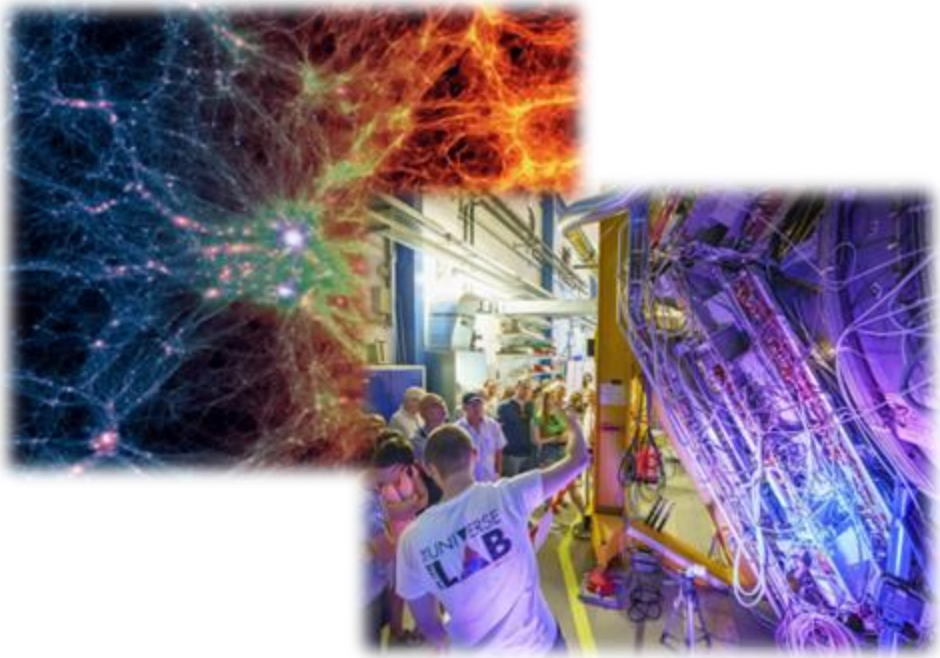
JAGIELLONIAN UNIVERSITY IN KRAKOW

HADES



Search for the Axion-Like-Particles in the η meson decay with the HADES Detector

APS Topical Group on Hadronic Physics GHP

APS Topical Group on Hadronic Physics (GHP2025)

Anaheim, March 15th, 2025

Marcin Zieliński

M. Smoluchowski Institute of Physics

Jagiellonian University, Kraków, Poland

NATIONAL SCIENCE CENTRE POLAND

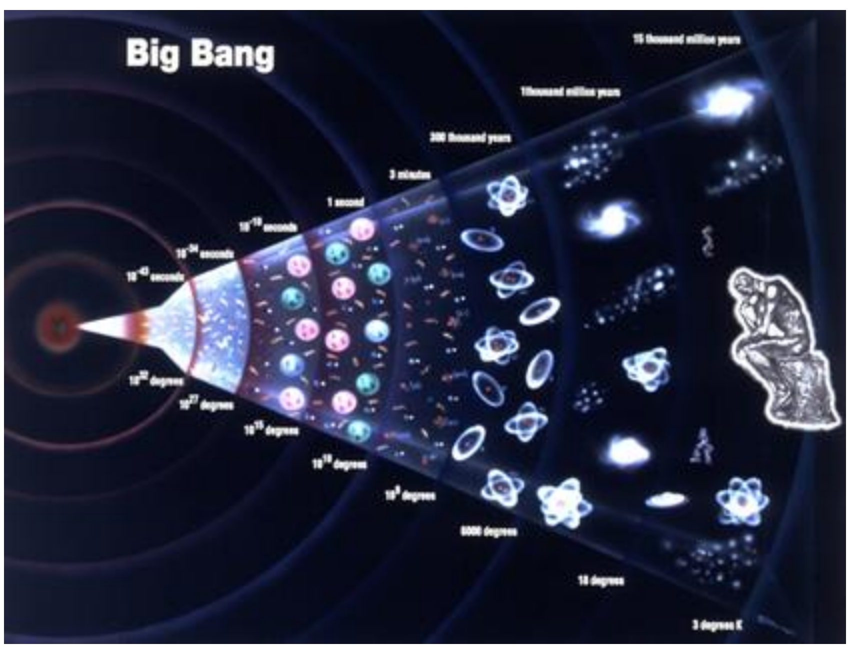
General motivation

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

Why does the Universe exist?

More specific question for physicists:

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

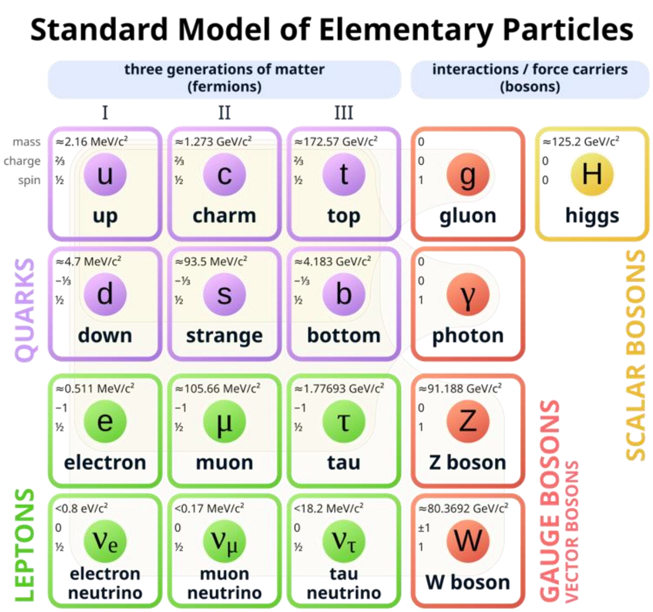
During cooling and expansion
matter and antimatter annihilated 😐

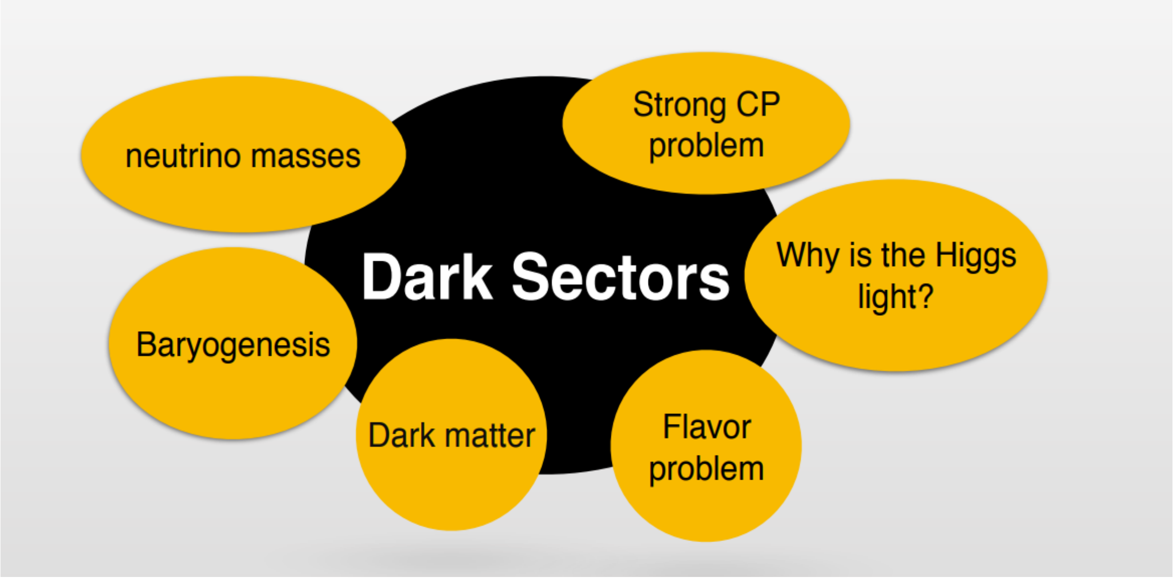
Most of the cosmic energy/matter budget is of an unknown form

General motivation

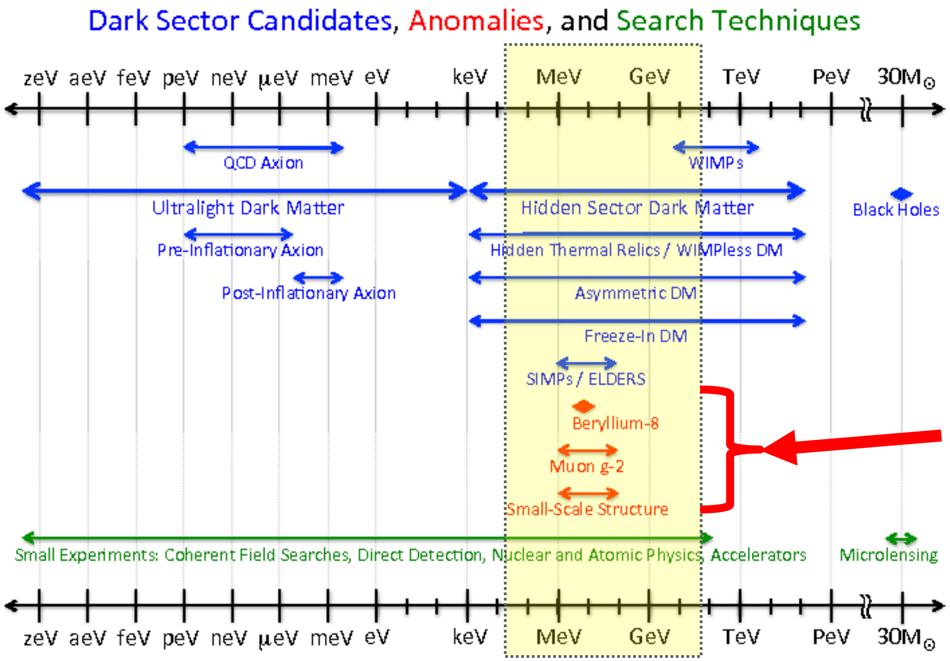
Status of Standard Model in HEP:

- **The Standard Model has served us well for 50 years!**
- **Recent measurements indicates SM can't be the final answer.**
- **Six categories of problems have arisen in SM.**





General motivation



- In SM: violation from weak interaction is not sufficient to create observed asymmetry
- Parameter space for BSM is running out at HEP
- several anomalies in experiments point to possible new physics, weakly coupled to familiar matter in the 1MeV - 1 GeV scale

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

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)*

How we can try to address SM problems experimentally?
- Searching for new particles
- Studying violation of discrete symmetries

