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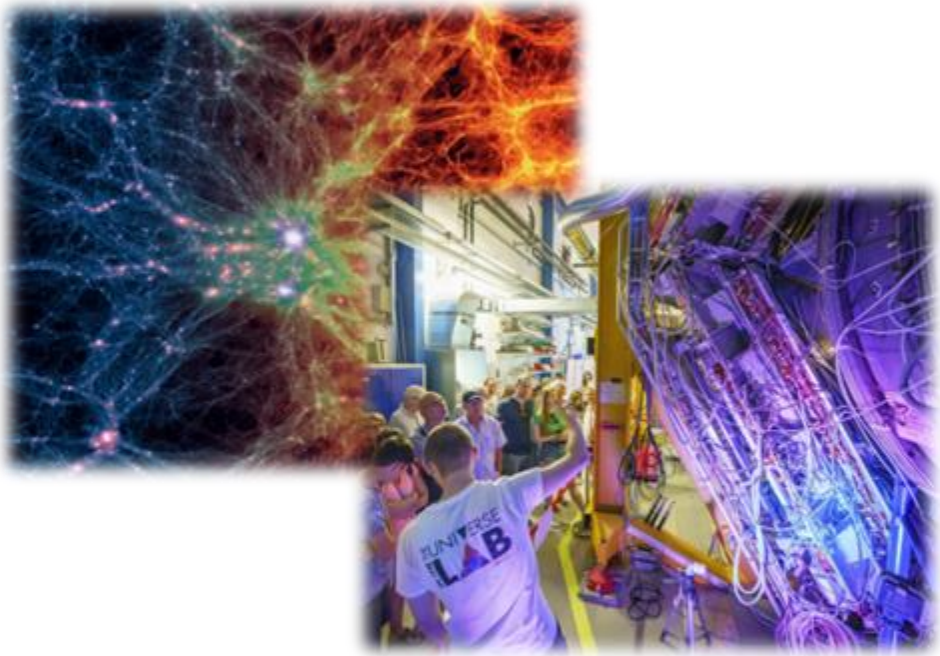


Search for the X_{17} QCD Axion in the $\eta \rightarrow \pi^{+} \pi^{-} e^{+} e^{-}$ decay with the HADES Detector

Marcin Zieliński

on behalf of HADES Collaboration

NATIONAL SCIENCE CENTRE POLAND

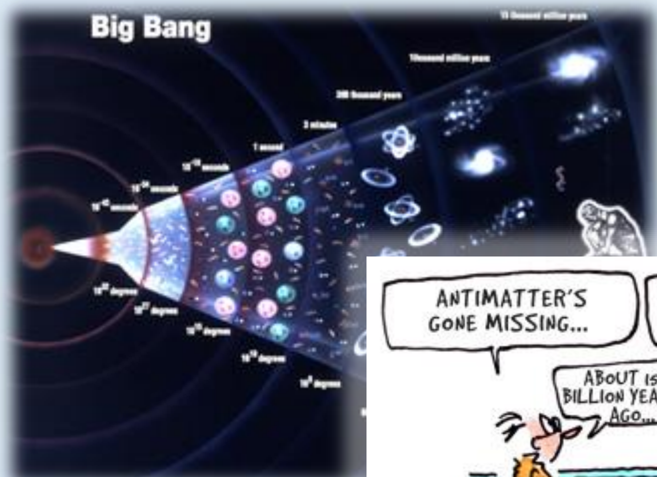
17th Workshop on Particle Correlations and Femtoscopy

Toulouse, November 5th 2024

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

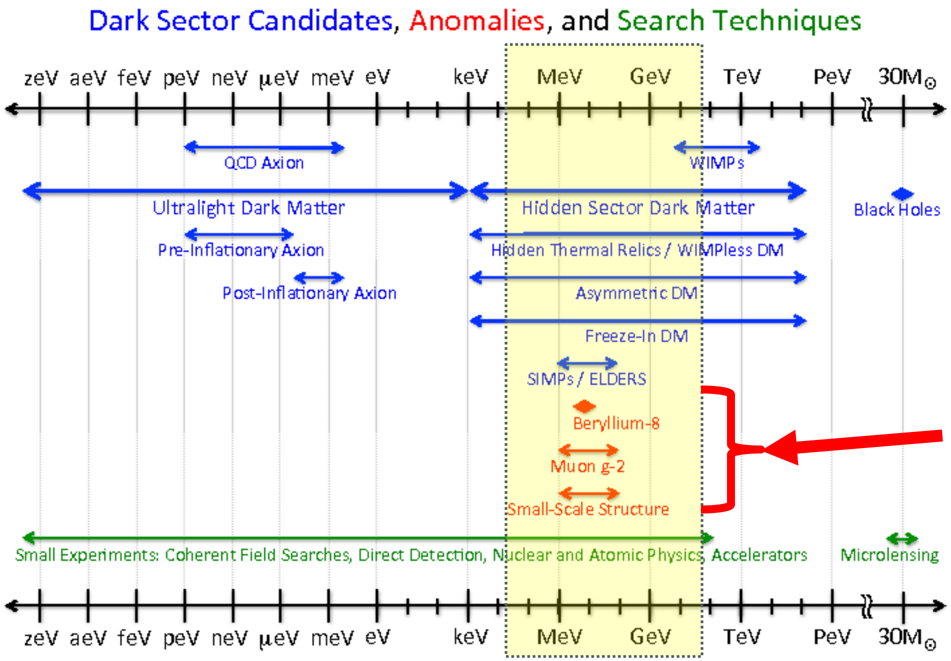
During cooling and expansion
matter and antimatter annihilated 😐

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)*

Anomalies not explained by Standard Model

Standard Model fails to explain several observed phenomena in particle physics: $(g-2)_\mu$, B-physics anomalie, KOTO anomaly ($K_L \to \pi^0 \nu\nu$), and ….


PHYSICAL REVIEW LETTERS

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Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

A. J. Krasznahorkay, M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, Zs. Vajta, T. J. Ketel, and A. Krasznahorkay

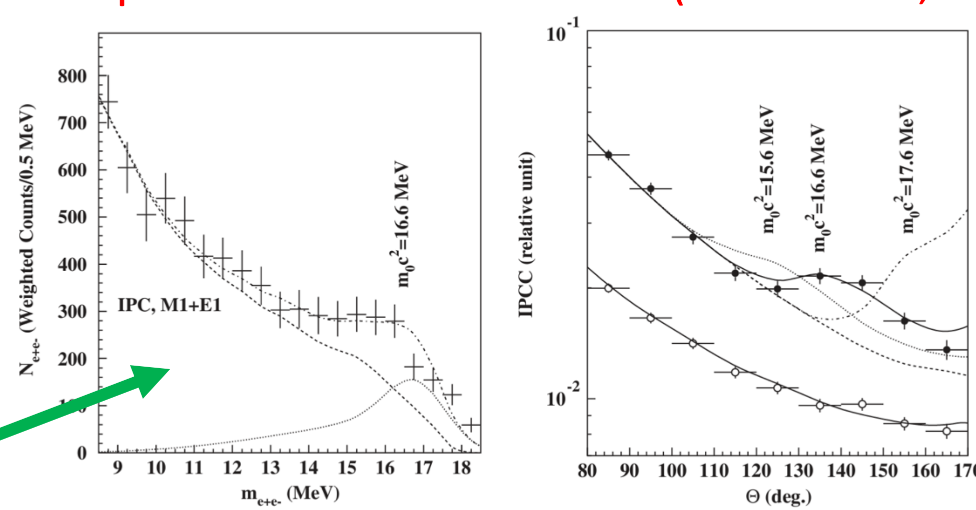
Phys. Rev. Lett. **116**, 042501 – Published 26 January 2016

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

$$J^\pi = 1^+ \to 0^+$$

$$^8\mathrm{Be}^*(17.64) \to {}^8\mathrm{Be}(0) + e^+e^-,$$
$$\Delta E = 17.64\ \mathrm{MeV}, \qquad \Delta I \approx 1,$$

$$^8\mathrm{Be}^*(18.15) \to {}^8\mathrm{Be}(0) + e^+e^-,$$
$$\Delta E = 18.15\ \mathrm{MeV}, \qquad \Delta I \approx 0.$$



$$m_X = (16.7 \pm 0.35_{\mathrm{stat}} \pm 0.5_{\mathrm{syst}})\ \mathrm{MeV}$$

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

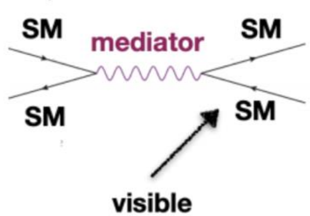
Dark Matter production

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

Visible, SM

Production of portal-mediators that decay to SM particles

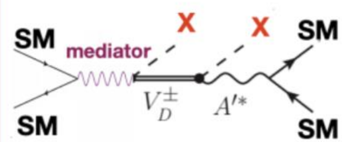
Systematically exploring the portal coupling to SM particles



Mixed visible-invisible

Production of "rich" dark sectors

Testing the structure of the dark sector



Light mesons studies:

η/η'

Stefania Gori, Mike Williams

Connection between Standard and Dark Matter

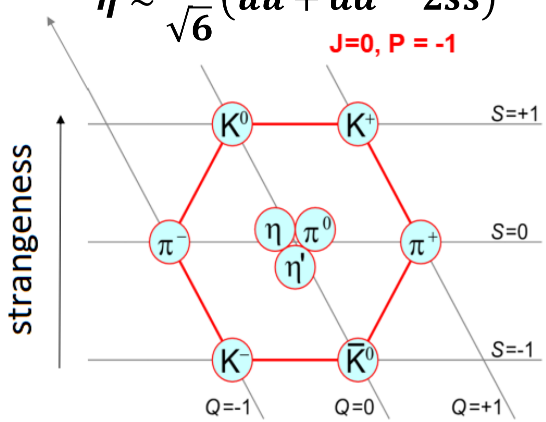
"Light dark matter must be neutral under SM charges, otherwise it would have been discovered at previous colliders"

