Search for the η-mesic helium in proton-deuteron and deuteron-deuteron reactions

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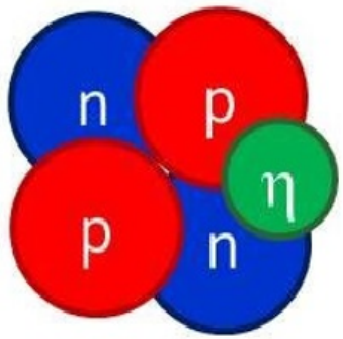
Outline

1. Introduction
2. Search for η-mesic He with WASA-at-COSY facility
3. Data analysis and obtained results
4. Summary and Conclusions

Introduction – η-mesic bound state

η-mesic nucleus

^4He-η



strong interaction

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

meson

uū, dd̄, ss̄

m_η=547.86 MeV
Γ=1.31 keV
t=10^{-18}s

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

attraction>absorption

Introduction – η-mesic bound state

Attractive and strong interaction between η and nucleon

R. Bhalerao, L. C. Liu, Phys. Lett. B54, 685 (1985)

$\Downarrow$

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

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

Prof. Metag talk

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

$(^3\text{He-}\eta)_{bound}$ $(^4\text{He-}\eta)_{bound}$

$\Gamma \in (4, 45)$ MeV, $B_s \in (2, 40)$ MeV

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

J.-J. Xie et al., Phys. Rev. C95 015202 (2017) → **Prof. Oset talk**
N. Barnea, E. Friedman, A. Gal, Phys. Lett B747 345 (2015) → **Prof. Gal talk**
E. Friedman, A. Gal, J. Mares, Phys. Lett B725 334 (2013)
N. Ikeno, H. Nagahiro, D. Jido, S. Hirenzaki, Eur. Phys. J. (subm.)→ **Prof. Hirenzaki talk**
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)

Status of the search for η-mesic Helium at WASA

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

- **2008**: $dd \rightarrow {}^3\text{He}p\pi^-$ reaction (W. Krzemień)
- **2010**: $dd \rightarrow {}^3\text{He}n\pi^0$ and $dd \rightarrow {}^3\text{He}p\pi^-$ reactions (M. Skurzok & W. Krzemień)

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

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

Poster session (Monday):
Luminosity determination based on $pd \rightarrow {}^3\text{He-}\eta$ reaction

Production of ^{4}He-η in dd collision

$$dd \to \left({}^4He - \eta\right)_{bs} \to {}^3He\ p\ \pi^-$$

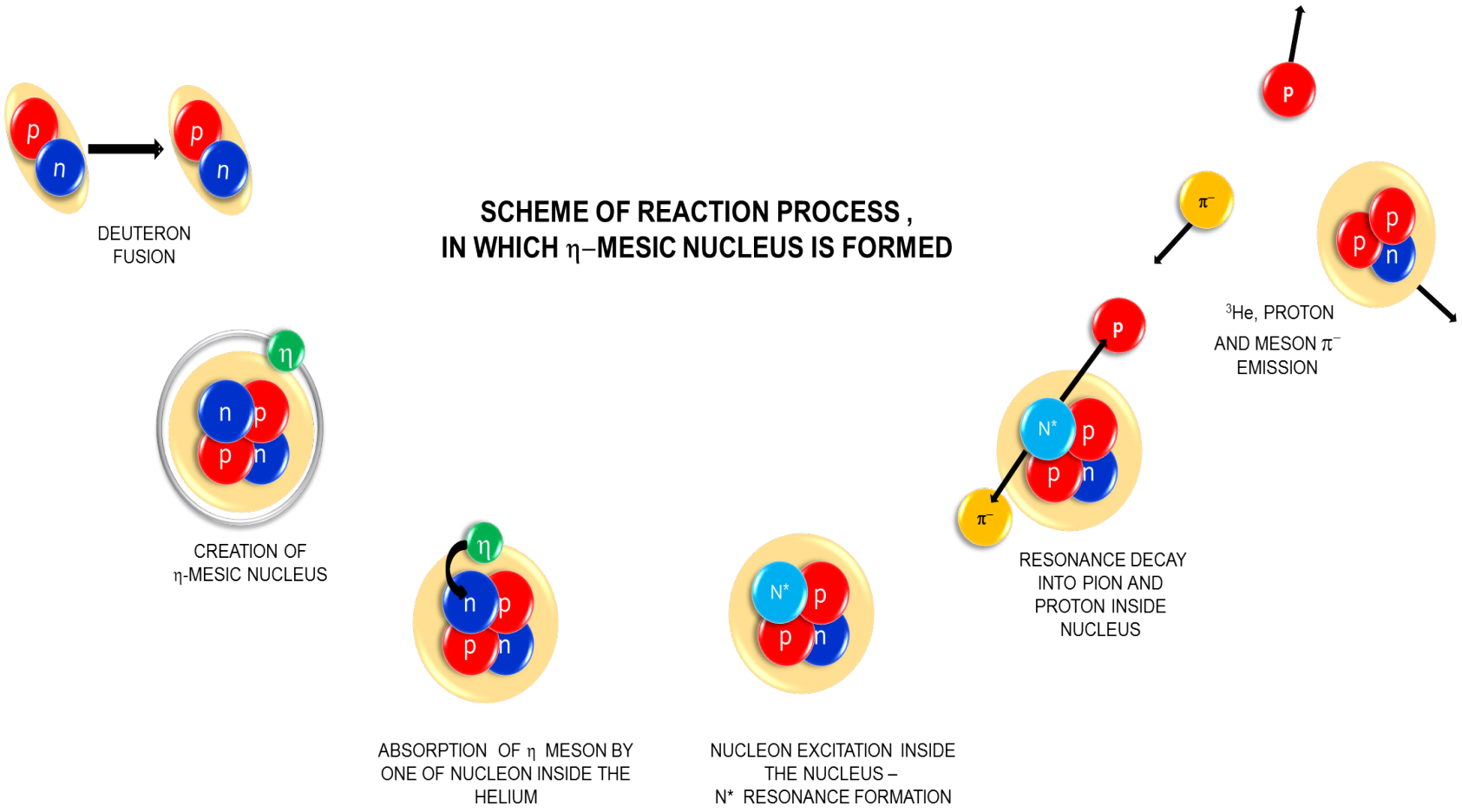
$$dd \to \left({}^4He - \eta\right)_{bs} \to {}^3He\ n\ \pi^0 \to {}^3He\ n\ \gamma\ \gamma$$

$$dd \to \left({}^4He - \eta\right)_{bs} \to d\ p\ p\ \pi^-$$

$$dd \to \left({}^4He - \eta\right)_{bs} \to T\ p\ \pi^0 \to T\ p\ \gamma\ \gamma$$

