Study of the fundamental symmetries with WASA-at-COSY

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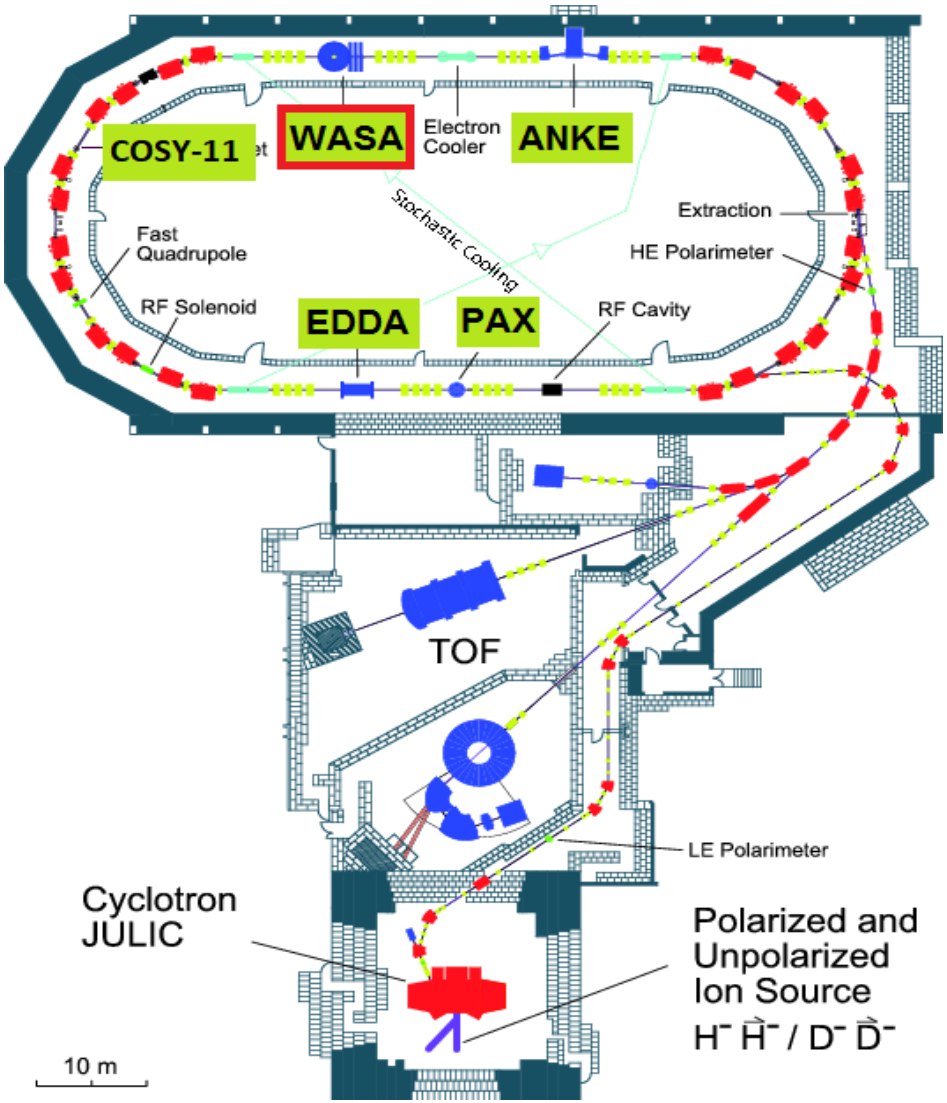
Workshop on Discrete Symmetries, Trento, 8-12 October 2018

Outline

Forschungszentrum Jülich, Germany

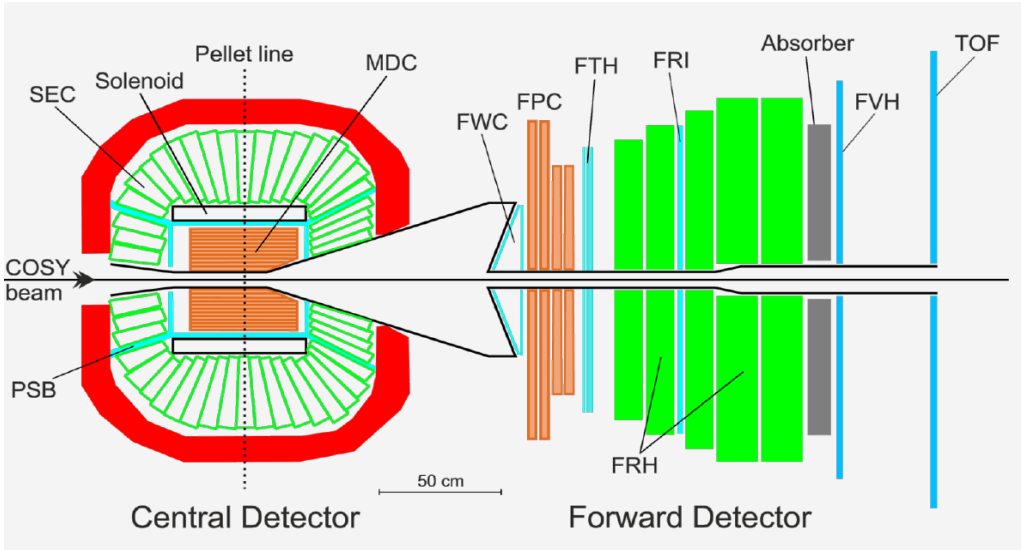
COoler SYnchrotron COSY



- 184 m circumference cooler synchrotron
- Polarized and unpolarized proton and deuteron beam
- Momentum range 0.3 - 3.7 GeV/c
- Stochastic and electron cooling
- 10^{11} particles in ring - luminosities 10^{31} - 10^{32} $cm^{-2}s^{-1}$
- Ramped beam (search for η-mesic nuclei)

COoler SYnchrotron COSY && WASA

WASA-at-COSY experiment



- **Pellet Target**
  - ▶ frozen pellets of hydrogen or deuterium

- **Forward Detector**
  - ▶ identification of heavier projectiles and target-recoil particles such as p, d and He in forward direction
  - ▶ angular information about the particles provided by FPC
  - ▶ PID based on measurement of energy loss in scintillators

- **Central Detector**
  - ▶ charged particles momenta reconstructed in magnetic field (MDC)
  - ▶ PID based on measurement of energy loss in scintillators
  - ▶ photons identified in calorimeter

WASA-at-COSY Collaboration

Collaboration:

32 member institutions from 8 countries (Germany. Sweeden, **Poland**, Russia, India, Japan, China, Bulgaria)

In Poland:

- Institute of Physics, Jagiellonian University, Cracow
- National Centre for Nuclear Research (NCBJ), Warsaw
- Institute of Nuclear Physics, Polish Acedemy of Science, Cracow
- Institute of Physics, University of Silesia, Katowice
- Institute of Experimental Physics, Faculty of Physics, Warsaw University

WASA-at-COSY studies

- **η production studies**
  - $\vec{p}p \to pp\eta$ (2 fixed energies)
  - $pd \to {}^3\mathrm{He}\eta$ (15 fixed energies)

  P. Adlarson, et al., Phys. Lett. B782, 297 (2018)

- **η decay studies**

  ($pd \to {}^3\mathrm{He}\eta$ $pp \to pp\eta$)
  - $\eta \to \pi^+\pi^- e^+e^-$ - **CP violation studies**
  - $\eta \to \pi^0 e^+e^-$ - **C violation studies**
  - other decay modes: $\eta \to \pi^+\pi^-\pi^0$, $\eta \to e^+e^-e^+e^-$, $\eta \to \pi^+\pi^-\gamma$, $\eta \to e^+e^-\gamma$

  P. Adlarson, et al., Phys. Rev. C94, 065206 (2016)
  P. Adlarson, et al., Phys. Lett. B784, 378 (2018)

- **Search for η-mesic Helium**
  - $dd \to ({}^4\mathrm{He}\text{-}\eta)_{bound} \to {}^3\mathrm{He}N\pi$ (ramped beam mode)
  - $pd \to ({}^3\mathrm{He}\text{-}\eta)_{bound} \to ppN\pi$ (${}^3\mathrm{He}\gamma\gamma$) (ramped beam mode)

  M. Skurzok, et al., Phys. Lett. B782, 6 (2018)
  P. Adlarson, et al., Nucl. Phys. A959, 102 (2017)

- **studies of dibarion production**
  - $pn \to d^*(2380) \to d\pi^0\pi^0 (d\pi^+\pi^-)$,
  - $pn \to d^*(2380) \to pp\pi^-\pi^0 (pn\pi^0\pi^0, pn\pi^+\pi^-)$,
  - $dd \to {}^4\mathrm{He}\pi^0\pi^0$