[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	$\eta \to \gamma\,\gamma$ (39.36%)
	$\eta \to \pi^0\,\pi^0\,\pi^0$ (32.57%)
	$\eta \to \pi^+\,\pi^-\,\pi^0$ (23.02%)
	$\eta \to \pi^+\,\pi^-\,\gamma$ (4.28%)
	$\eta \to \pi^+\,\pi^-\,e^+\,e^-$ (0.03%)

QCD Axion

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

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

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

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

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)

QCD Axion

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

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

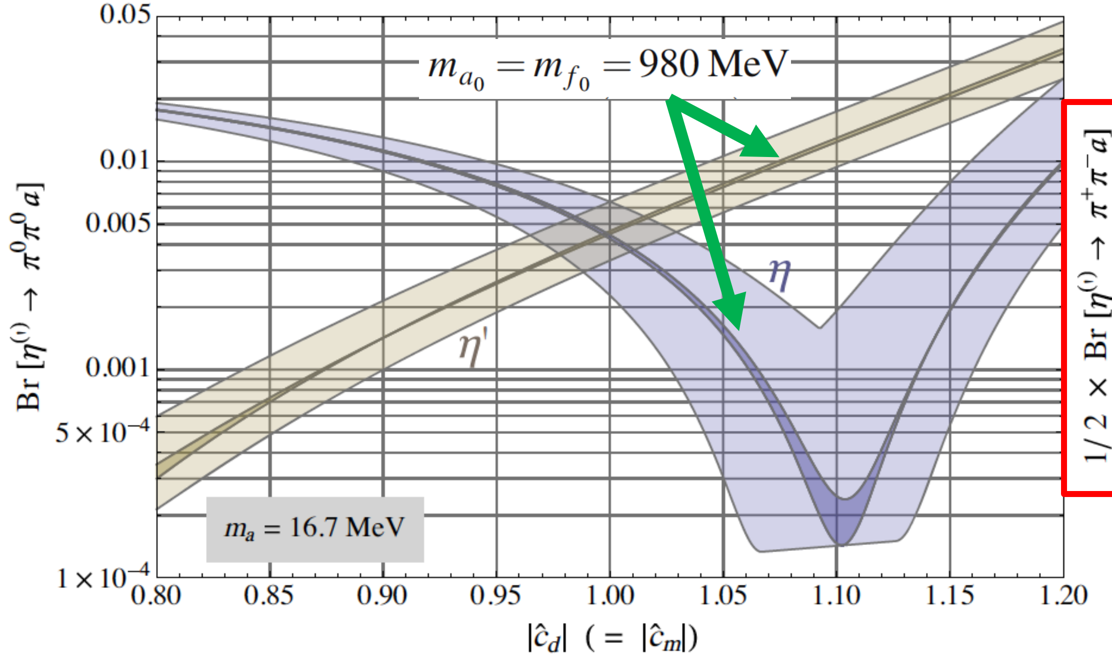
”axio-hadronic decay”

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.

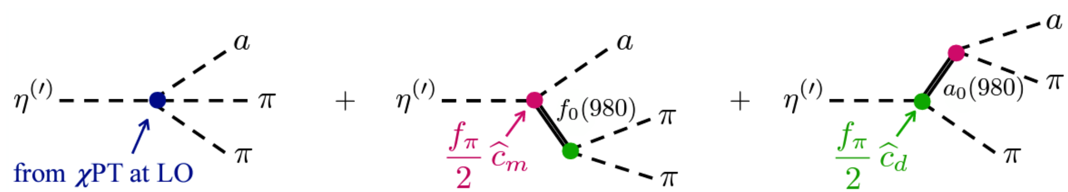
„.... O(10^{-2}), is probably excluded or in tension with observations but O(10^{-4} - 10^{-3}) likely remains experimentally allowed, and within the sensitivity.”

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



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

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



$$m_{a_0}, m_{f_0} = (960\text{–}1000)\ \text{MeV} \quad \Gamma_{a_0} = (40\text{–}100)\ \text{MeV} \quad \Gamma_{f_0} = (10\text{–}200)\ \text{MeV}$$

QCD Axion

NEW

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

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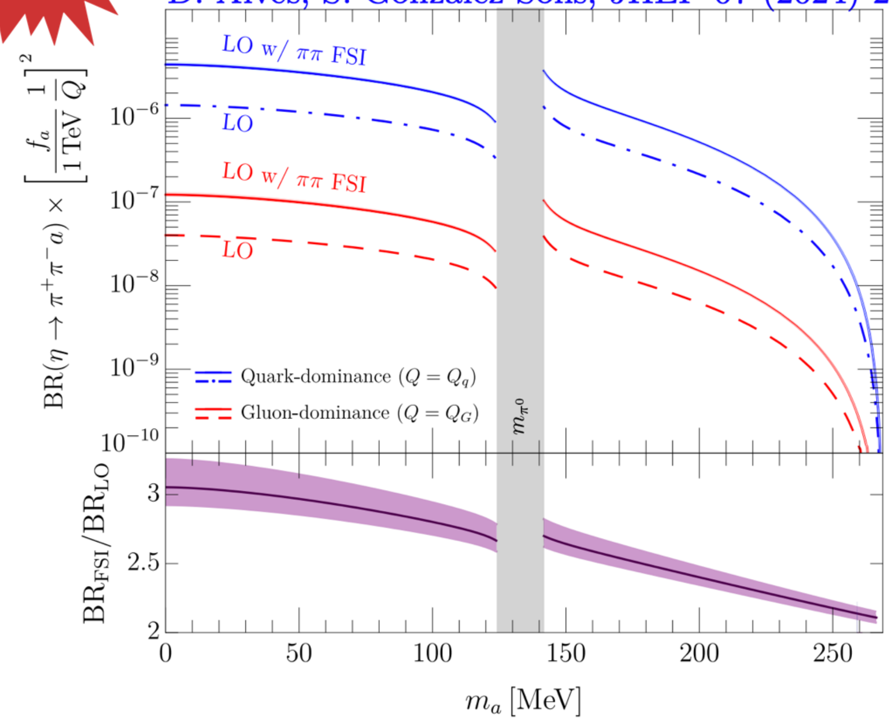
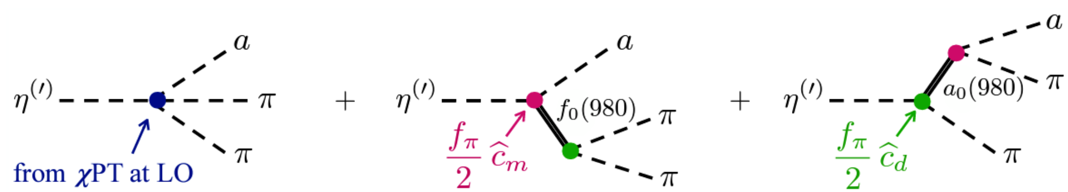
D. Alves, S. Gonzàlez-Solís, JHEP 07 (2024) 264



$\mathrm{BR}(\eta \rightarrow \pi\pi a)$- $3\cdot10^{-8} – 4\cdot10^{-6}$



$$m_{a_0}, m_{f_0} = (960–1000)\ \mathrm{MeV} \quad \Gamma_{a_0} = (40–100)\ \mathrm{MeV} \quad \Gamma_{f_0} = (10–200)\ \mathrm{MeV}$$

QCD Axion

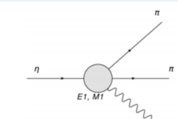
Why previous measurements $\eta(\eta') \rightarrow \pi^+ \pi^- e^+ e^-$ did not see Axion signatures ?

Previous exp. of the $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ studied CP invariance

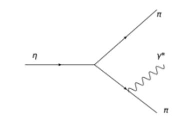
Not much experimental indications for the violation of CP symmetry in flavour-conserving reactions (KLOE 2009, WASA-at-COSY 2016).

polarization can be studied via asymmetry:

$$A_\phi = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$$

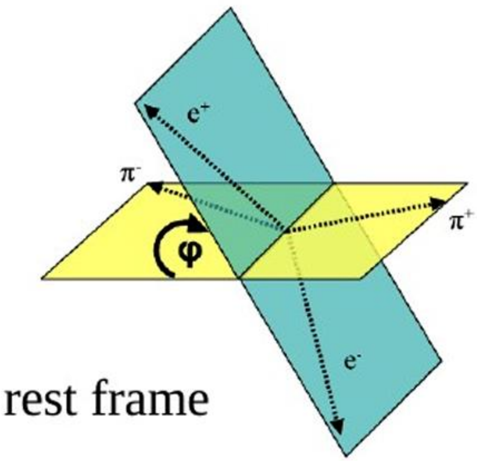


M1 transition allowed
E1 transition violates CP



$\eta \rightarrow \pi^+\pi^-$ violates CP directly

source of the CP violation in the decay could be an interference between electric and magnetic amplitudes responsible for significant linear polarization of the photon in the $\eta \rightarrow e^+ e^- g^*$



η rest frame

Experimental results up to now:

Year	Exp.	Events number	Asymmetry	BR ($\eta \rightarrow \pi^+ \pi^- e^+ e^-$)
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 $m(e^+e^-) < 15$ MeV

