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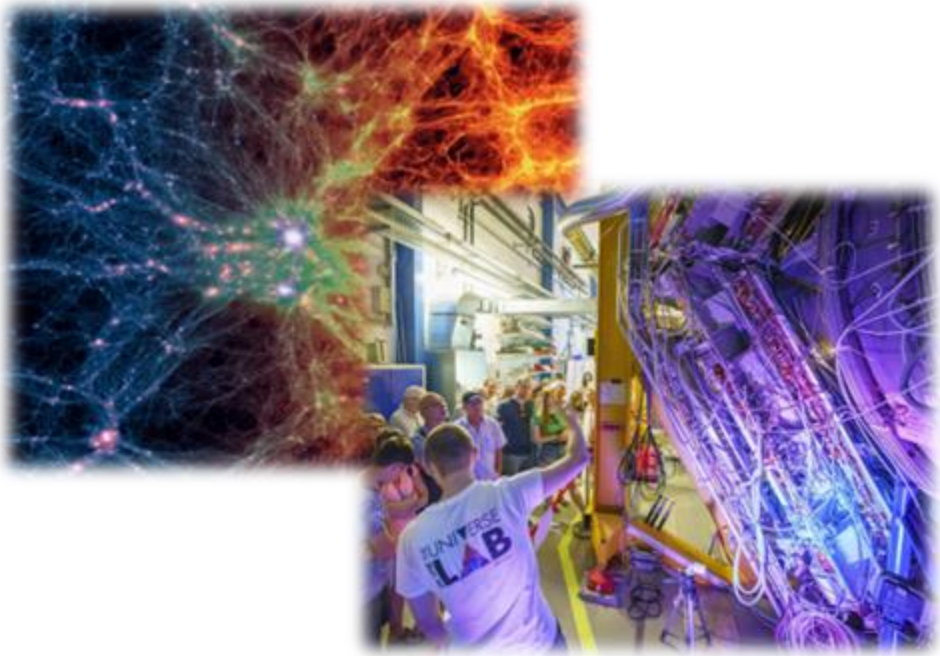

Search for the X_{17} QCD Axion in the $\eta \to \pi^+\pi^-e^+e^-$ decay with the HADES Detector

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NATIONAL SCIENCE CENTRE POLAND

Seminar on Particle Physics Phenomenology and Experiments

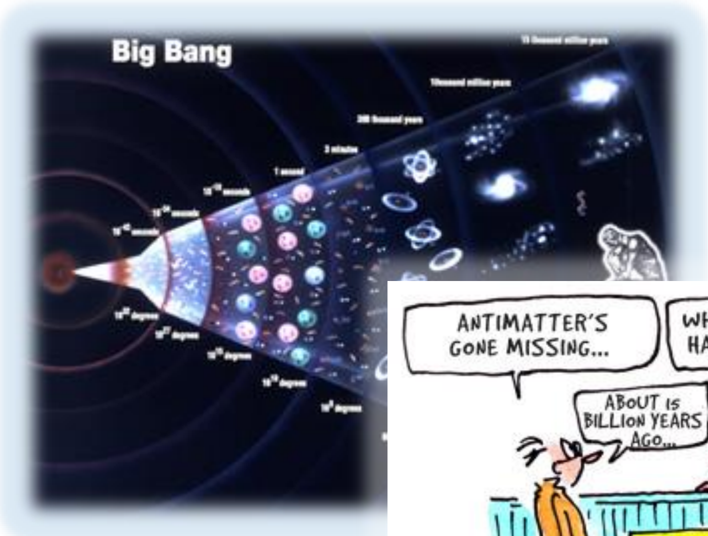
UJ, December 9th, 2024

I. General motivation

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

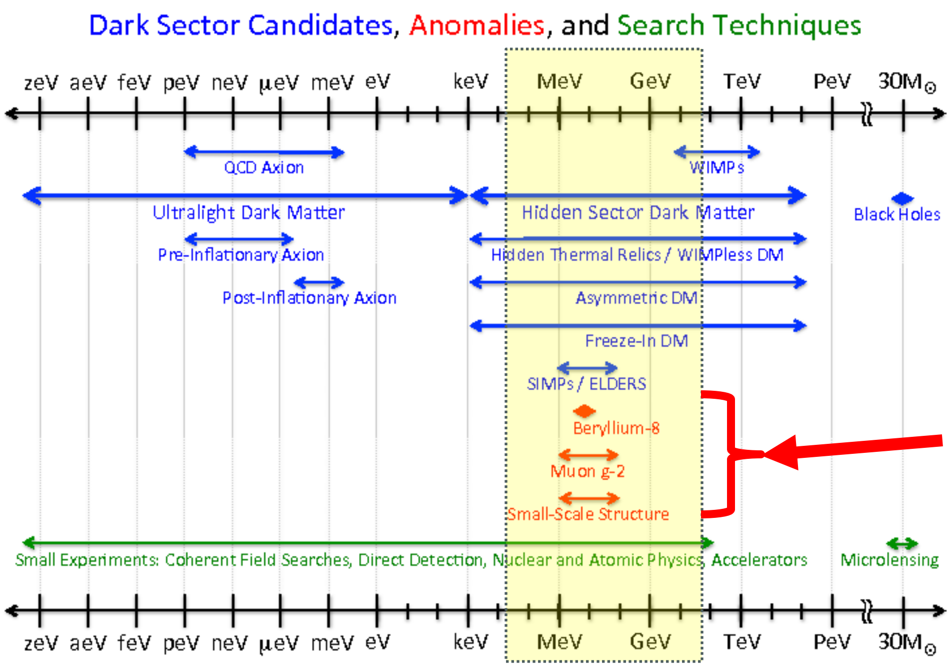
During cooling and expansion
matter and antimatter annihilated 😐

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)*

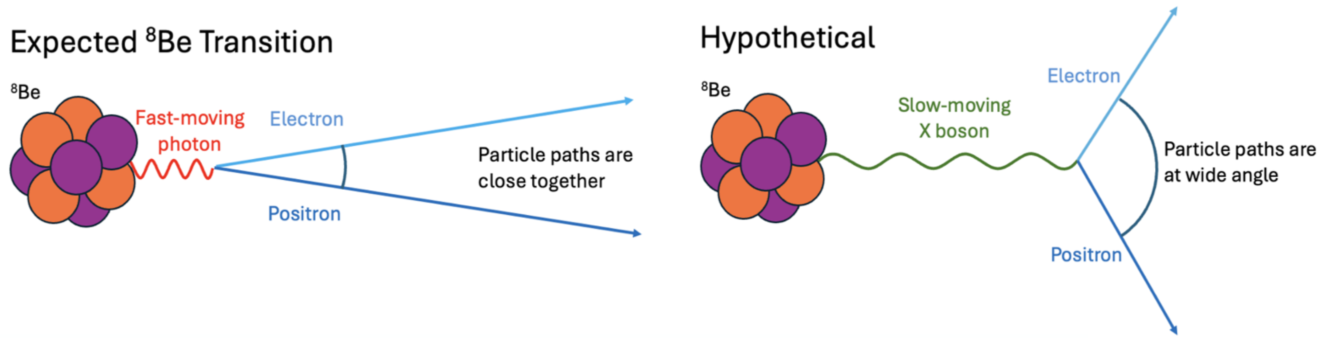
General motivation – ATOMKI results

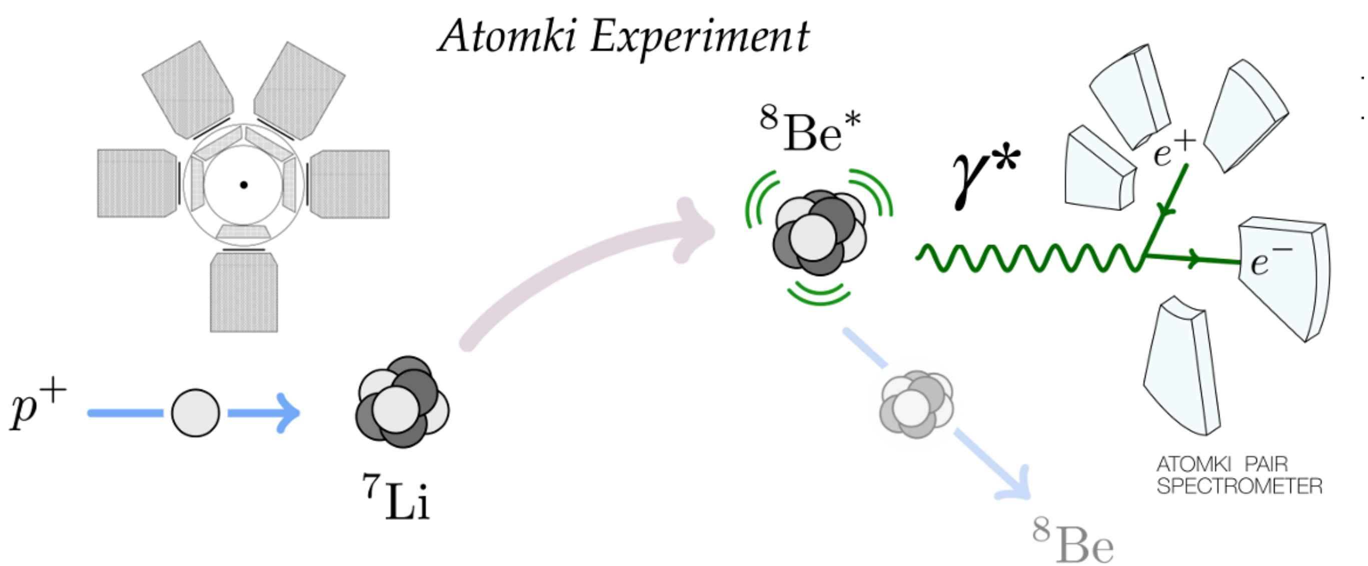
The ATOMKI group observed an excess of e^+e^- pairs emitted at large relative angle in the nuclear reactions:

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

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

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





General motivation – ATOMKI results

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

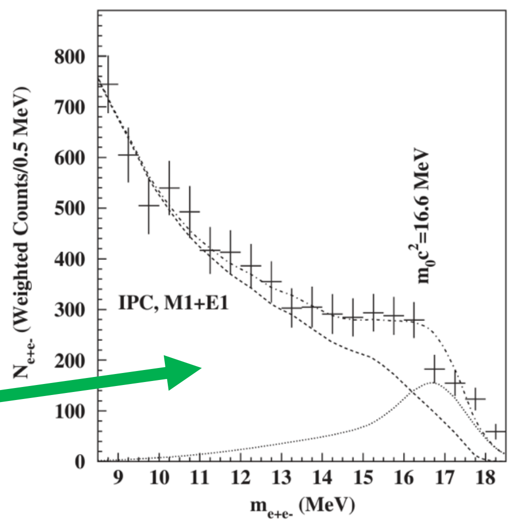
Phys. Rev. Lett. **116**, 042501 – Published 26 January 2016

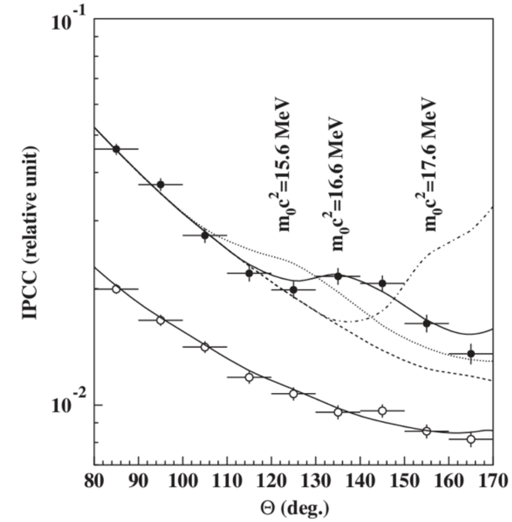
ATOMKI Exp. ^{8}Be : anomalies in the internal pair creation of isovector (17.64 MeV, I=1) and isoscalar (18.15 MeV, I=0) magnetic dipole M1 transitions in ^{8}Be

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

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

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





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

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General motivation – ATOMKI results

arXiv > nucl-ex > arXiv:1910.10459

Nuclear Experiment

[Submitted on 23 Oct 2019]

New evidence supporting the existence of the hypothetic X17 particle

A.J. Krasznahorkay, M. Csatlos, L. Csige, J. Gulyas, M. Koszta, B. Szihalmi, J. Timar, D.S. Firak, A. Nagy, N.J. Sas, A. Krasznahorkay

We observed electron-positron pairs from the electro-magnetically forbidden M0 transition depopulating the 21.01 MeV 0^- state in ^{4}He. A peak was observed in their e^+e^- angular correlations at 115° with 7.2σ significance, and could be described by assuming the creation and subsequent decay of a light particle with mass of $m_X c^2 = 16.84 \pm 0.16(stat) \pm 0.20(syst)$ MeV and $\Gamma_X = 3.9 \times 10^{-5}$ eV. According to the mass, it is likely the same X17 particle, which we recently suggested [Phys. Rev. Lett. 116, 052501 (2016)] for describing the anomaly observed in ^{8}Be.

ATOMKI Exp. ^{4}He : anomalies in the internal pair creation ^{4}He (21.01, I=0) magnetic monopole transition M0.

