
S.G., PRD(2014)
2017 run e⁻, 100 GeV



- X decays outside WCAL dump
- Signature: two separated showers from a single e-
  - $E_{WC} < E_0$, and $E_0 = E_{WC} + E_{EC}$
  - θ_{e+e-} too small to be resolved
  - background
    - Beam hadrons
    - SRD e⁻-tagging is a key point

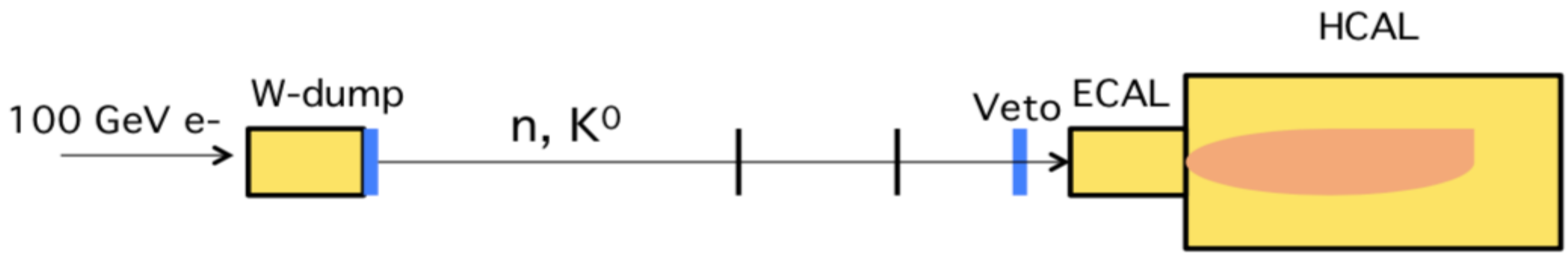
Event selection: criteria

- SRD tag
- E_{WCAL} < 70 GeV (preliminary trigger selection E_{WCAL}< ~75 GeV)
- E_{V2} < 0.6 MIP (no charged particles after WCAL).
- E_{S4} > 1.5 MIP (two charged particles in ECAL).
  Control region for neutrals: E_{S4} < 0.7 MIP
- E_{WCAL} + E_{ECAL} > 85 GeV
- Shower profile in ECAL compatible with electron (or with two very close electrons)
- Small energy in VETO and HCAL

Checks of efficiency to signal

- Dimuons (gamma to muons conversion) are used also in this configuration: efficiency corrections
- Electron calibration runs are used to compare the the distributions in the detectors used as veto: V2, VETO, HCAL
- Checking the shower profile. We cannot have a single electron in ECAL in this configuration. We selected muons from the hadron calibration runs that emit hard delta electron in ECAL. We require EECAL > 20 GeV and we select events with small activity in ECAL, VETO. All such events have χ^2 below our cut.

Main background from $K^0_S \to \pi^0 \pi^0 \to \gamma' s \to e^+e^-$ decay chain



We used two control samples to estimate this BG: fully neutral events with and without cut on E_{HCAL}.
Two methods to estimate this background:
First: sample with removed cut on E_{HCAL}. Main contribution from neutrons, also K^0_L contribute
Second: sample with cut on E_{HCAL}

