Search for a new X boson and Dark Photons in NA64 at the CERN SPS.

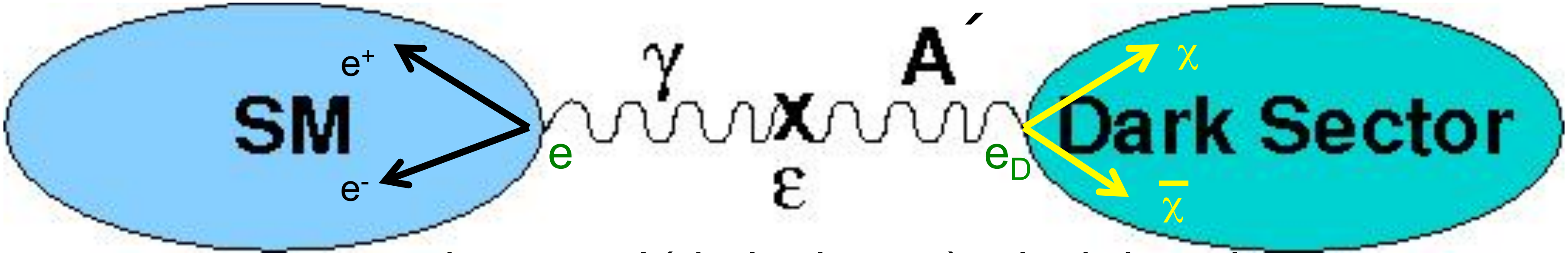
QUARKS-2018
Mai 2018 Valdai

Outline

- Motivation
- The NA64 experiment
- Runs 2016
- 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

Okun, Holdom' 86 .. $\alpha_D = e_D^2/4\pi$



- new massive boson A´ (dark photon) which has kinetic mixing with ordinary photon: $\Delta L = \varepsilon/2\ F^{\mu\nu} A'_{\mu\nu}$
- GUT prediction for the size of the γ-A´ mixing strength ($\varepsilon \ll 1$): 1-loop: $\varepsilon \sim 10^{-4}$ -10^{-2}; 2 loops: $\varepsilon \sim 10^{-5}$ -10^{-3}, $m_{A'} \sim \varepsilon^{1/2} M_Z$
- Production: A´ - bremsstrahlung $e^- Z \rightarrow e^- Z A'$, $\sigma \sim Z^2 \varepsilon^2 / m_{A'}^2$
- Decays:

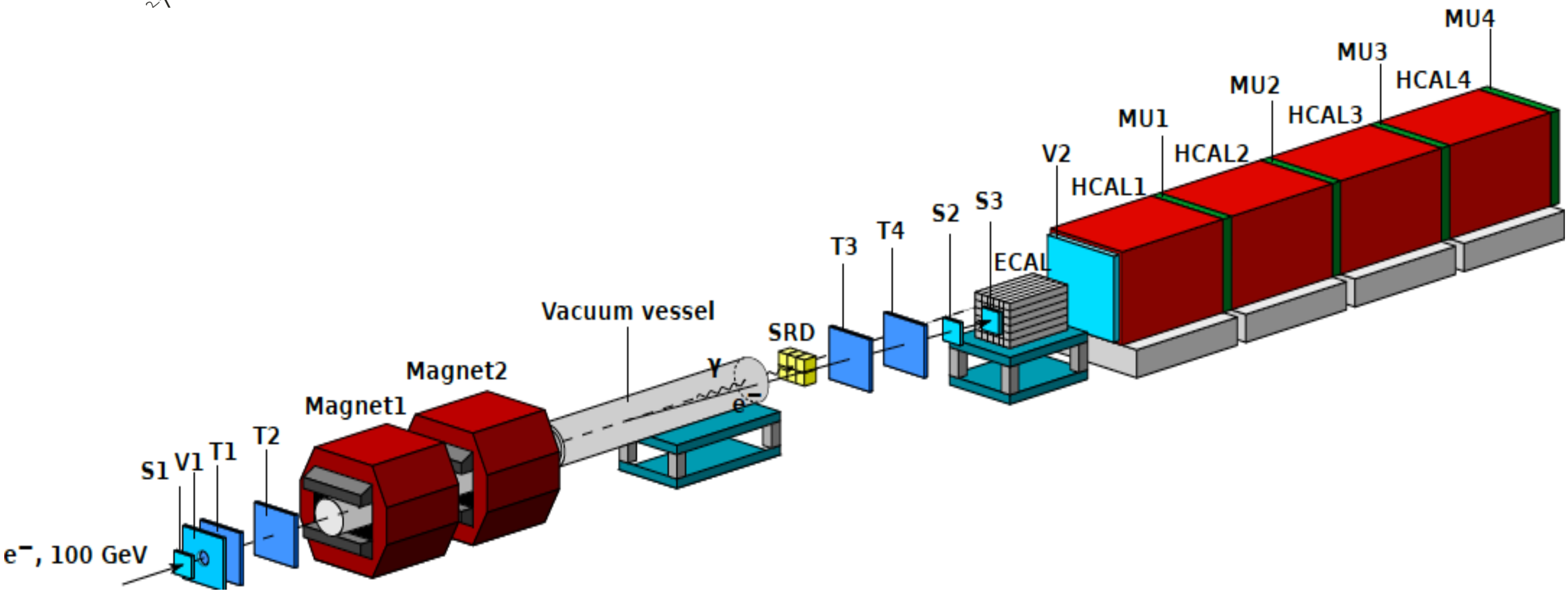
  - Visible: $A' \rightarrow e^+e^-, \mu^+\mu^-$, hadrons,..

  - Invisible: $A' \rightarrow \chi\bar{\chi}$ if $m_{A'} > 2m_\chi$ assuming $\alpha_{DM} \sim \alpha \gg \varepsilon$.

  Can explain $(g-2)_\mu$, astrophys. observations

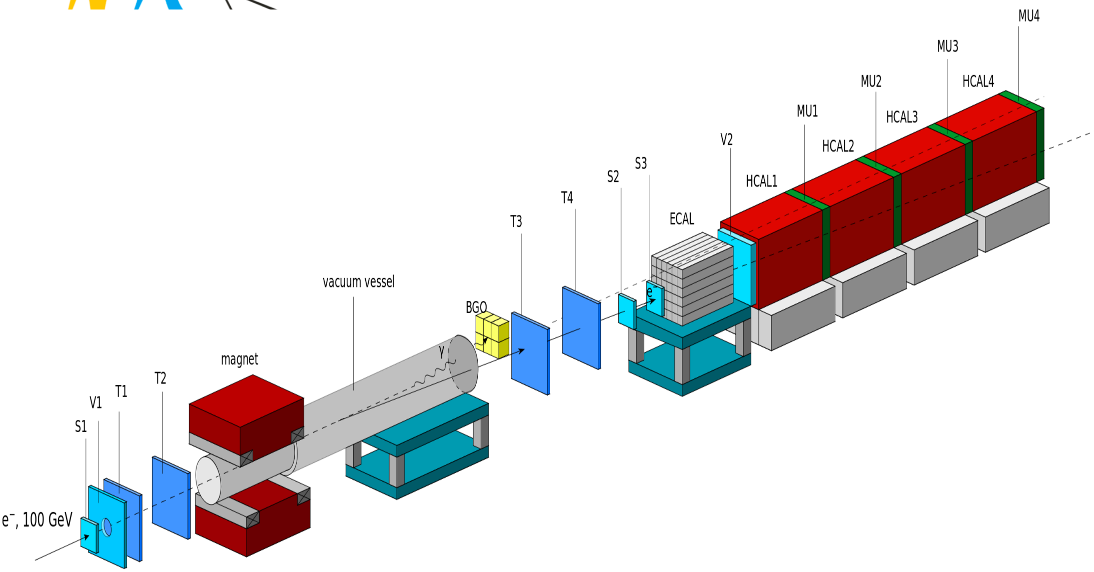
  - Cross section for χ–DM annihilation: $\sigma v \sim \overbrace{[\alpha_{DM}\, \varepsilon^2 (m_\chi/m_{A'})^4]}^{y}\ \alpha/m_\chi^2$

NA64 experiment setup (invisible mode)

