NA64 Status and Plans

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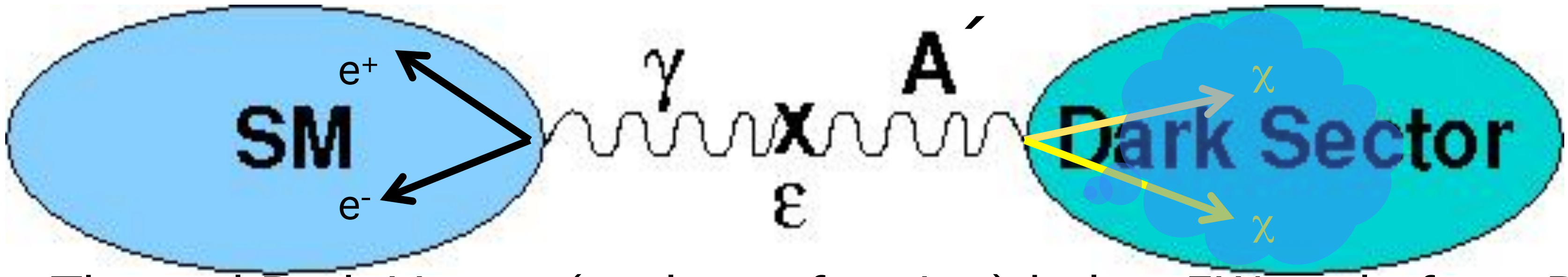
SPSC Open Session, CERN, June 7, 2018

Outline

- NA64 overview
- Search for sub-GeV Thermal Dark Matter
- Search for a new gauge boson from the ^{8}Be anomaly
- Search for the dark photon A´->e$^+$e- decay
- Plans and Summary

sub-GeV Thermal Dark Matter

Okun, Holdom



- Thermal Dark Matter (scalar or fermion) below EW scale from DS
- Early Universe: VM<->DM annihilate at equal rate ($T_\gamma >> m_\chi$)
- Vector boson A´(dark photon), mediate interaction to SM via $\gamma - A'$ kinetic mixing $\Delta L = \varepsilon/2\, F^{\mu\nu} A'_{\mu\nu}$, GUT: $\varepsilon \sim 10^{-5} - 10^{-3}$, $m_{A'} \sim \varepsilon^{1/2} M_Z$
- Cross section for χ–DM annihilation: $\sigma v \sim [\alpha_{DM}\, \varepsilon^2 (m_\chi / m_{A'})^4] = y$
- Hubble expansion: equilibrium lost – DM number density fixed
- The models predict a firm relationship between the dark-visible annihilation cross section and the cosmic DM abundance, making the ($\varepsilon, \alpha_D, m_{A'}, m_\chi$) parameter space a sharp sensitive target for NA64
- A´-production at SPS: bremsstrahlung $e^- Z \rightarrow e^- Z A'$, $\sigma \sim Z^2 \varepsilon^2 / m_{A'}^2$

- visible decays $A' \rightarrow e^+e^-, \mu^+\mu^-$, hadrons,..
- invisible decays: $A' \rightarrow \chi\chi$ if $m_{A'} > 2m_\chi$ assuming $\alpha_{DM} >> \varepsilon^2 \alpha$.

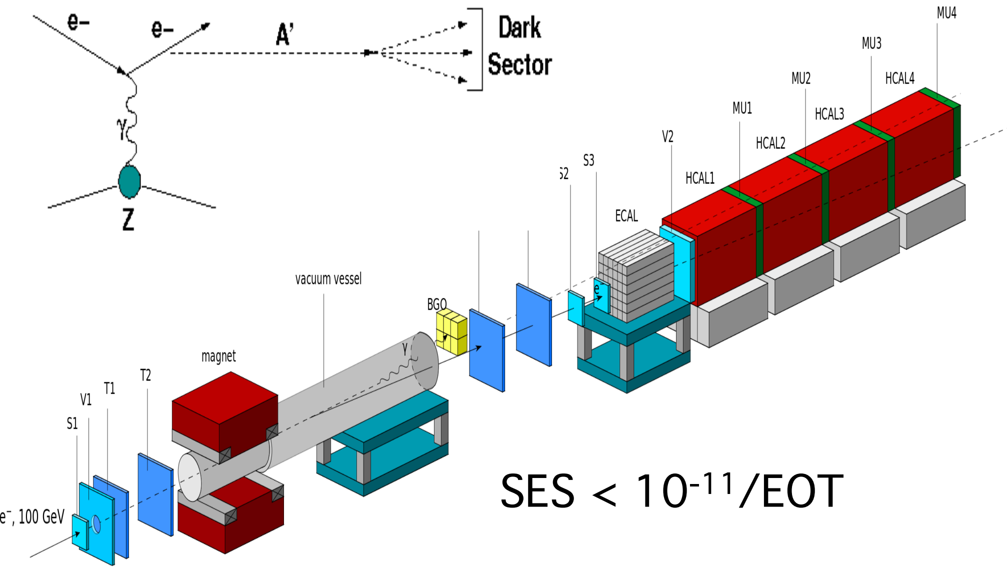
NA64

NA64 is designed to probe the Dark Sector physics in missing energy events. It has broad research program with e^-, μ, π, K, and p beams at SPC (PBC'16/17, input to the Europeen Strategy Group)

2016, 2017 run:

- Search for vector mediator A´ of LTDM dark matter production in invisible decay mode
- Search for the 17 MeV X-boson from the ^{8}Be excess and dark photon decays A´-> e^+e^-
- Feasibility of the search for the ALP a -> $\gamma\gamma$, *invisible* decays

NA64: Search for invisible A´ at the CERN SPS



SES < 10^{-11}/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

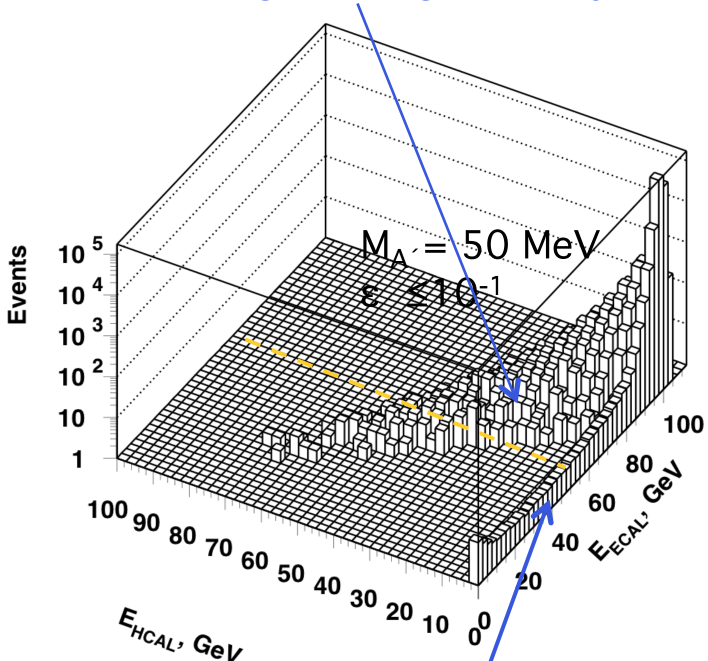
Background:

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

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

SM events:

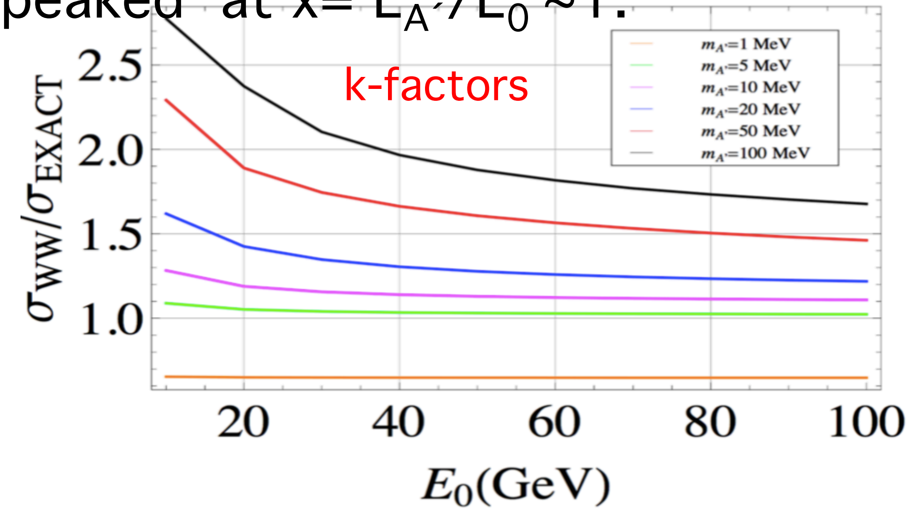
$E_{ECAL}+E_{HCAL} = E_0$



A´events:

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

- GEANT4+code for A´emission in the process of e-m shower development
- WW approximation for $\sigma(e^-Z\to e^-ZA')$ (Bjorken et al.'09)
- Corrections (k-factors) to WW from exact tree-level (ETL) calculations: large for higher A´masses
- arXiV:1712.05706, PLB
- The shape of WW and ETL differential cross sections is quite similar: strongly peaked at $x= E_{A'}/E_0 \sim 1$.



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

Data sample from 2016–17 runs

2016 run, 12.10–09.11, 4 w

- ~2×10^{10} EOT, S_0 rate $1.5\div2.2\times10^6$;
- ~1.3×10^{10} EOT, S_0 rate $2.4\div3.2\times10^6$;
- ~1.0×10^{10} EOT, S_0 rate $4.6\div5.0\times10^6$;

Total ~ 4.3 $\times10^{10}$ EOT

2017 run, 30.08–02.10, 5 w

A´-> invisible

- ~1.7×10^{10} EOT, S_0 rate $3.0\div3.5\times10^6$;
- ~3.2×10^{10} EOT, S_0 rate $5.4\div7.5\times10^6$;

