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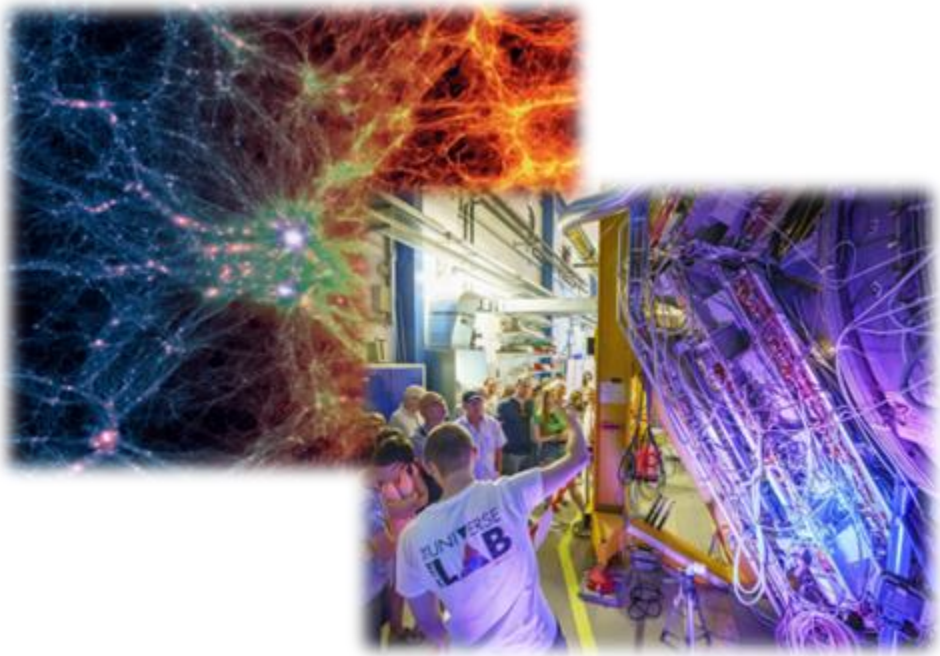

Search for the X_{17} QCD Axion in the $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ decay with the HADES Detector

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on behalf of HADES Collaboration

NATIONAL SCIENCE CENTRE POLAND

9th DISCRETE Symposium

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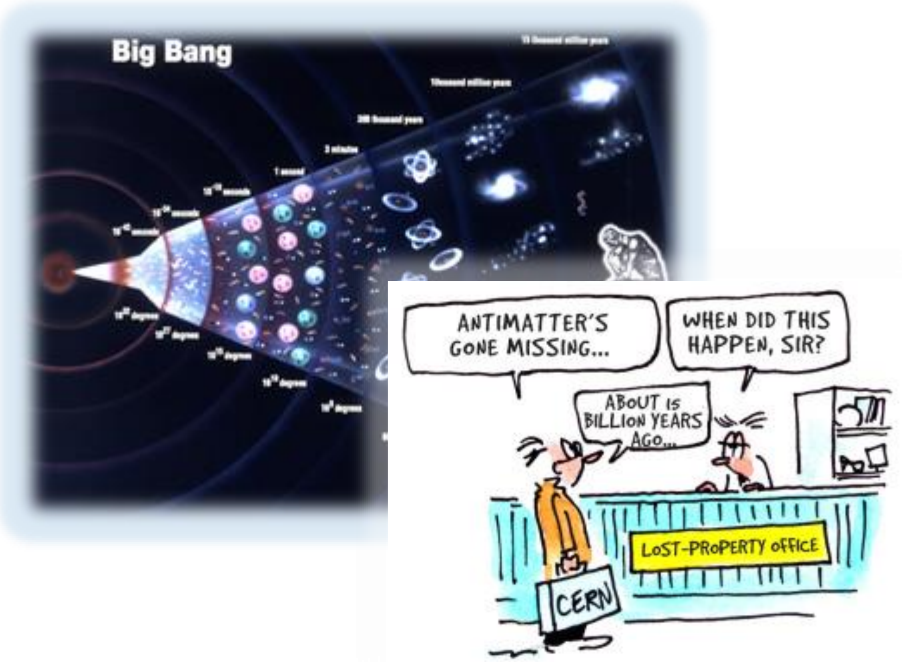
General motivation

The general and main motivation for research is to answer the question:

How did our 'Material Universe' survive the cooling after the Big Bang?



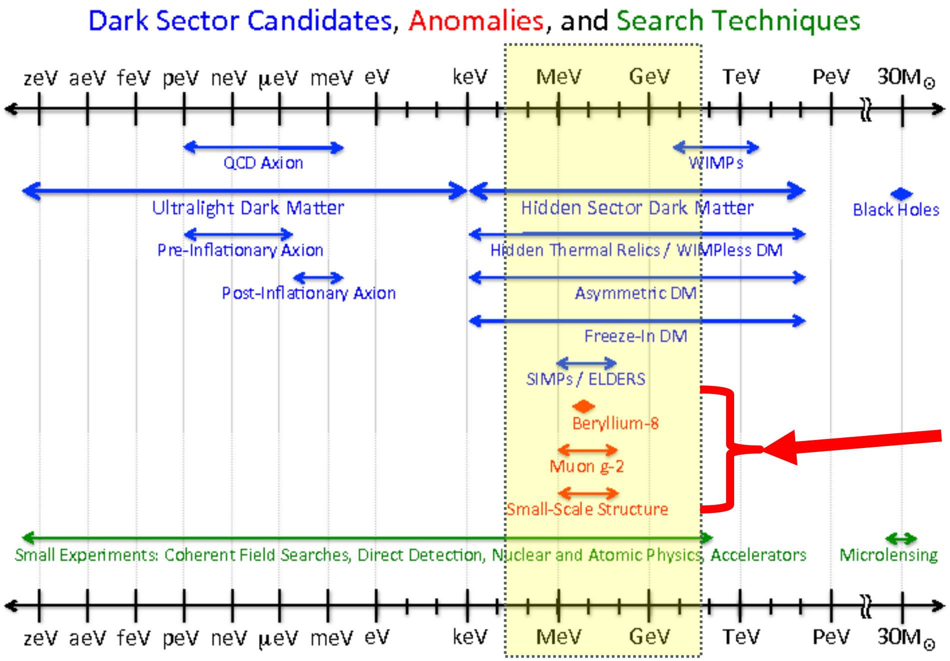
Big Bang:
an equal amount of matter and antimatter was produced during the hot phase
During cooling and expansion
matter and antimatter annihilated 😐

Baryon - Antibaryon
ASYMMETRY!

Most of the cosmic energy budget is of an unknown form

Where did the asymmetry come from, and how can it be experimentally investigated?
Searching for differences between particles and antiparticles
by studying symmetries with light mesons at scale of ~ 1 GeV → Physics Beyond SM

General motivation



- In SM: violation from weak interaction is not sufficient to create observed asymmetry
- DM mass range from a keV to several GeV
- DM annihilates directly into SM particles over most of the sub-GeV mass range
- several anomalies in experiments point to possible new physics, weakly coupled to familiar matter in the 1 - 100 MeV scale

Ref: Marco Battaglieri, arXiv:1707.04591 [hep-ph]

Strong CP problem → Peccei-Quinn-Weinberg-Wilczek (PQWW)

Axions and Axion-Like-Particles (ALP's)

Newest theoretical models prefer gauge bosons in MeV-GeV mass range as "...many of the more severe astrophysical and cosmological constraints that apply to lighter states are weakened or eliminated, while those from high energy colliders are often inapplicable" *(B. Batell , M. Pospelov, A. Ritz – 2009)*

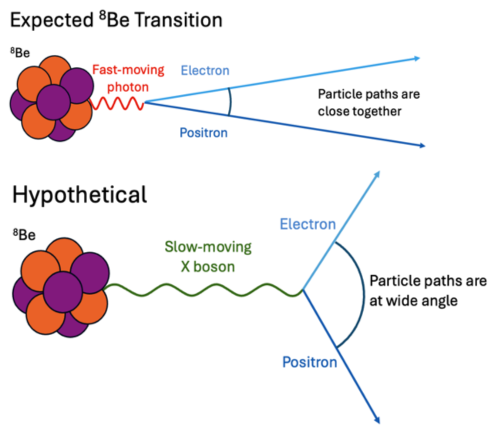
General motivation – ATOMKI results

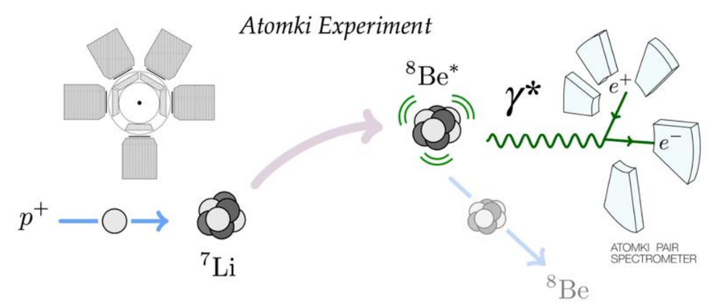
The ATOMKI group observed an excess of e^+e^- pairs emitted at large relative angle in the nuclear reactions:

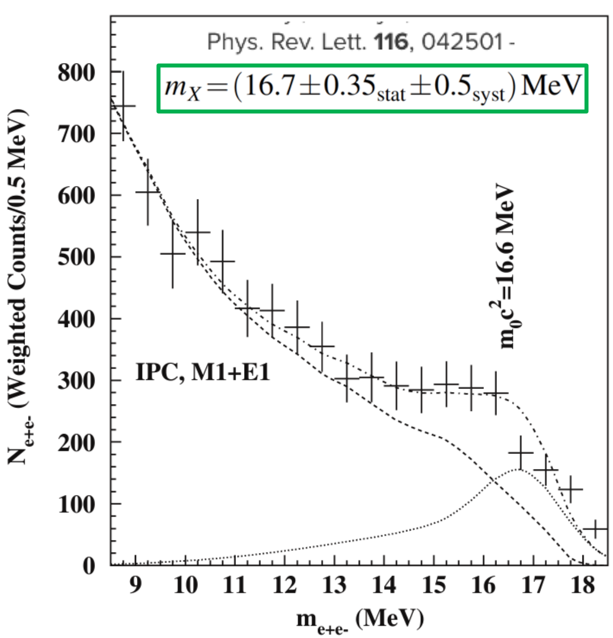
$^{3}H(p, e^+e^-)^{4}He$,

$^{11}B(p, e^+e^-)^{12}C$.

$^{7}Li(p, e^+e^-)^{8}Be$.

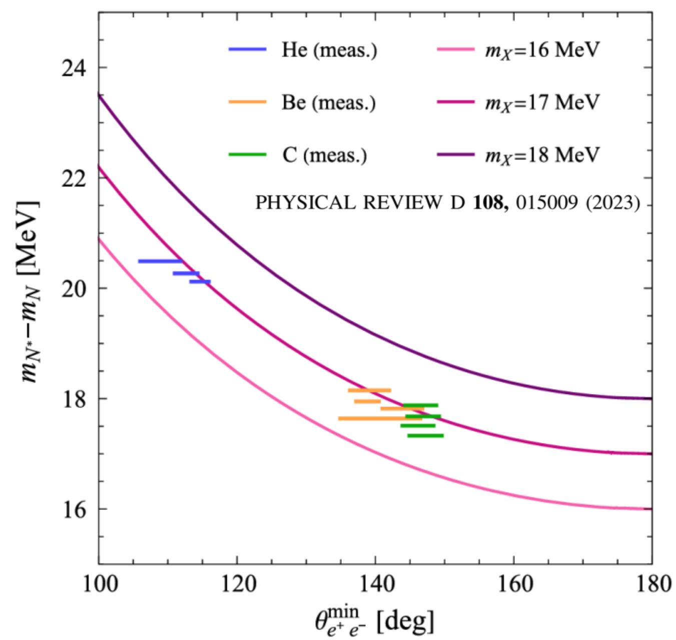






ATOMKI Exp. ^{8}Be :

anomalies in the internal pair creation of isovector (17.64 MeV, I=1) and isoscalar (18.15 MeV, I=0) magnetic dipole M1 transitions in ^{8}Be



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General motivation – anomalies interpretation

The Standard Model interpretation:

Physics Letters B 773 (2017) 159–165

1. The anomaly is described by using the Multipole interferences or Form factor. Zhang and Miller (2017) investigated the nuclear transition form factor as a possible origin of the anomaly.

   Nuclear Physics A 1008 (2021) 122143

2. Anomaly is a consequence of modified Bethe-Heitler process (Koch 2021).

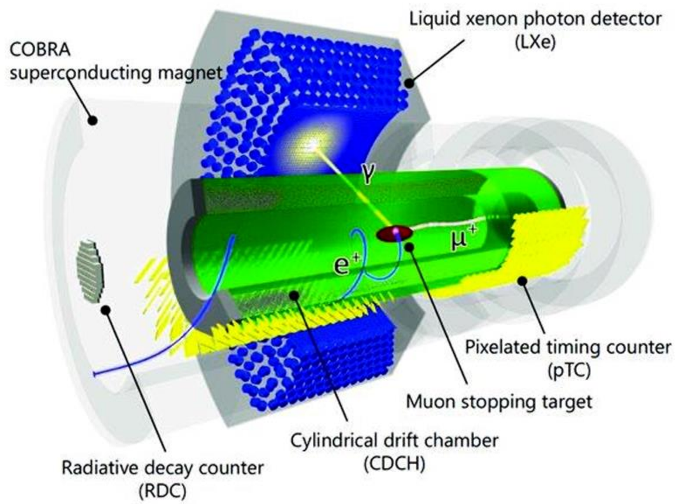
The Beyond Standard Model interpretation:

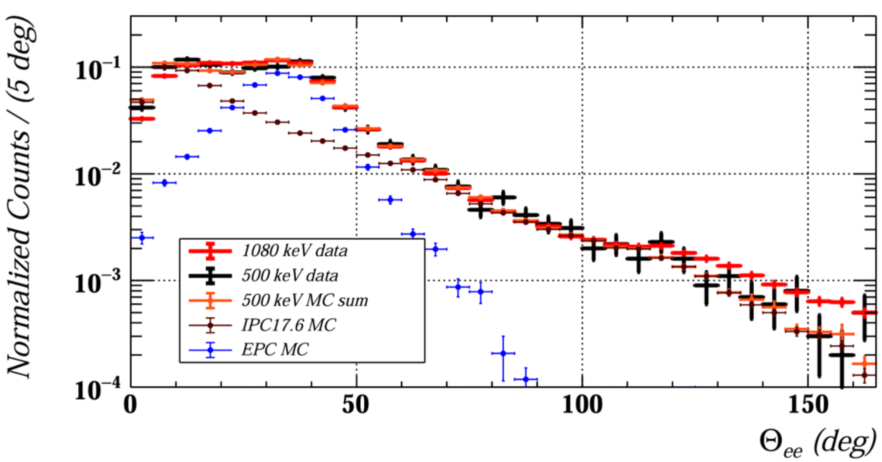
Phys. Rev. Lett. **117**, 071803

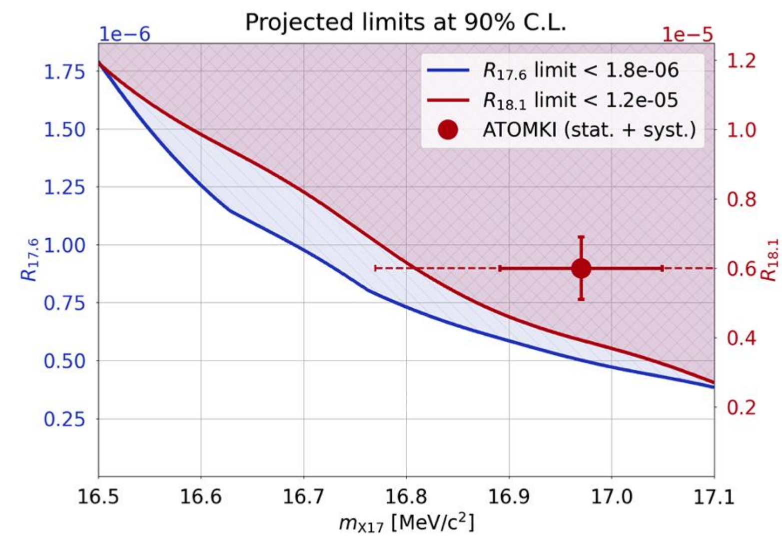
1. The first BSM theoretical interpretation of the ATOMKI experimental results was performed by Feng et. al. (2016). They explained the anomaly with a vector gauge boson X_{17}, which may mediate a fifth fundamental force with some coupling to Standard Model (SM) particles. From searches for $\pi^0 \rightarrow Z' + g$, by the NA48/2 experiment, Feng postulated that the X_{17} particle couples much more strongly to neutrons than to protons, **"proto-phobic force".**

General motivation – MEG-II result (from 12.11.2024)