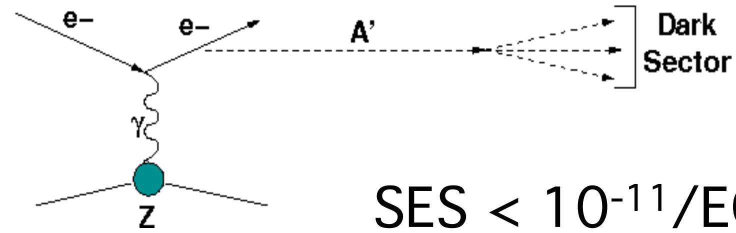


~50 researchers from 12 institutes
Proposed in 2014, first test runs in 2015

Search for A´->invisible decays at CERN SPS



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



SES < 10^{-11}/EOT

Signature:

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

Background:

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

Main components :

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

Summary of the 2016 runs

- First run period, 29.06-13.07, 2 w

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

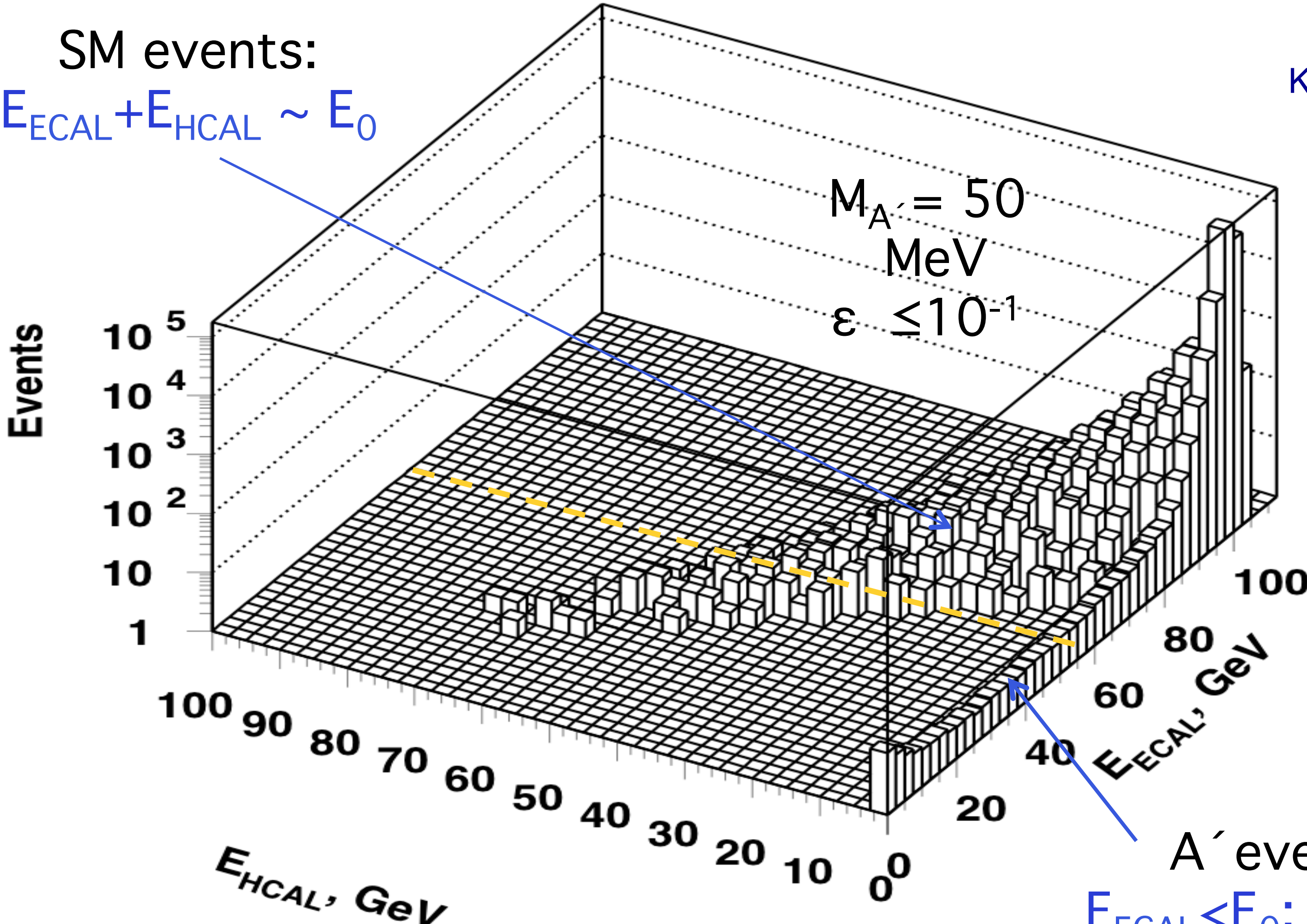
  - 0.88×10^9 eot, 0.3×10^6 e^-/spill, BGO run
  - 1.87×10^9 eot, 1.3×10^6 e^-/spill, PbSc run
  - Total number ~ 2.75×10^9 eot
  - Result published
- Second run period, 12.10-09.11, 4 w
  - 23 October → start data taking;
  - Total accumulated electrons ~2×10^{10}, S_0 rate $1.5 \div 2.2 \times 10^6$;
  - Total accumulated electrons ~1.5×10^{10}, S_0 rate $2.4 \div 3.2 \times 10^6$;
  - Total accumulated electrons ~1.0×10^{10}, S_0 rate $4.6 \div 5.0 \times 10^6$; ~0.6 day
  - Total number ~ 4.5×10^{10} eot

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

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

Gninenko, Kirsanov, Krasnikov, Kirpichnikov PRD(2016)