Total ~ 5.0 $\times10^{10}$ EOT

^{8}Be anomaly, A´->e^+e^- decays

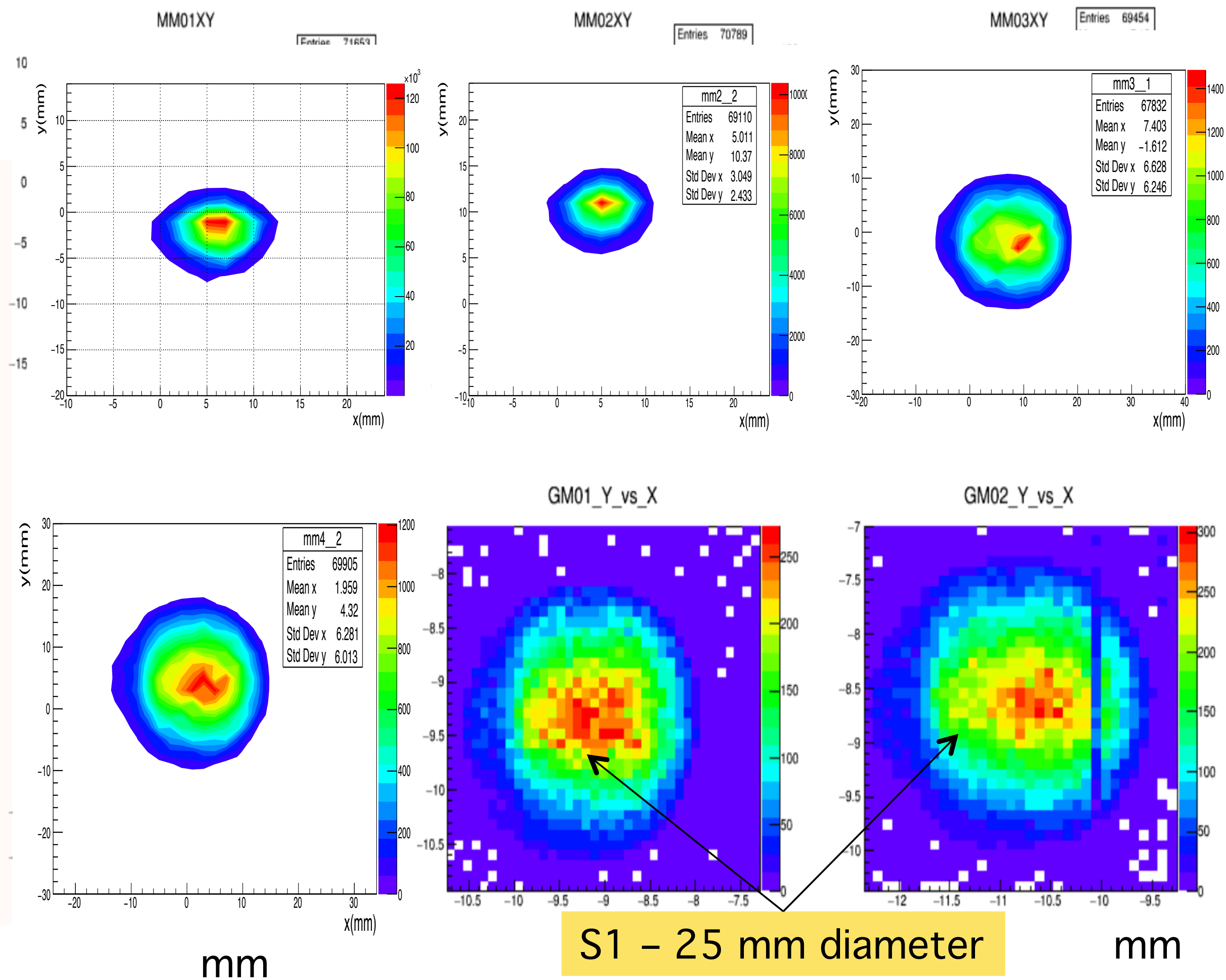
- ~ 2.4×10^{10} eot, $4.5\div5.0\times10^6$ e-/spill, dump(40 X_0)
- ~ 3.0×10^{10} eot, $4.5\div5.0\times10^6$ e-/spill, dump(30 X_0)

Total ~ 5.4 $\times10^{10}$ EOT

H4 beam line, 100 GeV e-

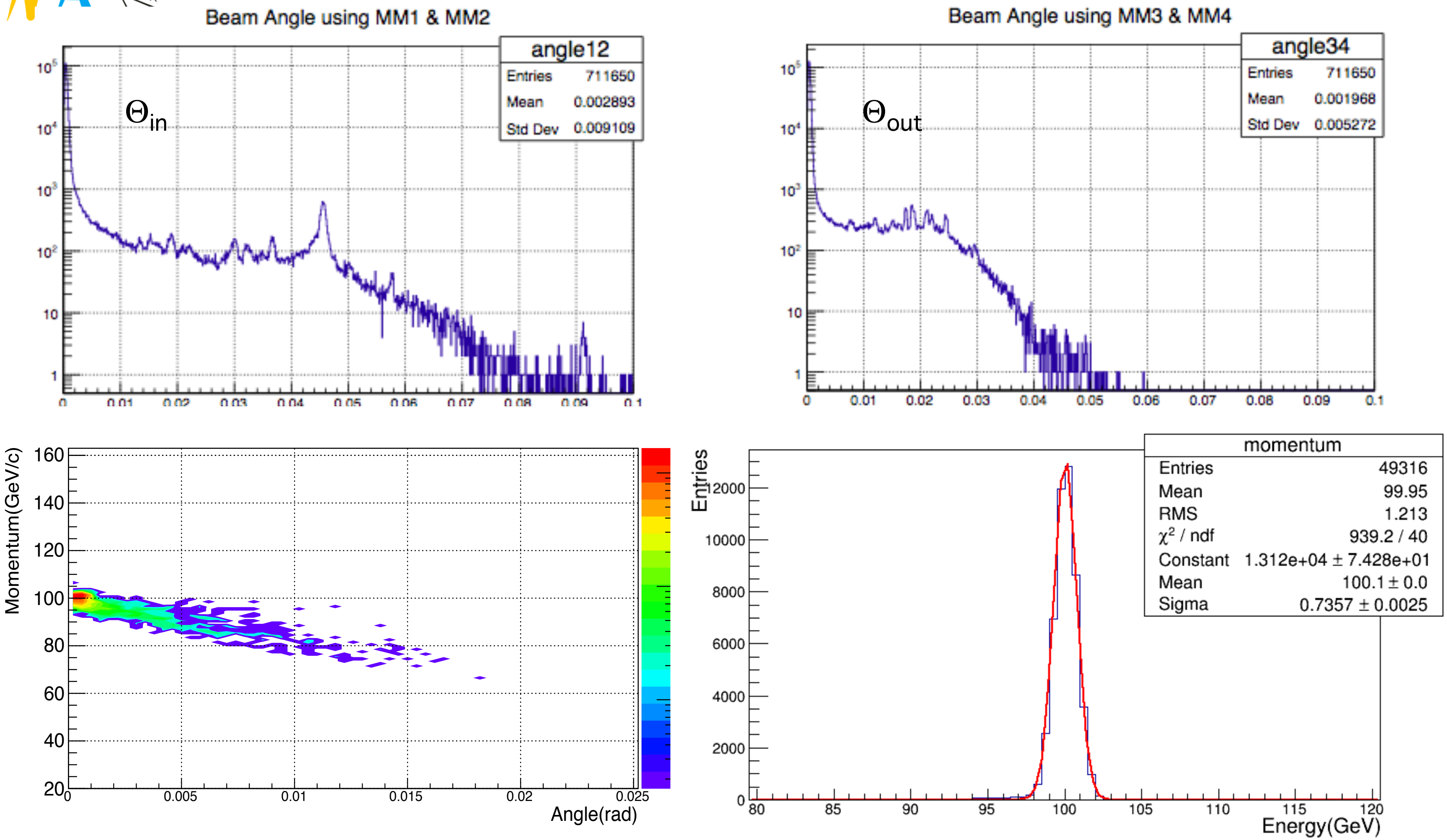
Beam parameters:

Intensity – up to 5×10^6
Hallo - less than 5%
Beam size upstream of MBPL: s_x = 3.0mm; s_y = 2.5mm; Beam size downstream of MBPL: s_x = 5.5mm; s_y = 5.5mm;
Hadron contamination in electron beam ~ 1%;
Muon contamination in electron beam ~ 0.2%;



2017 Beam optimization: Intensity up to a few 10^7 is feasible

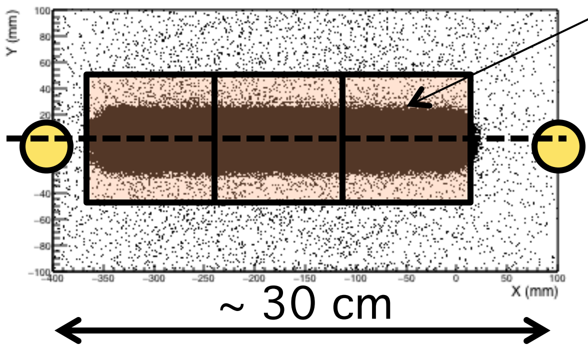
H4 beam line, 100 GeV e-



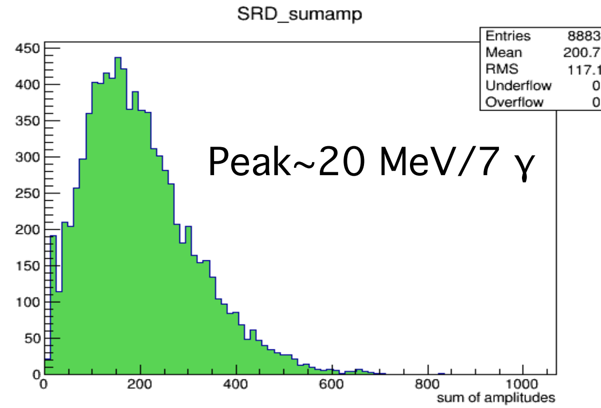
Typical pre-selection cuts used: Θ_{in} Θ_{out} < ~ 2 mrad

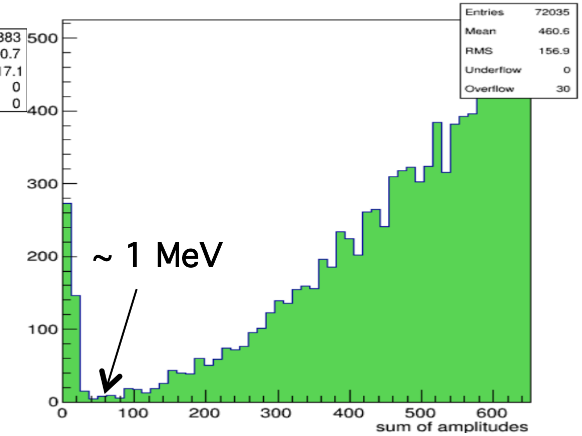
Electron tagging with synchrotron radiation (SR)

Deflected beam position



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

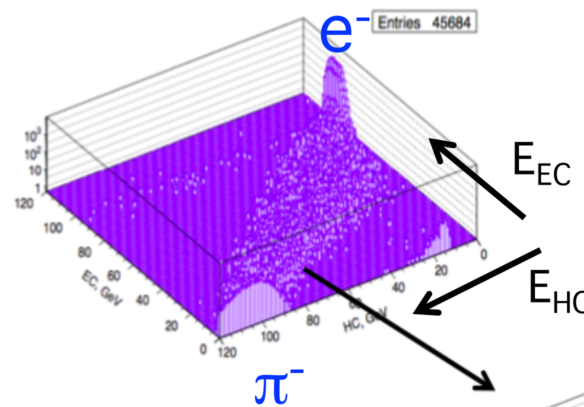


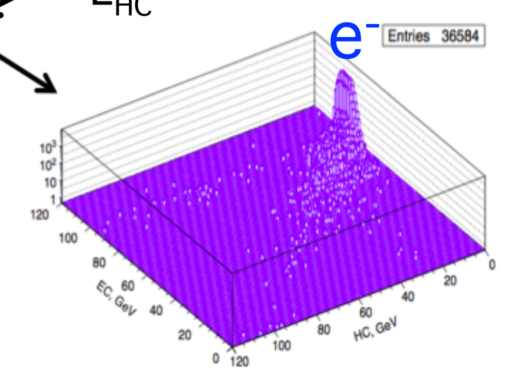


Amount of detected SR energy, γ's:
$\Delta E \sim E_0^3/m^4$, $<E\gamma> \sim$ 2 MeV, $<N\gamma> \sim$ 30