Axions and Axion-Like-Particles

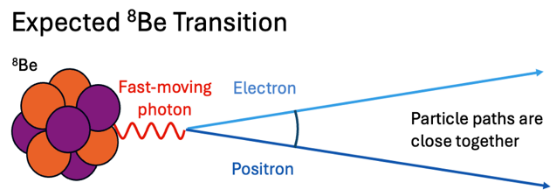
General motivation – ATOMKI results (X_{17} boson)

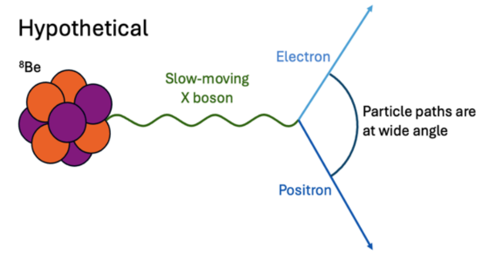
The ATOMKI group observed an excess of e^+e^- pairs emitted at large relative angle in the nuclear reactions:

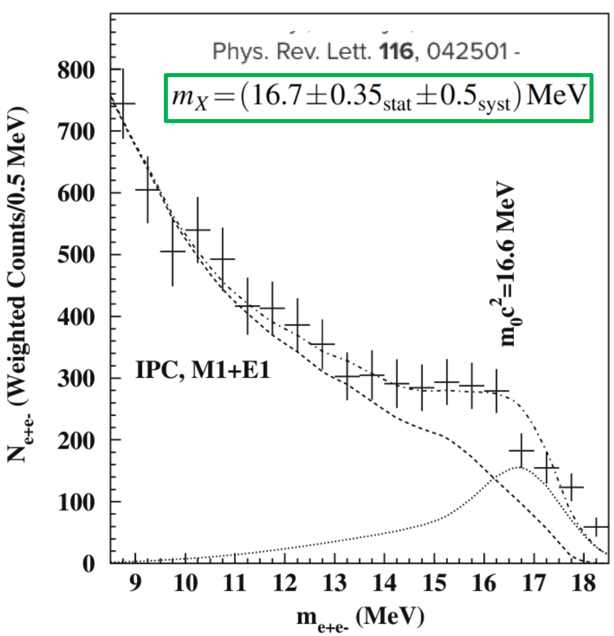
$^3H(p, e^+e^-)^4He$,

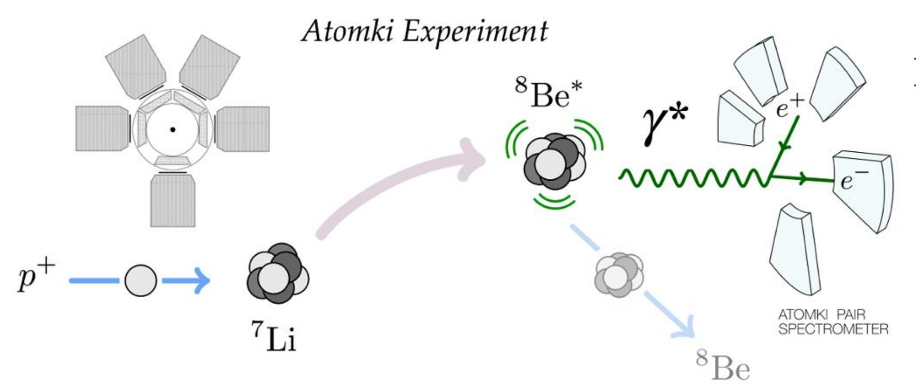
$^{11}B(p, e^+e^-)^{12}C$.

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





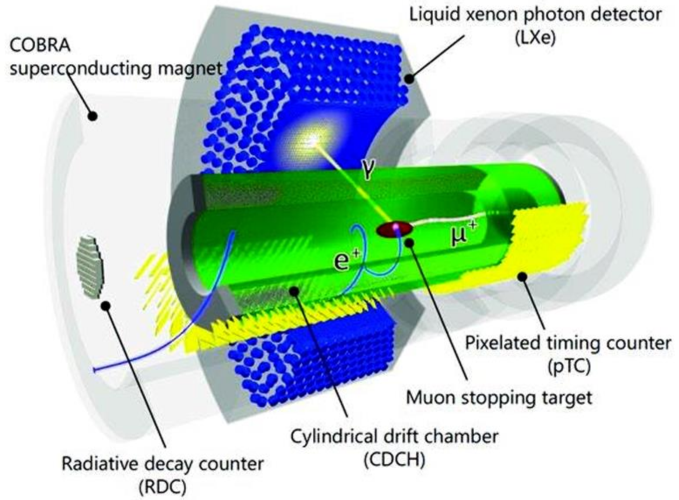


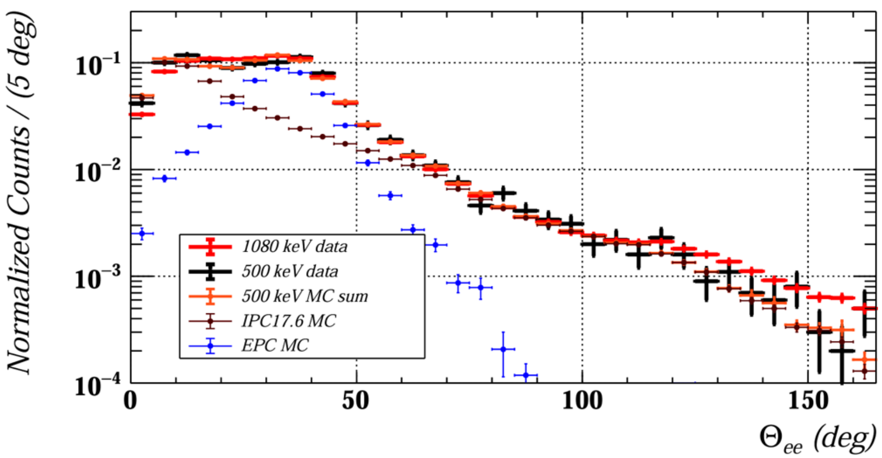


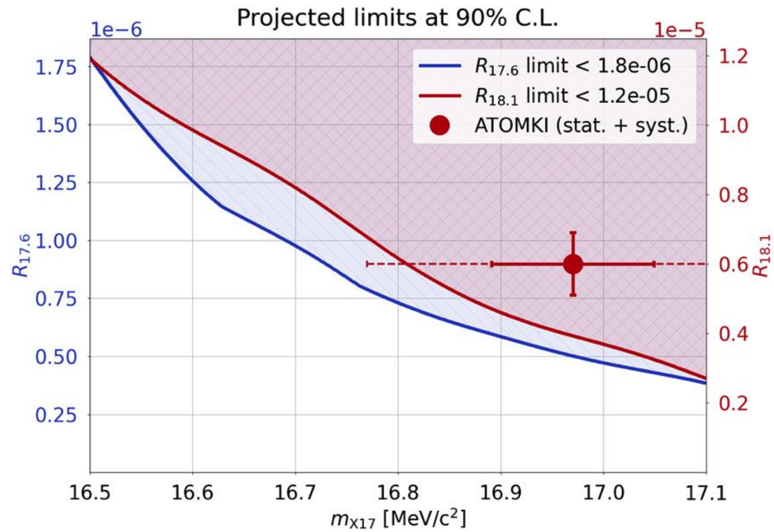
ATOMKI Exp. ^{8}Be : anomalies in the internal pair creation of isovector (17.64 MeV, I=1) and isoscalar (18.15 MeV, I=0) magnetic dipole M1 transitions in ^{8}Be

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 were set 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)

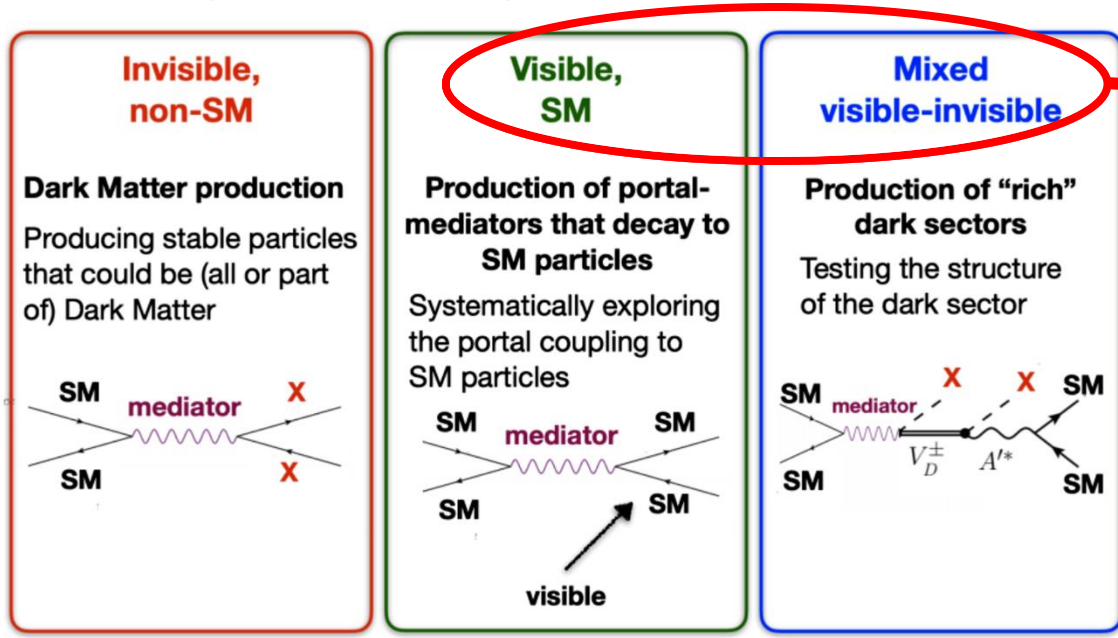
JAGIELLONIAN UNIVERSITY IN KRAKOW

HADES

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	$y_N L H N$



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

Experimental advantages:

- Hadronic production cross section is quite large (~ 0.1 barn) → much easier to produce than heavier mesons
- All its possible strong decays are forbidden in lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance.
- EM decays are forbidden in lowest order by C invariance and angular momentum conservation Branching Ratio of processes from New Physics are enhanced compared to SM.