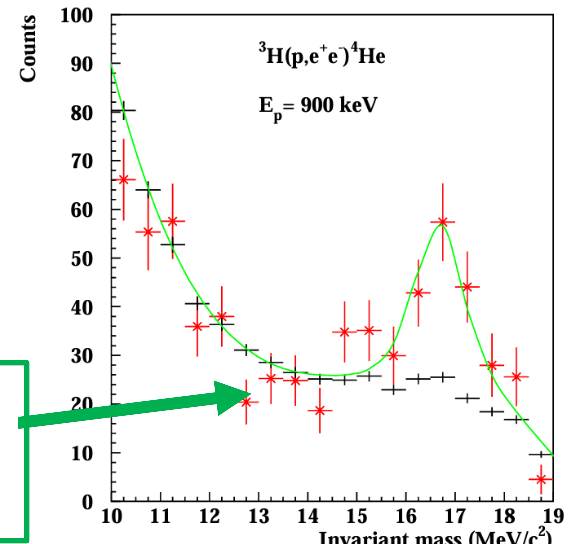
$$J^\pi = 0^+ \to 0^+$$

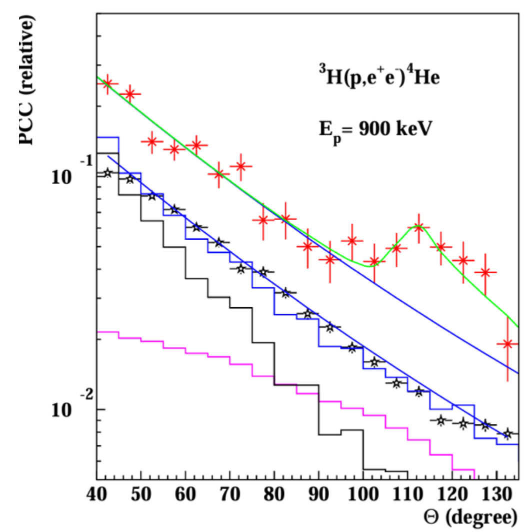
$$(\text{E0}) \quad {}^4\text{He}^*(20.49) \to {}^4\text{He}(0) + (\gamma^* \to e^+e^-), \quad \Delta E = 20.49\ \text{MeV}, \quad \Delta I = 0,$$

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

$$(\text{M0}) \quad {}^4\text{He}^*(21.01) \to {}^4\text{He}(0) + (a \to e^+e^-), \quad \Delta E = 21.01\ \text{MeV}, \quad \Delta I = 0,$$

Forbidden: $(\text{M0}) \quad {}^4\text{He}^*(21.01) \nrightarrow {}^4\text{He}(0) + (\gamma^* \to e^+e^-).$





$$m_a = (16.84 \pm 0.16_{\text{stat}} \pm 0.20_{\text{syst}})\ \text{MeV}$$

General motivation – ATOMKI results

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

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

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

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

Numerically analysis of the data and then put into context constraints from other experiments, notably neutrino scattering experiments.

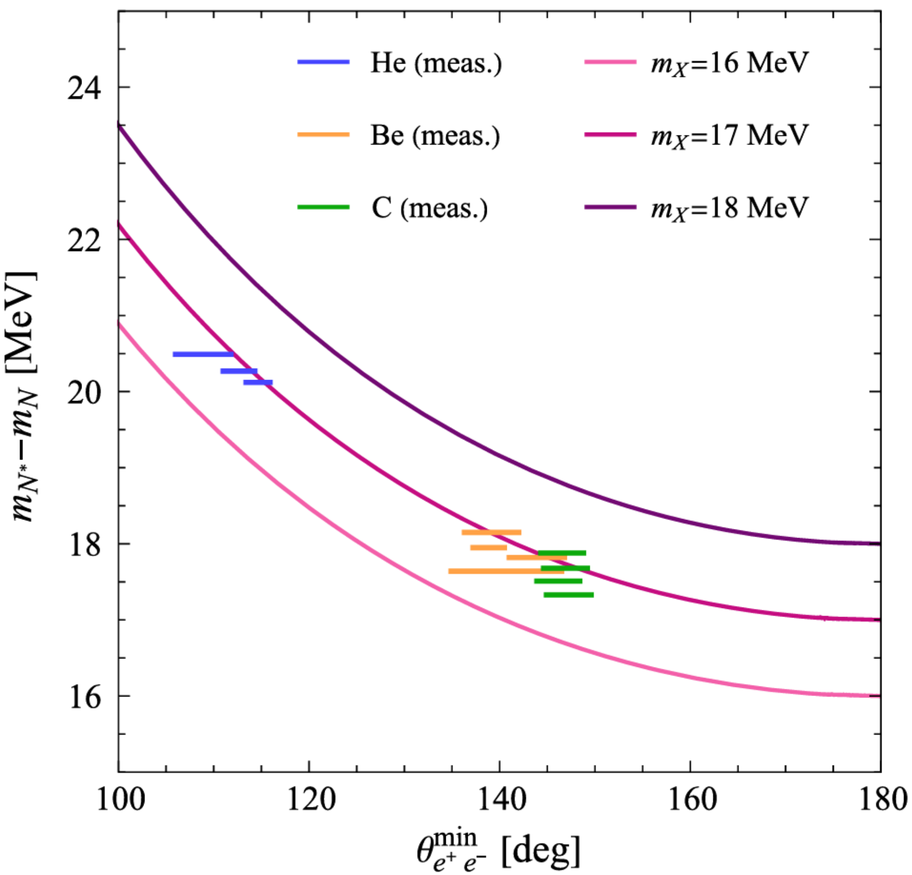


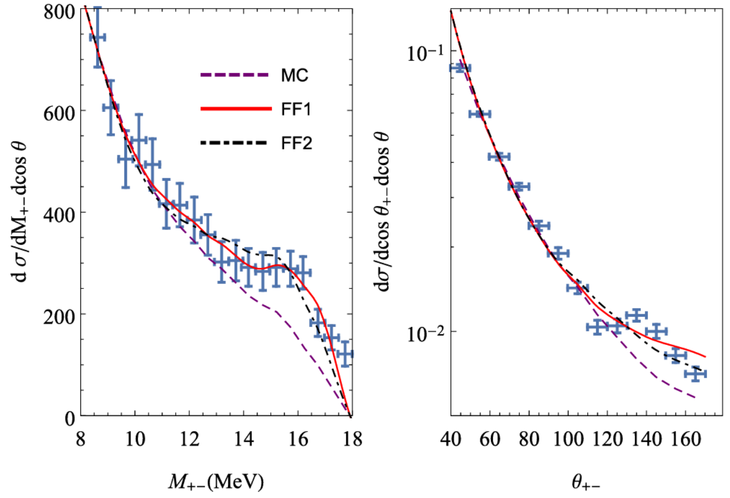
FIG. 1. Measured opening angles of the e^+e^- pairs using the mass differences between different excited states and the ground state of He (blue), Be (orange), C (green). We show contours of different m_X using the relation $\theta^{min}_{e^+e^-} \approx 2\arcsin(m_x/(m_{N^*} - m_N))$ [17].

PHYSICAL REVIEW D **108,** 015009 (2023)

General motivation – ATOMKI interpretation

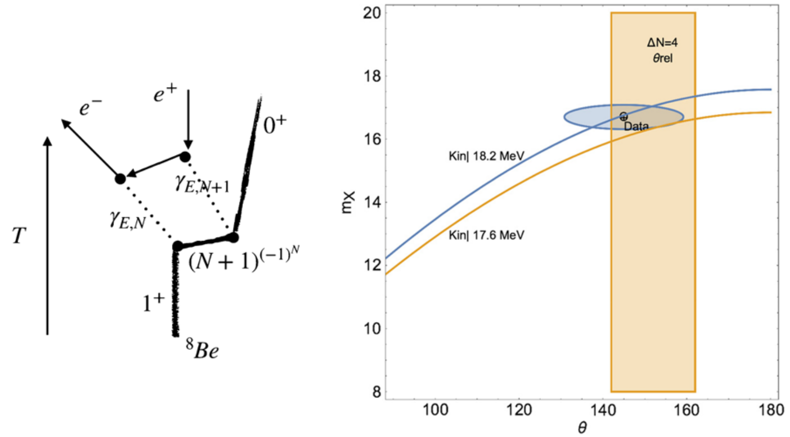
The Standard Model interpretation:

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.



Physics Letters B 773 (2017) 159–165

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



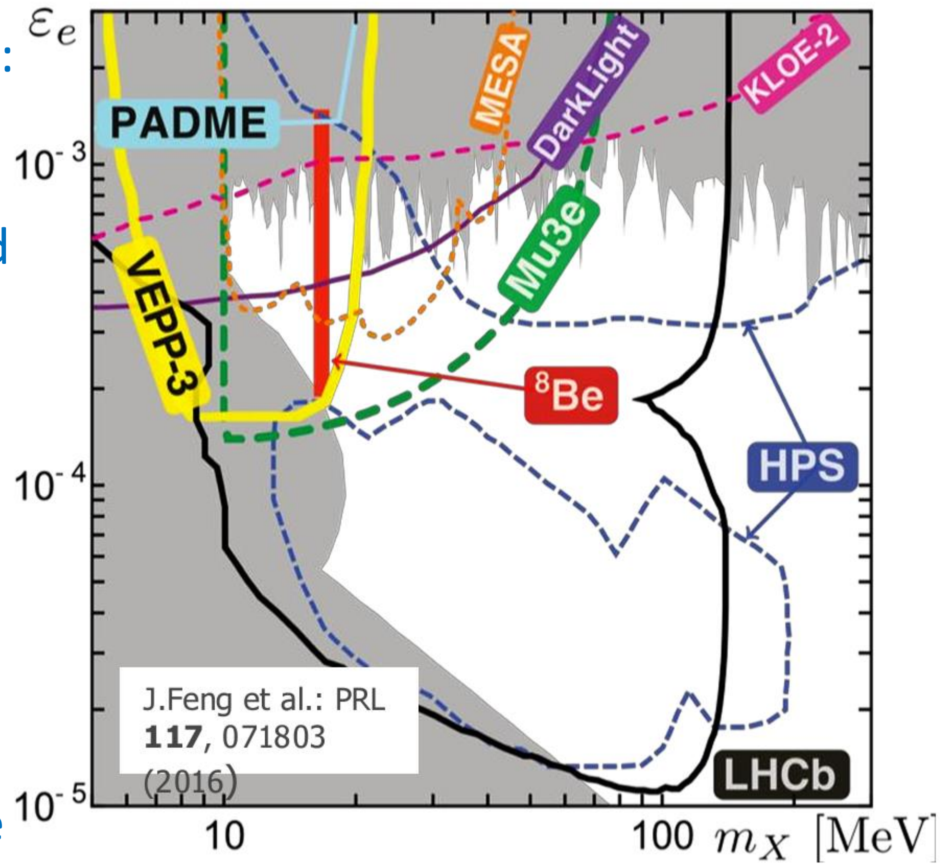
Nuclear Physics A 1008 (2021) 122143

General motivation – ATOMKI interpretation

The Beyond Standard Model interpretation:

- The first theoretical interpretation of the 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, **"protophobic force".**

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Protophobic Fifth-Force Interpretation of the Observed Anomaly in ^{8}Be Nuclear Transitions

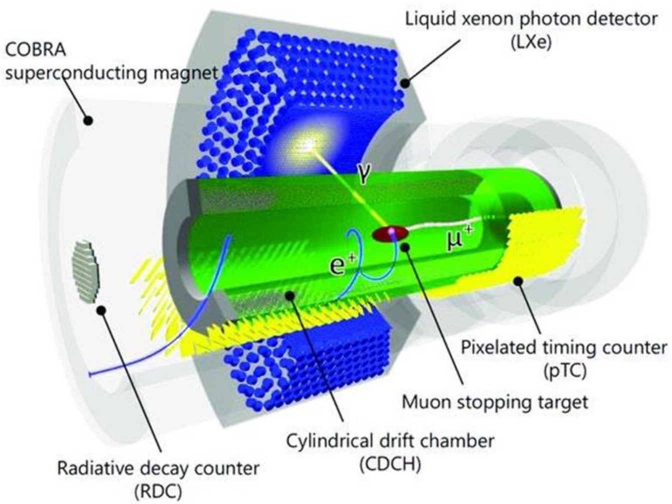
Jonathan L. Feng, Bartosz Fornal, Iftah Galon, Susan Gardner, Jordan Smolinsky, Tim M. P. Tait, and Philip Tanedo

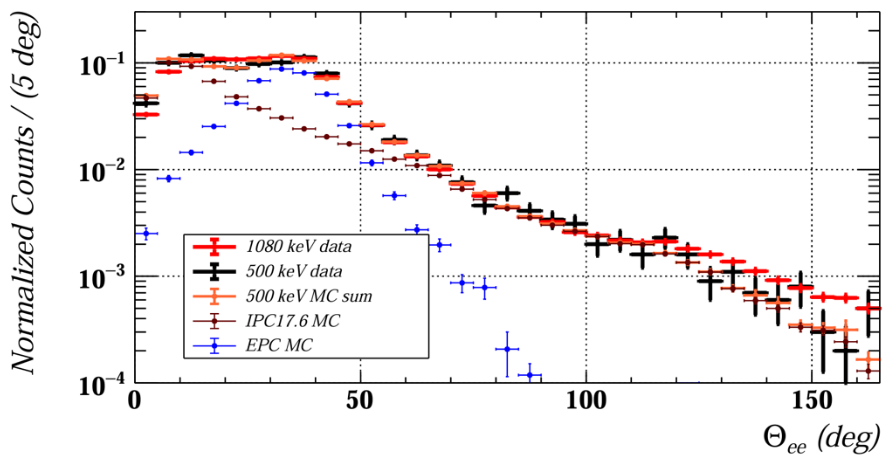
Phys. Rev. Lett. **117**, 071803 – Published 11 August 2016

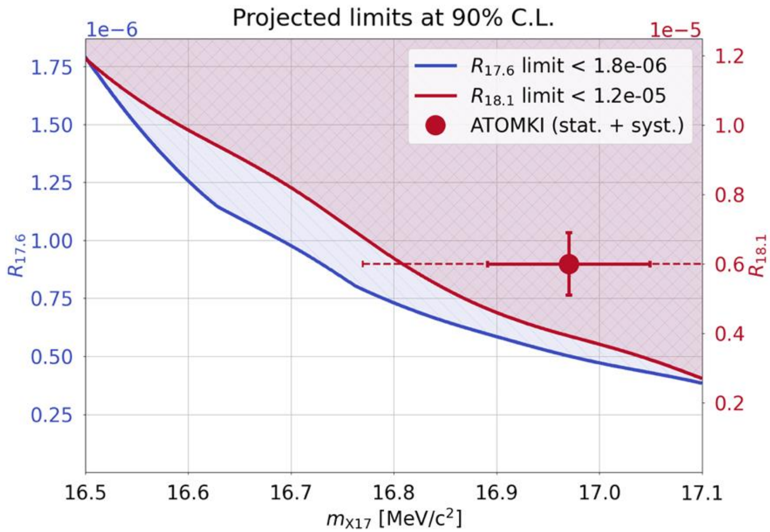
Dark photon

General motivation – MEG-II result (from 12.11.2024)

- MEG-II (PSI) experiment searches for charged lepton flavour violating decays $\mu^+ \rightarrow e^+\gamma$.
- 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)

Current experimental studies:

- Direct searches
- Proton beam dump
- Electron beam dump
- Fixed target electron scattering
- Fixed target proton experiments
- Colliders

Cosmic rays (Direct searches)

Higher Luminosity Accelerators (Proton beam dump, Electron beam dump, Fixed target electron scattering, Fixed target proton experiments)

Lower Luminosity Accelerators (Colliders)

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	$y_N L H N$

Invisible, non-SM

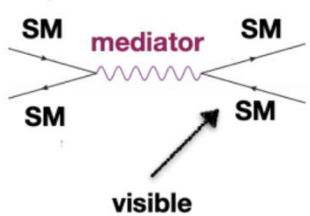
Dark Matter production

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

Visible, SM

Production of portal-mediators that decay to SM particles

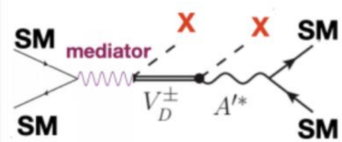
Systematically exploring the portal coupling to SM particles



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

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.