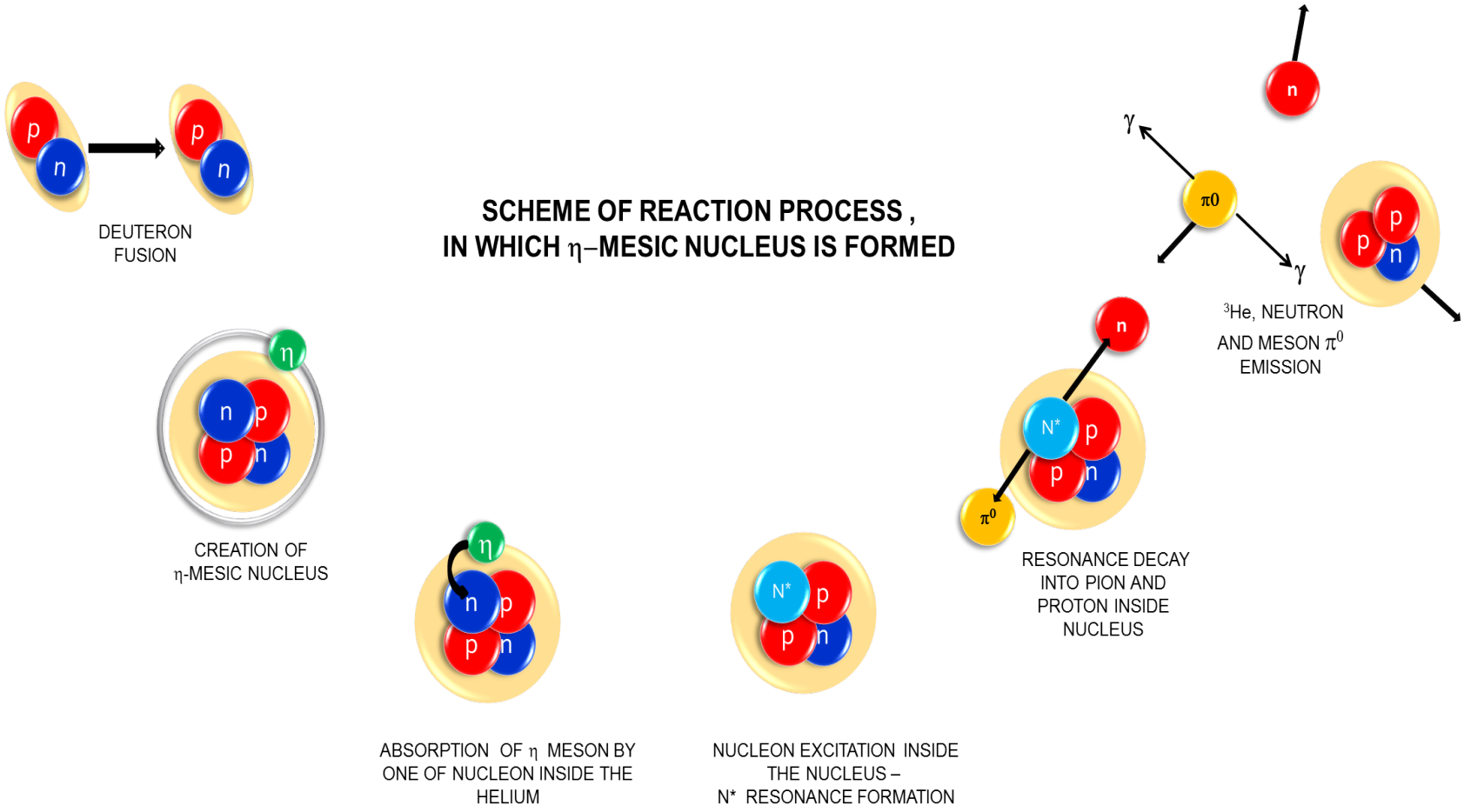
Kinematical mechanism of the reaction

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



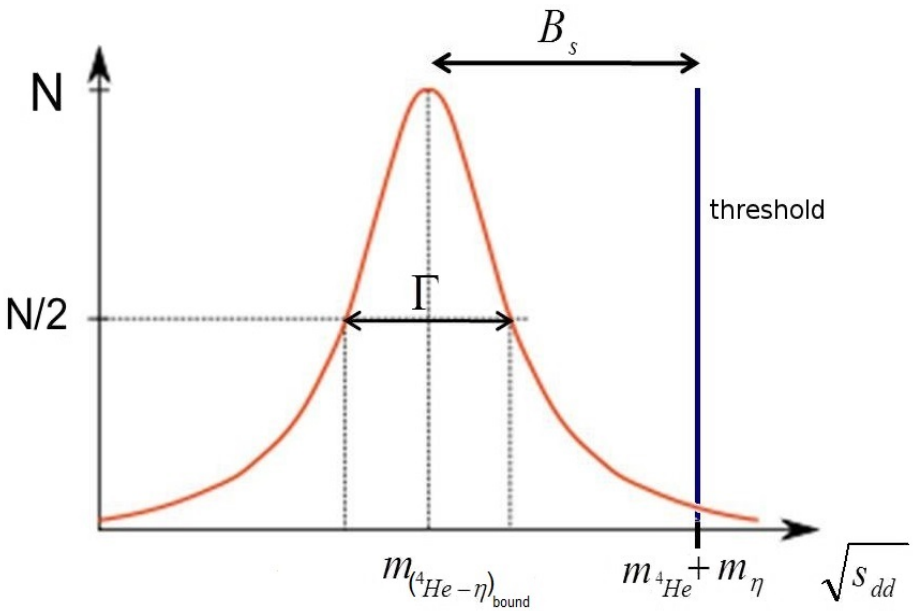
Kinematical mechanism of the reaction

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

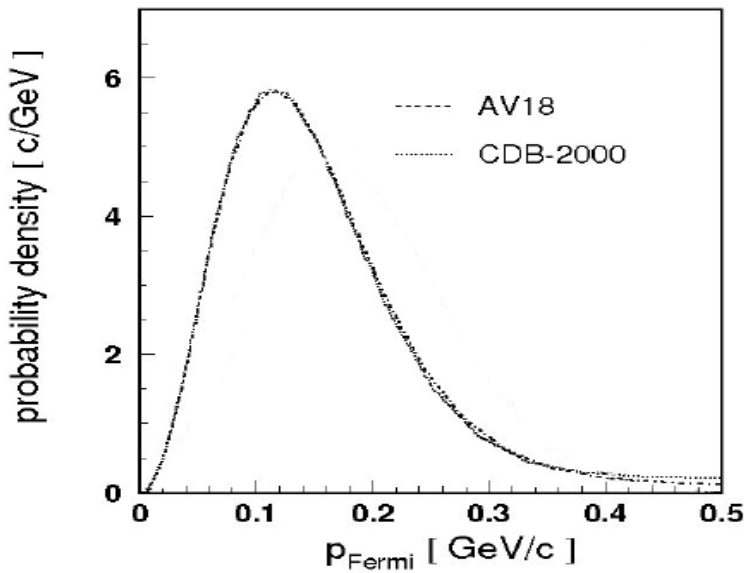


Simulation of $(^4\text{He}\text{-}\eta)_{bound}$ production and decay

Breit-Wigner distribution



Spectator Model



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

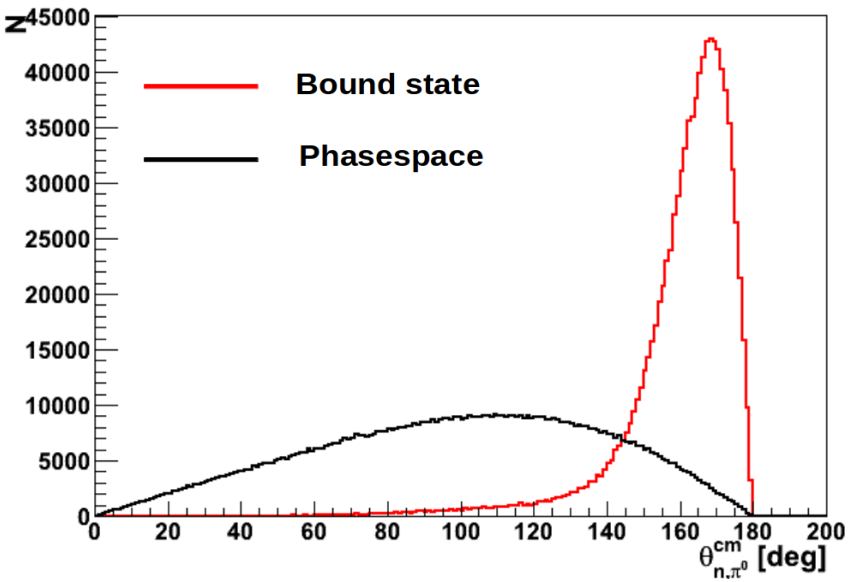
$$\left|\mathbb{P}_{^3He}\right|^2 = m^2_{^3He}$$

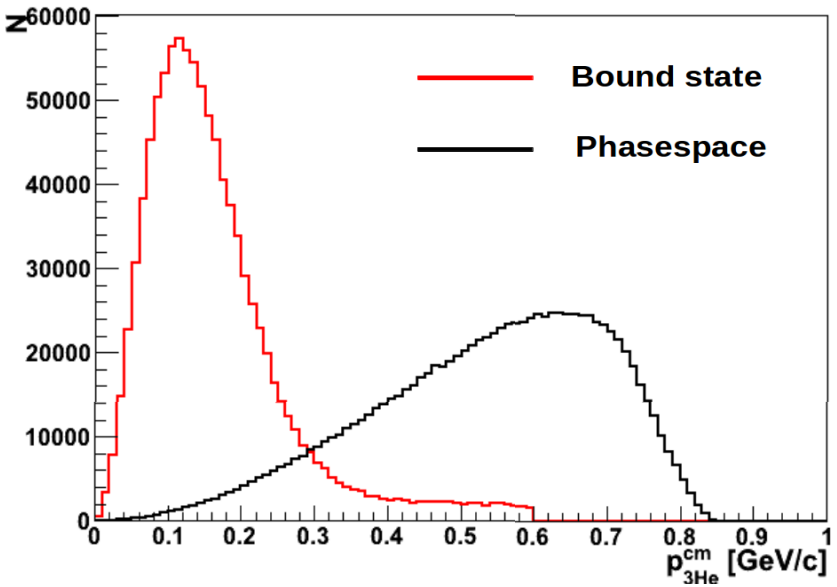
$$m_{(^4He-\eta)_{bound}} = m_{^4He} + m_\eta - B_s$$