  P. Adlarson, et al., Phys. Rev. Lett. 121, 052001 (2018)
  P. Adlarson, et al., Phys. Rev. C86, 032201 (2012)

- **ω decay studies**
  - $\omega \to \pi^+\pi^-\pi^0$

  P. Adlarson, et al., Phys. Lett. B770, 418 (2017)

- **charge symmetry breaking studies**
  - $dd \to {}^4\mathrm{He}\pi^0$

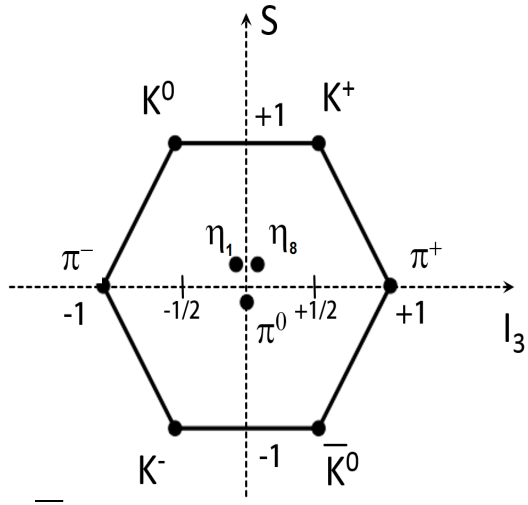
  P. Adlarson, et al., Phys. Lett. B781, 645 (2018)
  P. Adlarson, et al.,Phys. Lett. B739, 44 (2014)

Studies of symmetries in η decays

mass	547.862 ± 0.017 MeV
width	1.31 ± 0.05 keV
$I^G(J^{PC})$	$0^+(0^{-+})$
η is an eigenstate to	P, C, G and CP

Decay modes	**Branching ratio**
Charged modes	28.10±0.34 %
$\eta \to \pi^+\pi^-\pi^0$	22.92±0.28 %
$\eta \to \pi^+\pi^-\gamma$	4.22±0.16 %
other modes	0.76 %
Neutral modes	72.912±0.34 %
$\eta \to 2\gamma$	39.41±0.20 %
$\eta \to 3\pi^0$	32.68±0.23 %
other modes	0.03 %

all strong and electromagnetic decays forbidden to first order $\Rightarrow \tau = (5.02 \pm 0.19) \cdot 10^{-19}$s



$$\eta_1 = \frac{1}{\sqrt{3}}(d\bar{d} + u\bar{u} + s\bar{s}),$$
$$\eta_8 = \frac{1}{\sqrt{6}}(d\bar{d} + u\bar{u} - 2s\bar{s}).$$
$$|\eta> = \eta_8 cos\theta - \eta_1 sin\theta,$$

Hadronic decays (3π) (isospin breaking: $m_u - m_d$)

Radiative decays ($\gamma\gamma$ ($\pi\pi$))

(Semi-) leptonic decays (l l (γ))

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

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

M. Tanabashi, et al. (PDG), Phys. Rev. D98, 030001 (2018)

Studies of symmetries in η decays

- **η meson is an ideal laboratory for the study of rare processes:**
- $\eta \to e^+e^-\gamma$ BR=6.9±0.4 x 10^{-3}
- $\eta \to e^+e^-e^+e^-$ BR= 2.40±0.22 x 10^{-5}
- ...
- $\eta \to \pi^+\pi^-e^+e^-$ BR= (2.68±0.09 ± 0.07) x 10^{-4} $\Rightarrow$ search for a possible CP violation
- $\eta \to \pi^0e^+e^-$ BR$<$ 4 x 10^{-5} $\Rightarrow$ C violation studies

M. Tanabashi, et al. (PDG), Phys. Rev. D98, 030001 (2018)

Search for a CP violation in $\eta \to \pi^+\pi^- e^+ e^-$ process

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

  $\eta \to \pi^+\pi^-\gamma$
  - CP conservation for M transition $P_{\gamma_M} = 1,\ C_\gamma = -1$
  - CP violation for E transition $P_{\gamma_E} = -1,\ C_\gamma = -1$
  - would have to measure γ polarization

Idea of measurement

- conversion of a virtual photon $\eta \to \pi^+\pi^-[\gamma^* \to e^+e^-]$
- study asymmetry

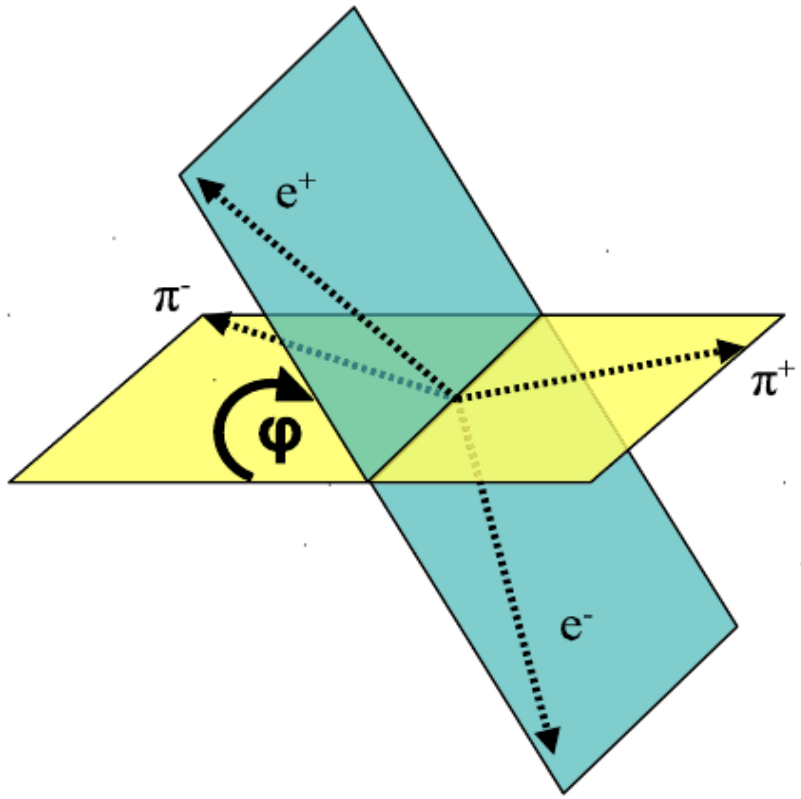
$$A_\phi = \frac{N(sin\phi cos\phi > 0) - N(sin\phi cos\phi < 0)}{N(sin\phi cos\phi > 0) + N(sin\phi cos\phi < 0)}$$

asymmetry of the dihedral angle distribution

$$\Downarrow$$

CP violation

PDG: A_ϕ=(-0.6 $\pm$ 2.5 $\pm$ 1.8) x 10^{-2} (KLOE Collaboration)



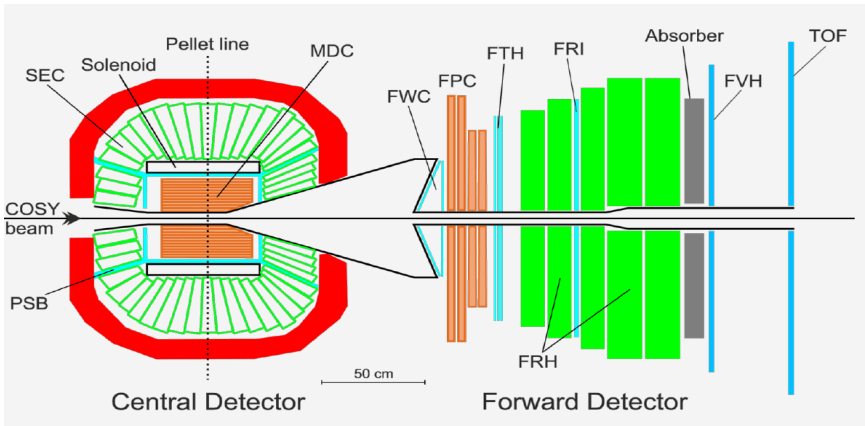
dihedral angle ϕ - angle between decay $\pi^+\pi^-$ and e^+e^- planes (CM frame)

Search for a CP violation in $\eta \to \pi^+\pi^- e^+ e^-$ process

- η **produced in** $pd \to {}^3\mathrm{He}\eta$ **reaction**
- proton beam T=1.0 GeV
- deuterium pellet target
- η produced close to production threshold ($\sigma_{tot} = 0.4\mu b$)