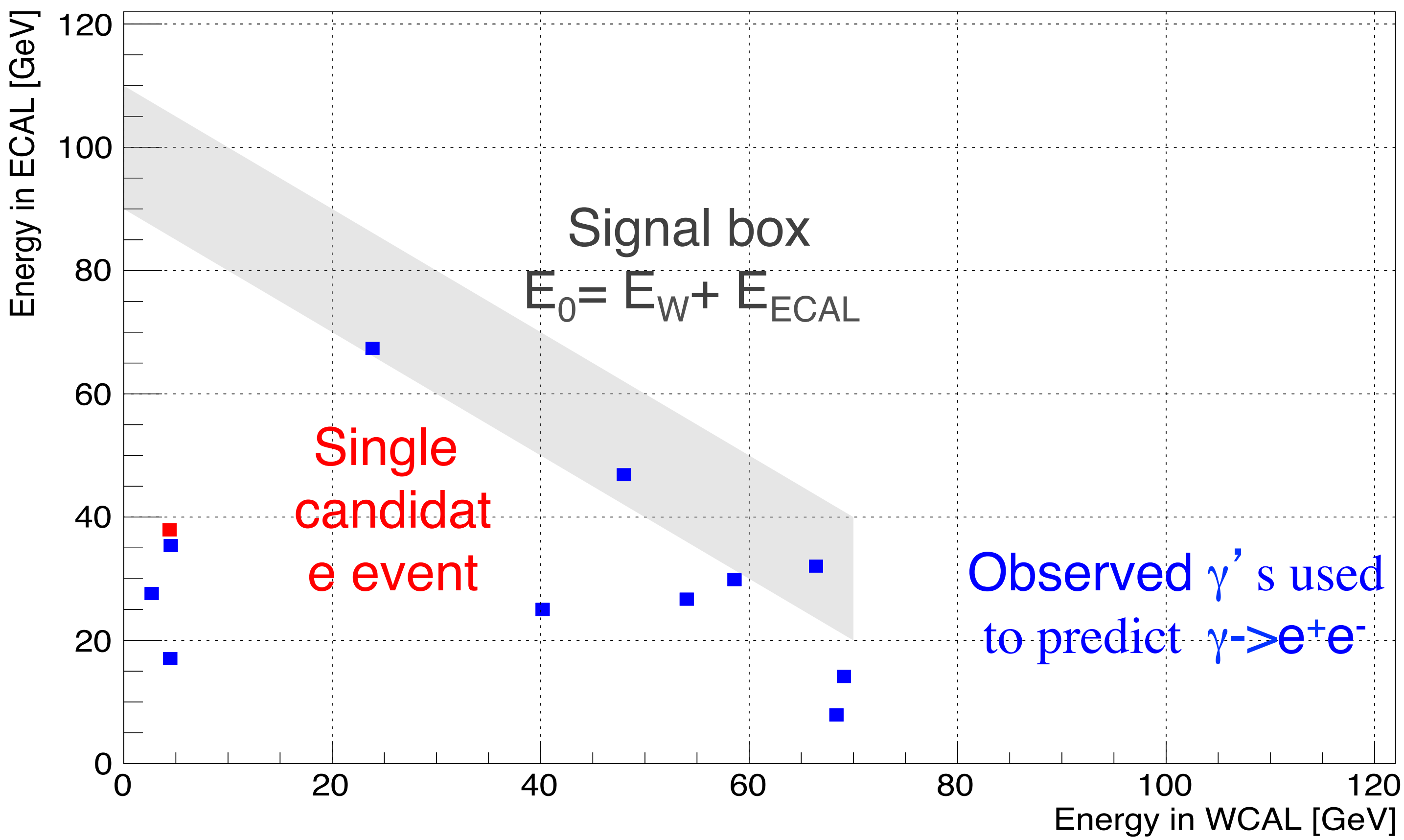
Method I: selection of neutral hadronic final state: n:K^0~ 10:1 => : n_{K0} ~10^2 K^0 **Method II:** selection of e.m. neutrals (γ' s from K^0_S chain) => n_{K0} ~1.5×10^2 K^0

Consistent estimates of K^0_S
Then use Geant4 MC to estimate the number of K^0_S events with conversion before S4

