Search for the η-mesic bound states with the WASA-at-COSY detector

Magdalena Skurzok

for WASA-at-COSY Collaboration

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7th - 12th June 2018

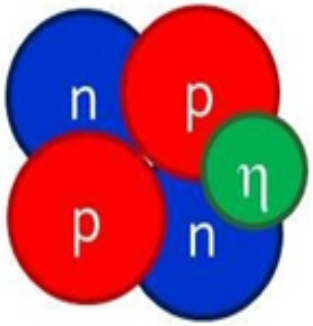
Outline

1. η-mesic nuclei - introduction
2. Search for η-mesic He with WASA-at-COSY facility
3. Summary and Conclusions

Introduction – η-mesic nuclei

η-mesic nucleus

^4He-η



strong interaction

$$m_{bound} = m_{^4He} + m_\eta - B_s$$

meson  $u\bar{u}$, $d\bar{d}$, $s\bar{s}$

m_η=547.86 MeV
Γ=1.31 keV
$\tau=10^{-18}$ s (PDG 2017)

main decay channels:

$\eta\to2\gamma$	~39%
$\eta\to3\pi^0$	~33%
$\eta\to\pi^0\pi^+\pi^-$	~23%

Studies of rare and forbidden η decay channels at WASA
Nils Husken talk, Friday 8 June

$|Re(a_{\eta N})| > Im(a_{\eta N})$

attraction > absorption

Introduction – η-mesic nuclei

Attractive and strong interaction between η and nucleon

R. Bhalerao, L. C. Liu, Phys. Lett. B54, 685 (1985) $(a_\eta N = 0.28 + i0.19\ \text{fm})$

$\Downarrow$

Possible existence of η-mesic bound states postulated for atomic nuclei with A$>$12

Q. Haider, L. C. Liu, Phys. Lett. B172, 257 (1986)

Recent theoretical studies of hadronic- and photoproduction of η meson support the existence of light η-mesic nuclei like

$(^3\text{He}\text{-}\eta)_{bound}\,(^4\text{He}\text{-}\eta)_{bound}$ $\quad 0.18\ \text{fm} < \text{Re}(a_\eta N) < 1.03\ \text{fm}$

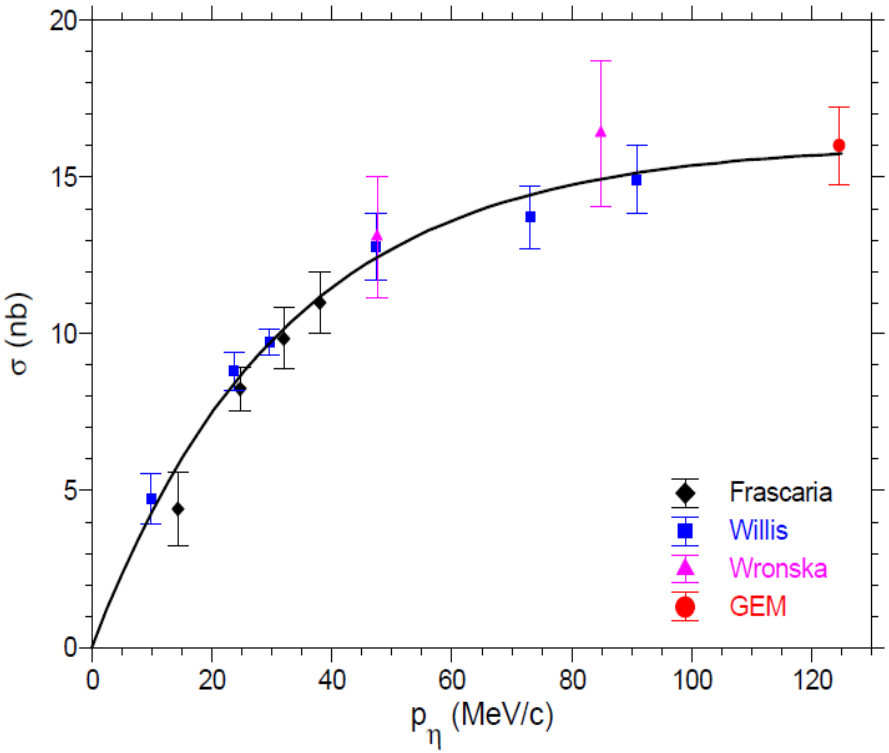
$B_s \in (0.3, 40)$ MeV, $\Gamma \in (1, 45)$ MeV $\quad 0.16\ \text{fm} < \text{Im}(a_\eta N) < 0.49\ \text{fm}$

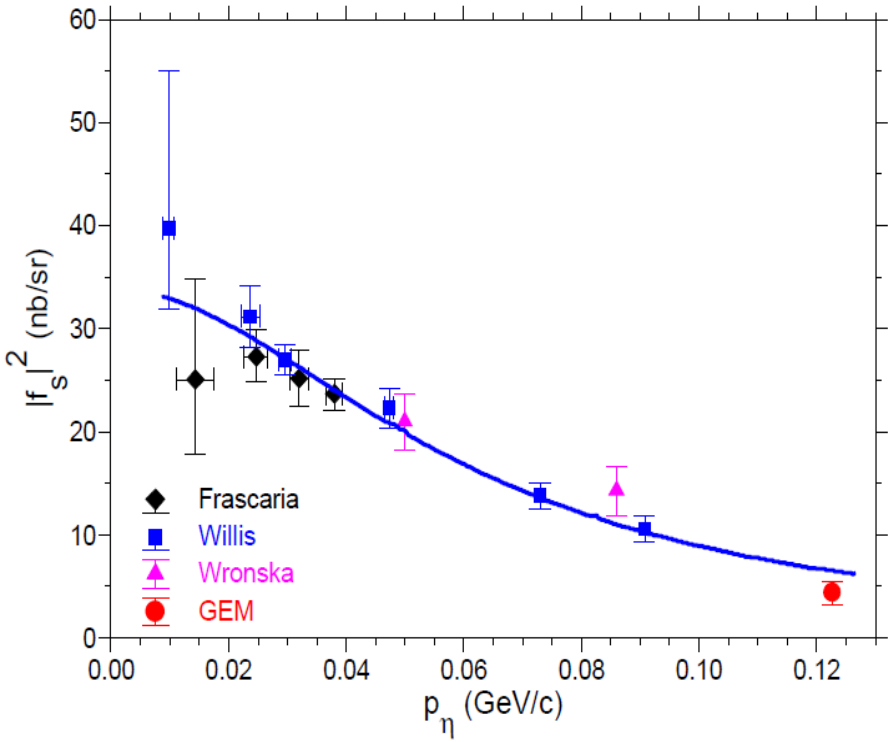
$dd \to (^4\text{He}\text{-}\eta)_{bound} \to {}^3\text{He}p\pi^-$: σ=**4.5 nb** | $pd \to (^3\text{He}\text{-}\eta)_{bound} \to Xp\pi^-$: σ=**80 nb**

J.-J. Xie et al., Phys. Rev. C95 015202 (2017)
N. Ikeno et al., Eur. Phys. J A53 no. 10, 194 (2017)
V. Metag, M. Nanova, E. Paryev, Prog. Part. Nucl. Phys. 97, 199 (2017).
N. Barnea, E. Friedman, A. Gal, Phys. Lett B747 345 (2015)
E. Friedman, A. Gal, J. Mares, Phys. Lett B725 334 (2013)
N. G. Kelkar et al., Rept. Progr. Phys. 76, 066301 (2013)
S. Wycech, W. Krzemien, Acta. Phys. Polon B45, 745 (2014)
C. Wilkin, Acta. Phys. Pol. B45, 603 (2014)

Exp. indications of the existence of the ^{4}He-η bound state

total cross section $dd \rightarrow {}^4\text{He-}\eta$ $\quad |f_s|^2 = \frac{p_d}{p_\eta}\frac{\sigma}{4\pi}$