Axion-Like-Particles

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

***Piophobic* 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})

Then in SM Lagrangian axionic phases are directly ascribed to quark masses

$$m_u \to m_u e^{i\gamma^5 q^u_{\mathrm{PQ}} a/f_a},$$
$$m_d \to m_d e^{i\gamma^5 q^d_{\mathrm{PQ}} a/f_a},$$
$$m_e \to m_e e^{i\gamma^5 q^e_{\mathrm{PQ}} a/f_a},$$

$$\frac{m_u}{m_d} \simeq \frac{Q_d^{\mathrm{PQ}}}{Q_u^{\mathrm{PQ}}} = \frac{1}{2}$$

$$m_{u,d} \ll m_s$$

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

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

Axion-Like-Particles

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

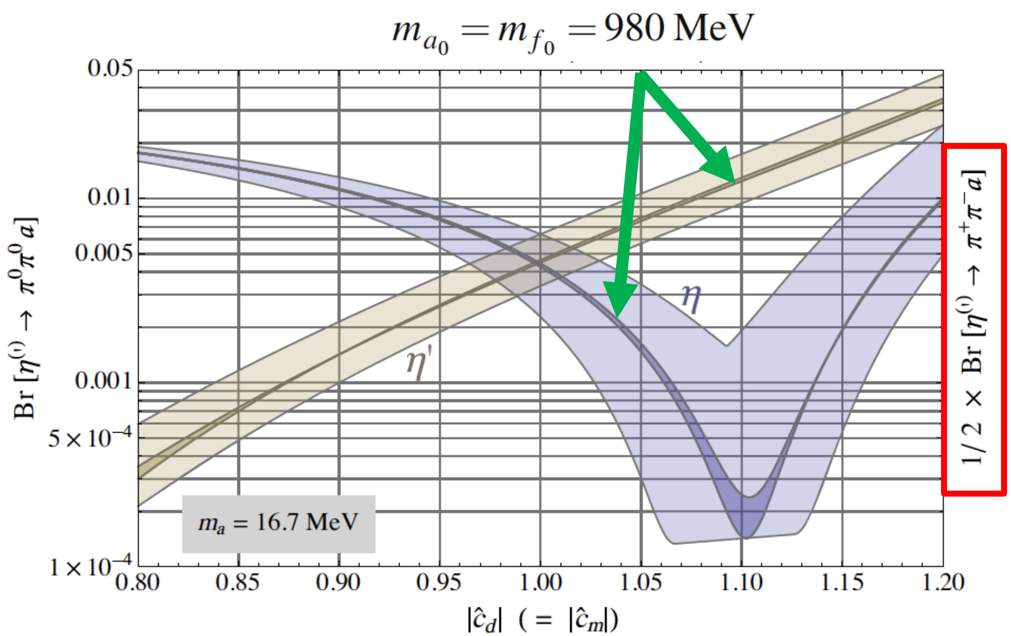
$$\eta \rightarrow \pi^{+}\pi^{-} a\ (\rightarrow e^{+}e^{-})$$

"axio-hadronic decay"

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

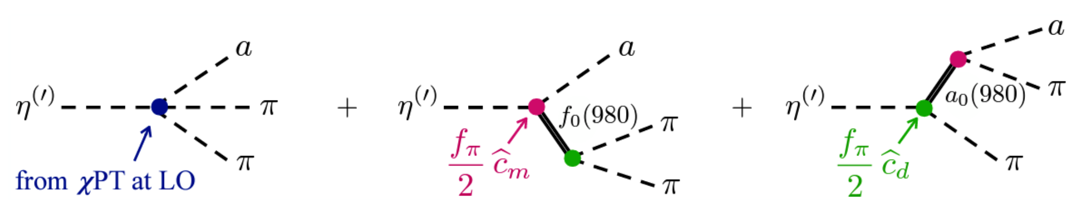
χPT predictions for decay rates significantly modified by inclusion of resonance exchange.

„.... $O(10^{-2})$, is probably excluded or in tension with observations but $O(10^{-4} - 10^{-3})$ likely remains experimentally allowed, and within the sensitivity."



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

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



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

Axion-Like-Particles

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

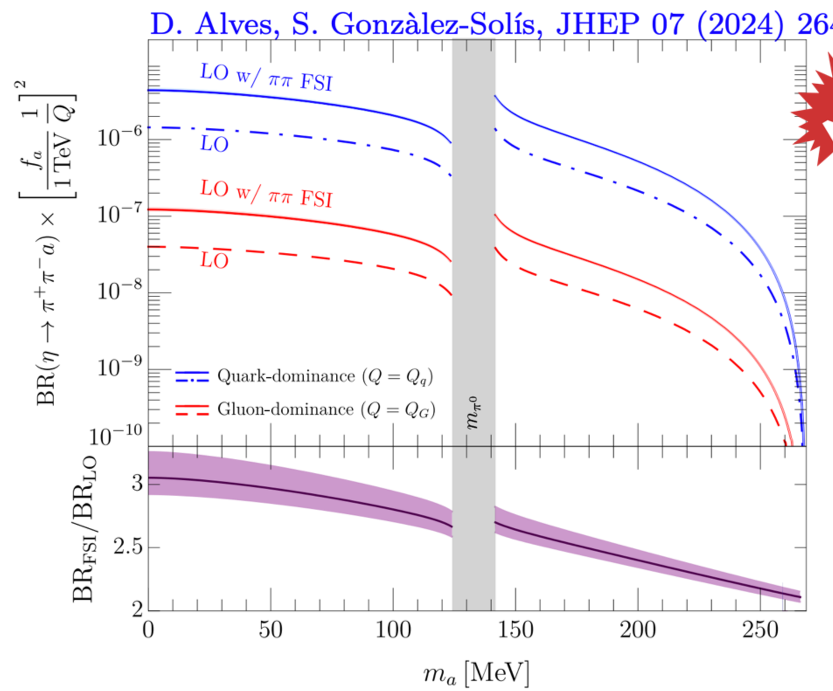
$$\eta \rightarrow \pi^+ \pi^- a\ (\rightarrow e^+ e^-)$$

"axio-hadronic decay"

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

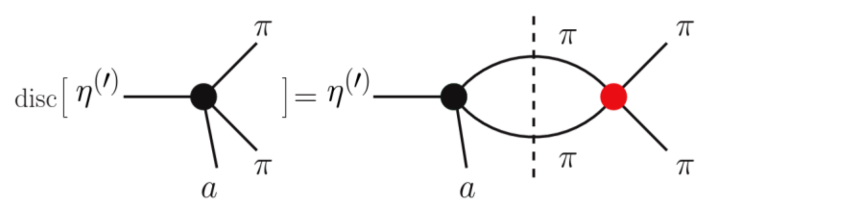
χPT predictions for decay rates significantly modified by inclusion of resonance exchange.

„.... $O(10^{-2})$, is probably excluded or in tension with observations but $O(10^{-4}$ - $10^{-3})$ likely remains experimentally allowed, and within the sensitivity."

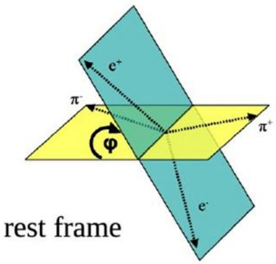


$BR(\eta \rightarrow \pi\pi a) \cdot 3 \cdot 10^{-8} – 4 \cdot 10^{-6}$

Effects of pion-pion final-state interactions (FSI)



Axion-Like-Particles



η rest frame

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

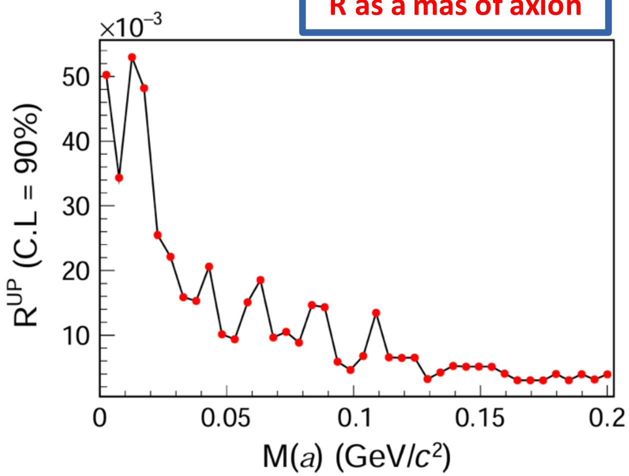
Experiments up to now focused on studies of CP invariance:

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

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

R as a mas of axion



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

↓

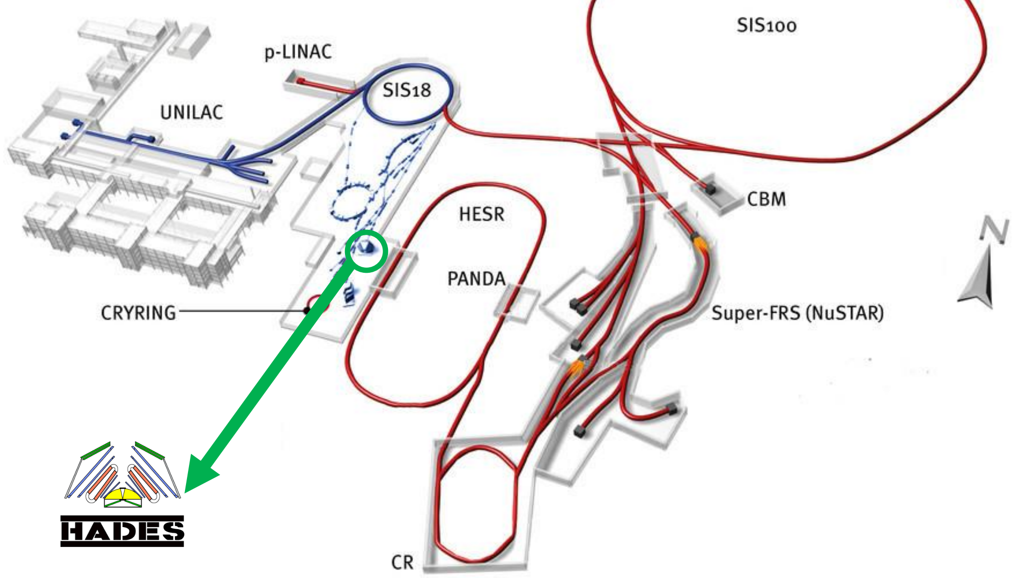
$$(3.0 - 53.0) \times 10^{-3}$$

Ref: BESIII Col. arXiv:2501.10130v1 (2025)