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

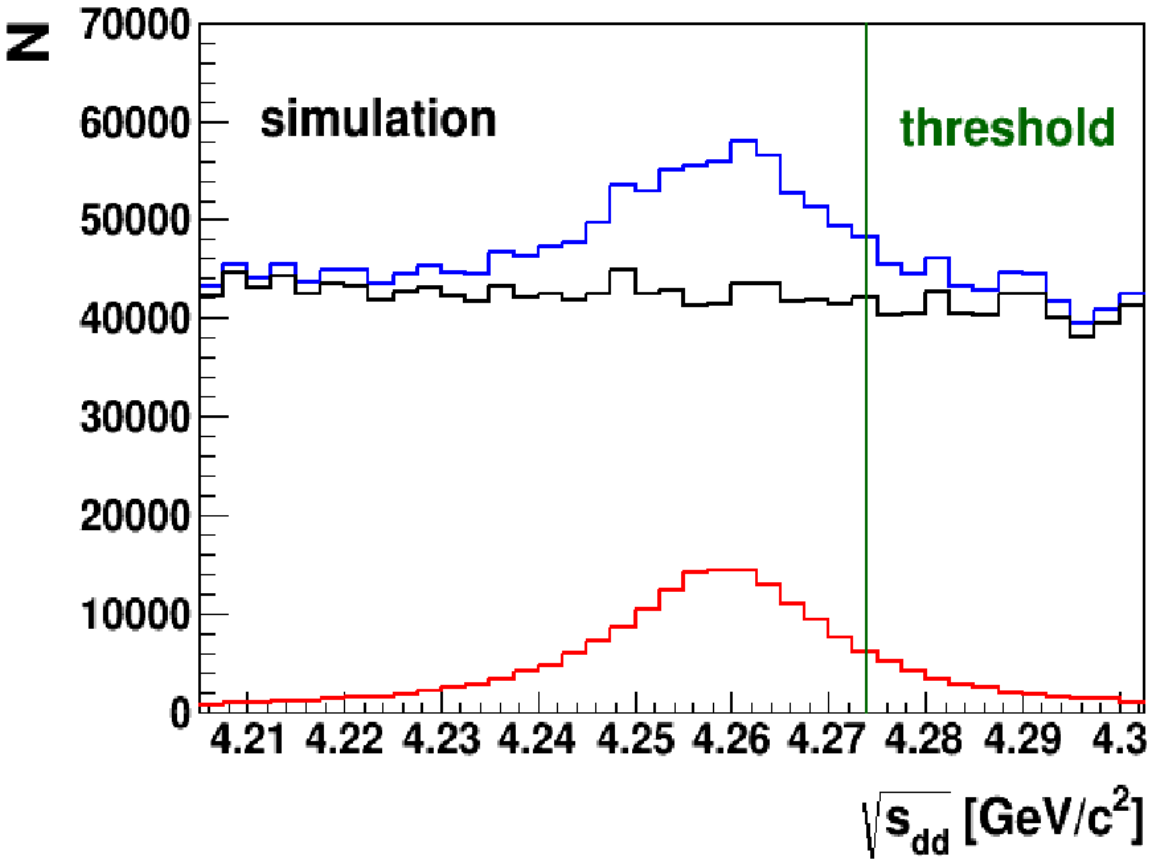
$$\eta + N \Rightarrow N^*(1535) \Rightarrow N + \pi = \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases}$$

- relative N-π angle in the CM: $\theta_{cm}^{N,\pi} \sim 180^\circ$
- low ^{3}He momentum in the CM





Experimental method



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

and

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

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

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

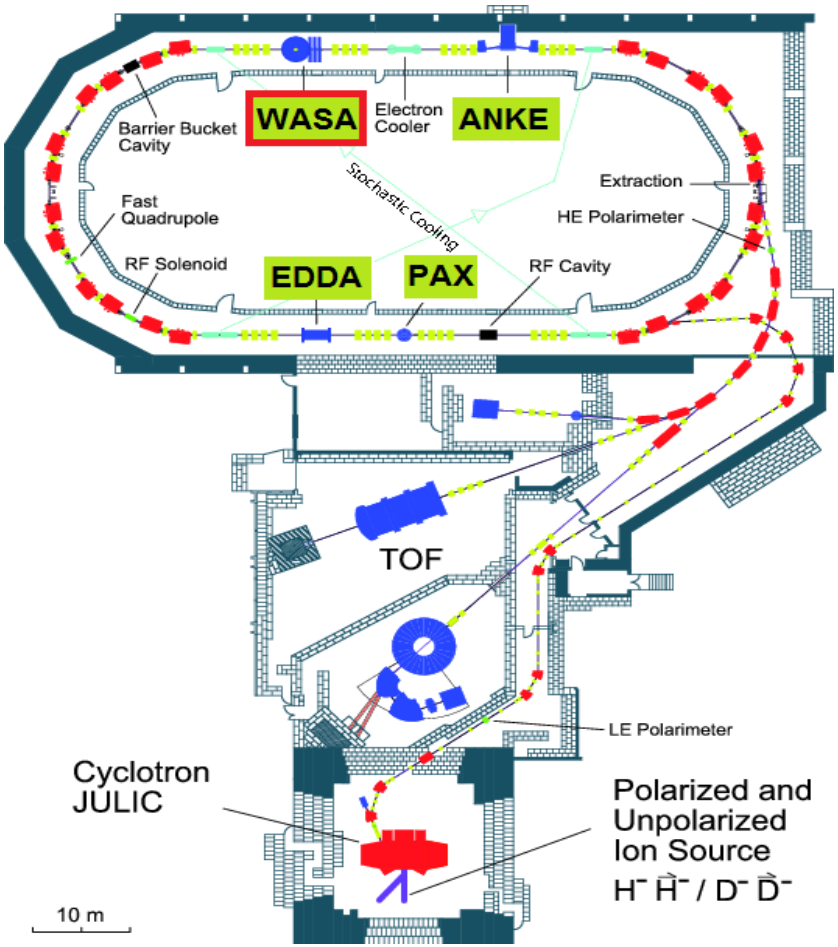
Excitation function

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

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

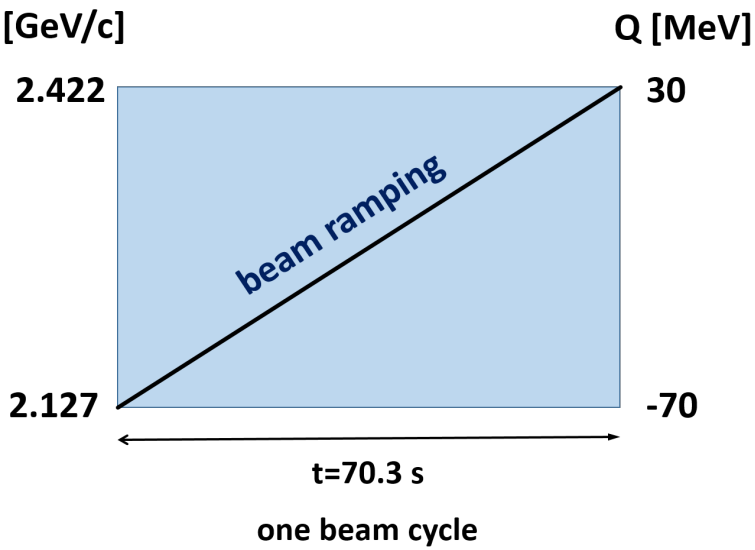
Exp. 186.1 & 186.2, FZ Jülich, Germany, 2008 and 2010

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



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

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



- **Data** were effectively taken about 160h with high acceptance (58%) and luminosity $(2.4{\cdot}10^{30}\frac{1}{cm^2 s})$

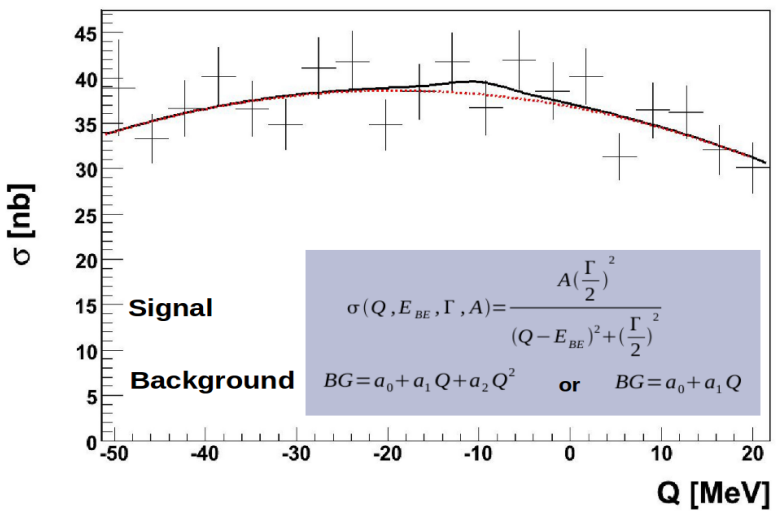
Experiment-May 2008

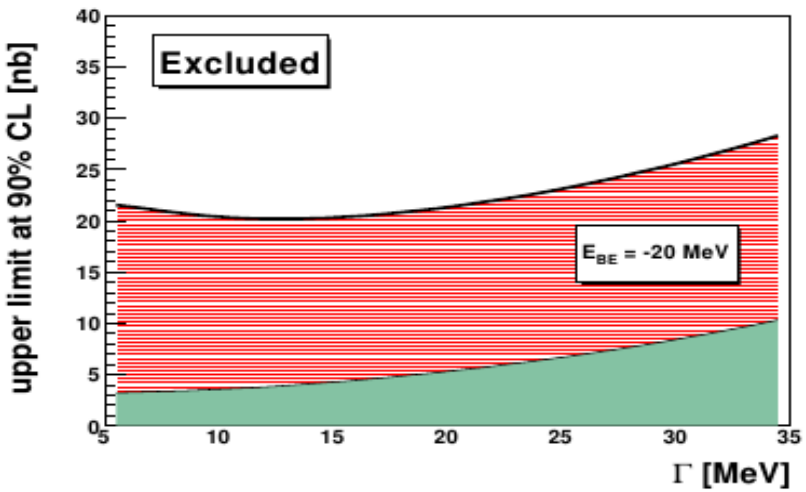
Channel: $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ (norm: $dd \rightarrow {}^3\text{He}n$)

Measurement: performed with the beam momentum ramped from **2.185GeV/c to 2.400GeV/c**, corresponding to the range of excess energy **Q∈(-51,22)MeV**

Luminosity: L=$118\frac{1}{nb}$

Acceptance: A=53%





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 $dd \rightarrow ppn_{sp}n_{sp}$)