2016 run: BGO SRD – replaced with a fine segmentation Pb-Sc SRD – fast, poor ΔE/E

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





SRD selection cuts:

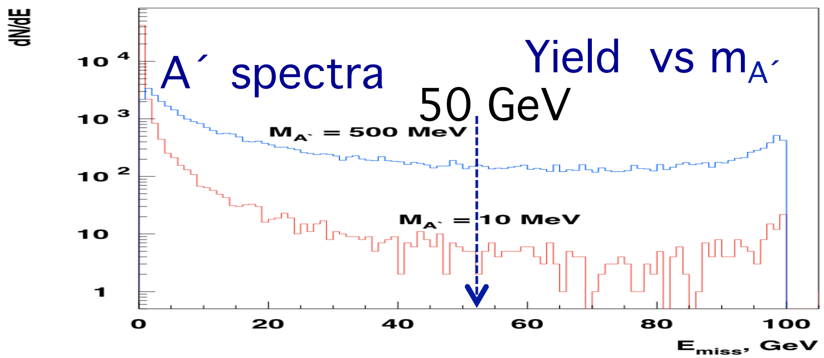
- $1 < SRD_i < 80$ MeV
- All SRD_i in time within ±2 ns
- $\varepsilon_{SRD} > 0.95$, $\pi/e \sim 10^{-6}$

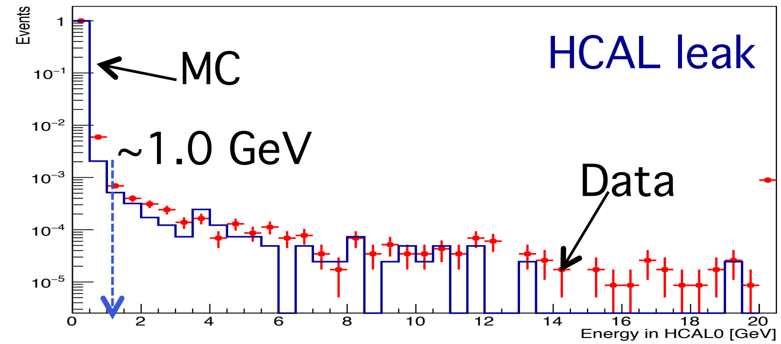
SR tagging :
π rejection ~10^4

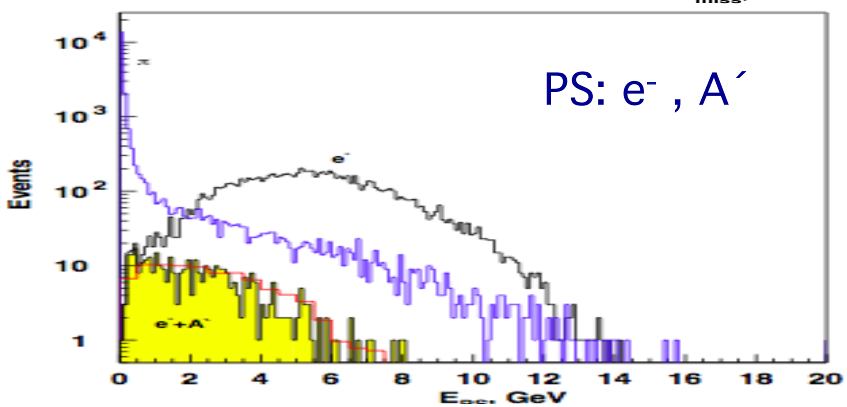
MC vs Data: A´yield and selection cuts

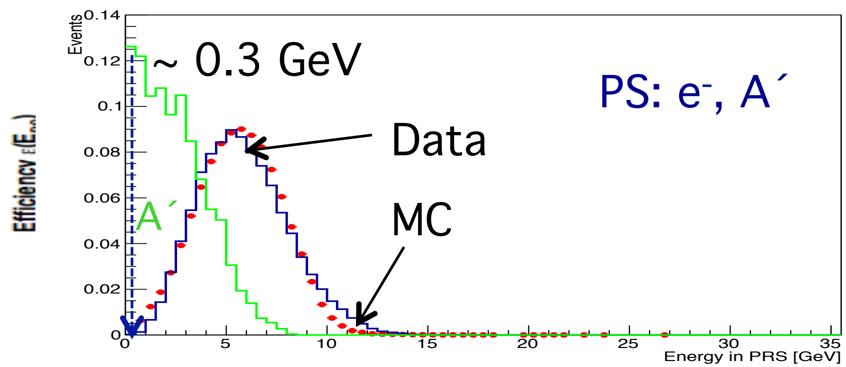
Geant4+ETL $\sigma(eZ \to eZA')$

$Tr_{A'} = \Pi s_i \times V1 \times PS(E>E_{PS}) \times ECAL(E<E_{ECAL})$

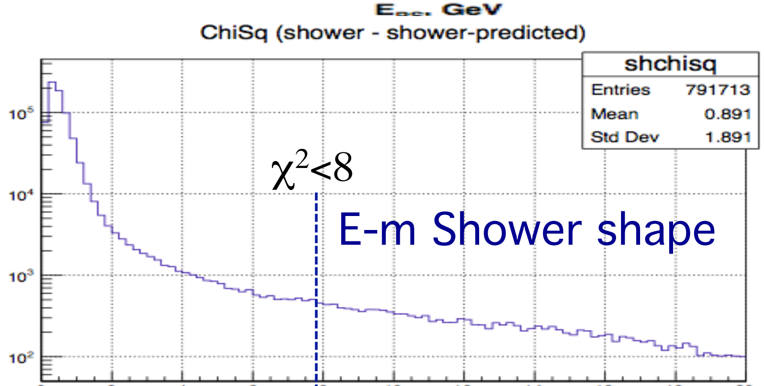


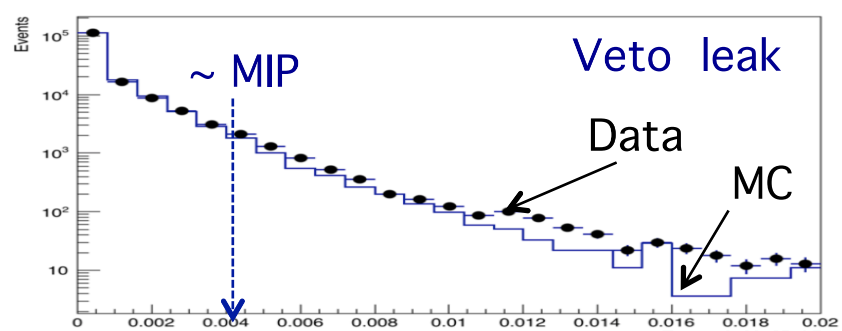






Calibration run 3400, comparison with MC





A´ selection efficiency

A´ selection criteria optimization:
- maximal A´ efficiency,
- minimal level of background

A´ selection efficiencies cross-checked with the data from e^- beams and MC.
The overall A´detection efficiency is $\varepsilon_{A'} \sim 0.5-0.6$ depending on $m_{A'}$

Systematics errors dominated by uncertainties in the A´ yield ~10%. Cross checked with dimuon production and WW vs ETL

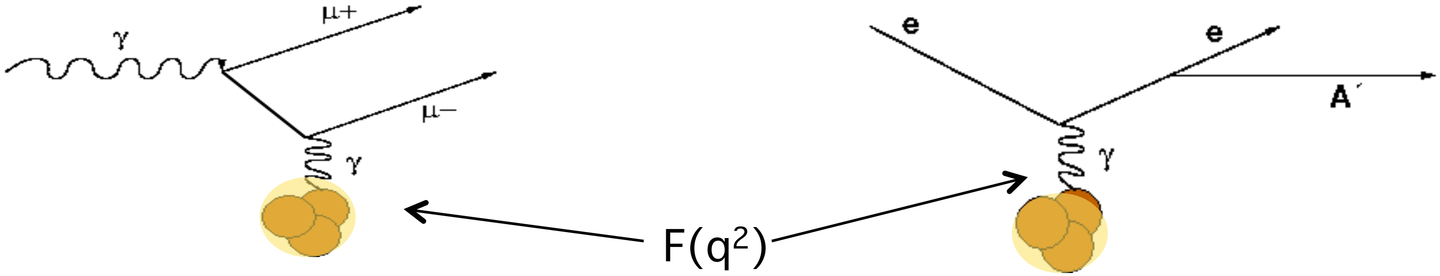
TABLE II. Summary of efficiencies for the signal event selection for the mass $m_{A'} = 10(100)$ MeV in the data sample obtained for the high intensity run III. For discussion of corresponding uncertainties, see Sec. VII.

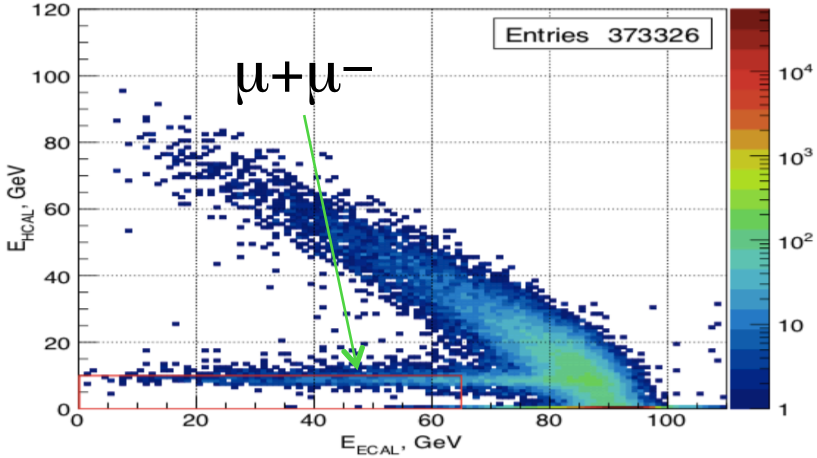
item	Efficiency	sample
primary e^-, ϵ_e	0.58	Data, Dimuons
ECAL, $\epsilon_{\rm ECAL}$	0.93(0.90)	Data, Dimuons
V_2, ϵ_V	0.94	Data, MC
HCAL, $\epsilon_{\rm HCAL}$	0.98	Data, MC
Total	0.50(0.48)	

TABLE III. Summary of systematic uncertainties for the mass $m_{A'} = 10(100)$ MeV in the high intensity run III.