- MEG-II (PSI) experiment searches for charged lepton flavour violating decays $\mu^+ \to e^+\gamma$.
- Experiment was adopted to search for X17 in the same reaction as ATOMKI: $^7Li(p, e^+e^-)^8Be$ (17.6 MeV and 18.1 MeV states).
- No significant evidence of the X_{17} particle was found.
- Upper limits for BR with respect to γ-ray emission: $R_{18.1} < 1.2\times10^{-5}$ and $R_{17.6} < 1.8\times10^{-6}$







The MEG II collaboration: K. Afanaciev et al., arXiv:2411.07994 (2024)

Connection between Standard and Dark Matter

New Physics connects to Standard Model particles through four portals:

Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu}F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a}F_{\mu\nu}\widetilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2)H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N LHN$

Invisible, non-SM

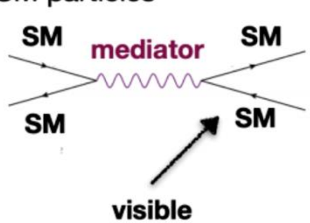
Dark Matter production

Producing stable particles that could be (all or part of) Dark Matter

Visible, SM

Production of portal-mediators that decay to SM particles

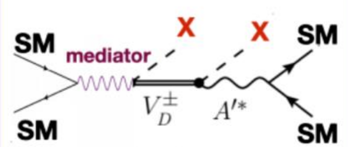
Systematically exploring the portal coupling to SM particles



Mixed visible-invisible

Production of "rich" dark sectors

Testing the structure of the dark sector



Stefania Gori, Mike Williams

Light mesons studies:

η/η'

Connection between Standard and Dark Matter

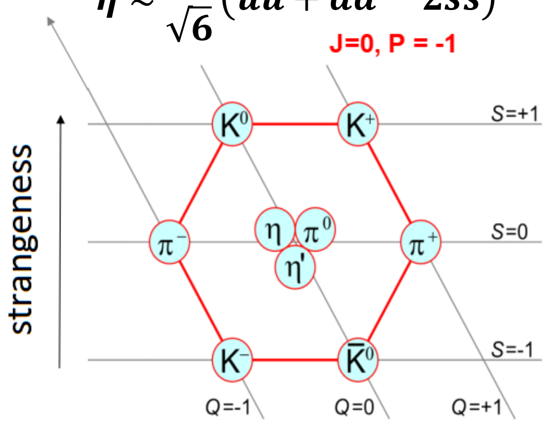
"Light dark matter must be neutral under SM charges, otherwise it would have been discovered at previous colliders"

[G. Krnjaic RF6 Meeting, 8/2020]

- The only known particles with all-zero quantum numbers: Q = I = J = S = B = L = 0 are the **η/η' mesons** and the **Higgs boson (also the vacuum!)** -> **very rare**
- The **η** meson is a Goldstone boson (the η' meson is not!)
- The **η/η'** decays are flavor-conserving reactions

$$\eta \approx \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

J=0, P = -1



Mass	547.862 ± 0.018 MeV
Main decay mods	η → γ γ (39.36%)
	η → π⁰ π⁰ π⁰ (32.57%)
	η → π⁺ π⁻ π⁰ (23.02%)
	η → π⁺ π⁻ γ (4.28%)
	η → π⁺ π⁻ e⁺ e⁻ (0.03%)

Axion-Like-Particles / QCD Axion

How to explain anomalies in view of experimental constrains for QCD Axion ?

Must be short lived (~10^{-13} s) and decay predominantly to $e^+ e^-$

QCD Axion couples predominantly to the first generation of SM fermions
(PQ charges vanish for second and third SM fermions)

The a - π^0 mixing at the level of $O(10^{-4})$

Using Resonance Chiral Theory (RχT), the low-lying resonances should be included as degrees of freedom in the RχT Lagrangian

$m_{u,d} \ll m_s$ → isovector ~~$\theta_{a\pi} \gg \theta_{a\eta}, \theta_{a\eta'}$~~

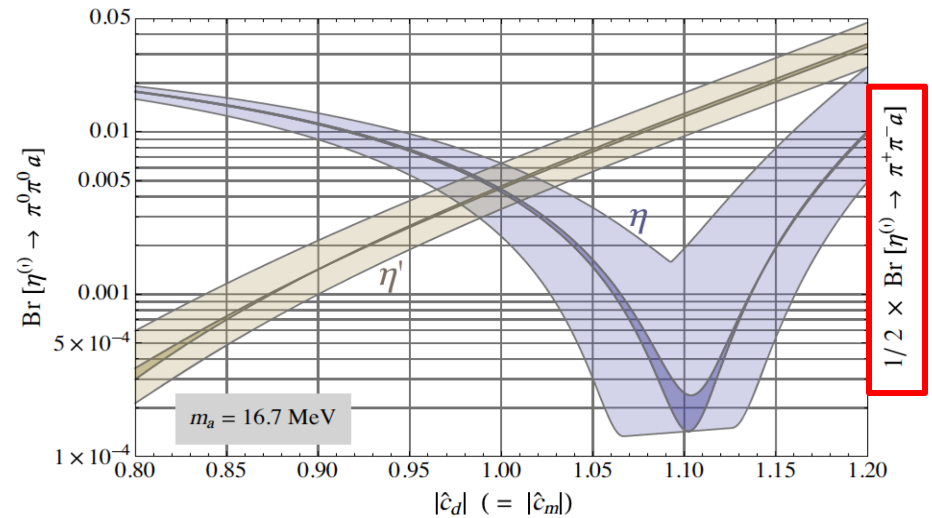
isoscalar $\theta_{a\pi} \ll \theta_{a\eta}, \theta_{a\eta'}$

Suppressed mixing-angle results in the isoscalar couplings of the axion

***Piophobic* QCD axion**

Hadronic decay channels of **η and η'** could be coupled to ALP's:

$$\eta \to \pi^+ \pi^- a\ (\to e^+ e^-)$$



(couplings of the low-lying scalar octet to the pseudoscalar mesons)

$$\mathrm{BR}(\eta \to \pi\pi a) \sim 10^{-4} - 10^{-2}$$

Ref: D. Alves et al., PHYS. REV. D 103, 055018 (2021)

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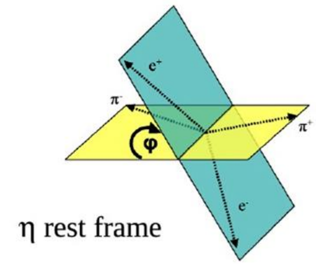
Axion-Like-Particles / QCD Axion



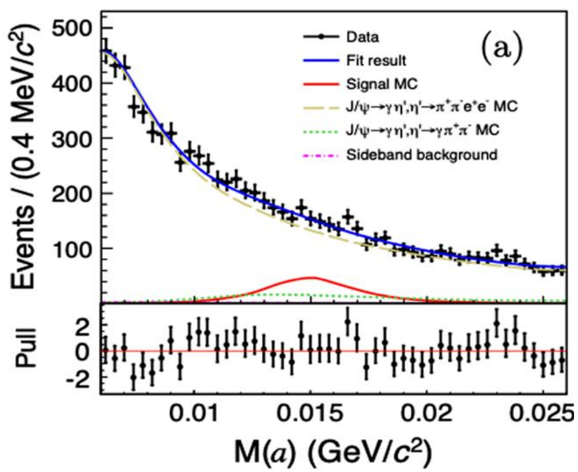
Why previous measurements $\eta(\eta') \to \pi^+ \pi^- e^+ e^-$ did not see Axion signatures ?