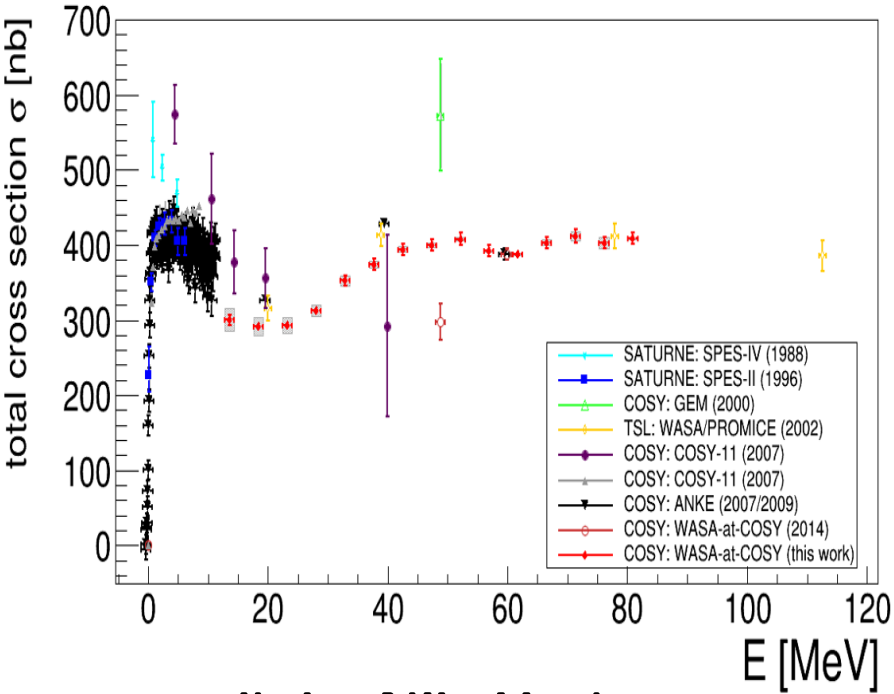




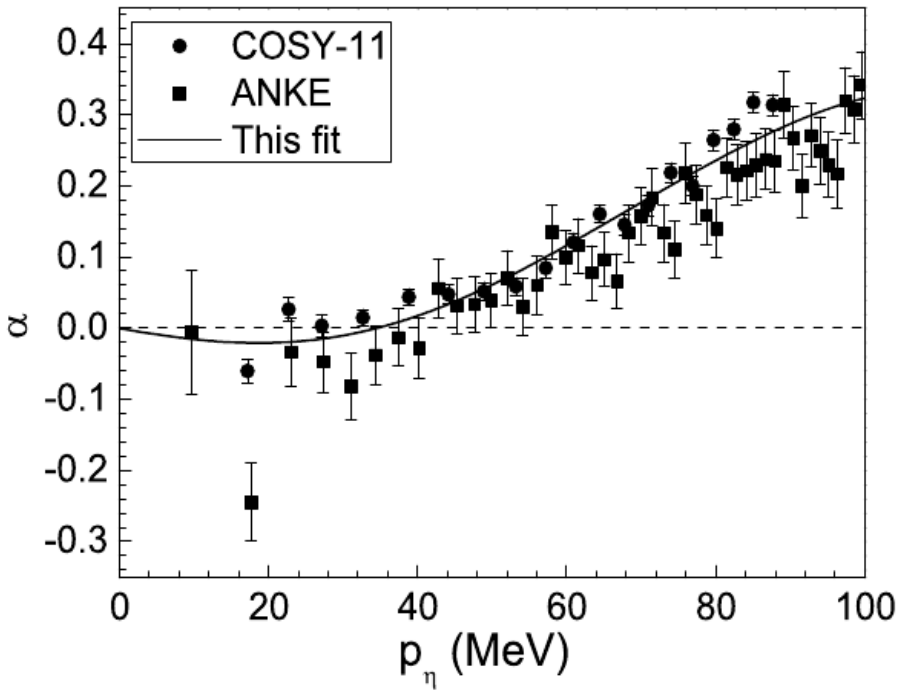
R. Frascaria et al., Phys. Rev. C50, 573 (1994)
N. Willis et al., Phys. Lett. B406, 14 (1997)
A. Wronska et al., Eur. Phys. J. A26, 421428 (2005)
A. Budzanowski et al., Nucl. Phys. A821, 193 (2009)

Exp. indications of the existence of the ^{3}He-η bound state

total cross section $pd \rightarrow {}^3\text{He-}\eta$ $\frac{d\sigma(\theta_\eta)}{d\Omega} = \frac{\sigma_{tot}}{4\pi}(1 - \alpha cos\theta_\eta)$



talk by Nils Husken



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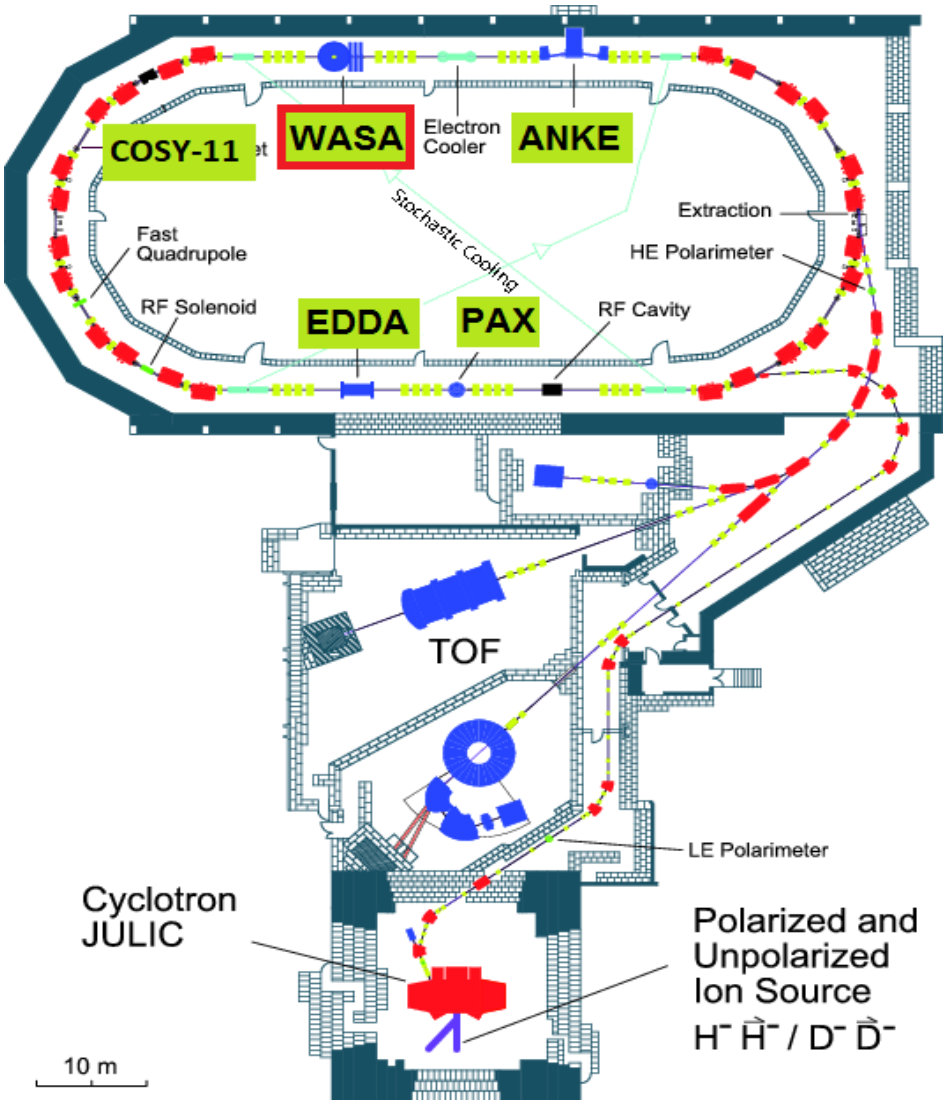
J.-J. Xie, et al., Phys. Rev. C 95, 015202 (2017)
J. Smyrski, et al., Phys. Lett. 649, 258 (2007)
T. Mersmann, et al., Phys. Rev. Lett. 98, 242301 (2007)
P. Adlarson, et al., Phys. Lett. B 782, 297 (2018)

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)

Status of the search for η-mesic Helium at COSY

$(^3\text{He}\text{-}\eta)_{bound}$

COSY-11

- **2005**: $dp \rightarrow {}^3\text{He}\pi^0$ and $dp \rightarrow pp p\pi^-$ reactions

  J. Smyrski et al., Nucl. Phys. A790, 438 (2007)

  W. Krzemien et al., Int. J. Mod. Phys. A24, 576 (2009)

WASA-at-COSY

- **2014**: search for bound state in pd reaction, in progress (O. Rundel & A. Khreptak - **poster session**)

$(^4\text{He}\text{-}\eta)_{bound}$

WASA-at-COSY

- **2008**: $dd \rightarrow {}^3\text{He}p\pi^-$ reaction

  P. Adlarson et al., Phys. Rev. C87, 035204 (2013)

- **2010**: $dd \rightarrow {}^3\text{He}n\pi^0$ and $dd \rightarrow {}^3\text{He}p\pi^-$ reactions

  P. Adlarson et al., Nucl. Phys. A 959, 102-115 (2017)

  M. Skurzok, P. Moskal, et al., Phys. Lett. B782, 6-12 (2018)

Status of the search for η-mesic Helium at COSY

$(^3\mathrm{He}\text{-}\eta)_{bound}$

COSY-11

- **2005**: $dp \to {}^3\mathrm{He}\pi^0$ and $dp \to ppp\pi^-$ reactions

$\sigma_{dp\to(^3He-\eta)_{bound}\to ppp\pi^-} < 270\ nb$

$\sigma_{dp\to(^3He-\eta)_{bound}\to {}^3He\pi^0} < 70\ nb$

WASA-at-COSY

- **2014**: search for bound state in pd reaction, in progress (O. Rundel & A. Khreptak - **poster session**)