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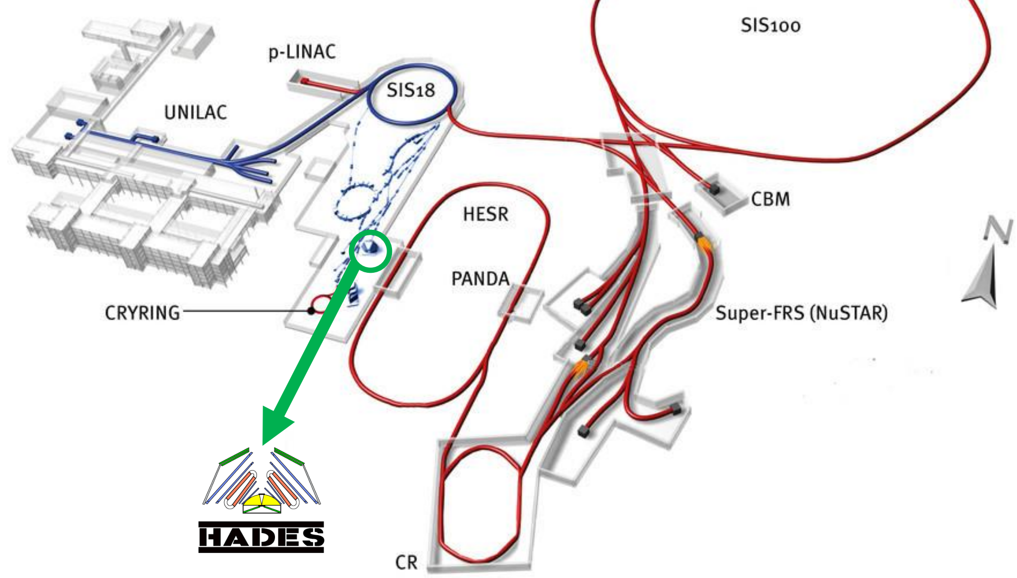
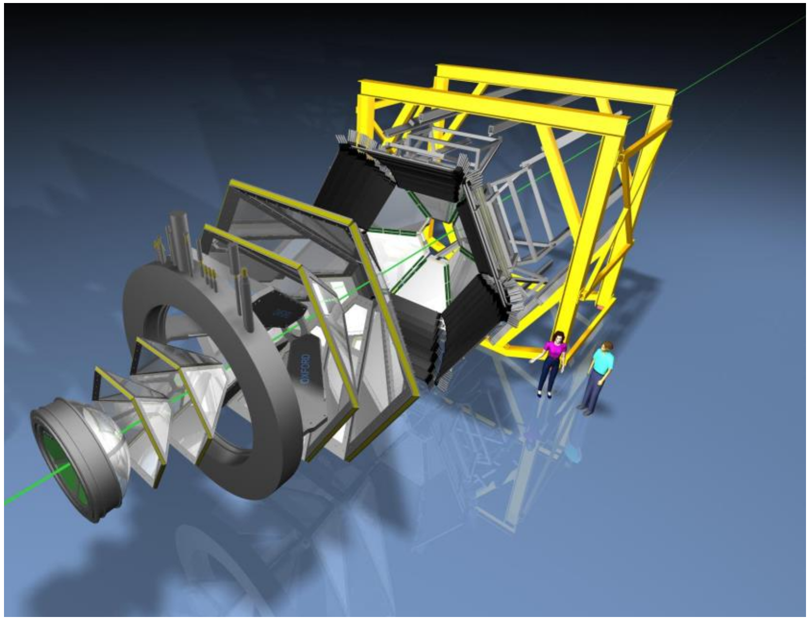
HADES - High Acceptance Di-Electron Spectrometer



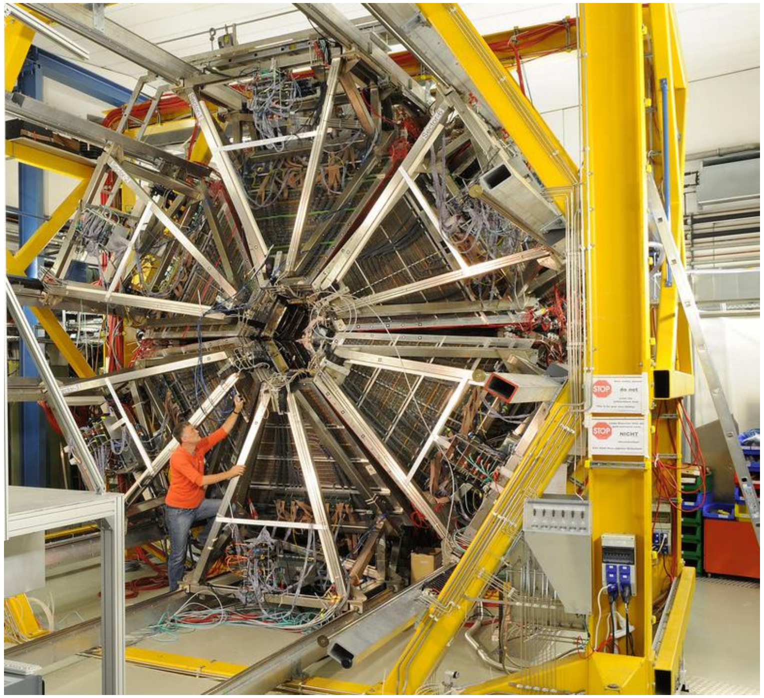
SIS 18

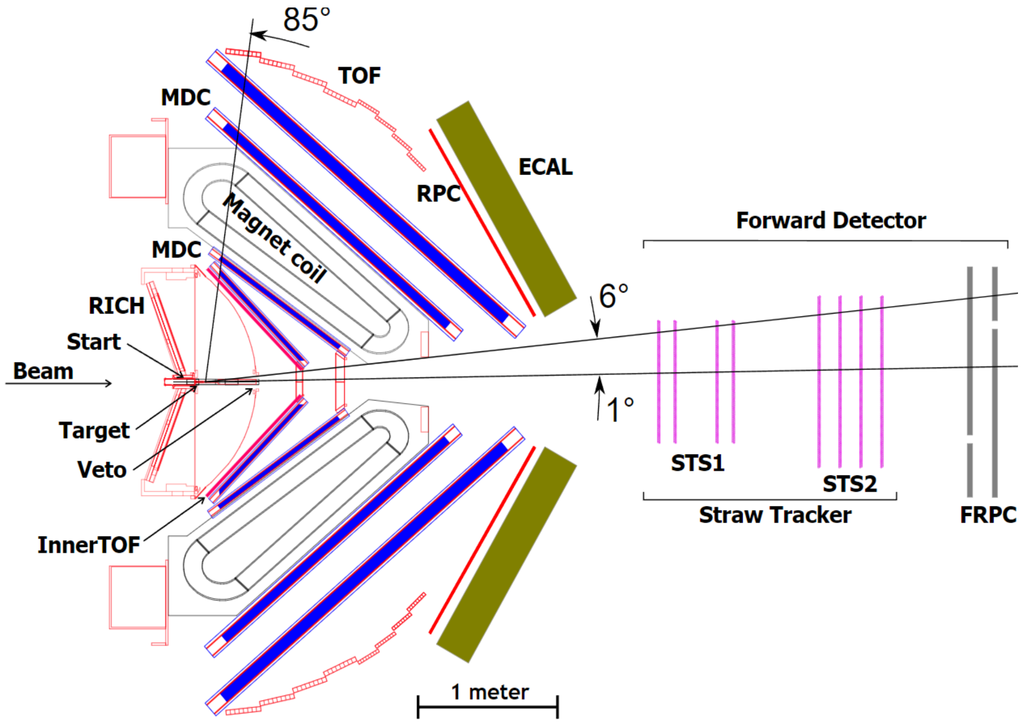
U^{73+}	1.0 GeV/u	10^9 ions/s
Protons	4.5 GeV	2.8×10^{13}/s
Pions	0.5-2 GeV/c	



➢ **hades.gsi.de**

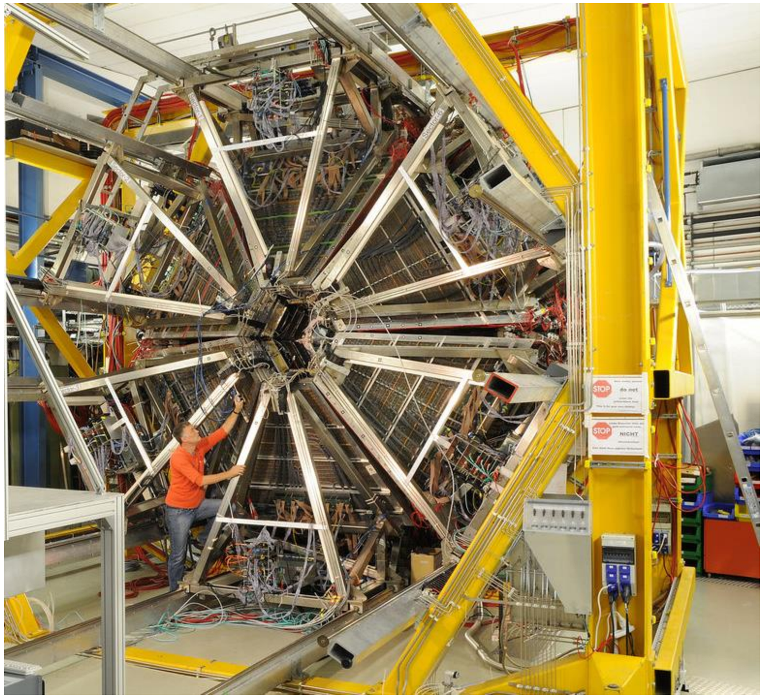
HADES - High Acceptance Di-Electron Spectrometer