Experiments up to now focused on studies of CP invariance:

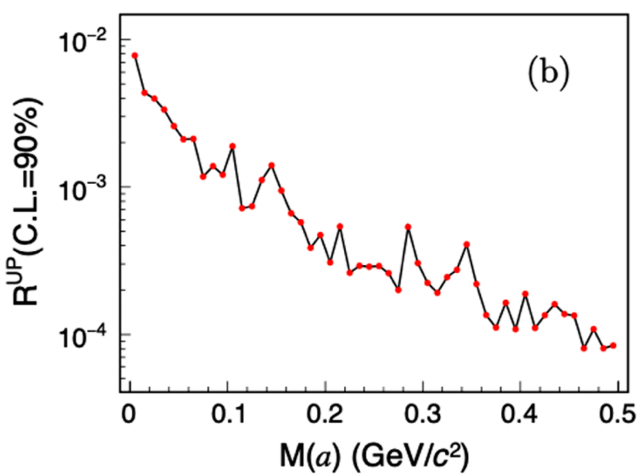
Year	Exp.	Events number	Asymmetry	BR ($\eta \to \pi^+ \pi^- e^+ e^-$)
2009	KLOE-2	1555 ± 52	$(-0.6 \pm 2.5_{stat} \pm 1.8_{sys}) \times 10^{-2}$	$(2.68 \pm 0.09_{stat} \pm 0.07_{syst}) \times 10^{-4}$
2016	WASA-at-COSY	251 ± 17	$(-1.1 \pm 6.6_{stat} \pm 0.2_{sys}) \times 10^{-2}$	$(2.7 \pm 0.2_{stat} \pm 0.2_{syst}) \times 10^{-4}$
2007	WASA-CELSIUS	16.3 ± 4.9± 2.0	-----	$(4.3 \pm 1.3_{stat} \pm 0.4_{syst}) \times 10^{-4}$

Rejected events $m(e^+e^-) < 20$ MeV (for KLOE-2 2009)

BES III – Result for the $\eta' \to \pi^+ \pi^- e^+ e^-$ decay (also CP invariance studies):



a = 15 MeV



R as a mas of axion

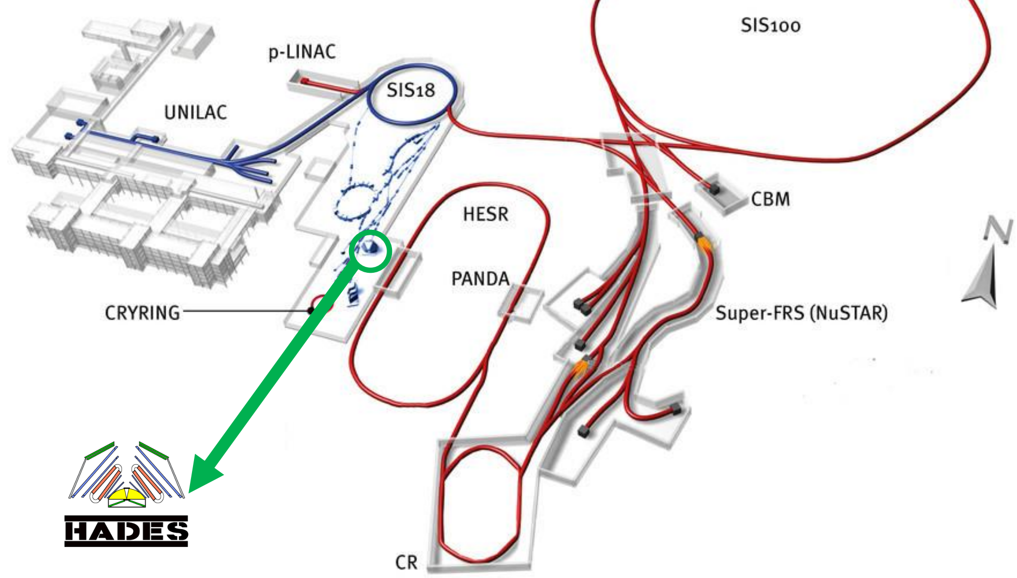
$$R^{UP} = \frac{\mathcal{B}(\eta' \to \pi^+ \pi^- a) \cdot \mathcal{B}(a \to e^+ e^-)}{\mathcal{B}(\eta' \to \pi^+ \pi^- e^+ e^-)}$$

$$\Downarrow$$

$$(0.1 - 7.8) \times 10^{-3}$$

Ref: BESIII Col. JHEP 07, 135 (2024)

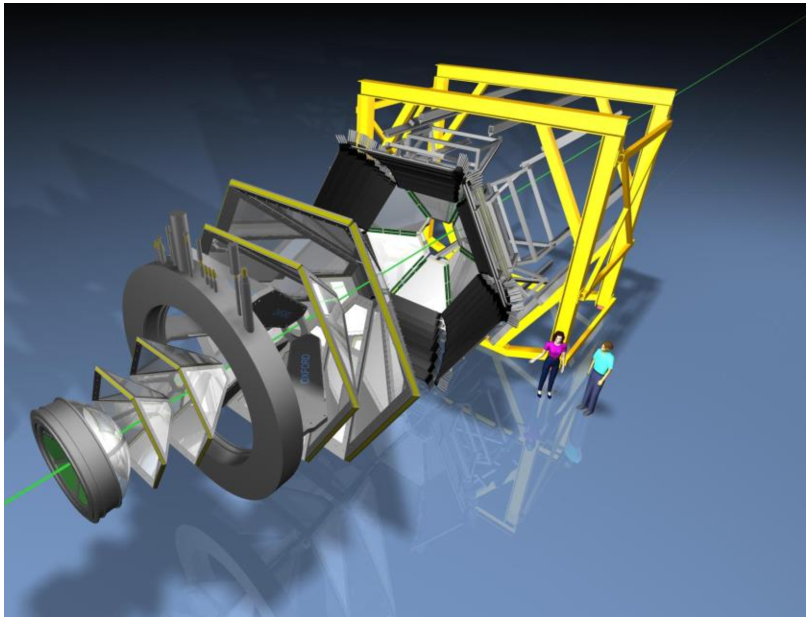
HADES - High Acceptance Di-Electron Spectrometer



SIS 18

U^{73+}	1.0 GeV/u	10^9 ions/s
Protons	4.5 GeV	2.8×10^{13}/s
Pions	0.5-2 GeV/c	

➢ hades.gsi.de



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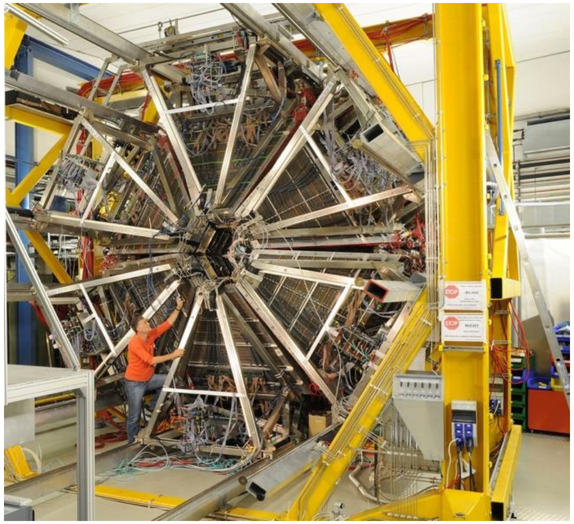
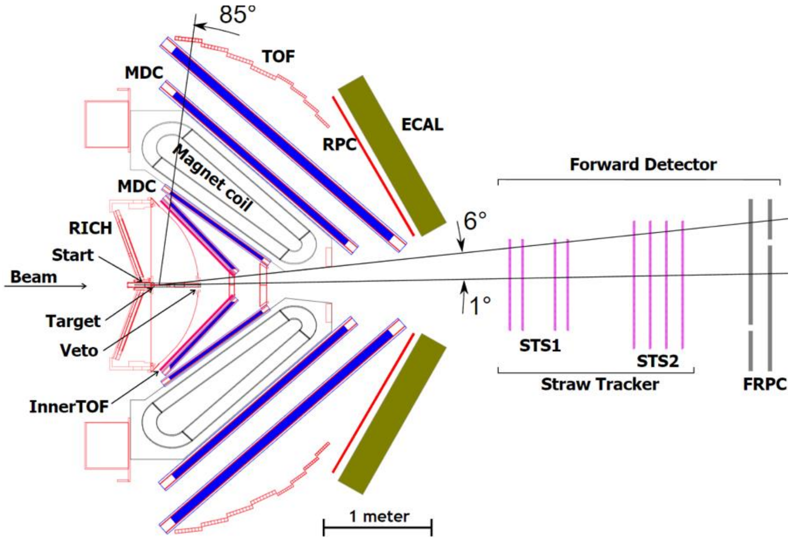




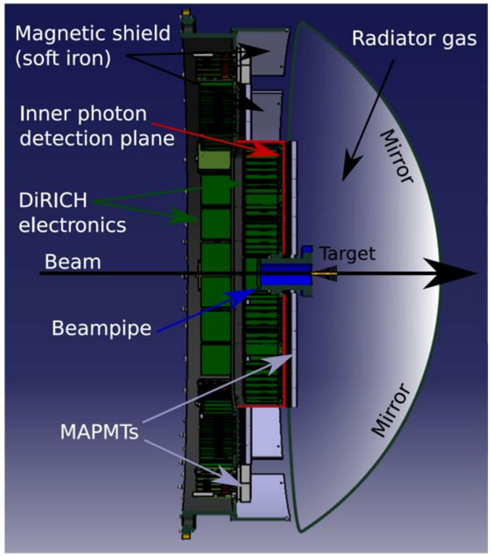
- **START** – T0 reaction for ToF
- **RICH – Cherenkov detector (di-electron e^+e^-)**
- **MDC and STS** – track reconstruction
- **Magnet Coil** – generates magnetic field
- **ToF & RPC** – Time-of-Flight META detectors
- **ECAL** – electromagnetic calorimeter (photons)
- **Trigger logic based on InnerToF and Meta**