SM events: $E_{ECAL}+E_{HCAL} \sim E_0$



$M_{A'} = 50$ MeV

$\varepsilon \le 10^{-1}$

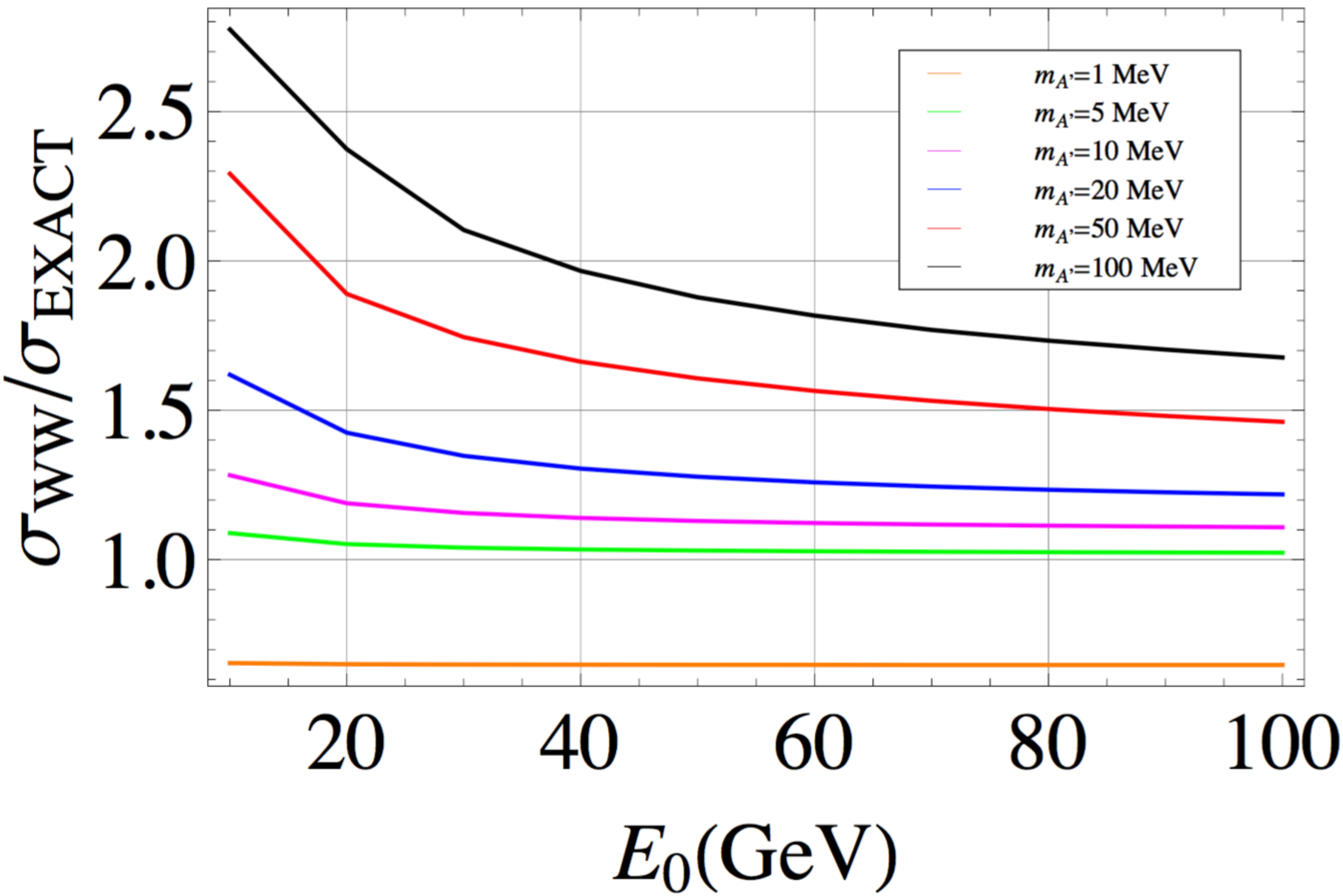
A´events: $E_{ECAL}<E_0$; $E_{HCAL}=0$

-

Simulation of eZ->eZA´

- The signal process is simulated using simplified Weizsaecker – Williams (WW) approximation (Bjorken et al., 2009)
- More exact calculations that use the full matrix element were performed recently (2016, 2017) (arXiV:1712.05706 [hep-ph], accepted in Phys. Lett. B)
- We started to use these calculations this year
- They are implemented as K-factors to the total cross section. The latter can be decreased by as much as factor 15 w.r.t. the simplified WW approximation 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

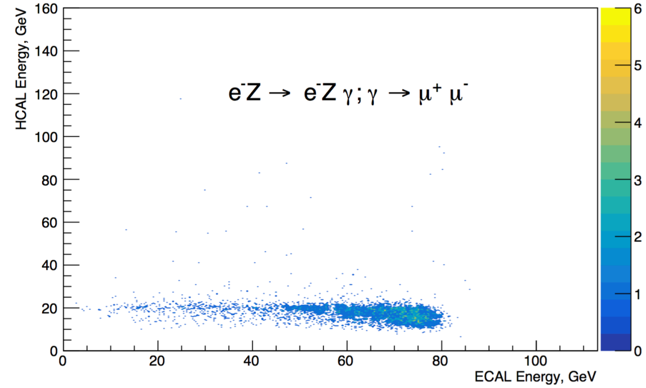
K-factors to eZ->eZA´



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.

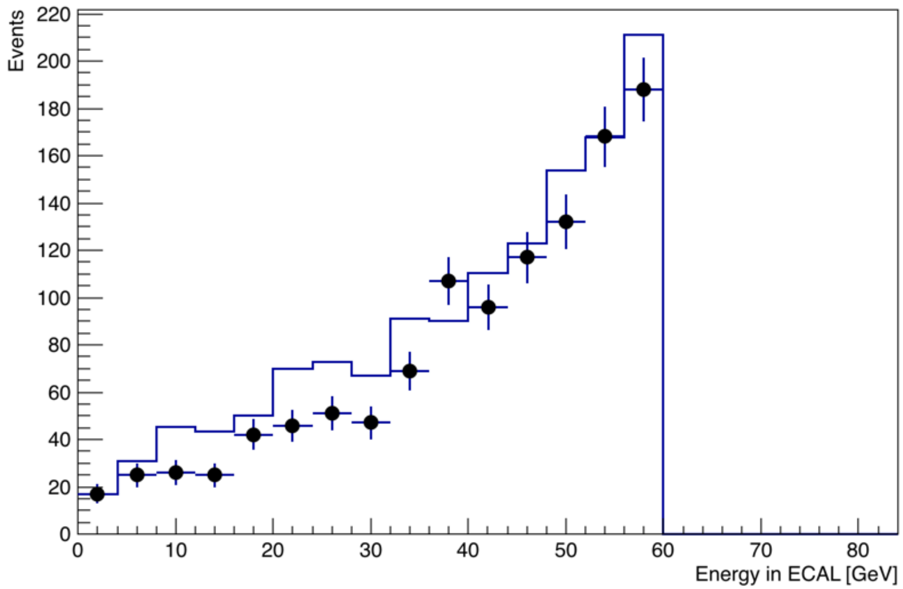
Dimuon production as a reference process

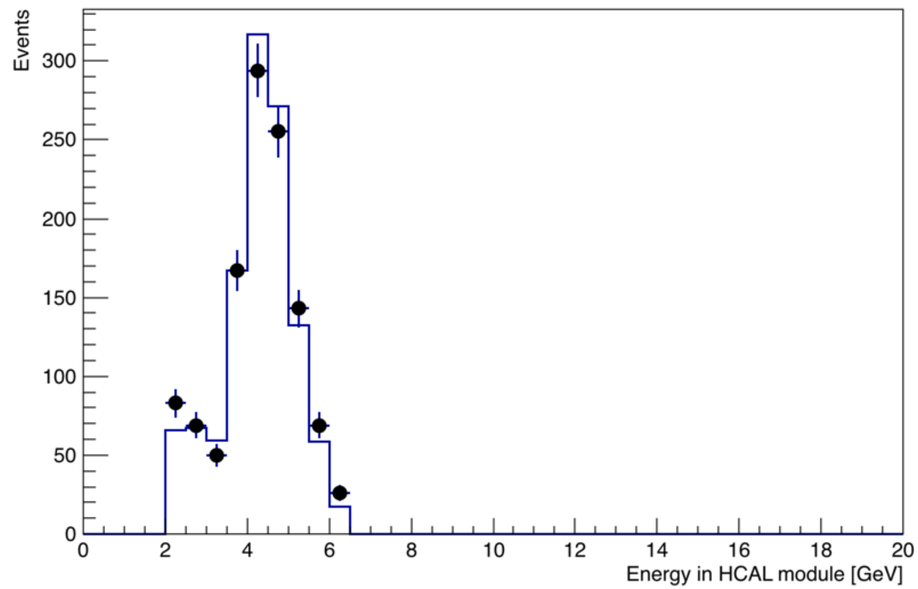


- There is an excellent reference process: gamma to muons conversion. It is rather rare and has many similarities with our signal
- Several 10^4 dimuon pairs with both muons reaching all HCAL modules are registered in the 2016 runs
- The process is available in GEANT4, off by default
- We bias the cross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