$(^4\mathrm{He}\text{-}\eta)_{bound}$

WASA-at-COSY

- **2008**: $dd \to {}^3\mathrm{He}p\pi^-$ reaction

$\sigma_{dd\to(^4He-\eta)_{bound}\to {}^3Hep\pi^-} < 27\ nb$

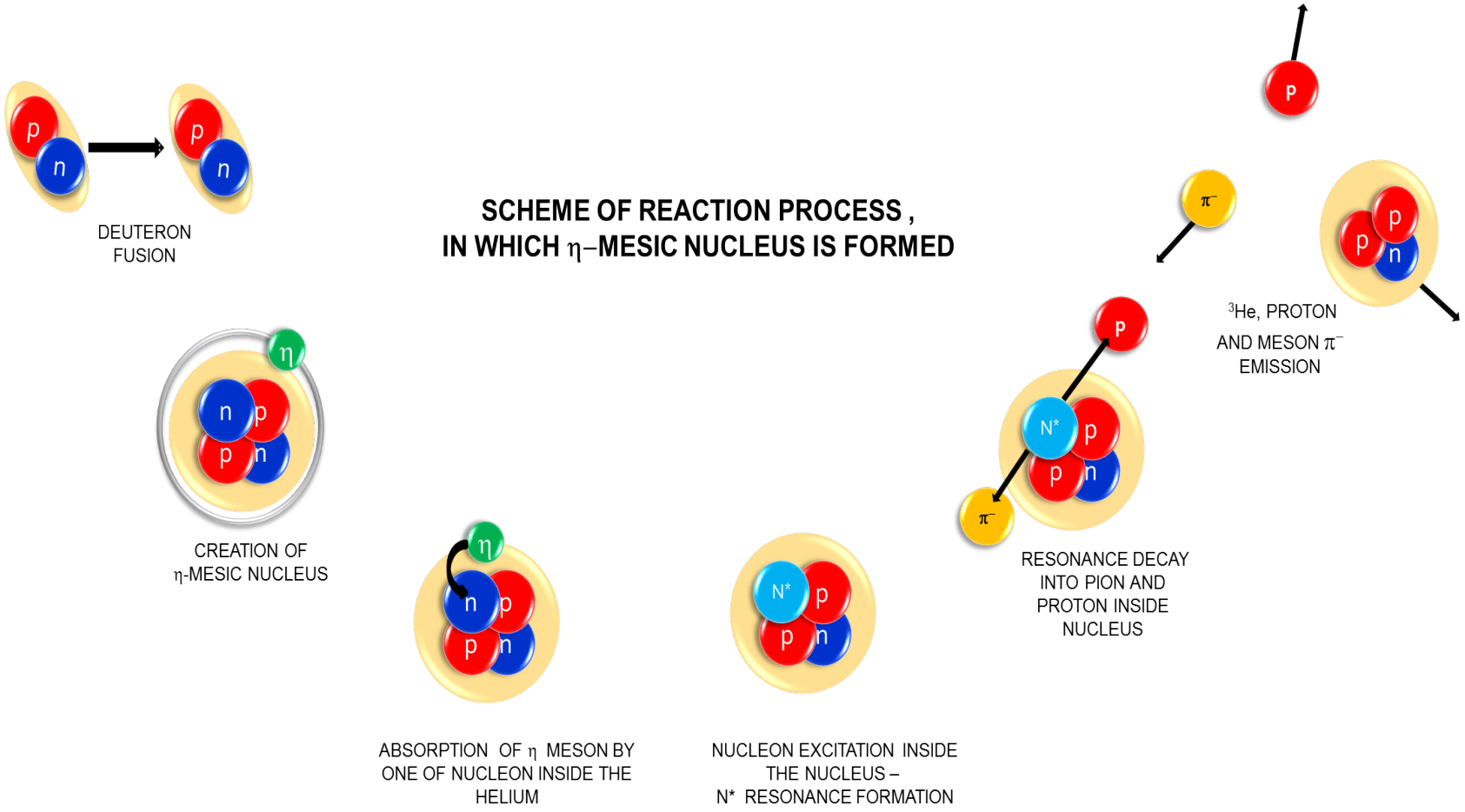
- **2010**: $dd \to {}^3\mathrm{He}n\pi^0$ and $dd \to {}^3\mathrm{He}p\pi^-$ reactions

$\sigma_{dd\to(^4He-\eta)_{bound}\to {}^3Hep\pi^-} < 7\ nb$

$\sigma_{dd\to(^4He-\eta)_{bound}\to {}^3Hen\pi^0} < 3.5\ nb$

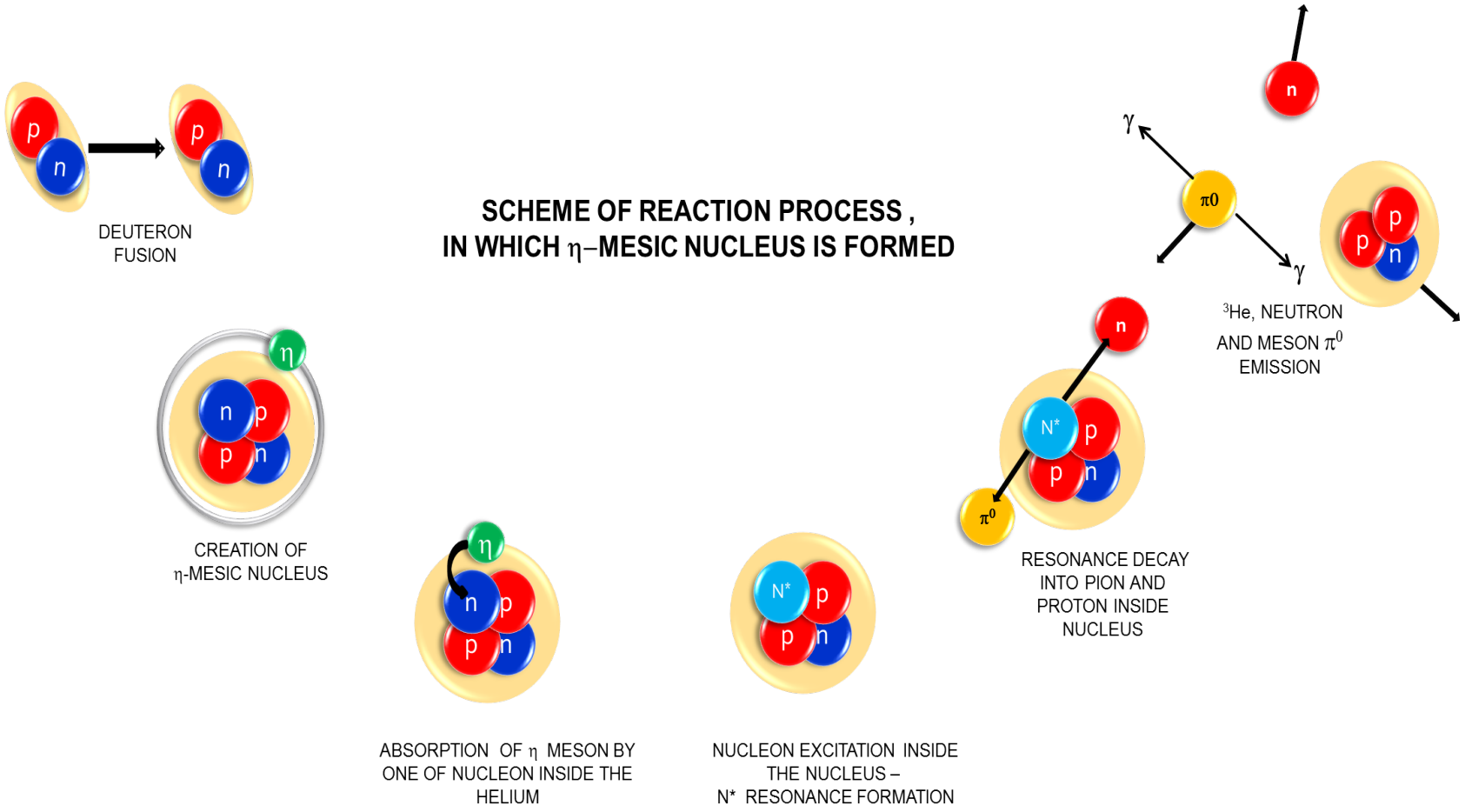
Kinematical mechanism of the reaction

$$dd \rightarrow (^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}p\pi^-$$



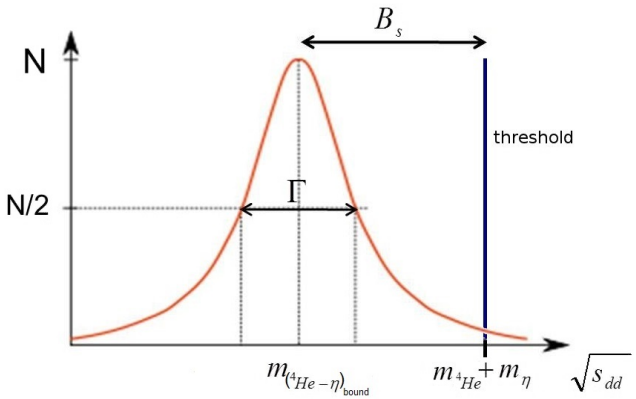
Kinematical mechanism of the reaction

$$dd \rightarrow ({}^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}n\pi^0$$



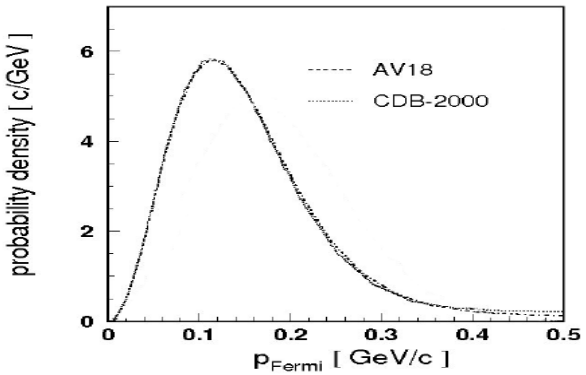
Simulation of $(^4\text{He}\text{-}\eta)_{bound}$ production and decay

Breit-Wigner distribution



$$N\left(\sqrt{s_{dd}}\right) = \frac{1}{2\pi}\frac{\Gamma^2/4}{\left(\sqrt{s_{dd}} - m_{(^4He-\eta)_{bound}}\right)^2 + \Gamma^2/4}$$

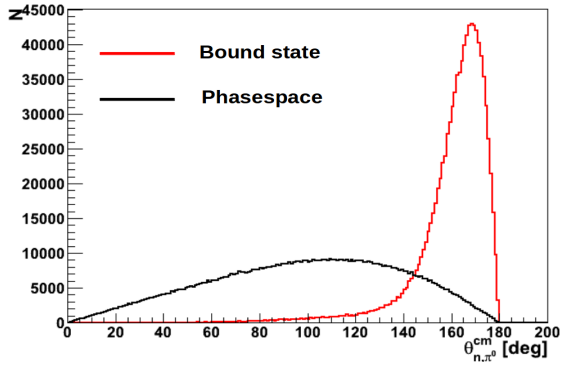
Spectator Model



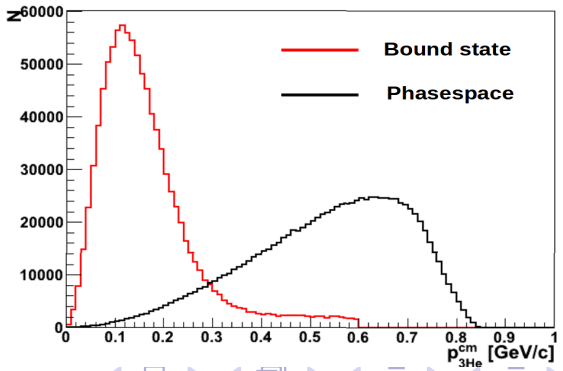
$$|\mathbb{P}_{^3He}|^2 = m^2_{^3He}$$

$$\eta + N \Rightarrow N^*(1535) \Rightarrow N + \pi = \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases}$$