Connection between Standard and Dark Matter

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[G. Krnjaic RF6 Meeting, 8/2020]

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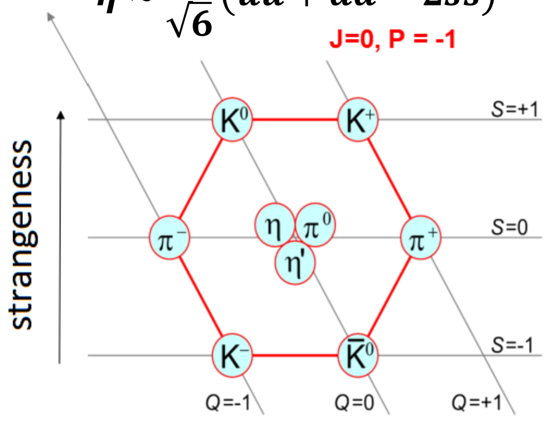
- The **η/η'** decays are flavor-conserving reactions

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



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%)

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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

Physical Axion current

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

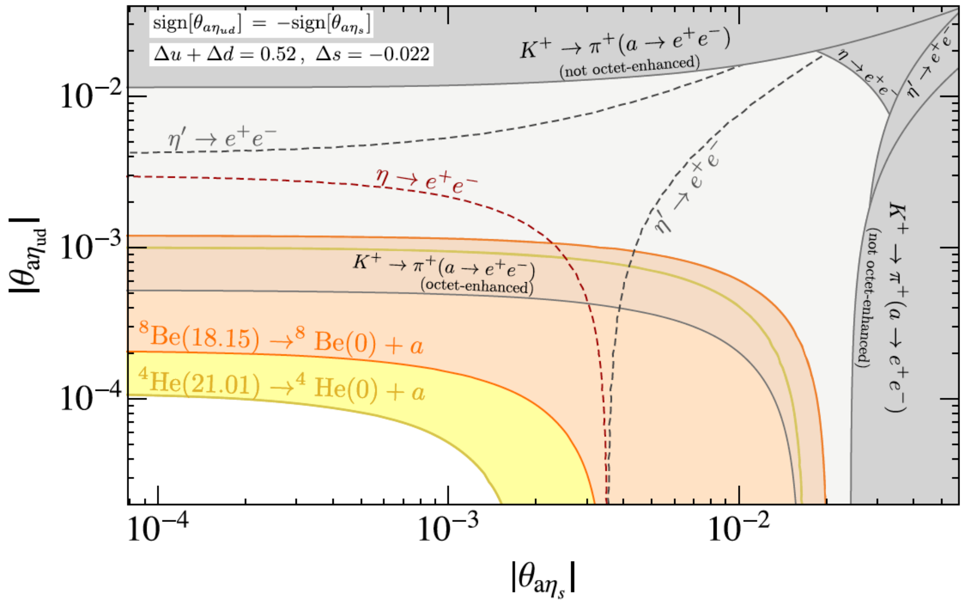
Axionic field and the neutral meson degrees of freedom mix among themselves to yield the physical degrees of freedom:

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

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

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

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



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)

QCD Axion

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

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

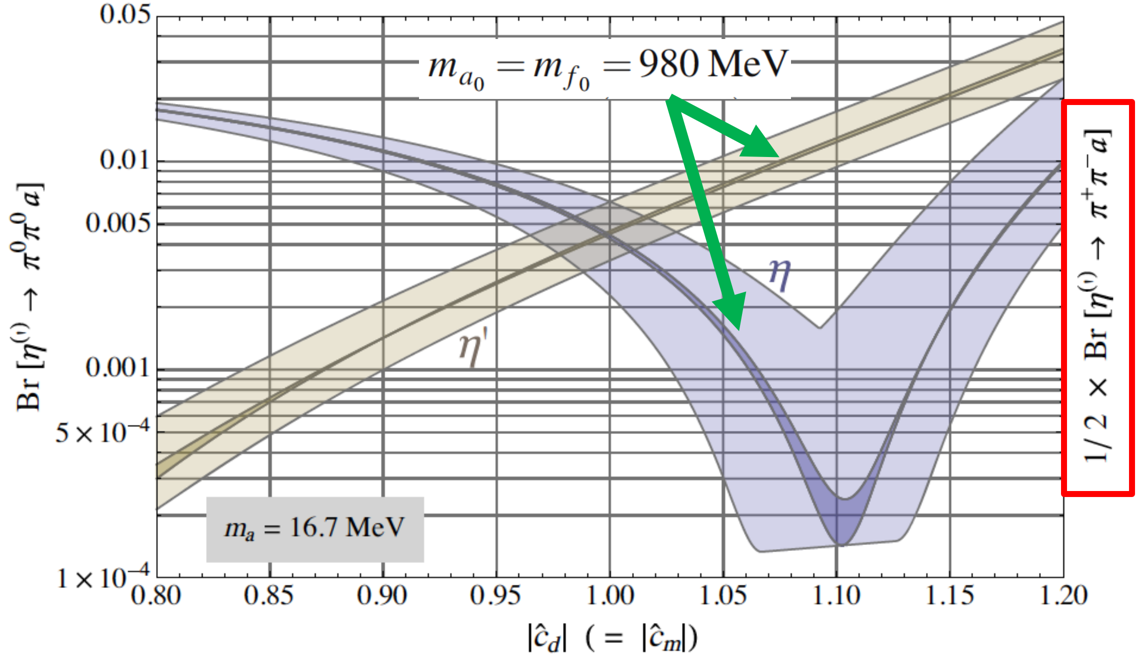
"axio-hadronic decay"

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.

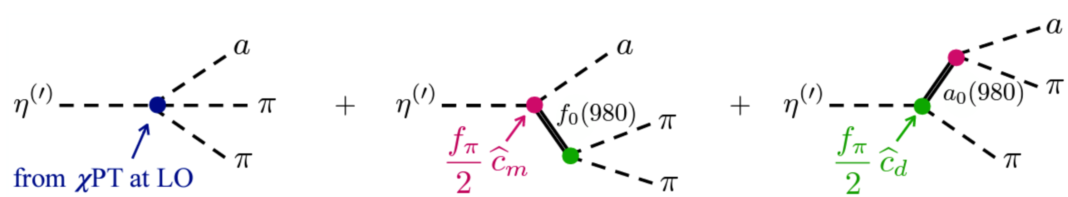
„…. O(10^{-2}), is probably excluded or in tension with observations but O(10^{-4} - 10^{-3}) likely remains experimentally allowed, and within the sensitivity."

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



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

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



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

QCD Axion

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

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"axio-hadronic decay"

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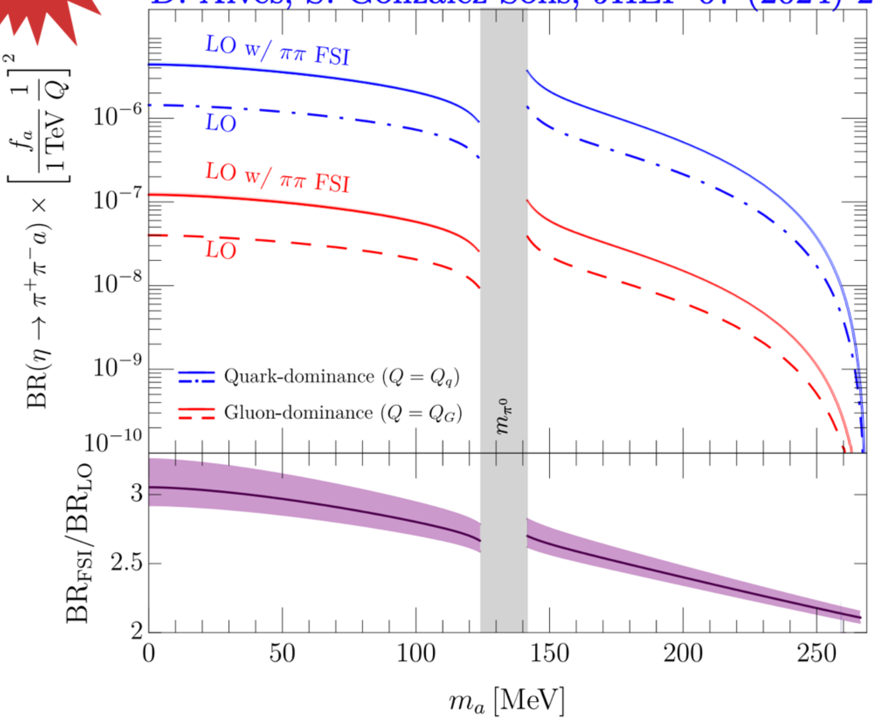
χPT predictions for decay rates significantly modified by inclusion of resonance exchange.

„.... 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."

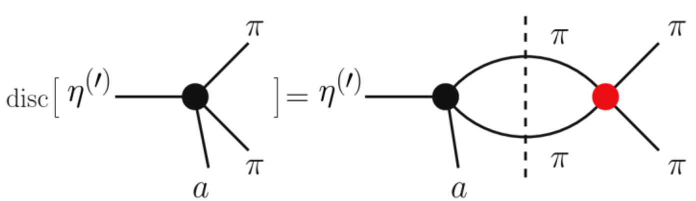
NEW

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



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

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



QCD Axion

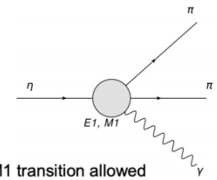
Why previous measurements $\eta(\eta') \to \pi^+ \pi^- e^+ e^-$ did not see Axion signatures ?

Previous exp. of the $\eta\ (\eta') \to \pi^+ \pi^- e^+ e^-$ studied CP invariance

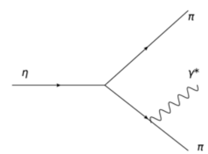
Not much experimental indications for the violation of CP symmetry in flavour-conserving reactions (KLOE 2009, WASA-at-COSY 2016).

polarization can be studied via asymmetry:

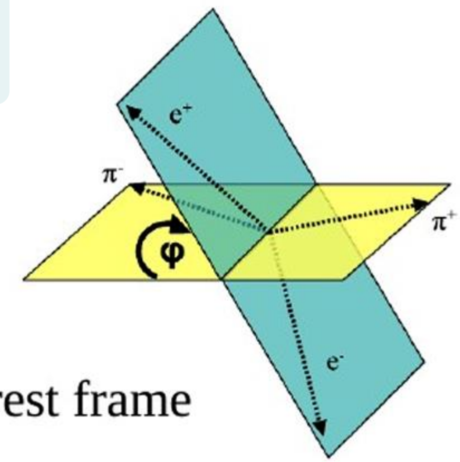
$$A_\phi = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$$



M1 transition allowed
E1 transition violates CP



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



η rest frame

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 $\eta \to e^+ e^- g^*$

Experimental results up to now:

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**	-	$(4.3 \pm 1.3_{stat} \pm 0.4_{syst}) \times 10^{-4}$

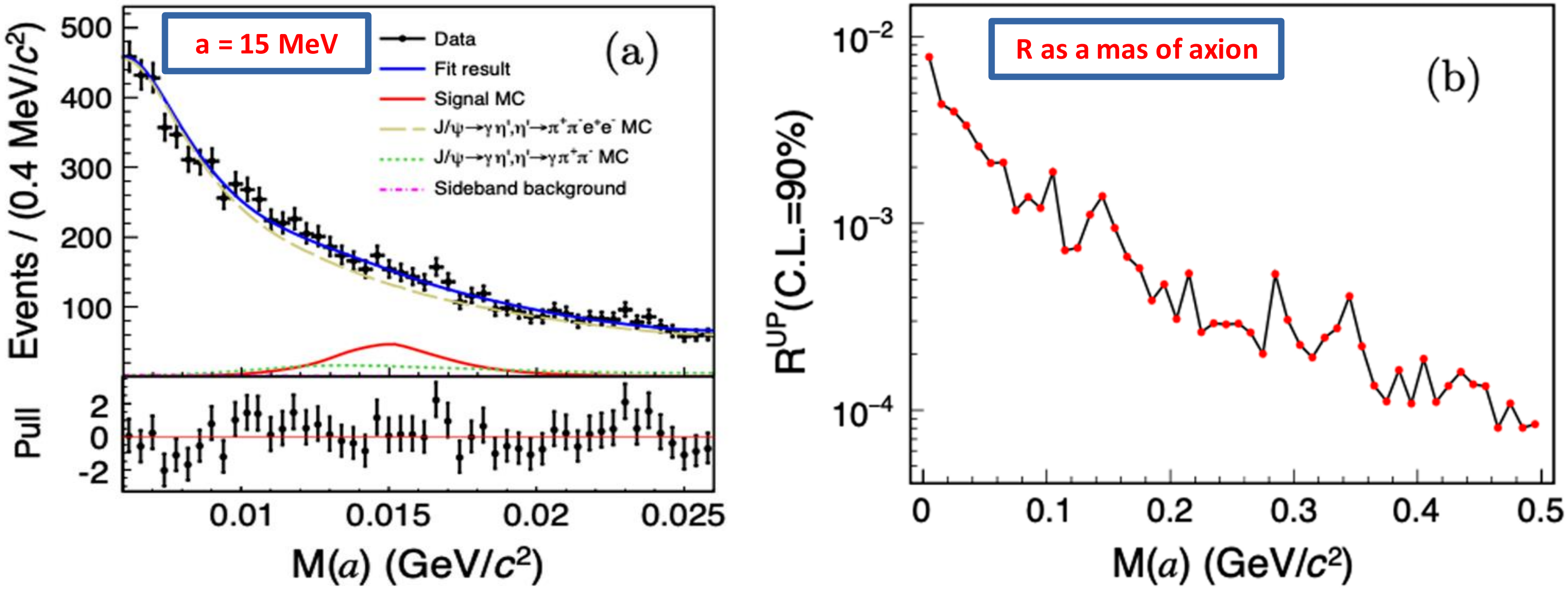
Rejected events $m(e^+e^-) < 15$ MeV

BES III – Result for the η’→ π+ π- e+ e- decay

BES III – Result for the η’→ π+ π- e+ e- decay (also CP invariance studies):