Dimuon reconstruction

HCAL module 3





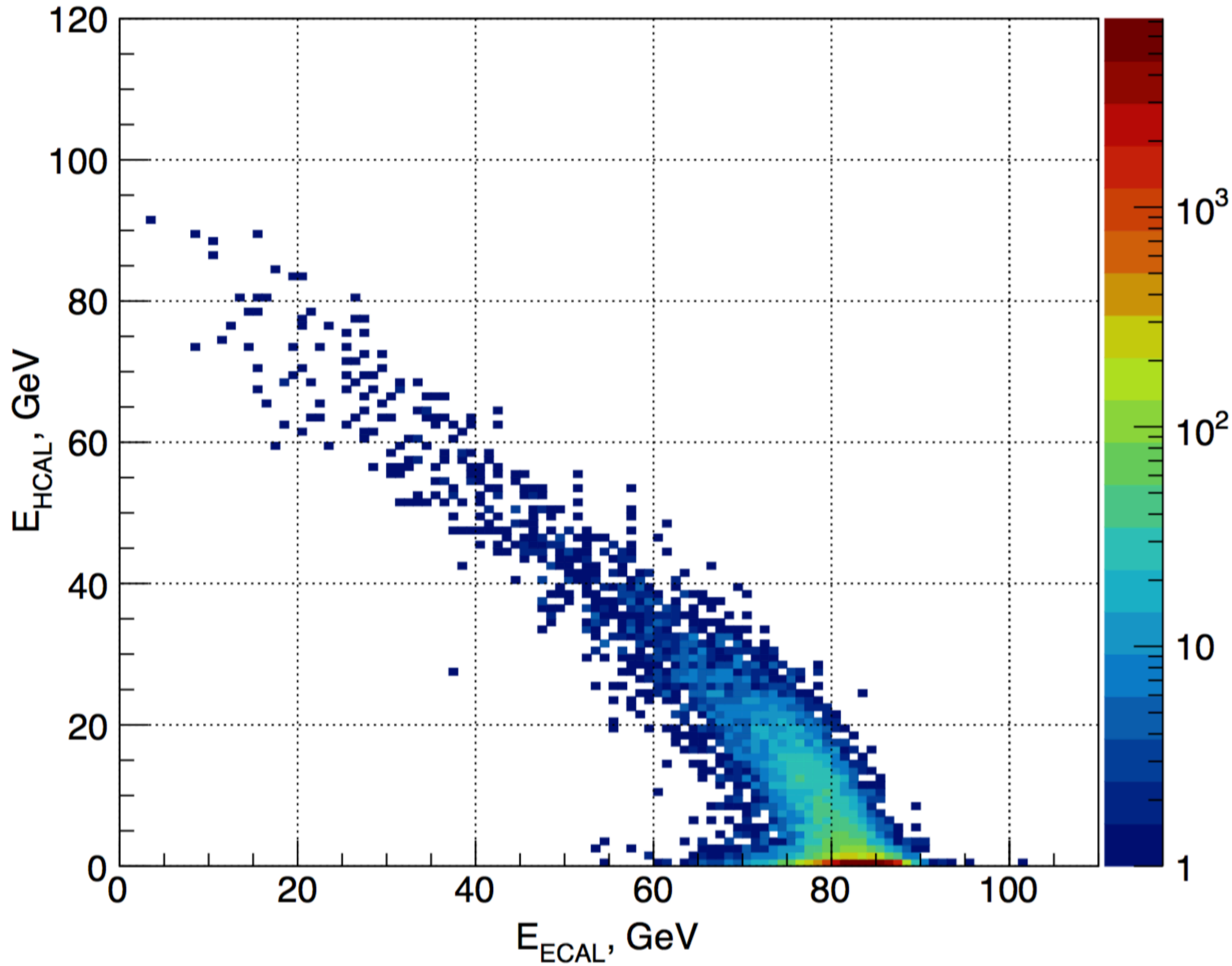
Dimuons selection: $E_{ECAL} < 60$ GeV

$2.5 < E_{HCAL1} < 6.35$

$2 < E_{HCAL3} < 6.35$

Left plot: number of dimuons in DATA ~ 0.92 of MC prediction -> efficiency correction

Background

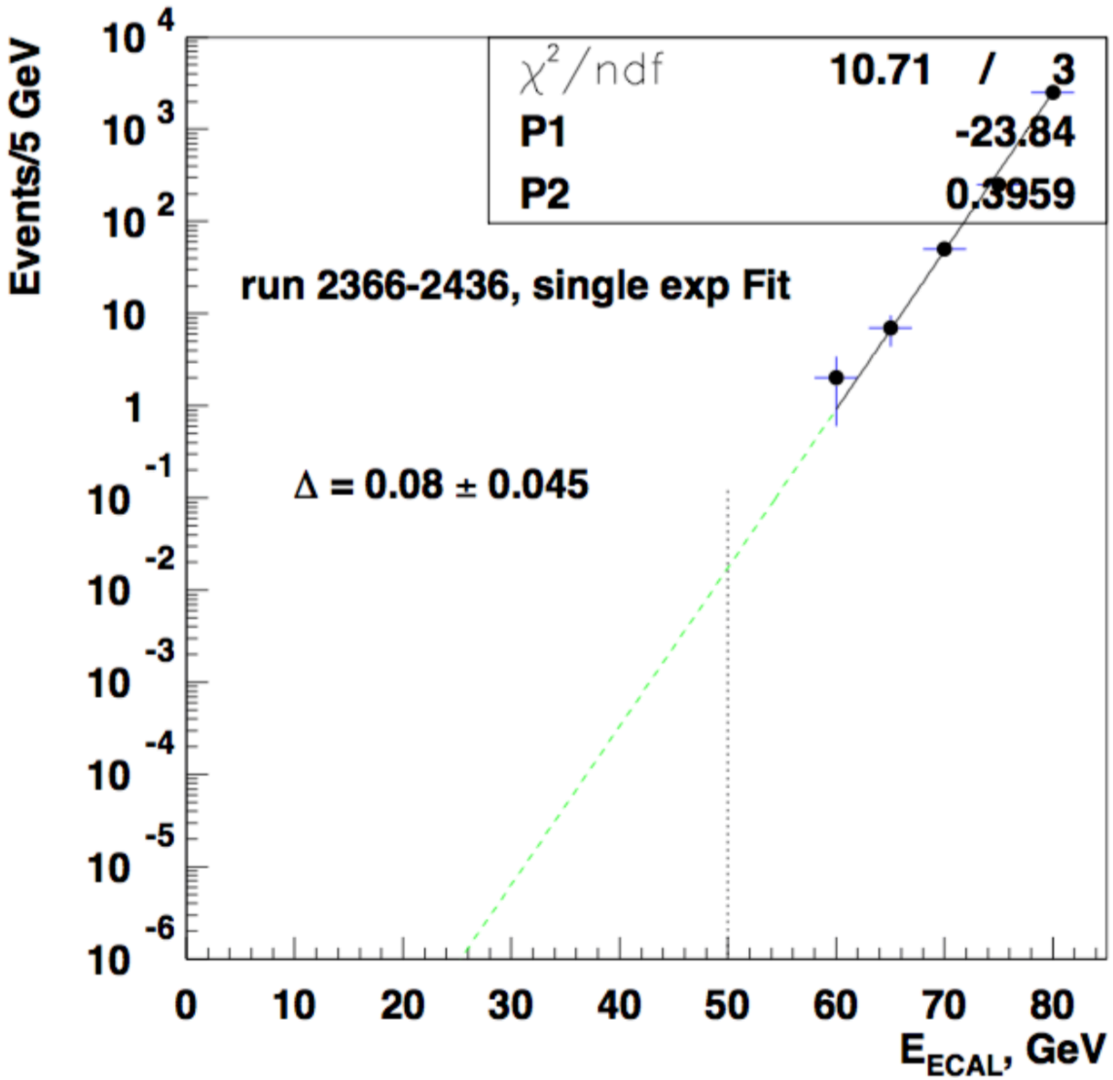


120
100
80
60
40
20
0
E_{HCAL}, GeV
0
20
40
60
80
100
E_{ECAL}, GeV
10^3
10^2
10
1

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”

Background: example of extrapolation

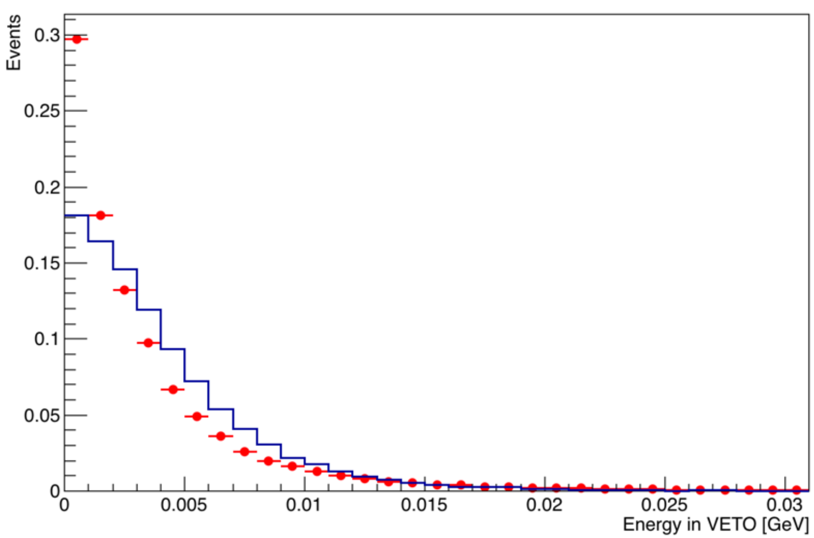


Total predicted background ~0.17

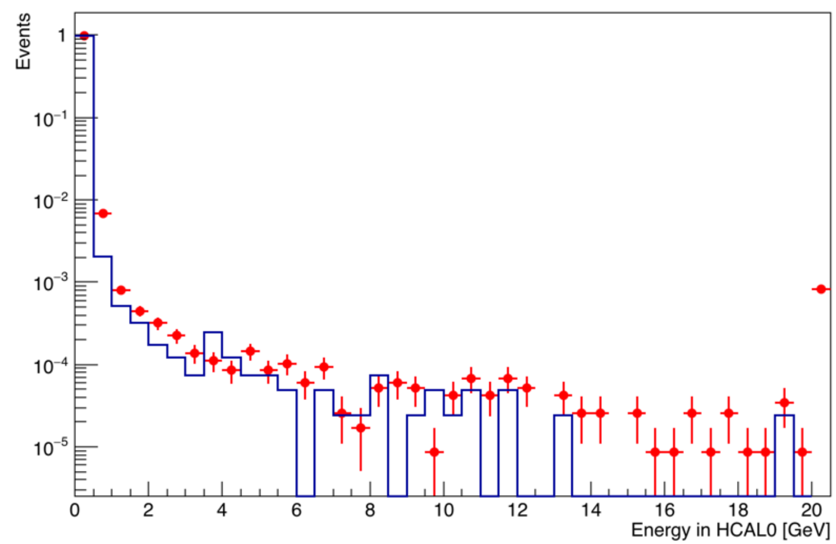
Analysis: efficiency corrections and uncertainties

