Search for η-mesic helium with WASA-at-COSY

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for WASA-at-COSY Collaboration

3rd Jagiellonian Symposium, Kraków, Poland,
23th - 28th June 2019

Introduction – η-mesic nuclei

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)

Recent theoretical studies of hadronic- and photoproduction of η meson support the existence of light η-mesic nuclei like $(^3\text{He}\text{-}\eta)_{bound}$ $(^4\text{He}\text{-}\eta)_{bound}$

$B_s \in (1, 40)$ MeV, $\Gamma \in (1, 45)$ MeV

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

J.-J. Xie et al., Eur. Phys. J. A55 no.1, 6 (2019)
J.-J. Xie et al., Phys. Rev. C95, 015202 (2017)
N. Ikeno et al., Eur. Phys. J A53 no. 10, 194 (2017)
T. Sekihara, H. Fujioka, T. Ishikawa, Phys. Rev. C 97, 045202 (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)

Talks: K. Itahashi, T. Ishikawa, S. Hirenzaki, J. Mares

Status of the search for η-mesic Helium at WASA

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

- **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)

$\Uparrow$

η meson absorption and excitation of one of the nucleons to an N^* resonance, which subsequently decays into an N - π pair

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

- **2014**:

  - $pd \rightarrow {}^3\text{He}2\gamma({}^3\text{He}6\gamma)$ reactions

  O. Rundel, PhD Thesis (2018), *arxiv:1905.04544*

  decay of the η - meson while it is still "orbiting" around a nucleus

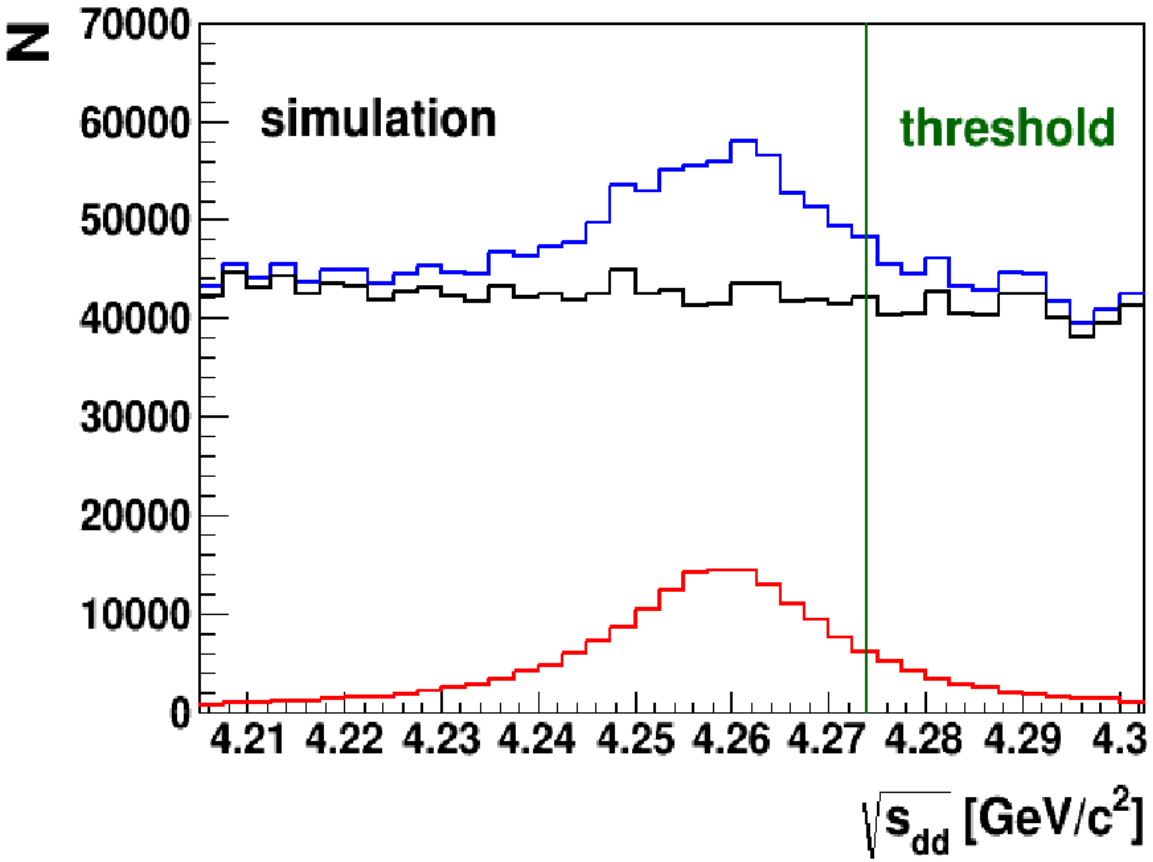
  - $pd \rightarrow ppp\pi^-(ppn\pi^0, dp\pi^0)$ reactions

  A. Khreptak, Analysis in progress

  Poster session (Tuesday)

η meson absorption and excitation of one of the nucleons to an N^* resonance, which subsequently decays into an N - π pair

Experimental method



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

and

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

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

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

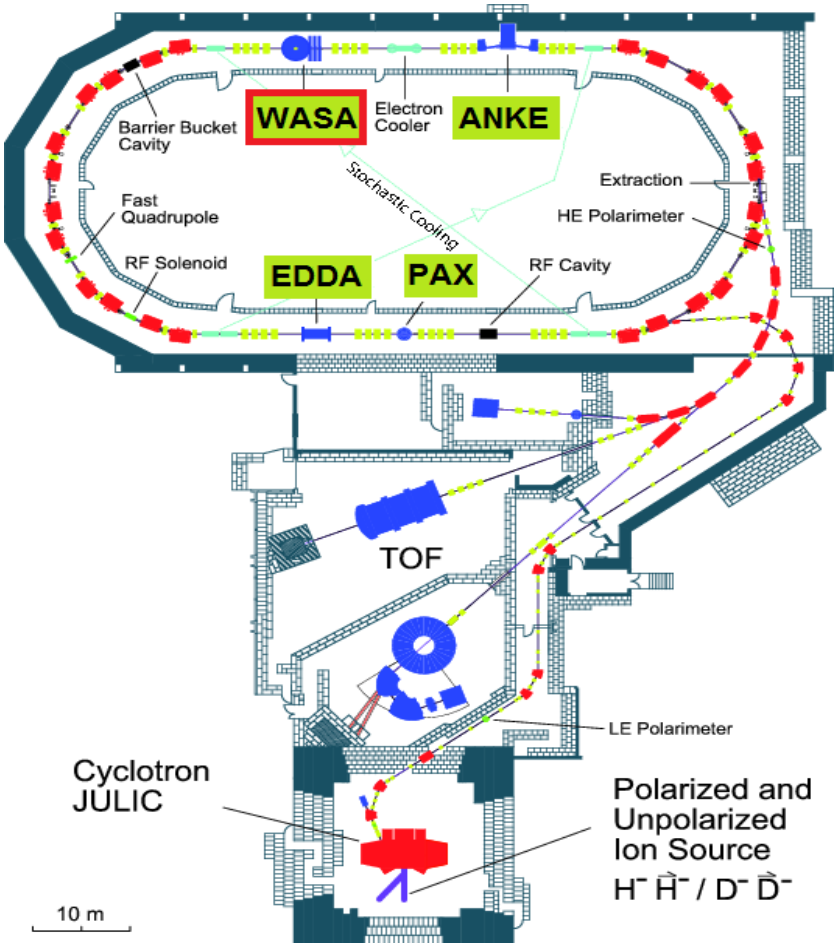
Excitation function

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

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

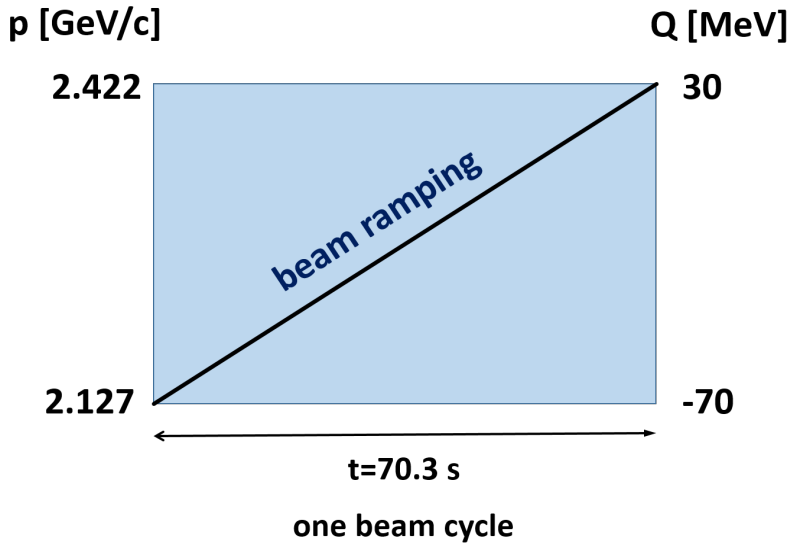
Exp. 186.1 & 186.2, FZ Jülich, Germany, 2008 and 2010

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

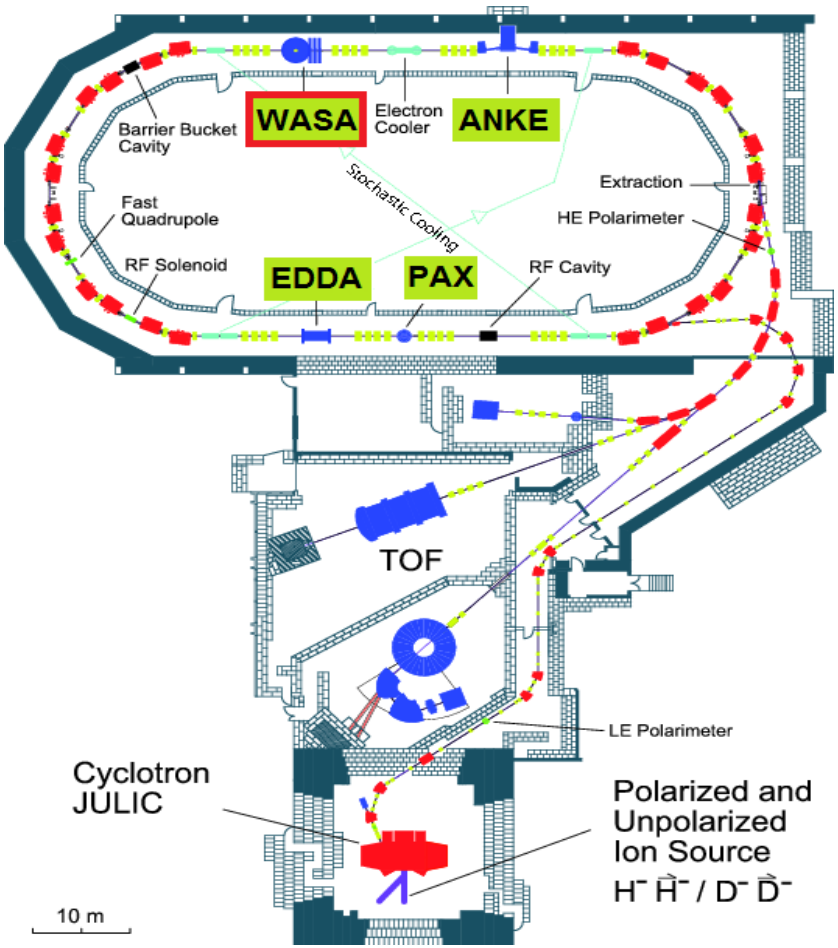


- **Data** were effectively taken with high acceptance (58%)

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

Exp. 186.3, FZ Jülich, Germany 2014

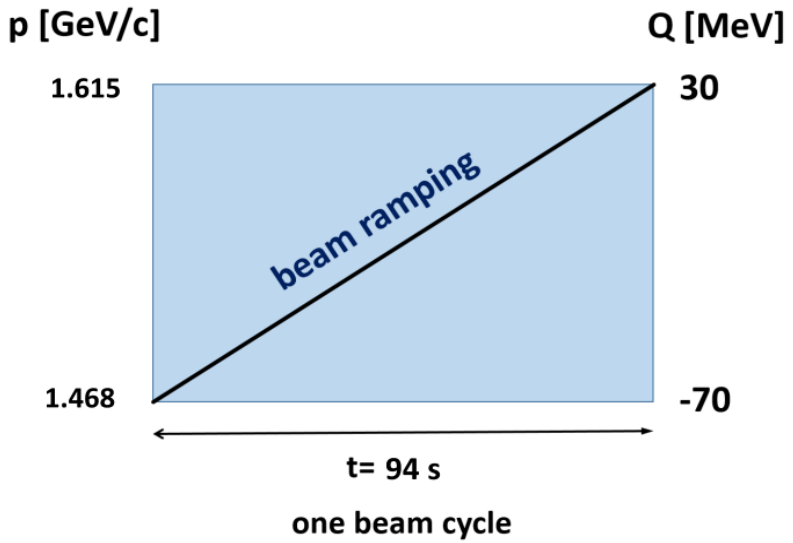
P. Moskal, W. Krzemien, M. Skurzok,
COSY proposal No. 186.3



$pd \to ppp\pi^-(ppn\pi^0, dp\pi^0)$

$pd \to {}^3\mathbf{He}2\gamma\ ({}^3\mathbf{He}6\gamma)$

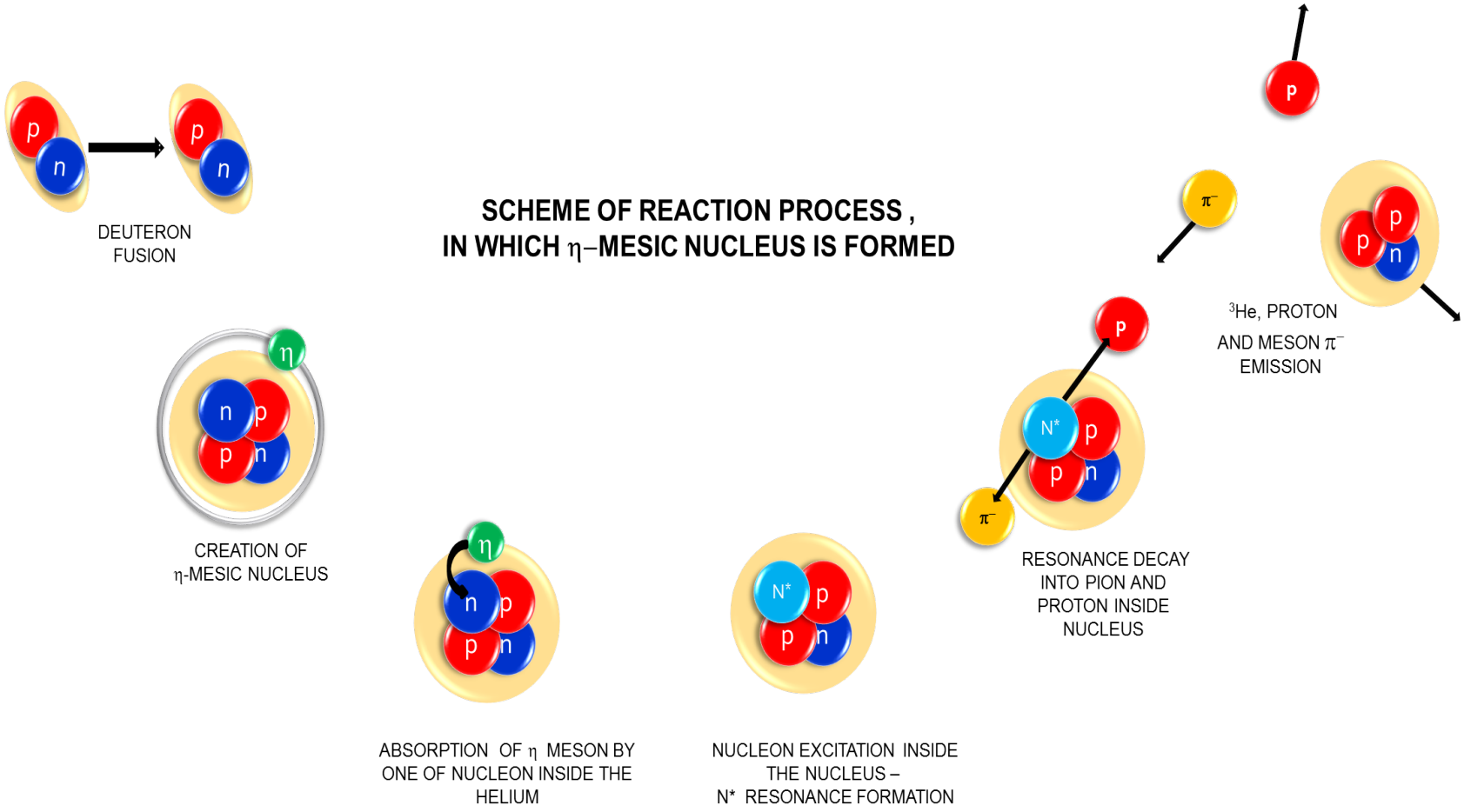
- **Measurement** with the **proton** beam momentum ramped and with the **deuteron** pellet target