The experimental sample: $J/\psi \rightarrow \gamma\eta' \rightarrow (10087 \pm 44) \times 10^6$

$$\eta' \rightarrow \pi^+\pi^-e^+e^- \rightarrow 2.3 \times 10^7$$



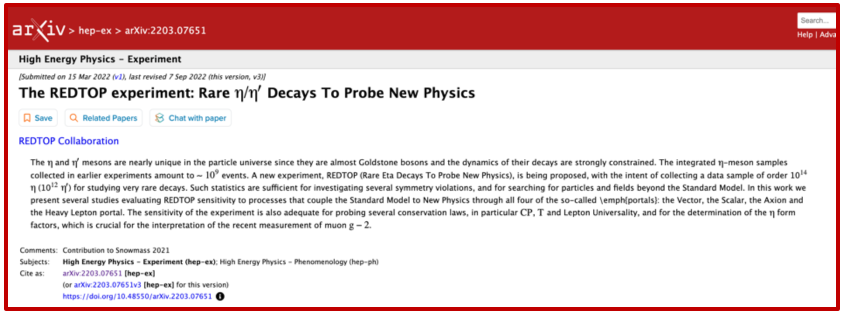
$$\mathcal{B}(\eta' \rightarrow \pi^+\pi^-e^+e^-) = (2.45 \pm 0.02(\text{stat.}) \pm 0.08(\text{syst.})) \times 10^{-3}$$

$$R^{\text{UP}} = \frac{\mathcal{B}(\eta' \rightarrow \pi^+\pi^- a) \cdot \mathcal{B}(a \rightarrow e^+e^-)}{\mathcal{B}(\eta' \rightarrow \pi^+\pi^-e^+e^-)} = (0.1 - 7.8) \times 10^{-3}$$

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

RED Top – future (?) η factory

Pseudoscalar Portal: $\eta \to \pi^+ \pi^- a \quad (a \to e^+ e^-)$


arXiv > hep-ex > arXiv:2203.07651

High Energy Physics – Experiment

[Submitted on 15 Mar 2022 (v1), last revised 7 Sep 2022 (this version, v3)]

The REDTOP experiment: Rare η/η′ Decays To Probe New Physics

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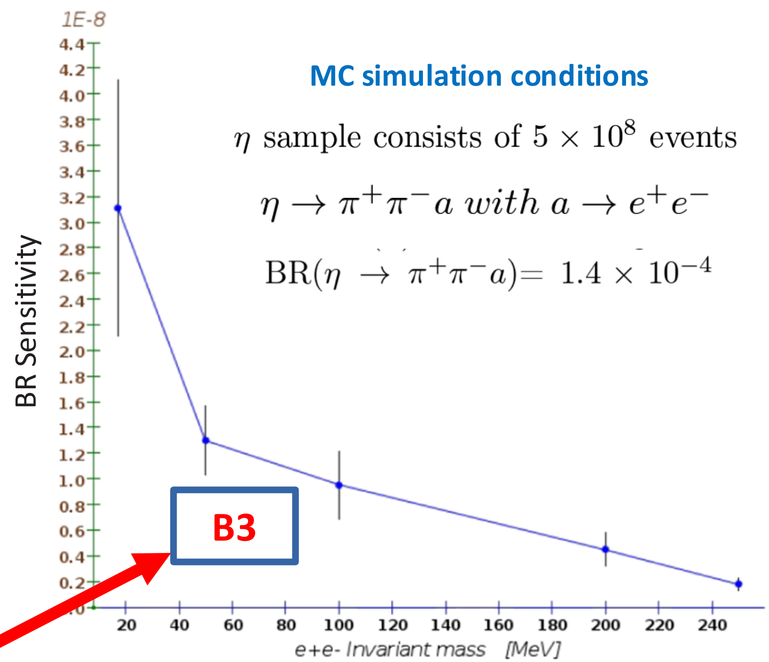
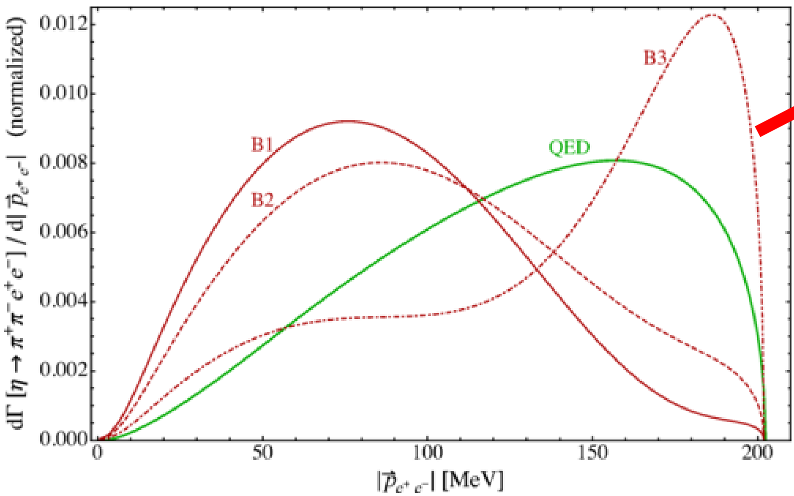
REDTOP Collaboration

The η and η′ mesons are nearly unique in the particle universe since they are almost Goldstone bosons and the dynamics of their decays are strongly constrained. The integrated η-meson samples collected in earlier experiments amount to ~ 10^9 events. A new experiment, REDTOP (Rare Eta Decays To Probe New Physics), is being proposed, with the intent of collecting a data sample of order 10^{14} η (10^{12} η′) for studying very rare decays. Such statistics are sufficient for investigating several symmetry violations, and for searching for particles and fields beyond the Standard Model. In this work we present several studies evaluating REDTOP sensitivity to processes that couple the Standard Model to New Physics through all four of the so-called \emph{portals}: the Vector, the Scalar, the Axion and the Heavy Lepton portal. The sensitivity of the experiment is also adequate for probing several conservation laws, in particular CP, T and Lepton Universality, and for the determination of the η form factors, which is crucial for the interpretation of the recent measurement of muon g – 2.

Comments: Contribution to Snowmass 2021
Subjects: High Energy Physics – Experiment (hep-ex); High Energy Physics – Phenomenology (hep-ph)
Cite as: arXiv:2203.07651 [hep-ex]
(or arXiv:2203.07651v3 [hep-ex] for this version)
https://doi.org/10.48550/arXiv.2203.07651

Process	Benchmark set	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction*	Analysis	**Total**	BR sensitivity
$\eta \to \pi^+\pi^- a\ ;\ a \to e^+e^-$	B1	55.28%	21.81%	76.41%	75.12%	42.94%	2.97%	2.07×10^{-8}
$\eta \to \pi^+\pi^- a\ ;\ a \to e^+e^-$	B2	56.15%	22.32%	76.76%	75.12%	42.83%	3.10%	1.98×10^{-8}
$\eta \to \pi^+\pi^- a\ ;\ a \to e^+e^-$	B3	59.67%	23.06%	79.81%	76.14%	44.03%	3.68%	1.67×10^{-8}
Urqmd		21.7%	1.7%	22.2%	0.26%	1.04%	2.31×10^{-6}%	





17 MeV piophobic QCD axion

Differential rate for η→π⁺π⁻a for three benchmark params.

The differential rate for $\eta \to \pi^+\pi^- a$ as a function of $|\vec{p}_{e^+e^-}| \equiv |\vec{p}_{e^+} + \vec{p}_{e^-}| = \vec{p}_a$, for three benchmark choices of RχT parameters specified in Table I. For comparison, we also show the differential rate of the SM process $\eta \to \pi^+\pi^- e^+e^-$, labeled "QED."

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

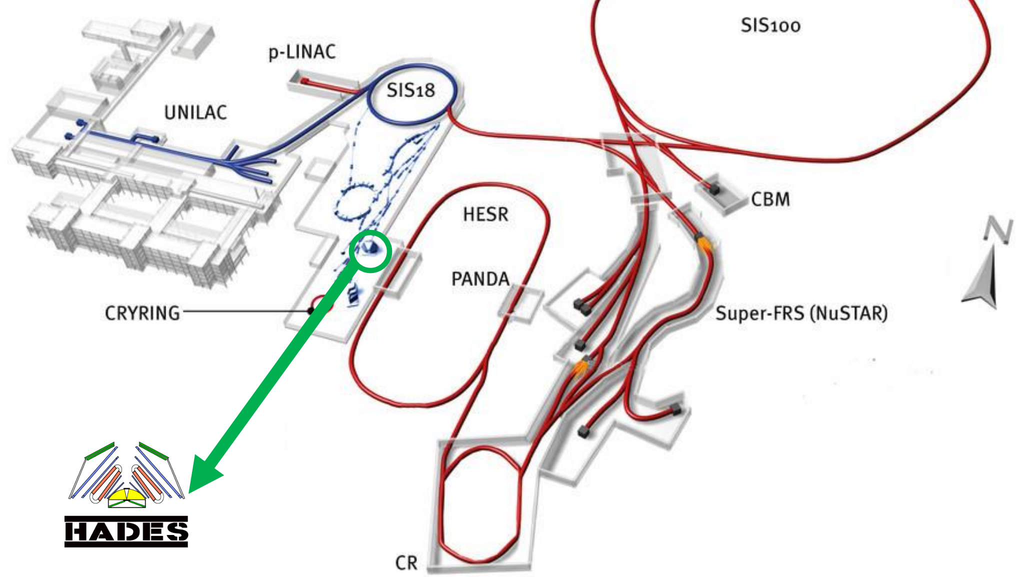
II. Analysis status of pp@4.5 GeV data

(analysis by K. Prościński)

HADES - High Acceptance Di-Electron Spectrometer

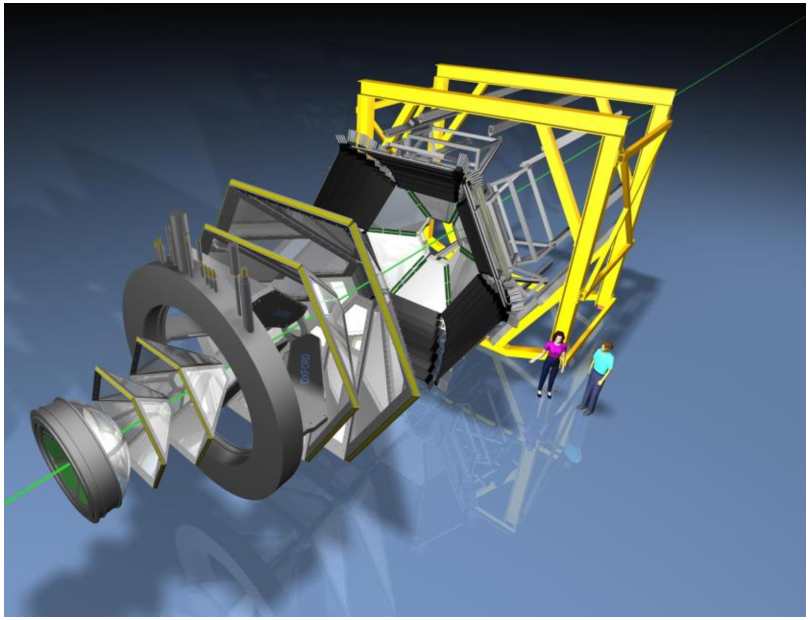
GSI Helmholtzzentrum für Schwerionenforschung

FAIR



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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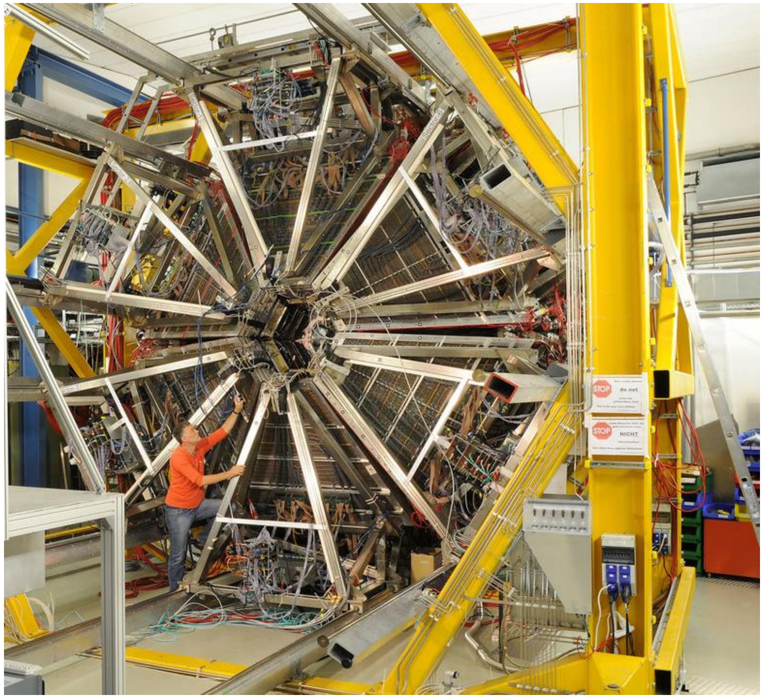
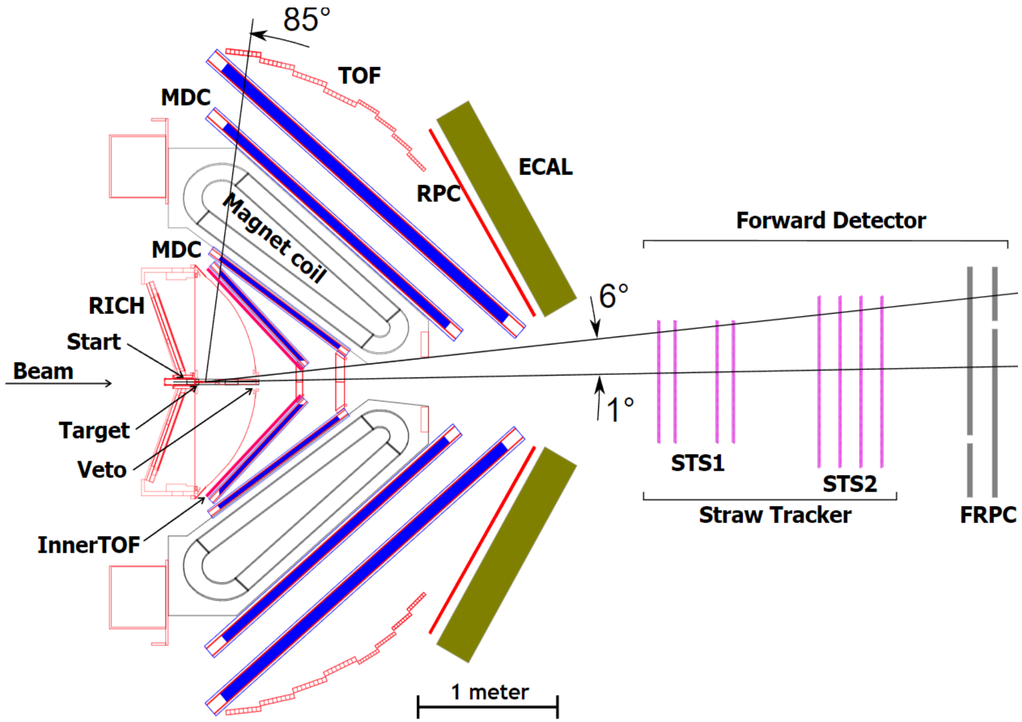
HADES - High Acceptance Di-Electron Spectrometer