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



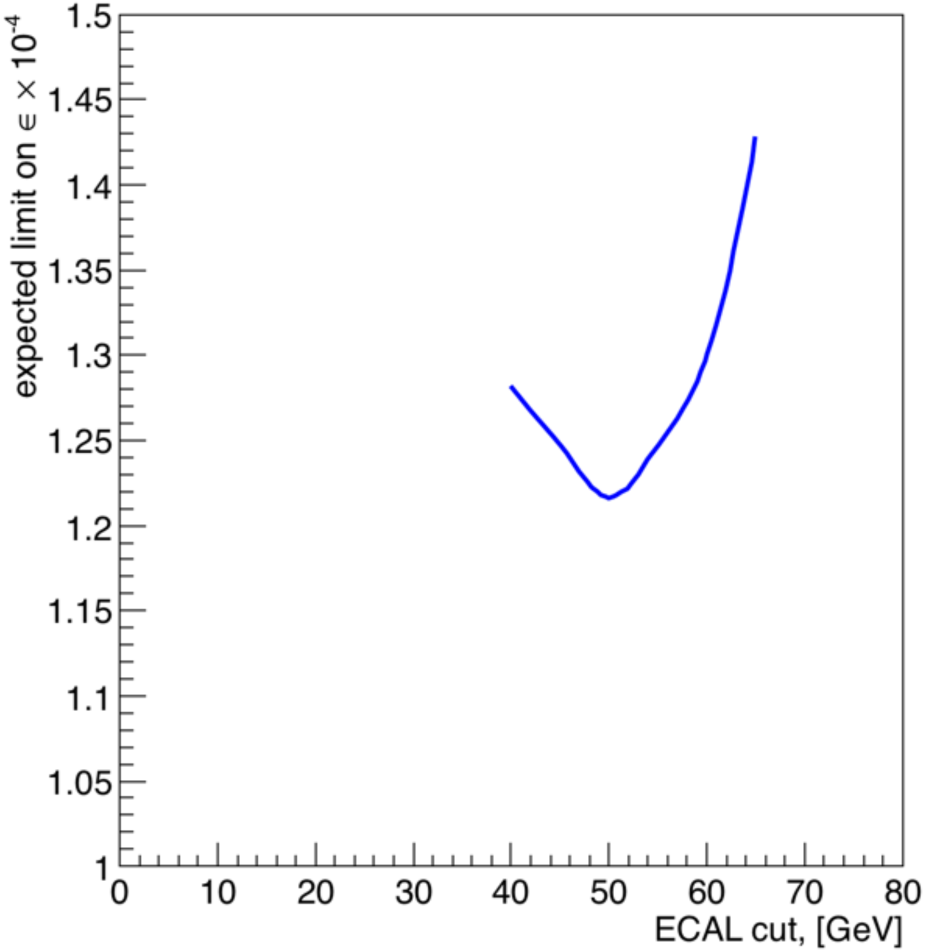
HCAL0: cut at 1 GeV



Analysis

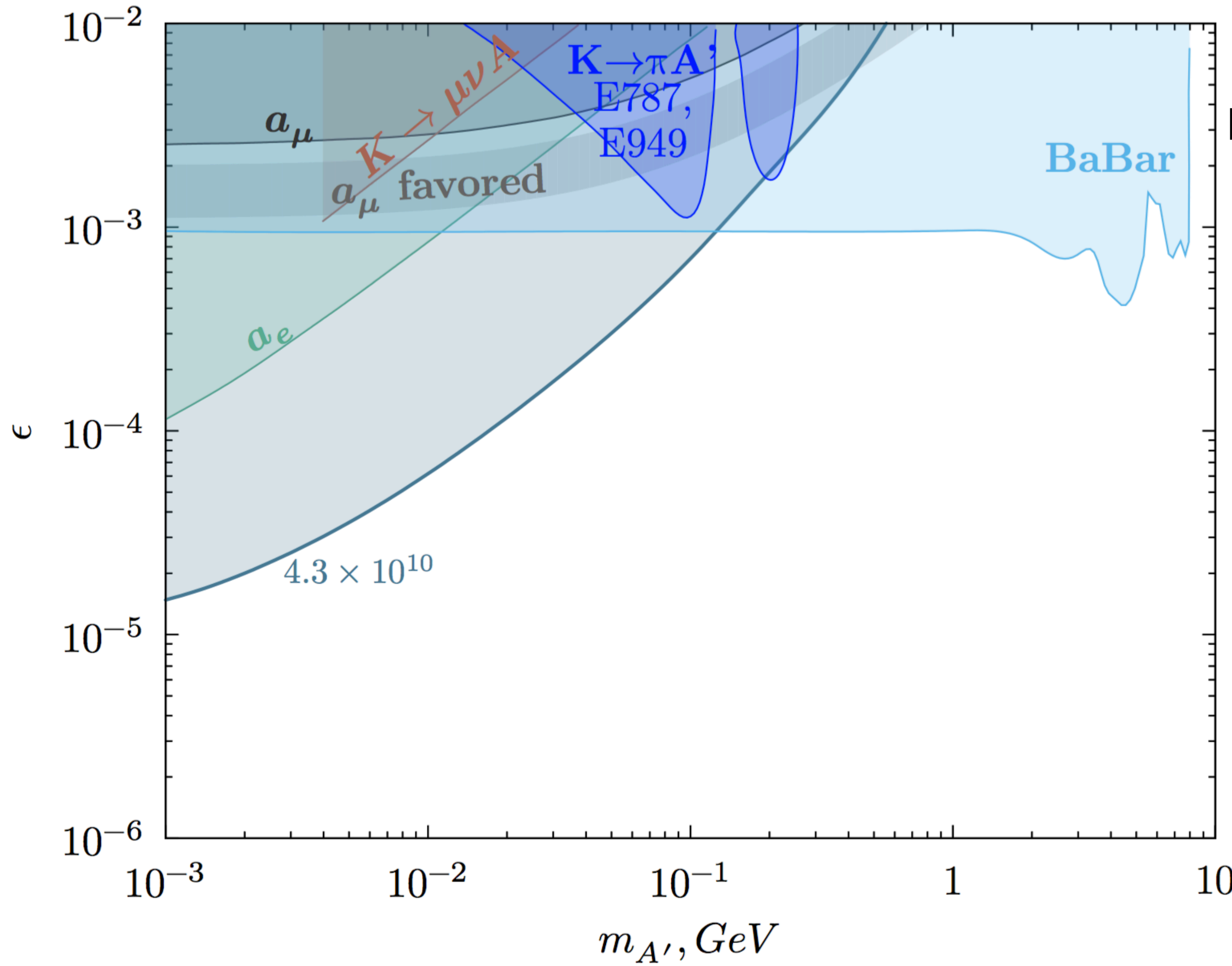
- Data collected in the automn 2016 run are divided in 3 bins: low, medium and high intensity
- For each bin the background, efficiency corrections and their uncertainties are estimated
- The expected sensitivity was calculated with ProfileLikelihood method
- The limits are calculated with CL_S method