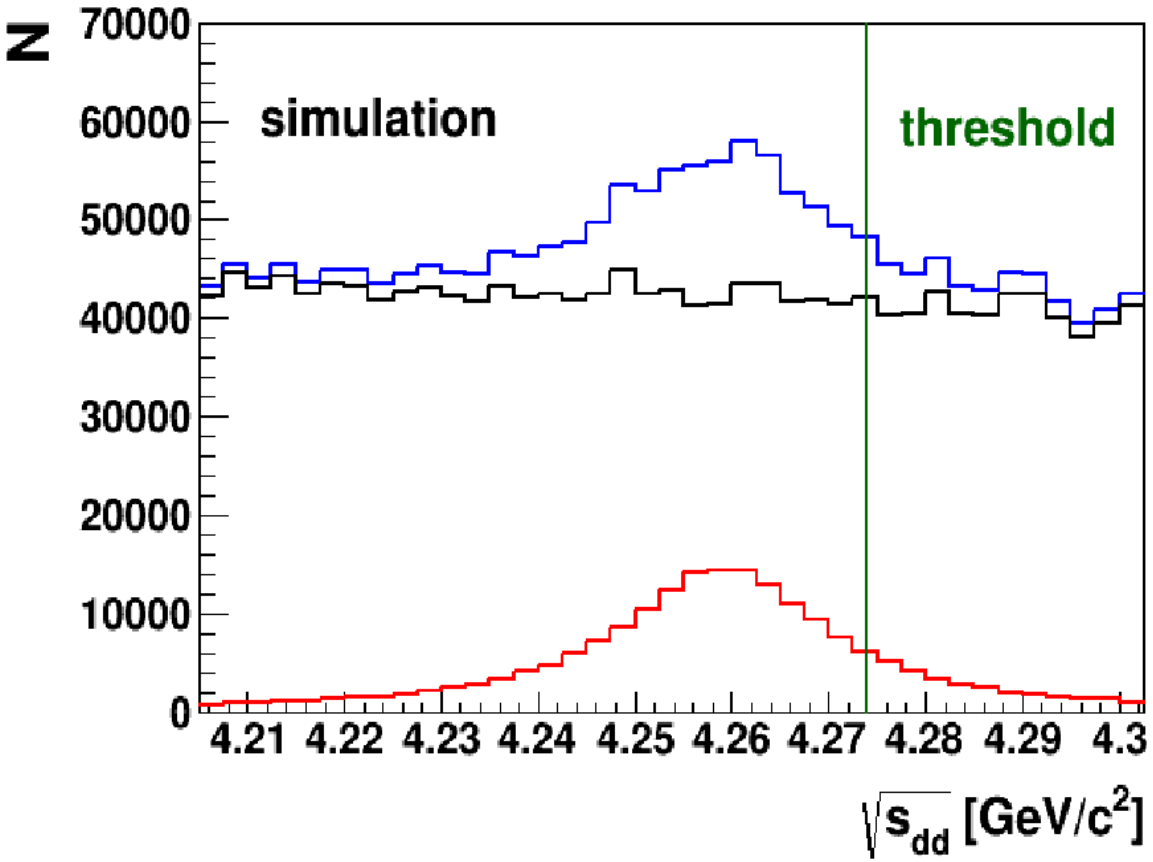
- relative N-π angle in the CM: $\theta^{N,\pi}_{cm} \sim 180^\circ$



- low ^{3}He momentum in the CM



Experimental method



$dd \rightarrow {}^3He n \pi^0$

and

$dd \rightarrow ({}^4He\text{-}\eta)_{bs} \rightarrow {}^3He n \pi^0$

$dd \rightarrow {}^3He n \pi^0$

$dd \rightarrow ({}^4He\text{-}\eta)_{bs} \rightarrow {}^3He n \pi^0$

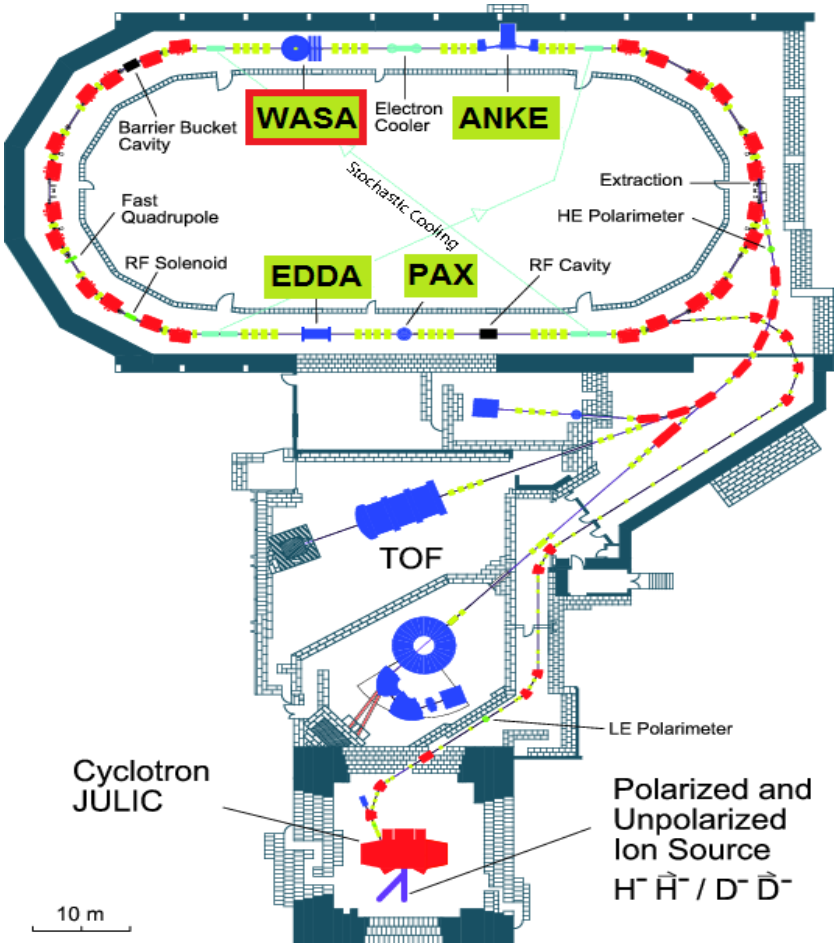
Excitation function

$({}^4He\text{-}\eta)_{bound}$ **existence manifested by resonant-like structure below** η **production threshold**

Search for $(^4\text{He-}\eta)_{bound}$ with WASA-at-COSY

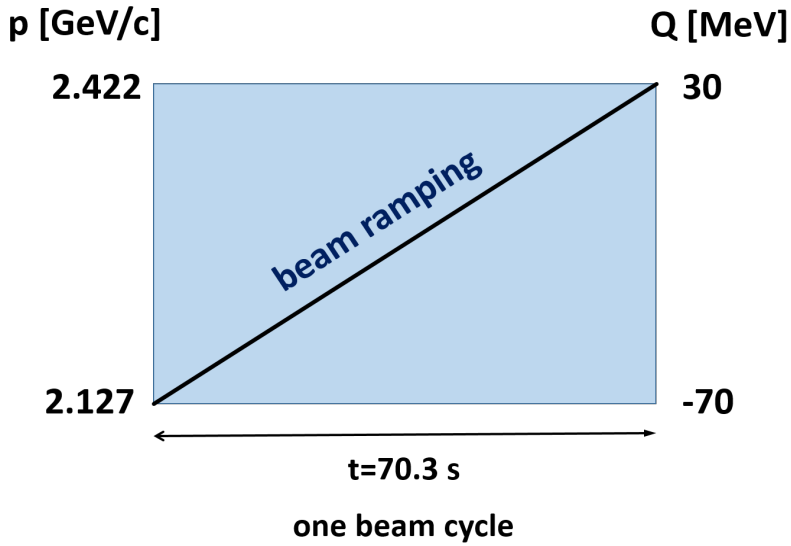
Exp. 186.1 & 186.2, FZ Jülich, Germany, 2008 and 2010

P. Moskal, W. Krzemien, J. Smyrski,
COSY proposal No. 186.1 & 186.2



$dd \to {}^3\text{He}n\pi^0$ | $dd \to {}^3\text{He}p\pi^-$

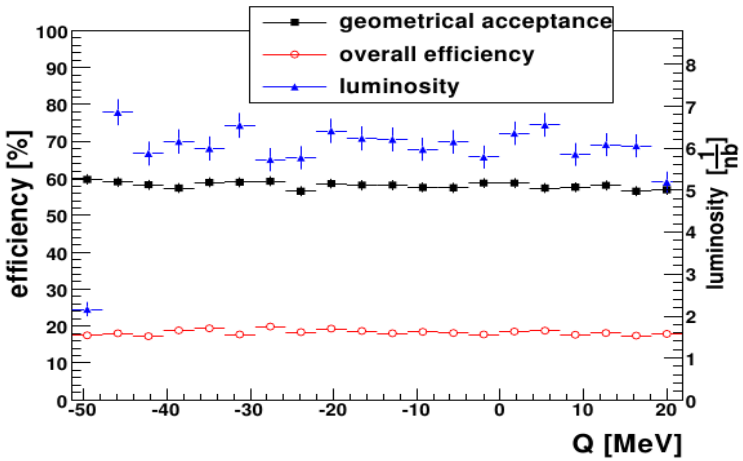
- **Measurement** with the deuteron beam momentum ramped and with the deuteron pellet target