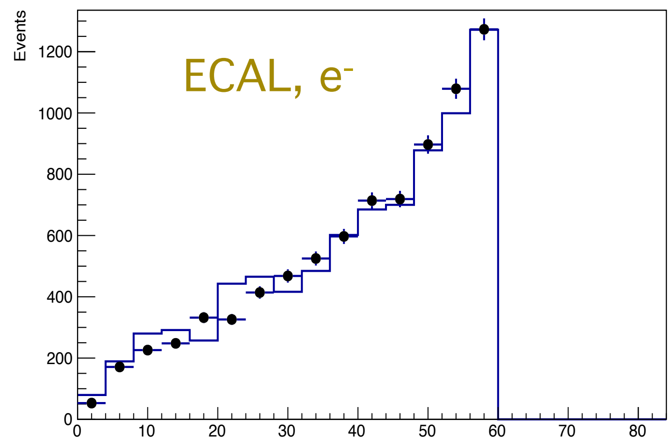
Source of the error	Estimated error
Normalization	
number of collected EOT, $n_{\rm EOT}$	2%
A' Yield	
signal cross section	10%
A' efficiency	
primary e^- selection	4%
ECAL selection	2% (3.5%)
ECAL spectrum reweighting	7% (5%)
V_2 cut threshold	3%
HCAL cut threshold	2%
Total	9%(8%)

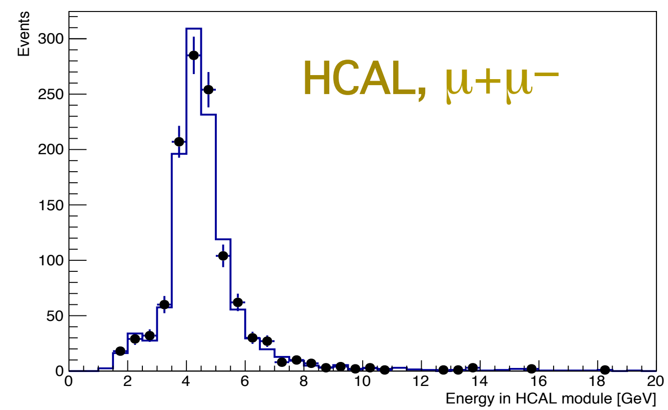
Gauge: dimuon production in eZ->eZγ, γ->μ⁺μ⁻





Dimuon Data vs MC



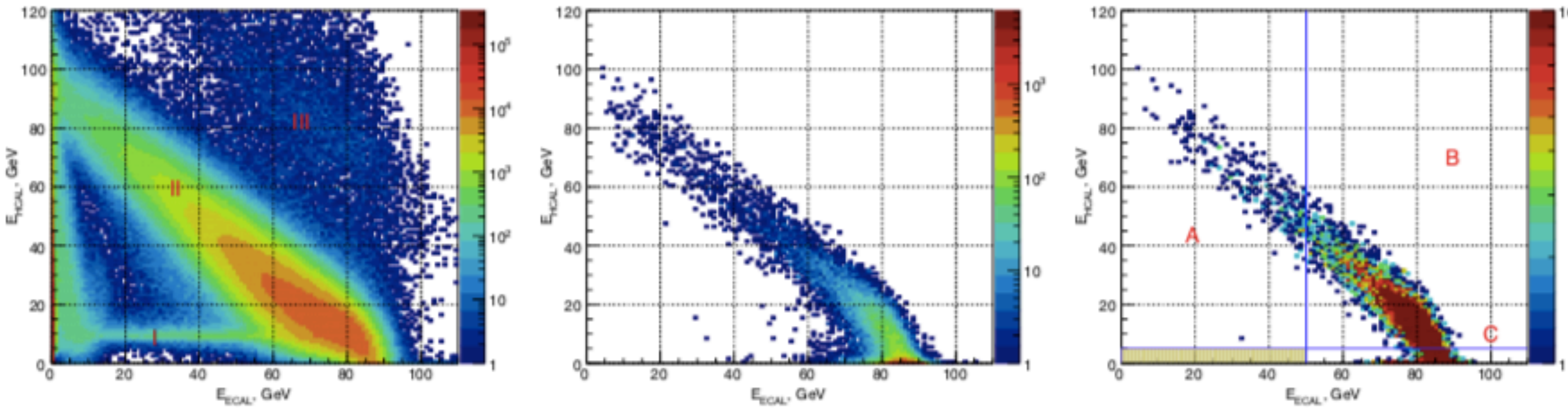


Rare QED reference process ~10^{-5}/EOT:

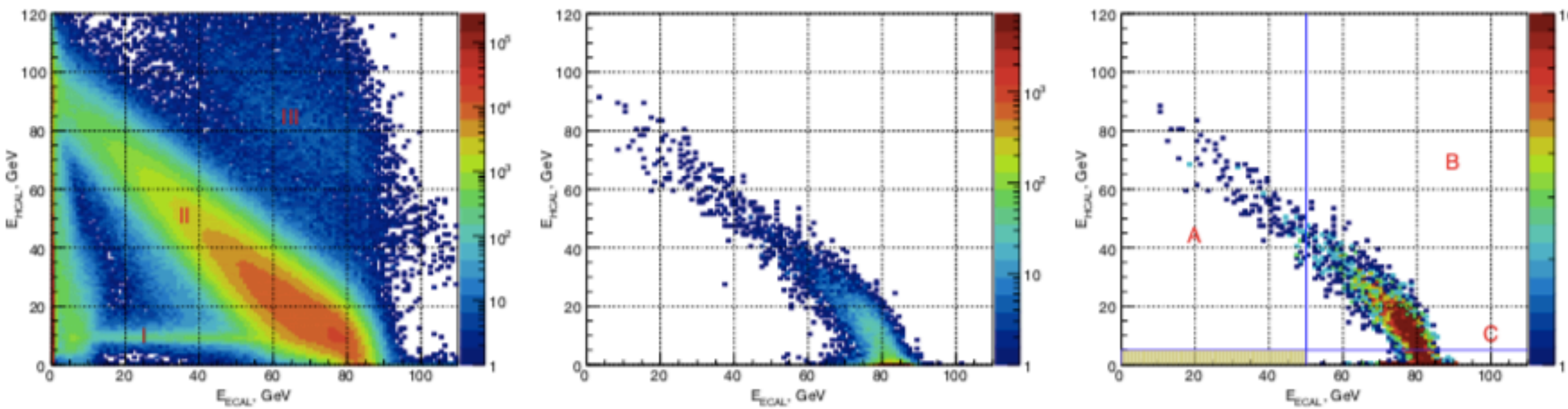
- similar to the A´ production
- same region of $q^2 \sim m^2_{A'}/E \sim m^2_{\mu\mu}/E$
- cross check of A´ yield, systematic error
- background prediction from data
- cross check of overall efficiency

Results from 2016 run, 4.3×10^{10} EOT

~3×10^6 e-/spill



~5×10^6 e-/spill



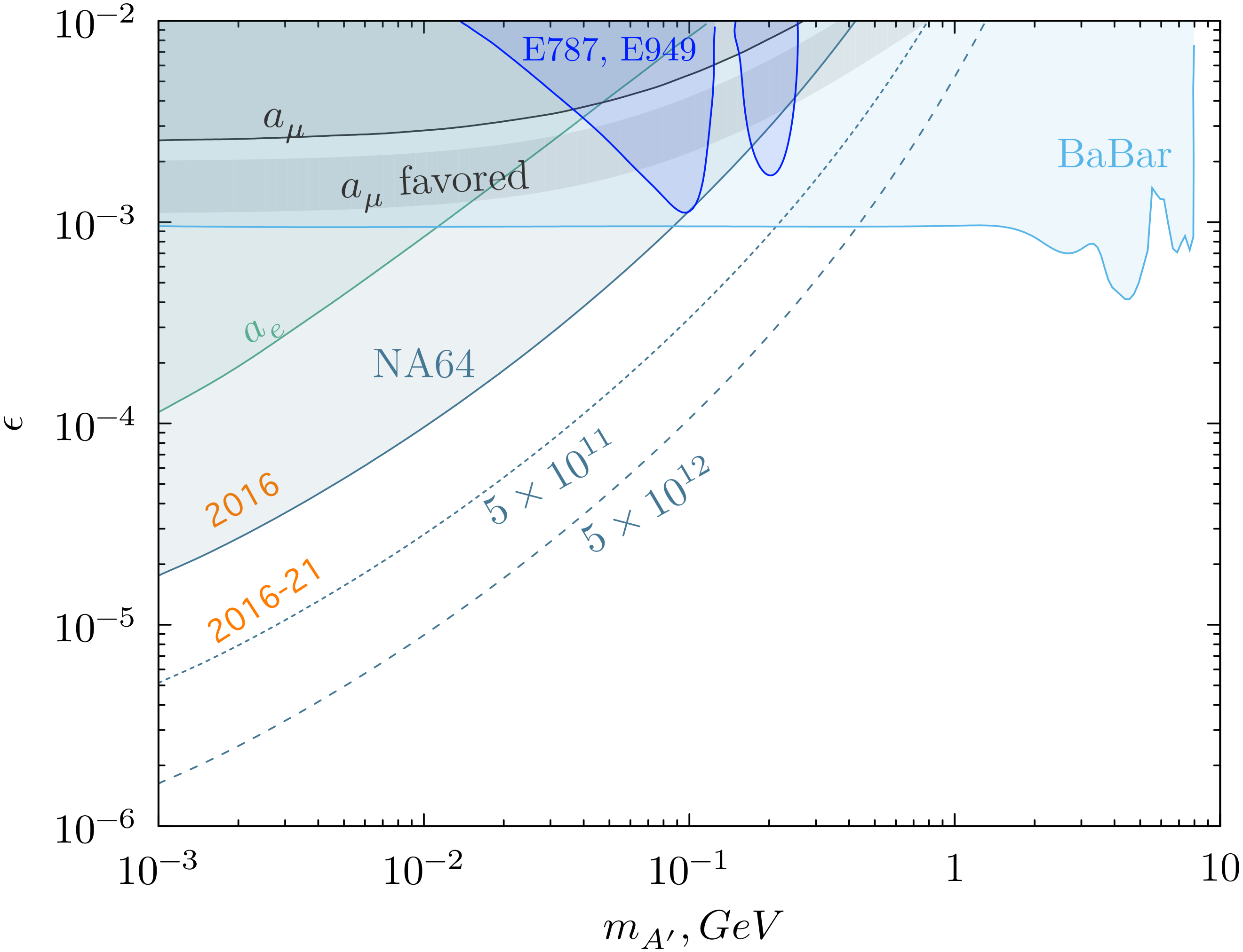
A´ signal box: $E_{EC} < 50$; $E_{HC} <$ ~1 GeV

Background from 2016 runs, 4.3×10^{10} EOT

TABLE IV: Summary of estimated numbers of background events inside the signal box for 4.3×10^{10} EOT.