Analysis: optimization



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

Results



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

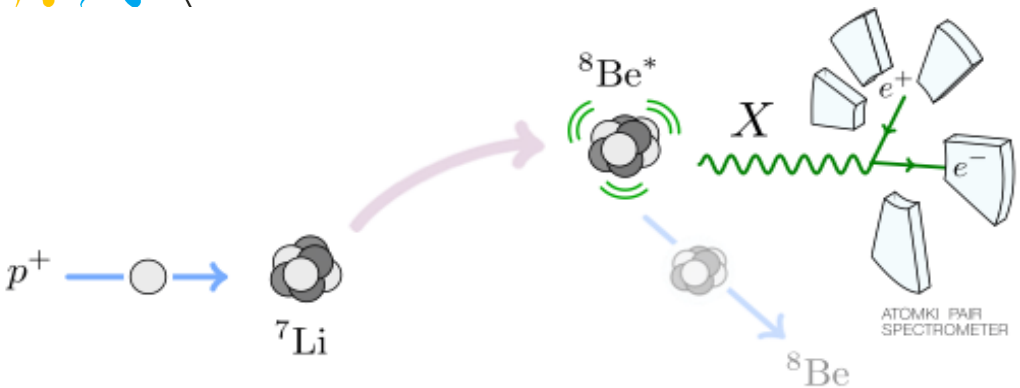
Future plans

- About 2 times more data in invisible mode are collected in 2017
- The analysis of these data is now been performed
- Right now NA64 is taking data
- New results are expected this and next year

Search for a new X-boson 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

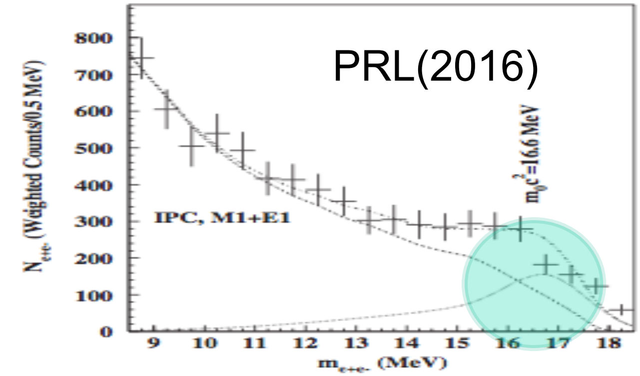
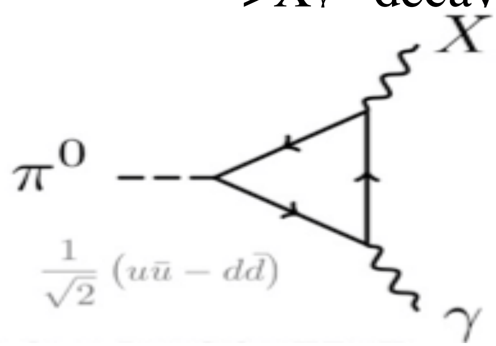
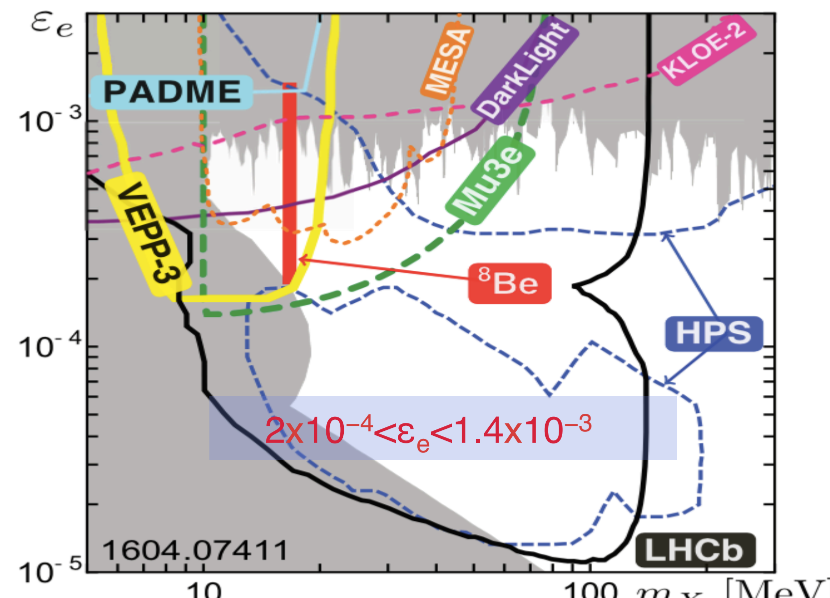


FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.

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

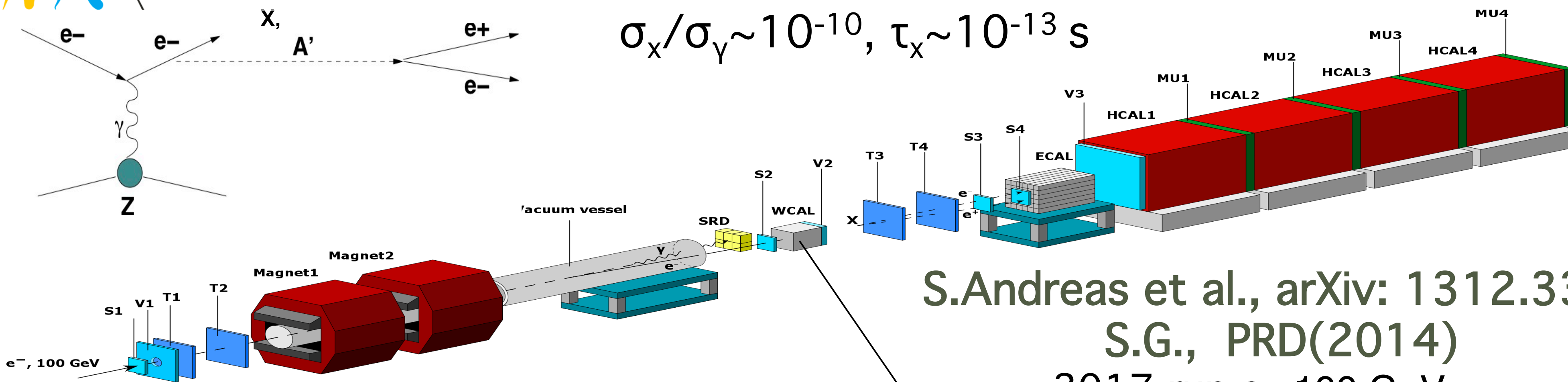




$\Gamma(\pi^0 \to X\gamma) \sim (\varepsilon_u q_u - \varepsilon_d q_d)^2 \sim 0$