  $\Downarrow$

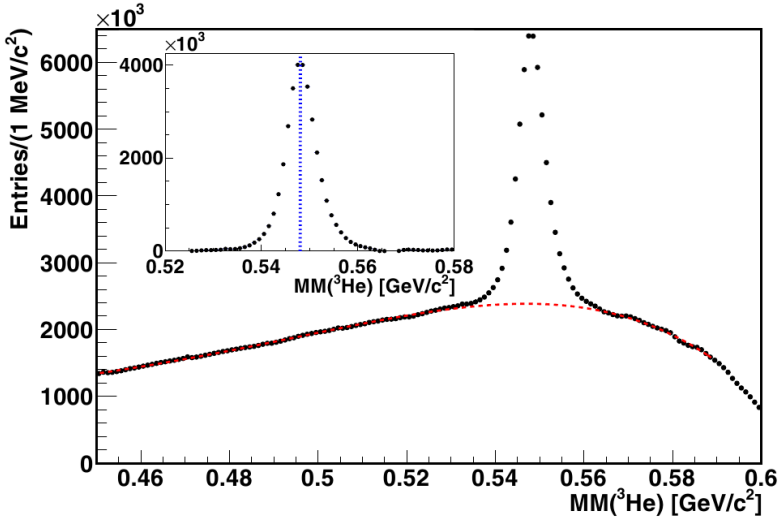
  good signal/background ratio
- 3×10^7 events collected (8 η/second at peak luminosity $2 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)



Events selection

- ^{3}He identification in Forward Detector:

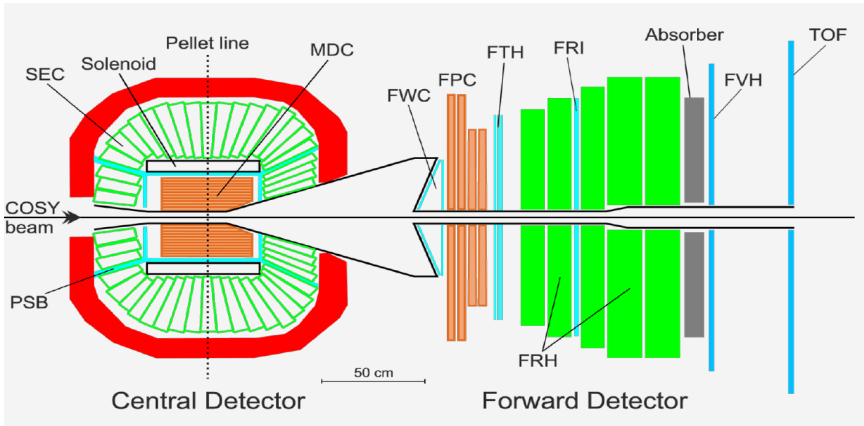
  -hit patterns in FPC matching wit signals in scintillators
  -selection based on ΔE-ΔE
- missing mass determined:
  $m_X^2 = (E_b + E_t - E_{3He})^2 - (\vec{p}_b + \vec{p}_t - \vec{p}_{3He})$



P. Adlarson, et al., Phys. Rev. C94, 065206 (2016)

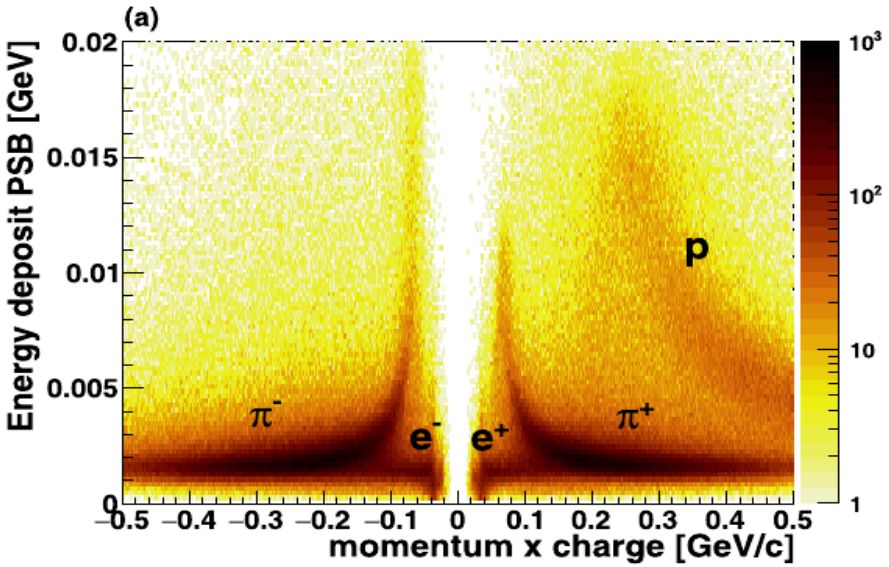
- event candidates: ^{3}He in time coincidence with minimum number of tracks/neutral clusters for chosen decay mode

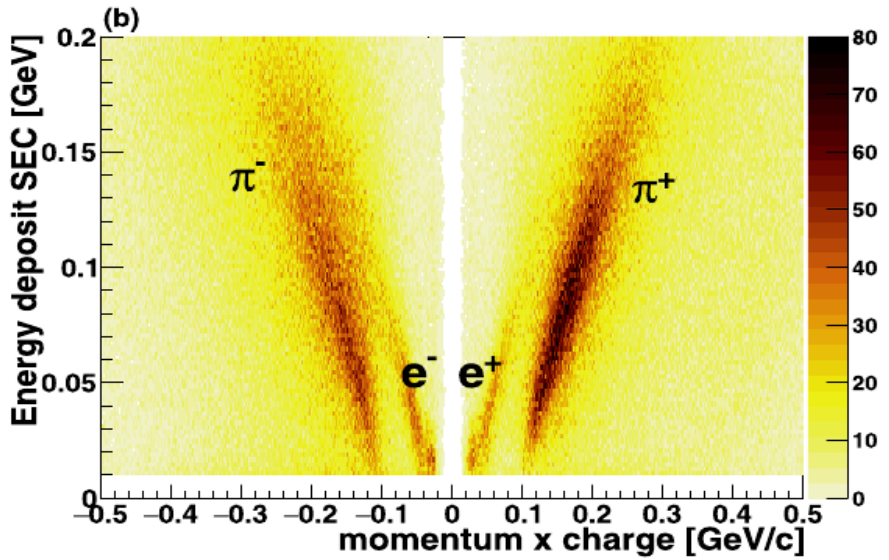
Search for a CP violation in $\eta \to \pi^+\pi^- e^+ e^-$ process



Particles identification (η decays)

- $\pi^\pm$, $e^\pm$ separated by ΔE vs. $p \cdot q$
  - ΔE - energy loss in PSB
  - p - measured in MDC
  - q - charge measured in PSB and Cal
  - at least 2 positive and negative reconstructed tracks
  - dedicated MC simulations performed
  - kinematic fit applied ($pd \to {}^3\mathrm{He}\pi^+\pi^- e^+ e^-$ hypothesis)
  - bcg reduced ($\eta \to \pi^+\pi^-\gamma$, $\eta \to \pi^+\pi^-\pi^0$, $\eta \to \pi^+\pi^-[\pi^0 \to e^+e^-\gamma]$)





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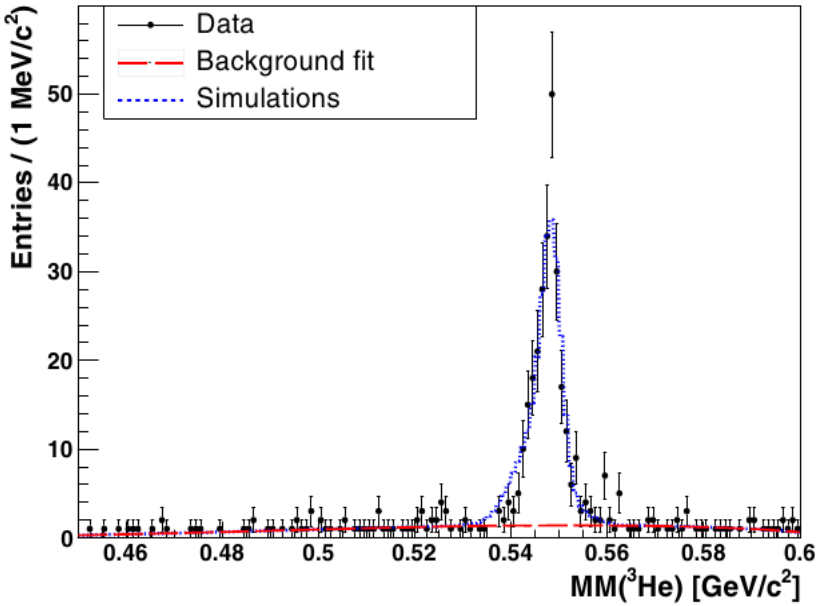
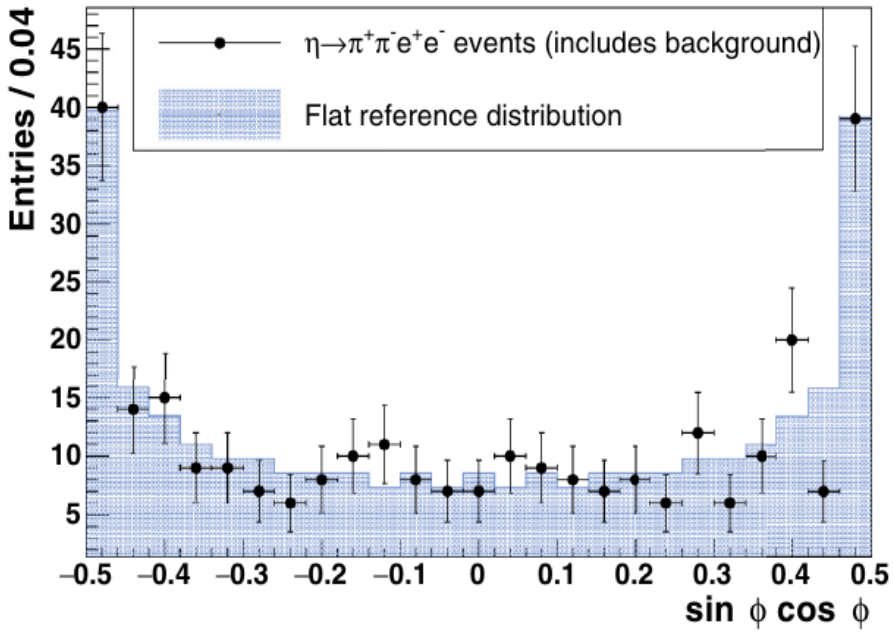
Search for a CP violation in $\eta \to \pi^+\pi^- e^+ e^-$ process