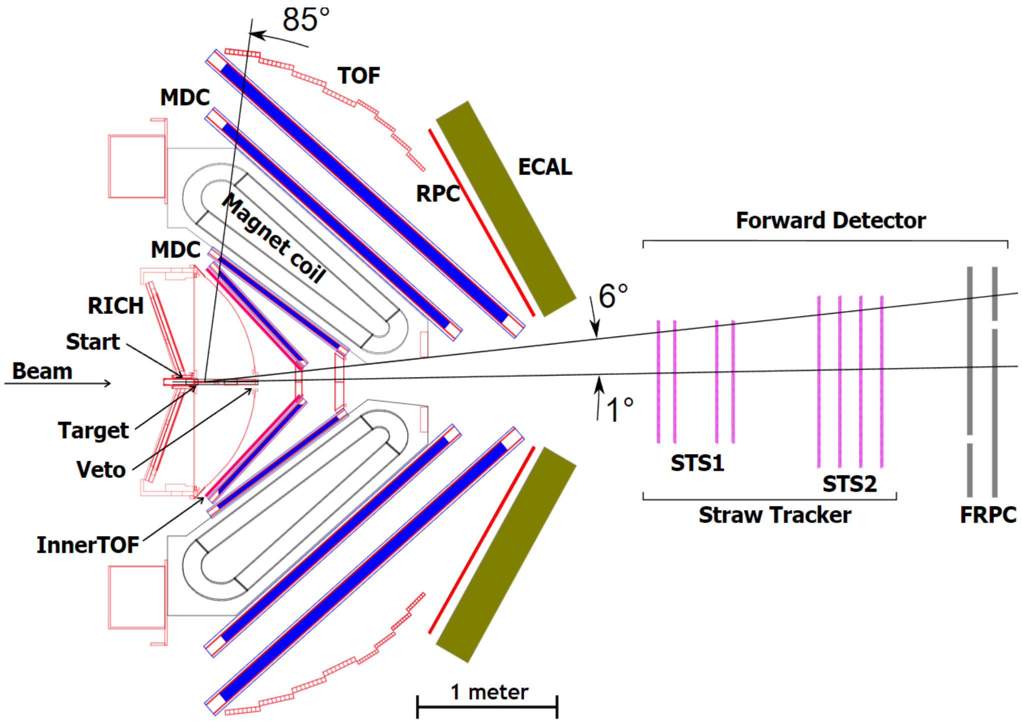




- **START** – T0 reaction for ToF
- **RICH** – Cherenkov detector (di-electron e^+e^-)
- **MDC and STS** – track reconstruction
- **Magnet Coil** – generates magnetic field
- **ToF & RPC** – Time-of-Flight META detectors
- **ECAL** – electromagnetic calorimeter (photons)
- **Trigger logic based on InnerToF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

HADES - High Acceptance Di-Electron Spectrometer

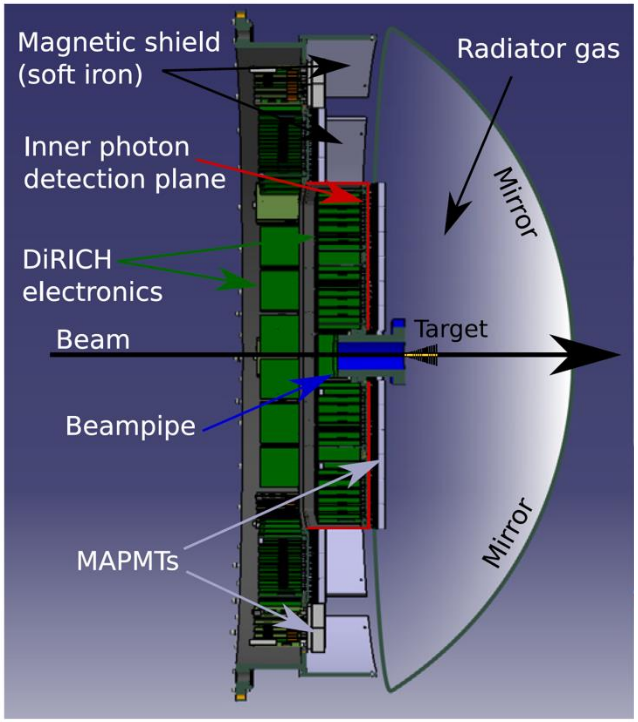


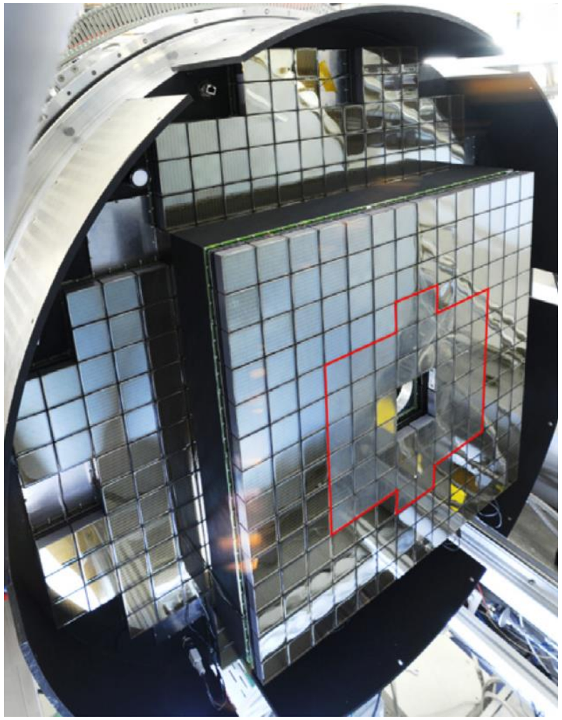


February 2022 measurement:

- **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}]**

Lepton identification using HADES RICH Detector



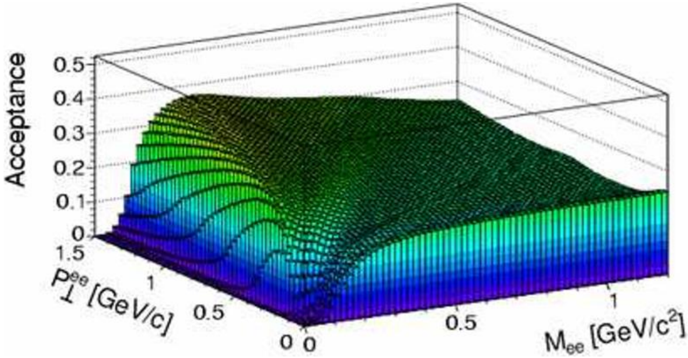


- Lepton identification base on signals in RICH.
- Threshold momentum for electrons 9 MeV and for pions 2500 MeV.
- Acceptance as a function of transverse momentum and $e^+ e^-$ invariant mass.
- In standard HADES analysis $e^+ e^-$ opening angle > 9° to subtract conversion.