- **Data** were effectively taken with high acceptance

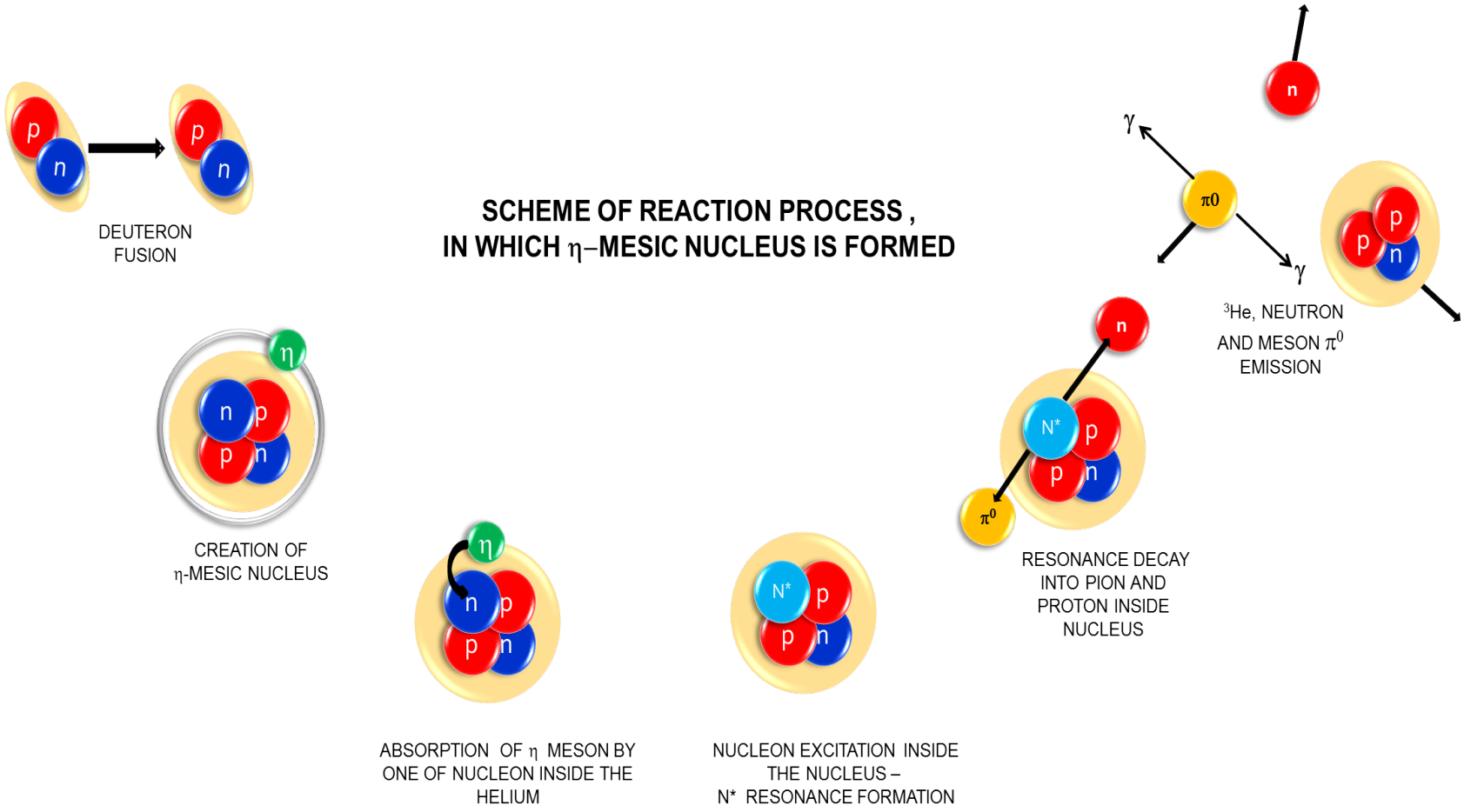
Kinematical mechanism of the reaction (via N^*)

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



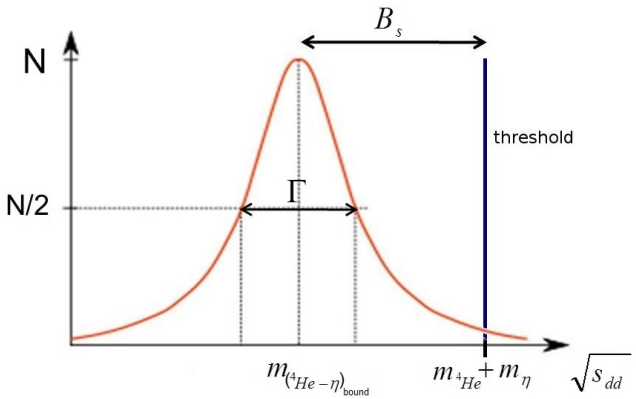
Kinematical mechanism of the reaction (via N^*)

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



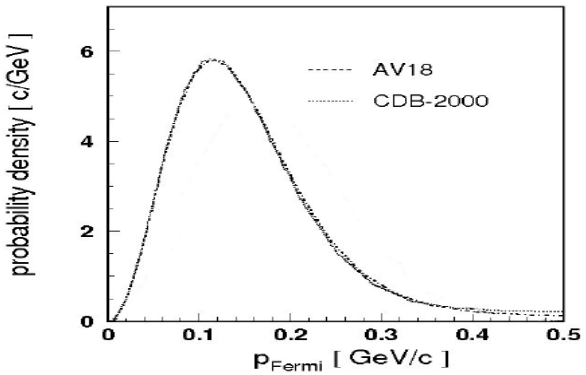
Simulation of $(^4\text{He-}\eta)_{bound}$ production and decay

Breit-Wigner distribution



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

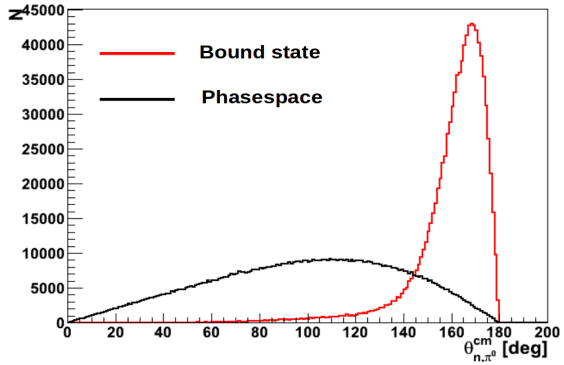
Spectator Model



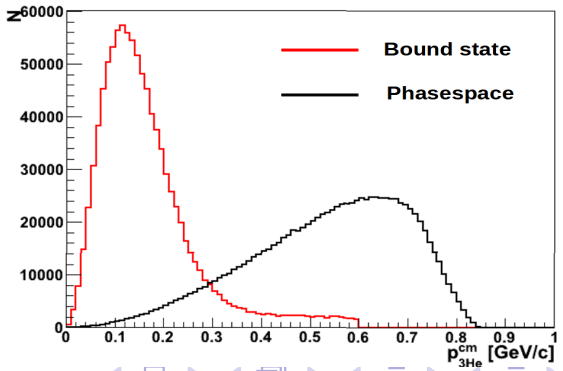
$$|\mathbb{P}_{^3He}|^2 = m^2_{^3He}$$

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

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

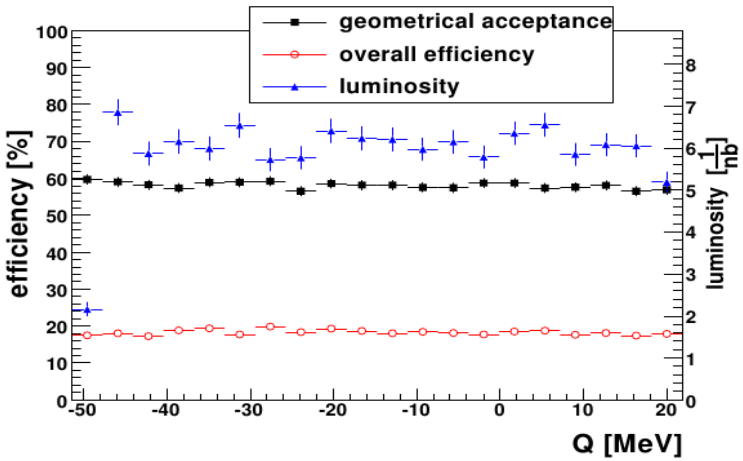


- low ^{3}He momentum in the CM

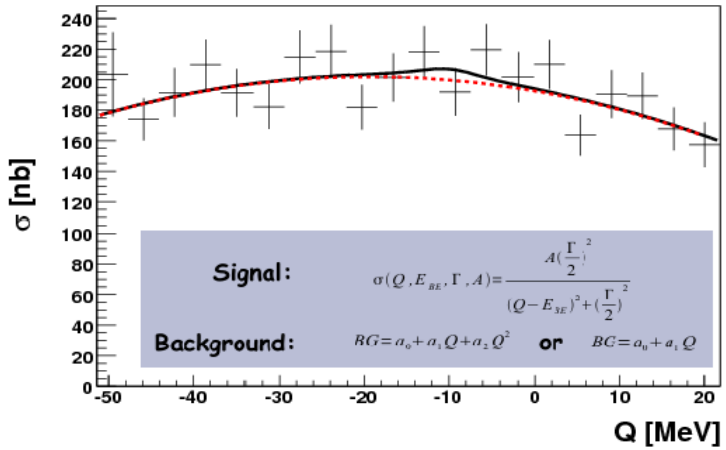


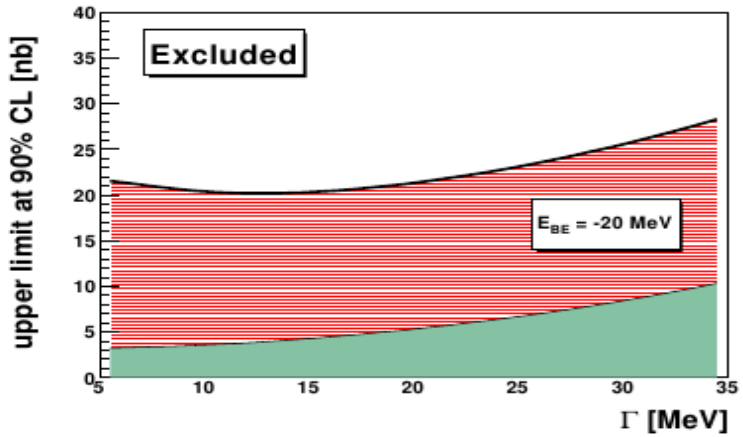
Experiment-May 2008

- **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





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

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

Experiment-Nov/Dec 2010

- **Channels:** $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$
  $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0$
  (norm: $dd \rightarrow {}^3\text{He}n$ and $dd \rightarrow ppn_{sp}n_{sp}$)
- **Measurement:** beam momentum ramped from **2.127GeV/c to 2.422GeV/c** $\Rightarrow$ the range of excess energy **Q$\in$(-70,30)MeV**
- **Luminosity:** L=1200$\frac{1}{nb}$
- **Acceptance:** A=53%

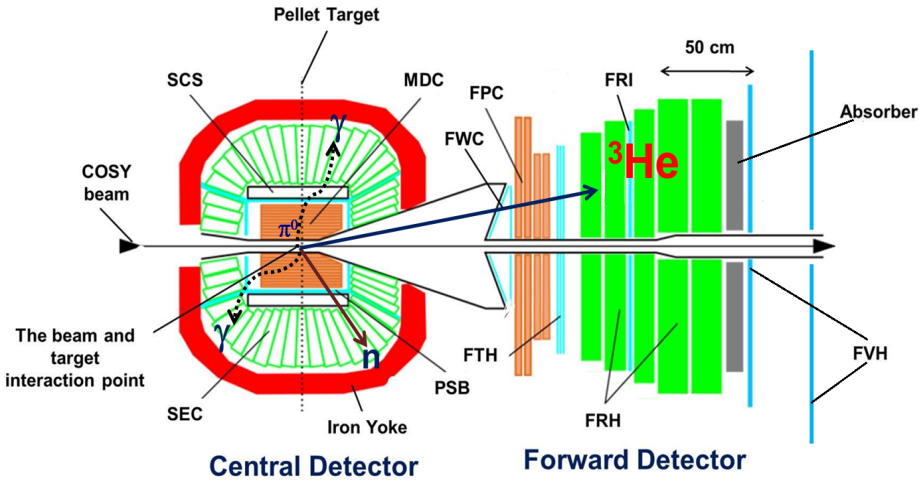
$\Downarrow$

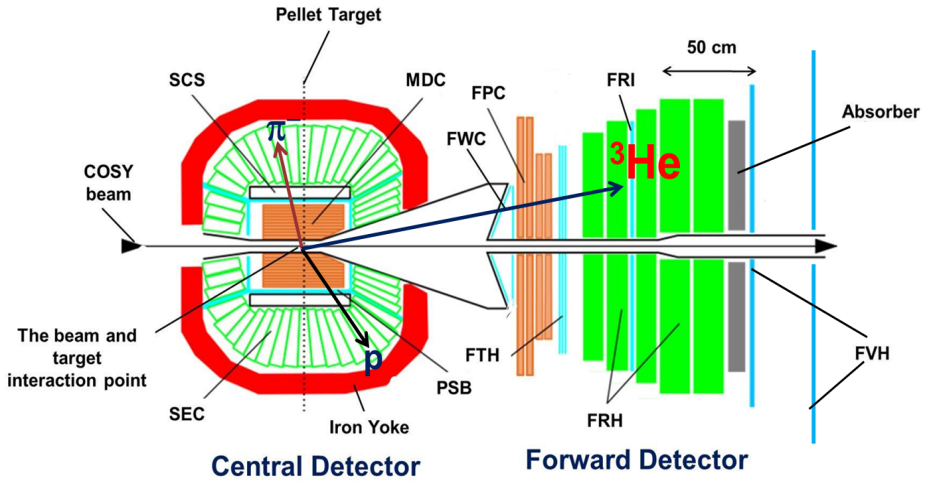
about 10 times higher statistics than in 2008