after selection criteria





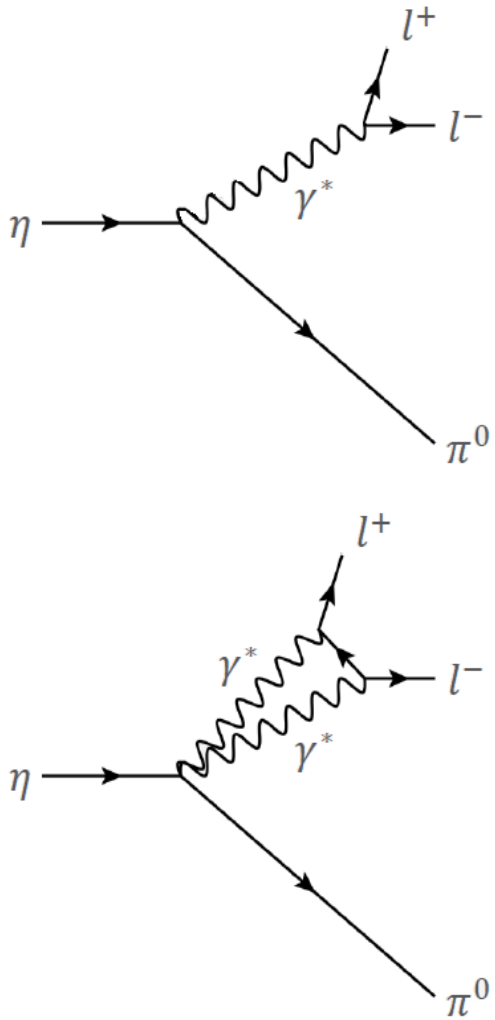
- 215 $\pm$17 $\eta \to \pi^+\pi^- e^+ e^-$ events
- BR($\eta \to \pi^+\pi^- e^+ e^-$)=(2.7 $\pm$ 0.2 $\pm$ 0.2) $\times$ 10^{-4}
- PDG: BR($\eta \to \pi^+\pi^- e^+ e^-$)=(2.68 $\pm$ 0.09 $\pm$ 0.07) $\times$ 10^{-4} (KLOE Collaboration)

- A_ϕ=(-1.1 $\pm$ 6.6 $\pm$ 0.2) $\times$ 10^{-2}
- PDG: A_ϕ=(-0.6 $\pm$ 2.5 $\pm$ 1.8) $\times$ 10^{-2} (KLOE Collaboration)
- analyses of the larger $pp \to pp\eta$ sample ongoing

P. Adlarson, et al., Phys. Rev. C94, 065206 (2016)

Search for a C violation in $\eta \to \pi^0 e^+ e^-$ process

- according Standard Model (SM) $\eta \to \pi^0 e^+ e^-$ forbidden (C parity conservation)
- $\eta \to \pi^0 e^+ e^-$ via $\eta \to \pi^0 \gamma^*$ would violate C parity
- present experimental upper limit (1975) of BR is **4 x 10^{-5}** (PDG)
- decay via $\gamma^* \gamma^*$ (physical background) allowed by SM (predicted BR $\approx$ **10^{-8}**)
- 3 orders of magnitude between best upper limit and highest SM prediction
- more stringent upper limit determined with WASA-at-COSY



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  $\Downarrow$

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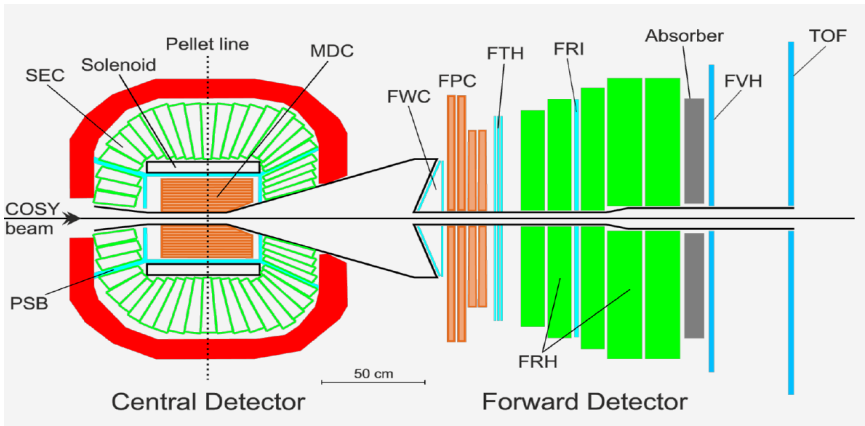

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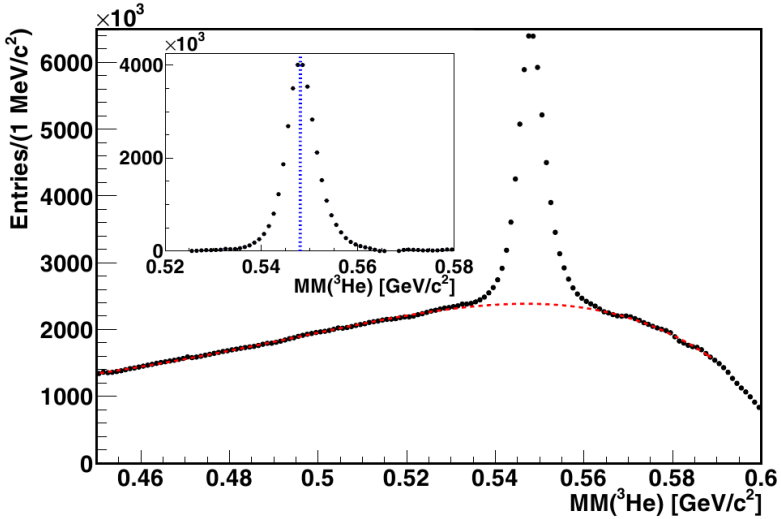

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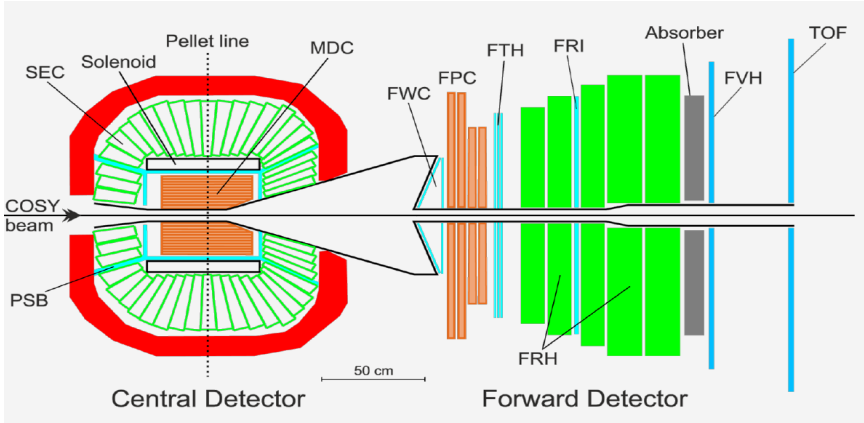
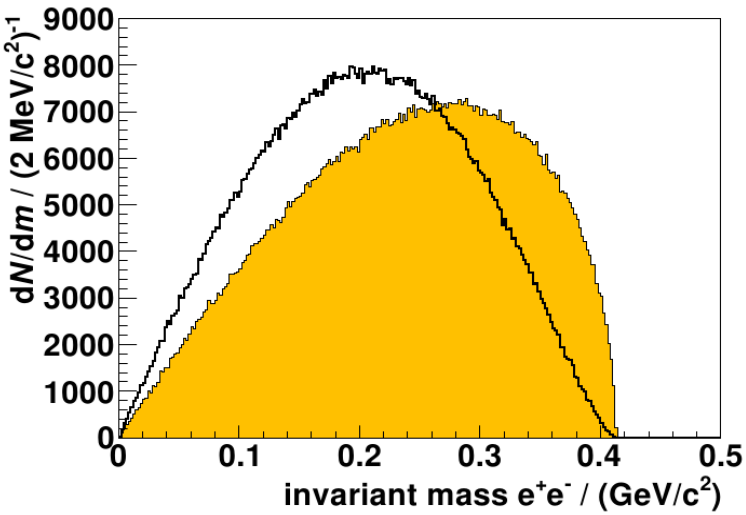