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

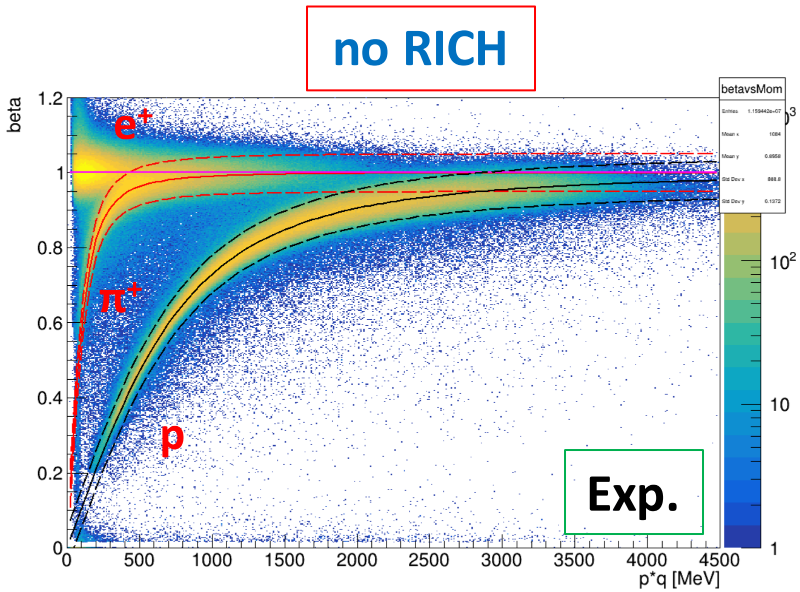
$$\beta_\pi < \beta_{Cher} < \beta_e$$

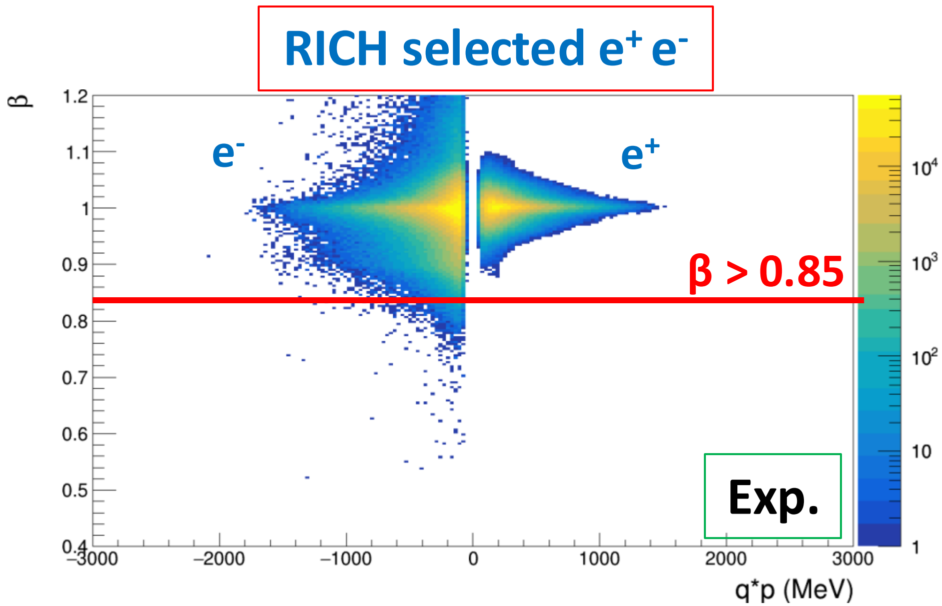
$e^+ e^-$ creates Cherenkov radiation



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



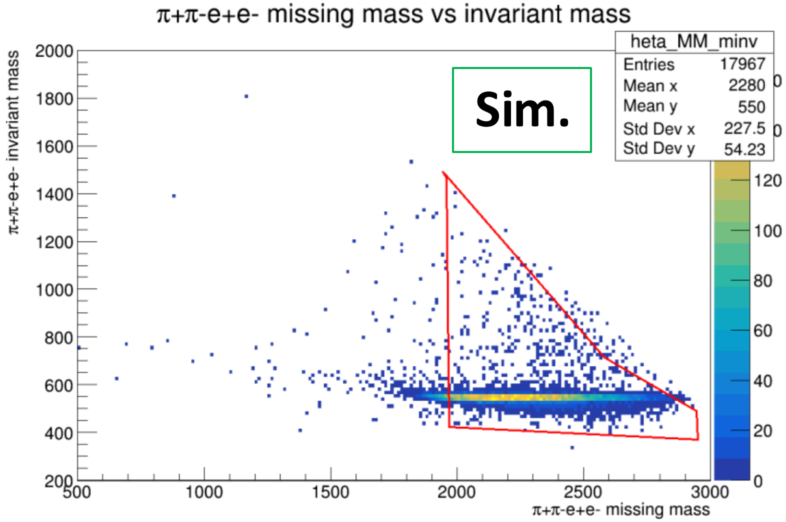


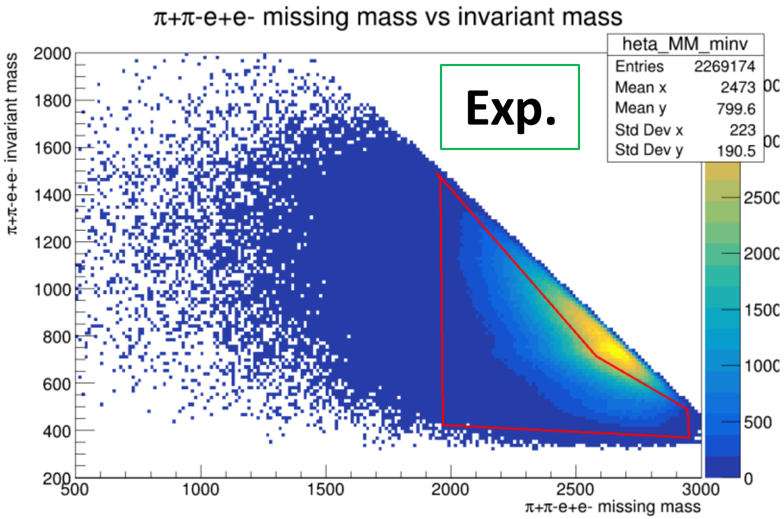
Following particles have to be selected: **π^+ π^- e^+ e^-**

- 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: **$\beta > 0.85$**

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°





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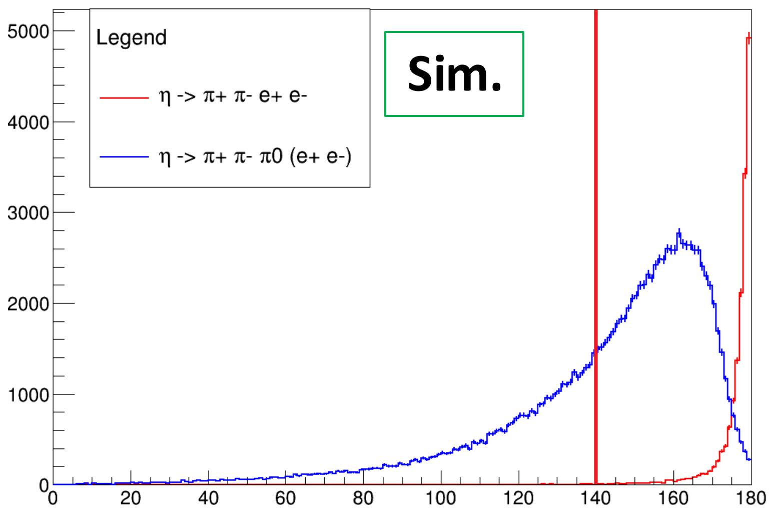
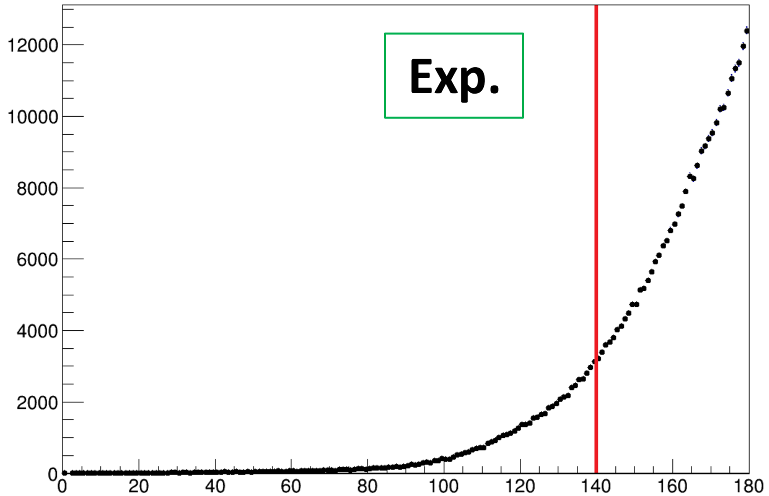
In CM frame OA found assuming $e^+e^-\pi^+\pi^-$ invariant mass is equal η mass

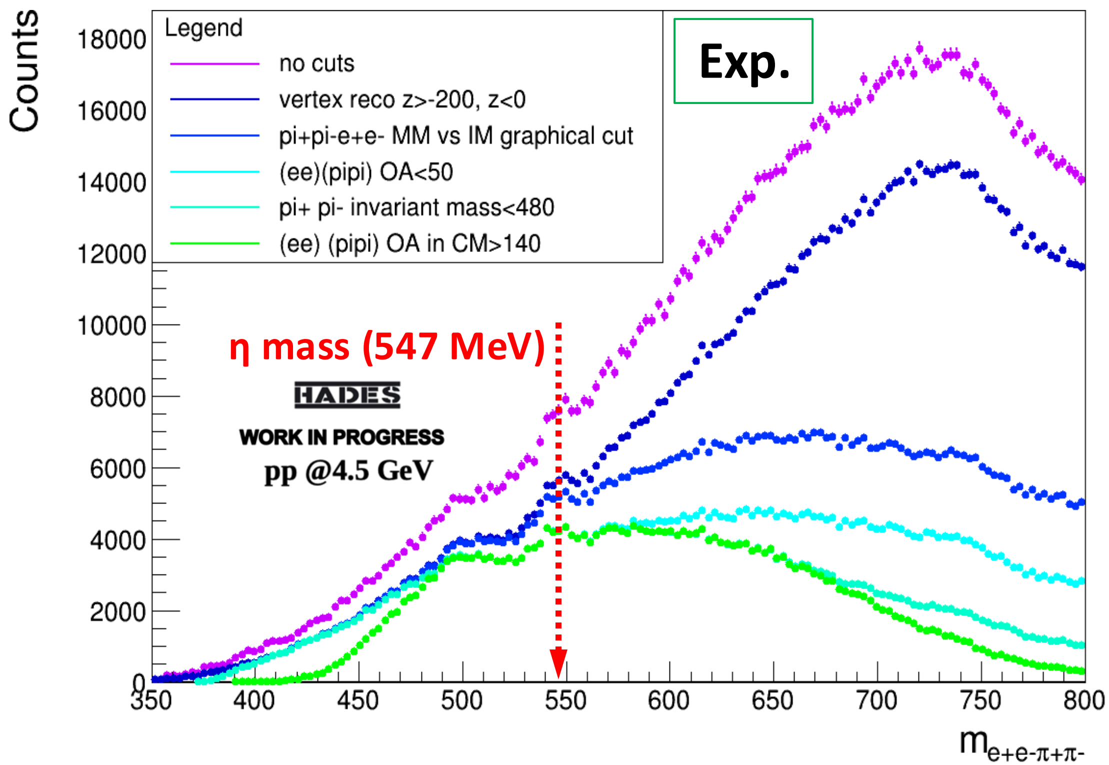




Event selection for the $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ decay