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

Search for the X(A´)->e^+e^- decays

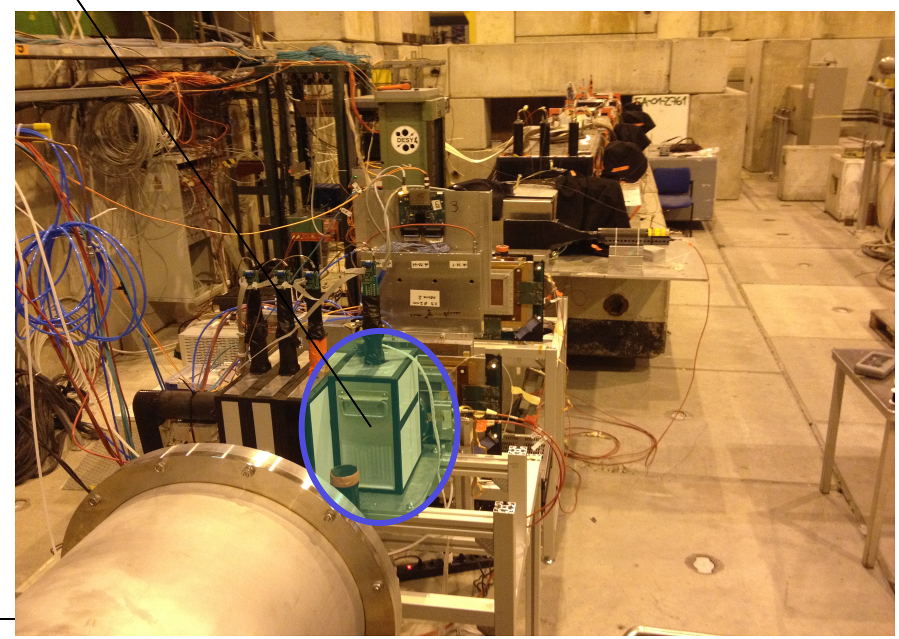


$\sigma_X/\sigma_\gamma \sim 10^{-10}$, $\tau_X \sim 10^{-13}$ s

S.Andreas et al., arXiv: 1312.330

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

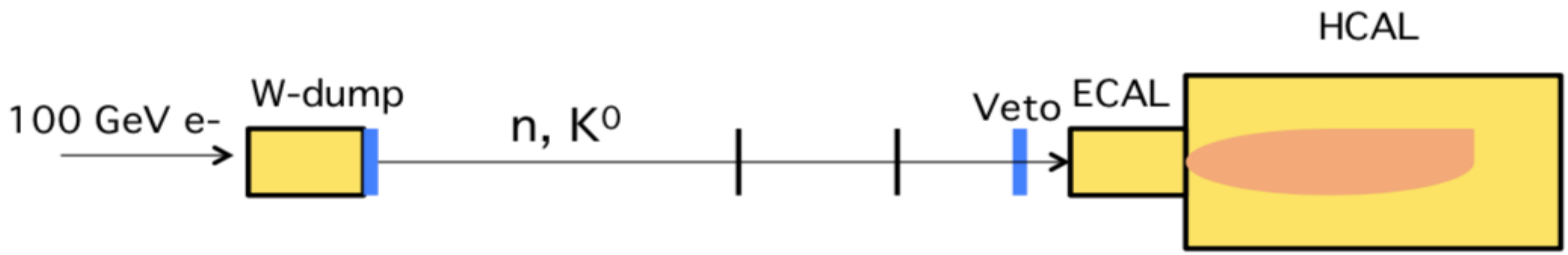
Event selection: criteria

- 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 => : $n_{K0} \sim 10^2$ K^0 **Method II:** selection of e.m. neutrals (γ's from K^0_S chain) => $n_{K0} \sim 1.5 \times 10^2$ K^0

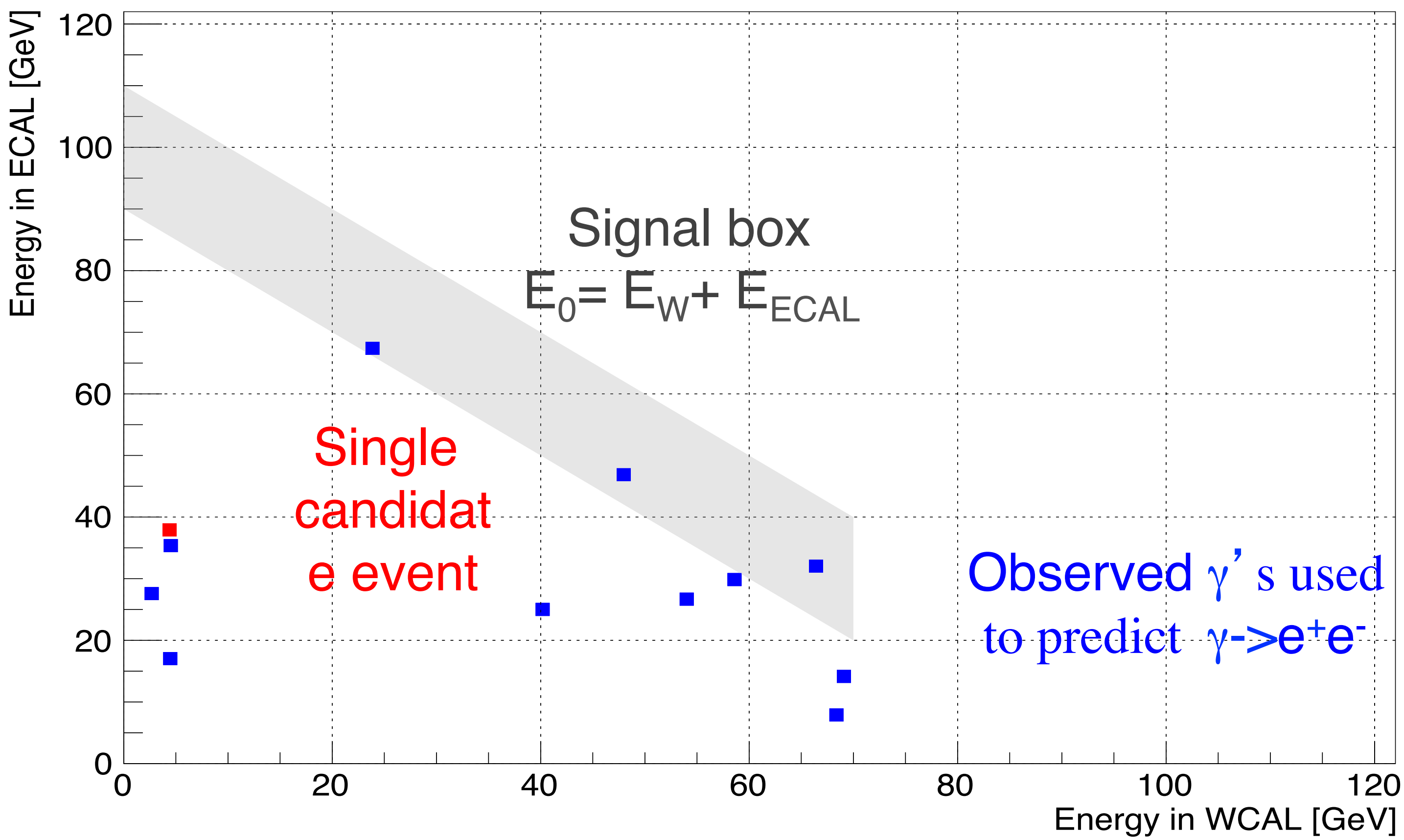
Consistent estimates of K^0_S

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

Final estimate of the background

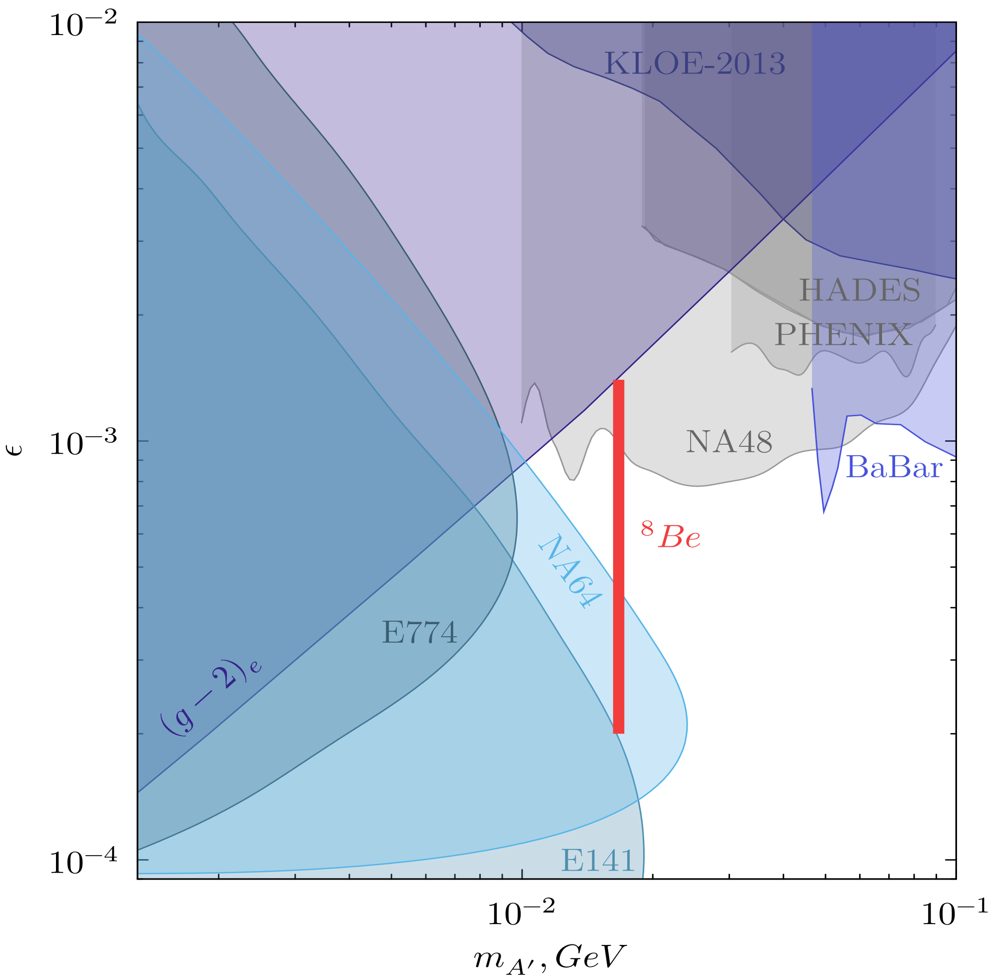
Source of background	Events
e^+e^- pair production by punchthrough γ	< 0.001
$K_S^0 \to 2\pi^0; \pi^0 \to \gamma e^+e^-$ or $\gamma \to e^+e^-$; $K_S^0 \to \pi^+\pi^-$	0.06 ± 0.034
$\pi N \to (\geq 1)\pi^0 + n + ...; \pi^0 \to \gamma e^+e^-$ or $\gamma \to e^+e^-$	0.01 ± 0.004
π^- hard bremsstrahlung 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, 5.4×10^{10} EOT