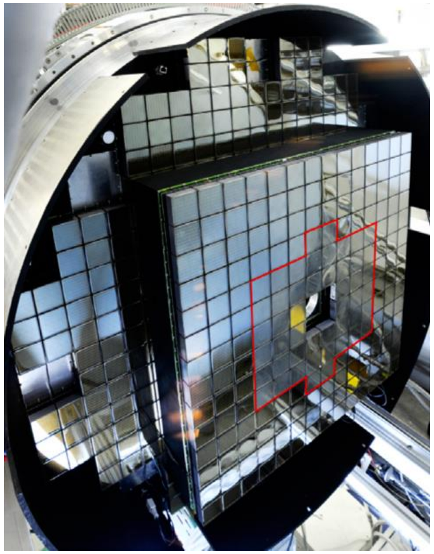
February 2022 measurement:

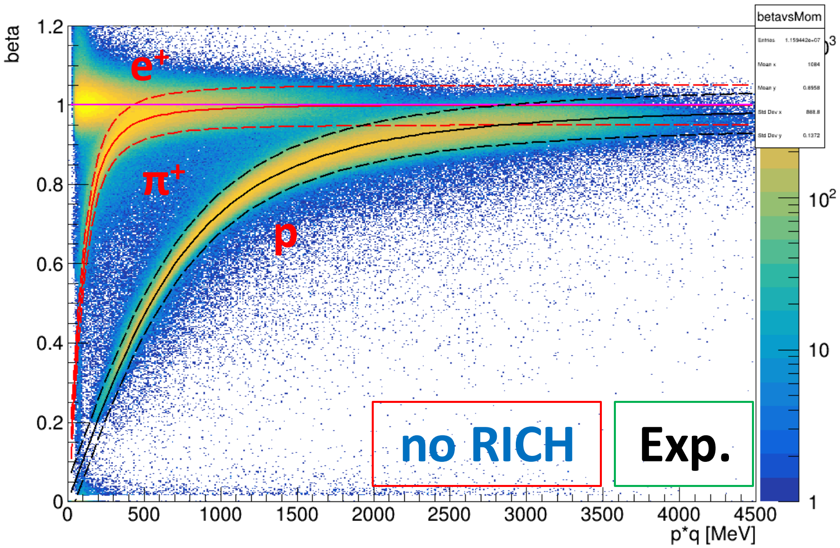
- **p – p** collisions at energy of **T = 4.5 GeV** using liquid hydrogen target (LH_2)
- **28 days** of measurement
- estimated total integrated luminosity

$L \sim 6.10$ [pb^{-1}]

Particle selection and identification

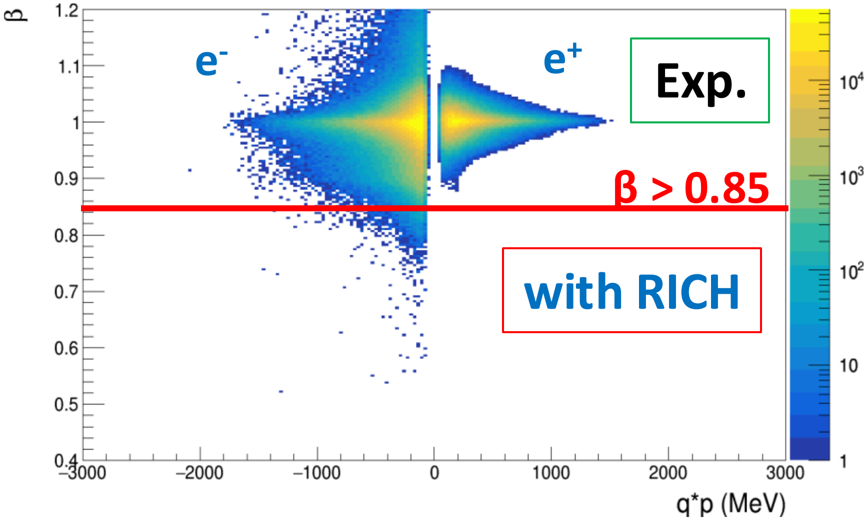






Following particles have to be selected: **π^+ π^- e^+ e^-**

- threshold momentum for **e^+/e^-** 9 MeV and for **π^+/π^-** 2500 MeV.
- leptons selected by correlation windows (θ_{RICH} - θ_{MDC}) in RICH and MDC
- pions selected by cuts on beta vs. momentum
- additional cuts for leptons: **$\beta > 0.85$**

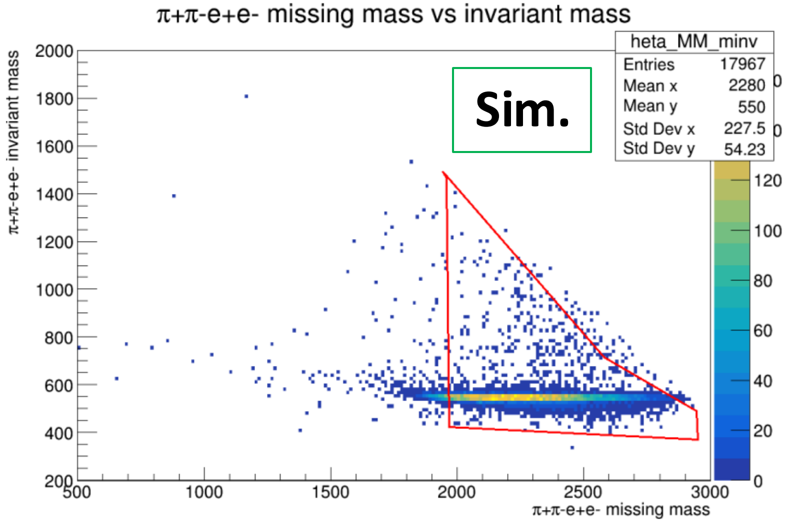


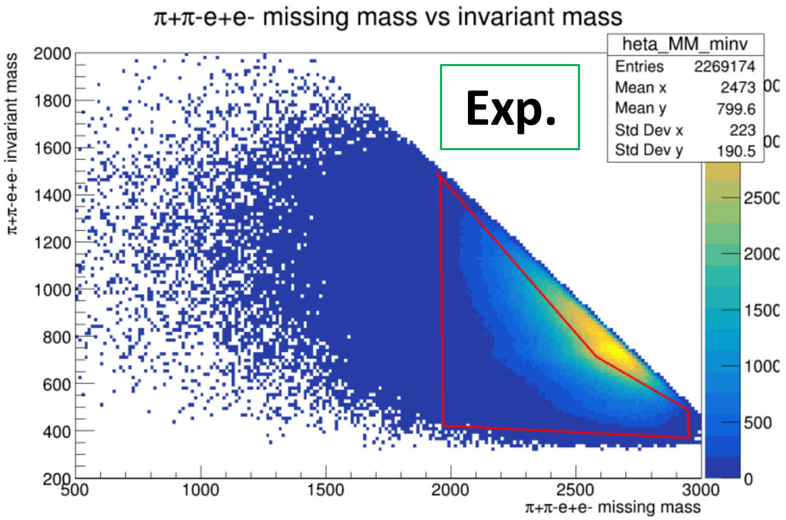
Ref.: M. Becker et al. Nucl. Inst. and Meth. A 1056:168697 (2023)

Ref.: G. Agakishiev et al. Eur. Phys. J. A (2009) 41:243-277

Event selection for the $\eta \to \pi^+ \pi^- e^+ e^-$ decay

- vertexReco z ∈ (-200 mm, 0)
- **$\pi^+ \pi^- e^+ e^-$ missing mass vs inv. mass (graphical cut)**
- $(e^+e^-)(\pi^+\pi^-)$ opening angle < 50°
- $\pi^+\pi^-$ invariant mass < 480 MeV
- $(e^+e^-)(\pi^+\pi^-)$ opening angle in CM > 140°





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Event selection for the **η → π⁺ π⁻ e⁺ e⁻** decay