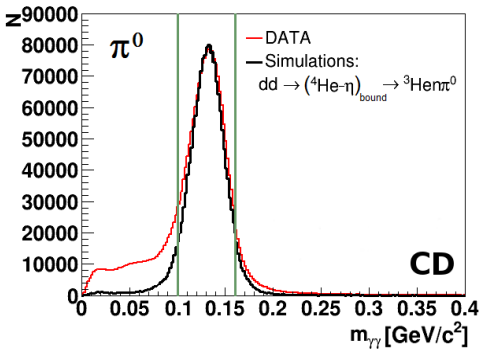
ANALYSIS:

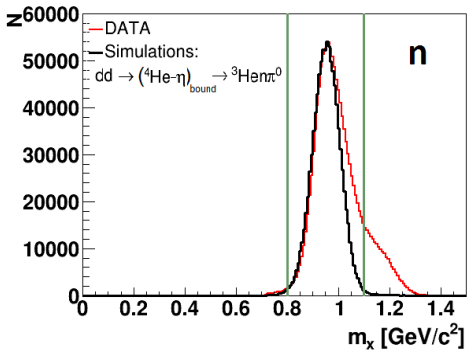
- Particles identification
- Selection bound state region
- Determination of excitation functions
- Determination the upper limit of the total cross section

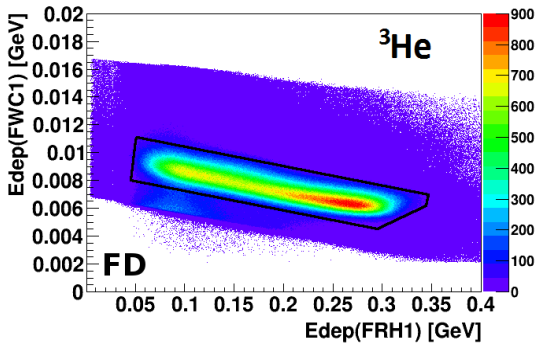
Search for $(^4\text{He-}\eta)_{bound}$ in $dd \rightarrow {}^3\text{He}N\pi$ reaction | PID

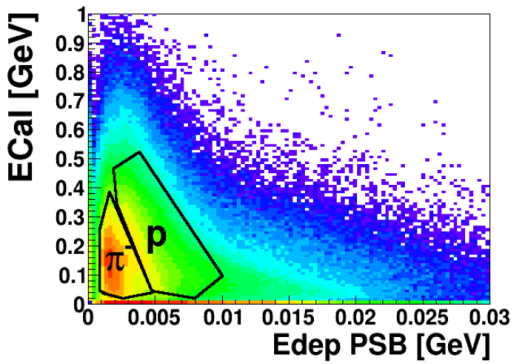


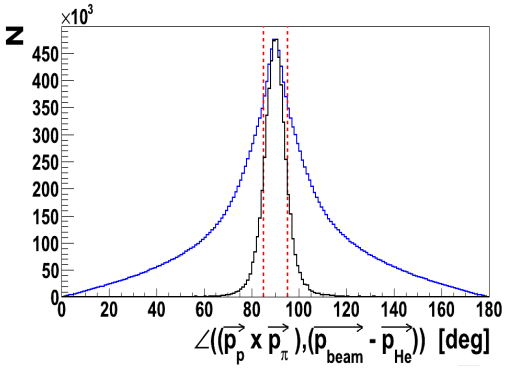




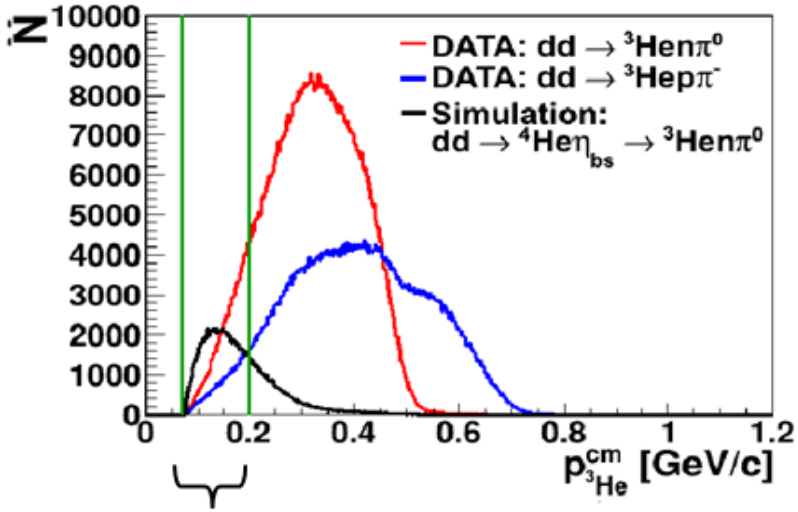




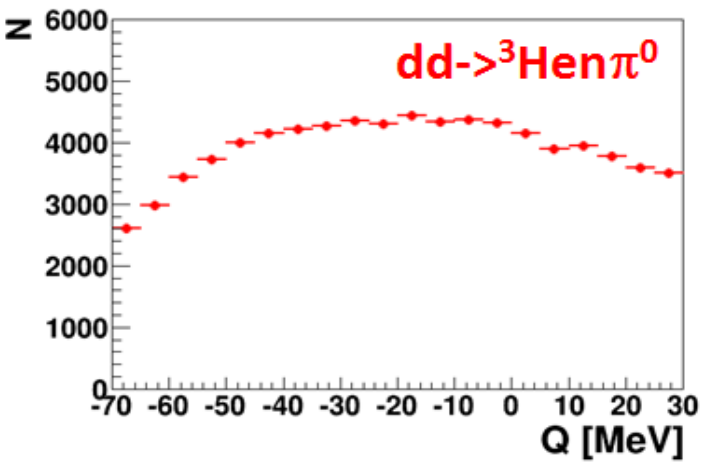


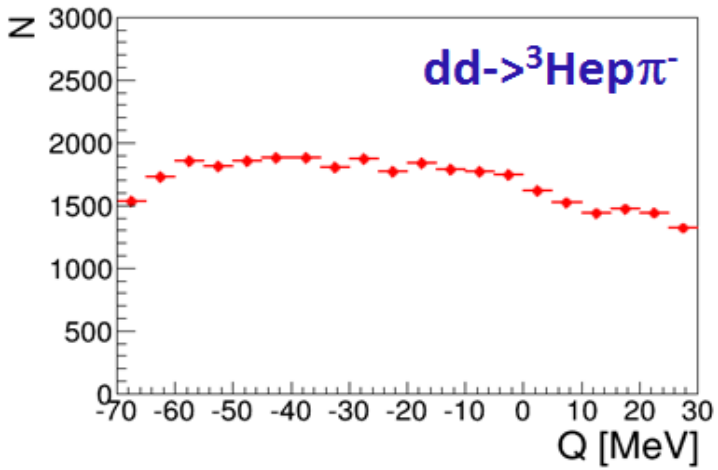


Search for $(^4\text{He-}\eta)_{bound}$ | Selection criterium



region rich in signal

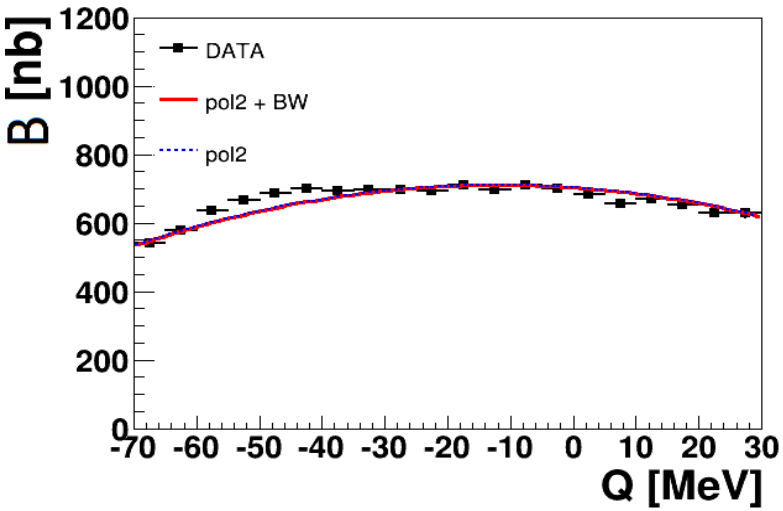




Determination of the upper limit of the total cross section for $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}N\pi$ processes at CL=90%

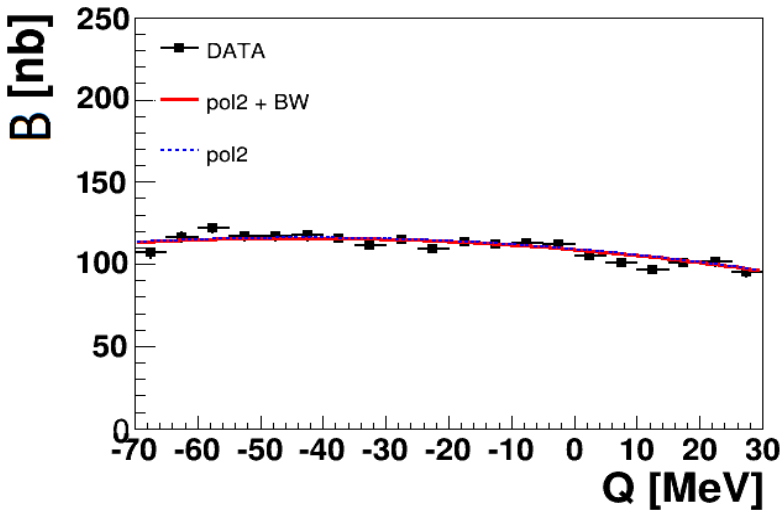
$dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0$

$\Downarrow$



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

$\Downarrow$



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:

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

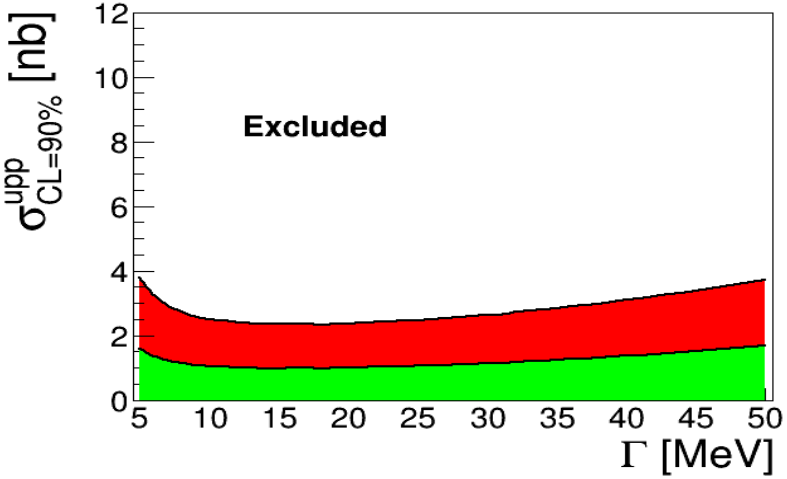
B_s,Γ - fixed parameters | A, B, C, D - free parameters $\| \ \sigma^{upp}_{CL=90\%} = k \cdot \sigma_A$, k=1.64 (for CL=90%)

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

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

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

$\Downarrow$



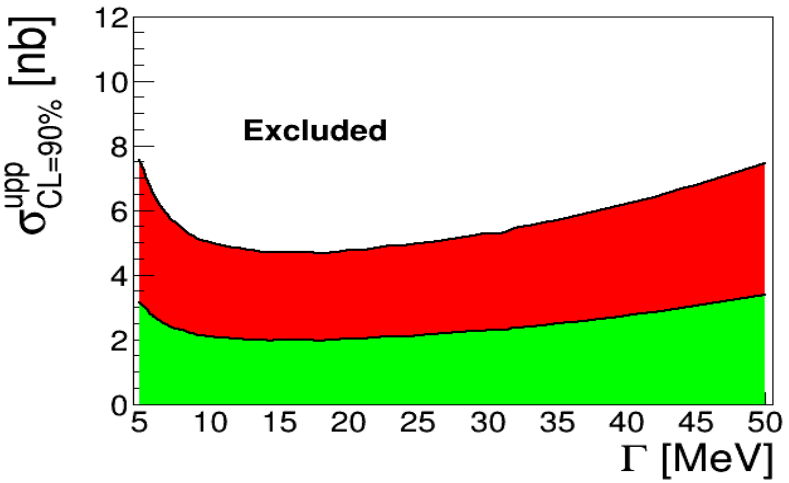
RESULT:

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

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

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

$\Downarrow$



RESULT:

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

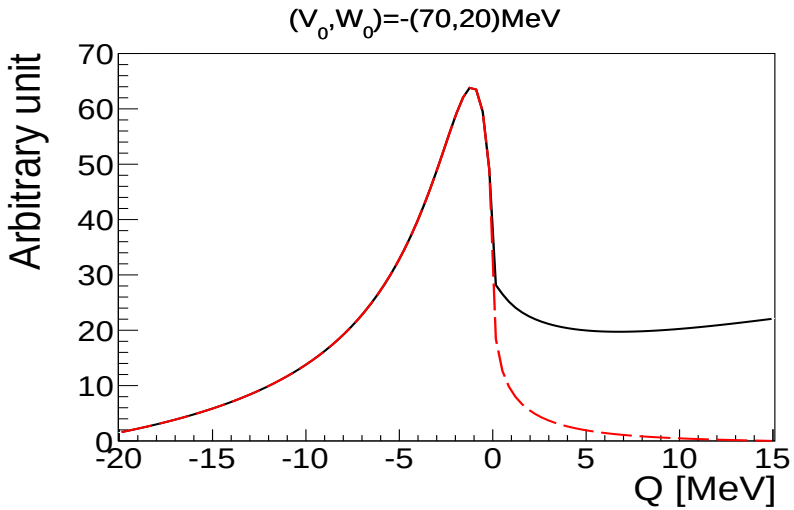
2008: $\sigma < 27\ nb$

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

Comparison with N. Ikeno et al. model prediction

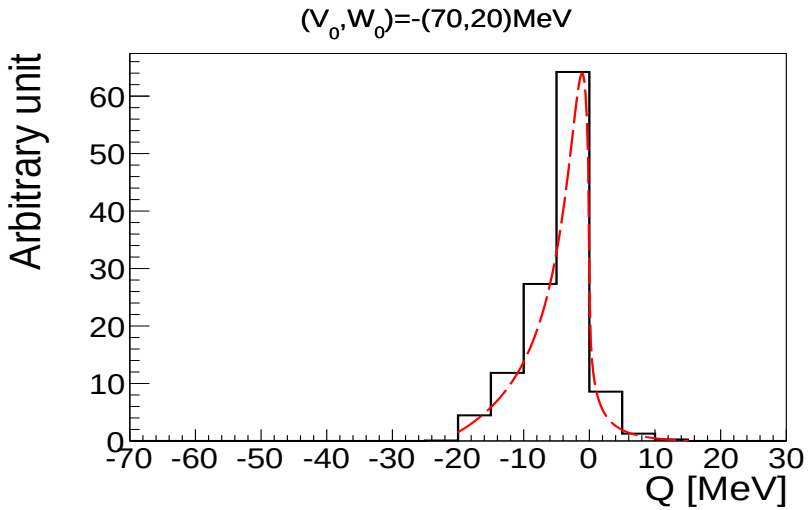
N. Ikeno, H. Nagahiro, D. Jido, S. Hirenzaki, Eur. Phys. J. A 53, 194 (2017)

- total cross sections for the $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}N\pi$ reaction determined based on phenomenological calculations
- the model reproduced the data on the $dd \rightarrow {}^4\text{He}\ \eta$ 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 $dd \rightarrow {}^4\text{He}\eta$ process