Final estimate of the background

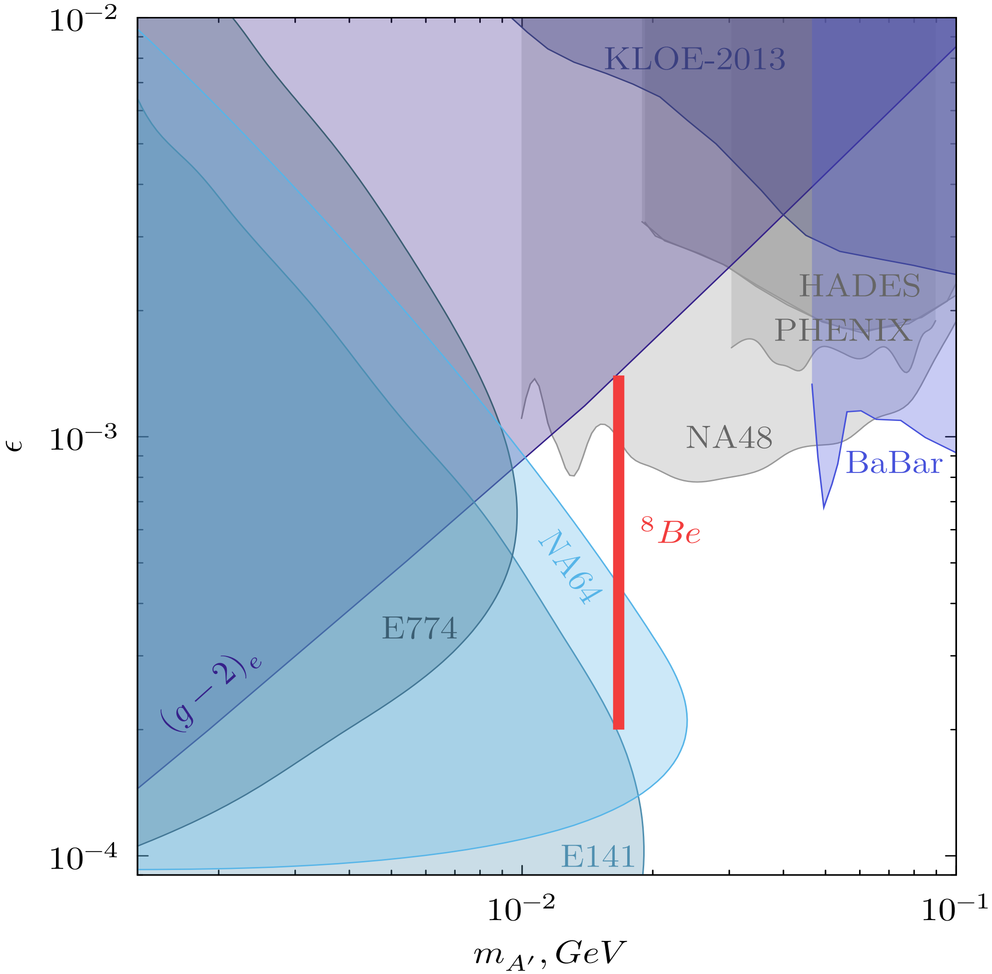
Source of background	Events
e^+e^- pair production by punchthrough γ	< 0.001
$K^0_S \to 2\pi^0; \pi^0 \to \gamma e^+e^-$ or $\gamma \to e^+e^-$; $K^0_S \to \pi^+\pi^-$	0.06 ± 0.034
$\pi N \to (\geq 1)\pi^0 + n + ...; \pi^0 \to \gamma e^+e^-$ or $\gamma \to e^+e^-$	0.01 ± 0.004
π^- hard bremsstrahlung in the WCAL , $\gamma \to e^+e^-$	< 0.0001
$\pi, K \to e\nu$, K_{e4} decays	< 0.001
$eZ \to eZ\mu^+\mu^-; \mu^\pm \to e^\pm\nu\nu$	< 0.001
punchthrough π	< 0.003
Total	0.07 ± 0.035

Results from 2017 run, $5.4x10^{10}$ EOT



Results from the 2017 run, 5.4×10^{10} EOT

NA64 exclusion area, 5.4×10^{10} EOT



X is simulated as A' in invisible mode, then decayed with $\Gamma \sim m\varepsilon^2$, **Br(X → e^+e^-)=1**