- **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)

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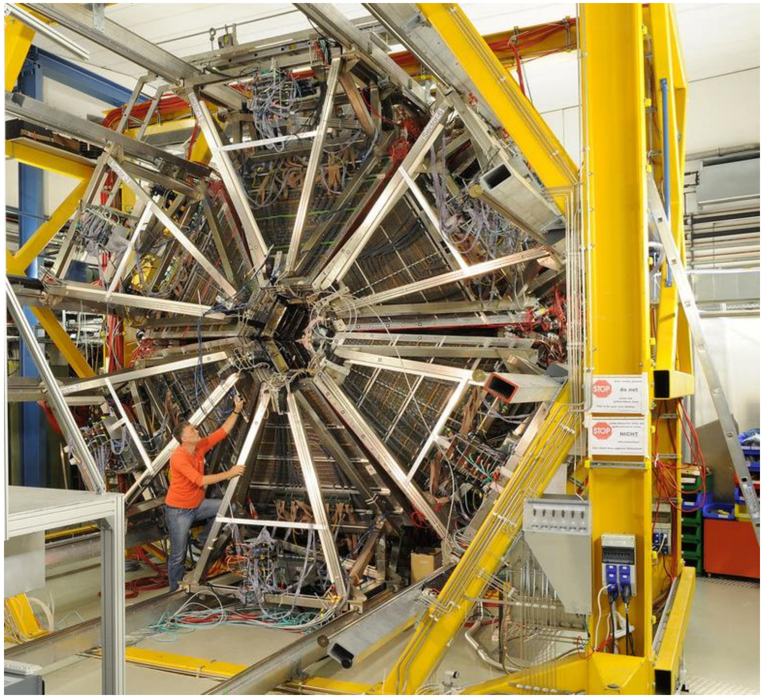
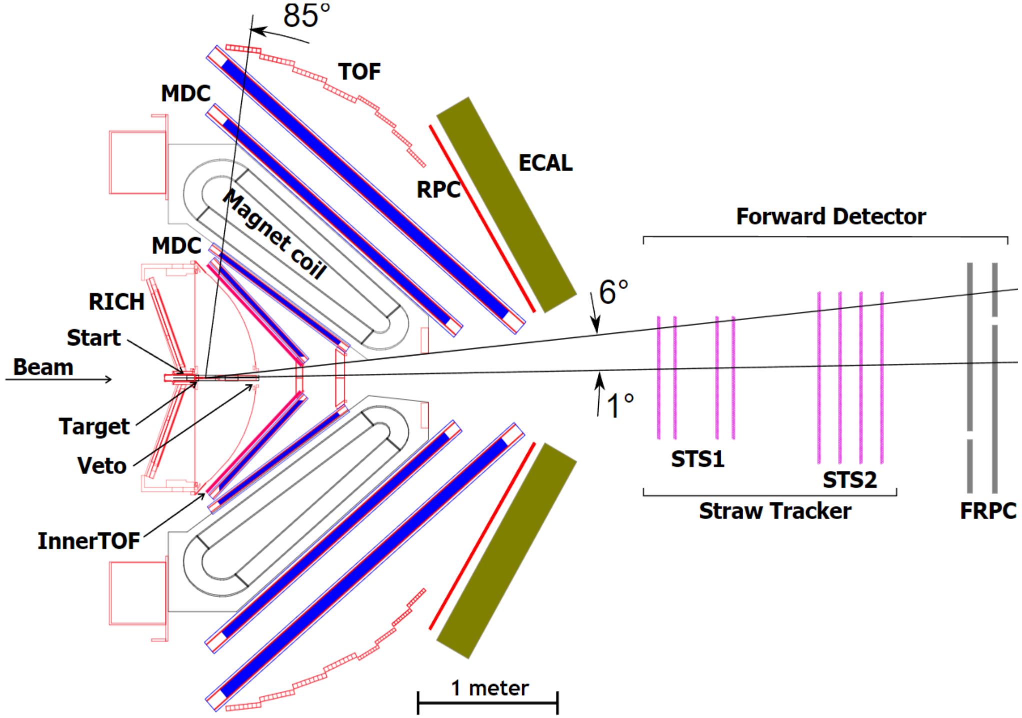
HADES - High Acceptance Di-Electron Spectrometer





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}]**

Other studies with light mesons using HADES

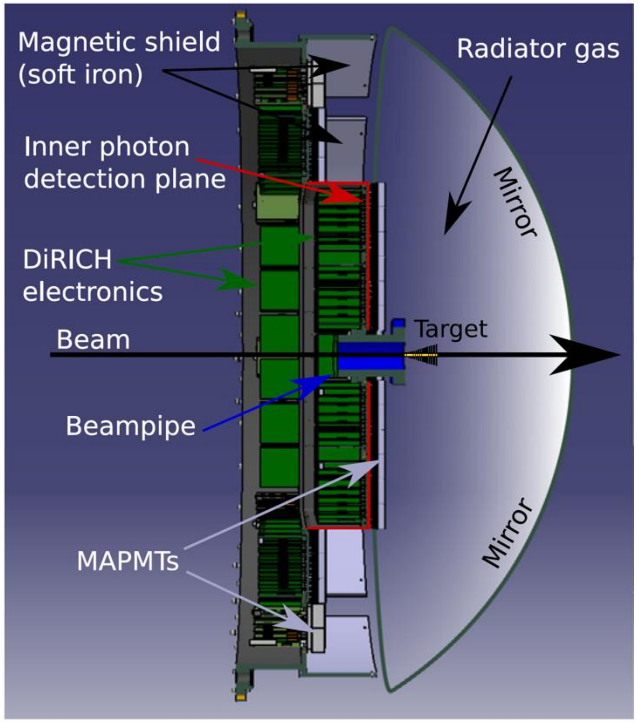
- Exclusive production of η and ω in proton-proton collisions (production mechanism at intermediate energies, cross section extraction, angular distributions).
- Inclusive production of η and ω in proton-proton (inclusive cross section extraction).
- Form Factor extraction for the $\eta \rightarrow \gamma e^+ e^-$ 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: $\eta \rightarrow \pi^+ \pi^- e^+ e^-$, $\eta \rightarrow \pi^0 e^+ e^-$, $\eta \rightarrow \pi^+ \pi^- \pi^0$.

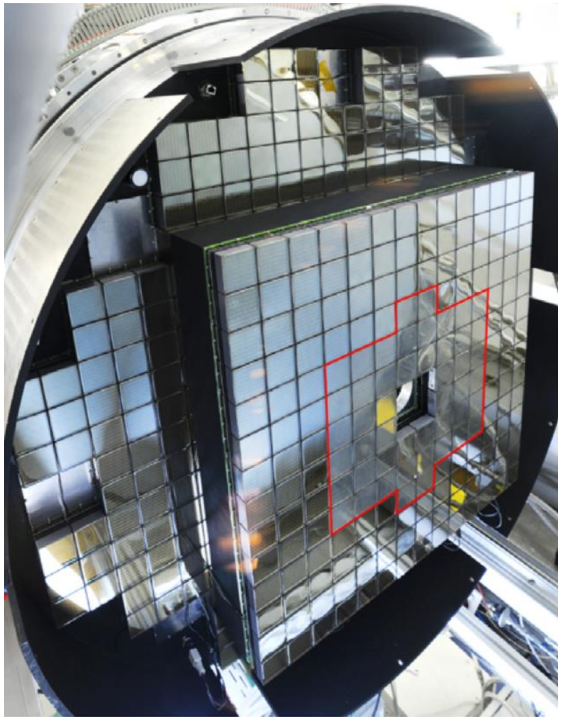
Szymon Treliński, Iza Ciepał

Adam Strach, Iza Ciepał

Future analysis

Lepton identification using HADES RICH Detector



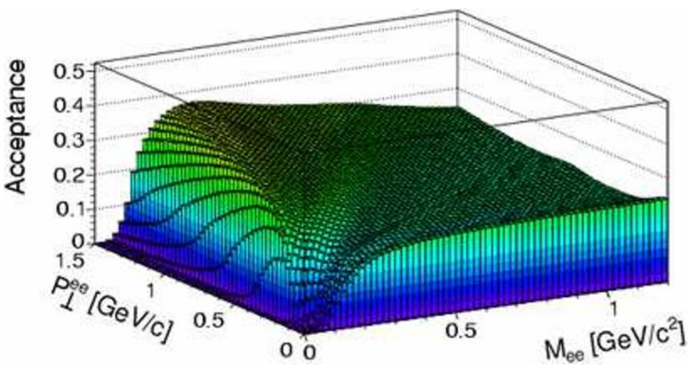


- Lepton identification base on signals in RICH.
- Threshold momentum for electrons 9 MeV and for pions 2500 MeV.
- Acceptance as a function of transverse momentum and e^+e^- invariant mass.
- In standard HADES analysis e^+e^- opening angle > 9° to subtract conversion.

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

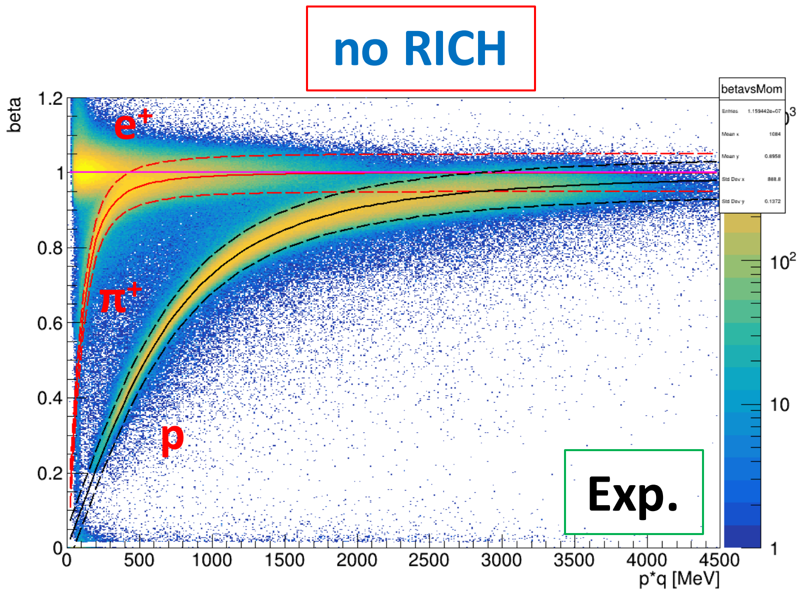
$\beta_\pi < \beta_{Cher} < \beta_e$

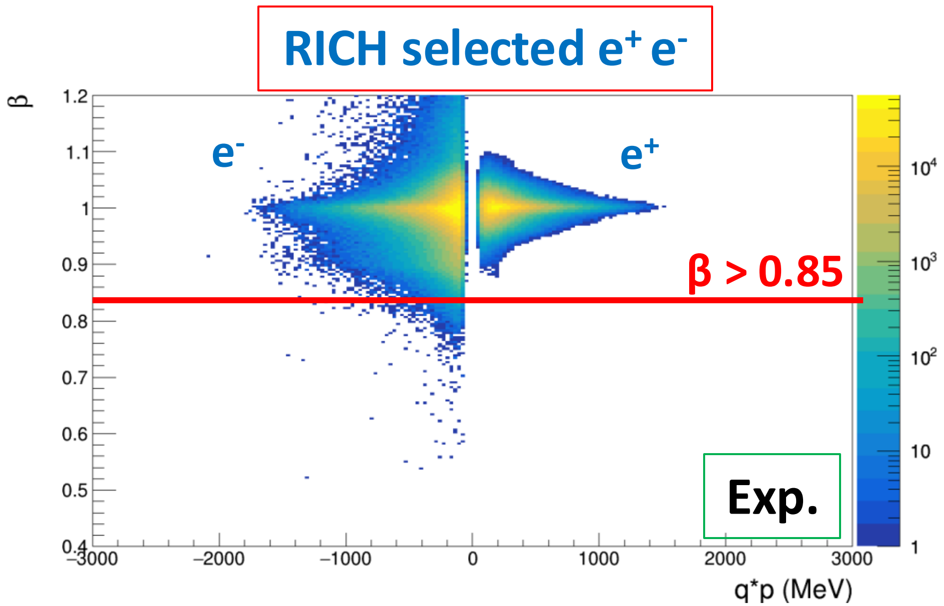
e^+e^- creates Cherenkov radiation



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



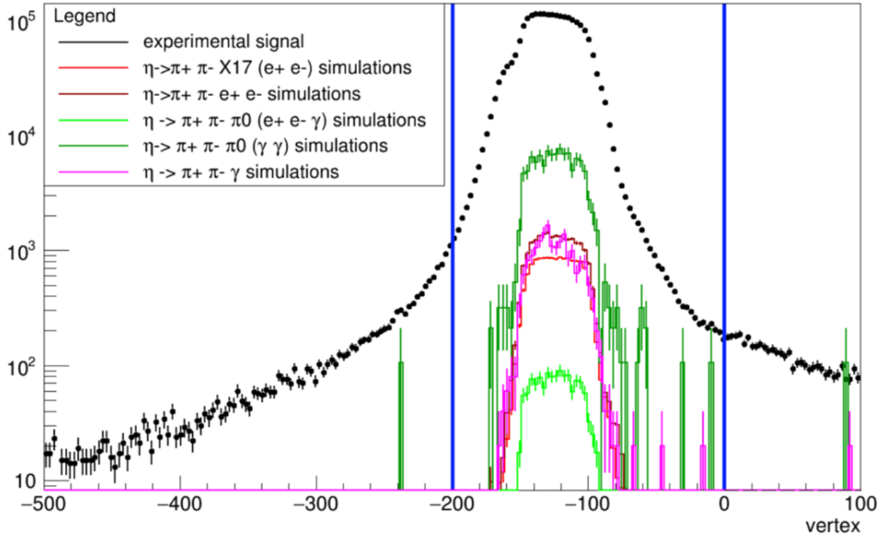


Following particles have to be selected: **π^+ π^- e^+ e^-**

- 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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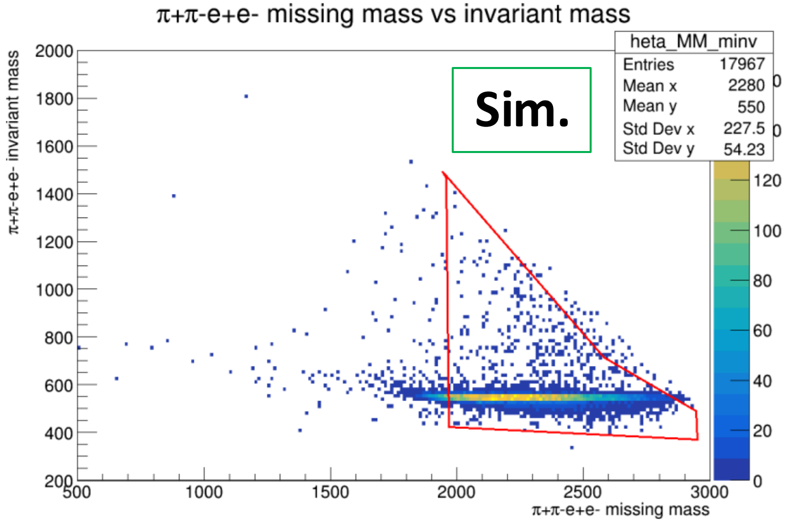