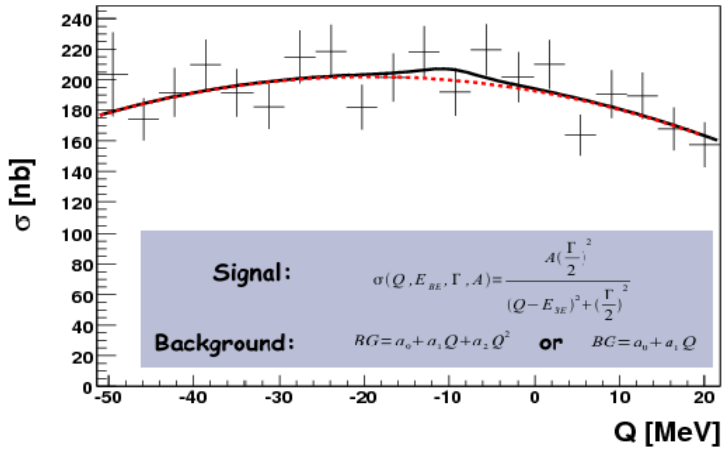
- **Data** were effectively taken with high acceptance (58%)

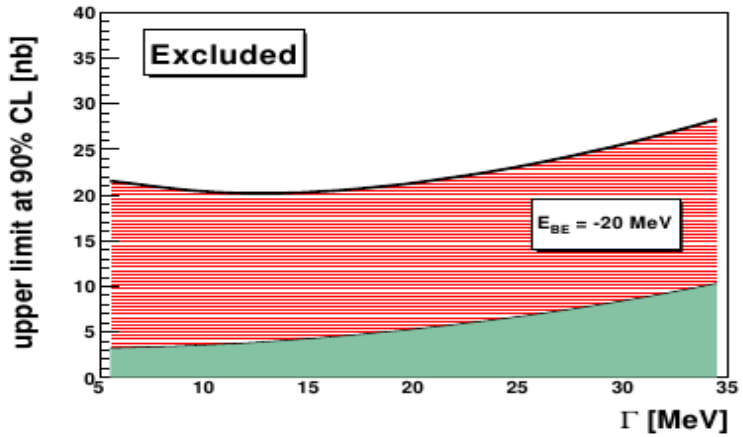
Experiment-May 2008

- **Channel:** $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ (norm: $dd \rightarrow {}^3\text{He}n$)
- **Measurement:** beam momentum ramped from **2.185GeV/c to 2.400GeV/c** $\Rightarrow$ the range of excess energy **Q$\in$(-51,22)MeV**
- **Luminosity:** L=118$\frac{1}{nb}$
- **Acceptance:** A=53%



Excitation function





RESULT: $\sigma_{dd \rightarrow (^4He-\eta)_{bound} \rightarrow {}^3Hep\pi-} < 27\ nb$

P. Adlarson et al., Phys. Rev. C87 (2013), 035204
W. Krzemien, Ph. D Thesis, Jagiellonian University (2012)

Experiment-Nov/Dec 2010

Beamtime: 26.11 - 13.12.2010

Channels: $dd \rightarrow ({}^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$
$dd \rightarrow ({}^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0 \rightarrow {}^3\text{He}n\gamma\gamma$

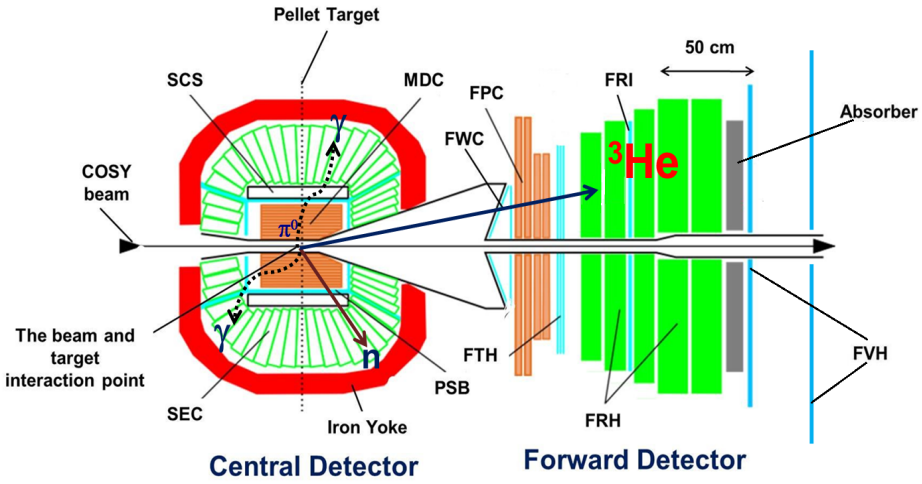
Measurement: performed with the beam momentum ramped from **2.127GeV/c to 2.422GeV/c**, corresponding to the range of excess energy **Q∈(-70,30)MeV**

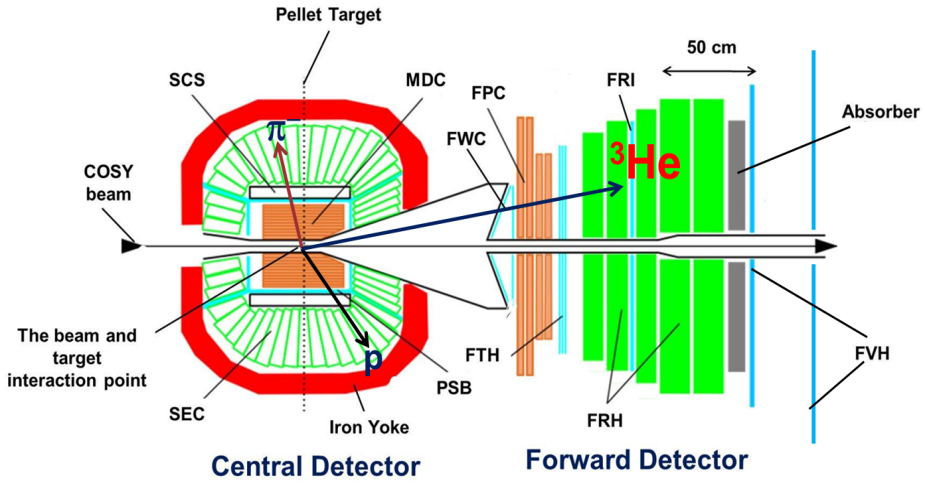
Acceptance: A=53%
Luminosity: L≈1200$\frac{1}{nb}$ ($dd \rightarrow {}^3\text{He}n$ and $dd \rightarrow ppn_{sp}n_{sp}$)

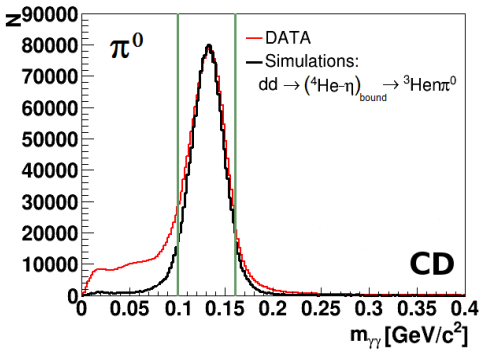
$\Downarrow$

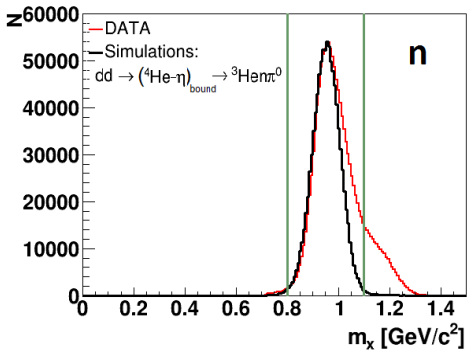
More than **10 times higher** statistics and two reactions were collected than in 2008 experiment.

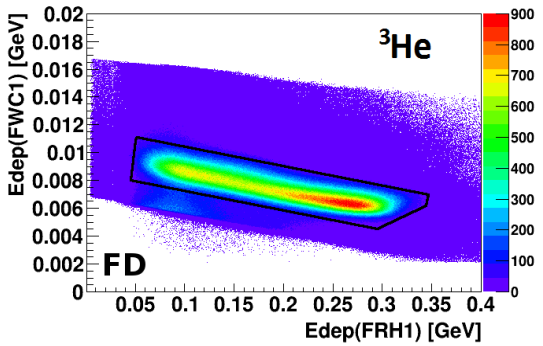
Search for $(^4\text{He-}\eta)_{bound}$ in $dd \rightarrow {}^3\text{He}N\pi$ reaction | PID