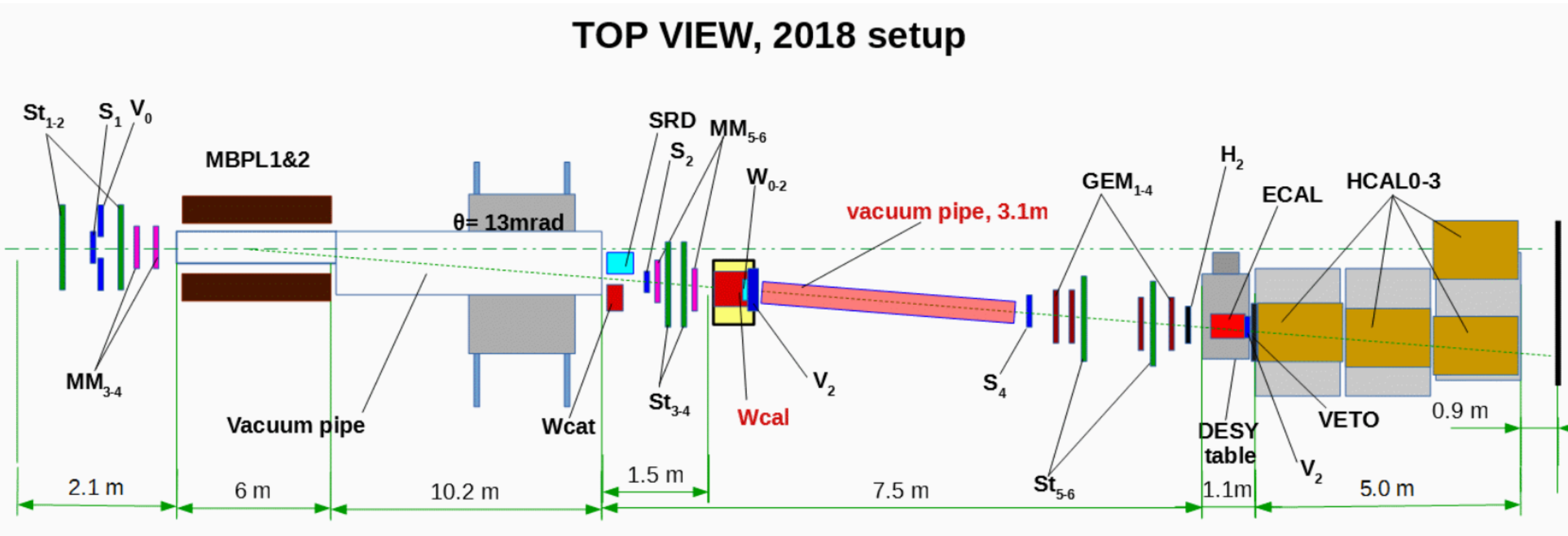
Part of the ^{8}Be* region (red vertical line) is excluded: $1.3\times10^{-4} < \varepsilon_e < 4.2\times10^{-4}$

Region of A' with different masses decaing to e^+e^- is excluded

arXiV:1803.07748 [hep-ph], published in Phys. Rev. Letters

2018 run

More data, 3×10^{10} EOT(less than expected, SPS problems) were taken in June 2018 with the visible mode configuration optimized for bigger ε (short-lived X): 150 GeV beam, veto counter inside WCAL box, vacuum decay tube, larger distance WCAL - ECAL



Event selection 2018 at 150 GeV: criteria

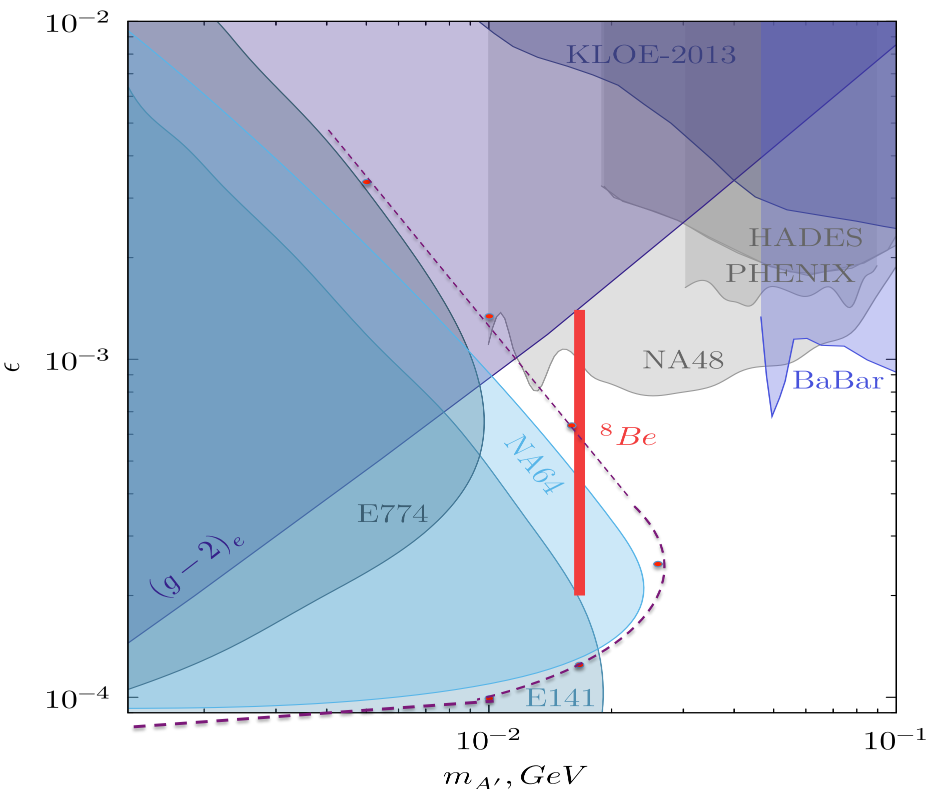
- SRD tag (with only 2 modules because of smaller bend)
- E_{WCAL} < 105 GeV (preliminary trigger selection E_{WCAL} < ~110 GeV)
- E_{V2} < 0.6 MIP (no charged particles after WCAL).
- E_{S4} > 1.5 MIP (two charged particles in ECAL).
  Control region for neutrals: E_{S4} < 0.7 MIP
- E_{WCAL} + E_{ECAL} > 125 GeV
- Shower profile in ECAL compatible with electron (or with two very close electrons)
- Small energy in VETO and HCAL