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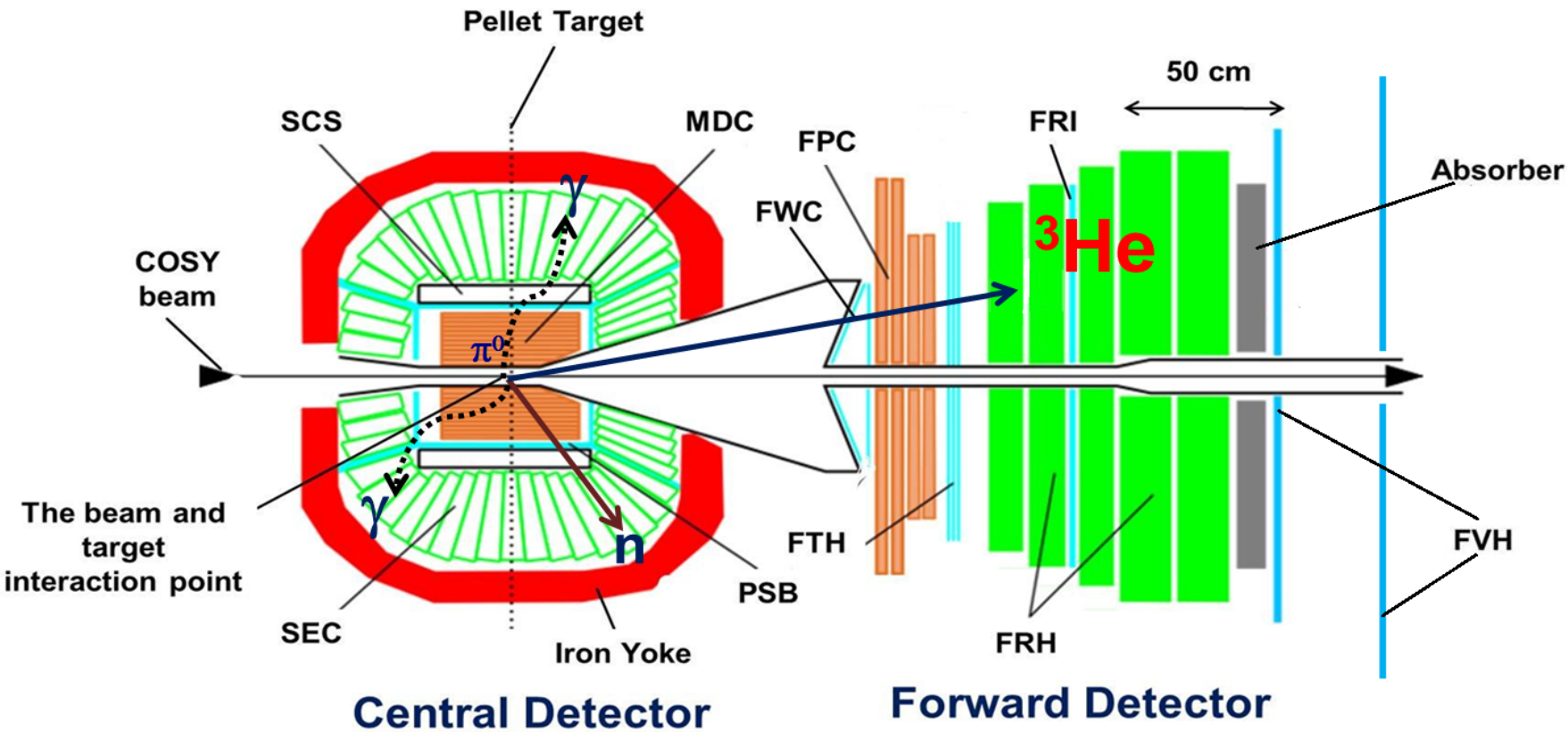
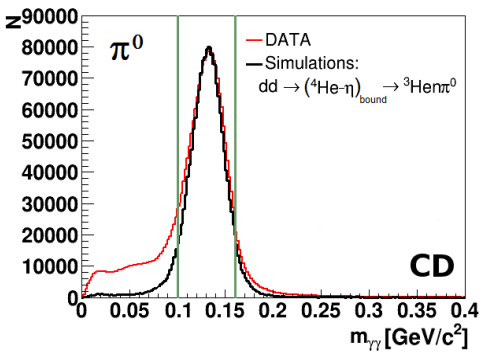
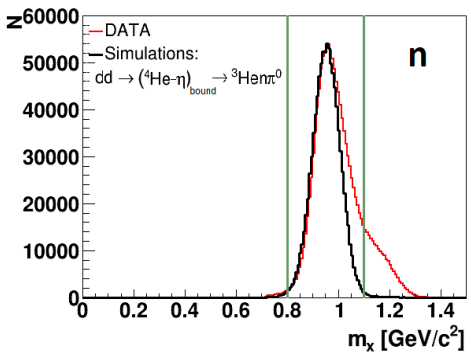
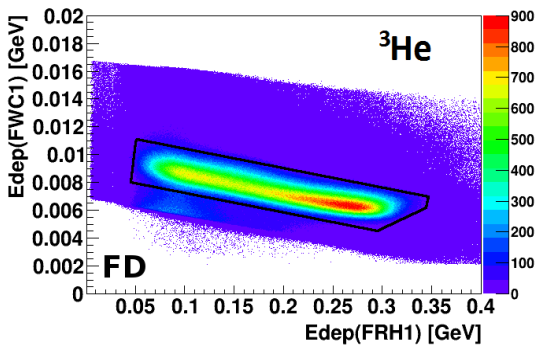
More than **10 times higher** statistics and two reactions were collected than in 2008 experiment.

Search for $(^4\text{He-}\eta)_{bound}$ in $dd \rightarrow {}^3\text{He}n\pi^0$ reaction | PID