Background source	Estimated number of events, n_b
hermeticity: punchthrough γ's, cracks, holes	< 0.001
loss of hadrons from $e^- Z \rightarrow e^- + hadrons$	< 0.001
loss of muons from $e^- Z \rightarrow e^- Z\gamma; \gamma \rightarrow \mu^+ \mu^-$	0.005 ± 0.001
$\mu \rightarrow e\nu\nu$, π, $K \rightarrow e\nu$, K_{e3} decays	0.02 ± 0.004
e^- interactions in the beam line materials	0.09 ± 0.03
μ, π, K interactions in the target	0.008 ± 0.002
accidental SR tag and e^- from μ, π, K decays	< 0.001
Total n_b	0.12 ± 0.04

Results from 2016 and beyond: kinetic mixing ε

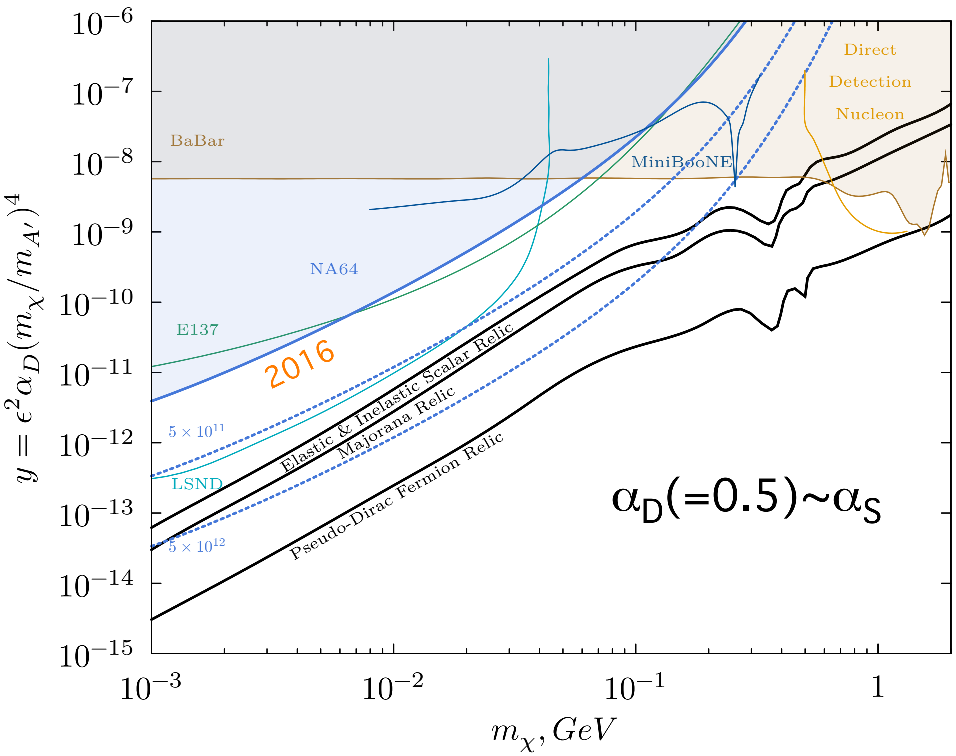


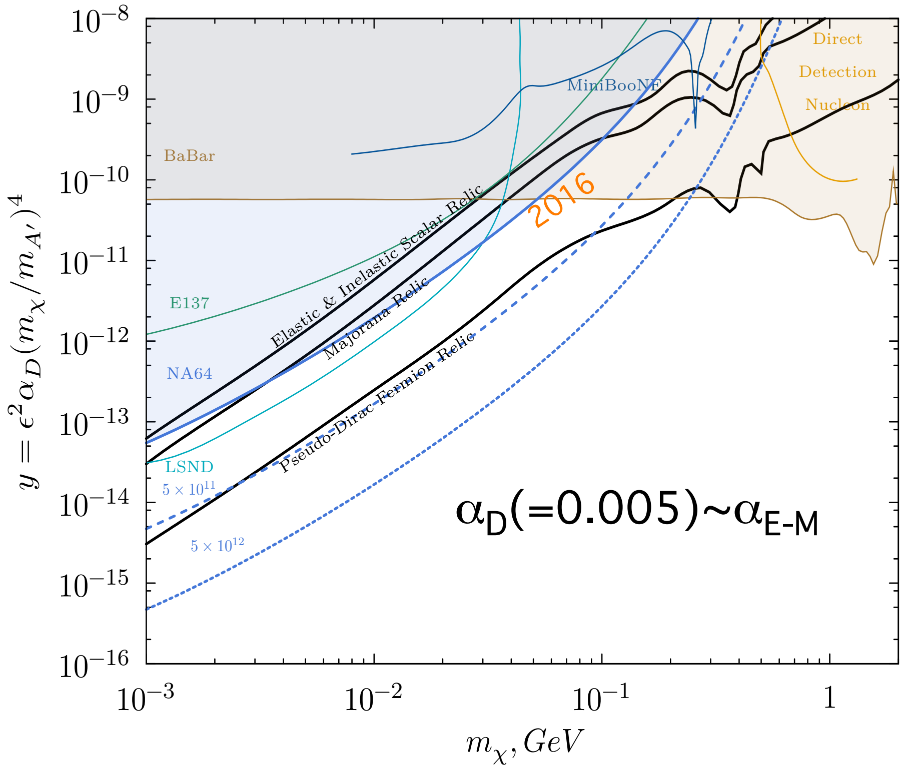
NA64 Collaboration, Phys. Rev. D (2018)

Invited talk at APS Meeting, April 14–17, 2018; Columbus, Ohio (P. Crivelli ETH)

Results from 2016 and beyond: light TDM

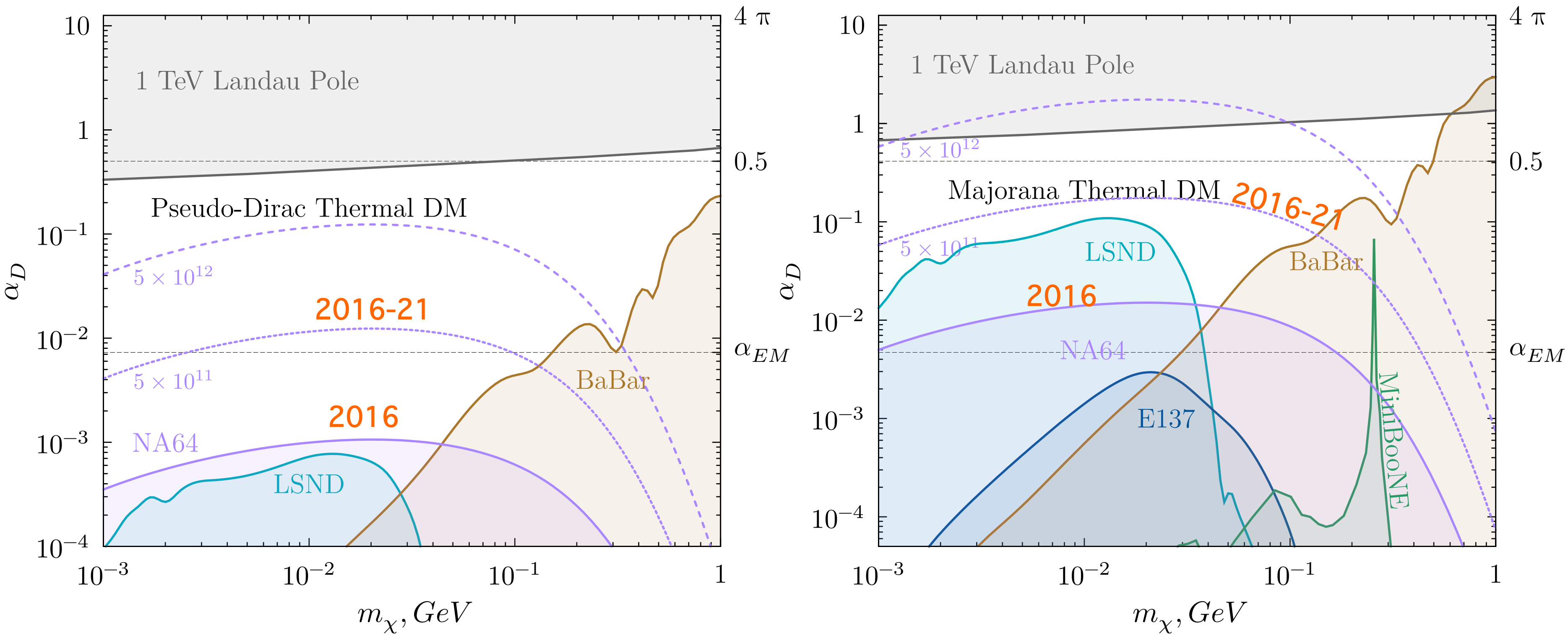
$m_{A'}=3m_\chi$





sub-GeV TDM: results from 2016 and beyond

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

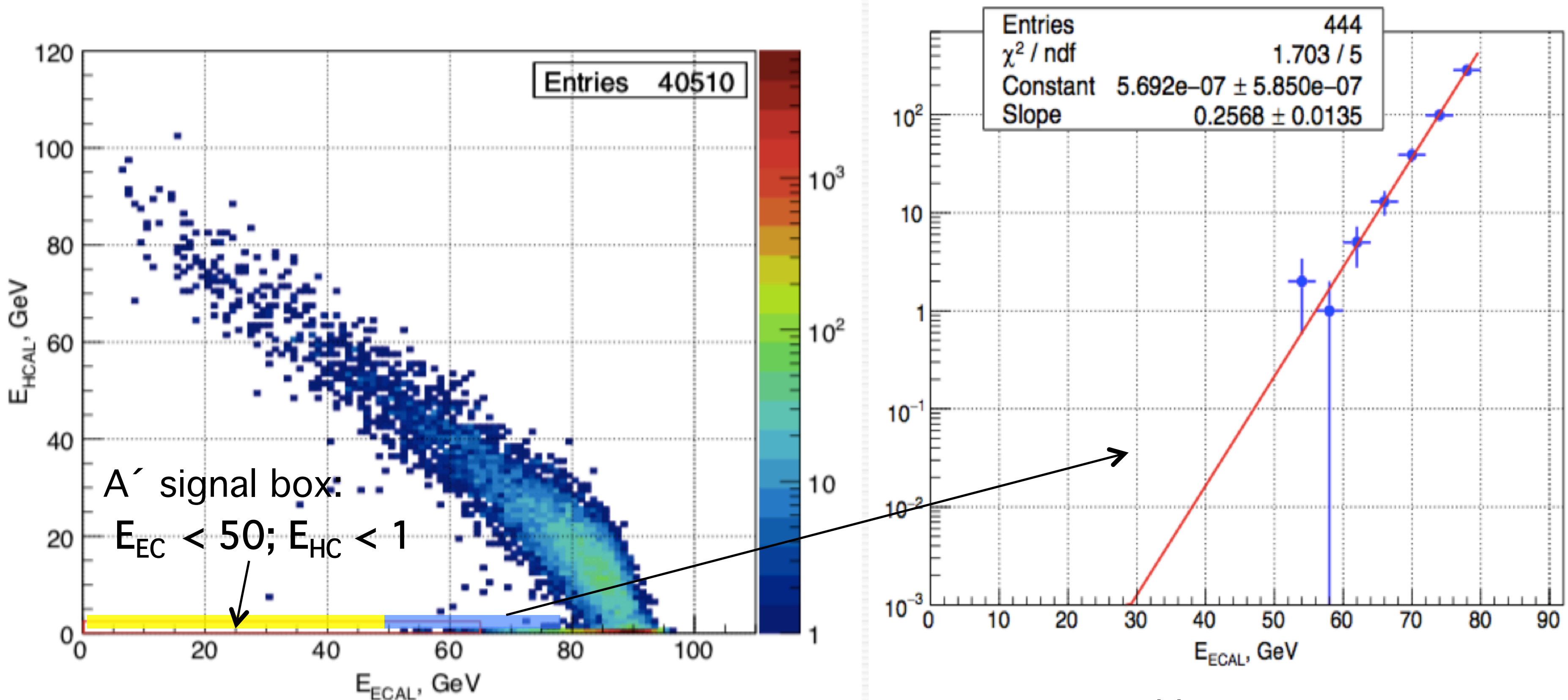


Goal with ~5×10^{11} EOT to exceed the sensitivity of beam-dump experiments (Majorana TDM) and to probe new areas of the mixing and parameters of the sub-GeV (Scalar, Majorana, Pseudo-Dirac) models.