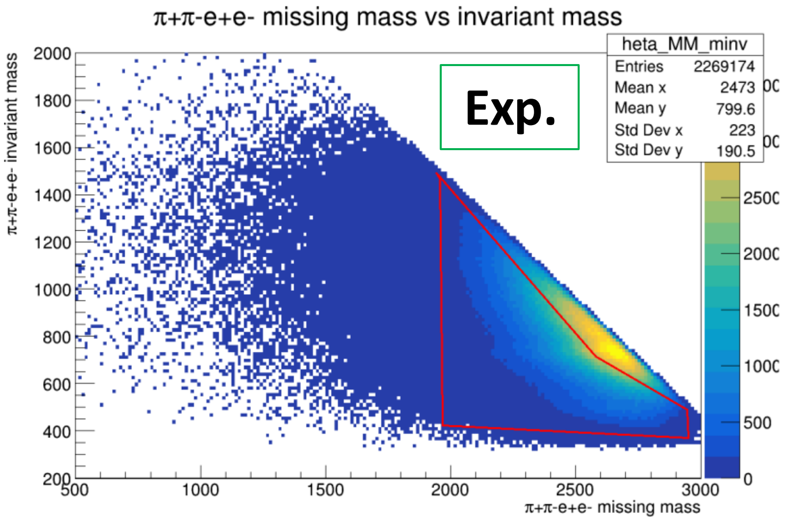

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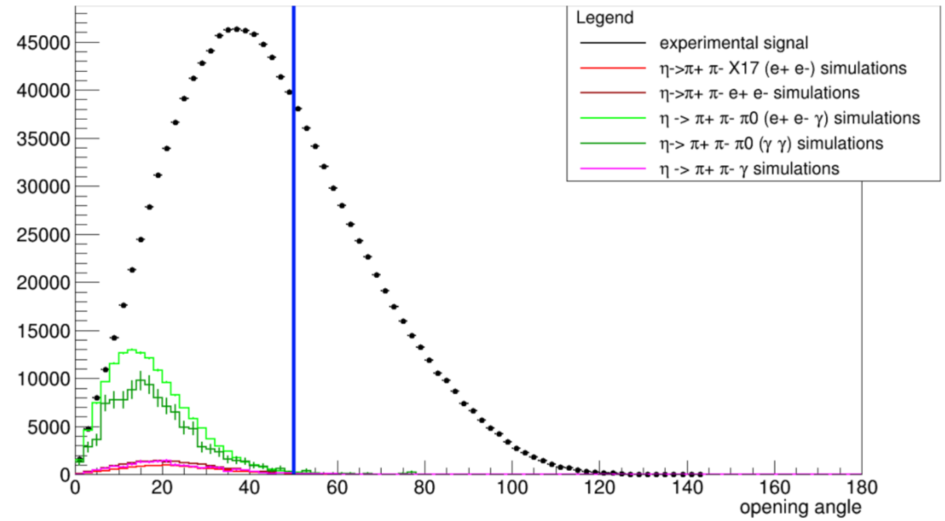
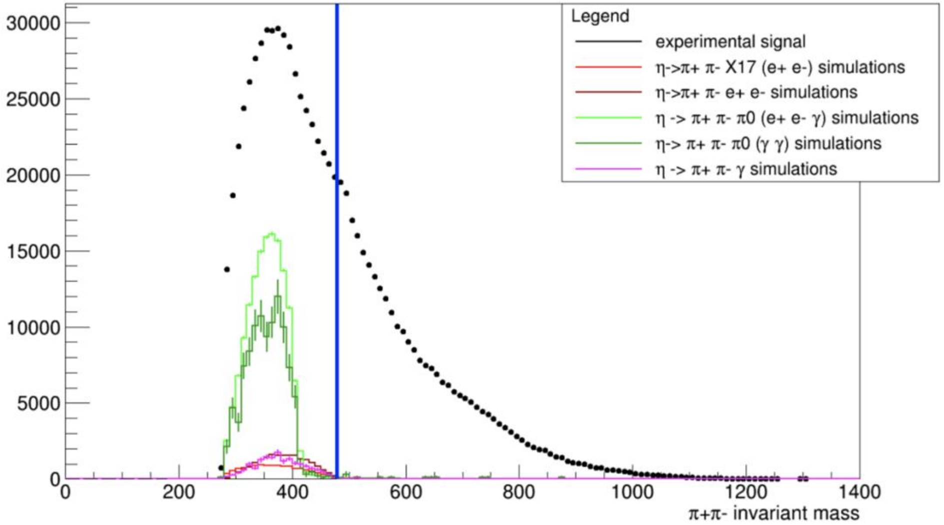


Event selection for the **η → π⁺ π⁻ e⁺ e⁻** decay

- 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 η → π⁺ π⁻ 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°
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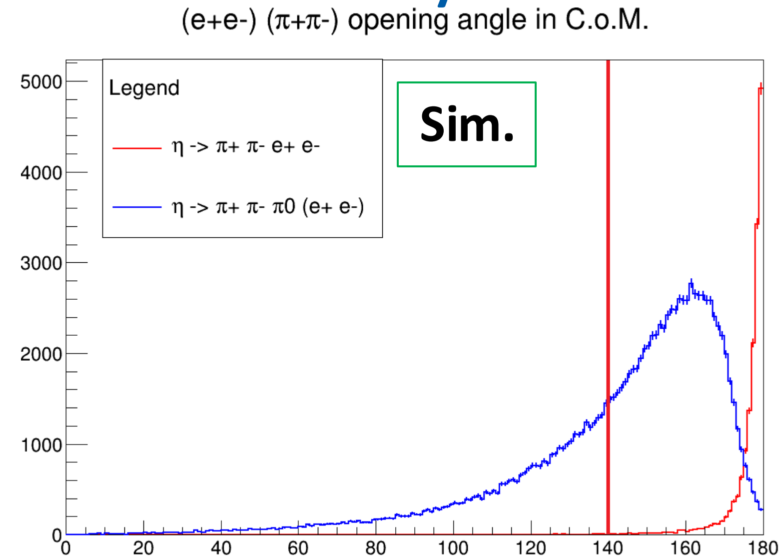
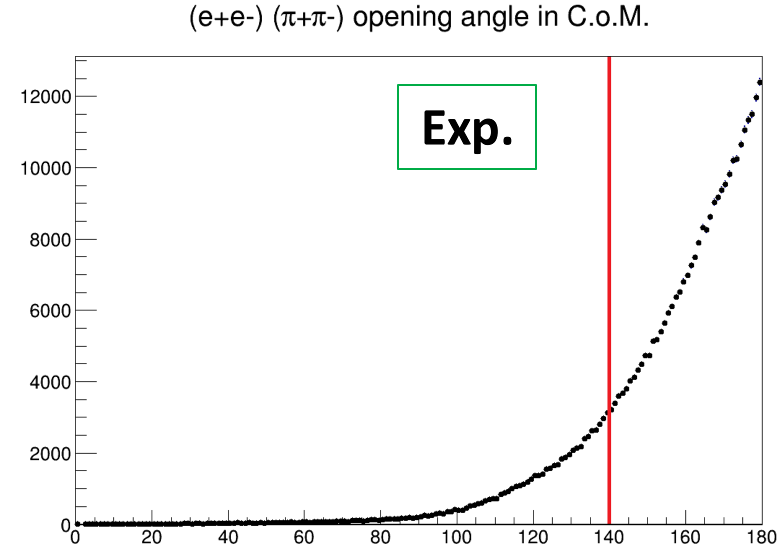
- **$(e^+e^-)(\pi^+\pi^-)$ opening angle in CM > 140°**

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

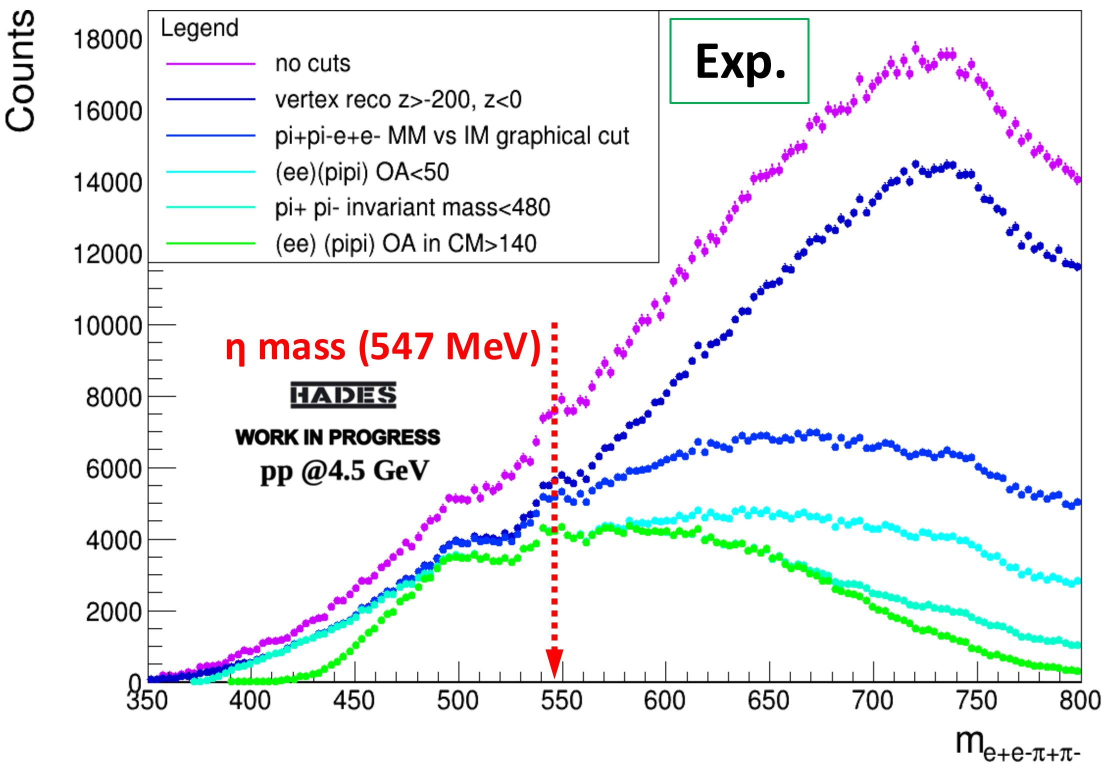




Event selection for the η → $\pi^+ \pi^- e^+ e^-$ decay

- 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.

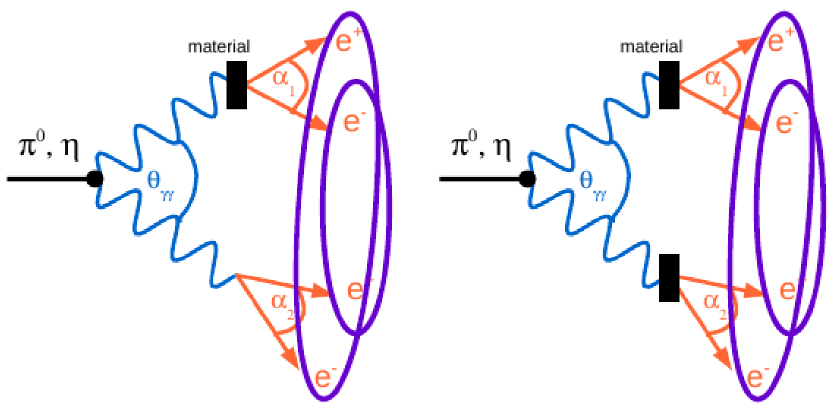


Event selection for the η → π⁺ π⁻ e⁺ e⁻ decay

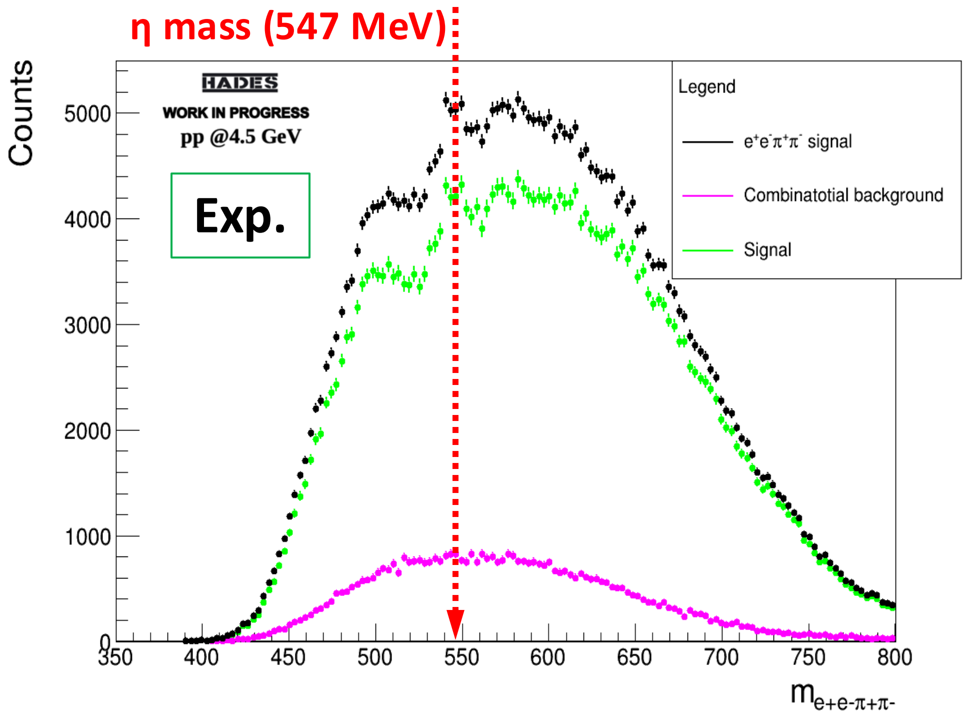
- Combinatorial background substraction:

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

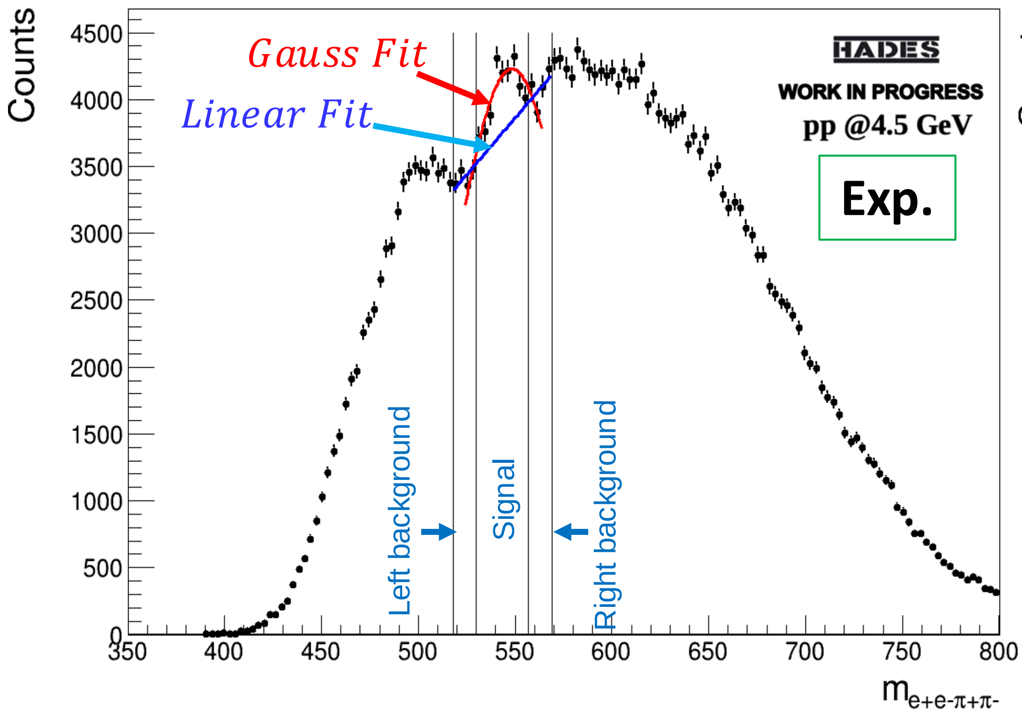
$$\langle N_{signal}\rangle = \langle N_{\pi^+\pi^-e^+e^-}\rangle - \langle N_{CB}\rangle$$

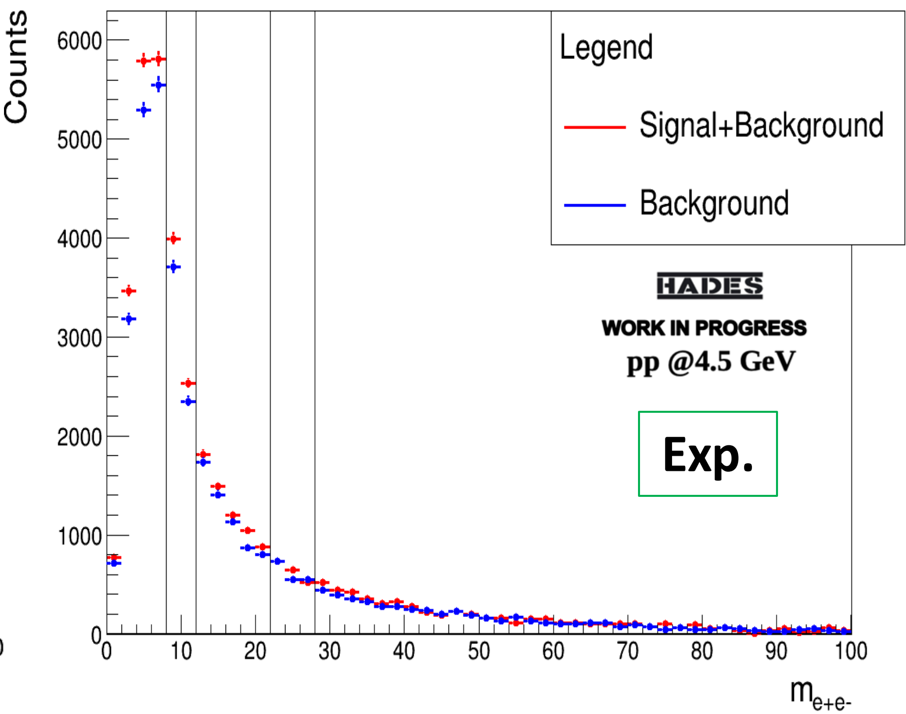


Ref.: *Szymon Harabasz, HADES PhD Thesis (2018)*



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



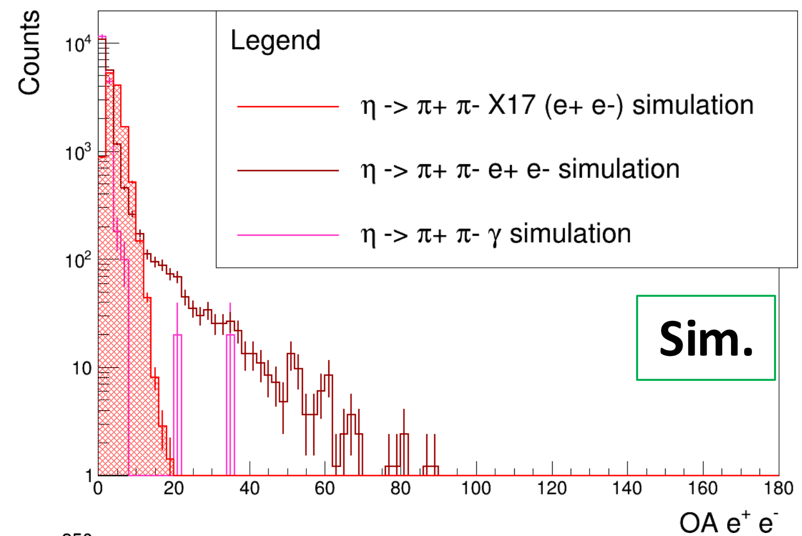


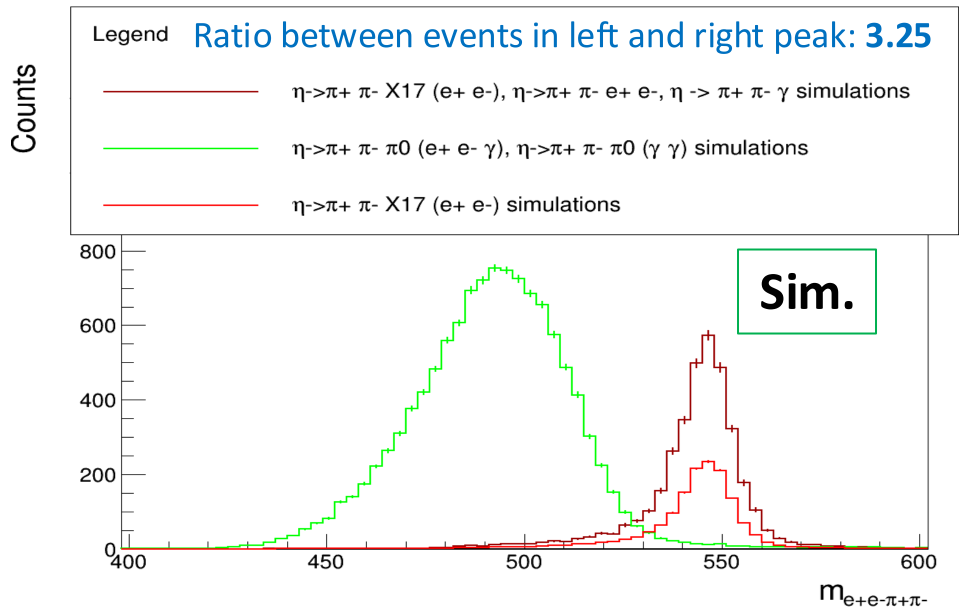
Estimated numer of signal events	2758
η peak mean (MeV)	548.40
η peak sigma (MeV)	32.59

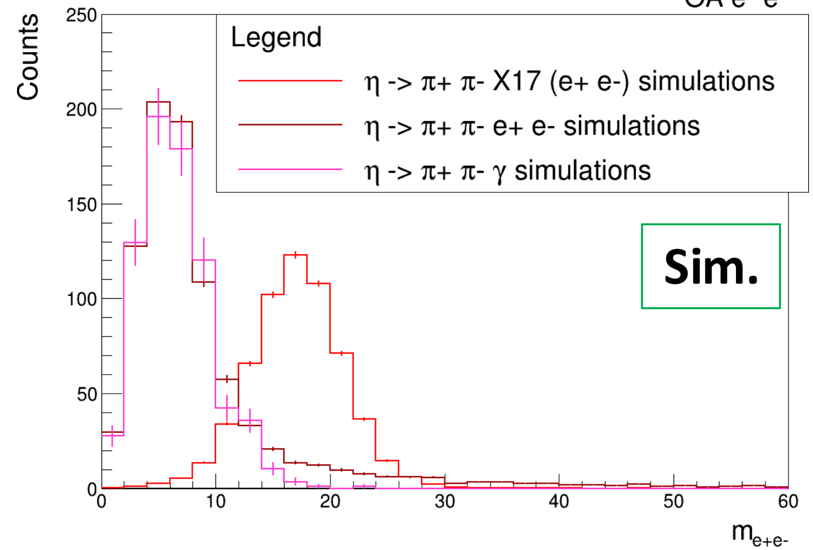
Simulations of signal and background

Signal and main background reactions:

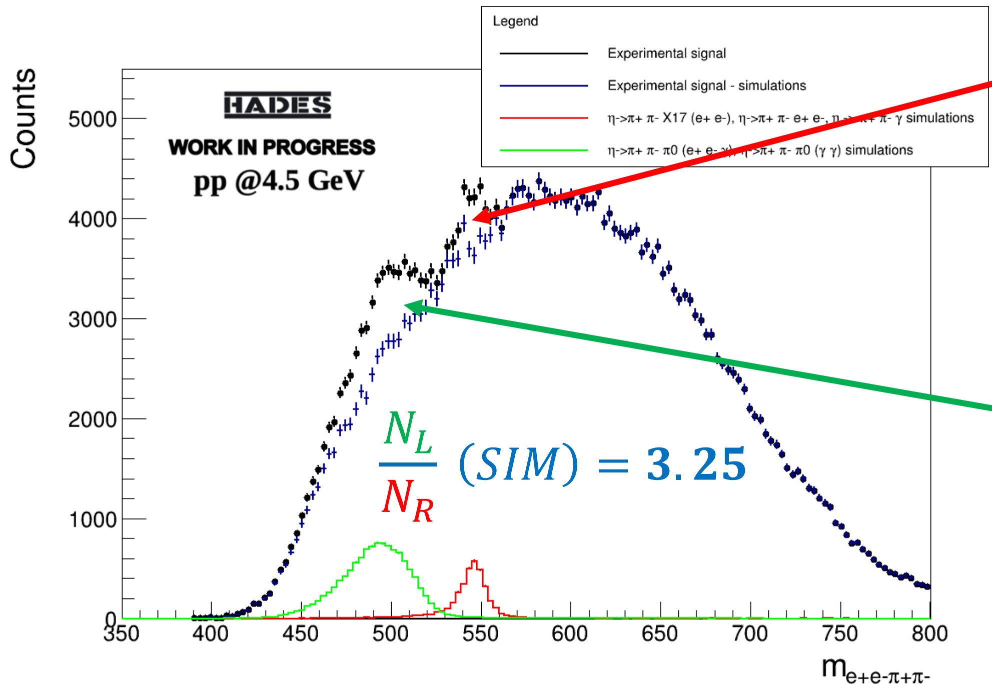
- $pp\,\eta \rightarrow pp\,\pi^+\,\pi^-\,e^+\,e^-$
- $pp\,\eta \rightarrow pp\,\pi^+\,\pi^-\,X17\,(e^+\,e^-)$
- $pp\,\eta \rightarrow pp\,\pi^+\,\pi^-\,\pi^0\,(e^+\,e^-\,\gamma)$
- $pp\,\eta \rightarrow pp\,\pi^+\,\pi^-\,\pi^0\,(\gamma\,\gamma)$
- $pp\,\eta \rightarrow pp\,\pi^+\,\pi^-\,\gamma$