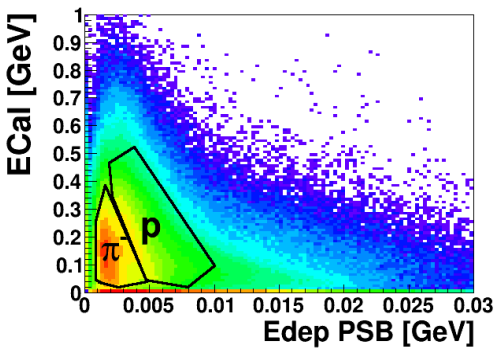


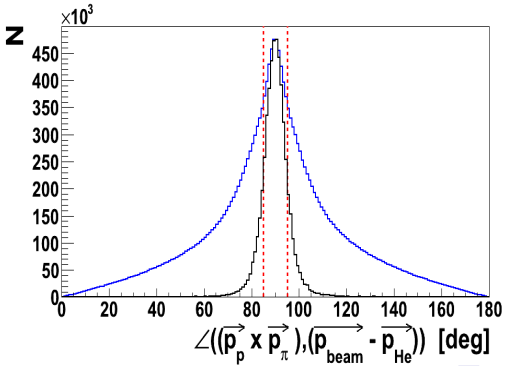




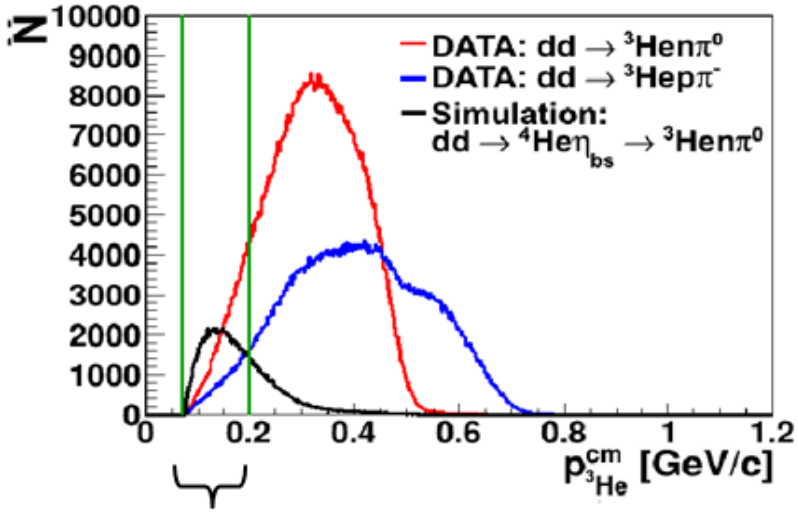




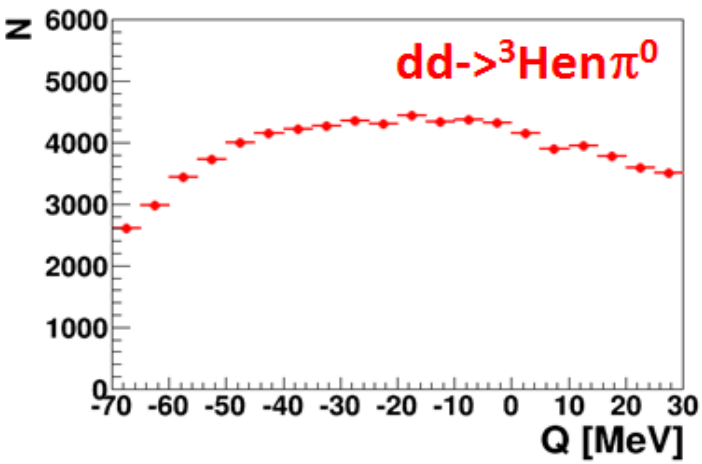


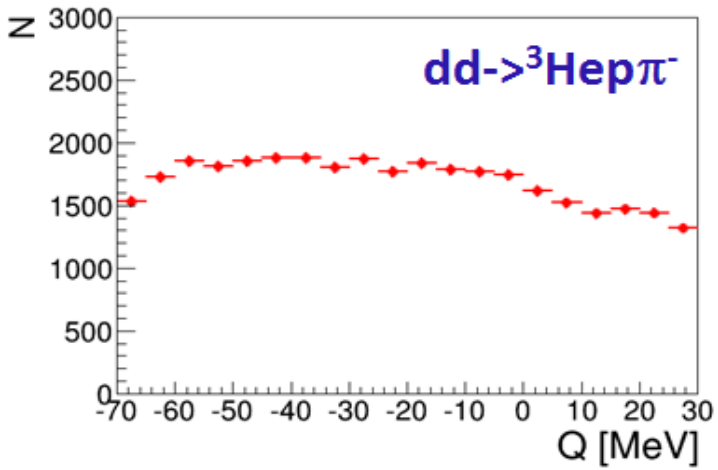


Search for $(^4\text{He-}\eta)_{bound}$ | Selection criterium



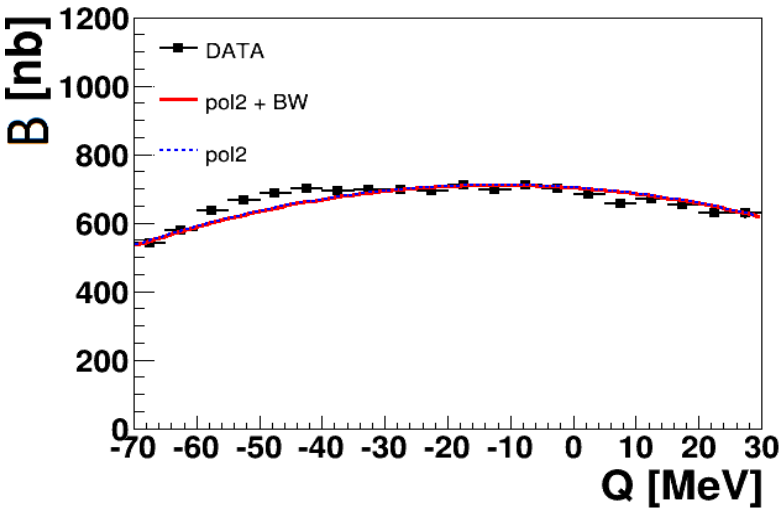
region rich in signal



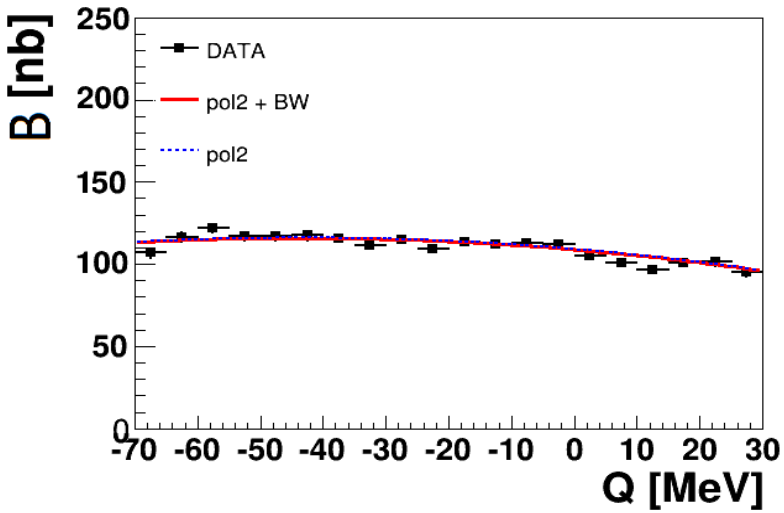


Determination of the upper limit of the total cross section for $dd \to ({}^4\text{He-}\eta)_{bound} \to {}^3\text{He}N\pi$ processes at CL=90%

$dd \to ({}^4\text{He-}\eta)_{bound} \to {}^3\text{He}n\pi^0$



$dd \to ({}^4\text{He-}\eta)_{bound} \to {}^3\text{He}p\pi^-$



simultaneous fit with $\frac{A\cdot\Gamma^2/4}{(Q-B_s)^2+\Gamma^2/4} + BQ^2 + CQ + D$

Breit-Wigner (signal) + pol2 (background)

taking into account the **isospin relation** between the both of the considered channels:

$$P(N^* \to p\pi^-) = 2P(N^* \to n\pi^0)$$

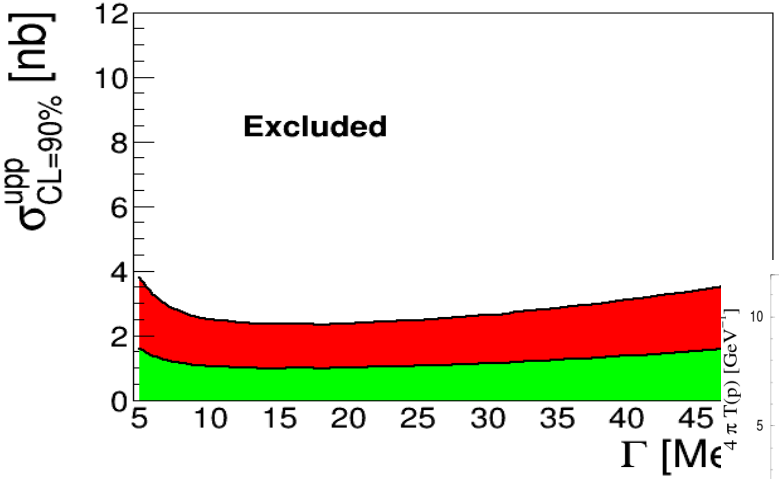
B_s,Γ - fixed parameters | A, B, C, D - free parameters $\| \sigma^{upp}_{CL=90\%} = k \cdot \sigma_A$, k=1.64 (for CL=90%)

Determination of the upper limit of the total cross section for $dd \to ({}^4\text{He-}\eta)_{bound} \to {}^3\text{He}p\pi^-$ process at CL=90%

$\sigma^{upp}_{CL=90\%}$ for

$dd \to ({}^4\text{He-}\eta)_{bound} \to {}^3\text{He}n\pi^0$

$\Downarrow$



$\sigma^{upp}_{CL=90\%}$ for

$dd \to ({}^4\text{He-}\eta)_{bound} \to {}^3\text{He}p\pi^-$

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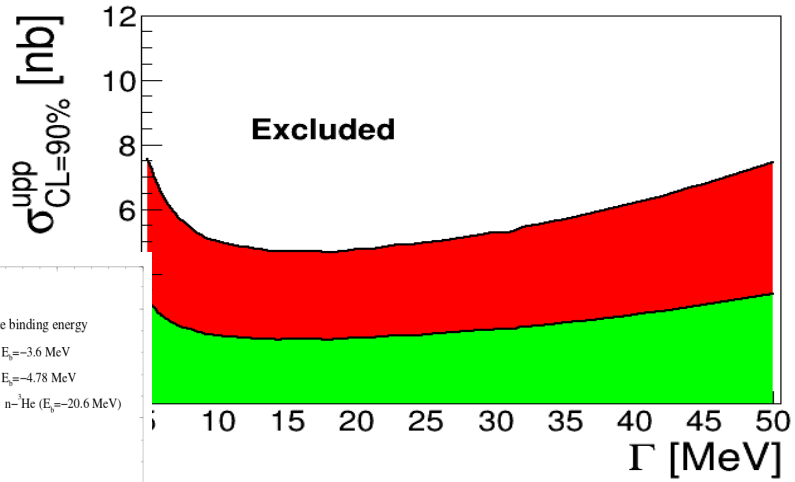
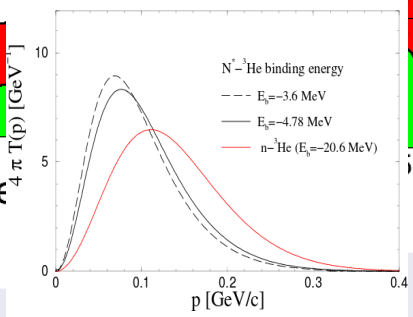