HADES - High Acceptance Di-Electron Spectrometer

GSI Helmholtzzentrum für Schwerionenforschung

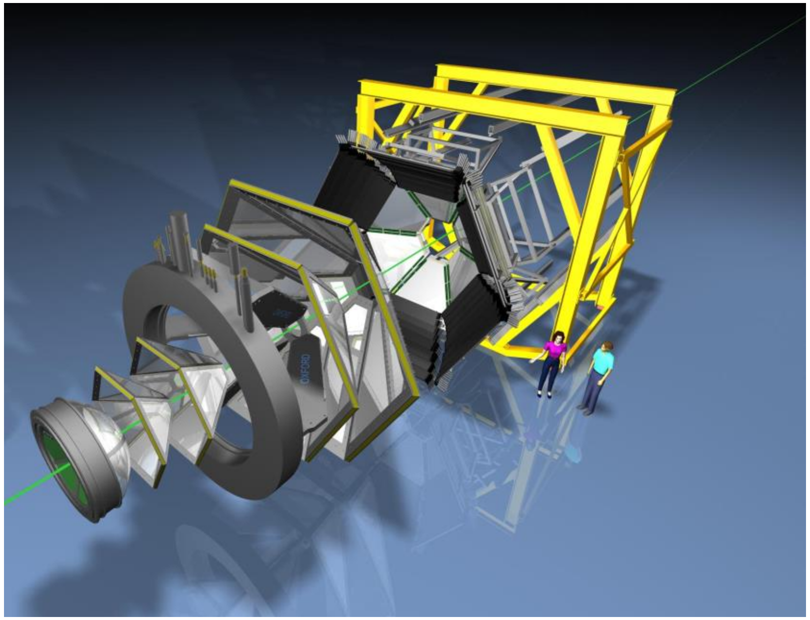
FAIR



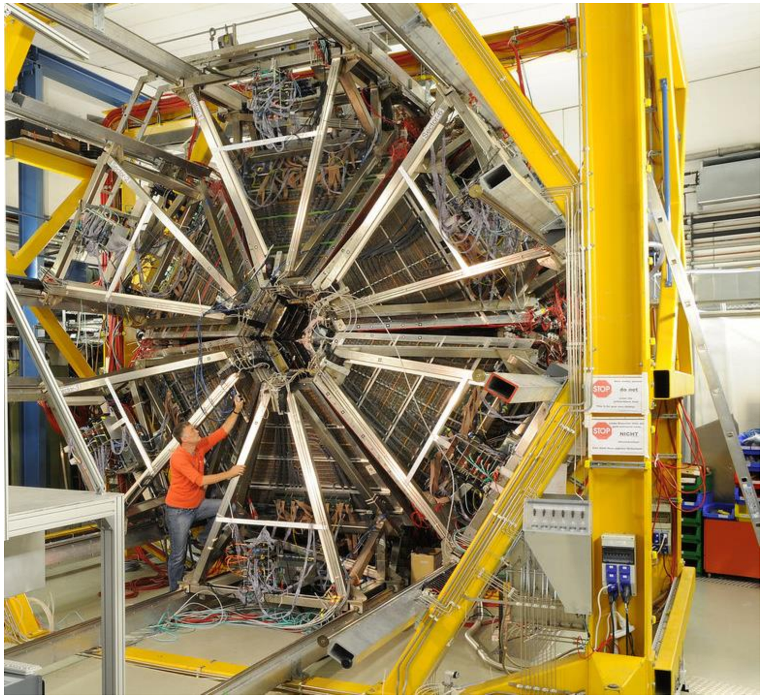
➢ hades.gsi.de

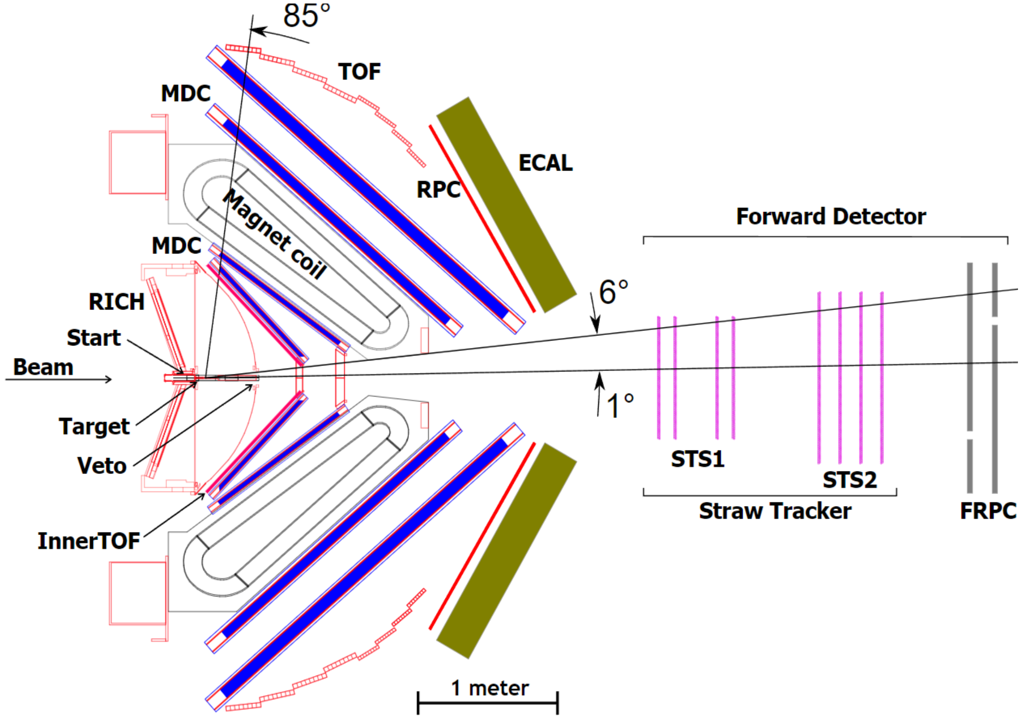
SIS 18

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 - High Acceptance Di-Electron Spectrometer



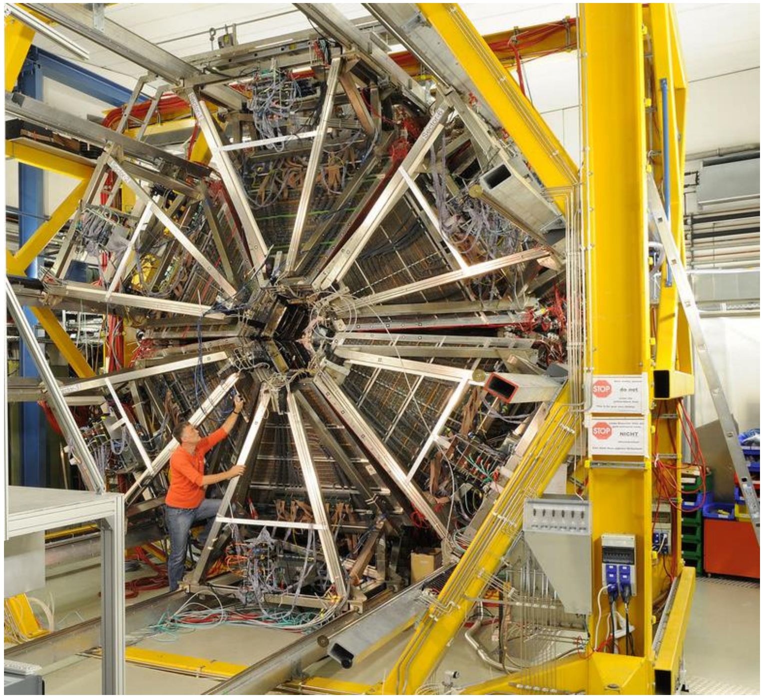


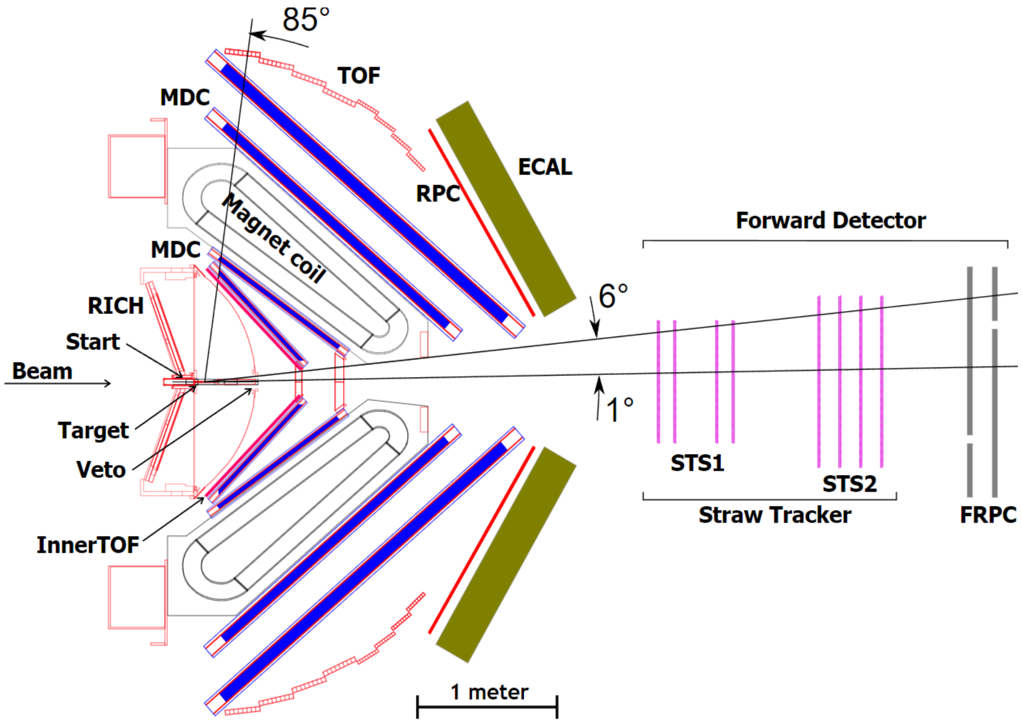
- **START** – T0 reaction for ToF
- **RICH** – Cherenkov detector (di-electron e^+e^-)
- **MDC and STS** – track reconstruction
- **Magnet Coil** – generates magnetic field
- **ToF & RPC** – Time-of-Flight META detectors
- **ECAL** – electromagnetic calorimeter (photons)
- **Trigger logic based on InnerToF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

JAGIELLONIAN UNIVERSITY IN KRAKOW

HADES

HADES - High Acceptance Di-Electron Spectrometer





February 2022 measurement:

- **proton – proton** (pp) collisions at energy of **T = 4.5 GeV** using liquid hydrogen target LH_2
- **28 days** of measurement
- estimated total integrated luminosity **6.1 [pb^{-1}]**

JAGIELLONIAN UNIVERSITY IN KRAKOW

HADES

Light η, ω, f_1 mesons studies using **HADES**

- **Searches for Axion-Like-Particles $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ Decay** ***(this presentation)***

Marcin Zielinski
Krzysztof Prościński
(PhD Student)