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

Experimental invariant mass after applying consecutive cuts

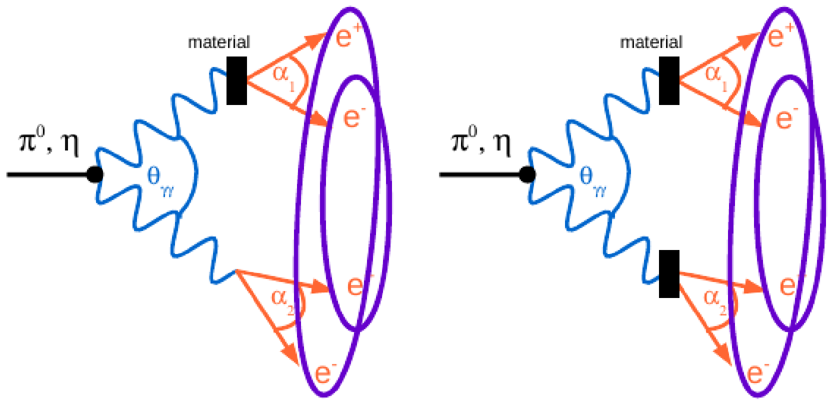


Event selection for the η → π⁺ π⁻ e⁺ e⁻ decay

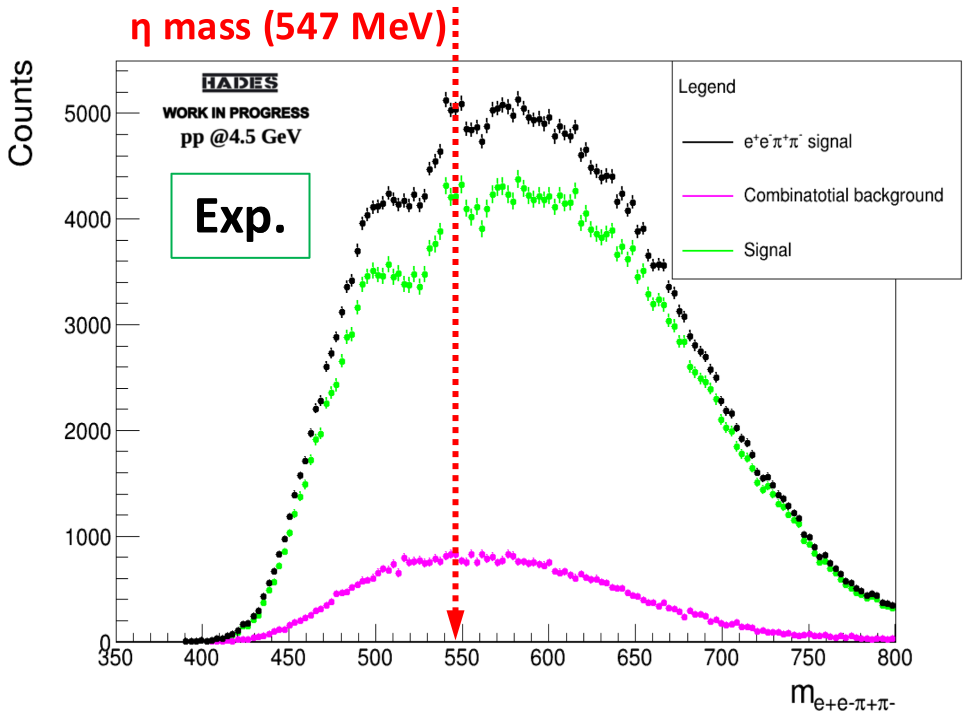
- Combinatorial background substraction:

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

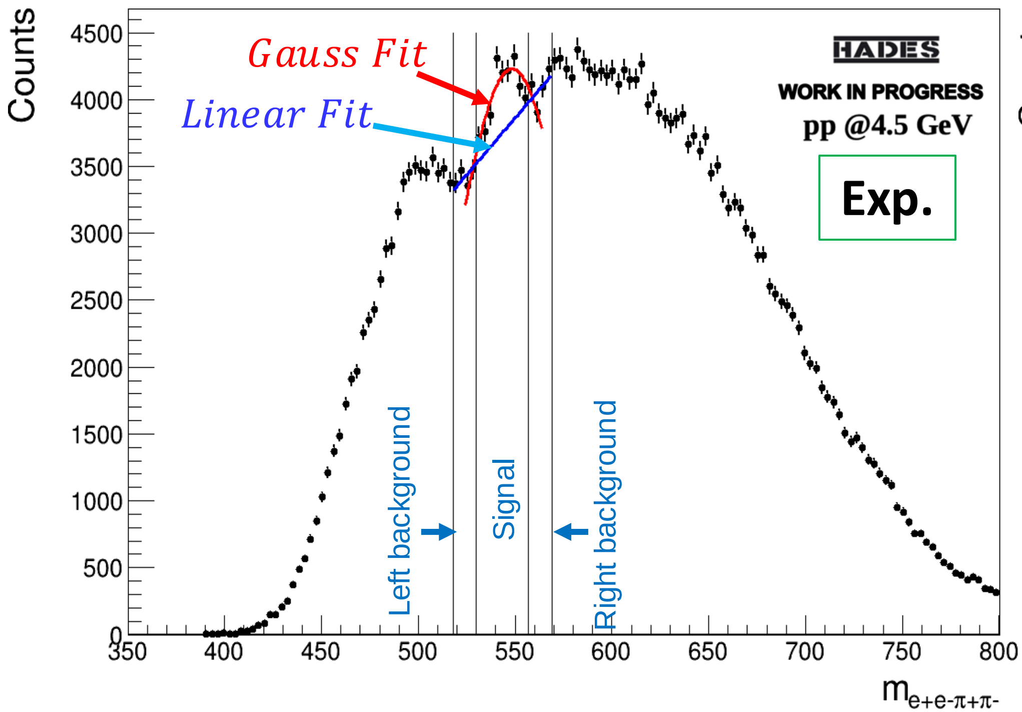
$$\langle N_{signal} \rangle = \langle N_{\pi^+\pi^-e^+e^-} \rangle - \langle N_{CB} \rangle$$