RESULT:

$\sigma_{dd \to ({}^4He-\eta)_{bound} \to {}^3Hen\pi^0} < 3.5\ nb$

N. G. Kelkar, Eur. Phys. J. A 52 (2016) 309.

RESULT:

$\sigma_{dd \to ({}^4He-\eta)_{bound} \to {}^3Hep\pi^-} < 7\ nb$

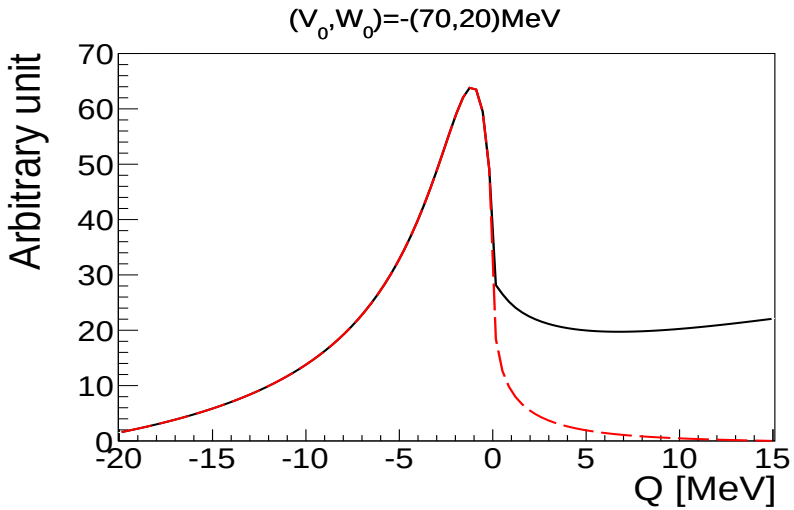
2008: $\sigma < 27\ nb$

More details in: P. Adlarson et al., Nucl. Phys. A 959, 102-115 (2017)

Comparison with N. Ikeno et al. model prediction

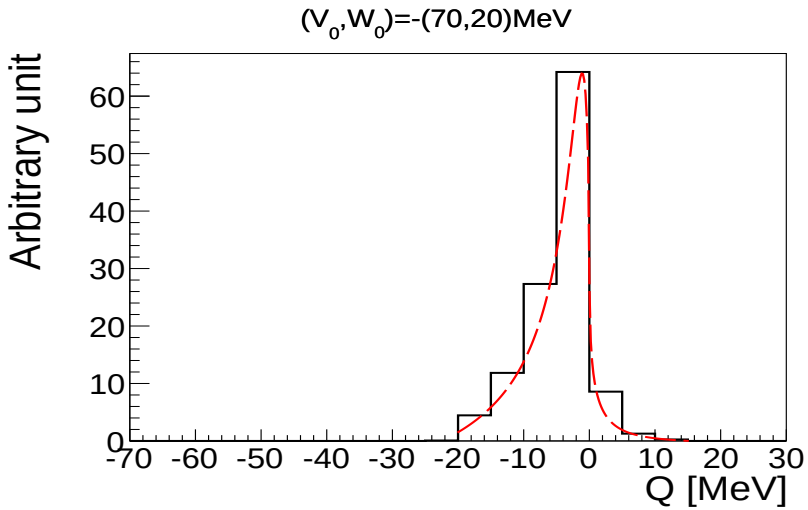
N. Ikeno, H. Nagahiro, D. Jido, S. Hirenzaki, Eur. Phys. J. A 53, 194 (2017)

- total cross sections for the $dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}N\pi$ reaction determined based on phenomenological calculations
- the model reproduced the data on the $dd \to {}^4\text{He}\,\eta$ reaction quite well
- $\sigma = \sigma_{conv} + \sigma_{esc}$
- σ_{conv} - determined for different parameters V_0 and W_0 of a spherical η-^{4}He optical potential $V(r) = (V_0 + iW_0)\frac{\rho_\alpha(r)}{\rho_\alpha(0)}$ (the total cross section in the subthreshold excess energy region where the η meson is absorbed by the nucleus)
- normalization in the sense that the escape part reproduces the measured cross sections for the $dd \to {}^4\text{He}\eta$ process



σ —

σ_{conv} - -

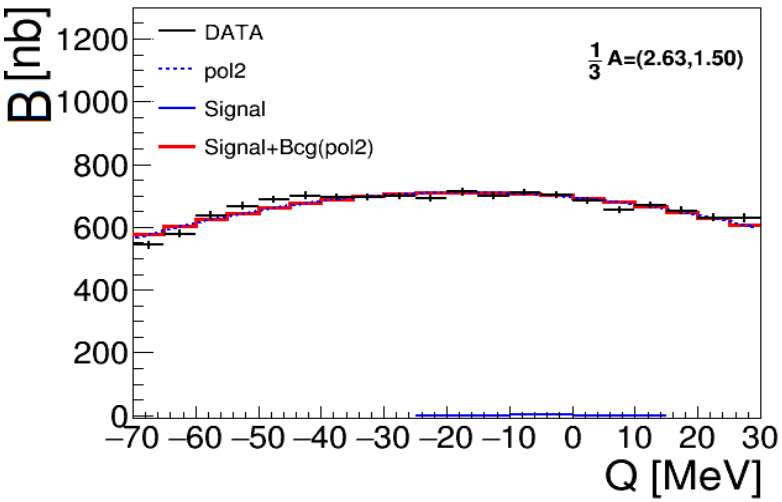


σ_{conv} spectrum convoluted with the experimental resolution functions

Comparison with N. Ikeno et al. model prediction

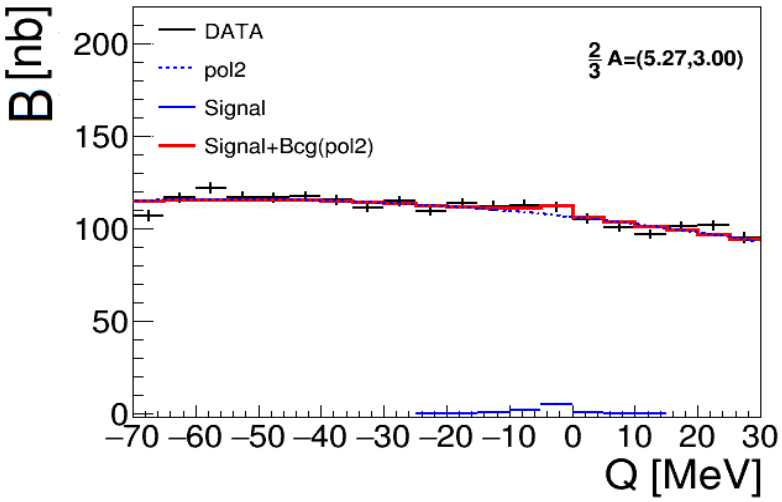
$dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0$

$\Downarrow$



$dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$

$\Downarrow$



$$\sigma_{n\pi^0}(Q) = \frac{1}{3}A \cdot Theory(Q) + B_1 Q^2 + C_1 Q + D_1$$

$$\sigma_{p\pi^-}(Q) = \frac{2}{3}A \cdot Theory(Q) + B_2 Q^2 + C_2 Q + D_2$$

isospin relation between the both of the considered channels

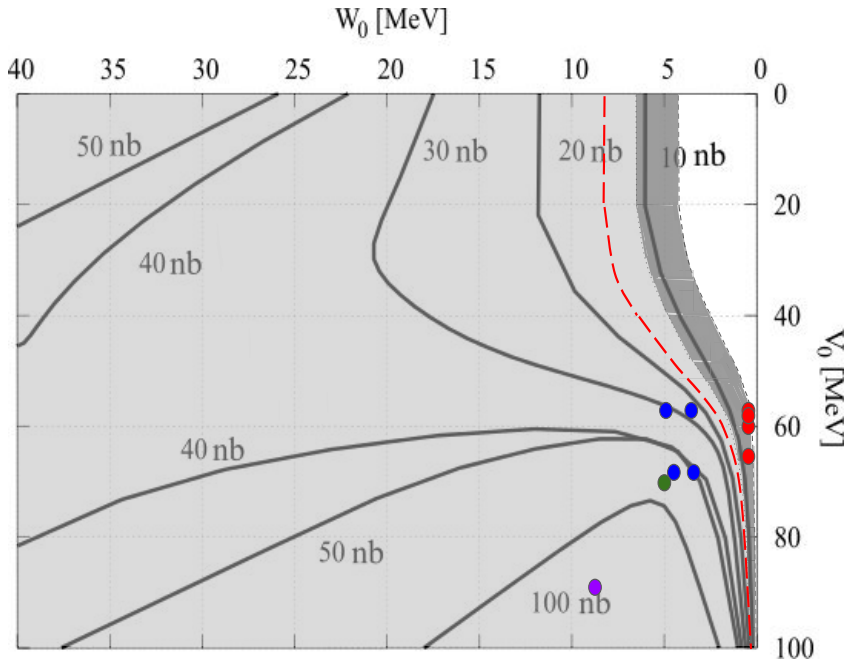
$Theory(Q)$ - theoretical function after binning with the amplitude normalized to unity
$B_{1,2}Q^2 + C_{1,2}Q + D_{1,2}$ - polynomial of the second order