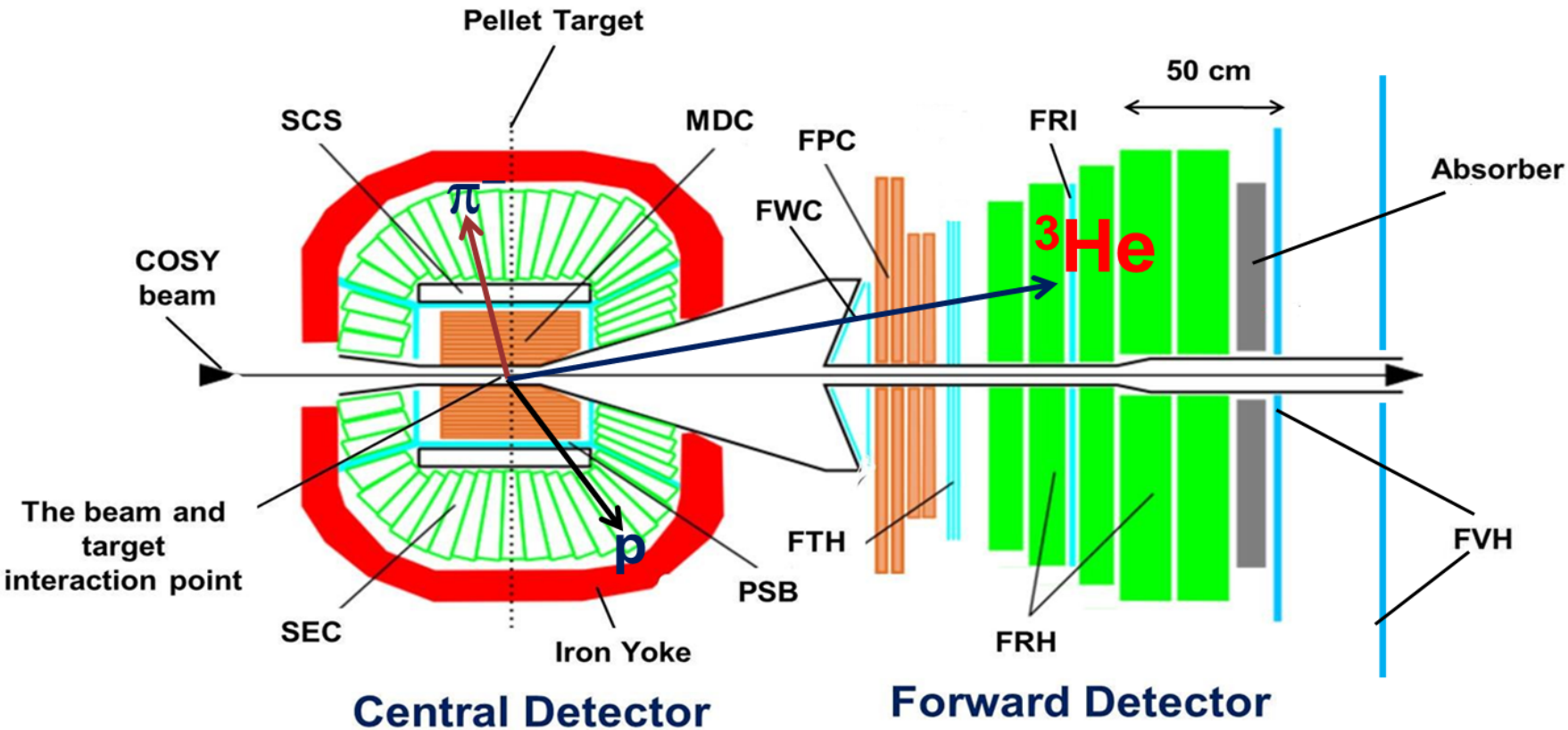


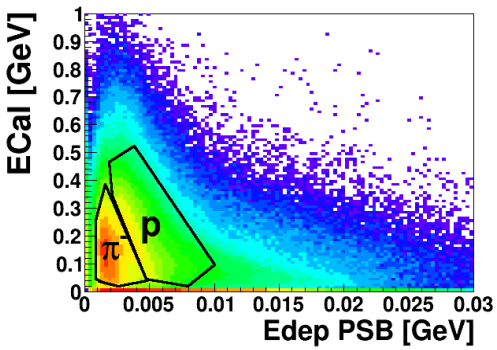


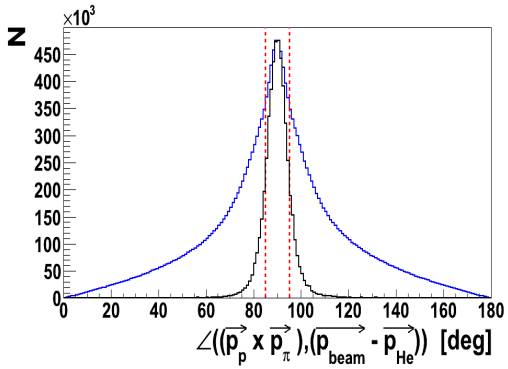


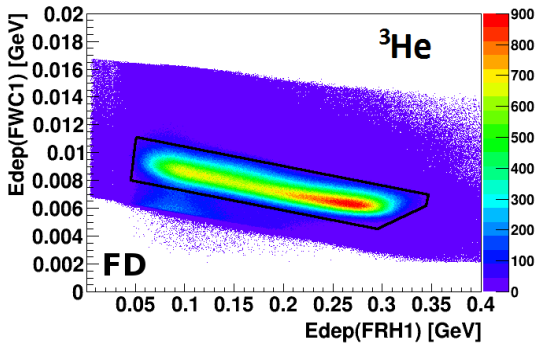


Search for $(^4\text{He-}\eta)_{bound}$ in $dd \rightarrow {}^3\text{He}p\pi^-$ reaction | PID

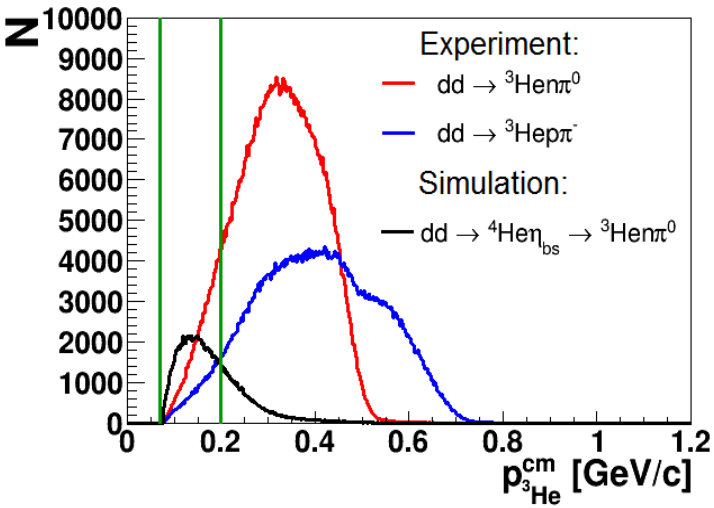


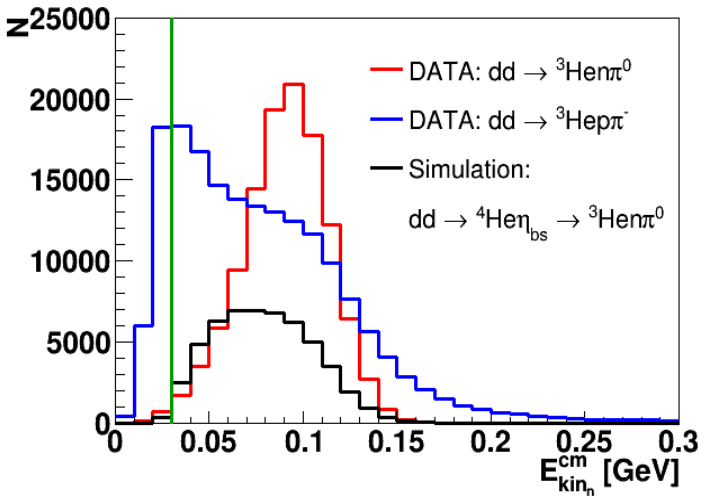


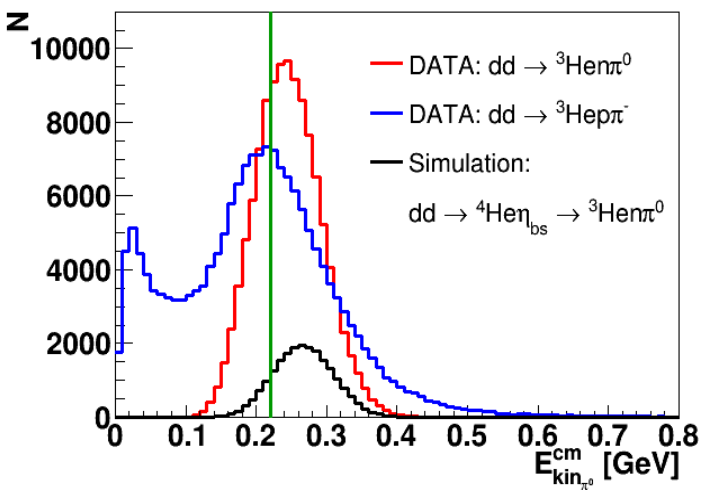


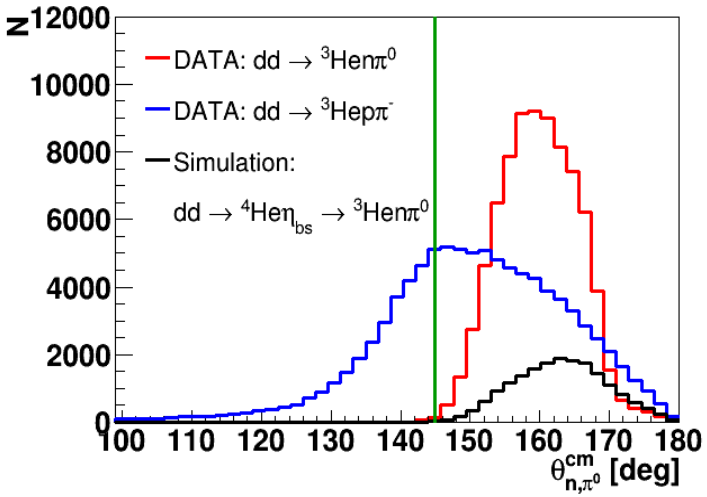


Search for $(^4\text{He-}\eta)_{bound}$ | Selection criteria





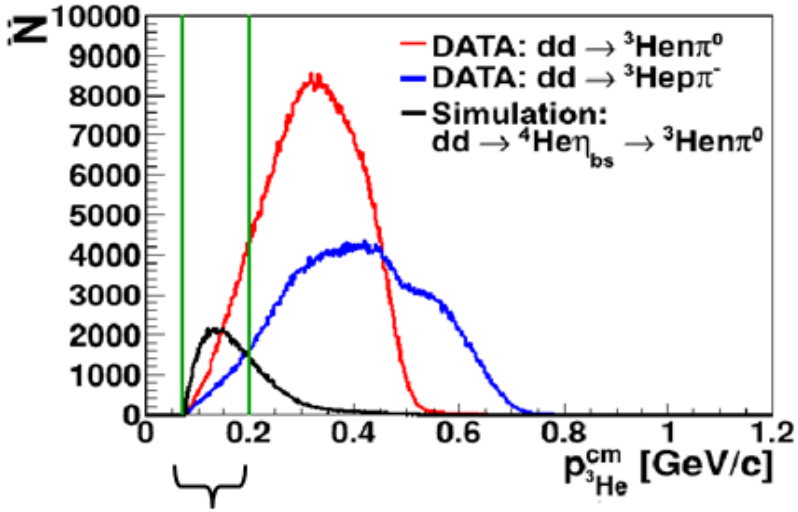




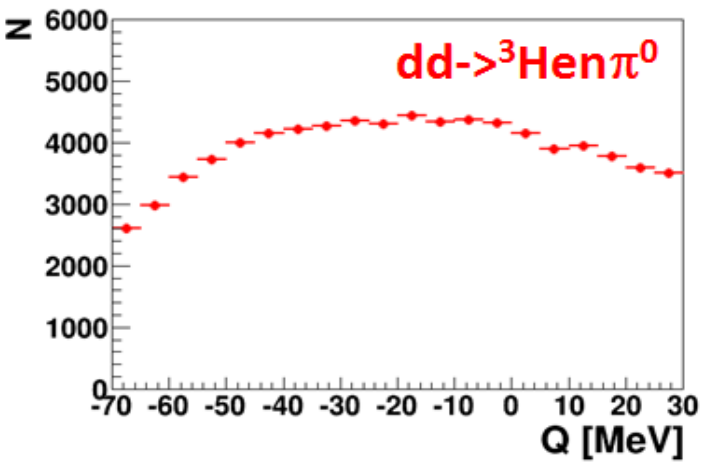
DATA: $dd \to {}^3\text{He}p\pi^-$
DATA: $dd \to {}^3\text{He}n\pi^0 \to {}^3\text{He}n\gamma\gamma$