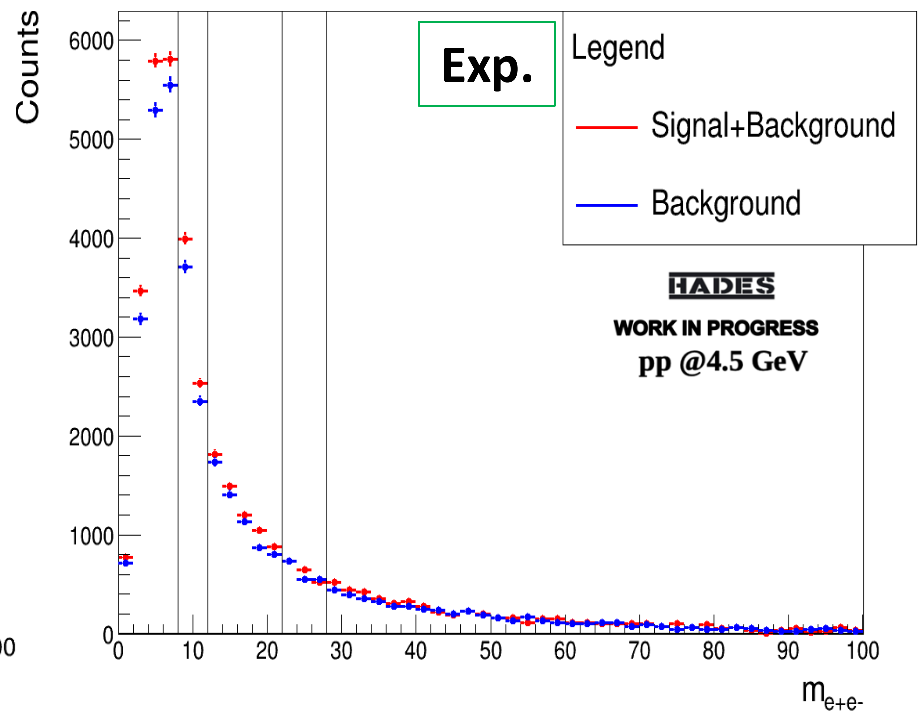


Ref.: *Szymon Harabasz, HADES PhD Thesis (2018)*



Extraction of η → 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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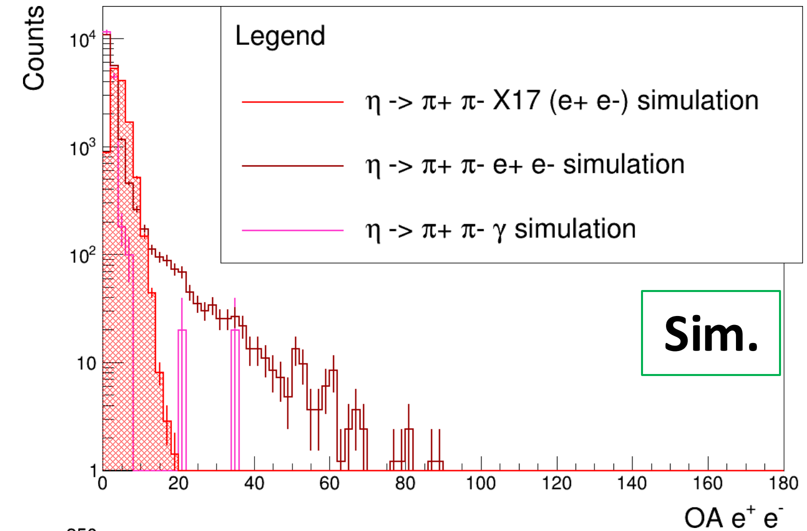
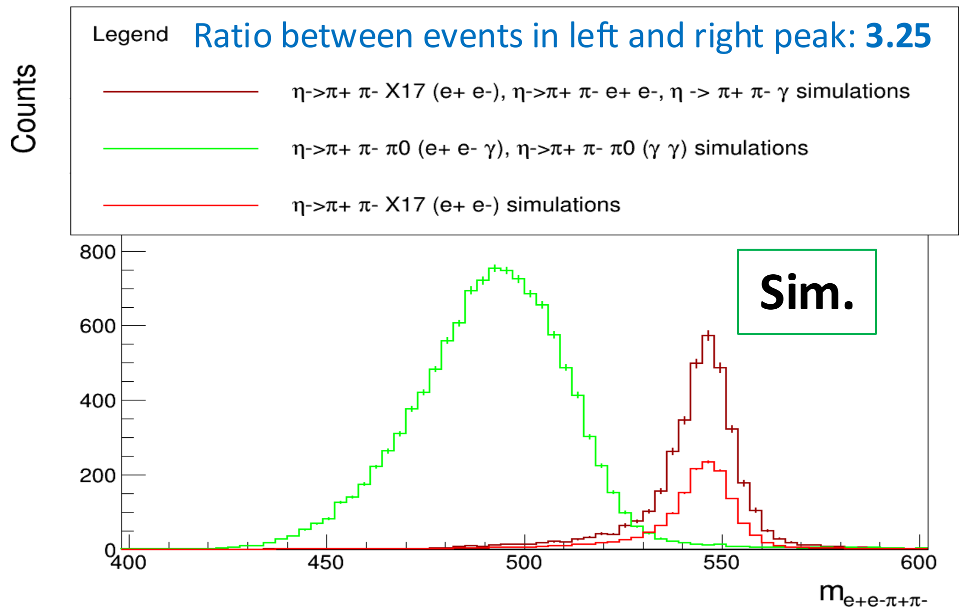
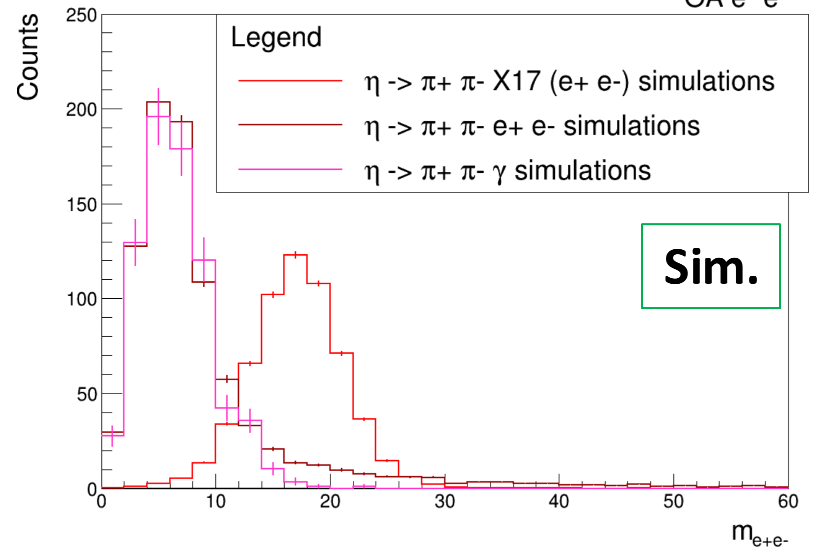
Simulations of signal and background

Signal and main background reactions:

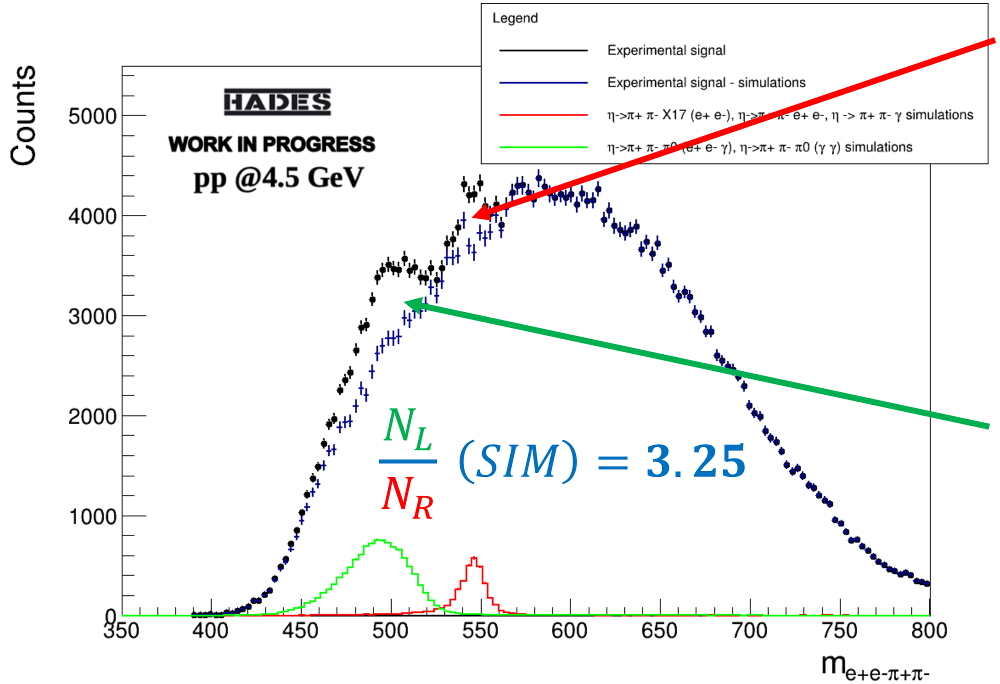
- **pp η → pp $\pi^+ \pi^- e^+ e^-$**
- **pp η → pp $\pi^+ \pi^-$ X17 ($e^+ e^-$)**
- **pp η → pp $\pi^+ \pi^- \pi^0$ ($e^+ e^- \gamma$)**
- **pp η → pp $\pi^+ \pi^- \pi^0$ ($\gamma \gamma$)**
- **pp η → pp $\pi^+ \pi^- \gamma$**







Estimation of X17 contribution to signal region



Right peak (R)

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

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

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

3 524 events (2 919 in peak region)

Left peak (L)

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

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

11 200 events

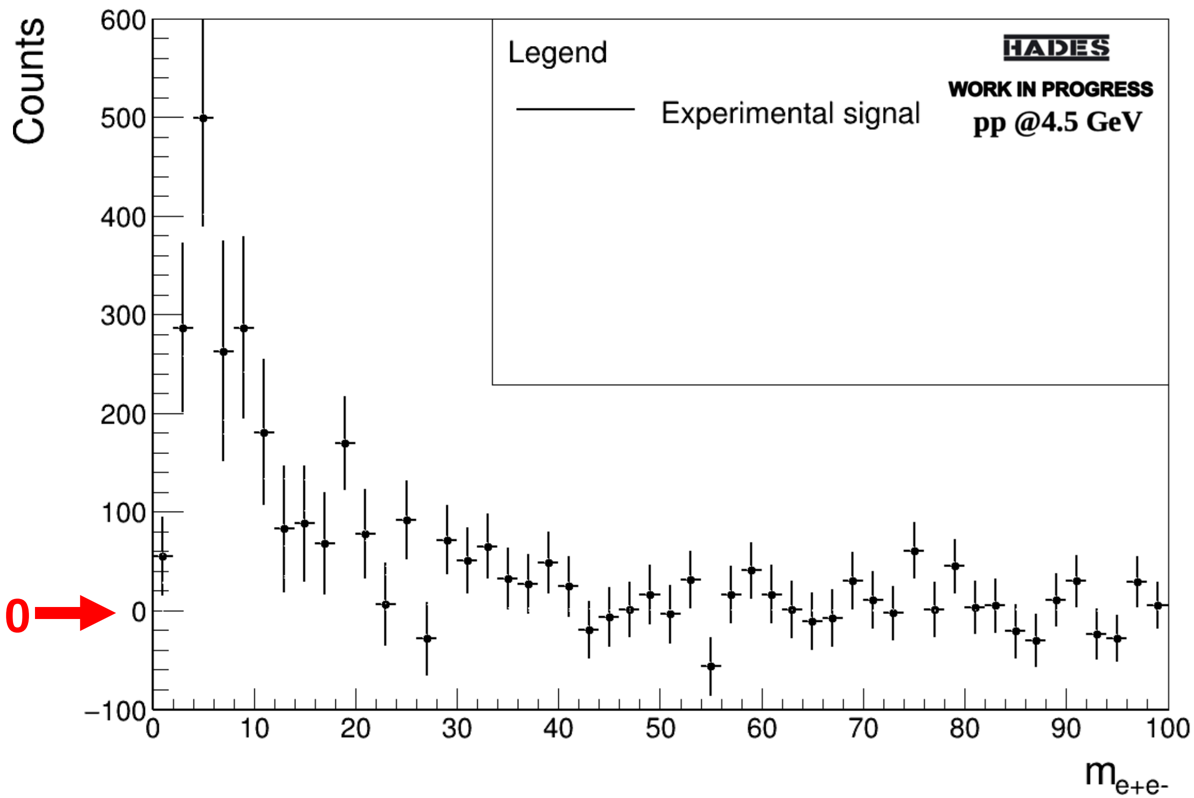
Reaction	Contribution	Branching ratio (BR)
$\eta \rightarrow \pi^+\pi^-e^+e^-$	39.95%	$2.68 \cdot 10^{-4}$
$\eta \rightarrow \pi^+\pi^- X17\,(e^+e^-)$	26.28%	$1 \cdot 10^{-4}$
$\eta \rightarrow \pi^+\pi^-\gamma$	33.77%	$4.28 \cdot 10^{-2}$