Background in 2018, preliminary

Source of background	Events
e^+e^- pair production by punchthrough γ	< 0.001
$K^0_S \to 2\pi^0; \pi^0 \to \gamma e^+e^-$ or $\gamma \to e^+e^-$; $K^0_S \to \pi^+\pi^-$	0.006 ± 0.004
$\pi N \to (\geq 1)\pi^0 + n + ...; \pi^0 \to \gamma e^+e^-$ or $\gamma \to e^+e^-$	0.005 ± 0.002
π^- hard bremsstrahlung in the WCAL , $\gamma \to e^+e^-$	< 0.0001
$\pi, K \to e\nu$, K_{e4} decays	< 0.001
$eZ \to eZ\mu^+\mu^-; \mu^\pm \to e^\pm\nu\nu$	< 0.001
punchthrough π	< 0.003
Total	0.011 ± 0.0045

Results from the 2017+2018 runs, 8.4×10^{10} EOT

NA64 exclusion area, 8.4×10^{10} EOT, preliminary



X is simulated as A' in invisible mode, then decayed with $\Gamma \sim m\varepsilon^2$, $Br(X \rightarrow e^+e^-)=1$

Part of the $^8Be^*$ region (red vertical line) is excluded: $1.3 \times 10^{-4} < \varepsilon_e < 5.6 \times 10^{-4}$ (upper bound was 4.2×10^{-4})

Region of A' with different masses decaing to e^+e^- is excluded

This result is not yet published

Conclusion on the data already collected, invisible mode

- A search is performed for sub-GeV dark photons (A′) mediated production of dark matter by the NA64 experiment with 2.89×10^{11} 100 GeV electrons on target (EOT)
- The samples corresponding to 5.4×10^{10} EOT are fully analysed, results published
- No evidence for such events is found. This allows to derive an upper limit on the $A' - \gamma$ mixing strength in the A′ mass range from 1 to 500 MeV and allows to exclude a vector mediator particle solution (universal or e - coupled) to the (g-2) anomaly
- The data collected in 2017 and 2018 are being analysed, in advanced stage. The sensitivity with these data will allow to fully probe some popular sub-GeV Dark Matter models

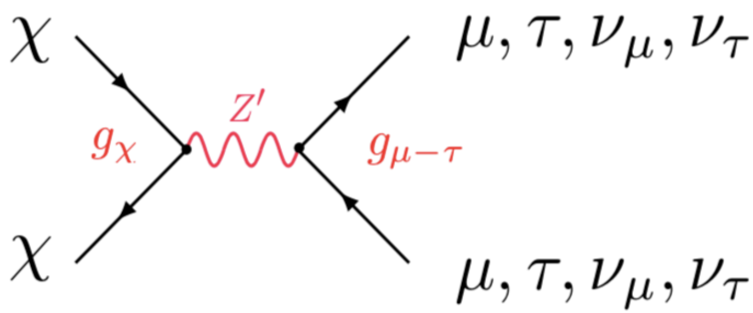
Conclusion on the data already collected, visible mode