σ —

σ_{conv} - -

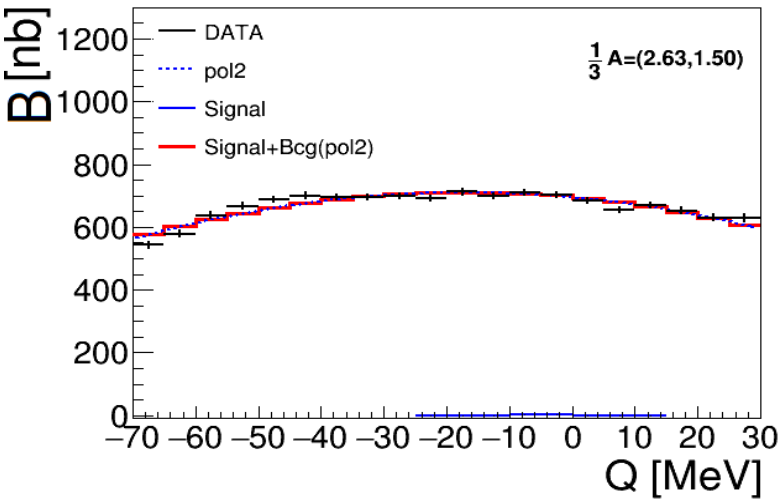


σ_{conv} spectrum convoluted with the experimental resolution functions

Comparison with N. Ikeno et al. model prediction

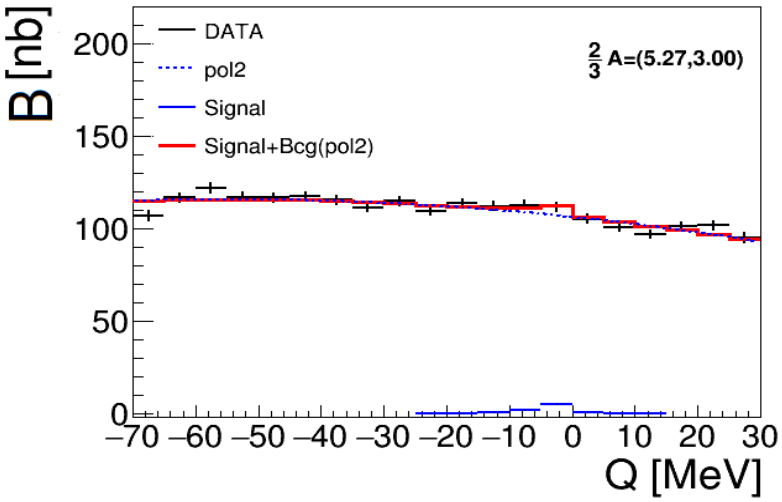
$dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0$

$\Downarrow$



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

$\Downarrow$



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

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

isospin relation between the both of the considered channels

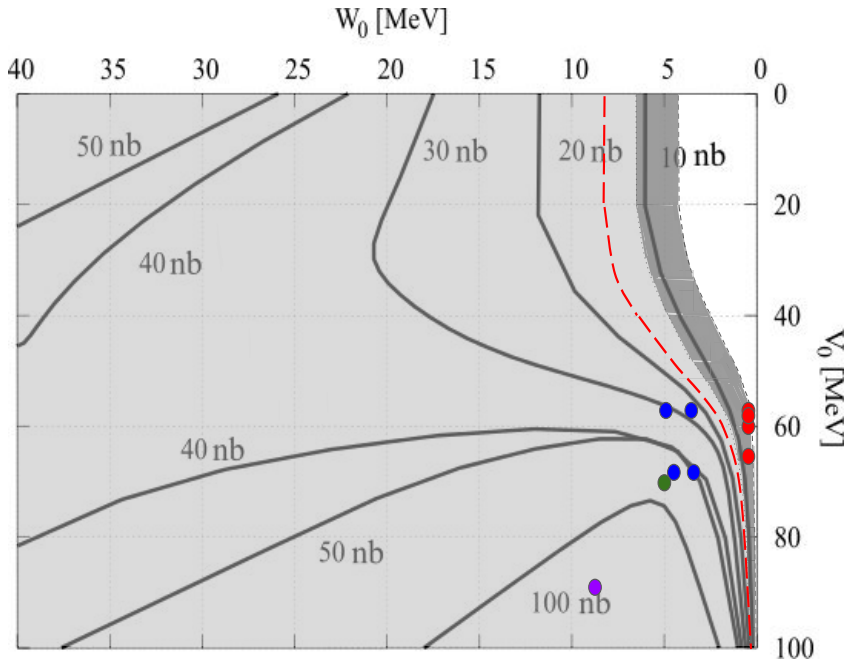
$Theory(Q)$ - theoretical function after binning with the amplitude normalized to unity
$B_{1,2}Q^2 + C_{1,2}Q + D_{1,2}$ - polynomial of the second order

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

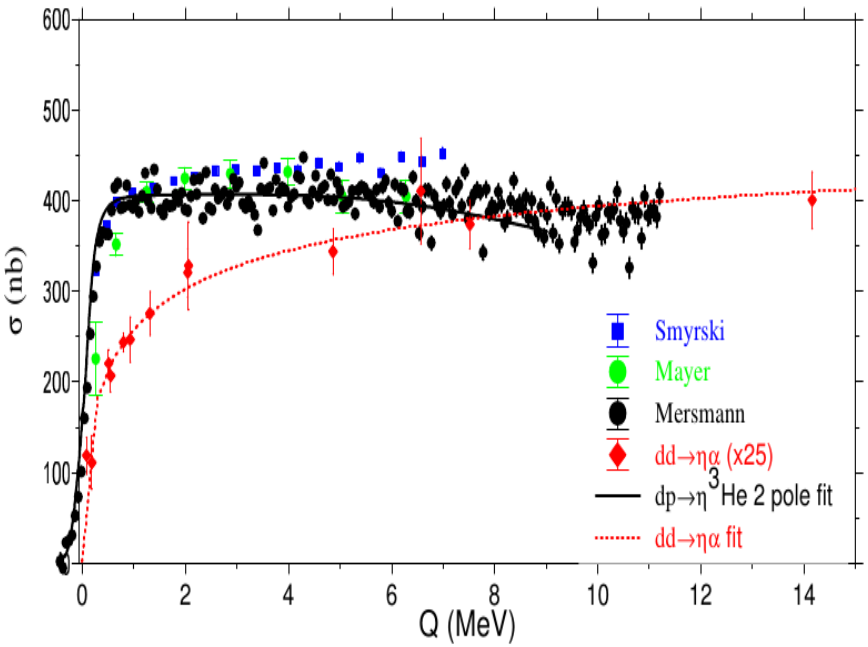


Contour plot of the theoretically determined conversion cross section in $V_0 - W_0$ plane.

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



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

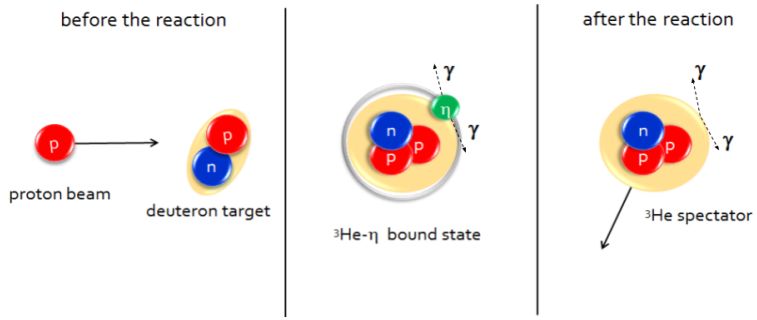
About 2 weeks of measurement
$(L \approx 2500\frac{1}{nb})$

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

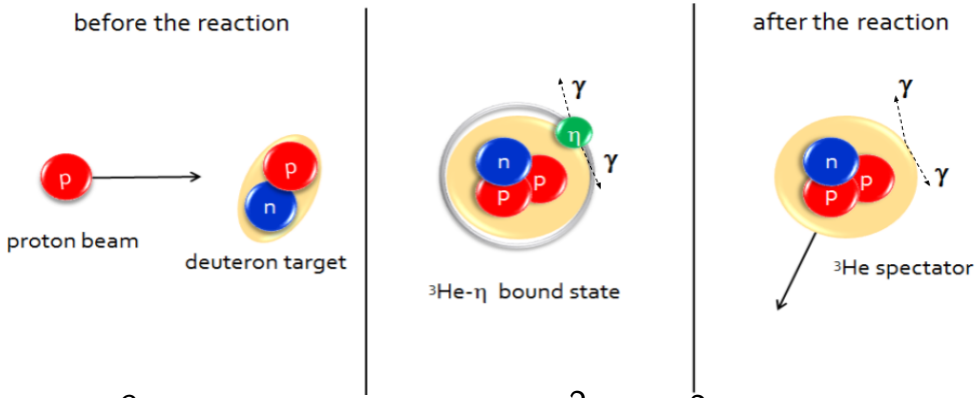
Channels:

- **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

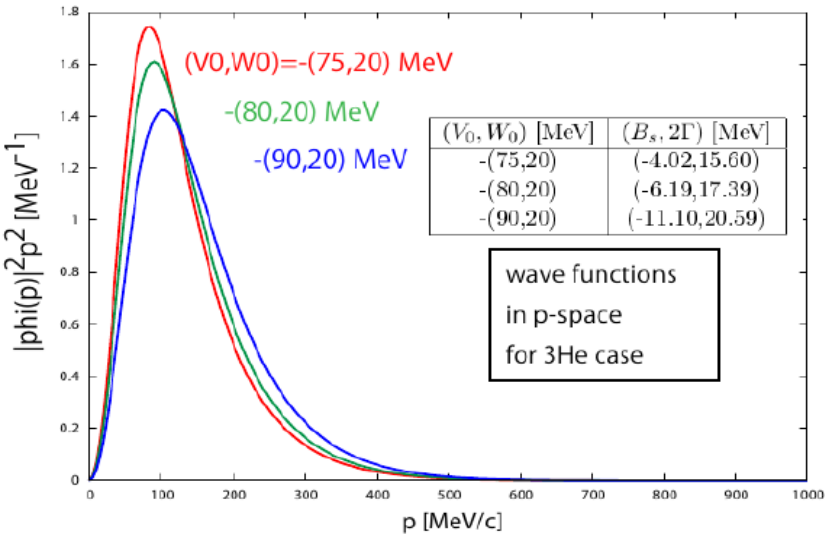
- **Absorption of orbiting η**
  4) $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}\ 2\gamma$
  5) $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}\ 6\gamma$



Simulation of $(^3\text{He-}\eta)_{bound}$ production and decay



- **^{3}He is spectator** $|\mathbb{P}_{^3He}|^2 = m^2_{^3He}$
- **Fermi momentum distribution of the η meson in ^{3}He-η bound system**



- **bound η decays to 2γ or $3\pi^0$**

Structure of hypothetical ^{3}He-η bound state can be described as a solution of Klein-Gordon equation:

$$\left[-\vec{\nabla}^2 + \mu^2 + 2\mu U_{opt}(r)\right]\psi(\vec{r}) = E^2_{KG}\psi(\vec{r})$$

where: E_{KG} - Klein -Gordon energy, μ - ^{3}He-η reduced mass,

optical potential:

$$U_{opt}(r) = (V_0 + iW0)\frac{\rho(r)}{\rho_0}$$

where: $\rho(r)$ - density distr. for ^{3}He, ρ_0 - normal nuclear density

KG equation solved for several sets of (V_0, W_0)

$$\Downarrow$$

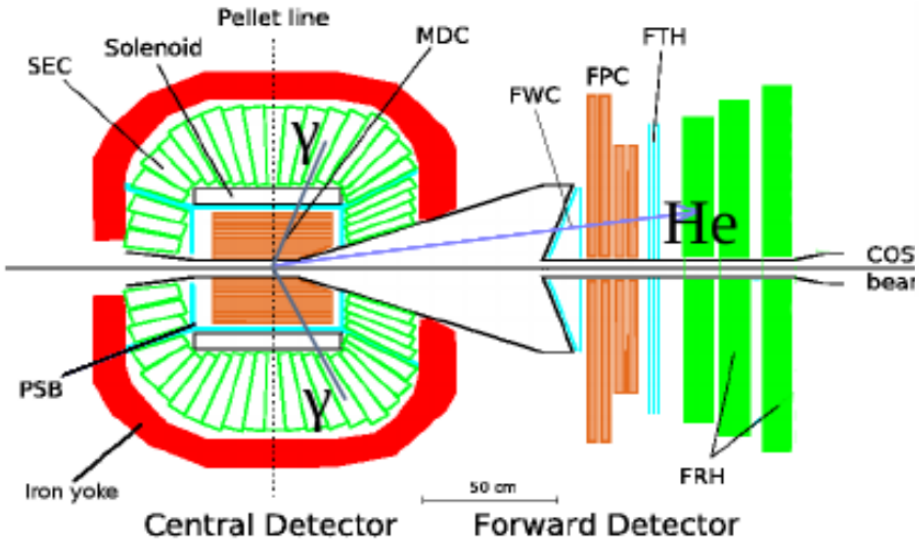
$$E_{KG},\ \psi(\vec{r})$$

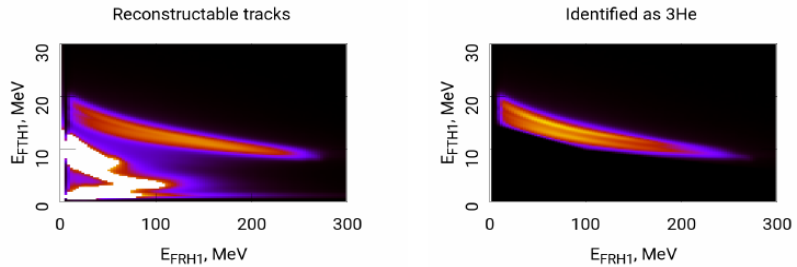
→ **S. Hirenzaki talk**

Search for $(^3\text{He-}\eta)_{bound}$ | Selection criteria

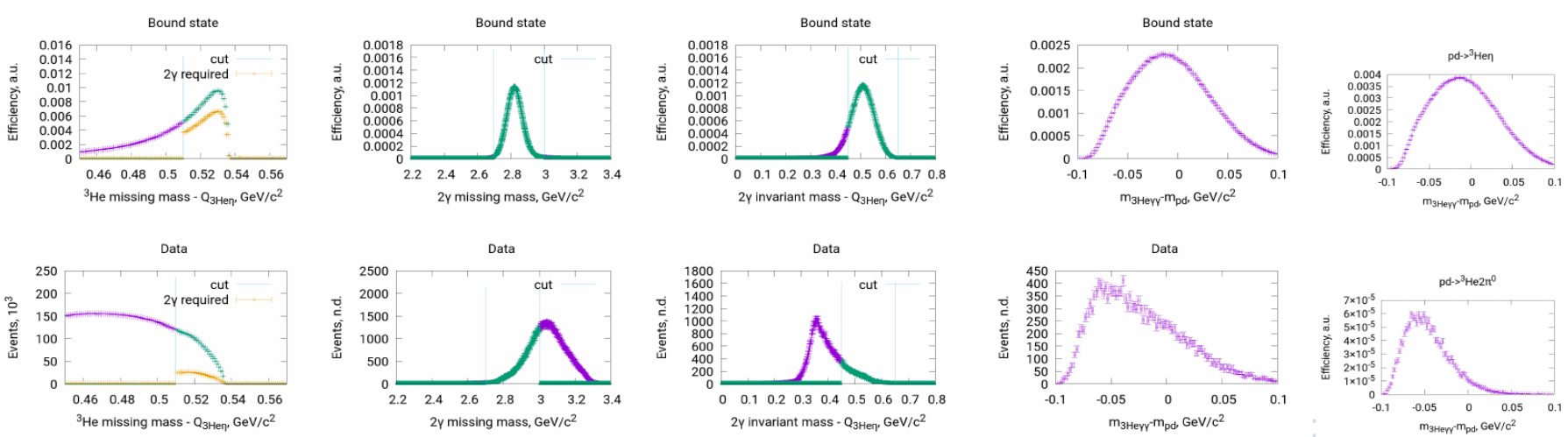
$$pd \rightarrow (^3He\eta)_{bound} \rightarrow ^3He2\gamma$$