Expected numer of X_{17} in signal peak

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

Results

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



Results

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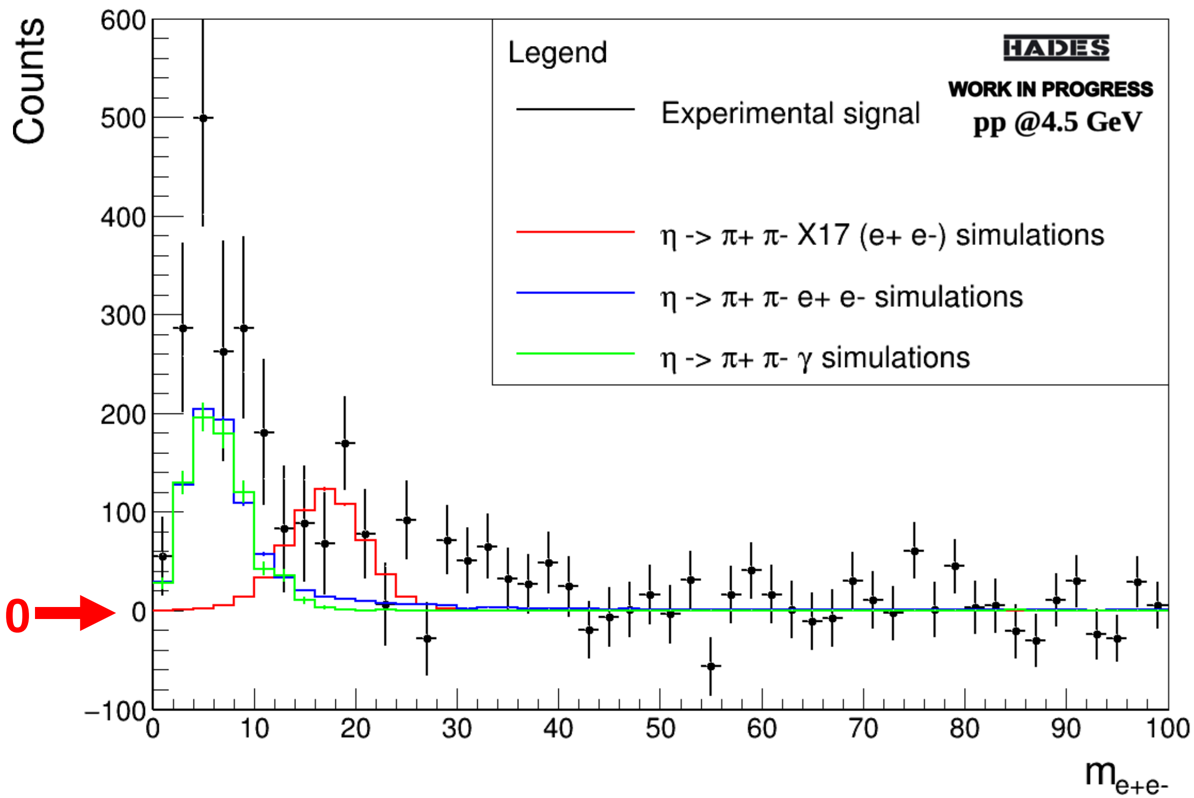

Results

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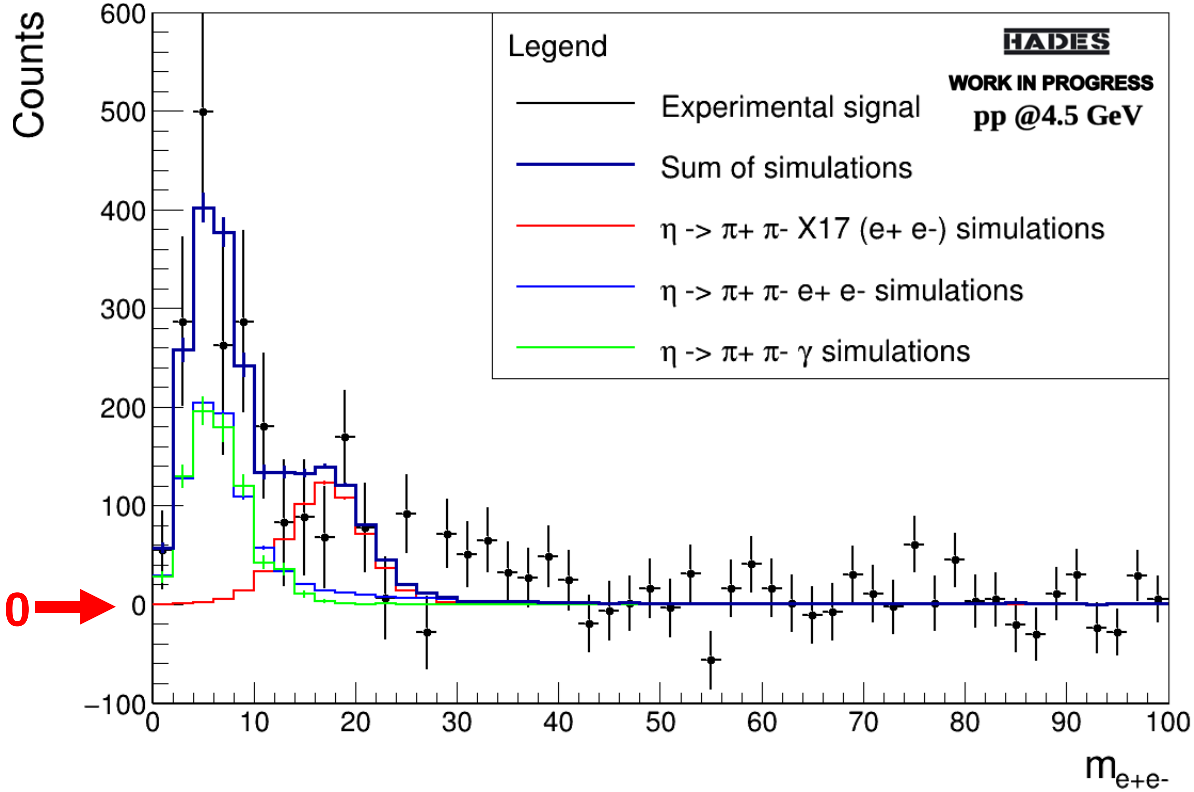


Upper limit for the number of event estimated based on W. A. Rolke method:

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.***
- ***First estimation of upper limit for the QCD Axion*** **$BR_{\eta \to \pi^+ \pi^- X17} < 2.58 \cdot 10^{-5}$**

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!

Backup

QCD Axion

Physical Axion current

$$J_\mu^{a_{\rm phys}} \equiv \frac{f_a}{f_\pi}\left(f_\pi \partial_\mu a + \theta_{a\pi} J_{5\mu}^{(3)} + \theta_{a\eta_{ud}} J_{5\mu}^{(ud)} + \theta_{a\eta_s} J_{5\mu}^{(s)}\right),$$

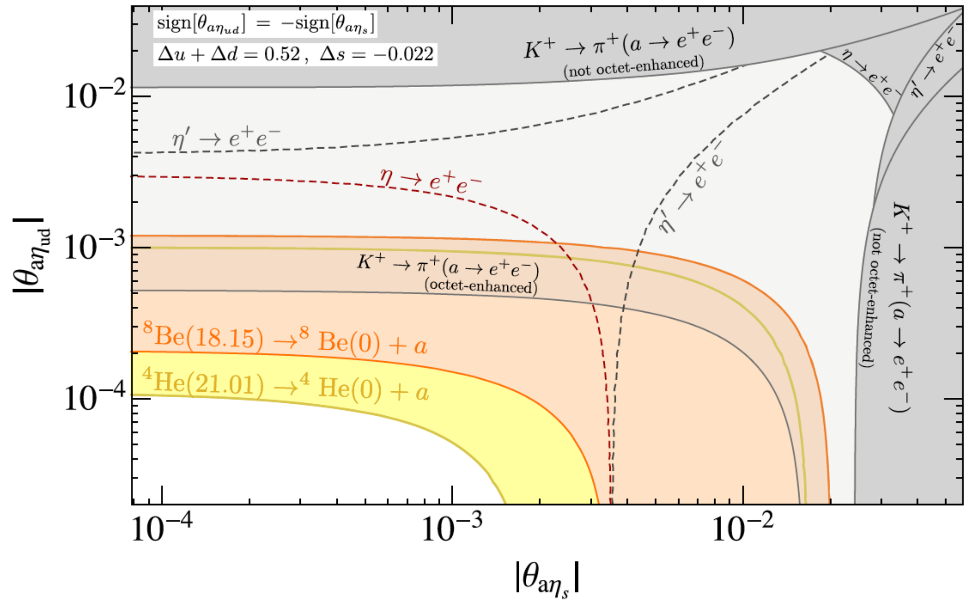
Axionic field and the neutral meson degrees of freedom mix among themselves to yield the physical degrees of freedom:

$$a_{\rm phys},\ \pi^0,\ \eta,\ \text{and}\ \eta'$$

$$\mathcal{L}_{aNN} = a\bar{N} i\gamma^5 (g_{aNN}^{(0)} + g_{aNN}^{(1)}\tau^3) N$$

$$g_{aNN}^{(1)} = \theta_{a\pi} g_{\pi NN} = \theta_{a\pi}(\Delta u - \Delta d)\frac{m_N}{f_\pi}$$

$$g_{aNN}^{(0)} = (\theta_{a\eta_{ud}}(\Delta u + \Delta d) + \sqrt{2}\theta_{a\eta_s}\Delta s)\frac{m_N}{f_\pi}$$



Contours can be interpreted as the sensitivity in scenario an *O(1)* deviation from the BR predicted in the SM

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

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

"axio-hadronic decay"

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

BES III - Results

Search for ALP in $\eta' \to \pi^+\pi^-e^+e^-$

JHEP 07 (2024) 135

<u>Ref:</u> Andrzej Kupść, Talk 20.09.2024 Kraków, Workshop @ 1 GeV Scale: From Mesons to Axions