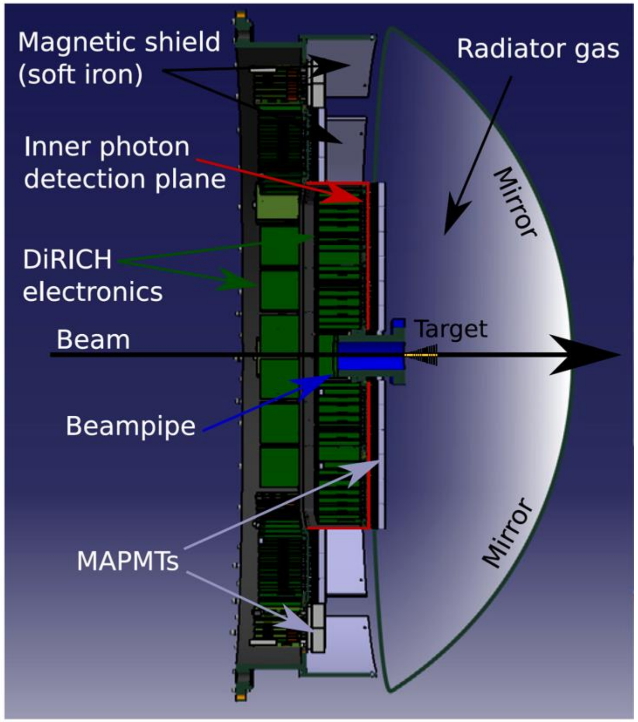
- **Exclusive and inclusive production of η and ω in proton-proton collisions (production mechanism at intermediate energies, cross section extraction, angular distributions).**

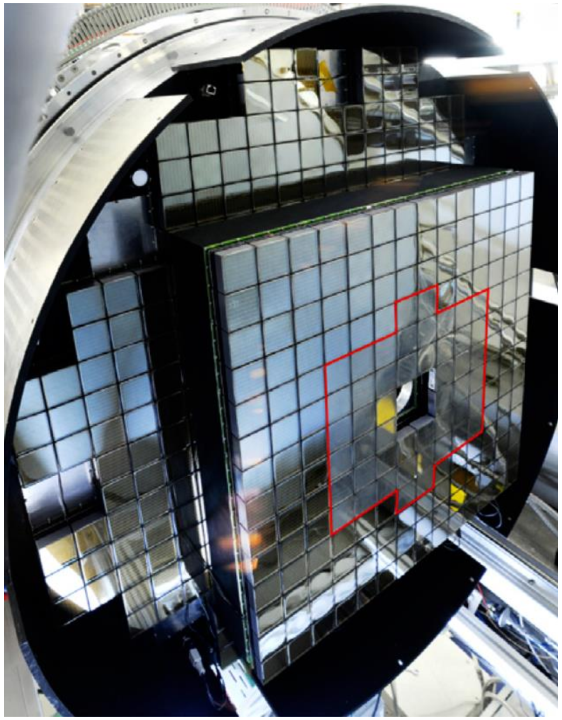
Iza Ciepał
Szymon Treliński
(PhD Student)

- **Form Factor extraction for the $\eta \rightarrow \gamma e^+ e^-$ and $\omega \rightarrow \pi^0 e^+ e^-$.**
- **Studies of the f_1 meson production in proton-proton (exclusive cross section extraction).**
- **Studies of symmetries C and CP using η decays:** **$\eta \rightarrow \pi^+ \pi^- e^+ e^-$, $\eta \rightarrow \pi^0 e^+ e^-$, $\eta \rightarrow \pi^+ \pi^- \pi^0$.**

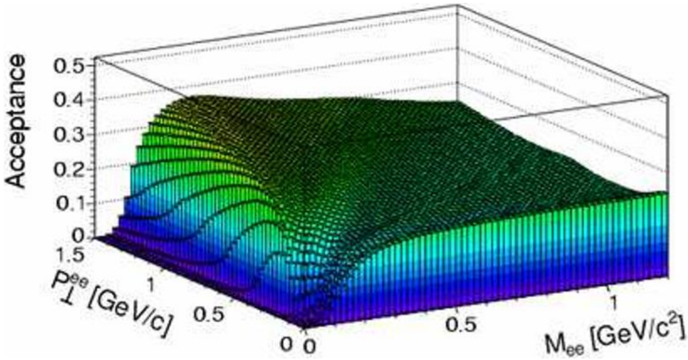
Next analysis

Lepton identification using HADES RICH Detector





- Lepton identification base on signals in RICH.
- Threshold momentum for electrons 9 MeV and for pions 2500 MeV.
- Acceptance as a function of transverse momentum and $e^+ e^-$ invariant mass.



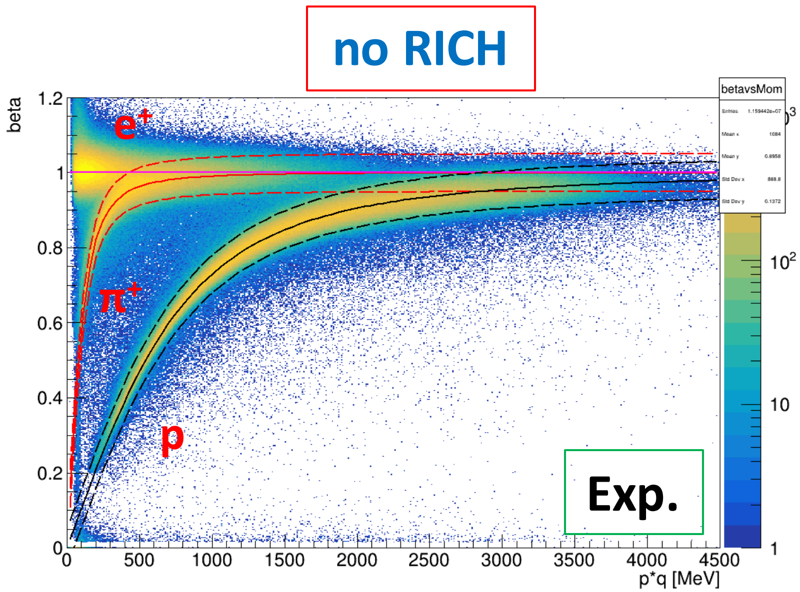
$m_\pi > m_e \quad \beta_\pi < \beta_e$

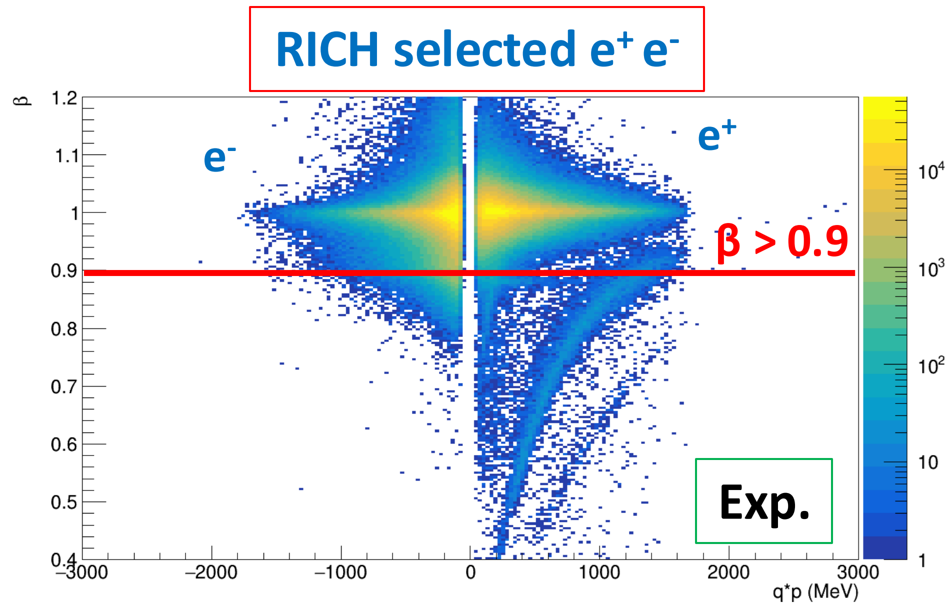
$\beta_\pi < \beta_{Cher} < \beta_e$

$e^+ e^-$ creates Cherenkov radiation

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

Particle selection and identification



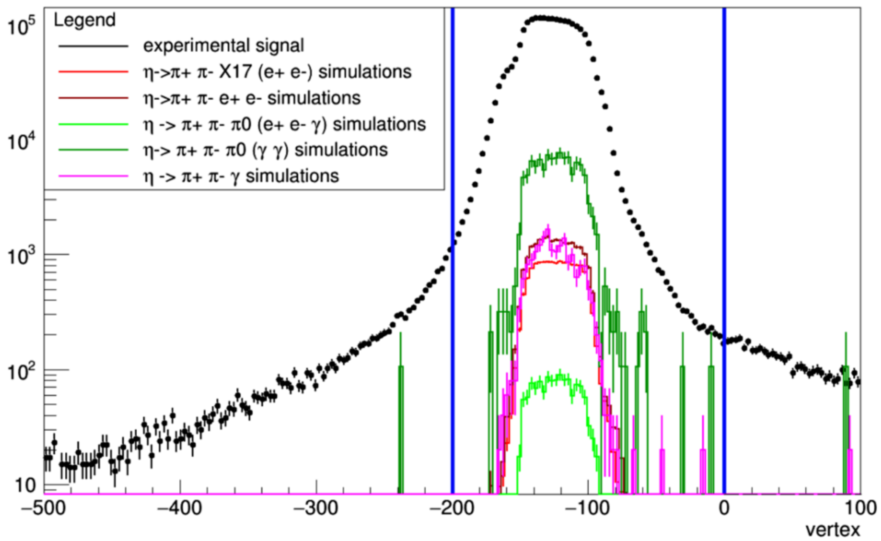


Following particles have to be selected: **π^+ π^- e^+ e^-**

- leptons selected by correlation windows (θ_{RICH} - θ_{MDC}) in RICH and MDC
- pions selected by cuts on beta vs momentum distribution
- additional cuts for leptons: **$\beta > 0.9$**

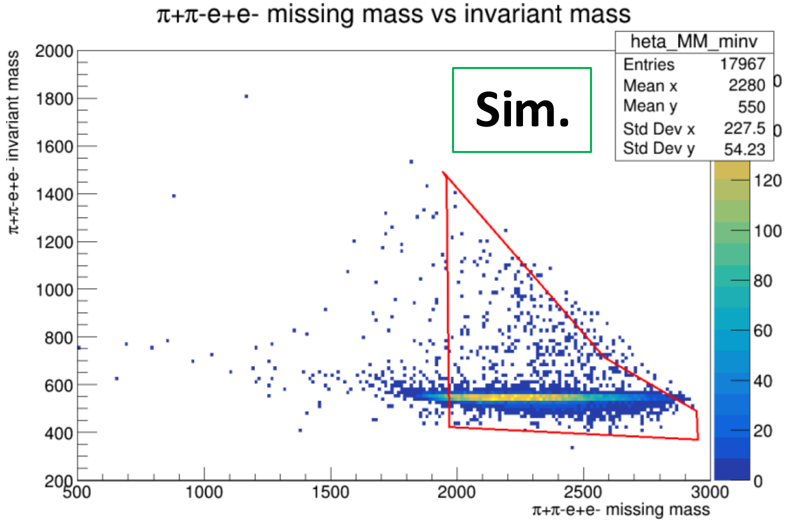
Event selection for the $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ decay