Require ^3He track in Forward Detector



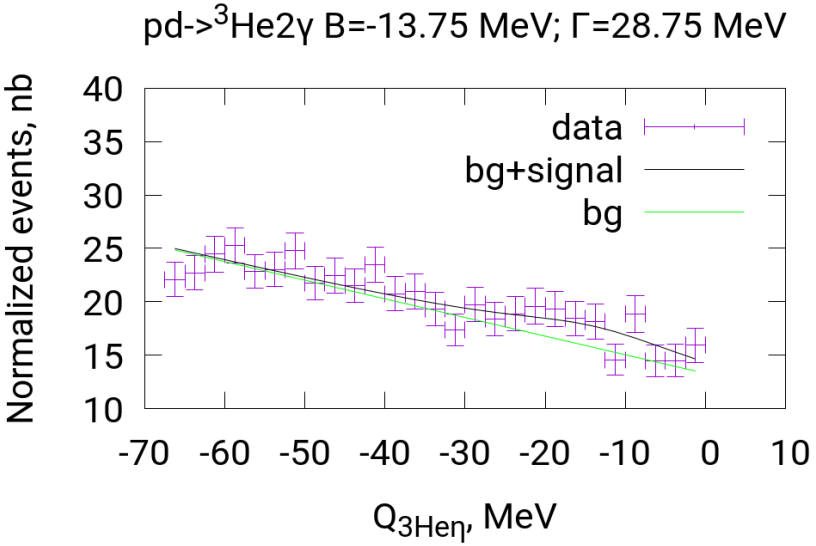


and two γ tracks in Central Detector

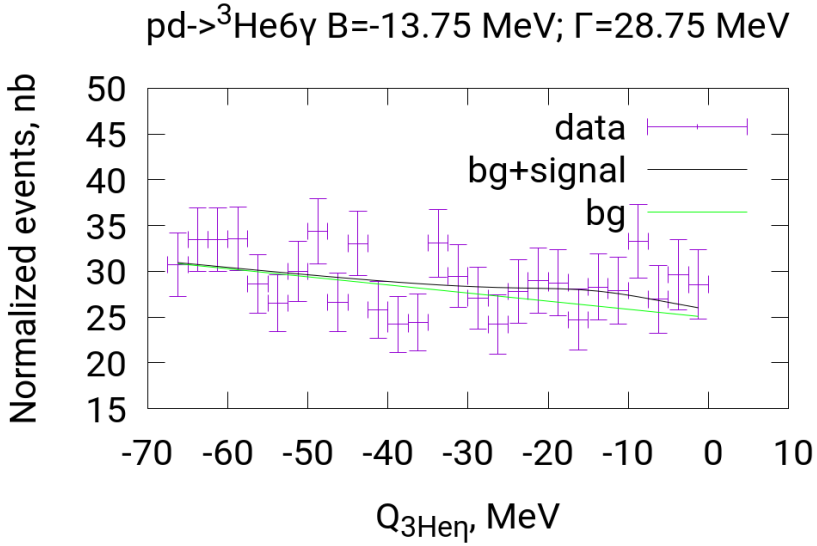


Determination of the upper limit of the total cross section for $pd \to ({}^3\text{He-}\eta)_{bound} \to {}^3\text{He}2\gamma(6\gamma)$ processes at CL=90%

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



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



simultaneous fit with $P_{\eta decay}\frac{A\cdot\Gamma^2/4}{(Q-B_s)^2+\Gamma^2/4} + BQ + C$

Breit-Wigner (signal) + pol2 (background)

where $P_{\eta decay}$ are branching ratios for η decays:
$P_{\eta\to 2\gamma}$=0.3941, $P_{\eta\to 3\pi^0}$=0.3268

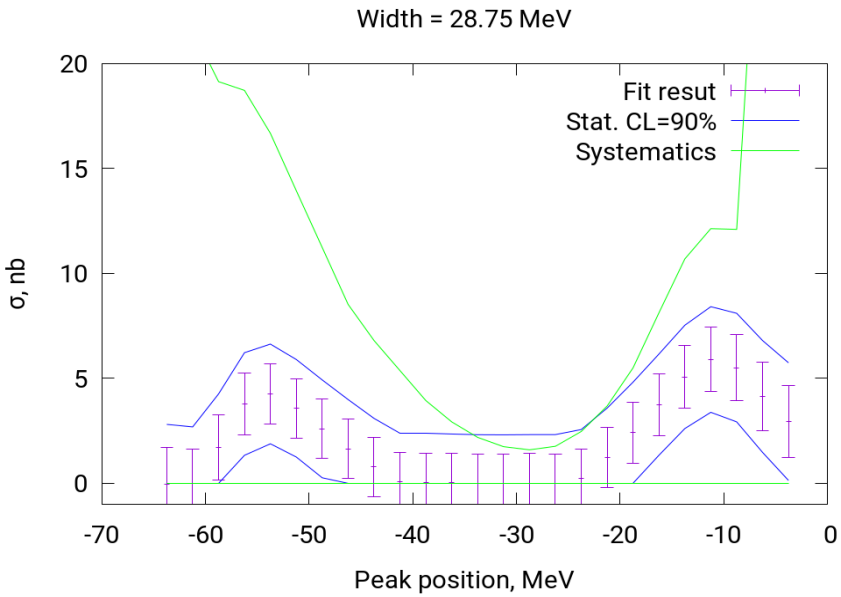
B_s,Γ - fixed parameters | A, B, C - free parameters || $\sigma^{upp}_{CL=90\%} = A + k\cdot\sigma_A$, k=1.64 (for CL=90%)

Determination of the upper limit of the total cross section for $pd \to ({}^3\text{He-}\eta)_{bound} \to {}^3\text{He}2\gamma(6\gamma)$ process at CL=90%

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

$pd \to ({}^3\text{He-}\eta)_{bound} \to {}^3\text{He}2\gamma(6\gamma)$

$\Downarrow$



PRELIMINARY

slight indication of the signal from the bound state for $\Gamma > 20$ MeV and $B_s \in (015)$ MeV

$\Downarrow$

However, the observed indication is within the range of the systematic error

$\Downarrow$

we cannot make a definite conclusion here on possible bound state formation

RESULT:

$\sigma_{pd \to ({}^3He-\eta)_{bound} \to {}^3He2\gamma(6\gamma)} < 15\ nb$

Previous result:
COSY-11

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

J. Smyrski et al., Nucl. Phys. A 790 (2007) 438

More details in: O. Rundel, PhD Thesis (2018), arxiv:1905.04544

Summary of the search for η-mesic Helium at WASA

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

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

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

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

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

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

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

- **2014**: $pd \to {}^3\text{He}2\gamma$ and $pd \to {}^3\text{He}6\gamma$ reactions

$$\sigma_{dp\to(^3He-\eta)_{bound}\to{}^3He2\gamma(6\gamma)} < 15\ nb$$

PRELIMINARY

- **2014**: $pd \to ppp\pi^-(ppn\pi^0, dp\pi^0)$ reactions

A. Khreptak,
Analysis in progress

Poster session (Tuesday)

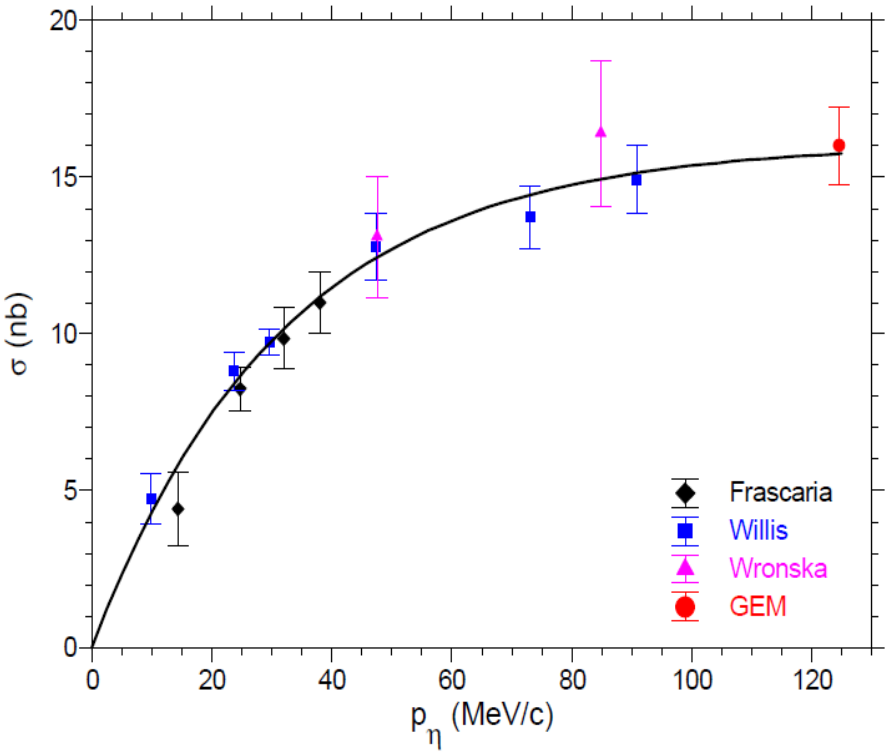
Summary and Conclusions

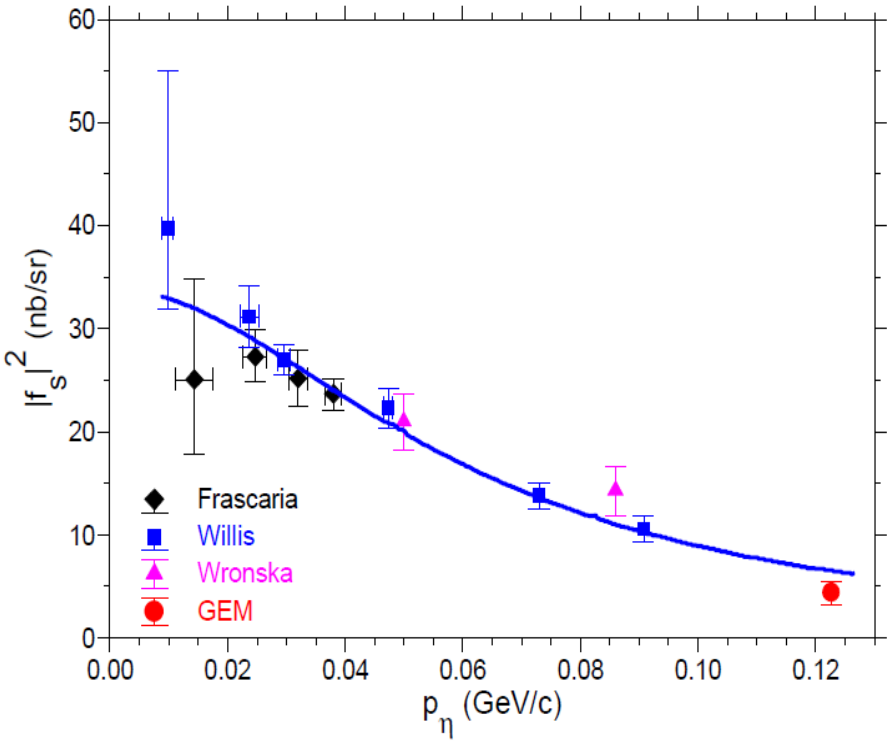
- Search for η-mesic helium was carried out using the ramped beam technique.
- No bound state signal visible in 2008 data (upper limit of the total cross section for the bound state production determined)
- 2010 measurement doesn't show a narrow signal of η-mesic nuclei in $dd \rightarrow {}^3\mathrm{He}n\pi^0$ and $dd \rightarrow {}^3\mathrm{He}p\pi^-$ channels
- 2014 measurement doesn't show a narrow signal of η-mesic nuclei in $pd \rightarrow {}^3\mathrm{He}2\gamma$ and $pd \rightarrow {}^3\mathrm{He}6\gamma$ channels
- 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**!
- The upper limits for $pd \rightarrow {}^3\mathrm{He}2\gamma(6\gamma)$ reactions $<$ **15 nb**!
- Analysis in progress for $pd \rightarrow ppp\pi^-(ppn\pi^0, dp\pi^0)$ channels

Thank you for attention

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

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





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)

Status of the search for η-mesic Helium at WASA

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

- **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)

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

- **2014**:

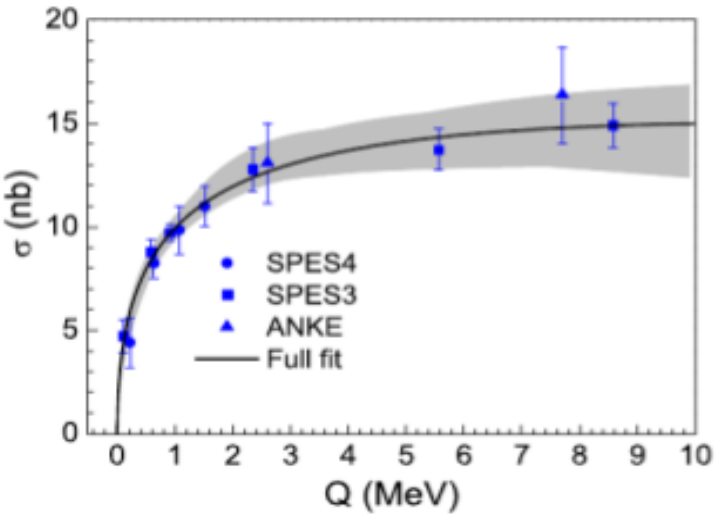
  $pd \rightarrow {}^3\text{He}2\gamma({}^3\text{He}6\gamma)$ reactions (O. Rundel)

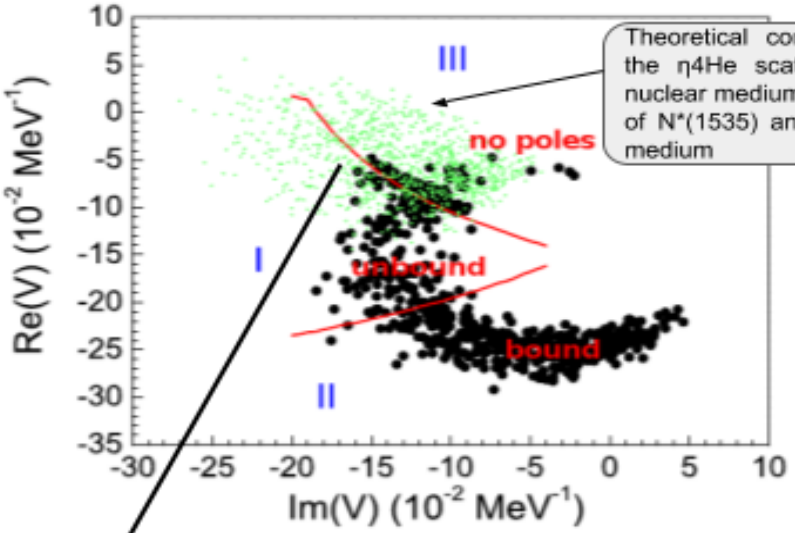
  $pd \rightarrow ppp\pi^-(ppn\pi^0, dp\pi^0)$ reactions (A. Khreptak)