Particles identification (η decay)

- at least 1 positive and 1 negative charge particle in CD
- at least 2 neutral particles in CD ($\pi^0 \to \gamma\gamma$)
- max p_{e^+,e^-}=250 MeV/c (as expected for $\eta \to \pi^0 e^+ e^-$ reaction)

$\eta \to \pi^0 e^+ e^-$ events selection conditions

- dedicated MC simulations performed for signal $\eta \to \gamma^* \to \pi^0 e^+ e^-$ with (i) VMD model assumption for virtual photon and (ii) decay according to 3-particle phase space

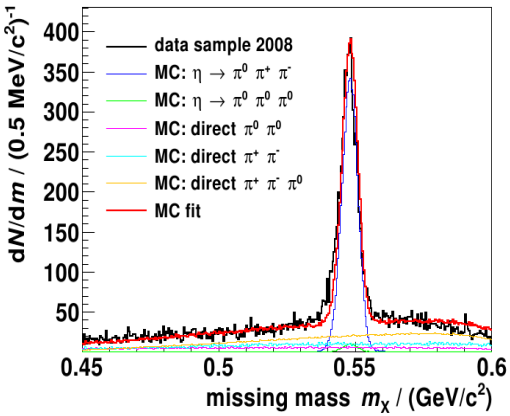


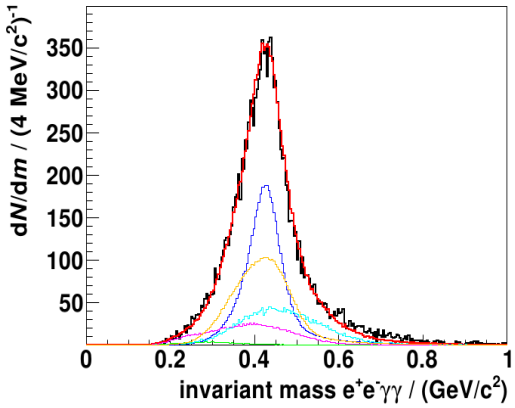
P. Adlarson, et al., Phys. Lett. B784, 378 (2018)

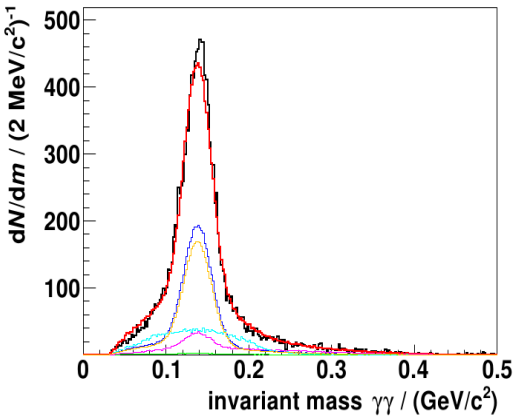
- background simulations: $\eta \to \pi^+\pi^-\pi^0$, $\eta \to 3\pi^0$, direct $\pi^0\pi^0$, $\pi^+\pi^-$, $\pi^+\pi^-\pi^0$ channels

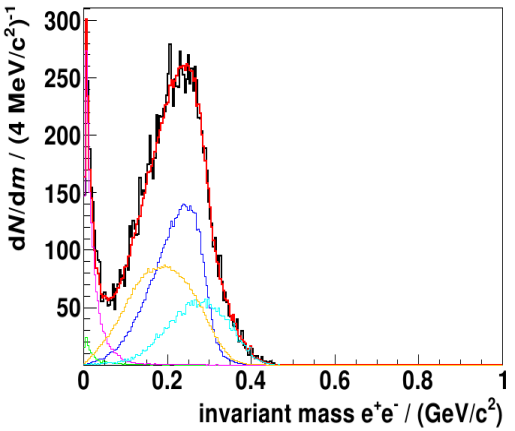
Search for a C violation in $\eta \to \pi^0 e^+ e^-$ process

- fit of MC simulations performed simultaneously for 8 $cos\theta^{CM}_{3He}$ bins
- fit for m_X, $m_{ee\gamma\gamma}$, m_{ee}, $m_{\gamma\gamma}$ taking into account BR of η decays



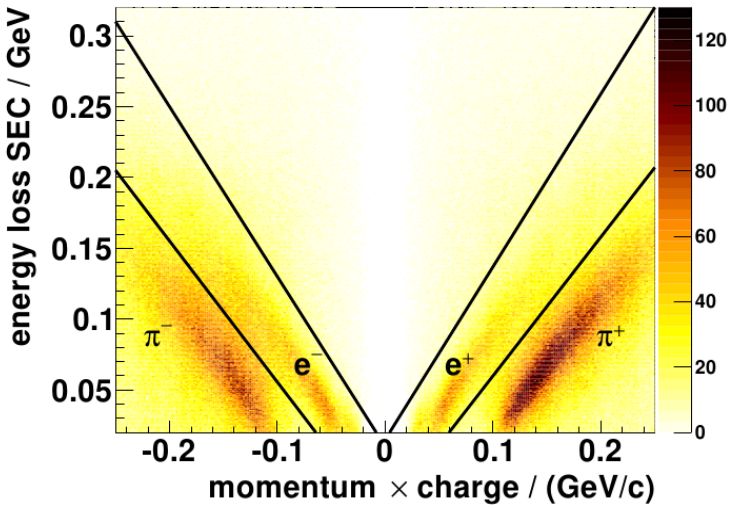






Selection conditions based on:

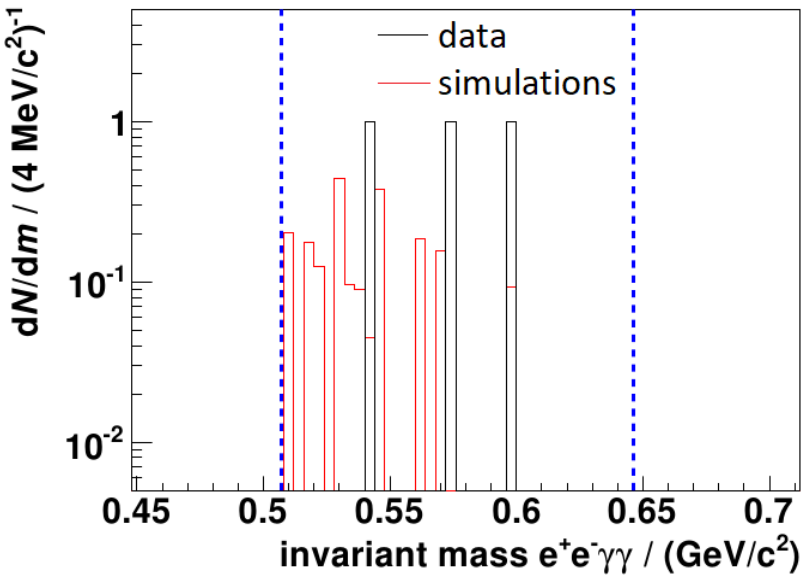
- m_X, $m_{ee\gamma\gamma}$, m_{ee}, $m_{\gamma\gamma}$
- χ^2 probability of kinematic fit ($pd \to {}^3He\gamma\gamma e^+ e^-$ hypothesis)
- ΔE vs. $q \cdot p$ in CD (charged particles)



Search for a C violation in $\eta \to \pi^0 e^+ e^-$ process

Results

- after all selection conditions only 3 events remains - 2 of them are expected from $pd \to {}^3\mathrm{He}\pi^0\pi^0$ (according MC)
- determination of the upper limit of BR($\eta \to \pi^0 e^+ e^-$)



- **Upper limit of BR:**

$$\frac{\Gamma(\eta\to\pi^0 e^+ e^-)}{\Gamma(\eta\to\pi^+\pi^-\pi^0)} < \frac{N_{S,up}}{N^{prod}_{\eta\to\pi^+\pi^-\pi^0}\epsilon_S}$$