- A search is performed for a new X-boson and A' decaying to e^+e^-
- No evidence for such particles are found. This allows to exclude part of the $^8Be^*$ preferred region and a region on the m – ε plane for similar particles with different masses
- We are working on the analysys of the 2018 data that uses tracker and vertex finding. In combination with the counter analysis reported here this can improve the sensitivity to high values of ε
- One more analysis on the search for exotic particles is been performed now

Future plans

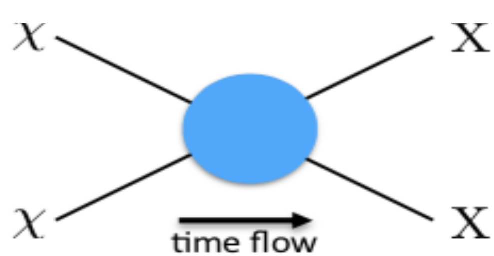
- Running in the electron beam after LS2 (2021+) is approved. Plan to collect up to $5*10^{12}$ EOT. This will require the modernization of the apparatus
- This statistics should allow to probe most of the popular sub-GeV Dark Matter models
- The project of running in the modified muon beam M2 is being prepared, the purpose is to probe the remaining explanations of $(g - 2)_{\mu}$, $\mu - \tau$ conversion etc.

L_μ-L_τ Charged Dark Matter and Z_μ mediator



Gninenko, Krasnikov 1801.10448
Kahn, Krnjaic, Tran, Whitbeck 1804.03144

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



- free parameters m_χ, $m_{Z\mu}$, g_χ, g_μ
- Z_μ 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: $Z_\mu \rightarrow \chi\chi, \nu\nu,$

$\alpha_D >> \alpha_{SM}$, $\alpha_D=g_\chi^2/4\pi$, $\alpha_{SM}=g_\mu^2/4\pi$

- Cross section for χ–DM annihilation:

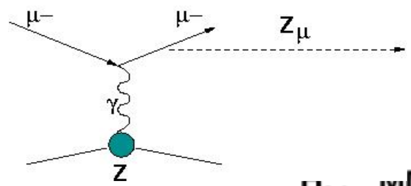
$\Gamma_{inel} = n_\chi < \sigma v >$

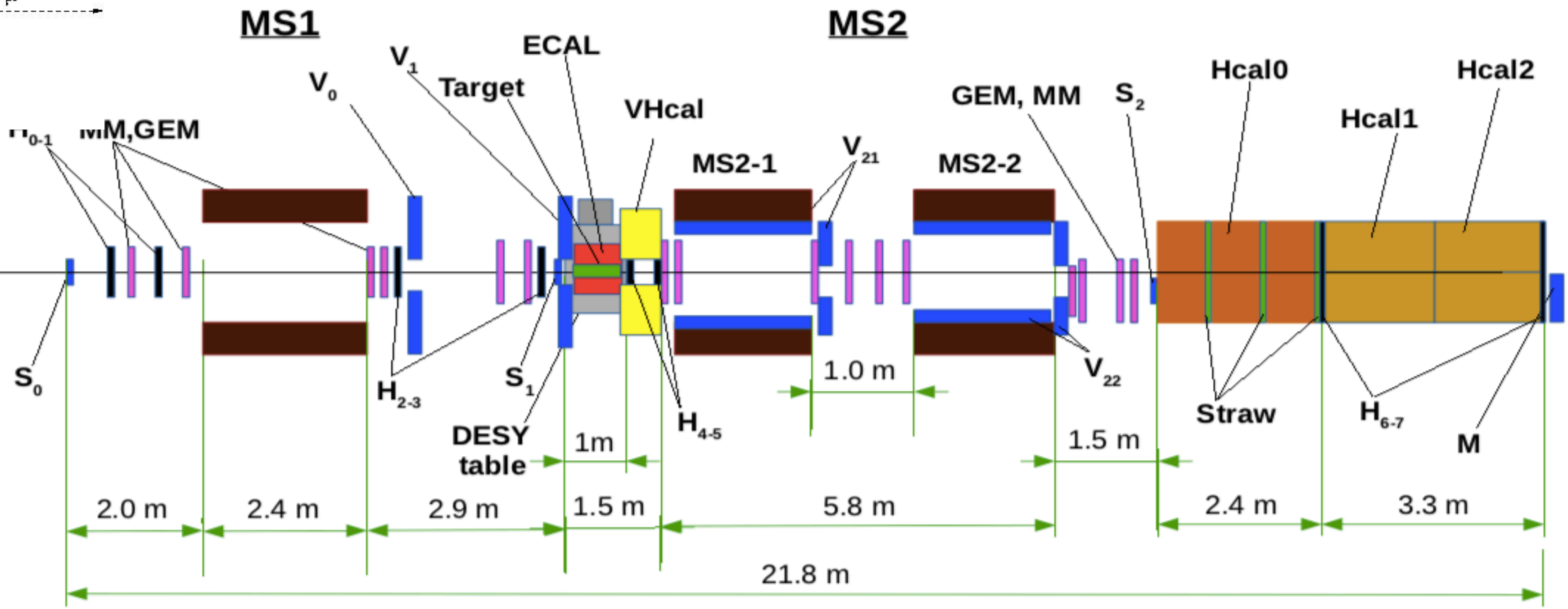
$\sigma v \approx [(g_\chi g_\mu)^2(m_\chi/m_{A'})^4]/m_\chi^2 = y/m_\chi^2$;