$\Downarrow$

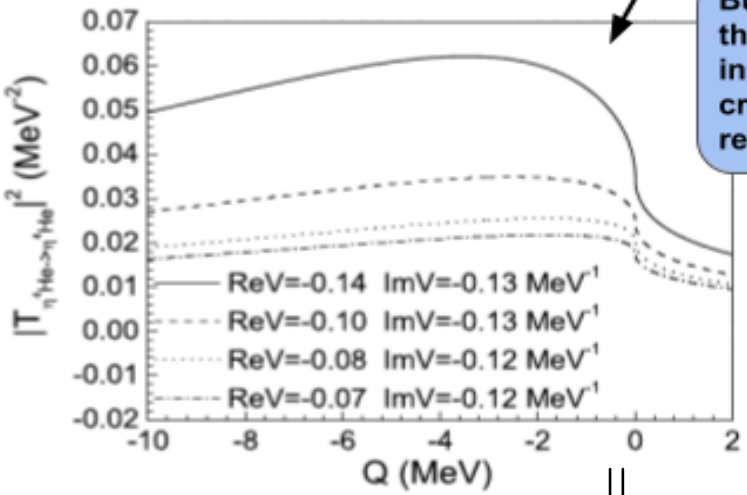
Poster session (Tuesday):
Search for the η-mesic Helium in $pd \rightarrow pd\pi^0$ Reaction with WASA-at-COSY

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





Theoretical constraints: model for the η4He scattering amplitude in nuclear medium based on excitation of N*(1535) and its modification in medium



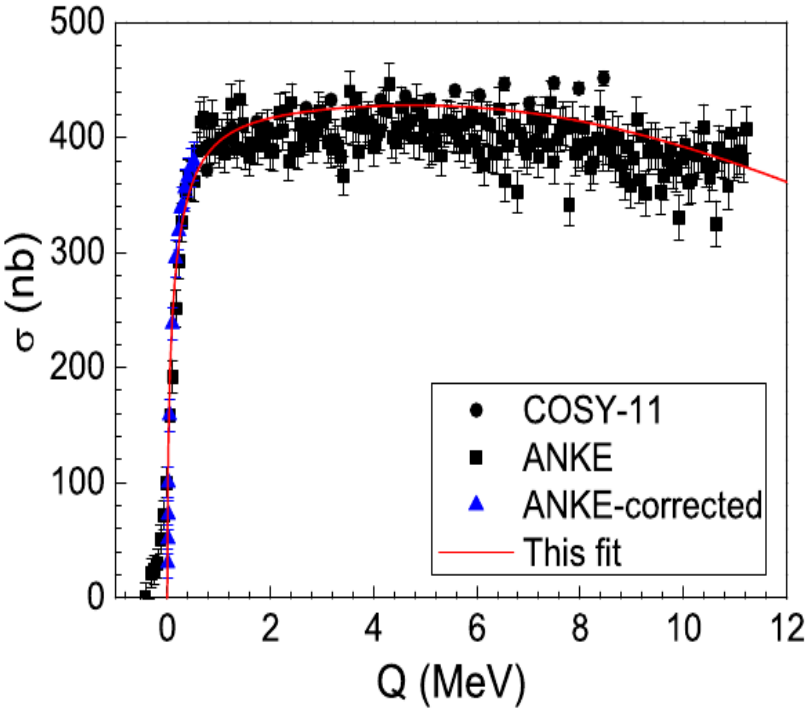
Bump structure below threshold related to the fast increase of the dd->4Heη cross section close to the reaction threshold

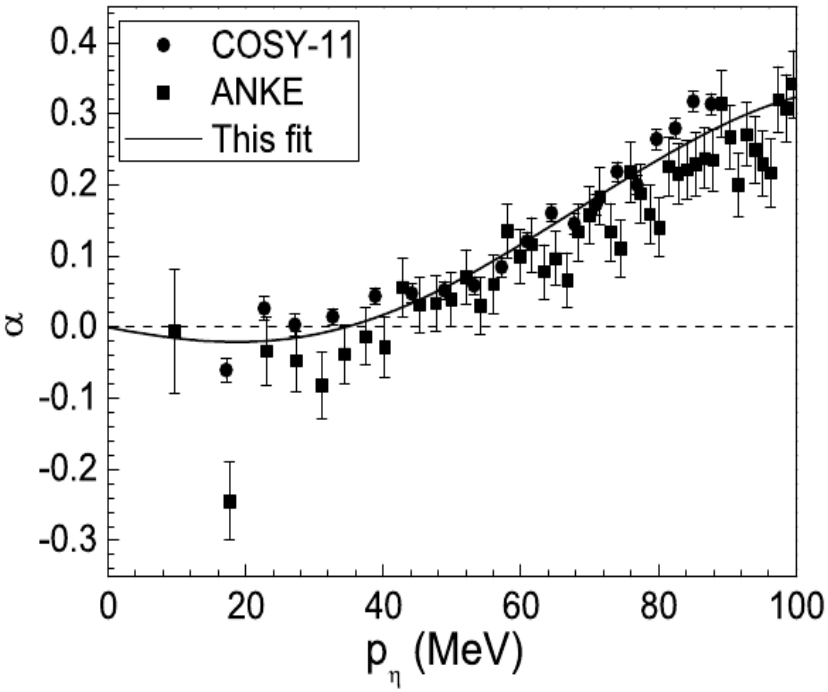
⇓

J.-J. Xie et al., Eur. Phys. J. A55 no.1, 6 (2019)

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

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



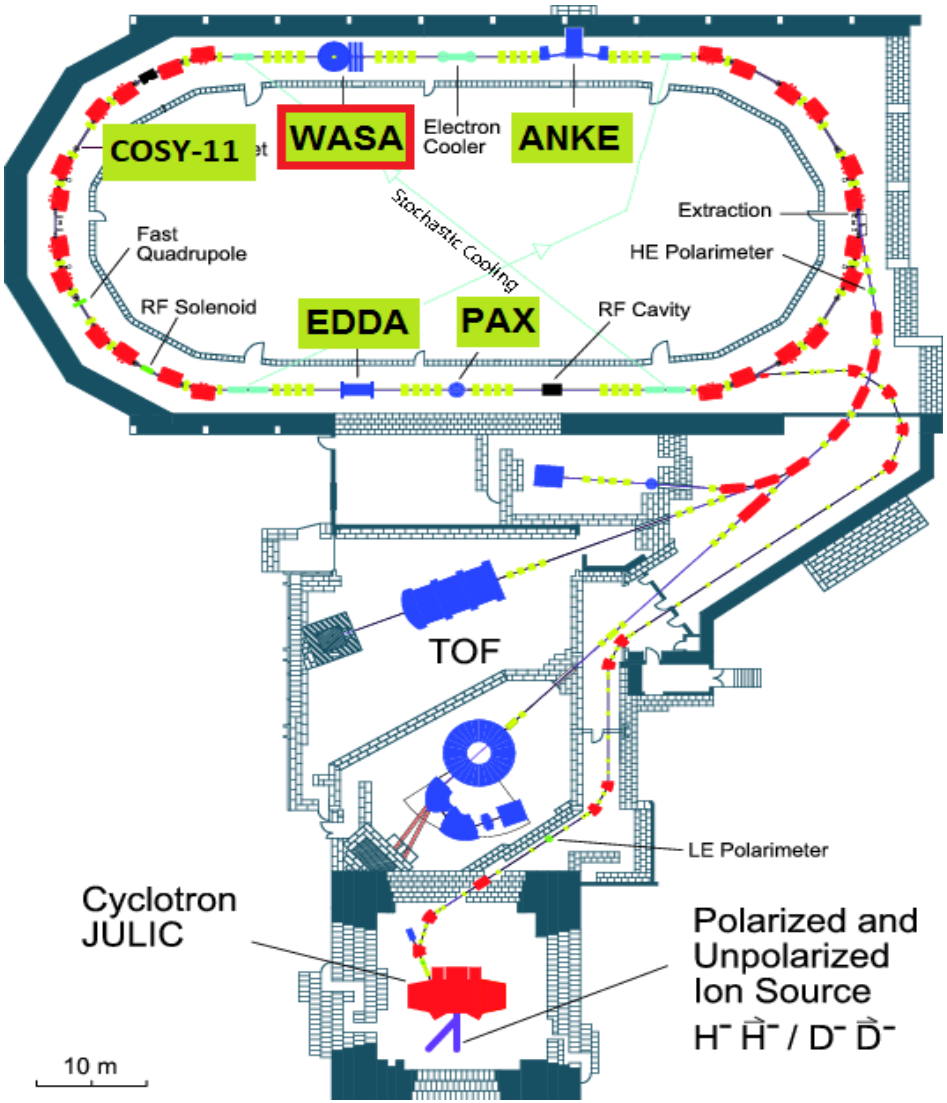


⇓

J.-J. Xie, et al., Phys. Rev. C 95, 015202 (2017)

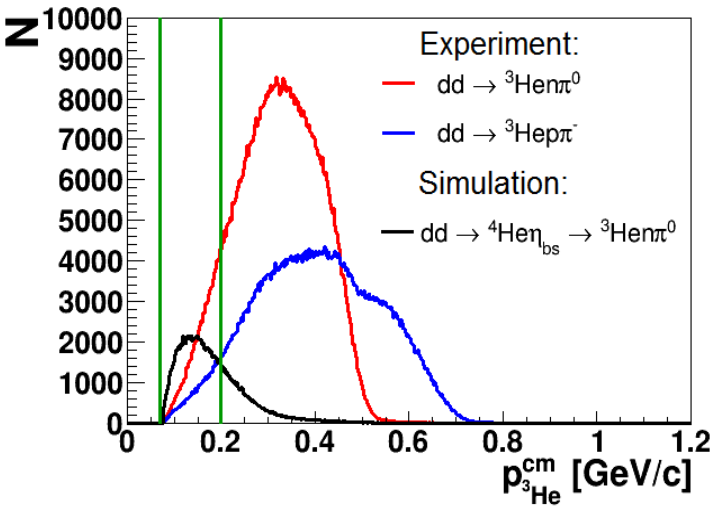
"weakly bound ^{3}He-η state with **binding energy** *of the order of* **0.3 MeV** *and a* **width** *of the order of* **3 MeV***", $a_{\eta 3He} = [(2.23 \pm 1.29) - i(4.89 \pm 0.57)]$ fm*

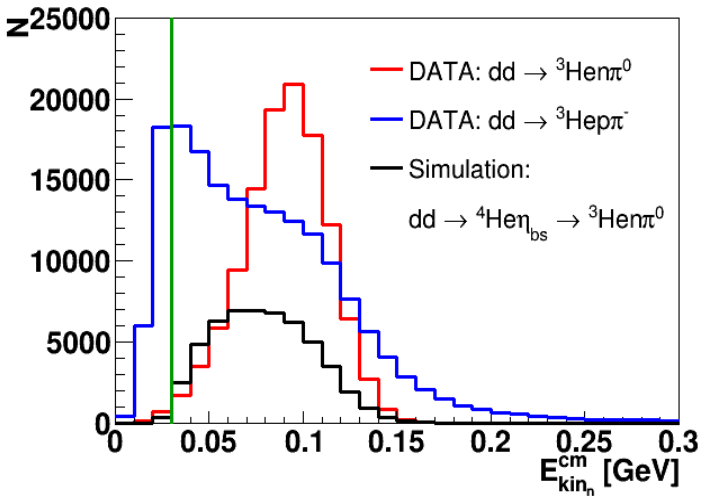
COoler SYnchrotron COSY

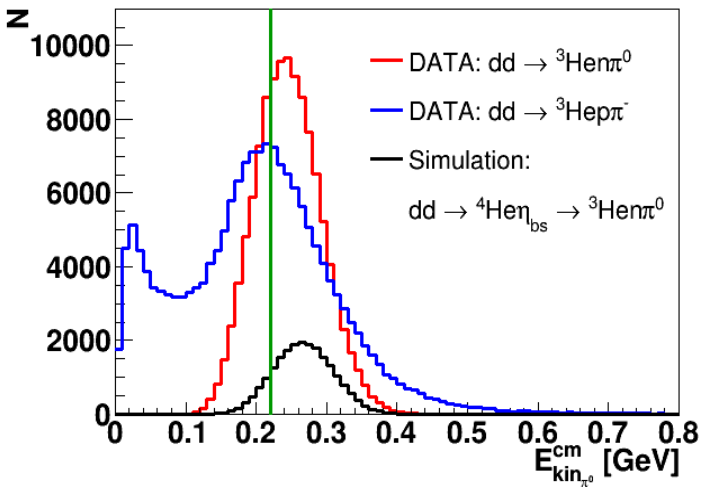


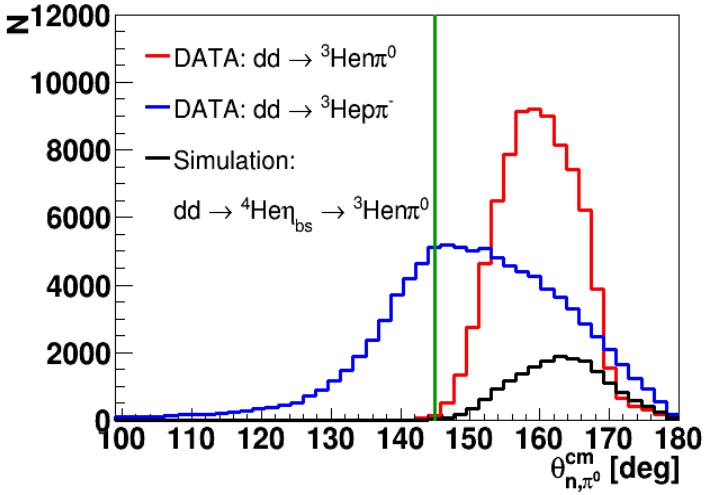
- 184 m circumference cooler synchrotron
- Polarized and unpolarized proton and deuteron beam
- Momentum range 0.3 - 3.7 GeV/c
- Stochastic and electron cooling
- 10^{11} particles in ring - luminosities 10^{31} - 10^{32} $cm^{-2}s^{-1}$
- Ramped beam (search for η-mesic nuclei)

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









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

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

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

Cross section

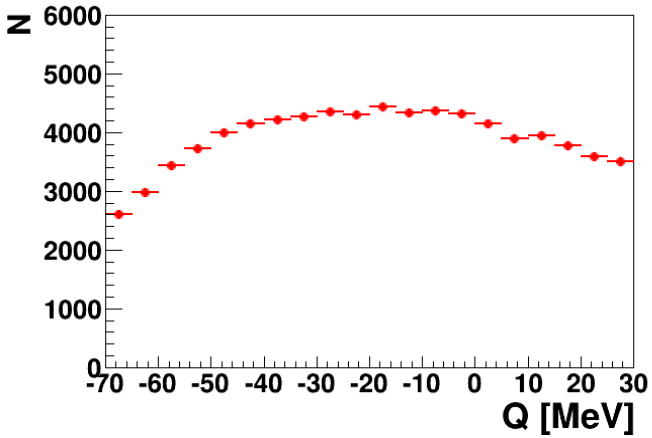
$$\sigma(Q) = \frac{N(Q)}{L(Q)\epsilon(Q)}$$