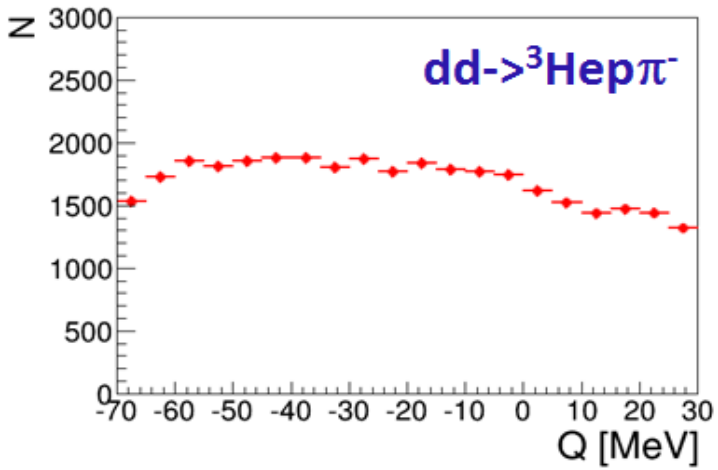
Signal: $dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}n\pi^0$

Determination of the excitation function



region rich in signal





Determination of the total cross section for $dd \rightarrow {}^3\mathrm{He}n\pi^0$ reaction

Excitation function

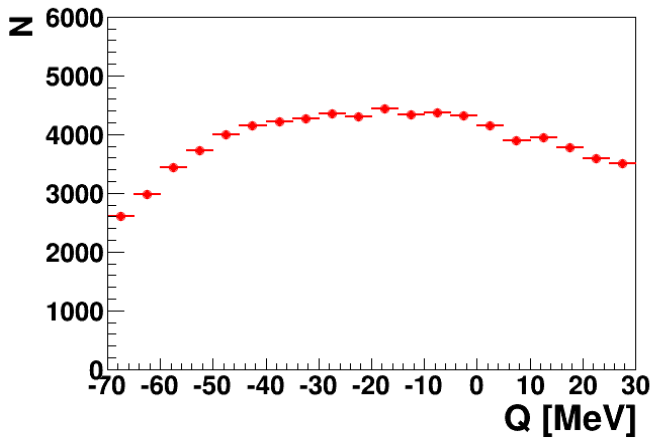
$$\sigma(Q) = \frac{N(Q)}{L(Q)\epsilon(Q)}$$

N - number of experimental events

L - integrated luminosity

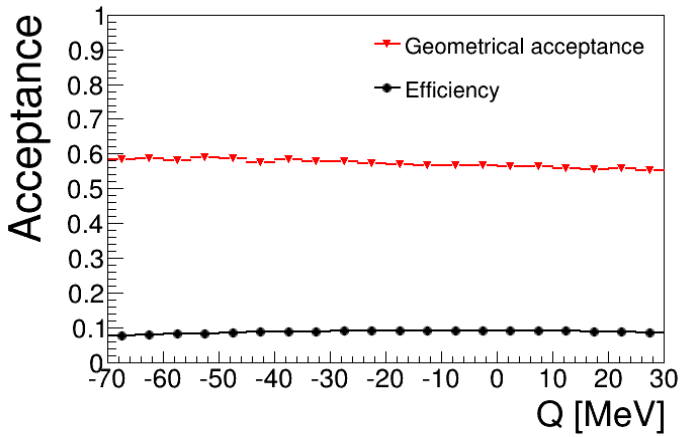
ϵ - full detection efficiency

Experimental N_{ev}



Efficiency

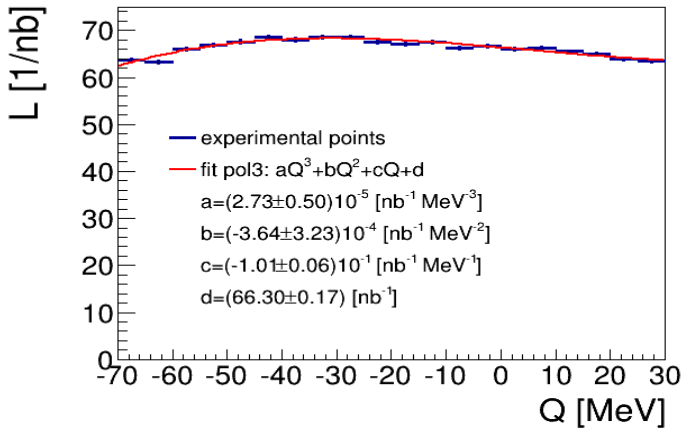
$dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}n\pi^0$



from simulations: $\epsilon = \frac{N_{acc}}{N_{gen}}$

Integrated luminosity

$dd \rightarrow ppn_{sp}n_{sp}$



$dd \rightarrow ppn_{sp}n_{sp}$: $\mathrm{L}=(1329 \pm 2_{stat} \pm 108_{syst} \pm 64_{norm})nb^{-1}$

$dd \rightarrow {}^3\mathrm{He}n$: $\mathrm{L}=(1102 \pm 2_{stat} \pm 28_{syst} \pm 107_{norm})nb^{-1}$

Determination of the total cross section for $dd \to {}^3\mathrm{He}p\pi^-$ reaction

Excitation function

$$\sigma(Q) = \frac{N(Q)}{L(Q)\epsilon(Q)}$$

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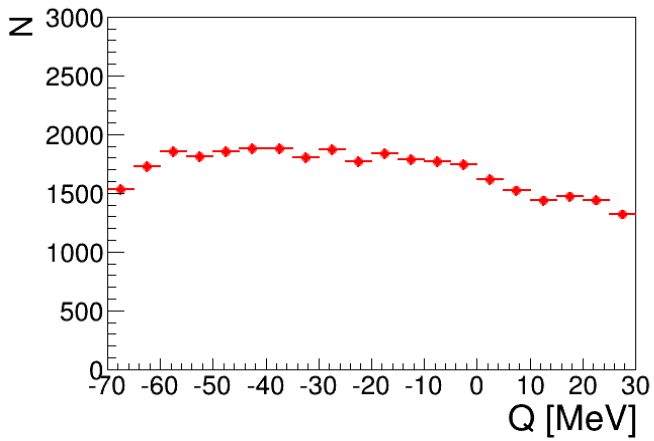
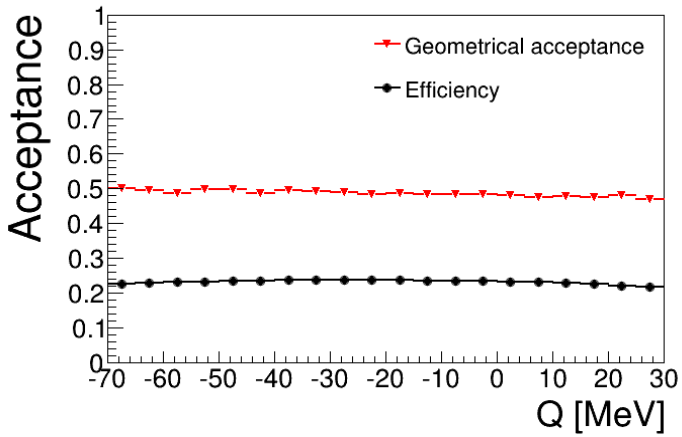
Experimental N_{ev}



Efficiency

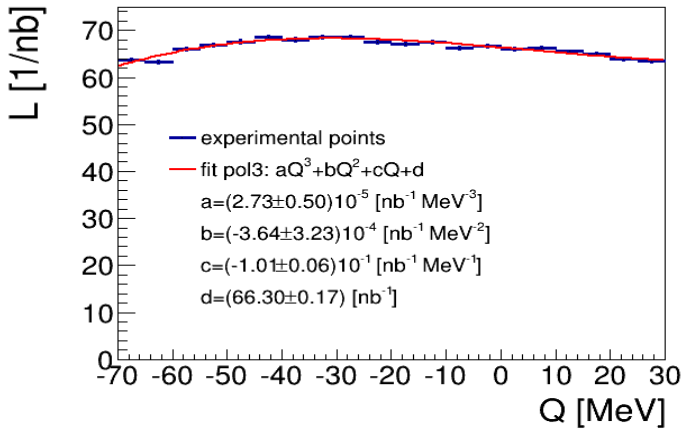
$dd \to ({}^4\mathrm{He}\text{-}\eta)_{bound} \to {}^3\mathrm{He}n\pi^0$