  - $N_{S,up}$ -upper limit of number of signal events (depends on observed sig events and expected bcg events)
  - ϵ_S - efficiency for $\eta \to \pi^0\gamma^*$ (based on MC simulations)

$$\frac{\Gamma(\eta\to\pi^0 e^+ e^-)_{virt}}{\Gamma(\eta\to\pi^+\pi^-\pi^0)} < 3.28\text{x}10^{-5}$$

$$\frac{\Gamma(\eta\to\pi^0 e^+ e^-)_{ph}}{\Gamma(\eta\to\pi^+\pi^-\pi^0)} < 4.14\text{x}10^{-5}$$

$$\Downarrow$$

$$\frac{\Gamma(\eta\to\pi^0 e^+ e^-)_{virt}}{\Gamma(\eta\to all)} < 7.5\text{x}10^{-6}$$

$$\frac{\Gamma(\eta\to\pi^0 e^+ e^-)_{ph}}{\Gamma(\eta\to all)} < 9.5\text{x}10^{-6}$$

$$\Downarrow$$

no events seen in data $\Rightarrow$ no hint on C violation in an electromagnetic process

P. Adlarson, et al., Phys. Lett. B784, 378 (2018)

$pp \to pp\eta$ data set analysis ongoing (an order of magnitude higher statistics)

Charge Symmetry Breaking studies in $dd \to {}^4\mathrm{He}\pi^0$ process

Isospin symmetry (IS)

- Two sources of violation (Standard Model)
  - electro-magnetic interactions (different charge of quarks)
  - strong interaction (lightest quark mass difference: window for probing quark mass ratio $\frac{m_u - m_d}{m_u + m_d}$)

$\Downarrow$

proton-neutron mass difference:
$\Delta M_{pn} = \Delta M_{pn}^{strong} + \Delta M_{pn}^{em}$

ΔM_{pn}^{em}=-0.7±0.3 MeV (QED + dispersion th)
ΔM_{pn}^{strong}=2.05±0.3 MeV (ΔM_{pn}-ΔM_{pn}^{em},lattice QCD/χPT)

χPT - link between ΔM_{pn}^{strong} and dynamic observable $a_{\pi N}$: e.g. $a_{\pi^0 N}$-$a_{\pi^0 p} = f(\Delta M_{pn}^{strong})$

- However:
  - no direct measurement of $\pi^0 N$
  - large e.m. corrections in $\pi^{\pm} N$

Isospin symmetry breaking - dominated by Δm_π (e.m.) $\Rightarrow$ Charge Symmetry Breaking

Charge symmetry breaking (CSB)

- Charge symmetry (subset of IS)
  - rotation in isospin space 180° around I_2 axis
  - interchange of u, d quarks ($|u> \to |d>, |d> \to -|u>$)
  - no contribution of Δm_π

- CSB observables measured:

- $np \to d\pi^0$ forward-backward asymmetry
$A_{fb} = (17.2 \pm 8.0 \pm 5.5) \cdot 10^{-4}$ (Q=2MeV)
Opper et al., PRL 91 (2003) 212302
ChPT in LO: ΔM_{pn}^{str}=1.5±0.8(exp)±0.5(th) MeV
Filin et al., PLB 681 (2009) 423

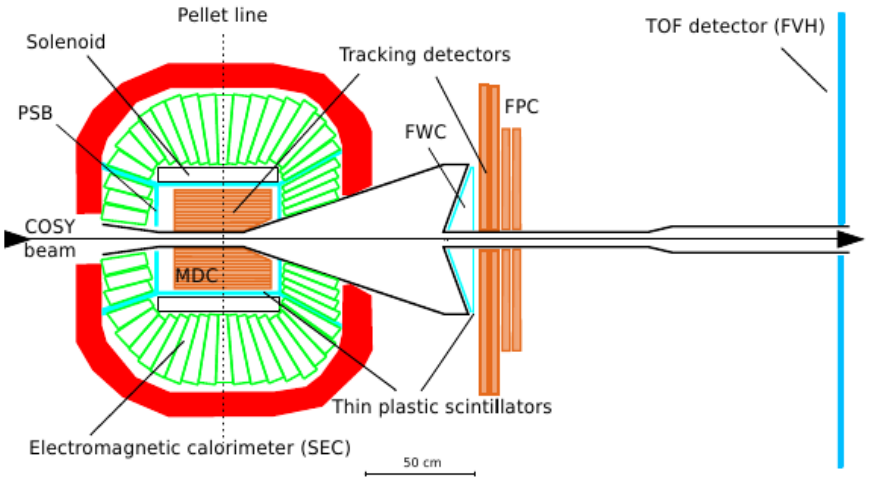
- $dd \to {}^4\mathrm{He}\pi^0$ σ_{tot} measured (at thr)
$\sigma_{tot}(Q = 1.4MeV) = 12.7 \pm 2.2pb$,
$\sigma_{tot}(Q = 3.0MeV) = 15.1 \pm 3.1pb$
Stephenson et al., PRL 91 (2003) 142302
energy dependence consistent with s-wave pion production at threshold

$\Downarrow \chi$PT

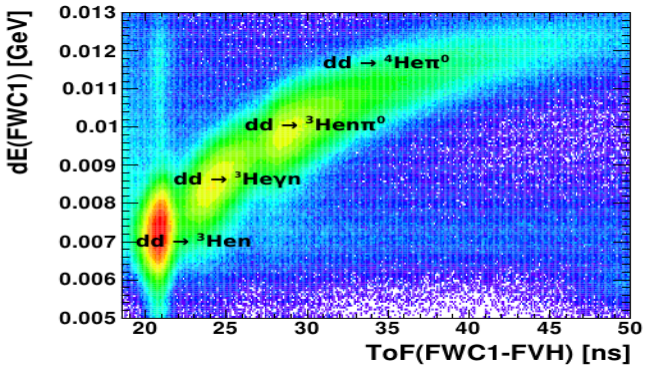
p-wave contribution at higher excess energies needed!!! $\Rightarrow$ **WASA**

Charge Symmetry Breaking studies in $dd \rightarrow {}^4\mathrm{He}\pi^0$ process

- deuteron beam p=1.2 GeV/c (Q=60 MeV)
- deuterium pellet target
- ^{4}He detected by the Forward Detector
- $\gamma\gamma$ from π^0 decay detected by the Central Detector
- Forward Detector optimized for TOF measurement (several layers of original detector were removed, free flight path of 1.5m)



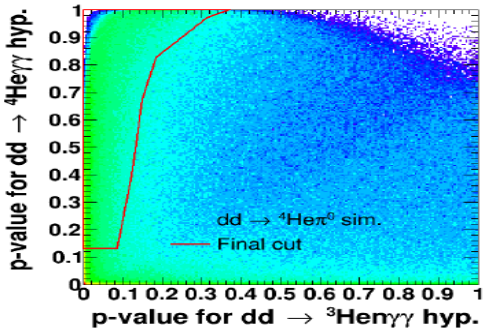
Events selection

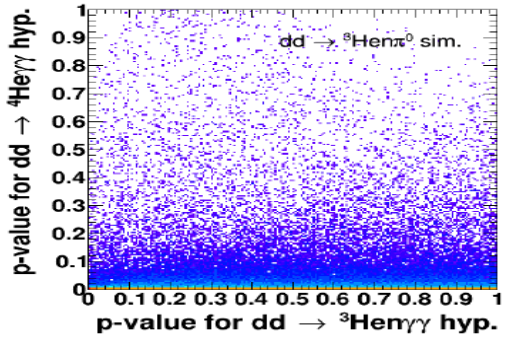


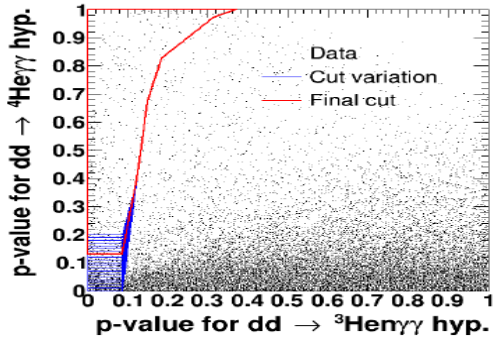
- $\geq$ 2 neutral clusters in CD, $E_{cl} \geq 20MeV$, $\theta_{cl1,2} \geq 30^\circ$
- $\geq$ 1 charged track in FD, dE cut in FWC
- kinematic fits applied (only E-p conserv.):
  - $dd \rightarrow {}^4\mathrm{He}\gamma\gamma$ hypothesis - tested to improve the description of the signal and separate it from the main background
  - $dd \rightarrow {}^4\mathrm{He}n\gamma\gamma$ hypothesis reaction - identify the contribution from the $dd \rightarrow {}^4\mathrm{He}n\pi^0$ reaction and to separate it from the signal

Charge Symmetry Breaking studies in $dd \rightarrow {}^4\mathrm{He}\pi^0$ process