Advantage of NA64 – its sensitivity~ε^2, while for beam-dump exp. ~$\varepsilon^2 \times \alpha_D\, \varepsilon^2$

Preliminary Results from 2017 run, 5.5×10^{10} EOT

~(5–8)x10^6 e-/spill



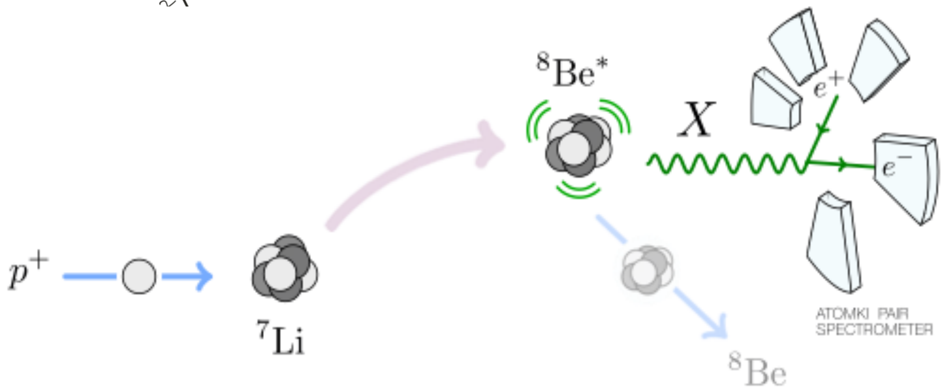
No signal observed in 2016–17 data sample of ~10^{11} EOT with combined background ~ 0.2 event

Data analysis almost completed. Further background rejection and signal efficiency improvements under study.

The ^{8}Be anomaly, A´->e^+e^- decays

- Feasibility study in Oct'2016
- Data taking run in Sept'2017

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



Feng et al, 2016

$^{7}Li(p,\gamma)^{8}Be$, $M_X = 17$ MeV

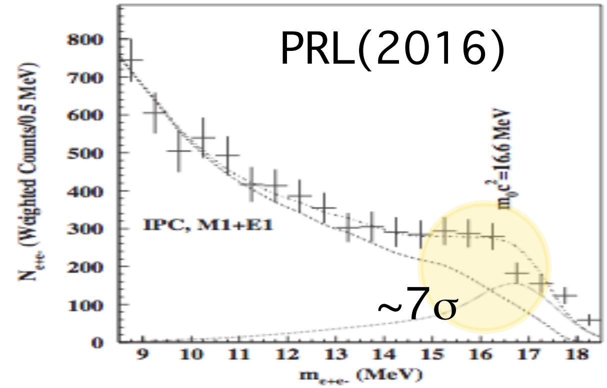
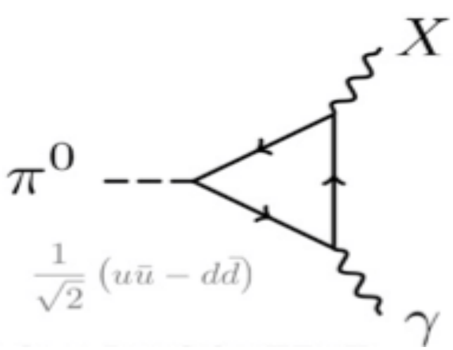


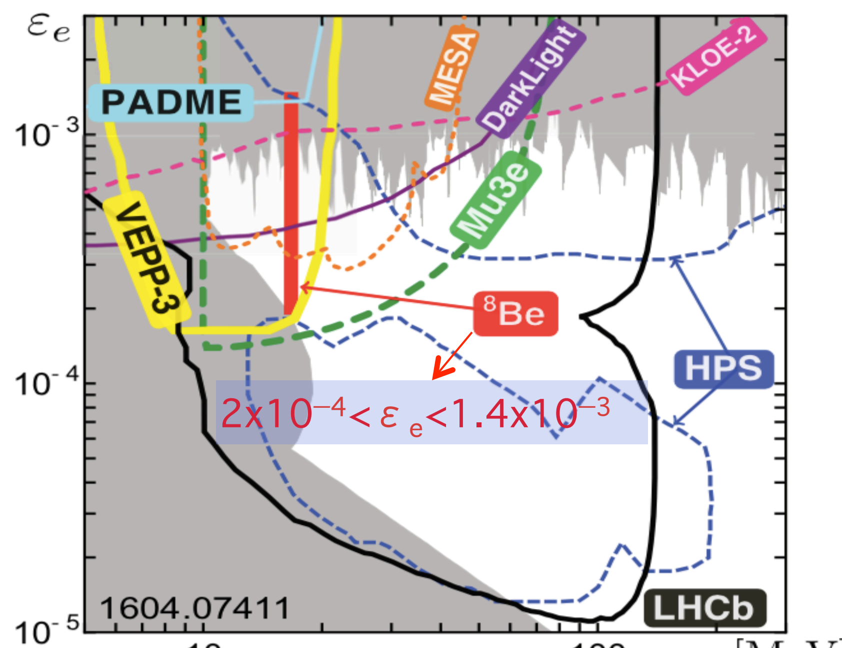
FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.

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



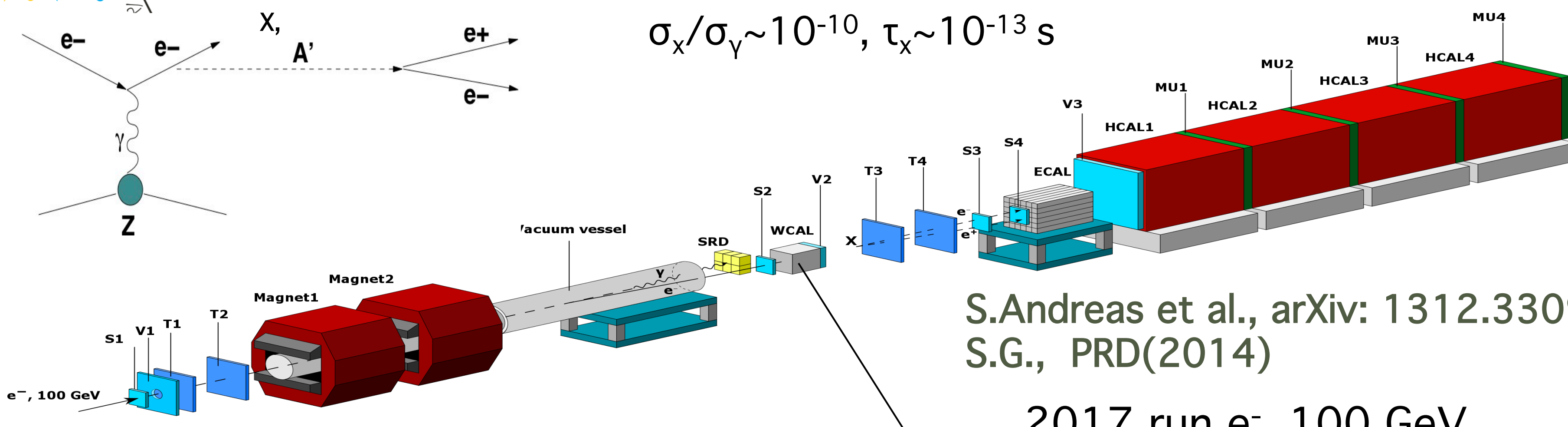
$\Gamma(\pi^0 \to X\gamma) \sim (\varepsilon_u q_u - \varepsilon_d q_d)^2 \sim 0$

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



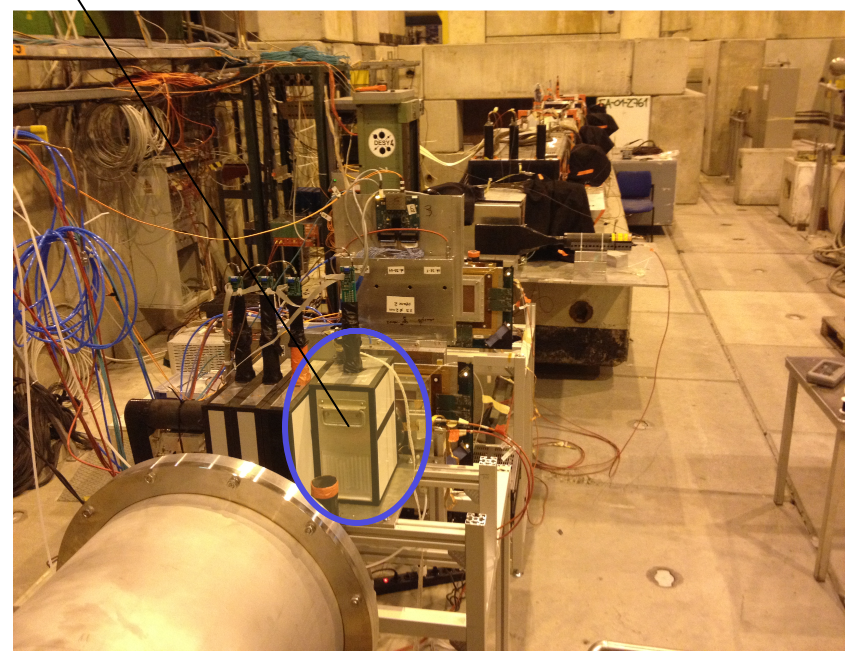
Search for the X(A´)->e^+e^- decays

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



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

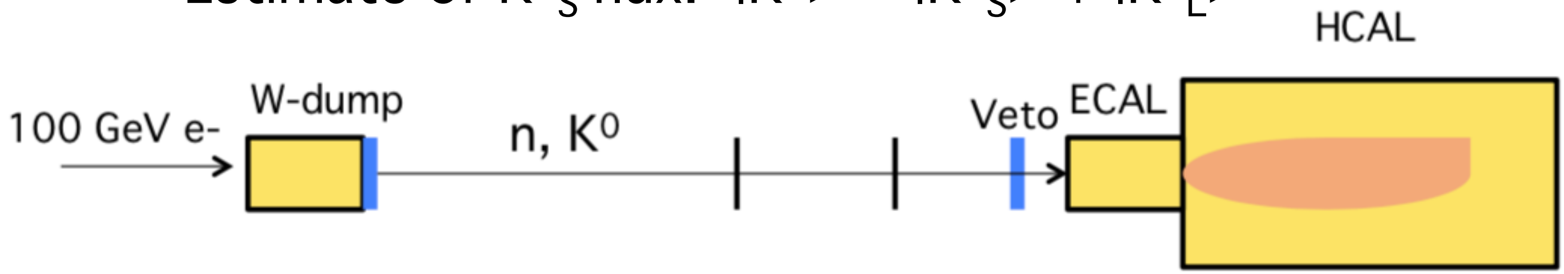
2017 run e^-, 100 GeV



- X decays outside W with good effic.
- 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^--tag is a key for rejection