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

Search for Z_μ in missing energy events at M2

Proposal NA64μ (2019)





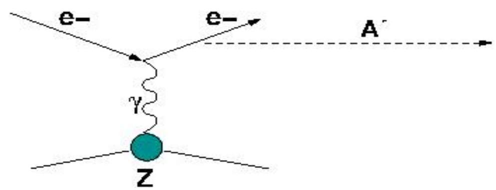
Main components :

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

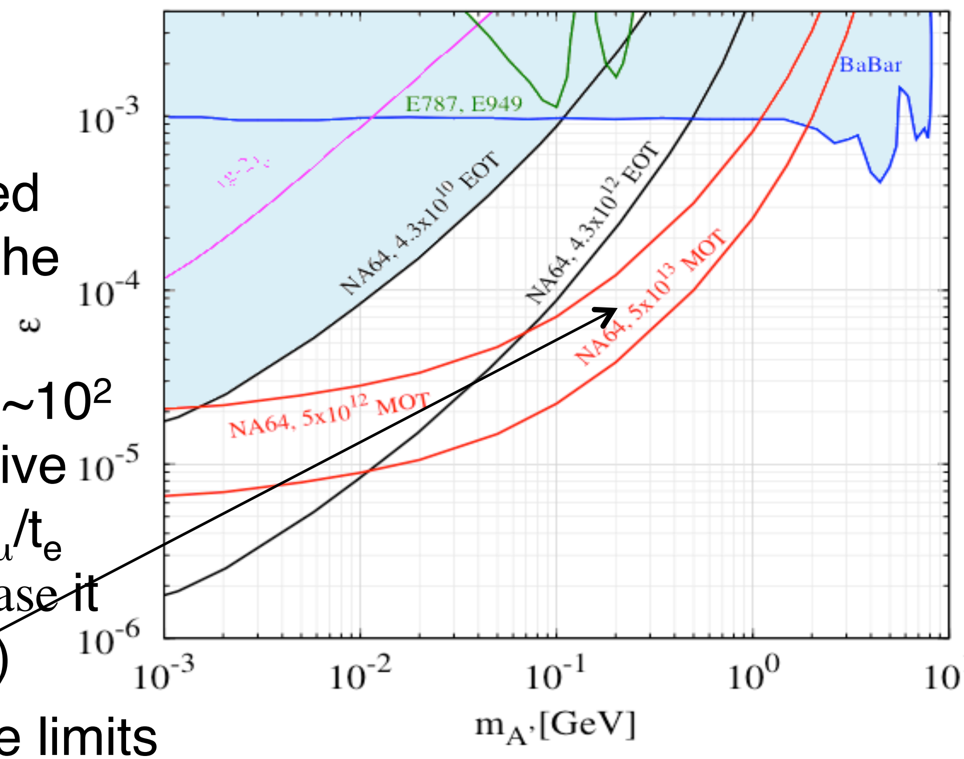
Signature:

- in: 160 GeV μ- track
- out: < 80 GeV μ- track
- no energy in the ECAL, Veto, HCAL
- Sensitivity $\sim g_\mu^2$

Search for the A´ with a muon beam



- $N_{A'} \sim N_e\, \varepsilon^2\, m_e^2/m_{A'}^2$ Cross-section is suppressed for $m_{A'} >\sim m_\mu$. This is not the case for the μ beam