Prob. of ^{4}He hypothesis vs. prob. of ^{3}He hypothesis

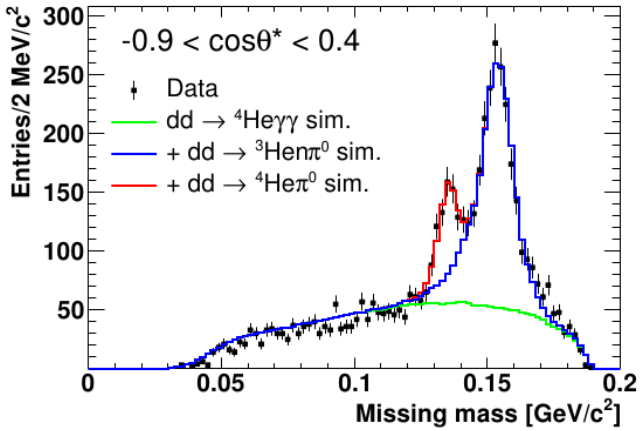




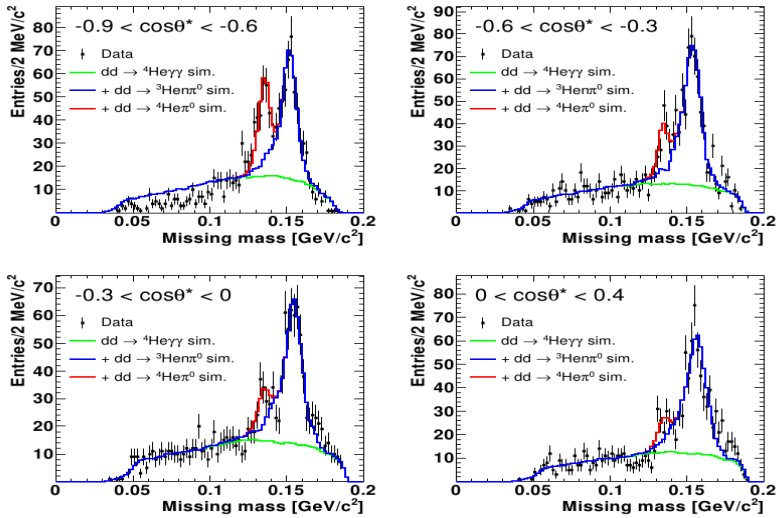


M. Zurek, PhD

missing mass $dd \rightarrow {}^4\mathrm{He}X$



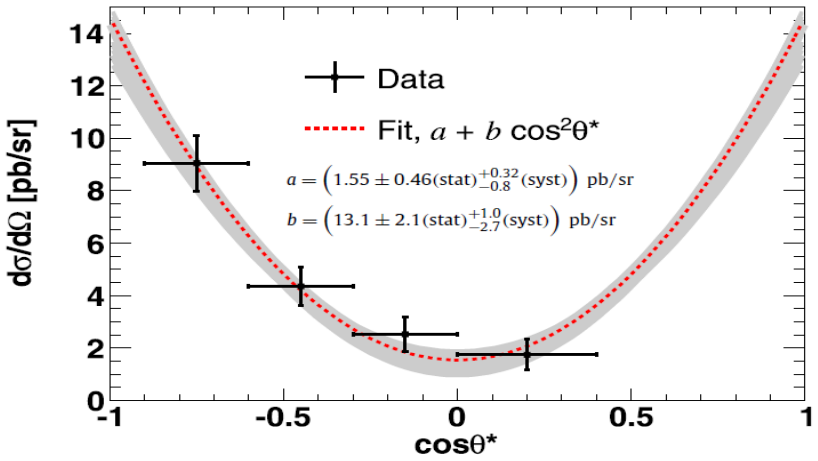
angular distributions



P. Adlarson, et al., Phys. Lett. B781, 645 (2018)

Charge Symmetry Breaking studies in $dd \to {}^4\mathrm{He}\pi^0$ process

Results



Identical particles in the initial state → symmetric: fit $d\sigma/d\Omega = a + b\cos^2\theta^*$

$$a = (1.55 \pm 0.46(stat)^{+0.32}_{-0.8}(syst))pb/sr$$
$$b = (13.1 \pm 2.1(stat)^{+1.0}_{-2.7}(syst))pb/sr$$

for only s- and p-waves: $b = \frac{-p_{\pi^0}}{p}\frac{2}{3}|C|^2 p^2_{\pi^0}$

[1] A. Wronska et al., Eur. Phys. J. A26, 421 (2005)

⇓

significant d wave contribution is present

s-wave s-d interference d-wave p-wave

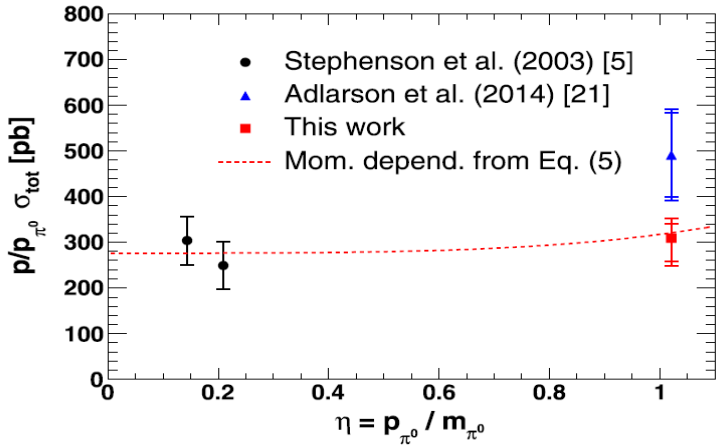
$$\frac{d\sigma}{d\Omega} = \frac{p_{\pi^0}}{p}\frac{2}{3}\left(|A_0|^2 + 2\mathrm{Re}(A_0^* A_2)P_2(\cos\theta^*)p^2_{\pi^0} + |A_2|^2 P_2^2(\cos\theta^*)p^4_{\pi^0} + |C|^2\sin^2\theta^* p^2_{\pi^0}\right.$$

d-wave

$$\left. + |B|^2\sin^2\theta^*\cos^2\theta^* p^4_{\pi^0}\right)$$

- Total cross section

$\sigma_{tot} = (74.3 \pm 6.8(stat)^{+1.2}_{-10.1} \pm 7.7(norm))pb$



P. Adlarson, et al., Phys. Lett. B781, 645 (2018)

$$\frac{p}{p_{\pi^0}}\sigma_{tot} = \frac{8\pi}{3}\left(|A_0|^2 + \frac{2}{3}|C|^2 p^2_{\pi^0} + \frac{1}{5}|A_2|^2 p^4_{\pi^0} + \frac{2}{15}|B|^2 p^4_{\pi^0}\right)$$

- A_0 -fixed param: $|A_0|_{thr} = (5.74 \pm 0.38(stat))(pb/sr)^{1/2}$ [5]
- data are not sensitive to $|B|$ and δ (=0) (RA_0^*, $A2 = |A_0||A_2|\cos\delta$)

$$|A_2| = 258^{+50}_{-42}(stat)^{+45}_{-38}(syst)^{+37}_{-12}(norm)\frac{(pb/sr)^{1/2}}{(GeV/c)^2}$$
$$|C| = 6^{+9}_{-21}(stat)^{+3}_{-10}(syst)^{+10}_{-5}(norm)\frac{(pb/sr)^{1/2}}{(GeV/c)^2}$$

⇓

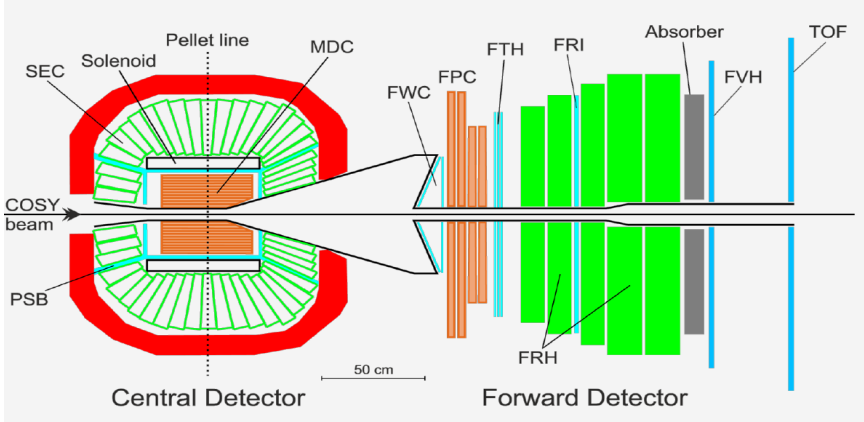
vanishing p-wave and sizable d-wave contribution