Results from Sept'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: $1.3 \times 10^{-4} < \varepsilon_e < 4.2 \times 10^{-4}$

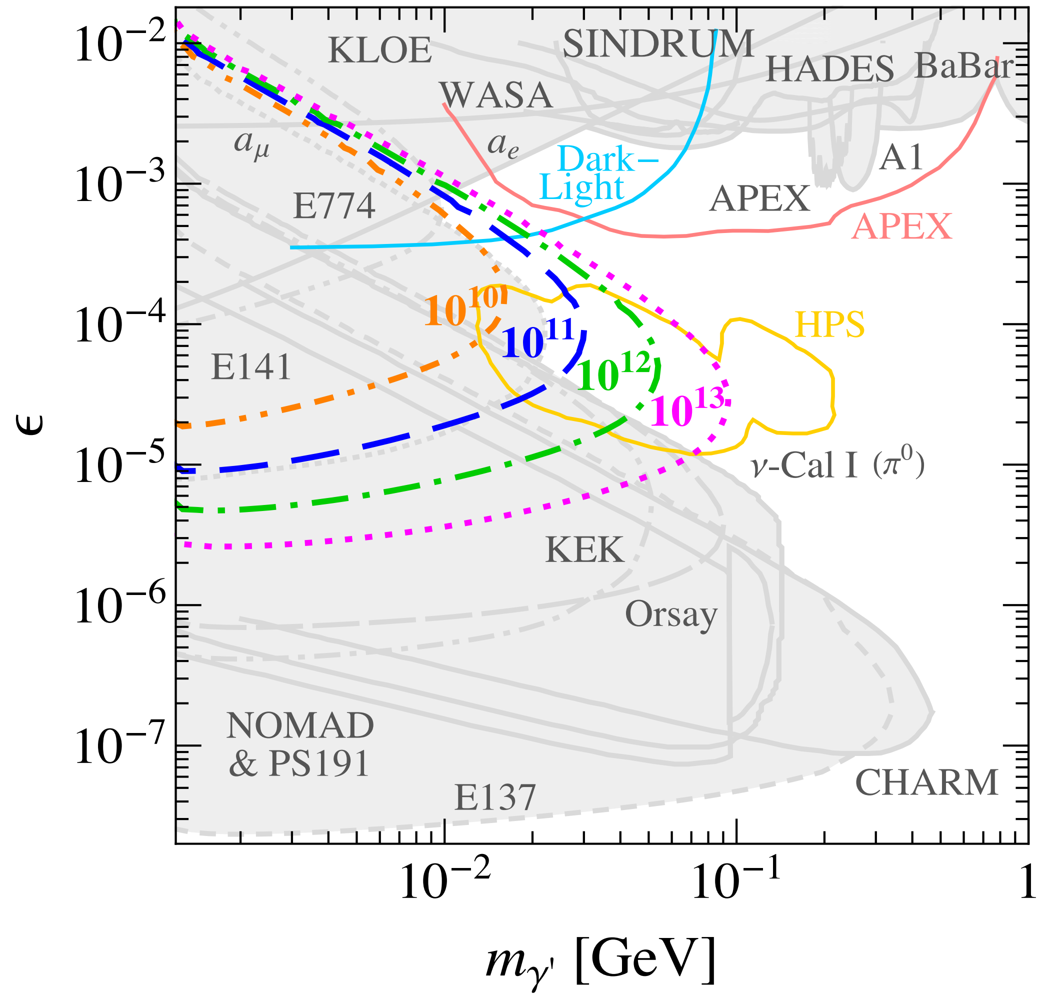
Region of A' with different masses decaing to e^+e^- is excluded

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

Further running and expected results

More data with the visible mode configuration will be taken in June
The plan is to extend sensitivity up to ε=6x10^{-4}

Exclusion area for A´ → e⁺e⁻ vs EOT

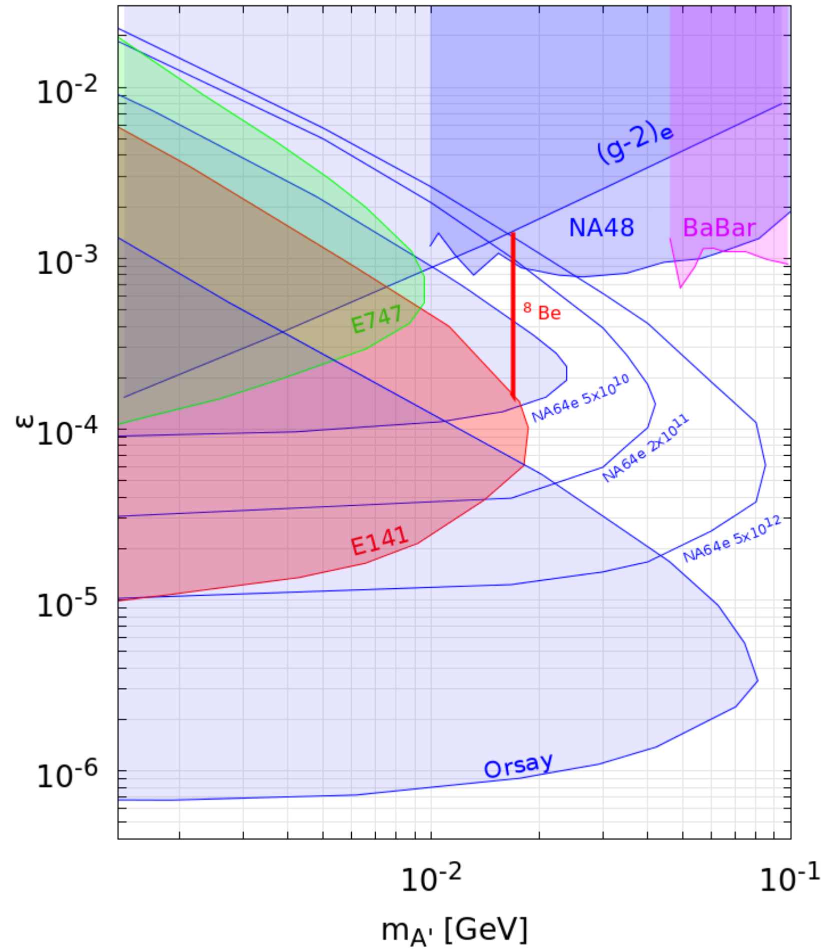


Further running and expected results (2)

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

More data with the visible mode configuration will be taken in June

The plan is to extend sensitivity up to ε=6x10^{-4}



Conclusion

- A search is performed for sub-GeV dark photons (A′) mediated production of dark matter by the NA64 experiment with $4.3*10^{10}$ 100 GeV electrons on target
- 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 to the g-2 anomaly
- A search is performed for a new X-boson 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 $m – \varepsilon$ plane for similar particles with different masses
- Right now NA64 is taking data, invisible, then visible mode configurations
- There are plans to search also for ALP, other exotic particles, study pion charge-exchange reaction, $e – \tau$ conversion etc.
- More distant plans are to move to the muon beam