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%	$4.28 \cdot 10^{-2}$

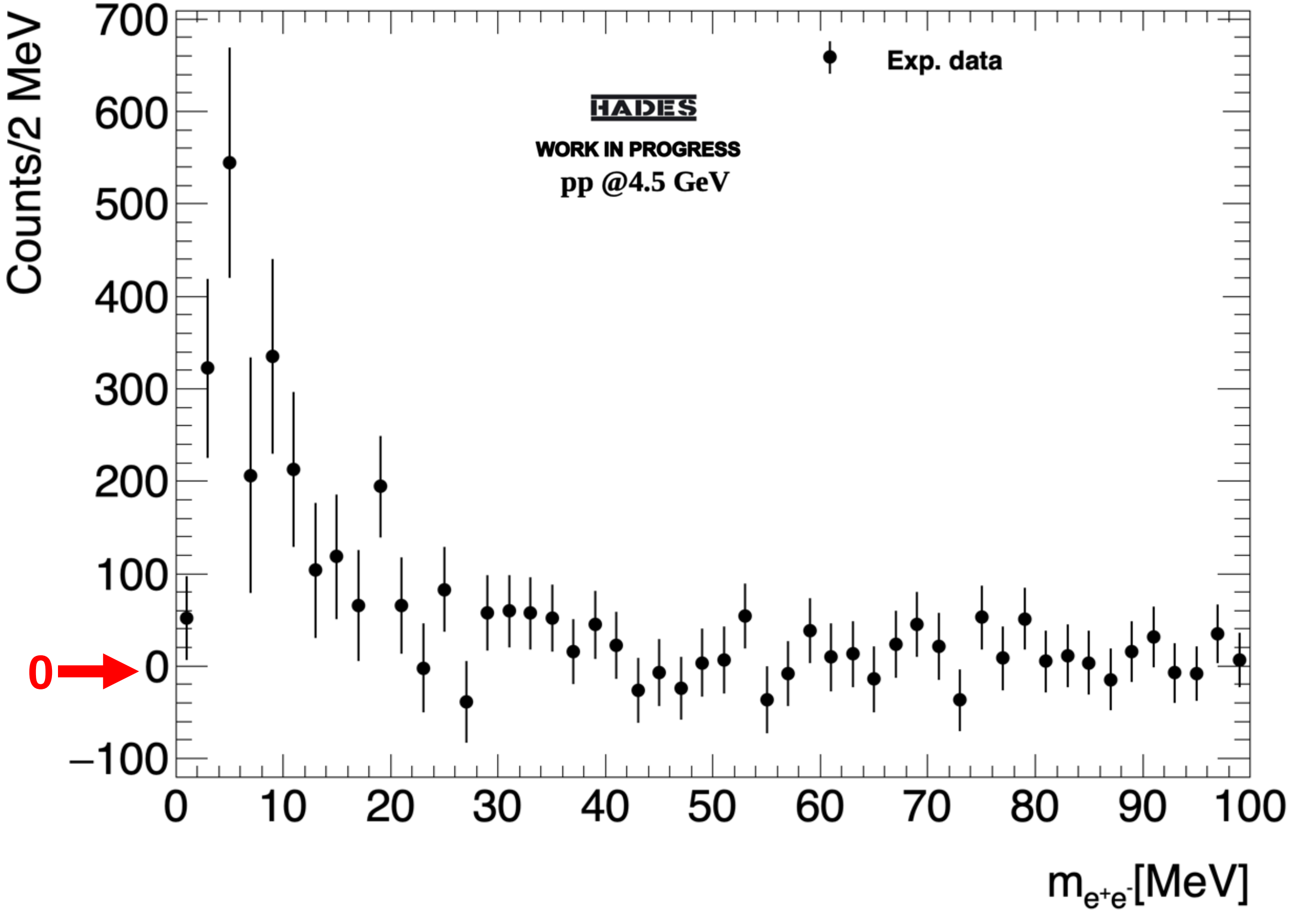
Expected numer of X_{17} in signal peak

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

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

Results

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



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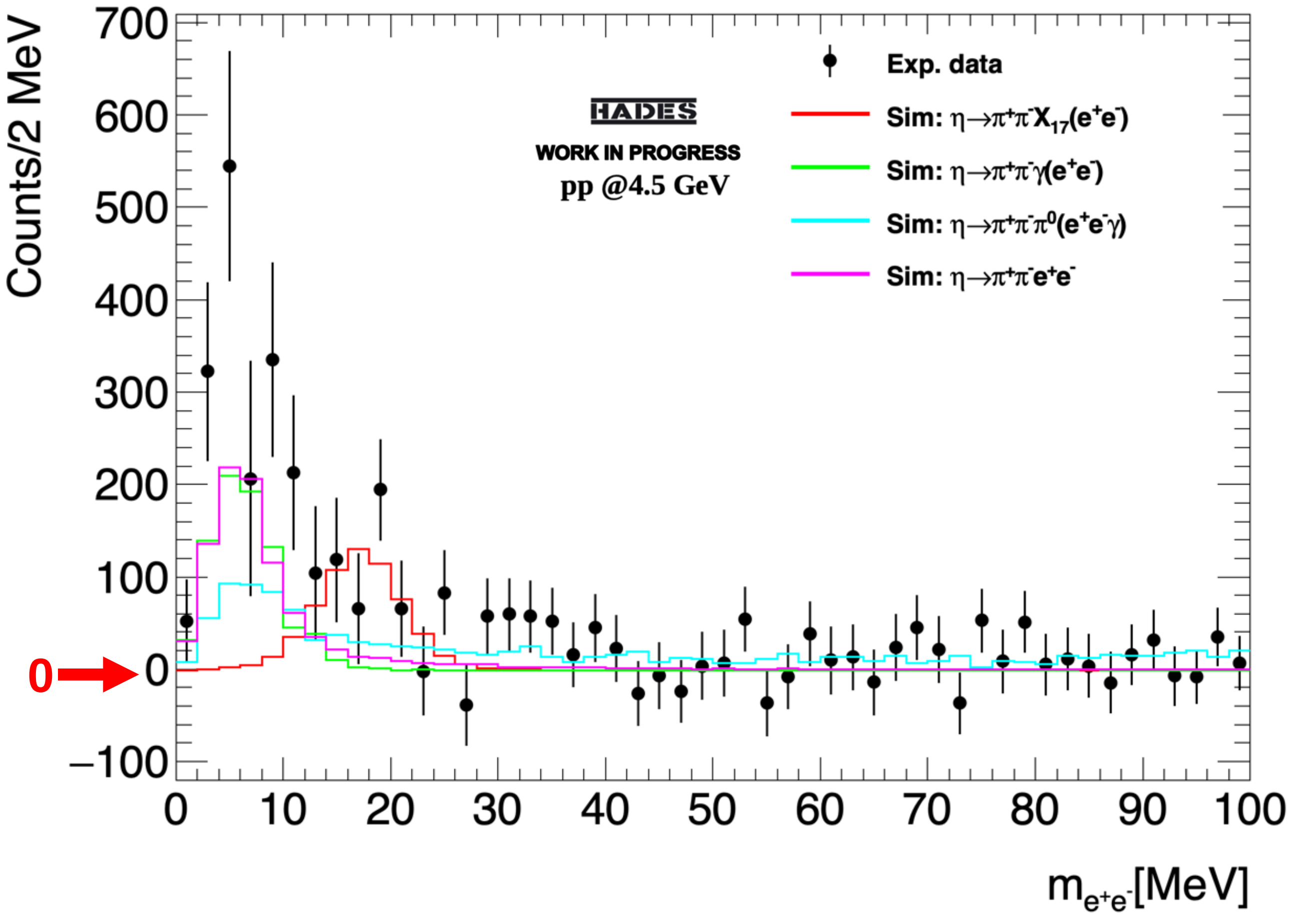

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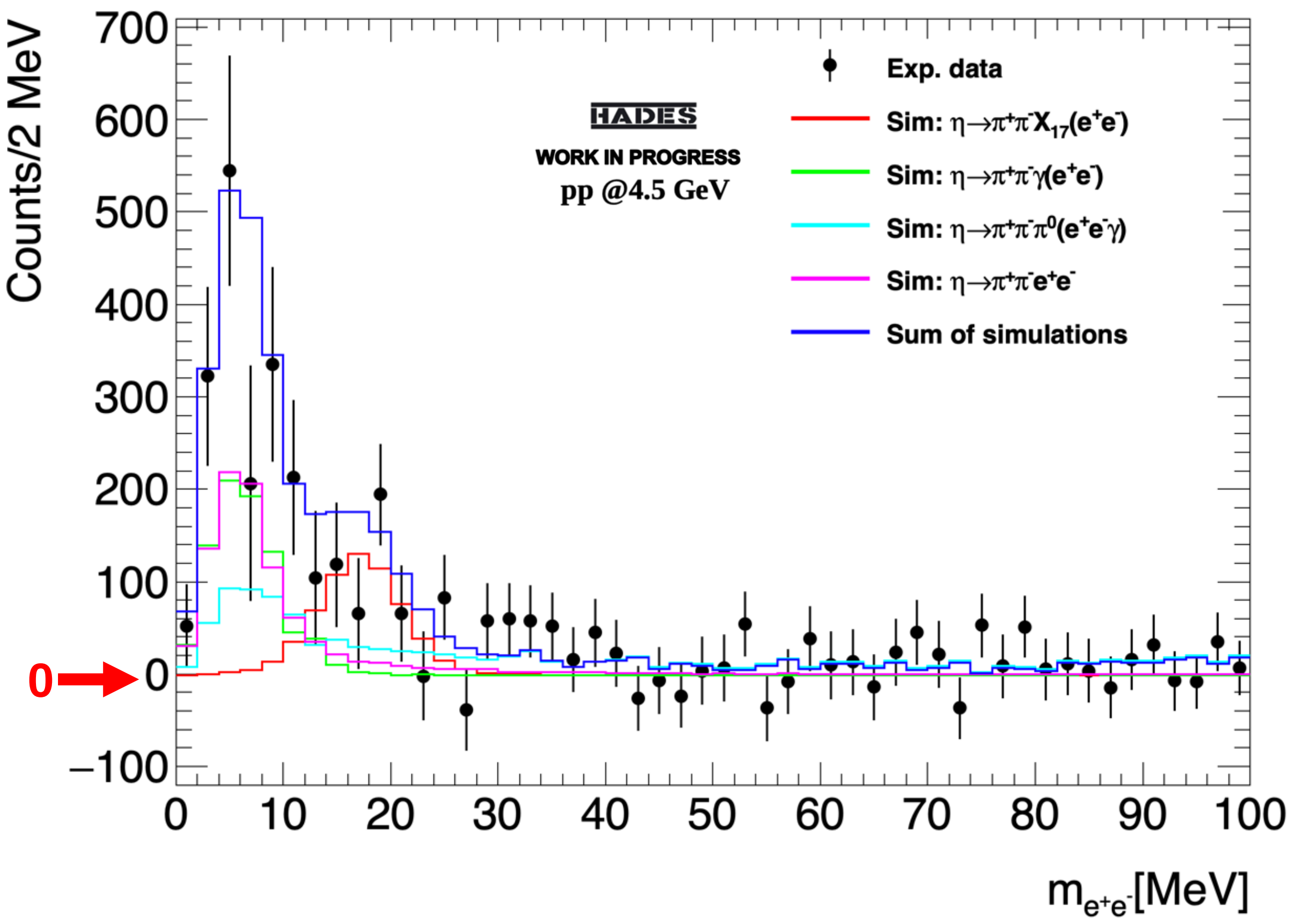

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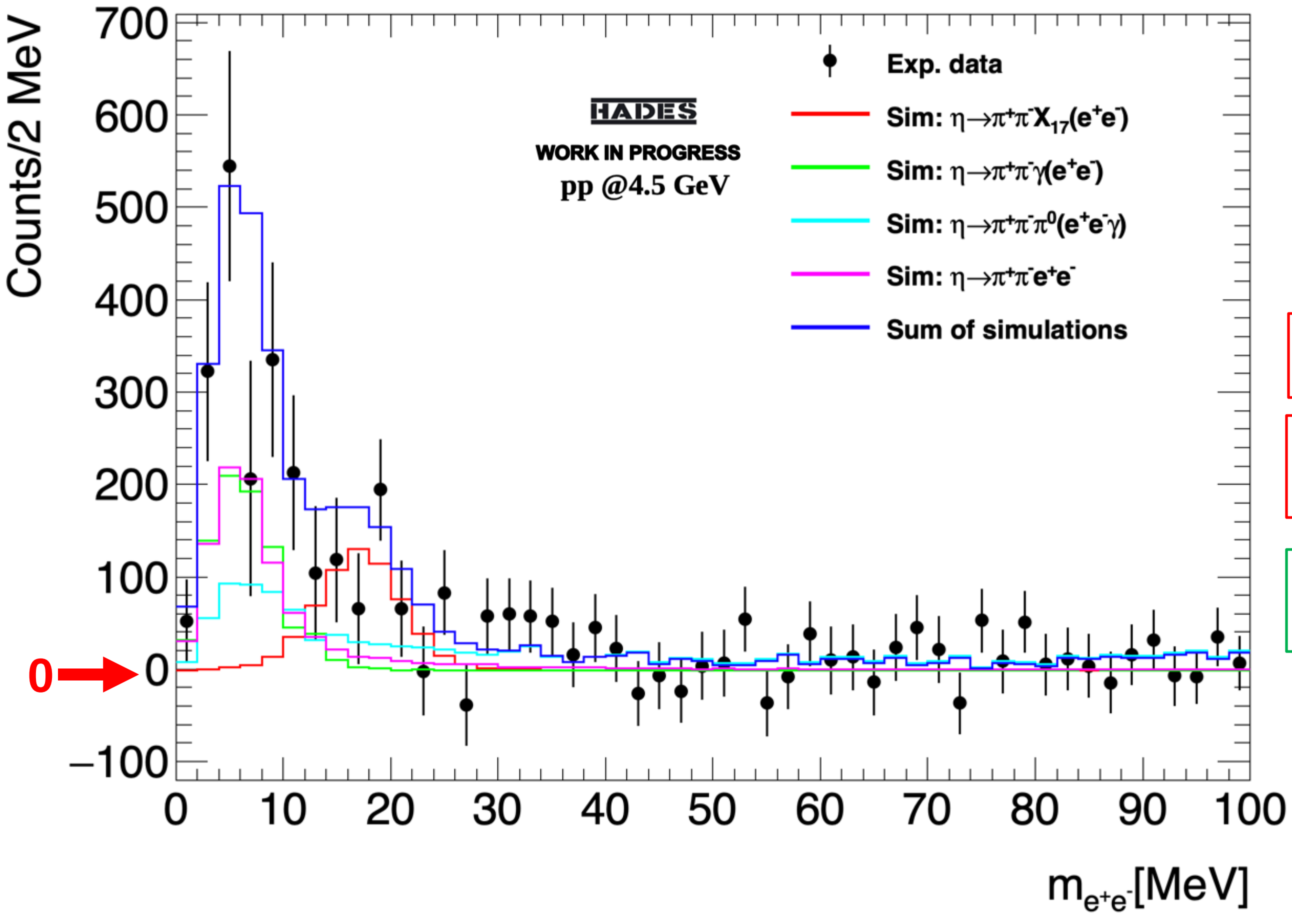

Upper limit for the number of event estimated based on W. A. Rolke method:

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* **$BR_{\eta\to\pi+\pi-X17} < 2.58 \cdot 10^{-5}$**
- *Also it is possible with 2758 η to extract the asymmetry parameter for CP invariance studies.*

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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

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Thank you for your attention!