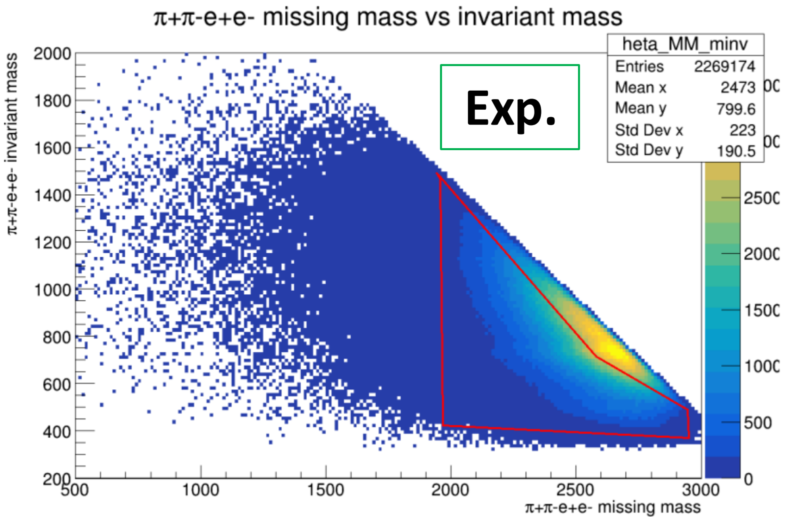
- **vertexReco z ∈ (-200 mm, 0)**
- $\pi^+ \pi^- e^+ e^-$ missing mass vs inv. mass (graphical cut)
- $(e^+e^-)(\pi^+\pi^-)$ opening angle < 50°
- $\pi^+\pi^-$ invariant mass < 480 MeV
- $(e^+e^-)(\pi^+\pi^-)$ opening angle in CM > 140°



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

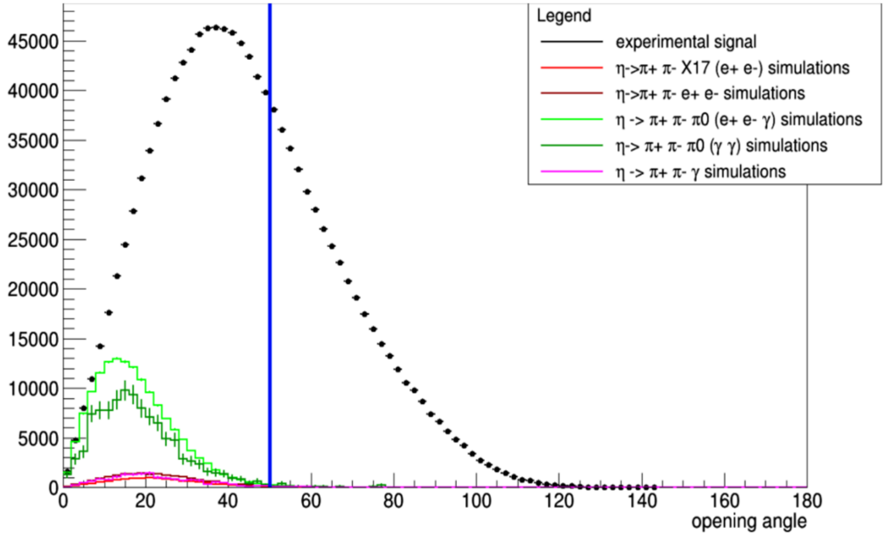
- vertexReco z ∈ (-200 mm, 0)
- **$\pi^+ \pi^- e^+ e^-$ missing mass vs inv. mass (graphical cut)**
- $(e^+e^-)(\pi^+\pi^-)$ opening angle < 50°
- $\pi^+\pi^-$ invariant mass < 480 MeV
- $(e^+e^-)(\pi^+\pi^-)$ opening angle in CM > 140°





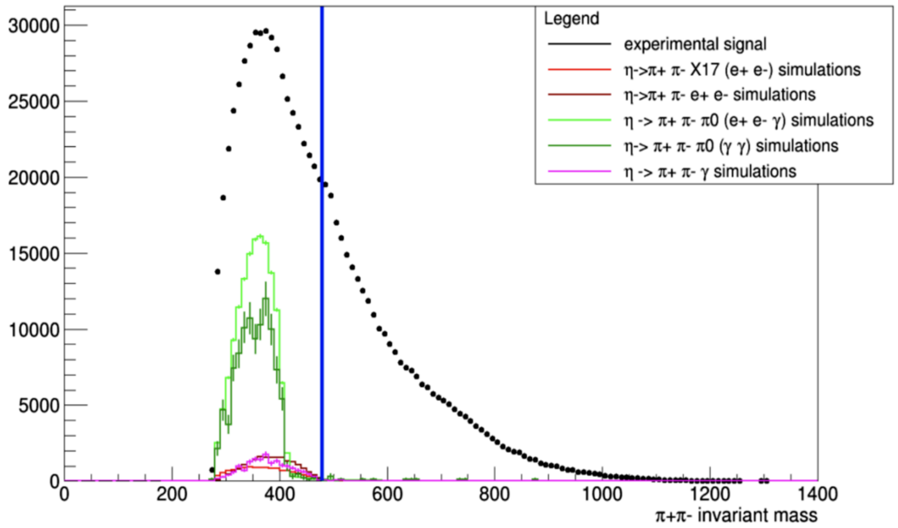
Event selection for the $\eta \to \pi^+ \pi^- e^+ e^-$ decay

- 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°



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

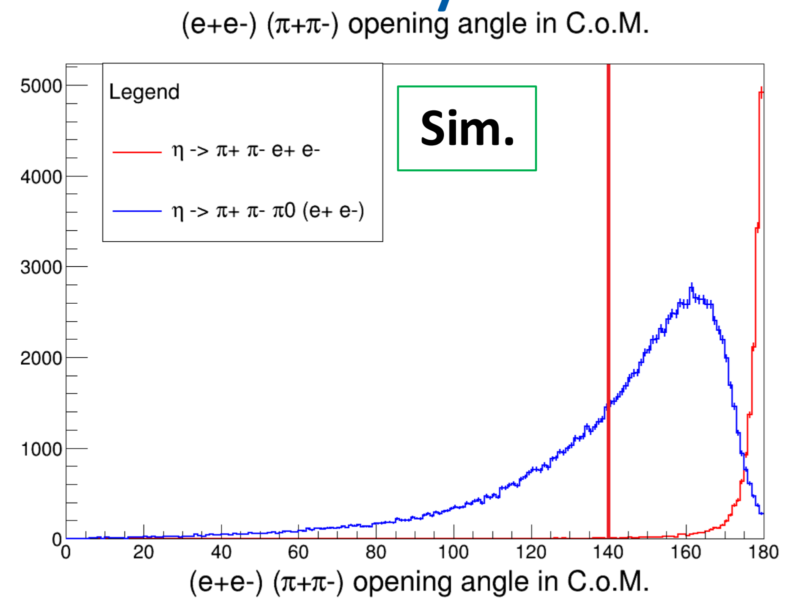


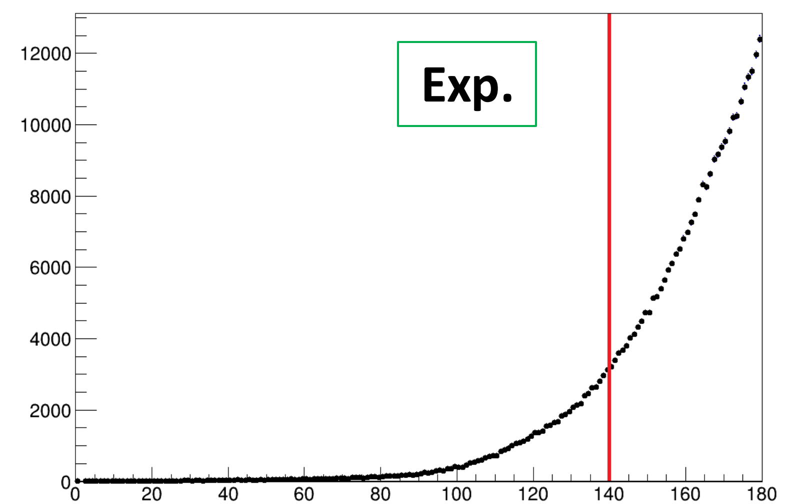
JAGIELLONIAN UNIVERSITY IN KRAKOW

HADES

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

- vertexReco $z \in (-200\ \text{mm}, 0)$
- $\pi^+ \pi^- e^+ e^-$ 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°**



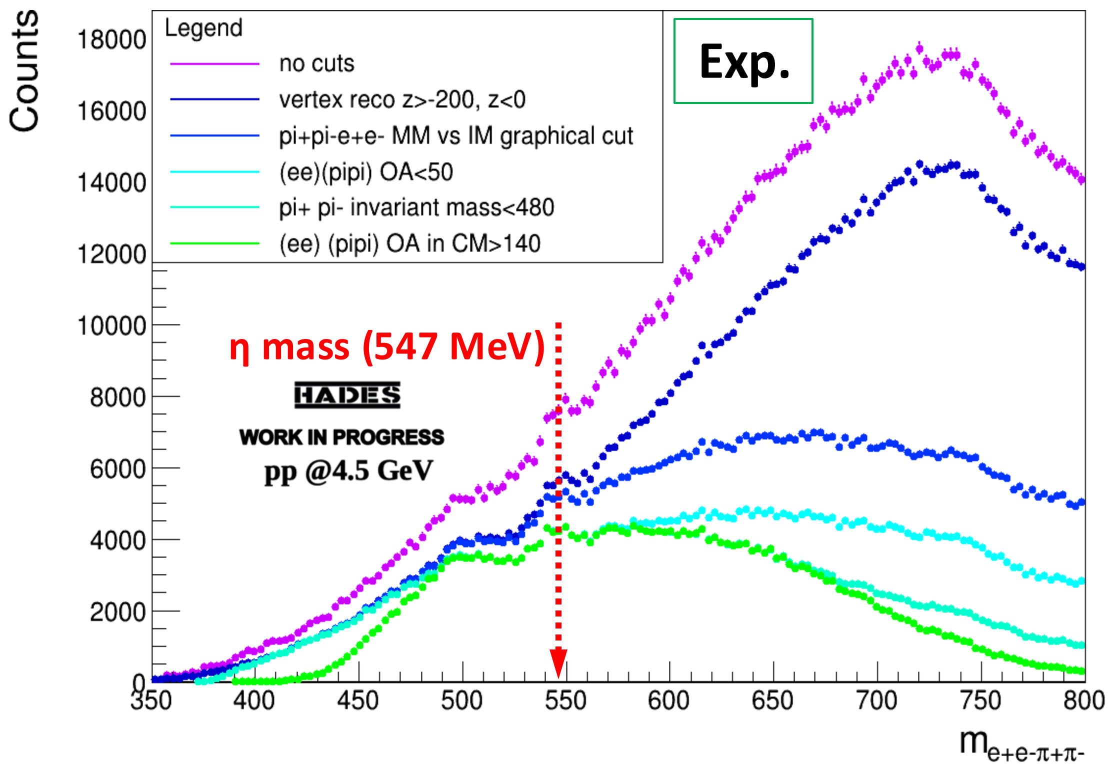


In CM frame OA found assuming $e^+e^-\pi^+\pi^-$ invariant mass is equal η mass

Event selection for the η → $\pi^+ \pi^- e^+ e^-$ decay

- all cuts were compared using $e^+e^-\pi^+\pi^-$ invariant mass
- Most of the multipion 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)

The experimental invariant mass after the application of consecutive cuts.