from simulations: $\epsilon = \frac{N_{acc}}{N_{gen}}$

Integrated luminosity

$dd \to ppn_{sp}n_{sp}$



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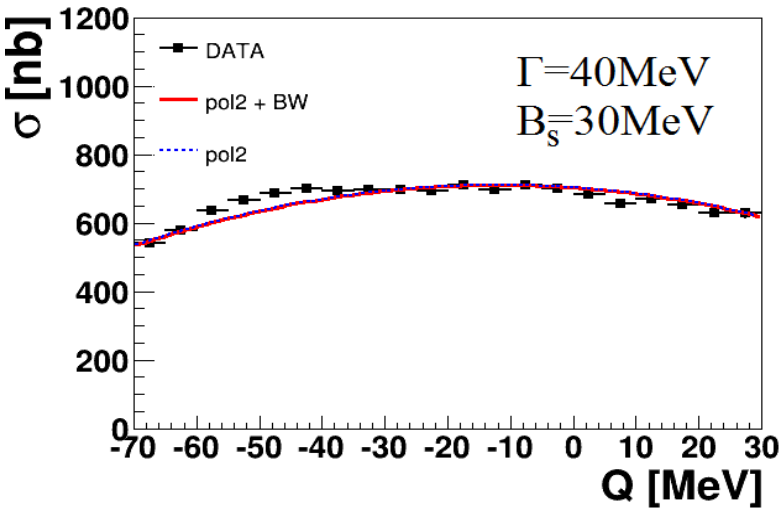
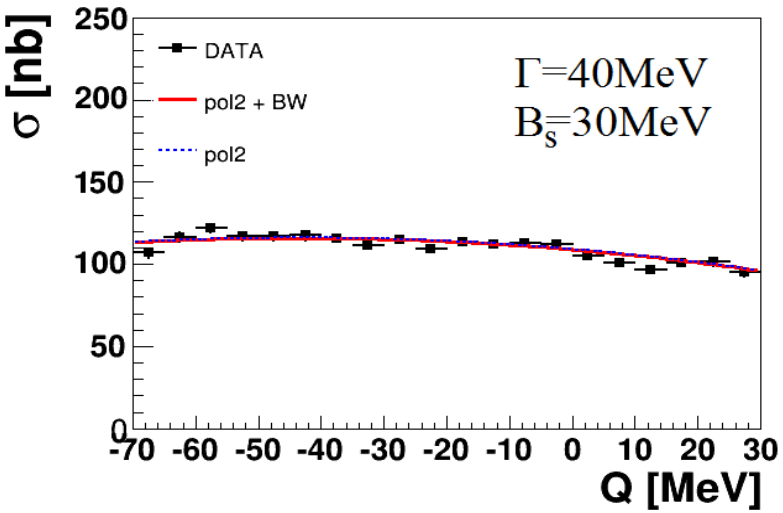
$dd \to {}^3\mathrm{He}n$: $\mathrm{L}=(1102 \pm 2_{stat} \pm 28_{syst} \pm 107_{norm})nb^{-1}$

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

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

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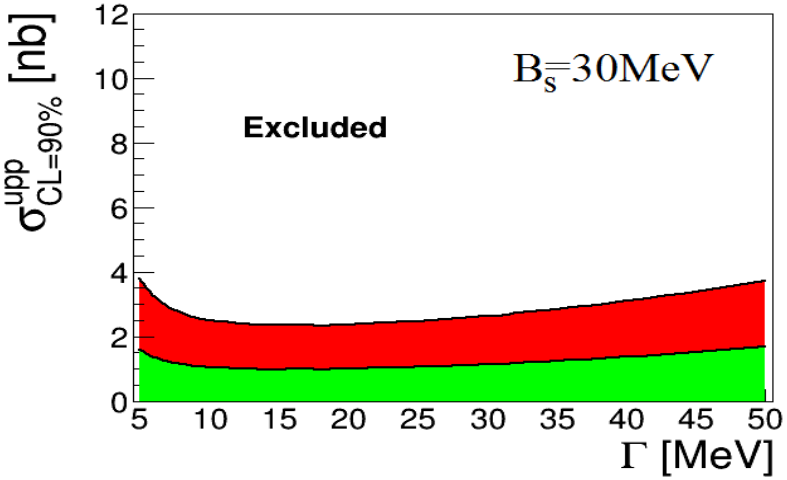

RESULT:

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

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

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

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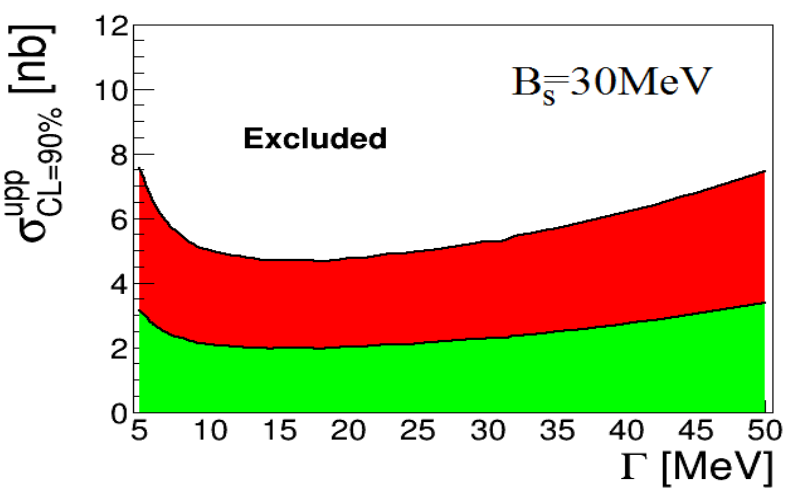


RESULT:

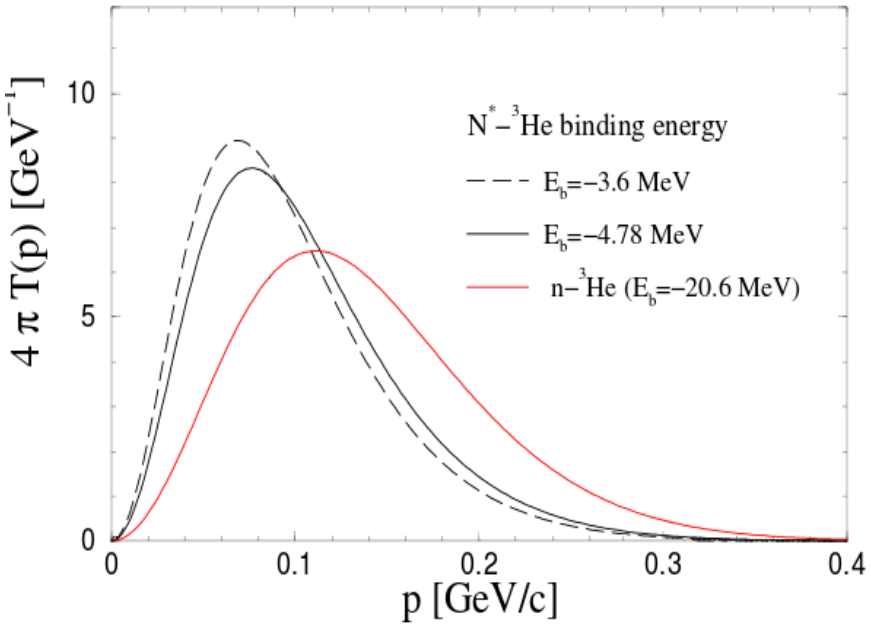
$\sigma_{dd \to ({}^4He-\eta)_{bound} \to {}^3Hep\pi^-} < 7\ nb$

2008: $\sigma < 27\ nb$

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

Systematics

Main contribution: assumption that N^* resonance has a momentum distribution identical to the distribution of nucleons inside He



N^*-^3He momentum distribution - model proposed by prof. Neelima G. Kelkar
(evaluation of N^*-nucleus potential by folding N^*N elementary interaction (constructed within $\pi + \eta$ exchange model) with nuclear density)

N. G. Kelkar, Eur. Phys. J. A 52 (2016) 309.
N. G. Kelkar, D. Bedoya Ferro, P. Moskal, Acta Phys. Pol. B 47 (2016) 299.

New experiment - May/Jun 2014 - $(^3\text{He-}\eta)_{bound}$

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

Via the resonance decay N^*:

1) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppp\pi^-$

2) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppn\pi^0$

3) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow dp\pi^0$

Absorption of orbiting η

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

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

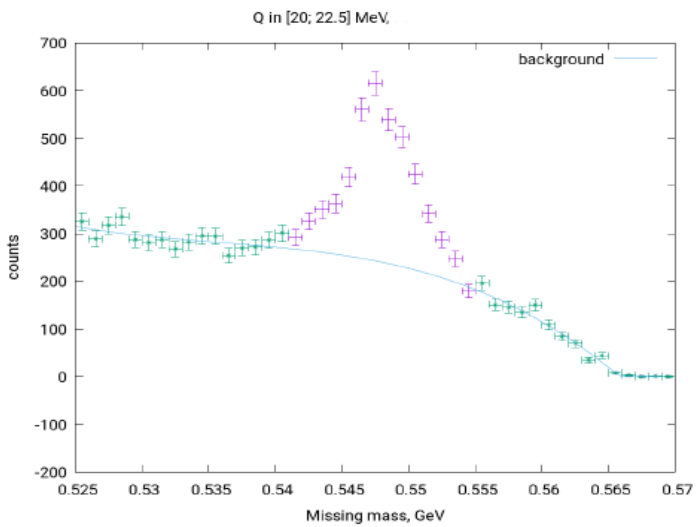
Nonresonant decay (absorption on two nucleons) as proposed by prof. Wycech

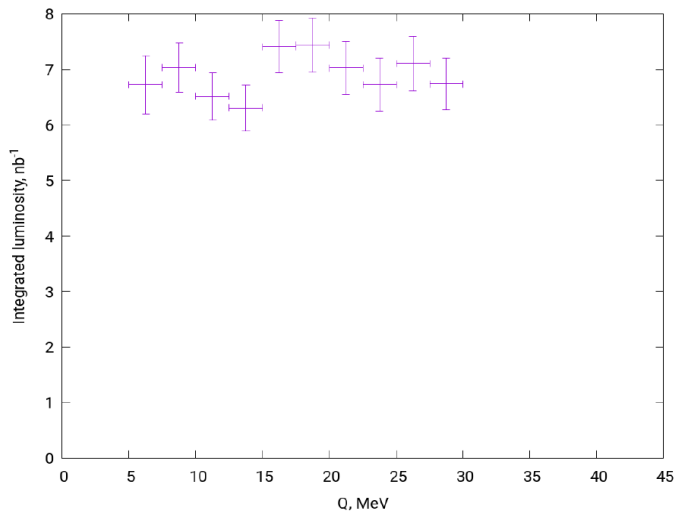
6) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppn$