N - number of experimental events

L - integrated luminosity

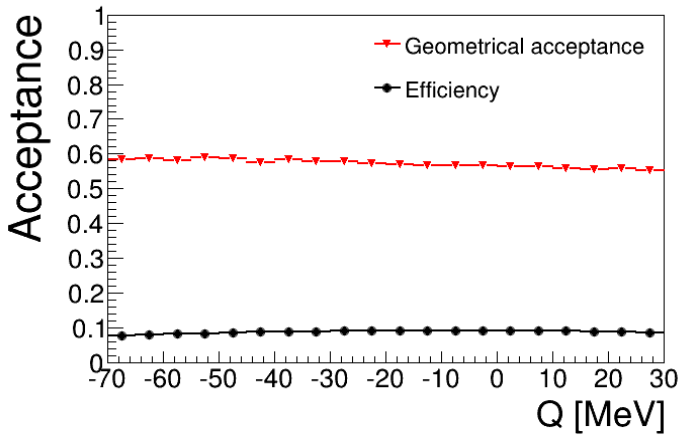
ϵ - full detection efficiency

Excitation function



Efficiency

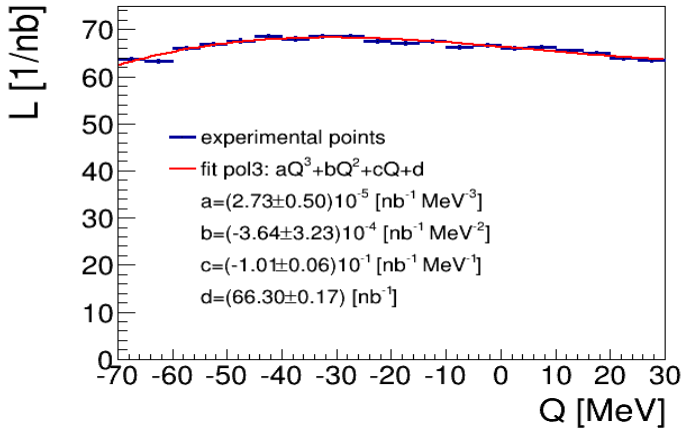
$dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}n\pi^0$



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 $dd \rightarrow {}^3\mathrm{He}p\pi^-$ reaction

Cross section

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

N - number of experimental events

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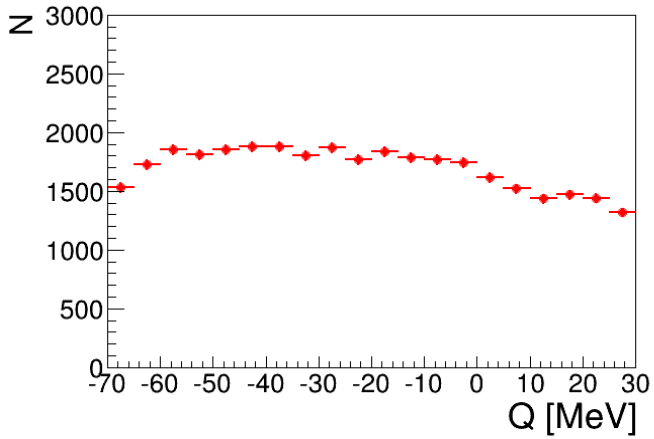
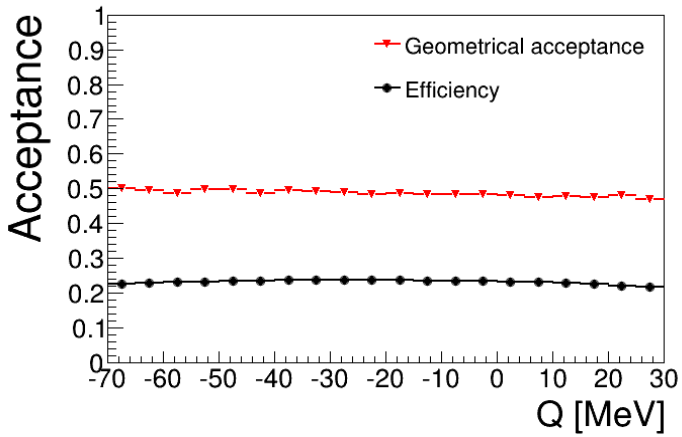
Excitation function



Efficiency

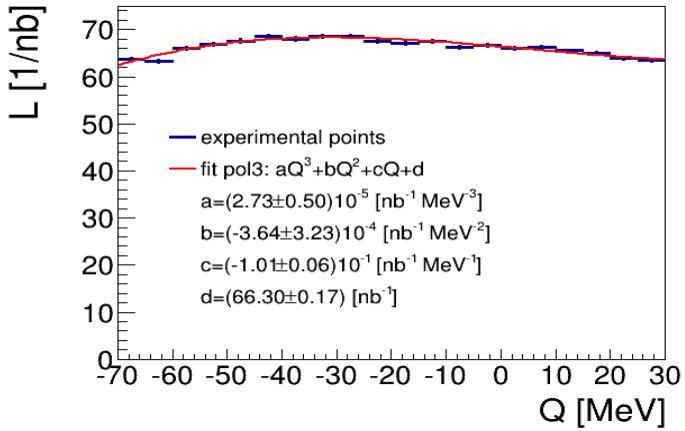
$dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}n\pi^0$



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

Integrated luminosity

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

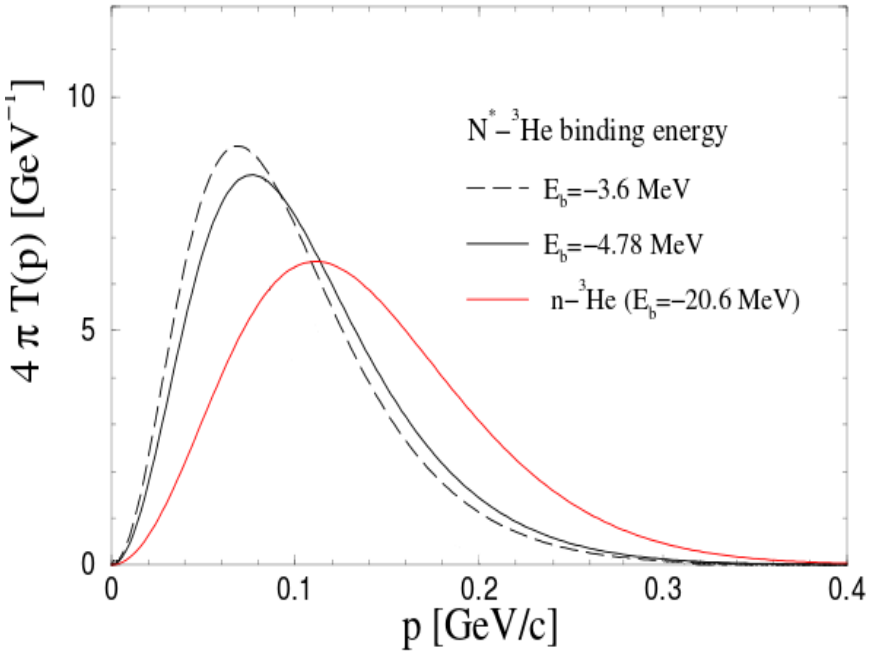


$dd \rightarrow ppn_{sp}n_{sp}$: $\mathrm{L}=(1329 \pm 2_{stat} \pm 108_{syst} \pm 64_{norm})nb^{-1}$

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

Systematics

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



N^*-^3He momentum distribution determined by prof. Neelima G. Kelkar

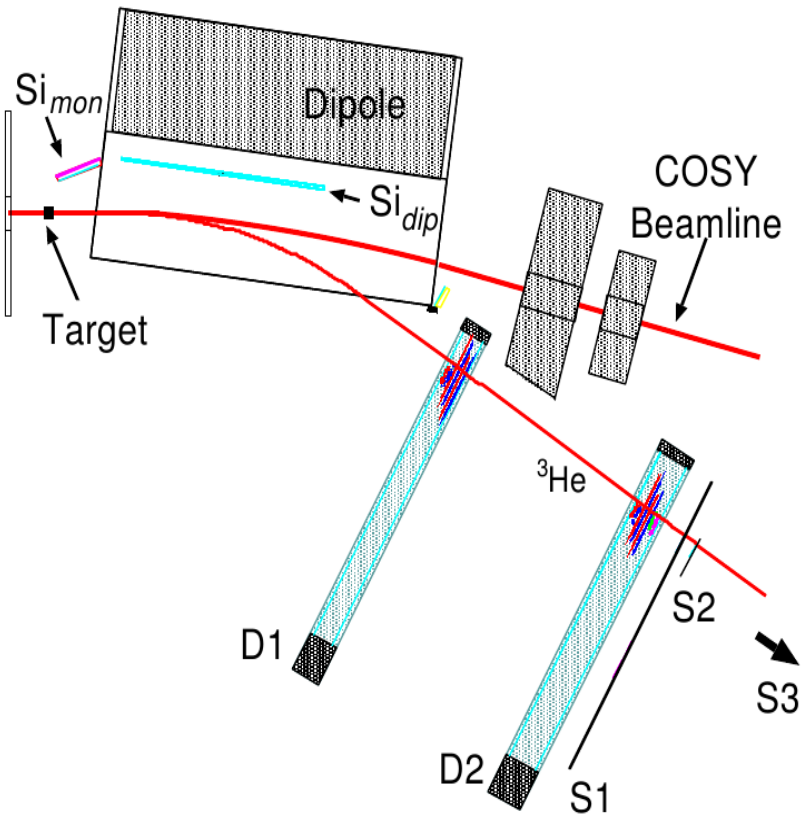
The elementary $NN^* \rightarrow NN^*$ interaction was constructed within a π plus η meson exchange model and the N^* -nucleus potential was then obtained by folding the elementary NN^* interaction with a nuclear density. A couple of possible bound states of the N^* - 3He system, depending on the choice of the πNN^* and ηNN^* coupling constants were predicted.
Details:

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.

Search for $(^3\text{He-}\eta)_{bound}$ with COSY-11

Exp. 142, FZ Jülich, Germany, 2005

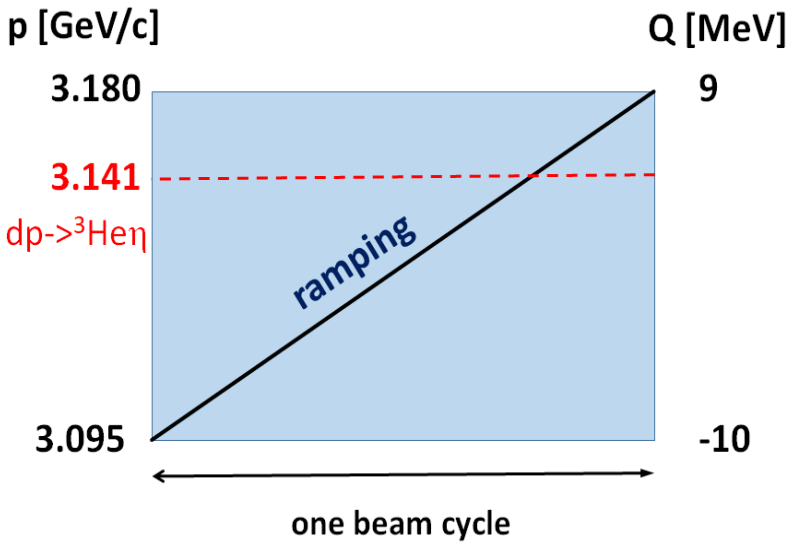
P. Moskal, W. Krzemien, J. Smyrski,
COSY proposal No. 142 (2004)



$dp \to {}^3\text{He}\pi^0 \mid dp \to ppp\pi^-$

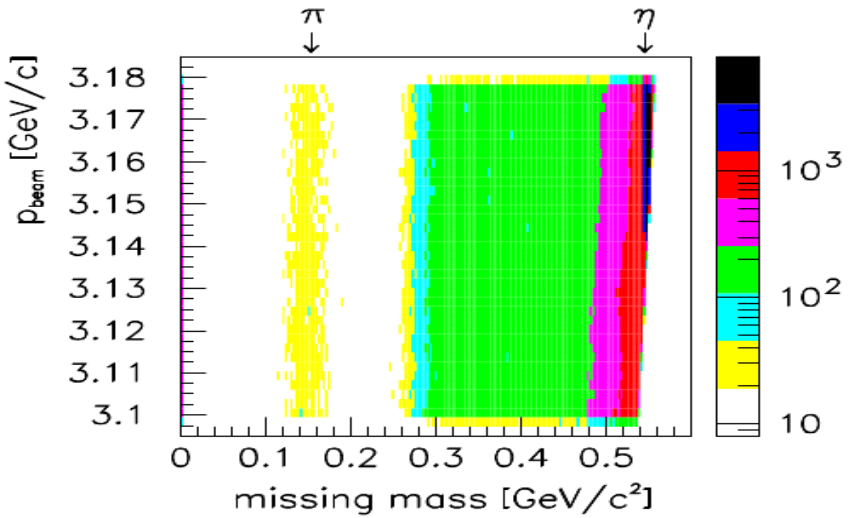
- **Measurement**
  -with the deuteron beam momentum varied continuously within each cycle from **3.095 - 3.180 GeV/c** crossing $^3\text{He}\eta$ kinematic threshold at $p_{beam} = 3.141$ GeV/c

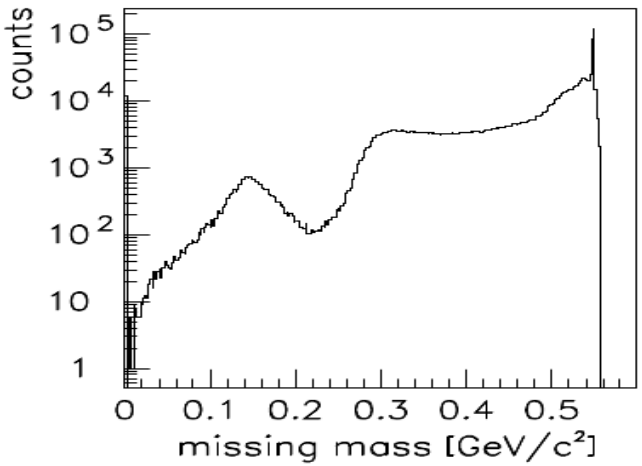
  -with the proton cluster target



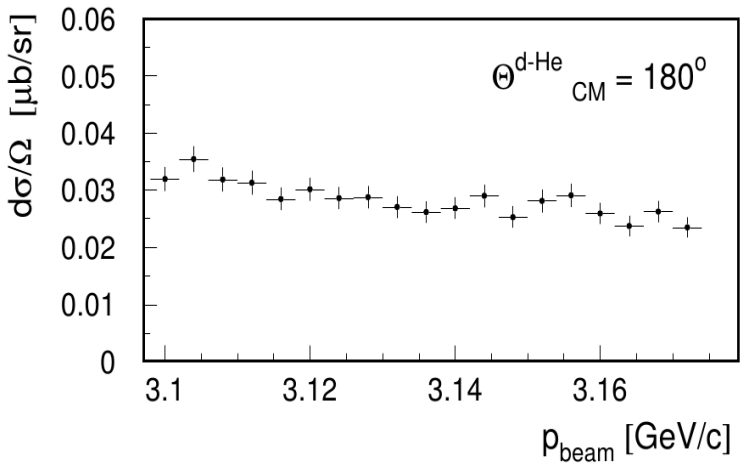
Search for $(^3\text{He-}\eta)_{bound}$ with COSY-11