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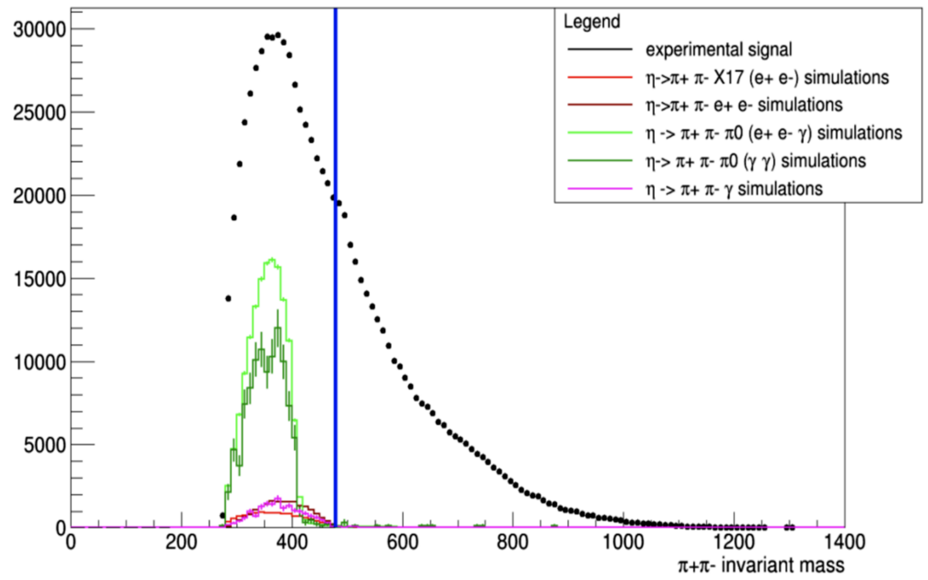

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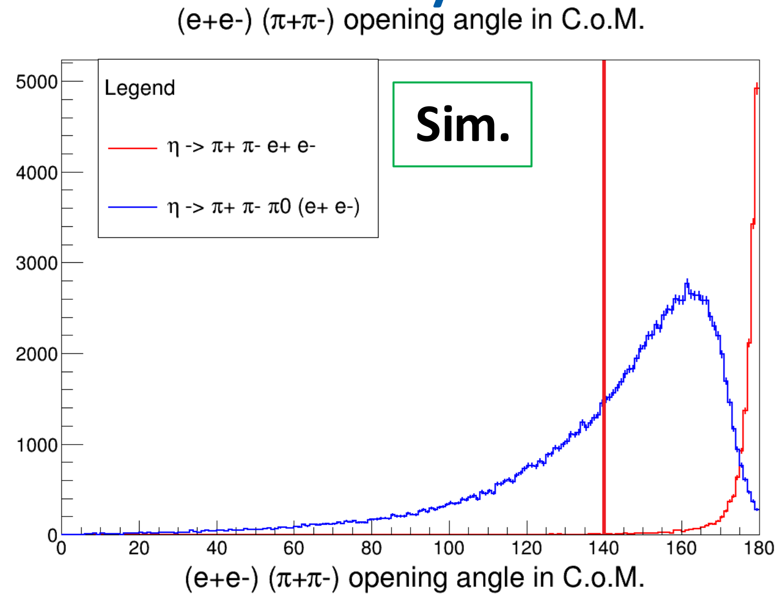
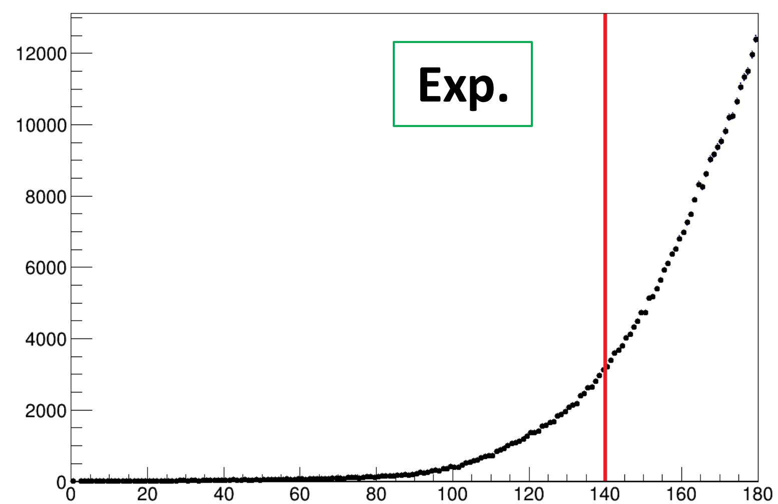
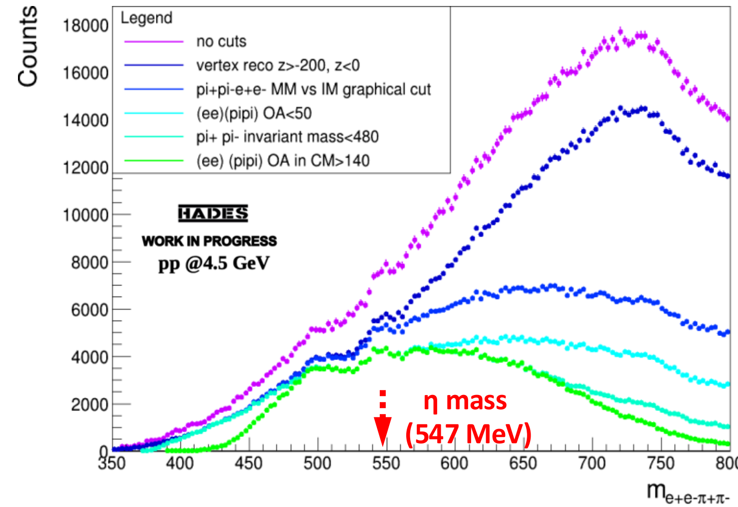
In CM frame OA found assuming $e^+e^-\pi^+\pi^-$ invariant mass is equal η mass





Event selection for the $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ decay

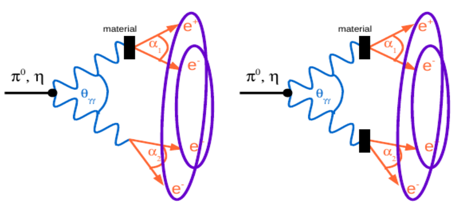
- all cuts were compared using $e^+e^-\pi^+\pi^-$ invariant mass
- most of the hadronic background was substracted
- reduction of 86.78% events in total range of $e^+e^-\pi^+\pi^-$ invariant mass distribution (data)
- reduction of 10.16% events in η signal range (simulations)

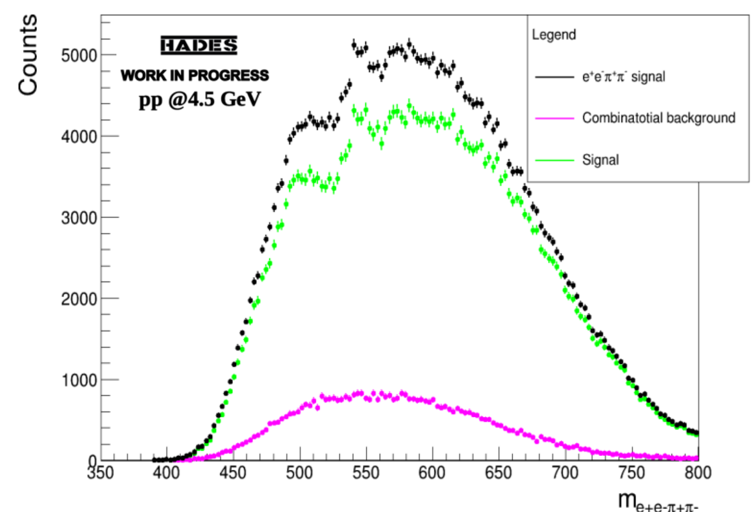


- Combinatorial background substraction:

$$\langle N_{CB}\rangle = 2\sqrt{\langle N_{\pi^+\pi^-e^+e^+}\rangle\langle N_{\pi^+\pi^-e^-e^-}\rangle}$$

$$\langle N_{signal}\rangle = \langle N_{\pi^+\pi^-e^+e^-}\rangle - \langle N_{CB}\rangle$$