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

Luminosity: L≈4000 $\frac{1}{nb}$ $(pd \rightarrow {}^3\text{He-}\eta)$ || in agreement with proposal $(5{\cdot}10^{30} s^{-1} cm^{-2})$

/P. Moskal, W. Krzemień, M. Skurzok, COSY proposal No. 186.3 (2014)/





More: Poster session (Monday) → Oleksandr Rundel

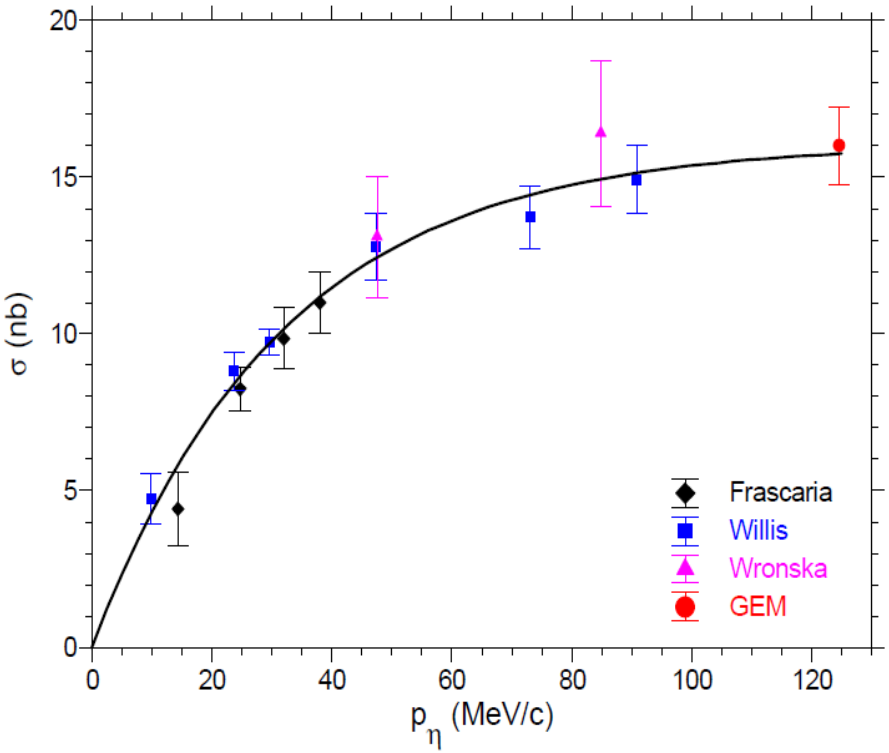
Summary and Conclusions

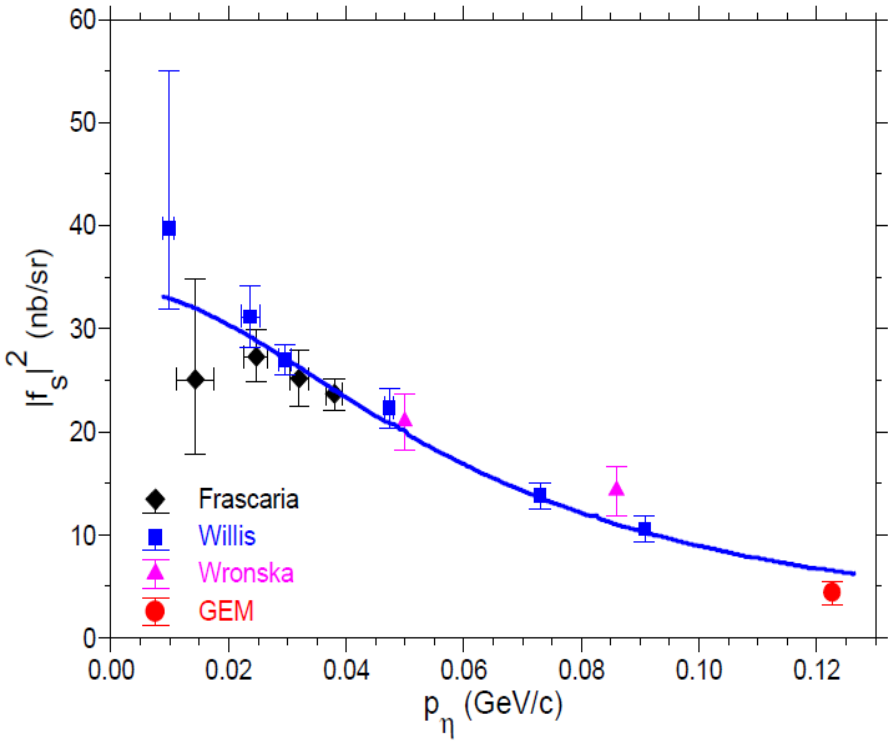
- Exclusive measurement of the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ and $dd \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$ reactions was carried out using the ramped beam technique.
- No bound state signal visible in 2008 data (upper limit of the total cross section for 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) - **the best statistics in the world!**

Thank you for attention

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

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

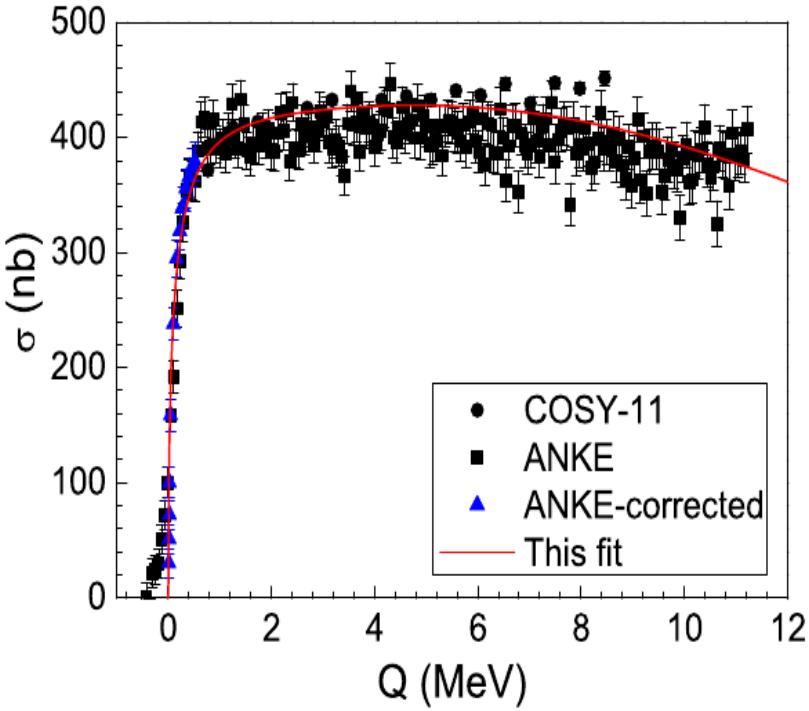


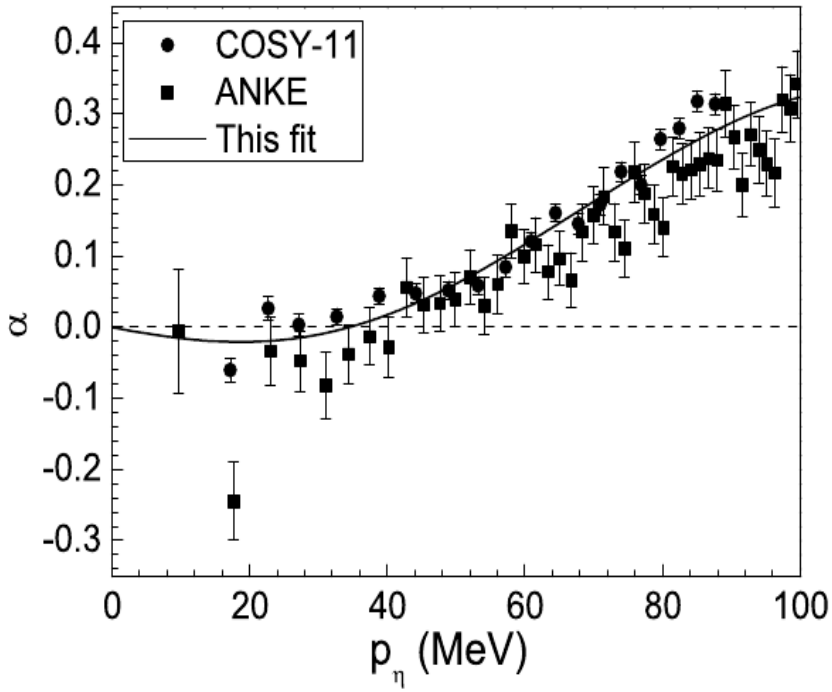


R. Frascaria et al., Phys. Rev. C50, 573 (1994)
N. Willis et al., Phys. Lett. B406, 14 (1997)
A. Wronska et al., Eur. Phys. J. A26, 421428 (2005)
A. Budzanowski et al., Nucl. Phys. A821, 193 (2009)

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

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





⇓

J.-J. Xie, W.-H. Liang, E. Oset, P. Moskal, M. Skurzok, C. Wilkin, PRC 95 (2017) 015202

"weakly bound ^{3}He-η state with **binding energy** *of the order of* **0.3 MeV** *and a* **width** *of the order of* **3 MeV***", $a_{\eta 3He} = [(2.23 \pm 1.29) + i(4.89 \pm 0.57)]$ fm*

→ **Prof. Oset talk**