Fit performed for theoretical spectra obtained for different optical potential parameters (V_0, W_0)

Comparison with N. Ikeno et al. model prediction

results obtained for different optical potential parameters (V_0, W_0)

V_0	W_0	A (fit) [nb]	$\sigma_{upp}^{CL=90\%}$ [nb]
-30	-5	-5.0±3.9	6.5
-30	-20	-2.2±3.5	5.8
-30	-40	0.2±3.8	6.3
-50	-5	0.1±3.8	6.3
-50	-20	3.3±4.1	6.8
-50	-40	6.0±4.2	6.9
-70	-5	6.4±4.5	7.4
-70	-20	7.9±4.5	7.4
-70	-40	7.5±3.7	6.1
-100	-5	6.3±4.5	7.4
-100	-20	6.9±3.9	6.4
-100	-40	5.3±3.1	5.2

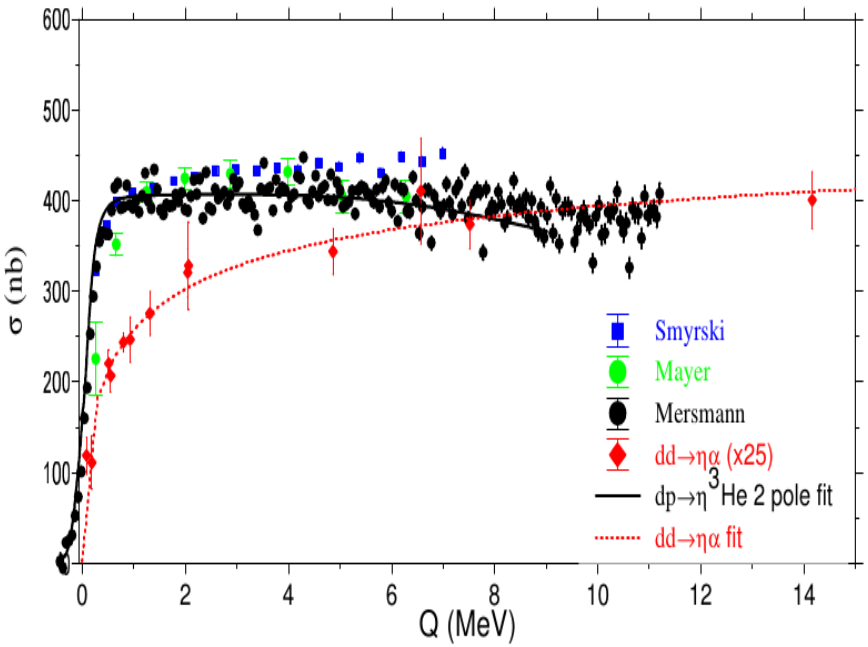


Contour plot of the theoretically determined conversion cross section in $V_0 - W_0$ plane.

The allowed parameter space ($|V_0| <\sim 60$ MeV and $|W_0| <\sim 7$ MeV) excludes most optical model predictions of $\eta-^4$He nuclei except for some loosely bound narrow states.

More details in: **M. Skurzok, P. Moskal, et al., Phys. Lett. B708, 6-12 (2018)**

Search for $(^3\text{He-}\eta)_{bound}$ with WASA-at-COSY



$$\sigma_{pd\to{}^3He-\eta} \approx 25\sigma_{dd\to{}^4He-\eta}$$

About 2 weeks of measurement allowed us to reach sensitivity of **few nb** ($L \approx 4500\frac{1}{nb}$)

Measurement: p_{beam} : 1.468-1.615GeV/c, **Q∈(-70,30)MeV**

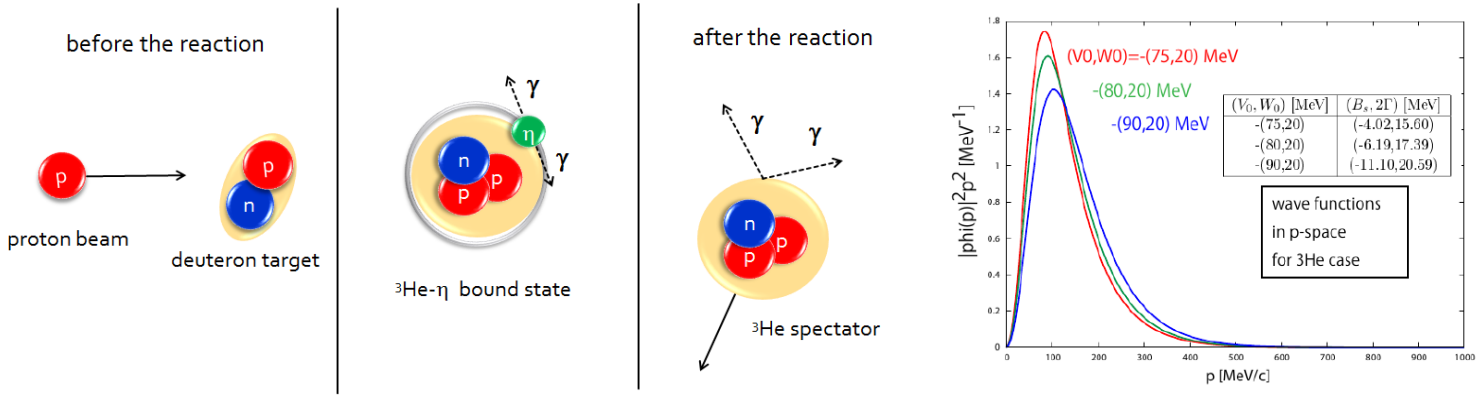
Channels:

- **Via the resonance decay N^*:**
  1) $pd \to (^3\text{He-}\eta)_{bound} \to ppp\pi^-$
  2) $pd \to (^3\text{He-}\eta)_{bound} \to ppn\pi^0$
  3) $pd \to (^3\text{He-}\eta)_{bound} \to dp\pi^0$
  Aleksander Khreptak → Poster Session

- **Absorption of orbiting η**
  4) $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}\ 2\gamma$
  5) $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}\ 6\gamma$
  Oleksandr Rundel → Poster Session

- **Nonresonant decay (absorption on two nucleons)**
  6) $pd \to (^3\text{He-}\eta)_{bound} \to ppn$
  7) $pd \to (^3\text{He-}\eta)_{bound} \to pd$

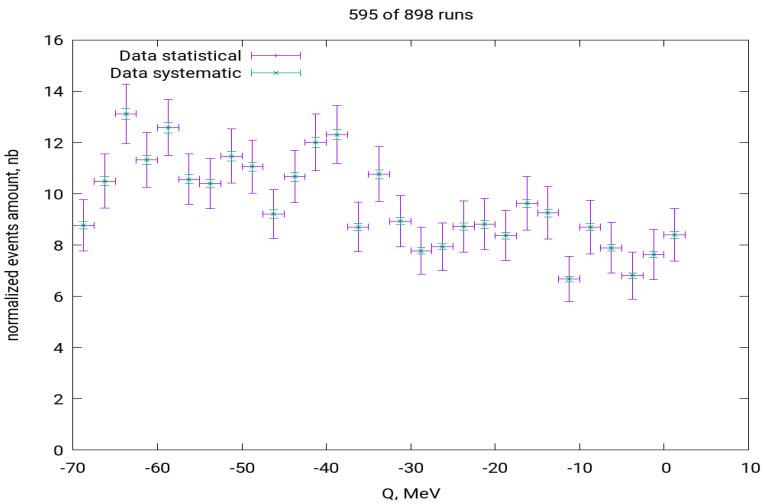
Perspectives



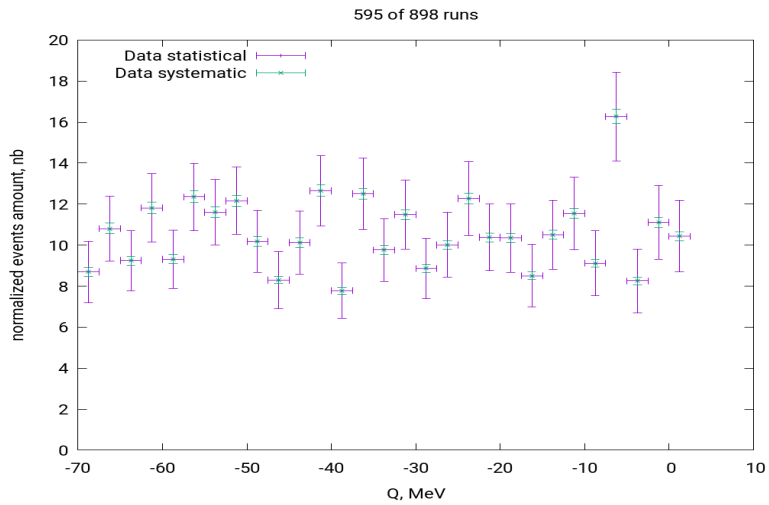
PRELIMINARY!

S. Hirenzaki, H. Nagahiro, Private communication (2016)

$pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\ 2\gamma$



$pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\ 6\gamma$



- precision of **few nb** (about 60% of analysed data)

Summary and Conclusions

- Exclusive measurement of the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ and $dd \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$ reactions was carried out using the ramped beam technique.
- No bound state signal visible in 2008 data (upper limit of the total cross section for the bound state production determined)
- 2010 measurement doesn't show a narrow signal of η-mesic nuclei
- The upper limit of the total cross section was for the first time determined for $dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}n\pi^0$ reaction
- The upper limits for $dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}p\pi^-$ and $dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}n\pi^0$reaction in order of **few nb**!
- New data set in ${}^3\mathrm{He}\text{-}\eta$ system (Experiment in May 2014) - **promissing!**

Thank you for attention