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

Estimate of K^0_S flux: $|K^0\rangle \sim |K^0_S\rangle + |K^0_L\rangle$



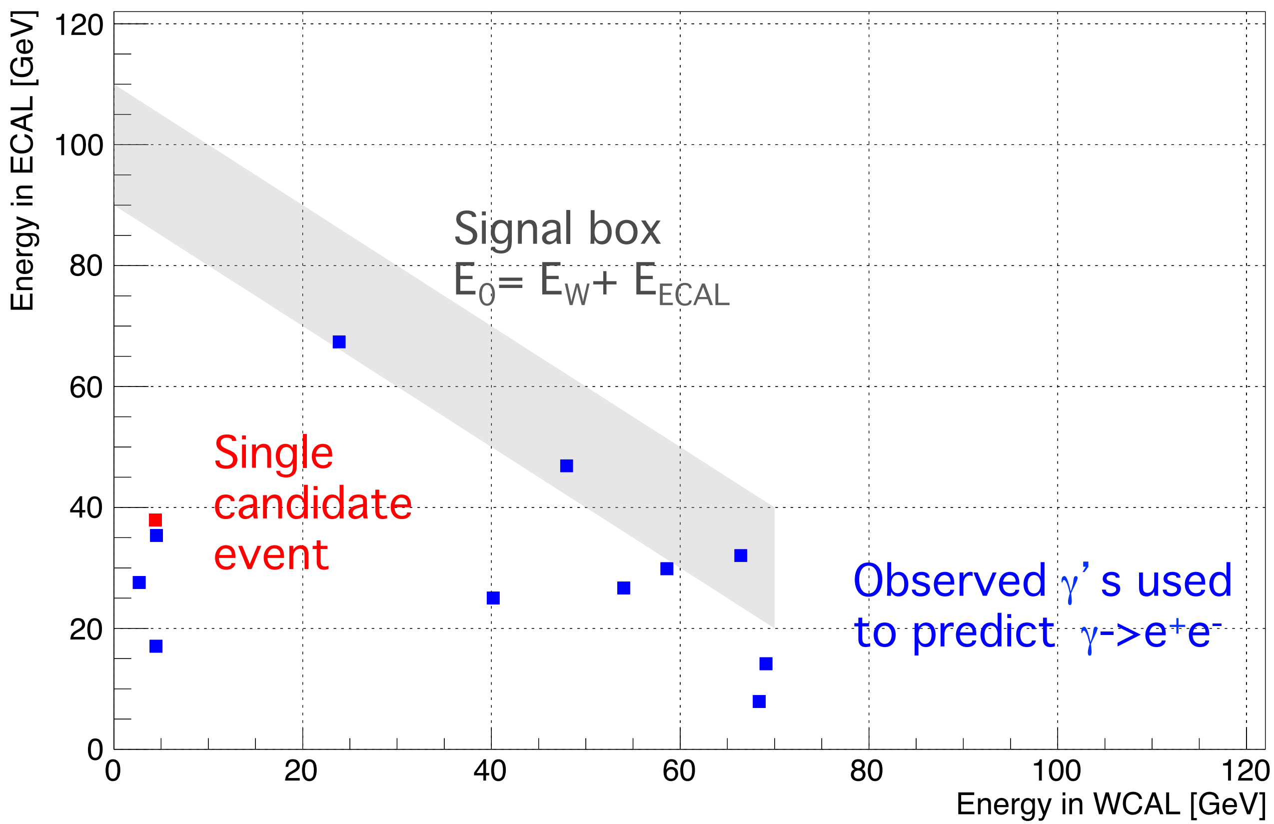
Method I: selection of neutral hadronic final state: n:$K^0 \sim$ 10:1 => : $n_{K0} \sim 10^2$ K^0
Method II: selection of e.m. neutrals (γ's from K^0_S chain) => $n_{K0} \sim 1.5\times10^2$ K^0

TABLE I. Expected numbers of background events in the signal box estimated for 5.4×10^{10} EOT.

Source of background	Events
e^+e^- pair production by punchthrough γ	< 0.001
$K^0_S \to 2\pi^0; \pi^0 \to \gamma e^+e^-; \gamma \to e^+e^-$; $K^0_S \to \pi^+\pi^-$	0.06 ± 0.034
$\pi N \to (\geq 1)\pi^0 + n + ...; \pi^0 \to \gamma e^+e^-; \gamma \to e^+e^-$	0.01 ± 0.004
π^- 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, ~5x10^{10} EOT

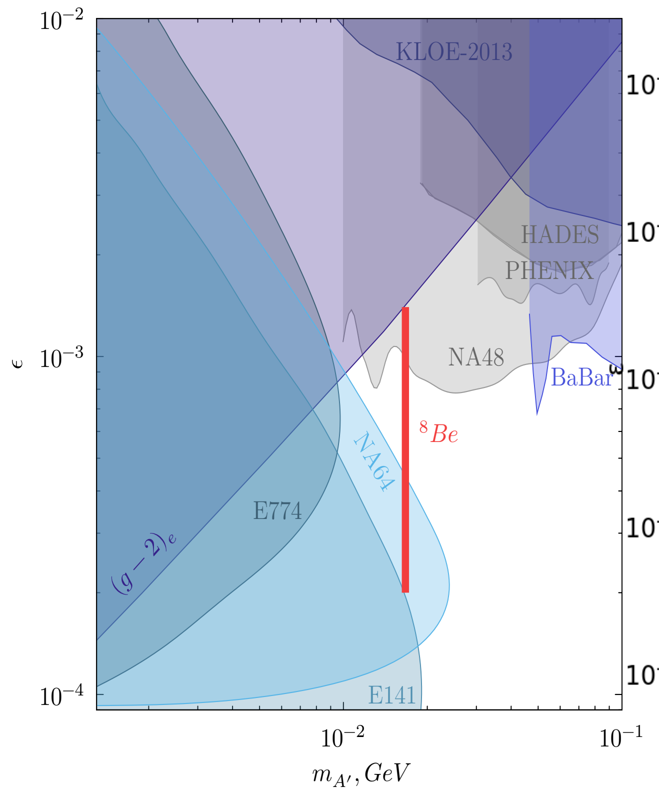
Br(X → e^+e^-)=1, ε^2~ 10^{-7}



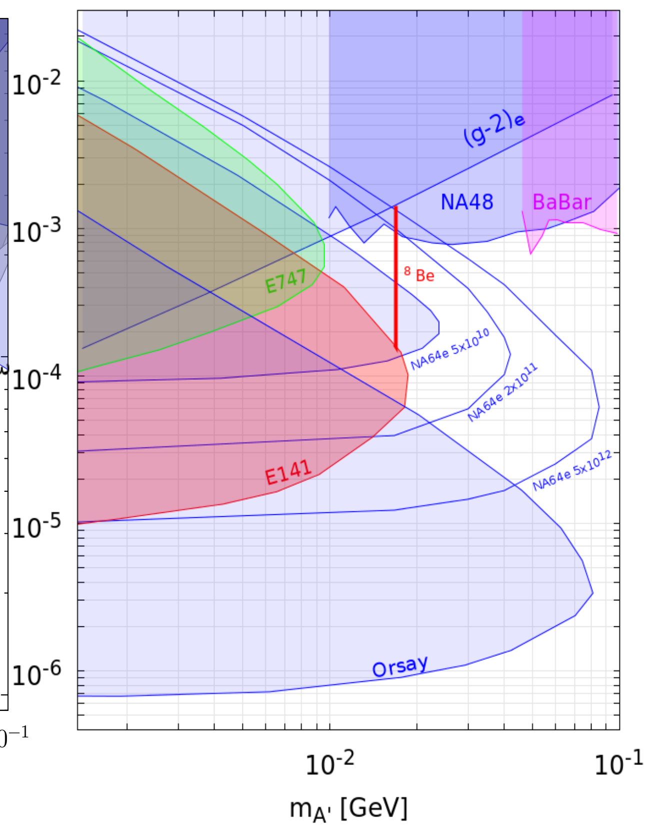
First results from Sept’2017 run, ~5x10^{10} EOT

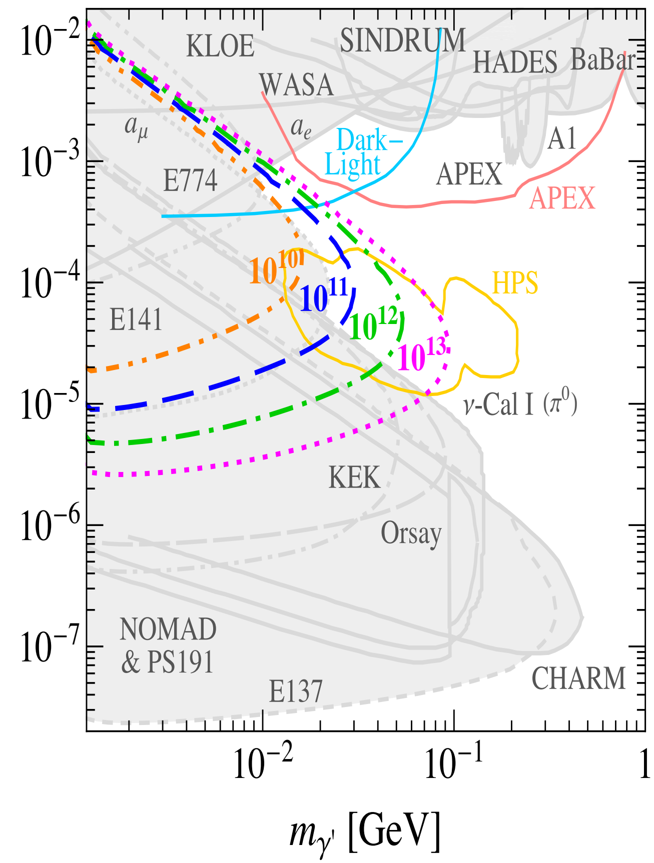
Exclusion areas for the X boson and A´

100 GeV, 5x10^{10} EOT



150 GeV, 2x10^{11}, 5x10^{12} EOT





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

NA64 Collaboration, Phys.Rev.Lett. (2018)

Plans for 2018 and 2021

A´-> invisible

- 2018: 100 GeV e^-, ~$5x10^6$ e^-/spill, $2x10^{11}$ EOT
- 2021: 100 GeV e^-, ~10^7 e^-/spill, $3x10^{11}$ EOT
- Goal with ~$5x10^{11}$ EOT to exceed the sensitivity of beam-dump experiments (Majorana TDM) and to probe new areas of the mixing and parameters of the sub-GeV TDD models.