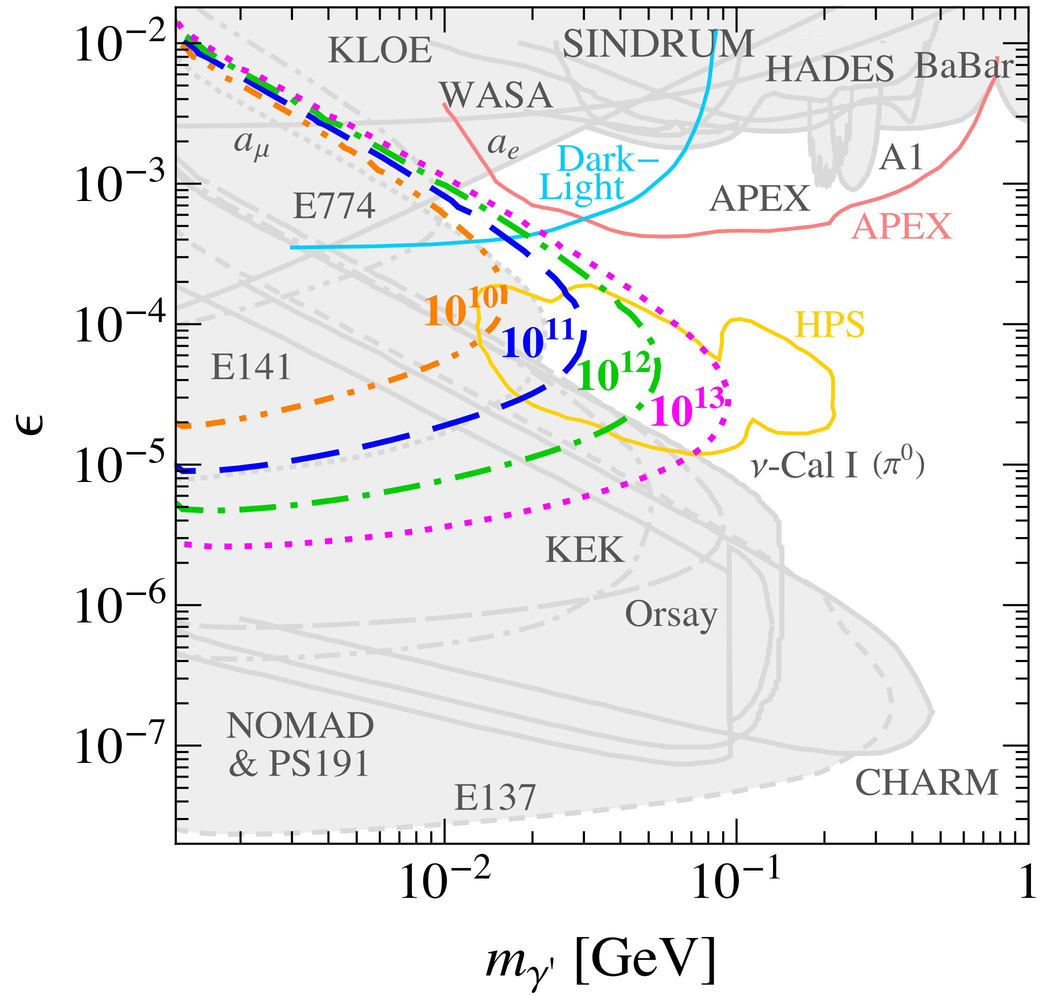
- Another enhancement factor ~10^2 is from the ratio of the effective e- and muon target length t_μ/t_e The $t_e \sim X^e_0$ while for the μ case it could be $t_e \ll t_\mu$ ($\ll X^\mu_0$)
- NA64μ can significantly improve limits for A´ mass ~ 0.1- 1 GeV, a factor 10^2 -10^3 for ε^2 or variables y and α_D (next slide)

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

Backup slides

Exclusion area for A´ → e^+e^- vs EOT

Old figure



Further running and expected results

Some more data (less than expected) were taken in June 2018 with the visible mode configuration optimized for bigger ε

NA64 running after LHC LS2 (in 2021) is preliminarily approved

Exclusion area for **A´ → e⁺e⁻** vs EOT