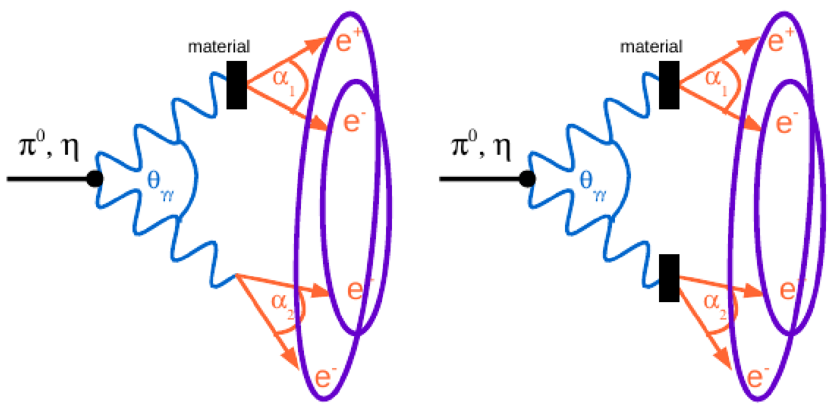


Event selection for the η → π⁺ π⁻ e⁺ e⁻ decay

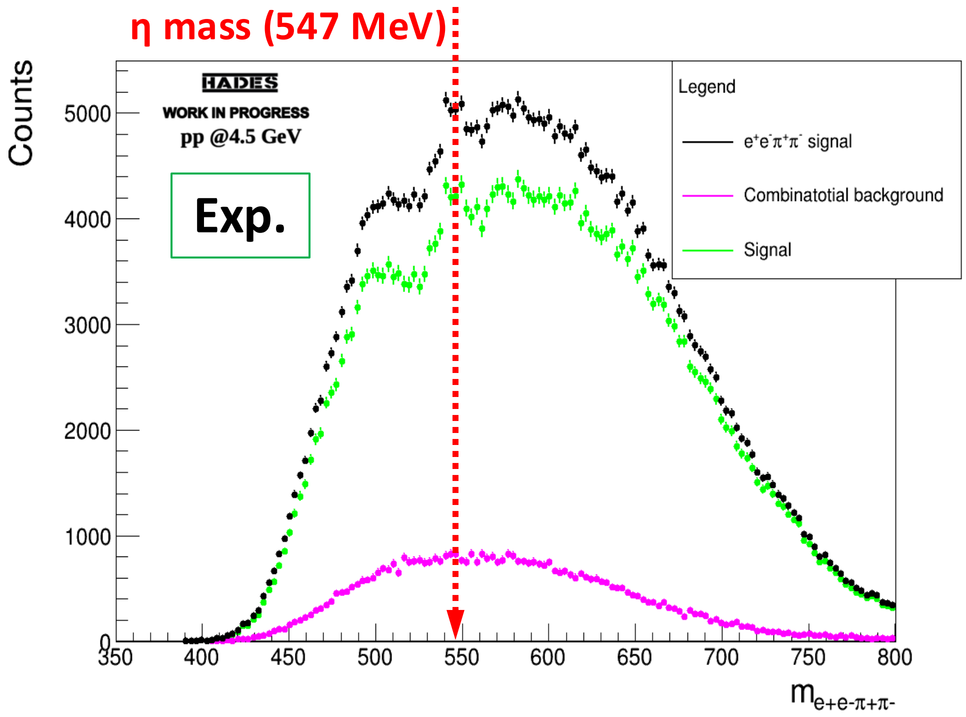
- Combinatorial background substraction:

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

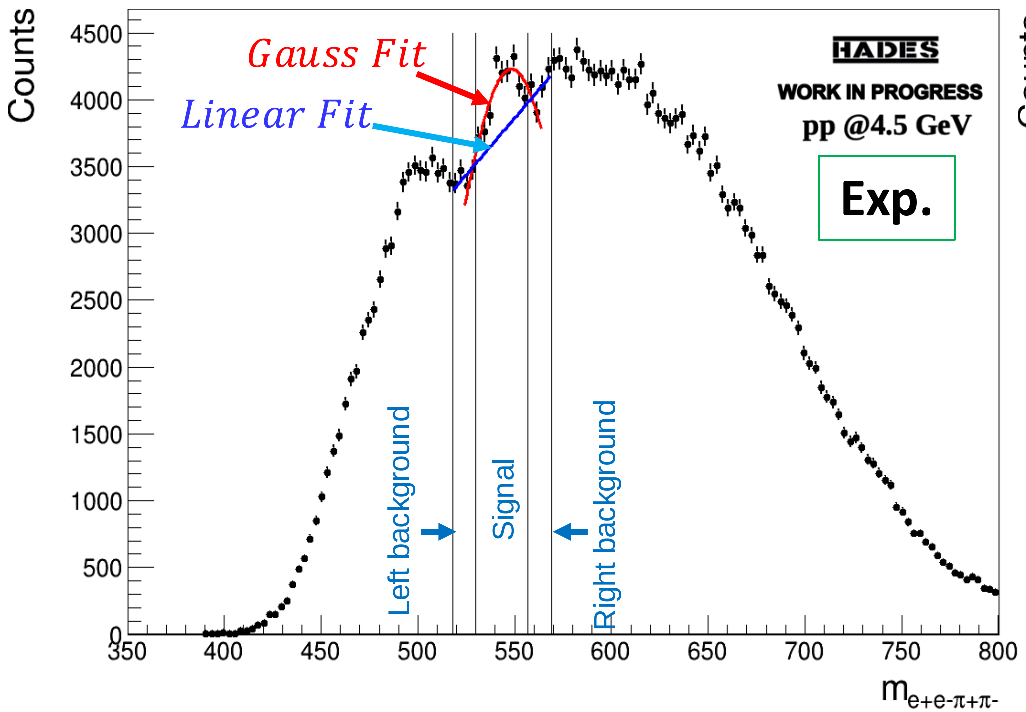
$$\langle N_{signal}\rangle = \langle N_{\pi^+\pi^-e^+e^-}\rangle - \langle N_{CB}\rangle$$