$dp \rightarrow {}^3\mathbf{He}\pi^0$





- Luminosity determined using dp elastic scattering
- Excitation function

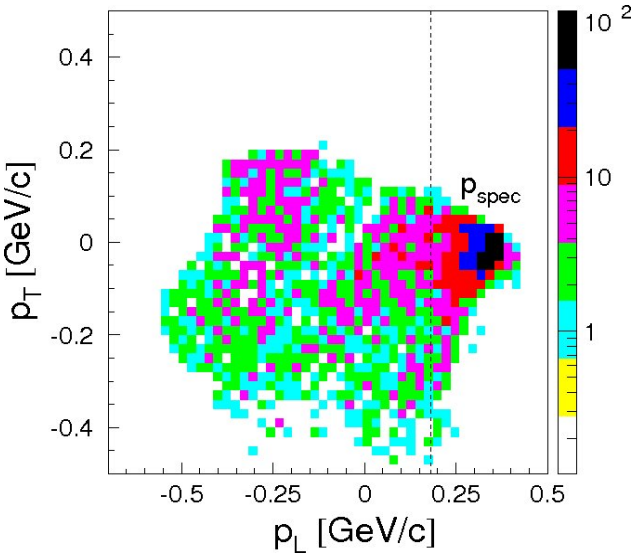


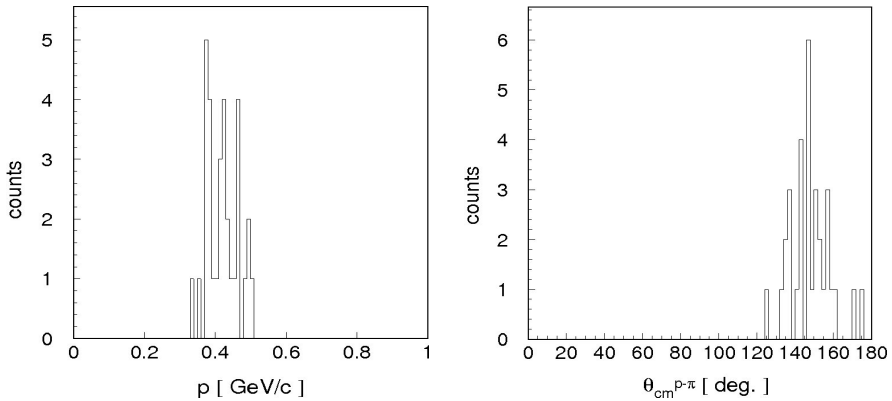
J. Smyrski et al., Nucl. Phys. A790, 438 (2007)

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

Search for $(^3\text{He-}\eta)_{bound}$ with COSY-11

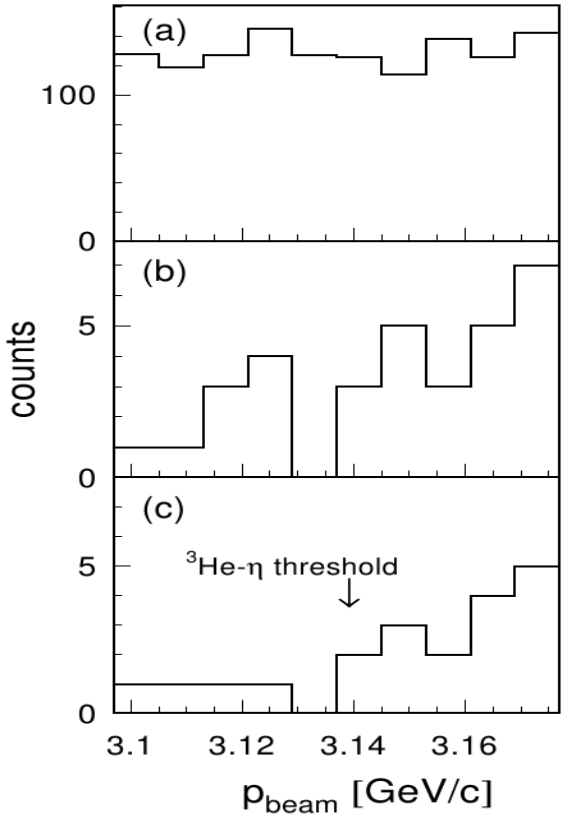
$dp \rightarrow ppp\pi^-$





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

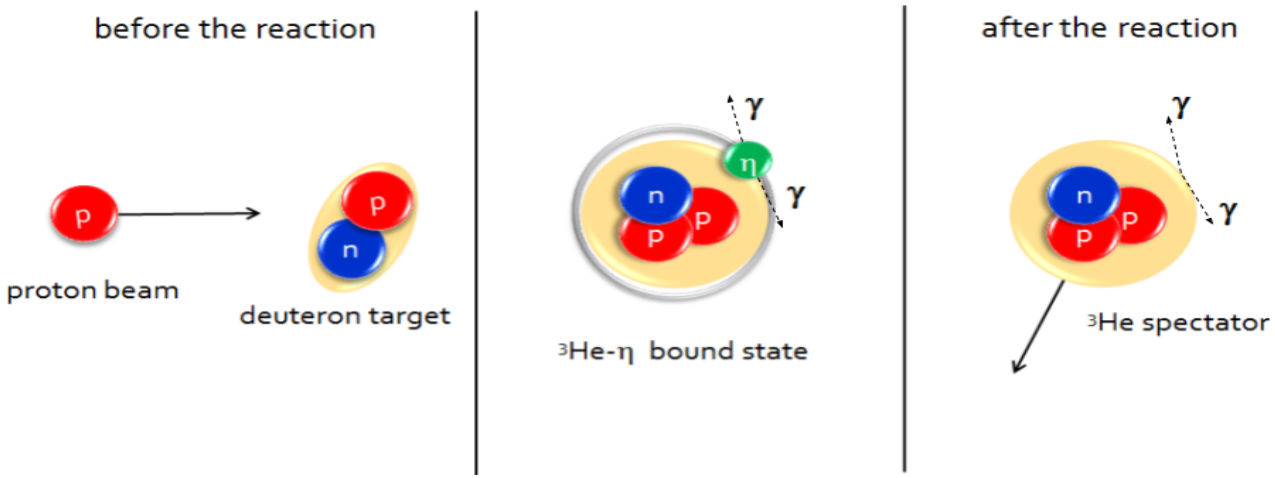
Excitation function

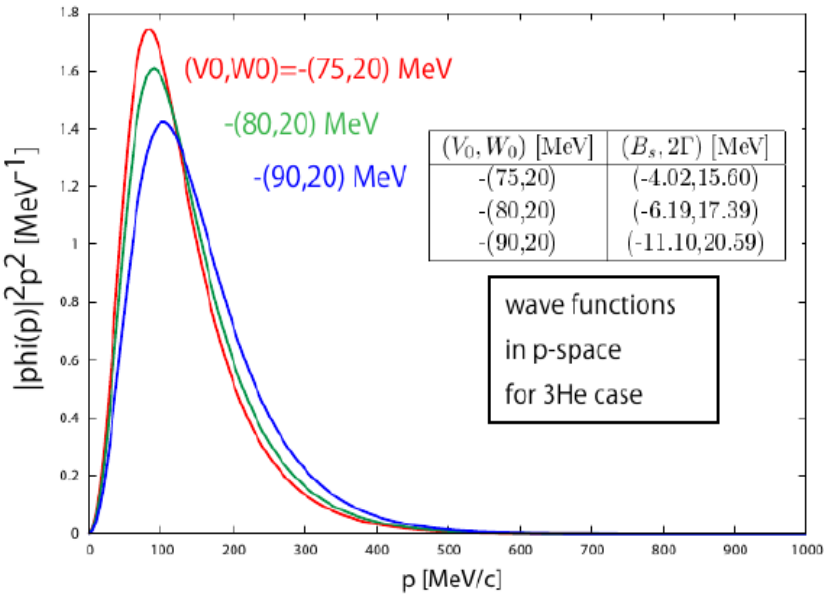


P. Moskal, J. Smyrski, Acta Phys. Polon. B41, 2281 (2010)

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

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





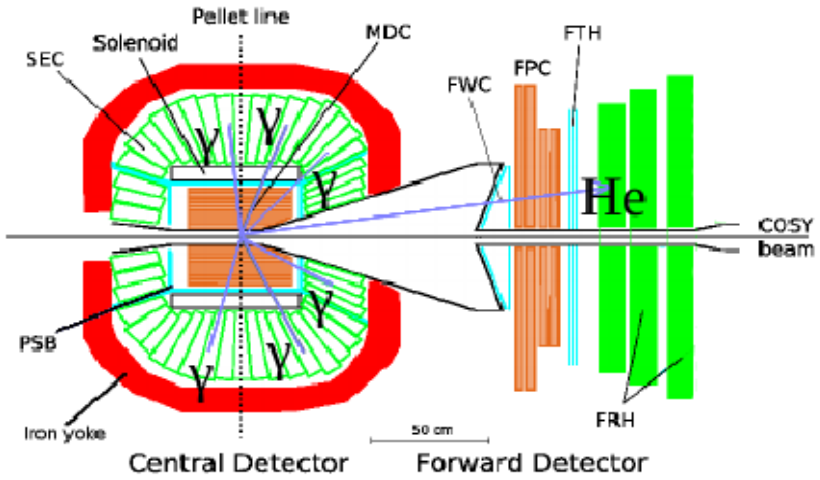
(V_0, W_0) [MeV]	$(B_s, 2\Gamma)$ [MeV]
-(75,20)	(-4.02,15.60)
-(80,20)	(-6.19,17.39)
-(90,20)	(-11.10,20.59)

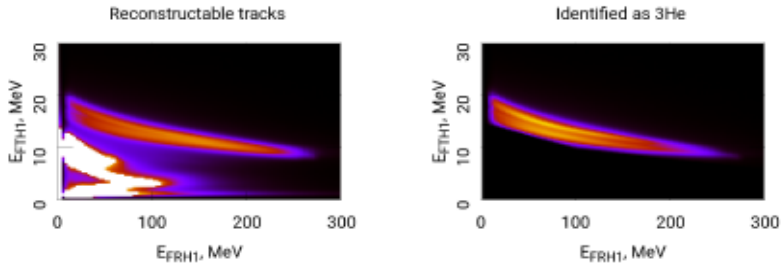
S. Hirenzaki, H. Nagahiro, Private communication (2016)

- ${}^3\text{He}$ spectator
- $P_{^3He} : p_{^3He} = \sqrt{m^2_{^3He} + p^2_{fermi}}$, distributed isotropically
- $P_{\eta_{bound}} = P_p + P_d - P_{^3He} \Rightarrow m_{\eta_{bound}} = |P_{\eta_{bound}}|$

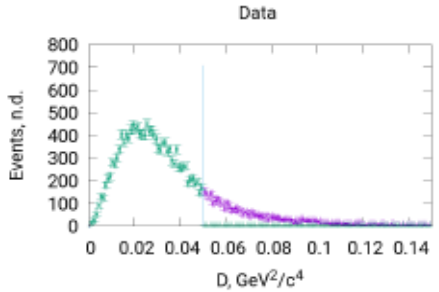
Search for $(^3\text{He-}\eta)_{bound}$ | Selection criteria

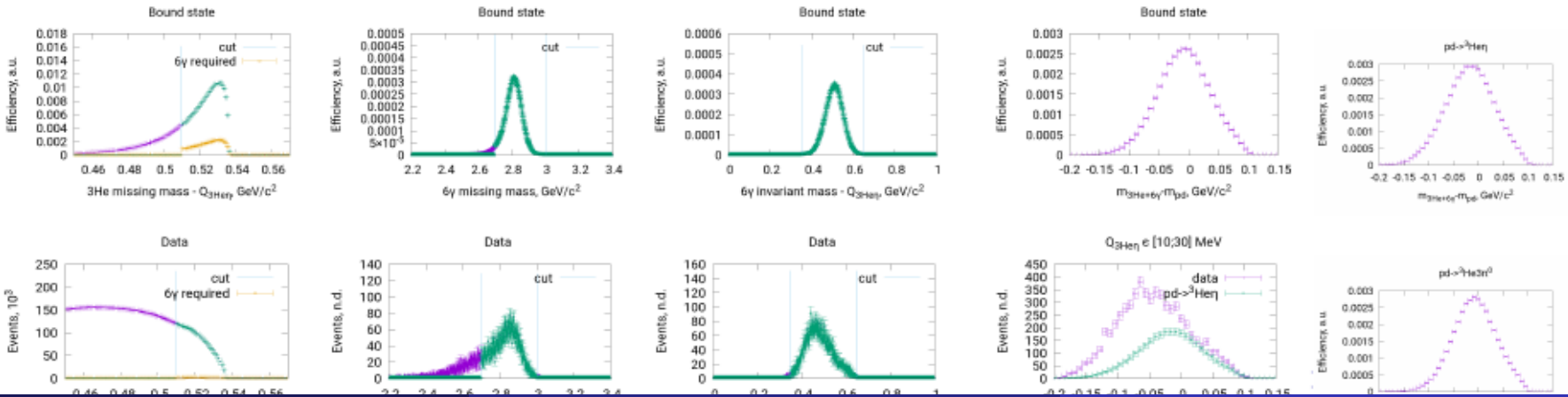
$$pd \rightarrow (^3He\eta)_{bound} \rightarrow {}^3He3\pi^0 \rightarrow {}^3He6\gamma$$



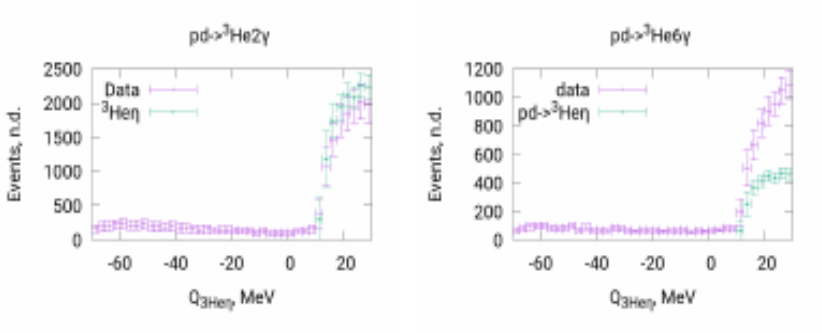


$$D = \sum_{i=1}^{3} (m_{\gamma_{(2i-1)}\gamma_{2i}} - m_{\pi^0})^2$$





Events count

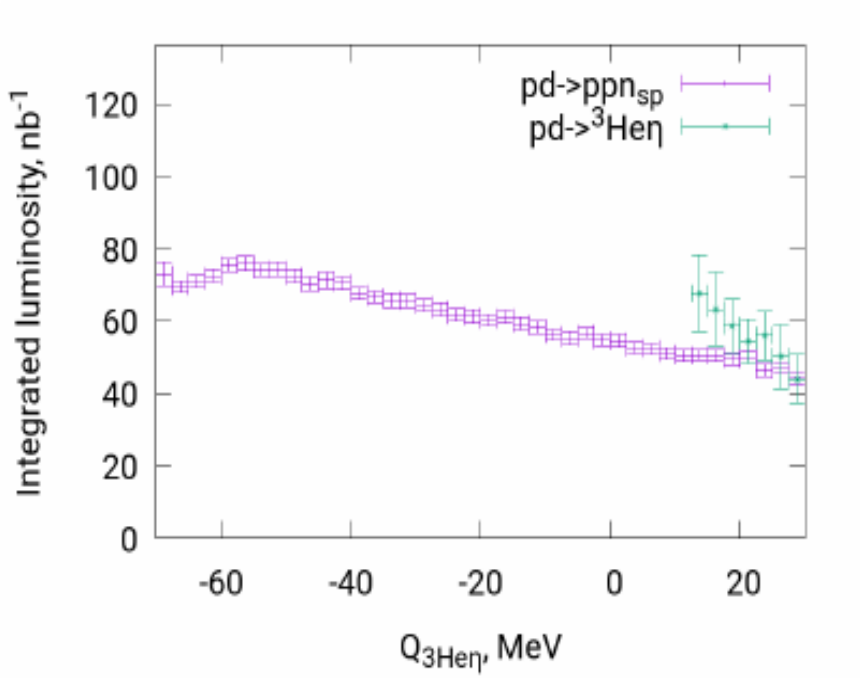


$$\sigma(Q_{^3He\eta}) = \frac{N(Q_{^3He\eta})}{L(Q_{^3He\eta})\epsilon(Q_{^3He\eta})}$$

$N(Q_{^3He\eta})$ - events count

$L(Q_{^3He\eta})$ - integrated luminosity

$\epsilon(Q_{^3He\eta})$ - registration efficiency



Normalized