Strategy for the Be-anomaly and A´-> e^+e^-

- Fully exploit the H4 beam potential for energy 150 GeV
- 2018: 150 GeV e^-, ~$3x10^6$ e^-/spill, > 5 $x10^{10}$ EOT
- 2021: 150 GeV e^-, ~$3x10^6$ e^-/spill, > 5 $x10^{10}$ EOT
- Search with the ~$5X_0$ WCAL and Si pixel in B-field
- Goal: with ~10^{11} EOT to rule out the region $1.3x10^{-4} < \varepsilon_e < \sim 7x10^{-3}$

Upgrade:

- Tracker: more stations (Straw), Si tracker, beam hodoscopes
- ECAL central part, trans. segmented WCAL
- Electronics: ~200 MHz MSADC, DAQ

Summary

2016 and 2017 data analysis:

- In 2016/17 ~10^{11} EOT were collected
- 2016: analysis for invisible mode is completed resilting in stringent constraints on the γ-A´mixing and parameters of the sub-GeV TDM.
- 2017: data analysis close to completion. Further background rejection and signal efficiency improvement under study.
- 2017: data analysis for visible mode is completed. First constraints on the X(17) boson from Be anomaly, and the A´->e^+e^- decays
- Promising results from the feasibility study of ALP decay search

2018 data taking in progress :

- ~1.2x10^{11} EOT collected for A´ invisible mode, more expected
- ~5x10^{10} EOT to be collected for Be-anomaly and A´ visible mode
- Data analysis expected in 2018–2020
- Goal for 2018/21: to collect in total ~(5+1)x10^{11} EOT to cover new parameter areas for sub-GeV TDM models, and the X,A´ ->ee decay

Summary

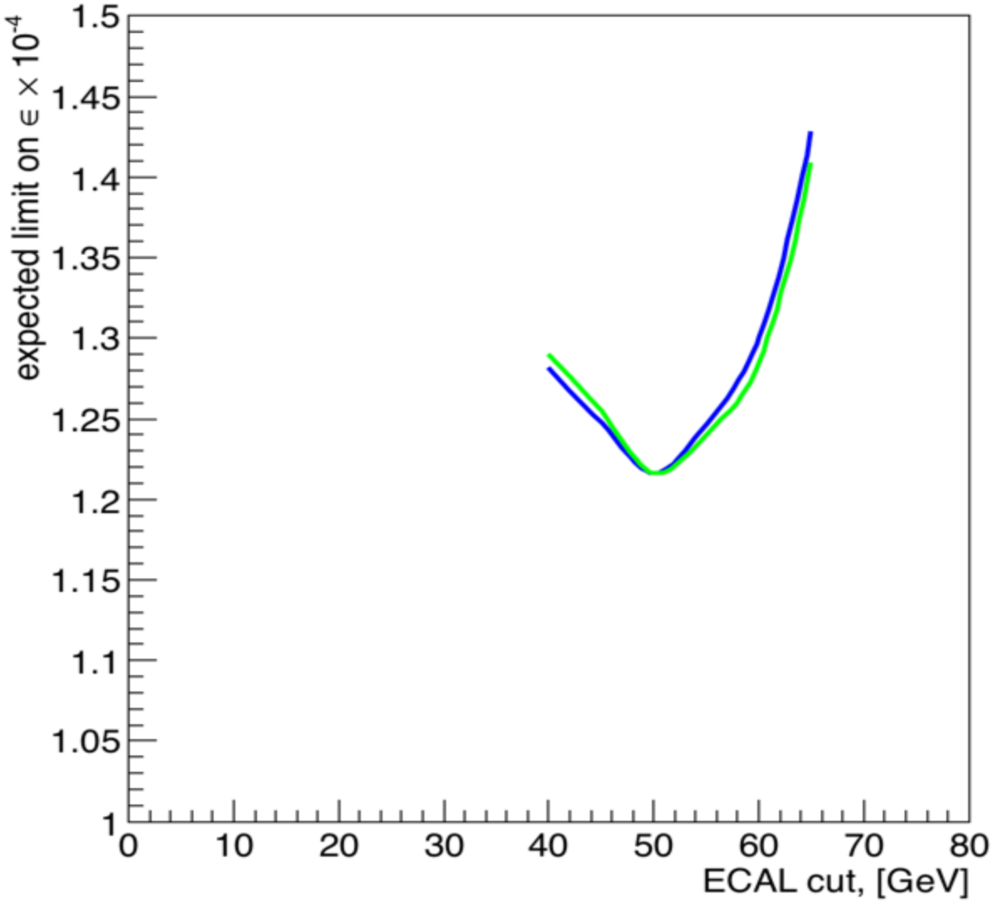
Dark sector physics below EW scale can effectively probed with the NA64 techniques in the medium term future. The experiment can

- firmly discover or rule-out nearly all predictive models of sub-GeV thermal DM,
- clarify the origin of the Be-anomaly,
- search for the APLs
- search for milliQ particles…

The new results are promise to be rich, and might be unexpected.

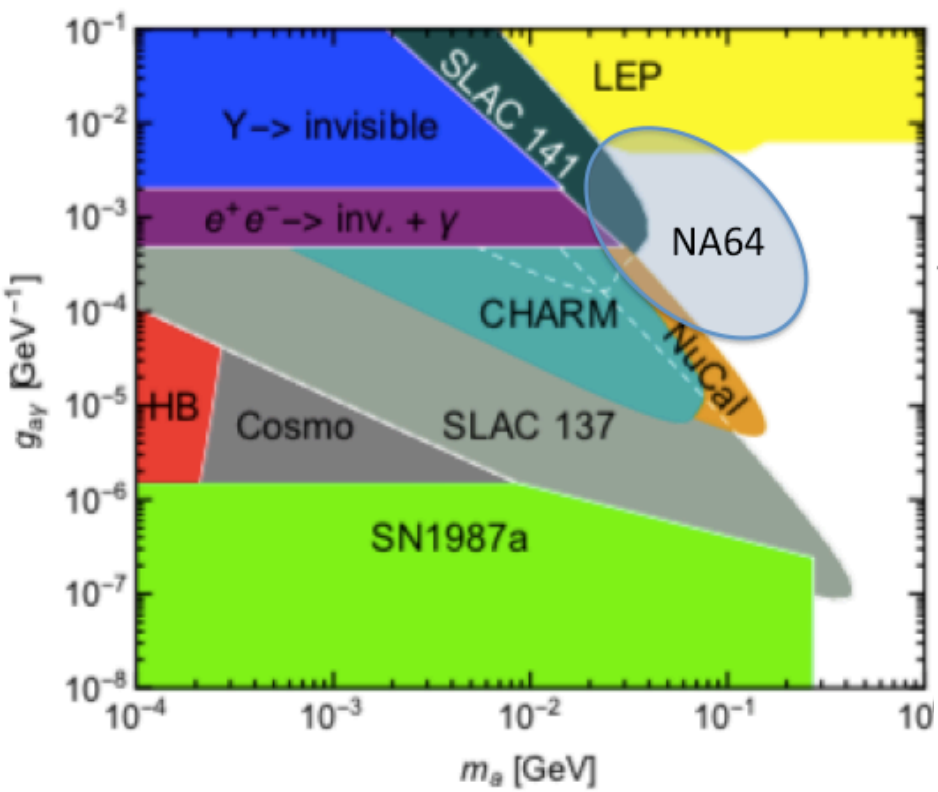
BACKUP

Data analysis: E_{miss} cut optimization

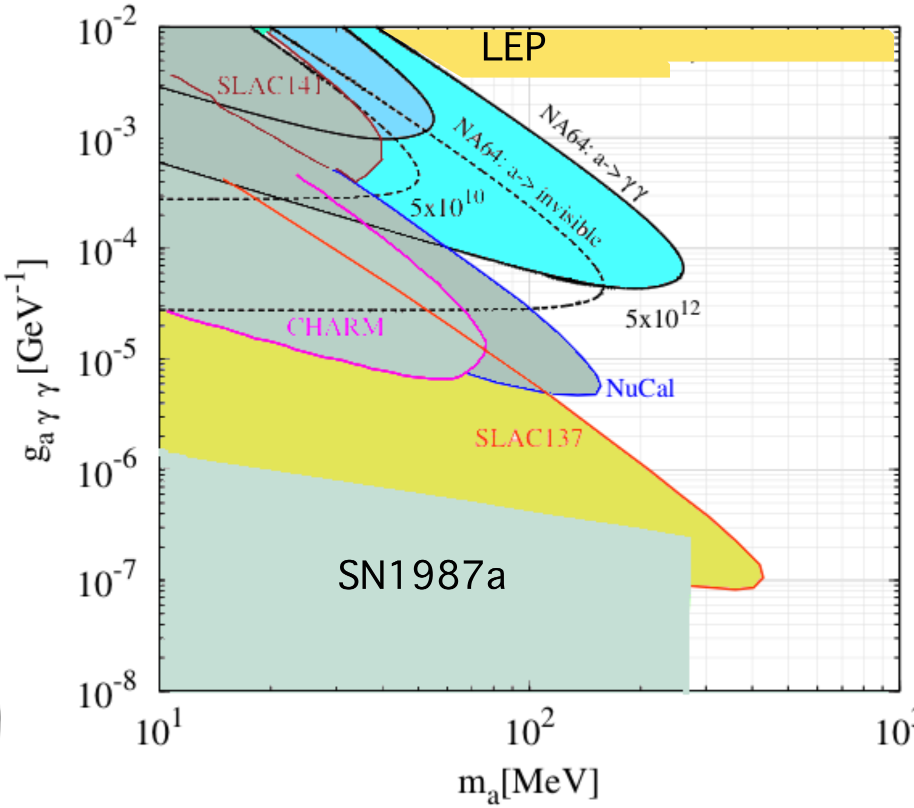


The optimization confirms the choice of the E_{miss} cut ~ 50 GeV

Projected sensitivity to APLs



Current constraints, arXiv:1512.03069



NA64 exclusion areas for **a** → γγ and a→ invisible for 5×10^{10}, 5×10^{12} EOT

The NA64 detector in 2017