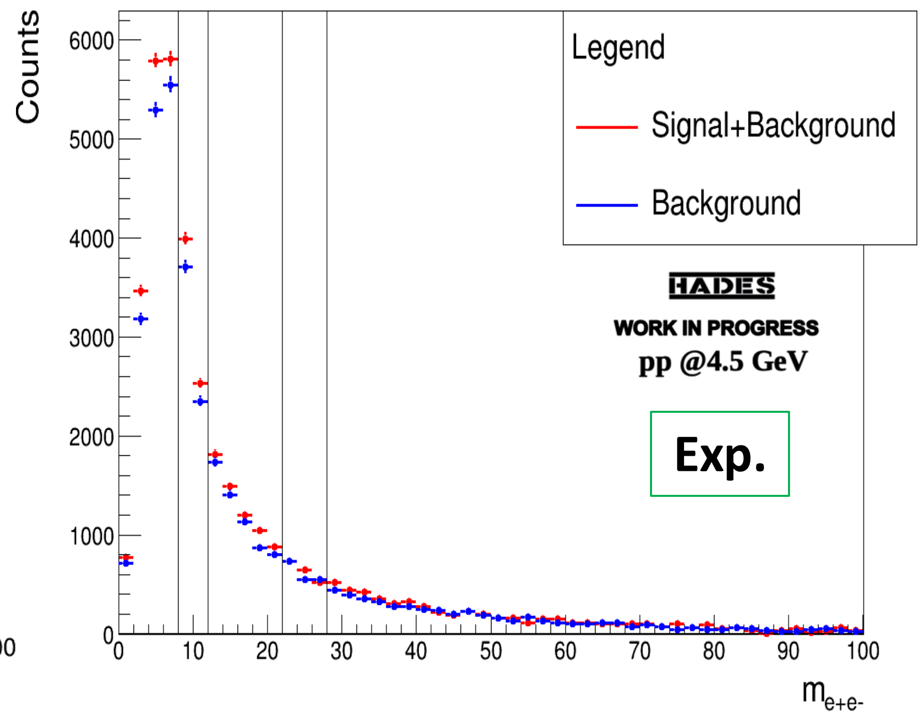


Ref.: *Szymon Harabasz, HADES PhD Thesis (2018)*



Extraction of η → $\pi^+ \pi^- e^+ e^-$ signal





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

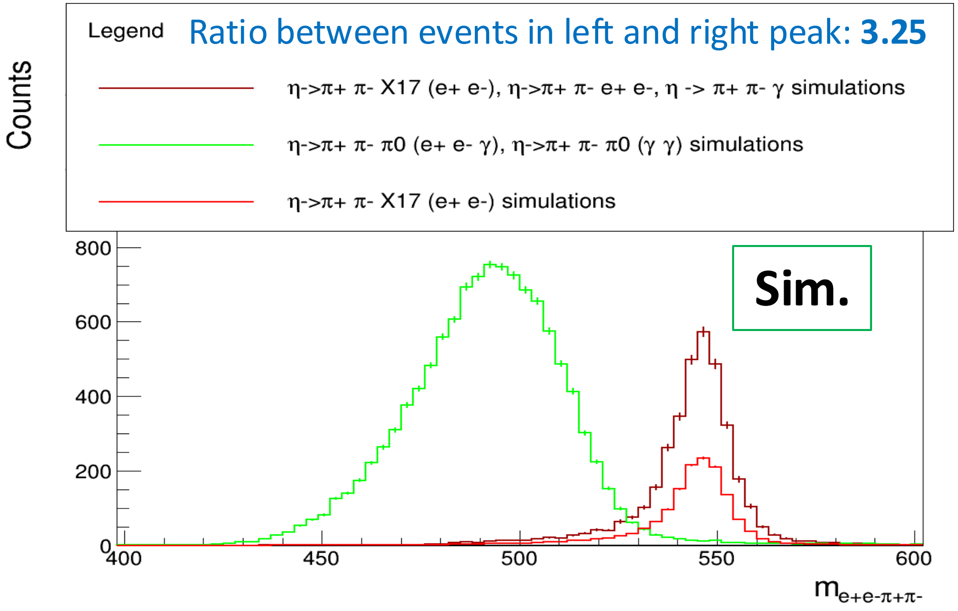
JAGIELLONIAN UNIVERSITY IN KRAKOW

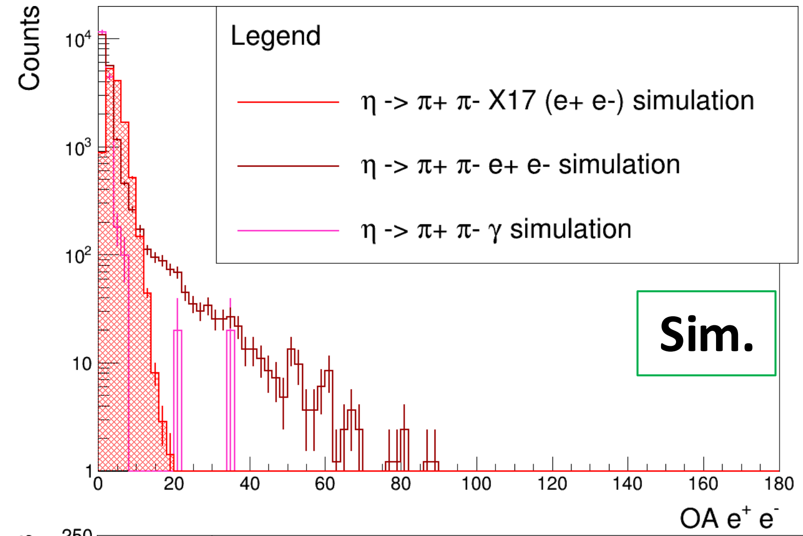
HADES

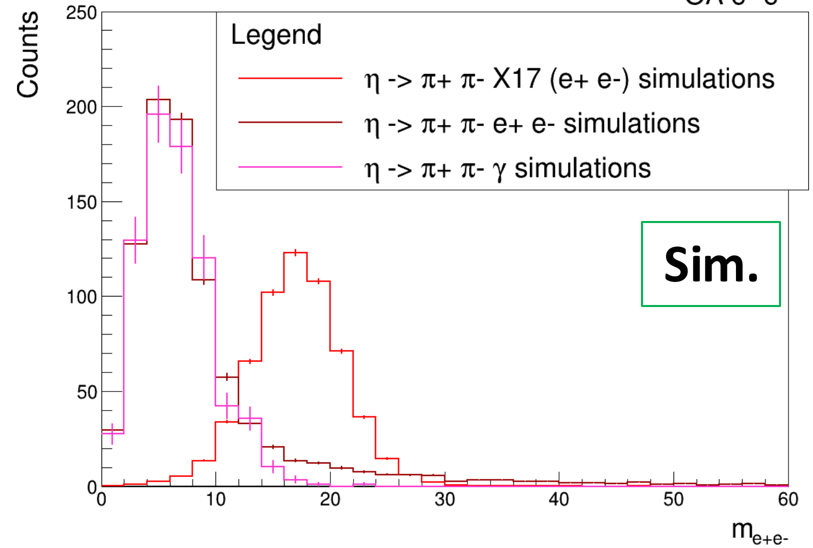
Simulations of signal and background

Signal and main background reactions:

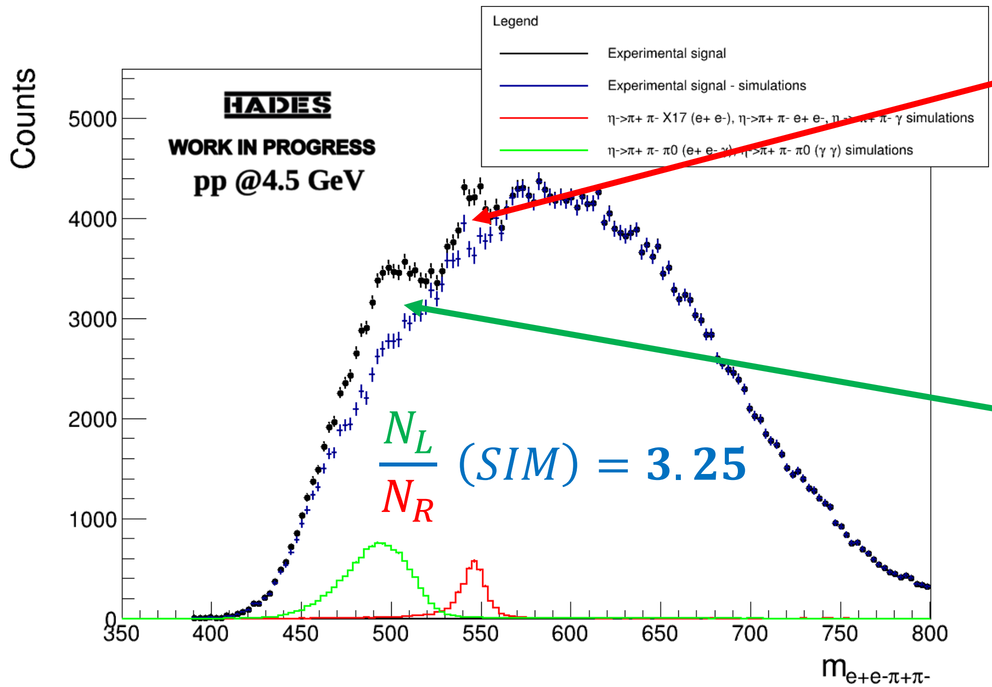
- **pp η → pp $\pi^+ \pi^- e^+ e^-$**
- **pp η → pp $\pi^+ \pi^-$ X17 ($e^+ e^-$)**
- **pp η → pp $\pi^+ \pi^- \pi^0$ ($e^+ e^- \gamma$)**
- **pp η → pp $\pi^+ \pi^- \pi^0$ ($\gamma \gamma$)**
- **pp η → pp $\pi^+ \pi^- \gamma$**







Estimation of X17 contribution to signal region



Right peak (R)

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

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

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

Left peak (L)

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

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

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

Expected numer of X_{17} in signal peak

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

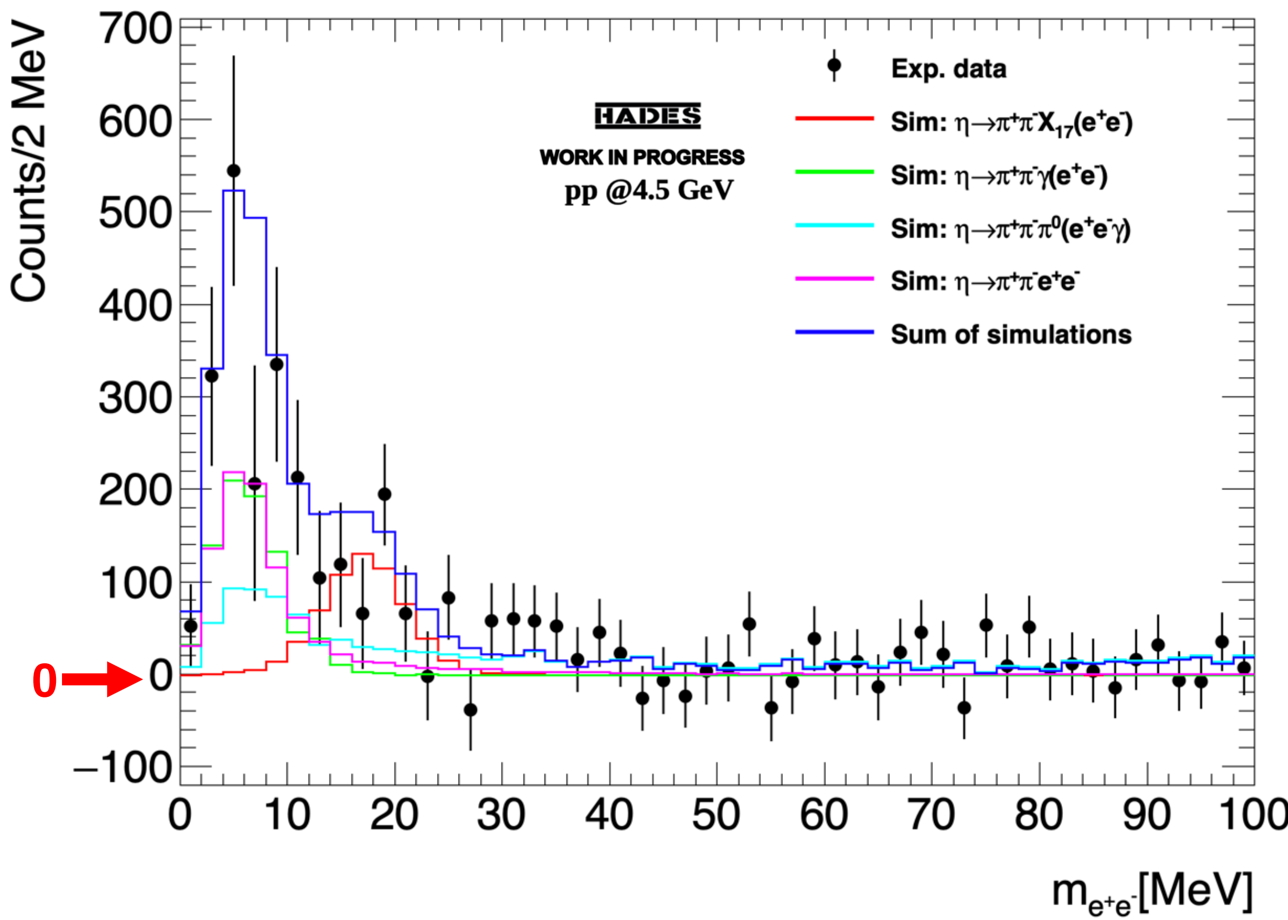
$$N_{X17} = 2758 \cdot 26.28\% = 725$$

JAGIELLONIAN UNIVERSITY IN KRAKOW

HADES

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%)

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

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

Conclusions

- *η/η' mesons are an interesting place to look for dark particles because probe coupling to light quarks and gluons.*
- *Preliminary estimation of upper limit for the Axion-Like-Particle in decay* $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ **BR < $2.58 \cdot 10^{-5}$**

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!