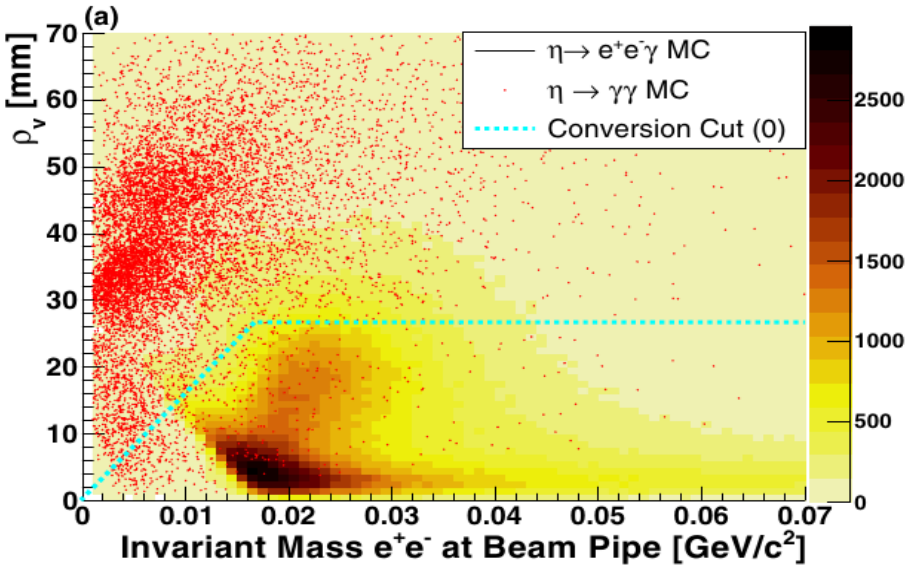
Summary and Conclusions

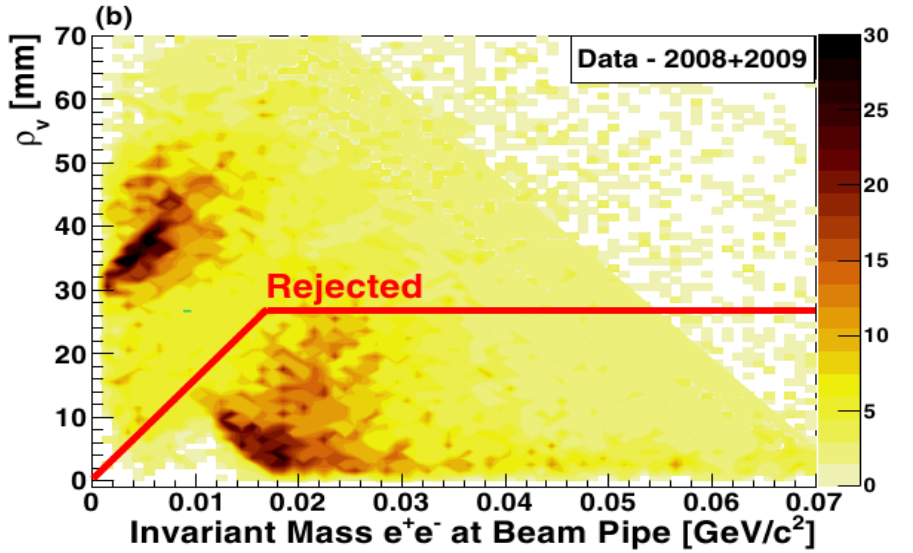
- Study of CP violation in $\eta \to \pi^+\pi^- e^+ e^-$ process
- Study of C violation in $\eta \to \pi^0 e^+ e^-$ process
- Charge Symmetry Breaking studies in $dd \to {}^4\mathrm{He}\pi^0$ process: total and differential cross sections measured $\to$ d-wave contribution (input for theoretical calculations)

Thank you for attention

Search for a CP violation in $\eta \to \pi^+\pi^- e^+ e^-$ process







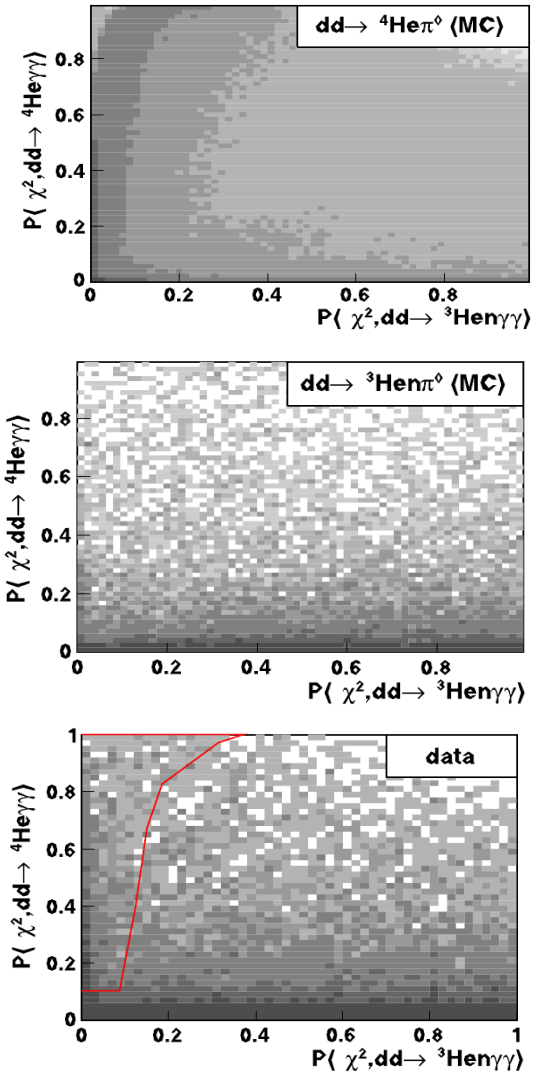
Background suppression

- $e^{\pm}$ from γ conversion
  - $\eta \to \pi^+\pi^-\gamma$ and $\eta \to \pi^+\pi^-\pi^0$
  - reduced to to 5% at the η peak
- $\eta \to \pi^+\pi^-[\pi^0 \to e^+e^-\gamma]$ - 15% at the η peak

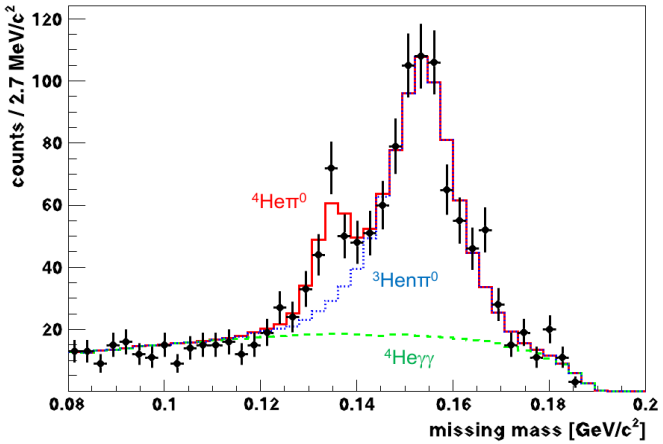
P. Adlarson, et al., Phys. Rev. C94, 065206 (2016)

Charge Symmetry Breaking studies in $dd \rightarrow {}^4\mathrm{He}\pi^0$ process

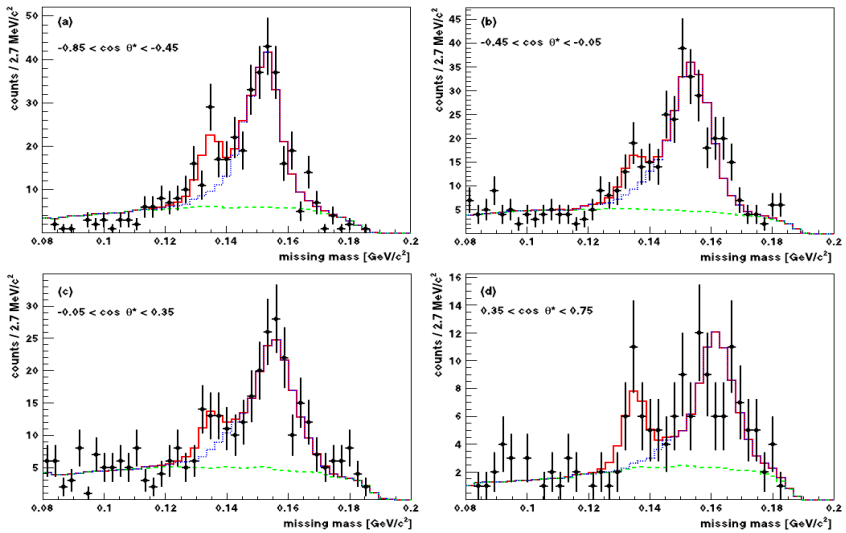
Prob. of ^{4}He hypothesis vs. prob. of ^{3}He hypothesis



missing mass $dd \rightarrow {}^4\mathrm{He}X$



angular distributions



P. Adlarson, et al., Phys. Lett. B739, 44 (2014)