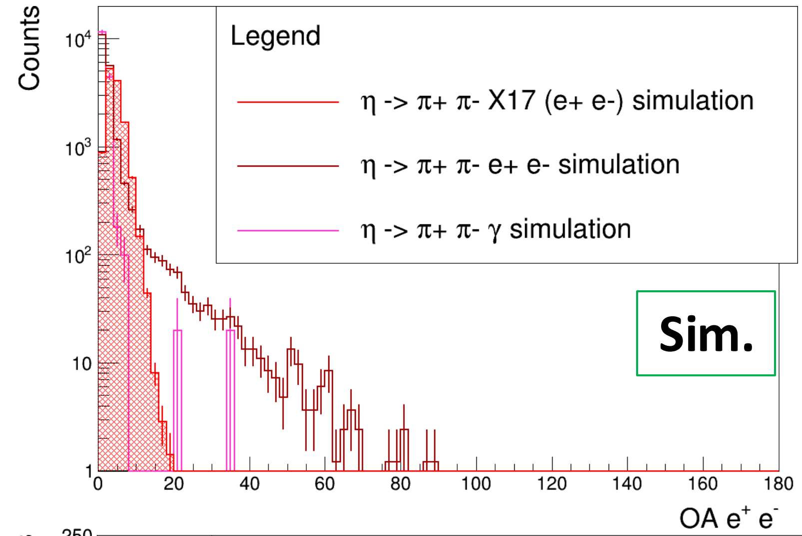


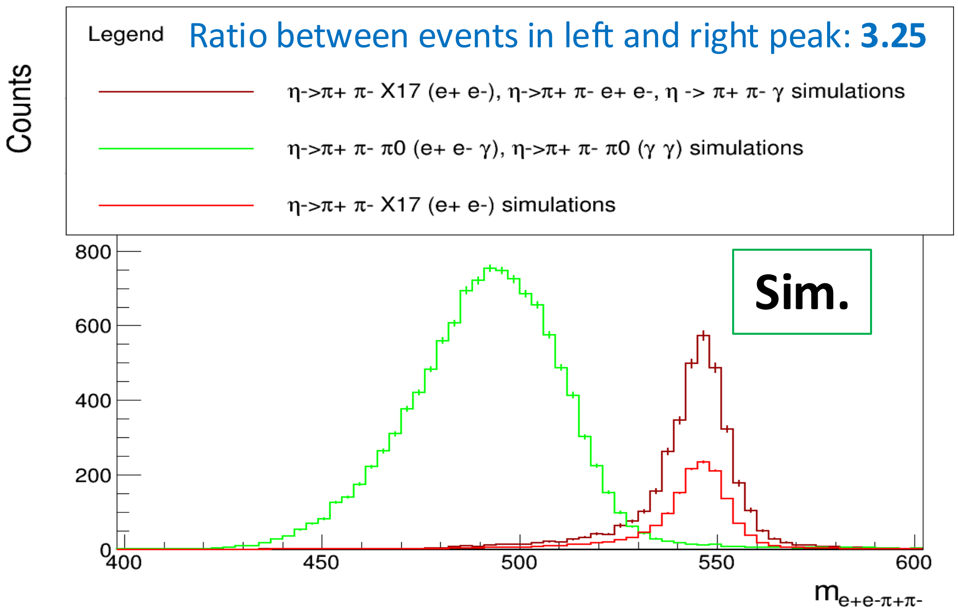
Ref.: Szymon Harabasz, HADES PhD Thesis (2018)

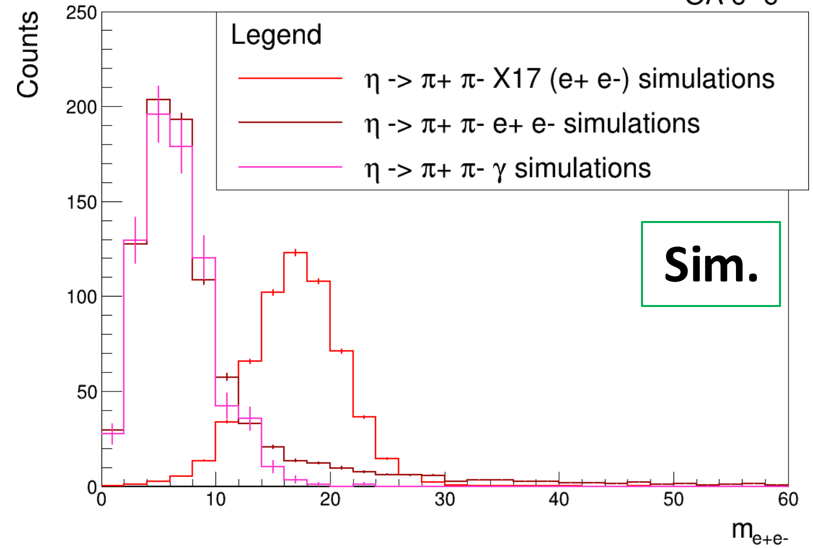
Simulations of signal and background

Signal and main background reactions:

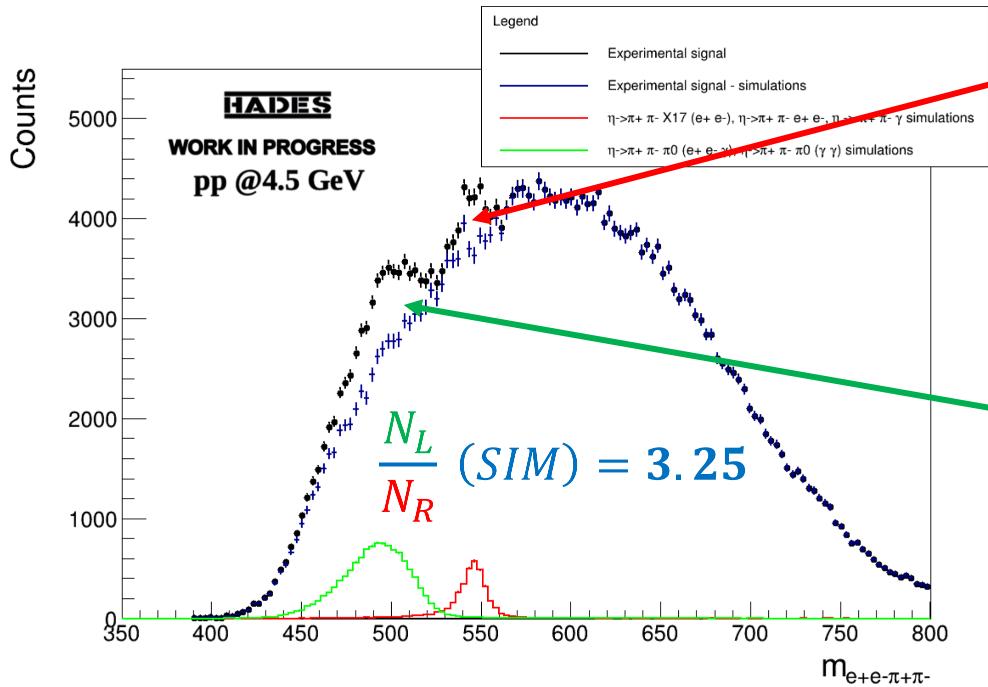
- $pp\,\eta \rightarrow pp\,\pi^+\,\pi^-\,e^+\,e^-$
- $pp\,\eta \rightarrow pp\,\pi^+\,\pi^-\,X17\,(e^+\,e^-)$
- $pp\,\eta \rightarrow pp\,\pi^+\,\pi^-\,\pi^0\,(e^+\,e^-\,\gamma)$
- $pp\,\eta \rightarrow pp\,\pi^+\,\pi^-\,\pi^0\,(\gamma\,\gamma)$
- $pp\,\eta \rightarrow pp\,\pi^+\,\pi^-\,\gamma$







Estimation of X17 contribution to signal region



Right peak (R)

$\eta \rightarrow \pi^+ \pi^- e^+ e^-$

$\eta \rightarrow \pi^+ \pi^- \gamma$

$\eta \rightarrow \pi^+ \pi^- X17\,(e^+ e^-)$

Left peak (L)

$\eta \rightarrow \pi^+ \pi^- \pi^0\,(e^+ e^- \gamma)$

$\eta \rightarrow \pi^+ \pi^- \pi^0\,(\gamma\gamma)$

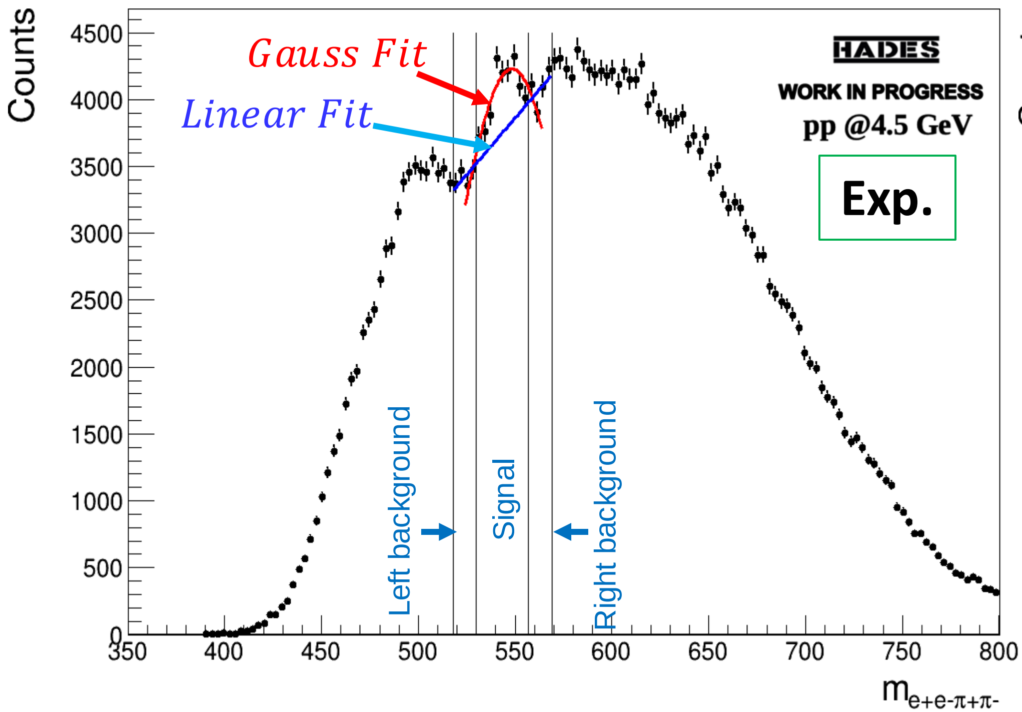
Reaction	Contribution	Branching ratio (BR)
$\eta \rightarrow \pi^+ \pi^- e^+ e^-$	39.95%	$2.68 \cdot 10^{-4}$
$\eta \rightarrow \pi^+ \pi^- X17\,(e^+ e^-)$	26.28%	$1 \cdot 10^{-4}$
$\eta \rightarrow \pi^+ \pi^- \gamma$	33.77%	$4.28 \cdot 10^{-2}$

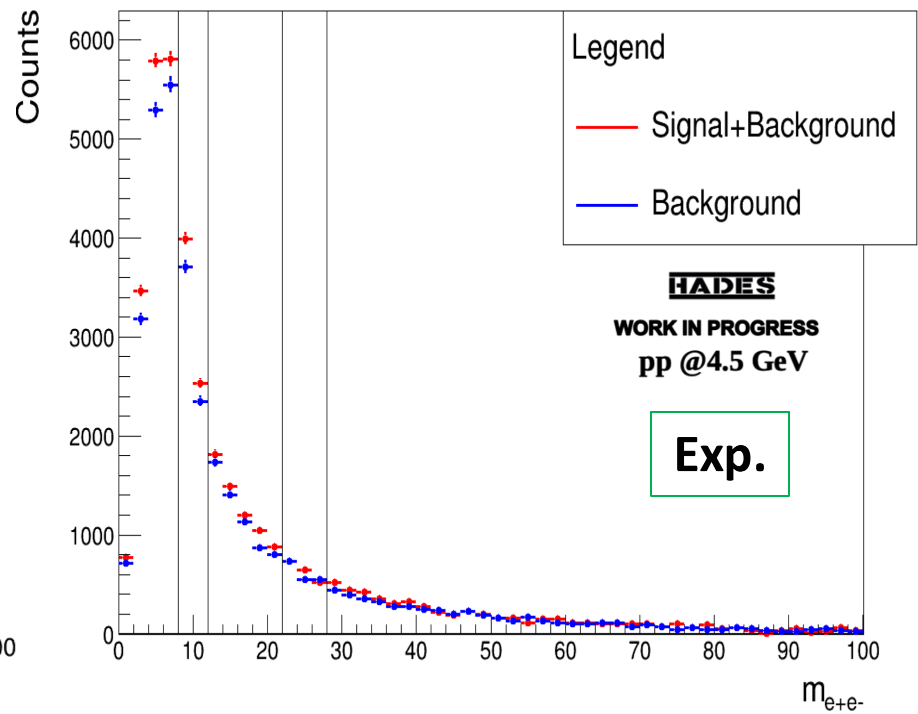
Expected numer of X_{17} in signal peak

$$N_{X17} = N_{ALL} \cdot f_{X17}$$

$$N_{X17} = 2758 \cdot 26.28\% = 725$$

Extraction of η → π⁺ π⁻ e⁺ e⁻ signal





Estimated numer of signal events	2758
η peak mean (MeV)	548.40
η peak sigma (MeV)	32.59

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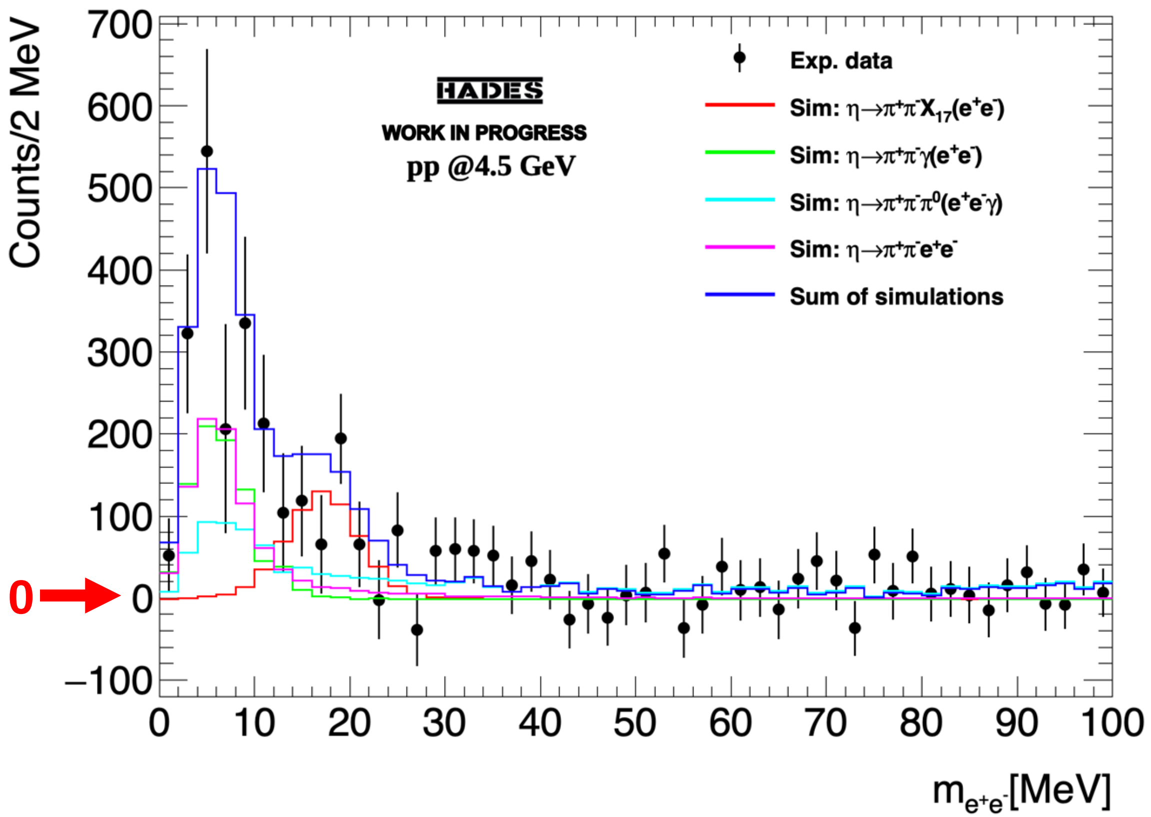
Preliminary results

- Final distribution of e^+e^- invariant mass after background subtraction
- Estimated total efficiency and acceptance factor: **$1.1 \cdot 10^{-3}$**



Upper limit for the number of event estimated based on W. A. Rolke method:

Ref. *Nuc. Instr. and Met. in Phys. A, 551, 2-3 (2012)*

$N^{UL}_{X17} = 255$ (CL=90%)

$BR_{\eta \to \pi+\pi-X17} < 2.58 \cdot 10^{-5}$

$BR^{theory}_{\eta \to \pi+\pi-a} < 1 \cdot 10^{-4}$

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Conclusions

- *η/η′ mesons are an interesting place to look for dark particles because probe coupling to light quarks and gluons.*
- *First estimation of upper limit for the QCD Axion* **$BR_{\eta\to\pi+\pi-X17} < 2.58 \cdot 10^{-5}$**
- *Also it is possible with 2758 η to extract the asymmetry parameter for CP invariance studies.*

Further steps:

- Studies of systematical effects
- More detailed simulations of η decays and background using transport models SMASH/GiBUU
- Application of Machine Learning techniques (MVA, BDT) to reduce background

Thank you for your attention!